FORWARD SEARCH EXPERIMENT

Deion Fellers

Introduction

FASER is a new experiment dedicated to searching for long-lived and weakly interacting particles beyond the standard model, such as the dark photon. Though extremely rare, such particles may be produced in the high intensity far-forward region of the LHC's proton-proton collisions at the ATLAS IP and can then travel for hundreds of meters before decaying into visible standard model particles within the FASER detector. The FASER detector construction was recently completed, as seen in the picture below, and it is now undergoing commissioning and preparation for taking data starting in 2022 during Run 3 of the LHC.

Figure 1: A picture of the fully installed FASER detector.

Dark Photon Production

The main source of dark photon production in the far forward region of the ATLAS IP comes from light meson decays such as $\pi^0 \to \gamma + A'$, as seen in Figure 2. With a kinetic mixing coupling constant on the order of 10^{-5}, it is quite rare that this process will occur, yet the extreme intensity of pion production in the far forward region allows us to be sensitive to such rare processes.

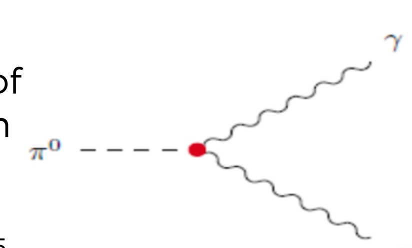

Figure 2: Dark photon production via pion decay where γ is a SM photon and A' is a dark photon which resulted from kinetic mixing of an off-shell SM photon.

Not only is there a high luminosity of pion decays in the far-forward region, but their decay products also tend to be tightly collimated. For extremely boosted pions, their small decay angle can be approximated as $\theta \sim p_T/E$, where their $p_T \sim \Lambda_{QCD} \sim 200$ MeV and their energy E is ~ TeV, producing an angle $\theta \sim 10^{-4}$ radians. A tightly collimated beam of decay products such as this means that dark photons produced via pion decay can travel hundreds of meters longitudinally while only spreading out a few cm transversely. Utilizing this high intensity and collimated spray of long-lived particles in the far forward region allows for a relatively small detector placed hundreds of meters downstream of the ATLAS IP to be sensitive in the search for extremely rare dark photons.

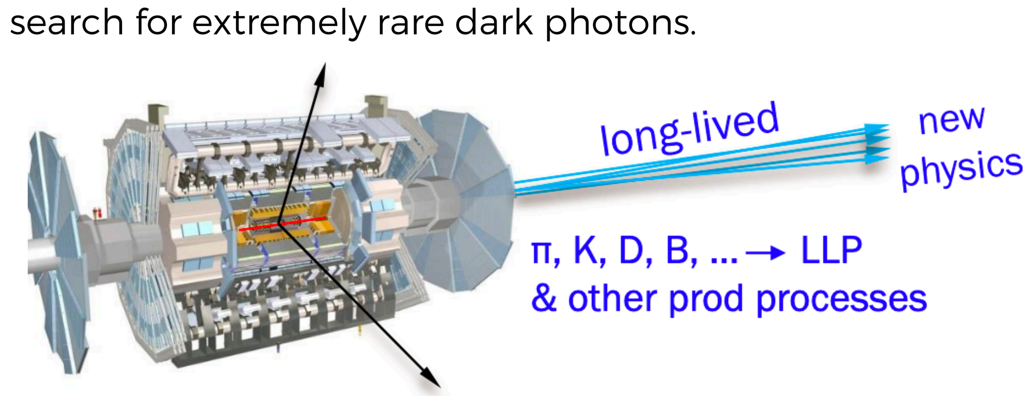

Figure 3: Diagram showing ATLAS and the currently unused collimated spray of long-lived particles in the far forward region.

FASER Location

FASER is placed in the LHC tunnel TI12, 480 m downstream of the ATLAS IP, as seen in figure 4, where it expects to see a large flux of long-lived particles.

