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Instrumentation and Energy-Scale Calibration for Precise Neutrino Oscillation Measurements with JUNO and DUNE

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Instrumentation and Energy-Scale Calibration for Precise Neutrino Oscillation  
Measurements with JUNO and DUNE

DISSERTATION

submitted in partial satisfaction of the requirements  
for the degree of

DOCTOR OF PHILOSOPHY

in Physics

by

Roberto Carlos Mandujano Bejarano

Dissertation Committee:  
Professor Juan Pedro Ochoa-Ricoux, Chair  
Professor Henry Sobel  
Professor Jianming Bian





# DEDICATION

To my wife Brianna, who followed me into this journey.

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”(...) el lenguaje de los locos mañana será el de los cuerdos.”

Luis Alberto Spinetta

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|-------------------------------------------------------------------------------------------------------------|-------------|
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| <b>Multi-calorimetry in light-based neutrino detectors</b><br>Journal of High-Energy Physics                | <b>2024</b> |
| <b>Initial performance results of the JUNO detector</b><br>Chinese Physics C                                | <b>2026</b> |
| <b>Measurement of reactor neutrino oscillation with the first JUNO data</b><br>Nature                       | <b>2026</b> |

## SOFTWARE

|                                                                                                                                     |                                                                                 |
|-------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| <b>GaRF</b><br><i>Python algorithm that fits gamma-ray charge or energy spectra in calorimeters interactively, or in batches.</i>   | <a href="https://github.com/robx97/GaRF">https://github.com/robx97/GaRF</a>     |
| <b>GEPRiS</b><br><i>Python framework that models and fits gamma, electron and positron energy non-linearities in scintillators.</i> | <a href="https://github.com/robx97/GEPRiS">https://github.com/robx97/GEPRiS</a> |



# ABSTRACT OF THE DISSERTATION

Instrumentation and Energy-Scale Calibration for Precise Neutrino Oscillation  
Measurements with JUNO and DUNE

By

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Doctor of Philosophy in Physics

University of California, Irvine, 2026

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Neutrino oscillations represent one of the most active fields of research in particle physics, yet key features of its three-flavor model remain undetermined. This dissertation presents instrumentation and calibration work carried out on two next-generation neutrino oscillation experiments, the Deep Underground Neutrino Experiment (DUNE) and the Jiangmen Underground Neutrino Observatory (JUNO), each pursuing complementary approaches to precision oscillation measurements.

On DUNE, this work addresses the readout electronics of the liquid argon Near Detector (ND-LAr). The integration of the DUNE Timing System endpoint into the PACMAN controller firmware is described, along with the design and validation of an optical timing testbench used to confirm nanosecond-level clock synchronization. Building on this instrumentation, a charge-scale calibration analysis is presented using cosmic-ray minimally-ionizing particles in three generations of pixelated LArTPC prototypes, extracting the most-probable  $dQ/dx$ . A dedicated simulation study further identifies and quantifies a systematic bias in the extracted electron lifetime introduced by the pixelated charge readout front-end and charge-diffusion effects, and proposes a path toward its mitigation.

On JUNO, this work develops and applies a novel dual-calorimetry approach to the cali-

bration of the experiment’s Large PMTs, exploiting the photon-counting response of the 25,600 Small PMTs to diagnose LPMT charge-level instrumental non-linearity using deployed radioactive  $\gamma$  sources (DCC-Gamma). This dissertation then presents the GEPRiS (Gamma-Electron Positron Response in Scintillator) framework, which combines  $\gamma$ -source calibration data with cosmogenic  $\beta^\pm$ -decay spectra selected from JUNO physics data to build a first-principles, Geant4-informed model of the liquid scintillator’s energy response from a global fit to multiple datasets. The resulting detector response model is propagated into an oscillation fit of JUNO’s early physics data, yielding measurements of  $\sin^2 \theta_{12}$ ,  $\Delta m_{21}^2$ , and  $\Delta m_{31}^2$  that are compared against JUNO’s recently published results.

# Chapter 1

## Neutrino Oscillations

### 1.1 Experimental Background

The neutrino was first postulated by Wolfgang Pauli as patchwork to cover an apparent lack of energy conservation in beta decays. The observation of a lower spectrum of energies rather than a mono-energetic  $\beta$  suggested that a neutral, invisible particle was being produced that would take away a small fraction of the initial energy [109]. In 1956, Reines and Cowan confirmed the existence of this particle by detecting what we now understand as electron antineutrinos produced at a nuclear reactor in the Savannah River plant. They constructed a detector using alternating layers of liquid scintillator and CdCl<sub>2</sub>-doped water. The experiment exploited the inverse beta decay (IBD) process, in which antineutrinos interact with hydrogen nuclei in the CdCl<sub>2</sub>-doped water target layers as:

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{1.1}$$

In the Reines and Cowan detector, the "prompt" positron signal comes from the two  $\gamma$ s that

result from its annihilation. The neutron travels for roughly  $5\mu s$  before it is captured by a Cd nucleus and creates a 9 MeV "delayed" signal. This time coincidence allowed them to measure a rate of  $2.88 \pm 0.22$  IBD candidates per hour when the nuclear reactor was running, and approximately a third of the rate otherwise. [55].

That same year, Lee and Yang [91] theorized that parity must be violated in weak interactions, which was experimentally observed by Wu using a super-cooled  $^{60}\text{Co}$  source. Later, by analyzing gamma rays from electron captures by  $^{125}\text{Eu}$ , Goldhaber, Grodzins, and Sunyar confirmed that neutrinos are left-handed particles and antineutrinos are right-handed [76].

In 1962, Lederman, Schwartz, and Steinberger [59] used the Alternating Gradient Synchrotron beam to accelerate protons into a 3 in thick Be target, generating a stream of pions in a decay pipe, becoming muons and neutrinos in-flight. A large steel shield at the end stopped most charged particles, but neutrinos passed undeterred, creating the world's first neutrino beam. A spark chamber of aluminum plates interleaved with gas gaps was placed behind the shield to detect the interactions produced by the neutrinos passing through. The idea was that, if there were only one type of neutrino, both muons and electrons should be detected in their interactions at the spark chamber. Nevertheless, they observed only muons, which confirmed the muon neutrino to be distinct from the electron neutrino.

By 1975, the tau lepton had been discovered [112], and lepton flavor conservation and the doublet structure in electroweak theory required a third neutrino. However, the high mass and short lifetime of the tau lepton allow it to travel about 1 mm before decaying, making its detection challenging. The DONuT (Direct Observation of the Nu-Tau) collaboration at Fermilab used an emulsion target to identify four  $\nu_\tau$  events [88], growing to nine by the end of their data-taking [89].

One might then ask whether three lepton families, and thus three neutrinos, complete the story. The Large Electron-Positron Collider at CERN was a 27 km accelerator ring outfitted

with 4 detectors: L3, DELPHI, ALEPH and OPAL to track particles produced in Z boson decays. In 1989, they provided definitive evidence that there are only three active neutrinos by measuring the hadronic and leptonic contributions to the Z boson resonance peak. The remaining invisible component of the decay width was consistent with  $2.9840 \pm 0.0082$  neutrinos [30], thus closing the page on searches for light, active neutrinos.

## 1.2 Neutrinos in the Standard Model

The Standard Model of Particle Physics (SM) emerged from unified electroweak theories by Glashow [75], Salam [116], and Weinberg [123]. The model describes elementary particles and their interactions. Particles are grouped by their intrinsic spin states: fermions have half integer spins, while bosons have integer spins.

Bosons are associated to the three fundamental forces they mediate: weak ( $Z^0$ ,  $W^\pm$ ), strong (gluon), and electromagnetic ( $\gamma$ ). The remaining boson, the Higgs boson, is associated with electroweak symmetry breaking and the generation of fermion and weak-boson masses.

Fermions are the particles that constitute matter and can be further split into quarks (up, down, top, bottom, charm, strange) and leptons, the latter involving three massless neutrinos: electron, muon, and tau neutrinos, each associated with another charged lepton of the same name.

Neutrinos are peculiar in that they only participate in the weak force, or in other words, only when mediated by a W boson, called charged current (CC) interaction, or a Z boson, called a neutral current (NC) interaction. This fact explains their previously observed elusiveness, as the weak force gets its name for its considerably smaller strength compared to the rest, making the neutrino cross-section tiny.

## 1.3 Oscillations as a Beyond-Standard-Model Phenomenon

The discovery of the three expected neutrinos and their inclusion into the rigorously tested Standard Model should read as a sound victory. Nevertheless, neutrinos still exhibited properties that were not inline with the original formulation of the Standard Model. In particular, the model describes massless neutrinos, but the observation of neutrino oscillations requires massive neutrinos. These observations started as lower rates of solar neutrinos compared to theoretical expectation. This chapter will go over the experimental background and theoretical framework for oscillations.

### 1.3.1 Where did the Neutrinos Go?

According to the Solar Standard model (SSM), developed by John Bahcall [39], the Sun emits a calculable flux of electron neutrinos as a product of the nuclear fusion that occurs within stars. In order to test this hypothesis, Ray Davis devised an experiment in South Dakota's Homestake Mine in order to measure the solar neutrino rate [47]. The detector consisted of a 610 t or 100,000 gal tank of perchloroethylene  $CCl_4$  where the conversion of Cl to Ar in the reaction:



provided a direct handle on the number of neutrino interactions inside the detector by counting  $^{37}\text{Ar}$  atoms. The experiment was successful in making a measurement of the neutrino rate, curiously detecting one third of the neutrinos predicted by SSM theory. This deficit became known as the Solar Neutrino problem, and fueled questions on solar models and neutrino interactions for three decades.

The atmosphere provides another source of neutrinos against which to test our understanding

ing. High-energy cosmic protons entering our planet collide with nuclei in the atmosphere, causing a cascade of unstable particles that subsequently decay into neutrinos. These are predominantly pions, with neutrino production following:

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \mu^+ &\rightarrow e^+ + \nu_e\end{aligned}\tag{1.3}$$

Predictions indicated a 2:1 ratio of muon neutrinos to electron neutrinos from the atmosphere. Placing detectors deep underground provided improved shielding from cosmic radiation. In 1963 the CASE-WITS experiment emerged as a collaboration between Case Institute of Technology and University of Witwatersrand. It was a 20 t liquid scintillator detector placed in a gold mine in South Africa to study the zenith-angle dependence of muons. The experiment measured about 40% less neutrinos than predicted, but its large uncertainties were still consistent with expectation [56].

In the 1980s, there was high interest in detecting proton decay, a key prediction of Grand Unified Theories (GUTs). Having a large number of protons increases the sensitivity to seeing such a decay, favoring the design of large water detectors to balance size and cost. One such experiment was the Irvine-Michigan-Brookhaven (IMB) 8 kt water Cherenkov detector. Although it did not observe proton decay [77], it did observe atmospheric neutrinos as a background to their main analysis, again at a lower rate with respect to predictions [43]. Similarly to the CASE-WITS experiment, no definitive conclusion could be made from these measurements due to large uncertainties, mainly from atmospheric neutrino flux and interaction models.

Another large water Cherenkov detector was Kamiokande, with 1 kt of fiducial mass and similar goals to the IMB experiment. It also did not observe proton decay, but it also collected a sample of atmospheric muon and electron neutrino events. The muon neutrino rate was

lower than expected while the electron neutrino rate was consistent with expectation. Backed by the previous observations, these findings by IMB and Kamiokande became known as the Atmospheric Neutrino Anomaly [81].

### 1.3.2 Discovery of Oscillations

To follow up on the measurements and science program of Kamiokande, an experiment named Super-Kamiokande started data-taking in 1996. Consisting of a 50 kt tank of ultra-pure water, it was able to extract both the direction and flavor of incoming neutrinos from the topology of the rings produced by Cherenkov light inside the detector. Downward-going muon neutrino rates matched the prediction yet upward-going muon neutrinos, which travel a longer distance from their production in the atmosphere, presented a deficit [72]. These neutrinos were oscillating into tau neutrinos as they traveled the Earth, a flavor the detector cannot identify easily. This conclusively showed that muon neutrinos that traveled longer distances were disappearing, which is consistent with neutrino oscillations.

The Solar Neutrino Problem was finally put to rest by SuperKamiokande's measurement of solar neutrino rates using the CC elastic scattering interaction, as well as by the Sudbury Neutrino Observatory (SNO). Based in a mine in Canada, it consisted of 1000 t of heavy water  $D_2O$  and had the capability of detecting all three neutrino flavors through the NC channel and the electron neutrinos only with the CC channel. The measured electron neutrino rates confirmed Davis's observation of approximately one third the expected neutrino rate, but the rate from all three flavors combined matched the SSM expectation. Both rate measurements were consistent with the neutrino oscillation hypothesis [29].

The Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) began operations in 2002 in the same mine that housed Kamiokande, this time detecting neutrinos from commercial nuclear reactors at an average distance of about 180 km. While previous experiments had determined neutrinos were disappearing, KamLAND was the first to measure the char-



characteristic energy dependence expected from oscillation, observing the survival probability modulate at different energies with a given frequency [64].

These numerous observations from a variety of detectors using a variety of neutrino sources determined that neutrinos undergo flavor oscillations and consequently have mass, which requires an extension to the SM. This was one of the first direct glimpses into physics beyond the SM.

### 1.3.3 Mixing

The discovery of oscillations necessitates the introduction of flavor mixing. We describe the relationship between flavor eigenstates  $|\nu_\alpha\rangle$  ( $\alpha = e, \mu, \tau$ ), in which neutrinos interact, and mass eigenstates  $|\nu_i\rangle$  ( $i = 1, 2, 3$ ), in which they propagate and have a definite mass, via a unitary mixing matrix:

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle \quad (1.4)$$

To calculate the oscillation probability, we begin by considering the mass eigenstates  $|\nu_i\rangle$ . In their own rest frame, these states are eigenstates of the Hamiltonian  $H$ . The time evolution of a mass eigenstate is described by the time-dependent Schrödinger equation:

$$i \frac{d}{dt} |\nu_i(t)\rangle = H |\nu_i(t)\rangle = E_i |\nu_i(t)\rangle \quad (1.5)$$

whose solution for a state with a definite momentum  $p$  is a plane wave:

$$|\nu_i(t)\rangle = e^{-iE_i t} |\nu_i(0)\rangle \quad (1.6)$$

Using the relativistic energy-momentum relation  $E_i = \sqrt{p^2 + m_i^2}$ , and applying a Taylor expansion for  $m_i \ll p$  (the ultra-relativistic limit):

$$E_i \approx p + \frac{m_i^2}{2p} \approx E + \frac{m_i^2}{2E} \quad (1.7)$$

where we approximate the total energy  $E \approx p$ . For ultra-relativistic neutrinos, we can also assume  $t \approx L$  (in natural units  $c = 1$ ), where  $L$  is the distance traveled. Thus:

$$|\nu_i(L)\rangle = e^{-i\frac{m_i^2 L}{2E}} |\nu_i(0)\rangle \quad (1.8)$$

The factor  $e^{-iEL}$  is a global phase and does not affect the oscillation probability, so it is omitted.

Now consider a neutrino produced at  $L = 0$  in a specific flavor state  $|\nu_\alpha\rangle$ . Using the matrix  $U$ , we express the initial flavor state as a superposition of mass states:

$$|\nu_\alpha(0)\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \quad (1.9)$$

After traveling a distance  $L$ , the state evolves to:

$$|\nu_\alpha(L)\rangle = \sum_i U_{\alpha i}^* e^{-i\frac{m_i^2 L}{2E}} |\nu_i\rangle \quad (1.10)$$

To find the probability of detecting flavor  $\beta$ , we project the evolved state back onto the flavor basis  $|\nu_\beta\rangle = \sum_j U_{\beta j}^* |\nu_j\rangle$ :

$$\langle \nu_\beta | \nu_\alpha(L) \rangle = \sum_i \sum_j U_{\alpha i}^* U_{\beta j} e^{-i\frac{m_i^2 L}{2E}} \langle \nu_j | \nu_i \rangle \quad (1.11)$$

Since mass eigenstates are orthonormal ( $\langle \nu_j | \nu_i \rangle = \delta_{ij}$ ), the amplitude  $A_{\alpha \rightarrow \beta}(L)$  is:

$$A_{\alpha \rightarrow \beta}(L) = \sum_i U_{\alpha i}^* U_{\beta i} e^{-i \frac{m_i^2 L}{2E}} \quad (1.12)$$

The transition probability is the square of the amplitude:

$$P_{\alpha \rightarrow \beta} = |A_{\alpha \rightarrow \beta}(L)|^2 = \sum_i \sum_j U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \exp \left( -i \frac{(m_i^2 - m_j^2)L}{2E} \right) \quad (1.13)$$

Using the identity  $\exp(-ix) = \cos(x) - i \sin(x)$  and the definition  $\Delta m_{ij}^2 = m_i^2 - m_j^2$ , we separate the real and imaginary parts. After algebraic simplification using the unitarity of  $U$  ( $\sum_i U_{\alpha i}^* U_{\beta i} = \delta_{\alpha\beta}$ ), we arrive at the full equation:

$$\begin{aligned} P_{\nu_\alpha \rightarrow \nu_\beta} = & \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) \\ & + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right) \end{aligned} \quad (1.14)$$

## Two Flavor Oscillations

In the two-flavor limit ( $\nu_e \rightarrow \nu_\mu$ ), the mixing matrix is a simple rotation:

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad (1.15)$$

Applying the probability formula for  $\alpha = e, \beta = \mu$ :

$$\begin{aligned}
P_{e \rightarrow \mu} &= |U_{e1}^* U_{\mu 1} e^{-iE_1 L} + U_{e2}^* U_{\mu 2} e^{-iE_2 L}|^2 = |-\cos \theta \sin \theta e^{-iE_1 L} + \sin \theta \cos \theta e^{-iE_2 L}|^2 \\
&= \sin^2 \theta \cos^2 \theta |e^{-iE_2 L} - e^{-iE_1 L}|^2 \\
&= \frac{1}{4} \sin^2(2\theta) |e^{-i(E_2 - E_1)L} - 1|^2
\end{aligned} \tag{1.16}$$

Using  $|e^{-ix} - 1|^2 = 4 \sin^2(x/2)$  and  $E_2 - E_1 \approx \Delta \frac{m^2}{2E}$ :

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \tag{1.17}$$

The survival probability, by construction, is then:

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \tag{1.18}$$

This is the simplest case for understanding the parametrization of the oscillation probability. The angle  $\theta$  determines the amplitude of the oscillation, with extrema at 0 and  $\pi/4$ , which represent the no-oscillation and maximal oscillation cases accordingly. The squared mass splitting  $\Delta m^2$  determines the frequency of the oscillation in the L/E dimension. The survival and disappearance probabilities for  $\nu_\mu$  are shown in Figure 1.1.

### Three Flavor Oscillations

For three flavor oscillations, which is our current knowledge, we use the full **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix,  $U$  [100]. The probability is more complex because it depends on three mixing angles ( $\theta_{12}, \theta_{13}, \theta_{23}$ ), three mass differences ( $\Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{32}^2$ ) as well as a CP-violating phase  $\delta_{cp}$ .

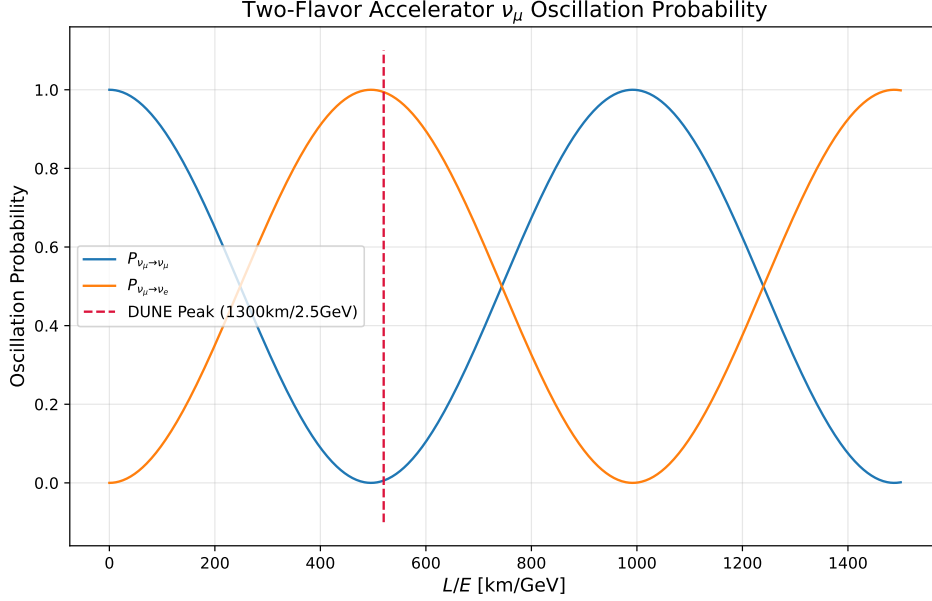


Figure 1.1: Two flavor oscillation probability for  $\nu_\mu$  disappearance in the accelerator neutrino scale. The chosen values  $\theta = \pi/4$  and  $\Delta m^2 = 2.5 \times 10^{-3} eV^2$  are representative of the current best knowledge in this regime. The planned peak neutrino energy over baseline for the DUNE far detector [25] is shown for reference, showing the choice of a maximal disappearance point.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.19)$$

where  $s_{ij} = \sin \theta_{ij}$  and  $c_{ij} = \cos \theta_{ij}$ . The matrix allows for CP violation, becoming complex, for  $\delta_{cp} \notin \{0, \pi\}$ . You may think of its three composing matrix terms, from left to right as shown in Equation 1.19, as:

- **Atmospheric/Accelerator Term (driven by  $\theta_{23}$ ):** Oscillations of neutrinos at GeV energies traveling for 10-1000s of km are dominated by this term. This falls in the energy range and baselines of atmospheric and accelerator neutrino experiments.
- **Reactor Term (driven by  $\theta_{13}$ ):** Low energy neutrinos, around a few MeV, and at

$\sim$  km baselines are influenced by this oscillation term.

- **Solar Term (driven by  $\theta_{12}$ ):** The average distance from the sun is roughly 150 million km, making it a neutrino source with one of the longest baselines available. This makes solar neutrinos a good sample to study  $\theta_{12}$ -driven oscillations.

Note that the labels are historical in nature and not exclusive: for example, "reactor" experiments are sensitive to solar neutrino oscillation parameters. To find the explicit dependence on mixing angles, we substitute the PMNS matrix elements into the probability equation. The electron neutrino survival probability  $P(\nu_e \rightarrow \nu_e)$ , expanded to second order in  $\alpha = \Delta m_{21}^2 / \Delta m_{31}^2$  and  $s_{13}$  is:

$$\begin{aligned}
P_{\nu_e \rightarrow \nu_e} = 1 &- 4s_{12}^2 c_{12}^2 c_{13}^4 \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) \\
&- 4c_{12}^2 c_{13}^2 s_{13}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \\
&- 4s_{12}^2 c_{13}^2 s_{13}^2 \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)
\end{aligned} \tag{1.20}$$

This probability holds for antineutrinos given CPT conservation.

## Matter Effects

When neutrinos traverse matter (like the Sun or Earth),  $\nu_e$  undergo coherent forward scattering with electrons via  $W^\pm$  exchange. This phenomenon, known as the Mikheyev-Smirnov-Wolfenstein effect [103, 125], creates an effective potential  $V_e = \sqrt{2}G_F n_e$ , where  $n_e$  is the electron density and  $G_F$  is the Fermi constant. The other two neutrino flavors do not experience this effect as matter is not composed of their corresponding leptons.

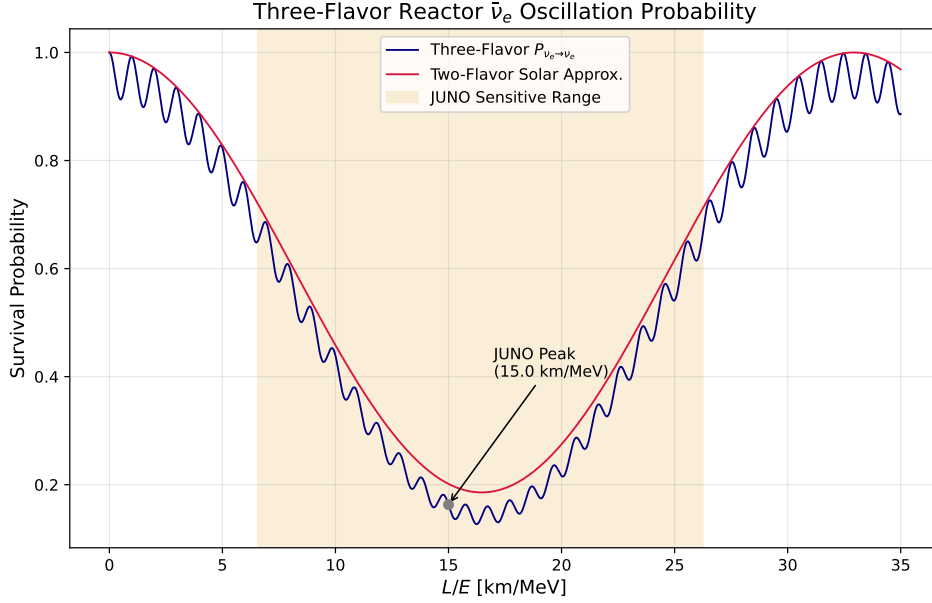


Figure 1.2: Three flavor oscillation probability in the reactor/solar neutrino scale, of interest for the JUNO experiment. Note how the introduction of a third neutrino creates an interference pattern with respect to the two neutrino solar oscillations case. The peak neutrino energy over baseline for JUNO is shown for reference.

The effective Hamiltonian in matter becomes:

$$H_{eff} = \frac{1}{2E} \left[ U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \quad (1.21)$$

where  $A = 2\sqrt{2}G_F n_e E$ . In a two-flavor system  $(\nu_e, \nu_x)$ , the mixing angle in matter  $\theta_m$  is given by:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - A/\Delta m^2)^2 + \sin^2 2\theta} \quad (1.22)$$

At the resonance condition  $A = \Delta m^2 \cos 2\theta$ , the mixing becomes maximal ( $\theta_m = 45^\circ$ ) even if the vacuum mixing angle  $\theta$  is small. This resonance explains the large magnitude of the

solar neutrino deficit.

## 1.4 Current Global Program and Outstanding Questions

Precisely measuring the values of the PMNS matrix elements is essential for constructing a particle interaction model that exceeds our current understanding. The shift between mass and flavor eigenstates suggests that neutrinos may hold the key to understanding the origin of masses beyond the known Higgs mechanism.

The various experimental techniques employed to probe these properties can be classified by their neutrino source and, subsequently, the design requirements around the chosen source. The phase space available to these experiments is primarily dictated by the ratio of their baseline distance ( $L$ ) to the neutrino energy ( $E$ ).

- **Accelerator Experiments:** These facilities use high-energy particle accelerators to strike a target, producing pions that decay primarily into muons and muon neutrinos. Experiments measuring oscillations at  $O(100\text{s})$  km baselines, such as NOvA [38], T2K [4], HyperK [5], and soon DUNE [25], utilize a "near detector" to characterize the initial flux and a "far detector" to observe the results of the oscillation. These experiments are well-suited for measurements of  $\theta_{23}$ -driven oscillations. Further details on this method are provided in Chapter 2.
- **Reactor Experiments:** By monitoring nuclear reactors, recent experiments like Daya Bay [35], RENO [118], Double Chooz [3], and now JUNO [34] measure the flux of electron antineutrinos produced by the beta decays of fission products. By sampling the flux of neutrinos from the reactor(s) and comparing with the prediction or with measurements done at other baselines, oscillation information can be extracted. With



energies typically in the MeV range, these experiments have been instrumental in providing high-precision measurements of the mixing angles  $\theta_{13}$  and  $\theta_{12}$ .

- **Atmospheric Experiments:** Neutrino production from high-energy cosmic rays acts much like an accelerator-based neutrino beam. Experiments like SuperK [71], IceCube [1], KM3Net [27] and the upcoming HyperK [5] study these neutrinos using large volumes of instrumented water or ice. By analyzing the ring pattern coming from the Cherenkov light produced by leptons from neutrino interactions, the flavor of the outgoing lepton (and of the incoming neutrino) can be inferred. They provide excellent measurements of  $\Delta m_{21}^2$  and  $\theta_{23}$ .
- **Solar Experiments:** Because of the Sun’s immense density, neutrinos produced by solar fusion undergo matter-enhanced oscillations, allowing probes of solar models and neutrino theory with solar neutrino experiments. Detectors like SNO [42] and Kamiokande [36] have proven equally adept at studying both solar and atmospheric fluxes.

### 1.4.1 Neutrino Mass Ordering and Absolute Mass Scale

Since neutrino oscillations depend on the difference in the square of the masses and not their magnitude, oscillation measurements cannot provide information on the absolute mass of neutrinos. Cosmic Microwave Background data suggests  $\sum m_i < 0.12 \text{ eV}$  [28]. The KATRIN experiment recently set a world-leading limit, establishing that the effective electron neutrino mass  $m_{\nu_e} < 0.8 \text{ eV}$  (90% CL) [87]. Future experiments like Project 8 aim to push this to  $0.04 \text{ eV}$  using the Cyclotron Radiation Emission Spectroscopy technique [113]. Moreover, it is not known whether the mass state with the most  $\nu_e$  is the lightest ( $m_1 < m_2 < m_3$ ), known as normal ordering (NO), or the heaviest ( $m_3 < m_1 < m_2$ ), known as inverted ordering (IO). The squared differences between the mass states and their flavor compositions in both cases are shown in Figure 1.3. Current global fits show a statistical

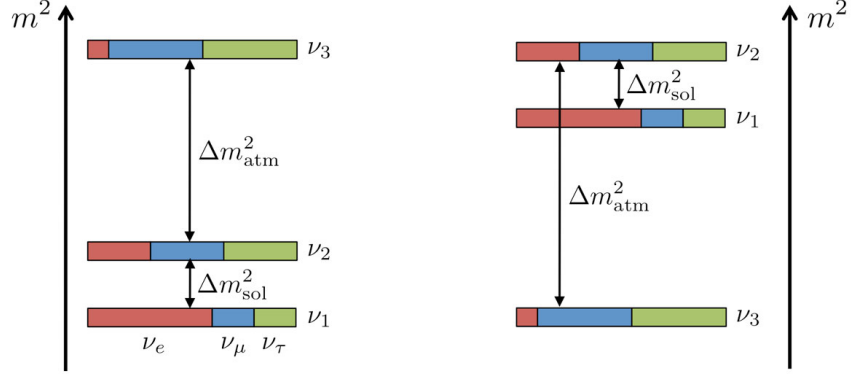


Figure 1.3: Normal (left) and Inverted (right) NMO with flavor composition of mass states shown [34].

preference for NO at approximately the  $2.5\text{-}3\sigma$  level, driven largely by atmospheric neutrinos in Super-Kamiokande and accelerator data from T2K and NOvA [65]. The JUNO experiment, described in detail in Chapter 5, seeks to determine the mass ordering using reactor neutrino oscillations, independent of matter effects, by looking at the interference pattern in the neutrino energy spectrum. A brand new result using this technique has been released, and will be covered in Chapter 7.

### 1.4.2 CP Violation in the Lepton Sector

The fact that all neutrino mixing angles measured to be non-zero opens the possibility to leptonic charge-parity (CP) violation, motivating the construction of next-generation experiments like DUNE and Hyper-K. The violation of CP conservation could provide insights to the matter-antimatter asymmetry in the Universe, as cosmological theory predicts matter and antimatter to have been produced in equal amounts. The T2K experiment has provided the most significant hints to date, with results consistent with non-zero  $\delta_{CP}$  at  $3\sigma$  confidence if IO is assumed [6]. However, a recent joint analysis between T2K and NOvA [120] has shown a slight tension. While T2K strongly prefers NO and maximal CP violation, NOvA's data is more consistent with a broader range of  $\delta_{CP}$  values if IO is assumed.

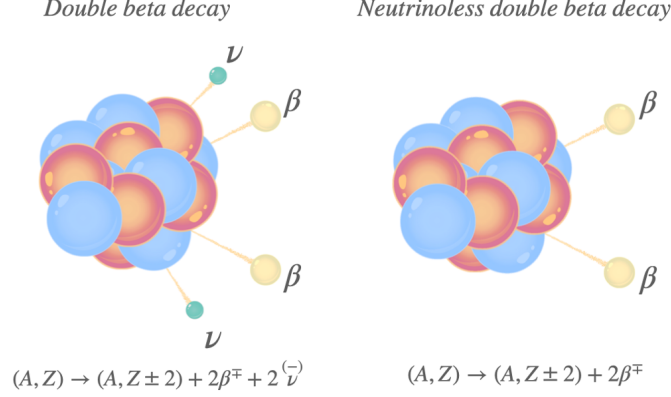


Figure 1.4: Illustration of double- $\beta$  decay and  $0\nu\beta\beta$  side-by-side [108].

| <i>Question</i>      | <i>Status</i>                  | <i>Probe</i>      |
|----------------------|--------------------------------|-------------------|
| Mass Ordering        | Hints to Normal                | JUNO, DUNE        |
| CP Violation         | $2\pi/3$ (T2K)                 | DUNE, Hyper-K     |
| $\theta_{23}$ octant | $< 45^\circ$ or $> 45^\circ$ ? | DUNE, T2K/NOvA    |
| Absolute Mass        | $< 0.8$ eV                     | KATRIN, Project 8 |

Table 1.1: Table of open questions in neutrino oscillations, with present status as well as current and future experimental probes.

### 1.4.3 Nature of Neutrino Masses

Another question that has not been answered is whether neutrinos are their own antiparticles. If neutrinos and antineutrinos are distinct, like standard fermions following Dirac statistics, the number of leptons in a particle interaction would remain constant. This is known as the current conservation principle. Conversely, if the particles are the same, known as Majorana particles, then this principle is violated. Moreover, this scenario could open the door to explaining the smallness of neutrino masses via the Seesaw Mechanism where the existence of an extremely heavy right-handed Majorana mass scale naturally suppresses the light neutrino masses we observe [73]. The only known practical way to test this is through Neutrinoless Double Beta Decay ( $0\nu\beta\beta$ ), shown in Figure 1.4. If observed, this process would prove that lepton number is not a conserved quantity. Current leading experiments like nEXO [106], LEGEND [92], and KamLAND-Zen [86] are searching for this decay in isotopes like  $^{136}\text{Xe}$  and  $^{76}\text{Ge}$ .

# Chapter 2

## The Deep Underground Neutrino Experiment

### 2.1 Introduction and Scientific Objectives

The Deep Underground Neutrino Experiment (DUNE) represents the next generation of long-baseline accelerator neutrino oscillation experiments. DUNE is designed to address the fundamental questions that remain unanswered. The experimental sites of DUNE are two geographic locations separated by 1300 km: the "Near Site" at Fermilab in Batavia, Illinois, and the "Far Site" at the Sanford Underground Research Facility (SURF) in Lead, South Dakota [25]. The Near Site will include the Near Detector Complex and the experiment beamline, which will produce primarily  $\nu_\mu$  or  $\bar{\nu}_\mu$  pointed to both detector sites [61].

LBNF will utilize the Proton Improvement Plan II (PIP-II) at Fermilab to deliver a proton beam with power exceeding 2 MW. Protons are accelerated to energies between 60 and 120 GeV and directed onto a graphite target, producing a secondary shower of charged mesons ( $\pi^\pm$  and  $K^\pm$ ). A system of parabolic magnetic focusing horns then acts as a charge-sign

filter. By utilizing high-current pulses to generate strong magnetic fields, the horns focus mesons of a specific sign into a 194-meter-long helium-filled decay pipe while deflecting those of the opposite sign. Inside this pipe, the mesons decay in-flight to produce a broadband neutrino flux peaking in the few-GeV range, optimized for the 1300 km baseline. The ability to switch the horn polarity allows DUNE to run in either a Forward Horn Current (FHC) neutrino-enhanced mode or a Reverse Horn Current (RHC) antineutrino-enhanced mode. The primary science goals of DUNE include:

- **Discovery of Leptonic CP Violation:** By comparing the oscillation probabilities of neutrinos and antineutrinos ( $\nu_\mu \rightarrow \nu_e$  vs.  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ), DUNE aims to measure the CP-violating phase  $\delta_{CP}$  with high precision.
- **Mass Ordering Determination:** DUNE's long baseline of 1300 km provides a significant matter effect, allowing for a determination of whether the neutrino mass ordering is normal or inverted by observing  $\nu_e$  enhancement or suppression, respectively. The opposite is expected for  $\bar{\nu}_e$ .
- **Precision Mixing Measurements:** DUNE will provide precise measurements of  $\theta_{23}$  and  $\Delta m_{31}^2$ , testing the maximality of  $\theta_{23}$  and searching for potential BSM physics.

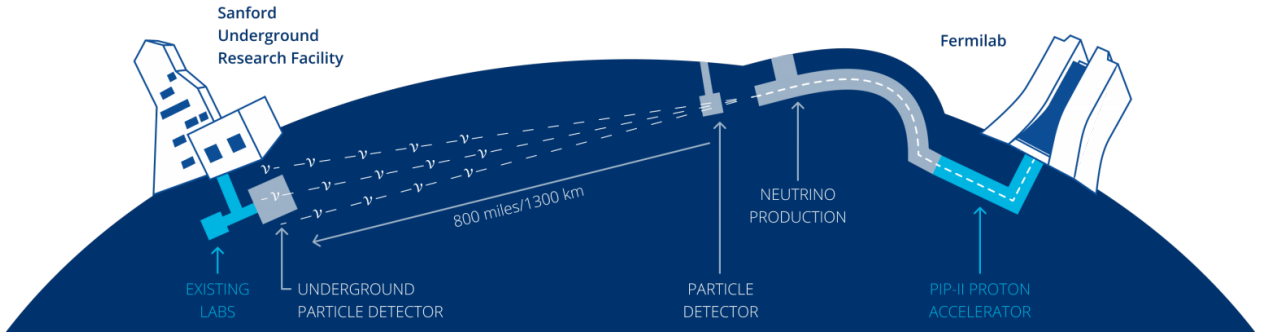


Figure 2.1: Schematic of DUNE experimental setup. Image obtained from [69]

## 2.2 Neutrino Oscillations in DUNE

DUNE extracts oscillation parameters by comparing the neutrino energy spectrum observed at the Far Detector to the spectrum predicted from an unoscillated flux, itself constrained by measurements at the Near Detector. DUNE’s primary beam consists of  $\nu_\mu$  (or  $\bar{\nu}_\mu$  in RHC mode). Two channels are used to constrain the oscillations:

- **$\nu_\mu$  disappearance:** the depletion of the muon-flavor content of the beam as a function of reconstructed energy, primarily sensitive to  $\theta_{23}$  and  $\Delta m_{32}^2$  through the survival probability

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right), \quad (2.1)$$

valid in the two-flavor approximation appropriate near the first oscillation maximum.

- **$\nu_e$  appearance:** the increase of electron-flavor content not present in the initial beam (shown in Figure 2.2), which carries the sensitivity to  $\delta_{CP}$  and the mass ordering. In the presence of matter, the full three-flavor appearance probability can be approximated as [44]:

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 \theta_{23} \sin^2(2\theta_{13}) \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & + \sin(2\theta_{23}) \sin(2\theta_{13}) \sin(2\theta_{12}) \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \cos(\Delta \pm \delta_{CP}) \\ & + \mathcal{O}\left[\left(\frac{\Delta m_{21}^2}{\Delta m_{32}^2}\right)^2\right], \end{aligned} \quad (2.2)$$

where  $\Delta \equiv \Delta m_{32}^2 L / 4E$ ,  $x \equiv 2\sqrt{2}G_F n_e E / \Delta m_{32}^2$  parametrizes the matter potential,  $n_e$  is the electron number density along the baseline, and the  $\pm$  sign on  $\delta_{CP}$  flips between neutrino and antineutrino running.

The term  $x$  above depends on the sign of  $\Delta m_{32}^2$ . For a Normal Ordering (NO,  $\Delta m_{32}^2 > 0$ ), the matter potential constructively interferes with the vacuum oscillation term for neutrinos,

enhancing  $P(\nu_\mu \rightarrow \nu_e)$  and suppressing  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ . For an Inverted Ordering (IO,  $\Delta m_{32}^2 < 0$ ) the effect is reversed. Because DUNE's 1300 km baseline traverses a large column density of Earth's crust, this asymmetry is large ( $\sim 40\%$  at the oscillation maximum). Comparing the observed  $\nu_e$  and  $\bar{\nu}_e$  appearance rates in FHC and RHC beam configurations therefore provides a resolution of the mass ordering that is, in principle, independent of the eventual measurement of  $\delta_{CP}$ , since the two parameters enter the appearance probability with different energy and baseline dependence.

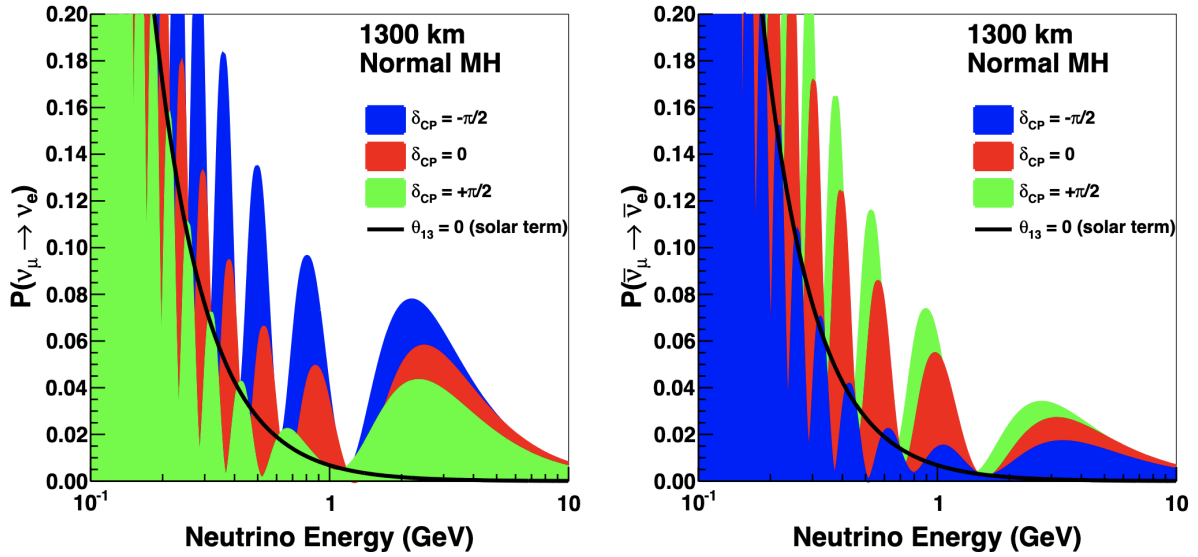


Figure 2.2: The electron-flavor appearance probability at DUNE for neutrinos (left) and antineutrinos (right) under different  $\delta_{CP}$  assumptions [12].

In practice, oscillation parameters are extracted through a joint fit to the reconstructed energy spectra of  $\nu_\mu$ ,  $\bar{\nu}_\mu$ ,  $\nu_e$ , and  $\bar{\nu}_e$  candidate events at the Far Detector, in both FHC and RHC running modes [9]. Because the unoscillated flux, cross-section model, and detector response all carry significant uncertainties, DUNE relies on the Near Detector (Section 2.5.1) to constrain the event rate prediction before extrapolating it to the Far Detector.

## 2.3 Liquid Argon Time Projection Chambers

### 2.3.1 Background and Choice for DUNE

The time projection chamber (TPC) was initially inceptioned in the 1970s [107, 124]. Ionization from charged particles creates a trail of electrons in their trajectory. An intense electric field drifts these electrons toward a set of anode wire planes or charge readout pads:

$$v_{\text{drift}} = \mu E \tag{2.3}$$

where  $v_{\text{drift}}$  is the drift velocity of the electrons,  $\mu$  is the electron mobility in liquid argon, and  $E$  is the applied electric field. Although this technology provides excellent imaging quality, it initially did not provide information on the initial time of the particle interaction, making it very challenging to separate interactions occurring within the same electron drift time window as well as not allowing the reconstruction of the absolute coordinate in the drift direction. Liquid Argon TPC (LArTPC) technology was proposed in the 1970s [115] to solve this problem given that several short lived atomic states of argon are created during ionization and decay, producing prompt scintillation light. The liquid argon is mostly transparent to the light produced, allowing for its collection with photon detectors. By combining the time of the interaction from the photon detectors with the 2D ionization information from the charge readout planes, the detector can reconstruct 3D images of neutrino interactions with excellent spatial resolution. Moreover, the increased density compared to earlier gas TPCs means a liquid detector has a higher target mass at any given volume. This excellent tracking and target mass combined with low energy thresholds (certainly much lower than the energies of interest for beam neutrino oscillation analysis) as well as calorimetry competitive with other technologies make LArTPCs a sound choice for the DUNE program.



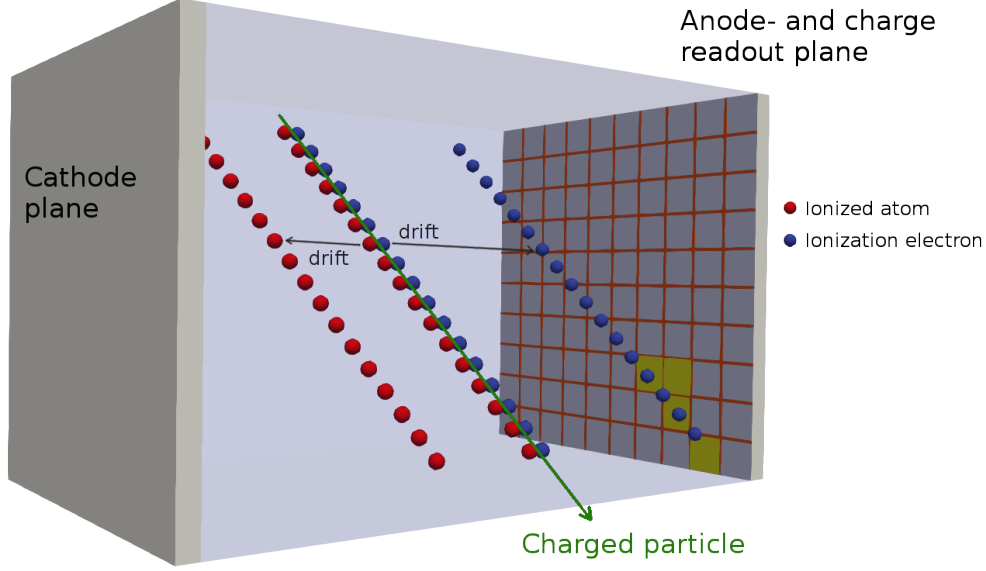


Figure 2.3: Diagram of a TPC. Image obtained from [93]

### 2.3.2 Charged Particles in Argon

The formation of a signal in a LArTPC begins with the deposition of energy by charged particles traversing the medium. As a charged particle travels through liquid argon, it loses energy primarily through inelastic interactions with atomic electrons, a process described by the Bethe-Bloch formula [126]:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (2.4)$$

where  $c$  is the speed of light,  $A$  is the number of nucleons in the material,  $Z$  is the atomic number of the material,  $I$  is the mean excitation energy,  $\beta = \frac{v}{c}$ ,  $z$  is the charge of the incident particle, and  $m_e$  is the electron mass. The constant  $K$  is equivalent to  $4\pi N_A r_e^2 m_e c^2$  where  $N_A$  is Avogadro's number and  $r_e$  is the classical electron radius. The energy lost per unit length  $-\langle dE/dx \rangle$  is largely a function of the particle's velocity ( $\beta\gamma$ ) and the atomic composition of the material the particle is traversing. At low energies, the  $1/\beta^2$  term dominates, causing a decrease in energy loss per unit length as the particle speeds up. At ultra-relativistic

energies, the logarithmic term and the density effect correction  $\delta(\beta\gamma)$  lead to a sharp rise.

A particle with energy at which these effects balance is known as a Minimally-Ionizing Particle (MIP). In this region, the stopping power reaches its global minimum, roughly 2.1 MeV/cm in liquid argon, and becomes relatively insensitive to the particle's momentum. MIPs are of particular interest in DUNE as they overwhelmingly comprise the  $\nu_\mu$  charged-current signal (few-GeV muons).

