# FACET: A new long-lived particle detector in the very forward region of the CMS experiment

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**Abstract**

We describe a proposal to add a set of very forward detectors to CMS for the high-luminosity era of the Large Hadron Collider to search for beyond the standard model long-lived particles, such as dark photons, heavy neutral leptons, axion-like particles, and dark Higgs bosons. The proposed subsystem is called **FACET** for **F**orward-**A**perture **C**MS **E**x**T**ension, and will be sensitive to any particles that can penetrate at least 50 m of magnetized iron and decay in an 18 m long, 1 m diameter vacuum pipe. The decay products will be measured in detectors using identical technology to the planned CMS Phase-2 upgrade.

## 1 Introduction

The existence of dark matter (DM) is well established from astronomical observations and cosmology. Dark matter is generally assumed to consist of particles beyond the standard model (BSM). While searches for such particles in the TeV region continue at the CERN Large Hadron Collider (LHC), the possibility that new particles may be relatively light ($\lesssim$50 GeV), and yet have escaped detection so far because of very weak coupling to standard model (SM) particles, is receiving considerable attention, as discussed in, e.g., Refs. [1–3]. There are many possible so-called *portals*; these are neutral particles that couple weakly to the SM and also to DM particles (but being unstable are not themselves DM candidates), such as dark photons [4–6], heavy neutral leptons [7,8], axion-like particles [9–11], and scalars or dark Higgs particles [12,13]. The proposed new CMS subsystem, FACET (**F**orward-**A**perture **C**MS **E**x**T**ension), can search for many such portals (called here $X^0$) depending only on their forward production cross section, momentum, mass $m_{X^0}$, and proper lifetime $c\tau$. We will show that FACET covers a region of parameter space not accessible to other experiments, neither existing nor proposed.

Low-mass particles typically imply production peaking in the forward direction. However, even decay products of a 125 GeV Higgs boson ($H(125)$) can have small enough polar angle $\theta$ to reach FACET [14]. Small couplings often imply long lifetimes, hence the focus on searches for long-lived particles (LLPs) that can manifest as displaced vertices, e.g., in the large central detectors at the LHC.

Longer lifetimes can be probed in the LHC experiment FASER (Run 3) [15, 16] in the beam direction ($\theta = 0^\circ$) at a distance $z = 480$ m from the collision point, and proposed experiments for the high-luminosity LHC era, such as MATHUSLA [17, 18], CODEX-b [19] and FASER-2 [20, 21]. Fixed-target experiments, such as NA62 [22, 23] at the CERN SPS, have sensitivity especially for dark photons with mass less than 1 GeV from $\pi^0$, $\eta$, and $\eta'$ meson decays.

FACET is not proposed to be a new experiment, but a new subsystem of the CMS experiment that, while overlapping in the parameter space with other searches, will cover an extended and unique region. FACET will be sensitive to particles produced with polar angle $1 < \theta < 4$ mrad (equivalently $7.6 > \eta > 6.2$). It is closer to the interaction region (IP5) than FASER-2 (at IP1), with four times the solid angle. FACET has an 18 m long decay volume from $z = 101$ to 119 m, followed by an 8 m long region instrumented with various particle detectors. FACET covers a range of proper lifetimes $c\tau$ of $\sim$0.1–100 m. We note that the Lorentz factor $\gamma$ is typically high in the forward direction. A unique feature among the LHC experiments is that the decay volume is at high vacuum (LHC quality, as it is part of the LHC beam pipe), eliminating any background from particle interactions inside a $\sim$14 $\mathrm{m}^3$ fiducial region.

Small couplings also imply the ability of an LLP to penetrate a large amount of absorbing material. Between IP5 and the decay volume LLPs have to penetrate 35–50 m (200–300 $\lambda_{\mathrm{int}}$) of magnetized iron in the LHC quadrupole magnets Q1–Q3 and the new (for Run 4) 35 T·m superconducting dipole D1. Since neutrinos are the only SM particles that can penetrate that much absorber, essentially all the SM backgrounds having *direct* paths from the IP are eliminated. Nevertheless, the detectors are in a region with high radiation levels and particle showers from upstream interactions in the beam pipe and surrounding material. The design of FACET takes these challenges into account.

