

UC Riverside

UC Riverside Electronic Theses and Dissertations

Title

The Suppression of Neutral Pion at Forward Rapidity in d+Au Collisions

Permalink

<https://escholarship.org/uc/item/51m4q0jt>

Author

Zou, Liankun

Publication Date

2021

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
RIVERSIDE

The Suppression of Neutral Pion at Forward Rapidity in d+Au Collisions

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

Liankun Zou

December 2021

Dissertation Committee:

Dr. Richard Seto, Chairperson
Dr. Kenneth Barish
Dr. John Ellison

The Dissertation of Liankun Zou is approved:

Committee Chairperson

University of California, Riverside

Acknowledgments

Finally, I got here. I want to express my sincere gratitude to those who helped me all this way. First and foremost, I would like to thank my advisor, Prof. Richard Seto, for his patience and support during some difficult times. His genuine care and mentoring benefited and helped me grow up a lot. Without that help, I would not have been here. I would also like to thank other members of the committee, Prof. Ken Barish and Prof. John Ellison.

I also would like to thank the MPC-EX group, Prof. John Lajoie, Prof. Nathan Grau, Prof. Tom Hemmick, Milap Patel, Jason Bryslawskyj, Chong Kim, Carlos Perez, N. Apadula, A. Sukhanov, Richard Hollis, Aneta Lordanova, Jaehyeon Do, Ashley Sexton and other members. Thanks for their hard work and help on the MPC-EX testing, installation, calibrations, and simulations. Besides, I would like to thank their support and guidance during the data analysis.

I also significantly appreciated help from the UCR group. During the analysis, Mike Beaumier and Sky Deva Rolnick gave me a lot of advice on coding.

Lastly, I would like to thank my parents, who gave me the confidence and courage all this way.

To my parents for all the support.

ABSTRACT OF THE DISSERTATION

The Suppression of Neutral Pion at Forward Rapidity in d+Au Collisions

by

Liankun Zou

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, December 2021
Dr. Richard Seto, Chairperson

The Quark-Gluon Plasma (QGP), a new hot dense matter created by melting the protons and neutrons in nucleus, was discovered at RHIC (Relativistic Heavy Ion Collider). The Universe passed through a QGP stage about $10 \mu\text{s}$ after the Big Bang before condensing into the familiar particles - primarily protons or neutrons. Experiments have shown that the QGP behaves like a strongly coupled liquid instead of a weakly couple gas - which was the original expectation. One key to understanding the QGP is the initial state. Experiments at HERA (Hadron Electron Ring Accelerator) suggest that protons and neutrons are dominated by gluons if we probe at small x (longitudinal momentum fraction). This effect should be more substantial in nuclei due to the large number of nucleons. One theory called Color Glass Condensate (CGC) proposed the gluon is saturated in nuclei if we probe below the saturation scale. We can use a dilute system (deuteron) to probe a dense system (gold) to investigate the saturation. Experiments have seen signs of saturation in the d+Au collisions, though these effects are subject to interpretation. In this thesis, using the MPC-EX (Muon Piston Calorimeter Extension) in the PHENIX experiment at RHIC, I explore

saturation effects in d+Au collision in the forward direction and present the suppression of neutral pions.

Contents

List of Figures	x
List of Tables	xxi
1 Introduction	1
1.1 Quarks	2
1.2 QCD	5
1.3 Heavy Ion Collisions	11
1.4 Quark Gluon Plasma	12
1.5 Initial State and Color Glass Condensate	20
1.6 Other models	27
1.7 Units, Kinetics and Centrality	29
1.7.1 Units	29
1.7.2 Kinematics	29
1.7.3 Centrality	32
2 Experimental Apparatus	33
2.1 RHIC	33
2.2 PHENIX	37
2.2.1 Magnets	37
2.2.2 Event Characterization Detectors	38
2.2.3 Central Arm Detectors	42
2.2.4 Muon Arm Detectors	44
2.2.5 Data Acquisition System	46
2.2.6 Trigger System	50
3 MPC and MPC-EX	54
3.1 MPC Detector	55
3.2 MPC-EX Detector	59
3.3 Test Beam Experiments	66
3.3.1 Fermilab Test Beam	66
3.3.2 SLAC test beam	71

3.4	Calibration of MPC-EX	75
3.4.1	Dead/Hot Channels	75
3.4.2	High Low Ratio	95
3.4.3	Energy Calibration	111
3.5	Calibration of the MPC	119
4	Data Analysis	121
4.1	The Shower Algorithm	122
4.2	Single Track π^0 Reconstruction Algorithms	125
4.2.1	TSpectrum algorithm	127
4.2.2	MiniCluster algorithm	129
4.3	Utilizing Machine Learning for π^0 Identification	134
4.3.1	The Convolutional Neural Network (CNN)	135
4.3.2	Signal and Background used for the Training Sample	139
4.3.3	Performance	142
4.4	Low Energy Two Track π^0 s	146
4.5	Centrality and Number of binary collisions: N_{coll}	151
4.5.1	Glauber Model	151
4.5.2	Centrality and N_{coll}	154
4.5.3	Centrality at Lower Energies	159
4.5.4	Uncertainty of the N_{coll}	161
4.5.5	N_{coll} Bias	163
4.6	Uncertainty of π^0 yields	167
4.7	Calculating R_{CP} , the π^0 Suppression factor.	170
5	Results and Conclusion	172
	Bibliography	176

List of Figures

1.1	The left figure shows the result of atom scattering, while the right figure shows the result of proton scattering. The departure of the experimental data from an exponential indicates substructure.	3
1.2	Three generations of quarks. From left to right, the mass increases. Up, charm, and top quarks have charge $+2/3e$ and down, strange, and bottom quarks have charges of $-1/3e$	4
1.3	The Eightfold Way of grouping particles. [42] [82] Top left is the pseudo-scalar meson octet, top right is the baryon octet and bottom is the baryon decuplet.	5
1.4	The coupling constant of QCD and QED. Left (QED): virtual photons split into electron, positron pairs, and the positron surrounds the electron. Hence, the electron is screened from far away, and the visible charge is smaller, making α smaller as the distance increases. Right(QCD): virtual gluons also split into quark, anti-quark pairs. However, gluons can also couple to each other and cause an anti-screen effect, making α_s larger as the distance increases. [39]	8
1.5	α_s as a function of energy scale Q . The different color data points show different experiments and methods to extract the α_s . [48]	9
1.6	Color confinement: at a certain range, quark-antiquark pairs will be created. In the final state, all the particles are color neutral.	10
1.7	Stages of a heavy ion collision.	11
1.8	The phase transition diagram of QCD(nuclear) matter. The x-axis is the baryon chemical potential, which is the difference between the baryon density and anti-baryon density. The Y-axis is the temperature. If we increase the baryon density and keep the temperature low, we will go through the neutron star state. If we increase temperature and keep the baryon density low, we will go through the crossover transition to a QGP where quarks and gluons are deconfined from hadrons. This happens at about the critical temperature ~ 150 MeV. At higher baryon density, the transition is believed to be first order. [57]	13
1.9	History of the Universe. The universe was in a QGP phase about $10 \mu s$ after the big bang.	14

1.10	The ratio R_{AA} (The ratio of the yields between p+p and Au+Au after the correction for the number of binary collisions) for charged hadrons and neutral pions [6]	16
1.11	Data from STAR shows the angular correlations between high transverse momentum particles. Compared with p+p collisions, the recoil peak becomes broader for dAu and disappears for Au+Au [8]	16
1.12	Elliptic flow as a function of transverse momentum for minimum bias events in Au+Au collisions at 130 GeV CM [3]	17
1.13	The nuclear modification factors of π^0 , η , and γ . The π^0 and η are heavy suppressed, whereas the γ is not.	18
1.14	The figure is from [75]. The data (circled) comes from STAR [2]. The color lines are hydrodynamic models with different η/s (η is the shear viscosity and s is the entropy density). All these models are based on Glauber-type initial conditions. The relevant data are the open circles, non-flow corrected.	20
1.15	Left plot: The PDFs as a function of x for gluons, valence quarks and sea quarks at $Q^2=10 \text{ GeV}^2$ as measured at HERA. Note the gluon and sea quark has been reduced by a factor of 20. At low x , gluons will dominate in the proton [51]. Right plot: cartoon of the phase diagram for the parton evolution in QCD. Each colored blob represents a parton with the transverse area $1/Q^2$ and longitudinal momentum $k_z = xP$. Q_s is the saturation scale [60]. $\lambda \approx 0.3$ is obtained from HERA Deep Inelastic Scattering data. From left to right, as Q^2 increases, the system becomes more dilute. From bottom to top, as the x decreases, the system becomes more crowded and finally gets saturated.	21
1.16	R_{d+Au} as a function of pT for central and forward pseudorapidities. The data is from BRAHMS for d+Au collisions at 200GeV [17]	25
1.17	The relative yield, J_{dA} , of correlated back-to-back hadron pairs compared to p+p collisions, in central (0-20%) and peripheral (60-88% in d+Au 200GeV collision. [10]	26
1.18	Two particle correlation at forward rapidity [23]	27
1.19	The gluons nuclear modification factor[37]. The uncertainty of lower Q^2 and x is huge.	28
1.20	The left plot shows an interaction in a proton-proton collision. E is the energy. p_x and p_y are zero. The right plot shows the coordinate system. The z -axis is the beam direction. The transverse momentum ($p_T = \sqrt{p_x^2 + p_y^2}$) is in the x - y plane. The azimuthal angle ϕ is the angle between the projection on the x - z plane and the x -axis. The polar angle θ is with respect to the z -axis.	31
2.1	RHIC is composed of a “chain” of the particle accelerators, starting with the Electron Beam Ion Source . The beam is then injected into the booster , then the Alternating Gradient Synchrotron , and finally to the main machine, RHIC . The beam gets accelerated at each step. The final focusing and collisions occur at the interactions regions in RHIC. (The image comes from https://science.osti.gov/np/Facilities/User-Facilities/RHIC)	35

2.2	An 3-D overview of PHENIX detector. The MPC-EX and the MPC are not shown in this view, since they are buried in the Magnet. The beams come from the left and right.	38
2.3	Top: Beam view of the PHENIX detector showing the central arms. The MPC (not labeled) and the MPC-EX are behind the BBC. Central arm detectors provide the tracking, particle identification, and energy/momentum measurement of the particles. Bottom: Side view of the PHENIX detector showing the Muon Arms. The MuTr, MuID provide detection for muons. The MPC (not shown, behind the MPC-EX) measures the energy of showers. The BBC provides centrality information and is the primary trigger detector. The (F)VTX provides tracking information in the high rapidity region. . .	39
2.4	Left picture: The BBC has 64 elements each for both North and South Arms. Right picture: each element consists of quartz Cherenkov radiator and meshed dynode PMT [81]	40
2.5	Top left: PMT array for both north and south showing the 64 elements. Top right: The BBC after installation. Bottom: How the Z-vertex of an event is measured using the BBC. The Z-vertex can be calculated by $z_{vertex} = (T_S - T_N)/2 \times c$ and the time zero $t_0 = (T_S + T_N - 2L/c)/2$, where c is the speed of light, L is 144.35cm, and $T_S(T_N)$ is the travel time particles to reach South(North) BBC from the collision point.[81]	41
2.6	The location of ZDC. After the collision, bunches are steered by the magnetic field, while neutrons travel in a straight line and are detected by the ZDC. .	41
2.7	The structure of the FVTX+VTX system. The top left picture is the FVTX detector, and the top right picture is the silicon vertex tracker (Tracker). The FVTX consists of two angular endcaps, each with four stations of silicon mini-strip sensors, and covers the rapidity range of $1.2 < \eta < 2.2$. There are two arms. Each arm has four disks, and each disk has 48 wedges. The size of a strip is about 2.8 - 11.2 mm long and 75 μm width. There are 1.1 million channels in total.[36]	45
2.8	3D model of MPC-EX and MPC [26]. The collision vertex is on the right. Incoming photons from the vertex enter the MPC-EX from right to left. . .	46
2.9	An overview of data flow in the data acquisition system for PHENIX[88] Data flows from the Detectors into Front End Modules (FEM), which are then read out by the Data Collection Modules (DCM). The data is passed on to the Sub-Event Buffers, which can hold several events in memory. The data is then passed through the Gigabit Switch, and Assembled in the Assembly Trigger Processor (ATP). Fully assembled events are then passed to the buffer boxes, which hold the data until it can be relayed to the RHIC Computing Facility	47
2.10	An HPSS-based tape robot system showing the tapes, and the robot in the foreground.	49
2.11	PHENIX Trigger System as explained in the text[20].	50
2.12	FVTX trigger definition for sectors, cages, and arms.	53

3.1	The location of MPC and MPC-EX in the PHENIX detector system (red circles).	55
3.2	The mechanical design of MPC [69]. The collision vertex is towards the bottom right. Particles travel from the collision through the APD readout electronics (Driver board, Frontplate, APD, preamp) and into the crystals where they are detected. The probability of interacting with the electronics is small.	57
3.3	Top: the $PbWO_4$ crystal. The length of the crystal is 18cm or about 7 inches (the ruler shown in the picture is in inches). Bottom: An avalanche photodetector (left photo) mounted on the preamp electronics board. The right photo shows the flip slide of the electronics board. [69]	58
3.4	The basic MPC tower structure.(1)the APD and preamp (2)the aluminum APD holder (3) the $PbWO_4$ crystal [69]	58
3.5	MPC-EX sensor and dual SVX4 readout card, where the pattern of the minipads on the silicon sensor is shown in the upper right, and the readout card is shown on the bottom right. The minipad sensor connections are made at the top of the board, through a set of decoupling capacitor arrays, and then into the SVX4 ASICs.	61
3.6	Top: A half layer of the MPC-EX(One layer consists of a sensor, readout card, carrier board, and the 2mm tungsten). Bottom: Minipad stack up on carrier board.	62
3.7	A high-energy π^0 decay into two photons. The two photons are so close that they merge into one shower in MPC. But with the MPC-EX, we can detect the separation of the two photons, as shown with the red dots.	63
3.8	Left: the whole MPC-EX. Right: a cross-sectional view. The X-Y style makes the resolution 2mm. There are 24576 minpads per arm.	63
3.9	A picture of the MPC-EX installed in PHENIX. The space in PHENIX is limited, which is why a compact detector design was needed.	64
3.10	The readout and control system of MPC-EX. The Data from MPC-EX goes to the FEM and is transformed into standard packets. The Ras-Pi is the micro-computer used to control the FEM. The GTM provides the global timing. The blue line is the optical fiber connecting to the DCM	65
3.11	The setup for the Fermilab test beam. During the test, a 5x5 array of MPC towers was tested. Varying thicknesses of tungsten were placed just in front of the array inside the light box.	67
3.12	The tracking system for the Fermilab test. The tungsten is placed at the front of the towers array (about 5cm away). The MWPCs provided the hit position on MPC towers. The active area of the tracking chambers was 20.3cm×20.3 cm. d1=301.8cm and d2=175.3cm.	68
3.13	The signal of a MIP for one channel (ADC crystal) in the Fermilab test. The prominent peak at zero is the pedestal. The first peak is fit by Gaussian, and the second peak is fit by Landau.	69

3.14	The energy deposited in a 3x3 array of towers by a 16 GeV electron beam for different thicknesses of tungsten. Since the beam loses energy when passing through the tungsten, the smearing effect becomes more significant as thickness increases.	70
3.15	Energy fraction vs. radius when a tungsten plate of thickness 0 mm, 8 mm, and 17 mm are placed in front of the MPC	70
3.16	The integrated scintillator signal energy distribution. One electron, two electrons, and three electrons events are clearly seen.	72
3.17	The SLAC test beam layout	73
3.18	A two electron event in the MPC-EX and MPC. Top: MPC-EX (The units in x and y are in cm and the color scheme represents the energy deposited in a minipad. The 8 panels correspond to the 8 layers of the MPC-EX. One can clearly see the development of the shower. The two showers are clearly distinguishable. Bottom: the 5x5 tower array (units along the x and y axis are μm and the color scheme represents the energy). In the MPC, only one shower is seen corresponding to the overlap of the showers from the two electrons.	74
3.19	A high gain channel ADC distribution and the five regions chosen for integrating the number of hits.	79
3.20	Left: the integral value in region one before the first pass. Right: after the first pass. The new key is ordered by row, sensor, layer, and arm. Note the scale of the y-axis.	81
3.21	Integrated hits of layer 0 in region 1, where each entry is one minipad. Smaller distances from the beam pipe have minipads covering a larger rapidity and phi-angle range. Deviations from the expectation can be seen	82
3.22	Integrated hits of layer 0 in region 1, where each entry is one minipad. Smaller distances from the beam pipe have minipads covering a larger rapidity and phi-angle range. After the two passes, the bad channels in the previous figure are gone.	83
3.23	Left: Run dependence of dead/hot channels for high gain. The number of dead/hot channels is quite stable. Right: Run dependence of dead/hot channels for low gain. The number of dead/hot channels is quite stable. . .	84
3.24	Left: The frequency of dead/hot high gain channels for the 44 groups where the X-axis stands for how many times the channel is identified as bad and the Y-axis is the number of the channel. Only channels which are identified at least once are in the plot. The straight line gives the boundary for dead/hot channels:27. Right: similar plot for the low gain.	85
3.25	One discrete channel, which is not identified as dead/hot previously. The blue line shows reference from distributions from neighboring channels, and the red is a discrete channel.	86
3.26	Top: Histogram of hits of the high gain channels in one sensor before any cuts. There are four rows in one sensor. One can see the variation across a row. Bottom: Histogram of hits in the high gain channels of one sensor after the first two passes of cuts discussed above. Some good channels are cut out.	89

3.27	Marked channels are different from their surrounding channels. The problem is that the RMS in these groups is large (as a result of the marked channels), so these channels are still within the 3-RMS limits.	90
3.28	Using the quadratic polynomial to fit the pattern. The difficult to identify deadhot channels can be easily found.	91
3.29	Sensor low gain ADC vs. Key (ordered by row) of North Arm Layer 1 of dAu 39 GeV: state phase = 43 cut is not applied. The corrupted pattern can be seen in many sensors. Examples are circled.	92
3.30	Sensor low gain ADC vs. Key (ordered by row) of North Arm Layer 1 of dAu 39 GeV: state phase = 43 cut is applied. The corrupted pattern is gone.	93
3.31	MPC-EX Hit distribution of North Arm(dAu200GeV): Some minipads (red) are still hot compared to others.	94
3.32	MPC-EX Hit distribution of North Arm(dAu200GeV) after new bad minipads are masked out	94
3.33	The linear relationship between high gain and low gain for one minipad - which we designate by a hardware key of 48458.	95
3.34	Left: low vs. high. Right: high vs. low. The Profile histogram of high vs. low is linear due to the nature of the Profile histogram, while the inverse is not. Hence the low vs. high will be fit in this analysis	96
3.35	Fits to the slope in various ranges of the Low to High Profile histogram as compared to reference values where a fit was done between 50 ad 150. Figures a and d show rather large variation. Hence the range 50-150 was chosen.	97
3.36	Plots show the fits for two keys (minipads) of the low and high ranges where deviations from the fits in the comparison range were the largest.	98
3.37	An example of a channel (key=1926) with multiple (split) High/low ratios.	99
3.38	The TSpectrum peaks found for the high/low histogram for the channel with key= 1926	100
3.39	The top is the south arm, and the bottom is the north arm. From left to right are Chi2/NDF of the low to ligh Ratio, low high ratio, and intercept.	101
3.40	Slope difference when compared to the reference for the South arm. The difference of the last group is a little more significant; however, the change is less than 5% with a mean difference of 1%.	102
3.41	Slope difference when compared to the reference for the North arm.	103
3.42	For the Minipad 24001, the split ratio causes a small change in the low-high ratio.	104
3.43	Left: high gain vs. Low gain for Minipad 3585. The orange line shows the perpendicular line along which the distance to the fit line can be calculated. Right: The distance from the point to the fit line (key 3585 from high gain ADC 50 to 150). By fitting with Gaussian, we can extract the width(sigma) of the L/H ratio. Note that the units of the x-axis are in ADC counts.	105
3.44	Plots of the means of fits as in the previous figure. There is one entry per minipad. A cut is made for minipads with entries further than 0.2 away from zero, as shown by the red lines. Note that the units of this plot are in ADC counts.	106

3.45	An example which illustrates the 5 sigma cut which eliminates split ratios. The cut is indicated with the orange envelope.	106
3.46	Plots of the high vs. low gain ADC recalibrated to energy for showers. Only hits with a distance in Hough space within 1/2 RMS (upper left) and 1 RMS (upper right) are plotted. The lower plot shows all points with no cut. Hits closer to the shower center have fewer hits with a spurious H/L ratio. Note that this plot is in keV, and where the effect of a saturated high gain ADC is important	108
3.47	Similar plots as the figure 3.46 but where the ADC has not been scaled to keV. This minimizes the effect of the saturated high gain ADC. Hits closer to the center of showers have fewer spurious hits with bad H/L ratios	109
3.48	The difference of slope and intercept of dAu62GeV compared with dAu200GeV.	109
3.49	The difference of slope and intercept of dAu39GeV compared with dAu200GeV.	110
3.50	The difference of slope of dAu20GeV compared with dAu200GeV.	110
3.51	The difference of intercept of dAu20GeV compared with dAu200GeV. . . .	110
3.52	The fit most probable ADC value (black), and width (red). The layers go from right to left, with layer-0 to the left, and separated by a red vertical line - layer 1, continuing to layer-7.	112
3.53	MIP value for all minipads, obtained after the second fit, showing the minipad by minipad deviations after rescaling to the sensor ADC MIP value.	112
3.54	Top: MIP fit to the ADC distribution for all minipads for an example sensor. Bottom: MIP fit to the ADC distribution for one particular minipad.	113
3.55	An example of sensor fitting for dAu39GeV	115
3.56	An example of minipad fitting for dAu62GeV	116
3.57	Distribution of run averaged scaled MIPs (deviation) for all minipads in 62GeV after rescaling all minipads for the sensor ADC MIP.	116
3.58	Distribution of run averaged scaled MIPs (deviation) for all minipads in 39GeV after rescaling all minipads for the sensor ADC MIP.	117
3.59	Distribution of run averaged scaled MIPs (deviation) for all minipads in 20GeV after rescaling all minipads for the sensor ADC MIP.	118
3.60	MPC tower energy distributions for BBC MB triggered events for a set of four the complementary towers in the north arm. Complementary towers, are towers in the same positions in each of four quadrants relative to the center of the MPC. The four complementary towers are in black, blue, red and green. The curve from a simulation of deuteron gold events[53] is shown in orange. The gains of the towers have been adjusted to match the slopes and yields at 5GeV.	120
4.1	The true energy vs. reconstructed (predicted) energy of photon in Hijing simulation. A 4 GeV cut is applied on the MPC energy. Because of the threshold energy cut in the MPC during data taking, this is equivalent to requiring no energy in the real data. Only information from the MPC-EX is used.	124

4.2	An illustration of an MPC-EX shower from the two photon decay of a π^0 , in which the showers from the two photons will overlap in the MPC since the radius of a shower is larger than the lateral size of a block.	125
4.3	A neutral pion decay into two photons. By using the MPC-EX, we can measure the distance between the two photons.	127
4.4	An example of single track π^0 (simulation), where the information from the MPC-EX is projected into one plane. Black is the true position and red is the reconstructed position. The X and Y axis are in cm. Note that these two showers would be contained within one MPC tower (size: 2.2cm x 2.2cm) and could not be resolved without the granularity of the MPC-EX.	128
4.5	Projections of 2d hits of a simulated π^0 along the X axis (left) or Y axis (right). The black line(dotted line) is the true position, and red line(dotted line) indicates the reconstructed position.	129
4.6	The schema for adjacent minipads.	130
4.7	Top: The projection a shower using the TSpectrum algorithm. Bottom: the projection of the same shower using the minipad algorithm. The background of the minipad algorithm is smaller and the peaks are clearer.	131
4.8	The iteration process starting from a peak and including the surrounding hits until converging to form a mini-cluster. Color scheme: the higher the energy, the brighter the color.	132
4.9	A π^0 candidate from data: the circled are mini-clusters found by the Mini-Cluster Algorithm.	133
4.10	π^0 mass vs Energy (simulation). Left: the result of the TSpectrum algorithm. Right: the result from using the MiniCluster algorithm.	134
4.11	A π^0 candidate event(from data) develops in MPC-EX. The top figure shows the eight MPC-EX layers and the figure on the bottom right picture is the sum of the eight layers.	135
4.12	A 5x5 image convolved with a 3x3 matrix(filter). The stride is the number of pixels the filter shifts. The outcome is the convolved feature matrix. The size and the value of the matrix are just examples. The next step would be to shift the filter by the stride=1. In the case of this illustration, that would give a 3 in the space to the right of the 4 in the right hand figure.	136
4.13	This picture shows how filters work. The first type is the identity filter. When acting on the image, the image stays the same. The second type is the edge filter. After using this type of filter, the edges of the image become more clear. The last one is the style filter which makes the image sharper. Each time a filter is used, an additional image layer is added. The values of the filters are just examples. The values in the filters are parameters that are set during the training of the machine learning algorithm.	137
4.14	There are many functions that are used as non-linear transformations. In this work, only the ReLU and Sigmoid are used. ReLU makes the training process faster, and Sigmoid provides the outcome between 0 and 1 used in last the layer, interpreted as a probability. In this study, it is the π^0 probability.	138

4.15	Value zeros are padded outside the image matrix. The padding layer, constrains the various CNN layers, to prevent non-zero values from extending beyond the actual image.	138
4.16	Max pooling layer: the image group is divided into 2x2 array groups. For each group, the maximum value is selected. Ungrouped pixels are ignored. .	139
4.17	The CNN model for MPC-EX. The inputs are 64x64x8 arrays formed in the following way. A 6 cm x 6 cm region centered around each shower is chosen. Each shower layer is represented by a 64x64 array, where each element in the array is a 2mmx2mm “pixel”. Each minipad is actually 8 such pixels. If a minipad is hit, array elements for all 8 pixels will be filled with the value for the energy deposited in the minipad (each minipad is about 16mm x 2 mm). Each layer of the detector for a particular shower will correspond to such an array, so the shower will be represented by a 64x64x8 array. It undergoes 6 layers of convolution and becomes a vector of size 512. This vector is the representation of the image and is passed to a four layer fully connected neural network. The final outcome is one number which is interpreted as π^0 probability.	141
4.18	The left plots show distributions of the signal and the right ones are background. The top two figures are the true energy distribution and the bottom two are the mass distribution.	142
4.19	The left figure is the result for the test dataset (this subset is not used in the training). The background and signal are well separated. If we use the 0.5 as the threshold, then the accuracy is 87%. The right figure is the result of HIJING simulation. The model is trained on the embedded data, and now works very well in simulation: the signal is enhanced, while the background is suppressed	144
4.20	The left plot is the π^0 mass when requiring the probability>0.75 showing the agreement between the data and simulation. The red is the HIJING simulation and the blue is the data. The right figure compares the mass distribution before and after a cut where the probability>0.75. The mass distribution improves significantly.	144
4.21	The hit pattern of the projection of minipads. Left: Data. Right: HIJING simulation. Top: low probability (bad) π^0 . Bottom: high probability (good) π^0 . The figures with a high probability of being π^0 s have two clear peaks while the others do not.	145
4.22	The signal(Red) and mix background(Blue) of two-track π^0 s (dAu200GeV). The normalization point is from 0.35GeV to 0.4GeV.	149
4.23	The background subtracted two-track invariant mass for different bins of p_T . The red curve is a Gaussian fit of the peak. The mass peak shifts to right as the p_T increases, as discussed in the text.	149
4.24	π^0 mass peak vs. p_T at 200GeV. HIJING Simulation and data have similar trends. The 4 GeV cut on the MPC tower is to mimic the low gain and threshold cut of the MPC as described in previous chapter.	150

4.25	The raw π^0 p_T spectrum. The counts are integrated from a region $\pm 3\sigma$ around the mean value (see Figure 4.23	150
4.26	A schematic representation of nuclei in the Glauber model. $\vec{b}$ is the impact parameter, which is the vector from the center of the projectile B to the center of the target A. $\vec{s}$ is the displacement to the center of the target A in x-y plane. $\vec{s} - \vec{b}$ is the displacement to the center of the projectile B. . . .	152
4.27	A cartoon showing the definition of centrality [27] and its connection to particle multiplicity. The X-axis is the yield of particles in a given detector. The Y-axis is the corresponding cross-section, which can be interpreted as the probability. From left to right, the collision goes from the peripheral to head-on.	156
4.28	Top: the Glauber+NBD fitting to the dAu200 data (open circles). The black curve is the Glauber+NBD. simulation. The centrality ranges from right to left are 0%-20%(red), 20%-40%(green), 40%-60%(blue) and 60%-88%(yellow). Since the detector is not fully efficient, especially in the low multiplicity region, we cannot reach 100% centrality. Bottom: the ratio of data and Glauber+NBD simulation giving the trigger efficiency of the BBC. The integration of the ratio is 88.8% . Hence the total efficiency of BBC is 88.8%.	157
4.29	The number of binary collisions (N_{coll}) for different centralities.	158
4.30	The left plot shows the BBC trigger efficiency vs. the impact parameter at different energies[80]. Except for the 200GeV, the efficiencies are below 100%. The right plot shows the ratio of triggers in the BBC and FVTX at 62 GeV in data and an AMPT simulation. The data matches simulation. . .	160
4.31	The Glauber+NBD fit to the low energies data. The left is the 62GeV. The centrality ranges from left to right are 60% - 78%, 40% - 60%, 20% - 40%, 0% - 20%. The right plot is the 39Gev. The centrality ranges are similar to 62Gev, except for the first one: 60% - 74%.	160
4.32	N_{ncoll} uncertainties in dAu200GeV. The X-axis is the centrality range and the Y-axis is the deviation. The z-axis is in arbitrary units given by the color	162
4.33	The comparison between the rescaled BBC south arm charges and the number of particles passing through the BBC south arm in HIJING. For 62GeV and 39GeV, they have a good agreement. For the 200GeV, the agreement is poor at a higher BBC charge, as explained in the text.	164
4.34	Results using the NBD+Glauber method on the HIJING simulation. The different colors are corresponding to different centrality ranges 0-20%(red), 20-40%(green), 40-60%(blue) 60-max(yellow), where max is 88% for the 200 GeV data, 78% for the 62 GeV data and 74% for the 39 GeV data . The bottom is the trigger efficiency curve. The open circles are the ratio of HIJING BBC particle yields to yields using the NBD+Glauber method on HIJING events. The blue line is the trigger turn on curve, which is a fit to the open circles.	165

4.35	The left plot shows N_{coll} from the HIJING directly (62GeV). The right plot shows N_{coll} extracted by the Glauber+NBD. They are quite similar. The difference gives the bias factor.	166
4.36	The embedding efficiencies of central and peripheral collisions in dAu200GeV.	169
4.37	The number of hits in the MPC-EX north arm. The red is the central collision and the blue is the peripheral collision.	169
4.38	The p_T spectra of dAu200GeV, dAu62GeV, and dAu39GeV. The right plot is the spectrum with the bias corrected. The bias effect is small and spectrum almost stay the same. The green systematic error	171
4.39	The R_{cp} of dAu200. The green is the systematic error	171
5.1	The Red is the R_{cp} from this thesis. The black is R_{dAu} from STAR[4]. . . .	173
5.2	The STAR R_{dAu} compared with several models, described in the text. . . .	174

List of Tables

1.1	Some useful conversion factors	29
3.1	Properties of $PbWO_4$	56
3.2	The effect of MPC-EX on MPC	69
3.3	Summary of number of dead/hot channels.	88
4.1	The detailed structure of the CNN model. Dropout is a method used to avoid overtraining. The number of the total training parameters is 1,195,569 . . .	140
4.2	AMPT simulation of the BBC and FVTX efficiency for minimum bias and central events [80].	160
4.3	N_{coll} and uncertainty for different energies	163
4.4	Bias factor of N_{coll} at different energies.	166
4.5	The systematic error of 200GeV, 62GeV and 39GeV.	168

Chapter 1

Introduction

All things on earth, including humans, are made of atoms. However, atoms are not elementary. They consist of electrons, protons, and neutrons. The electron is elementary since there is no evidence indicating it has a substructure. The proton and neutron, however, do have substructures. As we probe shorter distance scales by colliding particles at high energies, we find that the proton and neutron can be decomposed into more elementary particles: quarks. The properties of quarks are very different in that they cannot exist as single particles in nature, but are confined in protons and neutrons (nucleons) and other particles - the mesons. The quarks are held together by gluons which are the force carriers of the strong interaction. Scientists have found, however, that quarks can roam freely over larger volumes in a new form of matter, the quark-gluon plasma (QGP). The QGP is a state of nuclear matter in which the quarks are freed from their confinement into nucleons and mesons. The properties of the QGP are different than expected. When the existence of the QGP was first conjectured, it was hypothesized to behave like a gas. One of the

surprises was that contrary to expectations [52], it behaved as a strongly interacting fluid [52]. A key to understanding this is to understand the initial state from which the QGP is born. This initial state is the topic of this thesis.

1.1 Quarks

The hint of the proton's substructure comes from the elastic scattering experiments [77] similar to the famous Rutherford experiment [94] in which the atom was shown to be composed of a hard central nucleus surrounded by electrons. Figure 1.1 shows the result of the elastic scattering of a probe particle on an atom and on a proton. The similarity between them indicates the proton itself is like an atom - it has a substructure. From 1967 to 1973, a series of inelastic electron and nucleon scattering experiments were conducted at Stanford Linear Accelerator Center(SLAC), which provided evidence of point-like particles, which we call quarks, inside the proton [22].

Three generations (six quarks, with two quarks per generation) have been discovered (figure 1.2). The type of quark is called flavor. The classification of the generations is based on the mass. The first generation consists of up and down quarks, which make up the proton and neutron. The masses of the up and down quarks are small: 2.3 MeV for the up quark and 4.8 MeV for the down quark. The masses increase for the second generation. For example, the mass of the charmed quark is 1270 MeV and 101 MeV for the strange quark. The last generation has the largest mass: 172 GeV for the top quark and 4.19 GeV for the bottom quark.

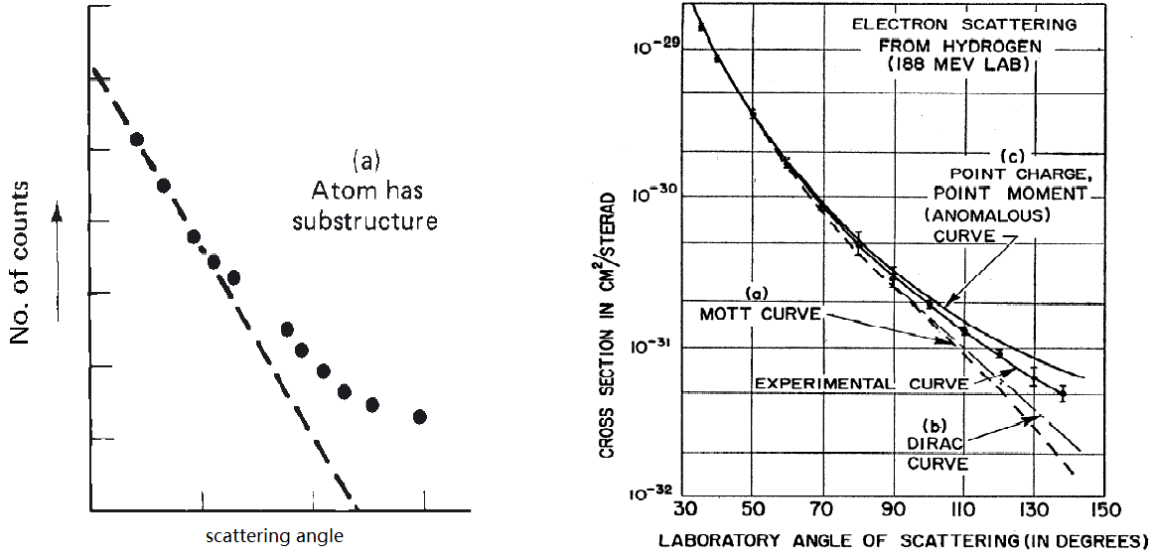


Figure 1.1: The left figure shows the result of atom scattering, while the right figure shows the result of proton scattering. The departure of the experimental data from an exponential indicates substructure.

Figure 1.2 also shows the charges of the quarks. It is fractional, which is a little strange since the charge we encounter is always an integer. Combining these six quarks is not arbitrary, and they follow strict rules (this is also why we don't see the fractional charge for the normal matter). For example, mesons are made of quark and anti-quark pairs. In the language of group theory, we can see how these quarks can be assembled to form the hadrons (mesons and baryons) that are familiar to us. We view u, d, s quarks as the eigenvectors in the fundamental representation of $SU(3)$ (3) and $\bar{u}, \bar{d}, \bar{s}$ (anti-particles) as the eigenvectors of the conjugate representation of $SU(3)$ (3^*). A meson built by one of u, d, s and the antiparticle is the irreducible representation of $3 \times 3 = 8 + 1$. The top left of figure 1.3 shows the common mesons ($K^0, K^+, K^-, \pi^0, \pi^-, \pi^+ \dots$) seen in experiments. The baryon made of three quarks can be built from $3 \times 3 \times 3 = 1 + 8 + 8 + 10$. The top right of figure 1.3 shows the octet of the irreducible representations, where one can see the familiar

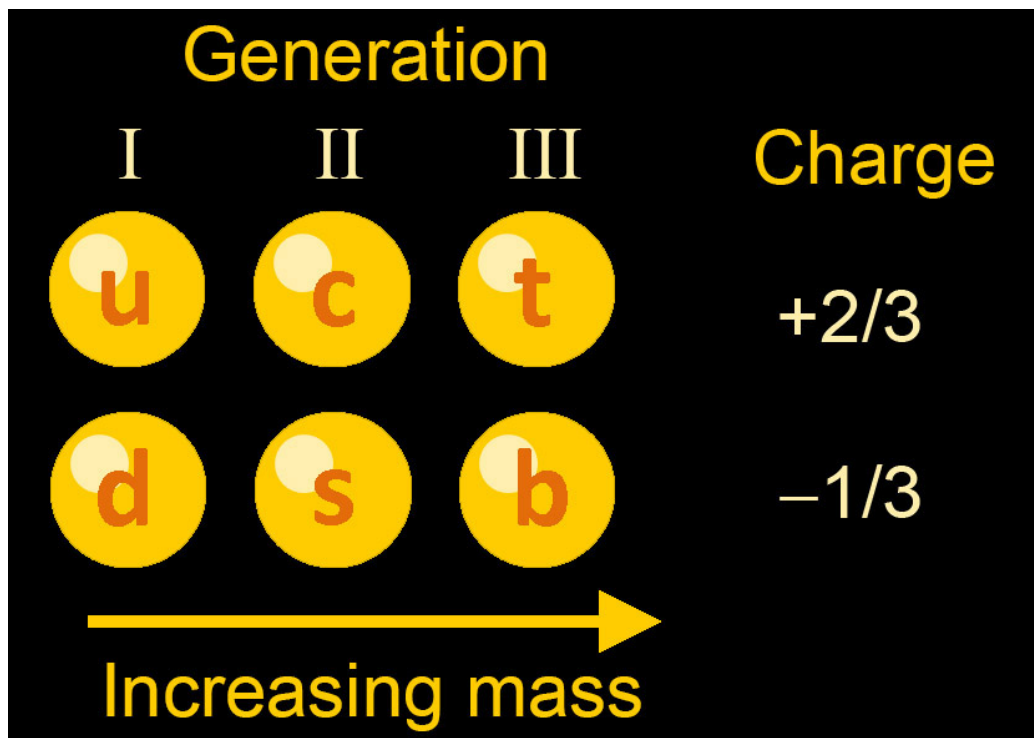


Figure 1.2: Three generations of quarks. From left to right, the mass increases. Up, charm, and top quarks have charge $+2/3e$ and down, strange, and bottom quarks have charges of $-1/3e$.

proton and neutron, and the bottom shows the decuplet. The remainder of the particles are less familiar, but all have been discovered. In this thesis, we are primarily interested in π^0 s. This way of grouping the hadrons is also called the Eightfold Way proposed by American physicist Murray Gell-Mann and Israeli physicist Yuval Ne'eman [42] [82]. The particles predicted by this theory all have integer charges, consistent with what we see in nature.

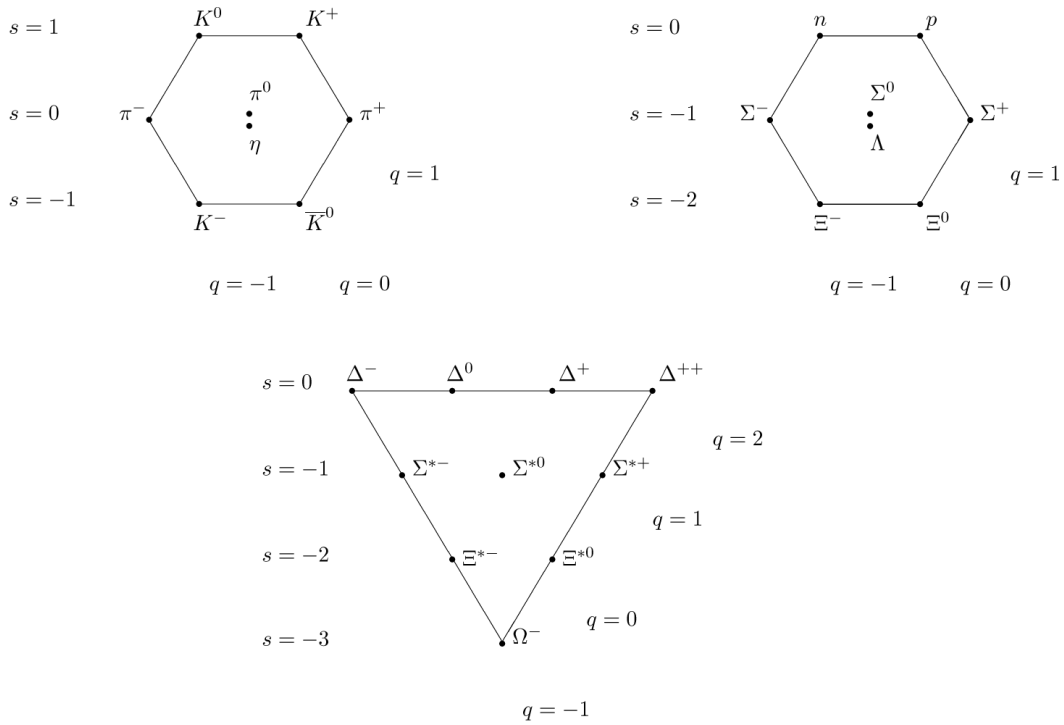


Figure 1.3: The Eightfold Way of grouping particles. [42] [82] Top left is the pseudo-scalar meson octet, top right is the baryon octet and bottom is the baryon decuplet.

1.2 QCD

Protons, neutrons, and all hadrons are made of quarks. The next question is how these quarks interact with each other. The answer is given by the theory of Quantum

Chromodynamics (QCD). The chromo here stands for the three colors: red, blue, and green (this has nothing to do with the ordinary colors). Color is a quantum number of the quark, which can be traced back to the discovery of the Ω^- . The Ω^- is a baryon composed of three strange quarks. Each quark carries a spin of either $+1/2$ or $-1/2$. No two quarks within a hadron can carry identical quantum numbers because of the Pauli exclusion principle. Having three strange quarks seemed to violate this principle, since two quarks could have opposite spins, but the third would have to have the same spin as one of the other quarks. The color quantum number is introduced to solve this problem. Color is similar to the charge in Quantum Electrodynamics (QED). One difference is that the color charges have three types, following the SU(3) symmetry. In QED (U(1)), the force between two charges is propagated by electromagnetic fields or photons. Similarly, for QCD, the force of the color charges is propagated by the color fields of gluons. The Lagrangian density of QCD [97] can be written as:

$$L = \sum_q \bar{\psi}_q^i (i\gamma^\mu) (D_\mu)_{ij} \psi_q^j - \sum_q m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} \quad (1.1)$$

Repeated indices in the expression are sum over. ψ_q^i is the quark field of q (flavor) with color i (red,blue,green). γ^μ is a Dirac matrix with μ being a Lorentz vector index. m_q denotes the quark mass. $F_{\mu\nu}^a$ is the gluon field strength tensor with the index a ($a = 1, 2, \dots, 8$). $F_{\mu\nu}^a$ is related to the gluon field (similar to the electromagnetic field in QED) by:

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f_{abc} A_\mu^b A_\nu^c \quad (1.2)$$

A_μ^a is the gluon field ($a = 1, 2, \dots, 8$). g_s is the strong coupling constant (related to α_s by $g_s^2 = 4\pi\alpha_s$). f_{abc} are the structure constants of SU(3) and the values are following:

1. $f_{123} = 1$
2. $f_{147} = f_{264} = f_{257} = f_{345} = \frac{1}{2}$
3. $f_{156} = f_{367} = -\frac{1}{2}$
4. $f_{458} = f_{678} = \frac{\sqrt{3}}{2}$
5. f_{abc} are antisymmetric in a,b and c. 0 for all others.

The structure constants define the representation of SU(3) by the following commutator relations:

$$t^a t^b - t^b t^a = [t^a, t^b] = i f^{abc} t_c \quad (1.3)$$

$$t^a = 1/2 \lambda^a \quad (1.4)$$

λ^a is hermitian and traceless Gell-Mann matrices of SU(3):

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad (1.5)$$

$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & -\frac{2}{\sqrt{3}} \end{pmatrix} \quad (1.6)$$

D_μ is the covariant derivative in QCD:

$$(D_\mu)_{ij} = \delta_{ij} \partial_\mu - i g_s t_{ij}^a A_\mu^a \quad (1.7)$$

One important feature is the evolution of the running coupling constant $\alpha_s(\frac{g^2}{4\pi})$, which is quite different from the α_{EM} in QED due to the non-Abelian nature of the SU(3)

group as shown in figure 1.4. This is a result of a crucial difference between Quantum-Electrodynamics (QED), which governs the electromagnetic interaction, and QCD. QED has one force carrier, the photon, which does not carry charges implying that photons do not interact with one another. QCD, however, has eight types of force carriers or gluons. These eight gluons do carry the color charge. Hence gluons can interact with one another. In QED, α_{EM} decreases with distance because of the charge screening, while in QCD, α_S increases with distance.

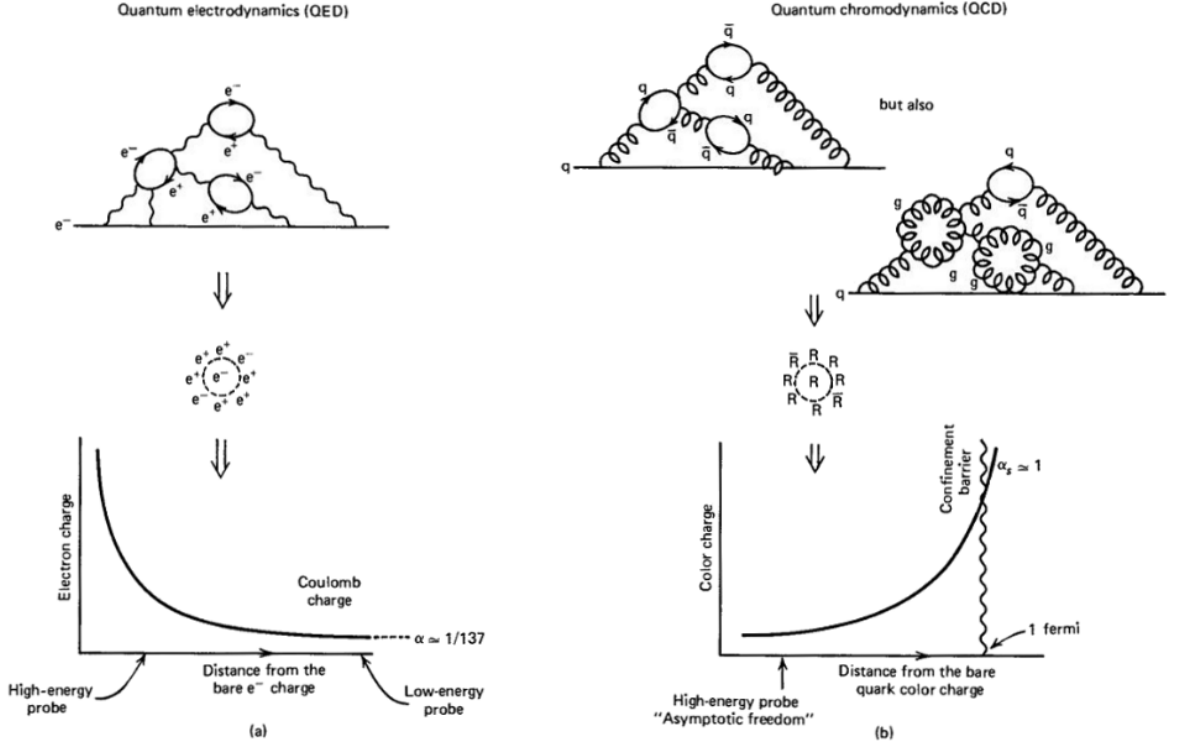


Figure 1.4: The coupling constant of QCD and QED. Left (QED): virtual photons split into electron, positron pairs, and the positron surrounds the electron. Hence, the electron is screened from far away, and the visible charge is smaller, making α smaller as the distance increases. Right(QCD): virtual gluons also split into quark, anti-quark pairs. However, gluons can also couple to each other and cause an anti-screen effect, making α_s larger as the distance increases. [39]

This picture of QCD leads to two important features of QCD. One is asymptotic freedom- at high energies or short distances, quarks and gluons interact weakly. Figure 1.5 shows the latest result of α_s as a function of energy scale Q . (The distance and energy are related via the Heisenberg Uncertainty principle.) As the energy increases or the distance decreases, the interaction becomes weak.

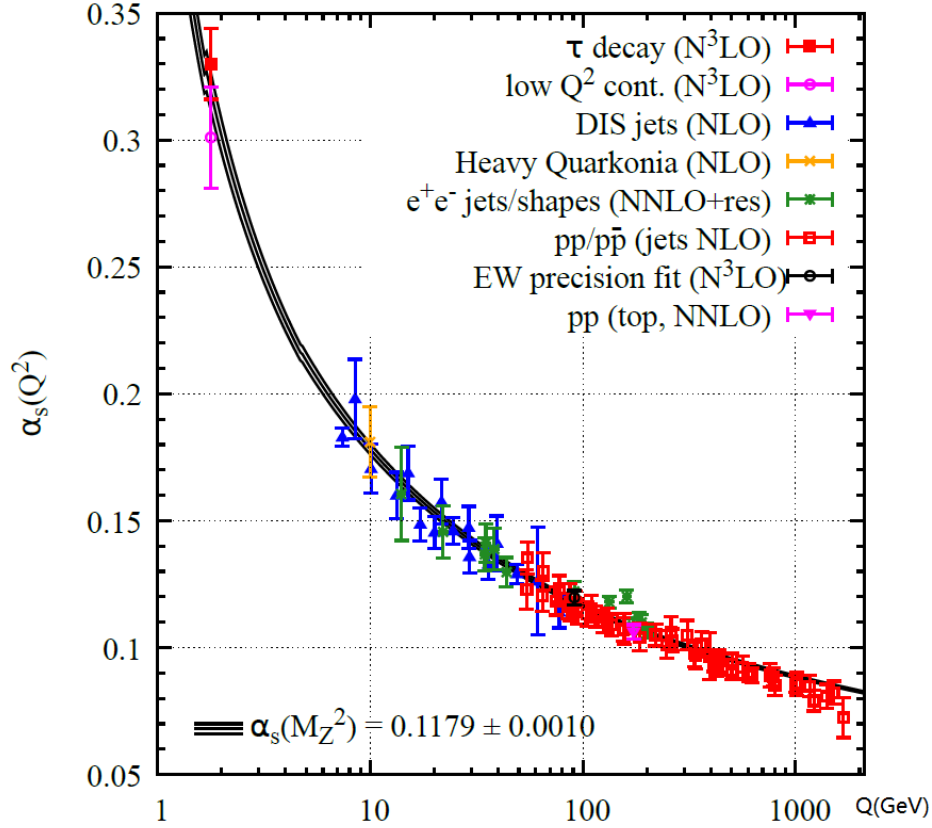


Figure 1.5: α_s as a function of energy scale Q . The different color data points show different experiments and methods to extract the α_s . [48]

The other is the color confinement - at lower energies or larger distances, the interaction becomes so huge that a colored particle (quarks or gluons) can not be isolated

under normal conditions (temperatures below two terakelvin, equivalent to a few hundred MeV) and thus can not be observed directly in experiments. This is because, in a non-Abelian group theory (like QCD) where the gluons attract each other, the force carriers - the gluons - form flux tubes at a larger distance. It is like a spring; the energy increases as they are pulled apart. At a certain range, a quark-antiquark pair will be created [1.6](#). Quarks and gluons must clump together to form hadrons. The distance scale at which this happens is $\sim 1\text{-}2$ femtometers, or equivalently a few hundred MeV, giving us the typical size of hadrons.