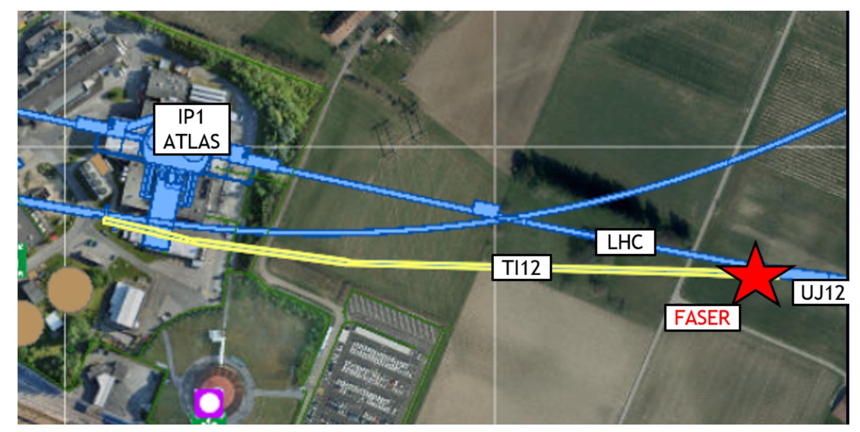

Figure 4: The location of FASER is depicted as a red star, which is placed in tunnel TI12 along the longitudinal lign-of-sight of the ATLAS IP.

The location of FASER was chosen such that it would be in line with the ATLAS IP at the closest accessible point after the LHC beamline curves out of the way, as seen in the picture below.

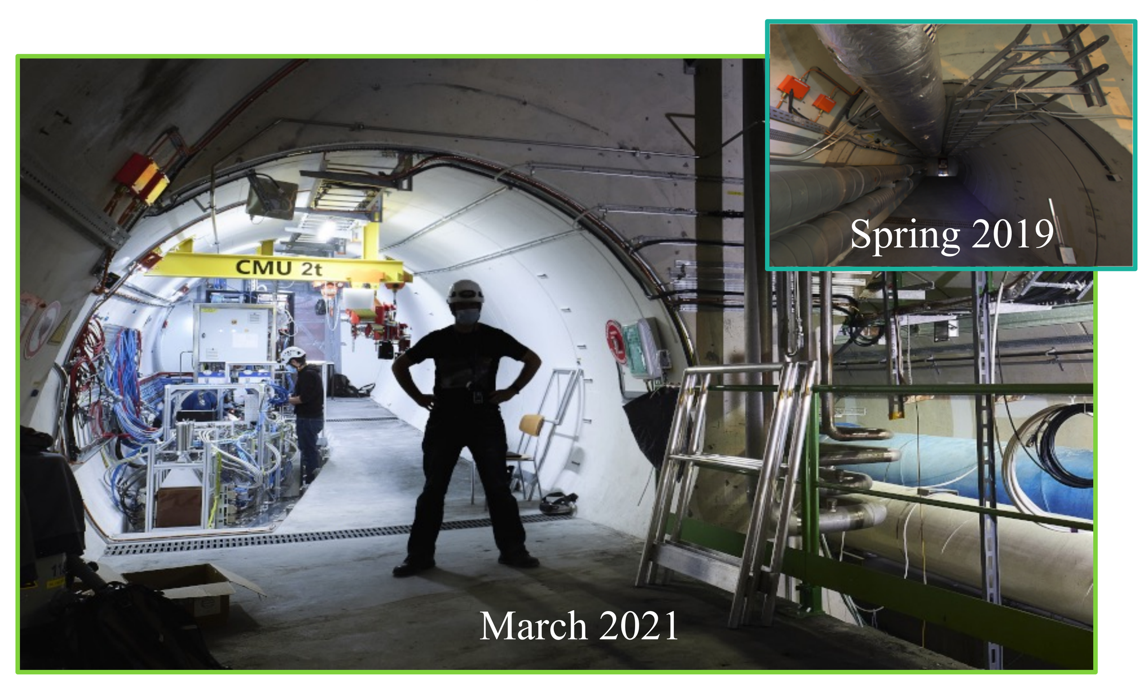

Figure 5: The picture depicts the completed FASER detector in tunnel TI12 to the left, which is closely situated next to the LHC beamline as seen as the blue pipe in the bottom right. The small picture in the top right shows what tunnel TI12 looked like before the installation of FASER.