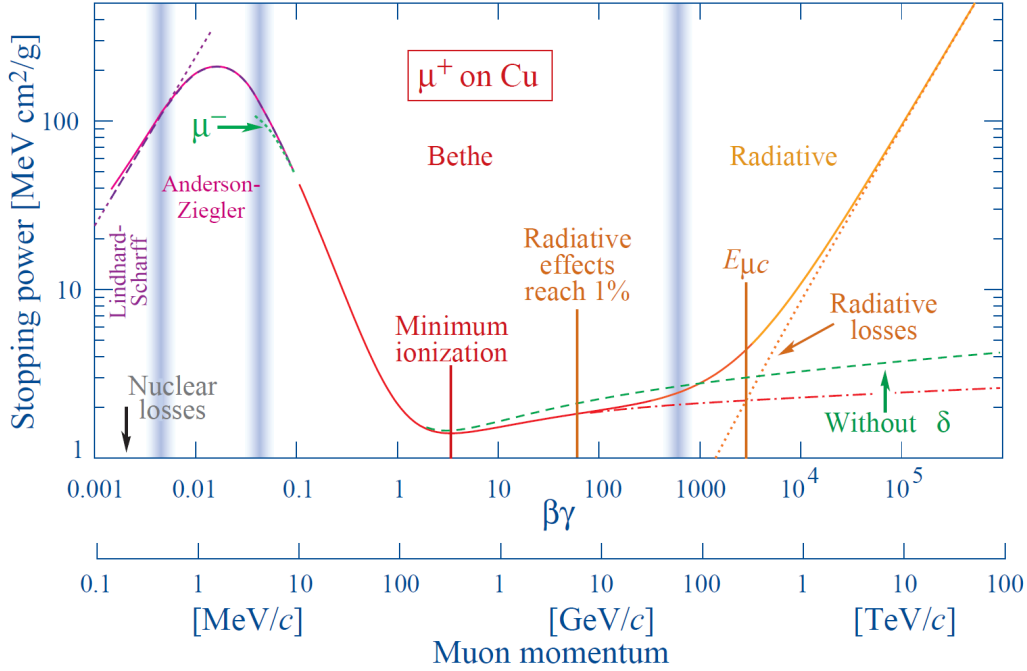


Figure 2.4: Stopping power as a function of momentum for muons in copper [126].

## Electron Production and Recombination

Energy depositions result in both the excitation and ionization of argon atoms, as described previously. The total number of electron-ion pairs produced,  $N_i$ , is given by  $N_i = \Delta E / W_{ion}$ , where  $W_{ion} = 23.6$  eV is the average energy required to produce an ion pair in argon and  $\Delta E$  is the total energy lost by the incident particle [104]. However, not all produced electrons are available for drift. A significant fraction of the ionization electrons will undergo recombination with the positive argon ions ( $\text{Ar}^+$ ) to form neutral atoms before they can be pulled away by the external electric field. The fraction of initial ionization charge that survives

recombination  $R$  is field-dependent and typically modeled using either the Birks' Model [40] or the Modified Box Model [24]. The charge  $Q$  remaining after recombination is related to the initial charge  $Q_0$  by:

$$R = \frac{Q}{Q_0} = \frac{A}{1 + \frac{k}{\mathcal{E}} \frac{dE}{dx}} \quad (2.5)$$

in the case of Birks' Law and:

$$R = \frac{\ln(A + \frac{B}{\rho \mathcal{E}} \frac{dE}{dx})}{\frac{B}{\rho \mathcal{E}} \frac{dE}{dx}} \quad (2.6)$$

for the Modified Box Model, where  $\mathcal{E}$  is the electric field,  $\rho$  is the argon density, and  $A$ ,  $B$ , and  $k$  are constants determined by experimental calibration. Recombination (quenching) for MIPs in liquid argon is around 30% while high  $dE/dx$  particles, such as protons, suffer from higher quenching, making the field strength a critical parameter to understand the energy scale in the detector.

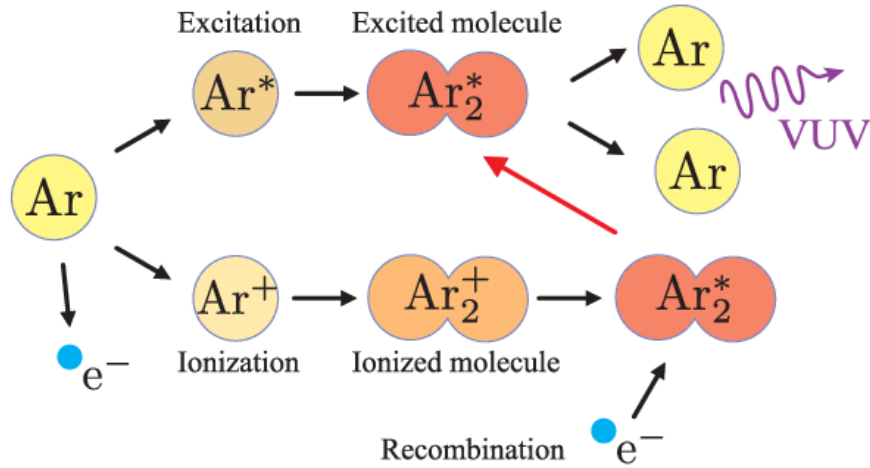


Figure 2.5: Ionization and recombination process in argon. Image obtained from [41].

## Argon Purity

Electrons remaining after recombination must drift over distances of up to several meters. The integrity of the signal during drift can be compromised by contaminants such as  $O_2$  and  $H_2O$  that can capture drifting electrons. The electron lifetime  $\tau$ , parametrizing the survival of drifting electrons, is used to characterize the purity of the argon, where the collected charge  $Q(t)$  at a drift time  $t$  is:

$$Q(t) = Q_0 e^{-t/\tau} \quad (2.7)$$

For DUNE, maintaining a lifetime in the millisecond range is required to ensure that signals in proximity to the cathode reach the charge-collecting anode without significant attenuation.

## Diffusion

As electrons drift, they also undergo elastic scattering with the surrounding argon. This stochastic process leads to a spatial spreading of the electron charge cloud, known as diffusion. Transverse diffusion (T) describes the lateral spreading of the charge in the readout plane. Longitudinal diffusion (L) refers to the spread of the electron cloud along the drift direction. The root-mean-square (RMS) spread of a point-like charge cloud after drifting for a time  $t$  is given by [94]:

$$\sigma_{L,T} = \sqrt{2D_{L,T}t} \quad (2.8)$$

In a LArTPC, the electrons gain energy from the field and their motion is no longer in thermal equilibrium with the liquid argon. Under these conditions, the diffusion coefficients are related to the mean electron energy  $\epsilon$  via the generalized Einstein relation:

$$D_{L,T} = \frac{\epsilon_{L,T}}{e} \mu \quad (2.9)$$

Understanding diffusion is critical for reconstruction, as it affects the temporal and calorimetric properties of the signal arriving at the anode. Transverse diffusion ( $\sigma_T$ ) impacts the spatial resolution across the readout plane, and can move fractions of charge to different channels, creating "lost" hits if these fractional charges fall under threshold. Longitudinal diffusion ( $\sigma_L$ ) can modulate the resolution of the reconstructed drift direction, widening the signal pulse in the time domain.

## 2.4 The DUNE Far Detector

The DUNE Far Detector (FD) is situated 1.5 km underground at SURF in Lead, South Dakota. This underground location provides roughly 4,300 meters water equivalent (m.w.e.) of shielding, reducing the cosmic muon flux by a factor of  $10^6$  relative to the surface and consequently greatly reducing cosmogenic backgrounds. The detector is designed as four massive cryostats approximately  $66 \times 19 \times 18$  m in size, each filled with 17.5 kt of liquid argon (LAr). Given the many technical complexities of the project and desire to begin physics data-taking as soon as possible, DUNE's ambitious design is scheduled to roll out in a two-phased approach.

### 2.4.1 Phase I

The first two modules of the Far Detector, comprising what is known as Phase I, utilize two distinct LArTPC designs to ensure both reliability and physics reach. FD1, also known as the Horizontal Drift detector, employs a traditional LArTPC design where the electric field is oriented horizontally. Ionization electrons drift toward Anode Plane Assemblies (APAs) located at the cryostat walls. Each APA consists of three layers of sense wires (two induction

planes and one collection plane) oriented at  $(0^\circ, \pm 35.7^\circ)$  to provide three 2D views of each interaction. This design is backed by the successful operation of detectors like ProtoDUNE-SP [8] and MicroBooNE [23].

FD2 on the other hand features a vertical drift orientation with a 6 m drift distance. It utilizes perforated Printed Circuit Boards (PCBs) as anodes, using a "hole-collection" method where electrons are guided through perforated holes in the PCB to sensor strips on the back. This "Vertical Drift" (VD) technology simplifies the mechanical structure and maximizes the active volume by embedding photon detectors in the cathode [11].

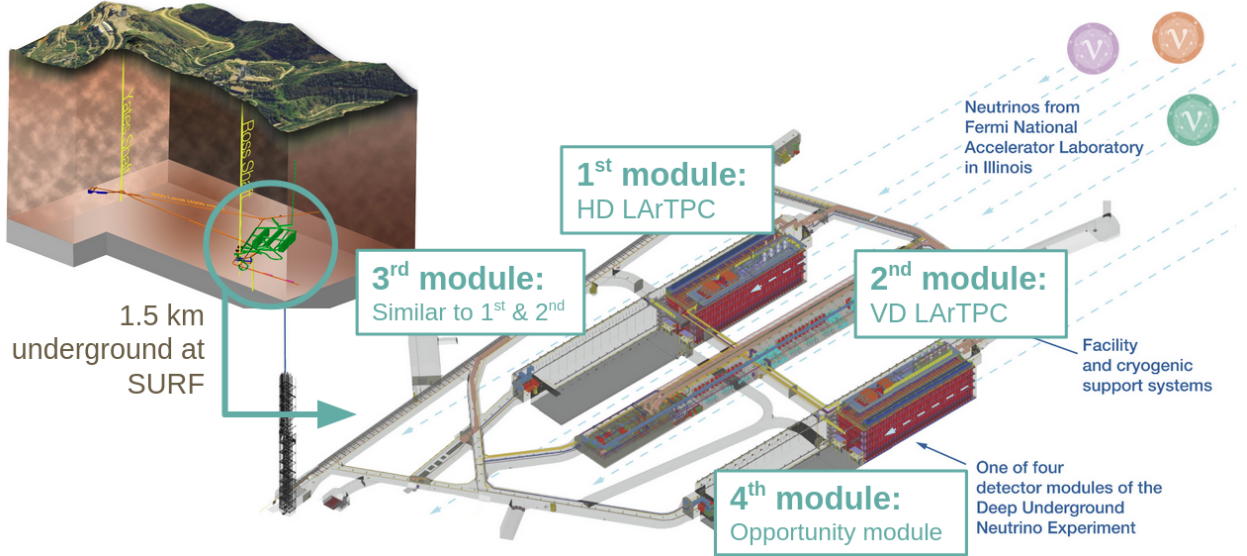


Figure 2.6: Diagram of the DUNE FD cavern at SURF [46].

## 2.4.2 Phase II

DUNE Phase II is the upgrade required for a  $5\sigma$  sensitivity for CP violation discovery across a wide range of  $\delta_{CP}$  values. This phase involves the installation of the final two modules (FD3 and FD4) and an upgrade of the beam power to 2.4 MW. The increase in beam power is expected to be achieved through improvements to beam cycling, decreasing the time between proton batches from 1.2 seconds to about 0.7 seconds, proton target upgrades, and replacing

the 8 GeV Booster synchrotron [12].

### **FD3 and the Module of Opportunity**

While FD3 is likely to utilize a refined version of the FD1/FD2 designs, FD4 (known as the "Module of Opportunity") is envisioned as an advanced detector that could incorporate emerging technologies to expand DUNE's non-beam physics program. For example, improved photon detection coverage can lower the energy threshold for solar neutrino and supernova neutrino detection. Another idea, inspired by the success of the LArPix system [63] which will be thoroughly touched upon in this and subsequent chapters, is exploring the feasibility of migrating from PCB/wire anodes to a fully 3D pixelated readout. Doping could also provide many opportunities in DUNE. There is active research on  $Xe$ -doping for  $0\nu\beta\beta$  searches or photosensitive dopants to further enhance the light yield and timing resolution of the LArTPC. Furthermore, R&D programs for water-based liquid scintillator [ ] and opaque scintillator detectors have proposed designs for DUNE's FD4, where they can boost DUNE's performance in low energy physics.

The combination of four modules and the 2.4 MW beam upgrade ensures that DUNE can observe over 1,000  $\nu_e$  appearance events for a 10-year exposure, even in the most challenging CP-violation scenarios [12].

## **2.5 The DUNE Near Detector Complex**

The DUNE Near Detector (ND) complex is located at Fermilab, approximately 574 m downstream from the neutrino production target. The ND serves a critical role in the DUNE physics program by constraining systematic uncertainties that would otherwise limit the sensitivity to severely limit the sensitivity to DUNE's oscillation goals [61]. These uncertainties primarily arise from the neutrino flux model, the neutrino-argon interaction cross-sections, and the detector response.

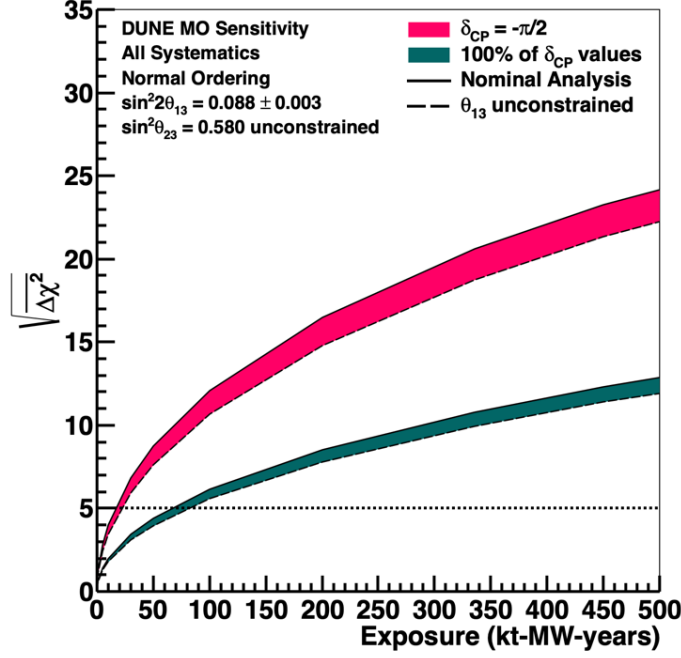


Figure 2.7: Mass ordering sensitivity for DUNE, for Phase I and Phase II configurations [12].

The ND complex consists of four components:

- **ND-LAr:** A modular LArTPC serving as primary target, which will be expanded upon in the following subsection. It is designed to be similar to the far detector design to facilitate near-far analysis but smaller given the higher flux intensity close to the beam.
- **Downstream Tracker:** Given the energy of particles produced within ND-LAr and its size, most particles will escape out the downstream face of the detector. A tracking detector will be placed behind ND-LAr in order to measure the momentum and charge of outgoing particles. Phase I will employ TMS (The Muon Spectrometer), a magnetized steel and scintillator detector. Phase II will replace TMS with a high-pressure gaseous argon TPC surrounded by a calorimeter and a magnet, known as ND-GAr.
- **DUNE-PRISM:** One of the most innovative aspects of the ND design is DUNE-



PRISM (Precision Reaction Independent Spectrum Measurement). Both ND-LAr and the downstream tracker are mounted on a movable Hilman rail system that allows them to be positioned up to 30 m off-axis. By taking measurements at various off-axis angles, DUNE can sample different neutrino energy spectra. This allows for the construction of a linear combination of off-axis spectra to mimic the oscillated far-detector spectrum. It also provides a robust method to disentangle the neutrino energy reconstruction from the cross-section model, which is one of the largest potential sources of systematic error in DUNE.

- **SAND (System for on-Axis Neutrino Detection):** A magnetized beam monitor that remains on-axis to provide continuous monitoring of the neutrino beam spectrum and intensity. SAND will consist of alternating scintillating and lead layers and deploy a novel silicon photomultiplier-based (SiPM) camera readout.

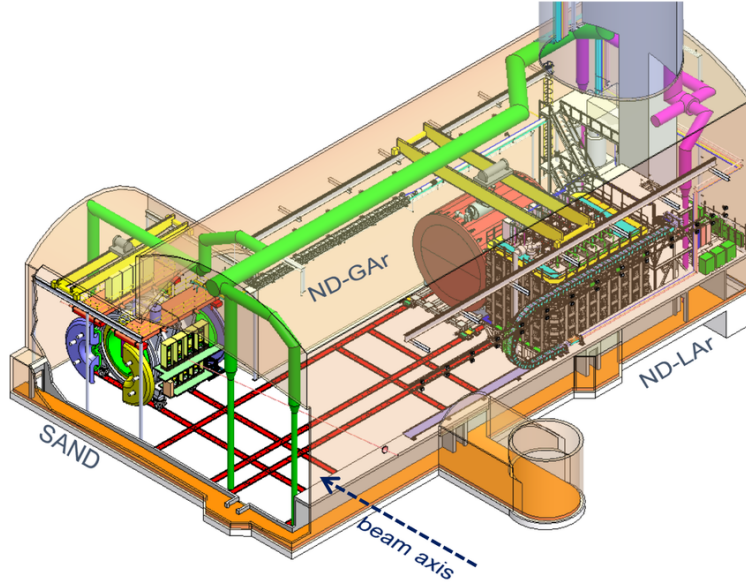


Figure 2.8: Diagram of the DUNE Near Detector Complex and its comprising detectors. ND-LAr is shown in an off-axis position with respect to the beam, allowed by DUNE PRISM [61].

### 2.5.1 The ND-LAr Detector

As the primary target for the DUNE beam, ND-LAr is designed to be functionally identical to the Far Detector in terms of target material (argon) and technology (LArTPC) to allow for a direct suppression of many systematic errors in a far-to-near comparison analysis. However, given the high neutrino flux at the near site, resulting in  $O(100)$  interactions per beam spill, placing a traditional LArTPC as a near detector would be insufficient, as the combinatorics of matching this quantity of ionization signals to their corresponding light peaks is practically impossible. To address this, ND-LAr employs a modular design with novel readouts, reducing the number of interactions per optical volume to a manageable amount and maintaining clear event reconstruction [61].

#### Modular Design

ND-LAr is composed of 35 individual LArTPC modules arranged in a  $5 \times 7$  grid. Each module is optically isolated, which significantly reduces reconstruction ambiguity from overlapping events by reducing the number of events to disentangle per optical volume, as shown in Figure 2.9. Moreover, a modular detector offers advantages in commissioning and reliability such as parallel construction of modules, looser requirements on electron lifetime and more uniform electric fields due to a shorter drift, and losing only 1/35th of the fiducial volume in the case of a catastrophic failure.

#### Charge Readout System

Another defining feature of ND-LAr is the use of a pixelated charge readout, based around the LArPix ASIC [63], instead of traditional projective wire planes. Wire readouts suffer from charge smearing in high occupancy environments because they integrate charge along their entire length for a given drift time. As the occupancy increases, several charge depositions occur along the same wire and drift times, resulting in unresolvable ambiguities. In contrast, pixelated anodes provide native 3D imaging with each pixel acting as an inde-

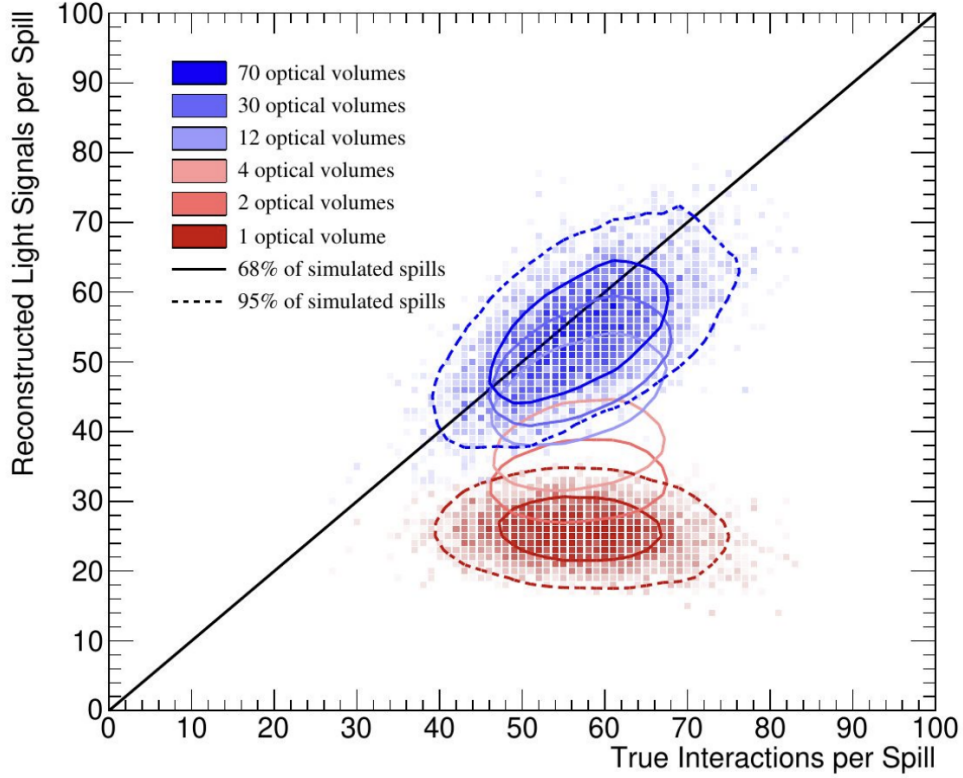


Figure 2.9: Number of interactions simulated vs. reconstructed based on light signals using DBSCAN clustering for different modularity schemes in ND-LAr. Interactions start being lost as the configuration approaches a monolithic setup. Image credit to Kevin Wood.

pendent sensor, providing a direct measurement of the  $z$  and  $y$  spatial coordinates, while the drift time provides the  $x$  coordinate, removing the need of plane matching as in wire readouts. Furthermore, LArPix utilizes a self-triggering architecture, recording only the hits that exceed a set charge threshold. This not only minimizes data rates but also improves the signal-to-noise ratio by reducing induction current noise.

### Light Readout System

To provide the precise event timing ( $t_0$ ) required for 3D reconstruction and to mitigate pile-up, ND-LAr utilizes a high-coverage light readout system. This system detects the vacuum ultraviolet (VUV) scintillation light at 127 nm produced by ionizing particles in liquid argon.

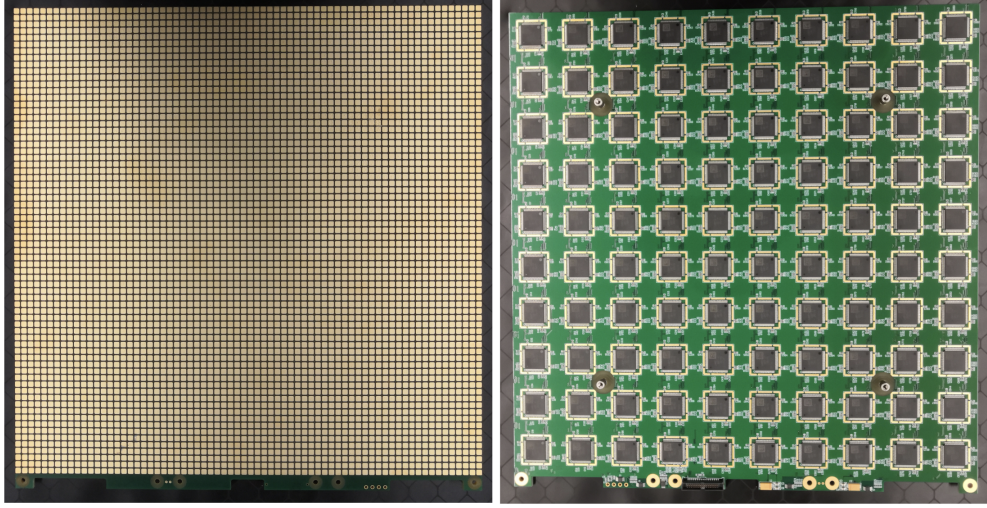


Figure 2.10: LArPix pixel anode tile, with 10,240 self-triggering charge-sensitive pixels in the front (left), and ASICs in the back (right) [13].

ND-LAr modules utilize two complementary light detectors inside its TPCs, based on the ARAPUCA design [98]. These systems use wavelength-shifting materials (such as TPB) to shift VUV light to the visible spectrum, where it is then captured by SiPMs. Light Collection Modules (LCMs) utilize WLS-doped fibers to collect light and shift its wavelength before routing it to the SiPMs [7]. The LCMs offer higher photon detection efficiency (PDE) in localized regions, providing the high-granularity timing needed to resolve multiple interactions within a single beam spill. ArcLight detectors consist of a WLS plastic sheet coupled to a dichroic filter [37]. They utilize total internal reflection to "trap" photons and guide them to SiPMs mounted at the edges, with both designs shown in Figure 2.11. This provides a large active area with very little material, minimizing the impact on the TPC's electric field. This dual technology approach ensures a timing resolution of better than 3 ns, allowing for precise  $t_0$  determination [2].

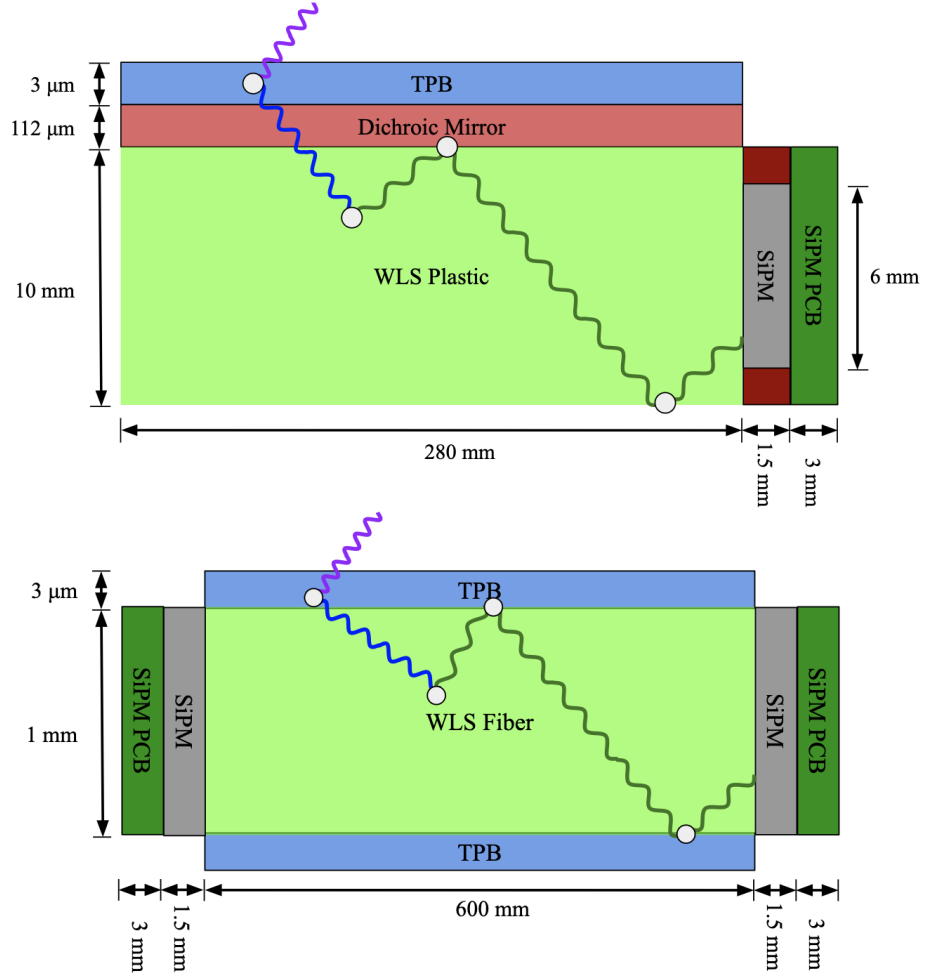


Figure 2.11: ArcLight (top) and LCM (bottom) light trap diagrams [13].

# Chapter 3

## ND-LAr Charge Readout Firmware

### 3.1 Signal Digitization in the LArPix ASIC

The transition from a physical ionization signal to a digital data stream begins at the pixel anode, where the LArPix ASIC [63] is mounted directly behind the sensor plane. When ionization electrons drift to a pixel, they induce a current on a dedicated input channel on the LArPix. The signal chain begins with a charge sensitive amplifier (CSA), which integrates the collected charge  $Q$  onto a feedback capacitor  $C_f$ , producing a voltage pulse:

$$V_{out}(t) \approx \frac{Q_{in}}{C_f} \cdot e^{-t/\tau} \quad (3.1)$$

where  $\tau$  is the decay constant of the feedback network. This analog voltage is then monitored by a high-speed discriminator.

As mentioned in the previous chapter, a key aspect of the LArPix architecture is its event-driven nature, where each of the 64 channels on an ASIC operates independently [63]. When the output of the CSA crosses the programmed threshold, a trigger is generated internally for

### Approach: Amplifier with Self-triggered Digitization and Readout

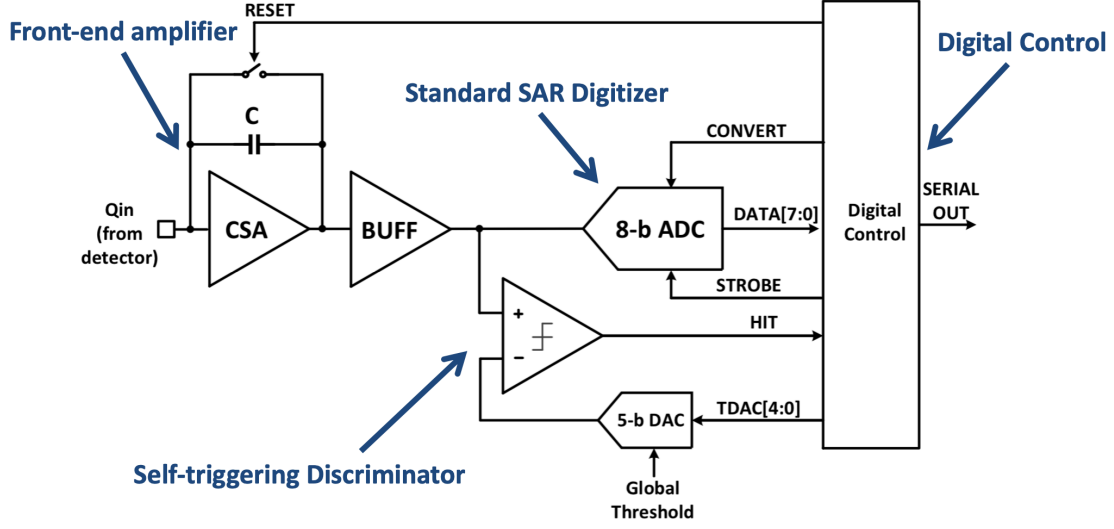


Figure 3.1: Schematic of the LArPix v2 circuit. [63]

that specific channel. This trigger initiates a 8-bit (10-bit in the newer v3 chip) Successive Approximation Register (SAR) Analog-to-Digital Converter (ADC). The SAR ADC is chosen for its low power consumption ( $< 100 \mu\text{W}$  per channel), which is critical to avoid boiling the surrounding liquid argon, an important consideration given the amount of channels in the detector [10]. At the moment of the trigger, the ASIC latches the value of its internal 31-bit local counter. This local counter is periodically synchronized using a 1 Hz reference pulse or an optical timing reference for the global DUNE clock, which will be expanded upon in 3.4.

Once a channel has completed digitization, the data is encapsulated into a LArPix-format packet. This packet contains the essential physics information required for reconstruction such as channel ID, chip ID, ADC dataword, timestamp, and a type word differentiating data from configuration or clock synchronization packets [63]. These packets are transmitted out of the ASIC using a custom asynchronous serial protocol, called the Hydra Network [63]. The Hydra Network allows each ASIC to communicate with any of its four physical neighbors. Moreover, it allows for signal re-routing in situ, mitigating issues from full FIFOs and malfunctioning chips. This behavior is precisely why an FPGA is required to control



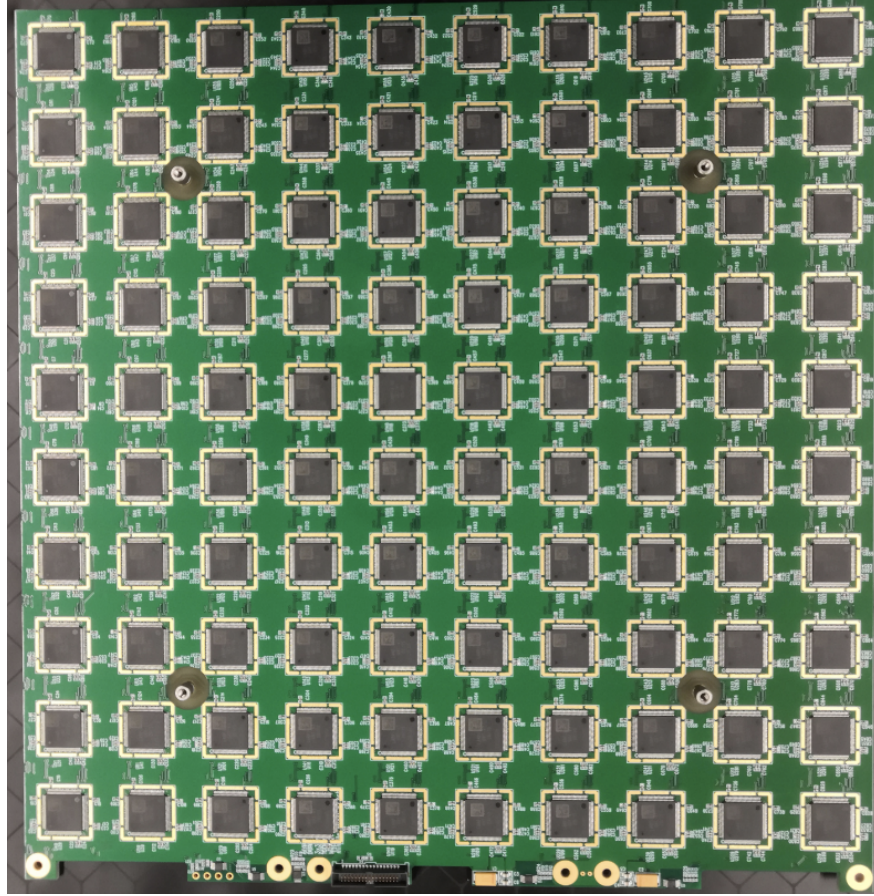


Figure 3.2: Back of LArPix pixel tile, showing the ASICs. The Hydra Network allows the user to re-route the data stream through different chips before reaching a tile output channel [13].

the LArPix readout. The controller must be ready to receive, buffer, and timestamp packets from many ASICs at any nanosecond, without the overhead of a polling-based processor.

## 3.2 PACMAN Controller

The high occupancy environment of the DUNE Near Detector requires a readout architecture capable of managing thousands of independent, self-triggering channels [10]. The PACMAN (Pixel Array Controller and Network) serves as the primary interface between the LArPix-based pixel anodes and the data acquisition (DAQ) system. The PACMAN board handles several critical functions such as providing low-noise analog and digital power to the LArPix



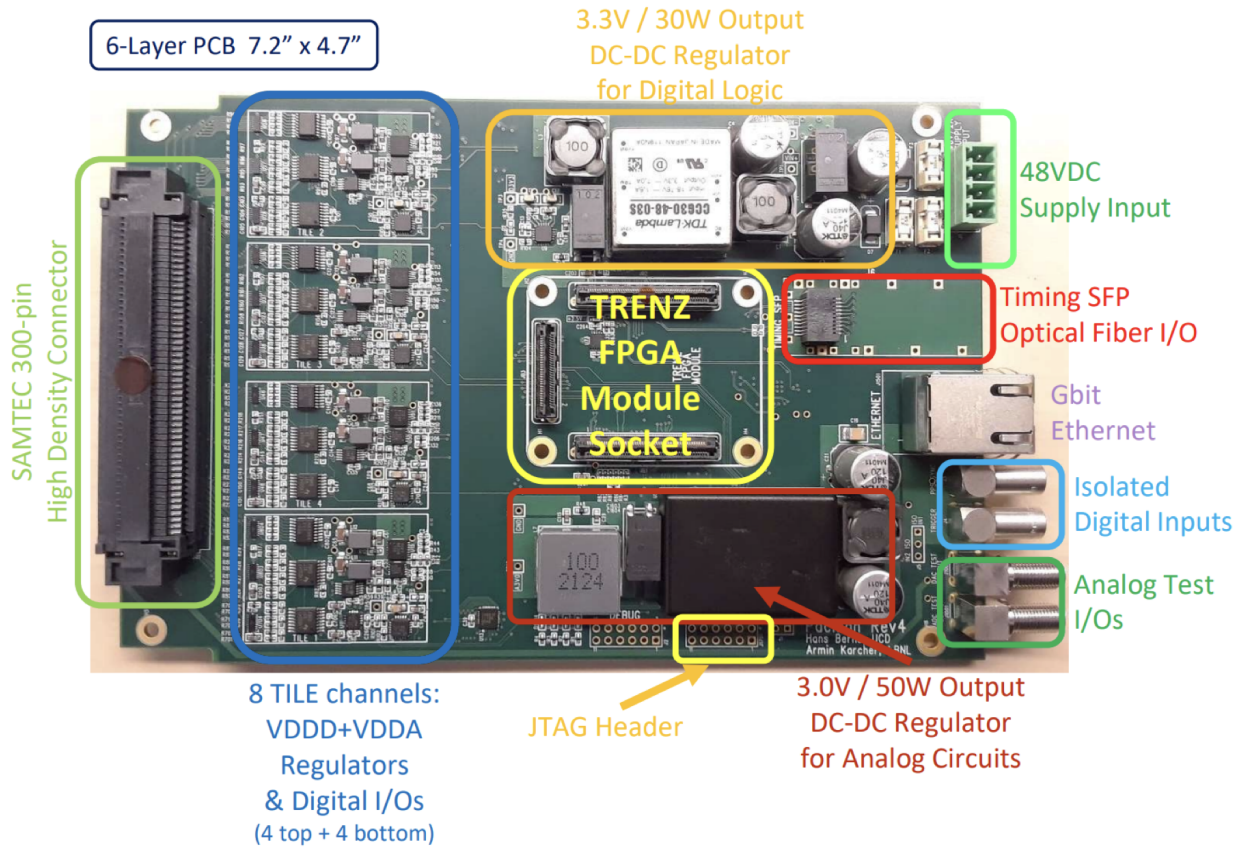


Figure 3.3: PACMAN rev4 with its components labelled.

ASICs, collecting data packets from multiple LArPix tiles and distributing a common clock and global timestamp to ensure every captured ionization event is recorded with high fidelity.

The heart of the PACMAN board is the Xilinx Zynq-7000 series SoC (System-on-Chip) manufactured by AMD. This device integrates a Processing System (PS), consisting of a dual-core ARM Cortex-A9 processor, with Programmable Logic (PL), consisting of the FPGA fabric. FPGAs allow you to instantiate independent logic slices for every single data stream, which do not compete for computing resources because they are distinct hardware circuits. The PL consequently excels at time-critical tasks such as managing the Hydra Network and clocks. The PS runs an embedded Linux environment, which manages "slow control" tasks such as configuring registers via the AXI-Lite bus and packaging data for transmission over Ethernet.

### 3.3 Firmware Architecture

The PACMAN firmware is written in VHDL, with its first iteration created by Peter Madigan at LBNL and further refinements under development at UCI and UC Davis [99]. The primary responsibility of the firmware is to manage the bidirectional UART (Universal Asynchronous Receiver/Transmitter) communication with the LArPix ASICs across a pixel tile, while maintaining synchronization with external trigger and timing. The firmware establishes a data-flow boundary between the PS and PL, mediated by a Direct Memory Access (DMA) engine and an AXI-Lite register interface. This allows the PS to not only probe registers in the FPGA fabric, but also send Transmit (TX) configuration commands and LArPix write packets [99]. The DMA engine streams these commands into channel-specific TX FIFOs before they are serialized and transmitted via UART.

To package all the incoming physics data, a Datastream Merge FIFO ( $4096 \times 16$  B) aggregates the data streams from the eight Shared RX FIFO groups, the physical trigger logic, and the timing synchronization block. Receive (RX) Packets generated by the ASICs are deserialized by the UART receivers. To optimize resource utilization on the FPGA, every group of four UART channels shares a local shared RX FIFO [99]. These streams are then consolidated into the Merge FIFO alongside trigger and synchronization data before the DMA engine transfers the merged blocks into the PS DDR RX memory buffer [99].

Nominally, timing in the PACMAN is referenced to an internal 10 MHz oscillator. When operating on this native clock, the PACMAN controller generates hardware timestamps using a free-running counter implemented within the Zynq's PL. The counter increments on every rising edge of the oscillator yielding a 100 ns time resolution. As raw data packets arrive, the firmware adds the current counter value, packages them with metadata, and streams them downstream via AXI DMA for reconstruction.

### 3.4 Integration of the DUNE Timing System Endpoint

DUNE requires a unified timing distribution system to synchronize hardware spanning both the Near and Far sites. The DUNE Timing System (DTS) [58] was developed at the University of Bristol following their successful timing implementation in the ProtoDUNE detector, using the earlier PDTS timing IP [57]. The DTS provides a high-precision reference clock running at a frequency of 62.5 MHz with jitter  $< 12$  ps as well as a global 64-bit timestamp to all DUNE detector subsystems, including ND-LAr. A primary focus of this work was the integration of the DTS Endpoint IP into the PACMAN firmware.

The DTS architecture is a hierarchical tree-based structure. At the "root" of the system is a Global Positioning System (GPS) disciplined clock, which anchors the experiment to Universal Coordinated Time (UTC). This provides the golden reference for the whole timing system. The timing information is encoded using a custom synchronous protocol over a serial link. The DTS IP recovers the global master clock and absolute timestamps from the incoming optical timing fiber via a Small Form-Factor Pluggable (SFP) transceiver. The transmission of clock, data, and fast commands from the central DTS master to local client endpoints (such as the PACMAN board) is carried over a single-mode bidirectional optical fiber link (1000Base-BX). Instead of relying on standard commercial clock and data recovery (CDR) protocols, the DTS utilizes a custom physical-layer protocol based on Duty Cycle Shift Keying (DCSK) combined with 8b/10b encoding to guarantee DC-balance on the line.

In the DCSK protocol, a serial stream is transmitted at a rate of 62.5 Mbit/s, perfectly matching the 62.5 MHz reference clock frequency. Each bit period contains a single pulse: 0 is represented by a pulse with a 25% duty cycle while 1 is represented by a pulse with a 75% duty cycle [58]. A low-jitter PLL on the endpoint can lock directly onto the incoming pulse's rising edges, extracting a consistent clock.

To establish timestamp alignment across separate detector modules, the DTS relies on a

propagation delay calibration. Each optical link uses two distinct wavelengths of light, 1310 nm for downstream (master-to-endpoint) and 1490 nm for upstream (endpoint-to-master) transmission, to communicate over a single physical fiber. During initialization, the timing master commands the endpoint to transmit loopback packets. The master measures the round-trip propagation delay, calculates the precise physical link latency, and instructs the endpoint’s hardware clock management to shift the phase of its local clock.

### 3.5 Firmware Build

The hardware logic is defined using VHDL and synthesized in Xilinx Vivado, while the software environment is nominally built using the PetaLinux toolkit in Vivado to ensure the Linux kernel is aware of the specific memory maps and IPs defined [127]. The firmware workflow is as follows. First, firmware source code and constraint files (.xdc) are pulled from version control and used to recreate the Vivado project. In the next step, the high-level VHDL code is synthesized into a list of logic blocks (Look Up Tables, Flip-Flops, and DSP slices) specific to the FPGA architecture. Next, Vivado performs placement and routing, mapping the blocks onto the physical FPGA fabric while ensuring all hardware and timing constraints are met. This is known as implementation. Once implementation is closed, a compressed bitstream (.bit) is generated. The hardware design is then exported as a .xsa file, which includes the Register Transfer Level (RTL) parameters and PS configuration.

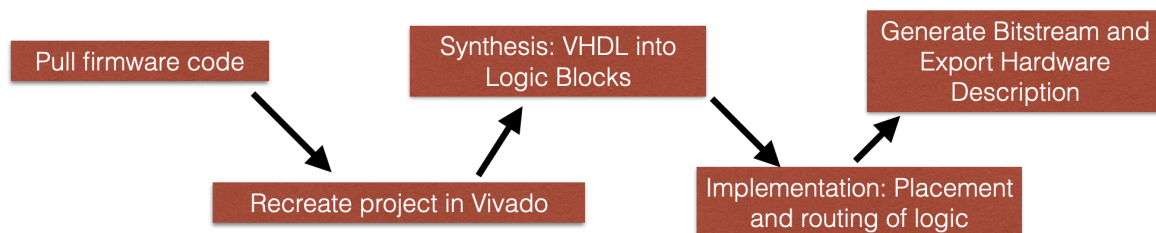


Figure 3.4: Flowchart of firmware build procedure in Xilinx Vivado tools.

## PetaLinux

The PetaLinux OS workflow consumes the hardware description and automates the generation of the first stage bootloader (FSBL), U-Boot script, and the Linux kernel. A new PetaLinux project is initialized, typically using a Board Support Package (BSP) provided by the manufacturer for the Zynq 7 family of FPGAs to ensure basic peripherals such as the Ethernet port are configured. When the `petalinux-config --get-hw-description` command is called, pointing to the `.xsa` file generated in the firmware flow, the device tree is updated, mapping FPGA-side IP (such as the timing endpoint) into the processor's memory space. The developer modifies the kernel boot arguments and selects required packages (e.g., Python, SSH, ZMQ) using a GUI to then generate a root file system (rootfs). The project is then compiled into a set of images. Finally, the `petalinux-package` command combines the bitstream, FSBL, and U-Boot into a single `BOOT.BIN` file, which is used to program the board's non-volatile memory or SD card.

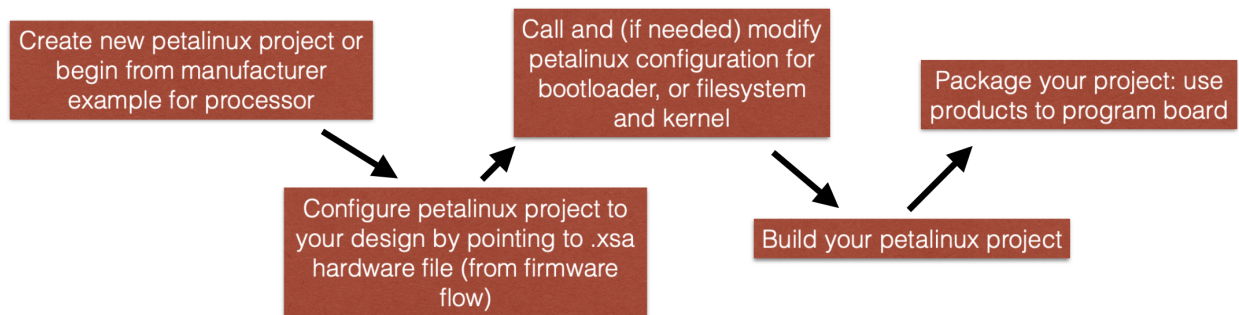


Figure 3.5: Flowchart of PetaLinux image build procedure in Xilinx Vivado tools.

## Debian 10 for ARM

The Xilinx Zynq-7000 SoC utilizes a dual-core ARM Cortex-A9 processor, as described earlier in Section 3.2. To provide a robust environment for complex DAQ software and firmware management, a full Debian-based Linux distribution was ultimately selected over a minimal Petalinux implementation. This choice enables the use of the `apt` package manager, facilitating the integration of complex libraries.

In this workflow, the rootfs is cross-compiled and built using the `debootstrap` utility on an `x86_64` host machine. This process ensures a clean, minimal installation of the Ubuntu 'Focal' or Debian 'Buster' distributions tailored for the `armhf` (ARM Hard Float) architecture.

The construction follows a two-stage process to account for the architecture mismatch between the host (work computer) and the target (PACMAN). First, the base system is downloaded and unpacked into a local directory. To allow the host to execute ARM-based binaries during the configuration phase, the `qemu-arm-static` interpreter is used in the root directory. Then, after going into a `chroot` (change root) environment, the second stage of `debootstrap` is executed. This installs the essential base packages and configures the package management system within the ARM environment without affecting the host configuration.

Once the base system is established, the environment is populated with the necessary tools for data acquisition and hardware debugging. The `libzmq3-dev` library was installed to support ZeroMQ-based (ZMQ) messaging [80]. ZMQ integration is paramount for the PACMAN, as it allows for the high-throughput, low-latency transmission of LArPix data packets to the DAQ servers. Tools such as `i2c-tools` are included for low-level communication with the PACMAN's onboard power monitoring and sensors. Standard tools including `gcc`, `git`, and `python3` are included to allow for compilation of diagnostic scripts and firmware loading utilities. The rootfs is then packaged in an SD card, along with the boot binaries, scripts and device tree blob from the manufacturer to provide the board with all products necessary for bring-up.

## 3.6 Optical Timing Testbench and Firmware Validation

To validate the DTS integration before deployment in a ND-LAr prototype, an optical timing testbench was developed. This setup simulates a potential LBNF timing master and allows

for the characterization of the PACMAN’s timing under realistic resource pressures.