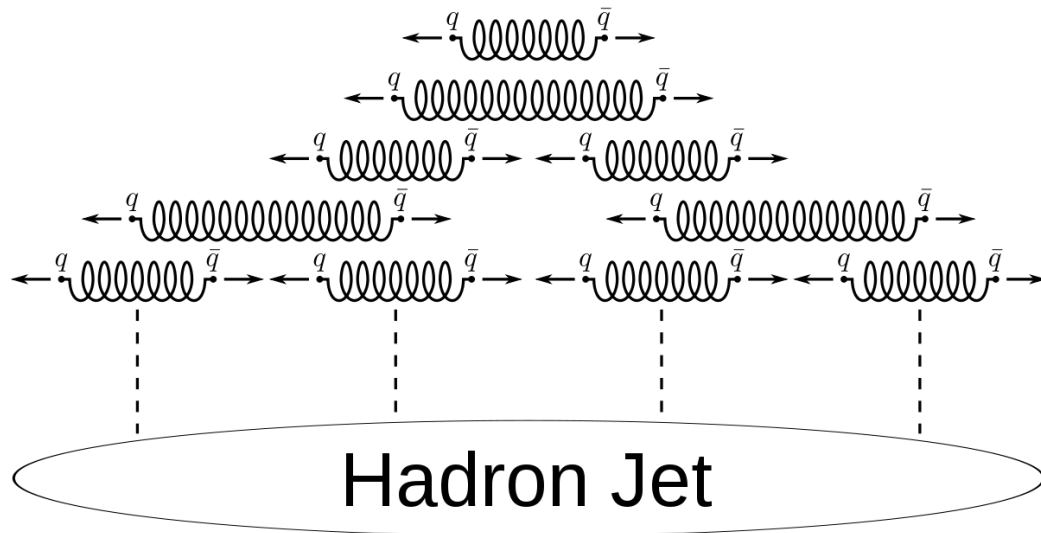


Figure 1.6: Color confinement: at a certain range, quark-antiquark pairs will be created. In the final state, all the particles are color neutral.

The large α_s in the low energy regime (normal conditions) makes QCD non-perturbative, making calculations very challenging. This limits our understanding of cold nuclear matter like protons. Current experimental results show that the proton is not simply composed of three quarks, but is a highly complex system: the uncertainty principle

allows virtual gluons to pop in and out of the vacuum inside the proton very quickly with a lifetime of about $\frac{\hbar}{\Delta E}$. The virtual gluon can further split into quark and anti-quark pairs (The inverse process can also happen). As a result, the primary quarks which make up the proton, which we call valence quarks, are embedded in a sea of quark anti-quark pairs and gluons.

1.3 Heavy Ion Collisions

The topic of this thesis is the study of the initial state of heavy-ion collisions. In this section, we introduce the stages of a heavy ion collision (figure 1.7) [60].

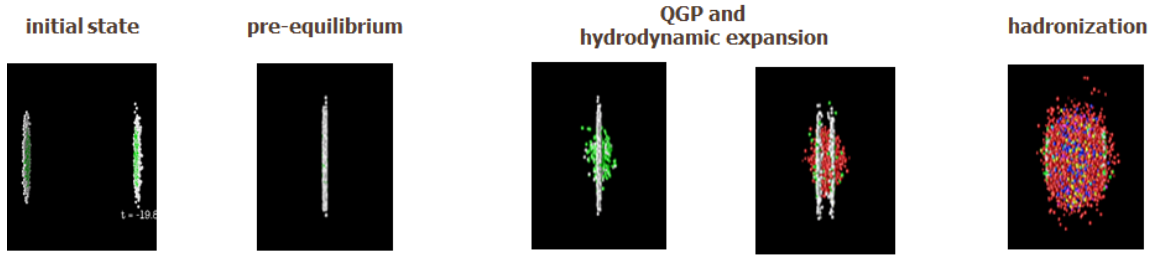


Figure 1.7: Stages of a heavy ion collision.

1. **Initial State:** In the center of the mass frame, the two colliding nuclei (Au at RHIC) look like two disks because of relativistic Lorentz contraction. At RHIC energies (200 GeV center-of-mass), the contraction is about 100 in the longitudinal direction. Since most outgoing particles from the collisions are soft, these particles are produced from gluons which carry a very small fraction of the total momentum (low- x gluons). Such gluons will play a central role in this thesis.

2. **Pre-Equilibrium:** The two disks hit each other, and the interaction begins. According to the uncertainty principle, the "hard particles" (like jets, direct photons, heavy flavor quarks, W, Z bosons, and so on) whose momentum transfer can be as large as 10 GeV, appear first. These particles compose the energetic objects in the final state. Later the bulk of partons which are constituents of colliding quarks and gluons at much lower energies, are liberated and are responsible for most of the particles we observe in the detector.
3. **QGP and Hydrodynamic Expansion:** Low energy partons, which were liberated in the pre-equilibrium stage, interact strongly with each other and evolve towards thermal equilibrium in a short time ~ 1 fm/c. Its temperature is a few hundred MeV, well above the critical temperature, $T_C \sim 150$ MeV/c, and a QGP is formed. The QGP will expand and cool.
4. **Hadronization:** The QGP continues to expand and cool back down to the critical temperature. The colored partons combine to form colorless hadrons. At this stage, the hadron density is high, and these hadrons interact with each other. However, as time goes on, the hot hadronic gas cools down until it freezes out so that is the hadrons stop interacting. These final state hadrons are the particles that are finally measured in the detector.

1.4 Quark Gluon Plasma

The Quark-Gluon Plasma (QGP) is a new hot dense state of matter composed of deconfined quarks and gluons created by the heavy-ion collision. Like ordinary matter, the

QGP also has different phases, as shown in figure 1.8. This matter corresponds to the state of the universe about $10\mu s$ of the Big Bang[95].

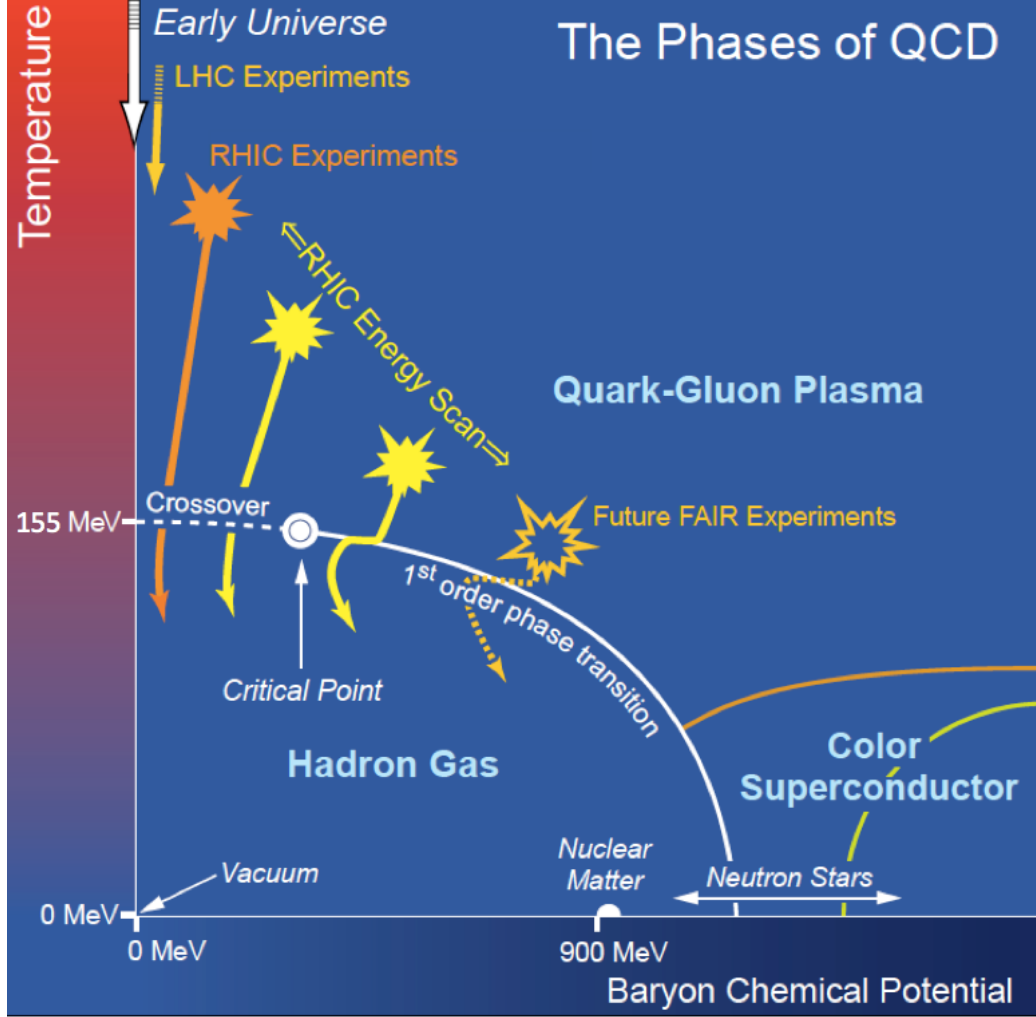


Figure 1.8: The phase transition diagram of QCD(nuclear) matter. The x-axis is the baryon chemical potential, which is the difference between the baryon density and anti-baryon density. The Y-axis is the temperature. If we increase the baryon density and keep the temperature low, we will go through the neutron star state. If we increase temperature and keep the baryon density low, we will go through the crossover transition to a QGP where quarks and gluons are deconfined from hadrons. This happens at about the critical temperature ~ 150 MeV. At higher baryon density, the transition is believed to be first order. [57]

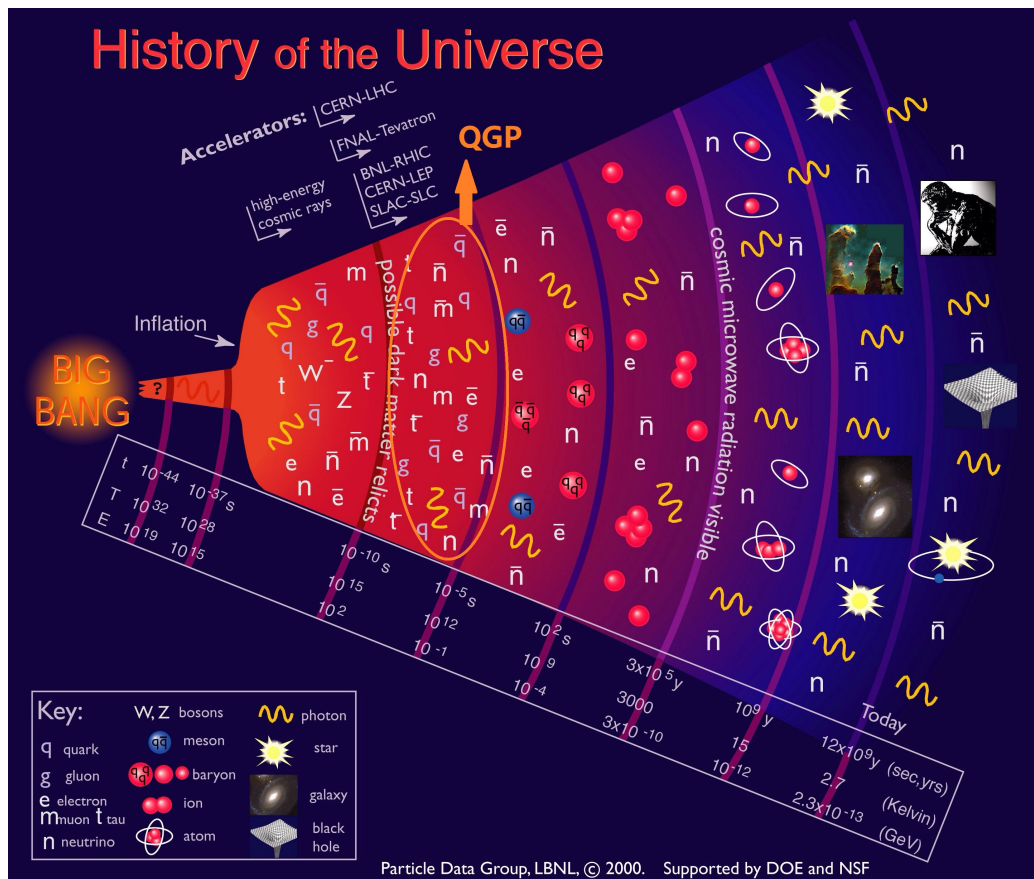


Figure 1.9: History of the Universe. The universe was in a QGP phase about $10 \mu\text{s}$ after the big bang.

There were several signatures seen in early RHIC experiments that convinced scientists that they had created the QGP. The first is jet quenching. When a quark or anti-quark is liberated in a proton-proton collision, it will leave the interaction region with the original energy at which it was created and form a jet of particles, as shown in figure 1.6. If, however, the quarks must traverse a QGP where the color charge is liberated, it will interact and lose energy to the QGP medium before emanating from the interaction region. Hence at particular energy or transverse momentum, the yields will decrease. Figure 1.10 shows a plot of R_{AA} , which is the ratio of the p_T spectrum of Au+Au collisions to the p_T spectrum p+p collisions after appropriate normalization for the difference in the number of initial nucleons in Au vs. p. If there is no suppression, i.e., no effect from a QGP, the ratio should be 1. However, one can see that R_{AA} is significantly below $1 \sim 0.25$. The suppression shows that the quarks interact with the QGP matter before combining into hadrons.

Figure 1.11 shows the angular correlations between high p_T particles. For p+p collisions, the back-to-back correlation peak is evident due to momentum conservation. But for the Au+Au collisions, the back-to-back peak is gone which means that one of the particles is absorbed by the QGP medium.

Later in the discussion of the Color Glass Condensate(CGC), a similar sign will be shown, attributing the suppression effect not to the QGP but to the suppression of gluons. It was important to physicists at the time to also make a comparison of R_{AA} directly in Au+Au collisions using a probe not affected by the strong interactions where R_{AA} should

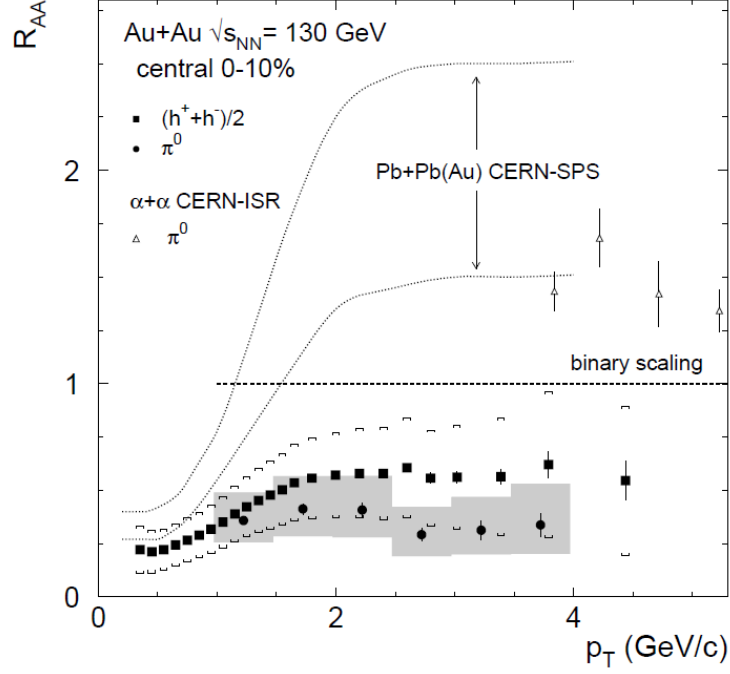


Figure 1.10: The ratio R_{AA} (The ratio of the yields between p+p and Au+Au after the correction for the number of binary collisions) for charged hadrons and neutral pions [6]

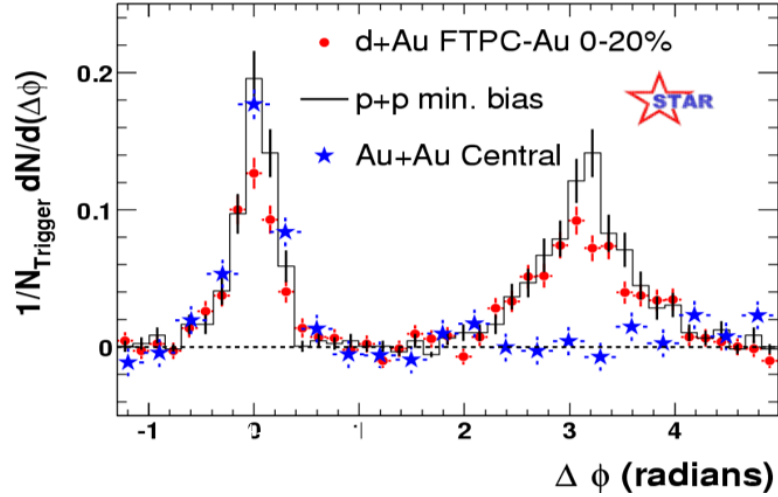


Figure 1.11: Data from STAR shows the angular correlations between high transverse momentum particles. Compared with p+p collisions, the recoil peak becomes broader for dAu and disappears for Au+Au [8]

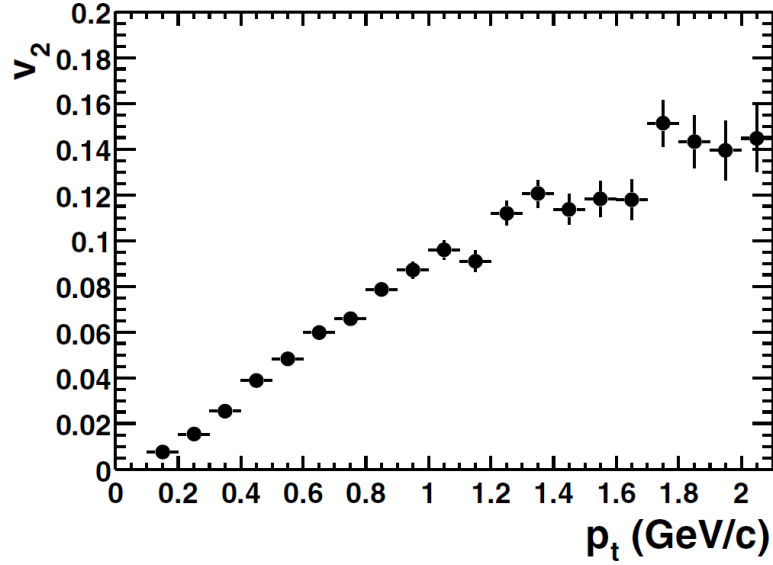


Figure 1.12: Elliptic flow as a function of transverse momentum for minimum bias events in Au+Au collisions at 130 GeV CM [3]

be unity since there would be essentially no energy loss to the QGP. The chosen probe was “direct” photons, that is, photons directly produced from the initial collision. Figure 1.13 shows the comparison of the suppression factor of direct photons with that of π^0 s, which are the result of quarks combining with each other during the freezeout process, showing that R_{AA} for direct photons ~ 1 but for the π^0 it is about 0.2. Note that the transverse momentum range is > 2.5 GeV/c, indicating that the quarks which formed the π^0 s were produced in the initial collision of partons early in the collision.

The second signature is the elliptic flow v_2 (shown in figure 1.12), which is a collective behavior of matter coming from the pressure gradients caused by the initial spatial anisotropy in non-central (non-head-on) collisions. The value of $v_2 > 0$ cannot be reproduced by theories in which the nucleon is modeled as a ball of individual nucleons but is

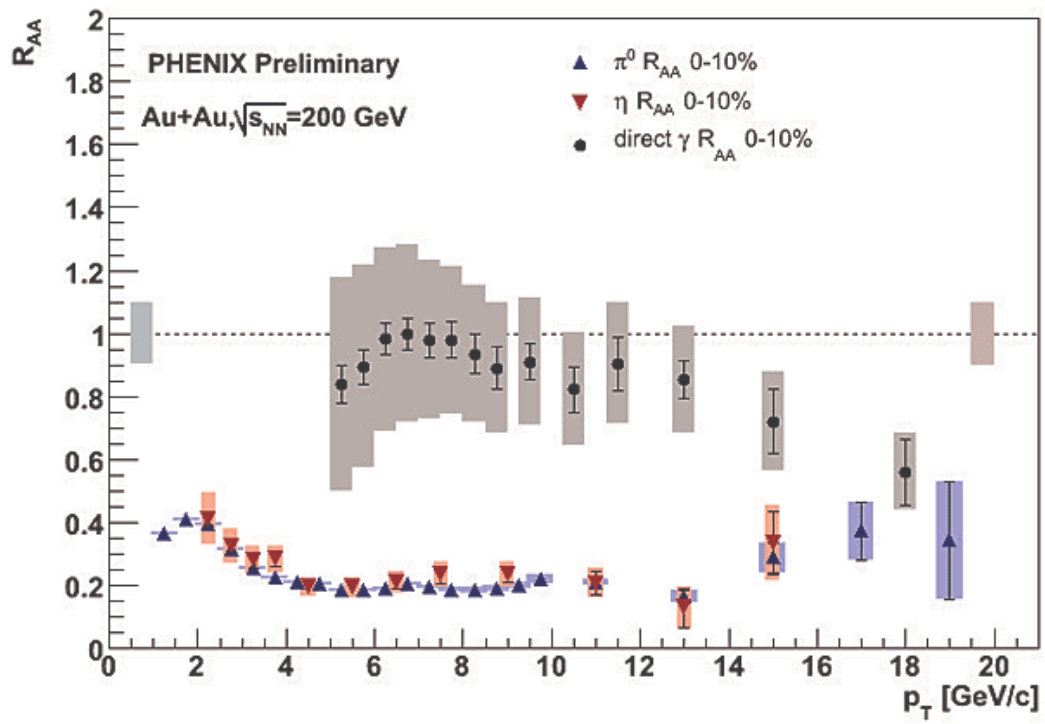


Figure 1.13: The nuclear modification factors of π^0 , η , and γ . The π^0 and η are heavy suppressed, whereas the γ is not.

consistent with hydrodynamic models, which assume that the medium is a QGP. This was also the first indication that the initial ideas about the QGP were wrong. The QGP turned out not to be like a gas but behaved more like a strongly interacting fluid.

One interesting property measured for the QGP is the ratio of shear viscosity to the entropy density characterizing how close the fluid is to a perfect liquid. Figure 1.14 shows the ratio is close to 0.08 (the quantum limit is $\frac{1}{4\pi}$) - the QGP is an almost ideal fluid and extremely strongly coupled.

This also indicates a major problem. The strong flow signal requires that equilibration happens in less than 1 fm/c. To reach equilibration, one side of the ball of matter must know what the other side is doing - this is what it means to be in equilibrium - all parts of the matter are behaving identically. The ball of QGP, is about the size of the initial nucleus or about 14 fm across. To reach equilibrium so rapidly, messages (or more to the point, waves) would have to propagate across the matter at several times the speed of light. To address this, it is crucial to understand the initial state.

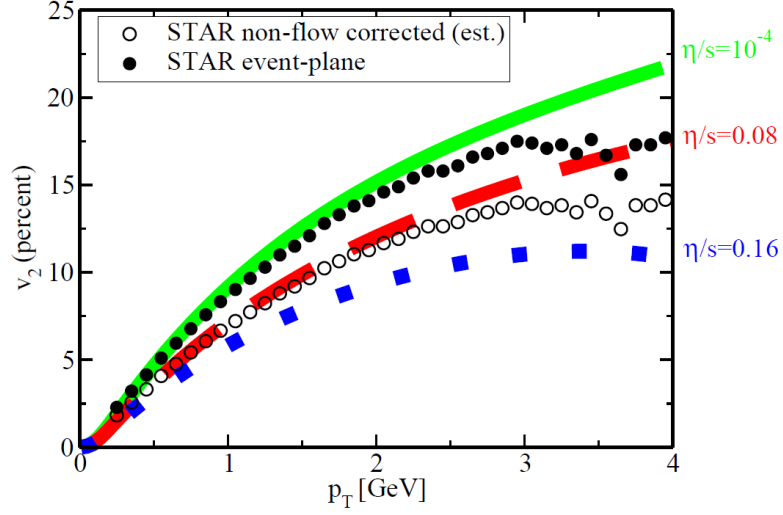


Figure 1.14: The figure is from [75]. The data (circled) comes from STAR [2]. The color lines are hydrodynamic models with different η/s (η is the shear viscosity and s is the entropy density). All these models are based on Glauber-type initial conditions. The relevant data are the open circles, non-flow corrected.

1.5 Initial State and Color Glass Condensate

The initial state refers to the state of the ions just before they interact with each other. A proton, as mentioned above, is a highly complex system and cannot be treated as just three quarks. The non-perturbative nature of QCD at low energy makes it challenging to calculate the proton's structure. To make predictions, we use the Parton Distribution functions (PDF) to represent the proton. The PDF is defined as the probability density to find a parton carrying a longitudinal momentum fraction x of the proton at an energy scale Q^2 (the negative square of the transfer momentum). The PDF cannot be obtained from perturbative QCD, where calculations are possible. Rather it is obtained from fitting measured data. With the PDF, the collision between the protons can be viewed as the interaction between single partons from each proton whose momentum distribution can be

described by the PDF as a function of x and Q^2 . The PDF of protons is reasonably well measured. The PDF of nucleons bound in a nucleus, however, is much less well known as it will be affected by other bound nucleons. The nuclear modification ratio, which is the ratio of the PDF in the nucleus to that in the proton, is used to describe its structure. This ratio is also gotten from fitting the data. Both the PDF and nuclear modification ratios are limited by the data used in the fits. A big uncertainty will be introduced if the range of Q^2 or x is beyond the data used to extract PDF or nuclear modification ratio. This method relies on using experimental input of PDF measurements and cannot be calculated from the first principles QCD theory. However, there is one situation in which we can calculate the initial state.

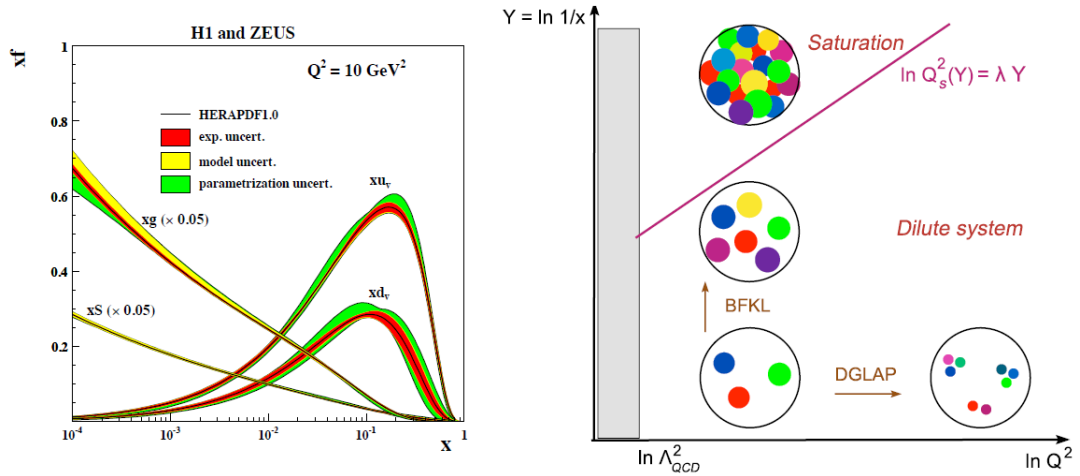


Figure 1.15: Left plot: The PDFs as a function of x for gluons, valence quarks and sea quarks at $Q^2=10 \text{ GeV}^2$ as measured at HERA. Note the gluon and sea quark has been reduced by a factor of 20. At low x , gluons will dominate in the proton [51]. Right plot: cartoon of the phase diagram for the parton evolution in QCD. Each colored blob represents a parton with the transverse area $1/Q^2$ and longitudinal momentum $k_z = xP$. Q_s is the saturation scale [60]. $\lambda \approx 0.3$ is obtained from HERA Deep Inelastic Scattering data. From left to right, as Q^2 increases, the system becomes more dilute. From bottom to top, as the x decreases, the system becomes more crowded and finally gets saturated.

This idea comes from an important observation: the number of gluons increases quickly with the decrease in the x . The left plot of figure 1.15 shows this in electron-proton collisions: for fixed Q^2 , the gluon number rises quickly as x becomes smaller and dominates at low x . This phenomenon can be explained by the following: the proton is a sea of virtual gluons and quarks, and these virtual gluons and quarks emerge and disappear with different lifetimes because of the Uncertainty principle. In a high-energy collision, these lifetimes are diluted by the Lorentz factor. Suppose we view the electron as the probe with the higher collision energy (larger Lorentz factor). The proton is the target. In that case, we should see more virtual gluons. The virtual quarks are suppressed by a factor of α_s since they come from $g \rightarrow q\bar{q}$ ($\approx -ig_s t^a \gamma^\mu$, $\alpha_s = \frac{g_s^2}{4\pi}$). Thus the number of gluons increases with the energy of the collision or lower x ($x = \frac{Q^2}{P \cdot q}$, $Q^2 = -q^2$. P is the collision energy).

A large number of gluons will initiate a recombination process $gg \rightarrow g$. At some point, when the product of the gluon transverse density and recombination cross-section is equal to the production rate, the saturation effect becomes obvious[41]:

$$\alpha_s Q^{-2} \times A^{-2/3} xG(x, Q^2) \geq 1 \quad (1.8)$$

where $\alpha_s Q^{-2}$ is the cross-section of $gg \rightarrow g$, A is the atomic number in a nucleus. The transverse area scales like $A^{2/3}$. $xG(x, Q^2)$ is the number of gluons. The term $A^{-2/3} xG(x, Q^2)$ is the gluon density in a transverse area. From this inequality, the saturation momentum can be obtained:

$$Q^2 \leq Q_s^2 = \frac{\alpha_s xG(x, Q_s^2)}{A^{2/3}} \sim A^{1/3} x^{-0.3} \quad (1.9)$$

where Q_s^2 is called saturation momentum. For a heavy nucleus, it is enhanced by a factor of $A^{1/3}$, simply because there are more gluons per transverse area because of the thickness of the nucleus.

The right plot of figure 1.15 shows the gluon density's evolution according to a function of Q^2 and x . From left to right (along the X-axis), as the Q^2 increases, the gluon's momentum increases. From the uncertainty principle $\Delta x = \frac{\hbar}{\Delta p}$, the size of the gluon decreases. Thus the system becomes more dilute. This process can be described by DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) equation [45] [12] [33] which ignores the recombination effect of gluons. From bottom to top (along the Y-axis), as the x decreases, the number of gluons increase, and the size of the gluon stays the same. The system becomes more crowded. This can be described by BFKL(Balitsky-Fadin-Kuraev-Lipatov) equation [74] [71] [19] by taking into account the process $gg \rightarrow g$. A line of $\ln Q_s^2(Y) = \lambda Y$ separates the region into two regions: the saturation region and the dilute region.

In the saturation region, the high density of gluons allows theorists to use a semi-classical method. Due to the time dilation, the gluons are classified into two groups: (i) fast gluons (large x) with longer lifetimes which are considered as the static color source J_μ during the interaction; (ii) slow gluons (small x) with shorter lifetimes, which are described by the usual gauge fields A^μ of the QCD. The interactions between these two types of gluons can be described by the term $J_\mu A^\mu$. Given a fixed color configuration ρ , the Yang-Mills equation can give the color fields. This is similar to calculating the electromagnetic fields by using Maxwell's equations with a given charge distribution. In the real case, the color configuration ρ is not fixed. We use the probability distribution function $W_\Lambda[\rho]$ to describe

the evolution of the color charge. Λ is the scale used to distinguish between the fast and slow gluons. At leading order, $W[\rho]$ obeys the JIMWLK equation[18]:

$$\frac{\partial W_\Lambda}{\partial \log \Lambda} = -H[\rho, \frac{\delta}{\delta \rho}]W_\Lambda \quad (1.10)$$

H is the JIMWLK Hamiltonian containing up to two derivatives $\frac{\partial}{\partial \delta}$ and arbitrary powers in ρ . In experiments, the observable is the average value over the $W[\rho]$.

The JIMWLK equation only gives the evolution of the color source configuration, and we still need the initial condition at some Λ_0 . One choice is the (Gaussian) McLerran-Venugopalan model[78], which is often viewed as a plausible initial configuration for a large nucleus at a large cutoff.

The matter described above is called the Color Glass Condensate (CGC):

- **Color:** The matter is colored.
- **Glass:** Because of Lorentz time dilation, the fast gluon at large x can act as the "frozen" source for dynamics of the slow gluons at small x . But the source can vary over a long time. So, this matter is similar to a disordered glass - a solid over a short time but a liquid over a long time.
- **Condensate:** The gluon density is very high and starts to saturate. It is a condensate. This high dense matter can be described by a classic field in the first-order approximation.

To explore the CGC, it is better to use a dilute system (like a deuteron) to probe a crowded system (like gold) at forward rapidity (the deuteron going side). Collisions producing particles in the forward region come from collisions of high- x partons in the

deuteron with small x gluons from the Au. There is some evidence of the CGC in dAu collisions. Figure 1.16 shows R_{dAu} vs. p_T at different rapidities. While this suppression may seem similar to that seen in Au+Au collisions, it is from a different source. It presumably comes from the suppression caused by the saturation of gluons at low- x . For the same rapidity, the suppression becomes weaker with the increase of p_T . For the same p_T , the suppression becomes stronger as the rapidity increases. The trends of these observations generally agree with the CGC prediction as illustrated in 1.15.

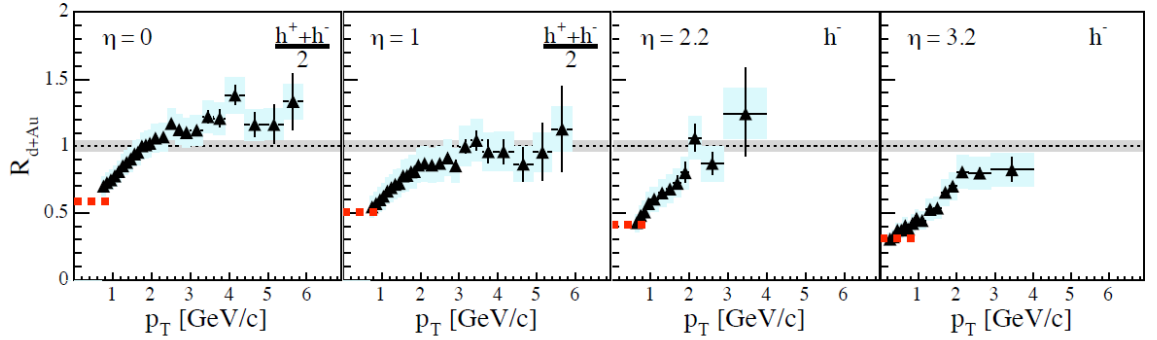


Figure 1.16: R_{d+Au} as a function of p_T for central and forward pseudorapidities. The data is from BRAHMS for d+Au collisions at 200GeV [17]

Figure 1.17 shows the relative yields of back to back pairs in d+Au collisions compared to p+p collision. For peripheral collisions (only a small number of nucleons participate in the interaction), the relative yields are close to one, while the yields are suppressed for central collisions. In this thesis, we continue to explore the saturation of Au in d+Au collisions with the newly installed detector MPC-EX, which has a spatial resolution of 2 mm for the XY plane, allowing us to reconstruct high energy π^0 s at high rapidity ($3.1 < |\eta| < 3.8$).

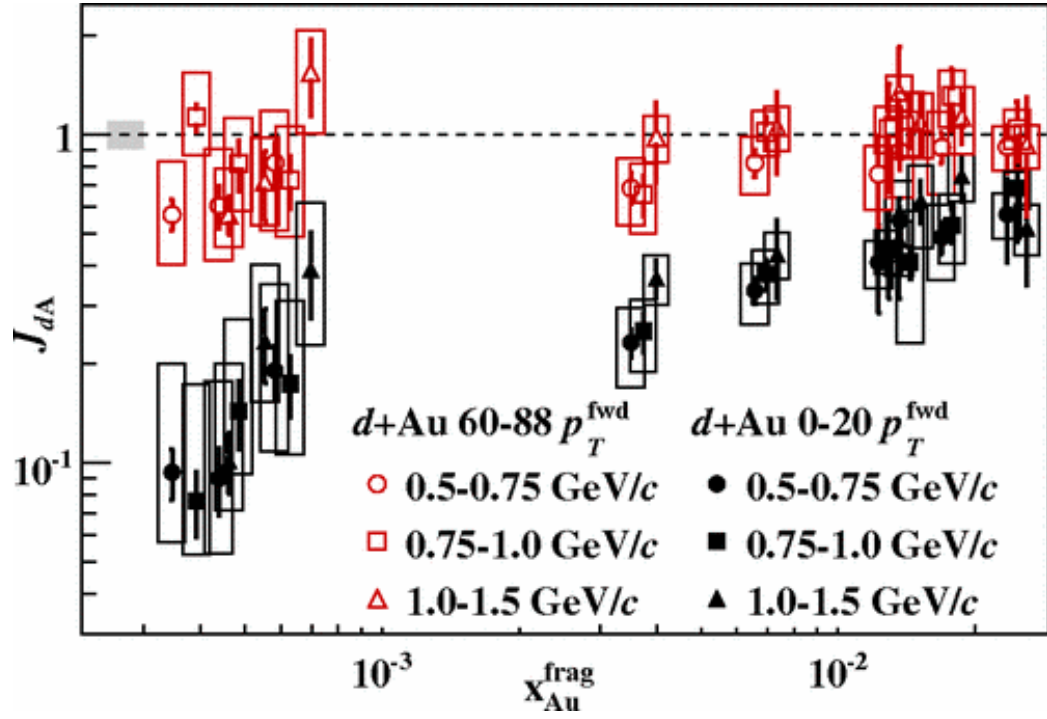


Figure 1.17: The relative yield, J_{dA} , of correlated back-to-back hadron pairs compared to p+p collisions, in central (0-20%) and peripheral (60-88%) in d+Au 200GeV collision. [10]

Figure 1.18 shows the two-particle correlation at forward rapidity between p+p and d+Au. Since the momentum is conserved in the ϕ direction, we should see two peaks at 0 and π . This is what the figure shows in the p+p collision. For the d+Au collision, the away-side peak is almost gone, presumably from the suppression of gluons as predicted by the CGC theory.

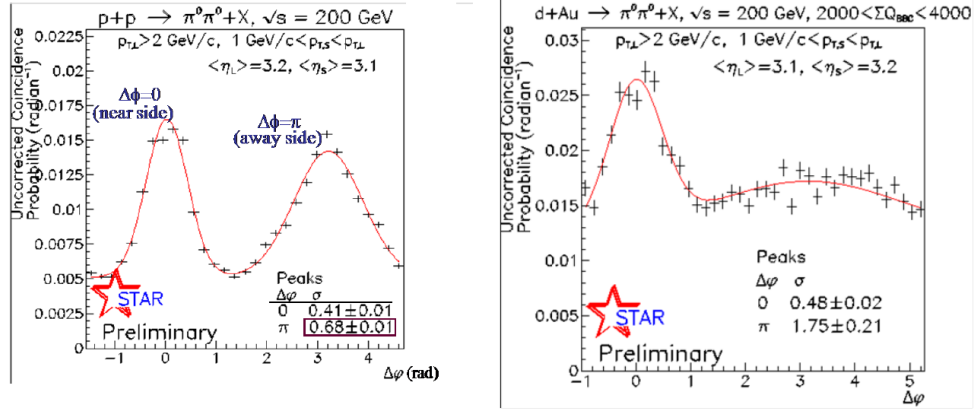


Figure 1.18: Two particle correlation at forward rapidity [23]

1.6 Other models

In addition to the CGC model, which starts from the first principles, there are other more phenomenological models. Of course, there are calculations using nuclear PDFs and various fragmentation functions [50]. An example of such nuclear PDFs is shown in Figure 1.19. For gluons, which are presumably the major source of pions at $x_2 \sim 10^{-1} - 10^{-2}$ relevant to the 200 GeV CM data. x_2 is the fraction of the total nucleon momentum carried by the gluon, as explained later in the kinematics section. Figure 1.19 shows the ratio of

the nuclear PDF to the nucleon PDF. As one can see, these functions are not well known. One of the projects of the MPC-EX is to measure the direct photon suppression, which will give us a better handle on these functions, though such a measurement would still not give us a first principles understanding. Other models attempt to be more closely connected to a first principle calculation, though only certain phenomena are assumed. [90] is such a calculation that looks at Leading Order multiple parton scattering through a nucleus. Still, others invoke a picture of a nucleon transversing the nucleus as a state which changes with each subsequent scatter [15].

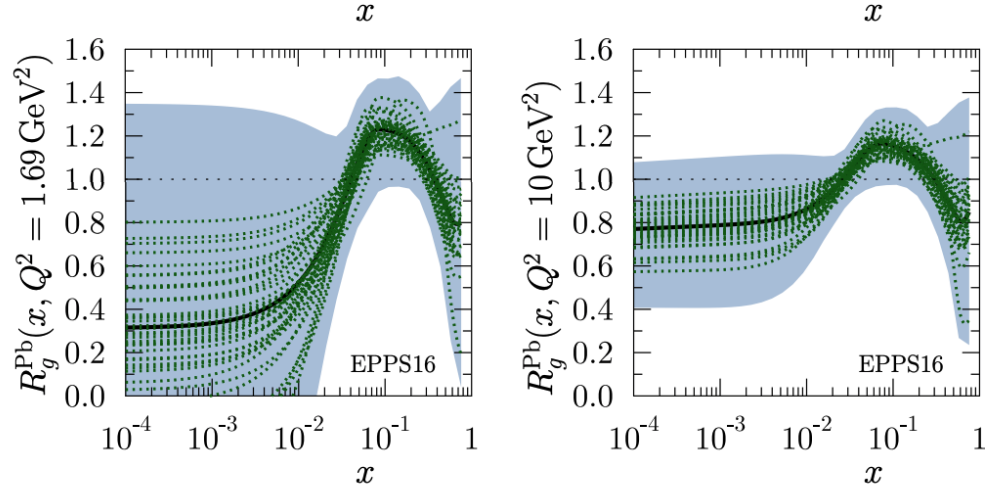


Figure 1.19: The gluons nuclear modification factor[37]. The uncertainty of lower Q^2 and x is huge.

1.7 Units, Kinetics and Centrality

1.7.1 Units

In this thesis, we use the natural units, where the Plank's constant $\hbar$ and the speed of light c are set to 1:

$$\hbar = c = 1 \quad (1.11)$$

The unit of the c is $[length] \cdot [time]^{-1}$ and unit of the $\hbar$ is $[energy] \cdot [time]$. The energy is also equal to $[mass] \cdot c^2$. We have the following relations the units describing different quantities:

$$[length] = [time] = [energy]^{-1} = [mass]^{-1} \quad (1.12)$$

In nuclear physics, we use the electronvolt (eV), which is the energy gained by an electron through one-volt electric potential, to represent the energy. Some useful conversion factors are listed in table 1.1.

$1TeV = 10^3GeV = 10^6MeV = 10^9KeV = 10^{12}eV$
$1kg = 5.61 \times 10^{26}GeV$
$1m = 5.07 \times 10^{15}GeV^{-1}$
$1sec = 1.52 \times 10^{24}GeV^{-1}$
$e = \sqrt{4\pi\alpha}$
$1fermi = 10^{-15}m = 5.07GeV^{-1}$
$100fermi = 1b = 10^3mb = 10^6\mu b = 10^9nb = 10^{12}pb = 10^{15}fb$

Table 1.1: Some useful conversion factors

1.7.2 Kinematics

In nuclear physics, we use the four momentum (E, p_x, p_y, p_z) to represent the kinetics of the particle. E is the energy, and p_x, p_y, p_z are the normal components of the

momentum. The transverse momentum is given by:

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (1.13)$$

One important quantity often used is the rapidity:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (1.14)$$

The energy and three momentum are related to the rapidity by:

$$E = m \cdot \cosh(\eta) \quad \text{and} \quad |\mathbf{p}| = m \cdot \sinh(\eta) \quad (1.15)$$

The rapidity has a very important feature. If A, B, C are reference frames and y_{AC} denotes the rapidity of C in reference frame A , then:

$$y_{AC} = y_{AB} + y_{BC} \quad (1.16)$$

In nuclear physics, pseudorapidity rapidity is often used:

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \quad (1.17)$$

Where θ is the polar angle with respect to the beam direction or z-axis. For particles with mass=0, $\eta=y$.

The left part of figure 1.20 shows the interaction between the proton-proton collision in the center mass frame. Due to the Lorentz contraction, each proton looks like a disk. In high energy collisions, we can ignore the mass of the proton ($E \approx P$). In such collisions, the partons with momenta k and p , carrying momentum fractions of x_1 and x_2 from each

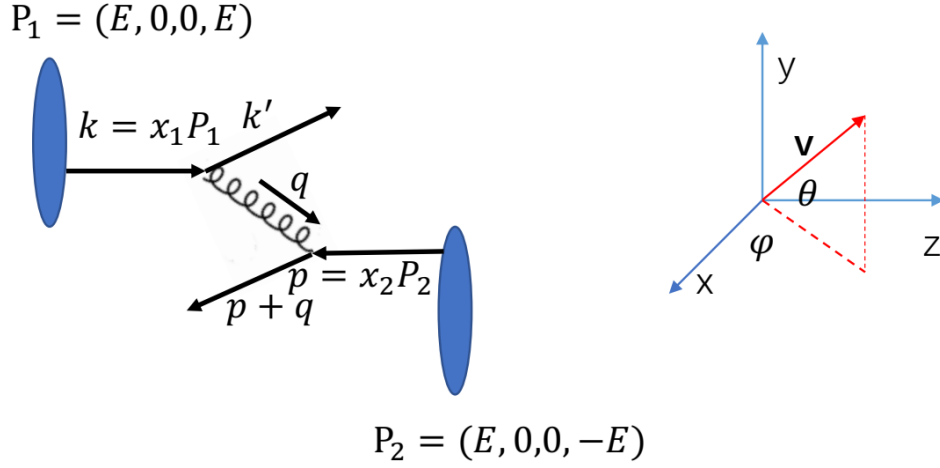


Figure 1.20: The left plot shows an interaction in a proton-proton collision. E is the energy. p_x and p_y are zero. The right plot shows the coordinate system. The z -axis is the beam direction. The transverse momentum ($p_T = \sqrt{p_x^2 + p_y^2}$) is in the x - y plane. The azimuthal angle ϕ is the angle between the projection on the x - z plane and the x -axis. The polar angle θ is with respect to the z -axis.

proton, interact by the gluon with momentum q . The transfer momentum is $q = k' - k$. q^2 and can be expressed as:

$$q^2 = k'^2 + k^2 - 2k'k \approx 0 + 0 - 2k'_0k_0(1 - \cos\alpha) \quad (1.18)$$

The mass of the parton is negligible compared with the collision energy (k'^2 and k^2 are 0). α here is the deflection angle. The k'_0 and k_0 are the parton's energies, which are always positive. The q^2 is space-like. For the convention, a positive Q is introduced:

$$Q^2 = -q^2 \quad (1.19)$$

The scattered parton's mass can be ignored:

$$0 \approx (p + q)^2 = 2p \cdot q + q^2 = 2x\mathbf{P} \cdot q - Q^2 \quad (1.20)$$

$x = x_2$ and the $\mathbf{P} = P_2$. Thus we have:

$$x = \frac{Q^2}{2\mathbf{P} \cdot q} \quad (1.21)$$

1.7.3 Centrality

In the collision of large nuclei, whether the collision is head-on or glancing changes the physics dramatically. The multiplicity of produced particles is much larger in a head-on collision. The centrality is used to describe this. A collision that is perfectly head-on is said to have a centrality of 0%, whereas a barely glancing collision will have a centrality of 100%. This particular definition is chosen since the centrality is closely related to the impact parameter, b , which is the distance between the centers of the two colliding nuclei. A collision with $b=0$ fm will have a centrality of 0%, whereas a collision with b equal to the sum of the radii of the two nuclei will have a centrality of 100%. Typically we assume that the centrality scales with the multiplicity of particles produced and detected in a given detector - in our case, the beam-beam counter (BBC). This will be discussed in more detail later.

Chapter 2

Experimental Apparatus

2.1 RHIC

The microscope is the instrument that we usually think of for observing small objects in the natural world. However, the nucleus is very small 10^{-15} m, and we need a much more powerful instrument. The Heisenberg uncertainty principle tells us that the smaller scale the object we wish to resolve, the higher the energy we need. Particle accelerators that can impart large energies via electromagnetic fields have been the tools used for this purpose. The data in this thesis used just such a machine - the Relativistic Heavy Ion Collider (RHIC). RHIC has the unique ability to accelerate various ion species, from protons to gold. Various species of ions, including gold, protons, copper, aluminum, helium, and deuterons, have been accelerated over a wide range of center-of-mass energies: among them, 19GeV, 39GeV, 62GeV, and 200GeV.

While not of relevance to this thesis, RHIC is the only machine that can accelerate polarized protons. RHIC primarily runs in a "collider" mode which produces very high

energy collisions by colliding particles head-on. RHIC was constructed to produce and discover the Quark-Gluon Plasma discussed in Chapter 1. The QGP has been conclusively found, and RHIC has turned to the task of understanding its properties, one of which is the initial conditions that lead to the formation of the QGP - the topic of this thesis. Central to this task is an increase in brightness or “luminosity” of the machine. Since 2012, stochastic cooling has been utilized, which significantly increases the luminosity[38]. The data used in this study uses an integrated luminosity $289nb^{-1}$ of d+Au collisions at 200GeV center of mass.

RHIC is located at the Brookhaven National Laboratory (BNL) in Upton, New York. Figure 2.1 shows an overview of the accelerator complex. The heavy-ion beam starts in the **Electron Beam Ion Source**, while for (polarized) protons, the beam starts in the **Linear Accelerator**. Then they travel to a small circular accelerator, the **booster**, and then into the **Alternating Gradient Synchrotron**, where it gains energy. The beam is then transferred to RHIC via AGS-to-RHIC (ATR) transfer line to **RHIC**.

- **Electron Beam Ion Source(EBIS):**Over the past 40 years, the workhorse injectors for nuclear physics were two Tandem van de Graaff accelerators. In 2012, a new injector, EBIS, was used to replace the Tandem accelerators. Unlike the Tandem accelerators, EBIS can provide any ion species and is simpler and less costly to operate [11]. EBIS uses an electron beam to peel off the electrons of an atom and leave a highly ionized nucleus which can easily be accelerated. EBIS consists of an electron beam ionization source, followed by a radio frequency quadrupole linac and an interdigital-H linac.

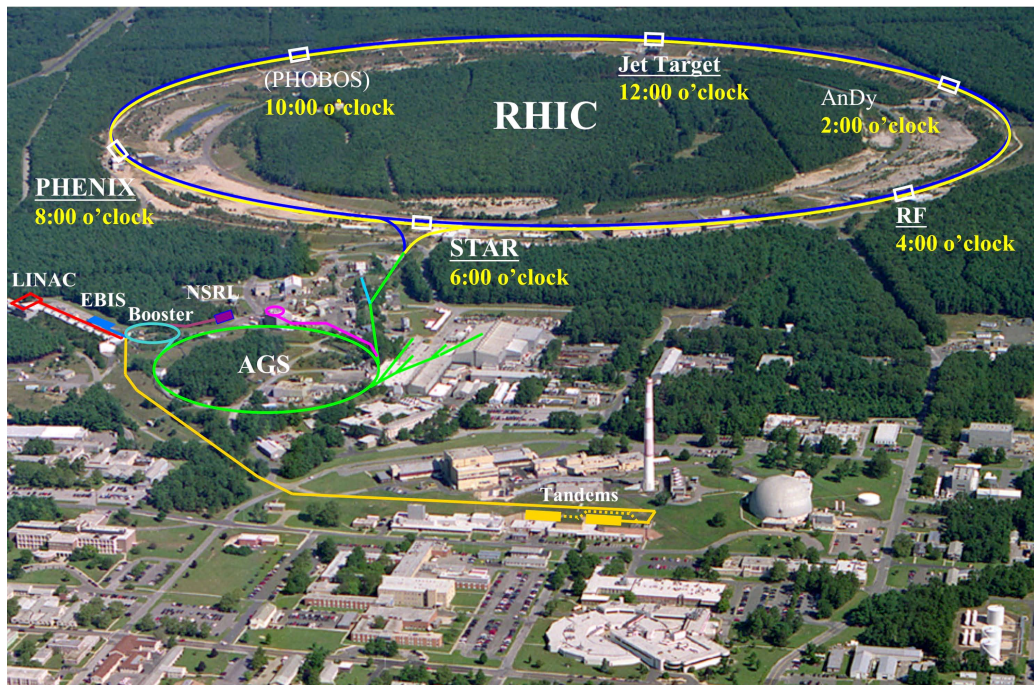


Figure 2.1: RHIC is composed of a “chain” of the particle accelerators, starting with the **Electron Beam Ion Source**. The beam is then injected into the **booster**, then the **Alternating Gradient Synchrotron**, and finally to the main machine, **RHIC**. The beam gets accelerated at each step. The final focusing and collisions occur at the interactions regions in RHIC. (The image comes from <https://science.osti.gov/np/Facilities/User-Facilities/RHIC>)

- **Booster Synchrotron:** The Booster accepts ions from EBIS or protons from 200MeV Linac. Because of the high vacuum in the Booster, its construction allowed for the acceleration of ions up to gold. After accelerating the beam to about 100 MeV, the beam is transferred to the AGS by the BTA (Booster to AGS transport line), where electrons are further stripped off (to 77+ for gold).
- **Alternating Gradient Synchrotron(AGS):** Since 1960, the AGS has been one of the premier particle accelerators in the world. It is now being used as an injector to RHIC. The AGS accelerates the beam to 10 GeV, and which is then transferred through the AtR (AGS to RHIC).
- **Relativistic Heavy Ion Collider:** A 2.4-mile ring consists of 1740 superconducting niobium-titanium magnets, which can independently accelerate the two counter-circulating beams. The beams are accelerated by an RF(radio frequency) system (a metallic chamber consisting of an electromagnetic field for accelerating charged particles). There are 120 bunches in the rings, and the crossing time is about 106ns. The chain starting from EBIS to RHIC is repeated many times to fill the two counter-circulating beams, called the blue beam (deuterons for this data set) and the yellow beam (gold for this data set). After RHIC is filled by the AGS, the beams are accelerated to the final energy and focused, such that collisions happen at the intersection regions where detectors are located. The high-energy beams are kept in the ring up to eight hours by the strong magnetic field (up to 3.5T) and dumped when the luminosity is low.