Dark Photon Decay

After traveling hundreds of meters from the ATLAS IP without interacting, dark photons can decay via e^+/e^- pair production through kinetically mixing back into an off-shell SM photon. Although a dark photon could decay into numerous different decay channels as seen in Figure 6, FASER is only sensitive to

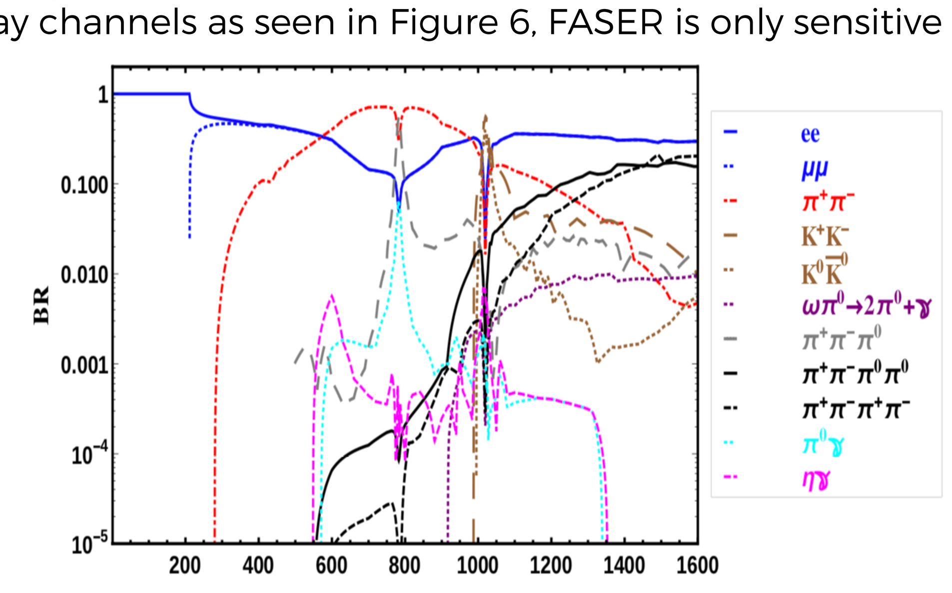

Figure 6: The branching ratios for different decays of the dark photon to visible standard model particles is shown as a function of the mass of the dark photon.

dark photons with a mass < $2m_\mu$ and thus we expect to only see decays to e^+/e^- pairs. A dark photon that is more massive than $2m_\mu$ would have a shorter lifetime and is not likely to make it 480 m from the IP to the detector before decaying.

FASER Detector

In addition to being a highly sensitive probe of new physics, the FASER detector was designed such that it would be relatively cheap, small, and quickly buildable in time for Run 3 of the LHC.