### 3.6.1 Testbench Components

The testbench design revolves around a Scientific Linux 7 server, which is used to run the DUNE DAQ software [62]. Its configuration matches the container images in the DUNE-DAQ/daq-docker git repository. This includes mounting the `dunedaq.opensciencegrid.org` repository through the CERN Virtual Machine File System (CVMFS), which allows access to version control of the DAQ software. The software is built against the desired DTS version in order to create a DTS virtual work area, enabling the `dtsbutler` utility used for control and monitoring of the timing system [62]. Because of latency concerns with packets transmitted through the UC Irvine network on a DHCP lease, a private Peer-to-Peer network is implemented using this server as host with IP address 192.168.1.16 to handle communication with the timing master through Ethernet.

The Enclustra PM3 board is based around an Artix-7 FPGA of the same Zynq 7 series as the FPGA utilized in the PACMAN. Combined with its AX3 carrier board, which adds peripherals, it is a low cost choice for a timing master. Using a JTAG-USB programming cable from Xilinx, the board is flashed with timing master firmware produced by the University of Bristol through the Vivado hardware manager utility. The optical signals are transmitted and received by the optical SFPs mounted on custom pc053/pc069a Timing FPGA Mezzanine Carrier (FMC) boards, installed on the timing master using a Samtec connector. A minimal processing system allows for the reading and writing of a configuration register through JTAG, which in turn allows specifying the IP address of the timing master as a hexadecimal value. The IP is set to 196.168.1.15 to match the address space of our private network using the `screen` utility at a baud rate of 19200. Ethernet communication between the server and timing master board is handled using a TCP protocol.

Timing signals are shared between master and endpoints using optic fibers. In order to



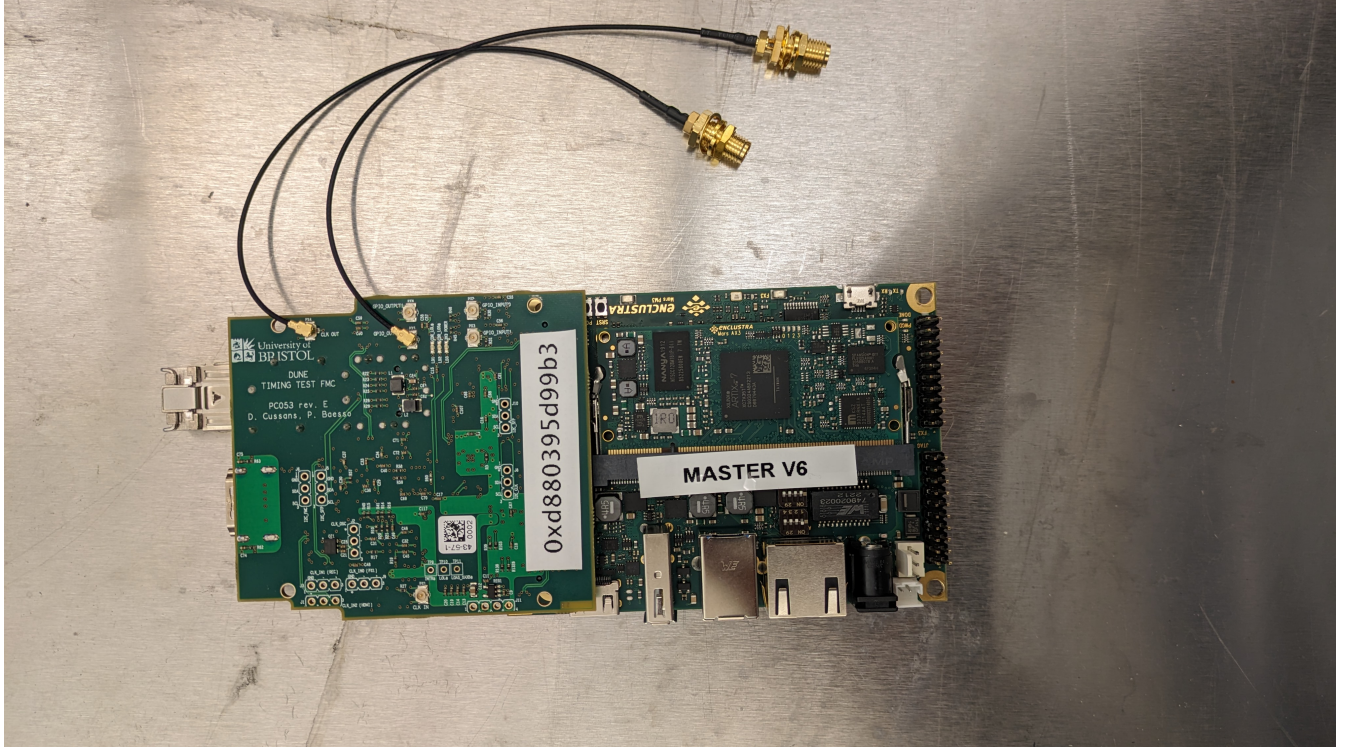


Figure 3.6: Enclustra PM3+AX3 with a pc053 FMC installed.

send signals from a single master to multiple PACMAN, a Fiberstore 1x4 Planar Lightwave Circuit Splitter is used to split the signal into four distinct fibers. Slow controls for the PACMAN are managed through Ethernet using a separate computer on the UCI network, in this case a firmware compilation server running Ubuntu in our laboratory.

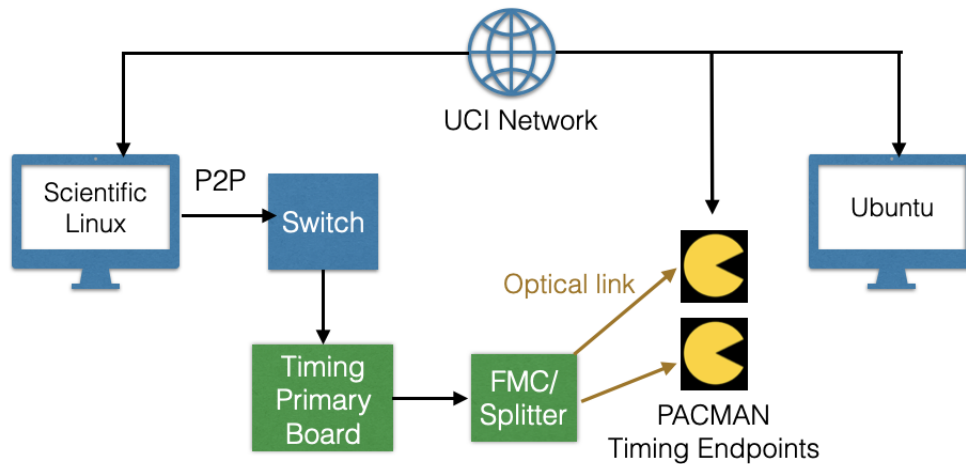


Figure 3.7: Schematic of the optical timing testbench used for PACMAN validation.



### 3.6.2 Testbench Operation

A testbench run begins by booting and configuring the timing master into its operational state using `dtsbutler`. The master begins broadcasting an idle pattern over the optical fiber to establish synchronization. Next, `dtsbutler` is used to query the status of the local SFP transceiver on the PACMAN board. Once a physical link is established, the internal DTS endpoint IP block on the PACMAN transitions through its multi-tiered initialization sequence [62]:

1. **Hardware Reset:** The timing master FMC hardware is reset to ensure all physical-layer components, PLLs, and transceivers start from a known, clean state:

```
dtsbutler -c connections.xml io MST_FMC reset
```

2. **Synchronization:** Once reset, the master's internal time is latched and aligned to the external reference clock, initiating the distribution of the 64-bit timestamp:

```
dtsbutler -c connections.xml mst MST_FMC synctime
```

3. **Phase and Latency Alignment:** Finally, the master measures the round-trip propagation delay across the fiber. This measurement is used by the timing master to calculate and apply the precise phase shifts required to guarantee that the endpoint clocks are perfectly aligned with the master clock. This step changes the status register for 0x6 to 0x8, announcing the timing is not only locked and running but phase-aligned as well:

```
dtsbutler -c connections.xml mst MST_FMC align /  
apply-delay 0x0 0x0 0x0 --force
```

Here, the `connections.xml` file specifies the IP addresses of all machines in your timing system, and the `MST_FMC` string specifies the master design defined by the master firmware. With the completion of this loopback alignment cycle, the PACMAN board's clock recovery and event timestamping remain synchronized with sub-nanosecond precision relative to the master node. In the current PACMAN firmware architecture, the timing register space has been mapped to the base address `0x5003_0000` in the AXI-Lite address space [99].

Table 3.1: PACMAN Timing Memory Map (Base Address `0x5000_0000`)

| Offset  | Register Name                         | Access | Description                                                                                             |
|---------|---------------------------------------|--------|---------------------------------------------------------------------------------------------------------|
| 0x00014 | Loopback Mode                         | R/W    | Controls internal TX-to-RX path routing. Write <code>0x2</code> to enable loopback mode.                |
| 0x01010 | Clock Select ( <code>Clk_sel</code> ) | R/W    | Selects hardware timing clock source.<br>0 = SoC clock<br>1 = DTS clock                                 |
| 0x30000 | Endpoint Status                       | R      | DTS state machine status. Value <code>0x8</code> indicates phase-aligned RUN state.                     |
| 0x30004 | Endpoint Debug                        | R      | Physical layer diagnostics (PLL lock, RX alignment, SFP LOS).                                           |
| 0x30008 | Signal Debug                          | R      | Checks if incoming timing clock signal is active. Returns <code>0x96</code> when link signal is stable. |
| 0x3000C | Timestamp Low                         | R      | Lower 32 bits of DTS timestamp.                                                                         |
| 0x30010 | Timestamp High                        | R      | Upper 32 bits of DTS timestamp.                                                                         |
| 0x30030 | Endpoint Reset                        | R/W    | Controls the timing block reset. Write <code>0x1</code> to reset, <code>0x0</code> to release.          |

After configuring the master to send optical timing signals, the endpoint from can be configured from the PACMAN by manipulating this register space, starting with changing the hardware clock to the DTS by using a utility such as `busybox devmem` to write a 1 to `Clk_sel`:

```
root@pacman-v4:~# busybox devmem 0x50001010 32 1
```

Then, the timing endpoint block must be taken out of reset by writing a 0 :

```
root@pacman-v4:~# busybox devmem 0x50030030 32 0
```

Finally, the state of the timing block can be checked:

```
root@pacman-v4:~# busybox devmem 0x50030000  
0x00000008
```

### 3.6.3 Loopback Testing

To validate the digital pathways of the PACMAN firmware without requiring physical LArPix ASICs or detector tiles, the firmware implements a hardware loopback mechanism that directly routes the transmitter (TX) path back to the receiver (RX) path. This feature enables complete end-to-end testing of the digital datapath with either the internal SoC and DTS clocks running.

#### Prerequisites and Server Initialization

Before initiating loopback testing, both the command server (`pacman_cmdserver`) and data server (`pacman_dataserver`) must be running. These executables reside in the server installation directory and must be built using the local `make` utility inside the board. Due to direct hardware access requirements, both servers must be executed with root privileges in separate terminals:

```
# Terminal 1: Start the data server
```

```
root@pacman-v4:~# sudo ./pacman_dataserver
```

```
# Terminal 2: Start the command server
```

```
root@pacman-v4:~# sudo ./pacman_cmdserver
```

Once running, the data server will continuously output available datastream metrics, while the command server will enter a polling loop waiting for incoming ZMQ requests on port 5555.

## Enabling Loopback Mode

Configuring the PL for loopback operation is done by interacting with the PACMAN configuration registers via the `pacman_util.py` script. First, loopback mode must be enabled in firmware:

```
root@pacman-v4:~# ./pacman_util.py --write 0x14 0x2
```

As before, the PACMAN firmware must be brought out of its reset state. By default, this utilizes the internal SoC clock source:

```
root@pacman-v4:~# ./pacman_util.py --write 0x30030 0
```

but the DTS clock can be used as well:

```
root@pacman-v4:~# ./pacman_util.py --write 0x30030 1
```

## Verifying Datastream

To verify the loopback connection, an RX monitoring process must be spawned in a separate terminal to capture loopback packets published by the data server on port 5556. Use the `--rx` flag to print up to N incoming packets listened over up to T seconds:

```
root@pacman-v4:~# ./pacman_util.py --rx N -t T
```

With the RX monitor active, transmission tests can be performed using the `--tx` flag. To broadcast a test word simultaneously across all UART channels, the broadcast destination address `0xff` can be used:

```
root@pacman-v4:~# ./pacman_util.py --tx 0xff 0xbabecafedeadbeef
```

Upon transmission, the RX monitor terminal should immediately report `0xbabecafedeadbeef` on all channels due to the active loopback. For channel-by-channel validation, individual

UARTs can be addressed. The `--tx` channel variable is an 8-bit word where the lower 4 bits (0 to 3) indicate the UART channel index and the upper 4 bits indicate the tile index. For instance, to target Tile 4, Channel 2, the addressing byte is `0x42`. The loopback transmission is executed as:

```
root@pacman-v4:~# ./pacman_util.py --tx 0x42 0xbabecafedeadbeef
```

The RX monitor will report the successful reception of the packet specifically on the looped-back Tile 4, Channel 2.

### 3.6.4 10 MHz Tile Clock Validation

While the DTS provides timing at 62.5 MHz [58], the LArPix ASICs on the tiles require a 10 MHz clock frequency for their internal timestamps [63]. To resolve this mismatch, a dedicated clock frequency conversion module is implemented within the PACMAN firmware. The recovered 50 MHz clock from the DTS endpoint is routed to a frequency divider block. This digital divider performs a strict operation to generate a phase-aligned 10 MHz clock dedicated for LArPix [99].

To experimentally validate this firmware-derived clock, the 10 MHz signal was routed in firmware to a physical diagnostic test point on the PACMAN board. A Tektronix Series 3 high-bandwidth digital oscilloscope was connected to the test point using a low-capacitance active probe. The oscilloscope measurements confirmed a signal with a stable mean frequency of 9.995 MHz and a symmetric square wave profile, slightly distorted due to mechanical disturbances caused by holding the probe by hand. This physical verification confirmed that the division logic implemented in the VHDL firmware successfully creates a 10 MHz reference clock from the DTS timing network for the anode tiles.



Figure 3.8: Bench measurement of the 10 MHz tile clock signal, with mean, maximum and other information provided by the oscilloscope.

### 3.7 Outlook

The timing testbench confirmed the successful integration of the DTS endpoint IP to the PACMAN board, marking a first step towards the operation of a ND-LAr prototype with DTS timestamps. Nevertheless, critical work remains to be done to reach this goal. The LArPix ASIC is under active development, which means that design changes requiring firmware accommodations may be necessary in the near future. The DUNE-DAQ and timing teams are also finalizing the deployment version of their software and firmware. While significant changes are unlikely, new versions are based on newer platforms. For example, the base OS has changed from Scientific Linux, now past its end-of-life, to AlmaLinux 9. The firmware, as well as the testbench, must be updated and validated to these changes in order to support modern DTS workflows.

Finally, as it exists now, the ND-LAr timing system is a collection of free standing electronics boards and components unfit for deployment. A prototype rack unit, shown in Figure 3.9, was put together at LBNL based around the timing testbench described in this chapter. A

rackmount assembly like it could provide a unified solution to run DTS in a future ND-LAr prototype run.

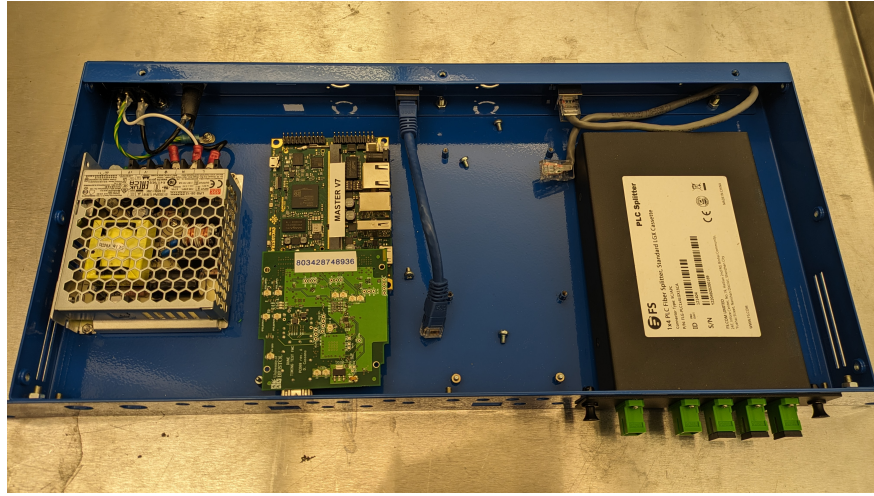


Figure 3.9: Prototype timing rack built at LBNL including Enclustra PM3+AX3 timing unit, Ethernet out, and optic fiber splitter as well as a power supply for all components that require it. A single rack can synchronize timing for 4 PACMAN boards.

# Chapter 4

## Minimally-Ionizing Particle Charge-Scale Calibration in ND-LAr Prototypes

In the previous chapter, the instrumentation required to get signals off the pixel anode was described. The natural step to take now is calibration: comparing the read charges produced by a well understood source in order to tune the detector response and extract physical observables with as minimal bias as possible.

As written in Section 2.3.2, for relativistic particles with  $\beta\gamma \approx 3$ , the mean energy loss per unit length lies in the minimum of the Bethe-Bloch formula, roughly 2.12 MeV/cm for a MIP in LAr. Because this value is only weakly sensitive to small fluctuations in particle momentum, any observed variations in the measured charge per unit length ( $dQ/dx$ ) can be attributed to detector-specific effects rather than the underlying physics of the particle kinematics. Moreover, the high flux of cosmic muons at MIP momentum on the surface provides a high statistics and free data sample. As a result, the study of the charge deposited



per unit length by cosmic MIPs in a LArTPC provides a uniquely controlled opportunity to assess the charge response of a detector. This chapter will describe some of the latest DUNE ND-LAr prototypes as well as an analysis of their charge scale.

## 4.1 ND-LAr Prototypes

### 4.1.1 The 2x2 Demonstrator

The 2x2 Demonstrator serves as the primary prototype for the Deep Underground Neutrino Experiment (DUNE) Near Detector Liquid Argon TPC (ND-LAr). Deployed in the MINOS Near Detector hall at Fermilab on the Neutrinos at the Main Injector (NuMI) beamline, the  $2 \times 2$  was designed to demonstrate the modular LArTPC concept and pixelated charge readout in a high-intensity, high-multiplicity neutrino beam environment [2].

The detector consists of a 2x2 array of four modular LArTPCs, providing a total active liquid argon mass of approximately 3 t with an active volume measuring  $1.34 \text{ m} \times 1.34 \text{ m} \times 1.40 \text{ m}$  [2]. Each module contains a central cathode operating at high voltage that divides the module into two optically-separated opposing drift regions with a maximum drift distance of 33 cm. The anode planes are instrumented with LArPix-v2/v2b ASICs, featuring a 4.43/3.88 mm pixel pitch. The v2b ASICs are installed in Module 2 only. Across the four modules, a total of 327,680 individual charge-sensitive pixels continuously stream ionization data with low noise ( $\text{ENC} < 1000 \text{ e}^-$ ). Each module utilizes two complementary photon detection systems designs to detect scintillation light and establish event  $t_0$  as described in 2.5.1.

The 2x2 is placed between repurposed MINERvA scintillator planes, named Mx2 [2]. The upstream MX2 planes serve as an active veto against beam-induced backgrounds and rock muons originating in the surrounding hall, while the downstream planes function as a spectrometer. By tracking charged particles that exit the active liquid argon volume, MX2

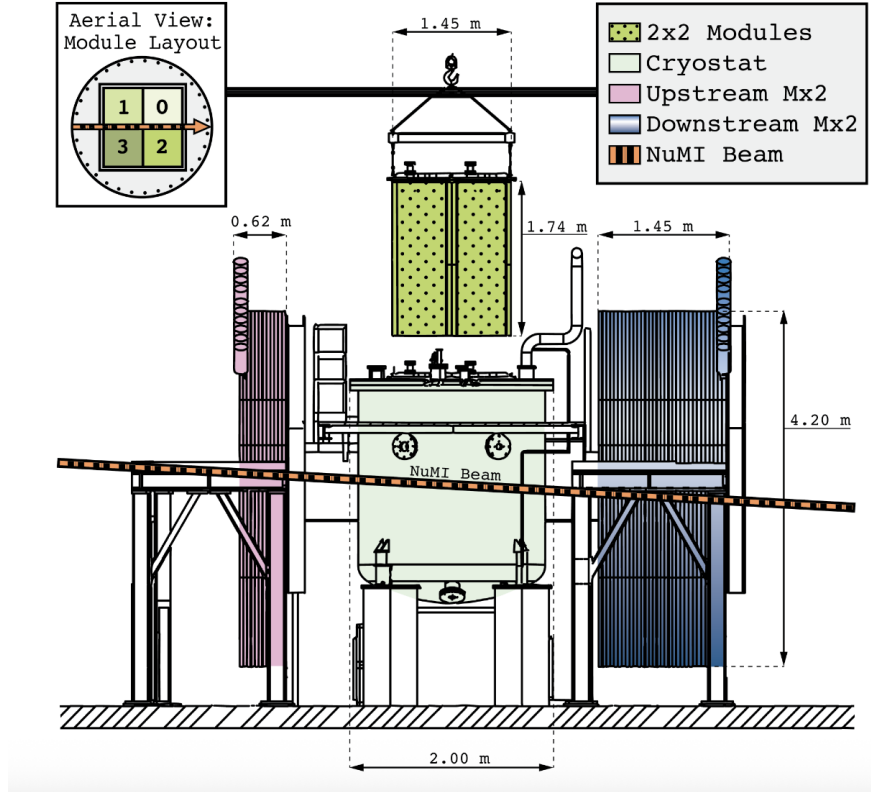


Figure 4.1: Diagram of 2x2 with the Mx2 planes and beam orientation included. Image obtained from [2].

enables momentum reconstruction via range and multiple Coulomb scattering, effectively extending the acceptance and particle containment capability of the 2x2 Demonstrator and mirroring the hybrid design of the ultimate DUNE Near Detector.

During its initial physics operational period (Run 1) during July 2024, the 2x2 took 4.5 days of physics quality data in the NuMI beam as well as beam-off data. A follow-up Run 2 was performed the following year using radioactive sources outside the detector. These runs successfully validated the 3D track reconstruction capabilities of pixelated anodes, track matching across modules, the HV stability of field cages, and the rejection of cosmic-ray and beam-induced backgrounds prior to scaling the technology to the full ND-LAr size.

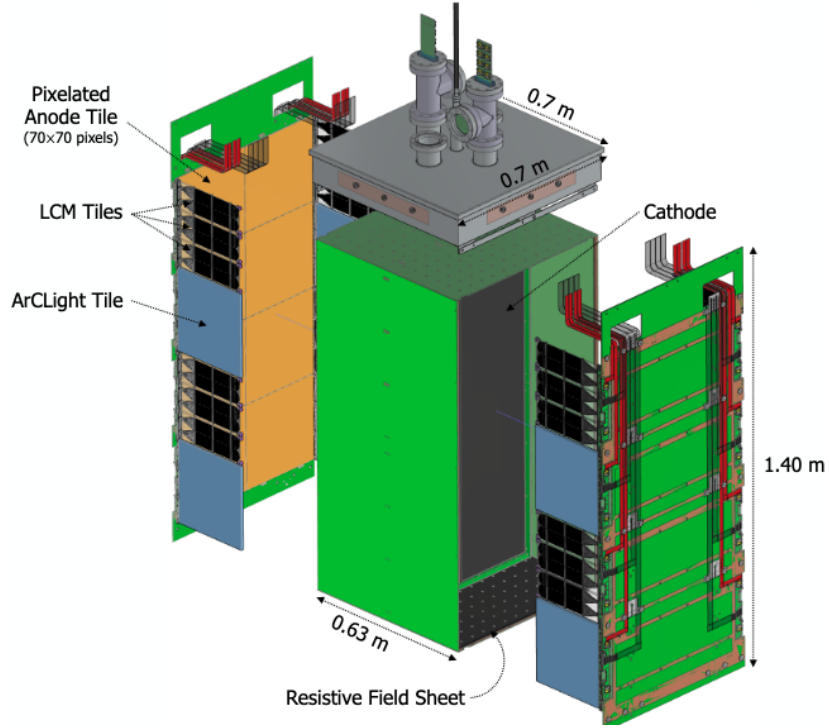


Figure 4.2: Diagram of exploded 2x2-era ND prototype TPC. It is roughly 0.6x the height of a full-scale TPC. Image obtained from [13].

#### 4.1.2 FSD

The Full Scale Demonstrator (FSD) is the final prototype detector for the validation of the ND-LAr design. Operating as a standalone dual-TPC module with dimensions matching the ultimate ND-LAr specifications ( $1 \text{ m} \times 1 \text{ m} \times 3 \text{ m}$  active volume), the FSD scales up the pixelated anode readout utilized during the 2x2 Demonstrator runs [2].

The FSD features a total active volume of  $2.74 \text{ m}^3$  of liquid argon, instrumented with a  $6 \text{ m}^2$  active anode surface area. This anode plane is tiled with 20 modular LArPix PCB tiles, each measuring  $30 \text{ cm} \times 48 \text{ cm}$ . In total, the system contains 409,600 charge-sensitive pixels placed at a 3.7 mm pitch, increasing both the channel count and density compared to 2x2 modules. It similarly features ArcLight and LCM photon detectors for scintillation light detection.

From the perspective of the charge readout, the primary technological advancement of the

FSD is the integration of the LArPix v2d system, which increased the charge bit depth to 10 bits using a new ASIC design. During its run at the University of Bern in November 2024, the FSD continuously streamed cosmic ray data at the surface, recording over 70 million events. This run demonstrated exceptional low-noise performance, achieving an ENC of less than  $530\ e^-$ .

### 4.1.3 FSD-Cube

Unfortunately, the ASIC manufacturer processed the v2d production order incorrectly, installing twice the amount of Metal-Insulator-Metal capacitors. This led to twice the value in the CSA capacitor, halving the gain and in turn biasing the pedestal and set thresholds. As a consequence, the charge scale of the FSD run is not representative of future ND-LAr operations, as both the nominal and low-setting thresholds were too high. The fact that the FSD was decommissioned once this was discovered created a need for another prototype run with revised hardware. For this purpose, a new ASIC design (LArPix v3a) was produced and installed in the **FSD-Cube**, operated specifically for testing at LBNL.

The FSD-Cube is a single TPC with active drift dimensions of approximately  $50\text{ cm} \times 50\text{ cm} \times 32\text{ cm}$ , halving the x (drift) and z dimensions from the FSD while being approximately 1/12 the height of the FSD. It does not count with light detectors. Instead, plastic scintillator pads are placed on top of the detector in order to provide an initial event time for cosmic muons. The pads do not cover the full extent of the detector, causing a selection inefficiency at high drift times, as shown in Figure 4.3. It is designed to act as a testbed for a single, 10,240-pixel LArPix anode tile rather than the 10 tiles present in a single ND-LAr TPC.

Running the FSD-Cube at LBNL allowed for studies of the drift properties and charge calibration under a uniform electric field of up to  $0.25\text{ kV/cm}$ , half the nominal electric field of the FSD. Most importantly, the improved understanding of the new v3 hardware allowed FSD-Cube runs to take data under more realistic conditions, allowing for improved studies

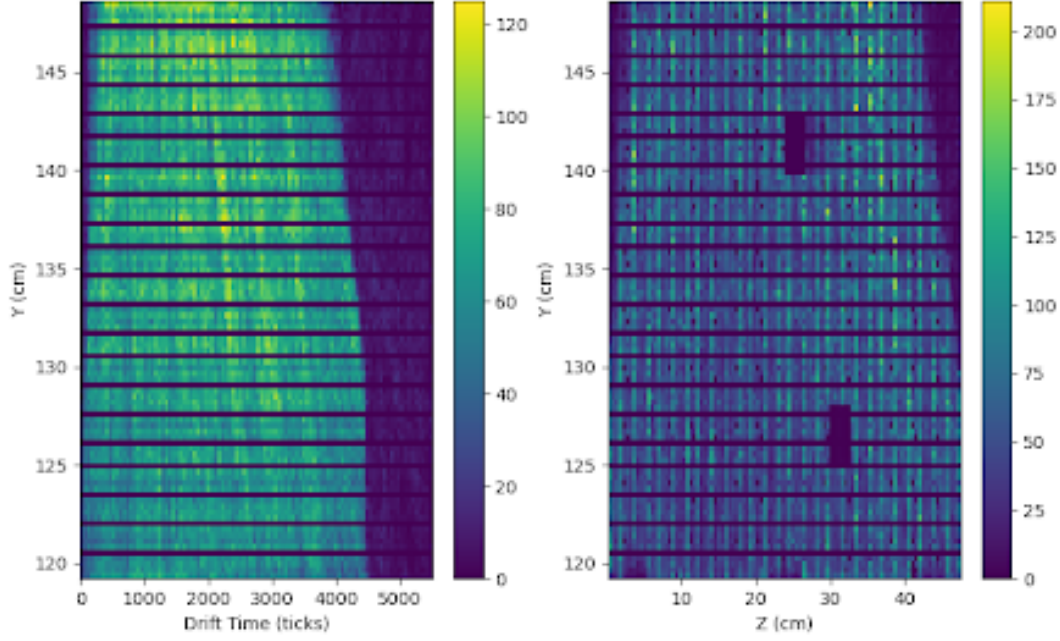


Figure 4.3: Two-dimensional distributions of hit Y vs. drift time and y vs. z, where each clock tick represents  $0.1 \mu s$ .

of the charge scale.

## 4.2 Input Data

The input datasets utilized in this analysis comprise both experimental data and Monte Carlo simulated samples. For simulated events, the cosmic-ray muon flux at the detector locations is simulated using `CORSIKA` [79]. Particle interactions and ionization energy deposits are then generated with `edep-sim`, a Geant4 wrapper, and passed to `larnd-sim`, a dedicated GPU-accelerated simulation package for LArTPCs [32]. It simulates the physical processes within the detector volume before modeling the response of the LArPix readout.

### 4.2.1 Digitization and Simulation with `larnd-sim`

During the front-end electronics simulation in `larnd-sim` and natively in the LArPix ASIC, drift electrons collected by a pixel are converted into digital values. The analog signal voltage  $V_{\text{signal}}$  resulting from the integrated charge  $Q$  is given by:

$$V_{\text{signal}} = (Q \times g) + V_{\text{pedestal}} - V_{\text{cm}} \quad (4.1)$$

where  $g$  is the channel gain in  $\text{mV}/e^-$ ,  $V_{\text{pedestal}}$  is the channel baseline voltage configuration, and  $V_{\text{cm}}$  is the common-mode voltage. This analog voltage is digitized into an integer dataword, with resolution defined by the ADC's Least Significant Bit (LSB):

$$\text{LSB} = \frac{(V_{\text{ref}} - V_{\text{cm}}) \times F_{\text{ADCscale}}}{2^{N_{\text{bits}}} - 1} \quad (4.2)$$

where  $V_{\text{ref}}$  is the reference voltage,  $F_{\text{ADCscale}}$  is the digital scaling factor, and  $N_{\text{bits}} = 10$  represents the 10-bit ADC resolution. The LSB is equivalent to 1 ADC count, and represents the smallest charge deposition or current that will cause a change in the quantized charge value. The resulting quantized integer dataword is then:

$$\text{ADC} = \text{floor} \left( \frac{V_{\text{signal}} - V_{\text{cm}} + V_{\text{pedestal}}}{\text{LSB}} \right) \quad (4.3)$$

bounded within the valid dynamic range  $[0, 2^{N_{\text{bits}}} - 1]$ . These digitized signals are formatted into LArPix data packets, with the simulation matching the format in data.

### 4.2.2 Basic Reconstruction with ndlar-flow

Packets coming from either the PACMAN or output from `larnd-sim` are reconstructed using the `ndlar-flow` software [48]. It is tailored to interpret and reconstruct the data packets from the LArPix datastream into HDF5 file storage. Packets' tile number, tile channel, chip, and channel number are mapped to the  $z, y$  position of the corresponding pixel. The missing  $x$  or drift coordinate is reconstructed from the packet's timestamp value. The software correlates this timestamp with the nearest synchronization message or external trigger packet to determine the clock cycle in which the channel fired, extracting the packet's arrival time  $t_{\text{arrival}}$ . The absolute event time  $t_0$  is then derived via cross-reference with prompt scintillation light or external trigger signals, like the scintillator pads in FSD-Cube or a beam trigger in ND-LAr. The difference  $t_{\text{arrival}} - t_0$  is the drift time  $t_{\text{drift}}$ , or the time it took the charge deposition to drift from the point of ionization to the pixel. Finally, the drift distance is calculated as:

$$x = x_{\text{anode}} \pm (t_{\text{drift}} \times v_{\text{drift}}) \quad (4.4)$$

where  $v_{\text{drift}}$  is the drift velocity of the detector, known from calibration or calculated from the applied electric field. The charge  $Q$  collected on the pixel is determined from the packet's 10-bit ADC value:

$$Q(\text{ADC}) = \frac{1}{g} \left[ \left( \frac{\text{ADC}}{2^{N_{\text{bits}}} - 1} \cdot F_{\text{ADCscale}} \cdot (V_{\text{ref}} - V_{\text{cm}}) \right) + V_{\text{cm}} - V_{\text{ped}} \right] \quad (4.5)$$

The  $Q, x, y, z$  objects reconstructed from packets are known as hits, as they represent charge depositions hitting the pixel. This calibrated hit information as well as geometry metadata is packaged in the HDF5 files.

## 4.3 MIP Selection Strategy

The code for the following track selection and analysis is available as the `nd-lar-mip-calib` package in GitHub [101].

### 4.3.1 Clustering of Hits

All hits included in an event are fed to DBSCAN (Density-Based Spatial Clustering of Applications with Noise) [66], a clustering algorithm that groups points that are closely packed together while marking points in low-density regions as noise, ideal for sparse data sets like those from LArTPC hits. The  $\epsilon$  parameter defines the maximum distance between two points for them to be considered as part of the same cluster, building a sphere of volume  $\frac{4\pi}{3}\epsilon^3$  around a given point. This is optimized to 20 pixel pitches or approximately 70 mm, which is large enough to bridge small gaps in the track caused by pixel thresholds but considerably smaller than the separation between distinct particle interactions. The minimum samples parameter is set to ensure that only significant charge depositions are considered in clusters. The neighborhood of a point  $\vec{p}$  in a dataset  $\mathcal{D}$  is defined as:

$$N_\epsilon(\vec{p}) = \{\vec{q} \in \mathcal{D} | \text{dist}(\vec{p}, \vec{q}) \leq \epsilon\} \quad (4.6)$$

where the distance metric  $\text{dist}(\vec{p}, \vec{q})$  is the standard Euclidean distance:

$$\text{dist}(\vec{p}, \vec{q}) = \sqrt{(x_p - x_q)^2 + (y_p - y_q)^2 + (z_p - z_q)^2} \quad (4.7)$$

All points in a dataset will fall under one of the following categories:

1. **Core Point:** A point  $\vec{p}$  with its  $\epsilon$ -neighborhood containing a number of points of at



least  $MinPts$ :

$$|N_\varepsilon(\vec{p})| \geq MinPts \quad (4.8)$$

2. **Neighborhood Point:** A point  $\vec{q}$  that is not a core point itself but lies within the  $\varepsilon$ -neighborhood of some core point  $\vec{p}$
3. **Noise Point:** A point  $\vec{n}$  that is neither a core point nor a border point.

To then form a cluster, DBSCAN uses the concept of density-based reachability. A point  $\vec{q}$  is directly density-reachable from a point  $\vec{p}$  if  $\vec{q} \in N_\varepsilon(\vec{p})$  and  $\vec{p}$  is a core point. A point is still density-reachable from a point  $\vec{p}$  if there exists a chain of intermediate points  $\vec{p}_1, \vec{p}_2, \dots, \vec{p}_n$  (where  $\vec{p}_1 = \vec{p}$  and  $\vec{p}_n = \vec{q}$ ) such that  $\vec{p}_{i+1}$  is directly density-reachable from  $\vec{p}_i$ . Every point in the chain must be a core point, except potentially the target  $\vec{q}$ . Finally, two points  $\vec{p}$  and  $\vec{q}$  are considered density-connected if there exists an anchor point  $\vec{o}$  such that both  $\vec{p}$  and  $\vec{q}$  are density-reachable from  $\vec{o}$ .

This density-connected relationships then lead to cluster assignment. A cluster  $C$  is defined as a non-empty subset of  $\mathcal{D}$  constructed if  $\vec{p} \in C$ ,  $\vec{q}$  is density-reachable from  $\vec{p}$ , and all points in  $C$  are density-connected to each other.

### 4.3.2 Fitting Track Candidates

Clusters identified by DBSCAN are then analyzed using Principal Component Analysis (PCA) [110, 82]. This procedure identifies a vector component, which is a linear combination of the input variables, that captures the most variance in the cluster data. For a track-like cluster's position data, this so-called principal component is the track direction, as the position of hits are the most spread along that line. For a 3D dataset, PCA will also find two components orthogonal to the principal component. These are used to determine the spread of hits orthogonal to the incident particle's direction, providing a tool to reduce

noise hits and contamination from shower-like clusters with higher orthogonal variance than MIP tracks. We then define the linearity of the track as a function of the three components' eigenvalues:

$$Linearity = \frac{\lambda_1}{\lambda_1 + \lambda_2 + \lambda_3} \quad (4.9)$$

Values close to 1 mean the cluster is highly linear along the principal component, in this case the track line. The fit also provides orientation and endpoint information for the track candidate. For FSD selection, we choose  $Linearity > 0.97$  and track length  $> 50$  cm to select clean, through-going MIP tracks. In the FSD-Cube, the length requirement is shortened to 25 cm to select the shorter vertical tracks.

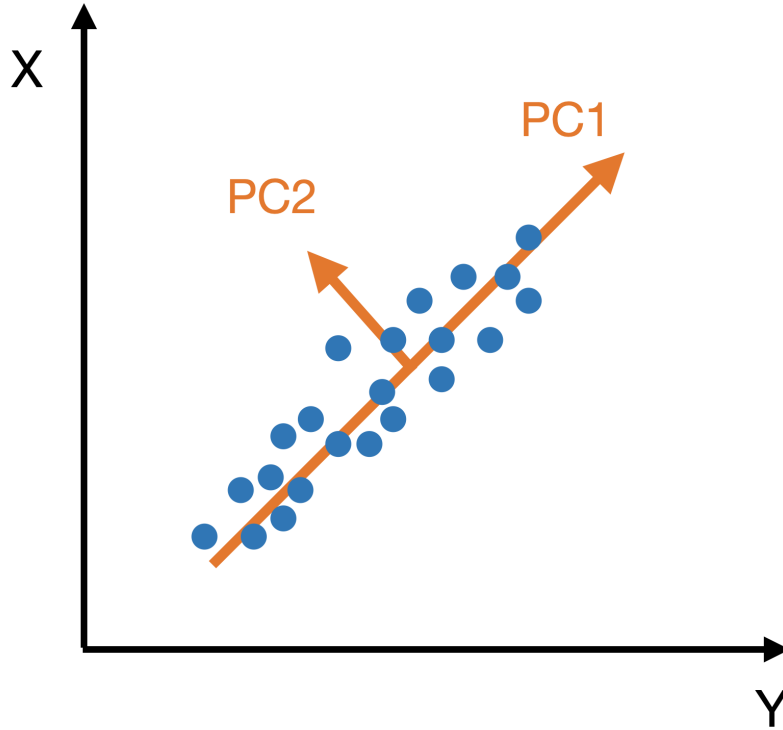


Figure 4.4: Diagram depicting how PCA looks in XY space for two dimensional track-like points. PC1 captures the XY direction of most variance in the data, and PC2 is orthogonal to PC1.

In order to remove any remaining noise and non-MIP ( $\delta$  rays, tight EM showers) hits, can-

didate tracks with a relative spread of their points w.r.t. the main PC1 axis  $i$ :  $\sqrt{\frac{Var_j Var_k}{Var_i}} > 0.07$  are discarded. Points that are 5 pixel pitches away from the main axis are also pruned out from track candidates.

### 4.3.3 "True" Track Hits

The PCA fit track can be described as:

$$\vec{x}(s) = \vec{x}_0 + s \cdot \vec{v} \quad (4.10)$$

where  $\vec{x}_0$  is the centroid,  $\vec{v}$  is the vector direction from the PCA fit and  $s$  is the distance along the track. For each point on a track candidate you can then find the  $s$  that minimizes the distance from the point on the track candidate: in other words, its closest point on the fit line. These "true" fit points are calculated in service of the electric field uniformity analysis, where hit positions are compared to a "straight-line" assumption for MIPs to assess positional distortions caused by non-uniformities in the electric field.

### 4.3.4 Output

Once tracks are selected and filtered, they are assigned a unique track label based on the file timestamp, event id within file, and a rolling value. To preserve information about the track's orientation with respect to the pixel anode, a spherical coordinate system tied to the detector's position and the incoming neutrino beam's expected axis is defined. Let  $\vec{v} = (v_x, v_y, v_z)$  be the unit direction vector of a reconstructed track candidate extracted via PCA. The polar angle  $\theta$  is measured relative to the vertical  $y$ -axis (where  $\theta = 0^\circ$  points parallel to gravity), and the azimuthal angle  $\phi$  is defined in the horizontal  $xz$ -plane relative to the  $z$ -axis (the nominal neutrino beam direction):

$$\theta = \arccos(v_y) \in [0^\circ, 180^\circ] \quad (4.11)$$

$$\phi = \text{atan2}(v_x, v_z) \pmod{360^\circ} \quad (4.12)$$

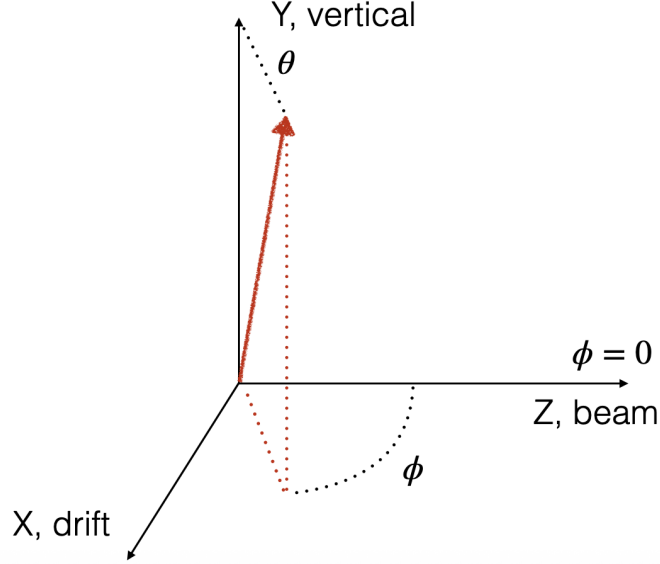


Figure 4.5: Spherical coordinate system for MIP  $dQ/dx$  analysis

The rolling label value, along with track hits, "true" hits calculated from the fit, charges, PCA fit variance, track direction,  $t_{drift}$  values, and PACMAN number are output to an HDF5 file for analysis.

### 4.3.5 Selection Criteria and Segmentation

MIP candidate tracks are discriminated further for charge calibration. Candidate tracks must be through-going, meaning they enter and exit detector faces, ensuring the charge depositions along their extent lie in the MIP region. The  $dQ/dx$  value also modulates slightly with track inclination, as measured by ICARUS [33], causing a broadening of the charge distribution in the order of a few percent. For the analysis of segment charge as a function of drift time, an additional cut can be imposed such that  $175 < \phi < 185$  or  $0 < \phi < 5$  or  $355 < \phi < 360$  from PCA direction to select charge depositions co-planar to anode, reducing the previously

Track number 0 with mean x 44.50034

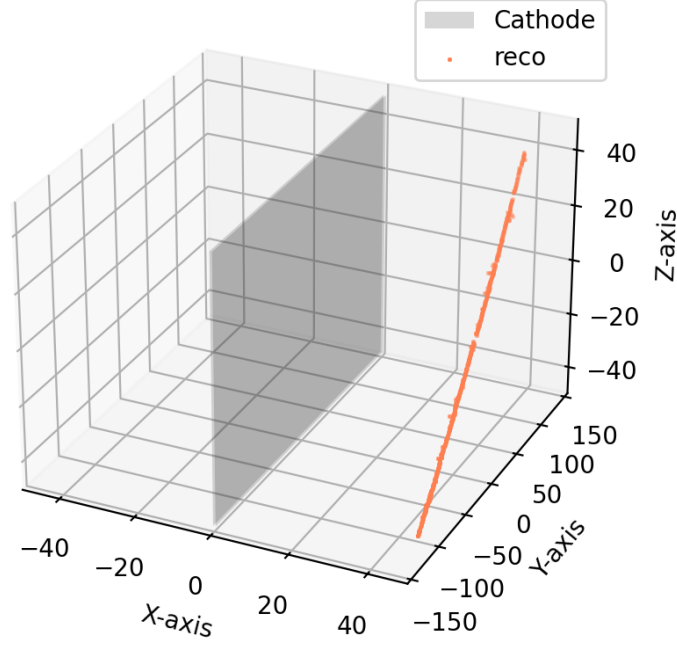


Figure 4.6: Example selected MIP candidate track from FSD data. Cathode drawn for reference. A small gap is present, likely due to high threshold settings during data-taking, which prompted the subsequent FSD-Cube runs.

mentioned charge broadening. The effect on the charge scale analysis is negligible aside from a slight reduction in the extracted FWHM.

Tracks are then divided along their reconstructed direction into segments of 3 cm. The sum of the charge for all hits in the segments is defined as  $dQ$ . If the distance between hits were used directly as  $dx$ , hits in the edge of a segment would have half the effective deposition length than hits in the center of the segment. Hence, the average distance between segment hits is calculated and added as a correction to  $dx$ , whose distribution for FSD-Cube simulation is shown in Figure 4.7. The  $dQ$ ,  $dx$ , median position,  $t_{drift}$ , and other information for each charge segment are saved in HDF5 format for subsequent analysis.

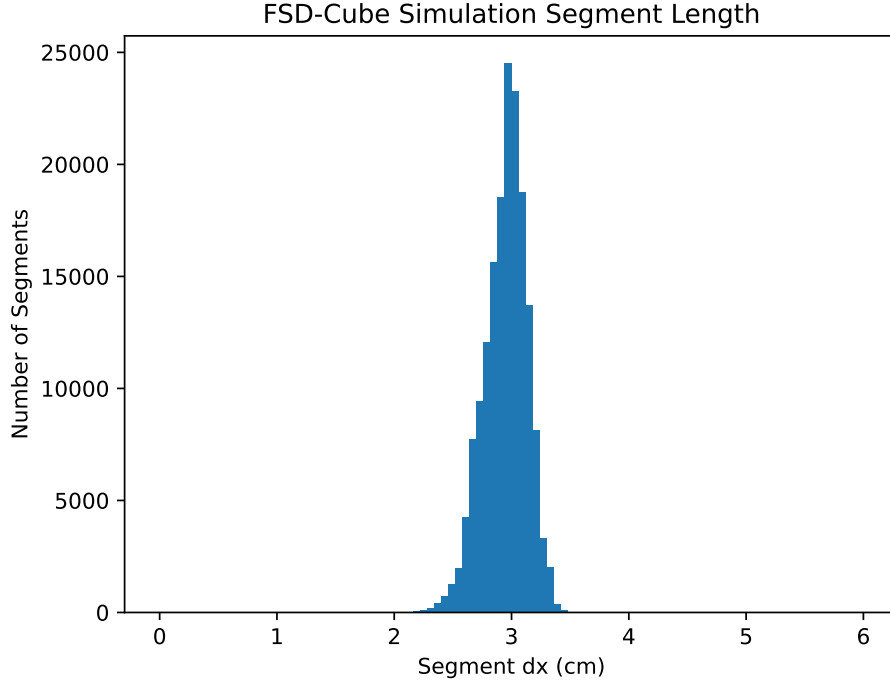


Figure 4.7: Simulated FSD-Cube segment  $dx$  distribution for 3 cm segments.

## 4.4 MIP $dQ/dx$

After identifying a sample of MIPs, their charge depositions can be used to study the charge response of the ND-LAr prototypes. The segment  $dQ/dx \in \{0, 100\}$  ke-/cm for data and simulation divided into 100 bins of width 1 ke-/cm are presented for the three ND-LAr prototypes. Only segments from a single TPC are shown in Figures 4.8, 4.9, 4.10, and 4.12 for simplicity. The simulation distributions are normalized to the data sample size.

### 4.4.1 2x2 Run 1

MIP track candidates from physics-quality data taken during July 8 and July 10 of 2024, during its Run 1 [2], were segmented for the distribution in Figure 4.8. No trigger cuts were required in order to select both cosmic muons and through-going muons produced from neutrino-rock interactions. The 2x2 exhibits excellent charge-scale agreement between Run 1 data and simulation.