There have been four experiments at RHIC. Two smaller experiments, PHOBOS and BRAHMS, ended data taking in 2005 and 2006, respectively. The STAR experiment, which is an azimuthally symmetric detector specializing in tracking a majority of particles produced by each ion collision, is still operating. Data for this thesis was taken by the PHENIX experiment, which completed data taking in 2016.

2.2 PHENIX

The PHENIX (Pioneering High Energy Nuclear Interaction eXperiment) detector is the largest of the four experiments at RHIC. The conceptual design for PHENIX was begun in 1991, and data taking began in 2000. It consists of various detector systems that can track, identify and measure the energies of hadrons, muons, electrons, and photons with high spatial and momentum resolution. PHENIX features an advanced high-speed data acquisition system. Figures 2.2 and 2.3 show several schematics of the PHENIX detector. There are four main parts (see Figure 2.3): Magnets, Event Characterization Detectors (Global Detectors), Central Arm Detectors, and Muon Arm Detectors. The two most important detectors for this thesis are the MPC and MPC-EX.

2.2.1 Magnets

The magnets in PHENIX provide magnetic fields (figure 2.3) which bend the charged particles. The deflection can yield a measurement of the momentum - $|\vec{p}_\perp| = \frac{e}{c} B \cdot R$, where $\vec{p}_\perp$ is the transverse momentum, e is the charge, c is the speed of light, B is the

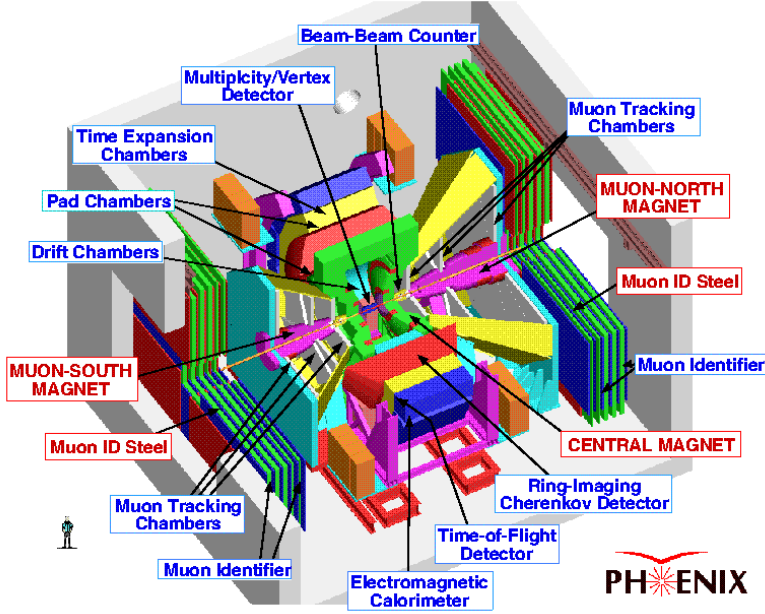


Figure 2.2: An 3-D overview of PHENIX detector. The MPC-EX and the MPC are not shown in this view, since they are buried in the Magnet. The beams come from the left and right.

magnetic field, and R is the bend radius. There are two types of magnets: (1) The Central Magnet (two pairs of concentric coils) generating an axial magnetic field (2) South and North Muon Magnet (two solenoidal coils) generating radial magnetic fields. Particles detected by the MPC and MPC-EX are close to the beam pipe, outside the influence of the magnetic field, and do not bend.

2.2.2 Event Characterization Detectors

Event characterization detectors provide global information such as particle multiplicity, start time, and z -position of the collision vertex. Two essential detectors are Beam Beam Counter (BBC) and Zero Degree Calorimeter(ZDC).

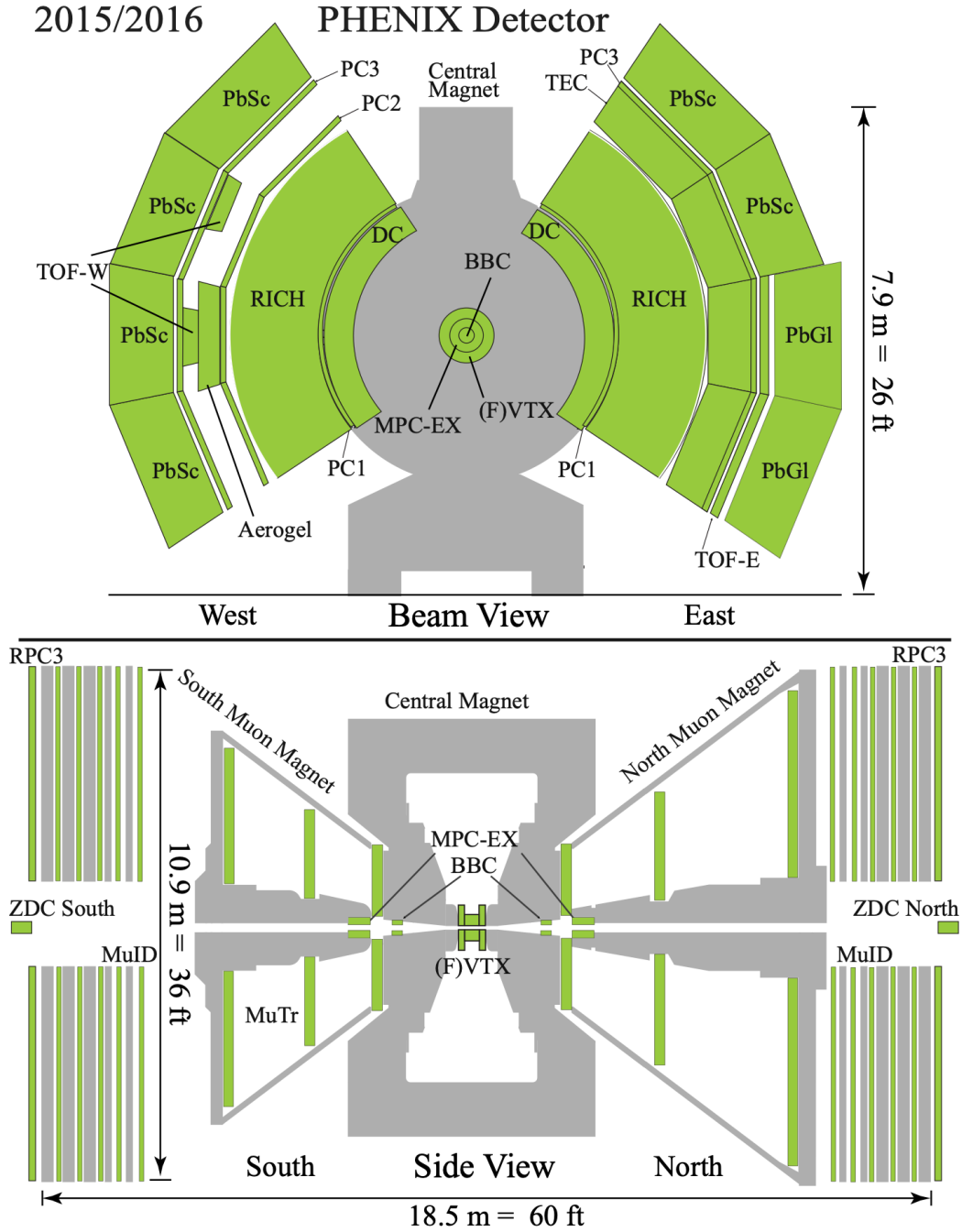


Figure 2.3: Top: Beam view of the PHENIX detector showing the central arms. The MPC (not labeled) and the MPC-EX are behind the BBC. Central arm detectors provide the tracking, particle identification, and energy/momentum measurement of the particles. Bottom: Side view of the PHENIX detector showing the Muon Arms. The MuTr, MuID provide detection for muons. The MPC (not shown, behind the MPC-EX) measures the energy of showers. The BBC provides centrality information and is the primary trigger detector. The (F)VTX provides tracking information in the high rapidity region.

- **Beam Beam Counter (BBC)**[62](Figure 2.4): The BBC is located at about 144cm from the center, covering a rapidity of 3.1 to 4.0, and 2π in ϕ . (Figure 2.3) Each arm of the BBC has 64 quartz Cherenkov radiators. Figure 2.5 shows the array of PMTs and how the vertex and time zero are calculated. The resolution of the time zero is about 20ps, giving a z-vertex resolution of about 0.6cm. The BBC has four functions:(i) Providing a Minimum Bias Trigger (Combined with the ZDC); (ii) Centrality Determination (with the ZDC); (iii) Start time for the time of flight measurement; (iv) Collision Vertex location.

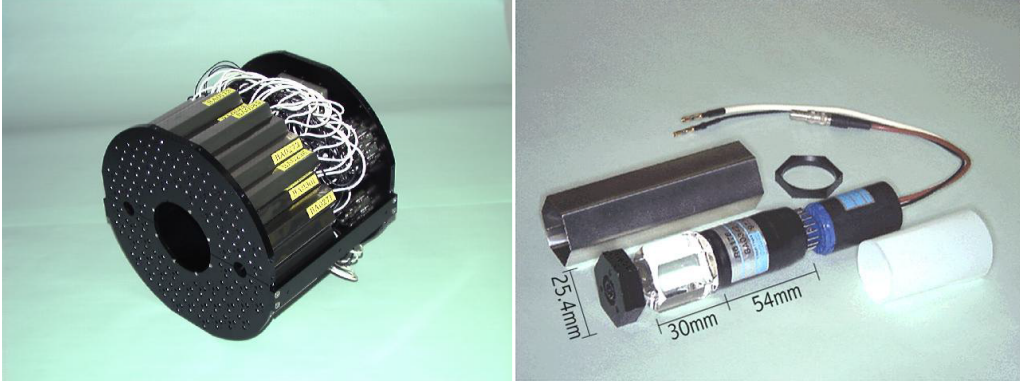


Figure 2.4: Left picture: The BBC has 64 elements each for both North and South Arms. Right picture: each element consists of quartz Cherenkov radiator and meshed dynode PMT [81]

- **Zero Degree Calorimeter (ZDC)**: The ZDC is located about 20 meters from interaction point (Figure 2.6). It is primarily sensitive to neutral particles (neutrons) since the RHIC dipole magnets sweep away all charged particles. The ZDC provides a common luminosity measurement for all RHIC experiments, aids in the centrality determination, and minimum bias trigger[28].

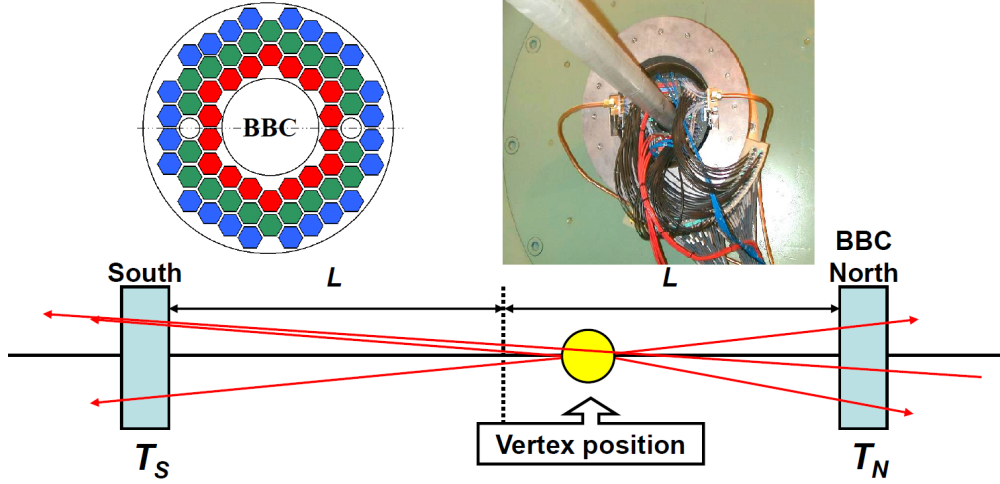


Figure 2.5: Top left: PMT array for both north and south showing the 64 elements. Top right: The BBC after installation. Bottom: How the Z-vertex of an event is measured using the BBC. The Z-vertex can be calculated by $z_{vertex} = (T_S - T_N)/2 \times c$ and the time zero $t_0 = (T_S + T_N - 2L/c)/2$, where c is the speed of light, L is 144.35cm, and $T_S(T_N)$ is the travel time particles to reach South(North) BBC from the collision point.[81]

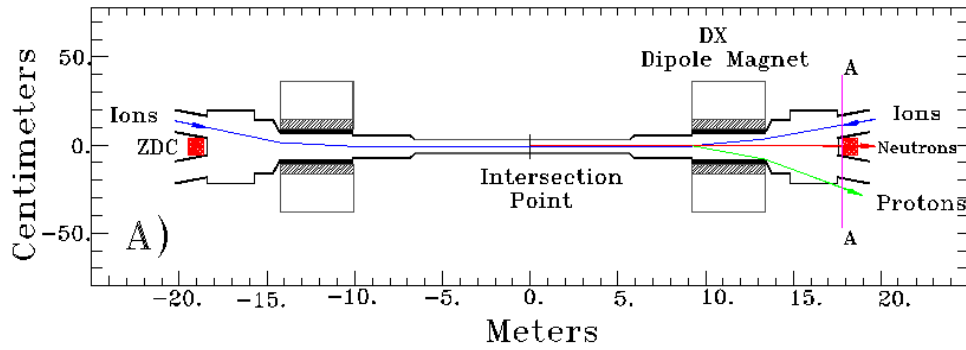


Figure 2.6: The location of ZDC. After the collision, bunches are steered by the magnetic field, while neutrons travel in a straight line and are detected by the ZDC.

2.2.3 Central Arm Detectors

Many detectors in the central arm provide the functions of tracking, particle identification, and energy measurement (figure 2.3 top). While these detectors are not used in this analysis, for completeness, we give a short description of them here.

- **Particle Tracking:** The main detectors for tracking (figure 2.3) are the Drift Chambers (DC) [25], Pad Chambers (PC1,PC2,PC3)[84], and Time Expansion Chamber (TEC)[92]. The DC is a multiwire gaseous detector, while the PCs and TEC are multiwire proportional detectors. The DC can record the trajectory of charged particles in the magnetic field. The transverse momentum is obtained by measuring the deflection. The PCs provide 3D points to aid in track reconstruction, can help us get better tracking resolution, and provide points at which particles enter or exit the Ring Image Cherenkov Detector (RICH) and the Electromagnetic Calorimeter(EMCal). The TEC tracks charged particles between the RICH and EMCal, and provides complete tracking determination combined with DC and PCs and improves the resolution at high momentum.
- **Particle Identification:** PHENIX has two primary detectors used in particle identification (PID) - the Ring Imaging Cherenkov Detector (RICH) and the Time of Flight Detector (TOF).
 - *Ring Imaging Cherenkov Detector*[85]: If a charged particle travels faster than the speed of light in a medium, Cherenkov photons are radiated. The speed of light in a medium is affected by the refractive index. By choosing a particular value

of the refraction index, we can set the threshold for the production of Cherenkov radiation. The medium used is CO_2 , whose refraction index is about 1.000410. The threshold for electrons is 0.02GeV, while for pions (the lightest hadron) is 4.9GeV. So the RHIC can separate electrons from hadrons up to 4.9GeV.

- *Time of Flight Detector*: By directly measuring the time of flight, we can obtain the particle speed. There are two detectors: Time of Flight East (2.3 TOF-E)[76] and Time of Flight West (figure 2.3 TOF-W)[32]. The TOF-E is a scintillation detector, while TOF-W is the multi-gap resistive plate chamber (MRPC). TOF-E and TOF-W aim to identify hadrons like pions, kaons, protons, and deuterons. The resolution of the TOF is about 90 ps.

- **Calorimeter**: The outermost part of the central arm is the Electromagnetic Calorimeter(EMCAL). There are two technologies used in PHENIX: The first is the Lead Scintillating sampling calorimeter(PbSc), which is composed of alternating layers of lead and scintillator. The second is the Lead Glass Calorimeter (PbGl) calorimeter, where Lead Glass is used as a Cherenkov radiator. Each is designed to measure the energy and give a rough position. Additionally, the PbGl can give a rough Time-of-Flight measurement.
- **Forward Silicon Vertex Tracker(figure 2.3 VTX)[83]**: The forward Silicon Vertex Tracker (FVTX) located in at higher rapidities, and the Silicon Vertex Tracker (VTX) at midrapidity, form a single system. For long lived particles, the travel distance before a particle decays will reflect that lifetime. The vertex detectors (FVTX, VTX) can reconstruct the secondary vertex formed when the particle decays. This

is particularly important for separating contributions from the bottom quark and charmed quark.

2.2.4 Muon Arm Detectors

The Muon Arms (figure 2.3 bottom) consist of the Muon Tracker (MuTr)[30], Muon Identifier (MuID)[35], Muon Piston Calorimeter(MPC), Muon Piston Calorimeter Extension (MPC-EX) and Forward Silicon Vertex Detector (FVTX)[36]. The rapidity coverage of the FVTX is $1.2 < |\eta| < 2.2$, for the BBC is $3.1 < |\eta| < 4.0$, and for the MPC/MPC-EX is $3.0 < |\eta| < 3.8$. The MuTr is a drift chamber and measures the bending of charged particles in the muon magnet. The MuID consists of a 5-layer sandwich of steel and chambers(Iarocci tubes). It stops hadrons and identifies the muons which can penetrate the steel. As with the VTX, the FVTX is used to detect secondary vertices. In addition, the FVTX electronics has a fast circuit, capable of sending signals very quickly to the trigger system, allowing it to serve as a multiplicity trigger. Though the lower energy data is not being presented in this thesis, the FVTX information provided an important trigger for this lower energy data. Figure 2.7 shows the structure of the FVTX+VTX system.

Figure 2.8 shows a 3D model of MPC and MPC-EX. The MPC is an electromagnetic calorimeter consisting of lead tungstate crystals used to measure the photon. The MPC-EX is a compact silicon tungsten pre-shower detector with a good spatial resolution ten times better than the MPC. The combination of the MPC-EX and MPC can identify π^0 s up to 80GeV. The MPC and MPC-EX are the main focus of this thesis and will discuss more in detail in the next chapter.

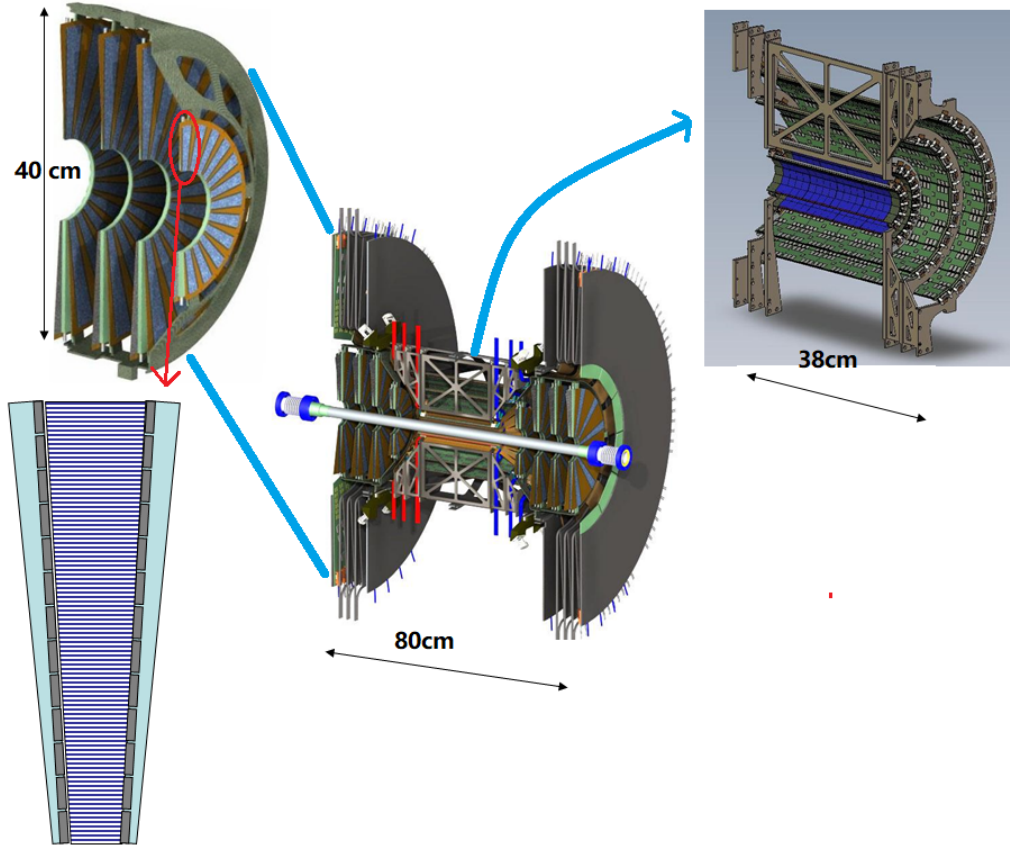


Figure 2.7: The structure of the FVTX+VTX system. The top left picture is the FVTX detector, and the top right picture is the silicon vertex tracker (Tracker). The FVTX consists of two angular endcaps, each with four stations of silicon mini-strip sensors, and covers the rapidity range of $1.2 < |\eta| < 2.2$. There are two arms. Each arm has four disks, and each disk has 48 wedges. The size of a strip is about 2.8 - 11.2 mm long and $75 \mu m$ width. There are 1.1 million channels in total.[36]

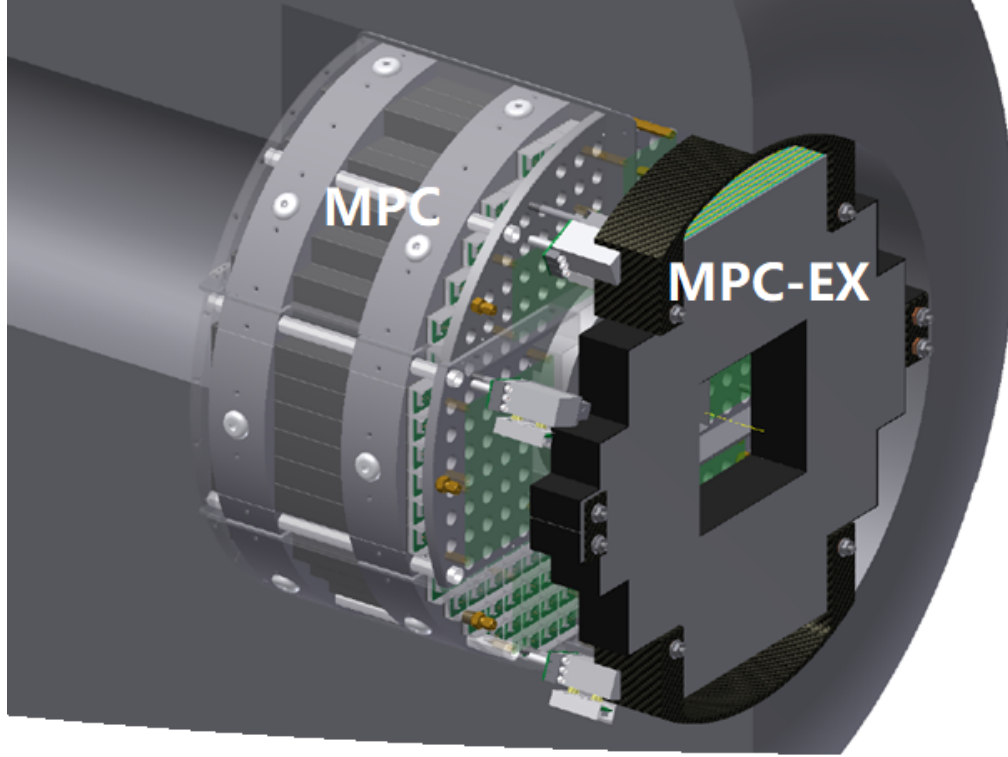


Figure 2.8: 3D model of MPC-EX and MPC [26]. The collision vertex is on the right. Incoming photons from the vertex enter the MPC-EX from right to left.

2.2.5 Data Acquisition System

The PHENIX detector is a large system with about 650,000 readout channels, giving out a typical event size of about 220KB/event before compression. The typical readout rate for Au-Au collisions is about 5KHZ, and the data rate can be as high as 1.8GB/s [88]. The DAQ is a unified system and is the same for all detectors, while the Front-End Models are unique to each detector. Figure 2.9 shows an overall schematic of the PHENIX data acquisition system (DAQ):

- **Front-End Model (FEM):** The FEMs provide the control signals to the front-end electronics, collect and transmit data, and manages the command interface (time and

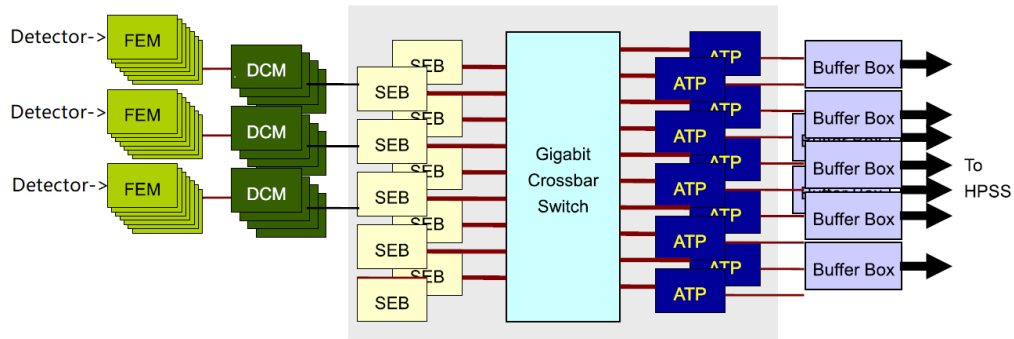


Figure 2.9: An overview of data flow in the data acquisition system for PHENIX[88] Data flows from the Detectors into Front End Modules (FEM), which are then read out by the Data Collection Modules (DCM). The data is passed on to the Sub-Event Buffers, which can hold several events in memory. The data is then passed through the Gigabit Switch, and Assembled in the Assembly Trigger Processor (ATP). Fully assembled events are then passed to the buffer boxes, which hold the data until it can be relayed to the RHIC Computing Facility

control)[98]. The data from the detector will be first buffered in the FEM, where it waits for a command from the trigger, which will inform the FEM whether to take the event or discard it. If it is to keep the event, the data will be transferred to the Data Collection Module (DCM). All the signals from detectors will be transformed into the same format by the FEM, and thus the processes after the FEMs are similar.

- **Data Collection Modules (DCM):** The DCM is responsible for collecting the data from FEMs. They can buffer up to 5 events. The DCM also performs zero suppression, error checking, data reformatting, and then transfers data to the SEB.
- **SubEvent Buffer (SEB):** The SEB receives data from the DCM and sends parts of one event to the ATP by the Crossbar Switch.
- **Assembly Trigger Processor (ATP):** The ATP assembles events by requesting data from SEB and then outputs to the short-term storage: the Buffer Boxes.

- **Buffer Box:** the buffer boxes provide temporary storage (there are 7 buffer boxes each with 15TB storage capability). When requested and data will be transferred to the HPSS-based tape robot system at the RHIC Computing Facility.
- **High Performance Storage System (HPSS):** A storage management system dealing with large files. Figure [2.10](#).



Figure 2.10: An HPSS-based tape robot system showing the tapes, and the robot in the foreground.

2.2.6 Trigger System

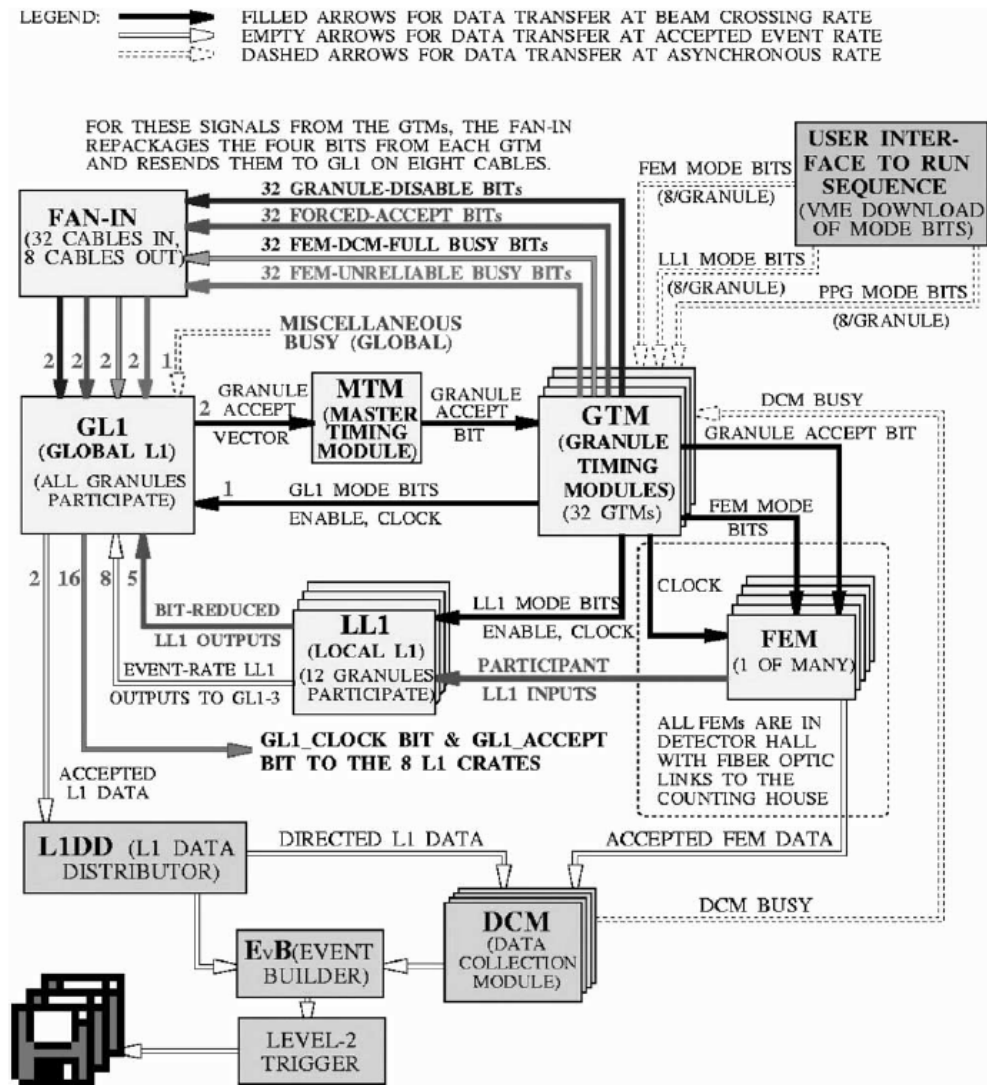


Figure 2.11: PHENIX Trigger System as explained in the text[20].

At RHIC, the collision rate varies from 10KHz for Au-Au to 10MHz for p+p. Only a tiny part of the events can be recorded. The responsibility of the trigger system is to select the events of interest while keeping the detector dead time as low as possible [20].

Figure 2.11 shows the PHENIX trigger system as well as the data acquisition system. In PHENIX, a two-level trigger system is used:

- **Level 1 trigger (LL1 and GL1)**(See center of figure): This trigger receives information from the FEMs. It is at the hardware-level. Information is used from six subsystems: BBC, ZDC, FVTX, NTC(Normalization Trigger Counters), MUID, EMC, and RICH. These subsystems have fast timing. As an example, the BBCLL1 (Local Level 1 from the BBC) can check if the collision vertex is in the desired range. The LL1 trigger information will be sent to the Global Level 1 (GL1) trigger system. Using the LL1 data and information from other parts of DAQ, GL1 issues an accept signal transmitted to the FEMs of all PHENIX subsystems by optical fiber, instructing them that this is a “good” event.
- **Timing modules(GTM and MTM)**: All timing in PHENIX is synchronized to the 9.4 MHz RHIC clock. The task of the timing modules is to distribute this clock to all of the relevant electronics.
- **Level 2 Trigger(LVL2)**: (bottom of figure) The LVL2 triggers are performed at the software level (written in C++). The goal is to reduce the rate of the data keeping all interesting events. For example, LVL2 can search for single/paired muons, high p_T EMC clusters, coherent peripheral events, and so on.

Triggers used in the Analysis

- **MinBias Trigger**: We need to know whether a collision has happened. This is that task of the BBC trigger. The particles generated by the collision fire the PMTs of

the BBC. By requiring the coincidence of the signals from the south and north BBCs, we can define the BBC triggers - e.g., "BBCLL1(>0 tubes)" requiring at least 1 BBC module hit in each arm.

- FVTX Trigger:** There are two modes for the FVTX trigger: Multi-Track and Multi-Hit. Figure 2.12 shows the definition of the FVTX trigger. The basic unit is the sector that consists of four stations. For the Multi-Hit mode, a sector is fired when the total number of hits in four stations is larger than some threshold. A sector is fired for the Multi-Track mode when at least three of the four stations are fired (a track). Whether a FEM is fired depends on the two adjacent sectors to which it is connected. There are two options: AND (two sectors are both fired), OR (at least one sector is fired). When the number of FEMs fired is larger than some threshold, a cage is signaled as fired. The two cages decide a fired arm (AND: both cages fired; OR: at least one cage fired).
- MPC Trigger:** These are generated when the energy deposited in a 4x4 overlapping set of towers of the MPC is above a predefined threshold. The 4x4B (for example, $p_T \sim 3.5\text{GeV}$) triggers the higher threshold while the 4x4A (for instance, $p_T \sim 2.5\text{GeV}$) corresponds to the lower threshold. The triggers are generated by both arms. There are four types: "MPC_N_A" (north low threshold), "MPC_N_B" (north high threshold), "MPC_S_A" (south low threshold), and "MPC_S_B" (south high threshold). These triggers are not used in this thesis.

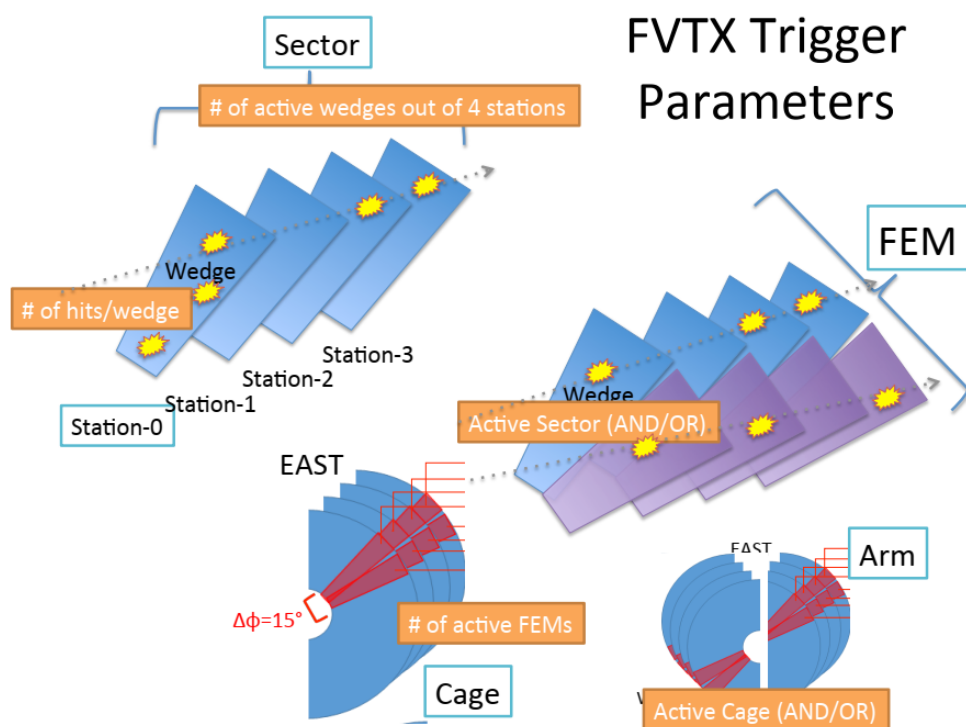


Figure 2.12: FVTX trigger definition for sectors, cages, and arms.

Chapter 3

MPC and MPC-EX

The Muon Piston Calorimeter (MPC) and the Muon Piston Calorimeter Extension (MPC-EX) together provide a powerful electromagnetic calorimeter which is located at forward rapidity (figure 3.1). The calorimeter system extends our ability to measure neutral pions and direct photons and explore nuclear structure at low- x and look for gluon saturation effects. Neutral pions decay to two photons more than 99% of the time. Before the installation of the MPC-EX, the 2.2cm granularity of the MPC towers limited our ability to reconstruct π^0 s at high-energy ($E > 15\text{GeV}$) since the opening angle of the two photons is small and merges into one shower. In 2016, a new detector, the Muon Piston Calorimeter Extension, was installed in front of the MPC. The MPC-EX is a pre-shower detector and silicon tracker with a resolution of 2mm, allowing for the measurement of π^0 s up to 80GeV. The following section will introduce the MPC-EX and MPC and the calibration procedure. The calibration of the MPC is only now being completed. Hence we have chosen not to use the MPC in the thesis. However, as it is a crucial detector for the success of the physics

program, and because much effort has been expended on it, which is only now coming to fruition, it will be described here. The thesis will consider only “two-track” π^0 s as will be described in the following chapter. These “two-track” π^0 can be measured at low p_T in the forward region.

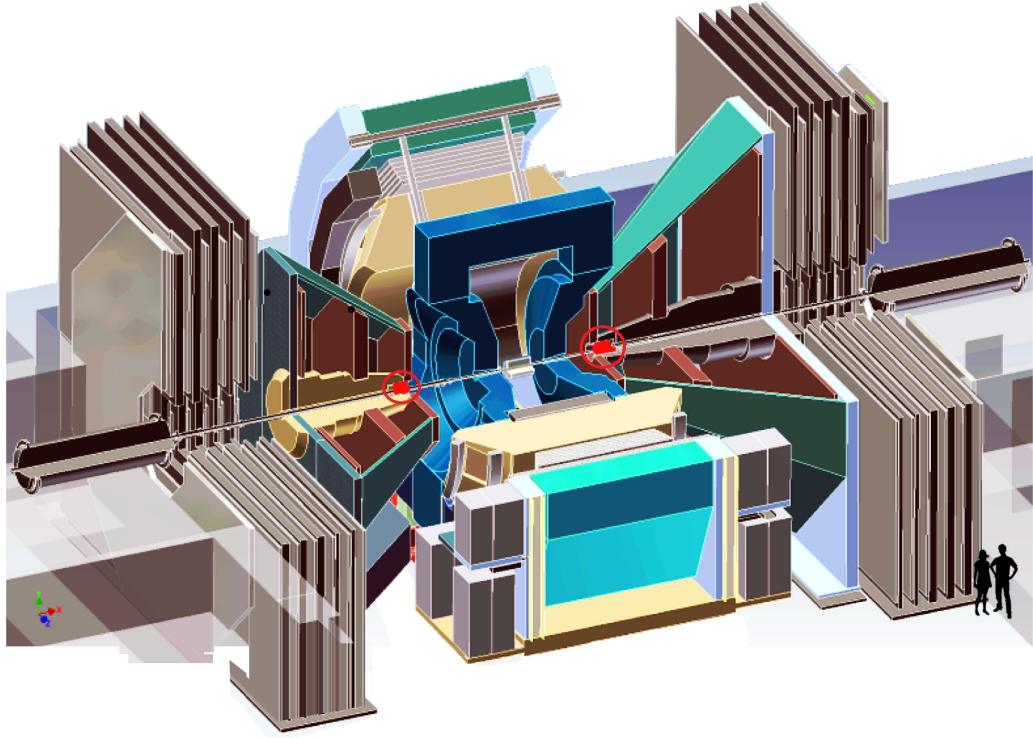


Figure 3.1: The location of MPC and MPC-EX in the PHENIX detector system (red circles).

3.1 MPC Detector

The Muon Piston Calorimeter (MPC) is very close to the beamline ($3.1 < |\eta| < 3.8$) and about 200 cm from the interaction point. Figure 3.2 shows the structure of MPC. The radius of the MPC is about 45cm. The basic detection elements consist of $PbWO_4$

scintillating crystals read out by avalanche photo-diodes (APD) (figure 3.3). $PbWO_4$ was chosen for its good energy resolution. Figure 3.4 shows how the crystal and APD are connected. The table 3.1 lists the properties of $PbWO_4$. The crystal length is about 18 cm or about $20X_0$, where X_0 is the radiation length, which can be interpreted as the average distance an electron or a photon needs to travel to interact once with the $PbWO_4$. $20X_0$ is required to ensure that the electron or photon will deposit all its energy. The 2.2 cm size is slightly bigger than the Moliere Radius. The Moliere radius is the radius within which a shower will deposit 90% of its total energy. The energy resolution of MPC is $\sigma(E)/E = 14\%/\sqrt{E} + 3\%$ [69].

Size of crystals	2.2 x 2.2 x 18 cm^3
Density	8.28 g/cm^3
Moliere Radius	2.0 cm
Radiation Length (X_0)	0.89 cm
Interaction Length (λ_I)	22.4 cm
Hardness	4 Moh
Refraction Index ($\lambda = 632$ nm)	2.16
Main Emission Lines	420,480-520 nm
Temperature Coefficient	-2%/°C
Radiation Hardness	1000Gy

Table 3.1: Properties of $PbWO_4$

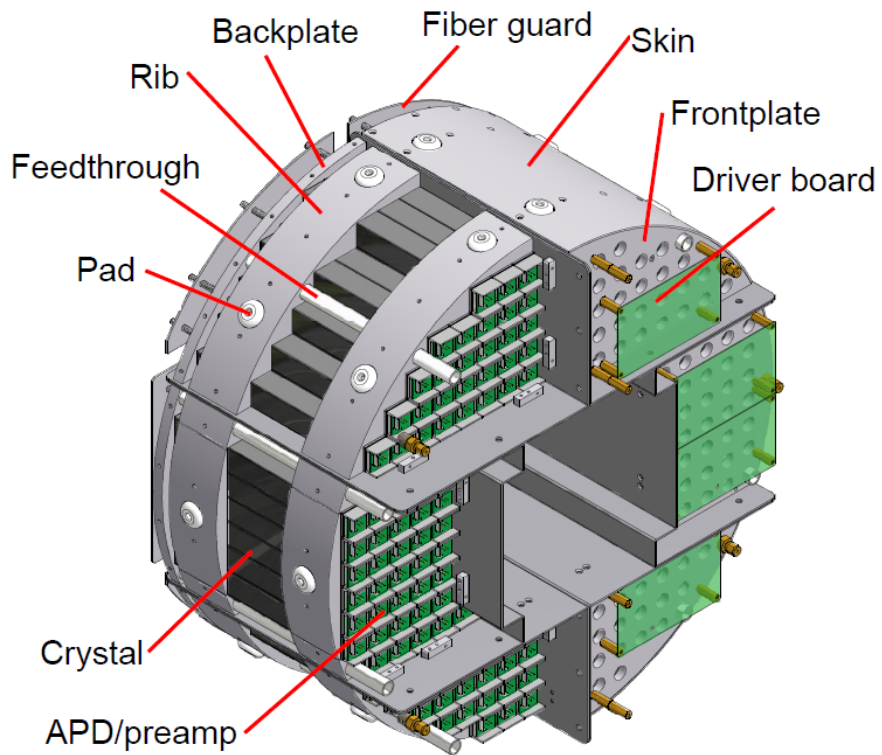


Figure 3.2: The mechanical design of MPC [69]. The collision vertex is towards the bottom right. Particles travel from the collision through the APD readout electronics (Driver board, Frontplate, APD, preamp) and into the crystals where they are detected. The probability of interacting with the electronics is small.

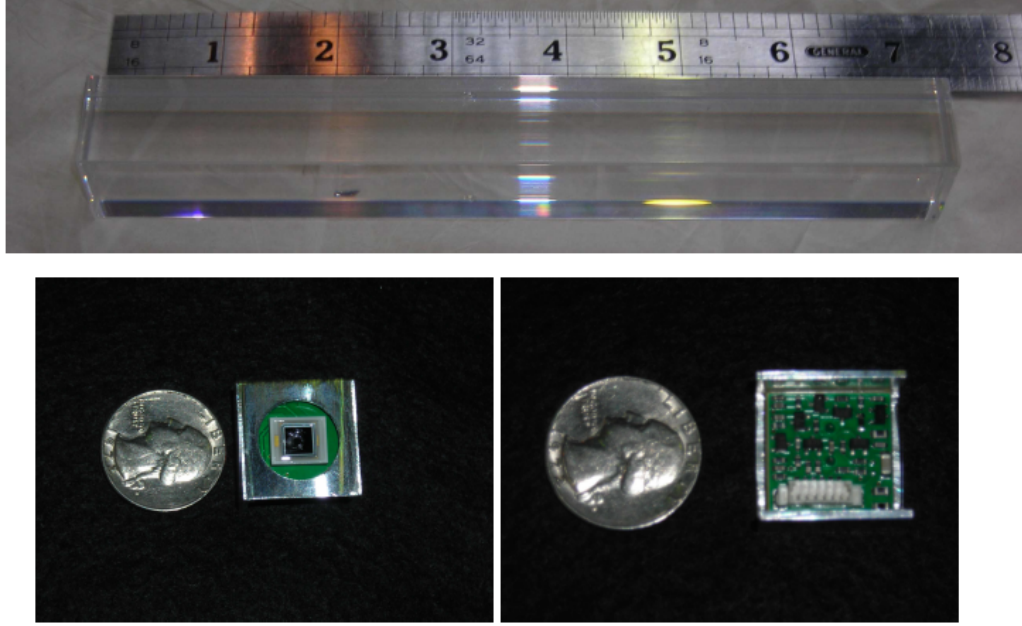


Figure 3.3: Top: the $PbWO_4$ crystal. The length of the crystal is 18cm or about 7 inches (the ruler shown in the picture is in inches). Bottom: An avalanche photodiode (left photo) mounted on the preamp electronics board. The right photo shows the flip side of the electronics board. [69]

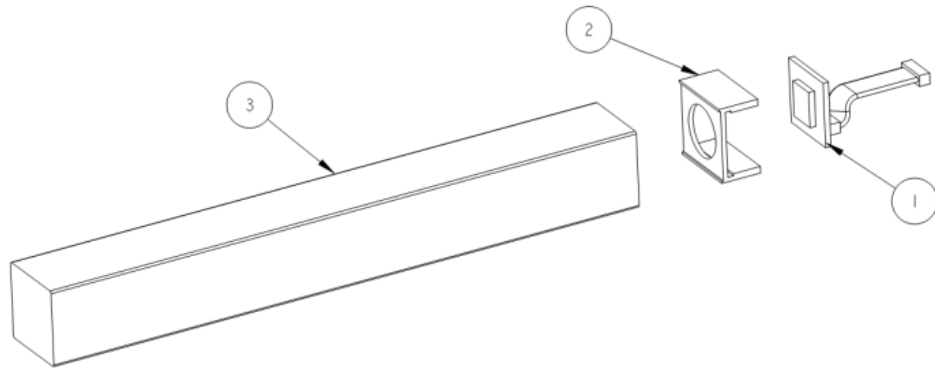


Figure 3.4: The basic MPC tower structure.(1)the APD and preamp (2)the aluminum APD holder (3) the $PbWO_4$ crystal [69]

3.2 MPC-EX Detector

The Muon Piston Calorimeter Extension (MPC-EX) is a combination of high resolution charged particle tracker and electromagnetic pre-shower detector. As a pre-shower detector, the MPC-EX can distinguish hadrons from photons or electrons. Most hadrons leave only a trail of electromagnetic energy in the detector. These are designated as minimum ionizing particles (MIPS) since they lose only a small amount of energy via ionization as they pass through matter. In some rare instances, hadrons can interact via the strong interaction, leaving hadronic showers. Electrons or photons almost always interact, causing an electromagnetic shower depositing almost all their energy in the calorimeter. In most cases, these showers begin to develop in the MPC-EX (a 10-20 GeV shower deposits roughly 10% - 20% of the energy in the MPC-EX, with the rest being deposited in the MPC). As a tracker with 2 mm resolution, the MPC-EX provides us with a picture of the fine structure of the early development of a shower. The profile of an electromagnetic shower is very narrow at the beginning, becoming wider later in the shower, which at its widest is typically the Moliere radius. Hence early in the development, the two photon showers from the decay of a π^0 can be resolved in the MPC-EX.

A 3D model of MPC-EX is shown in figure 2.8. Each arm consists of eight layers of silicon detector interleaved with tungsten absorber forming a very compact detector. Tungsten was chosen as the absorber since it has a short interaction length ($X_0=0.35$ cm)¹, while a silicon based sensor was chosen since it could provide very fine granularity. Figure 3.5 shows the basic structure: the MPC-EX sensor is attached to the dual SVX4 readout

¹For comparison, iron has an $X_0=1.8$ cm.

card (The SVX4 is a 128-channel analog to digital converter chip developed by Fermilab [29]). Each sensor is composed of a 4×32 array of minipads. The size of the minipad is about $1.8\text{mm} \times 15\text{mm}$. The signal from the minipad is split according to the ratio 4.5:1. The two split signals are sent to two SVX4 readout chips and digitized via a 256 bit ADC in the SVX4 chip. The high gain channel is more sensitive and enables us to detect MIPs (minimum ionization particles), which can be used to calibrate the MPC-EX (a MIP leaves 150keV in a minipad). The low gain channel extends our ability to measure the higher energy showers.

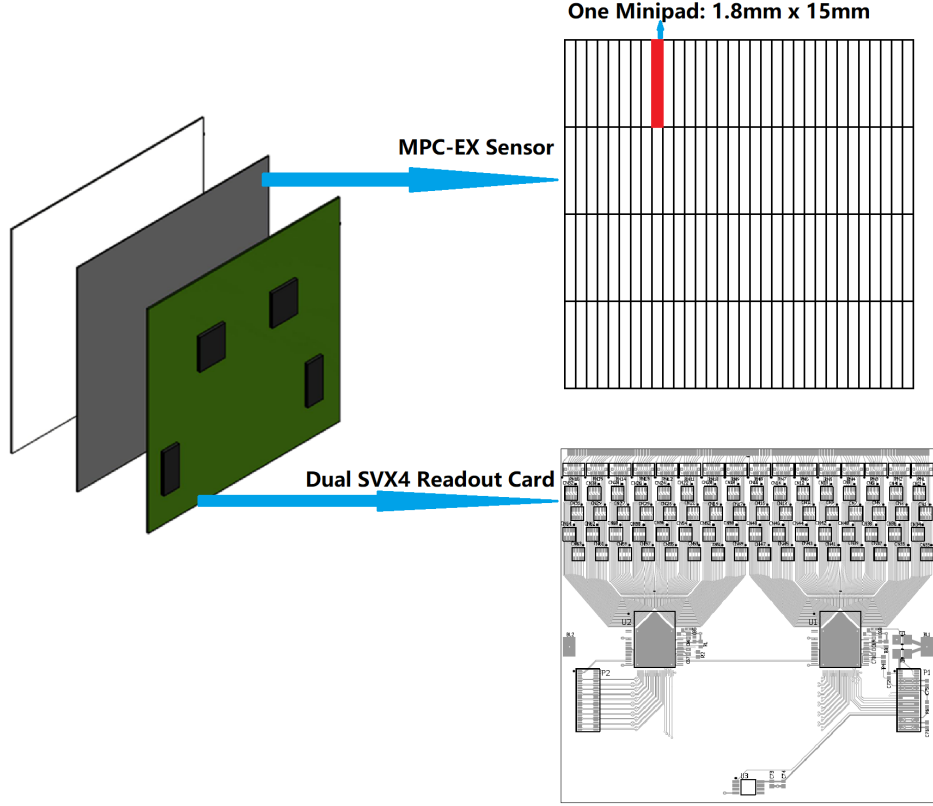


Figure 3.5: MPC-EX sensor and dual SVX4 readout card, where the pattern of the minipads on the silicon sensor is shown in the upper right, and the readout card is shown on the bottom right. The minipad sensor connections are made at the top of the board, through a set of decoupling capacitor arrays, and then into the SVX4 ASICs.

Figure 3.6 shows half of one layer of the MPC-EX: 12 silicon sensors, 12 dual readout cards, carrier board, and 2mm tungsten. The Moliere Radius of tungsten is about 1 cm, hence the electromagnetic shower is relatively compact in the MPC-EX, reducing the overlap between two close showers. Figure 3.6 also shows how the layers are stacked. The layers are stacked such that even layers are X-axis oriented, while odd layers are Y-axis oriented. This gives us an overall resolution of 2 mm, which allows us to reconstruct π^0 s up to 80GeV (4.5GeV in p_T) (see Figure 3.7). The MPC alone cannot distinguish high energy

π^0 s since the two decay photons merge into one shower. With the resolution of the MPC-EX, the separation can still be detected. Figure 3.8 shows the entire MPC-EX detector for one arm and its cross-sectional view. Also shown is the interleaving of X-style layers and Y-style layers. Figure 3.9 shows the actual pictures of installed MPC-EX in PHENIX.

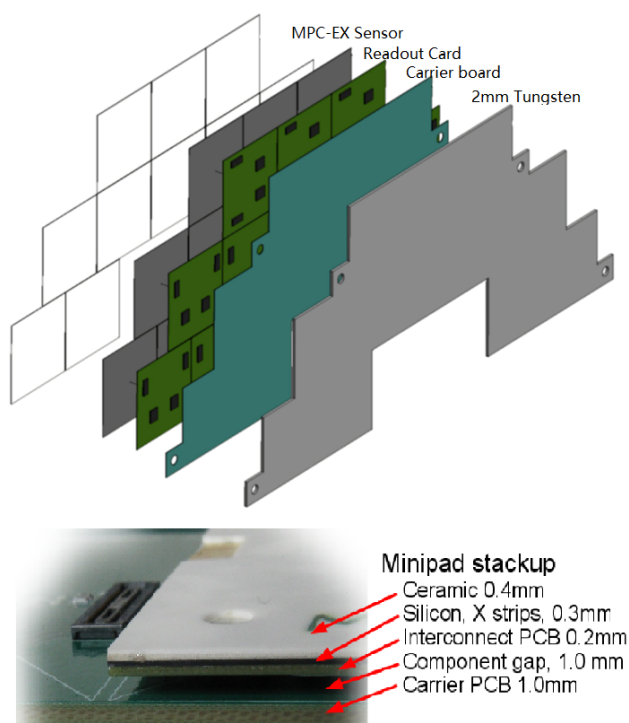


Figure 3.6: Top: A half layer of the MPC-EX (One layer consists of a sensor, readout card, carrier board, and the 2mm tungsten). Bottom: Minipad stack up on carrier board.