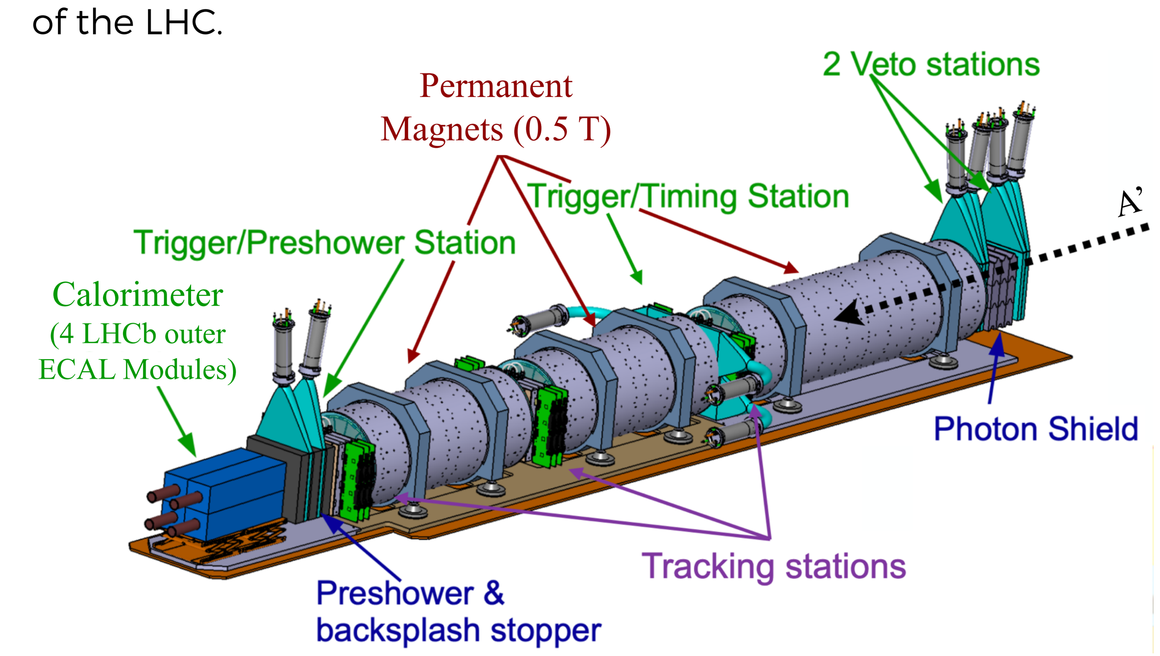

Figure 7: FASER detector diagram with all main components labeled and a dashed arrow depicting the direction from which a dark photon (A') would enter the detector.

The FASER detector's main components as seen in Figure 7, consist of:

- **Three magnets**, with each magnet being composed of a Halbach array of permanent dipole magnets that result in a 0.5 T homogeneous field within the inner 20cm diameter bore. The largest magnet (1.5m long) acts as the decay volume and, with the help of the other two shorter magnets (1m long), separates the e^+/e^- particles from the dark photon decay into two distinct tracks.

- **Three tracking stations**, where a single tracking station consists of three tracking planes and each tracking plane is composed of 8 silicon strip tracking (SCT) modules as seen in Figure 8. With a 17 µm position accuracy in the charged

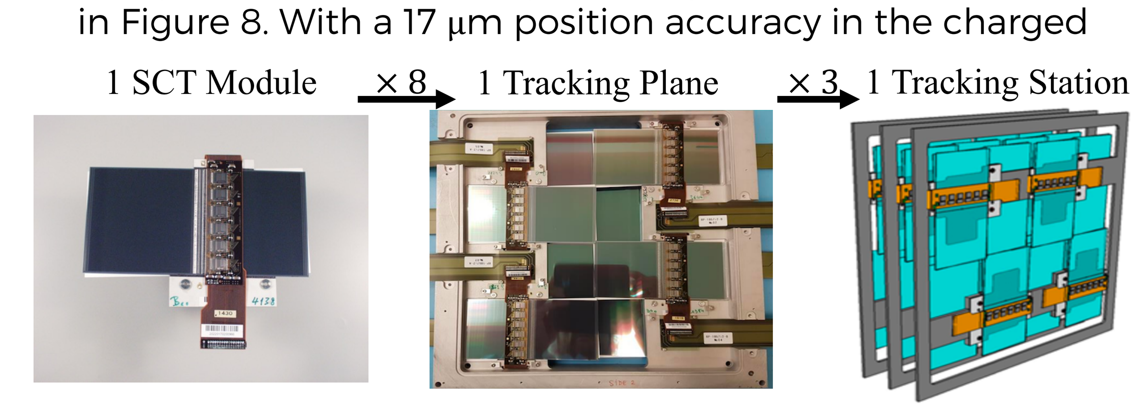

Figure 8: Tracking station composition.

particle bending direction, the tracking stations allow for the detection of even highly boosted (~TeV) oppositely charged particle pairs.