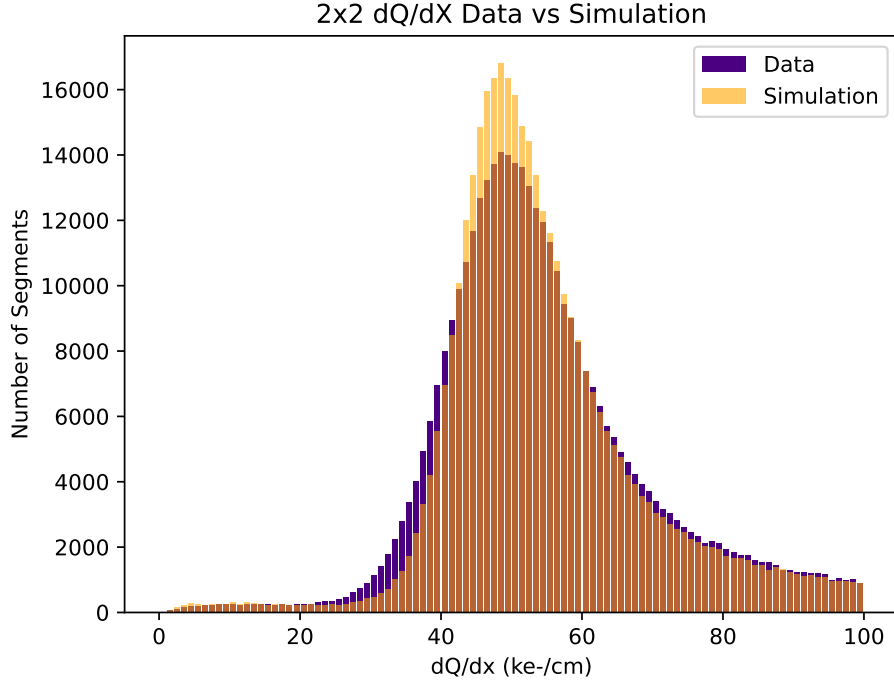


Figure 4.8: Data and Simulated  $dQ/dx$  distributions for TPC 0 of the 2x2 Demonstrator.

#### 4.4.2 FSD

FSD data taken in July 8, 2024 is shown in 4.9, by far the sample presented with the largest statistics. The  $dQ/dx$  distributions in the FSD show a considerable broadening, deviating from the Landau-Gaussian expectation. Moreover, a 30% difference between the observed and simulated charge scale was found by this analysis. The result prompted investigations that found the hardware bug mentioned in 4.1.3, and motivated FSD-Cube operations.

#### Angular Analysis in the FSD

To achieve a precise energy scale calibration, the calibrated  $dQ/dx$  should be invariant under spatial rotation. Mapping the reconstructed  $dQ/dx$  as a function of the track inclination angles  $(\theta, \phi)$  then becomes a valuable calibration diagnostic. Given its larger size and surface location, the FSD is uniquely capable among the available prototypes of producing such a map with reasonable precision, and thus this section focuses only on those data.

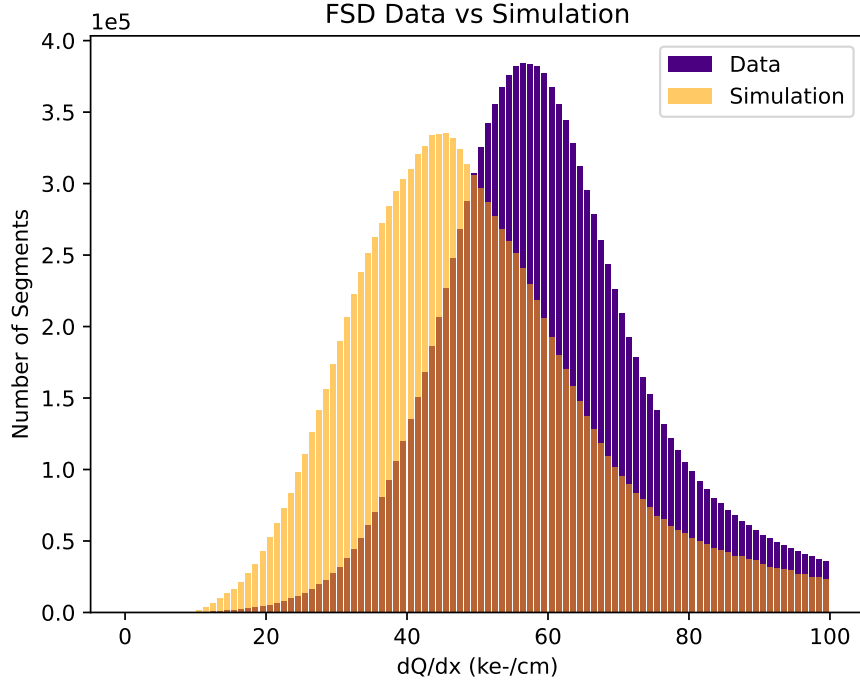


Figure 4.9: Data and Simulated  $dQ/dx$  distributions for TPC 0 of the FSD.

To appreciate the unique capabilities of a pixelated readout as in FSD, it is instructive to contrast it with wire-readout LArTPCs. In a wire-readout TPC, the 3D position of a hit is inferred by combining the wire orientation angle in the 2D plane with the drift time of the drifted electrons. When a track is parallel to the wire orientation, all ionization electrons generated along that segment arrive at the wire simultaneously. This charge topology yields an overlapping, highly extended induction signal that can saturate pre-amplifiers, trigger electronic cross-talk, and compromise the deconvolution of the raw waveform. Consequently, wire-based analyses must enforce angular dead-zones, throwing out substantial portions of  $(\theta, \phi)$  phase space where the reconstruction efficiency drops to zero, or perform additional reconstructions. A pixelated readout natively mitigates this by having isotropic acceptance due to its independence from projections.

In order to explore this advantage, segment  $dQ/dx$  distributions are constructed by binning in  $(\theta, \phi)$ . While statistics at the surface are not an issue with enough data-taking, performing



a fit to each bin with adequate granularity would be very time consuming. To mitigate this, fast estimations for a truncated  $dQ/dx$  mean and MPV are implemented. For a collection of mapped segments  $S_{i,j}$ , the truncated mean  $\mu_{i,j}$  is calculated by applying an upper truncation cutoff at  $100 \text{ ke}^-/\text{cm}$  before taking the mean:

$$\mu_{i,j} = \frac{1}{|S_{i,j}|} \sum_{y \in S_{i,j}} y \quad (4.13)$$

The  $\text{MPV}_{i,j}$  per bin is estimated by locating the maximum of the corresponding histogram over  $dQ/dx \in [0, 100] \text{ ke}^-/\text{cm}$  divided into 50 uniform bins with width  $2 \text{ ke}^-/\text{cm}$ . Although both measurements closely track each other's features in angular space, the truncated mean method has a higher  $dQ/dx$  scale due to the partial inclusion of the high energy tail. On the other hand, the MPV map is noisier because of the fast estimation method implemented, whose resolution is limited by the bin width of the per-angle-bin segment distribution and, consequently, by the MIP statistics. Both issues can be tuned in the future by decreasing the truncation endpoint and search bin width respectively, wherever statistics allow.

As shown in Figure 4.10, with a  $\theta$  and  $\phi$  bin width of  $5^\circ$  both methods present a maximum variation in  $dQ/dx$  of roughly 20% depending on track inclination, with a ring-line pattern of higher values that centers around perfectly horizontal tracks that run perpendicular to the anode plane, a particularly difficult topology to reconstruct as track charges are collected on only a few pixels. Furthermore, lower values are observed when the track is parallel to the beam direction and not perfectly vertical.

While the map shows that pixelated readouts are inherently sensitive to charges from tracks incident at virtually all angles, the variation in  $dQ/dx$  is larger than expected from previous measurements [33]. This is likely due to the fact that the segment charges are not corrected for electron lifetime or diffusion, which can cause additional inclination-sensitive effects. Moreover, these patterns are also reproduced in the official simulation. By either extracting

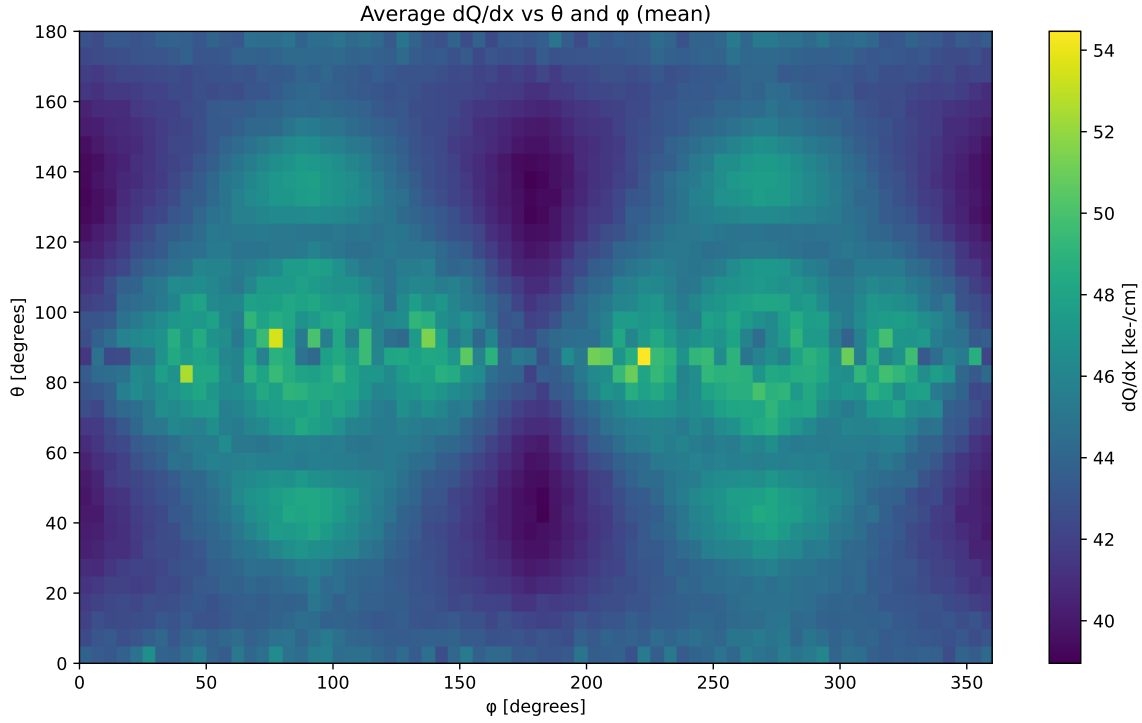


Figure 4.10: Truncated MIP dQ/dx mean binned in track angle phase space from FSD data taken during November 8, 2024.

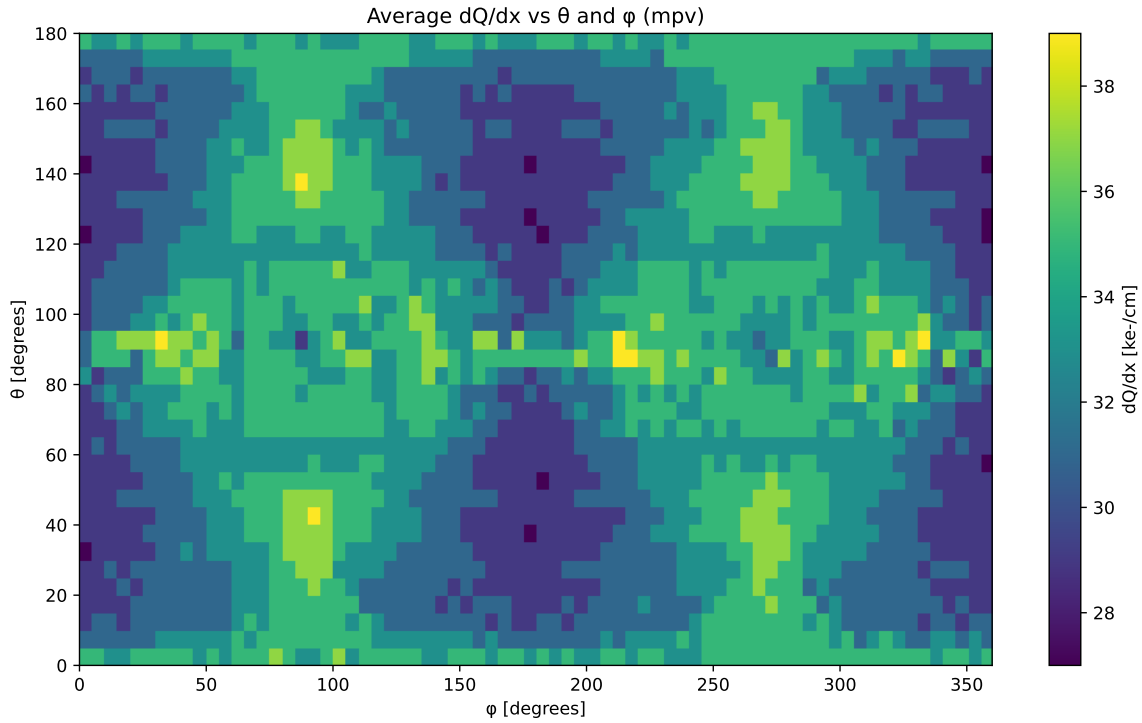


Figure 4.11: Estimated MIP dQ/dx MPV binned in angular track angle phase space FSD data taken during November 8, 2024.

and applying these additional corrections or only considering a thin slice of the detector close to the anode, the angular  $dQ/dx$  map can be used for an additional correction to account for the charge response variation with angle.

#### 4.4.3 FSD-Cube

The charge scale of the FSD-Cube, which was ran at a half-nominal electric field of 250 V/cm, is shown in 4.12. Only events with a trigger in the top plastic scintillator pads are considered. The distributions peak lower compared to the 2x2 and FSD due to the lower electric field. FSD-Cube data improved on the charge response and data-to-simulation agreement compared to FSD runs, which were taken on similar hardware.

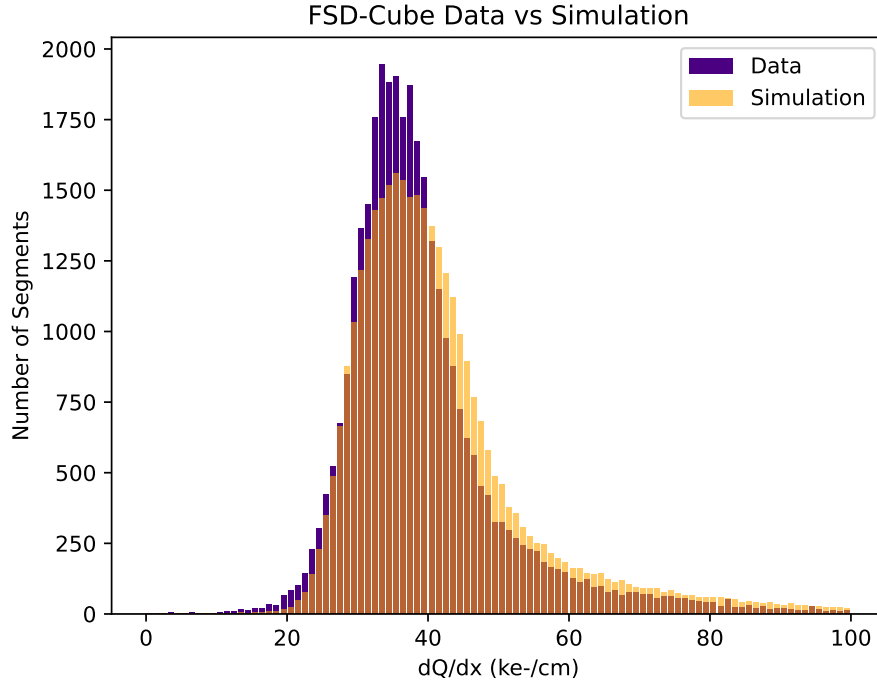


Figure 4.12: Data and Simulated  $dQ/dx$  distributions for TPC 0 of the FSD-Cube.

#### 4.4.4 MPV Extraction through Landau-Gaussian Fit

The distribution of energy loss for thin absorbers (like a few pixels' worth of LAr) is described by a Landau distribution, which accounts for the rare, high-energy  $\delta$  electron collisions.

However, detector effects such as electronic noise and pixel-to-pixel gain variations introduce an additional Gaussian broadening. To extract the Most Probable Value (MPV) of charge depositions with high fidelity, a fit of the segment  $dQ/dx$  distributions to a Landau-Gaussian convolution is performed using the `SciPy` package [121]:

$$f(x; \Delta, \eta, \sigma) = (L * G)(x) = \int_{-\infty}^{\infty} \text{Landau}(x - \tau; \Delta, \eta) \cdot \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\tau^2}{2\sigma^2}} d\tau \quad (4.14)$$

where  $\Delta$  is the MPV,  $\eta$  is the Landau scale parameter, and  $\sigma$  is the Gaussian standard deviation. The MPV represents the most likely charge deposition for a MIP and serves as the main calibration variable. The distribution mean is another valid statistic, although it is disfavored given that it sits higher than the MPV due to the tail caused by higher energy collisions. The uncertainty on the MPV is calculated from the covariance matrix of the fit.

#### 4.4.5 Electron Lifetime Extraction

As ionization electrons drift through the liquid argon volume towards the anode plane, they are subject to attenuation via capture by impurities in LAr. As described in section 2.3.2, the charge loss follows a characteristic exponential decay as a function of  $t_{drift}$ :

$$Q(t) = Q_0 \cdot \exp\left(-\frac{t_{drift}}{\tau_e}\right) \quad (4.15)$$

where  $Q(t)$  is the observed charge deposition,  $Q_0$  is the initial ionization charge before drift attenuation, and  $\tau_e$  is the electron lifetime. Measuring  $\tau_e$  is necessary to compute the attenuation correction factors of different TPCs. Since the electron lifetime affects the charge signal as a function of drift time, comparing  $dQ/dx$  as a function of time drift time or distance provides a monitor of the LAr purity. The segments are then binned in drift time, and the resulting distributions fit to obtain their MPVs, which are finally fit to measure  $\tau_e$

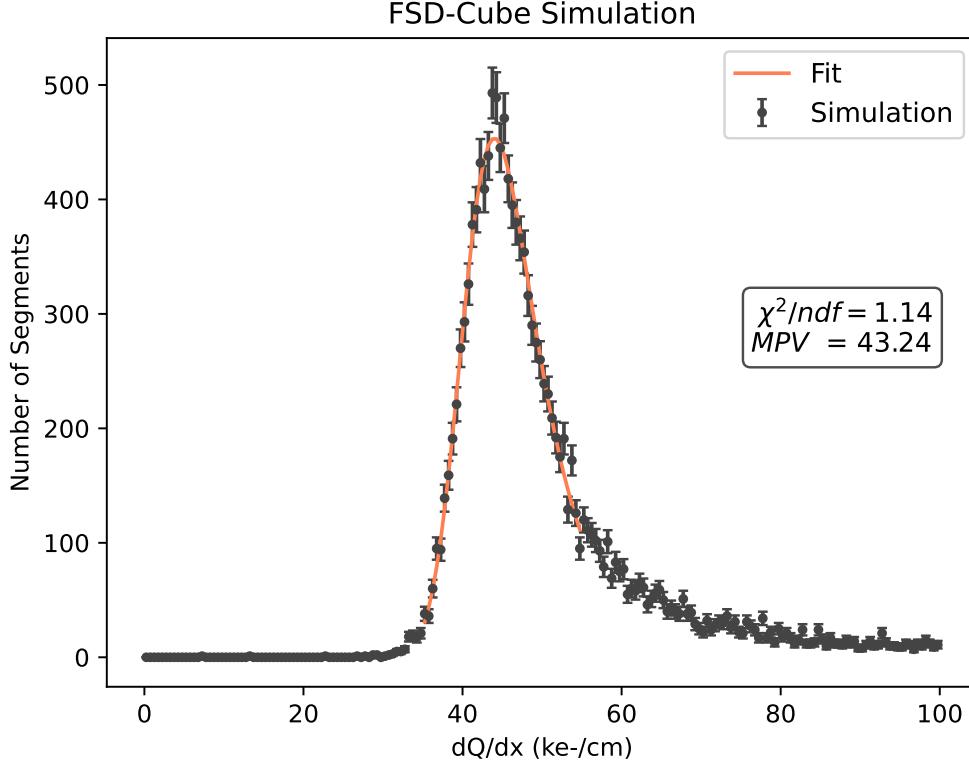


Figure 4.13: Simulated FSD-Cube segment  $dQ/dx$  distributed in 0.5 ke-/cm bins, fit to a Landau-Gaussian convolution.

in the detector volume.

To avoid potential convergence issues associated with exponential regressions as well as make effects unrelated to purity (like diffusion) visually apparent, the calibration linearizes the data by evaluating the natural logarithm of the extracted  $dQ/dx$  MPVs:

$$\ln\left(\frac{dQ}{dx}\right) = -\frac{1}{\tau_e} \cdot t_{drift} + \ln(Q_0) \equiv m \cdot t_{drift} + b \quad (4.16)$$

where the slope  $m = -1/\tau_e$  and the intercept  $b = \ln(Q_0)$ .

The experimental uncertainties associated with the binned MPV parameters must be propagated into log-space. For a given charge MPV  $y$  with a corresponding fit error  $\sigma_y$ , the

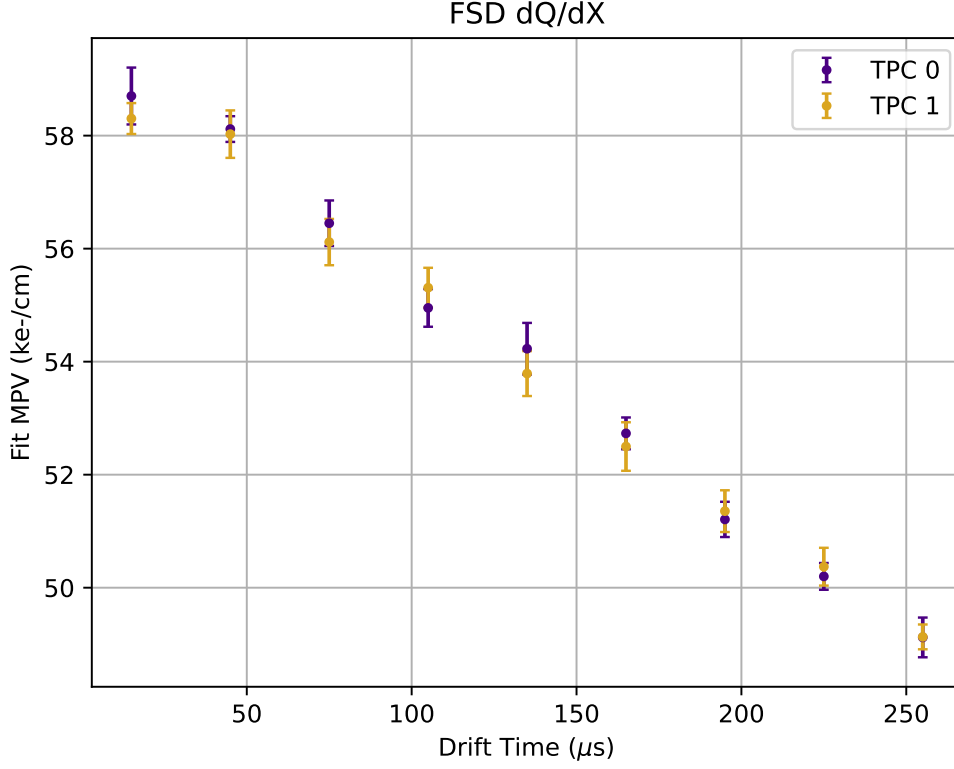


Figure 4.14: FSD Data  $dQ/dx$  Fit MPVs for segments separated into 33  $\mu s$  drift time bins, shown for both of its TPCs.

log-space uncertainty  $\sigma_{\ln(y)}$  is derived via first-order Taylor expansion:

$$\sigma_{\ln(y)} = \left| \frac{d}{dy} \ln(y) \right| \cdot \sigma_y = \frac{\sigma_y}{y} \quad (4.17)$$

Because of non-uniformities in the electric field near cathode and anode planes, as well as reconstruction artifacts in the track segments in this detector region, the TPC edges are isolated from the fit. This effectively removes the earliest  $t_{drift}$  bins closest to the anode and the latest  $t_{drift}$  bins closest to the cathode plane, preventing edge distortions and induction effects from biasing the bulk lifetime. A weighted linear least-squares regression is then performed by minimizing the  $\chi^2$  function:

$$\chi^2 = \sum_i \left( \frac{y_{fit,i} - (m \cdot t_{fit,i} + b)}{\sigma_{\ln(y),fit,i}} \right)^2 \quad (4.18)$$

The uncertainty on the calculated lifetime,  $\sigma_{\tau_e}$ , is propagated analytically from the standard error of the slope ( $\sigma_m = \sqrt{\mathcal{M}_{0,0}}$ , where  $\mathcal{M}$  is the parameter covariance matrix) using the variance formula:

$$\sigma_{\tau_e} = \left| \frac{\partial \tau_e}{\partial m} \right| \cdot \sigma_m = \frac{1}{m^2} \cdot \sigma_m = \tau_e^2 \cdot \sigma_m \quad (4.19)$$

An example lifetime fit for FSD data is shown in Figure 4.15.

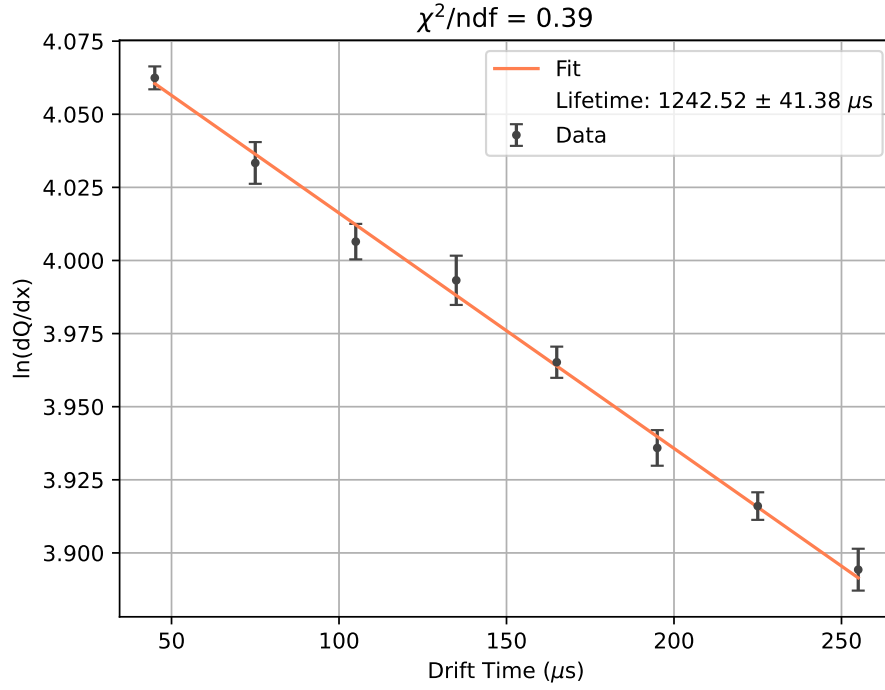


Figure 4.15:  $\ln(dQ/dx)$  Fit to FSD data, binned in 33  $\mu s$  drift time bins.

## 4.5 Study of ADC Digitization Impact on Measured Electron Lifetime using FSD-Cube Simulation

To evaluate the systematic effects introduced by quantization noise and thresholding, a dedicated study was performed using modified simulation routines within `larnd-sim` and `larpix-control`, inspired by earlier work performed by DeMario Ross for the 2x2. The primary goal was to quantify how the LArPix ASIC Least Significant Bit (LSB) resolution biases the extracted electron drift lifetime, hoping to explain differences between the extracted and injected lifetimes in simulation across prototypes.

### 4.5.1 Methodology

Front-end electronics simulations in `larnd-sim` perform quantization on charges during packet creation. Custom branches of `larpix-control` and `larnd-sim` store unrounded floating-point charge datawords directly inside the packets. This provides an "infinite precision" dataset free of quantization and threshold artifacts. To scan varying LSB resolutions, floating-point datawords were converted back to analog voltages and re-digitized under target LSB settings in mV:

$$V_{\text{signal}} = (\text{Dataword}_{\text{float}} \times \text{LSB}_{\text{nominal}}) + V_{\text{cm}} - V_{\text{pedestal}} \quad (4.20)$$

$$\text{Dataword}_{\text{quantized}} = \text{floor} \left( \frac{V_{\text{signal}} - V_{\text{cm}} + V_{\text{pedestal}}}{\text{LSB}_{\text{target}}} \right) \quad (4.21)$$

where for LArPix-v3 in FSD-Cube, nominal parameters ( $V_{\text{ref}} = 1734.375$  mV,  $V_{\text{cm}} = 0$  mV,  $V_{\text{pedestal}} = 980$  mV,  $F_{\text{ADCscale}} = 2$ ) yield a nominal  $\text{LSB}_{\text{nominal}} \approx 3.39$  mV.

Hits were subsequently reconstructed using `ndlar-flow`, segmented into drift time slices



( $33\mu s$  width), and fit with Landau-Gaussian convolutions to extract the  $dQ/dx$  MPVs, as described in the previous sections.

### 4.5.2 Lifetime Bias under Nominal Digitization

For an injected true simulation electron lifetime of  $\tau_e = 1100\mu s$ , extracting the lifetime under the nominal LArPix-v3 digitization by using the fit MPVs significantly underestimates the true value, returning an extracted lifetime of  $\tau_e = 765 \pm 6.06\mu s$ . If the digitization is turned off, the lifetime is then overestimated at  $\tau_e = 1272 \pm 13.82\mu s$  as shown in Figure 4.16. While extracting a higher lifetime seems counterintuitive, a study from 2022 predicts this effect to arise from diffusion [114].

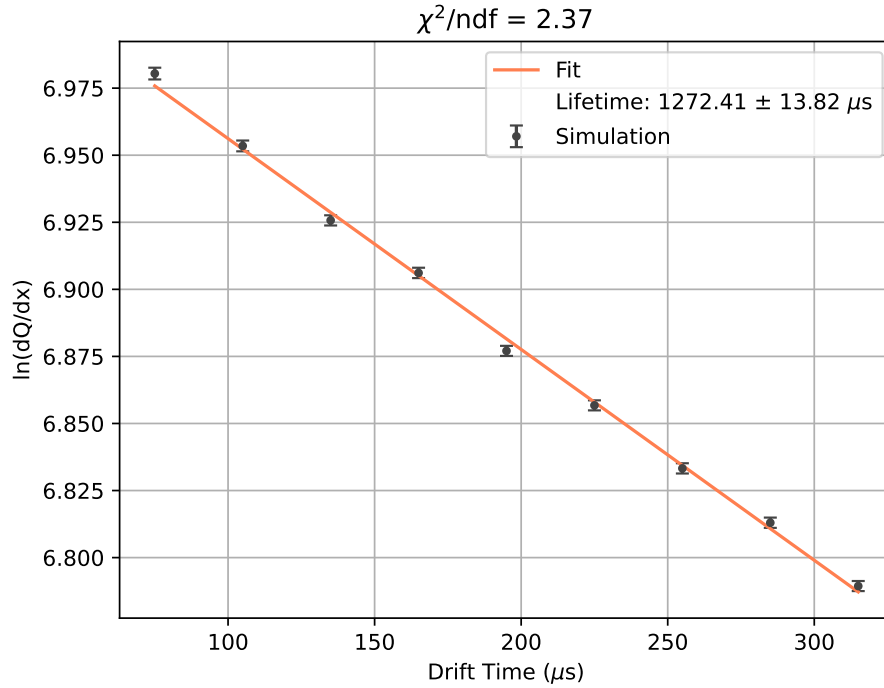


Figure 4.16: FSD-Cube simulated  $\ln(dQ/dx)$  fit in the absence of digitization. The injected lifetime value is over-estimated with diffusion on.

The next step is naturally to repeat the LSB study with the electron diffusion turned off in the simulation. In this case, the nominal LSB setting still underestimates the lifetime with a value of  $\tau_e = 967 \pm 16.83\mu s$ . Nevertheless, the true value is recovered ( $\tau_e = 1105 \pm 12.76\mu s$ )

in the absence of both diffusion or digitization, as shown in Figure 4.17.

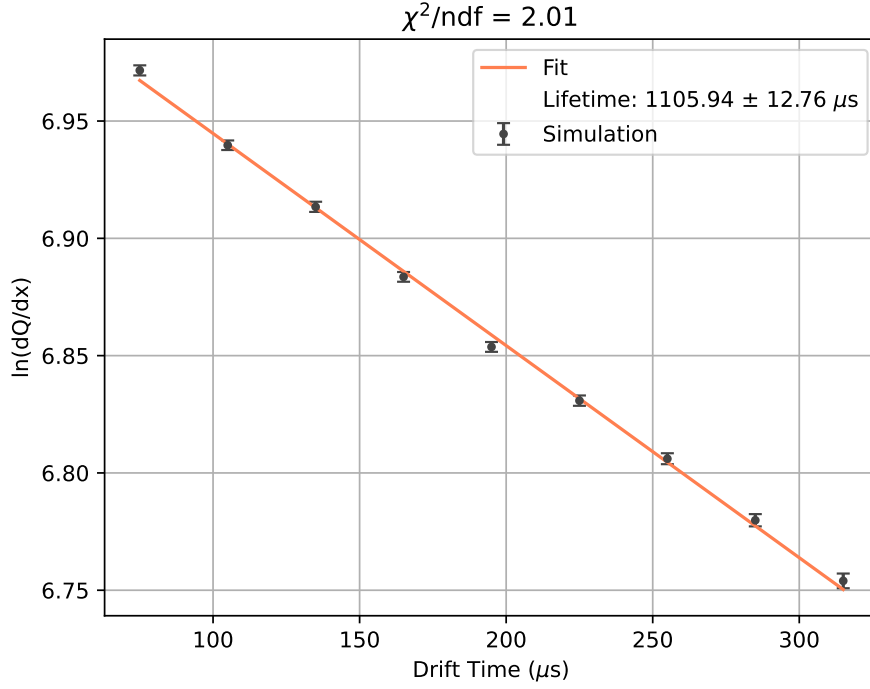


Figure 4.17: FSD-Cube simulated  $\ln(dQ/dx)$  fit in the absence of digitization and diffusion. The injected lifetime value is recovered in this case only.

Scanning the LSB from 0 mV (unrounded float) to 4 mV revealed two key behaviors. At  $\text{LSB} > 1.2$  mV, coarse digitization truncates attenuated signals and flattens the measured  $dQ/dx$  slope over drift time and artificially decreasing the extracted lifetime. At values  $< 1.2$  mV, a steep transition occurs around 0.995 before overshooting the injected lifetime value at near-zero LSB. Achieving the optimal target LSB without hardware dynamic range loss would require increasing LArPix ADC resolution from 10 bits to approximately 12 bits. Nevertheless, this naive prediction ignores complexities in ADC design as well as the influence noise might have at very fine LSB and further investigation on this matter is certainly in order.

## 4.6 Outlook

The MIP charge scale calibration studies presented in this chapter demonstrate the distinct advantages of a pixelated LArTPC readout, particularly its ability to reconstruct cosmic tracks across the entire angular  $(\theta, \phi)$  phase space with minimal reconstruction. Moreover, the ND-LAr prototype simulation reproduces the data well in terms of MIP  $dQ/dx$ . However, building a precise energy scale for the full DUNE ND-LAr modules requires addressing several detector and electronics effects uncovered in these prototype runs.

To establish a robust calibration for the final DUNE ND-LAr detector, future work should focus on lifetime extraction algorithms that account for the effects of diffusion, allowing them to be disentangled from electron attenuation. It is worth noting that the fundamental theoretical understanding of charge diffusion in a TPC has not changed much since the inception of the technology [107], although some efforts have been made to expand current knowledge for modern LArTPCs [97, 114]. Furthermore, results from the LSB scan suggest that fine-tuning baseline ASIC parameters or transitioning towards a 12-bit ADC can eliminate the quantization-driven bias on  $\tau_e$  without compromising high-energy dynamic range. Ideally, these results should be carefully reproduced in an ASIC bench test and compared to the simulation-based LSB scan presented here.

# Chapter 5

## The Jiangmen Underground Neutrino Observatory

### 5.1 Introduction and Scientific Objectives

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kt liquid scintillator (LS) detector located in Jiangmen, China [20]. Unlike DUNE, which utilizes two detector complexes separated by  $O(1000)$  km and illuminated by an accelerator neutrino beam, JUNO is placed at a 53 km baseline to observe the oscillation of electron antineutrinos ( $\bar{\nu}_e$ ) emitted from fission in nuclear power plants (NPP) [20]. The JUNO detector is situated 700 m underground, built 463 m into Dashi hill, providing a shielding of about 1900 m.w.e to suppress cosmic rays and their correlated backgrounds [20].

The behavior of low energy particles in LS does not lend itself to exquisite particle tracking as in DUNE. Instead, JUNO relies heavily on precise calorimetry to achieve its desired measurements, especially the determination of the NMO by measuring the fine structure of the reactor  $\bar{\nu}_e$  energy spectrum [34]. The interference between oscillation modes driven

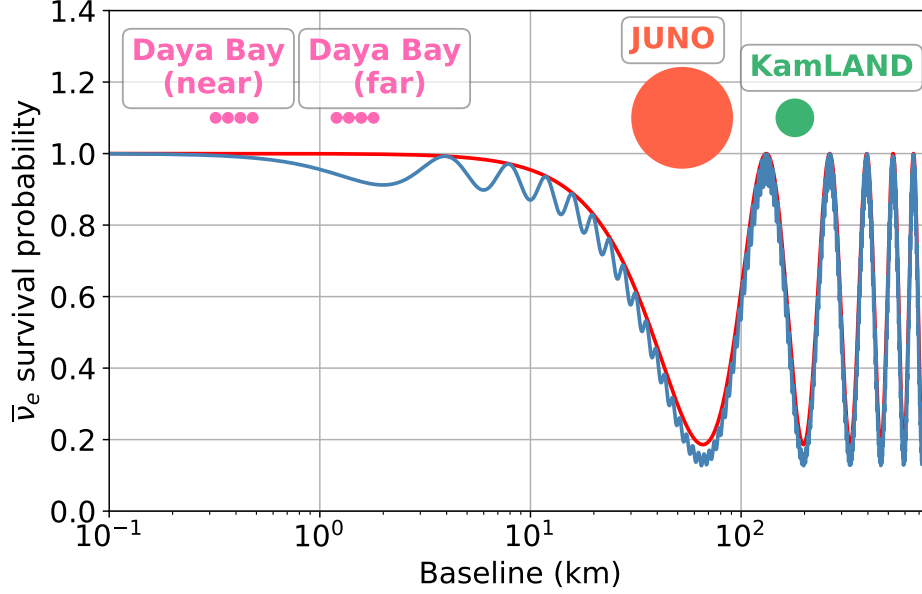


Figure 5.1: Placement and scale of JUNO and other reactor neutrino detectors with respect to the survival probability of a 3 MeV  $\bar{\nu}_e$  and the experimental baseline.

by  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$  produces a secondary oscillation pattern, as described in Chapter 1 and shown in Figure 5.1. The phase of this interference depends on whether the NMO is normal or inverted. The relatively small magnitude of  $\theta_{13}$ , and thus of this interference pattern, requires not only a large statistical sample (hence the incredibly large detector), but also excellent control of systematic uncertainties. In particular, an energy resolution of approximately  $3\%/\sqrt{E(\text{MeV})}$  and sub-percent control of the absolute energy scale are needed [20, 15].

A measurement of the energy spectrum also allows JUNO to measure key neutrino oscillation parameters, including  $\sin^2 \theta_{12}$ ,  $\Delta m_{21}^2$ , and  $\Delta m_{31}^2$ , with sub-percent precision in the case of the former two parameters [50]. These measurements will enable increasingly stringent tests of the three-flavor oscillation framework and the unitarity of the PMNS matrix.

Besides its oscillation program, the detector's large volume and low energy threshold also make it sensitive to a wide range of neutrino sources, including supernova burst neutrinos,

solar neutrinos [16], and geoneutrinos produced by radioactive decays within the Earth’s crust [51]. JUNO therefore also functions as a general neutrino observatory.

## 5.2 Nuclear Reactors as an Antineutrino Source

NPP reactors are, by a wide margin, the most intense artificial source of  $\bar{\nu}_e$  and have served as the workhorse source for neutrino physics since Cowan and Reines’ original discovery of the neutrino at the Savannah River reactor [55]. Inside a commercial power reactor, thermal energy is generated by the fission of predominantly  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ , and  $^{241}\text{Pu}$  following neutron capture. Each fission event produces two neutron-rich fission fragments that subsequently undergo a chain of  $\beta^-$  decays back toward the valley of stability, emitting on average about six  $\bar{\nu}_e$  per fission. Because the reactor antineutrino spectrum is the incoherent sum of many hundreds of individual  $\beta$ -decay branches from the fission-fragment inventory, its shape cannot be derived from first principles with the required precision; instead, it is obtained either from the "conversion" method, in which measured aggregate  $\beta$  spectra of irradiated fissile samples are converted into the corresponding  $\bar{\nu}_e$  spectra branch-by-branch (the Huber-Mueller approach) [83, 105], or from ab-initio summation from nuclear database data [68, 67, 117]. The resulting antineutrino spectrum extends up to 12 MeV with its shape and normalization constituting some of the larger systematics to any reactor oscillation analysis, JUNO’s included.

The relationship between a reactor’s thermal power  $P_{\text{th}}$  and its antineutrino output follows from energy conservation: each fission releases, on average,  $\sim 200$  MeV of recoverable thermal energy in addition to the emitted  $\bar{\nu}_e$ ’s, so that the fission rate, and hence the  $\bar{\nu}_e$  emission rate, scales directly with  $P_{\text{th}}$  once the relative contributions of the four dominant fissile isotopes (and their fuel evolution) are known [49]. At a detector located a distance  $L$  from the reactor

core, the resulting antineutrino flux at the LS target follows the classic inverse-square-law:

$$\phi_{\bar{\nu}_e}(E_\nu) \propto \frac{P_{\text{th}}}{4\pi L^2} S(E_\nu), \quad (5.1)$$

where  $S(E_\nu)$  is the reactor antineutrino energy spectrum per fission discussed above.

JUNO's site was chosen so the detector hall sits at an equal 53 km baseline from the Yangjiang and Taishan Nuclear Power Plants, two of the highest-power reactor complexes in the world, whose combined output is 26.6 GW<sub>th</sub> [20]. This provides JUNO with by far the largest antineutrino flux of any O(10-100)km baseline reactor experiment to date. A handful of additional, more distant power plants (including Daya Bay and Huizhou) contribute a small residual flux at the percent level and are included in the oscillation analysis as background [50].

### 5.3 Neutrino Detection through Inverse Beta Decay

JUNO detects reactor antineutrinos through the Inverse Beta Decay (IBD) reaction on free protons in the liquid scintillator [122]:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (5.2)$$

The IBD provides a distinct "delayed coincidence" signature that begins with the **prompt** signal. The positron deposits its kinetic energy and promptly annihilates with an electron, producing two 0.511 MeV  $\gamma$ . The visible energy is related to the neutrino energy by  $E_{\text{prompt}} \approx E_{\bar{\nu}_e} - 0.782$  MeV, making a precise measurement of the prompt energy a main goal of JUNO's energy-scale calibration [15].

The second part of the IBD reaction is the **delayed** signal, where the neutron thermalizes and is captured in most cases by a hydrogen nucleus (typically within  $\sim 200$   $\mu$ s), releasing

a monoenergetic 2.22 MeV gamma ray [20]. This spatial-temporal correlation significantly reduces environmental backgrounds, allowing JUNO to identify  $\bar{\nu}_e$  events with high purity.

## 5.4 Liquid Scintillator and Purification

The target 3% energy resolution at 1 MeV sets stringent constraints on the optical performance and purity of the primary detection medium. This section details the chemical selection of the LS components, the quantum mechanics governing the generation of scintillation light, and the multi-stage purification plants built onsite to achieve and confirm adequate radiopurity.

### 5.4.1 Choice of Medium and Chemical Composition

Historically, scintillator detectors utilized solvents like pseudocumene (PC) or dodecylbenzene. For JUNO, Linear Alkyl Benzene (LAB) is used as the baseline solvent [17]. LAB is an alkylated hydrocarbon that is non-toxic, biodegradable, and chemically compatible with the acrylic containment sphere. LAB also exhibits a long attenuation length exceeding 20 m at the primary emission wavelength, minimizing self-absorption [17].

The scintillation properties of pure LAB are optimized by adding a primary fluor and a secondary wavelength shifter [17]. The primary fluor 2,5-diphenyloxazole (PPO) is added at 2.5 g/L, acting as the primary activator to trap localized electronic excitations from the solvent before quenching can occur. The wavelength shifter, 1,4-bis(2-methylstyryl)benzene (bis-MSB), is also added at a concentration of 3 mg/L. It shifts the primary optical emission spectrum toward longer wavelengths where the liquid scintillator is more transparent.



### 5.4.2 Physics of Scintillation Light Generation

Energy depositions by ionizing particles initiate a complex energy transfer cascade within a LS molecule. This process can be split into three steps for didactic purposes.

First, the incident particle primarily interacts with the bulk solvent, ionizing and exciting the  $\pi$ -electron clouds in the benzene rings of the LAB molecules. The initial excitation populates high-lying singlet  $S_n$  and triplet  $T_n$  electronic states. Through rapid internal conversion and vibrational relaxation occurring at time scales of  $\sim 10^{-12}$  s, these states cascade down to the lowest excited singlet state  $S_1$  and long-lived triplet states  $T_1$ .

Next, given that the de-excitation of LAB via fluorescence is slow and heavily quenched, the excitation energy of the LAB  $S_1$  state must be transferred to the PPO. Because of the relatively high concentration of PPO, the average intermolecular distance is small enough that this transfer is dominated by Förster Resonance Energy Transfer [70]. It is a non-radiative, electrodynamic dipole-dipole interaction:

$$k_{DA} = \frac{1}{\tau_D} \left( \frac{R_0}{r} \right)^6 \quad (5.3)$$

where  $\tau_D$  is the (LAB) lifetime,  $r$  is the intermolecular distance, and  $R_0$  is the characteristic Förster radius defined by the spectral overlap between LAB emission and PPO absorption.

Once populated, the  $S_1$  state of the PPO molecule decays radiatively, emitting ultraviolet photons in the 340-380 nm range. However, LAB still exhibits non-negligible optical absorption within this UV window. To prevent light loss, the added bis-MSB absorbs the PPO photons. The subsequent fluorescence of bis-MSB emits isotropic, visible blue light centered around 430 nm.

### 5.4.3 Onsite Production Plants and Purification

In order to achieve its LS radiopurity targets, JUNO is fed by a continuous, four-stage online purification plant at the above and underground experimental sites. Each facility targets a distinct class of optical and radioactive contaminants. Raw LAB is passed through columns packed with activated alumina  $Al_2O_3$ . This process removes polar impurities, oxides, and synthetic chemical byproducts that contribute to optical attenuation. The liquid then undergoes more stages of distillation under high vacuum. This separates the solvent from heavy metals, optical absorbers, and deep internal radioisotopes ( $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) through differences in boiling points. The distilled stream is processed through a liquid-liquid counter-current extraction column using ultra-pure water (UPW). This stage aggressively strips out residual water-soluble impurities, targeting  $^{226}\text{Ra}$  and Th daughters that mimic low-energy neutrino signals. The final stage of the process passes the LS through a stripping column using a combination of UPW steam and nitrogen gas. This process removes dissolved gaseous impurities, specifically targeting noble radioactive gases like  $^{222}\text{Rn}$ ,  $^{85}\text{Kr}$ , and  $\text{O}_2$  molecules that diminish the overall light yield [90].

### 5.4.4 Radiopurity Requirements and Background Thresholds

The physical reach of JUNO in its low energy regime depends directly on its control of radiopurity. JUNO has set milestones targeting two distinct purity assumptions depending on the physics of interest [90], as shown in Table 5.1.

Table 5.1: Internal radiopurity target limits for the JUNO liquid scintillator medium.

| Radioisotope                  | Reactor $\bar{\nu}_e$ (Baseline) | Solar $\nu$ (Ideal)         |
|-------------------------------|----------------------------------|-----------------------------|
| $^{238}\text{U}$              | $\leq 10^{-15} \text{ g/g}$      | $\leq 10^{-17} \text{ g/g}$ |
| $^{232}\text{Th}$             | $\leq 10^{-15} \text{ g/g}$      | $\leq 10^{-17} \text{ g/g}$ |
| $^{40}\text{K}$               | $\leq 10^{-16} \text{ g/g}$      | $\leq 10^{-18} \text{ g/g}$ |
| $^{14}\text{C}/^{12}\text{C}$ | $\leq 10^{-18}$                  | $\leq 10^{-18}$             |

While the reactor antineutrino analysis is highly resilient against low-energy backgrounds due to the prompt-delayed coincidence signature of IBD events, the detection of sub-MeV

solar neutrinos ( ${}^7\text{Be}$  and  $pep$ ) requires single-hit counting. Thus, their study demands the "ideal" purity tier shown in Table 5.1 [90]. Maintaining  ${}^{238}\text{U}$  and  ${}^{232}\text{Th}$  concentrations below  $10^{-17}$  g/g ensures that internal  $\beta/\gamma$  pile-up does not obfuscate the solar neutrino spectrum.