Figure 3.10 shows the electronics system of the MPC-EX detector (half detector of one arm). A power rack provides the power for the detector and the Front End Modules (FEM), mentioned in the previous chapter. The blower is used to cool the MPC-EX. Two adjacent half layers connect to the same FEM. There are sixteen FEMs for the whole de-

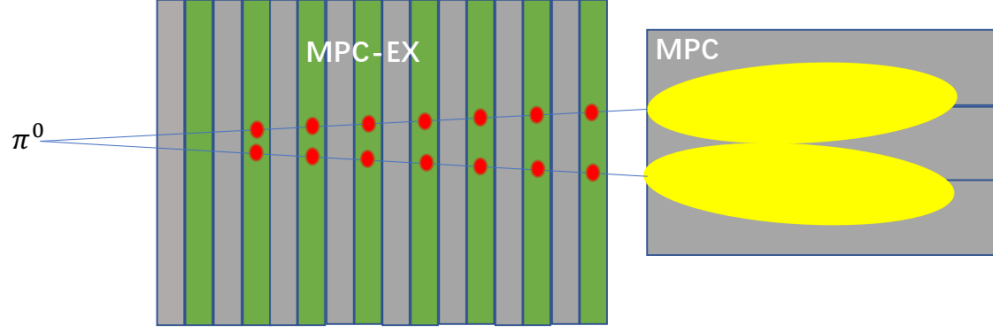


Figure 3.7: A high-energy π^0 decay into two photons. The two photons are so close that they merge into one shower in MPC. But with the MPC-EX, we can detect the separation of the two photons, as shown with the red dots.

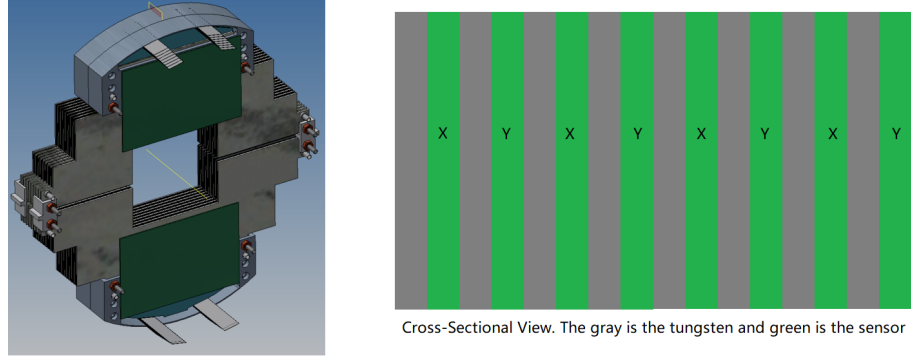


Figure 3.8: Left: the whole MPC-EX. Right: a cross-sectional view. The X-Y style makes the resolution 2mm. There are 24576 minipads per arm.

tector(both arms). The yellow line connects to the GTM providing the timing information. The red line connects to the Raspberry Pi (a microcomputer), providing the interface for controlling and programming the SVX4 chips. The blue lines are optical fibers connecting the FEMs to the DCMs. Zero suppression, in which a signal, lower than a threshold is rejected, is performed in DCM to eliminate the events caused by the pedestal. The number of readout channels for MPC-EX is large. There are 128 minipads per sensor, 3072 minipads per layer, 24576 minipads per arm, and 49152 minipads for the whole detector. For each minipad, we have two high and low channels.

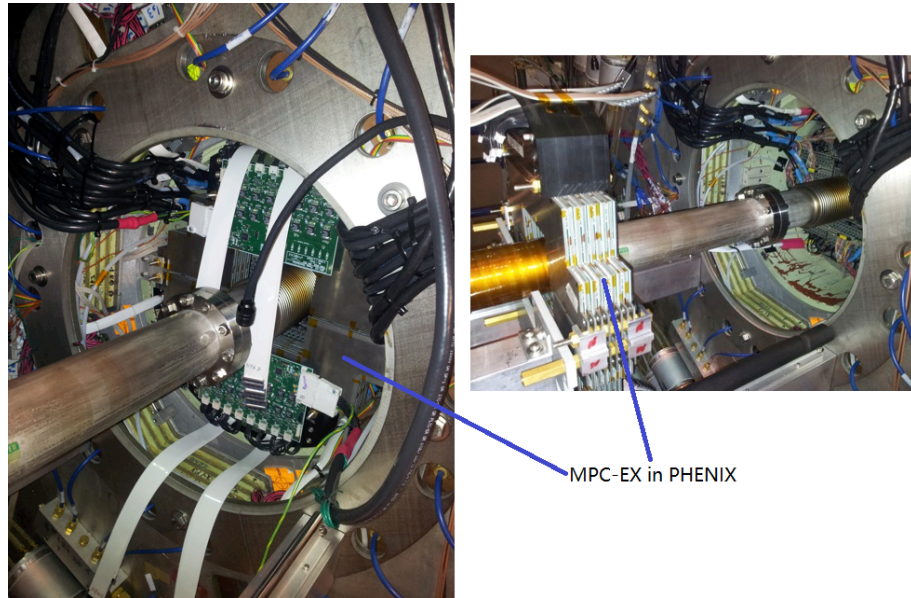


Figure 3.9: A picture of the MPC-EX installed in PHENIX. The space in PHENIX is limited, which is why a compact detector design was needed.

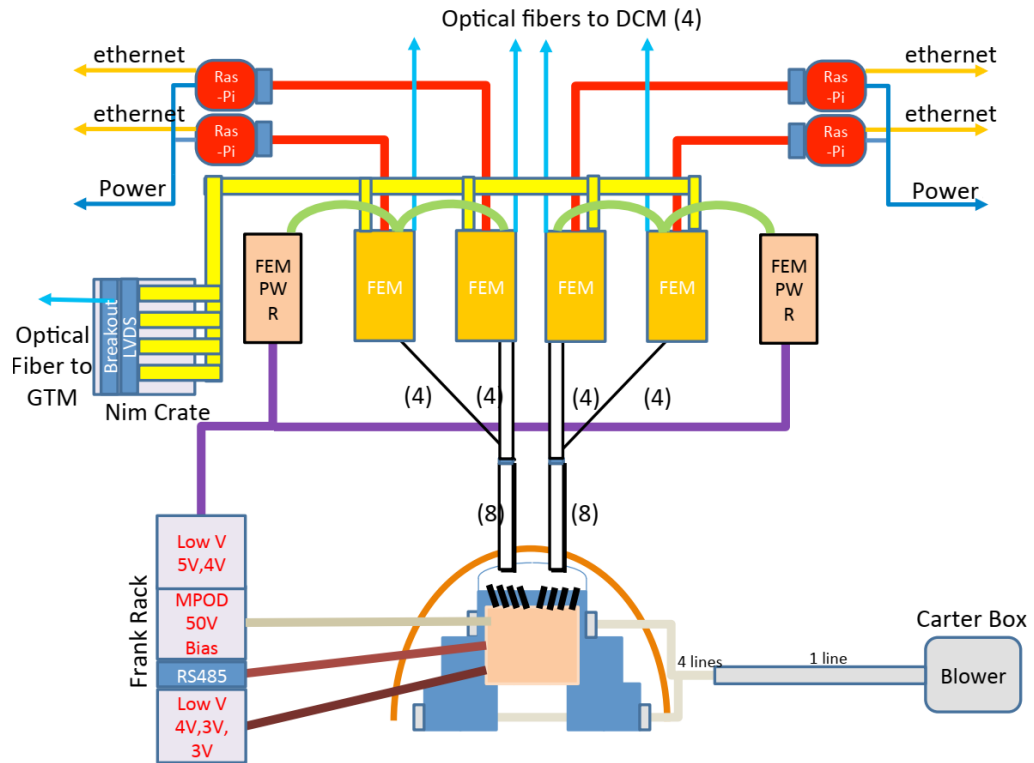


Figure 3.10: The readout and control system of MPC-EX. The Data from MPC-EX goes to the FEM and is transformed into standard packets. The Ras-Pi is the micro-computer used to control the FEM. The GTM provides the global timing. The blue line is the optical fiber connecting to the DCM

3.3 Test Beam Experiments

During the development of the MPC-EX design, we had two test beam experiments. The first one was at Fermilab, a large accelerator laboratory near Chicago, where we studied the effect of having the MPC-EX in front of the MPC. The second was at SLAC (Stanford Linear Accelerator Center). The goal of this test was to understand the ability of the MPC-EX to separate two very closely spaced showers.

3.3.1 Fermilab Test Beam

In 2013, we performed a test beam experiment at Fermilab. The goal was to test the performance of MPC crystals when layers of tungsten (MPC-EX) were placed directly in front of the MPC. Figure 3.11 shows the Fermilab test beam setup. Three MWPCs (multiwire proportional chambers) were used for tracking (Figure 3.12 shows the geometric setup). The scintillators before and after the box provided the trigger. The target we tested was the 5x5 array of MPC towers (in the light box).

A Cherenkov detector was used to select hadrons or electrons from the beam. The towers were calibrated using charged pions - which were mostly MIPs. Figure 3.13 shows the MIP peak. It is known that the energy of a MIP deposited in a tower is about 268MeV. We could then associate an ADC reading of about 2600 with 268MeV of energy being deposited in the tower.

Electron beams were then used to study the effect of tungsten being placed directly in front of the crystal array. Figure 3.14 shows the energy smearing of the shower energy

Wall thickness - 7.2

MT6-2.C

Wall thickness - 7.8

BEAM

MWPCs

108.3

34.6

114 +/- 1 cm

24.9

RACK

Table

Light Box

tungsten and towers

21

11.7

8.6

20

Trigger scint

20.1

90.3

59.3

MWPC

All measurements in cm

All errors +/- 1mm unless noted

deposited in the crystals when 0mm, 8mm, and 17 mm of tungsten are placed between the beam and the crystals. This is expected since some of the energy is now being deposited in the tungsten. Figure 3.15 shows the increase in radius of 90% energy containment, which increases from 2.2 cm to 2.9 cm.

R is the distance of the tower to the center of the shower (in crystal module units), which is calculated from the energy deposited in the crystals using the following equation:

$$x_c = \frac{\sum x_i \cdot w_i}{\sum w_i} \quad y_c = \frac{\sum y_i \cdot w_i}{\sum w_i} \quad w_i = 4 + \ln(\Delta E_i / E_{total}) \quad (3.1)$$

where (x_i, y_i) is the center position (in module unit) of the tower i (i is the index run

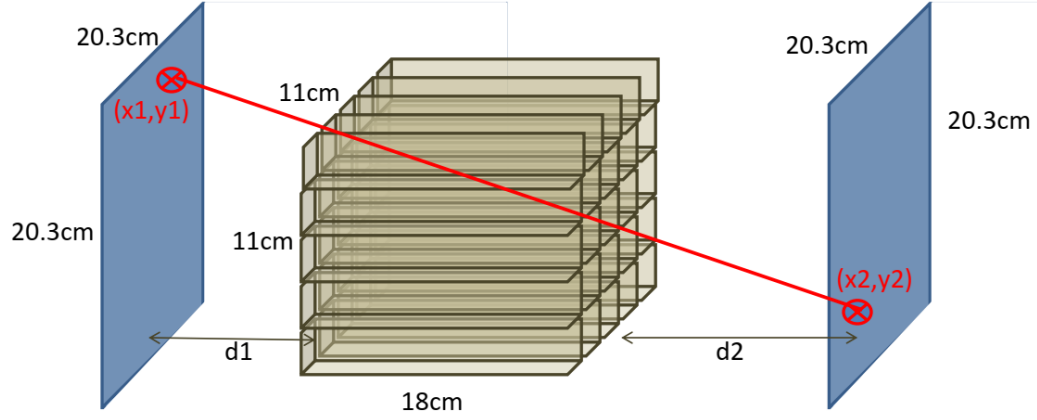


Figure 3.12: The tracking system for the Fermilab test. The tungsten is placed at the front of the towers array (about 5cm away). The MWPCs provided the hit position on MPC towers. The active area of the tracking chambers was 20.3cm $\times$ 20.3 cm. d1=301.8cm and d2=175.3cm.

over the 3x3 array of towers). ΔE_i is the i th crystal energy. E_{total} is the sum of the 3x3 array of towers closest to the center of the shower as measured by the tracking system. w_i is the log energy weight (if the value is less than zero, we ignore it). (x_c, y_c) is the log-weighted center (compared with the gravity center, the log-weight is better at describing the concentration of the deposited energy). R can then be calculated: $R = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2}$ for the i th tower. The vertical axis of Figure 3.15 is the tower energy ratio. We fit to the following function:

$$f(R) = p_0 e^{-p_1 R} + p_2 e^{-p_3 R^3} + p_4 e^{-p_5 R^5} \quad (3.2)$$

$p_0 - p_6$ are fitting parameters. We then integrated this function to encompass 90% of the area to yield the 90% containment radius. Table 3.2 shows the effect of tungsten on the MPC. The shower size becomes larger as expected. 17mm tungsten is very close to the eight-layer MPC-EX detector(16mm), and the radius containing 90% of energy is about 2.93cm.

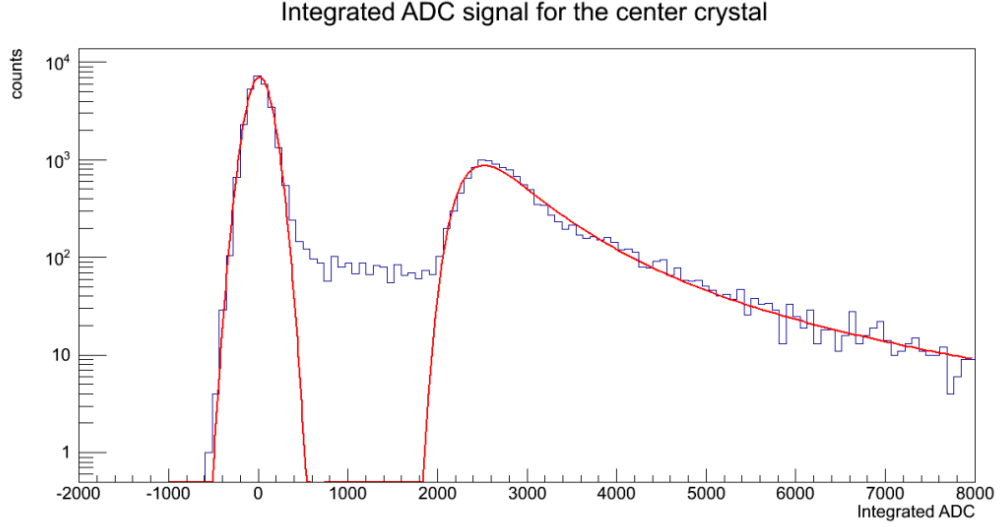


Figure 3.13: The signal of a MIP for one channel (ADC crystal) in the Fermilab test. The prominent peak at zero is the pedestal. The first peak is fit by Gaussian, and the second peak is fit by Landau.

Thickness	90% Energy radius	Tungsten Effect
0 mm	2.18 cm	0 cm
8 mm	2.44 cm	1.10 cm
17 mm	2.93 cm	1.96 cm

Table 3.2: The effect of MPC-EX on MPC

The appearance of MPC-EX did affect the shower radius on MPC. The shower reconstruction algorithm uses a 3x3 tower array with a radius is about 3.3cm, behind the MPC-EX as the energy for MPC, which is reasonable according to this test beam result.

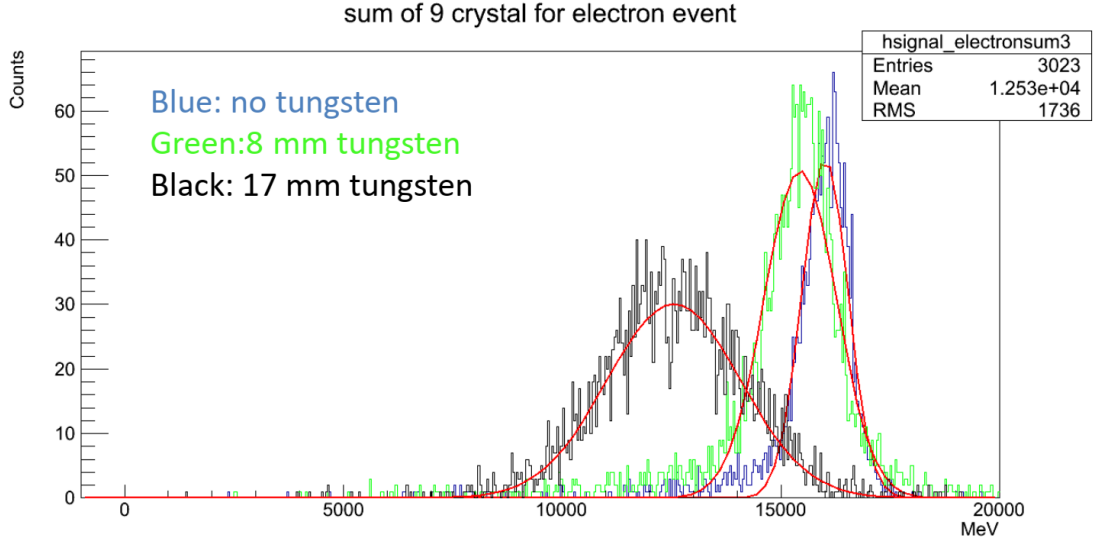


Figure 3.14: The energy deposited in a 3x3 array of towers by a 16 GeV electron beam for different thicknesses of tungsten. Since the beam loses energy when passing through the tungsten, the smearing effect becomes more significant as thickness increases.

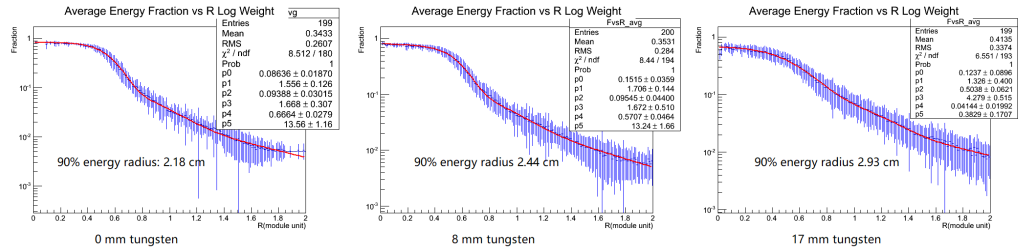


Figure 3.15: Energy fraction vs. radius when a tungsten place of thickness 0 mm, 8 mm, and 17 mm are placed in front of the MPC

3.3.2 SLAC test beam

In 2014, a test beam experiment was done in an electron beam at SLAC. This test included a 5x5 MPC array of MPC crystals and eight half layers of the MPC-EX. In this test beam run, we were interested in the ability of MPC-EX to separate the two close showers. Figure 3.17 shows the layout: GEM trackers were used to track the particle position. The high intensity of the beam meant that we had a relatively high probability of detecting two electrons in an event simultaneously, which could be used to test the separation ability of the MPC-EX. A scintillator installed upstream counted the number of electrons. Figure 3.16 shows an integrated scintillator signal: the second peak indicated events with two electrons. Figure 3.18 shows an example of such a two electron event. In the MPC (lower panel), a shower cluster can be seen in the center, but the position of each individual electron can not be distinguished from one another. However, we can recognize two-electron hits with the MPC-EX (upper panel). The distance between these two showers is 1.4cm corresponding to a symmetrically decaying 40GeV π^0 in the MPC-EX when installed into the PHENIX experiment.

The test beam in SLAC clearly showed that the MPC-EX addition to the MPC enabled the detection of two closely spaced showers as we had expected, especially in cases where two showers were indistinguishable in the MPC. This demonstrated the ability of MPC-EX in combination with the MPC to reconstruct the high energy π^0 s.

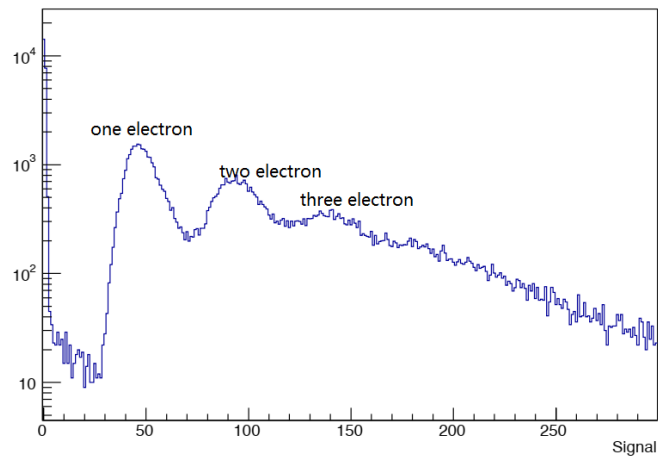


Figure 3.16: The integrated scintillator signal energy distribution. One electron, two electrons, and three electrons events are clearly seen.

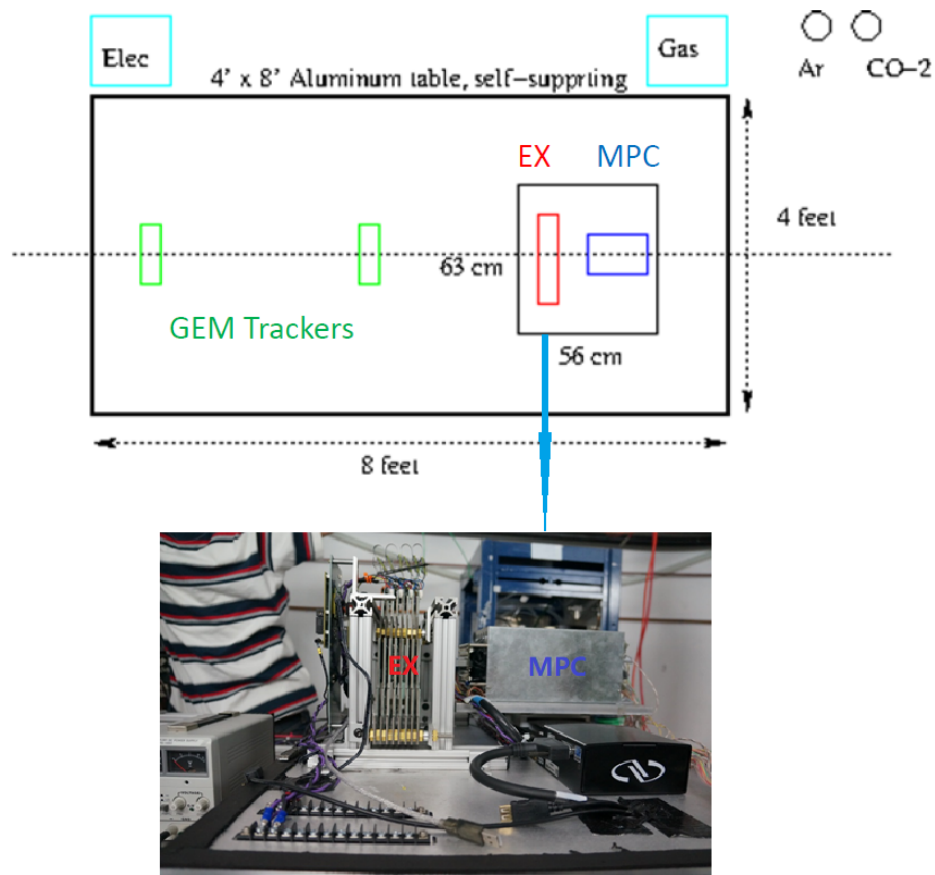


Figure 3.17: The SLAC test beam layout

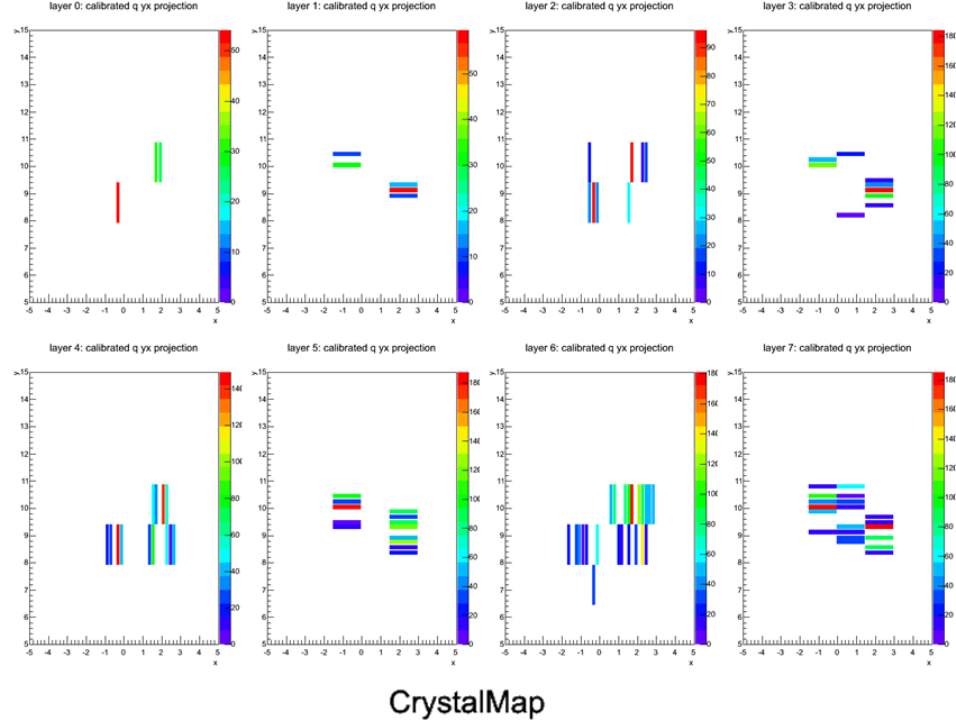


Figure 3.18: A two electron event in the MPC-EX and MPC. Top: MPC-EX (The units in x and y are in cm and the color scheme represents the energy deposited in a minipad. The 8 panels correspond to the 8 layers of the MPC-EX. One can clearly see the development of the shower. The two showers are clearly distinguishable. Bottom: the 5×5 tower array (units along the x and y axis are μm and the color scheme represents the energy). In the MPC, only one shower is seen corresponding to the overlap of the showers from the two electrons.

The MPC-EX detector was installed in front of the MPC, and 200 GeV center-of-mass deuteron on Gold (d+Au) data taking commenced in 2016. Later in the run, data was taken at 62 GeV, 39 GeV and 20GeV. Before the data was usable, however, calibrations were necessary to set the scale between the measured signal in ADC units and the real energy.

3.4 Calibration of MPC-EX

Our initial step was to detect bad channels, which accounted for less than 5% of all channels.

3.4.1 Dead/Hot Channels

This section describes how dead or hot channels are identified. The procedure turned out to be rather more complex than originally thought due to the fact that the natural distribution of hits varied by region because of physics. We had four energies to analyze, but the methods are similar. 200 GeV center of mass (CM) data is used as an example[\[14\]](#). A summary of steps for the dead/hot map are following:

1. Select good runs, where a “run”, is a set of data taken typically over one hour, and given a “run number”, used to organize the data.
2. A set of cuts is used to prepare a sample for fitting. The cuts used in this preparation are similar to those used for cutting channels in the final hot/dead map. The cuts use integrals of several regions of the ADC.
 - (a) by row of minipads in a sensor.

- (b) by radius in the MPC-EX.
- 3. The run dependence of the hot/dead channels is studied but turns out to be very small.
- 4. Some of the channels exhibit a discretized behavior. These are found and cut.
- 5. The selected channels are summed over the entire data sample and can then be used to do a polynomial fit by row. The cutting procedure, using the integral method, begins again. However the comparison is now made to the fit.
- 6. Channels that are found to be discretized channels from before remain in the hot/dead list.
- 7. If a channel has a run dependence in which it is hot or dead for part of the run, it is cut.

Data Set and Event Selection

The data we used for analysis is from the “fast production” of d+Au 200GeV data. This is data made available rather soon after the data has been taken, where only preliminary processing has been done. Runs can be of varying lengths, depending on a variety of things such as machine performance, scheduled down time, and detector status. Each run is divided into several segments, where a segment is reasonable unit of data for manipulating on computer disk. By checking the run status, we selected 92 good runs. The first 64 runs are divided into 8 or 9 segments, and the remaining runs are divided into 20 to 40 segments, depending on the length of the run. The following are the good runs data:

454789 454794 454798 454799 454802 454808 454809 454810 454811 454935 454936
454937 454944 454945 454946 454947 454948 455049 455051 455052 455053 455056 455060
455062 455063 455064 455065 455066 455071 455073 455074 455077 455078 455080 455081
455082 455083 455200 455201 455202 455203 455206 455207 455208 455209 455211 455212
455213 455218 455220 455221 455222 455223 455302 455303 455304 455306 455342 455344
455346 455351 455352 455353 455355 455362 455364 455366 455367 455446 455447 455450
455451 455452 455476 455477 455478 455545 455547 455550 455551 455552 455585 455586
455587 455589 455590 455592 455604 455605 455637 455638 455639

To get enough statistics for each channel, the 92 runs are grouped into 44 groups, where each group has 20 to 30 segments :

- Runs 454789 to 455355 (64 runs) are divided into 16 groups (each group has four runs).
- The remaining 28 runs are divided into 28 groups (each group has one run).

Trigger and cuts:

- Minbias Trigger
- Single Event Buffer
- PARSTTIME cut. This cut refers to the preamp reset for the SVX4 chips. For each arm, all the packets have the same PARSTTIME. The following PARSTTIMES are excluded for both arms: 32, 33, 44, 45, 46.
- StatePhase cut. This cut refers to the state of the SVX4 chips. Each packet from the DAQ has a StatePhase, and the following StatePhase for both arms were excluded:

39, 40, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 84, 85, 86, 118, 119, 150, 151, 182, 183, 184, 201, 213, 214, 215, 216, 248, 249, 250, 281, 282, 283, 312, 313, 346, 347, 378, 388, 411, 443, 475, 476, 499.

- **Cell ID Cut.** Each SVX4 chip readout has a CellID, and all SVX4 chips should be the same in one event. We first find the most common CellID and then cut out the SVX4 chips whose CellIDs are different.
- **Valid Pedestal** (the χ^2 fit of a Gaussian function to the pedestal is reasonable). Note: all ADC values are after pedestal subtraction.

The Overview of the Integral Method

Each high gain and low gain ADC distribution is divided into five regions, and the number of hits is integrated. Since the gains of the South and North arm are different as well as the first two layers of both arms, the ranges are set differently. The ADC values dividing the regions are:

- **High Gain**

- **South Arm**

- * **First two Layers:** 0,15,45,80,120,200

- * **Other layers :** 0,10,40,75,115,195

- **North Arm**

- * **First two Layers:** 0,15,30,50,80,150

- * **Other layers :** 0,10,25,45,75,145

- **Low Gain**

- **All Layers:** 0,5,15,25,40,100

There are two main considerations in choosing the regions. First, the integrated hits should have enough statistics; second, those five regions should overall describe the ADC distribution curve. Figure 3.19 shows how the five regions are divided.

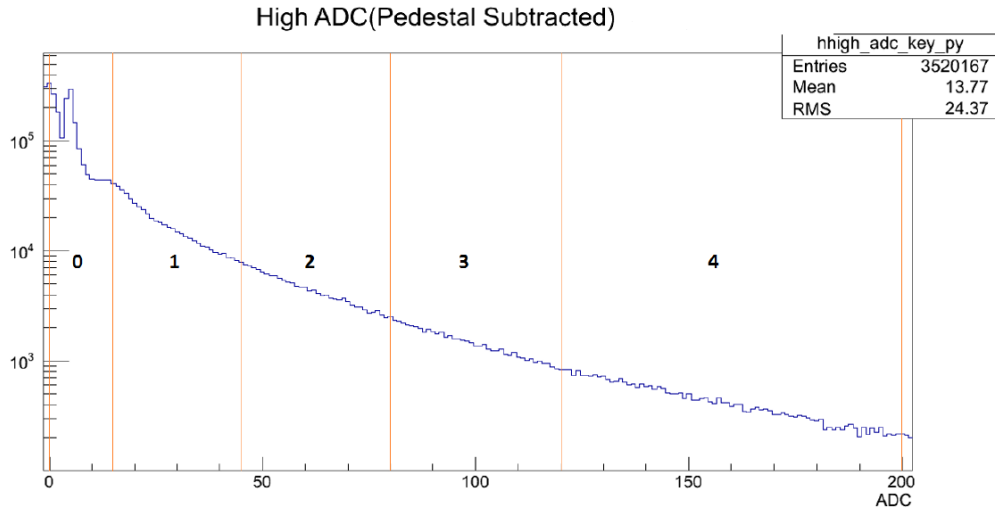


Figure 3.19: A high gain channel ADC distribution and the five regions chosen for integrating the number of hits.

Before continuing, it is worth understanding the logic of the analysis which was followed. Initially, it was thought that a simple cut by row, as explained later, would be enough. This turned out not to be the case, and a cut by radius in the MPC-EX detector was implemented, which still had deficiencies. Finally, a fit was done (as explained later), which proved to be sufficient. The first two cuts were still of use, as they provided the basic set of minipads used in the fit.

First Pass: Cut by Row

The basic MPC-EX unit is the sensor. Each sensor has 128 minipads (4×32). For each row, there are 32 minipads that have similar behavior (from the electronics environment). Hence grouping them is a reasonable choice. A special key identifying each minipad is used for the identification of dead/hot channels. It is defined as $24576 \times arm + 3072 \times layer + 128 \times sensor + 32 \times ly + lx$ (We will return to the normal hardware key in the High-Low ratio determination). The cut is performed using the following steps (for one of the regions):

1. calculate the average integral value
2. calculate the RMS of integral value
3. check the deviation of the channel when compared to the mean value
4. if the deviation is more significant than 3-RMS, the channel will be identified as bad
5. repeat first 4 steps 3 times, each time ignoring the bad channels

The 3-RMS cut was chosen by checking if the bad channels are cut out successfully, as shown in figure [3.20](#). Region 0 is not used to find the bad channels since it contains pedestal. If one channel is identified as bad in one region, it will be marked as dead/hot. The first pass cuts out the prominent hot channels. Note the difference in the y-axis in the two plots.

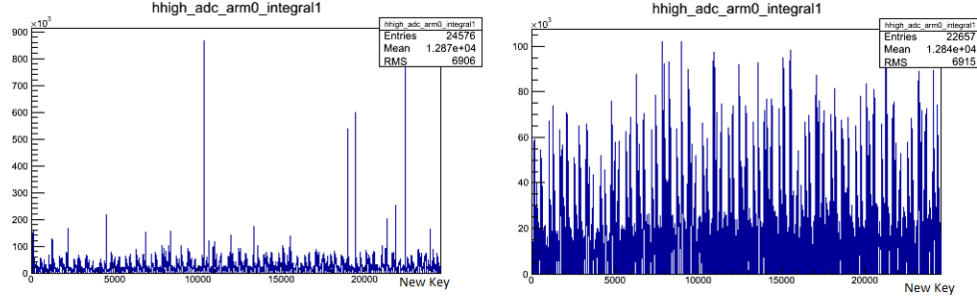


Figure 3.20: Left: the integral value in region one before the first pass. Right: after the first pass. The new key is ordered by row, sensor, layer, and arm. Note the scale of the y-axis.

Second Pass: Cut by Radius in the MPC-EX

Cutting by row is not enough if we look at the integrated values by the distance to the beam pipe as shown in figure 3.21. The channels in one layer are divided into 9 groups according to their distance to beam pipe: 6.5cm, 9cm, 10.5cm, 12.1cm, 13.5cm, 14.4cm, 15.6cm, 16.8cm, 18.1cm, 21.5cm. A radial dependence is expected since the pads closer to the beampipe subtend a larger $\Delta\eta\Delta\phi$. To cut out the bad channels based on radius dependence, the following steps are followed:

1. Perform Row Cut (previous section)
2. Calculate the mean integral hits of each radial group
3. Calculate the RMS of each group
4. Cut out channels if the deviation $> 3RMS$ in the same group or $> 6RMS$ in the next left group (in figure 3.21) or $< 6RMS$ in the next right group
5. Repeat the second to fourth steps 3 times

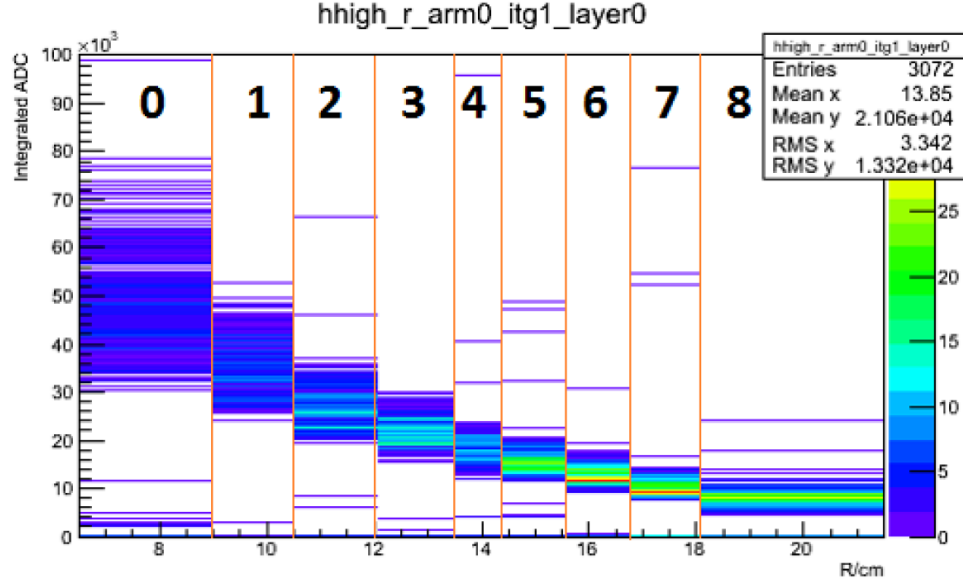


Figure 3.21: Integrated hits of layer 0 in region 1, where each entry is one minipad. Smaller distances from the beam pipe have minipads covering a larger rapidity and phi-angle range. Deviations from the expectation can be seen

The 3-RMS and 6-RMS cuts are decided by checking figures like figure 3.22 and determining by eye. One can see that the cuts are effective.

Run Dependence and Third Pass

The analysis of the first and second passes is based on the data groups. By repeating the same process, we can get the run dependence of the dead/hot channels. Figure 3.23 shows the number of dead/hot channels is very stable for both high and low gain. Figure 3.24 shows the dead/hot channel frequency of high and low gain. Only channels which are identified at least once are in the plot. Some channels are identified as bad a very few times. This is presumably from statistical fluctuation. Some channels are always bad (i.e. 44 times); these should be identified as dead or hot. Hence a third pass is used: if a

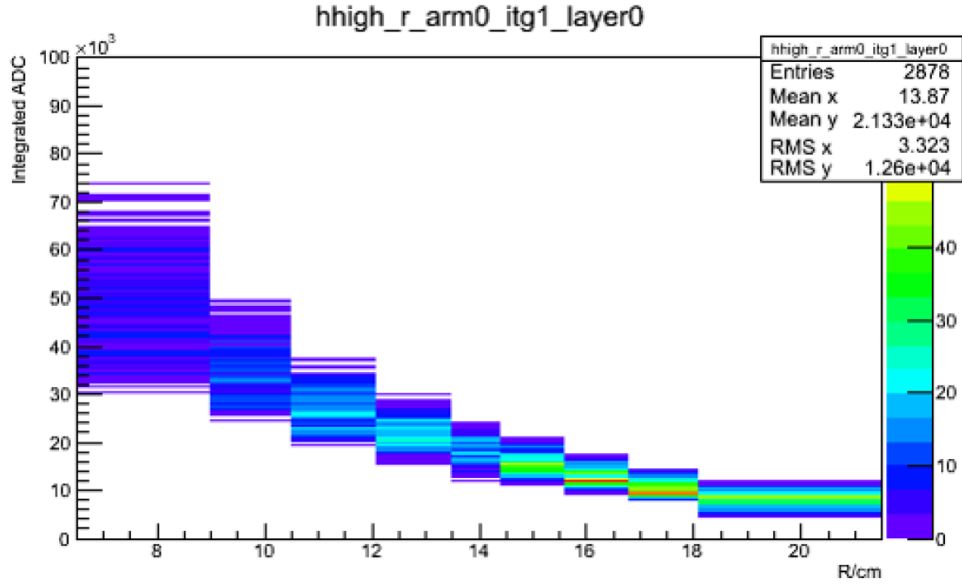


Figure 3.22: Integrated hits of layer 0 in region 1, where each entry is one minipad. Smaller distances from the beam pipe have minipads covering a larger rapidity and phi-angle range. After the two passes, the bad channels in the previous figure are gone.

channel is identified as dead/hot channels more than 27 times, it will be marked as bad. It must be stressed that these dead/hot channels are NOT used in the database. Rather they are the sample used for the polynomial fit discussed later.

Discrete Channels

There exist some channels which we will describe as discreet, in which the ADC distribution is not contiguous as shown in figure 3.25. For these channels, the missing ADC values seem to be added to the next highest ADC value (presumably from a missing bit in the readout chain), and the integral method will smooth them out. To find the discrete channels, a special method is used:

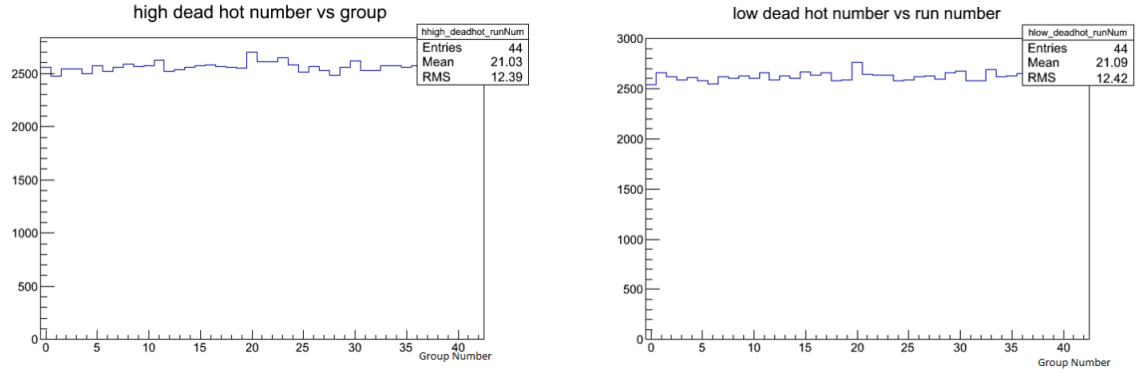


Figure 3.23: Left: Run dependence of dead/hot channels for high gain. The number of dead/hot channels is quite stable. Right: Run dependence of dead/hot channels for low gain. The number of dead/hot channels is quite stable.

1. Check ADC value: High Gain from 15 to 110 and Low Gain from 5 to 40
2. Check if $|Bin_i - Bin_{i-1}| > |Bin_i + Bin_{i-1}|/2$ or $|Bin_i - Bin_{i+1}| > |Bin_i + Bin_{i+1}|/2$
3. if the previous occurrence happens 8 times or more, mark the channel as a discrete channel

Finally, we found about 700 discrete high gain channels and 75 discrete low gain channels. Unlike the previously identified channels, these WILL make it into the final hot/dead database list.

Next Pass: Finding dead/hot channels by comparing to a fit

The first pass groups channels locally, while the second pass groups channels globally. For both of them, we assume the behavior of the channels in the same group is similar. However, this is typically not the case; the distributions have a distribution and good channels are cut out (Figure 3.26). In addition, some bad channels are missed by the methods

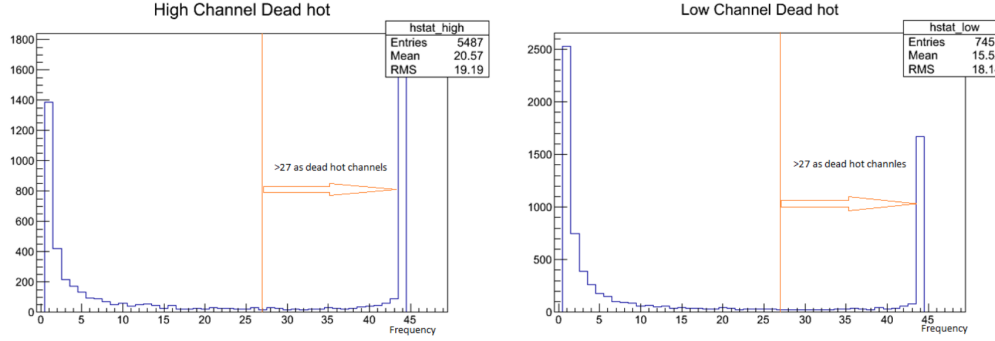


Figure 3.24: Left: The frequency of dead/hot high gain channels for the 44 groups where the X-axis stands for how many times the channel is identified as bad and the Y-axis is the number of the channel. Only channels which are identified at least once are in the plot. The straight line gives the boundary for dead/hot channels:27. Right: similar plot for the low gain.

described above (figure 3.27). It is important to characterize the distribution of hits in each row. Hence a fitting method is used as follows:

- Use the first and second passes to get an initial set of channels.
- For these channels, do a quadratic polynomial fit for each row (If the number of the degrees of freedom is small, back off and use only first pass "row cut")
- Starting with the initial uncut data, cut a channel if it is 40% away from the fit.

Figure 3.28 shows an example of how well the method works. The dead/hot channels in the database come from this final fitting pass where the data set used is the sum of all runs of the dAu200 GeV fast production. At the end of the procedure, the final plots were checked visually for significant problems. None were found. Finally, the dAu200 GeV data set's run dependence was checked, and it was found to be stable enough that only one dead/hot channel map was deemed necessary.

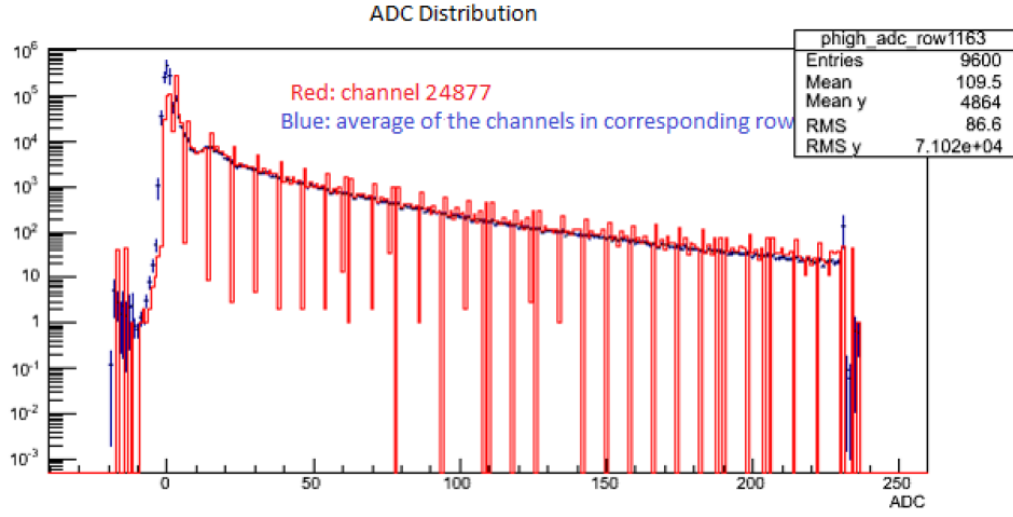


Figure 3.25: One discrete channel, which is not identified as dead/hot previously. The blue line shows reference from distributions from neighboring channels, and the red is a discrete channel.

Dead/Hot Channels of dAu62GeV, dAu39GeV and dAu20GeV

The method used to identify the dead/hot map at low energy is similar to dAu 200 GeV as described above. However, there are some differences:

- Data Set: from full production using the Analysis Train (not from fast production).
- No Single-Event buffer cut since the multi-event buffer was working.
- Add state phase = 43 cut. This will be explained below. following
- In addition to the 200, 62, and 39 GeV data, a sample of 20 GeV data was taken.

For this data we removed 6 bad runs: 456655,456727,456733,457099,457115,457118.

These were identified by looking at ADC distributions. When checking with the online logbook, it was found that these were runs where there were MPC-EX problems - e.g. DAQ stopped due to the MPC-EX problem.

The State Phase tells one what the FEM logic is doing ,e.g., reading out. Hence, if for instance, data is being taken while it is also being read out, the data is corrupted. This will affect the multi-event buffering. Some state phase cuts have already been done. However, it was found that an additional state phase (=43) needed to be excluded for the lower energy running. Figure 3.29 shows an example of this where one can see this corruption in the circled channels. A closer inspection shows that state phase 43 needs to be added to the list of bad state phases. The 200 GeV Hot/Dead map was made using only single-buffered events from the online production - hence we did not see this problem. An additional cut for the state phase =43 cleans up the issue. Figure 3.30 shows the ADC vs. key distribution with all the relevant state phases (including 43) are cut. The corrupted channels are gone. While it should not affect anything, this cut is added for the 200 GeV data as well.

Summary

The following is the table of the dead/hot map. For dead/hot channels at low energy, more than 95% of them are the same when compared with dAu 200 GeV. The bad channels at high gain increase slowly.

Energy	Only Bad in high	Only Bad in low	Both bad in high or low	Total Bad Channels
200GeV	1062	352	816	2230
62GeV	1057	440	848	2345
39GeV	1079	664	878	2616
20GeV	1134	739	960	2833

Table 3.3: Summary of number of dead/hot channels.

Dead/Hot Hot Map after Calibration

The previous dead/hot map is on the ADC level. However, after the MIP calibration, there are still some dead/hot minipads (figure 3.31). To remove them, a similar "cut by radius" method is used (this time, after the energy calibration). The number of new dead/hot channels is small. we found 40 minipads for dAu200GeV, 98 for dAu62GeV, 485 for dAu39GeV and 104 for dAu20GeV. Figure 3.32 shows the distribution of the hits after masking out the new dead/hot channels.

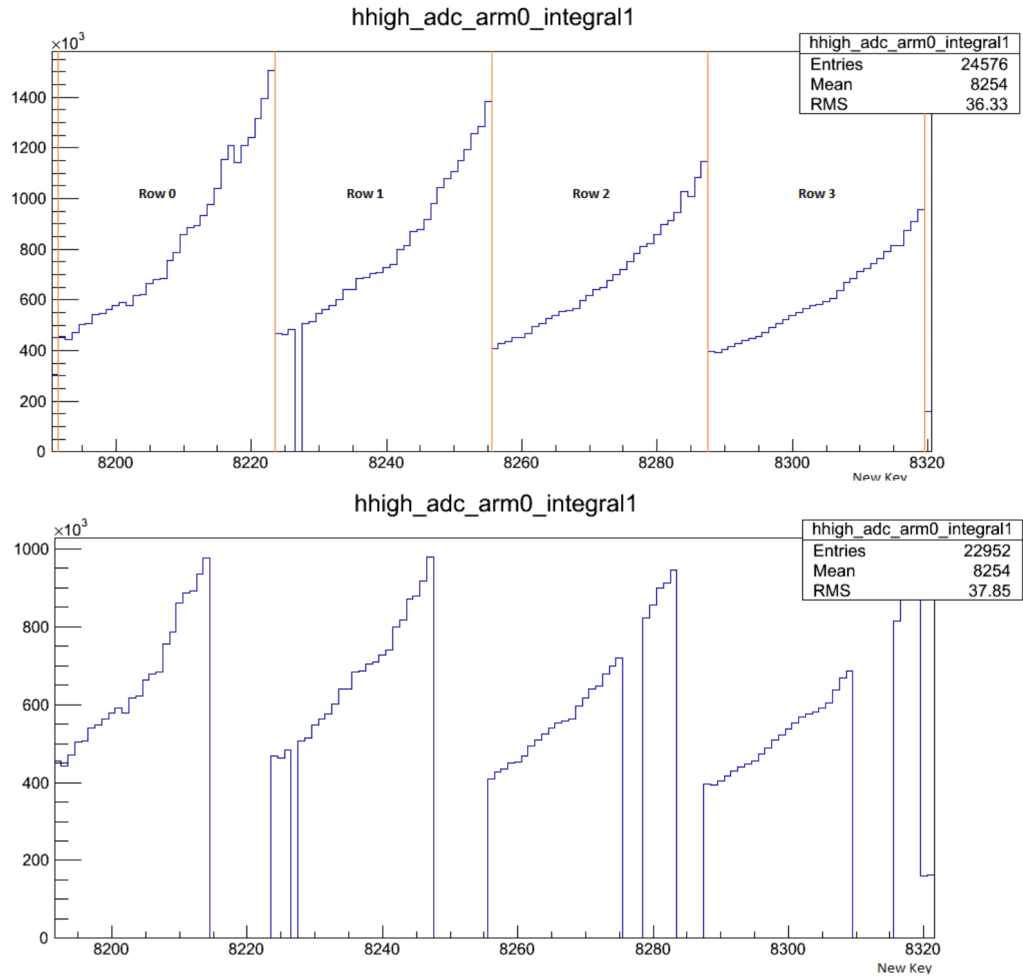


Figure 3.26: Top: Histogram of hits of the high gain channels in one sensor before any cuts. There are four rows in one sensor. One can see the variation across a row. Bottom: Histogram of hits in the high gain channels of one sensor after the first two passes of cuts discussed above. Some good channels are cut out.

