Title

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FASER and the Search for Light and Weakly Interacting Particles

Jonathan L. Feng

Abstract For decades, the leading examples of new physics targets at particle colliders were particles with TeV-scale masses and $\mathcal{O}(1)$ couplings to the standard model. More recently, however, there is a growing and complementary interest in new particles that are much lighter and more weakly coupled. I review the motivations for this shift and the importance of renormalizable portals. I then present FASER, a proposed LHC experiment that is specifically designed to discover light and weakly interacting particles, including those that interact through renormalizable portal interactions.

Keywords Dark matter · Long-lived particles · LHC · FASER

1 Introduction

Since the 1930s, beginning with the work of Ernest Lawrence and others, particle accelerators have been the workhorse tool for discovering new particles. With each significant increase in collision energy, new particles have been produced, providing profound insights into the fundamental building blocks of the universe. In the last few decades, as colliders have approached and reached TeV energies, the expectation for new particles has again been strong, with most of the attention focused on heavy particles with TeV-scale masses and $\mathcal{O}(1)$ couplings to the standard model.

More recently, however, there is a growing interest in new particles that are much lighter and more weakly coupled [1]. This complementary direction has many motivations. From the point of view of astrophysics and cosmology, the WIMP miracle continues to provide a compelling reason to search for WIMP dark matter with TeV masses. However, since the thermal relic density scales as m^2/g^4, where m and g are the dark matter's mass and coupling strength, respectively, light and weakly interacting particles may also yield the correct thermal relic density [2, 3]. The existence of

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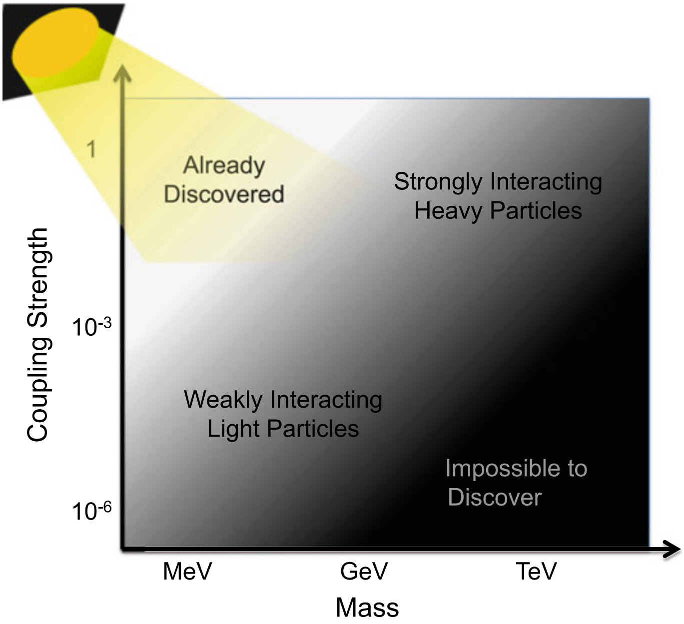

Fig. 1 The lamppost landscape for particle discovery at colliders. Strongly interacting and light particles have already been discovered; weakly interacting and heavy particles are beyond reach. The frontier for new particle discovery, therefore, lies along the diagonal and includes the traditional target of strongly interacting and heavy particles and the new target of weakly interacting and light particles

dark matter and the appeal of thermal relics with the observed abundance therefore also favors searching for light and weakly interacting particles.

From the viewpoint of particle physics, there are also strong motivations for searches for this new class of particle. Searches for new TeV-scale particles at the LHC and elsewhere have come up empty so far. These searches remain of great interest, especially given upcoming runs of the LHC and HL-LHC, but at the same time, it is natural to look elsewhere. Light and weakly interacting particles are of interest in part because they may resolve outstanding discrepancies between theory and low-energy experiments [4–6]. But perhaps most important, light and weakly interacting particles are amenable to experimental searches; see Fig. 1. As evident from the contributions of Bertrand Echenard, Mauro Raggi, and others to these proceedings, this possibility has opened the floodgates to innovative ideas for accelerator experiments that are relatively small, cheap, and fast, and may nevertheless have revolutionary implications for particle physics and cosmology.

2 Renormalizable Portals

Perhaps, the most natural origin for light and weakly interacting particles is a dark sector, containing dark matter and also possibly other matter and forces, and interacting only gravitationally with the standard model at tree level.