## 2 FACET as a new Subsystem of CMS

A schematic view of the detector is shown in Fig. 1. The project requires that an 18 m long section of the LHC beam pipe, between $z = 101$ and 119 m on one side of the IP5 collision region be replaced with a circular pipe of a 50 cm radius[1]. The transition from $R = 10.6$ to 50 cm is a $\sim$45° cone to mitigate the beam impedance mismatch. This section is downstream of the focusing quadrupole magnets and beam separation dipole magnet D1. Additional shielding will be placed upstream of the first detector, which is a multilayer counter hodoscope, made of radiation-hard scintillator or quartz bars and/or pads. The hodoscope must have very high efficiency to tag charged particles from interactions in the upstream shielding, most of which have large enough polar angles to miss the tracker.

Dedicated FLUKA [24, 25] simulation predicts that with the present design there will be $\sim$30 charged particles in the tracker per bunch crossing, most of which have large enough polar angles to miss the tracker. These are all background tracks, which are ignored in the subsequent analysis. The FLUKA simulation also predicts that there will be, on average, one neutral hadron (mostly $K^0$ or $\Lambda$) decaying inside the decay volume. All bunch crossings will be examined for candidate decays inside the vacuum volume, giving a sensitivity to an integrated luminosity of $\sim$3 $\mathrm{ab}^{-1}$ in

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[1] A large beam pipe with a similar radius already exists downstream of the ALICE experiment.

the high-luminosity LHC era. The highly segmented upstream hodoscope, precision tracking, and imaging calorimetry will reduce these backgrounds to very low levels, even eliminating them in some channels, as discussed below. In addition, we are investigating the possibility to further mitigate these backgrounds by installing additional shielding closer to the D1 dipole and possibly shortening the vacuum decay volume by 1–2 m to make space for more shielding, including a magnetized iron toroid, in front of the hodoscope.