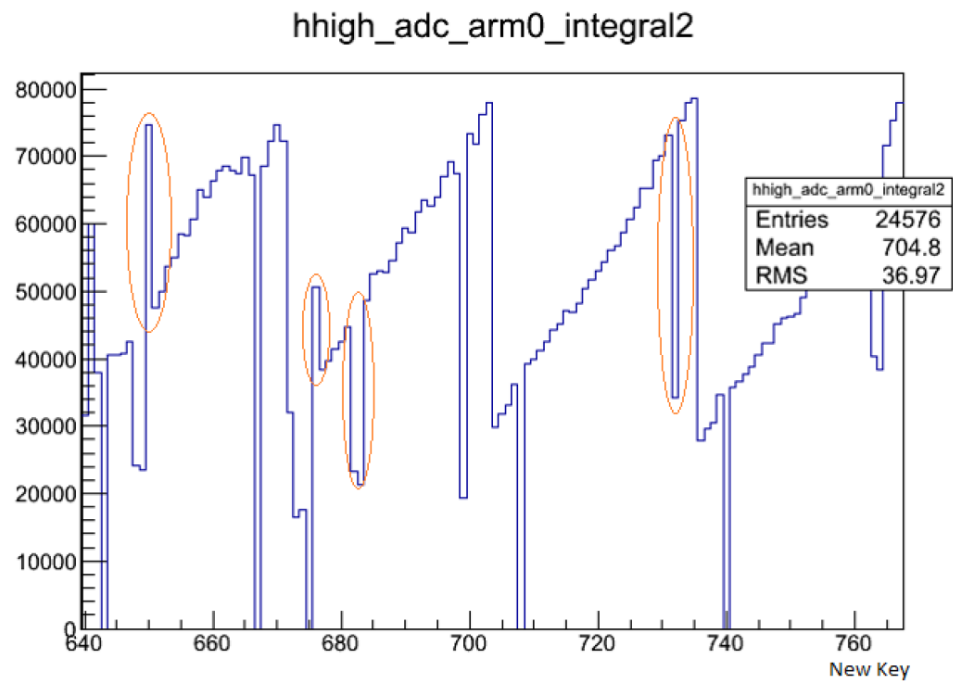


Figure 3.27: Marked channels are different from their surrounding channels. The problem is that the RMS in these groups is large (as a result of the marked channels), so these channels are still within the 3-RMS limits.

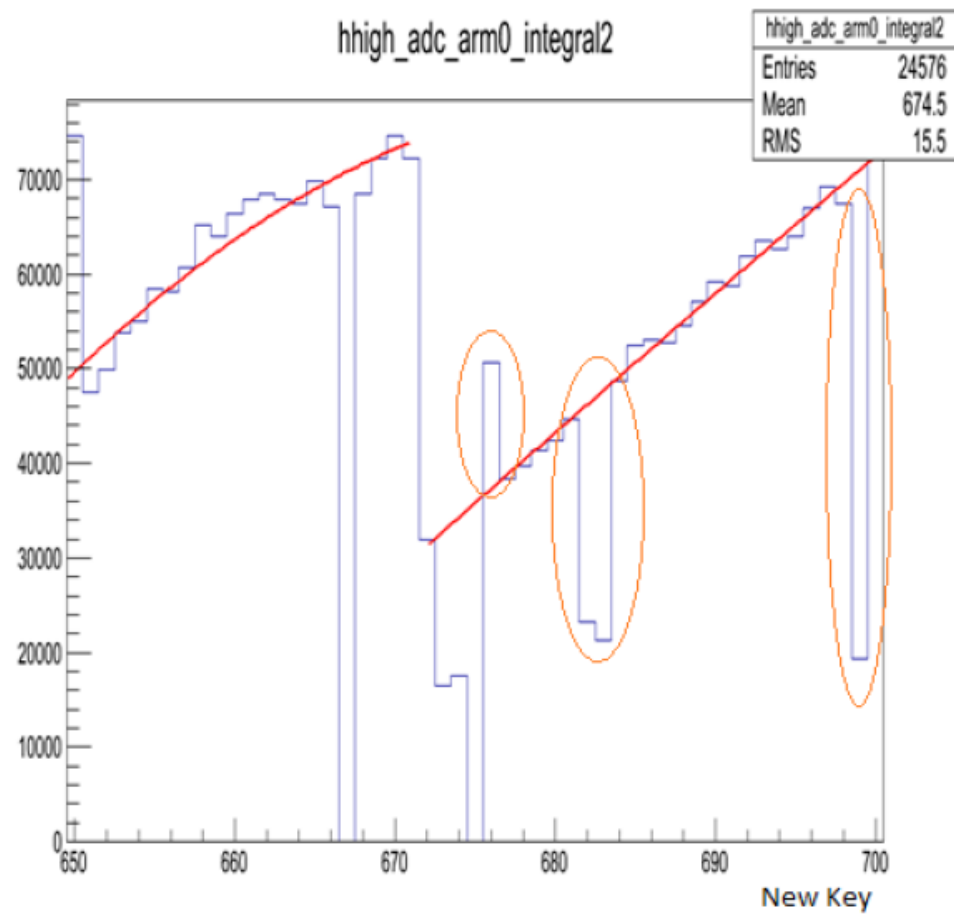


Figure 3.28: Using the quadratic polynomial to fit the pattern. The difficult to identify deadhot channels can be easily found.

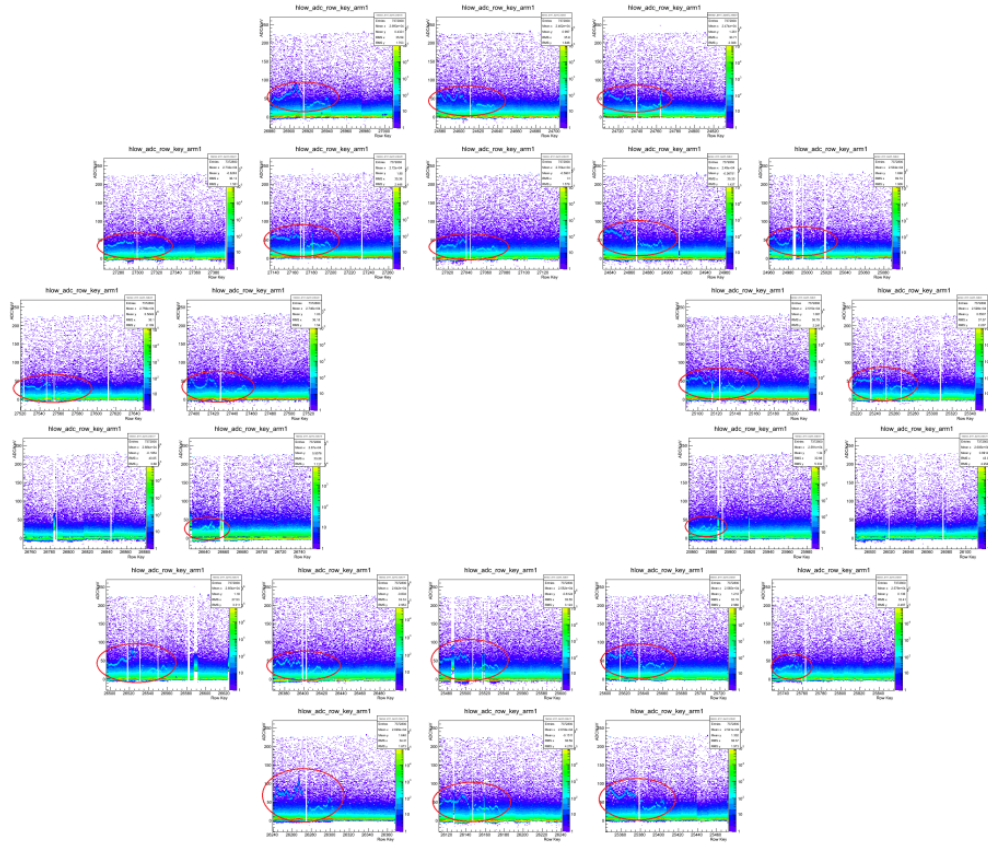


Figure 3.29: Sensor low gain ADC vs. Key (ordered by row) of North Arm Layer 1 of dAu 39 GeV: state phase = 43 cut is not applied. The corrupted pattern can be seen in many sensors. Examples are circled.

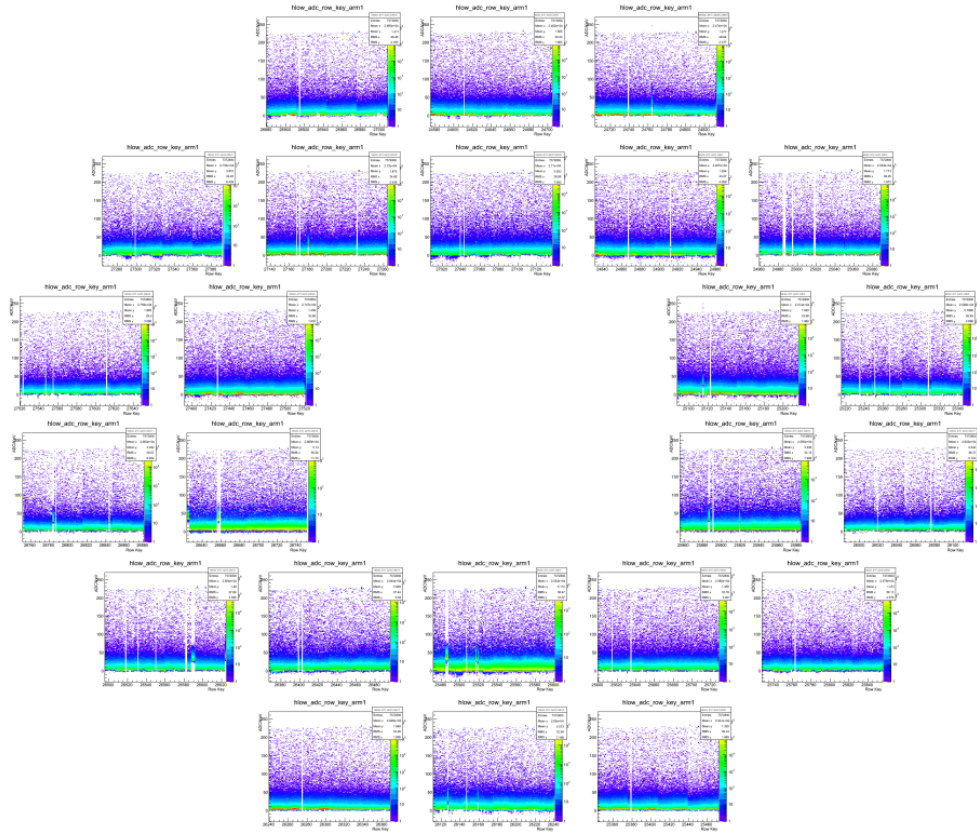


Figure 3.30: Sensor low gain ADC vs. Key (ordered by row) of North Arm Layer 1 of dAu 39 GeV: state phase = 43 cut is applied. The corrupted pattern is gone.

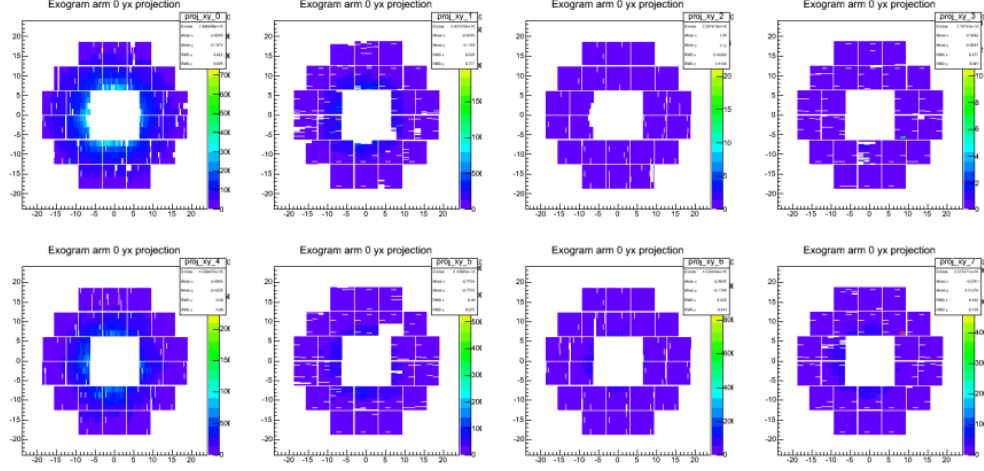


Figure 3.31: MPC-EX Hit distribution of North Arm(dAu200GeV): Some minipads (red) are still hot compared to others.

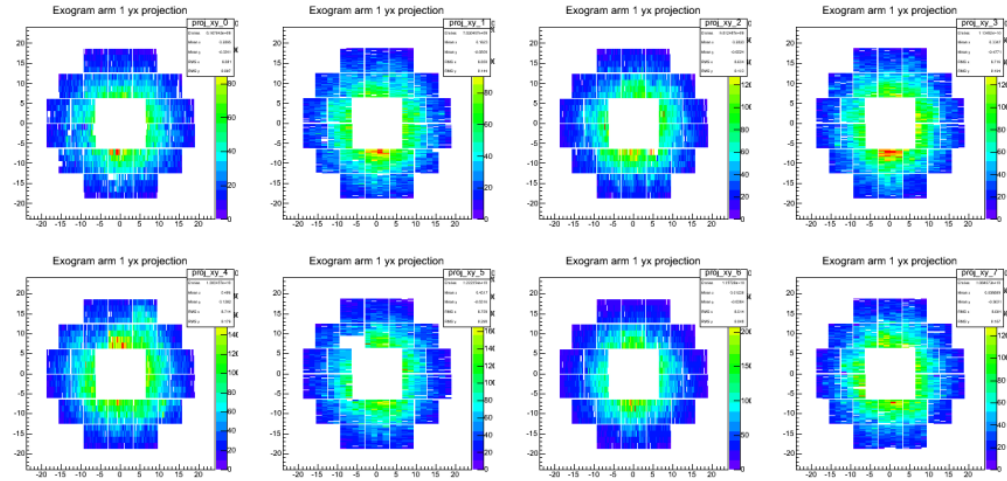


Figure 3.32: MPC-EX Hit distribution of North Arm(dAu200GeV) after new bad minipads are masked out

3.4.2 High Low Ratio

The MPC-EX has a dual-range readout allowing the detector to be sensitive to a more extensive range of values necessary for the MIP signal to the highest energy (80 GeV) electromagnetic showers. The calibration of high gain can be achieved using the MIP peak, while the low gain can be calibrated by using the ratio of the high and low gain ADCs. Figure 3.33 shows an example of the relation between high gain and low gain. The data sets we used is the sum of all runs of online production - the same data set as was used for the Hot/Dead Channel identification

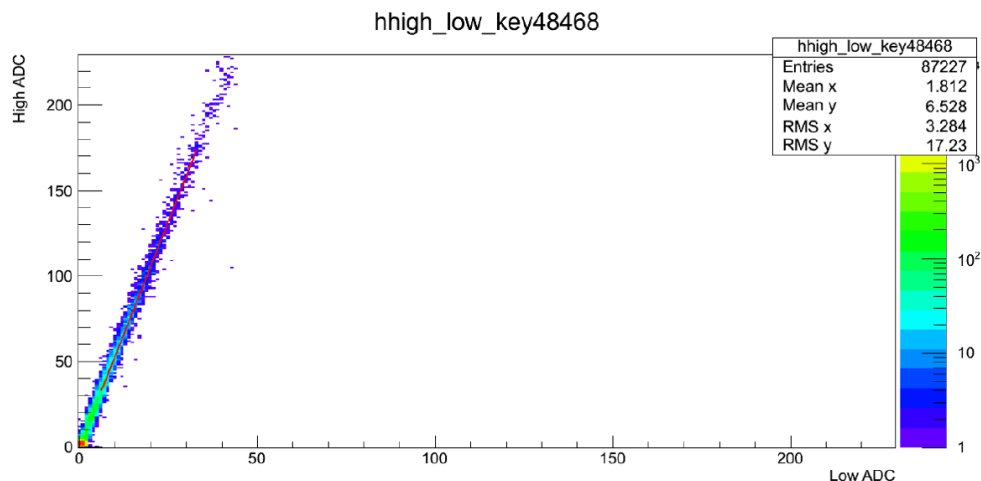


Figure 3.33: The linear relationship between high gain and low gain for one minipad - which we designate by a hardware key of 48458.

Dead/Hot Channel

The Dead and/or Hot Channels can affect the high-low ratio significantly. Hence the dead/hot channel cut will be applied in the following analysis.

High vs Low or Low vs High

In principle, fitting low vs. high or high vs. low should be the same. However, since the fitting is performed on a TProfile histogram, the two choices are different - low vs high is linear while the other is not. In a TProfile histogram, each bin in X is the mean of all of the y values in the 2D histogram. Because the High gain channel overflows when the high gain is greater than about 50, the high gain channel is not linear for all values of the Low. However, there will always be a reasonable high (modulo minor effects mentioned later). This is illustrated in figure 3.34. In the following analysis, we will always use fit a TProfile with the High Gain ADC on the x-axis and the Low Gain on the y-axis.

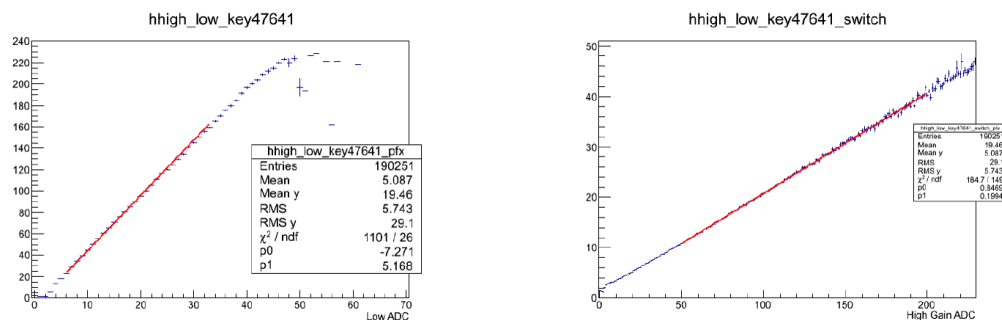


Figure 3.34: Left: low vs. high. Right: high vs. low. The Profile histogram of high vs. low is linear due to the nature of the Profile histogram, while the inverse is not. Hence the low vs. high will be fit in this analysis

Fitting Range

There is still some non-linearity in the low to high profile histogram, and we optimize the fitting range to avoid going near the saturation region of the high gain channel

(in addition to preventing saturation, the statistics are low) and the very low (pedestal) region of the low gain ADC. We divide the ADC of the high gain into four different ranges: 30 - 50, 50 - 100, 100 - 150, 150 - 200. We use the range 50 - 150 as the reference. For each minipad, we fit the low-high ratio in each of the ranges and then calculate the difference with the reference. Figure 3.35 shows that the lowest and highest ranges have deviations. Figure 3.36 shows that the large deviations come, for the low range - the nonlinear nature of the ADC near the pedestal region, and for the higher range - lack of statistics. In the following analysis, we will use the range 50 - 150.

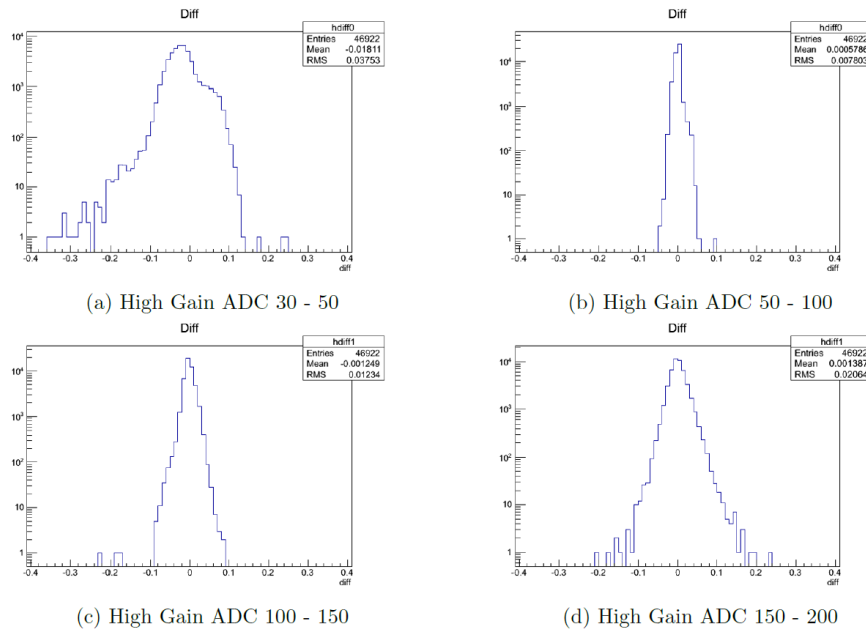
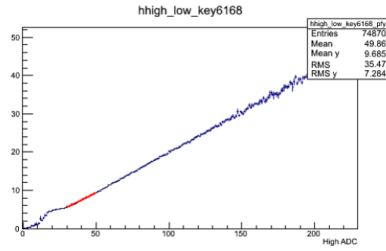
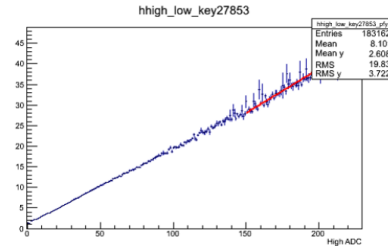


Figure 3.35: Fits to the slope in various ranges of the Low to High Profile histogram as compared to reference values where a fit was done between 50 ad 150. Figures a and d show rather large variation. Hence the range 50-150 was chosen.



(a) The fitting range is close to nonlinear part



(b) The statistics in the fitting range is low

Figure 3.36: Plots show the fits for two keys (minipads) of the low and high ranges where deviations from the fits in the comparison range were the largest.

Split Ratios

After applying the dead/hot channel map, the High-Low ratios were fit as just described. Some minipads were found with several values of the ratio (figure 3.37). To identify and reject those channels, we use the following steps:

1. Histogram the distribution of High vs. Low Ratio. Note that we are using the High vs. Low ratio. This was simply because we had initially thought that the high/low ratio would be used.
2. Use TSpectrum to find the number of Peaks in the High/Low ratio(Figure 3.38).
3. If the number of the Peaks is bigger than or equal 2, the channel will be examined.
4. Examine the channels with more than 2 peaks visually and make the final decision.

In the 2nd step, we found about 300 channels. However by checking visually, only 12 channels had split high/low ratios.

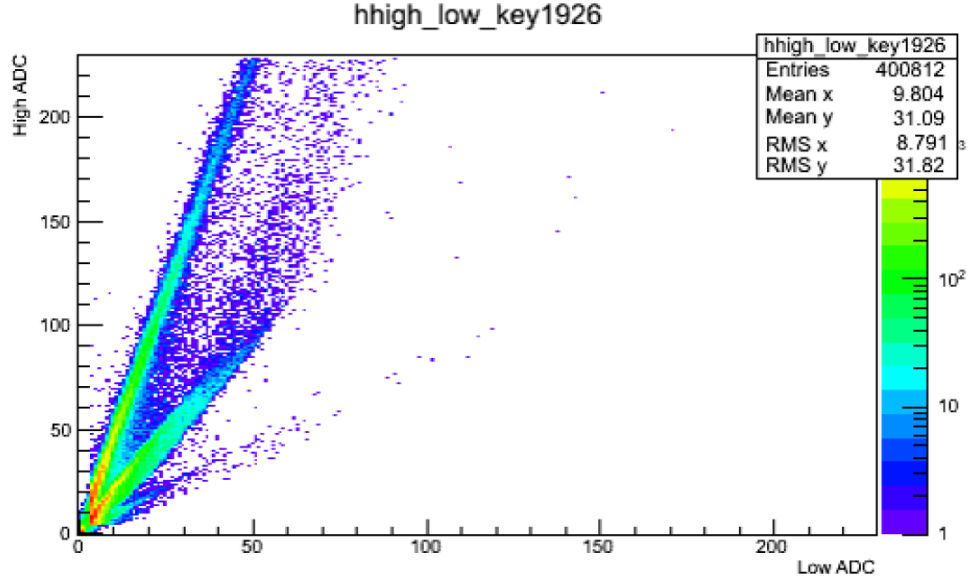


Figure 3.37: An example of a channel (key=1926) with multiple (split) High/low ratios.

The Low-High Ratio and Intercept

After the above analysis, the final cuts and settings are the following:

1. Data Set : the sum of all runs of online fast production of dA200 GeV
2. Trigger and standard cuts: we use the Minbias Triggers, and standard cuts are the same as those in the dead/hot analysis
3. Dead/Hot channel map is used, and channels with split ratios are excluded
4. The linear fit is based on the Low vs. High
5. Fitting range: high ADC from 50 to 150

Figure 3.39 shows the fitting result of the Low-High ratio, intercept, and Chi2/NDF.

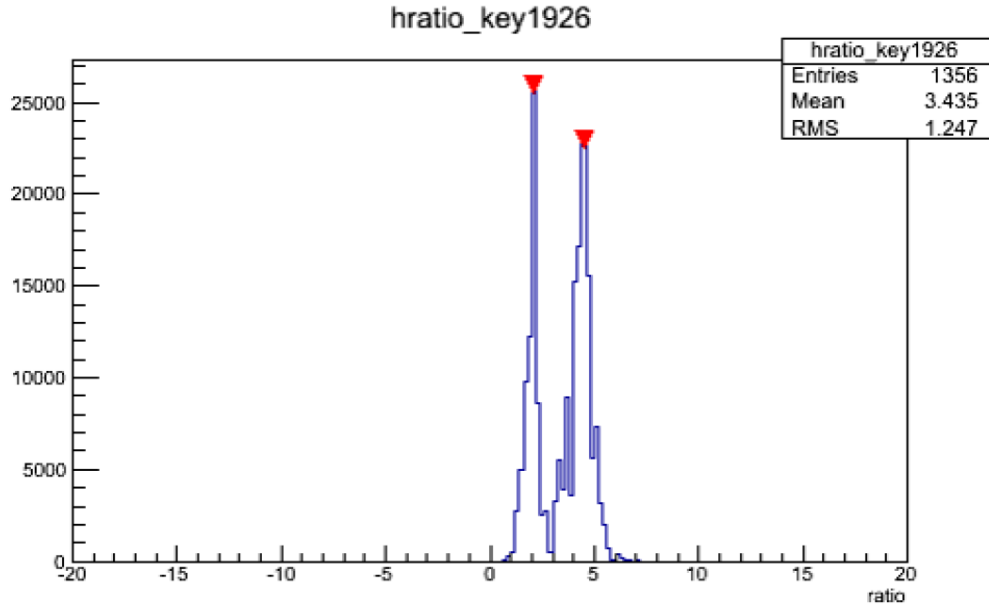


Figure 3.38: The TSpectrum peaks found for the high/low histogram for the channel with key= 1926

The Low High Ratio and Intercept

After the above preparation, The final cuts and settings are the following:

- Data Set: Online fast production of dAu200GeV
- Trigger: MinBias Trigger
- Cuts: Same as the dead/hot channel analysis. The dead/hot and bad low high ratio minipads are removed.
- Fit Range: 50 - 150

Figure 3.39 shows the result: Chi2/NDF, low high ratio and the intercept.

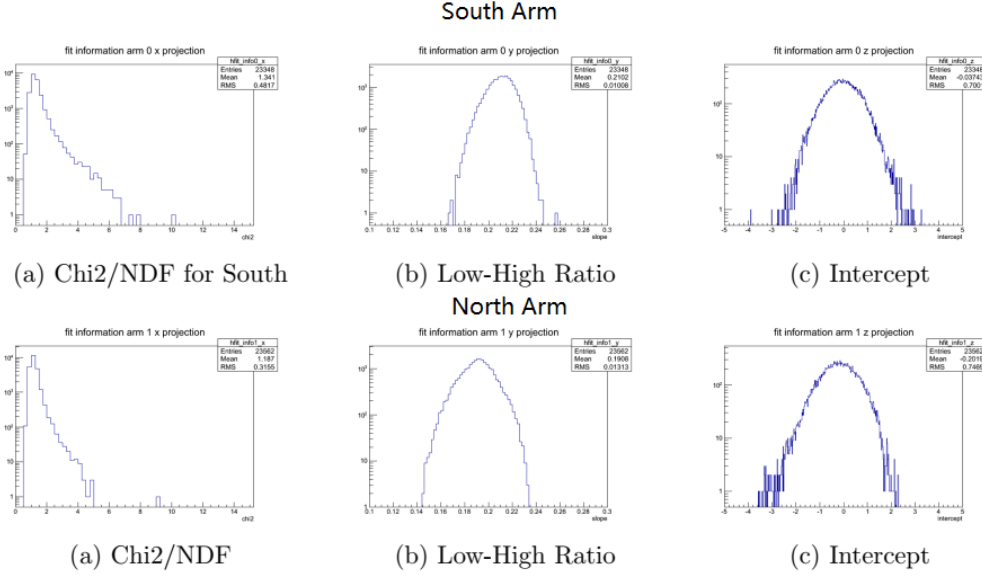


Figure 3.39: The top is the south arm, and the bottom is the north arm. From left to right are Chi2/NDF of the low to high Ratio, low high ratio, and intercept.

Run Dependence

To check the run dependence, we divide the runs into 5 groups. Each group has about 400 segments except the last one, which has only 100 segments. The data set of all runs will be taken as the reference. We then did a linear fit and compared it with the respect by calculating two quantities:

- $(Slope_{group} - Slope_{ref})/Slope_{ref}$
- $(Slope_{group} - Slope_{ref})/(Error_{ref} + Error_{group})$

Figure 3.40 and 3.41 show that the differences to the reference are small and consistent with being due to statistical errors. Hence, we can use a single low-high ratio list for the dA200 GeV. There are a few channels that show a stronger run dependence. An example is shown

in figure 3.42. Those channels usually have a small split in the ratios, as can be seen from the figure. We will deal with these in the next section.

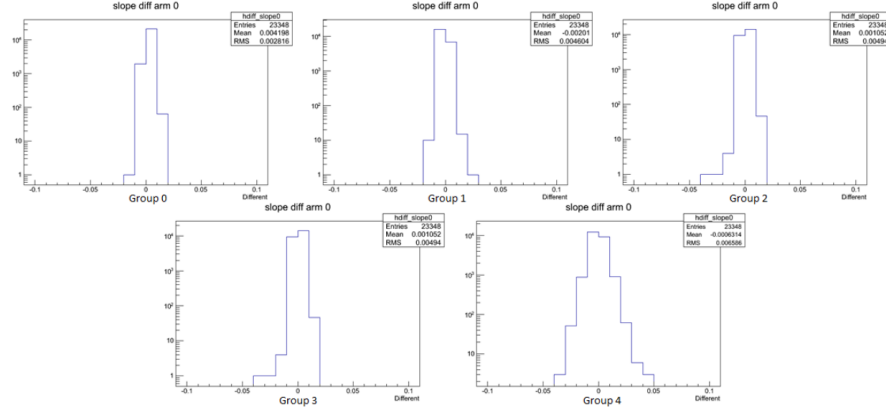


Figure 3.40: Slope difference when compared to the reference for the South arm. The difference of the last group is a little more significant; however, the change is less than 5% with a mean difference of 1%.

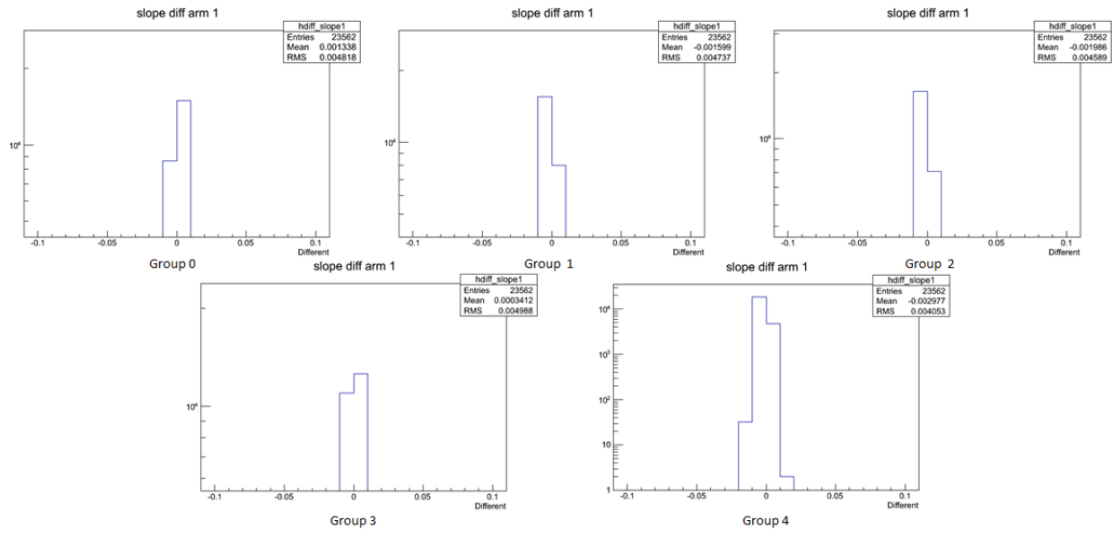
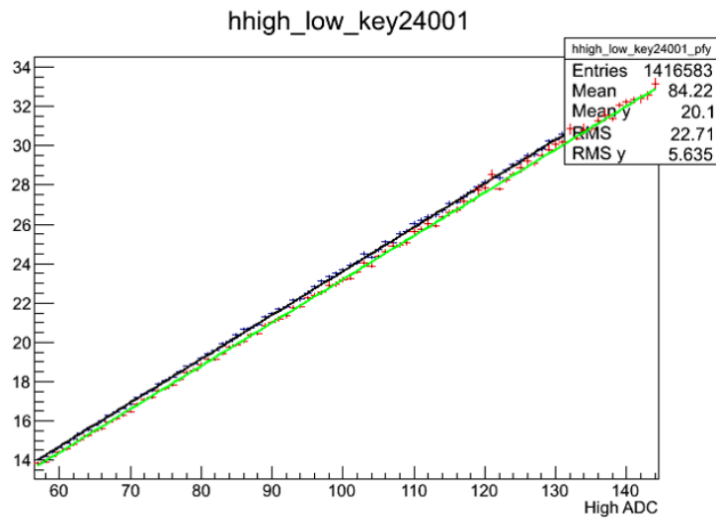
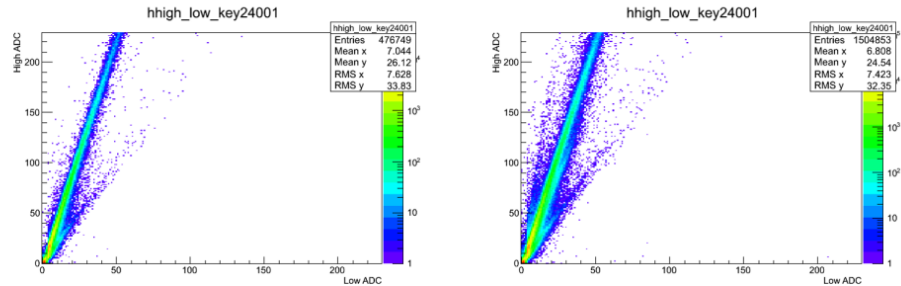


Figure 3.41: Slope difference when compared to the reference for the North arm.



(a) Low(y-axis) vs High ADC, for all runs (black) and run group 0(green) A small difference in the ratio (slope) of run group 0 as compared with all runs can be seen.



(b) High gain vs Low gain in run group 0, showing the split. (c) High gain vs Low gain in all runs, also showing the split

Figure 3.42: For the Minipad 24001, the split ratio causes a small change in the low-high ratio.

The Width (Sigma) of the Low-High Ratio distribution

As just discussed, the L/H ratio of some channels can be affected by a split in the ratios. To deal with this problem, the width (sigma) of the low-high ratio distribution is examined.

The sigma is defined as the variation of the perpendicular distance to the fit line. This sigma is found to be independent of the L/H ratio. Figure 3.43 left shows an example of this. By plotting the perpendicular distance of points to the fit line as in the figure, we obtain a Gaussian distribution (Figure 3.43 right), where the width (sigma) can be extracted from a Gaussian fit.

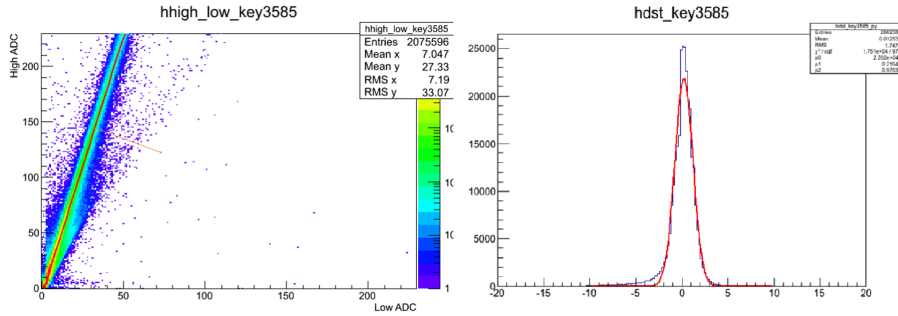


Figure 3.43: Left: high gain vs. Low gain for Minipad 3585. The orange line shows the perpendicular line along which the distance to the fit line can be calculated. Right: The distance from the point to the fit line (key 3585 from high gain ADC 50 to 150). By fitting with Gaussian, we can extract the width (sigma) of the L/H ratio. Note that the units of the x-axis are in ADC counts.

Such fits are used to eliminate 12 more minipads which show a significant deviation from zero. For each minipad a plot such as in figure 3.43 right is fit to obtain a mean. These means are shown in figure 3.44. If the mean is greater than 0.2 away from zero, it is cut. Ordinarily, if there is no split ratio, the mean should be almost exactly zero. However, if

there is a split ratio, this will shift the mean from the center. A split ratio will also cause tails on the original distribution; one can even see this in figure 3.43 left, where there is a low side tail. A final total of 30 minipads with bad L/H ratios are cut.

Figure 3.45 shows how we remove the points far away from the fit line and thereby the points which cause the split ratio. In the next section, we will discuss the legitimacy of this cut.

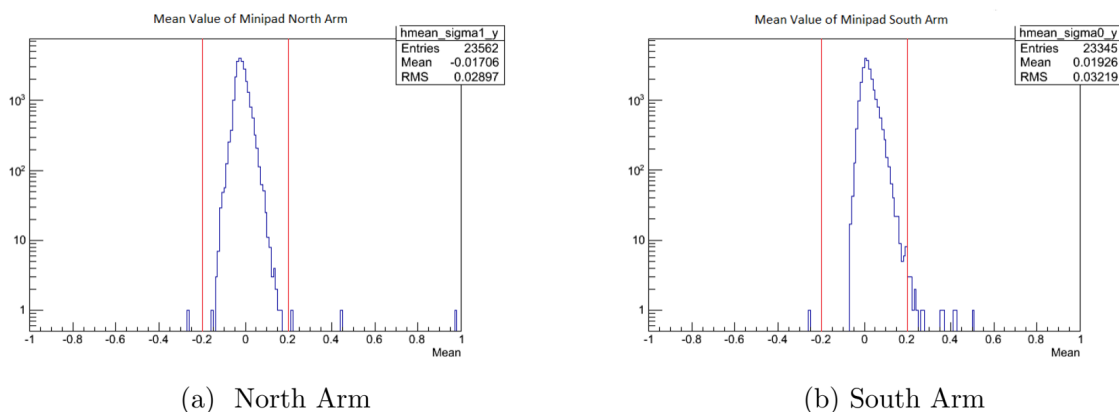


Figure 3.44: Plots of the means of fits as in the previous figure. There is one entry per minipad. A cut is made for minipads with entries further than 0.2 away from zero, as shown by the red lines. Note that the units of this plot are in ADC counts.

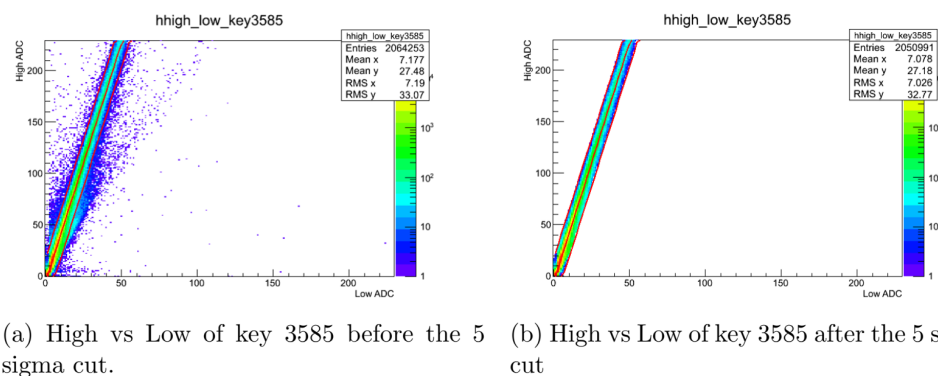


Figure 3.45: An example which illustrates the 5 sigma cut which eliminates split ratios. The cut is indicated with the orange envelope.

Low-High ratio in Showers

The 5 sigma cut can efficiently remove the points far away from the fit line, thereby removing split ratios. However, we must show that we remove isolated hits (presumably from noise) and not remove hits from showers or tracks. To examine this, we use a sample of showers as given by the standard shower module. The data set and cuts used are:

- Data Set : Run 454789
- Trigger: Minbais.
- Standard cuts used in Dead/Hot Map Analysis
- Shower Setting: Remove bad hits and disable South
- Shower Cut: fired layers = 8 and Number of hits in shower ≥ 15

In a shower, we assume that points closer to the shower center are more important and less likely to be spurious(e.g., noise) hits. We classify the points by using the RMS in Hough space of the shower. From figure 3.46 and figure 3.47, the hits which are closer to the center of the shower (e.g., within one-half RMS, or one RMS) have fewer hits with bad low-high ratios than the plots with no cut. Note that figure 3.47 is easier to understand. Figure 3.46 which has recalibrated the hits to keV, includes the effect of the saturation of the high ADCs. The five sigma cut is offered as an option for the apply calibration module. By applying the five sigma cut, less than 1% of the hits are removed, so the effect should be minimal.

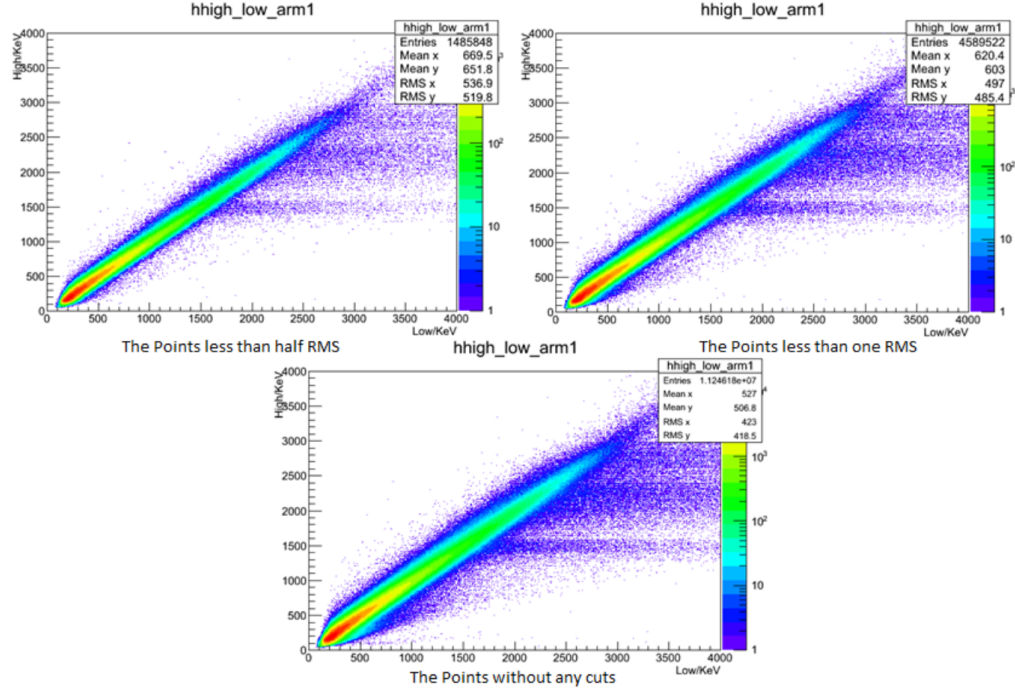


Figure 3.46: Plots of the high vs. low gain ADC recalibrated to energy for showers. Only hits with a distance in Hough space within 1/2 RMS (upper left) and 1 RMS (upper right) are plotted. The lower plot shows all points with no cut. Hits closer to the shower center have fewer hits with a spurious H/L ratio. Note that this plot is in keV, and where the effect of a saturated high gain ADC is important

High Low Ratio at 62 GeV, 39GeV and 20GeV

The method used at low energies is the same as dAu 200GeV. The data set and cuts are the same in the dead/hot analysis. The fitting range for the dAu 20GeV north arm is much lower, ADC 30 - ADC 100. When comparing with dAu200GeV, the difference of dAu62GeV and dAu39 is within 10% (figure 3.48 and 3.49). However, for dAu20GeV, the difference for south arm is small and large for north arm (figure 3.50 and 3.51).

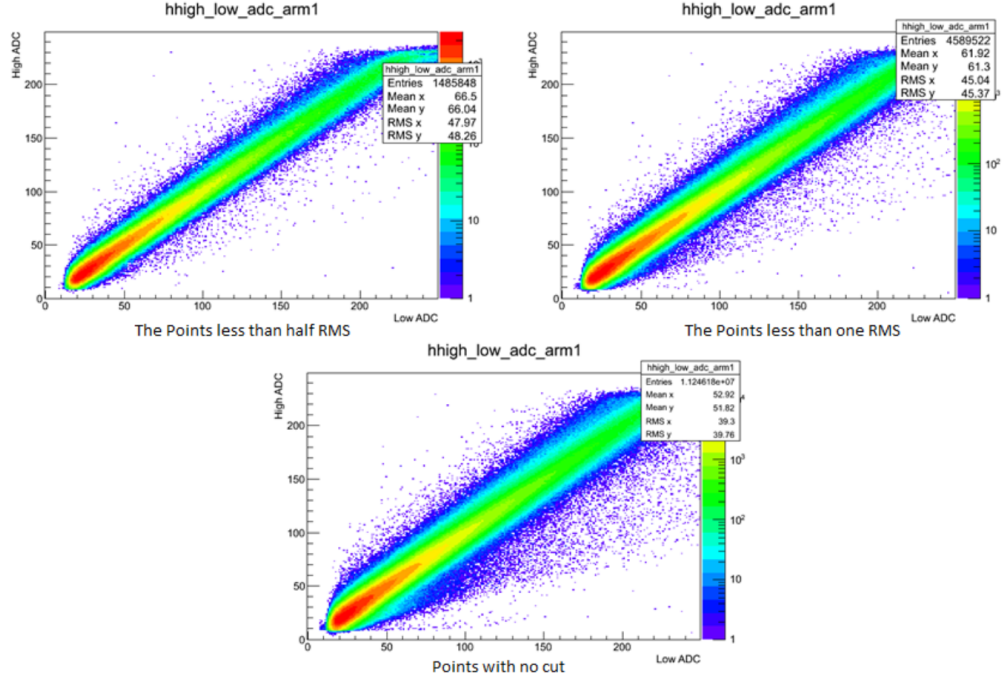


Figure 3.47: Similar plots as the figure 3.46 but where the ADC has not been scaled to keV. This minimizes the effect of the saturated high gain ADC. Hits closer to the center of showers have fewer spurious hits with bad H/L ratios

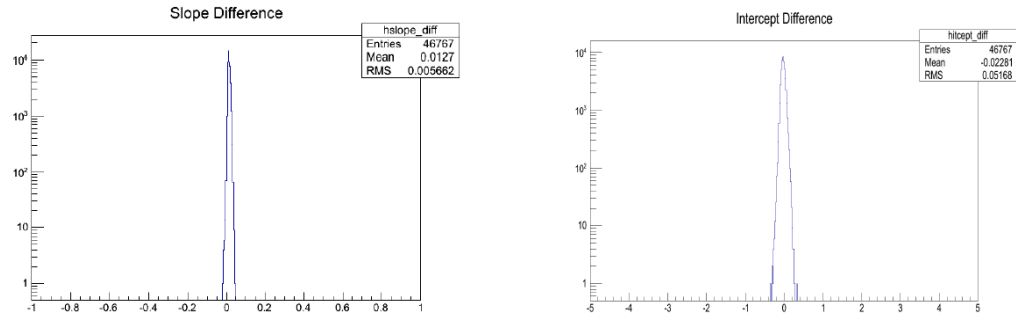


Figure 3.48: The difference of slope and intercept of dAu62GeV compared with dAu200GeV.

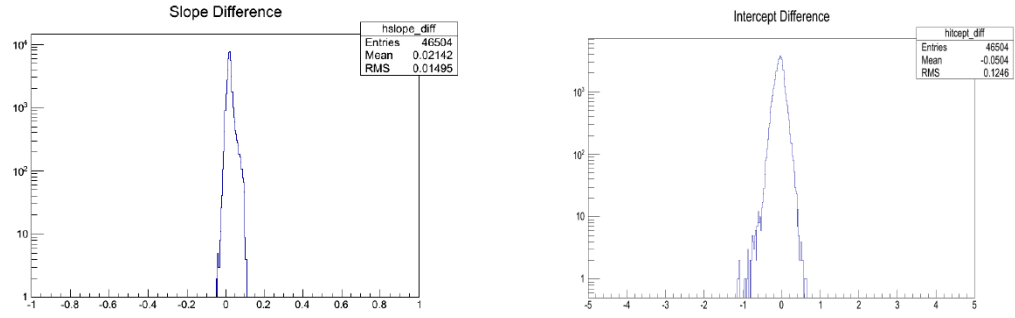


Figure 3.49: The difference of slope and intercept of dAu39GeV compared with dAu200GeV.

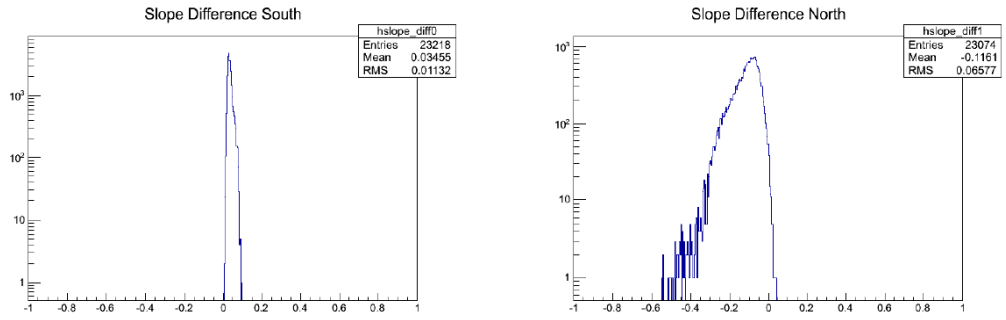


Figure 3.50: The difference of slope of dAu20GeV compared with dAu200GeV.

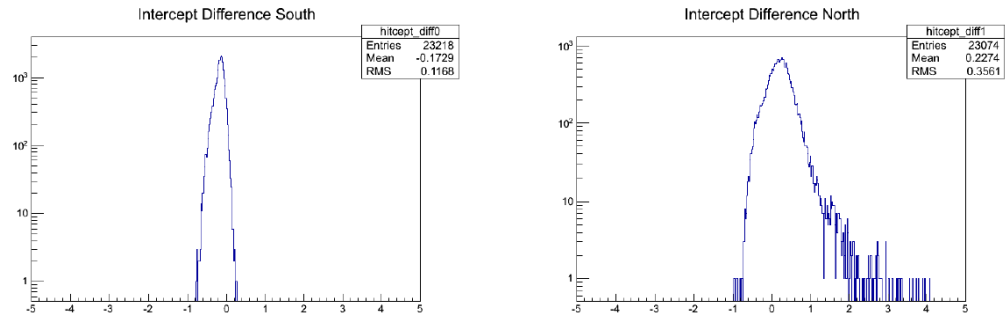


Figure 3.51: The difference of intercept of dAu20GeV compared with dAu200GeV.

3.4.3 Energy Calibration

The way to calibrate the minipad is to use the MIP (minimum ionizing particle). The energy of a MIP left in minipad can be calculated by "Bethe equation" [48] is 150keV (400 μm Si). After we get the corresponding ADC MIP value, we can calibrate the minipad. This is done only for the high gain ADC. The MIP is fit in two stages: At the sensor level and at the minipad level. For the sensor level, all minipads in one sensor are summed up run by run and then the MIP signal is fit to a Landau distribution. At the minipad level, each ADC is scaled by the MIP of the sensor and again the MIP signal is fit to a Landau distribution[24].

dAu 200GeV

The fitting function for the sensor is given by the following $F = Sn + [Bg] = p_0 \cdot \text{Landau}(p_1, p_2) + [p_3 \cdot \text{Landau}(p_4, p_5) + p_6 \cdot \text{Gauss}(p_7, p_8)]$. The first Landau corresponds to the first MIP, and the second Landau corresponds to the second MIP. The Gaussian models the background at low ADC (primarily the pedestal). p_1 is the MPV (most probably value) for the MIP, and p_2 is the "width", from the ROOT analysis package implementation of the Landau function. Figure 3.52 shows the ADC value corresponding to a MIP for different sensors. The first two layers are higher than others as the gains were deliberately set higher for these layers because the energies expected in these layers are lower. All of the ADC values in a particular sensor are then rescaled by the value of the sensor MIP ADC value to give a scaled MIP. A second fit is then done on these scaled MIPS for each minipad in a particular sensor using the same function as before. Figure 3.53 shows the value of scaled

MIP of the minipads showing the minipad by minipad deviation. Each minipad is then again rescaled. All rescaling value are then put into the database. Figure 3.54 shows an example: the top plot is the fitting to a sensor, and the bottom plot is the fitting of one of the the minipads after rescaling for the sensor ADC MIP value.