- **Four calorimeter modules** (borrowed from LHCb Outer ECAL) which use a Shashlik design composed of 66 layers of 2 mm lead and 4 mm plastic scintillator as seen in Figure 9.

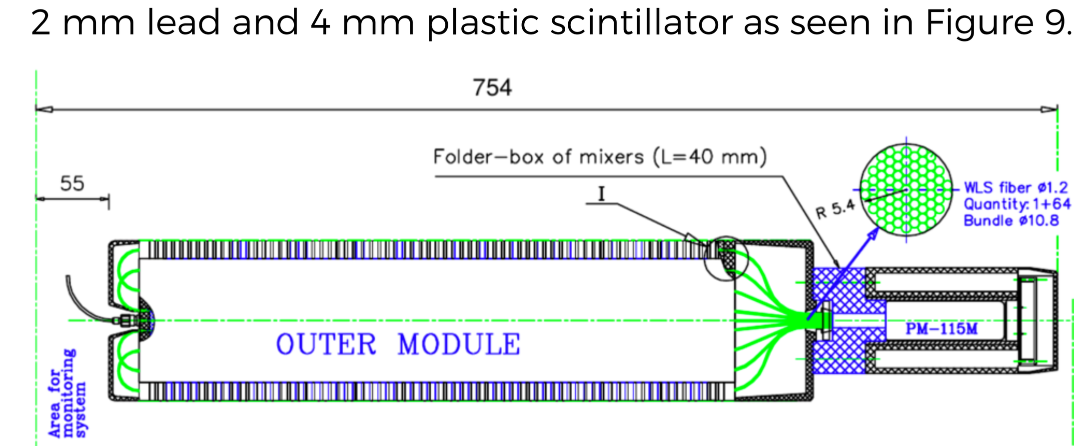

Figure 9: Diagram showing the inner workings of a calorimeter module.

The calorimeters will be useful in discerning between the different particle types such as electrons, muons, and pions.

- **Various scintillator planes** which are used for event triggering/timing and for vetoing SM particles that would otherwise mimic the signal of a dark photon.

Signal

The exact dark photon signal that FASER is looking for consists of two extremely energetic (~ TeV) oppositely charged tracks that have a common vertex inside the FASER decay volume and point back to the ATLAS IP. Figure 10 shows a clear depiction of the signal in which a dark photon enters the decay volume without activating the veto scintillator panels

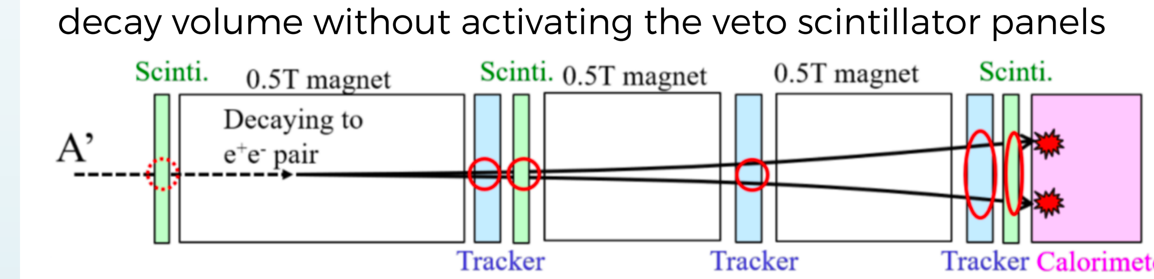

Figure 10: FASER dark photon signal diagram showing a dark photon as a dashed black line and the e+e- pair as two solid black curves. The detector components that would be triggered from a dark photon signal are shown with solid red circles whereas the components that are not triggered are shown as a dashed red circle.

and then decays via pair production into an e^+/e^- pair. The two oppositely charged particles are then separated via the magnets, tracked with the three tracking stations, and leave a splash of energy in the calorimeter modules at the end.