Continuous quality control of this purification chain is monitored online by the OSIRIS (Online Scintillator Internal Radioactive Isotope System) detector loop prior to final filling of the main acrylic sphere by routing a portion of the incoming liquid scintillator to OSIRIS [18].

## 5.5 The JUNO Central Detector

With the procurement and purification of a luminous scintillator cocktail in check, the JUNO program now requires a massive, high-precision instrument optimized to capture scintillation signals while aggressively suppressing environmental and cosmic backgrounds. The experiment centers around a spherical Central Detector (CD) nested within a multi-tiered cosmic muon veto system [20]. The following sections detail the structural, optical, and electronic design elements that constitute the CD.

The JUNO CD is a spherical structure in order to maximize the target volume and internal surface area for photosensors while minimizing mechanical stress and pressure applied to them. The structural engineering of the sphere represents a unique milestone in detector design [20]. The acrylic sphere is constructed from 265 independent acrylic panels, structurally bonded onsite to form a continuous shell with a nominal thickness of 120 mm. The acrylic chemical composition is highly controlled to guarantee a high optical transmittance ( $> 96\%$  at 430 nm) and extreme radiopurity, limiting internal  ${}^{238}\text{U}$  and  ${}^{232}\text{Th}$  contamination to less than 1 ppt.

The acrylic sphere is supported from the outside by a rigid stainless steel truss. The connection between the acrylic shell and the steel truss is done through 590 connecting nodes. Because the density of the LS ( $0.86 \text{ g/cm}^3$ ) is significantly lower than that of the surrounding

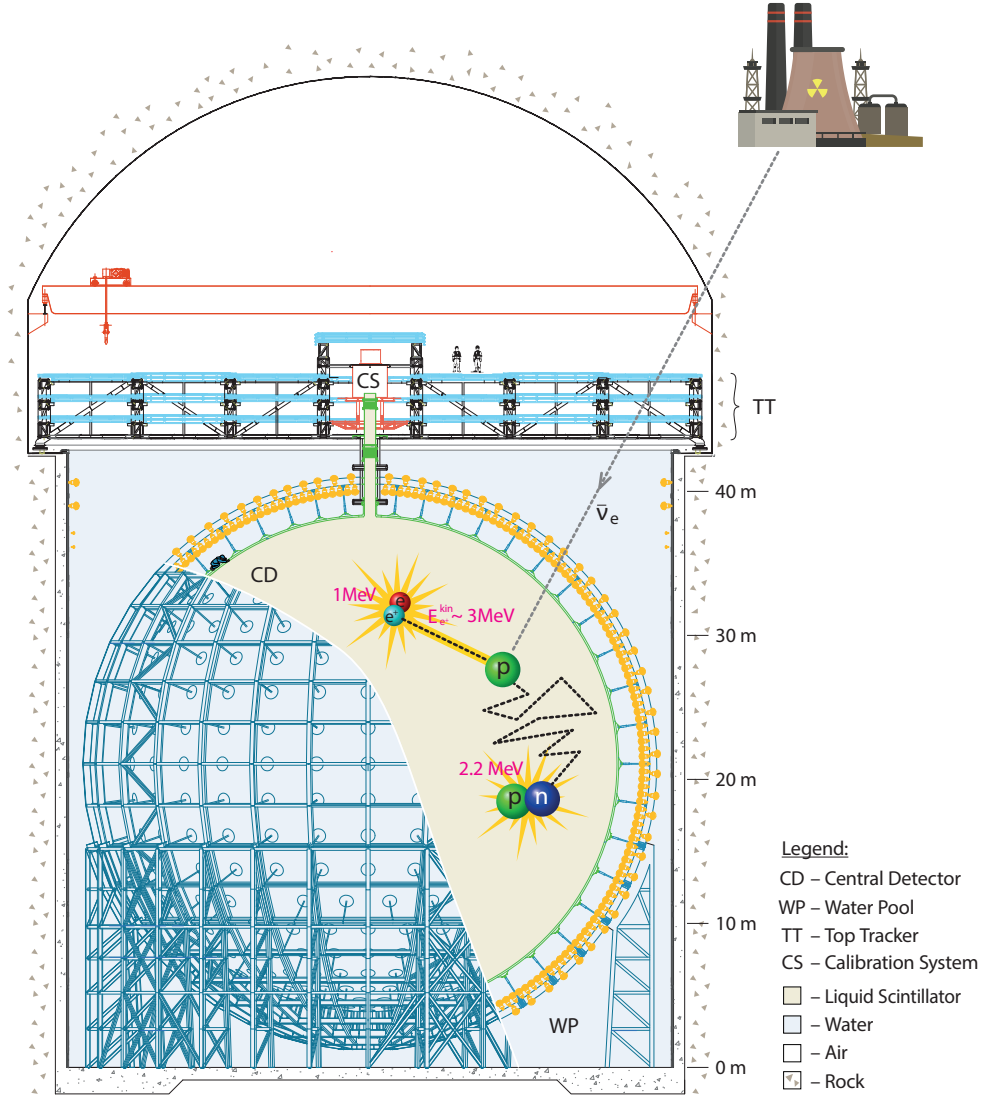


Figure 5.2: Diagram of the JUNO detector with the IBD reaction drawn inside the detector.

ultra-pure water, the completely submerged acrylic sphere experiences a net upward buoyant force of approximately 3000 t. The steel truss and its anchoring pillars are engineered to counteract this stress and maintain stability under continuous tension [20].

Light inside the detector is collected by photomultiplier tubes (PMTs) mounted on the stainless steel truss, behind the acrylic shell. PMTs detect low-intensity light by converting incident photons into photoelectrons (PE) via the photoelectric effect at a photocathode

enclosed in a glass bulb at near vacuum. These primary electrons are then accelerated and successively multiplied through a chain of dynodes via secondary electron emission, generating an amplified electrical pulse.

### 5.5.1 Calibration Hardware

As mentioned in the beginning of the chapter, JUNO demands an unprecedented energy resolution of  $3\%/\sqrt{E(\text{MeV})}$  and an energy scale uncertainty of less than 1%. Achieving this level of precision requires a comprehensive calibration program capable of probing non-linear charge responses, detector spatial non-uniformities, PMT efficiency variations, and particle-dependent effects.

To systematically study these effects, JUNO utilizes four complementary calibration subsystems: the Cable Loop System (CLS) for 2D coverage, the Guide Tube (GT) system for outer-boundary tracking, a Remotely Operated Vehicle (ROV) for 3D deployment, and the **Automated Calibration Unit (ACU)** [15]. The ACU serves as the primary system for the more frequent central-axis calibrations and is the relevant system for the work described in Chapters 6 and 7.

The ACU is mounted directly atop the central chimney flange of the CD, marked as Calibration System in Figure 5.2. Its primary function is to automatically lower and retract radioactive calibration sources and laser optical diffusers along the central vertical axis ( $z$ ) of the detector, spanning a full 34 m vertical range from  $z = +17$  m down to  $z = -17$  m. The ACU operates as an automated, enclosed mechanical assembly designed to maintain strict radio-purity and gas tightness. Inside the upper chamber of the unit, a motorized rotating carousel holds multiple radioactive gamma and neutron source capsules as well as a fiber-coupled laser diffuser ball for PMT timing and gain calibrations. Further details on both types of sources will be provided in Chapter 6.

The ACU’s motion is driven by a motor connected to a winding spool. A low-background wire attached to a counter-weighted source housing lowers the enclosure into the LS. Optical sensors coupled to the spool shaft corroborate the calibration position, achieving a spatial resolution in the few mm range [15]. To prevent LS contamination, the entire ACU enclosure is maintained under a positive pressure of high-purity nitrogen gas. Dynamic gas-tight seals isolate the interior from ambient air, preventing radon and oxygen ingress. During calibration runs, the ACU moves to pre-programmed positions, lowering sources in discrete steps along the  $z$ -axis. The produced charge and energy distributions anchor the energy scale calibration and allow continuous monitoring of the LS and PMT time stabilities.

### 5.5.2 Large PMT Subsystem

The primary system for light collection is an array of 17,612 20-inch Large PMTs positioned with 5 mm spacing along the sphere’s inner surface [20]. This array provides a total geometric photocathode coverage of approximately 75.2%. To optimize both timing resolution and cost, the LPMT system features two distinct technologies:

1. **Micro-Channel Plate PMTs (MCP-PMTs):** Produced by Northern Night Vision Technology (NNVT), 15,012 of the LPMTs utilize micro-channel plates instead of traditional dynode structures [22]. This design provides a high photon detection efficiency ( $\text{PDE} \sim 30\%$ ) and an expanded angular acceptance, which is crucial for capturing diffused light from peripheral vertices.
2. **Dynode PMTs:** The remaining 2,600 LPMTs are Hamamatsu R12860 high-quantum-efficiency dynode photomultipliers [22]. These tubes exhibit an exceptional single-photoelectron (SPE) resolution and a narrow transit time spread ( $\text{TTS} < 3 \text{ ns}$ ), providing the timing information for vertex reconstruction.

Each LPMT pulse is processed by a custom front-end chip that splits the signal into low-



Figure 5.3: Image of MCP-PMTs. Courtesy of the Institute of High Energy Physics in Beijing, China.

and high-gain branches to extend the dynamic range, before digitization by a custom, 14-bit, 1 GS/s flash ADC (FADC) per channel. The digitized waveforms are used on-chip to reconstruct the pulse charge and arrival time, generate a local trigger request, and timestamp hits, with data buffered temporarily in FPGA memory pending a global trigger decision. Data and power are routed out of the front-end electronics to the surface control room.

## 5.6 Small PMT Subsystem

Densely packed within the triangular clearances between the LPMTs is another system composed of 25,600 3-inch Small PMTs (sPMT), manufactured by HZC Photonics [19]. The sPMTs contribute an additional 2.7% of geometric coverage, bringing the total active photocoverage of the CD boundary to nearly 78%. The sPMT electronics operate completely independently of the LPMT high-voltage and digitization.

The motivation for a second system, beyond the marginal improvement in photocoverage, is rooted in the very different photon occupancy regimes in which the two PMT systems

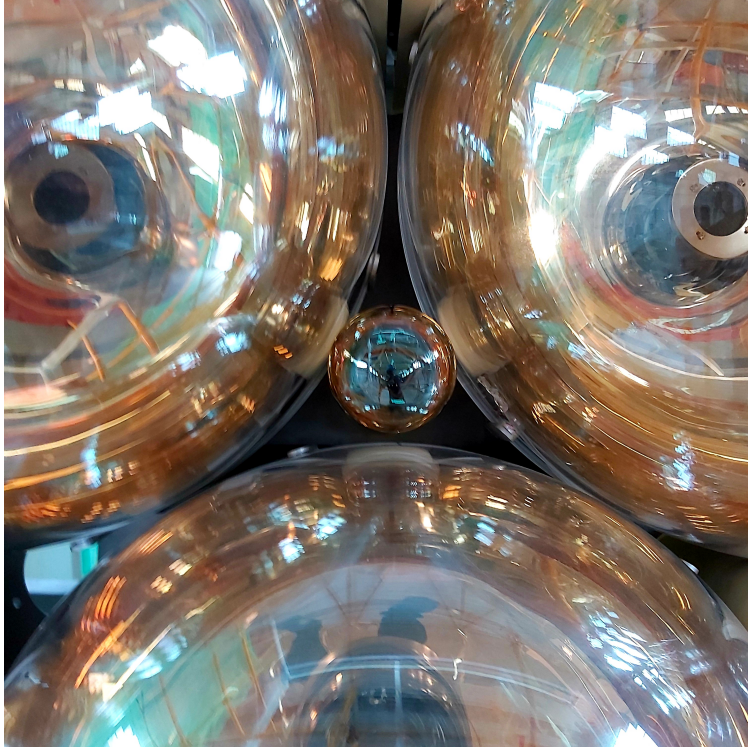


Figure 5.4: Image of sPMT installed between three LPMTs in support bracket. Courtesy of the Institute of High Energy Physics in Beijing, China.

detect light in JUNO. With a light yield  $\sim 1600$  PE/MeV at the detector center and a LPMT photocathode roughly 40 times the area of the sPMTs, a single 20-inch LPMT can collect anywhere from a handful to several tens of PEs per event, depending on energy and vertex position. In this analog charge-integrating regime, the PMT response must be linear (or its non-linearity well constrained) over nearly two orders of magnitude in light intensity. By contrast, each sPMT subtends a much smaller solid angle, overwhelmingly detecting either zero or exactly one PE for a few-MeV event. The SPMT system therefore operates in a *photon-counting regime* (PCR): rather than integrating charge, the energy estimator is simply the number of PMTs that fired (a digital hit-counting measurement), largely insensitive to gain calibration, non-linearity, or non-stability biases that affect analog charge integration.

This is a new approach relative to previous large LS and water-Cherenkov experiments,



which relied on a single PMT population and thus on one calorimetric technique alone. The energy scale and resolution, along with their systematic uncertainties were tied entirely to the stability and linearity of that single charge measurement. JUNO’s sPMT system provides a largely uncorrelated measurement of the same energy depositions observed by the LPMTs. Comparing the LPMT charge-based (analog) and sPMT count-based (digital) energy estimates for the same events allows the LPMT non-linearity to be calibrated in situ, which will be the focus of Chapter 6. As a secondary benefit, the sPMT occupancy and charge measurements remain valid even when the LPMT system saturates at very high light yields, extending the detector’s dynamic range to cover energetic events such as cosmic muons and atmospheric neutrinos.

### 5.6.1 sPMT Design

The 3-inch small PMTs were custom-developed for the JUNO collaboration by Hainan Zhanchuang Photonics Technology Co., Ltd (HZC), designated as model XP72B22 [19]. The XP72B22 utilizes a 10-stage linear-focused dynode multiplier structure enclosed in a compact glass bulb. Because the sPMT is intended to operate in the PCR at reactor antineutrino energies, the tube was specifically tuned for SPE signals rather than high-amplitude multi-photoelectron signals.

Table 5.2: Key design parameters of the HZC XP72B22 3-inch PMT subsystem evaluated at a nominal working gain of  $3.0 \times 10^6$ .

| Parameter                                            | Value / Specification               |
|------------------------------------------------------|-------------------------------------|
| Photocathode Type                                    | Bialkali                            |
| Multiplier Geometry                                  | 10-stage linear dynode              |
| Photon Detection Efficiency (PDE) @ 420 nm           | $\sim 25\%$                         |
| Transit Time Spread (TTS, FWHM)                      | $< 5$ ns ( $\sigma \approx 1.6$ ns) |
| Peak-to-Valley (P/V) Ratio for SPE                   | $\sim 3.0$                          |
| Single Photoelectron (SPE) Resolution                | $\sim 33\%$ – $35\%$                |
| Mean Dark Count Rate (Potted, at 1/3 p.e. threshold) | $\sim 400$ – $500$ Hz               |
| Pre-pulse / After-pulse Ratio                        | $< 5\%$ / $< 15\%$                  |

The physical parameters listed above provide several performance advantages [19]. Main-

taining a high P/V ratio of  $\sim 3.0$  alongside an SPE resolution of roughly 33% guarantees and unambiguous SPE response that is well separated from electronic noise. The sPMTs also exhibit a low mean dark count rate of less than 500 Hz when fully potted and submerged in the water pool.

### 5.6.2 Underwater Electronics

Routing HV lines from the PMTs all the way to the surface electronics room would cause a few complications. The different cable lengths can cause non-uniformities related to signal attenuation and cross-talk. To solve this, the front-end readout and high-voltage electronics for the 25,600 sPMTs are decentralized and submerged inside the water pool [19, 111]. To reliably manage this massive number of channels, the electronics system is distributed across 200 underwater boxes (UWBs), each processing 128 channels.

A single coaxial cable is used per photosensor, handling both the High Voltage (HV) supply and the analog signal return. This requires that signal decoupling and individual HV generation must happen completely underwater within the sealed UWB [111]. As illustrated in Figure 5.5, the internal electronics inside each UWB are divided into three distinct tiers of PCBs.

#### High-Voltage Splitter Boards

Each UWB houses two identical 64-channel High-Voltage Splitter (HVS) boards (8-layer PCBs measuring  $36.5 \text{ cm} \times 19 \text{ cm}$ ) [111]. The HVS acts as the direct physical interface to the incoming PMT coaxial cables. The HV generation is driven by eight high voltage units (HVUs) per board, transforming a baseline 24 V input from the surface into an adjustable 800–1500 V bias. To guarantee survival against component wear, internal redundancy is implemented. The generated HV output is split across 16 channels via  $20 \text{ M}\Omega$  resistors, which also isolate short circuits and limit fault currents in case of a single-tube failure. The

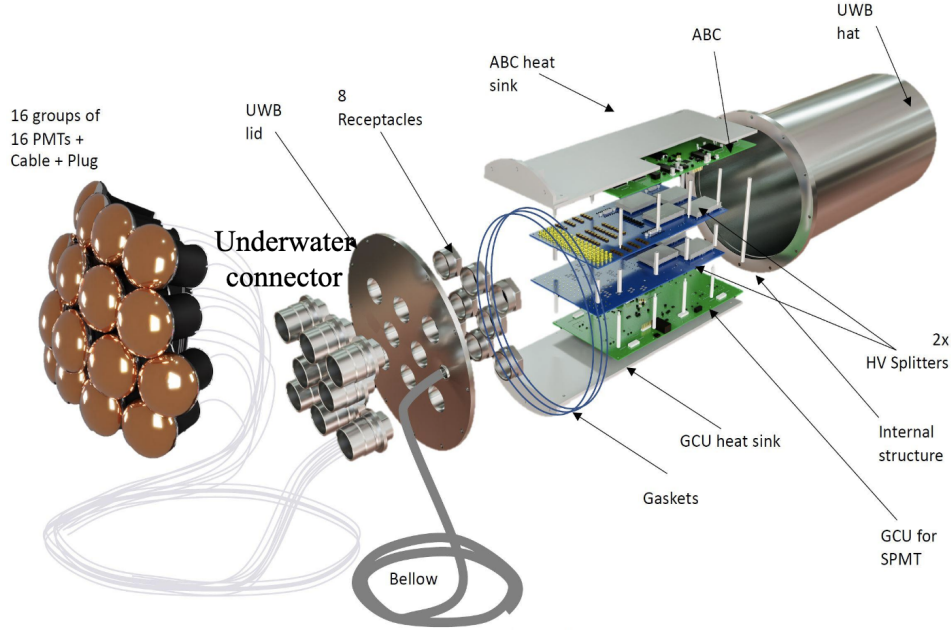


Figure 5.5: Diagram of exploded UWB.

high-frequency analog SPE signals are separated from the DC high-voltage carrier using 3.9 nF decoupling capacitors. These capacitors are screened to keep the physical cross-talk between adjacent channels in the few percent level.

### Analog Readout Board

The analog signals are routed directly to the Analog Readout Board (ABC), which handles triggering and analog-to-digital processing for all 128 channels [111]. The management of the ABC board is done by eight **CATIROC** (Charge and Time Integrated Read Out Chip) ASICs [54]. Manufactured using a 0.35  $\mu\text{m}$  SiGe technology, each 16-channel SoC operates in a self-triggered acquisition mode. The CATIROC fires on single photoelectrons with 100% efficiency down to an ultra-low threshold of 1/3 p.e..

When a channel fires, the CATIROC records a dual-stream dataset with a 10-bit charge measurement over a wide dynamic range (160 fC to 100 pC) alongside a high-precision time-of-arrival measurement [54]. The time signature comprises a 26-bit coarse time timestamp

(derived from a 40 MHz master clock with 25 ns resolution) and a 10-bit fine time from a time-to-digital converter ramp, yielding an overall timing resolution of  $\sim 167$  ps RMS. A dual Time and Hold system working in a ping-pong buffer mode reduces channel dead time to less than  $9\ \mu\text{s}$ .

## **Global Control Unit (GCU)**

The top-tier PCB inside the UWB is the **Global Control Unit (GCU)**, which serves as the primary communications bridge between the submerged front-end components and the surface-level DAQ systems [111]. The GCU board consists of a 16-layer PCB controlled by a Xilinx Kintex-7 FPGA and a secondary Spartan-6 FPGA. The Spartan-6 is dedicated exclusively to managing safe, remote firmware reprogramming, allowing hardware-level updates without risking a permanent bricking of the submerged unit.

The Kintex-7 FPGA aggregates the serialized 50-bit hit packets from the eight CATIROC ASICs, cushions the data stream using an internal 16 Gb DDR3 memory buffer, and manages data transmission over network links. Clock and trigger management are communicated to the surface Back-End Card (BEC) over FTP cables, while slow control and data-writing is pushed over standard UTP lines to a central Gigabit Ethernet switch at a target bandwidth of 57 MB/s [111].

## **Enclosure and Thermal Management**

The physical enclosure of the UWB is a cylindrical stainless steel vessel with an internal length of 50 cm and a diameter of 273 mm [111]. The removable top lid is secured via structural screws and hermetically sealed against the ambient water pressure using a triple O-ring arrangement. The lid acts as the feedthrough for 8 custom Axon multi-channel underwater connectors linked to the sPMT bundles and a flexible metallic bellows routing the surface power and data cables.

Because the closed box must dissipate heat generated by the dense electronics ( $\sim 30$  mW/channel for the ASICs alone), thermal design is critical. The UWB implements a sandwich layout where the high-power FPGAs and DC-DC converters are directly coupled to massive copper heat sinks through a high-conductivity thermal silicone rubber ( $4 \text{ W}/(\text{m} \cdot \text{K})$ ). These heat sinks route the thermal energy directly into the outer stainless steel shell, utilizing the surrounding 35 kton water pool veto as an effectively infinite cold source to maintain an internal operating temperature well below  $40^\circ\text{C}$  [111].

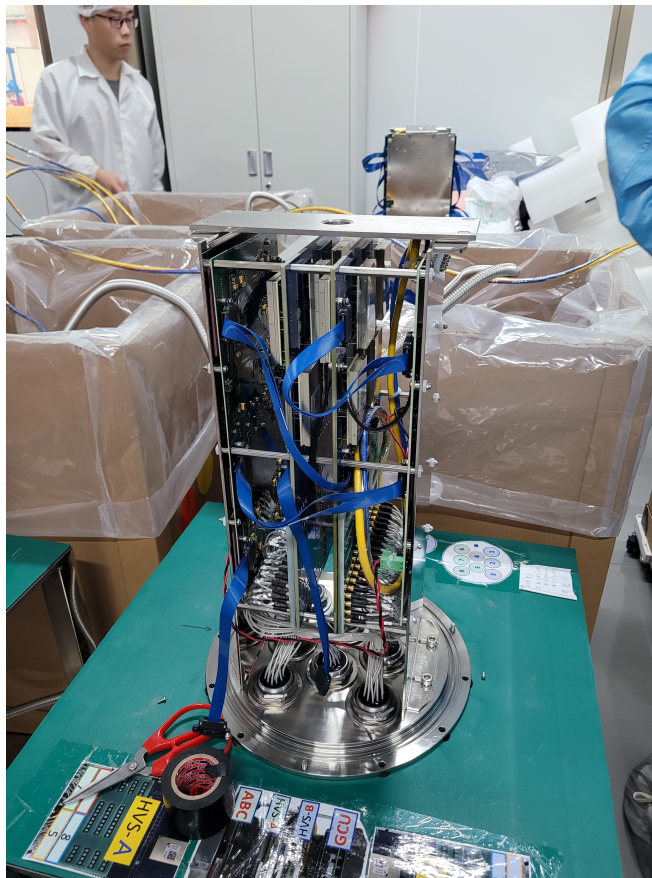


Figure 5.6: UWB before placement of steel hood.

### 5.6.3 Cross-talk Calibration

The level of cross-talk in the HVS board was corroborated experimentally with a special data-taking campaign. An LED driven by a NIM 24V DC power supply was installed in the clean surface room and pulsed at a variable frequency in the kHz range, checked using an

oscilloscope. The LED is then fed to an optic fiber which is routed through the wall into a test dark room.

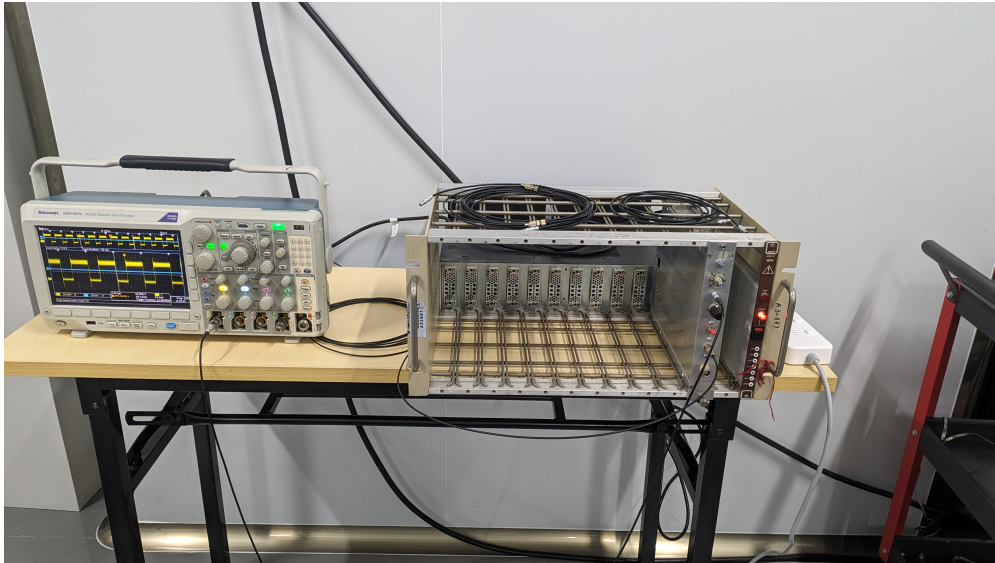


Figure 5.7: LED testbench for cross-talk study consisting of the power supply and LED driver, mounted on the bracket to the right, and an oscilloscope on the left to corroborate the LED pulse frequency. The background wall covers the dark room.

Inside the dark room, 16 PMTs (corresponding to a single connector) are each placed on a bracket inside a cover with a miniscule opening as shown in Figure 5.8. The far end of the optic fiber can then be inserted into the cover to deliver light signals to that PMT only.

The PMTs are connected to an UWB in the dark room which communicates to the DAQ system in the clean room. By changing the placement and multiplicity of the optic fiber as well as the connector inside the UWB the cross-talk in the HV lines going through the HVS board can be understood through matching channel numbers with circuit traces from schematics.

Data was taken at 5 kHz and 10 kHz LED frequencies and analyzed. Cross-talk hits were identified by selecting signals in non-illuminated PMTs correlated in time and charge with an LED pulse. The intensity at 5 kHz was found to be insufficient to reliably find charge signals correlated to LED pulses in other channels. For the 10 kHz run, most cross-talk



Figure 5.8: Mounting bracket with PMT covers for cross-talk study. The dark room is illuminated whenever its door is opened with a low-intensity red light to keep dark noise counts low.

was found to occur within 25 ns of an LED pulse, and the fraction of charge induced in a neighboring channel was under 0.4% as shown in Figure 5.10.

#### 5.6.4 Installation

Given the massive amount of sPMTs to be installed in conjunction with the LPMT installation while taking tight data-taking schedules into account, a highly coordinated installation



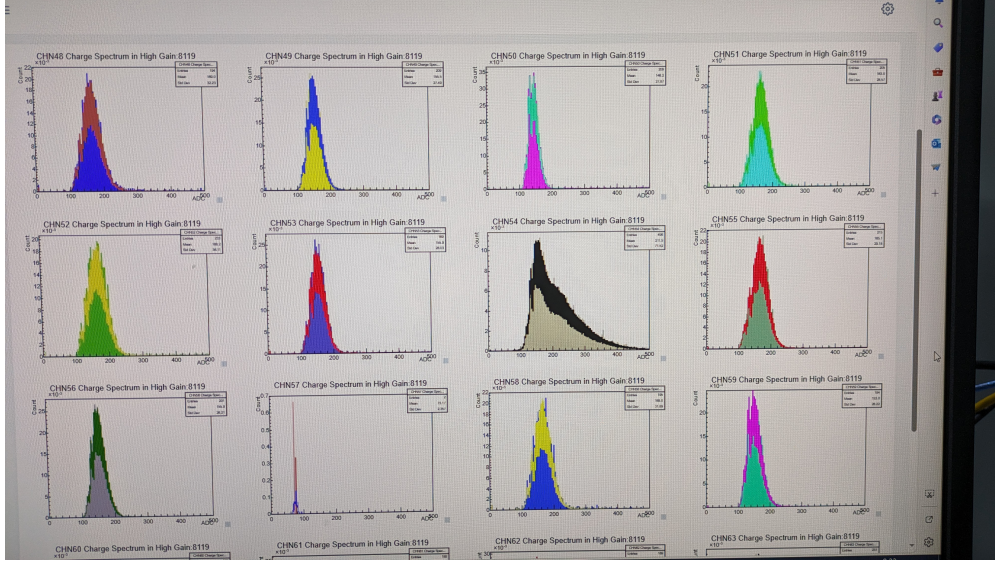


Figure 5.9: Clean room DAQ system during a cross-talk run, showing Ping and Pong charge distributions for all channels in the CATIROC. Most channels read a SPE spectrum from dark noise while the LED-injected channel (middle row, third column from the left) sees a higher charge distribution.

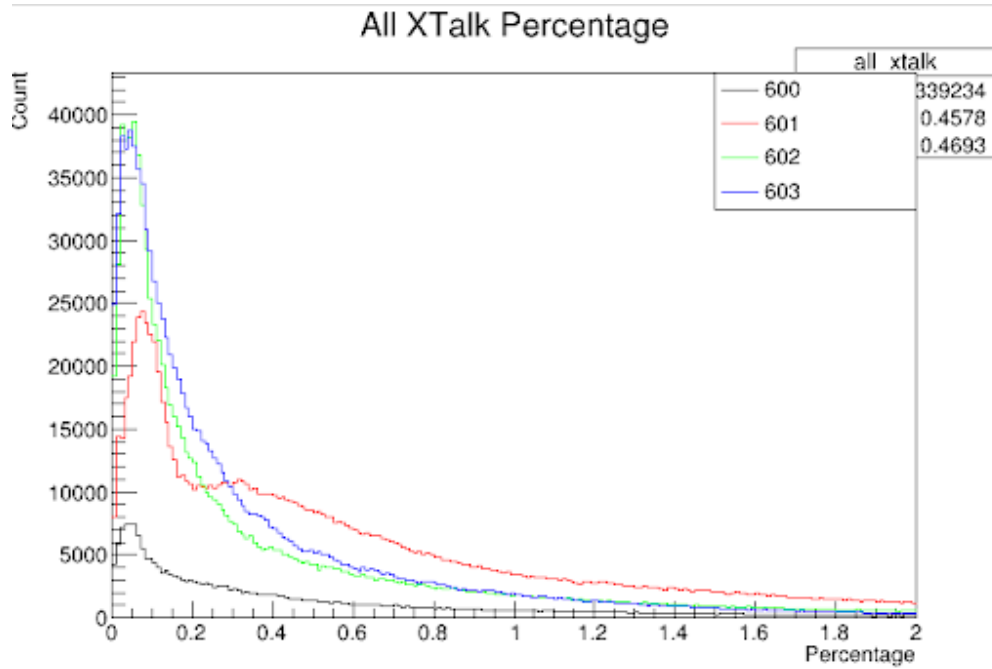


Figure 5.10: Cross-talk analysis result. Credit to Adrienne Jacobi.

methodology is key for the successful installation and operation of the sPMT system [19].

The sPMTs are pre-assembled into sub-modules. Each sub-module houses a cluster of sPMTs



secured via custom stainless steel mounting brackets and lined with protective EPDM rubber gaskets to avoid scratching the glass envelopes. These brackets are lowered by crane into the sphere and directly bolted onto the primary structural beams of the SSST, maintaining a strict clearance tolerance of a few millimeters relative to the neighboring LPMT magnetic shielding covers.



Figure 5.11: Top of JUNO experimental hall with yellow crane rails pictured along the ceiling.

### Waterproof Potting and Cabling

Because a single water leak at the base of a PMT would permanently disable the channel, every PMT undergoes a rigorous waterproof potting procedure before installation [19]. The high-voltage divider base is soldered to the PMT pins and enclosed in a protective plastic potting shell. This shell is backfilled with an optical-grade, low radioactivity polyurethane and epoxy compound. The compound seals the junction between the glass tube, the divider component, and the outgoing front-end cable, ensuring insulation against the 8 bar

hydrostatic pressure at the bottom of the water pool.

Prior to submerging sPMT components, a rigorous Quality Assurance (QA) protocol was executed on every UWB [52]. Following final assembly and lid closure, each UWB was pressurized internally with Sulfur Hexafluoride ( $\text{SF}_6$ ) tracer gas. The boxes were monitored using specialized electron-capture leak detectors over several hours to accumulate enough gas for a reliable measurement of the leakage rate. The system achieved a leak rate threshold of less than  $2.3 \times 10^{-9} \text{ Pa} \cdot \text{m}^3/\text{s}$ , well within design specifications.

To prevent a tangle of cables from casting optical shadows on the photosensors, the cables are organized into distinct 16-channel bundles. These bundles are routed along the structural ribs of the truss, completely away from the clear fields-of-view of the PMTs. Each bundle plugs into a designated multi-channel waterproof connector on the top flange of its UWB. The heavy transmission lines exiting the UWBs are routed upward along the main vertical structural columns of the cavern, leading out to the dry electronics room.

### 5.6.5 Commissioning

Before filling the cavern with water, finished tiers of the detector were powered up and operated. To do so, all ambient and artificial light present in the experimental hall had to be powered down or removed, thus these tests were colloquially named Lights-off Tests (LoT). This testing allowed control, monitoring, and DAQ to be exercised as well as isolating dead channels, verifying high-voltage ramping, and measuring electronic noise.

High voltage ramping was staged both to protect the freshly-installed PMTs and dividers and to allow any channel exhibiting an unstable draw or a short to be identified and isolated before it could affect its neighbors within the same UWB. Once biased, each channel's dark-noise waveform was continuously digitized by the front-end. This checked for every channel that the full signal chain was functioning end-to-end, well before any scintillation or



Figure 5.12: JUNO electronics room.

Cherenkov light was present to serve as a diagnostic.

With the data taken during the LoT, the pedestal, gain, thresholds and dark noise rates were assessed and tuned for physics data-taking. Channels with no response, an anomalously low or unstable gain, a poorly-separated pedestal, or a dark count rate inconsistent with acceptance testing were flagged for further investigation. The resulting settings established during the LoT campaigns provided the baseline operating configuration subsequently refined during full detector commissioning in the presence of water or LS.

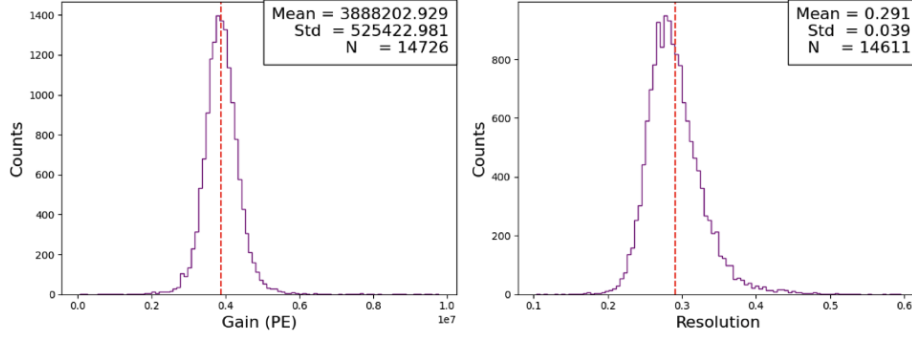


Figure 5.13: Gain and Resolution distributions for sPMTs from commissioning.

## 5.7 Cosmic Muon Veto Systems

Operating a large liquid scintillator detector near the surface or at shallow depths exposes the active volume to a high flux of atmospheric cosmic muons, which generate problematic cosmogenic radioisotopes ( $^9\text{Li}/^8\text{He}$ ) via spallation on  $^{12}\text{C}$  [20]. To suppress these backgrounds, the central detector is surrounded by two distinct active and passive veto subsystems.

### 5.7.1 The Water Cherenkov Detector

The entire central detector structure is entirely submerged inside a cylindrical underground pool filled with 35 kton of ultra-pure water, measuring 44 m in depth and 44 m in diameter [20]. This water pool fulfills two essential roles. The water volume provides passive shielding of several meters around the acrylic sphere, attenuating environmental  $\gamma$ -rays and fast neutrons emanating from the surrounding rock. The pool also operates as an active water Cherenkov detector. The inner walls and support truss are lined with highly reflective Tyvek sheets and monitored by 2,400 independent 20-inch veto PMTs. Cosmic muons traversing the water emit directional Cherenkov light, which is captured to flag cosmic events with a total detection efficiency exceeding 99.5% [20].

### 5.7.2 The Top Tracker

Directly above the cylindrical water pool sits the Top Tracker (TT), a high-granularity plastic scintillator detector re-purposed from the targets of the OPERA experiment [26, 20]. The TT consists of three sequential horizontal layers of plastic scintillator strips arranged in an orthogonal configuration.

When a cosmic muon passes through the tracker before entering the water pool, the scintillator strips record its entry point. Light generated within the strips is routed via embedded wavelength-shifting (WLS) fibers to multi-anode photomultiplier tubes (MaPMTs). The Top Tracker achieves an angular reconstruction resolution of approximately  $1^\circ$  [20].

### 5.7.3 Magnetic Field Shielding Coils

Another important consideration is the impact of the Earth’s magnetic field. LPMTs, in particular the NNVT MCP-PMTs, possess a large internal vacuum volume where photoelectron trajectories span tens of centimeters from the photocathode to the amplification stage [20, 22]. The ambient magnetic field ( $\sim 0.5$  Gauss) exerts a Lorentz force that deflects these low-energy electrons, severely degrading the collection efficiency and distorting the uniform gain response of the detector.

To compensate for this bias, JUNO features a dual-axis system of circular EMF shielding coils wrapped coaxially around the exterior concrete structure of the water pool cavern [20]. These coils are continuously driven with actively regulated direct currents to generate an opposing magnetic bucking field. This shielding actively reduces the residual magnetic field within the internal volume of a PMT matrix to less than 10% of its ambient value ( $< 0.05$  Gauss), preserving the photoelectron collection efficiency [22].

## 5.8 Taishan Antineutrino Observatory

To achieve the sub-percent precision required for determining the neutrino mass ordering, the JUNO experiment relies on the Taishan Antineutrino Observatory (TAO) as a satellite detector. Placed only about 40 m from one of the Taishan nuclear reactor cores, TAO serves as a high resolution reference detector to precisely measure the unoscillated reactor antineutrino spectrum [14]. Its smaller design resembles the CD but boasts calorimetric properties that would be too expensive to implement in the main detector, like cryogenic operation.

TAO holds 2.8 tons of the JUNO LS doped with 1% gadolinium, contained within a spherical acrylic vessel [14]. The gadolinium capture signal has a higher cross-section compared to hydrogen and provides higher signal-to-background separation due to its more energetic gamma emission. To achieve an energy resolution targeting  $\sim 1.5\%$  at 1 MeV, TAO is instrumented with SiPMs providing roughly 95% optical coverage and operated at  $-50^\circ\text{C}$  to suppress dark noise [14].

In the context of the oscillation analysis, TAO is critical for providing a model-independent reference spectrum [14]. Reactor antineutrino spectrum models historically suffer from significant discrepancies with data [74]. While using previous data like that from Daya Bay [49] is an option, measuring the unoscillated reactor spectrum directly with higher granularity further eliminates model-dependent systematics, ensuring that fine structures in the spectrum are not misidentified as oscillation-induced neutrino mass splitting effects.



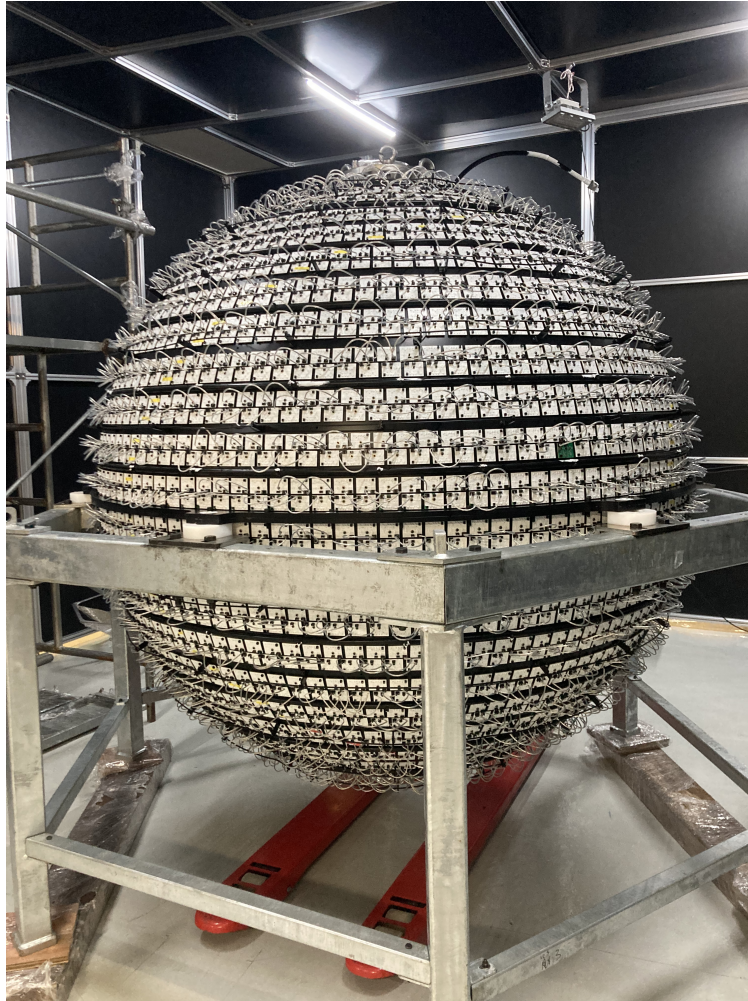


Figure 5.14: TAO detector. Courtesy of the Institute of High Energy Physics in Beijing, China.

# Chapter 6

## Dual-Calorimetry Calibration

As stressed in Chapters 1 and 5, the success of JUNO hinges on its capabilities in precision calorimetry. Achieving this level of precision demands the detailed study of two distinct sources of energy non-linearity: *physics non-linearity* (originating from scintillator quenching and Cherenkov light production) and *instrumental non-linearity* (originating from voltage dividers, readout electronics digitization and charge calculation).

The massive light yield of JUNO combined with its large physical dimensions make these studies particularly complex and interesting. For high-energy events or events localized near the boundaries of the sphere, the closest PMTs are illuminated intensely (about 2 orders of magnitude more than for events localized at the center). This pushes the tubes and their front-ends past their linear operational charge regimes. To isolate and correct for this potential instrumental distortion, JUNO implements a unique dual-readout calibration technique known as Dual-Calorimetry Calibration or DCC.



## 6.1 Dual Calorimetry at JUNO

The DCC concept is based on having two different photosensor systems operating in fundamentally different modes at the same time, as described in Section 5.6. For typical IBD events up to 10 MeV, the LPMTs collect multiple overlapping single photoelectrons within a single timing window of 1000 ns. To first order, the readout electronics integrate the PMT anode current waveform to extract the total collected charge ( $Q_{\text{LPMT}}$ ) as:

$$Q_{\text{LPMT}} = \int I_{\text{anode}}(t) dt \quad (6.1)$$

At higher energies or for edge events, charge effects from the dynodes/MCPs and systematic effects from the waveform reconstruction and integration cause gain suppression. This causes the relationship between the deposited light intensity and the integrated charge output to bend non-linearly.

On the other hand, the probability  $\mu$  of a single sPMT receiving a photon during a reactor neutrino event is exceptionally small ( $\mu \ll 1$ ) due to their size. According to Poisson statistics, the probability of a given channel experiencing a multi-photoelectron hit is:

$$P(k > 1; \mu) = 1 - e^{-\mu}(1 + \mu) \approx 0 \quad (6.2)$$

Consequently, the sPMT subsystem does not need to rely on charge integration and can operate via digital photon counting. The total light yield observed by the sPMT array is determined through the total number of hit channels  $N_{\text{hit}}$ . Because hit counting is inherently binary, it is completely immune to instrumental charge non-linearity.

The charge response of a PMT depends on:

1. the incident particle's energy and physics in LS

2. the position of the interaction in the detector
3. the time of interaction (non-stability in detector conditions)
4. the instrumental non-linearity from the hardware

Exposing two PMT systems to the same detector allows for the cancellation of the first three, as they both detect light from the same interactions simultaneously. This effectively isolates the instrumental non-linearity, and given that the sPMTs are immune to it, they serve as an ideal linear reference for the LPMT instrumental non-linearity. Constraining the instrumental non-linearity in a target LPMT using sPMT photo counting is then the focus of this chapter.

## 6.2 DCC-Laser

### 6.2.1 Laser Calibration

The nominal execution of DCC in JUNO is performed with a laser calibration system, which provides an external light source capable of sweeping across multiple orders of magnitude in intensity, effectively probing the entire light dynamic range of the electronics.

The laser module consists a sub-nanosecond pulsed laser, typically operating at a 266 nm wavelength. The laser source above the water pool cavern is routed down into the CD through a specialized, high-transmittance quartz fiber-optic cable. The fiber ends at the detector center, coupled to an isotropic optical diffuser ball using the ACU. The diffuser ball is engineered to ensure a photon emission profile highly uniform in a  $4\pi$  solid angle, illuminating all 17,612 LPMTs and 25,600 sPMTs simultaneously from a central vertex. The absolute intensity of the laser pulses is dynamically adjusted using a motorized, high-precision neutral-density filter wheel, allowing the calibration loop to inject events ranging from sub-MeV solar neutrino-like depositions up to multi-GeV energies [129].

The primary advantage of using a central laser source for DCC is that it provides a controlled light input that bypasses the charged-particle energy-deposition processes responsible for effects such as ionization quenching, particle-dependent scintillation yield, and Cherenkov-light production. As a result, observed deviations from linearity in the detector response can be directly attributed to instrumental effects in the photosensor and readout chain, rather than to the scintillator response itself. For each laser pulse intensity step, the charge in every LPMT and the fired channels in the sPMT system  $N_{hit}$  are recorded. The charge estimation from the  $N_{hit}$  should be perfectly linear, so plotting the LPMT charge against the linear benchmark using the occupancy method described later in this chapter (named  $\mu_{LPMT}$  in Figure 6.1) extracts a calibration curve by comparing the result against a  $y=x$  assumption. The non-linearity in data using the laser method was found to be under the 1% level in the reactor antineutrino illumination range, and with an undershoot present in the NNV tubes at low energies. As illumination increases, the Hamamatsu PMTs exhibit a larger negative charge non-linearity.,

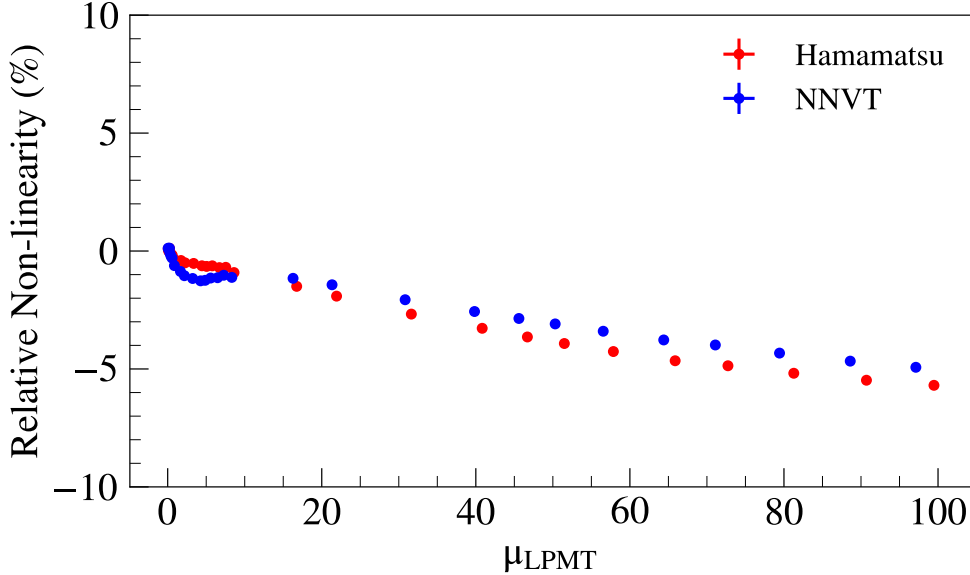


Figure 6.1: Results of Laser DCC on JUNO data. Curves for both the Hamamatsu and NNV tubes produced are shown. Credit to Yujie Niu.