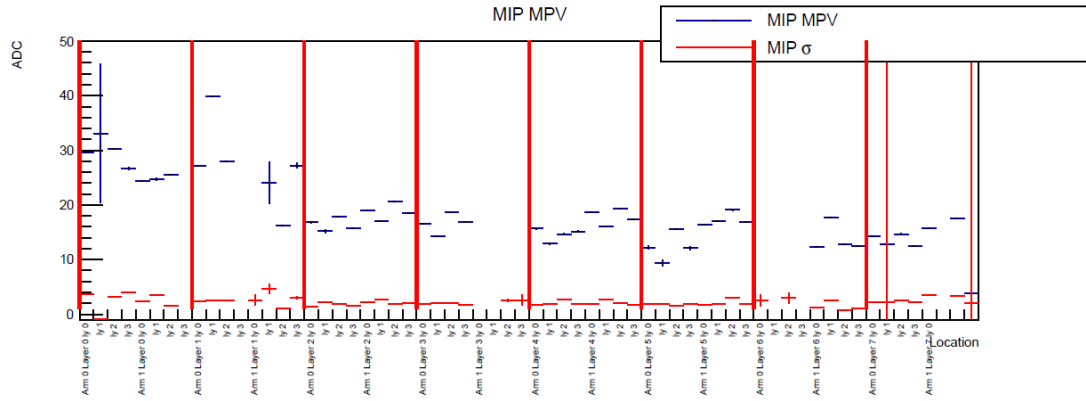


Figure 3.52: The fit most probable ADC value (black), and width (red). The layers go from right to left, with layer-0 to the left, and separated by a red vertical line - layer 1, continuing to layer-7.

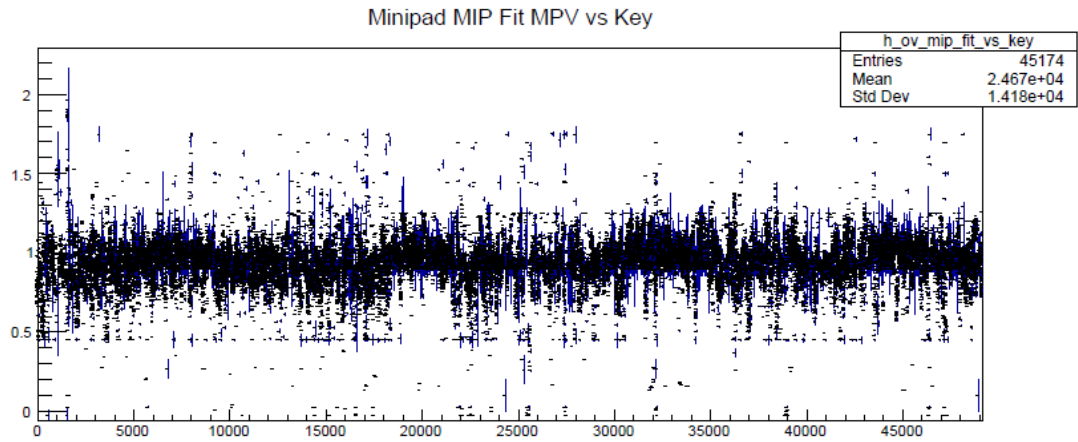


Figure 3.53: MIP value for all minipads, obtained after the second fit, showing the minipad by minipad deviations after rescaling to the sensor ADC MIP value.

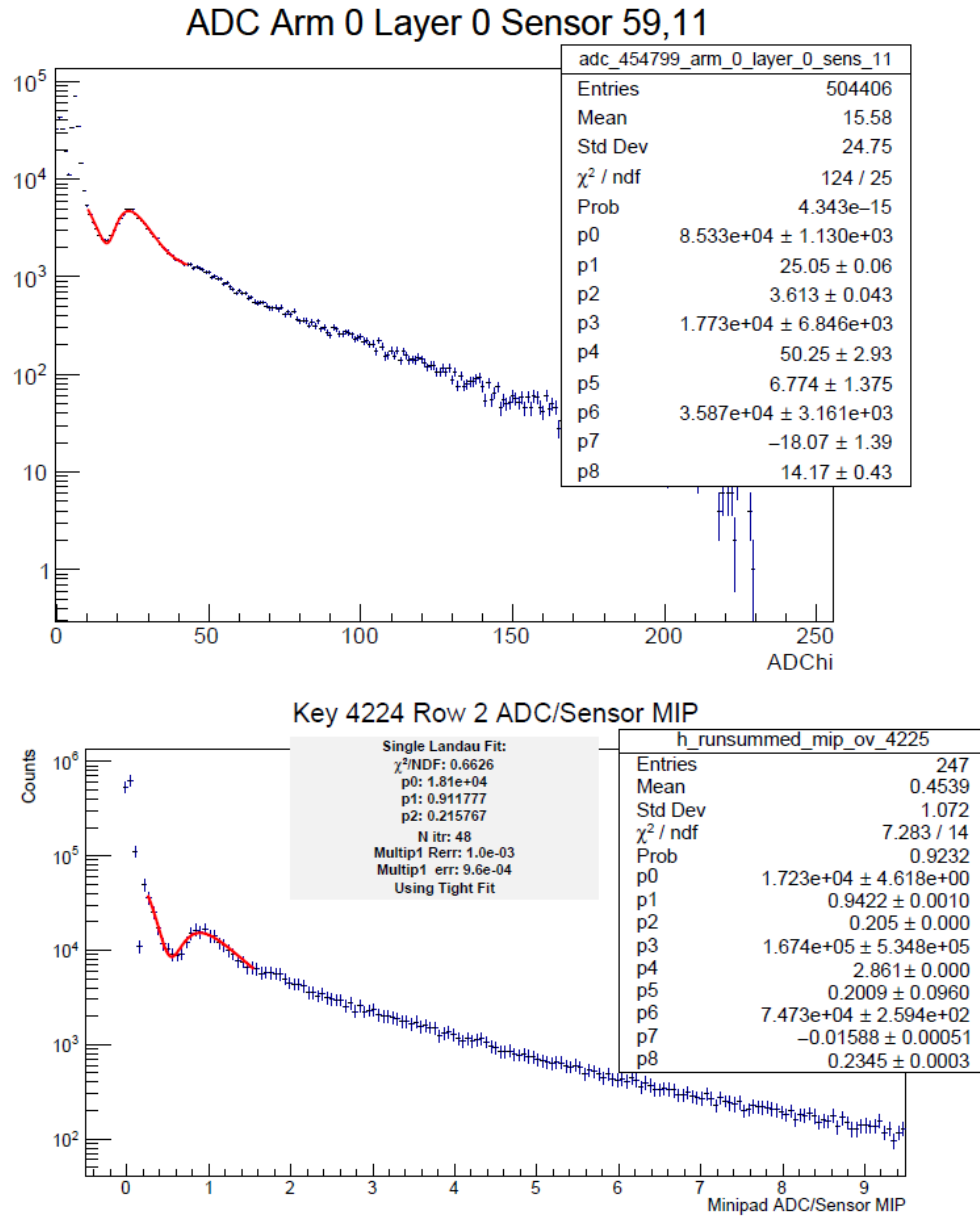


Figure 3.54: Top: MIP fit to the ADC distribution for all minipads for an example sensor. Bottom: MIP fit to the ADC distribution for one particular minipad.

Fitting for the ADC MIP values for the dAu62GeV,dAu39GeV and dAu20GeV

Data Sets

The background was worse in the lower energy running, so the fitting function for the lower energies is different from the dAu200GeV. The new function has fewer parameters. The new fitting function is $F = p_0[(1 - p_3)Landau(p_1, p_2) + p_3Landau(2p_1 + 1.4p_2, 2p_2) + p_4e^{-p_5x}]$ The parameters of the second Landau are a function of the parameters of the first MIP, where we now assume that the second MIP peak is twice the value of the first. An exponential function models the ADC background. Figure 3.55 shows a sensor fitting example for dAu39GeV ,and figure 3.56 shows a minipad fitting example for dAu62GeV. The Blue line is the first MIP, the black line is the second MIP, and the yellow is the exponential high ADC background. Figures 3.57,3.58 and 3.59 show the fitting result of minipads for different energies.

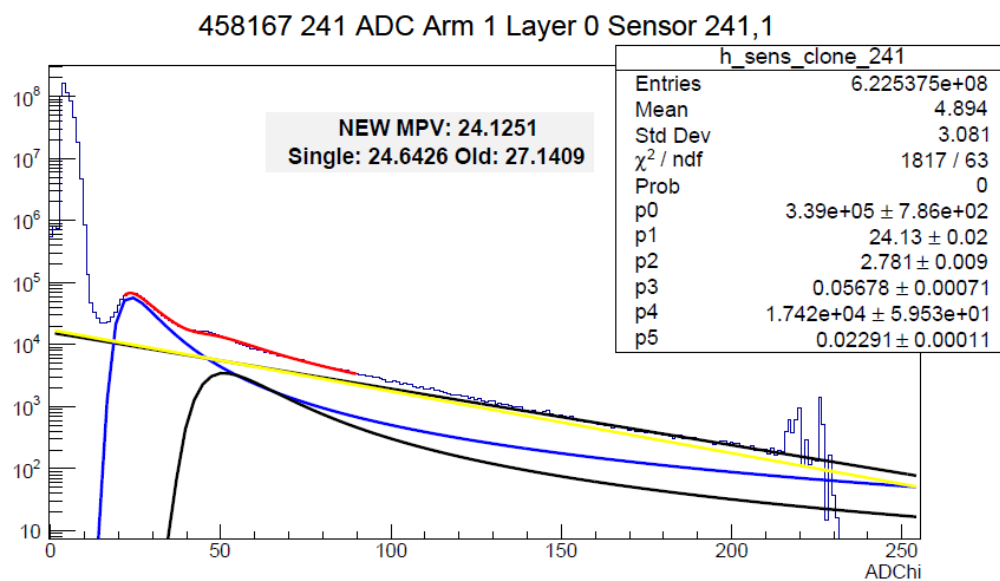


Figure 3.55: An example of sensor fitting for dAu39GeV

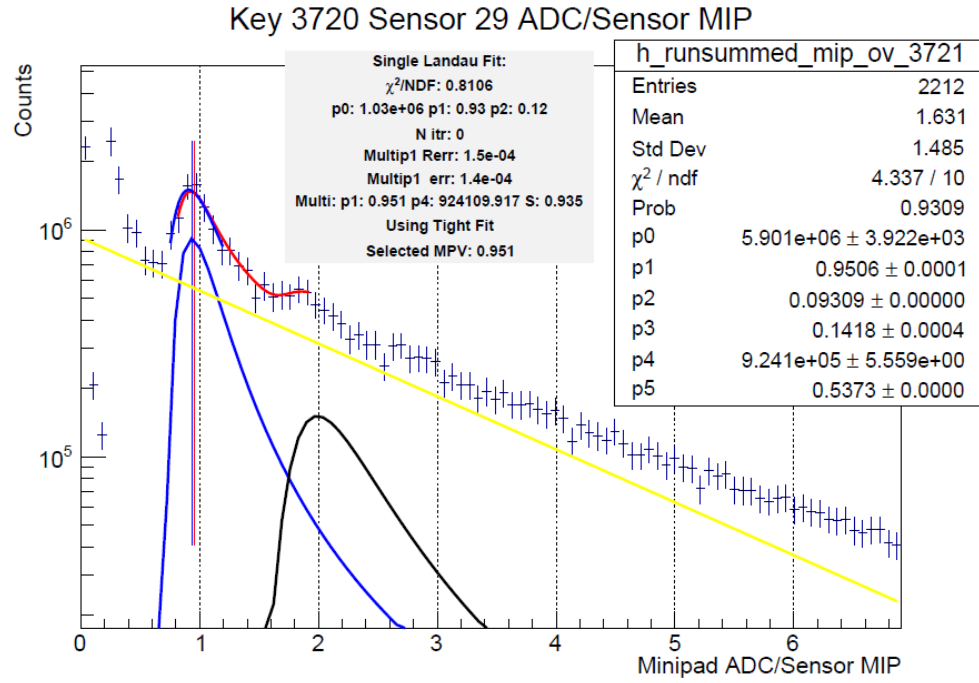


Figure 3.56: An example of minipad fitting for dAu62GeV

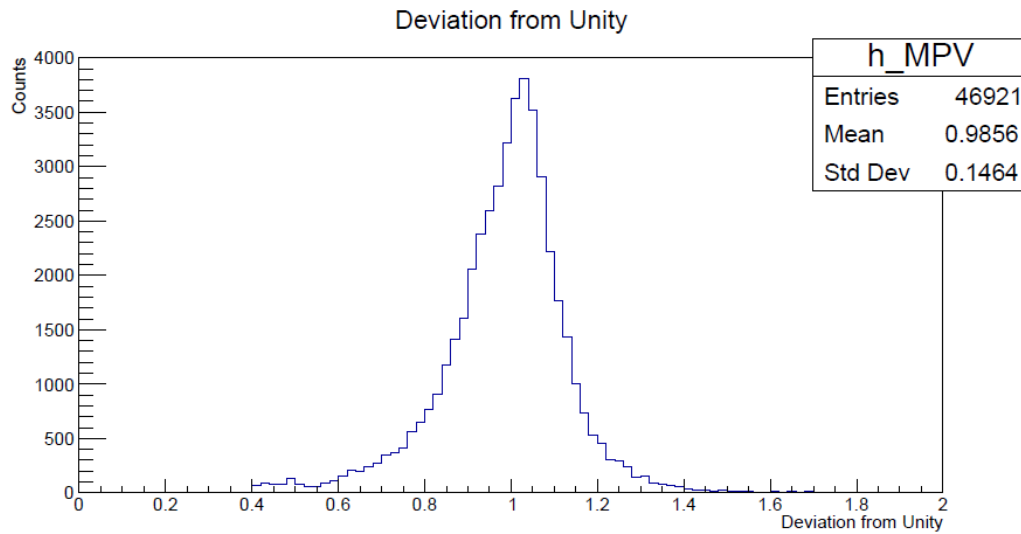


Figure 3.57: Distribution of run averaged scaled MIPs (deviation) for all minipads in 62GeV after rescaling all minipads for the sensor ADC MIP.

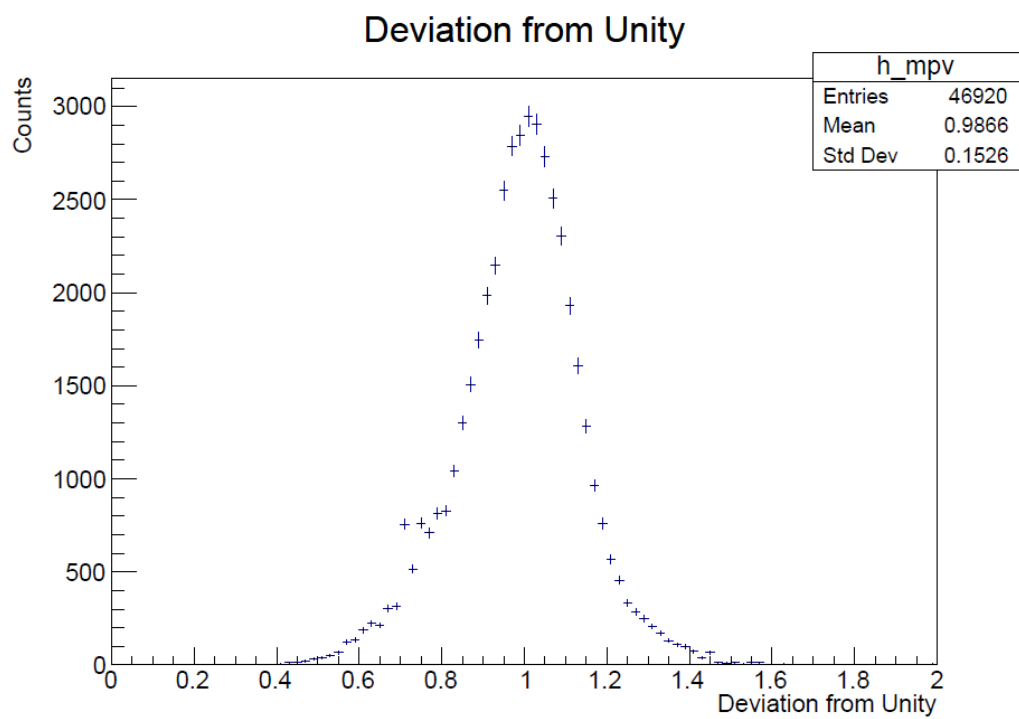


Figure 3.58: Distribution of run averaged scaled MIPs (deviation) for all minipads in 39GeV after rescaling all minipads for the sensor ADC MIP.

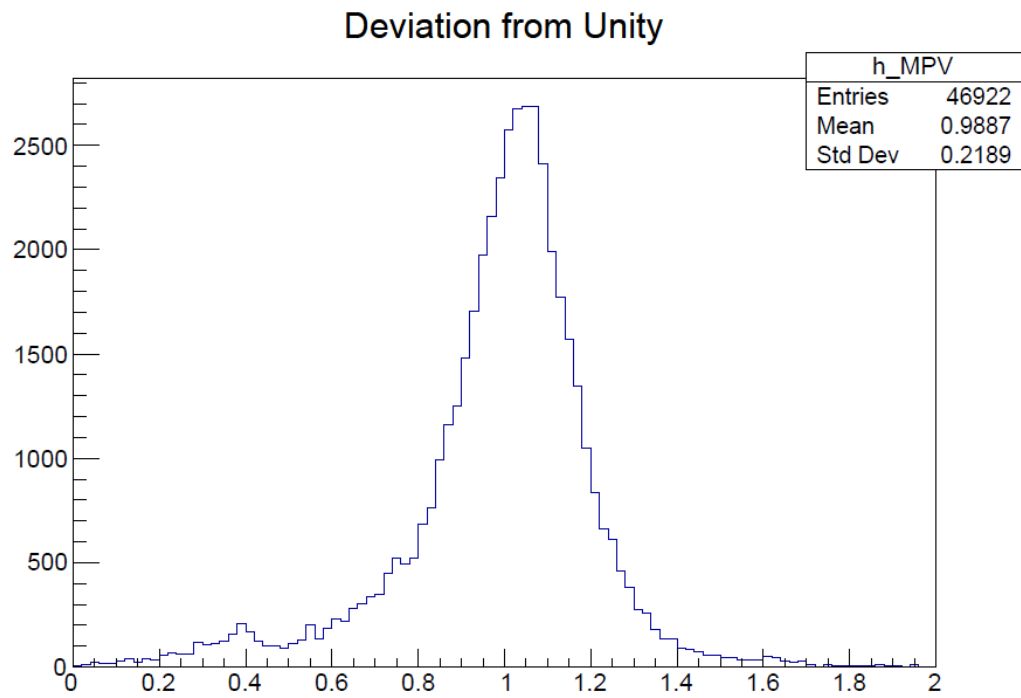


Figure 3.59: Distribution of run averaged scaled MIPs (deviation) for all minipads in 20GeV after rescaling all minipads for the sensor ADC MIP.

3.5 Calibration of the MPC

The calibration of the MPC is turned out to be rather involved. Due to the low gain of the MPC, we could not calibrate it using MIPs. Another challenge is that at low energy, the efficiency dropped off as shown in figure 3.60. This calibration, which is being done by our collaborators, is critical for the measurement of what will be called “single track” π^0 s necessary to measure π^0 s at high energy. Because this process is not yet complete, we did not use the MPC energies in this thesis and the process of the calibration will not be discussed here. This thesis will exclusively use π^0 s from two photons measured in the MPC-EX, as will be described later.

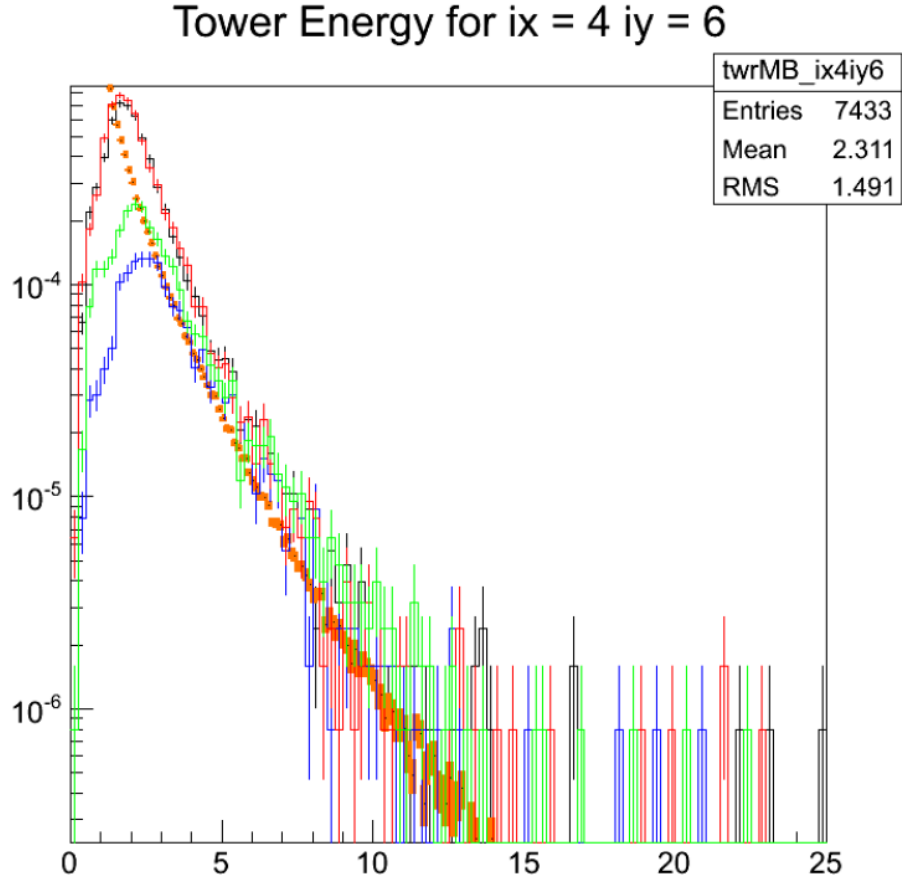


Figure 3.60: MPC tower energy distributions for BBC MB triggered events for a set of four the complementary towers in the north arm. Complementary towers, are towers in the same positions in each of four quadrants relative to the center of the MPC. The four complementary towers are in black, blue, red and green. The curve from a simulation of deuteron gold events[53] is shown in orange. The gains of the towers have been adjusted to match the slopes and yields at 5GeV.

Chapter 4

Data Analysis

This chapter describes the data analysis. As mentioned previously, this thesis presents results only using the MPC-EX and only at 200 GeV. Nevertheless, we will describe the work done on the MPC “single track” shower algorithm, as well the work on the lower energy data. As mentioned previously, the MPC data will be crucial to measuring π^0 s at high energy, central to the program of the MPC-EX, particularly for the measurement of direct photons. Analysis subsequent to this thesis, on the low energy data will allow a measurement of the energy dependence of π^0 suppression, thereby giving us a handle on the onset of suppression effects in the nucleus. Questions arose late in the analysis of the low-energy data, and out of an abundance of caution, we have decided not to present the final results on the low energy data in this thesis. This does not affect distributions shown, particularly the raw minimum bias p_T distributions of π^0 s at low energy. Work described in this thesis, on both the “single track” π^0 reconstruction algorithm, and the low energy data is critical for later analysis. This thesis will concentrate on the measurement of “two

track” π^0 s using only the data from the MPC-EX. A machine learning model of energy measurement will allow for this possibility.

First, we discuss algorithms to reconstruct showers from the hits in the MPC-EX minipads and the energy in the towers of the MPC. This then is followed by a description of the π^0 reconstruction algorithm. π^0 ’s are reconstructed in two ways. The first is the standard way in which the invariant mass of two showers is required to give the π^0 mass. The second is the so called “single track” algorithm which uses showers that, because of their lateral extent, overlap and form a single shower, particularly in the MPC. Figure 4.2 shows a schematic of such a case. The high granularity of the MPC-EX allows for the reconstruction of π^0 s using the single track π^0 reconstruction algorithm. A machine learning technique is deployed for single track π^0 identification. This allows for π^0 s to be reconstructed to high p_T .

4.1 The Shower Algorithm

As mentioned previously, the MPC-EX has 24576 channels per arm. Grouping hits into different showers efficiently is time consuming in terms of CPU. The shower algorithm [72] runs in a reasonable amount of time on the north arm, the deuteron going direction. In the south arm, the number of hits is about eight times larger and the speed to run the shower algorithm takes considerably more time. However, in this thesis, only the north arm is of importance. The shower algorithm can be divided into six steps:

- **Step One:** For the north arm, order the hits by the energy from high to low into a hit list.

- **Step Two:** The next steps use a Hough space representation of the positions of hits. The Hough space coordinate is defined using the (x, y, z) coordinate of the hit in the MPC-EX and the z-position of the vertex. The Hough space coordinate for a hit is defined as $(x/z, y/z, z)$ where the z position is measured with respect to the vertex. The algorithm starts with the Hough space coordinate of the highest energy minipad and includes all hits within a cone around the Hough “x” and “y” positions. The radius, R_1 , of this cone is 0.8 cm in the first layer and 1.6 cm in the last.
- **Step Three:** At this point, some showers which are broader than the radius used (R_1) may be missing many hits which should belong to the shower. To include these hits, the shower radius is expanded by a factor of 1.3, and new hits are added to the shower. The energy and size (the number of hits) of the new shower is compared with the original shower and the radius is expanded once more. This process is continued until the change of energy, or the size of the shower, is small. To avoid unphysically large sizes, the limit for the shower expansion factor is four: this means the final size of the shower should be less than four times of the initial shower size in step one.
- **Step Four:** After the process is finished, the shower direction is projected onto the MPC, where the closest 3x3 tower array is associated with the shower.
- **Step Five:** Using the information on the shower from the MPC-EX and MPC in the shower as input, a machine learning (ML) algorithm (not described here) is used to get the total shower energy. This technique depends on using all of the energy given by the MPC-EX, including the number of hits, and the distribution of the energy both laterally and longitudinally. Figure 4.1 shows the comparison of the energy

reconstructed by the algorithm to the true energy in simulation when a cut is made requiring no energy in the MPC in data, a cut that will be used later. Because of threshold set for the MPC during the data taking, this is actually a requirement that there be less than 4 GeV in the MPC.

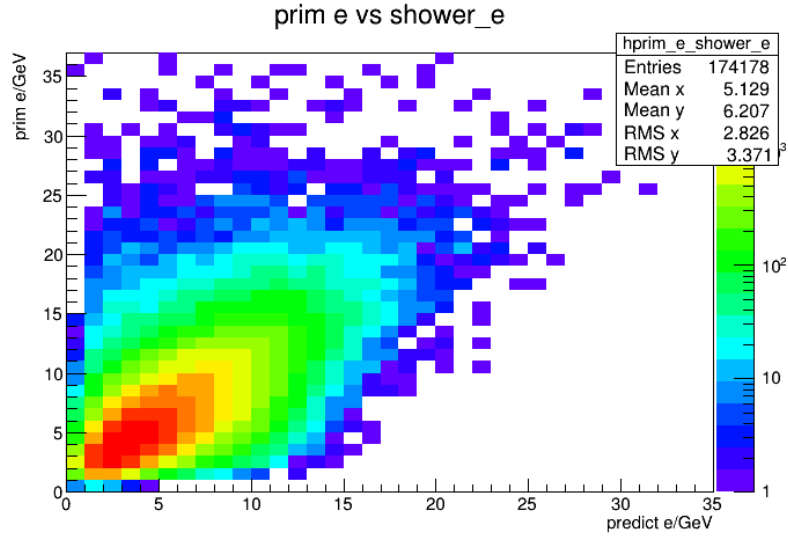


Figure 4.1: The true energy vs. reconstructed (predicted) energy of photon in Hijing simulation. A 4 GeV cut is applied on the MPC energy. Because of the threshold energy cut in the MPC during data taking, this is equivalent to requiring no energy in the real data. Only information from the MPC-EX is used.

- **Step Six:** All hits from the shower are removed from this hit list. Starting with the next highest energy unused hit, the process is repeated.

The algorithm is ended when all the hits are used. All showers will be stored in a container for further analysis. Small showers (e.g., those with only one or two hits) will be eliminated later, when a minimum number of hits are required for a shower to be used in the analysis stage.

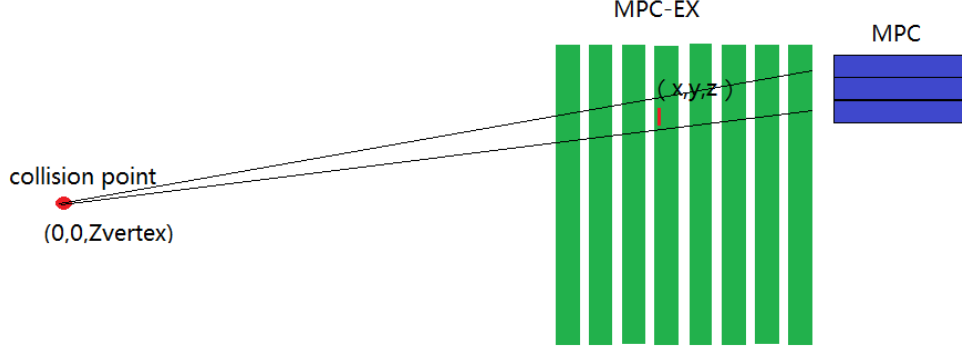


Figure 4.2: An illustration of an MPC-EX shower from the two photon decay of a π^0 , in which the showers from the two photons will overlap in the MPC since the radius of a shower is larger than the lateral size of a block.

4.2 Single Track π^0 Reconstruction Algorithms

This section explains the algorithms that have been developed to reconstruct single track π^0 s. These are the TSpectrum algorithm and the MiniCluster algorithm. The Machine Learning (ML) algorithm does not attempt to reconstruct the π^0 , but it uses the information from the MPC-EX to classify the shower source as either a π^0 or “not a π^0 ”. Since the final calibrations of the MPC are not yet complete, single track π^0 s are not used in this thesis. However, they are explained here for two reasons. First, reconstruction of single track π^0 s was a unique ingredient in the capability of the MPC-EX since it will allow the reconstruction of high p_T π^0 s. Second, they form a logical progression in the general analysis of data from the MPC-EX. Figure 4.3 shows a neutral pion decay into two photons. The lifetime of the π^0 is small, so the two photons essentially emerge directly from the collision vertex. For high energy π^0 s, the opening angle is small, and the two photon showers overlap and reconstruct to a single shower, particularly in the MPC. As mentioned above, the high

granularity of the MPC-EX allows us to resolve the two photons and reconstruct the π^0 . The four momentum of decayed photons is $p_{\mu 1} = (\vec{p}_1, E_1)$ and $p_{\mu 2} = (\vec{p}_2, E_2)$, where $\vec{p}$ is the three momentum and E is the energy. The reconstructed π^0 four momentum is $p_\mu = p_{\mu 1} + p_{\mu 2} = (\vec{p}_1 + \vec{p}_2, E_1 + E_2)$. By measuring the distance between the two photons on MPC-EX, we can reconstruct the mass of the photon from the single shower; the “single track” π^0 mass is: $mass = \sqrt{0.5 \times E^2 \times (1 - \cos\theta)}$. E is the shower energy, where the energy of $E/2$ is assigned to each photon, θ is the opening angle $\theta \approx d/z$ where d is the distance between the photons. For the reconstruction algorithm, the key is to find the distance of the two photons in the MPC-EX. An error is introduced because of the way the energies of the two photons are assigned, however for the kinematics of interest, where our ability to reconstruct the π^0 mass is best, the error is less than 20%. Since the mass is used only for identification purposes, this introduces very little uncertainty into the final measurement. Two reconstruction algorithms are developed and are explained here. The goal of each of these algorithms is to resolve showers into its two components- the two photons. Each of them works shower by shower.

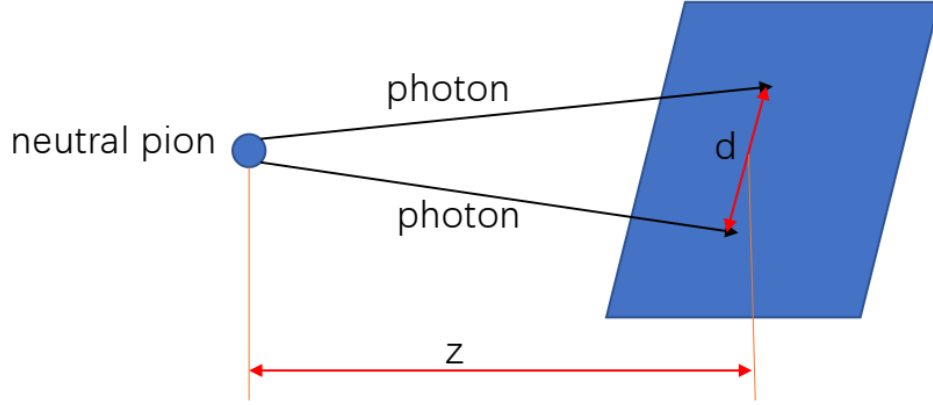


Figure 4.3: A neutral pion decay into two photons. By using the MPC-EX, we can measure the distance between the two photons.

4.2.1 TSpectrum algorithm

The first step in the TSpectrum algorithm is to project all the layers onto a single plane, as shown in a figure of a simulated π^0 decay (Figure 4.4). There are two clusters from decay photons in this figure. The next step is to project onto the X axis (even planes) or Y axis (odd planes). Figure 4.5 shows the result. The left figure shows the projection on the X axis, and right figure shows the projection on the Y axis. Two peaks are seen in both the X or Y axis. The TSpectrum algorithm [1] is used to identify the peaks and measure their positions (x_1, x_2) and (y_1, y_2) . In some cases, the TSpectrum algorithm fails to find two or more peaks. In this case the shower is classified as “not a π^0 ”. The figure shows (for a simulated π^0) the reconstructed positions from TSpectrum (red) compared to the true position from the truth information (black). To get the photon positions, we need to combine them. There are two possibilities: $(x_1, y_1), (x_2, y_2)$ or $(x_1, y_2), (x_2, y_1)$. However, what we are interested is the distance between these two photons. In either case, the

distance is the same: $d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$. In some cases, two more peaks are possible, but we only pick the largest two peaks. Reference [67] describes the process more in detail.

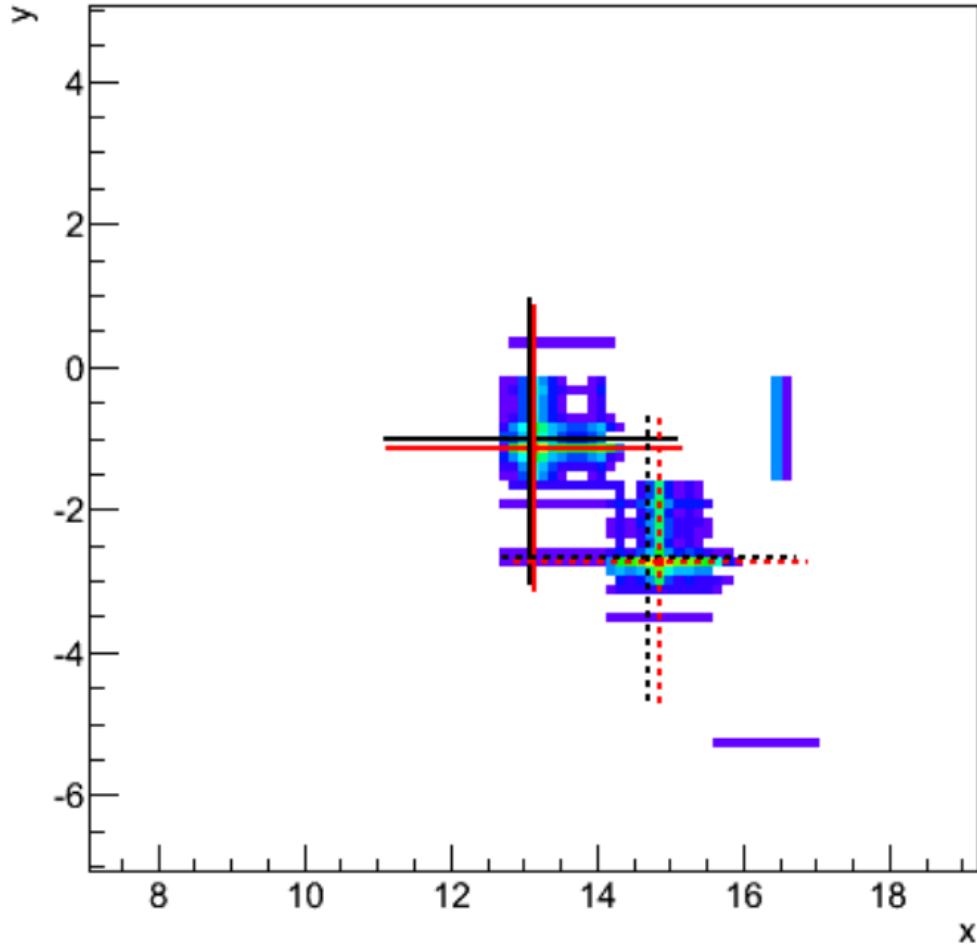


Figure 4.4: An example of single track π^0 (simulation), where the information from the MPC-EX is projected into one plane. Black is the true position and red is the reconstructed position. The X and Y axis are in cm. Note that these two showers would be contained within one MPC tower (size: 2.2cm x 2.2cm) and could not be resolved without the granularity of the MPC-EX.

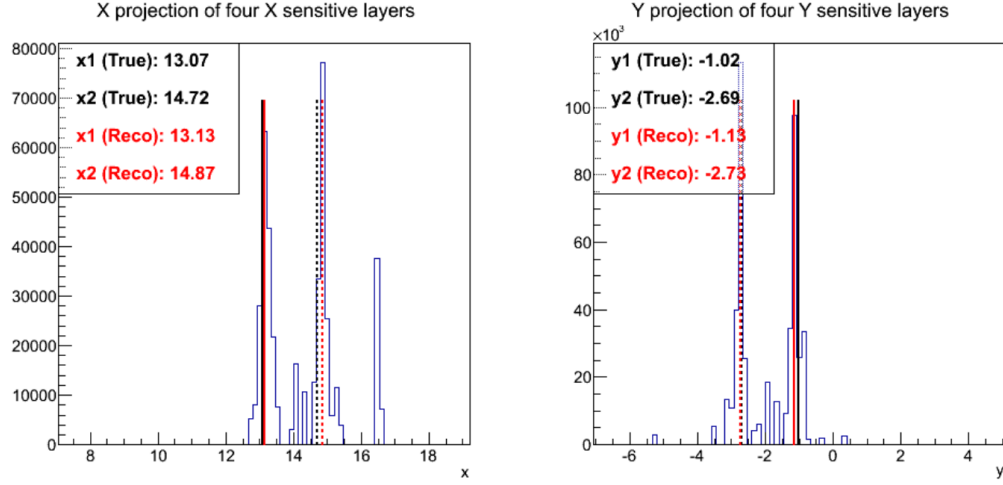


Figure 4.5: Projections of 2d hits of a simulated π^0 along the X axis (left) or Y axis (right). The black line(dotted line) is the true position, and red line(dotted line) indicates the reconstructed position.

4.2.2 MiniCluster algorithm

This algorithm utilizes one of the design features of the MPC-EX. The X and Y layers are alternately distributed in the MPC-EX effectively using the aspect ratio of the minipads, which are 2mm x 15 mm. In the TSpectrum algorithm, when projecting the minipads, the whole minipad area is included. The MiniCluster routine, in contrast, uses adjacent planes to improve the resolutions of each hit to 2mm x 2mm. The left section of figure 4.6 shows the projection from the TSpectrum algorithm, while the right section shows a projection using the MiniCluster algorithm, where the x-y layer information is used to locate the hit to an area 1/8 the size of a minipad. The figure also indicates how energies are split in the case of ambiguities. Figure 4.7 shows the comparison between the TSpectrum and the minipad projections for a somewhat more difficult situation than was shown for the TSpectrum algorithm. The MiniCluster algorithm reduces the background, and the peaks

are clearer.

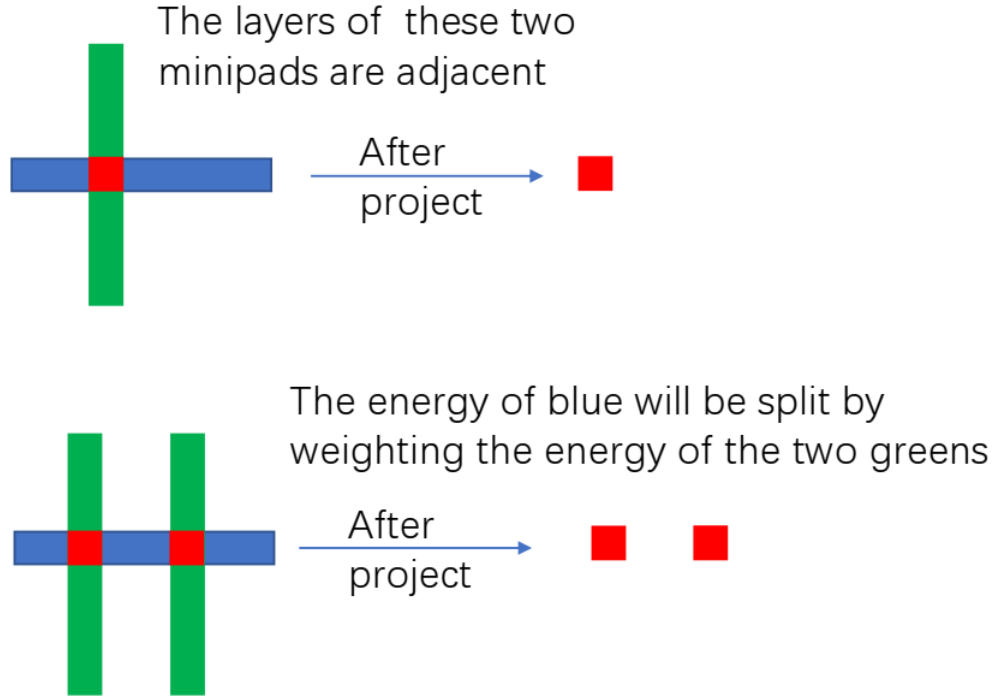


Figure 4.6: The schema for adjacent minipads.

The next step is to group these newly identified hits after the projection into mini-clusters. It is important to note that “hits” in this section refers to the hits formed from the adjacent planes just described. This algorithm bears a resemblance to the one used in reconstructing showers. First, a 2-D projection for a particular shower is made using these hits. The algorithm then searches the projection for peaks (A peak is defined when the energy of the hit is larger than the surrounding hits). The peaks are then ordered by the energy from high to low. Figure 4.8 shows how a mini-cluster is formed. The iterating process starts from 3x3 array hits, including the highest peak as the center hit. The RMS

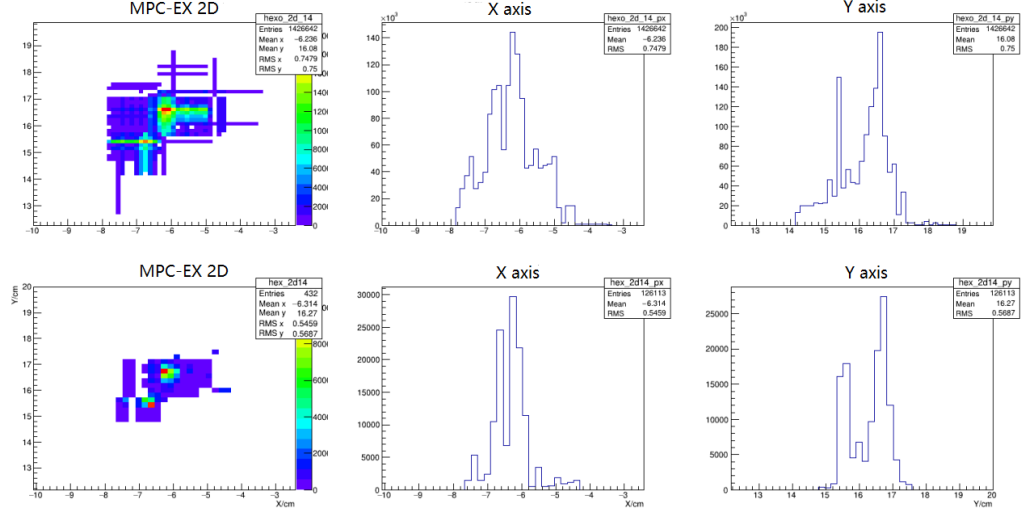


Figure 4.7: Top: The projection a shower using the TSpectrum algorithm. Bottom: the projection of the same shower using the minipad algorithm. The background of the minipad algorithm is smaller and the peaks are clearer.

and the energy weighted center is calculated. The next step is to expand in four directions: $+x$, $+y$, $-x$, $-y$. The expansion criteria is decided by the convergence of the cluster (i.e. the RMS). For example, if the cluster expands in the positive y direction then an attempt is made to include the hits in that direction. The algorithm compares the distance of the candidate hit to the center of the cluster with the cluster's RMS. If the cluster is already converging and the RMS is small, then the ratio of the distance to the RMS will be large. In contrast, if the cluster is not converging and the RMS is large, then the ratio will be small. In this algorithm, a threshold of 2.5 is used, which means if the ratio is smaller than 2.5, the cluster will expand. The expansion ends when hits are no longer being added to the cluster. The algorithm has a limit of a max number of 100 iterations to avoid building up an unphysically large cluster. After a cluster is completely formed, the algorithm goes to the next unused hit, and the process is repeated. The algorithm stops when all hits in

the shower are used. If only one mini-cluster is found, the shower is classified as a “not a π^0 ”. Later, if the mass of the reconstructed π^0 is very low, the shower is also classified as a “not a π^0 ”. Very likely “not a π^0 ” in these cases, means the shower is a single photon.

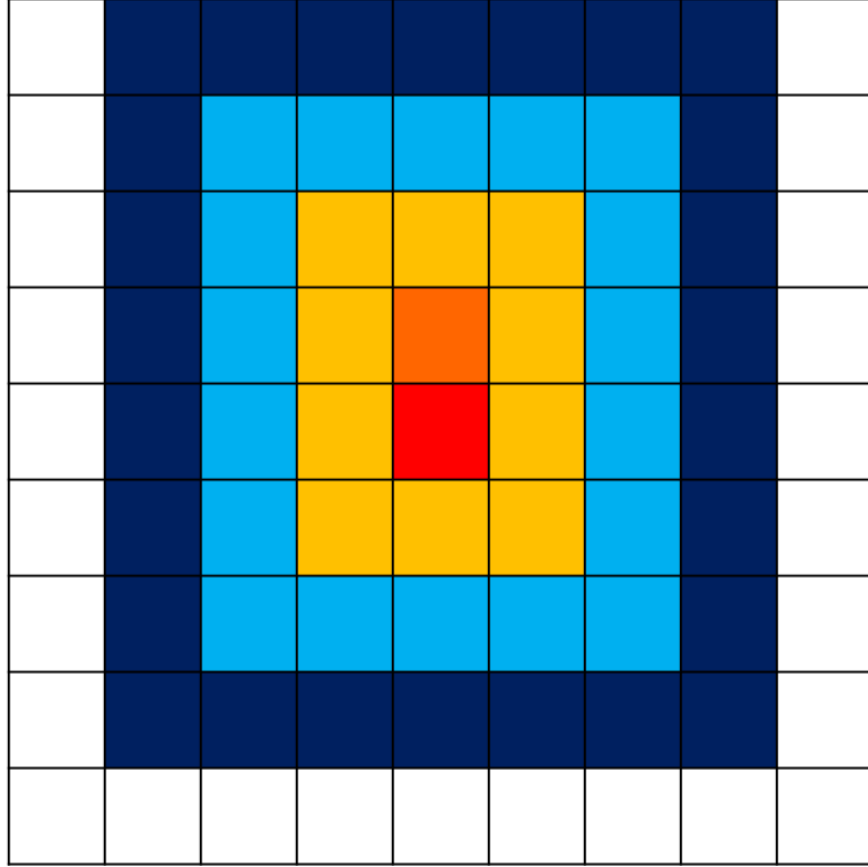


Figure 4.8: The iteration process starting from a peak and including the surrounding hits until converging to form a mini-cluster. Color scheme: the higher the energy, the brighter the color.

Figure 4.9 shows a π^0 candidate from the data. The red circles are mini-clusters. The largest two mini-clusters can be easily selected by using an energy cut. Figure 4.10 shows the reconstructed π^0 mass comparison between the two algorithms as a function of energy. For the TSpectrum algorithm, the π^0 mass becomes discretized when the energy

is bigger than 40GeV. The reason is that the peak positions come from minipad positions. For the MiniCluster algorithm, the peak positions come from the energy weighted centers, which smooths out this effect. The low mass peak comes from single photons, where the algorithm finds two peaks. In such cases, the mass is very small. Recently we have decided to use only the MiniCluster algorithm.

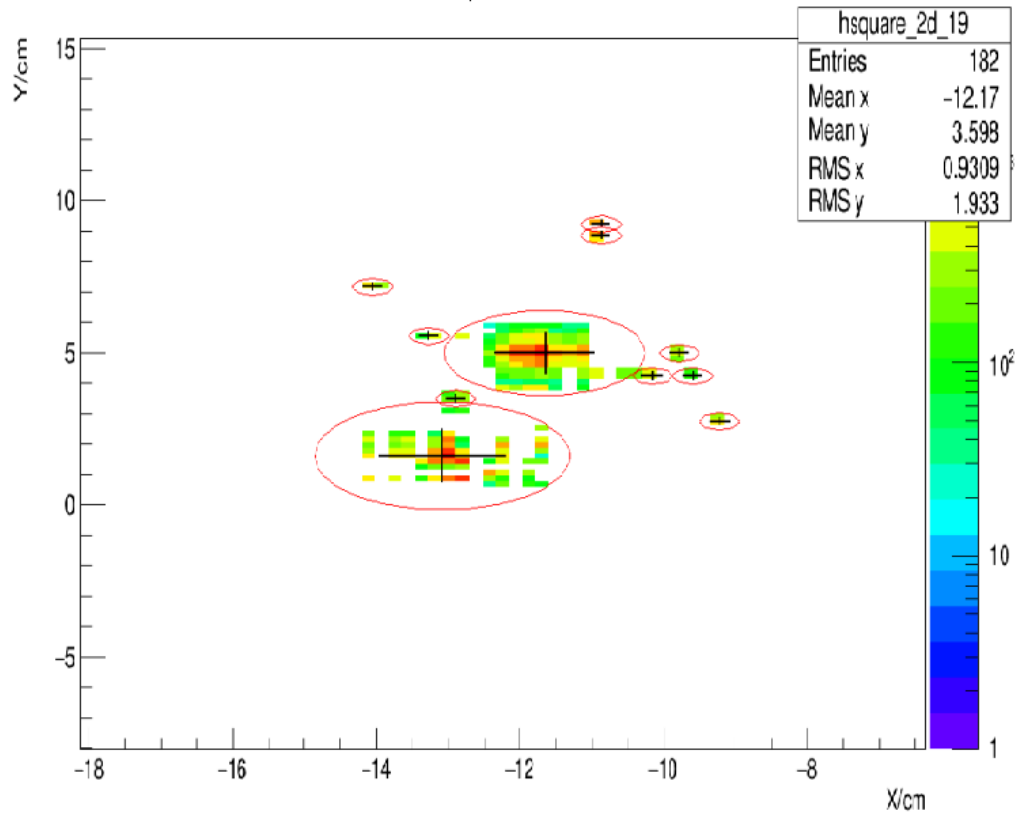


Figure 4.9: A π^0 candidate from data: the circled are mini-clusters found by the MiniCluster Algorithm.

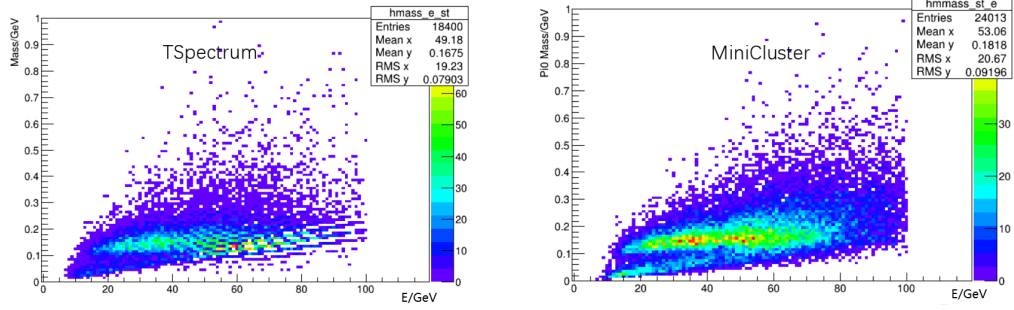


Figure 4.10: π^0 mass vs Energy (simulation). Left: the result of the TSpectrum algorithm. Right: the result from using the MiniCluster algorithm.

4.3 Utilizing Machine Learning for π^0 Identification

The high resolution of MPC-EX provides a snapshot of the fine structure of the shower. The minipads hits can be thought of as an image. Figure 4.11 shows the hit pattern in the MPC-EX plane by plane, showing a π^0 candidate developing in MPC-EX. The two showers (red circles) start in the second layer. As the layer number gets larger, more hits are fired. The bottom part of figure 4.11 shows the projection of these eight layers, where the energies of the corresponding hits in the different layers are added: the profiles of two showers are more obvious. In recent years, the machine learning technique (especially deep learning) has been widely used in image recognition and has achieved very good results. For example, machine learning techniques are used for the identification of animals or humans. The input is the image, and the output is the probability of being the target. This method can be used in the single track π^0 identification. The input is the eight images of the hit patterns in the different layers, and the output is the probability of being a π^0 . The next section introduces this technique for the identification of π^0 s. We will then show the performance.