The veto station at the front of the detector is composed of 20 radiation lengths of lead sandwiched between two high efficiency scintillator panels such that pair production from SM photons cannot mimic the dark photon signal as the SM photons are either completely absorbed in the lead or they shower and trigger the veto scintillator panels before entering the decay volume. With the veto station in place, there is no obvious SM process that would mimic the signal from a dark photon.

Sensitivity

Such a distinct signal in the FASER detector allows for a high sensitivity search of dark photons. Figure 11 depicts the dark photon phase space and the expected reach of the FASER detector. As you can see, even with just the first fb^{-1} of data collected, FASER is expected to probe untouched phase space and thus has the potential to discover the dark photon.

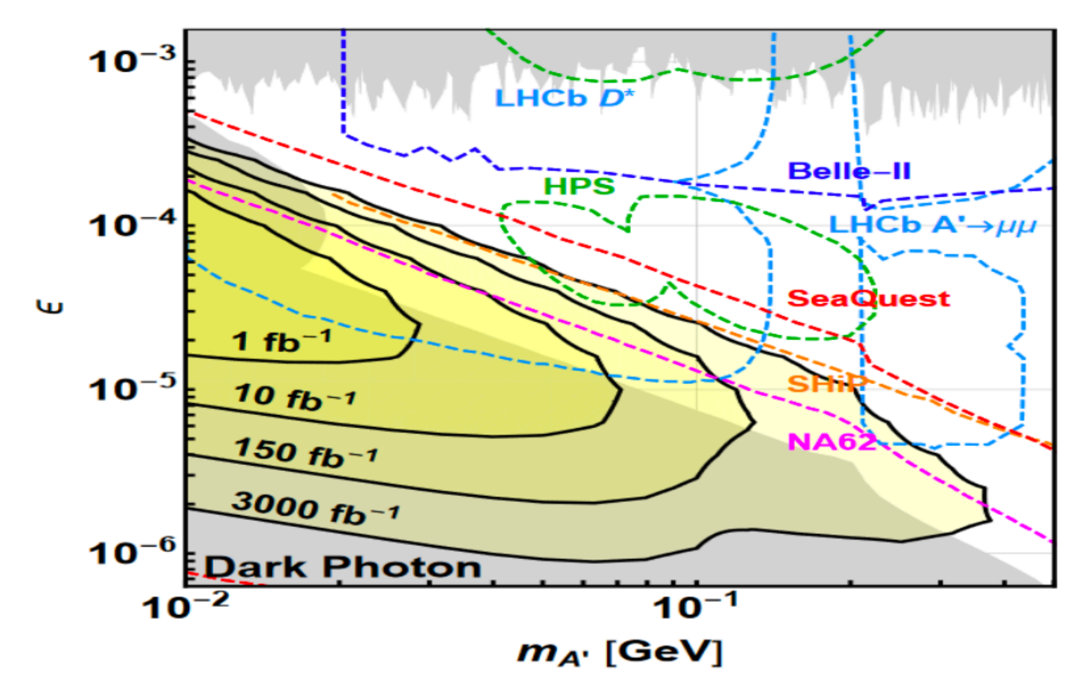

Figure 11: Dark Photon phase space with its mass as the x-axis and its kinetic mixing coupling constant as the y-axis. The expected sensitivity of the FASER detector is shown with the yellow shaded regions representing the reach given varying amounts of luminosity. The gray-shaded regions are excluded by current bounds, and the projected future sensitivities of other experiments are shown as colored contours.

FASER Links

Public homepage: https://faser.web.cern.ch/
Theory paper: https://arxiv.org/abs/1811.12522
Detector design: https://arxiv.org/abs/1812.09139