The FACET Project: Forward Aperture CMS ExTension to search for new Long-Lived Particles

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FACET is a proposed new subsystem for CMS to search for portals such as dark photons, dark higgs, heavy neutral leptons and axion-like particles in the very forward direction at the High Luminosity LHC. Such particles can penetrate up to 50 m of iron and then decay inside a 14 m$^3$ vacuum pipe made by enlarging an 18 m long section of the LHC pipe to a radius of 50 cm.

1 Introduction

FACET, short for Forward Aperture CMS ExTension, is a project under development to add a subsystem to CMS to search for beyond the standard model (BSM) long-lived particles (LLPs) in the high luminosity era of the LHC, in Run 4 (2028) and beyond. The project was initiated with a two-day meeting in April 2020 [1, 2], with one day discussing a forward hadron spectrometer for strong interaction physics, and one day on searching for long-lived particles. A description and more details of the physics potential are given in Ref. [3].

We can compare FACET to the pioneering FASER experiment [4] which is approved to search for LLPs in the very forward direction in Run 3, and an upgrade FASER-2 [5] which is being developed for Run 4. Major differences with FACET are (a) FASER-2 is 480 m from IR5 (with ATLAS) while FACET is 100 - 127 m from IR1 (with CMS). (b) FACET has 4× the solid angle: 54.5 μsr cf. 13.6 μsr. (c) FASER-2 has a 5 m-long decay volume; FACET has 18 m which is evacuated to eliminate background from particle interactions. (d) FASER-2 is centered at polar angle $\theta = 0^\circ$ while FACET covers 1 mrad $< \theta < 4$ mrad. (e) FASER-2 is behind $\sim 100$ m of rock absorber while FACET has $\sim 50$ m of iron. However FACET is located inside the main LHC tunnel where radiation levels are much higher while FASER is located in a side tunnel.

An important difference is that FASER is an independent experiment while FACET is not; it is proposed to be a new subsystem of CMS, fully integrated and using the same advanced technology for its detectors. This has the added benefit of allowing the study of correlations with the central event, and enables a standard model physics program especially in low pileup $pp, pA$ and $AA$ collisions.
FACET will be located downstream of IR5 (at $z = 0$) in an LHC straight section between the new (for Run 4) superconducting beam separation dipole D1 at $z = 80$ m and the TAXN absorber at $z = 128$ m. A schematic layout of the spectrometer is shown in Fig. 1. The beam pipe between $z = 101$ m and 119 m will be enlarged to a radius of 50 cm. In front of the entrance window will be a radiation-hard “tagging” hodoscope, with 2 - 3 planes of $\sim 1$ cm$^2$ quartz or radiation-hard scintillator blocks. This must have very high efficiency with a precision time measurement for charged particles entering the pipe. These are all background particles to be ignored in the subsequent analysis. Excellent time resolution, $\sim 30$ ps, together with fast timing on the tracks from another plane between the tracker and the calorimeter will not only help the rejection of incoming background tracks but allows a study of their momenta and composition.

Neutral LLPs produced with polar angle $1 < \theta < 4$ mrad penetrate the iron of the LHC elements (quadrupoles Q1 - Q3 and dipole D1) and enter the big vacuum tank where decays to SM particles can occur. The LHC-quality vacuum completely eliminates any background from interacting particles inside a fiducial region starting behind the front window. The back window of the big pipe, where it transitions from $R = 50$ cm to $R = 18$ cm, will be thin, e.g. 0.5 mm of Be with strengthening ribs, to minimise multiple scattering of the decay tracks. Behind that window, in air, the detector elements will be 3 m of silicon tracking (resolution $\sigma_{x} = \sigma_{y} \sim 30$ µm per plane) followed by a layer of fast timing ($\sigma_{t} \sim 30$ ps$^2$).

The tracking and timing will be followed by a high granularity electromagnetic and hadronic calorimeter, the HGCAL design. Muons that penetrate the HGCAL are detected in more silicon tracking through an iron toroid.