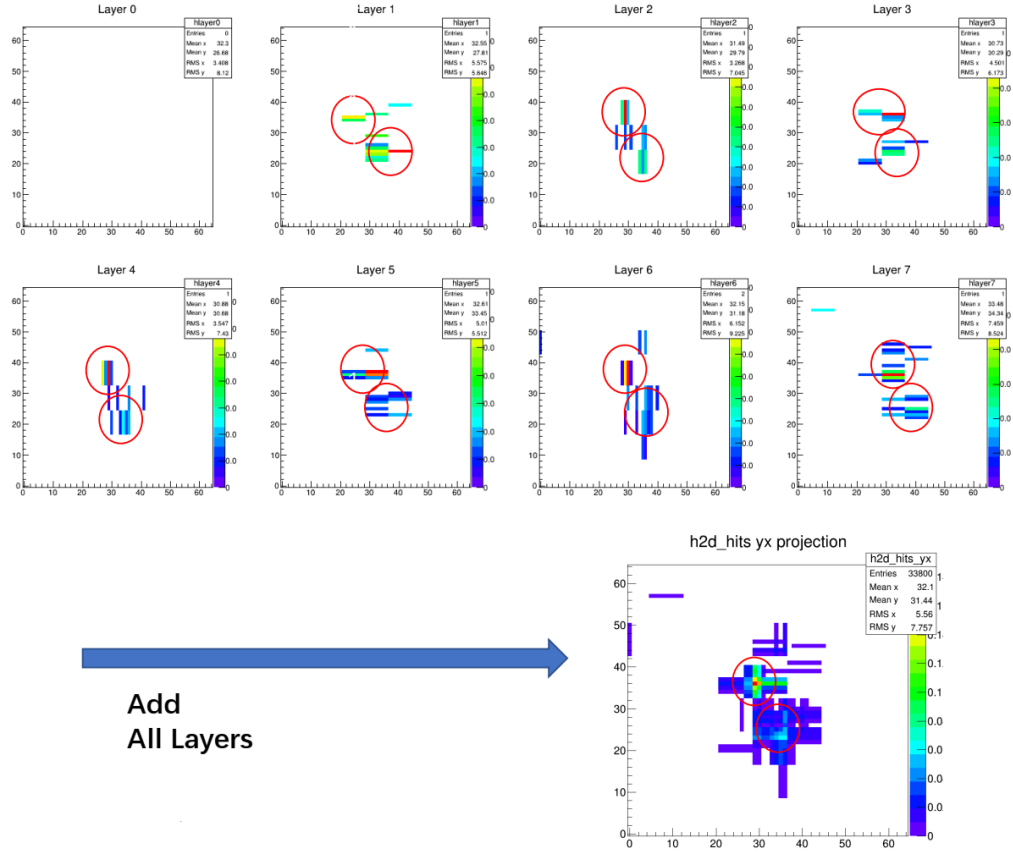


Figure 4.11: A π^0 candidate event(from data) develops in MPC-EX. The top figure shows the eight MPC-EX layers and the figure on the bottom right picture is the sum of the eight layers.

4.3.1 The Convolutional Neural Network (CNN)

Neural Networks are a subset of machine learning and are at the heart of deep learning techniques. Convolutional Neural Networks are a Neural Network technique with superior performance in image recognition. There are two reasons for this: (i) the number of training parameters is small when compared with the traditional neural network; (ii) they can capture the spatial and temporal dependency in an image.

There are five main structures, or layers (not to be confused with the layers of the MPC-EX, which form an 8 layer image) for the CNN:

- **Convolutional layer:** Figure 4.12 shows how a convolutional layer works. The key component is the filter, which detects the edge and style of the image. Figure 4.13 shows how different types of filters work. In our case, multiple filters are used to detect different features.

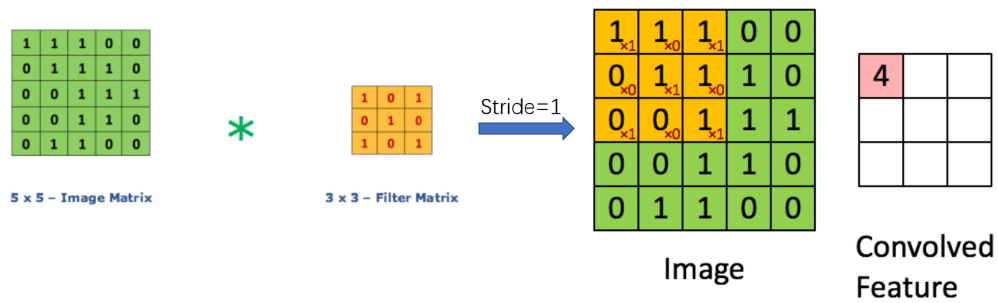


Figure 4.12: A 5x5 image convolved with a 3x3 matrix(filter). The stride is the number of pixels the filter shifts. The outcome is the convolved feature matrix. The size and the value of the matrix are just examples. The next step would be to shift the filter by the stride=1. In the case of this illustration, that would give a 3 in the space to the right of the 4 in the right hand figure.

- **Activation Layer:** This Layer provides the non-linear transformations. This makes the function space larger. Figure 4.14 shows several activation functions used in CNNs. Only sigmoid and ReLU are used in this work.
- **Padding Layer:** This layer deals with the edge pixels. As shown in figure 4.12, the frequency of edge pixels getting convolved is smaller than the internal pixels. In order to make up the frequency of edge pixels, zeros are padded outside the image matrix. Figure 4.15 shows how this works.
- **Pooling Layer:** This layer is used to compress the information matrix into a lower

Operation	Kernel	Image result
Identity	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	
Edge detection	$\begin{bmatrix} 1 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 1 \end{bmatrix}$	
	$\begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}$	
	$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$	
Sharpen	$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{bmatrix}$	

Figure 4.13: This picture shows how filters work. The first type is the identity filter. When acting on the image, the image stays the same. The second type is the edge filter. After using this type of filter, the edges of the image become more clear. The last one is the style filter which makes the image sharper. Each time a filter is used, an additional image layer is added. The values of the filters are just examples. The values in the filters are parameters that are set during the training of the machine learning algorithm.

dimensional matrix. Figure 4.16 shows how this works: the image pixels are divided into different blocks (2x2 in this example). For each block, only the maximum value is selected. This operation reduces the size by a factor of two in each direction.

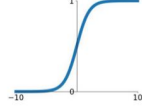
- **Dense Layer:** A fully connected neural network is then used for the classification.

The key idea is the following: using the above operations to extract the features of the image, we get a vector representation. This representation can be used to classify π^0 s. Figure 4.17 shows the structure of the CNN model: as the model goes deeper, the information of the image is reduced (by pooling layers). Each filter, however, extends

Activation Functions

Sigmoid

$$\sigma(x) = \frac{1}{1+e^{-x}}$$



tanh

$$\tanh(x)$$



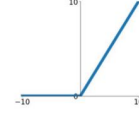
Leaky ReLU

$$\max(0.1x, x)$$



ReLU

$$\max(0, x)$$



Maxout

$$\max(w_1^T x + b_1, w_2^T x + b_2)$$

ELU

$$\begin{cases} x & x \geq 0 \\ \alpha(e^x - 1) & x < 0 \end{cases}$$



Convolved Feature

4	3	4
2	-4	3
-2	3	-4

Apply ReLU

4	3	4
2	0	3
0	3	0

Figure 4.14: There are many functions that are used as non-linear transformations. In this work, only the ReLU and Sigmoid are used. ReLU makes the training process faster, and Sigmoid provides the outcome between 0 and 1 used in last the layer, interpreted as a probability. In this study, it is the π^0 probability.

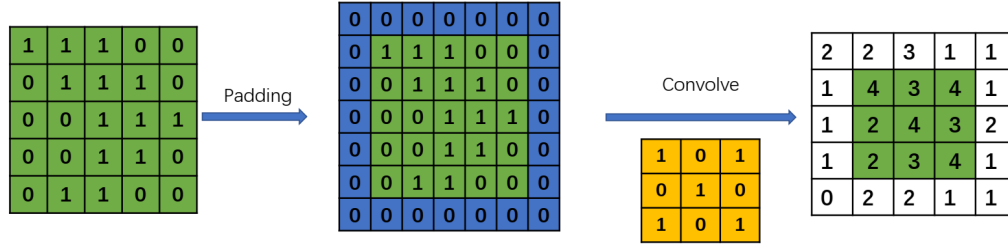


Figure 4.15: Value zeros are padded outside the image matrix. The padding layer, constrains the various CNN layers, to prevent non-zero values from extending beyond the actual image.

the image representation in the longitudinal direction, as shown in the figure. Immediately before the Dense layer, the image is represented by a vector of length 512. Note that each of the boxes in the figure includes all types of CNN layers (Padding, Convolution, Activation, and Polling). This 512 long vector representation undergoes a four layer fully connected neural network which outputs a number that is interpreted as π^0 probability. Table 4.1 shows the detailed structure of the network. The ML algorithm will have many parameters. To set these, it must be trained. To do this, we construct a training sample. Then the model is trained on a GTX 1070 GPU using the Keras [64] framework (The backend is the

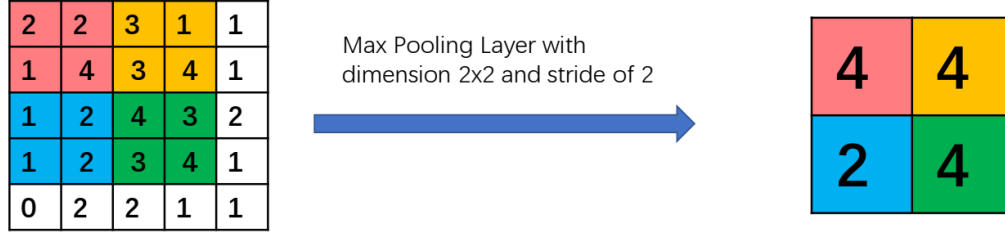


Figure 4.16: Max pooling layer: the image group is divided into 2x2 array groups. For each group, the maximum value is selected. Ungrouped pixels are ignored.

tensorflow platform[44] developed by Google). After training, the values of the parameters are fixed, and the algorithm can then be used for identifying π^0 s.

4.3.2 Signal and Background used for the Training Sample

The signal and background for the training sample are generated by embedding simulated π^0 s into the data. The followings are the cuts and parameters for signal and background.

- **Embedded Data Set:** Minimum Bias Narrow Vertex Trigger.
- **Cuts:**
 - $|\text{Vertex}| < 30\text{cm}$
 - Center tower must not be located at the outer edge of the detector.
 - First Fired Layer ≤ 3
 - The shower must be contiguous from the first layer to last layer.
 - Good Tower Pulse

Layers	Type	Configuration	Output Shape	# Params
1	Convolution + Padding + ReLu	16 7x7 filters	(65,65,16)	6288
2	Max Pooling	2x2	(32,32,16)	0
3	Convolution + Padding + ReLu	32 6x6 filters	(32,32,32)	18464
4	Max Pooling + Padding + ReLu	2x2	(16,16,32)	0
5	Convolution + Padding + ReLu	64 5x5 filters	(16,16,64)	51264
6	Max Pooling	2x2	(8,8,64)	0
7	Convolution + Padding + ReLu	128 4x4 filters	(8,8,128)	131200
8	Max Pooling	2x2	(4,4,128)	0
9	Convolution + Padding + ReLu	256 3x3 filters	(4,4,256)	295168
10	Max Pooling	2x2	(2,2,256)	0
11	Convolution + Padding + ReLu	512 2x2 filters	(2,2,512)	524800
12	Max Pooling	2x2	(1,1,512)	0
13	Flatten		(512)	0
14	Dense + ReLu	256 nodes	(256)	131328
15	Dropout	prob = 0.3	(256)	0
16	Dense + ReLu	128 nodes	(128)	32896
17	Dropout	prob = 0.3	(128)	0
18	Dense + ReLu	32 nodes	(32)	4128
19	Dense + Sigmoid	1 nodes	(1)	33

Table 4.1: The detailed structure of the CNN model. Dropout is a method used to avoid overtraining. The number of the total training parameters is 1,195,569

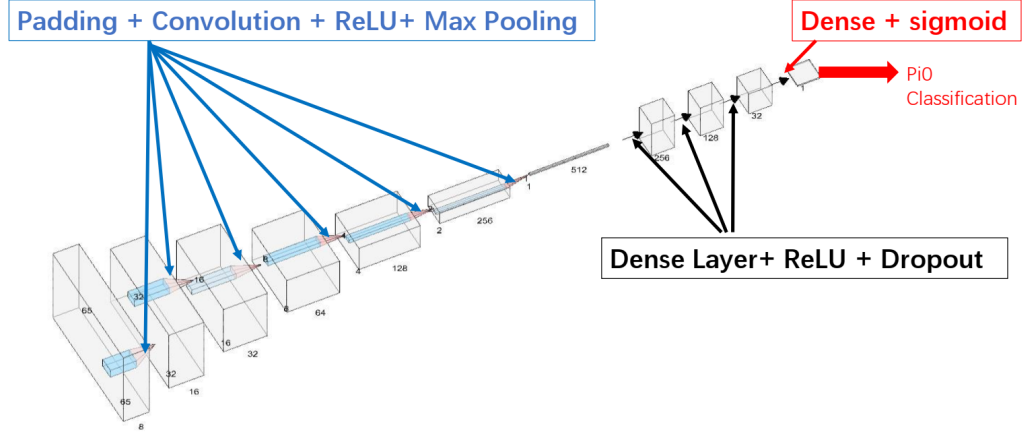


Figure 4.17: The CNN model for MPC-EX. The inputs are 64x64x8 arrays formed in the following way. A 6 cm x 6 cm region centered around each shower is chosen. Each shower layer is represented by a 64x64 array, where each element in the array is a 2mmx2mm “pixel”. Each minipad is actually 8 such pixels. If a minipad is hit, array elements for all 8 pixels will be filled with the value for the energy deposited in the minipad (each minipad is about 16mm x 2 mm). Each layer of the detector for a particular shower will correspond to such an array, so the shower will be represented by a 64x64x8 array. It undergoes 6 layers of convolution and becomes a vector of size 512. This vector is the representation of the image and is passed to a four layer fully connected neural network. The final outcome is one number which is interpreted as π^0 probability.

- 10GeV < Shower E < 100GeV
- The energy sum of MPC 3x3 Tower must be larger than 0GeV.
- The decayed photons must contribute the shower.

- **Signal:**

- The distance between the shower and the embedded π^0 must be less than 1.5 cm
- The total energy contribution of the embedded π^0 must be larger than 80%
- The asymmetry between the decayed photons $((E_1 - E_2)/(E_1 + E_2))$ must be less than 0.8

- **Background:** Showers in the data which don't match the conditions of the signal.

Figure 4.18 shows the input signal and background energy, and mass distributions.

The energies are sampled so that each of the energies has a similar size of the training sample.

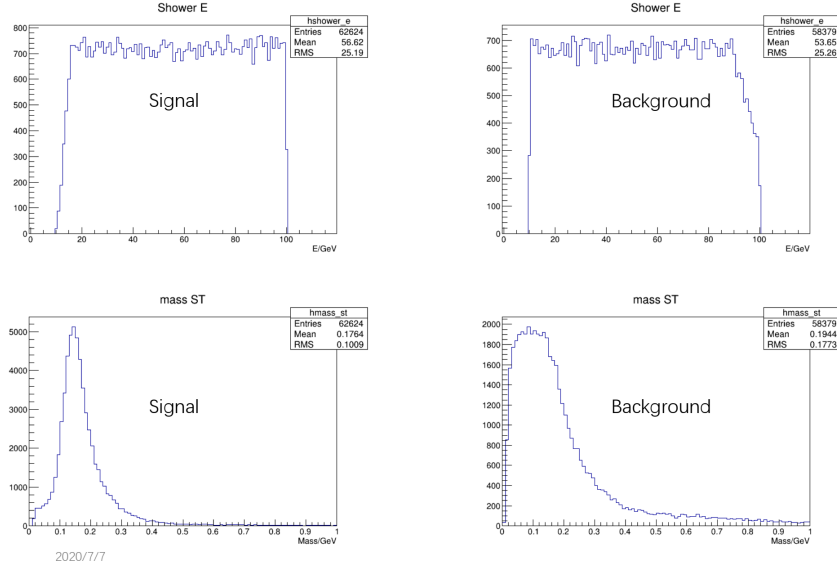


Figure 4.18: The left plots show distributions of the signal and the right ones are background. The top two figures are the true energy distribution and the bottom two are the mass distribution.

4.3.3 Performance

The CNN shows excellent performance in identifying π^0 s. Figure 4.19 shows the result of the π^0 probability. The left figure is the result from the test data set, made up of a part of the training sample which was not used in the training itself and reserved for testing. The accuracy is very high. To test the CNN, we use an event generator HIJING[53], which is a heavy ion event generator which is based on QCD-inspired models (e.g. Pythia [96]). The model incorporates mechanisms such as multiple minijet production, and soft excitations, and depending on a variety of switches, effects such as energy loss in dense matter, and

nuclear parton distributions. We use the default parameters, which excludes these effects, since we wish to test against a baseline. The right figure is the test on a HIJING simulation, where the red histograms indicate showers for which 80% of the energy results from π^0 s. The peak at lower efficiency results from π^0 s which decay very asymmetrically, and one of the photons, either has very low energy, or misses the detector completely. Figure 4.20 shows the improvement on the mass distribution when compared with the mass distribution without using the CNN for π^0 identification(right). The mass distribution from the data also compares well with the simulation. Figure 4.21 shows example events for both data and HIJING, which either show two good peaks and return a high ML probability, or which do not show two clear peaks and return a low ML probability demonstrating the ability of the deep learning method to identify the π^0 s.

While this method is excellent at identifying π^0 s, the final calibrations of the MPC are still in progress as the present analysis was being completed. Hence we will not show results on the single track π^0 spectrum in this thesis. However, the method will be used subsequently for other analysis topics in the collaboration.

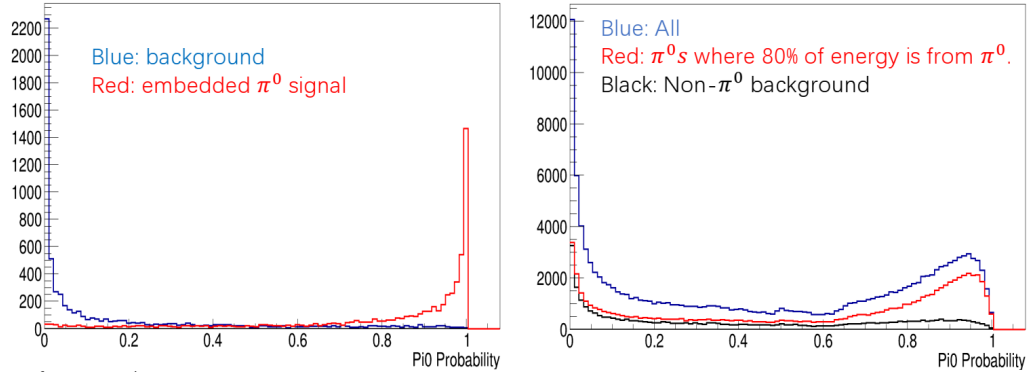


Figure 4.19: The left figure is the result for the test dataset (this subset is not used in the training). The background and signal are well separated. If we use the 0.5 as the threshold, then the accuracy is 87%. The right figure is the result of HIJING simulation. The model is trained on the embedded data, and now works very well in simulation: the signal is enhanced, while the background is suppressed

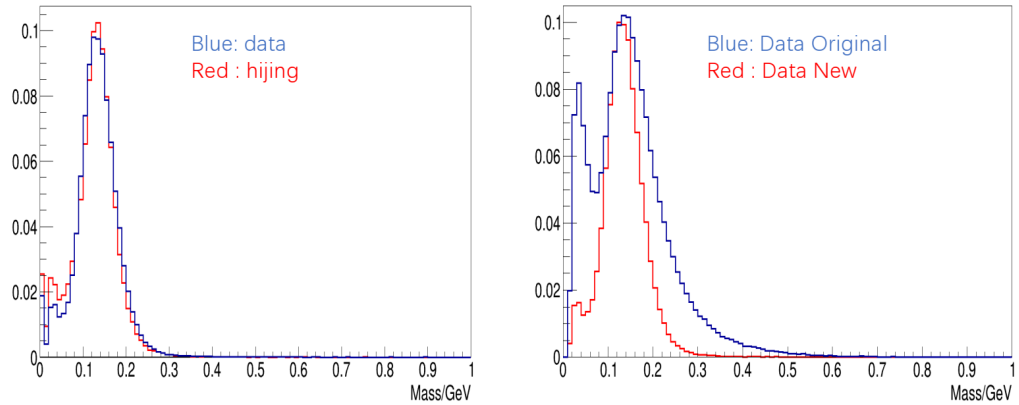


Figure 4.20: The left plot is the π^0 mass when requiring the probability > 0.75 showing the agreement between the data and simulation. The red is the HIJING simulation and the blue is the data. The right figure compares the mass distribution before and after a cut where the probability > 0.75 . The mass distribution improves significantly.

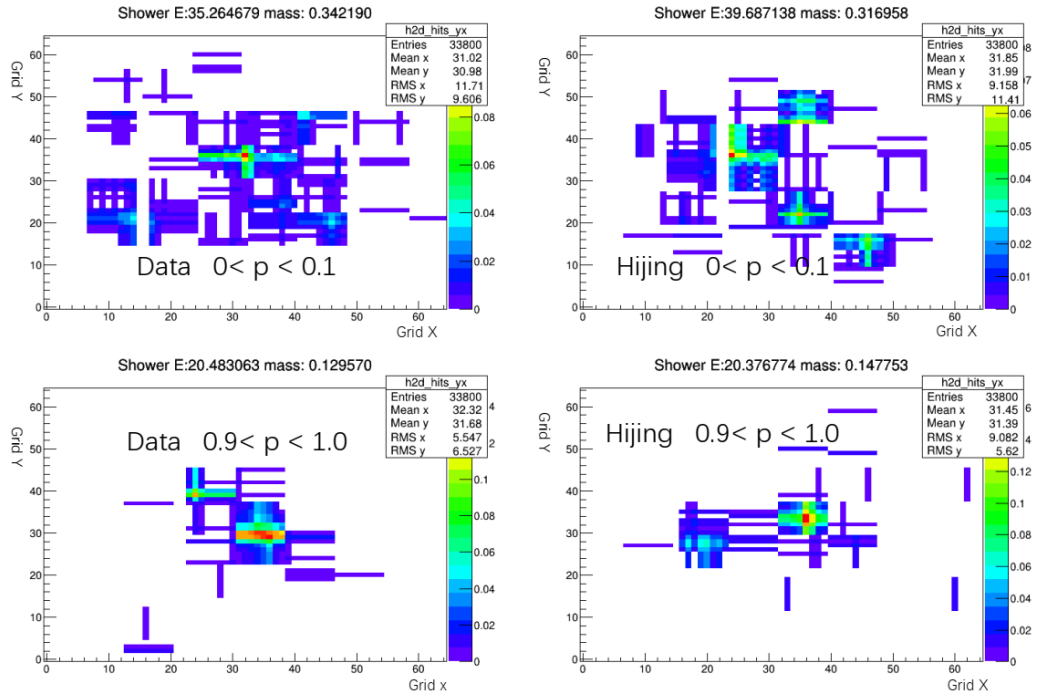


Figure 4.21: The hit pattern of the projection of minipads. Left: Data. Right: HIJING simulation. Top: low probability (bad) π^0 . Bottom: high probability (good) π^0 . The figures with a high probability of being π^0 s have two clear peaks while the others do not.

4.4 Low Energy Two Track π^0 s

Low energy π^0 s ($E < 20\text{GeV}$) can be reconstructed using the energy in the MPC-EX alone, where well separated showers are used to reconstruct π^0 s in the standard way by forming the invariant mass of pairs of showers. Of course, this will limit this measurement to $p_T < 2\text{ GeV}/c$. The machine learning method used to get the shower energy by combining the MPC and the MPC-EX energies is also valid when there is no energy in the MPC. The following cuts are used to select the showers for the two-track π^0 :

1. $|vertex| < 30\text{cm}$
2. First fired layer < 3
3. Shower is contiguous from the fired layer to the last layer
4. Number of MPC-EX hits > 15
5. Shower center to the edge of the MPC-EX $> 1\text{cm}$
6. $0\text{GeV} < p_T < 2\text{GeV}$
7. $E \leq 20\text{GeV}$
8. $0.2\text{cm} < RMS_r < 1.3\text{cm}$
9. $\text{MpcE3x3} \leq 0$

where RMS_r is the RMS in the radius direction, and MpcE3x3 is the energy in the MPC 3x3 set of towers behind the shower in the MPC-EX. The latter cut means that there is no energy in the MPC from the shower in question. As was mentioned, because of

the thresholds set during data taking on the MPC, this effectively means that the shower energy in the MPC was < 4 GeV.

After applying the cuts listed above, we get a good list of showers and reconstruct the two-shower (called two-track from now on) invariant mass for every possible pair in the same event. At the same time, we also obtain the background by using the showers from different events to form the “mixed event” background. The events used in mixing have similar vertex (within 2cm) and the same centrality group. To get a good mass reconstruction, the following cuts are applied:

1. Opening Angle between the two showers > 0.015
2. $\sqrt{(\frac{HSX_0-HSX_1}{RMS_{X0}+RMS_{X1}})^2 + (\frac{HSY_0-HSY_1}{RMS_{Y0}+RMS_{Y1}})^2} < 3.$
3. $E < 25 \text{ GeV}$
4. $3.1 < \eta < 3.8$

The HSX or HSY are the distance in Hough space: $HSX = \frac{x}{z-Z_{vertex}}$. The RMS here is also in Hough space. The first two cuts make sure the showers are well separated. Cut 3 is used to select low energy π^0 s. The triggers used for dAu200GeV, 62GeV, and 39GeV are different:

- dAu200GeV: BBCLL1(>0 tubes) narrowvtx
- dAu62GeV: FVTX_NS&BBC_S(>0), $|Z_{FVTX}| < 10 \text{ cm}$
- dAu39GeV: FVTX_NS&BBC_S(>0), $|Z_{FVTX}| < 10 \text{ cm}$

“BBCLL1(>0 tubes) narrowvtx” is the BBC trigger that requires at least one tube fired in both arms and a cut on the collision z vertex (for example, less than 30cm). “FVTX_NS” is the FVTX trigger requiring both arms to be fired. “BBC_S(>0)” means that one of the BBC south arm tubes is fired. Z_{FVTX} is the collision Z vertex reconstructed by the FVTX (the vertex we used usually comes from the BBC reconstruction. However, at low energies, if the BBC is not fired, we will use the vertex reconstructed from the FVTX).

Figure 4.22 shows the two-track invariant mass of signal and mixed background in different bins of p_T , where the two histograms are normalized in a region 0.35 and 0.4 GeV/c, above the π^0 signal and below any possible η signal. The mixed background matches the signal well in the high mass region. At lower mass there is a clear π^0 peak. The kinematical cuts and the geometry of the MPC-EX do not allow for the identification of η mesons in all but the highest p_T bins, where there is not enough statistics. Figure 4.23 shows the two-track invariant mass after the background is subtracted and the peak is fit to a Gaussian. The peak value increases with p_T which is typically true of π^0 s measured in calorimeters in PHENIX. Figure 4.24 gives a comparison between the HIJING simulation and data. They have similar trends, and the values are very close. A raw p_T spectrum can then be obtained simply by integrating the counts in a $\pm 3\sigma$ region around the peak (Fig. 4.25).

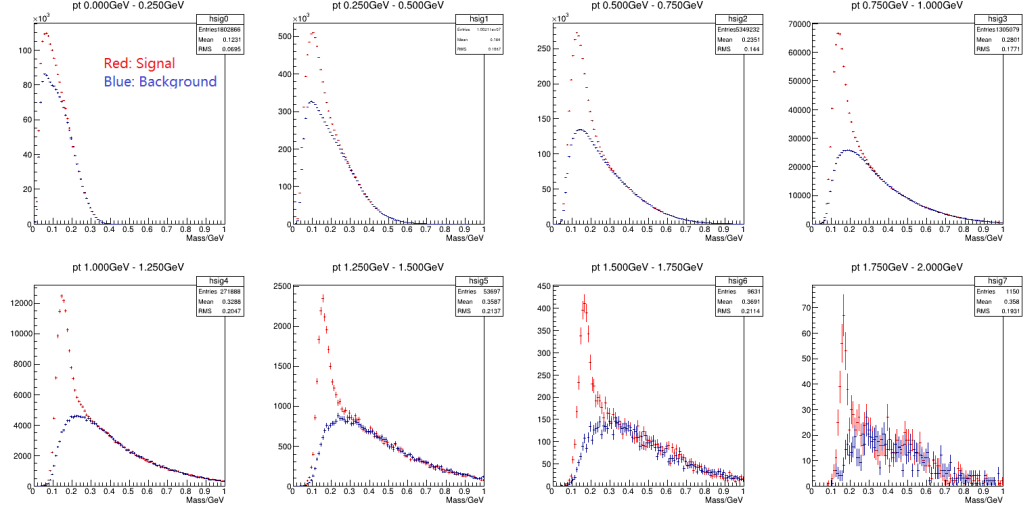


Figure 4.22: The signal(Red) and mix background(Blue) of two-track π^0 s (dAu200GeV). The normalization point is from 0.35GeV to 0.4GeV.

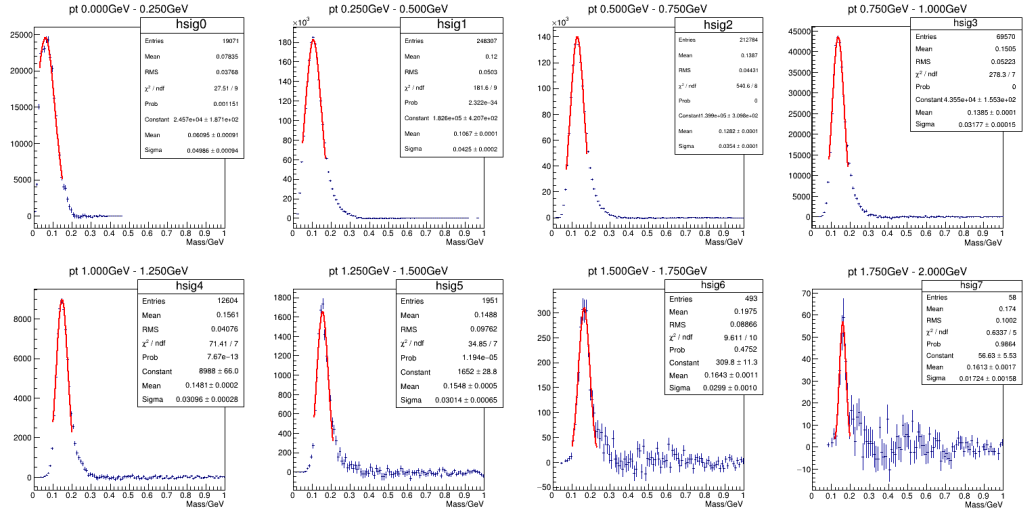


Figure 4.23: The background subtracted two-track invariant mass for different bins of p_T . The red curve is a Gaussian fit of the peak. The mass peak shifts to right as the p_T increases, as discussed in the text.

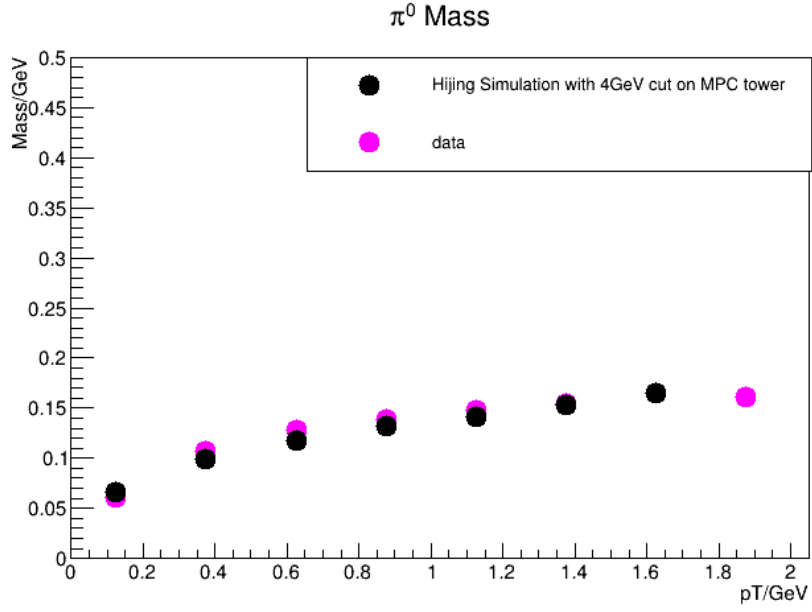


Figure 4.24: π^0 mass peak vs. p_T at 200 GeV. HIJING Simulation and data have similar trends. The 4 GeV cut on the MPC tower is to mimic the low gain and threshold cut of the MPC as described in previous chapter.

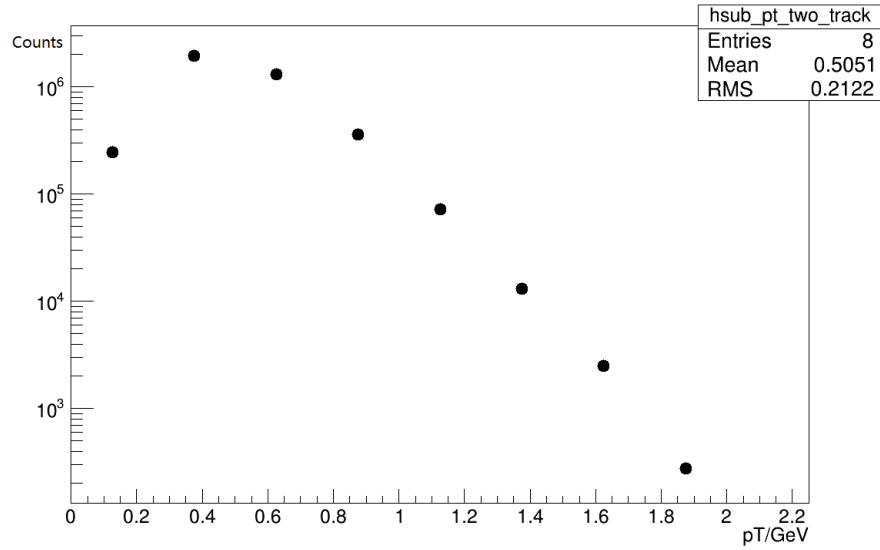


Figure 4.25: The raw π^0 p_T spectrum. The counts are integrated from a region $\pm 3\sigma$ around the mean value (see Figure 4.23)

4.5 Centrality and Number of binary collisions: N_{coll}

Heavy ion collisions are different than proton-proton collisions in that we need consider the relative positions of the two nuclei when they collide. Figure 4.27 shows two extreme cases - peripheral collisions, where the two nuclei collide in a glancing blow, and central collisions, where the two nuclei collide head-on and the impact parameter, b (the distance between the centers of the two nuclei) is equal to zero. As mentioned in the introduction, we define a quantity, the centrality, which goes from 0 to 100%. 0% refers to head on collisions, and 100% refers to collisions in which the nuclei barely touch each other. A central collision has more nucleons participating in the reaction (N_{part}), which leads to a larger particle yield. In order to compare spectra from different centralities, it is important to normalize them in some way. This is done by calculating the total number of nucleon-nucleon collisions which occur in an event, N_{coll} (number of binary collisions). N_{part} is generally not equal to N_{coll} since a nucleon in one nucleus could interact with several nuclei in the other. To find N_{coll} we use a Glauber model for the nucleus (which has associated with it a N_{coll} since it is a model) and a Negative Binomial distribution (NBD) for the multiplicity for each nucleon-nucleon collision to predict the multiplicity. This distribution is then fit to the data to obtain the N_{coll} . We will call this the NBD+Glauber method.

4.5.1 Glauber Model

To calculate the N_{coll} in a heavy ion collision, a model often used is the Glauber model [79]. In this model, the nucleon density can be derived using the Fermi distribution

to yield a modified Woods Saxon distribution.

$$\rho(r) = \rho_0 \cdot \frac{1 + w(r/R)^2}{1 + \exp(\frac{r-R}{a})} \quad (4.1)$$

ρ_0 is the nucleon's center density; R is the nuclear radius; a is the "skin depth" and w characterizes deviations from a spherical shape. For the deuteron, the wave function is represented by the Hulthén form [58]:

$$\phi(r_{pn}) = \frac{1}{\sqrt{2\pi}} \frac{\sqrt{ab(a+b)}}{b-a} \cdot \frac{e^{-ar_{pn}} - e^{-br_{pn}}}{r_{pn}} \quad (4.2)$$

where $a = 0.228 fm^{-1}$ and $b = 1.18 fm^{-1}$ [9]. r_{pn} is the distance between the proton and the neutron.

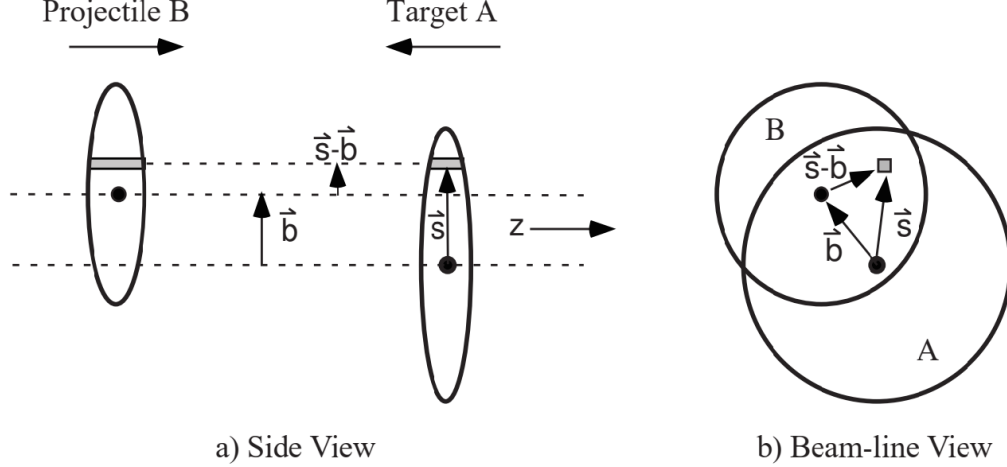


Figure 4.26: A schematic representation of nuclei in the Glauber model. $\vec{b}$ is the impact parameter, which is the vector from the center of the projectile B to the center of the target A. $\vec{s}$ is the displacement to the center of the target A in x-y plane. $\vec{s} - \vec{b}$ is the displacement to the center of the projectile B.

Figure 4.26 shows a nuclear collision in the Glauber model. $\vec{b}$ is the impact parameter, which is the vector from the center of the projectile B to the center of target A. In a

colliding beam configuration, such as the one in this experiment, B is considered to be the deuteron and A is considered to be the Au nucleus. $\vec{s}$ is the displacement to the center of the target A in x-y plane. $\vec{s} - \vec{b}$ is the displacement to the center of the projectile B. The probability to find a given nucleon at a position, s , in A is given by $\hat{T}_A(s) = \int \hat{\rho}_A(\vec{s}, z_A) dz_A$, where $\hat{\rho}_A(\vec{s}, z_A)$ is the nuclear density function after being normalized to unity. For the overlap region, the nucleon probability in the transverse plane can be written as $\hat{T}_A(\vec{s})\hat{T}_B(\vec{s} - \vec{b})d^2s$. Integrating this over $\vec{s}$, we will get the "thickness function":

$$\hat{T}_{AB}(\vec{b}) = \int \hat{T}_A(\vec{s})\hat{T}_B(\vec{s} - \vec{b})d^2s. \quad (4.3)$$

We can interpret $\hat{T}_{AB}(\vec{b})$ as the effective overlap area for which a nucleon from A collides with that from B. If the nucleon-nucleon inelastic cross section is σ_{inel}^{NN} , the probability of an interaction collision happening at an impact parameter b is $\hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN}$. If we have n such interactions, the probability is given by a binomial distribution:

$$P(n, \vec{b}) = \binom{AB}{n} [\hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN}]^n [1 - \hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN}]^{AB-n} \quad (4.4)$$

The total probability of any number of interactions happening at an impact parameter b between A and B is:

$$\frac{d^2\sigma_{inel}^{A+B}}{db^2} \equiv P_{inel}^{A+B}(b) = \sum_{n=1}^{AB} P(n, \vec{b}) = 1 - [1 - \hat{T}_{AB}(\vec{b})\sigma_{inel}^{NN}]^{AB} \quad (4.5)$$

where A and B are the number of nucleons in A or B. The total cross section can be obtained by integrating over d^2b :

$$\sigma_{inel}^{A+B} = \int_0^\infty 2\pi b db \{1 - [1 - \hat{T}_{AB}(b)\sigma_{inel}^{NN}]^{AB}\} \quad (4.6)$$

The total number of nucleon-nucleon collision is:

$$N_{coll}(b) = \sum_{n=1}^{AB} nP(n, b) = AB\hat{T}_{AB}(b)\sigma_{inel}^{NN} \quad (4.7)$$

In the Glauber model, there are two types of input parameters. One is the parameters describing the nucleon distributions. The other is the the inelastic nucleon-nucleon cross section, σ^{NN} , taken from experiment[103] and interpolating to the correct center of mass energy. In this thesis, the σ^{NN} s used for 200GeV, 62GeV and 39GeV are 42mb, 35.6mb and 34mb, respectively.

4.5.2 Centrality and N_{coll}

In the real experiment, it is impossible to measure the N_{coll} directly. What we can measure is the multiplicity(number of charged particles). The multiplicities are grouped into different classes, which we call centrality. By comparing with the simulation (Glauber model), we can map these centralities to the N_{coll} . Figure 4.27 shows a cartoon of how we classify the centrality: the X-axis is the number of particles measured by a given detector and the Y-axis is the corresponding probability. Head-on collisions generate the largest number of particles, while peripheral collisions generate fewer particles. We can define the 0-10% centrality as the highest ten percent of events yielding the highest multiplicity. Then 10-20%, 20-30% and so on.

In this thesis, we use the sum of the BBC south arm charges to measure multiplicity. The charge measured in BBC south obeys the Glauber+NBD distribution. The Negative Binomial Distribution (NBD)[34] is given by:

$$P(n, \mu, k) = \Gamma(n+k)/(\Gamma(k)n!) \times (\mu/k)^n / (1+\mu k)^{n+k} \quad (4.8)$$

where n is the number of the particles; μ and k are the parameters that describe N_{coll} . The total BBC south charge distribution is the sum of the NBD over different numbers of particles n and N_{coll} . n is uniformly distributed from 0 to infinity. The N_{coll} distribution comes from a simulation of the Glauber model described above[79]. The top plot in figure 4.28 shows the Glauber+NBD fitting to the BBC south arm charge in dAu200GeV collisions. The open circles are the data and the line is the Glauber+NBD distribution. The filled colors represent different centralities. For example, the red area is 0% - 20% centrality. In the low charge region, the data goes below the Glauber+NBD curve, since the detector is not fully efficient. This is also the reason why we can't achieve 100% centrality). The ratio of the data to the Glauber+NBD curve from simulations is the trigger efficiency as shown in the bottom plot of figure 4.28. The integration of the ratio gives 88%, which is the total trigger efficiency of the BBC detector. Figure 4.29 shows N_{coll} distributions for different centralities and also gives the mean N_{coll} values for different centrality ranges.

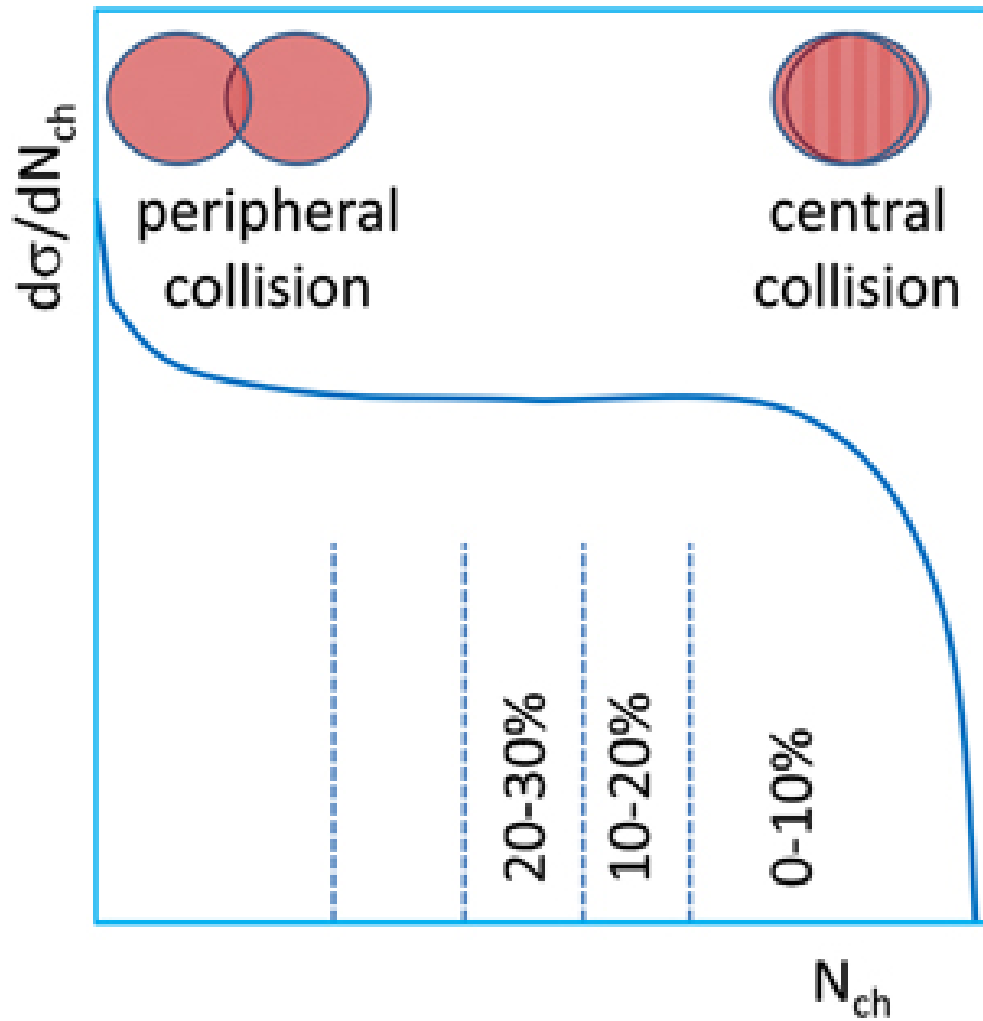


Figure 4.27: A cartoon showing the definition of centrality [27] and its connection to particle multiplicity. The X-axis is the yield of particles in a given detector. The Y-axis is the corresponding cross-section, which can be interpreted as the probability. From left to right, the collision goes from the peripheral to head-on.

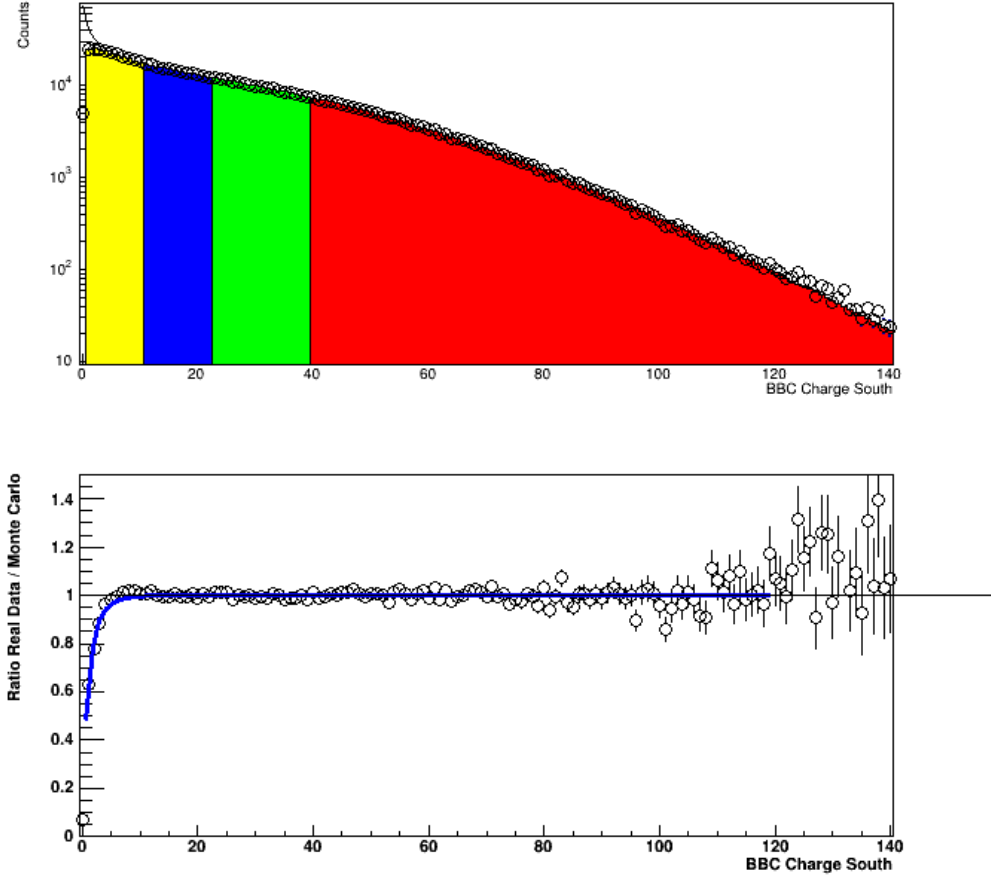


Figure 4.28: Top: the Glauber+NBD fitting to the dAu200 data (open circles). The black curve is the Glauber+NBD. simulation. The centrality ranges from right to left are 0%-20%(red), 20%-40%(green),40%-60%(blue) and 60%-88%(yellow). Since the detector is not fully efficient, especially in the low multiplicity region, we cannot reach 100% centrality. Bottom: the ratio of data and Glauber+NBD simulation giving the trigger efficiency of the BBC. The integration of the ratio is 88.8% . Hence the total efficiency of BBC is 88.8%.

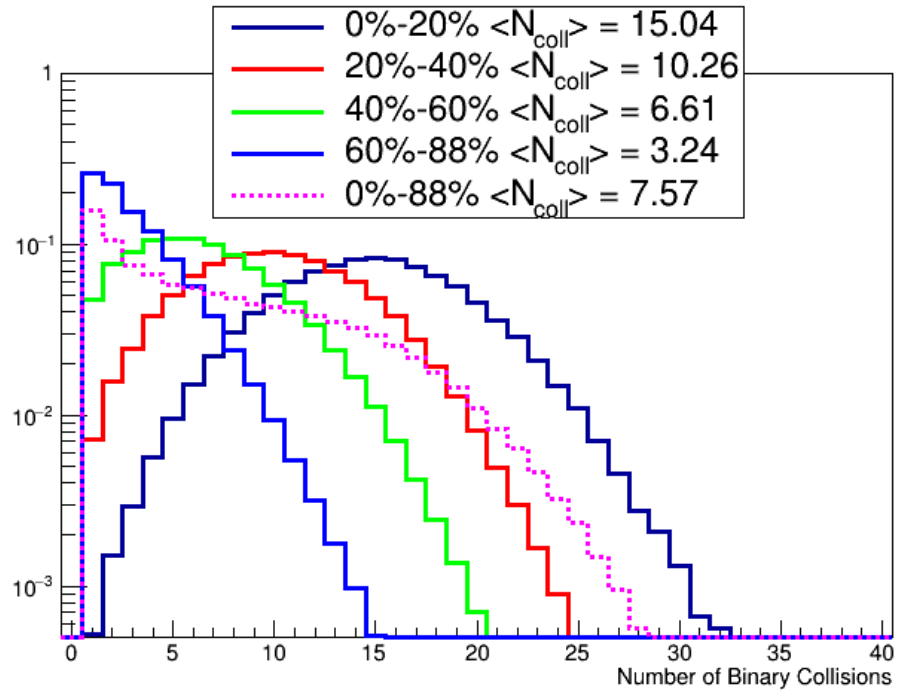


Figure 4.29: The number of binary collisions (N_{coll}) for different centralities.

4.5.3 Centrality at Lower Energies

For 200 GeV center of mass collisions, the centrality is obtained by fitting the Glauber+NBD to the BBC south arm charge distribution. The fitting range is above 20 (south arm charge), based on the assumption that the BBC is fully efficient in central collisions. However, this is not true for the lower energies. Table 4.2 shows the trigger efficiencies of different energies in simulation. There are two types of events in the table: minimum bias and central events. For the minbias events, both the BBC and FVTXNS's efficiency decreases with the energy. 39GeV has the most severe affect: 51% events fire the BBC. For central collision events, the BBC efficiency reaches 99% at 200GeV. However, for the lower energies, the BBC fails to achieve 99% efficiency, and hence we cannot use the Glauber+NBD to fit the BBC trigger only events to get the centrality and N_{coll} . Fortunately, The FVTXNS is still fully efficient at 39GeV. If we use the sample of "FVTX_NS& BBC_S>0" triggers, it is still valid to get the centrality and N_{coll} . The left plot of figure 4.30 shows the efficiency of the BBC trigger with different impact parameters at various energies in the AMPT[73] simulation. AMPT is another event generator often used in heavy ion physics, very similar to HIJING, but giving more control and access to parameters such as N_{coll} . Only at 200 GeV does the BBC trigger efficiency reach 100%. The right plot shows the trigger ratio of BBC trigger to FVTX triggers in the simulation and data at 62 GeV. As one can see, the data and simulation agree. Thus, due to the low efficiency of BBC triggers in central collisions, we use the trigger "FVTX_NS& BBC_S>0" to define the Minbias events at lower energies. Figure 4.31 shows the result of the low energies.