### 6.2.2 A Second Calibration

While the DCC-Laser method allows for the fast calibration of all LPMT channels across a large illumination range, there are important physical differences between the detector's response to laser light and to  $\gamma$ /positron-induced scintillation that can be addressed to improve the correctness of the calibration. The most relevant of these arises from the time profile of the detected PEs, which can bias the charge response, particularly for the LPMTs.

In LS, the multi-step energy transfers a  $\gamma$  or  $e^\pm$  initiate give rise to a characteristic light emission profile, typically featuring a fast component with a decay time of a few nanoseconds and one or more slower components extending to tens or even hundreds of nanoseconds. The relative weight of these components depends on the local ionization density along the particle track and is in fact what drives pulse-shape discrimination techniques. On the other hand, the laser UV photons are absorbed by the LS solvent and promptly re-emitted at 420 nm. The resulting PE arrival-time distribution at the PMTs is therefore significantly narrower than the one produced by a true  $\gamma/e^\pm$  event of comparable light yield [78].

Because the LPMT charge integration is affected by how a given number of PEs are distributed in time, and not only on their total number, this discrepancy in pulse shape creates a particle-dependent systematic. The non-linearity curve extracted from laser data does not, in principle, guarantee a perfectly identical response for real scintillation light of the same total charge.

This effect can be mitigated by a second calibration campaign using radioactive  $\gamma$  sources. Like the positrons produced in the IBD signal,  $\gamma$ s deposit their energy through ionization in the LS and therefore excite the solvent-fluor system in the same way. The resulting scintillation light follows a time profile consistent with that of IBD-like events as shown in Figure 6.2, providing an instrumental non-linearity calibration that is free of the laser-specific temporal bias. While the energy or light intensity from radioactive sources cannot

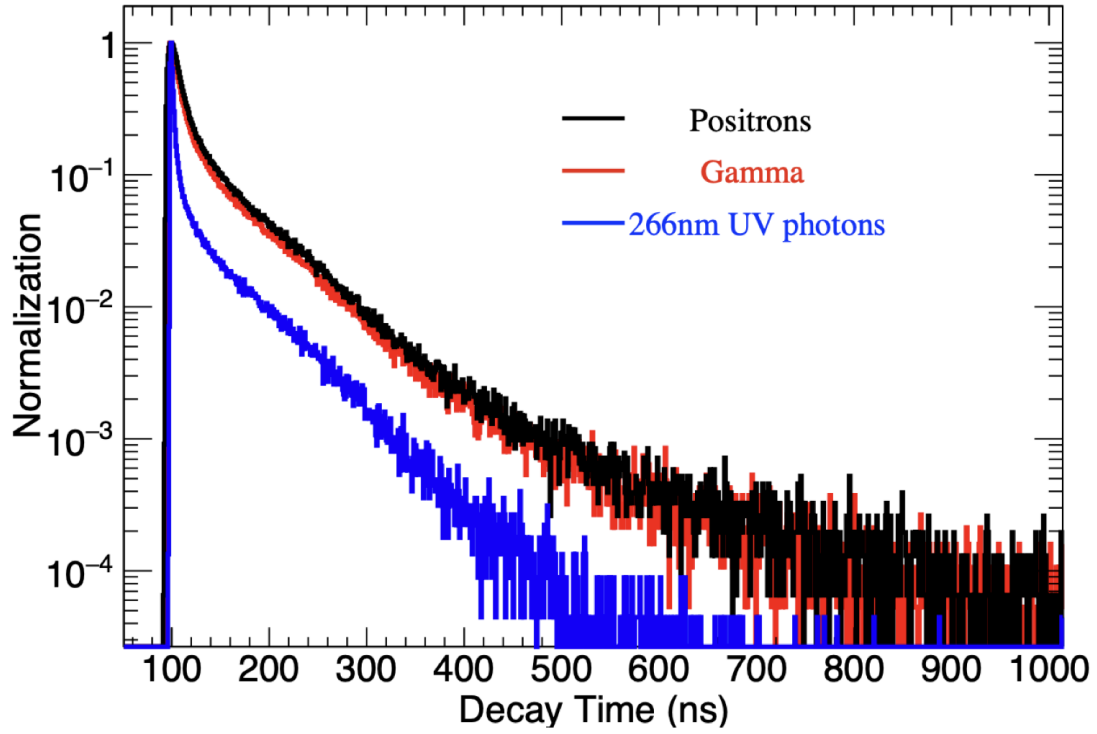


Figure 6.2: Simulated hit arrival-time (decay time) distributions for 266 nm laser photons, positrons and gammas. The distributions are normalized to 1 at their maximum. The charge-time profiles for the latter two are slower than for laser photons. Image obtained from [78].

be increased on a dial like the laser, the source can be lowered increasingly closer to a single **target** LPMT of interest, increasing its illumination to allow the intensity coverage needed to supplement the DCC-Laser results. This technique is known as DCC-Gamma. The work presented in this chapter seeks to use the full detector simulation assuming deployment times of gamma sources that are representative of what JUNO performs currently to see the kind of precision that could be achieved with this calibration.

## 6.3 DCC-Gamma

### 6.3.1 JUNO Offline Software and Simulation

The generation and reconstruction of all JUNO simulation samples presented in this thesis are performed within the JUNO offline software (JUNOSW), built on top of the SNI<sub>PER</sub> (Software for Non-collider PhysIcs expERiment) framework [95, 96]. SNI<sub>PER</sub> was developed drawing on experience from the Daya Bay offline software and provides a lightweight, modular kernel for managing event data, job configuration, and the execution flow of a data processing chain.

#### Detector Simulation and Radioactive Source Generation

The detector simulation stage is based on Geant4 [31], interfaced to SNI<sub>PER</sub> as a service. The full detector geometry, including the surrounding rock, is implemented with the corresponding optical and physical material properties so that optical photon propagation and PMT hit generation are modeled consistently.

For the calibration source samples used in this work, radioactive decays are generated using the Geant4 Radioactive Decay Module (GRDM), accessed through the particle-gun generator. A source’s activity and branching ratios are defined through an input file. At each generated event, an isotope is sampled according to the specified ratios and handed to

GRDM, which produces the associated decay products. These Geant4 primaries are then injected (or shot, hence the name particle-gun) directly into the detector simulation while also modeling the enclosure around the source. The  $\gamma$ s emitted by GRDM are subsequently tracked, scattered, and absorbed within the LS or enclosure materials. The injected position is specified at runtime, allowing the same isotope to be simulated anywhere within the central detector.

For this analysis, dedicated  $\gamma$ -source samples were generated with GRDM at a selection of positions spanning the lower half of the central axis within the LS volume, as shown in Table 6.1. Each simulated position constitutes one input data point used throughout this chapter: for every source and every position, a GRDM-generated sample of decay  $\gamma$ s is propagated through the full detector simulation, producing photon-level and PMT-hit-level truth information. The number of events simulated was chosen to be representative of the duration of a JUNO calibration run, with the exception of the center simulations where the sample size is 4x larger to reduce their statistical uncertainty by half. This in turn reduces the systematic uncertainty of the final calibration, given that the center points are used to correct the rest of the data as discussed later.

| Source            | Energy (MeV) | Z-axis Positions (m)       | Events (Center, Off-Center) |
|-------------------|--------------|----------------------------|-----------------------------|
| $^{137}\text{Cs}$ | 0.662        | 0, -10, -14, -15, -16, -17 | (600k, 150k)                |
| $^{54}\text{Mn}$  | 0.835        | 0, -10, -14, -15, -16, -17 | (600k, 150k)                |
| $^{68}\text{Ge}$  | 1.022        | 0, -10, -14, -15, -16, -17 | (600k, 150k)                |
| $^{40}\text{K}$   | 1.461        | 0, -10, -14, -15, -16, -17 | (1.2M, 300k)                |
| $^{60}\text{Co}$  | 2.505        | 0, -10, -14, -15, -16      | (600k, 150k)                |

Table 6.1: List of Radioactive Sources and their visible energies

## Electronics Simulation and Waveform Reconstruction

Following detector simulation, the true PMT hit information is passed to the electronics simulation. This stage emulates the full front-end response of both PMT systems: the SPE pulse shape and gain of each PMT, the low- to high-gain transfer in the analog front-end, and the digitization performed by the custom ADCs. This stage generates simulated raw

waveforms that are practically identical to those produced by the real electronics.

The resulting simulated waveforms are then processed by the same waveform reconstruction algorithms used on real detector data, which extract, for each hit channel, a calibrated charge and hit time by fitting or de-convoluting the digitized pulse. This yields the per-channel charge for both PMT systems. Running simulated  $\gamma$ -source events through this electronics-simulation and waveform-reconstruction chain ensures that the Monte Carlo-based non-linearity is directly comparable, channel-by-channel, to the corresponding measurement performed with real calibration data.

### 6.3.2 Selecting Calibration Events

Sources deployed as part of the calibration program provide monoenergetic, or near-monoenergetic, energy depositions in the LS. However, the emitted  $\gamma$  must first interact with the LS, and the physics of that interaction shapes the resulting charge spectrum.

In a low-Z medium such as the LS, the photoelectric cross-section is such that at few-MeV energies Compton scattering is the dominant interaction mechanism. A  $\gamma$  ray therefore typically deposits only a fraction of its energy in a single scatter, with the photon free to escape or undergo further interactions. Because JUNO's volume is large compared to the photon mean free path at these energies, a sizable fraction of  $\gamma$  rays undergo one or more subsequent Compton scatters, allowing the full photon energy to be deposited within the active volume. This produces two features in the measured charge spectrum: a Compton background, extending from zero up to the Compton edge and populated by events in which the scattered photon escapes, and a photopeak centered at the total  $\gamma$  energy, populated by events in which the entire photon energy is deposited in the LS.

Only the photopeak events correspond to a well-defined energy deposition proportional to the true source energy. Compton-continuum events, by construction, deposit less energy and



would bias any estimate of the charge response if included. However, the two components cannot be cleanly separated by a simple charge threshold, and a dedicated fit is required to statistically disentangle them. Fitting for this analysis is performed using **GaRF** (Gamma-Ray Fitter) [102]. **GaRF** provides a modern, physically-motivated fitting framework developed specifically for this work that can automatically or interactively fit a set of charge spectra in photoelectrons, as well as reconstructed energy distributions, the latter being relevant to the next chapter. The extracted means ( $\mu$ ) and energy resolutions ( $\sigma$ ) of the photopeaks across the set of radioactive sources are then used to select a clean sample of events.

## Model

The total spectrum model  $S(E)$  fit to a gamma charge spectrum includes a photopeak core, background model, and tail contributions:

$$S(E) = B(E) + N [(1 - f_{\text{esc}}) P_{\text{core}}(E) + f_{\text{esc}} T_{\text{esc}}(E)] \quad (6.3)$$

where  $N$  represents the total peak area, and the individual components are defined as follows:

- **Photopeak ( $P_{\text{core}}$ ):** Nominally modeled as a Gaussian centered at  $\mu$  with width  $\sigma$ . For high-energy lines or sources subject to significant low-energy leakage (e.g., pair-production escape in AmC sources), **GaRF** supports optional Crystal Ball or Novosibirsk functional shapes.
- **Compton Escape / Partial Absorption ( $T_{\text{esc}}$ ):** To model gammas that undergo partial energy deposition prior to escaping, **GaRF** incorporates a low-energy tail based on [45]. This component assumes a constant or exponentially decaying distribution on  $[0, \mu]$  convolved with Gaussian resolution, determined by the area fraction  $f_{\text{esc}}$ .
- **Background ( $B(E)$ ):** Backgrounds are parameterized as monotonic (**flat**), a first-order polynomial (**linear**), or a smooth step-down function (**left\_flat**) utilizing an

error function (erf) that suppresses the background past the photopeak [45]. While the simulated samples in this work have no backgrounds, the `left_flat` can help capture events prone to leakage.

The nominal configuration is to use a Gaussian core with the `left_flat` option, as it reproduces the charge distribution shapes exceedingly well, as shown in Figure 6.3.

## Minimization and Robust Fitting

GaRF utilizes the `iminuit` python package [60, 84] as its primary optimization algorithm, using `Migrad` for parameter minimization and `Hesse` for full covariance matrix computation and error propagation. Depending on the sample size of the calibration source, fits can be evaluated using either Pearson’s  $\chi^2$  or Poisson Negative Log-Likelihood (NLL or  $\ell$ ) as the loss metric.

To increase the success of automation during batch calibration runs, GaRF incorporates a robust fitting routine. If an initial fit encounters non-convergence, hits parameter boundary limits, or exceeds a specified  $\chi^2/\text{ndf}$  or  $-2\ln(\ell)/\text{ndf}$  threshold, the algorithm automatically re-executes the fit up to  $N_{\text{retries}}$  times. During each retry, random perturbations are applied to the initial mean guess  $\mu_{\text{guess}}$  and fit window width to escape shallow local minima and ensure convergence on the true solution.

After fitting, events are selected for calibration if their total LPMT charge lies  $2\sigma$  from the extracted mean of the photopeak.

### 6.3.3 LPMT-sPMT Charge Comparison

After identifying calibration source events through total LPMT charge fitting, the next step is to compare the charge estimators of both the target LPMT to be diagnosed and the total sPMT system for this set of events. Given that the ACU is being lowered closer to

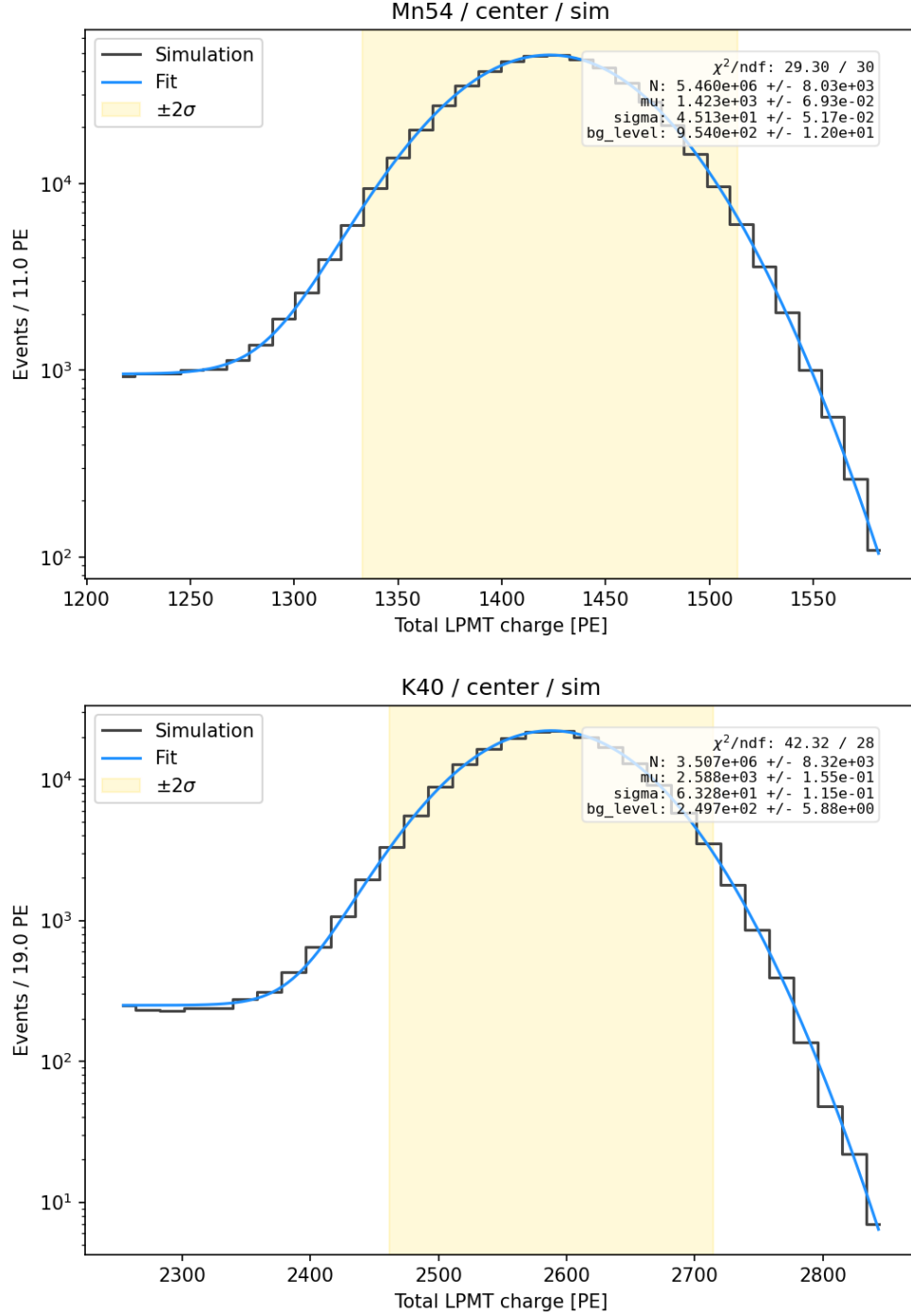


Figure 6.3: Total LPMT simulated charge distribution for  $^{54}\text{Mn}$  (top) and  $^{40}\text{K}$  (bottom) sources placed at the center of the detector, with **GarF** fit overlaid. The  $2\sigma$  window around the fit mean is also shown.

the detector bottom, LPMT 17611 installed at this location is chosen as the target for this study.

### Target LPMT Charge Estimation

The target LPMT charge is expected to follow a Poisson distribution with higher means with respect to the sPMT charge for a given energy deposition. Because the charge response of the LPMTs is to be diagnosed, the LPMT charge distribution is practically left untouched. The nominal charge estimator is the statistical mean of the distribution:

$$\mu = \frac{1}{N_{peak}} \sum_{i=0}^{N_{peak}} Q_{target,i} \quad (6.4)$$

The mean extracted from fitting the target LPMT charge distribution to a Poisson distribution is also a valid option for a charge estimator, as shown in Figure 6.4. Nevertheless, fit quality quickly deteriorates when the source is placed away from the detector center. In this region of higher illumination and large spatial non-uniformities, electronics effects in the charge response and the mobility of the  $\gamma$  bias the Poisson assumption.

### Total sPMT Charge Estimation

Similarly to the LPMT case, the total sPMT charge distribution (shown for  $^{54}\text{Mn}$  in Figure 6.5, can be fit to a model similar to the one utilized in **GaRF** or the statistical mean can be calculated from its population. This however relinquishes the advantages that the single photon counting described earlier provides. The total sPMT charge means are for this purpose "corrected" using a method based on the sPMT occupancy.

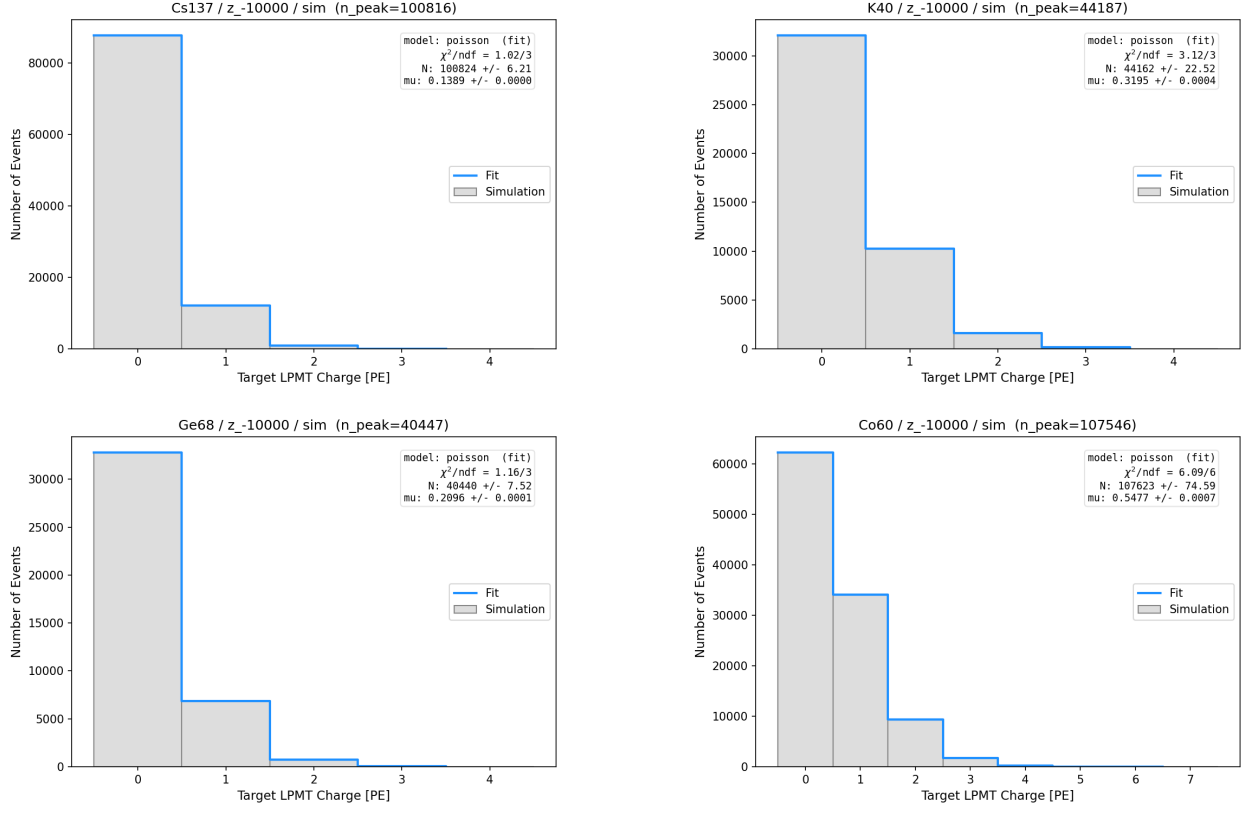


Figure 6.4: Target LPMT 17611 simulated charge distribution for  $^{137}\text{Cs}$  (top left),  $^{68}\text{Ge}$  (bottom left),  $^{40}\text{K}$  (top right), and  $^{60}\text{Co}$  (bottom right) sources placed at  $z = -10,000$  mm, with Poisson best-fit overlaid. The number of events the pass the  $2\sigma$  selection is printed in the title.

## 6.4 DCC-Gamma Corrections

### 6.4.1 Poisson Zero Correction

Assuming our PMTs follow Poisson statistics,

$$P(k) = \frac{\mu^k e^{-\mu}}{k!} \quad (6.5)$$

we can calculate a statistical charge mean based on the number of events where a PMT was hit ( $N_{hit}$ ). From the full-detector information we know  $N_{total}$ , the total number of events in the detector, which we can use to calculate the number of events where a given PMT was

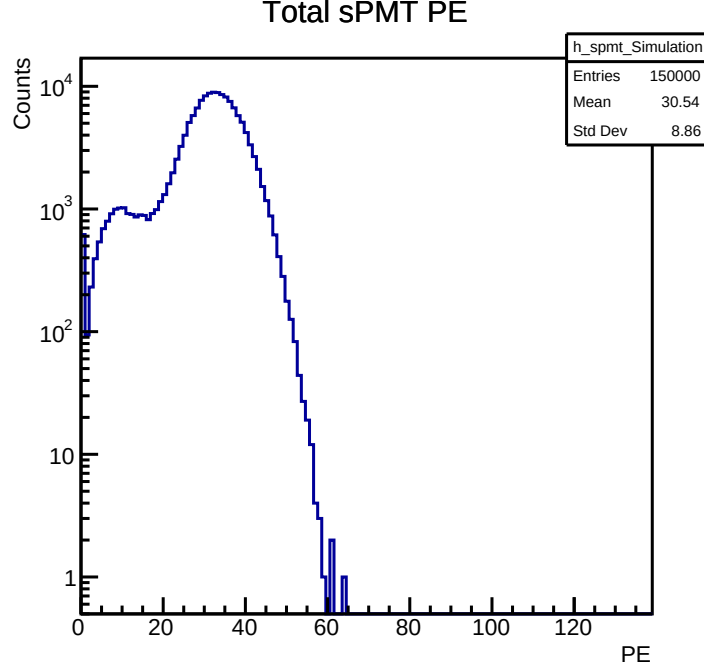


Figure 6.5: Total sPMT system simulated charge distribution for a  $^{54}\text{Mn}$  source placed at  $z = -10,000$  mm.

unfired:  $N_{unfired} = N_{total} - N_{hit}$ . The Poisson charge mean for a single sPMT can then be extracted from these variables:

$$\mu = -\ln\left(\frac{N_{unfired}}{N_{total}}\right) \quad (6.6)$$

This procedure is known as the Poisson Zero or  $\text{Pois}(0)$  correction. The total sPMT charge mean is then the sum of the individual sPMT  $\text{Pois}(0)$  means from 6.6. Given that we are trying to diagnose the instrumental QNL in the target LPMT, the  $\text{Pois}(0)$  correction is not applied to it. Moreover, given JUNO's illumination, the  $\text{Pois}(0)$  correction cannot be applied to its LPMTs for sources with energy greater than 2 MeV, as all events trigger the PMT in this illumination regime. This would also undermine the technological advancements of the LPMTs, as they were designed for sensitive waveform-based measurements.

To assign an uncertainty to this Poisson corrected mean  $\mu$ , we use the Delta method for a

binomial variable given that  $N_{zero}$  follows a binomial distribution as a function of  $N_{total}$ . By making the variable substitution  $\mu = -\ln(p)$ ,  $p \equiv \frac{N_{zero}}{N_{total}}$  for the ratio in the Poisson mean, we can thus write the variance as:

$$Var(\mu) = \left( \frac{d\mu}{dp} \right)^2 Var(p) \quad (6.7)$$

$$Var(p) = \frac{p(1-p)}{N_{total}} \rightarrow Var(\mu) = \frac{1-p}{pN_{total}} \quad (6.8)$$

We then calculate the uncertainty from the variance and restore our original variables:

$$\delta\mu = \sqrt{Var(\mu)} = \sqrt{\frac{N_{total} - N_{zero}}{N_{zero}N_{total}}} \quad (6.9)$$

This uncertainty method was corroborated using a Toy MC based on the extracted means and statistics of the simulated  $^{137}\text{Cs}$  source. This result along with errors for the mean of a Poisson distribution are shown in Figure 6.6.

## 6.4.2 Dark Noise and Threshold Corrections

Instrumental effects that can bias both waveform-based charge measurements and the Poisson(0) correction need to be considered. Dark noise hits, for example, can affect either method by changing both the charge response and the number of events triggered. We apply a statistical treatment of dark noise and threshold effects following [128]. The most probable dark noise contribution to an event for a given PMT is

$$\mu_{DN} = R_{DN} \times t_{readout} \quad (6.10)$$

where  $t_{readout}$  is the duration of the readout window and  $R_{DN}$  is the dark counting rate of the PMT, obtainable from bench tests or off-window analyses. This mean contribution is

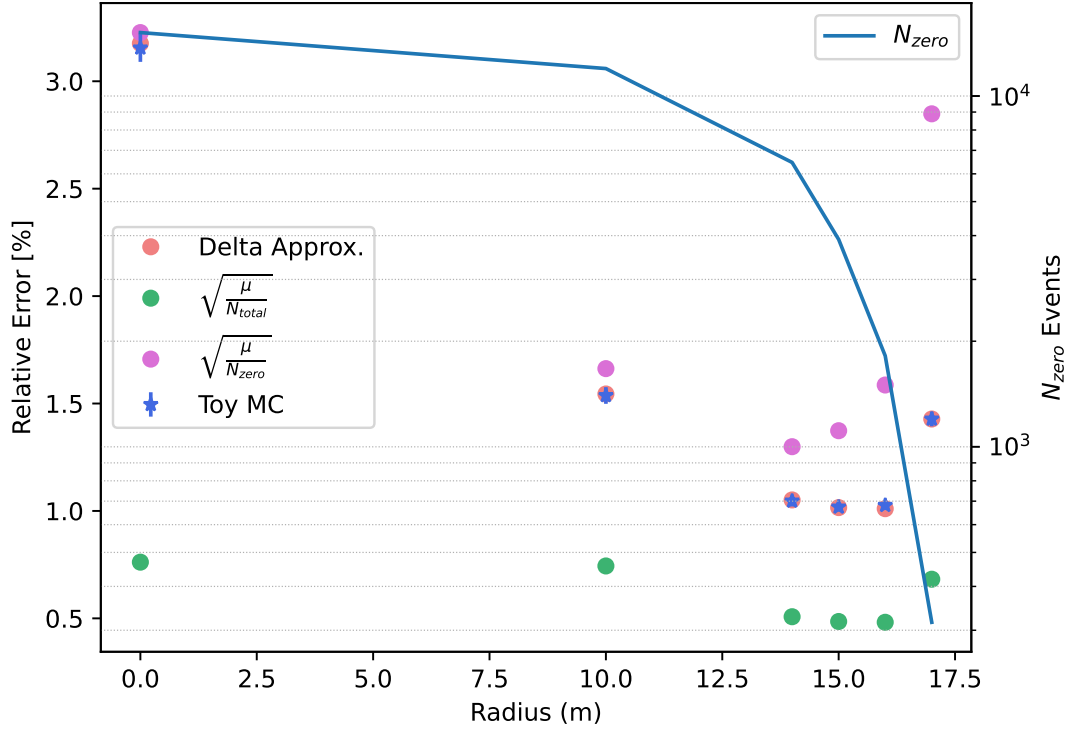


Figure 6.6: Error on a single PMT mean calculated with the Delta approximation and following naive Poisson statistics. On the right Y-axis, the number of events with no hits  $N_{zero}$  is shown as the blue curve.

then subtracted from the Poisson corrected mean calculated in the previous section to get the true mean:

$$\mu_{true} = \mu_{det} - \mu_{DN} \quad (6.11)$$

Due to the 0.3 PE threshold applied to the sPMTs, some events that would trigger a sPMT are not accounted for, thus biasing the Poisson Zero correction. The threshold correction from [128] is applied as follows:

$$P_{ThresLoss}(\mu_i^{true}) = \sum_{k_i=1}^n [Poisson(k_i|\mu_i^{true}) \times \int_0^{q_i^{thres}} Gaus(q_i|g_i, \sigma(g_i)) dq_i] \quad (6.12)$$



For each sPMT, we assume its charge distribution follows Poisson statistics, with our calculated mean  $\mu_i^{true}$ . For each PE multiplicity bin  $k_i$  in this Poisson distribution, a gaussian function can be constructed to represent the probability a  $k_i$  number of PEs get reconstructed as a given charge quantity. Its mean

$$g_i = S_{gain}^i \times k_i \quad (6.13)$$

maps the given number of PEs to their most likely charge, modulated by the normalized gain  $S_{gain}^{pmt} = \frac{Gain_{pmt}}{3 \times 10^6}$  where the denominator is the nominal sPMT gain for JUNO. The standard deviation

$$\sigma(g_i) = \sqrt{g_i} \times \sigma_i^{spe} \quad (6.14)$$

gives the charge resolution for a given number of PEs as a function of the single PE resolution. By integrating this gaussian function up to the charge threshold (as shown in Figure 6.7) and multiplying by the sPMT Poisson charge contribution for the  $k_i$  PEs bin, the amount of charge lost to the threshold is estimated. The sum of these lost charges for all bins can be added back to the Poisson-Zero-corrected mean:

$$\mu = -\ln(P_{unfired} + P_{ThresLoss}) = -\ln\left(\frac{N_{unfired}}{N_{total}} + P_{ThresLoss}\right) \quad (6.15)$$

Threshold correction is only applied to sPMTs as LPMTs have a more sophisticated definition of its threshold.

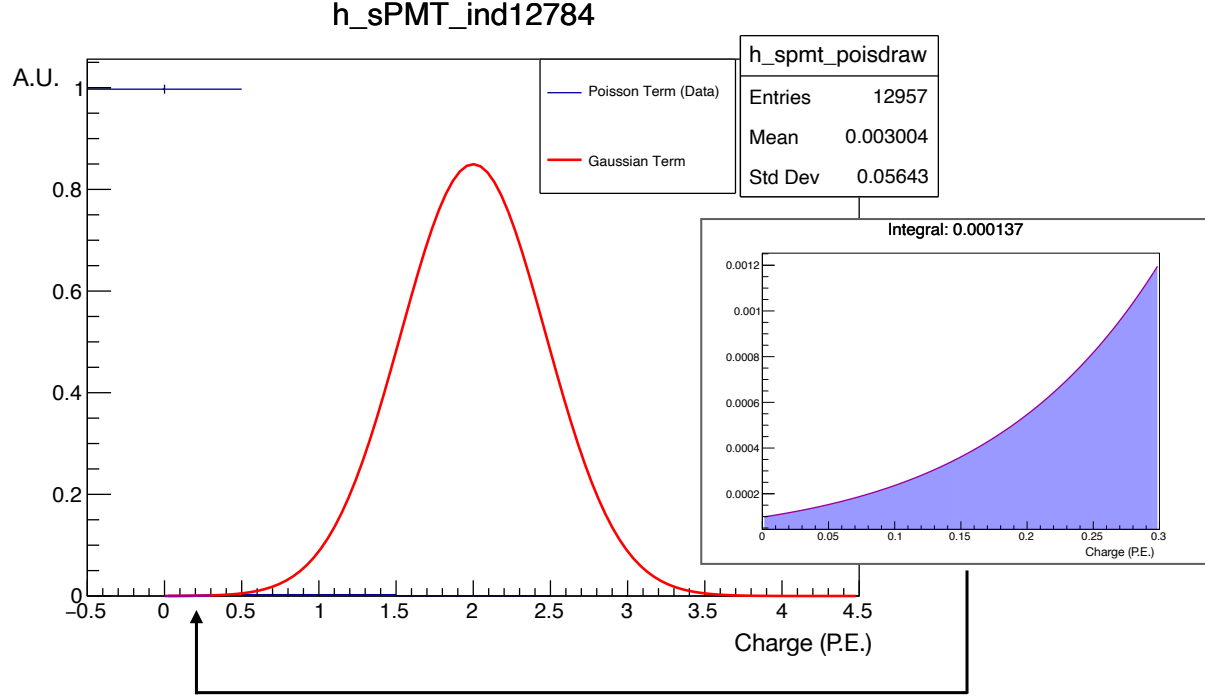


Figure 6.7: Single sPMT (ID 12784) Poisson distribution from simulated  $^{60}\text{Co}$  placed at the center drawn with Gaussian distribution centered at 2 PE with resolution equal twice the sPMT single photon resolution. The integral of the 2 PE distribution under the 0.3 PE threshold is zoomed into, finding a  $P_{ThresLoss}$  of 0.0137%.

### 6.4.3 Alignment of Charge Responses

In order to extract a single calibration from the source simulations, whose charge means are shown in Figure 6.8, it is necessary to align all the points in total sPMT charge vs target LPMT charge space by further correcting the sPMT charge mean estimator. Doing so essentially answers the question: "If the very linear sPMTs could make a charge measurement in the LPMT illumination regime, what would that charge response be?"

In the absence of instrumental non-linearity, this alignment should result in a perfectly linear relationship between the target LPMT charge and the total sPMT  $\text{Pois}(0)$  corrected means. Any instrumental non-linearity present in the LPMT charge response would deviate the aligned points from the line assumption at higher charge values, constraining this non-linearity akin to the DCC-Laser technique.

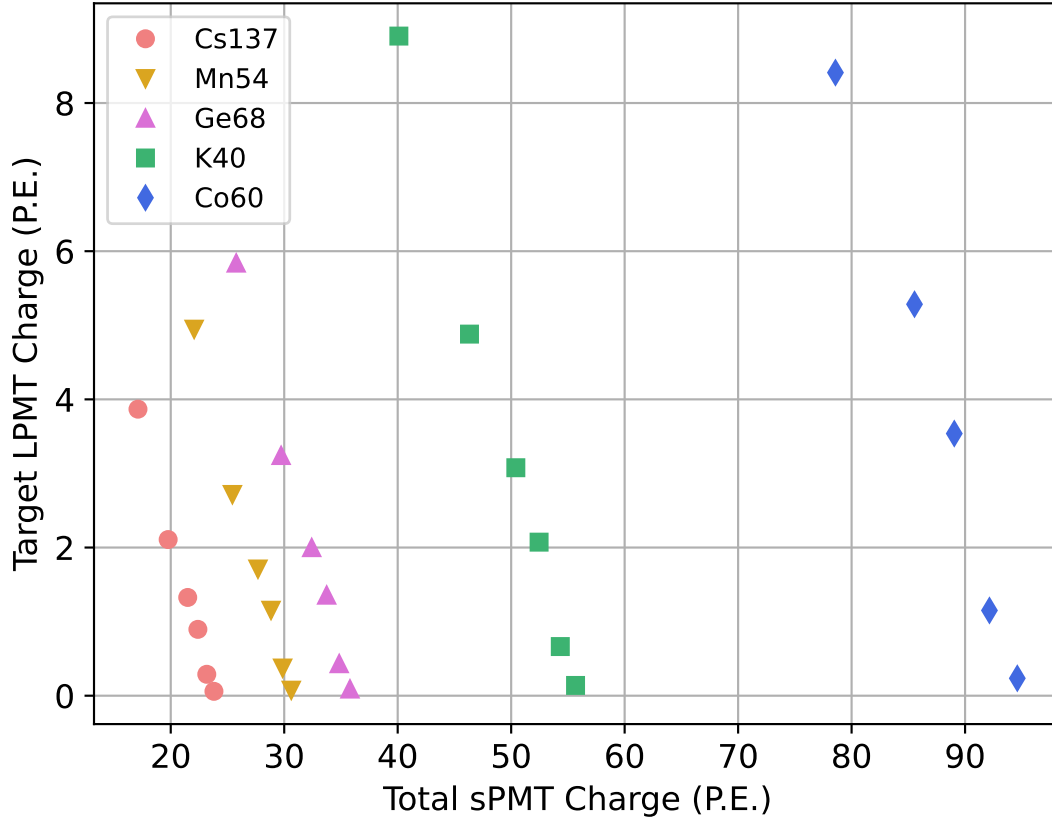


Figure 6.8: Simulated  $\gamma$  source points charge means for total sPMT ( $x$ ) and target LPMT ( $y$ ), before any corrections.

### sPMT Non-Uniformity Correction

When scanning the detector response along a detector axis, sPMTs in different areas of the detector will see a change in their illumination. This results in a spatial non-uniformity for the sPMT system charge which is shown, normalized to make any source-to-source differences clear, in Figure 6.9.

The non-uniformity in the total sPMT charge response is corrected empirically through the source deployments, bringing the charge for a given source and off-center position to what it would be at the center.

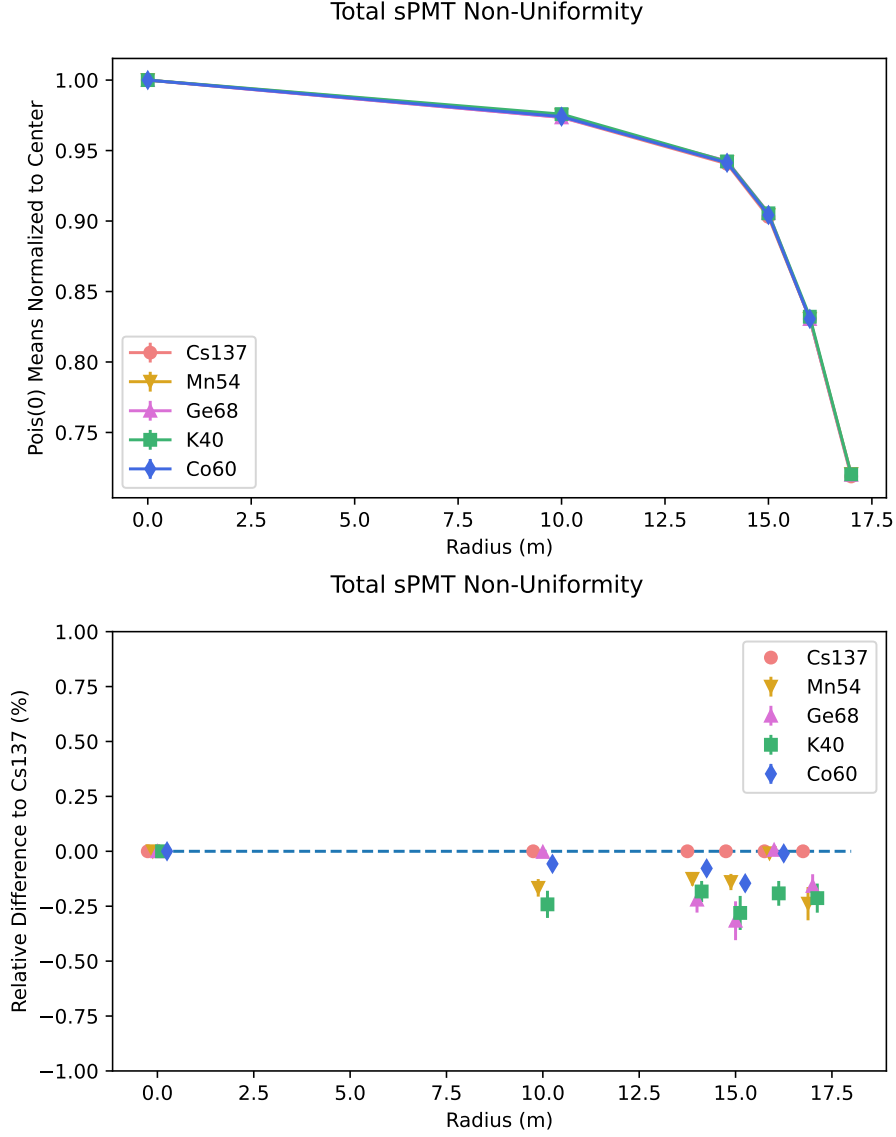


Figure 6.9: DetSim DCC Calibration Line Fit.

$$\mu_{sPMT,source,NU_{corr}}^{z \neq 0} \equiv \mu_{sPMT,source}^{z=0} \quad (6.16)$$

### LPMT Solid-Angle Correction

As previously established, the sPMTs were designed to subtend a smaller solid angle than the LPMTs in order to detect single photons during events where the LPMTs see multiple. In order to adequately estimate a linear LPMT charge response from the sPMTs, the latter's

charge mean must be corrected in order to be representative of the target LPMT's charge regime for a given energy deposition. Naturally, the target LPMT charge means also exhibit a spatial dependence. As such, a similar correction derived from the LPMTs can be applied to the sPMT charge response position-by-position, shifting it to a higher charge range.

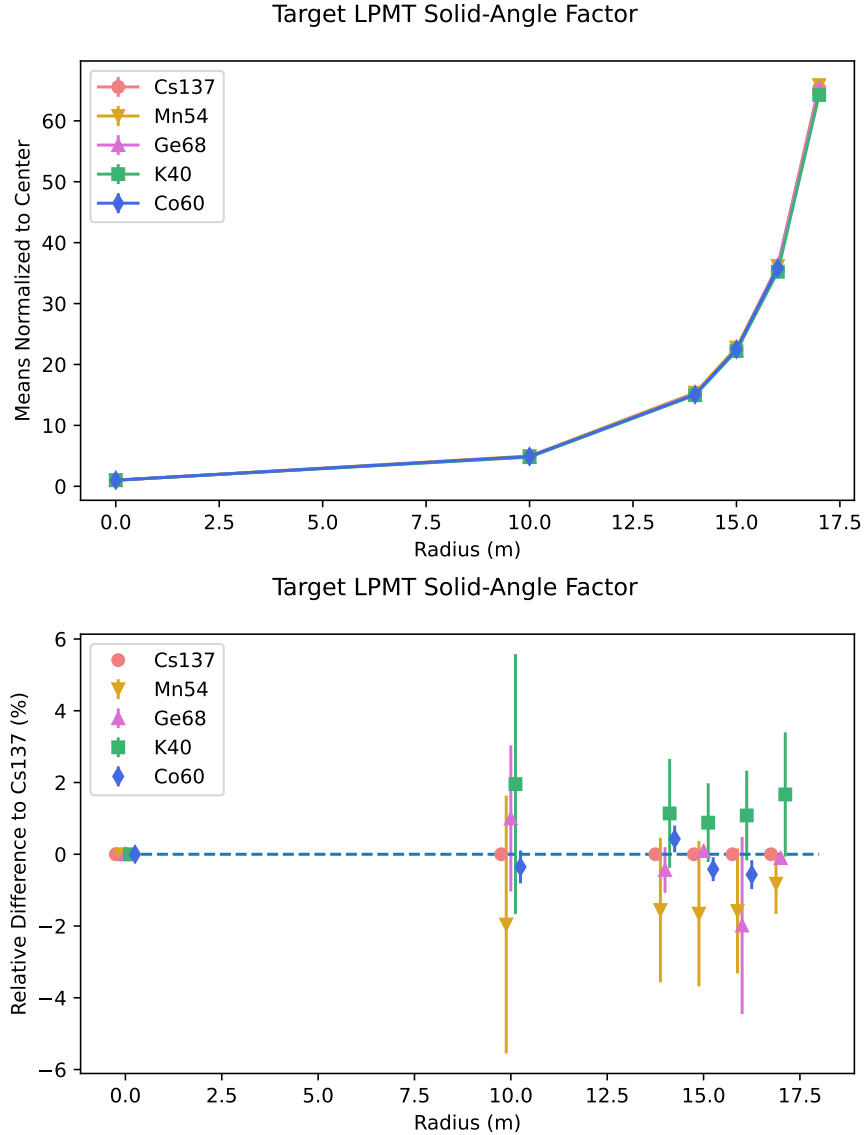


Figure 6.10: DCC Calibration Line Fit for JUNO simulation without electronics simulated.

In the context of Poisson statistics, we can interpret the total sPMT charge mean as the average number of channels in the sPMT system that will fire for a given source and position. We can then shift this sum of individual sPMT SPE hits (or to preserve units, digital or

binomial hit probabilities) to the target LPMT charge through multiplication:

$$\mu_{sPMT,source,corrected}^z \equiv \mu_{sPMT,source,NU_{corr}}^z \times \mu_{LPMT,source}^z \quad (6.17)$$

Unlike the sPMT non-uniformity, which is very consistent source-to-source, the LPMT solid-angle correction sees variations at the few-percent level as shown in Figure 6.10. The cause for the variations is still under investigation. For sources at higher energies, the LPMT instrumental non-linearity itself can bias the correction. For this reason, the solid-angle correction is calculated from a single, low-energy source where these considerations are negligible (e.g.  $^{137}\text{Cs}$ ).

## 6.5 Calibration Results with DCC-Gamma

### 6.5.1 Linear Fit to Reference Region

Following the same logic used for DCC-Laser, a linear reference region must be identified. At sufficiently low illumination, the number of photoelectrons collected by the target LPMT is small enough that the PMT and its front-end electronics are mostly linear and thus reconstructed charge scales proportionally with the number of PEs. In this low-illumination region, the measured charge means are expected to trace out a straight line, unaffected by the instrumental non-linearity that becomes significant at higher illumination and whose extraction is the main goal of the analysis.

The linear reference region is used to construct a linear reference despite the presence of LPMT instrumental non-linearity. This subset of points is fit to a linear model, which is then extrapolated across the full illumination range spanned by the calibration data. In the analysis presented here, the first ten points are used to perform the fit and define the reference line. The result estimates the response the target LPMT would exhibit *in the*

*absence of* any charge-level non-linearity. The deviation from the line of the remaining, higher-illumination points then diagnoses the instrumental non-linearity as a function of illumination. For the analyses shown in this chapter, the 10 points lowest in illumination constitute the linear reference region.

### 6.5.2 Detector Simulation

The detector simulation, with its absence of electronics effects, provides an ideal baseline to test the technique. Figure 6.11 shows the results at this simulation stage. The solid-angle correction, calculated from a single source, was derived from the  $^{137}\text{Cs}$  target LPMT charges. The line fit finds the points to be consistent with the straight-line assumption at the 2% level.

The analysis at this stage was repeated with a second set of simulation files using the latest J26 JUNOSW simulation. This version includes updates to detector characteristics that reflect the information learned after data-taking (changes to the light yield, optical model, etc). A similar behavior is extracted from the new calibration points as shown in Figure 6.12, where a linear relationship between the target LPMT charge and the corrected total sPMT charge estimation is recovered with 2% precision.

### 6.5.3 Electronics Reconstruction

After applying electronics effects to the previous detector simulation files, the analysis seeks to extract the instrumental non-linearity curve JUNOSW applies during simulation from deviations from the line fit. In this stage of the analysis, the  $^{137}\text{Cs}$  points were removed due to inconsistent charge distributions after electronics reconstruction, and thus the solid-angle correction is calculated from  $^{54}\text{Mn}$ .