FACET is complementary to all other searches with unique access to regions of mass and coupling (or lifetime) for many portals, hypothetical particles that couple very weakly to both standard model particles (directly or through mixing) and to dark matter particles. Unlike most searches in the central detectors FACET is sensitive to a wide variety of possible LLPs. It has the potential to discover dark photons ($A'$), dark higgs ($h$ or $\phi$), heavy neutral leptons ($N_1$) and axion-like particles ($ALPs$ or $a$) if they have large enough production cross section in the very forward direction, small enough coupling to penetrate 300 $\lambda_{int}$ of iron, and lifetime in the range $c\tau = 10$ cm - 100 m before decaying to standard model charged particles and/or photons. A key feature is the high (LHC quality) vacuum tank for decays, 1 m diameter and 18 m long (14 m$^3$), made by enlarging a section of the LHC beam pipe. This allows some channels, e.g. $X^0 \rightarrow$ multihadrons, $\tau^+\tau^-, e + \bar{e}$ and $b + \bar{b}$ to have zero background even in 3 ab$^{-1}$, while $e^+e^-$ and $\mu^+\mu^-$ decays may have very low backgrounds especially for masses $\gtrsim 0.8$ GeV. In 3 ab$^{-1}$ we expect to observe several thousand $K^0_L \rightarrow \mu^+\mu^-$ and also $K^0$ decays to 4 charged tracks, compromising the region around $\sqrt{M(X^0)} = 0.5$ GeV.

Dark photons $A'$ are hypothetical neutral gauge bosons that do not have direct couplings with SM particles, but they can interact indirectly by mixing with SM photons. If $M(A') < 1$ GeV their main production mechanism is via the decays $\pi^0, \eta^0, \eta' \rightarrow \gamma\gamma$, the fluxes being highest at small polar angle $\theta$. Fixed target experiments such as NA62 have higher luminosity, and the higher $\sqrt{s}$ of the LHC is not advantageous for dark photons from these sources. For $M(A') > 1$ GeV

$^1$The front window may also need to be thin to minimize interactions behind the tagging hodoscope; this is under study.

$^2$Since this Low-$x$ Workshop we note that measuring the time-of-flight of these background tracks over the 22 m between the two hodoscopes, with a resolution $\delta\beta \lesssim 5 \times 10^{-4}$, together with the energy measured in the calorimeter, will be very interesting. For example, consider particles with a delay relative to $\beta = 1$ of 1 ns $\pm 50$ ps with a shower of energy $E_{cal}$. These can be 0.63 GeV/c $\mu^\pm$, 0.83 GeV/c $\pi^\pm$, 3 GeV/c $K^\pm$, or 5.6 GeV/c $p$ or $\bar{p}$, easily distinguished thereby measuring the identify and spectrum of these background tracks. That would be useful for testing and tuning FLUKA, the LHC standard for machine protection etc. It also uniquely enables calibration of the HGCAL with hadrons of known momenta up to tens of GeV with high statistics even in short runs. The charge $Q$ is known from the Cherenkov light amplitude and track $dE/dx$ enabling measurements of light isotopes with lifetimes $\gtrsim 10^{-6}$ s in the showers, and to search for objects such as strangelets (nuclei with extra strange quarks and therefore anomalous low charge:mass ratio).
the higher $\sqrt{s}$ of the LHC is important, as additional sources such as Drell-Yan and quark- and proton-bremsstrahlung dominate. The LHC is essential if the source is a massive state such as a Z' in the model of Ref.[6], which would give FACET sensitivity up to $\sim 20\text{ GeV}$. The decay modes are the same as the final states in $e^+e^-\rightarrow \gamma^*$, with $\tau^+\tau^-$, $c\bar{c}$ and multihadron decays being background-free above their thresholds. Measuring the relative rates of different channels could establish the identity of candidates as dark photons.

Heavy neutral leptons $N_i$ (where $i$ represents flavor, perhaps with three different mass states to discover) are present in many BSM theories; they may explain the light neutrino masses through the seesaw mechanism. Possible decay modes are $N_{\mu}\rightarrow \mu^+W^+\bar{\tau}$ with the virtual $W^*$ decaying to kinematically allowed leptonic or hadronic channels, and the same modes but with $\mu$ replaced by $e^\pm, \tau^\pm$. If $N_i$ have masses in the few-GeV region even a few good candidate events would be a discovery that would open a very rich new field of neutrino physics. In the model of Ref.[7] FACET has unique discovery reach up to $\sim 25\text{ GeV}$.

Also very exciting would be the discovery of another Higgs boson, a dark higgs, $h$ or in general a scalar $\phi$, having the same vacuum quantum numbers as the H(125) but with mass possibly in the several GeV region. Present measurements of H(125) decays allow an invisible decay fraction up to 5%, which could be explained by an $h$ through mixing $H(125)\leftrightarrow h$ or decay $H(125)\rightarrow h+h^3$. If $M(h)\lesssim 4.5\text{ GeV}$ rare $b$-decays are a potential source, with competition especially from B-factories and LHC-b. For $4.5\text{ GeV} < M(h) < 60\text{ GeV}$ and a range of mixing angles FACET has unique coverage, as shown in Fig. 2. The most spectacular decays are $h\rightarrow \tau^+\tau^-, c\bar{c}$ and $b\bar{b}$ if kinematically allowed, and with the heaviest states favored; the scalar nature can be demonstrated by the relative decay fractions as well as the isotopic decay. FACET has more sensitivity than FASER-2 due to its larger solid angle and longer decay volume, e.g. if there is no background and

\[ \text{If one } h \text{ is detected in FACET the other should be more central and give rise to missing transverse energy } E_T. \] Whether it is possible to detect this in a high pileup bunch crossing remains to be seen.
if 10 candidates were to be detected in FACET, FASER-2 would expect < 1