Event Type	MinBias Events		Central Events	
Energy	%firing BBC	%firing FVTXNS	%firing BBC	%firing FVTXNS
200GeV	93	85	99	100
62GeV	75	79	82	99
39GeV	51	74	52	99

Table 4.2: AMPT simulation of the BBC and FVTX efficiency for minimum bias and central events [80].

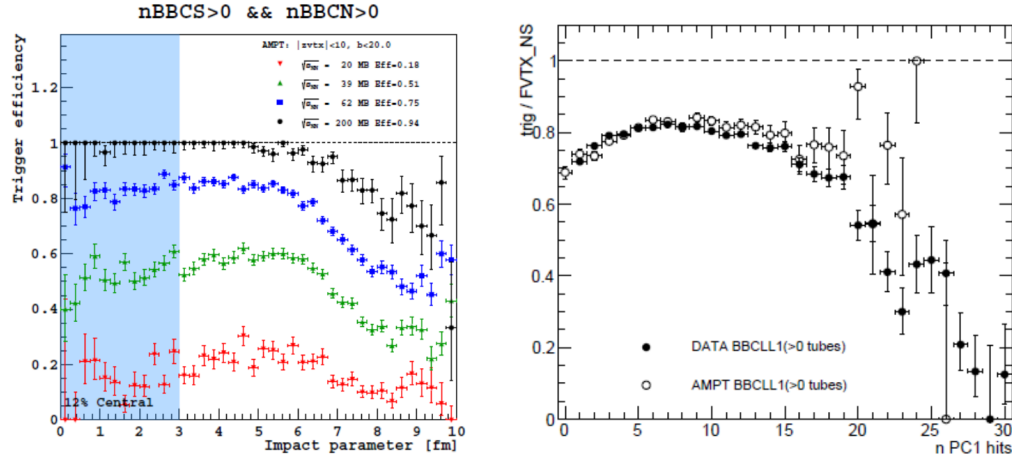


Figure 4.30: The left plot shows the BBC trigger efficiency vs. the impact parameter at different energies[80]. Except for the 200GeV, the efficiencies are below 100%. The right plot shows the ratio of triggers in the BBC and FVTX at 62 GeV in data and an AMPT simulation. The data matches simulation.

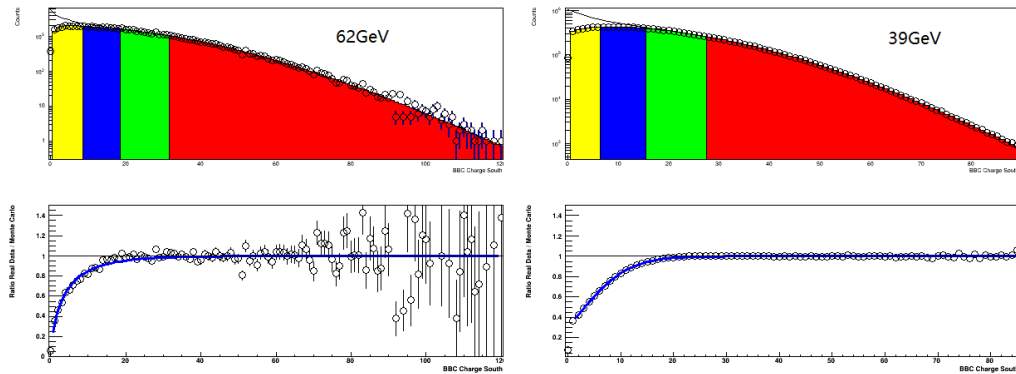


Figure 4.31: The Glauber+NBD fit to the low energies data. The left is the 62GeV. The centrality ranges from left to right are 60% - 78%, 40% - 60%, 20% - 40%, 0% - 20%. The right plot is the 39Gev. The centrality ranges are similar to 62Gev, except for the first one: 60% - 74%.

4.5.4 Uncertainty of the N_{coll}

The systematic uncertainty of the N_{coll} is obtained by varying the following input parameters, within values constrained by measurements or parameter sets given in the literature [56]:

- σ_{NN} (the cross section of nucleon-nucleon collision)
 - dAu200GeV: 39mb, 42mb(default), 45mb
 - dAu62GeV: 32.6mb, 35.6mb(default), 38.6mb
 - dAu39GeV: 31mb, 34mb(default), 37mb
- Nuclear Parameters(R is nuclear radius; a is the skin depth) from equation 4.1
 - $R = 6.25\text{fm}$, $a = 0.53\text{fm}$
 - $R = 6.38\text{fm}$, $a = 0.54\text{fm}$ (default)
 - $R = 6.65\text{fm}$, $a = 0.55\text{fm}$
- α (multiplicity is proportional to N_{ncoll}^α)
 - $\alpha = 0.98$
 - $\alpha = 1.00$ (default)
 - $\alpha = 1.02$
- Collision Z Vertex:
 - dAu200GeV: [-30cm, -25cm], [-10cm, 10cm](default), [25cm, 30cm]
 - dAu62GeV: [-10cm, -5cm], [-2.5cm, 2.5cm](default), [5cm, 10cm]

– dAu39GeV: [-10cm, -5cm], [-2.5cm, 2.5cm](default), [5cm, 10cm]

For each energy, we will have 81 combinations. Then, we can calculate the deviations compared with the default values. We take the systematic uncertainty of N_{coll} to be the RMS of these deviations. Figure 4.32 shows the N_{coll} deviations at dAu200GeV. The uncertainty will be the RMS along the Y-axis. A summary of the N_{coll} and uncertainty is listed in table 4.3.

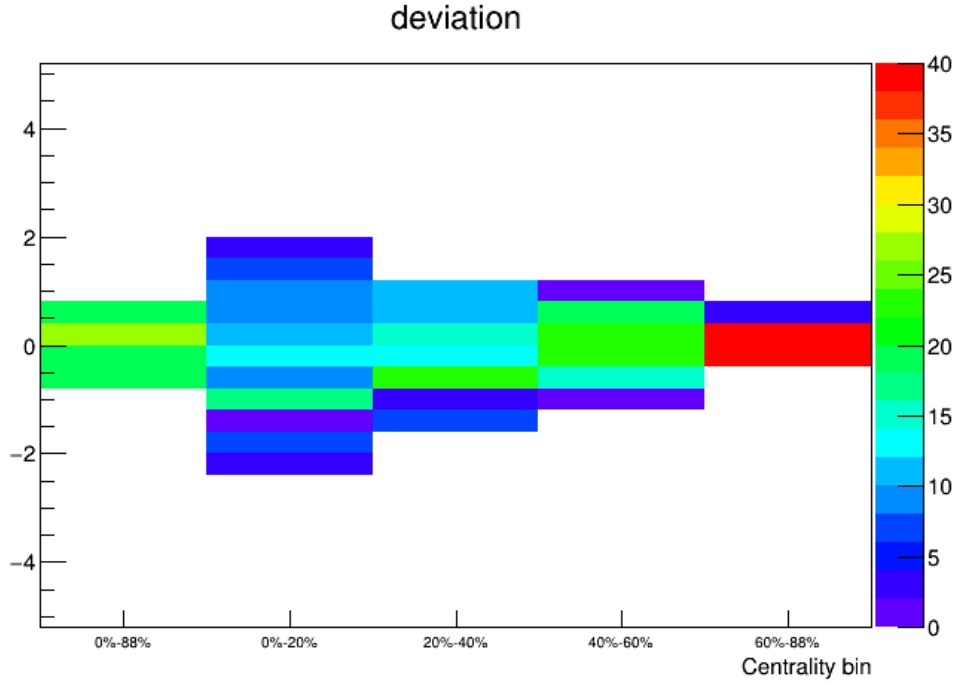


Figure 4.32: N_{coll} uncertainties in dAu200GeV. The X-axis is the centrality range and the Y-axis is the deviation. The z-axis is in arbitrary units given by the color

Energy	Centrality Range				
200GeV	0% - 88%	0% - 20%	20% - 40%	40% - 60%	60% - 88%
N_{coll}	7.57	15.04	10.26	6.61	3.24
Uncertainty	0.43	1.00	0.69	0.44	0.23
62GeV	0%-78%	0% - 20%	20% - 40%	40% - 60%	60% - 78%
N_{coll}	6.65	13.35	8.67	5.12	2.46
Uncertainty	0.43	0.96	0.69	0.50	0.26
39GeV	0%-74%	0% - 20%	20% - 40%	40% - 60%	60% - 74%
N_{coll}	6.43	12.76	8.26	4.93	2.36
Uncertainty	0.43	0.96	0.69	0.44	0.22

Table 4.3: N_{coll} and uncertainty for different energies

4.5.5 N_{coll} Bias

If a hard process, which typically has more multiplicity, happens during a peripheral collision, the centrality category can shift to the next more central bin. This effect can cause a bias in N_{coll} . In addition, at low energies, we use the trigger "FVTX_NS&BBC_S>0" to define the minimum bias events, which is different from the minimum bias events at 200 GeV. Hence the bias should be checked. In this section, we use the HIJING simulation to mimic the process of the NBD+Glauber method and compare N_{coll} to the true value of N_{coll} , since in the simulation, we know the N_{coll} of each event. To simulate the triggers and BBC south arm charge, we count the particles in the simulation:

- BBC north multiplicity (multiBBCN): number of $K^\pm, \pi^\pm, p^\pm$ in $3.0 < \eta < 3.9$
- BBC south multiplicity (multiBBCS): number of $K^\pm, \pi^\pm, p^\pm$ in $-3.9 < \eta < -3.0$
- FVTX north multiplicity (multiFVTXN): number of $K^\pm, \pi^\pm, p^\pm$ in $1.0 < \eta < 3.0$
- FVTX south multiplicity (multiFVTXS): number of $K^\pm, \pi^\pm, p^\pm$ in $-3.0 < \eta < -1.0$

- BBC south arm charges: number of all particles in $-3.9 < \eta < -3.0$
- FVTX_NS&BBC_S>0 trigger: multFVTXN>0, multFVTXS>0, and multiBBCS>0
- BBC Trigger: multiBBCN>0 and multiBBCS>0

We use the number of particles in the HIJING output to determine if the trigger is fired. We also assume that the number of particles in the BBC south is proportional to the charge. Figure 4.33 shows the comparison between the rescaled BBC south arm charges and the number of particles. The match for the 62 GeV and 39 GeV data is reasonable, but for the 200 GeV data, the agreement is poor. At a higher charge, the data has higher efficiency than in the simulation. The reason for this is that the particle's energy in the 200GeV data is higher and generates more secondary particles when passing through the BBC, resulting in more charge.

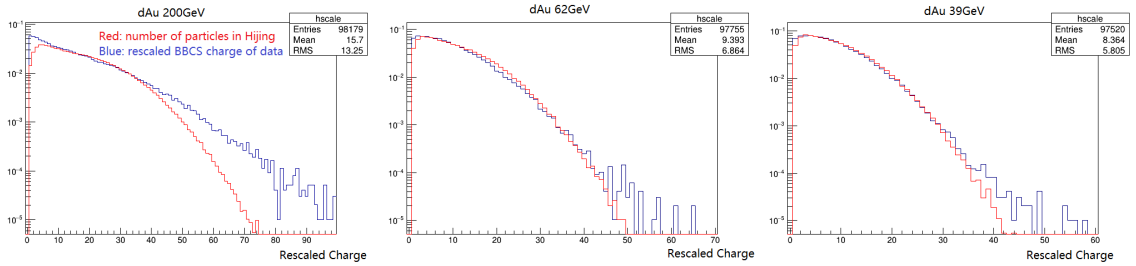


Figure 4.33: The comparison between the rescaled BBC south arm charges and the number of particles passing through the BBC south arm in HIJING. For 62GeV and 39GeV, they have a good agreement. For the 200GeV, the agreement is poor at a higher BBC charge, as explained in the text.

We now follow the same method as used for the data - i.e., the NBD+Glauber method to predict the multiplicity (or BBC charge). Figure 4.34 shows the results for the NBD+Glauber method (Top plots, open circles). We can then compare the N_{coll} from these

fits with the values directly from the simulation and obtain the bias factor (Bottom plot, open circles). Table 4.4 shows extracted N_{coll} values and the bias factors which are all less than about 10%. Figure 4.35 shows an example of the N_{coll} distributions both from the NBD+Glauber method and directly from the HIJING truth data at 62GeV. They are similar as might be expected. This difference between these yields the bias factor as shown in the table.

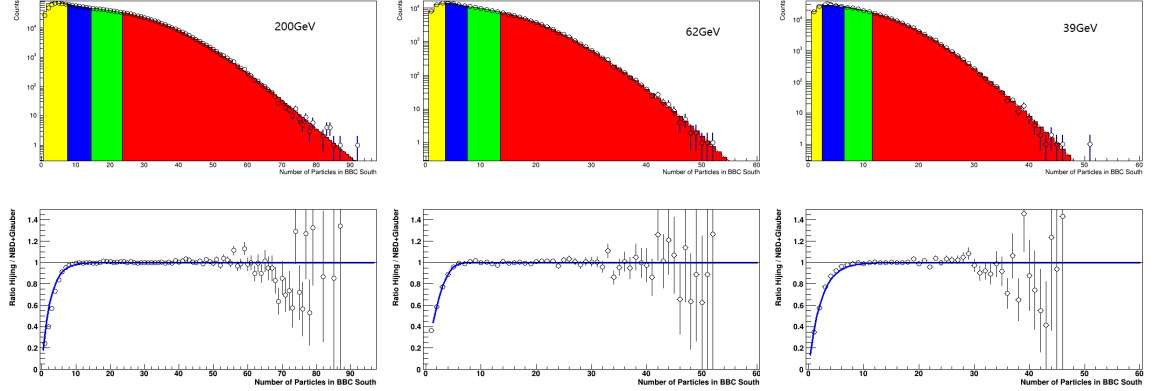


Figure 4.34: Results using the NBD+Glauber method on the HIJING simulation. The different colors are corresponding to different centrality ranges 0-20%(red), 20-40%(green), 40-60%(blue) 60-max%(yellow), where max is 88% for the 200 GeV data, 78% for the 62 GeV data and 74% for the 39 GeV data. The bottom is the trigger efficiency curve. The open circles are the ratio of HIJING BBC particle yields to yields using the NBD+Glauber method on HIJING events. The blue line is the trigger turn on curve, which is a fit to the open circles.

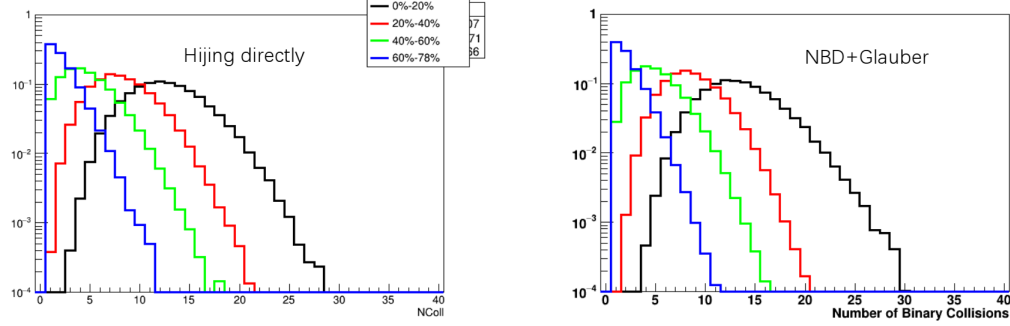


Figure 4.35: The left plot shows N_{coll} from the HIJING directly (62GeV). The right plot shows N_{coll} extracted by the Glauber+NBD. They are quite similar. The difference gives the bias factor.

200GeV	0%-88%	0% - 20%	20% - 40%	40% - 60%	60% - 88%
Particle Number Range	0 -	0-7	8-14	15-23	23 -
NBD+Glauber N_{coll}	7.57	16.31	10.34	6.21	2.58
HIJING N_{coll}	8.12	14.92	9.68	5.72	2.58
Bias Factor	1.07	0.915	0.936	0.92	1
62GeV	0% - 78%	0% - 20%	20% - 40%	40% - 60%	60% - 78%
Particle Number Range	0 -	0 - 3	4 - 8	9 - 13	14 -
NBD+Glauber N_{coll}	6.66	13.53	8.63	5.00	2.18
HIJING N_{coll}	7.35	12.7	8.19	4.76	2.33
Bias Factor	1.104	0.939	0.945	0.952	1.069
39GeV	0% - 74%	0% - 20%	20% - 40%	40% - 60%	60% - 74%
Particle Number Range	0 -	0 - 2	3 - 6	7 - 11	12 -
NBD+Glauber N_{coll}	6.43	13.192	8.29	4.56	2.08
HIJING N_{coll}	7.34	12.31	7.87	4.43	2.30
Bias Factor	1.14	0.933	0.949	0.971	1.106

Table 4.4: Bias factor of N_{coll} at different energies.

4.6 Uncertainty of π^0 yields

Using the similar method as described above, we can vary the cuts by and calculate the systematic error on the yields. Firstly, 7 of 13 cuts, which have the largest effect, are selected. Secondly, we vary each of the selected cuts and calculate the difference to the central value. We assume that the difference follows a flat distribution and assume the RMS to be $difference/\sqrt{12}$ which we take to be the uncertainty in the yields. The selected cuts and the variation are listed in following:

1. $|vertex| < 27\text{cm}$ (default 30cm)
2. Number of MPC-EX shower hits > 17 (default 15)
3. $0\text{GeV} < p_T < 2\text{GeV}$ (default 2.2GeV)
4. Shower E $< 22\text{GeV}$ (default 20GeV)
5. $0.2\text{cm} < RMS_r < 1.4\text{cm}$ (default 1.3cm)
6. Opening Angle between the two showers > 0.0165 (default 0.015)
7. reconstructed π^0 E $< 27.5\text{GeV}$ (25GeV)

Table 4.5 shows the result of the yields systematic errors. These errors have already combined the uncertainties of central and peripheral collision, which will be used in the following suppression section.

A final factor we need to consider is the reconstruction efficiency which we obtain by embedding simulated π^0 s in to data. The multiplicity of central collision is higher

Energy	200GeV		62GeV		39GeV	
p_T/GeV	System	Statistic	System	Statistic	System	Statistic
0-0.25	7%	0.6%	15%	10%	8.9%	1.7%
0.25-0.50	3%	0.2%	4.7%	4.1%	5%	0.6%
0.50-0.75	1.4%	0.2%	2.2%	5.7%	1.5%	1%
0.75-1.00	1.4%	0.4%	1.6%	12.9%	1%	2.9%
1.00-1.25	2.7%	1%			1%	10%
1.25-1.50	3.9%	2.4%				
1.50-1.75	5.7%	6%				
1.75-2.00	8.7%	17%				

Table 4.5: The systematic error of 200GeV, 62GeV and 39GeV.

and thus has a larger background. The probability to find a π^0 with different amounts of background may be different. To study this effect, we embed the π^0 into the data (dAu200GeV) and calculate the efficiency in central and peripheral collisions. Figure 4.36 shows their differences are very small, and we will not make a correction for this. Figure 4.37 shows the number of hits in the MPC-EX north arm. The number of hits can be viewed as the background level. For the dAu200GeV, the change of the number of hits from the central to the peripheral collision is much larger than the lower energies. Thus the effect of lower energies on efficiency should be smaller.

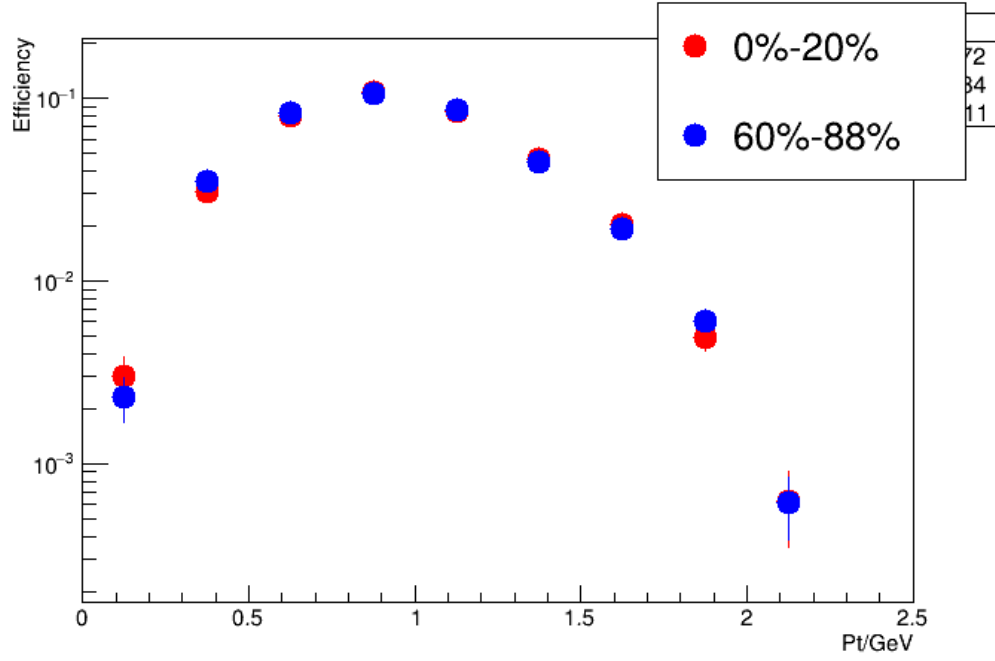


Figure 4.36: The embedding efficiencies of central and peripheral collisions in dAu200GeV.

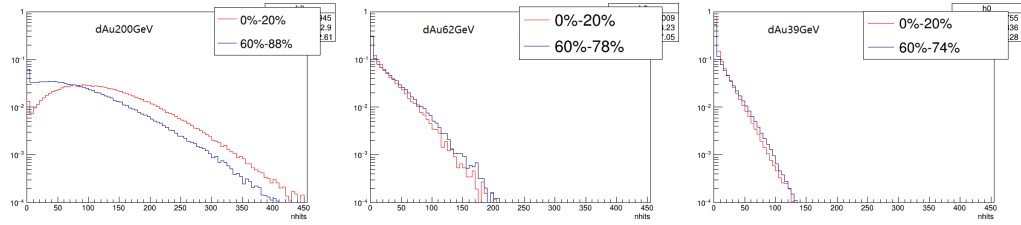


Figure 4.37: The number of hits in the MPC-EX north arm. The red is the central collision and the blue is the peripheral collision.

4.7 Calculating R_{CP} , the π^0 Suppression factor.

Having the p_T spectrum and N_{coll} , it is time to obtain R_{cp} , the ratio of central to peripheral yields, which is the final goal of this thesis. This represents the reduction in capacity for collisions in central events to produce π^0 s. Figure 4.38 shows raw p_T spectra of the dAu 200GeV, 62GeV, and 39GeV data. These spectra have already been normalized by the N_{coll}, N_{tot} (total events) to give the raw invariant yields. Since we are calculating a ratio of two p_T spectra, the geometric acceptance drops out in the ratio.

As mentioned previously, we have chosen to show only the data at the highest energy in this thesis.

We then take these spectra and calculate the ratio:

$$R_{cp} = \frac{\frac{d^2 N_{central}}{2\pi N_{tot}^{central} N_{coll}^{central} p_T dp_T d\eta}}{\frac{d^2 N_{peripheral}}{2\pi N_{tot}^{peripheral} N_{coll}^{peripheral} p_T dp_T d\eta}} \quad (4.9)$$

Figure 4.39 shows the final result for R_{cp} in dAu collisions at 200 GeV. The suppression is substantial, starting at 0.4 at low p_T and perhaps a slow rise to 2 GeV. This means one of two things. Either the production of π^0 s when a collision happens deep in the nucleus is reduced by more than a factor of 2, or the π^0 loses a good fraction of its energy leaving the nucleus, with those at low p_T being totally suppressed.

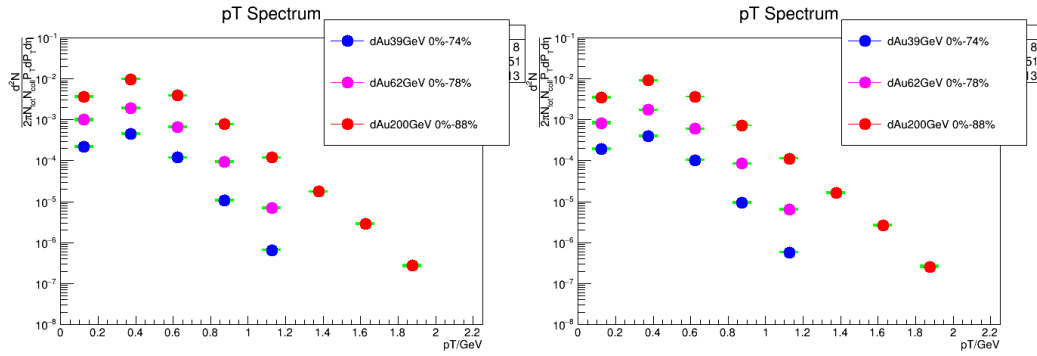


Figure 4.38: The p_T spectra of dAu200GeV, dAu62GeV, and dAu39GeV. The right plot is the spectrum with the bias corrected. The bias effect is small and spectrum almost stay the same. The green systematic error

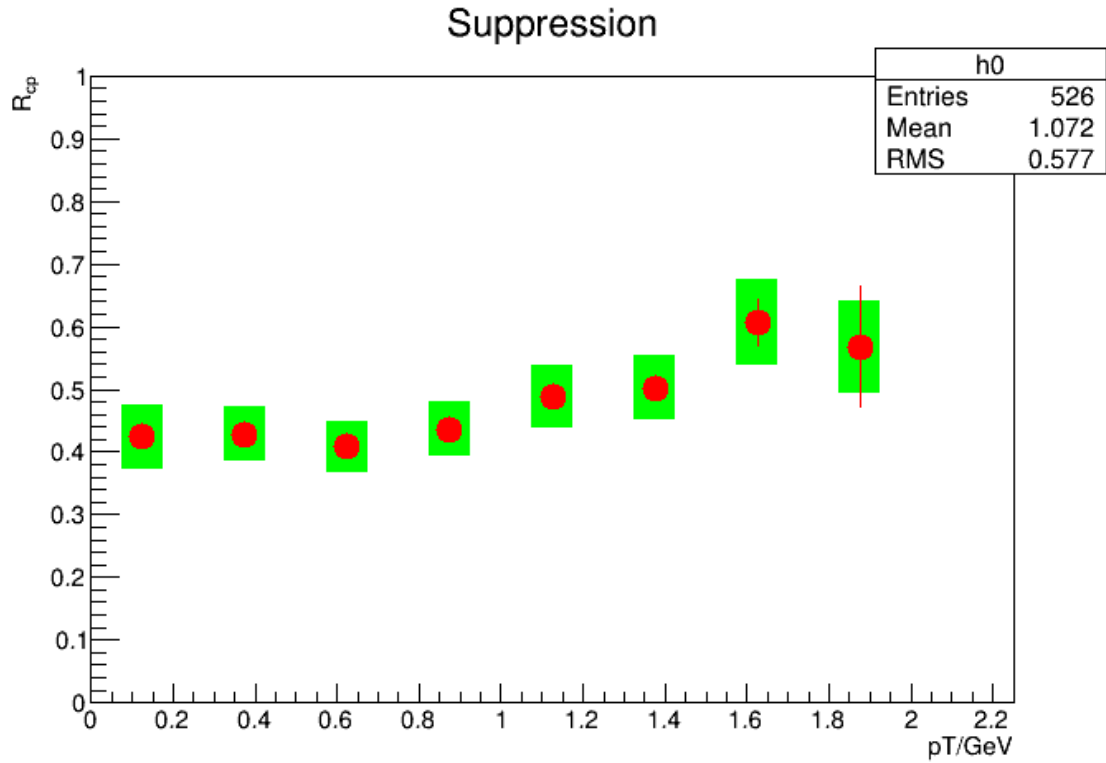


Figure 4.39: The R_{cp} of dAu200. The green is the systematic error

Chapter 5

Results and Conclusion

R_{CP} in d+Au collisions at 200 GeV center of mass as presented in this thesis (Figure 5.1) shows a substantial suppression of about a factor of 2, with perhaps a slow rise, as one goes to higher p_T , which is consistent with suppression ideas from the CGC. The only other similar data is from STAR shown in black. The Brahms data (Figure 1.16) shown in the introduction is for charged hadrons, which would have a contamination from primordial protons. A similar contamination is seen at mid-rapidity in the PHENIX data [7]. The measurement from STAR shown in the figure is different than the measurement in this thesis in two ways. First, the rapidity is slightly higher at $\eta=4.$, whereas the average η for this measurement is about 3.4. More importantly, the quantity plotted is R_{dAu} where the normalization is with p+p collisions. Since the suppression factor R_{CP} is relative to peripheral collisions, it is very likely that some suppression has already occurred in peripheral collisions. These effects are generally true in heavy ion collision as can be seen in [7], although the suppression there is due to the formation of the QGP. Hence the STAR

measurement is probably consistent with our measurement. The measurement shown in this thesis covers a broader range to low p_T made possible because of the fine granularity of the MPC-EX, allowing the machine learning calculation to extract the energy of low energy photons.

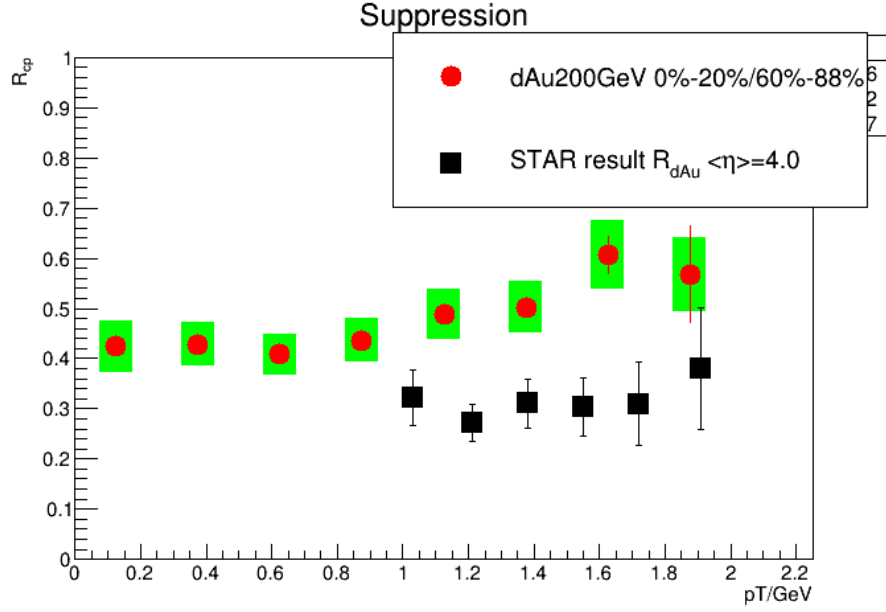


Figure 5.1: The Red is the R_{cp} from this thesis. The black is R_{dAu} from STAR[4].

The only theoretical calculations that have been done to this point are comparisons to the STAR data as shown in Figure 5.2. Shown are calculations invoking multiple parton scattering[89] (dotted line). Also shown is a model of shadowing using nuclear PDFs[50] where the solid(dashed) line uses KKP[68] (Kretzer[70]) fragmentation functions. These appear not to fit the data. However, given the present uncertainty of the nuclear PDFs as shown in Figure 1.19, such a fit would probably work.

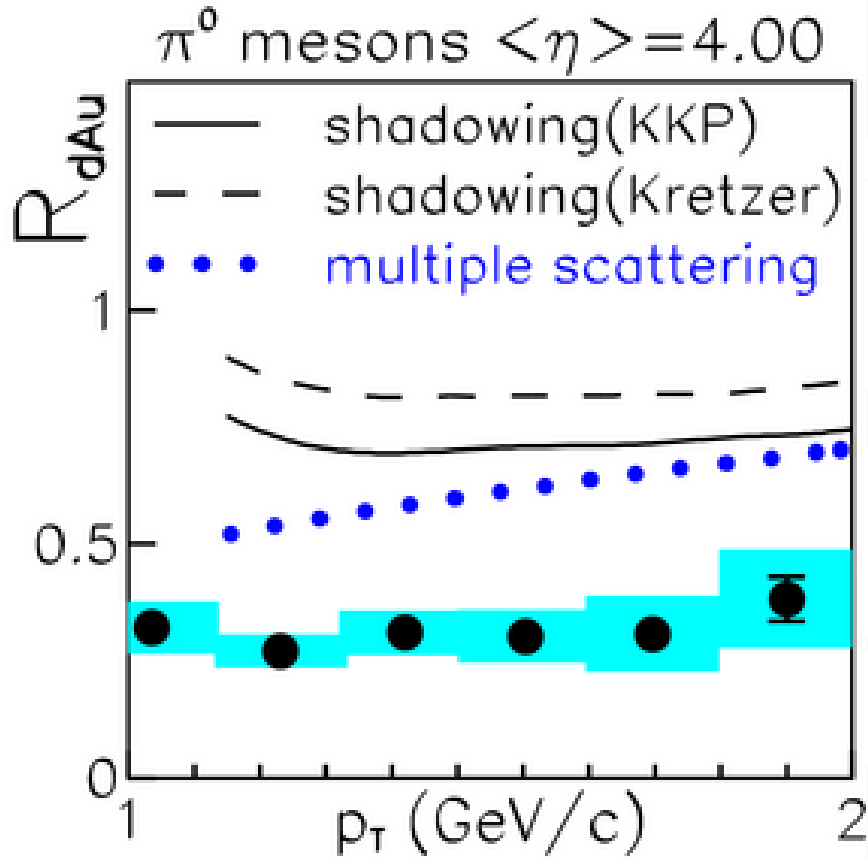


Figure 5.2: The STAR R_{dAu} compared with several models, described in the text.

The results here are broadly consistent with the suppression predicted by the Color Glass Condensate Model. A couple of comments are in order. The cartoon in Figure 1.15 indicates that as one goes to lower Q_s the value of x increases. Q_s is the saturation scale. For a given x , you must be below this value to be in the saturation regime. As one goes to higher x , Q_s gets smaller. Hence the lower the p_T , the more likely one is in the saturation regime. Rough estimates put Q_s^2 at RHIC to be between 1 and 2 GeV^2 or about 1.4 GeV for Q_s [66, 65]. The data in this thesis takes us to low p_T , below the rough value of Q_s just mentioned. The caveat, however, is that at such low Q^2 , α_s becomes large, and the

assumptions used in the CGC formulation break down. This however, may lead us into an unknown, but perhaps more interesting part of the cartoon, far to the left - a non-perturbative region, where α_S becomes very large, and one is in a strongly coupled regime. Theoretical methods to calculate observables in this region are needed.

Our result indicate the nucleus is very complex. Part of the problem is that a deuteron, which is itself a complicated structure was used as a probe, and theoretical calculations of observables are difficult. In the future, the EIC (Electron Ion Collider), which will use a simple probe - electrons, may shed light into this physics as theoretical calculations become cleaner.

Bibliography

- [1] Rene brun and fons rademakers, root - an object oriented data analysis framework, proceedings aihenp'96 workshop, lausanne, sep. 1996, nucl. inst. & meth. in phys. res. a 389 (1997) 81-86.
- [2] B.I. Abelev et al. Centrality dependence of charged hadron and strange hadron elliptic flow from $\sqrt{s_{NN}} = 200\text{GeV}$ Au + Au collisions. *Phys. Rev. C*, 77:054901, 2008.
- [3] K.H. Ackermann et al. Elliptic flow in Au + Au collisions at $(S(NN))^{1/2} = 130$ GeV. *Phys. Rev. Lett.*, 86:402-407, 2001.
- [4] J Adams, Manav Aggarwal, Zubayer Ahammed, J Amonett, B Anderson, D Arkhipkin, G Averichev, S Badyal, Y Bai, J Balewski, O Barannikova, Lee Barnby, Jerome Baudot, S Bekele, Victoria Belaga, A Bellingeri-Laurikainen, Rene Bellwied, J Berger, B Bezverkhny, and Xiangsheng Zuo. Forward neutral pion production in p + p and d + au collisions at square root snn=200 gev. *Physical review letters*, 97:152302, 11 2006.
- [5] Star Collaboration J. Adams and et. al. Forward neutral pion production in p+p and d+au collisions at sqrt(s_nn)=200 gev. *Physical Review Letters*, 2006.
- [6] K. et al. Adcox. Suppression of hadrons with large transverse momentum in central au + au collisions at $\sqrt{s_{NN}} = 130\text{GeV}$. *Phys. Rev. Lett.*, 88:022301, Dec 2001.
- [7] Adler and et al. High- p_T charged hadron suppression in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. C*, 69:034910, Mar 2004.
- [8] C. et al. Adler. Disappearance of back-to-back high-pt hadron correlations in central au + au collisions at $\sqrt{s_{NN}} = 200$ gev. *Physical Review Letters*, 90, 03 2003.
- [9] S. S. Adler and et al. Absence of suppression in particle production at large transverse momentum in $\sqrt{s_{NN}} = 200$ GeV d + Au collisions. *Phys. Rev. Lett.*, 91:072303, Aug 2003.
- [10] S. et al. Afanasiev. Suppression of back-to-back hadron pairs at forward rapidity in d + au collisions at snn =200 gev. *Physical Review Letters*, 107:172301, 04 2011.

- [11] J Alessi, D Barton, E Beebe, Steven Bellavia, O Gould, A Kponou, R. Lambiase, R Lockety, A. Mcnerney, M Mapes, Y Marneris, M Okamura, Dalva Phillips, Alexander Pikin, Deepak Raparia, J Ritter, L. Snedstrup, C Theisen, and M Wilinski. The brookhaven national laboratory electron beam ion source for rhic. *The Review of scientific instruments*, 81:02A509, 02 2010.
- [12] G. Altarelli and G. Parisi. Asymptotic freedom in parton language. *Nuclear Physics B*, 126(2):298 – 318, 1977.
- [13] Victor Roy Amaresh Jaiswal. Relativistic hydrodynamics in heavy-ion collisions: General aspects and recent developments. *Advances in High Energy Physics*, 10 2016.
- [14] Nicole Apadula, Jason Bryslawskyj, John Lajoie, Carlos PerezLara, Richard Seto, Ashley Sexton, and Liankun Zou. Phenix analysis note 1293.
- [15] Néstor Armesto. Nuclear shadowing. *Journal of Physics G: Nuclear and Particle Physics*, 32(11):R367–R393, sep 2006.
- [16] I. Arsene, I. G. Bearden, D. Beavis, S. Bekele, C. Besliu, B. Budick, H. Bøggild, C. Chasman, C. H. Christensen, H. H. Dalsgaard, R. Debbé, J. J. Gaardhøje, K. Hagel, H. Ito, A. Jipa, E. B. Johnson, C. E. Jørgensen, R. Karabowicz, N. Katrynska, E. J. Kim, T. M. Larsen, J. H. Lee, S. Lindal, G. Løvholden, Z. Majka, M. Murray, J. Natowitz, B. S. Nielsen, C. Nygaard, R. Płaneta, F. Rami, F. Renault, C. Ristea, O. Ristea, D. Röhrich, B. H. Samset, S. J. Sanders, R. A. Scheetz, P. Staszczel, T. S. Tvetter, F. Videbæk, R. Wada, Z. Yin, H. Yang, and I. S. Zgura. Production of mesons and baryons at high rapidity and high p_T in proton-proton collisions at $\sqrt{s} = 200$ GeV. *Phys. Rev. Lett.*, 98:252001, Jun 2007.
- [17] I. Arsene et al. On the evolution of the nuclear modification factors with rapidity and centrality in d + Au collisions at $\sqrt{s(NN)} = 200$ -GeV. *Phys. Rev. Lett.*, 93:242303, 2004.
- [18] Alejandro Ayala, Jamal Jalilian-Marian, Larry McLerran, and Raju Venugopalan. Quantum corrections to the weizsäcker-williams gluon distribution function at small x. *Phys. Rev. D*, 53:458–475, Jan 1996.
- [19] I.I. Balitsky and L.N. Lipatov. The Pomeranchuk Singularity in Quantum Chromodynamics. *Sov. J. Nucl. Phys.*, 28:822–829, 1978.
- [20] Sergey Belikov, John Hill, John Lajoie, Harold Skank, and Gary Sleege. Phenix trigger system. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 494(1):541 – 547, 2002. Proceedings of the 8th International Conference on Instrumentation for Colliding Beam Physics.
- [21] Barbara Betz. Jet propagation and mach-cone formation in (3+1)-dimensional ideal hydrodynamics, 10 2009.

- [22] E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, G. Miller, L. W. Mo, R. E. Taylor, M. Breidenbach, J. I. Friedman, G. C. Hartmann, and H. W. Kendall. High-energy inelastic $e - p$ scattering at 6° and 10° . *Phys. Rev. Lett.*, 23:930–934, Oct 1969.
- [23] Ermes Braidot. Two-particle correlations at forward rapidity in star. *Nuclear Physics A*, 854(1):168 – 174, 2011. Saturation, the Color Glass Condensate and the Glasma: What Have We Learned from RHIC?
- [24] Jason Bryslawskyj. Phenix analysis note 1346, 2018.
- [25] Sergey Butsyk. Phenix focus: Drift chamber operation principles.
- [26] Stacey Campbell, R. Hollis, A. Iordanova, Edouard Kistenev, Xiushan Jiang, Yihyun Kwon, J. Lajoie, J. Perry, Richard Seto, A. Sukhanov, and A. Timilsina. A proposal for the muon piston calorimeter extension (mpc-ex) to the phenix experiment at rhic, 01 2013.
- [27] A K Chaudhuri. The glauber model. In *A Short Course on Relativistic Heavy Ion Collisions*, 2053-2563, pages 3–1 to 3–19. IOP Publishing, 2014.
- [28] Mickey Chiu. Description of the zero-degree calorimeter (zdc) of the phenix experiment.
- [29] L Christofek, K Hanagaki, J Hoff, B Kreiger, P Rapidis, M Garcia-Sciveres, M Utes, M Weber, R Yarema, T Zimmerman, and Fermilab. Svx4 user’s manual, 6 2005.
- [30] Yann Cobigo. A description of the muon tracking system of the phenix experiment.
- [31] Gabor David. Phenix focus: The electromagnetic calorimeter.
- [32] Gabor David. Phenix time-of-flight detector west (tofw) – detector basics.
- [33] Yuri L. Dokshitzer. Calculation of the Structure Functions for Deep Inelastic Scattering and $e^+ e^-$ Annihilation by Perturbation Theory in Quantum Chromodynamics. *Sov. Phys. JETP*, 46:641–653, 1977.
- [34] Axel Drees, Tom Hemmick, Barbara Jacak, Jiangyong Jia, Sean Leckey, Alexander Milov, Michael Reuter, Anne Sickles, and Ron Soltz. Phenix anaysis note 210.
- [35] Vasily Dzhordzhadze. Introduction to the muon identifier system of the phenix experiment.
- [36] C. Aidala *et al.* The phenix forward silicon vertex detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 755:44 – 61, 2014.
- [37] Paukkunen Hannu Eskola Kari J., Paakkinen Petja and Salgado Carlos A. Epps16: nuclear parton distributions with lhc data. *The European Physical Journal C*, 77:163, Mar 2017.

- [38] Wolfram Fischer et al. RHIC Performance with Stochastic Cooling for Ions and Head-on Beam-beam Compensation for Protons. In *7th International Particle Accelerator Conference*, page WEZA01, 2016.
- [39] Alan D. Martin Francis Halzen. *Quarks and Leptons: An introduction Course on Modern Particle Physics*. John Wiley & sons, 1984.
- [40] H. Fritzsch, M. Gell-Mann, and H. Leutwyler. Advantages of the color octet gluon picture. *Physics Letters B*, 47(4):365 – 368, 1973.
- [41] F. Gelis. Color Glass Condensate and Glasma. *Int. J. Mod. Phys. A*, 28:1330001, 2013.
- [42] Murray Gell-Mann. The Eightfold Way: A Theory of strong interaction symmetry, 3 1961.
- [43] Dave Goldberg. *The standard model in a nutshell*. Princeton University Press, 2017.
- [44] Google. Tensorflow.
- [45] V.N. Gribov and L.N. Lipatov. Deep inelastic e p scattering in perturbation theory. *Sov. J. Nucl. Phys.*, 15:438–450, 1972.
- [46] David Griffiths. *Introduction to elementary particles*. Wiley-VCH, 1987.
- [47] David J. Gross and Frank Wilczek. Ultraviolet behavior of non-abelian gauge theories. *Phys. Rev. Lett.*, 30:1343–1346, Jun 1973.
- [48] Particle Data Group and *et al.* Review of Particle Physics. *Progress of Theoretical and Experimental Physics*, 2020(8), 08 2020. 083C01.
- [49] Rajan Gupta. Introduction to lattice QCD: Course. In *Les Houches Summer School in Theoretical Physics, Session 68: Probing the Standard Model of Particle Interactions*, pages 83–219, 7 1997.
- [50] V. Guzey, M. Strikman, and W. Vogelsang. Observations on da scattering at forward rapidities. *Physics Letters B*, 603(3):173–183, 2004.
- [51] C. Gwenlan. Combined hera deep inelastic scattering data and nlo qcd fits. *Nuclear Physics B - Proceedings Supplements*, 191:5 – 15, 2009. Proceedings of the Ringberg Workshop.
- [52] Miklos Gyulassy and Larry McLerran. New forms of QCD matter discovered at RHIC. *Nucl. Phys. A*, 750:30–63, 2005.
- [53] Miklos Gyulassy and Xin-Nian Wang. Hijing 1.0: A monte carlo program for parton and particle production in high energy hadronic and nuclear collisions. *Computer Physics Communications*, 83(2):307–331, 1994.
- [54] Takashi Hachiya. Phenix focus: Silicon vertex tracker (vtx).

- [55] Ernest Marsden Hans Geiger. On a diffuse reflection of the α -particles. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 82(557):495–500, 1909.
- [56] hawn Beckman, Darren McGlinchey, James Nagle, Javier Orjuela Koop, and Anne Sickles. Phenix analysis note 1087.
- [57] U. Heinz, P. Sorensen, Abhay Deshpande, C. Gagliardi, F. Karsch, T. Lappi, Zein-Eddine Meziani, Richard Milner, B. Muller, J. Nagle, J. Qiu, K. Rajagopal, G. Roland, and R. Venugopalan. Exploring the properties of the phases of qcd matter - research opportunities and priorities for the next decade, 01 2015.
- [58] P. E. (Peter Edward) Hodgson. *Nuclear reactions and nuclear structure*. Clarendon Press, 1971.
- [59] Andreas Hoecker, Peter Speckmayer, Joerg Stelzer, Jan Therhaag, Eckhard von Toerne, and Helge Voss. TMVA: Toolkit for Multivariate Data Analysis. *PoS, ACAT:040*, 2007.
- [60] E. Iancu. Qcd in heavy ion collisions. *2011 European School of High-Energy Physics, ESHEP 2011 - Proceedings*, 05 2012.
- [61] Edmond Iancu, Andrei Leonidov, and Larry McLerran. *The Colour Glass Condensate: An Introduction*, pages 73–145. Springer Netherlands, Dordrecht, 2002.
- [62] K. Ikematsu, Y. Iwata, K. Kaimi, M. Kaneta, T. Kohama, N. Maeda, K. Matsukado, H. Ohnishi, K. Ono, A. Sakaguchi, T. Sugitate, Y. Sumi, Y. Takata, M. Tanabe, and A. Yokoro. A start-timing detector for the collider experiment phenix at rhic-bnl. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 411(2):238 – 248, 1998.
- [63] Henry W. Kendall. Deep inelastic scattering: Experiments on the proton and the observation of scaling. *Rev. Mod. Phys.*, 63:597–614, Jul 1991.
- [64] keras team. Keras: Deep learning for humans.
- [65] D. E. Kharzeev and Eugene Levin. Manifestations of high density qcd in the first rhic data. *Physics Letters B*, 523:79–87, 2001.
- [66] Dmitri Kharzeev and Marzia Nardi. Hadron production in nuclear collisions at rhic and high-density qcd. *Physics Letters B*, 507(1):121–128, 2001.
- [67] Chong Kim. Phenix analysis note 1347.
- [68] B.A. Kniehl, G. Kramer, and B. Pötter. Fragmentation functions for pions, kaons, and protons at next-to-leading order. *Nuclear Physics B*, 582(1):514–536, 2000.
- [69] John Koster. *Measurement of Transverse Spin Asymmetries in Polarized proton-proton Collisions, and the Realization of New Electromagnetic Calorimeters for Forward Physics*. PhD thesis, Illinois U., Urbana, 2010.

- [70] S. Kretzer. Fragmentation functions from flavor inclusive and flavor tagged e^+e^- annihilations. *Phys. Rev. D*, 62:054001, 2000.
- [71] E.A. Kuraev, L.N. Lipatov, and Victor S. Fadin. The Pommeranchuk Singularity in Nonabelian Gauge Theories. *Sov. Phys. JETP*, 45:199–204, 1977.
- [72] John Lajoie. This shower algorithm is developed by dr. john lajoie.
- [73] Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, and Subrata Pal. Multiphase transport model for relativistic heavy ion collisions. *Phys. Rev. C*, 72:064901, Dec 2005.
- [74] L.N. Lipatov. Reggeization of the Vector Meson and the Vacuum Singularity in Nonabelian Gauge Theories. *Sov. J. Nucl. Phys.*, 23:338–345, 1976.
- [75] Matthew Luzum and P. Romatschke. Flow study in relativistic nuclear collisions by fourier expansion of azimuthal particle distributions. *Physical Review C*, 78, 04 2008.
- [76] Hiroshi Masui. Description of the phenix time-of-flight system.
- [77] R. W. McAllister and R. Hofstadter. Elastic scattering of 188-mev electrons from the proton and the alpha particle. *Phys. Rev.*, 102(3):851–856, 1956.
- [78] Larry McLerran and Raju Venugopalan. Computing quark and gluon distribution functions for very large nuclei. *Phys. Rev. D*, 49:2233–2241, Mar 1994.
- [79] Michael L. Miller, Klaus Reygers, Stephen J. Sanders, and Peter Steinberg. Glauber modeling in high energy nuclear collisions. *Ann. Rev. Nucl. Part. Sci.*, 57:205–243, 2007.
- [80] Jamie Nagle. slides: Run-16 d+au beam energy scan centrality and event categorization.
- [81] Tomoaki Nakamura. Introduction to phenix beam beam counter (bbc).
- [82] Yuval Ne’eman. Derivation of strong interactions from a gauge invariance. *Nucl. Phys.*, 26:222–229, 1961.
- [83] Rachid Nouicer. Silicon vertex tracker for phenix upgrade at rich: Capabilities and detector technology, 01 2007.
- [84] Anders Oskarsson. Phenix focus: Pad chambers.
- [85] Kyoichiro Ozawa. Description of the rich component (gas, mirror, pmt and electronics) and how it’s used in analysis.
- [86] H. David Politzer. Reliable perturbative results for strong interactions? *Phys. Rev. Lett.*, 30:1346–1349, Jun 1973.
- [87] Stefano Profumo. Smallest $SU(N)$ hadrons. *Phys. Rev. D*, 102(3):035008, 2020.

- [88] M. L. Purschke. Upgrades for the phenix data acquisition system. In *2010 17th IEEE-NPSS Real Time Conference*, pages 1–3, 2010.
- [89] Jian-wei Qiu and Ivan Vitev. Resummed QCD power corrections to nuclear shadowing. *Phys. Rev. Lett.*, 93:262301, 2004.
- [90] Jian-Wei Qiu and Ivan Vitev. Coherent qcd multiple scattering in proton–nucleus collisions. *Physics Letters B*, 632(4):507–511, 2006.
- [91] Michael Riordan. The discovery of quarks. *Science*, 256(5061):1287–1293, 1992.
- [92] M. Rosati et al. The PHENIX time expansion chamber. *Nucl. Phys. A*, 661:669–672, 1999.
- [93] T. Roser, L. Ahrens, J. Alessi, M. Bai, J. Wang, G. Bunce, P. Cameron, A. Drees, and W. Fischer. Accelerating and colliding polarized protons in rhic with siberian snakes., 2002.
- [94] E. Rutherford. The scattering of α and β particles by matter and the structure of the atom. *Philosophical Magazine and Journal of Science*, 21(125):669–688, 1911.
- [95] Joseph Silk. *Horizons of Cosmology: Exploring Worlds Seen and Unseen*. Templeton Foundation Press,U.S., 2009.
- [96] Torbjörn Sjöstrand. High-energy-physics event generation with pythia 5.7 and jetset 7.4. *Computer Physics Communications*, 82:74–89, 1994.
- [97] Peter Skands. Introduction to QCD. In *Theoretical Advanced Study Institute in Elementary Particle Physics: Searching for New Physics at Small and Large Scales*, 7 2012.
- [98] M. C. Smith, W. L. Bryan, D. Smith, U. Jagadish, D. McMillan, J. Walker, G. R. Young, A. Oskarsson, L. Osterman, V. Greene, and L. Nikkinen. A front-end electronics module for the phenix pad chamber. In *1998 IEEE Nuclear Science Symposium Conference Record. 1998 IEEE Nuclear Science Symposium and Medical Imaging Conference (Cat. No.98CH36255)*, volume 2, pages 910–913 vol.2, 1998.
- [99] Satoshi Takagi. A description of the phenix aerogel cherenkov counter.
- [100] D.N. Triantafyllopoulos. The energy dependence of the saturation momentum from rg improved bfl evolution. *Nuclear Physics B*, 648:293–316, 09 2002.
- [101] Zhang Y. Voloshin S. Flow study in relativistic nuclear collisions by fourier expansion of azimuthal particle distributions. *Z Phys C - Particles and Fields*, pages 665–671, 12 1996.
- [102] C. N. Yang and R. L. Mills. Conservation of isotopic spin and isotopic gauge invariance. *Phys. Rev.*, 96:191–195, Oct 1954.
- [103] W. M. Yao et al. Review of Particle Physics. *J. Phys. G*, 33:1–1232, 2006.