As shown in Figure 6.13, the DCC-Gamma calibration sees a very small deviation from the line in the presence of instrumental non-linearity. Nevertheless, the means and error bars of

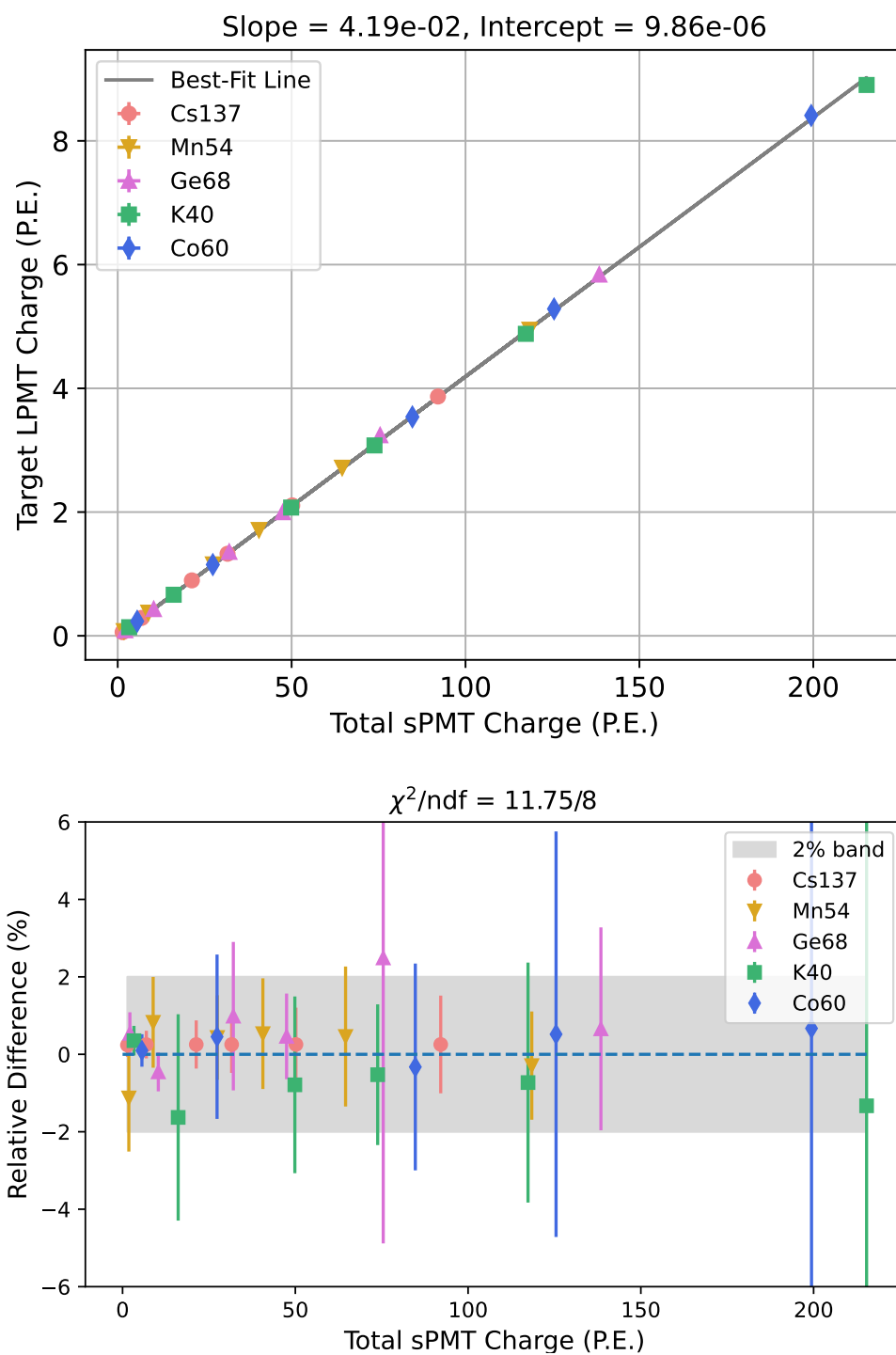


Figure 6.11: DCC-Gamma Calibration in the absence of electronics effects. The corrected points and best-fit line (top) and fit residuals along with a 2% uncertainty band in gray (bottom) are shown.



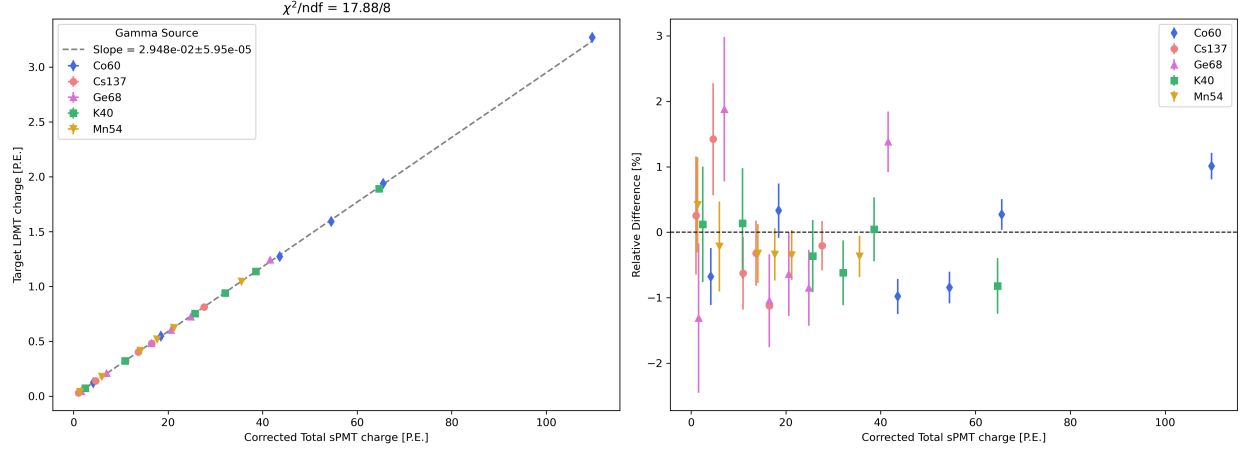


Figure 6.12: DCC-Gamma Calibration in the absence of electronics effects for the latest J26 simulation. The corrected points and best-fit line (left) and fit residuals (right) are shown.

the residuals are mostly consistent with the predicted line from the linear reference region, again to the 2% level. At the magnitude of non-linearity injected to the official JUNO simulation and with the simulated sample size, the analysis presented is not sensitive to the LPMT instrumental non-linearity.

## 6.6 Outlook

This chapter presents the DCC-Gamma technique as a supplement to the DCC-Laser performed with JUNO's dual PMT systems to extract the instrumental non-linearity of the LPMTs. An application of the DCC-Gamma technique to a full, realistic JUNO detector simulation successfully recovers a linear relationship between the linear, corrected sPMT-derived LPMT charge estimation and the target LPMT charge in the absence of electronics effects, with a precision of roughly 2%. This holds true when electronics simulation and waveform reconstruction are included.

Both the simulated and measured non-linearities are in the percent level or below [53]. In order to extract instrumental non-linearities this small with the DCC-Gamma technique, gamma source deployments in JUNO would have to be much longer than currently performed,

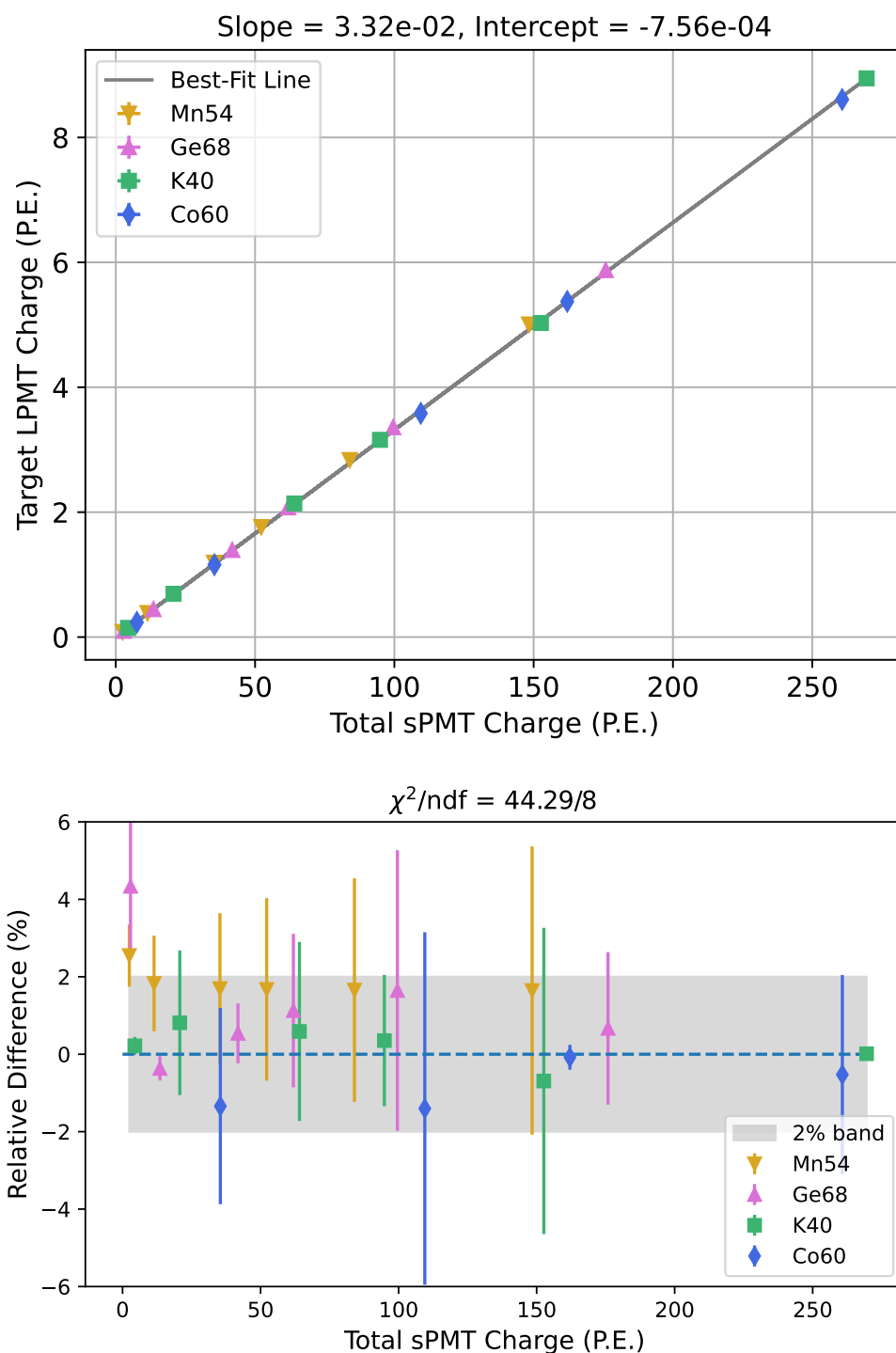


Figure 6.13: Simulation DCC-Calibration Line Fit, with electronics effects and waveform reconstruction applied. The corrected points and best-fit line (top) and fit residuals along with a 2% uncertainty band in gray (bottom) are shown.

in the order of several hours and multiple times that for data taken with sources at the center.

While real-life studies of the instrumental non-linearity in JUNO's LPMTs will require an increase in statistics, simulation studies can look to inject a larger non-linearity into JUNOSW, and therefore more easily probe the DCC-Gamma technique. More sophisticated methods to select calibration events, and thus preserve precious statistics could also be of use in this context.

# Chapter 7

## Assessment of Energy Response in JUNO for Oscillation Analyses

### 7.1 Detector Response in JUNO

The primary objectives of JUNO are the determination of the NMO and the precise measurement of various oscillation parameters. This physics program demands an unprecedented energy resolution of  $3\%/\sqrt{E(\text{MeV})}$  and a systematic uncertainty on the energy scale of better than 1% [20]. JUNO therefore requires a comprehensive calibration scheme to achieve these requirements [15].

For IBDs, the prompt signal is produced by a positron. However, most calibration sources that span the energy range of interest for reactor  $\bar{\nu}_e$  are  $\gamma$  emitters. Moreover, using  $e^+/\beta^+$  sources directly presents the added complication of the calibration enclosure, in which most  $e^+$  would lose their energy and subsequently annihilate before reaching the scintillator. Therefore, the  $e^\pm$  energy responses must be constrained using continuous spectra from the  $\beta^\pm$  decays of cosmogenic isotopes. Constructing a robust model to translate deployed ra-

radioactive  $\gamma$  source and cosmogenic isotope  $\beta^\pm$  data into a precise positron energy response is the challenge taken by the GEPriS framework.

### 7.1.1 Energy Resolution

Following the standard approach used in previous reactor LS experiments [35], the fractional energy resolution of JUNO is parameterized as:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}, \quad (7.1)$$

Each term has a distinct physical meaning relevant to JUNO's design:

- **Stochastic term ( $a$ ):** This term reflects the Poisson statistics of photoelectron production and collection. For a given deposited energy, the number of photons produced in the LS, the fraction transmitted to the photocathodes, and the photon-to-photoelectron conversion at each PMT are all subject to counting fluctuations. As such,  $a$  is set almost entirely by the achieved light yield (LY), and scales inversely with the square root of the total number of detected photoelectrons per MeV. Reaching  $a \simeq 3\%$  therefore requires an exceptionally high LY ( $> 1200$  PE/MeV for JUNO [34]).
- **Constant term ( $b$ ):** This term reflects residual systematic effects in the event-by-event energy reconstruction, dominated by the spatial non-uniformity [15]. Because it does not average away with more collected light,  $b$  becomes the dominant contribution to the resolution budget at higher energies. The magnitude of this term is controlled through calibration.
- **Noise term ( $c$ ):** This term captures noise contributions such as PMT dark noise, electronic pedestal fluctuations, and the intrinsic width of the single-photoelectron charge response [15].

### 7.1.2 Energy Non-linearity

The relationship between the deposited energy of a particle ( $E_{true}$ ) and the reconstructed energy ( $E_{rec}$ ) in LS is inherently non-linear. As described in the previous chapter, the energy non-linearity in LS can be decomposed into an instrumental component and two physical components: quenching effects in the scintillation process and the emission of Cherenkov radiation.

$$\frac{E_{vis}}{E_{true}} = f_{scint}(E_{true}) \cdot f_{Cherenkov}(E_{true}) \cdot f_{instrumental}(E_{vis}) \quad (7.2)$$

The physical terms define the conversion  $E_{true} \rightarrow E_{vis}$ . The latter is observed by the PMTs and thus affected by the instrumental non-linearity.

#### Scintillation Quenching

The ionization density along the track of a charged particle affects the light yield. For high  $dE/dx$ , the density of excited molecules leads to non-radiative de-excitation, also known as quenching. This effect becomes increasingly important at low energies.

This quenching is described by Birks' law, as discussed in 2.3.2. Birks' constant  $k_B$  in this case is considered to be specific to the LS composition and thus a primary free parameter in the energy scale fit.

#### Cherenkov Radiation

When a charged particle travels faster than the speed of light in the LS (starting around 160 keV for  $e^-$ ), it emits Cherenkov radiation. While the scintillation light is isotropic and dominant, the directional Cherenkov light becomes more important at higher energies.

A direct measurement of the Cherenkov light yield as a function of particle energy in a JUNO-

like LS has not been performed. Unlike the scintillation (quenching) non-linearity, which can be isolated and measured directly using low-energy electron/Compton-scattering data, the Cherenkov contribution cannot easily be separated experimentally from the scintillation light with which it is always produced. Dedicated wavelength- or timing-based separation techniques have been explored, but have not yet provided a measurement of the Cherenkov light yield with the energy dependence and precision required for a non-linearity model.

As a result, the energy non-linearity analysis parametrizes the Cherenkov contribution using  $f_C$  which scales the relative weight of Cherenkov light. The energy dependence of the Cherenkov yield is generated within the Geant4-based detector simulation while the overall normalization of the Cherenkov-to-scintillation photon ratio is left as a free parameter in the fit to calibration data.

### **Instrumental Non-linearity**

As discussed extensively in Chapter 6, JUNO was built with the sPMT + LPMT system design to, among other things, directly constrain the LPMT instrumental non-linearity in situ. As shown in Figure 6.1, the DCC-Laser calibration measured the non-linearity in both the NNVT and Hamamatsu PMTs better than the 1% level. This result directly informs the wider energy non-linearity analysis, which will be further touched upon later in this chapter.

## **7.2 Gamma-Source Calibration Campaign**

Following the completion of the LS filling on August 22nd 2025, an initial calibration campaign was carried out between August 23rd and 26th 2025 to establish the energy scale of the detector, ahead of the start of physics data-taking on August 26th 2025 [53]. This campaign made use of the full set of  $\gamma$  calibration sources described in Chapter 6 together with the Am-C neutron source, which provides prompt/delayed  $\gamma$  signatures from neutron capture on both hydrogen (2.223 MeV) and, less frequently, carbon (4.94 MeV) and source enclo-

sure materials such as Fe, Cr, and Ni (7-10 MeV), extending the calibration higher energies. The charge distributions for the initial gamma calibration runs are shown superimposed in Figure 7.1.

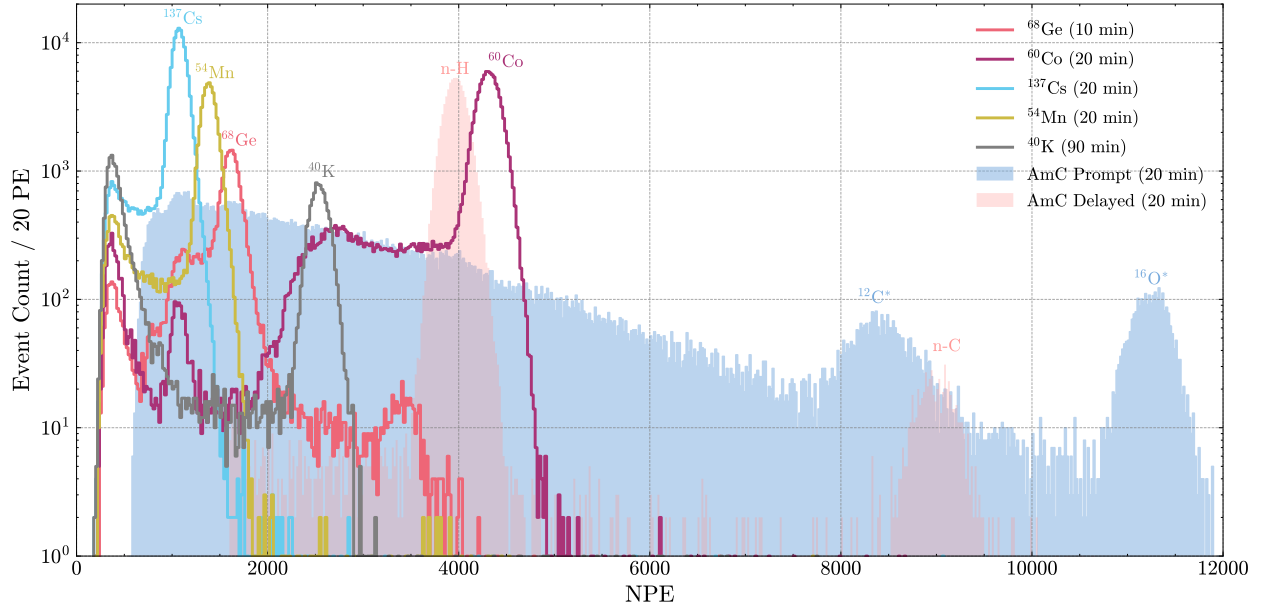


Figure 7.1: Charge spectra for initial JUNO gamma-source calibration runs [53].

For source positions along the central axis of the CD, all  $\gamma$  sources were deployed with the ACU. The reconstructed charge from these runs was dark-noise subtracted using the rates measured from periodic-trigger runs. At the detector center, the measured light yield (LY) obtained from the 2.223 MeV  $\gamma$ , was found to be 1785 PE/MeV, while the  $^{68}\text{Ge}$  full-energy peak at 1.022 MeV yields around 1600 PE/MeV [53]. The difference between the two reflects the non-linear response in the LS rather than a change in illumination. Both values exceed pre-filling expectations [21], a result attributed to the LS and water attenuation lengths measured to be better than the values assumed in earlier detector simulations.

Figure 7.3 shows the energy non-linearity as measured by the LPMTs and sPMTs during the initial calibration run. The 0.5% band on the residuals shows that, for few-MeV energies at the center of the detector such the illumination is small, the non-linearity present in the LPMTs lies under this magnitude [53].



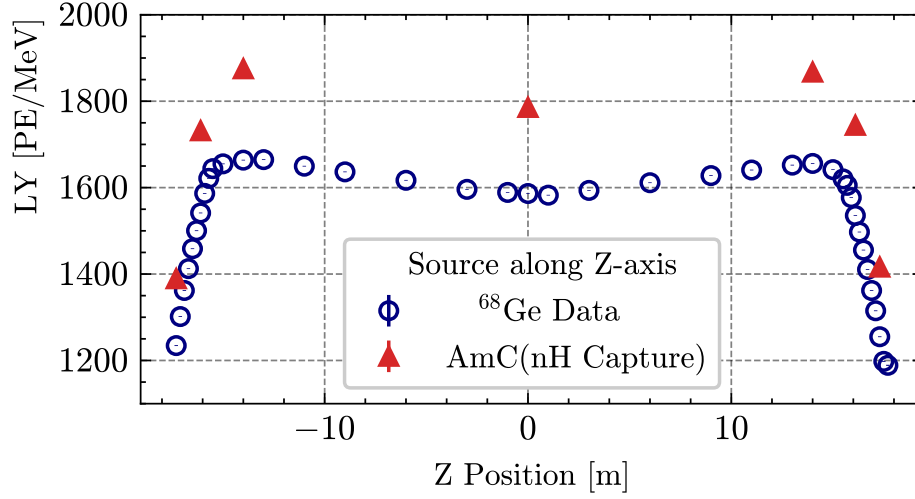


Figure 7.2: Light yield for  $^{68}\text{Ge}$  and Am-C radioactive sources. [53].

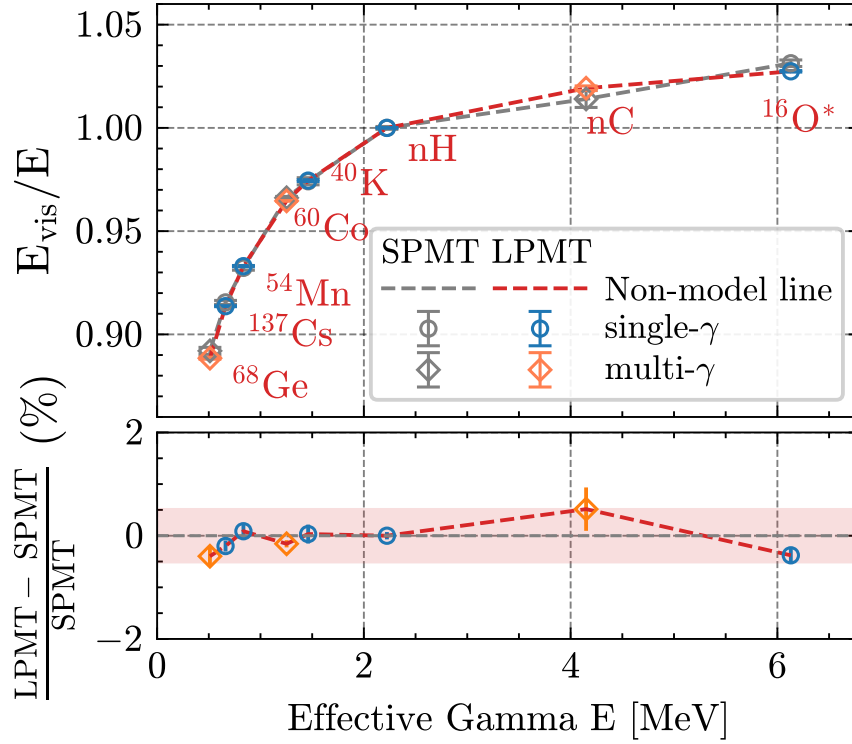


Figure 7.3: Energy non-linearity for  $\gamma$  sources as measured by both PMT systems [53].

Following this initial calibration, routine calibration runs continued throughout data-taking, with the  $^{68}\text{Ge}$  and Am-C sources deployed bi-weekly as well as dedicated laser runs taken weekly (or after any hardware change) to monitor detector stability.

### 7.3 Energy Reconstruction using OMILREC

To translate charges from the LPMT waveforms into reconstructed energy, this analysis uses **OMILREC**, a combined time- and charge-likelihood reconstructor, and **JVertex** for event vertex reconstruction within the **JUNOSW** offline framework [53, 119].

The event vertex  $\vec{x}_{\text{rec}} = (x, y, z)$  and energy  $E_{\text{rec}}$  are reconstructed by maximizing a joint likelihood built from the observed hit time of each fired LPMT and the observed charge collected by every LPMT, fired or not. The time-likelihood component uses the difference between the hit time of each channel and the time of the event's first hit compared against probability density functions (PDFs)  $f(\Delta t_i)$ . These PDFs are constructed separately for Hamamatsu and NNVLT LPMTs from  $^{68}\text{Ge}$  calibration data taken at the CD center [119]:

$$\mathcal{L}_T(\vec{x}_{\text{rec}}, t_0) = \prod_{i \in \text{hit LPMTs}} f(\Delta t_i) \quad (7.3)$$

The charge-likelihood component compares the observed charge (or absence of a hit) at every LPMT against the expected charge predicted for the trial vertex and energy, again using PDFs for the "hit" and "unhit" hypotheses,  $P(Q_{\text{obs}}|\mu_{\text{exp}})$  and  $P(\text{unhit}|\mu_{\text{exp}})$  [119]:

$$\mathcal{L}_Q(E_{\text{rec}}) = \prod_{j \in \text{unhit LPMTs}} P_j(\text{unhit} | \mu_{j,\text{exp}}) \times \prod_{i \in \text{hit LPMTs}} P_i(Q_{i,\text{obs}} | \mu_{i,\text{exp}}), \quad (7.4)$$

The expected charge  $\mu_i$  at the  $i$ -th LPMT is not computed from a simple analytic point-source model, but is evaluated from a pre-calibrated position- and angle-dependent charge map, built directly from  $^{68}\text{Ge}$  calibration data taken along the ACU central axis together with  $^{214}\text{Po}$   $\alpha$ -decay events distributed throughout the LS volume. The full likelihood in Equation 7.5 is maximized over  $(\vec{x}_{\text{rec}}, E_{\text{rec}})$  over all LPMTs [119]:

$$(\vec{x}_{\text{rec}}, E_{\text{rec}}, t_0) = \arg \max_{\vec{x}, E, t_0} [\mathcal{L}_Q(E) \cdot \mathcal{L}_T(\vec{x}, t_0)]. \quad (7.5)$$

Using the  $^{68}\text{Ge}$  source scanned along the CD central axis, the reconstructed vertex has been shown to have a bias smaller than 10 cm for  $R < 17.0$  m [53]. The resulting reconstructed energy is uniform to better than  $\pm 1\%$  within the  $R < 16.5$  m fiducial volume, as verified using  $^{214}\text{Po}$   $\alpha$ -decays and neutron captures from IBD events distributed throughout the detector [53].

## 7.4 Gamma Point Extraction

Having collected radioactive source data and reconstructed it with OMILREC, their energy distribution means must be extracted to pass as input to the detector energy response fit. While the **GaRF** software introduced in Section 6.3.2 models the photopeak, background, and calorimeter escape tail, fitting radioactive sources in data requires accounting for pileup events as well. Due to the intrinsic  $^{14}\text{C}$  activity in the scintillator,  $\gamma$  interactions frequently coincide with one or more  $^{14}\text{C}$   $\beta^-$  decays within the integration window. This summing effect adds energy on the high-energy side ( $E > \mu$ ) of the photopeak.

To model this effect, the total peak spectrum  $S(E)$  is extended to partition the total peak area  $N$  across the core, escape tail, and high-energy pileup contributions:

$$S(E) = B(E) + N [f_{\text{core}} P_{\text{core}}(E) + f_{\text{pu1}} T_{\text{pu},1}(E) + f_{\text{pu2}} T_{\text{pu},2}(E) + f_{\text{esc}} T_{\text{esc}}(E)] \quad (7.6)$$

where  $f_{\text{core}} = 1 - f_{\text{pu1}} - f_{\text{pu2}} - f_{\text{esc}}$  to preserve signal normalizations, and  $B(E)$  and  $T_{\text{esc}}(E)$  retain their definitions from the previous chapter.

## <sup>14</sup>C $\beta$ -Decay Pileup Models

The high-energy pileup tails  $T_{\text{pu},1}(E)$  and  $T_{\text{pu},2}(E)$  represent the convolution of the primary peak response  $P_{\text{core}}(E)$  with the energy distribution of single ( $T_{\text{pu},1}$ ) and double ( $T_{\text{pu},2}$ ) accidental <sup>14</sup>C decays. Single-event pileup is modeled as the primary peak convolved with the normalized allowed <sup>14</sup>C  $\beta^-$  spectrum  $S_\beta(T)$  up to its endpoint  $Q_{^{14}\text{C}} = 156$  keV:

$$T_{\text{pu},1}(E) = (P_{\text{core}} * S_\beta)(E) = \int_0^{Q_{^{14}\text{C}}} P_{\text{core}}(E - T) S_\beta(T) dT \quad (7.7)$$

where  $S_\beta(T) \propto pE_e(Q_{^{14}\text{C}} - T)^2$  represents the energy spectrum of the emitted electron. To account for rare double coincidences within the readout window, **GaRF** incorporates a two-event pileup term convolved over the energy range  $[0, 2Q_{^{14}\text{C}}]$ :

$$T_{\text{pu},2}(E) = (P_{\text{core}} * S_{\beta,2})(E) \quad (7.8)$$

where  $S_{\beta,2}(T) = (S_\beta * S_\beta)(T)$  is the self-convolved double-beta decay energy distribution.

The double-pileup fraction  $f_{\text{pu}2}$  is estimated (and passed to the fitter either as a fixed parameter or as an initial guess) via Poisson statistics to follow the single-pileup fraction  $f_{\text{pu}1}$ :

$$f_{\text{pu}2} = \frac{1}{2} f_{\text{pu}1}^2 \quad (7.9)$$

While **GaRF** can fit the data energy distributions, the remainder of the chapter will use the gamma points used in the official detector response analysis, produced by INFN Milano using a similar photopeak + background + pileup model.

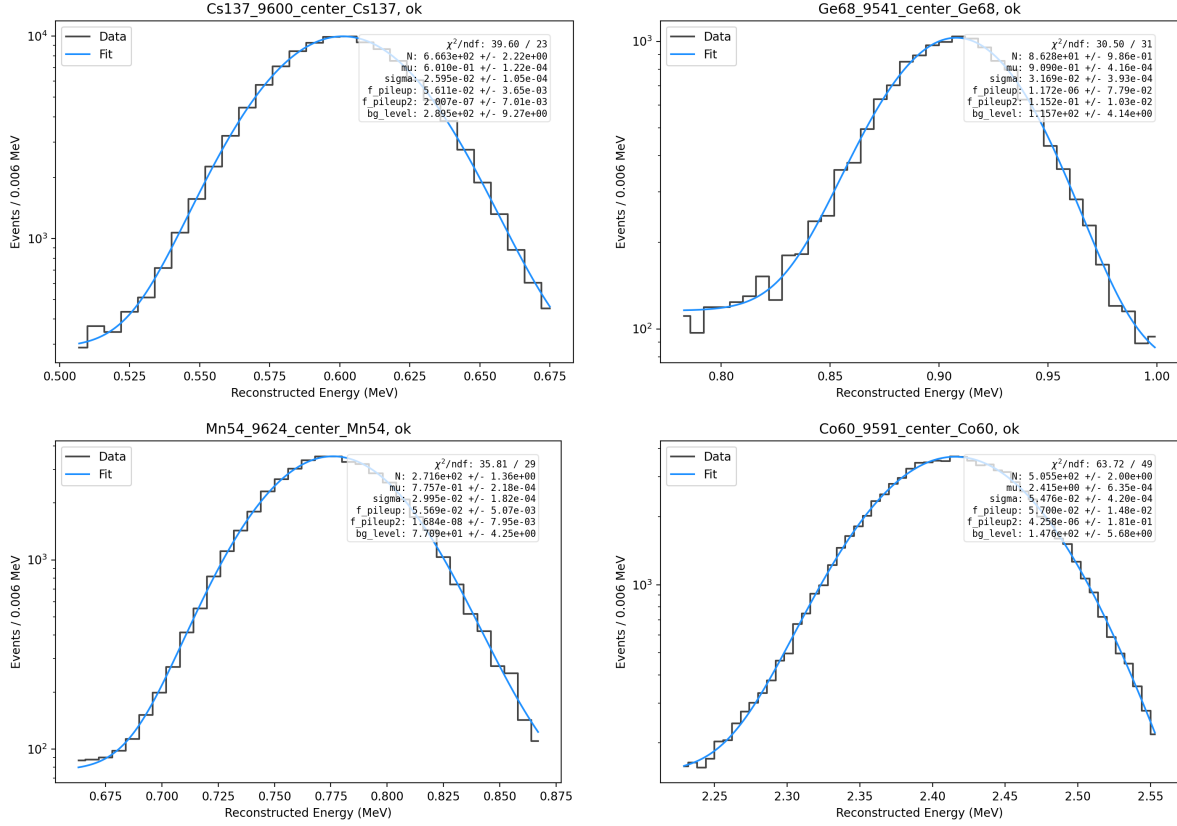


Figure 7.4: GaRF fits of calibration data during which  $^{137}\text{Cs}$  (top left),  $^{54}\text{Mn}$  (bottom left),  $^{68}\text{Ge}$  (top right), or  $^{60}\text{Co}$  (bottom right) (top) sources were placed at the center of the detector. The automated fitting algorithm preserves run, position, source, and fit result flag information, as shown in the title.

## 7.5 Spectral Datasets

Radioactive gamma sources provide high-precision monoenergetic signals, yet they suffer from two primary limitations: the complexity of modeling the multi-body gamma-to-electron conversion and a lack of available isotopes with decay energies past 6 MeV. To robustly map and constrain the energy non-linearity up to the high-energy endpoint of the reactor antineutrino spectrum, the GEPRIS framework incorporates a suite of continuous spectra from cosmogenic isotopes and the IBD signal, both produced in-situ within the active volume of the liquid scintillator.

### 7.5.1 Cosmogenic Isotopes from Muon Spallation

High-energy cosmic muons traversing the JUNO central detector interact with the carbon atoms ( $^{12}\text{C}$ ) in LAB. These interactions induce muon spallation, fracturing the target nuclei and generating a diverse spectrum of unstable radioactive isotopes. These  $\beta$ -decaying isotopes are distributed uniformly across the detector, making them excellent volume-wide calibration sources.

The practicality of selecting these cosmogenic events extends beyond calibration. The long-lived isotopes  $^9\text{Li}$  and  $^8\text{He}$  produced become backgrounds to the IBD signal, as their  $\beta$ -neutron cascade mimics the prompt-delayed IBD coincidence. Isolating a pure sample of these decays is necessary for measuring their production yields and for subsequently subtracting them from the IBD candidate sample.

JUCIA (JUNO Coincidence Investigation & Analysis Architecture) performs this selection by scanning the CD event loop and looking for non-muon "singles" that are spatially and temporally correlated with a preceding muon. Events are catalogued as muons if they exceed a certain threshold (300 PE in WP and 30,000 PE in the CD). Muons that additionally carry a reconstructed CD track are pushed into a time-ordered buffer together with their reconstructed track(s) and any associated spallation-neutron captures. No further processing is performed on the muon event itself. For every subsequent non-muon event, the buffer is reduced by discarding muons older than a configurable search window (by default  $5 \times 10^2$  s), measured relative to the current event time. The search window determines the isotopes the selection is able to distinguish.

Before a candidate event is considered, three independent vetoes of 10 ms are applied, rejecting the event if it falls within this window of:

1. the most recent tagged muon,

2. the most recent event with a missing or invalid header
3. or the most recent large gap in the CD data stream, identified whenever the time since the previous CD-calibrated event exceeds 50 ms.

These vetoes remove residual muon afterpulse and post-muon activity, as well as periods of unstable or discontinuous data taking, before any physics selection is applied.

### Spatial-temporal Correlation with the Parent Muon

Events surviving the data-quality vetoes are required to have energy above 0.6 MeV and to be located in the CD. For each such candidate, the algorithm then loops over muon candidates retained in the buffer and evaluates two independent spatial cuts:

- **Track-distance cut:** the minimum distance between the candidate vertex and each reconstructed muon track segment is computed. Muons for which this distance exceeds 10 m are discarded as parent candidates, since spallation products are expected to be produced along, and remain localized close to, the muon track.
- **Neutron-proximity cut:** if the muon produced one or more spallation neutrons, the neutron capture closest to the candidate vertex is identified and the corresponding distance and time separation are recorded. Candidates farther than 5 m from the nearest associated neutron capture are rejected for that muon.

### 7.5.2 Selected Cosmogenic Spectra

The selection described previously selects decay chains that span a wide range of  $Q$  values, providing non-linearity information from sub-MeV energies up to 15 MeV. The selected distributions are shown along with the corresponding GEPriS predictions using a nominal set of parameters.

## $^{12}\text{B}$ and $^{12}\text{N}$

$^{12}\text{B}$  is a  $\beta^-$  emitter with a high  $Q$ -value of 13.3 MeV and a short half-life of  $\tau_{1/2} = 20.2$  ms. It provides a smooth, continuous electron spectrum covering the entire IBD energy range with high statistics. This spectrum is fit in conjunction with its irreducible, shorter-lived background isotope  $^{12}\text{N}$  that emits  $\beta^+$  ( $Q = 17.3$  MeV,  $\tau_{1/2} = 11.0$  ms).

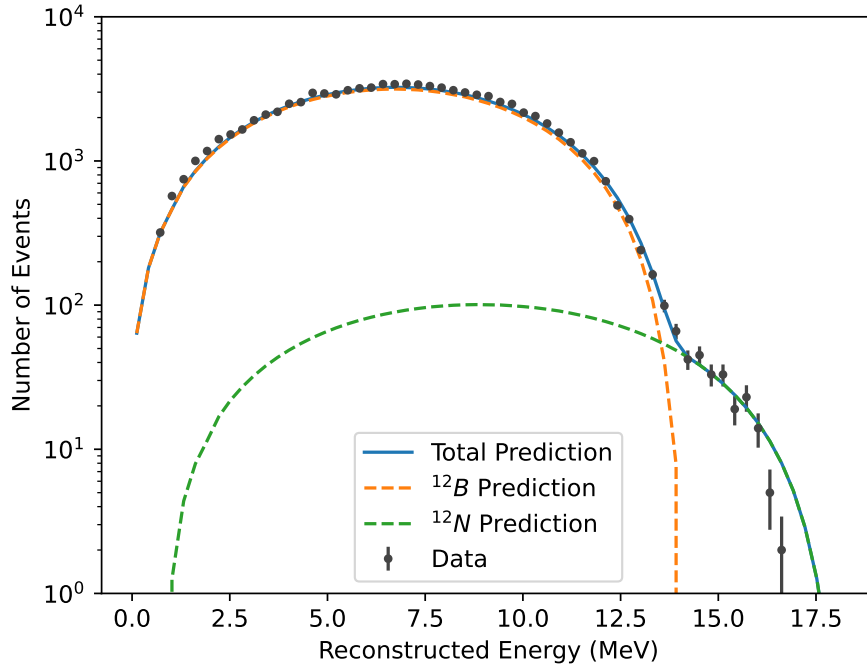


Figure 7.5:  $^{12}\text{B}$  spectrum from JUNO data using JUCIA selection with GEPRIS spectral predictions shown.

## $^{11}\text{C}$ and $^{10}\text{C}$

$^{11}\text{C}$  is the most abundantly produced  $\beta^+$  emitter ( $Q = 0.96$  MeV,  $\tau_{1/2} = 20.3$  min). Given its long lifetime, the buffer window in JUCIA is extended to 2 hours for this selection only. It is also modeled alongside the shorter-lived  $^{10}\text{C}$  ( $\beta^+$ ,  $Q = 1.91$  MeV plus an associated 0.72 MeV prompt  $\gamma$ -ray), where  $^{11}\text{C}$  acts as a background inside the  $^{10}\text{C}$  selection window.



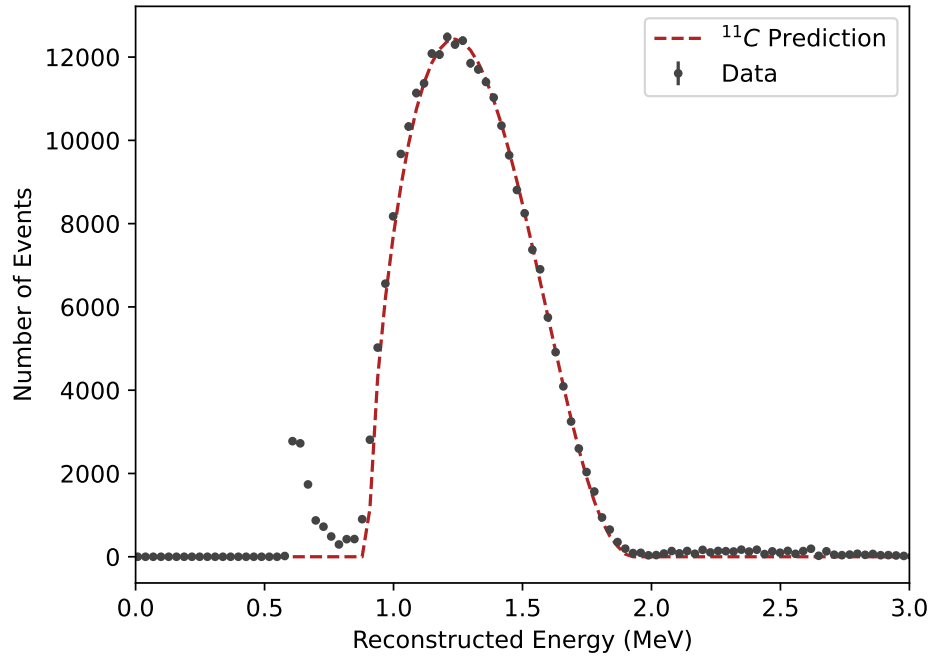
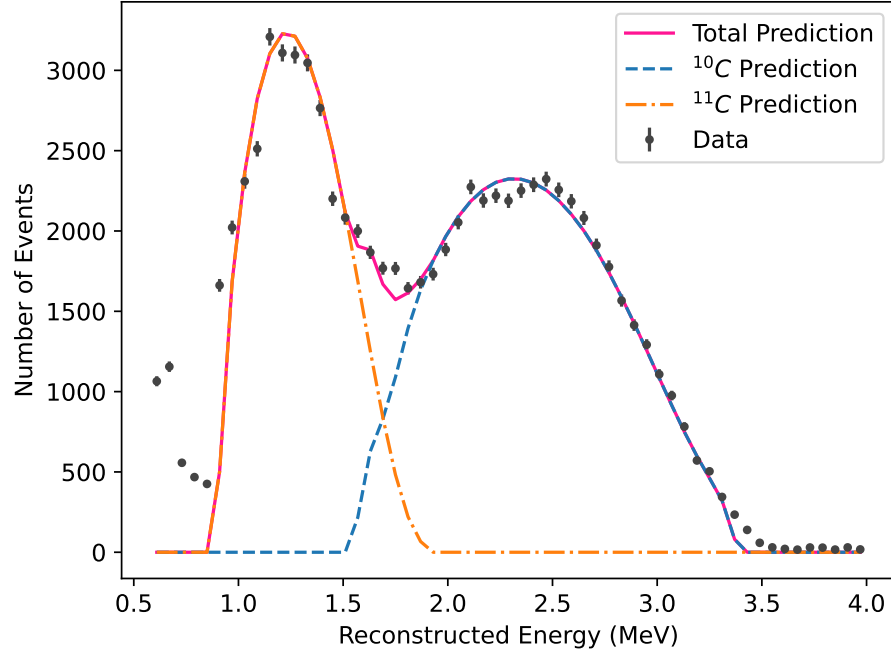


Figure 7.6:  $^{10}\text{C}$  (top) and  $^{11}\text{C}$  (bottom) spectra from JUNO data using JUCIA selection with GEPRIS spectral predictions shown. A  $^{11}\text{C}$  component is included as a background to the  $^{10}\text{C}$  spectrum, shown in the top panel.

## $^8\text{C}$ , $^6\text{He}$ , and $^8\text{Li}$ :

Following deep-inelastic hadronic interactions of cosmic-ray muons, several nucleon-rich spallation fragments are produced:  $^6\text{He}$ ,  $^8\text{Li}$ , and  $^8\text{B}$ . In particular,  $^8\text{B}$  and  $^8\text{Li}$  do not decay to a stable ground state: both proceed via allowed  $\beta$  transitions to the broad  $2^+$  resonance of  $^8\text{Be}$  at 3.03 MeV, which is unbound and disintegrates almost instantaneously into two  $\alpha$ . The comparatively short-lived  $^6\text{He}$  ( $\tau_{1/2} = 806.7$  ms,  $Q_{\beta^-} = 3.51$  MeV) complements this pair with a pure  $\beta^-$  spectrum in the same production channel, at an energy scale intermediate between the  $^{12}\text{B}$  and  $^{10}\text{C}/^{11}\text{C}$  samples, informing the fit in this region. Together with  $^8\text{Li}$ 's similarly short half-life ( $\tau_{1/2} = 838.8$  ms), all three isotopes can be cleanly selected together.

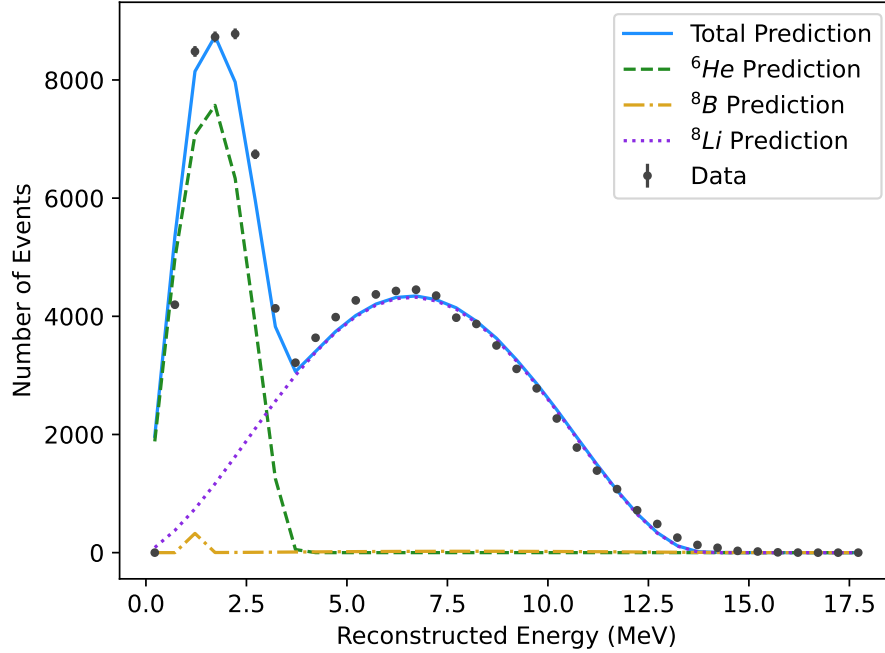


Figure 7.7:  $^6\text{He}$ ,  $^8\text{B}$ , and  $^8\text{Li}$  combined spectrum from JUNO data using JUCIA selection with GEPRiS spectral predictions shown.

### 7.5.3 IBD Selection

In order to inform the model about the energy differences between events at the center and those distributed uniformly in the detector, reactor  $\bar{\nu}_e$  IBD candidates are included as a

spectral dataset. JUCIA is also capable of isolating a high-purity sample of IBD candidates from JUNO data using a similar time buffer strategy, pairing prompt-like and delayed-like events rather than muons and correlated decays. The following selection criteria are enforced:

1. **Fiducial Volume Cut:** To eliminate external  $\gamma$ -ray backgrounds from the acrylic vessel and surrounding PMT glass, the reconstructed vertex must satisfy  $R_{rec}^3 < (16.5 \text{ m})^3$
2. **Prompt Energy Window:** The prompt candidate's reconstructed energy must fall within  $0.7 \text{ MeV} < E_{prompt} < 12.0 \text{ MeV}$ .
3. **Delayed Energy Window:** The delayed candidate must be consistent with neutron capture on either hydrogen or carbon, satisfying  $2.0 \text{ MeV} < E_{delayed} < 2.5 \text{ MeV}$  or  $4.5 \text{ MeV} < E_{delayed} < 5.5 \text{ MeV}$ .
4. **Coincidence Time Interval:** The time difference between the prompt and delayed signal must satisfy  $5.0 \mu\text{s} < \Delta t < 1000.0 \mu\text{s}$ .
5. **Spatial Coincidence Distance:** To reject random accidental coincidences, the spatial distance between the prompt and delayed vertices must be tightly bounded:  $\Delta R = |\vec{x}_{prompt} - \vec{x}_{delayed}| < 1.5 \text{ m}$ .
6. **Flasher Cut:** To remove flashing PMTs,  $\left(\frac{\sigma_{nhit}-0.55}{0.45}\right)^2 + \left(\frac{\sigma_{hit-time}-170}{80}\right)^2 < 1$  is required where the  $\sigma$ s come from the number of hit and hit time distributions of fired PMTs.
7. **Multiplicity Cut:** No events of energy  $2.0 \text{ MeV} < E < 12.0 \text{ MeV}$  in the full CD within 1 ms before the prompt and after the delayed candidates or between the pair.
8. **Muon Veto Criteria:** Cosmic-ray muons passing through the Water Cherenkov Veto or Top Tracker produce long-lived radioisotopes. A multi-tier veto is applied:
  - *Water Pool Muons:* Veto the entire CD for 2 ms after any muon detected in the water pool.