At loop-level, mediator particles with both standard model and dark sector interactions may induce dark sector-standard model interactions. What sort of interactions are most likely? For most such interactions, the induced interaction decouples as the mediator particle becomes heavy. However, for renormalizable interactions, this is not the case. There are, in fact, only a few possible renormalizable interactions:

- Spin 1 dark gauge bosons may interact through the kinetic mixing term $F_{\mu\nu} F_D^{\mu\nu}$. These interactions imply the existence of dark photons [7–9] with couplings to standard model fermions proportional to $q_f \epsilon$, where q_f is the fermion's charge, and ϵ is a small kinetic mixing parameter.
- Spin 0 dark scalars may interact through the quartic scalar coupling $h^\dagger h \phi_D^\dagger \phi_D$ [10]. These interactions imply the existence of dark Higgs bosons with couplings to standard model fermions proportional to $m_f \sin\theta$, where m_f is the fermion's mass, and $\sin\theta$ is a small mixing angle.
- Spin 1/2 dark fermions may interact through the Yukawa coupling $hL\psi_D$. These interactions imply the existence of dark fermions, also known as sterile neutrinos [11] or heavy neutral leptons, which mix with standard model neutrinos with a small mixing angle $\sin\theta_\nu$.

The importance of these renormalizable portal interactions is that they are non-decoupling and so may be significant even if the mediator particles have GUT- or Planck-scale masses. They rely only on the fact that the mediators exist, not that they be light. Such interactions are therefore generic in this sense and provide an organizing principle that focuses attention on a small number of dark sector candidates.

3 FASER

The possibility of light and weakly interacting new particles has motivated a number of new initiatives at particle colliders. Here, we focus on FASER [12–21], a proposed small and inexpensive experiment designed to search for light and weakly interacting particles at the LHC. Other LHC experiments with similar physics goals include the existing experiments LHCb [22, 23] and NA62 [24], as well as the proposed experiments SHiP [25], MATHUSLA [26], and CODEX-b [27], and there are, of course, also exciting opportunities at other laboratories around the world.

In contrast to heavy and strongly interacting particles, light and weakly interacting particles are dominantly produced along the beam collision axis and are typically long-lived particles (LLPs), traveling hundreds of meters before decaying. To exploit

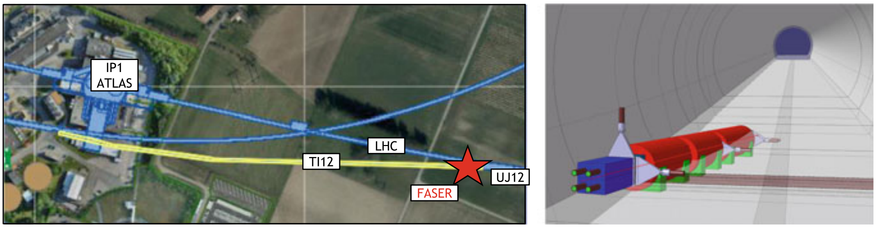

Fig. 2 FASER's Location. Left: FASER's location is indicated by the red star in service tunnel TI12, 480 m east of the ATLAS interaction point. Credit: CERN Geographical Information System. Right: The view, looking toward the west, of FASER as it will be installed in tunnel TI12. The floor shown will be lowered by 45 cm to allow FASER to be centered on the beam collision axis. Credit: CERN Site Management and Buildings Department

both of these properties, FASER is to be located along the beam collision axis, 480 m downstream from the ATLAS interaction point (IP). At this location, FASER and a larger successor, FASER 2, will enhance the LHC's discovery potential by providing exceptional sensitivity to dark photons, dark Higgs bosons, heavy neutral leptons, axion-like particles, and many other proposed new particles.

3.1 Location and Timeline

FASER will be located 480 m downstream from the ATLAS IP in service tunnel TI12, as shown in Fig. 2. A similar tunnel, TI18, on the other side of ATLAS is also possible. These tunnels were formerly used to connect the SPS to the LEP tunnel, but are currently empty and unused.

The proposed timeline is for FASER to be installed during Long Shutdown 2 (LS2) from 2019 to 20, in time to collect data during Run 3 of the 14 TeV LHC from 2021 to 23. FASER's cylindrical active decay volume has a radius $R = 10$ cm and length $L = 1.5$ m, and the detector's total length is under 5 m. To allow FASER to maximally intersect the beam collision axis, the floor of TI12 should be lowered by 45 cm. This will not disrupt essential services, and no other excavation is required. FASER will run concurrently with the LHC and require no beam modifications. Its interactions with existing experiments are limited only to requiring bunch crossing timing and luminosity information from ATLAS.

