FASER 2: Forward Search Experiment at the HL LHC

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Abstract

FASER 2 is a proposed experiment dedicated to the search for new long-lived particles at the High Luminosity LHC. FASER 2 builds on the experience of FASER, now under construction for Run 3, and will occupy a similar far-forward location, approximately 480 m from the ATLAS interaction point. With a decay volume of ~ 10 m^3, FASER 2 will extend FASER's sensitivity by four orders of magnitude, with discovery potential for all renormalizabile portal particles, axion-like particles, and many other models, significantly extending the HL LHC physics program.

Introduction A new era of particle searches in the far-forward region at the LHC is now beginning with the FASER experiment [1, 2]. FASER is currently under construction and will collect data throughout Run 3 at the LHC. Already with the first 1 fb^{-1} of data, FASER will have the potential to discover dark photons and other proposed light and long-lived particles (LLPs). With the full integrated luminosity of ~ 150 fb^{-1} expected for Run 3, FASER will significantly extend this sensitivity, probing regions of parameter space that are inaccessible to all other LHC experiments.

In this LOI, we briefly describe plans for an upgraded FASER 2 detector to operate during the High Luminosity LHC era. With a decay volume roughly three orders of magnitude larger than FASER and the expected 3 ab^{-1} of luminosity at the HL LHC, FASER 2 will be able to probe all portal particles with renormalizable couplings, axion-like particles with all types of standard model couplings, and many other models. FASER 2 therefore provides a significant extension of the HL LHC physics program, with many implications for both particle physics and cosmology [3, 4].

Forward-going LLPs at the LHC For LLPs with masses in the MeV to GeV range, one of the main production mechanisms is rare meson decays. At the HL LHC, all mesons will be produced in extraordinary numbers, ranging from $\sim 10^{19}$ pions to $\sim 10^{15}$ B mesons. The decays of these mesons can produce a large flux of energetic forward-going LLPs with typical transverse momenta of $p_T \sim m_{\text{meson}}/E$. For the typical energy $E \sim$ TeV, and a distance to the detector of $L \simeq 480$ m, the expected transverse displacement of LLPs from the beam collision axis is only ~ 10 cm and ~ 1 m for LLPs produced in the rare decays of pions and B mesons, respectively. This implies that a potentially large flux of LLPs will pass through even relatively small detectors, provided they are placed on or near the beam collision axis. The expected shifts in the beam collision axis from varying beam crossing angles at the HL LHC have only mild effects on the expected sensitivity reaches [5].

Experimental Facility and Detector The current location of FASER in the LHC side tunnel TI12 can accommodate a larger detector with a cylindrical decay volume with a radius of 1 m and a length of 5 m, given civil engineering work to enlarge the tunnel. Alternatively, the nearby cavern UJ12 could be enlarged to create a Forward Physics Facility, which could accommodate both FASER 2 and additional experiments. Similar locations exist on the opposite side of ATLAS in tunnel TI18 and cavern UJ18. These locations are shielded from the ATLAS IP by approximately 100 m of concrete and rock, making them extremely low-background environments that are well-suited to searches for extremely rare processes. Alternatively, nearer locations could be considered at the beginning of the arc section of the LHC tunnel or close to the TAXN neutral particle absorber. Such locations allow one to probe shorter LLP lifetimes and require smaller detectors to probe the same solid angle, provided the large standard model background and beam backgrounds can be brought under control.

The signal of decaying LLPs typically consists of two oppositely charged, high-energy, and highly collimated tracks. To separate them, one can use a magnetic field, such as the superconducting CCT dipole design also considered for the FCC [6]. Alternatively, for a sufficiently long detector, the tracks may be separated enough to distinguish even without the use of a magnet; in this case, a weaker magnet installed in front of the detector would be useful to sweep away the low-energy background and reduce the trigger rate. A large-scale and cost-effective spectrometer could employ the scintillating fibre tracker (SciFi) technology currently in use for the LHCb upgrade [7].

Physics Potential The FASER 2 physics case has been thoroughly discussed in Ref. [5] and as part of Physics Beyond Collider activities [3]. FASER 2 will probe new parameter space for all models with