- *Water Pool + CD Muons*: Veto the entire CD for 7 ms after any muon detected in the water pool with correlated activity in the CD within a window of 500 ns.
- *CD-only Muons*: Veto the entire detector for 7 ms after any muon detected in the CD.
- *Spallation Neutron Veto*: Veto a 4 m radius sphere around neutron spallation candidates for 1.2 s.

For the detector response model, the delayed signal on hydrogen specifically is used as a dataset, as shown in Figure 7.8.

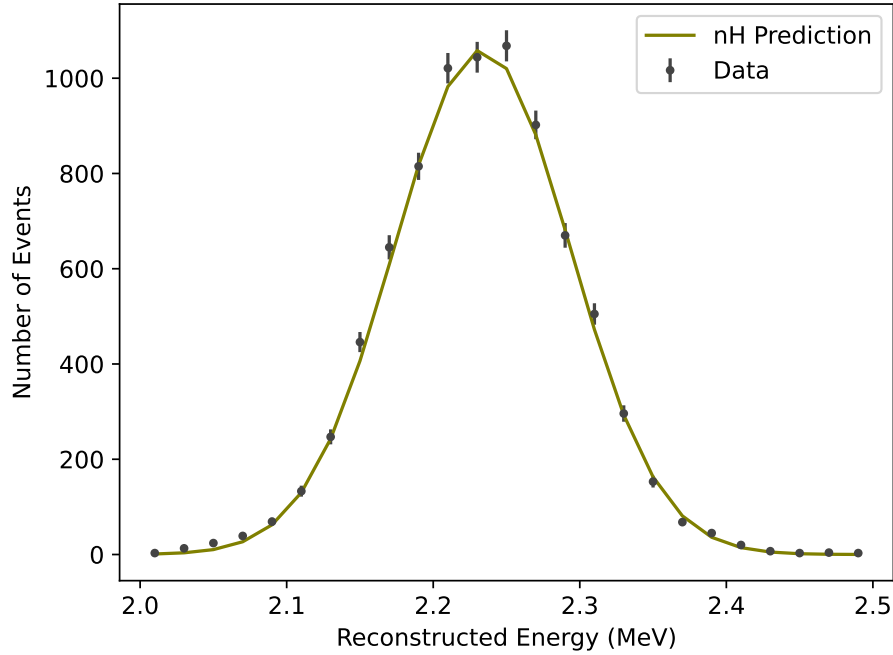


Figure 7.8: nH spectrum from JUNO data using JUCIA IBD selection with GEPRiS prediction shown.

## 7.6 The GEPRiS Methodology

The GEPRiS package is based around a global fit approach, with a selection of fitting algorithms available for cross-checking. The main goal is to constrain primary detector model parameters ( $k_B, f_C, k_I, LY_{shared}$ ) and the overall normalization of the non-linearity curve  $A$ . The uniqueness of GEPRiS lies in its ability to combine the discrete  $\gamma$  lines with the continuous  $\beta$  spectra from cosmogenic isotopes while providing a high level of flexibility in defining datasets and optimizing fitting. The details of the model are described in the following section, starting with  $\beta$ s and building up to  $\gamma$ s and their combined fit.

### 7.6.1 $\beta^\pm$ Energy Non-linearity Model

#### Quenching Integration

For a charged particle of kinetic energy  $T$ , Birks' law is recast as an quenching factor:

$$Q(T; k_B) = \frac{1}{T} \int_0^T \frac{dE'}{1 + k_B \frac{dE}{dx}(E')}, \quad (7.10)$$

where  $dE/dx(E')$  is the particle's stopping power in the LS. The algorithm reads a tabulated electron mass-stopping power (in  $\text{MeV cm}^2/\text{g}$ ) from the NIST ESTAR database, requested by specifying the JUNO LS composition before being converted to a linear stopping power using the LS density. Equation (7.10) is then evaluated numerically. The denominator is sampled logarithmically-then-linearly: densely at low energies, where the stopping power varies rapidly, and more coarsely at high energies. The quenching term  $Q(T)$  is finally obtained from its cumulative trapezoidal integral divided by  $T$ .

Separate stopping-power tables are used for  $e^\pm$  and for  $\alpha$  particles, since the much higher ionization density of  $\alpha$  tracks produces significantly stronger quenching. Because this integral must be re-evaluated many times for different trial values of  $k_B$  during minimization, GEPRiS

cached the result keyed on a value of  $k_B$ , so that repeated calls with the same  $k_B$  during a fit re-use the cached curve rather than re-integrating.

### Instrumental Non-Linearity

The residual charge-level or instrumental non-linearity of the LPMT system is folded in as a linear multiplicative correction applied to the total visible energy,

$$f_{\text{inst}}(E_{\text{vis}}; k_I) = 1 - k_I E_{\text{vis}}, \quad (7.11)$$

consistent with the shape of the diagnostic extracted from the DCC-Laser calibration in Section 6.2.

### $e^\pm$ and $\alpha$ Response

The energy non-linearity  $\eta_e$  of an electron of kinetic energy  $T$  combines the Birks-quenched scintillation light with a Cherenkov contribution,

$$\eta_e(T; A, k_B, f_C) = A \left[ Q(T; k_B) + f_C \frac{C(T)}{T} \right], \quad E_{\text{vis},e}(T) = T \cdot \eta_e(T), \quad (7.12)$$

where  $C(T)$  is the integrated Cherenkov photon yield as a function of initial electron energy, obtained from a pre-computed, Geant4-derived lookup table and linearly interpolated (with extrapolation beyond the simulation range). Since a positron's kinetic energy deposition is followed by  $e^+e^-$  annihilation into two 511 keV  $\gamma$ 's, and in some decays by an additional nuclear de-excitation  $\gamma$  (e.g. the 0.718 MeV transition accompanying  $^{10}\text{C}$  decay), their visible energy and deposited energy are also taken into account:

$$E_{\text{vis},\beta^+}(T) = E_{\text{vis},e}(T) + 2 E_{\text{vis},\gamma}(0.511 \text{ MeV}) + E_{\text{vis},\gamma}(E_{\text{extra}}), \quad (7.13)$$

$$E_{\text{dep},\beta^+}(T) = T + 1.022 \text{ MeV} + E_{\text{extra}}, \quad (7.14)$$

where  $E_{\text{vis},e}(T)$  is the electron-model visible energy of the positron's kinetic energy loss (Eq. (7.12)) and  $E_{\text{vis},\gamma}(0.511 \text{ MeV}) / E_{\text{vis},\gamma}(E_{\text{extra}})$  are the visible energies from the  $\gamma$  model in Section 7.6.2 for the relevant energies. The instrumental correction, Eq. (7.11), is applied once to the *total* visible energy rather than to each component separately, and the resulting non-linearity is:

$$\eta_{\beta^+}(T) = \frac{E_{\text{vis}}(T) \cdot f_{\text{inst}}(E_{\text{vis}}(T))}{E_{\text{dep}}(T)}. \quad (7.15)$$

For  $\alpha$  particles, the same functional form is used but without a Cherenkov term, since  $\alpha$  particles in this energy range remain below their Cherenkov threshold in the LS:

$$\eta_{\alpha}(T; A, k_B) = A Q_{\alpha}(T; k_B), \quad E_{\text{vis},\alpha}(T) = T \cdot \eta_{\alpha}(T). \quad (7.16)$$

## Theoretical $\beta$ Spectrum Modeling

The true  $\beta$ -decay energy spectra for each isotope of interest are taken from **BetaShape** calculations, which account for forbidden-decay shape corrections. Each true spectrum is passed through Equations (7.12) or (7.15) to obtain the corresponding visible-energy spectrum. For the  $\beta$ -delayed  $\alpha$  emitters  $^8\text{B}$  and  $^8\text{Li}$ , which proceed through the  $2^+$  resonance of  $^8\text{Be}^*$ , an additional two- $\alpha$  visible-energy contribution is computed from a Breit-Wigner-shaped resonance model and added to the corresponding  $\beta$  visible energy before smearing. Each predicted visible-energy spectrum is then smeared with the JUNO energy resolution function from Equation 7.1 using Gaussian convolution and rebinned.

### 7.6.2 Gamma Energy Non-linearity Model

$\gamma$  rays do not deposit energy directly via ionization. Instead, they transfer energy to electrons predominantly through Compton scattering, pair production, and the photoelectric effect. The visible energy of a  $\gamma$  ray with energy  $E_{\gamma}$  can be described as the sum of the visible

energies of all secondary particles produced:

$$E_{vis,\gamma} = \int \frac{dN}{dE_e}(E_\gamma) \cdot E_{vis,e}(E_e) dE_e \quad (7.17)$$

where  $\frac{dN}{dE_e}$  is the secondary particle energy distribution obtained via Geant4 simulations. By utilizing a variety of gamma sources, the  $\gamma$  non-linearity is sampled at multiple discrete points. The points are then interpolated to provide predictions at any requested  $\gamma$  energy.

The theoretical nH  $\gamma$  spectrum is modeled as a Gaussian distribution width equal to Equation 7.1 and mean:

$$\mu = LY_{shared} \cdot E_{vis,\gamma}(2.223\text{MeV}) \quad (7.18)$$

where  $LY_{shared}$  enters as a shift allowed to the peak of the IBD nH spectrum to account for the different LY with respect to the calibration AmC-source nH spectrum, given that the former is uniformly-distributed while the latter is localized at the detector center. The prediction is added over a linear background to account for accidentals.

## 7.7 Combined Fit

With the modeling of all required particle species done, the final task of GEPRIS is to find the parameter vector

$$\mathbf{\Pi} = (A, kB, f_C, k_I, LY_{shared}, a, b, b', c; \mathbf{N}_{spectrum}) \quad (7.19)$$

that simultaneously best describes all calibration datasets. Here  $A$  is the non-linearity normalization,  $kB$  is Birks' constant for JUNO LS,  $f_C$  scales the Cherenkov contribution,  $k_I$  captures the residual instrumental non-linearity, and  $(a, b, b', c)$  parameterize the energy resolution function in Equation 7.1. The parameter  $b'$  enters as an additive correction to  $b$ ,



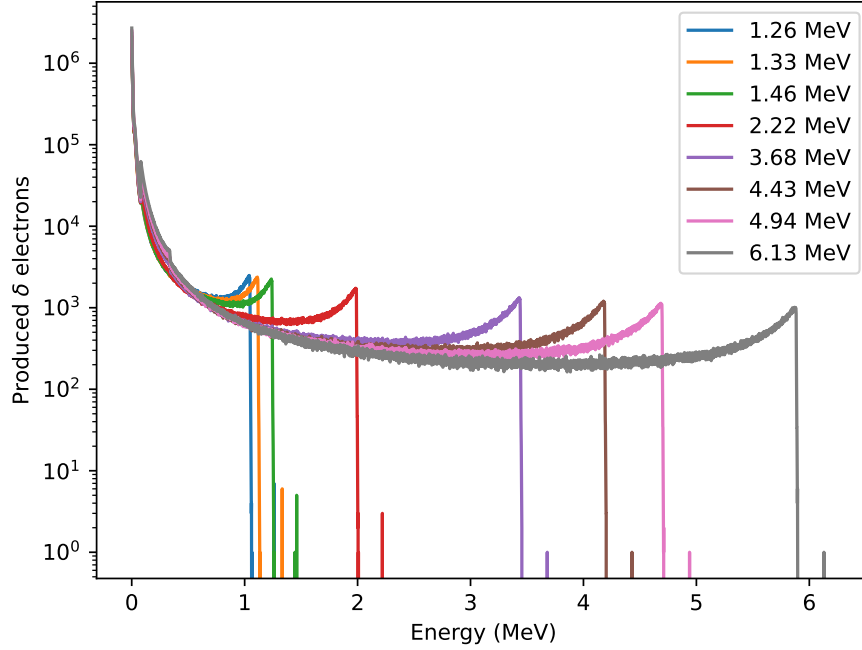


Figure 7.9: Kinetic energy distributions of secondary  $e^\pm$  induced in LAB by  $\gamma$  of different energies modeled by Geant4/JUNOSW J.25.

allowing a larger resolution to the uniformly-distributed cosmogenic spectra. The normalizations for each spectrum and its background components are also included.

Information from each calibration source is encapsulated in a **Dataset** object. The implementations each have a common **prediction( $\Pi$ )** method that evaluates the corresponding theoretical visible-energy for an arbitrary parameter point, together with a **chi2** method that returns the associated goodness-of-fit contribution. This allows, for example, the instrumental non-linearity dataset a Gaussian penalty term for  $k_I$ , constraining it to zero within its measured uncertainty of  $\sigma_{k_I} = 1 \times 10^{-2}$  from the DCC-Laser calibration described in 6.2. This object-oriented design ensures that calibration sources can be added and removed from consideration with ease by defining a **Dataset** without having to alter the fit algorithm.

### 7.7.1 Chi-squared Construction and Minimization

The global  $\chi^2_{total}$  is the sum of individual  $\chi^2$  contributions:

$$\chi^2_{total}(\mathbf{\Pi}) = \chi^2_{\gamma} + \chi^2_{^{12}\text{B}/^{12}\text{N}} + \chi^2_{^{11}\text{C}} + \chi^2_{^{10}\text{C}} + \chi^2_{\text{HeBLi}} + \chi^2_{nH} + \chi^2_{\text{resol.}} + \left( \frac{k_I}{\sigma_{k_I}} \right)^2, \quad (7.20)$$

where each spectral term is the standard:

$$\chi^2_i = \sum_b \frac{[d_b^{(i)} - p_b^{(i)}(\mathbf{\Pi})]^2}{[\sigma_b^{(i)}]^2}, \quad (7.21)$$

with  $d_b^{(i)}$ ,  $p_b^{(i)}$ , and  $\sigma_b^{(i)}$  denote the observed bin content, predicted bin content, and total bin uncertainty in the  $b$ -th bin of dataset  $i$ , respectively. The spectral model predictions are normalized to unit area before being multiplied by the amplitude parameters ( $N_{^{12}\text{B}}$ ,  $N_{^{12}\text{N}}$ , etc.). The minimization of  $\chi^2_{total}$  is performed with `iminuit` [60, 84], with a secondary `SciPy` [121] implementation of the L-BFGS-B algorithm as a cross-check.

Aside from caching the Birks'-derived quenching factor, spectrum-level predictions are similarly cached, keyed on the full set of parameters that enter that dataset's model, so that the cost of a  $\chi^2$  evaluation falls to a single cache lookup in the majority of steps.

Table 7.1 summarizes the full parameter vector, the associated prior constraints or bounds, and which datasets are sensitive to each parameter. The scintillation and Cherenkov parameters ( $A, kB, f_C$ ) are shared across all datasets.

The instrumental non-linearity is degenerate with  $f_C$ , as they both increase quasi-linearly with energy. The penalty term  $(k_I/\sigma_{k_I})^2$  derived from the DCC-Laser result is used to break this degeneracy, with  $\sigma_{k_I}$  set to 1%.

Table 7.1: GEPRiS fit parameters, their default initial values, applied bounds, and the datasets that constrain them.

| Parameter             | Symbol        | Default                                                  | Bounds / Prior                     | Datasets |
|-----------------------|---------------|----------------------------------------------------------|------------------------------------|----------|
| Normalization         | $A$           | 1.0                                                      | (0.8, 1.2)                         | all      |
| Birks constant        | $kB$          | $1.33 \times 10^{-3} \text{ g cm}^{-2} \text{ MeV}^{-1}$ | $(1, 50) \times 10^{-3}$           | all      |
| Cherenkov scale       | $f_C$         | 0.118                                                    | (0, 1)                             | all      |
| nH Light Yield        | $LY_{shared}$ | 1.0                                                      | (0.9, 1.2)                         | nH       |
| Instrumental NL       | $k_I$         | 0.0                                                      | $\mathcal{N}(0, 1 \times 10^{-2})$ | spectral |
| Stochastic term       | $a$           | 0.033                                                    | (0.02, 0.06)                       | spectral |
| Constant term         | $b$           | 0.009                                                    | (0, 0.05)                          | spectral |
| Non-uniformity offset | $b'$          | 0.0                                                      | (-0.02, 0.02)                      | spectral |
| Noise term            | $c$           | 0.0                                                      | (0, 0.01)                          | spectral |

### 7.7.2 Uncertainty Estimation via Monte Carlo Propagation

Parameter uncertainties are extracted from the  $\chi^2_{\text{total}}$  Hessian matrix evaluated at the best-fit point. When using L-BFGS-B, the Hessian is not provided analytically by the optimiser; instead, GEPRiS computes it numerically:

$$H_{ij} = \frac{\chi^2(\mathbf{\Pi}_0 + \epsilon \hat{e}_i + \epsilon \hat{e}_j) - \chi^2(\mathbf{\Pi}_0 + \epsilon \hat{e}_i - \epsilon \hat{e}_j) - \chi^2(\mathbf{\Pi}_0 - \epsilon \hat{e}_i + \epsilon \hat{e}_j) + \chi^2(\mathbf{\Pi}_0 - \epsilon \hat{e}_i - \epsilon \hat{e}_j)}{4\epsilon^2}, \quad (7.22)$$

with step size  $\epsilon$  set 6 orders of magnitude smaller than that of the parameter value. The parameter covariance matrix is then

$$\mathbf{C} = 2\mathbf{H}^{-1}, \quad (7.23)$$

where the factor of two accounts for the least-squares normalization convention. Diagonal elements of  $\mathbf{C}$  yield the squared  $1\sigma$  uncertainties on individual parameters while off-diagonal elements encode parameter correlations that are propagated to derived quantities.

Uncertainties on predicted spectra and derived curves are estimated by Monte Carlo propagation. The `Dataset.uncertainty` method draws 300 correlated parameter vectors from the multivariate Gaussian  $\mathcal{N}(\hat{\mathbf{\Pi}}, \mathbf{C})$ , evaluates the model prediction at each draw, and returns

their standard deviation in every bin with parameter correlations correctly reflected in the uncertainty bands. An additional perturbation of the input **BetaShape** spectra using their provided theoretical uncertainties is applied, which allows the impact of nuclear-structure uncertainties to be included in the final band.

## 7.8 Detector Response Results

Figure 7.10 shows the detector response fit performed with the **GEPRiS** framework on JUNO’s ReProd26B data, taken between August 2025 and June 2026. Given that multiple radioactive source calibration runs occurred during this period, the multiple  $\gamma$  spectrum fit points are fit simultaneously in the  $\gamma$  energy non-linearity and energy resolution datasets. The points are well-fit by the extracted line except for energies above 7 MeV, where the uncertainty of those rare neutron-capture points is high.

The detector response fit finds a  $\gamma$  energy resolution at 1 MeV of 3.62% at the detector center and 3.78% in the total fiducial volume. The LY of the uniformly-distributed nH IBD spectrum is found to be 0.464% higher than for the AmC source spectrum at the center of the CD. For the cosmogenic isotope spectra, the most significant deviations from the model predictions are observed towards low energies.

The correlogram in Figure 7.11 displays unit-normalized correlations between fit parameters. As expected, significant correlations and anti-correlations between main detector parameters  $A$ ,  $k_B$ ,  $f_C$ , and  $k_I$  exist. The same holds true between this set of parameters and the spectra normalizations.

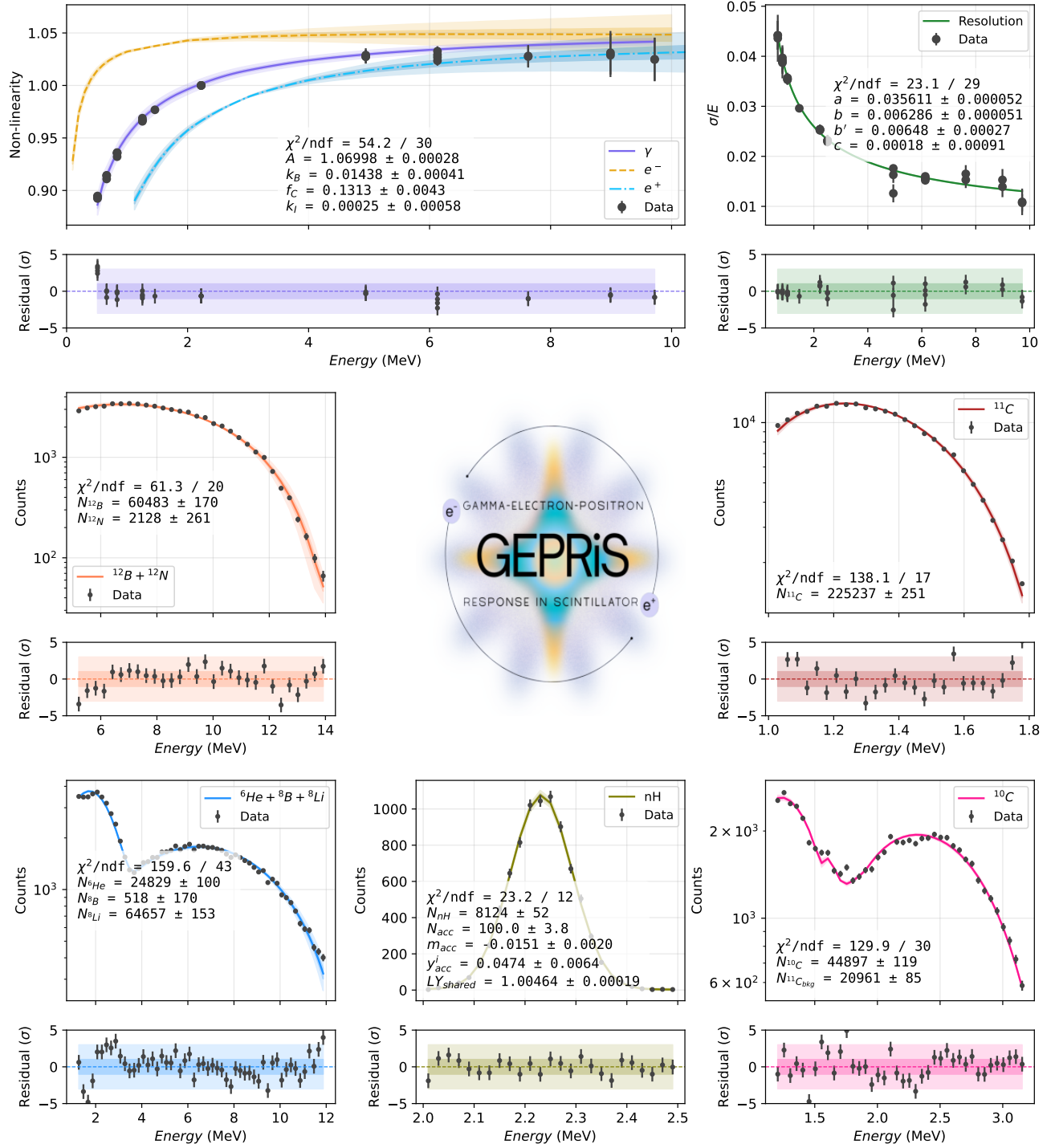


Figure 7.10: GEPRiS fit of JUNE gamma source and cosmogenic isotope data.

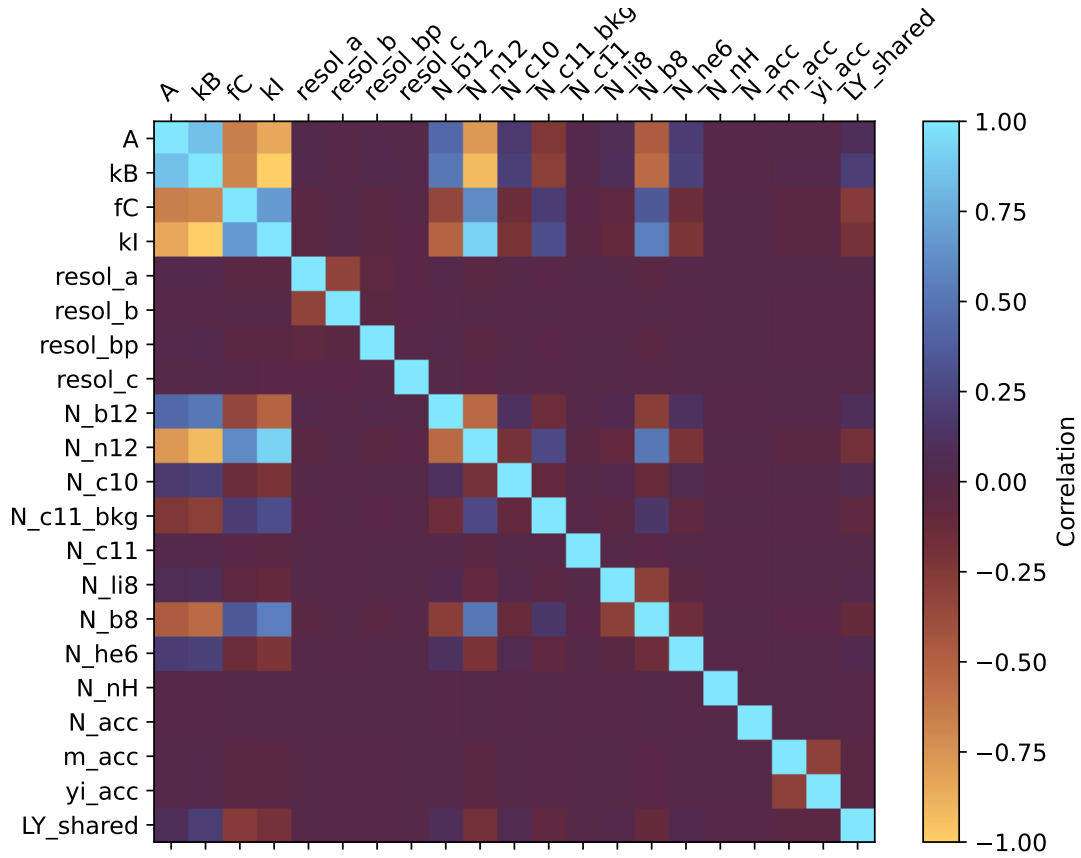


Figure 7.11: Correlogram for GEPRiS fit parameters.

## 7.9 Oscillation Measurement using GEPRiS Detector Response

In the previous chapters and sections, the design and installation of JUNO, the calorimetric capabilities enabled by its sPMTs, and the precise energy non-linearity measurement possible using its LPMT system were all described. It is now possible to integrate this information and perform a neutrino oscillation measurement. This section presents a semi-independent measurement of  $\sin^2\theta_{12}$ ,  $\Delta m_{21}^2$ , and  $\Delta m_{31}^2$  using JUNO's early data-taking and inputs derived from analyses authored fully or partially at the University of California Irvine, including the GEPRiS detector response result just described.

### 7.9.1 Background Estimation

Despite the overburden at the detector site, residual backgrounds still contaminate the final IBD sample. These are evaluated using data-driven techniques and sideband channels:

Table 7.2: Summary of expected background contributions to the IBD selection in JUNO data [85].

| Background Source                           | Rate (per day) | Systematic Uncertainty |
|---------------------------------------------|----------------|------------------------|
| Cosmogenic ${}^9\text{Li}/{}^8\text{He}$    | 4.3            | $\pm 33\%$             |
| Geo-neutrinos                               | 1.2            | $\pm 42\%$             |
| World Reactors                              | 0.88           | $\pm 10\%$             |
| ${}^{214}\text{Bi}$ - ${}^{214}\text{Po}$   | 0.18           | $\pm 56\%$             |
| ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ | 0.04           | $\pm 50\%$             |
| Atmospheric Neutrinos                       | 0.08           | $\pm 50\%$             |
| Double Neutrons                             | 0.05           | $\pm 100\%$            |
| Fast Neutrons                               | 0.02           | $\pm 100\%$            |
| Accidental Coincidences                     | 0.049          | $\pm 6\%$              |

- **Accidental Coincidences:** Occur when an ambient environmental radioactivity event satisfies the prompt criteria and a subsequent independent radioisotope satisfies the delayed criteria. This is measured precisely by pairing un-associated prompts with off-time delayed windows.
- **Cosmogenic  ${}^9\text{Li}/{}^8\text{He}$ :** Produced via muon spallation on  ${}^{12}\text{C}$  nuclei. These isotopes undergo  $\beta^-$  decay followed by immediate neutron emission, perfectly mimicking an IBD event. The background is isolated by fitting the decay time profile relative to preceding showers.
- **Geo-neutrinos:** Antineutrinos produced from the radioactive decay of Uranium ( ${}^{238}\text{U}$ ) and Thorium ( ${}^{232}\text{Th}$ ) inside the Earth’s mantle and crust. They represent an irreducible physics background below 3.3 MeV, and their rate is kept free in the oscillation fit.
- **World Reactors:** Antineutrinos emitted by nuclear power plants beyond the primary Yangjiang and Taishan cores, contributing a small but non-negligible flux at the

JUNO site. The expected contribution is derived from operational data of Chinese plants together with the global reactor databases, rather than from a dedicated in-situ measurement.

- **$^{214}\text{Bi}$ - $^{214}\text{Po}$ :** A rare branch of the natural radon-daughter  $\beta$ - $\alpha$  cascade in which the delayed  $\alpha$  signal is pushed into the neutron-capture energy window, either through de-excitation  $\gamma$ 's from excited  $^{214}\text{Po}$  states or through  $\alpha$ -proton elastic scattering. Its rate is calibrated by scaling the measured high-energy tail fraction, observed during the high-radon filling phase, to the  $^{214}\text{Bi}$ - $^{214}\text{Po}$  rate present in the physics dataset [53].
- **$^{13}\text{C}(\alpha, n)^{16}\text{O}$ :** Alpha particles from residual  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and out-of-equilibrium  $^{210}\text{Po}$  contamination in the liquid scintillator can be captured on the naturally abundant  $^{13}\text{C}$  isotope, releasing a neutron whose recoil and capture signals mimic an IBD pair.
- **Atmospheric Neutrinos:** Neutral-current interactions of atmospheric neutrinos on carbon nuclei can knock out neutrons that, together with associated nuclear de-excitation products, reproduce the IBD coincidence signature.
- **Double Neutrons:** Arise when two neutrons from an untagged muon are sequentially captured within the coincidence window, with the first capture faking the prompt signal and the second the delayed one. This background is concentrated near the edge of the LS volume and is constrained using the same delayed-capture energy shape as IBD events.
- **Fast Neutrons:** Energetic neutrons generated by muons that pass through the surrounding rock without being tagged by the water-pool veto can enter the detector, where a proton recoil followed by neutron capture mimics the IBD prompt-delayed pair. The residual rate after the fiducial-volume and veto cuts is estimated from muon-tagged neutron samples and corner-clipping muon data.



### 7.9.2 Fit Strategy

The oscillation fit shown in this chapter is performed using the **NODA** (Neutrino Oscillation Data Analysis) framework. The unoscillated reactor antineutrino energy spectrum prediction is subject to large uncertainties (Section 5.2), making it preferable to constrain the flux using measurements close to the reactor cores. To mitigate this systematic, **NODA** divides the unoscillated flux into segments in reconstructed energy  $\alpha$ , each with a nuisance parameter associated to each segment. The nuisances are then constrained through a combined fit to the Daya Bay near-detector and TAO data, which detect antineutrinos at shorter baselines where oscillation effects are negligible and the measured spectral shape directly constrains the underlying flux model:

$$\chi_{\text{Ext}}^2(\alpha) = \chi_{\text{DYB}}^2(\alpha) + \chi_{\text{TAO}}^2(\alpha) \longrightarrow \mu_\alpha, V(\mu_\alpha), \quad (7.24)$$

yielding the best-fit segment values  $\mu_\alpha$  and their covariance  $V(\mu_\alpha)$ . Only their covariance on the JUNO reconstructed spectrum is retained in the final fit. This best-fit DYB+TAO reactor model is propagated through the JUNO detector response calculated earlier in this chapter, transforming the segment-space covariance into an effective covariance on JUNO's reconstructed-energy spectrum,

$$V(\mu_\alpha) \xrightarrow{\text{JUNO response}} V_\alpha(E_{\text{rec}}), \quad (7.25)$$

which is added directly to JUNO's own statistical and systematic covariance,  $V_{\text{JUNO}}$ . The JUNO fit is then performed at the fixed, externally-determined segment values  $\mu_\alpha$  rather than floating  $\alpha$  itself:

$$\chi^2 = \chi_{\text{JUNO}}^2(\theta, \mu_\alpha) = (D - M(\theta, \mu_\alpha))^T (V_{\text{JUNO}} + V_\alpha)^{-1} (D - M(\theta, \mu_\alpha)), \quad (7.26)$$

where  $D$  is the observed JUNO spectrum and  $M(\theta, \mu_\alpha)$  is the oscillated prediction for oscillation parameters  $\theta$ . This approach has been shown to be consistent with a simultaneous joint fit of JUNO, Daya Bay and TAO, with the added advantage of saving significant computational resources and time.

Within the JUNO-detector  $\chi^2$  itself, the predicted spectrum  $M(\theta, \mu_\alpha)$  is built from the oscillated reactor flux together with a set of nuisance terms:

1. reactor related nuisances: flux norm (1.5%), core power and fission fractions of the cores (0.8%), non-equilibrium and spent nuclear corrections (0.3%)
2. IBD detection efficiency nuisance for all the IBD spectral components (1.9%)
3. the energy-resolution parameters  $(a, b, c)$  of Eq. (7.1)
4. the energy non-linearity  $(A, kB, fC, kI, LY_{shared})$  in 7.15
5. background rate pulls for each background component
6. Th/U ratio in the geoneutrino spectral component (10%)

Particularly, the fit varies the physical parameters of the GEPRiS-derived by their covariance seeded at the best-fit values obtained from the calibration-data fit described earlier in this chapter. This is the mechanism by which the calibration-derived non-linearity model of this thesis directly enters JUNO's oscillation analysis.

### 7.9.3 Minimization

The configuration selects the Combined Neyman-Pearson (CNP) statistic for the per-bin statistical covariance, in which the diagonal statistical variance in bin  $i$  is estimated from a

combination of the observed and expected bin content:

$$\sigma_{\text{CNP},i}^2 = \frac{3}{\frac{1}{N_{\text{obs},i}} + \frac{2}{N_{\text{exp},i}}}, \quad (7.27)$$

avoiding the bias of a purely  $N_{\text{obs}}$ - or  $N_{\text{exp}}$ -based  $\chi^2$  at the low statistics available. This statistical covariance is added, bin by bin, to the systematic covariance matrices for each nuisance source and to the prefit-propagated  $C_{\text{reco}}$  described above, to form the full covariance entering the JUNO  $\chi^2$ .

The resulting combined  $\chi^2$ , a function of the oscillation parameters together with all detector-specific nuisance parameters is minimized using the `iminuit` python package [60, 84]. The assumed NMO is selected at runtime, to report the associated  $\Delta m_{31}^2$  value.

The fit reports a  $\chi^2/\text{ndf} = 1.013$  when NO is assumed and  $\chi^2/\text{ndf} = 1.03$  when IO is assumed.

## 7.9.4 Results

The fit is able to resolve  $\sin^2 \theta_{12}$ ,  $\Delta m_{21}^2$ , and  $\Delta m_{31}^2$  neutrino oscillation parameters. Figure 7.13 shows the extracted oscillation parameters compared with JUNO's two previous results. While  $\sin^2 \theta_{12}$  has a slight tension with the official result from the Neutrino 2026 conference, it agrees well with its first solar oscillation parameter publication [85]. On the other hand,  $\Delta m_{21}^2$  has better agreement with the Neutrino 2026 results.

Parameter  $\Delta m_{31}^2$ , which enabled by ever-growing statistics has very recently started to be reported by JUNO, is almost identical to the official result from the Neutrino 2026 conference under both NMO assumptions. Unlike the official result, this work does not consider Feldman-Cousins statistical treatment for the  $\Delta m_{31}^2$  uncertainty.

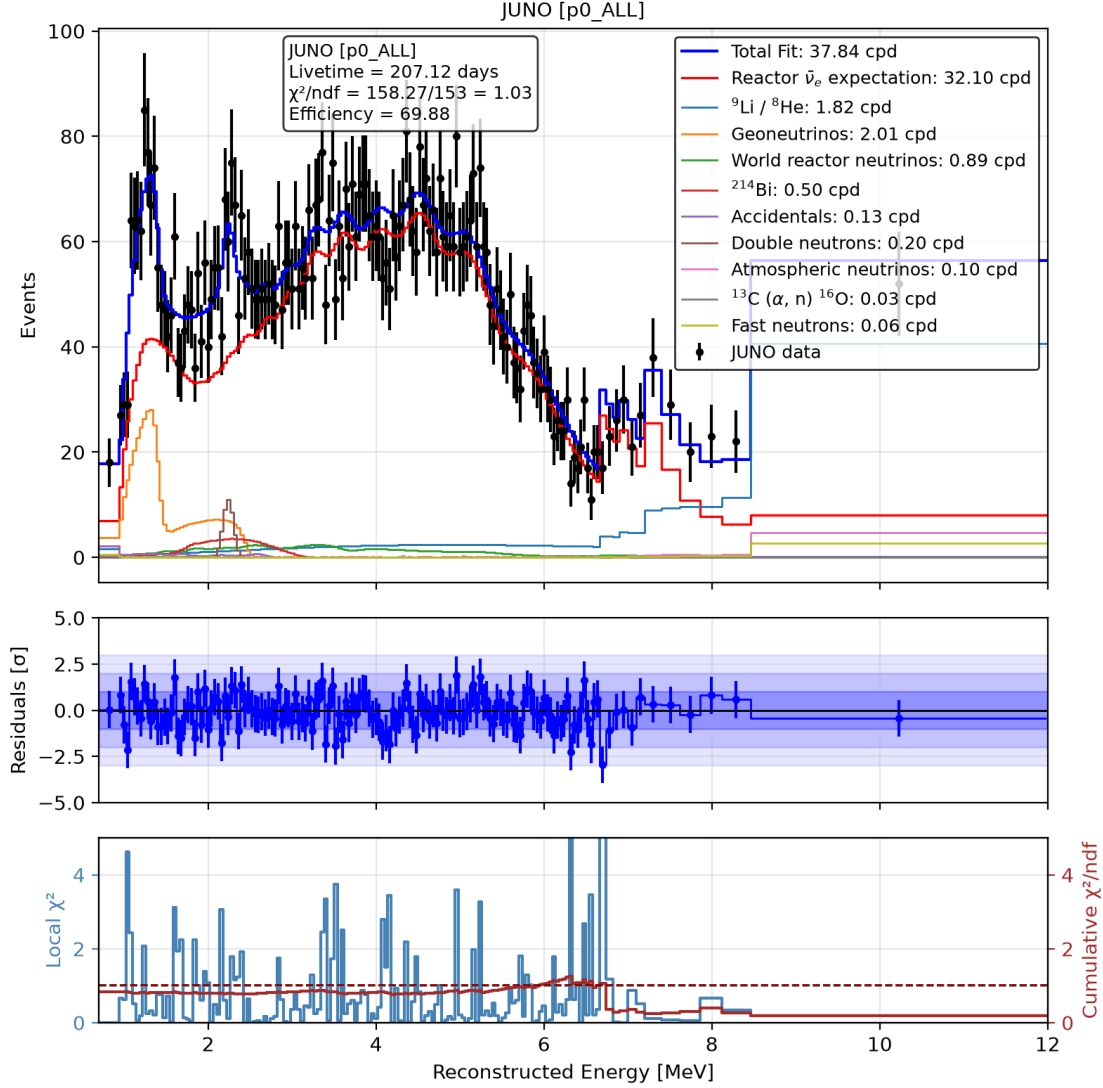


Figure 7.12: IBD prompt energy spectrum fit from NODA under IO assumption.

Within the JUNO collaboration, different sophisticated strategies are employed to corroborate results between analysis groups. It is worth nothing that, the latest official JUNO analysis uses a fiducial volume of  $R < 17.2$  m while this analysis only considers  $R < 16.5$  m. Nevertheless, this independent check shows good agreement with previous reports.

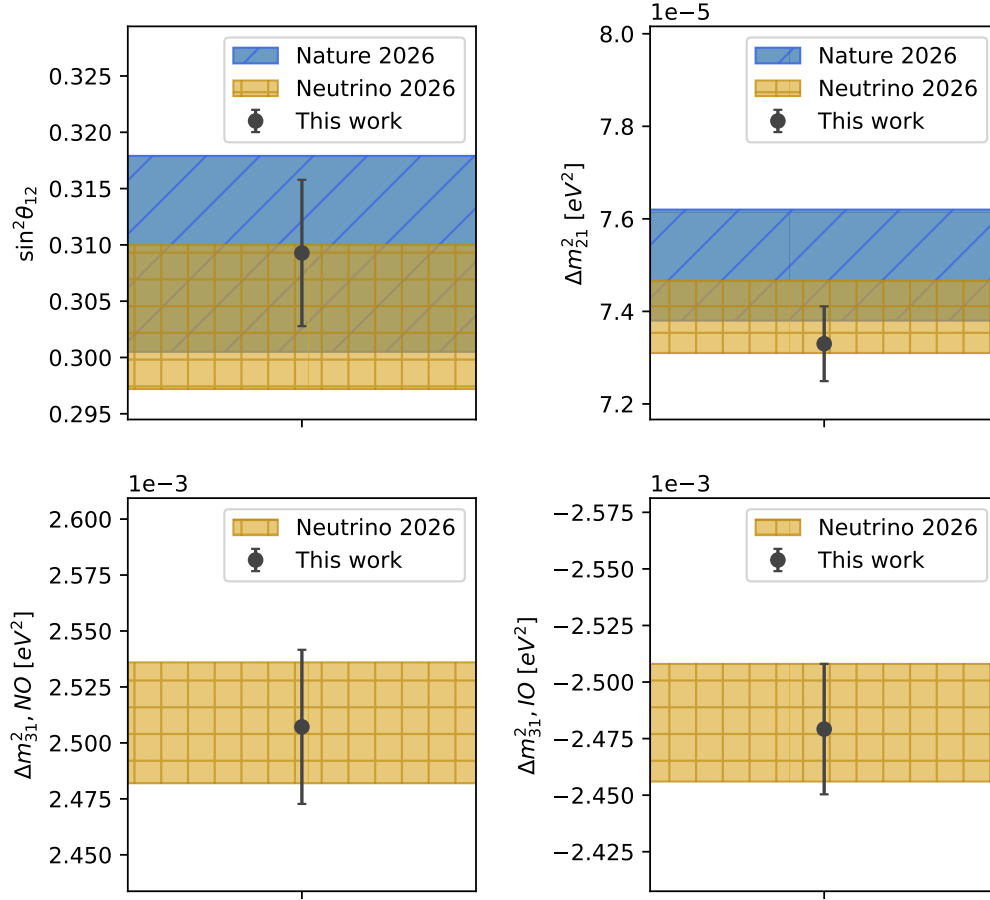


Figure 7.13: Comparison of fit neutrino oscillation parameters with JUNO's 2026 Nature publication [85] as well as their report during Neutrino 2026.

# Chapter 8

## Summary and Outlook

This dissertation has followed a story of leveraging novel detector designs to perform new calibrations for two different next-generation neutrino oscillation experiments, DUNE and JUNO, each pursuing precision oscillation measurements through complementary techniques with their own unique challenges. This closing chapter summarizes the results so-far presented and discusses the outstanding work and open questions that arise from them.

### 8.1 DUNE Pixel-readout LArTPC Technology

Chapters 2-4 addressed the instrumentation and calibration for DUNE’s ND-LAr detector. Chapter 3 described the integration of the DUNE Timing System (DTS) endpoint IP into the PACMAN controller firmware, and the construction and operation of a dedicated optical timing testbench used to validate this integration ahead of deployment. This work presents a concrete path to a unified timestamp between ND and, more generally, DUNE ND+FD detector systems.

Chapter 4 then used cosmic-ray MIPs, selected and reconstructed in three generations of ND-LAr pixel-readout prototypes (the 2x2 Demonstrator, the FSD, and FSD-Cube), to char-

acterize the charge scale of a pixelated LArTPC. The most-probable  $dQ/dx$  was calculated around the full  $4\pi$  track inclination phase space afforded by the pixelated readout, and the electron drift lifetime was measured from the attenuation of  $dQ/dx$  with drift time. A dedicated FSD-Cube simulation study also found a previously under-appreciated systematic. At the LArPix-v3's nominal least-significant-bit (LSB) setting, ADC quantization alone biases the extracted electron lifetime low by roughly 30% relative to its injected value. This effect is distinct from the charge-diffusion-driven lifetime overestimation found by this analysis and reported elsewhere in the literature [114].

The most direct extensions of this work are:

1. Reproducing the simulated LSB scan on ASIC bench hardware, to confirm the predicted bias and probe the charge response of the technology
2. Studying the effect of diffusion on pixelated charge collection to excruciating detail in order to derive drift-dependent corrections to the charge-scale
3. Maintaining DTS support in PACMAN firmware and porting the validated DTS firmware described in Chapter 3 to a ND-LAr prototype run

## 8.2 JUNO Dual Calorimetry, Energy Scale and Resolution

Chapters 5-7 turned to JUNO, whose ambitious reactor antineutrino oscillation program places an unprecedented demand on the detector's absolute energy scale and resolution. Chapter 6 described a secondary dual-calorimetry approach to LPMT calibration, exploiting the fact that JUNO's 25,600 sPMTs are insensitive to charge-scale non-linearities. Using deployed  $\gamma$  calibration sources (DCC-Gamma), a linear reference region was identified at low illumination, extrapolated, and compared against a single LPMT's charge response to diag-

nose residual instrumental non-linearity. Applied to full-simulation samples this method was shown to recover the injected linear response to within a 2% band, though at the magnitude of non-linearity currently injected into the official JUNO simulation and with the sample sizes available, the technique is not yet sensitive to the underlying LPMT instrumental non-linearity curve itself.

Chapter 7 then built on this instrumental diagnostic to construct GEPRiS, a combined physical model of the LS energy response and global fit to  $\gamma$ -source calibration spectra and cosmogenic  $\beta^\pm$ -decay spectra. Applied to JUNO’s ReProd26B dataset (spanning data taken between August 2025 and June 2026), the fit achieves a  $\gamma$  energy resolution of 3.62% at 1 MeV at the detector center and a  $e^+$  energy non-linearity constrained with  $\leq 0.61\%$  uncertainty from 1-12 MeV. Propagating this detector response model into a combined oscillation fit of JUNO’s early data yields measurements of  $\sin^2 \theta_{12}$ ,  $\Delta m_{21}^2$ , and  $\Delta m_{31}^2$  that are broadly consistent with JUNO’s officially reported results.

Several paths of study follow directly from these results. First, the DCC methodology of Chapter 6 should be revisited with a larger injected instrumental non-linearity and/or larger simulated statistics, to establish the smallest non-linearity DCC-Gamma can extract and determine whether it can meaningfully constrain the LPMT charge response beyond what the GEPRiS global fit already performs through the  $k_I$  parameter.

The residual GEPRiS fit discrepancies must be investigated, including a closer look at whether additional physics (e.g. finer treatment of the  $^8\text{Be}^*$  two- $\alpha$  decay) needs to be modeled. The impact of different cosmogenic spectra selections and binning should be corroborated as well. In this analysis, the results from multiple calibration campaigns were fit together to provide a general detector response for the ReProd26B data-taking period. Alternate approaches should be considered, for example, applying different detector responses period-by-period or instead deriving a combined curve from their multiple energy non-linearity curves.



Finally, the energy resolution extracted by this analysis is still 0.6% higher than the design target [20]. While it is adequate for the oscillation analyses available at the current statistics level, the sensitivity to the NMO is driven by this quantity. Values higher than the target, even deviations as small as reported, represent additional data-taking time required for a significant JUNO-only NMO measurement. The inclusion of sPMT information in the energy reconstruction, perhaps even correcting the instrumental non-linearity hit-by-hit, could help control the non-stochastic  $b, c$  terms of the energy resolution. Additionally, a further-refined  $\gamma$  ray spectrum fitting model could improve the energy resolution.

### 8.3 Closing Remarks

DUNE and JUNO approach the similar questions in neutrino oscillations from differing philosophies in detector design. Where DUNE relies on fine-grained tracking in LAr at GeV energies, JUNO relies on high-resolution calorimetry in LS at MeV energies. Nevertheless, the work presented here re-affirms that, in both cases, the ultimate physics reach of the experiment is constrained not by statistics alone, but by how well the detector is designed and how well its response is understood and calibrated.

The installation, testing, firmware, modeling, and calibration contributions described in this dissertation are incremental steps to a more precise understanding of particle behavior and detector response in next-generation neutrino experiments in order to boost the reach of their programs. In a way, the increasingly sophisticated technologies and precision-physics goals envisioned by these experiments beseech increasingly sophisticated and precise calibrations. It is the author's hope that his own and other's future work follow along this line of thought.

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