Another possible portal is a heavy ALP, but the main decay mode to $\gamma + \gamma$ will have a high background from random pairs of photons from $\pi^0$ and $\eta$ decay, etc. Even though the electromagnetic section of the HGCAL measures the shower direction the vertex resolution is much worse than for charged tracks.

FACET will be live for every bunch crossing, with an expected pileup of $\sim 140$ inelastic collisions, giving a total integrated luminosity of $\sim 3 \text{ ab}^{-1}$. The FLUKA code, which is the LHC standard, predicts about 25 charged particle tracks with $18 \text{ cm} < R < 50 \text{ cm}$ in each bunch crossing. Their origin (apart from any BSM signal!) is (a) from interactions of beam halo and secondary particles with the beam pipe, collimators, magnets, etc. (b) from decays of neutral hadrons, mainly $K^0_L$, $K^0_S$, and $\Lambda^0$. (c) Very small angle ($\theta < 1 \text{ mrad}$) charged particles that pass through the D1 aperture, which deflects them to the left and right sides. The acceptance for the latter is limited to $\sim 2 \text{ TeV}$, but they allow some standard model physics (e.g. measuring $\mu^+\mu^-$ pairs at Feynman-$x_F \sim 0.5$).

In a fast Level-1 trigger the tracks will be projected upstream to the 2D hodoscope in front of the front window. The main purpose of the hodoscope is to tag all entering charged particles with very high efficiency (inefficiency $\lesssim 10^{-5}$) and ignore them; they are all background. Because of the high resolution of the tracker and because there is no significant magnetic field the uncertainty on the projected entrance point is < 1 mm. Since in $3 \text{ ab}^{-1}$ there will be about $2 \times 10^{15}$ bunch crossings, we still expect $\sim 10^{-5} - 10^{0}$ bunch crossings with two untagged tracks from different collisions entering the decay volume, depending on the tagger inefficiency. However, the probability that these two background tracks intersect in space, i.e. have a distance of closest approach $\lesssim 100 \mu \text{m}$ inside the fiducial decay volume and matching in time effectively kills this pileup background.

Decays of $K^0_L$, $K^0_S$, and $\Lambda^0$ inside the pipe are a serious background for any LLPs with mass $M(X^0) \lesssim 0.8 \text{ GeV}$ decaying to hadrons. Their mass and momentum are reconstructed from the tracks and calorimeter energies (or muon momenta in the toroid), and one can require pointing back to the IR, good timing and a flat distribution of decay distance (as it would be for an LLP). However the background to a search for 2-body hadronic decays of an LLP is expected to be overwhelming except for $M(X^0) \gtrsim 0.8 \text{ GeV}$. For higher masses 4-body decays become more probable, and a well-defined vertex with $\geq 4$ charged tracks should have zero background. The probability of two unrelated $K^0$ decays occurring within the resolution in $x, y, z, t$ is very small but is being evaluated, as are all expected possible backgrounds.

A Letter of Intent to CMS is being prepared to officially propose FACET as a new subsystem and initiate a technical design study. The most critical item is the enlarged beam pipe, since that cannot be installed in short technical stops, and the next planned long shutdown LS4 is in 2031. New sources of funding will be sought. The detectors required represent $\lesssim 5\%$ of the CMS forward upgrades, and could be installed (and upgraded if needed) in technical stops.

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\footnote{While the coverage of FACET is limited by LHC restrictions in the horizontal direction, the solid angle could be increased nearly a factor $\times 2$ in the vertical direction with a non-circular beam pipe.}
Figure 2: Reach of FACET and other existing and proposed experiments for a dark Higgs boson $\phi$ with the assumption of either 0% (red lines) or 2.5% (yellow lines) branching fraction for the $H(125) \rightarrow \phi\phi$ decays. FACET offers a unique coverage all the way to half $M_H$ for a range of mixing angles. FACET and FASER-2 contours are calculated with FORESEE [8]. Figure from Ref. [3] which gives citations.

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