If FASER is successful, a larger version, FASER 2, with a cylindrical active decay volume with radius $R = 1$ m and length $L = 5$ m, could be installed during LS3 from 2024 to 25 and take data in the 14 TeV HL-LHC era, starting in 2026. FASER 2 would require extending TI12 or TI18 or widening the staging area UJ18.

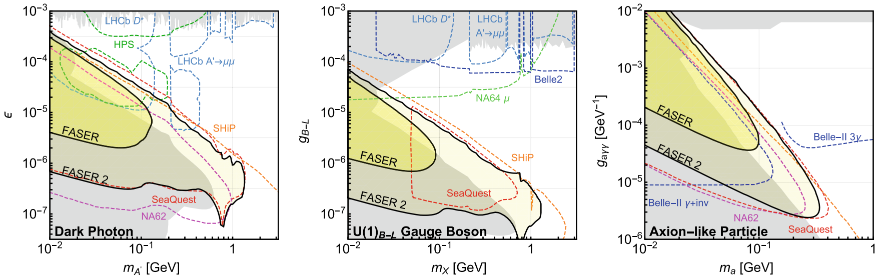

Fig. 3 Sensitivity reaches for FASER (Run 3) and FASER 2 (HL-LHC) for dark photons (left), $U(1)_{B-L}$ gauge bosons (center), and axion-like particles (right). The gray-shaded regions are excluded by current bounds, and the projected reaches of other experiments are also shown

3.2 Signals and Discovery Potential

The FASER signal is LLPs that are produced at or close to the IP, travel along the beam collision axis, and decay visibly in FASER:

$$pp \to \text{LLP} + X, \quad \text{LLP travels} \sim 480\text{ m}, \quad \text{LLP} \to e^+e^-, \mu^+\mu^-, \gamma\gamma \ldots \qquad (1)$$

These signals are striking: two oppositely charged tracks (or two photons) with ~ TeV energies that start inside the detector and have a combined momentum that points back through 100 m of concrete and 90 m of rock to the IP.

The sensitivity reach of FASER has been investigated for a large number of new physics scenarios. Examples are shown in Fig. 3. FASER will have the potential to discover a broad array of new particles, including dark photons, other light gauge bosons, and axion-like particles. FASER 2 will extend FASER's physics reach in these models to larger masses and also probe currently uncharted territory for dark Higgs bosons, heavy neutral leptons, and many other possibilities.

3.3 Detector and Backgrounds

The FASER signals are two extremely energetic (~ TeV) coincident tracks or photons that start inside the detector and point back to the ATLAS IP. Muons and neutrinos are the only known particles that can transport such energies through the 190 m of concrete and rock between the IP and FASER. Muons entering the detector can be vetoed, and preliminary estimates show that muon-associated radiative processes may be reduced to negligible levels. Neutrinos may interact in the detector, but given the requirement of TeV energies and small neutrino interactions, neutrino-induced backgrounds are also negligible. The layout of the FASER detector is illustrated in Fig. 4.

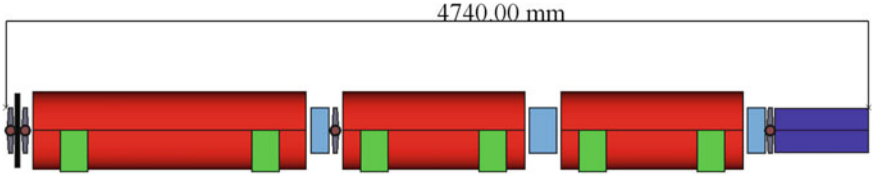

Fig. 4 Layout of the FASER detector. Particles produced at the ATLAS IIP enter from the left. The detector components include scintillators for vetoing and triggering (gray), 0.5 T dipole magnets (red), tracking stations (blue), and an electromagnetic calorimeter (purple)

Recently a FLUKA study [28–30] from the CERN Sources, Targets, and Interactions group has been carried out to assess possible backgrounds and the radiation level in the FASER location. The study shows that no high energy (>100 GeV) particles are expected to enter FASER from proton showers in the dispersion suppressor or from beam–gas interactions. In addition, the radiation level expected at the FASER location is very low due to the dispersion function in the LHC cell closest to FASER.

An emulsion detector and a battery-operated radiation monitor were installed at the FASER site in June 2018. The results from these first *in situ* measurements will complement and validate the background estimates and inform future work, which includes refining background estimates, evaluating signal efficiencies, and optimizing the detector.

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