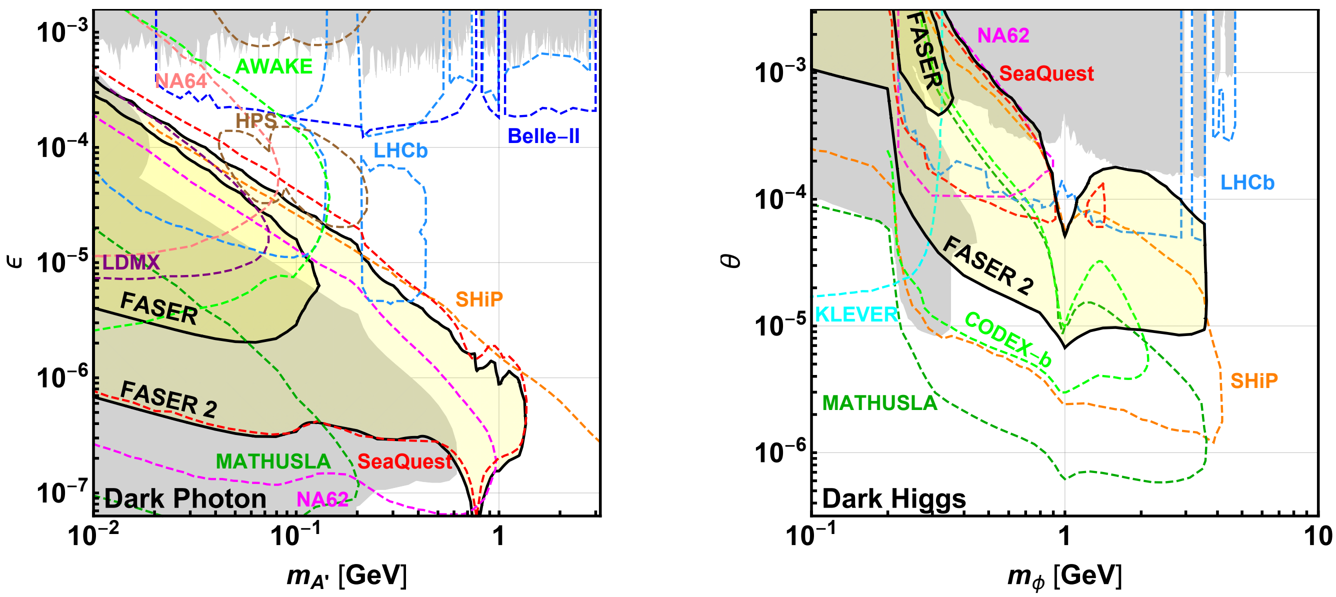

Figure 1. Sensitivity reaches for FASER and FASER 2 for dark photons (left) and dark Higgs bosons (right). The gray-shaded regions are excluded by current bounds, and the projected future sensitivities of other experiments are shown as colored contours. Taken from Ref. [5].

renormalizable portals, including dark photons [8], dark Higgs bosons [9], and heavy neutral leptons [10, 11], axion-like particles with photon, fermion, gluon, and weak gauge boson couplings [5, 12–14], inelastic dark matter [15, 16], R-parity violating suppersymmetry [17], less-simplified models that contain both dark Higgs bosons and dark photons [16], and many others.

The larger radius of FASER 2 with respect to FASER will be particularly important in improving the reach for larger LLP masses, as well as in models in which LLPs are produced in the rare decays of heavy mesons. We illustrate this in Fig. 1 for the dark photon A' and dark Higgs boson ϕ. The latter is mainly produced in rare B-meson decays, especially for $m_\phi \sim$ GeV, due to its Yukawa-like couplings. It is notable that invisible decays of the off-shell standard model Higgs boson, $(B \to) h^* \to \phi\phi$, also contributes to the flux of forward-going light scalars [9]. This implies that FASER 2 will indirectly probe the properties of the standard model Higgs boson, one of the main physics motivation for the HL LHC.

The physics opportunities at FASER 2 also extend beyond LLP searches. For example, a possible interface between FASER 2 and the proposed FASERν 2 experiment will allow charge identification and improve the energy measurement of outgoing muons from neutrino interactions [18, 19]. FASER 2 will therefore discriminate between ν_μ and $\bar{\nu}_\mu$, allowing FASERν 2 to measure the TeV interaction cross sections of neutrinos and anti-neutrinos separately. FASER 2 will also measure the forward-going muon spectrum with great accuracy and characterize its distribution in energy and distance from the beam collision axis. This information, along with neutrino flux measurements from FASERν 2, will complement hadron flux measurements from other experiments and help improve forward hadron production simulations, with new insights for forward QCD and the longstanding muon deficit problem in cosmic-ray physics [20].

Conclusion The quest for new light and weakly-coupled particles has attracted a great deal of attention in the last few years, given its connection to dark matter and dark sectors and the general affordability of qualitatively new probes [4]. FASER 2 will provide a unique opportunity to probe new physics at the energy frontier with the statistics typically associated with intensity frontier experiments. The large energy of the LHC allows FASER 2 to probe new particles dominantly coupled to heavy flavor, while the large statistics allows FASER 2 to discover new particles that are extremely weakly-coupled to the standard model. Building on experience with FASER, FASER 2 will greatly extend the LHC's discovery potential for new physics. We hope that this brief description of the FASER 2 project will lead to further fruitful discussions of such opportunities.

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