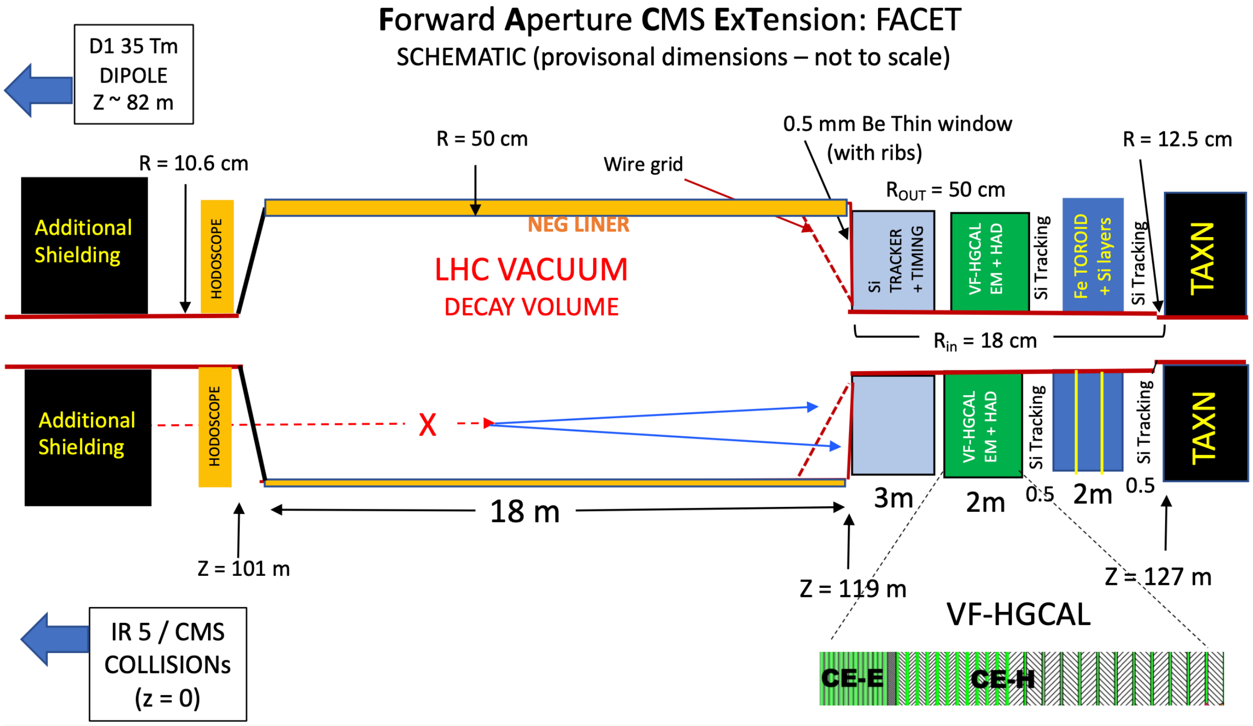

Figure 1: Schematic layout of the proposed FACET spectrometer. Side view and top view are essentially the same since it is azimuthally symmetric. Upstream (to the left) is the IP5 collision region followed by the machine elements Q1–Q3 and D1 comprising 35–50 m of iron shielding. The TAXN limits the extension in the $z$ direction; it provides shielding for the superconducting LHC elements downstream. The superimposed red dashed line shows schematically an LLP from the IP5 decaying into two charged tracks shown in blue.

The back end of the enlarged beam pipe, where it transitions from $R = 50$ to 18 cm, is a thin ($\sim$0.5 mm) beryllium window to minimize multiple scattering of the charged particles. Strengthening ribs can cover $\lesssim$2% of the area. An internal wire cone mitigates impedance mismatch. Behind that window (in air) precision tracking, high-granularity electromagnetic and hadron calorimetry, and a toroidal magnet interspersed with tracking detectors measure charged-particle tracks and identify and measure the energies of photons, electrons, hadrons, and muons. There is no magnetic field between the $X^0$ decay and the precision tracker, making accurate reconstruction of decay vertices simple. A layer of fast timing with Low-Gain Avalanche Detectors, LGADs, will be included. This high-resolution timing, with $\sigma_t \sim 30$ ps, will be used to reduce backgrounds from interactions in upstream material, providing vertex positioning in 4D $(x, y, z, t)$, and a time-of-flight measurement for candidates.

The tracking is followed by electromagnetic and hadron calorimetry, using identical technology to the CMS HGCAL (High-Granularity Calorimeter) [26] planned for the forward direction in the

CMS Phase-2 upgrade. Copper or tungsten plates interspersed with silicon pads provide imaging in 4D. The high granularity is important to measure individual showers above a threshold energy (e.g., 10 GeV, but tunable) and their directions in the presence of many low-energy showers. Behind the calorimeter, an iron toroid with magnetic field of $B \sim 1.75$ T instrumented with additional silicon tracking measures the charge of muons and allows an approximate measurement of the muon momentum and the dimuon mass for any muon pairs. Muons are also detected through the active layers of the calorimeter.

The approximate number of channels in the FACET detector amounts to about 5% of that for the CMS Phase-2 upgrade, making the detector relatively inexpensive, as most of it could be built using the same modules as are going to be used for the central CMS detector upgrade, thus minimizing the R&D and engineering needs.

# 3 Sensitivity to Long-Lived Particles

The reach in LLP parameter space has been calculated for dark photons, heavy neutral leptons, axion-like particles, and dark Higgs bosons in several benchmark scenarios. Predictions are generally model dependent and some also depend on the nature of other BSM particles, e.g., a heavy $Z'$ boson and its mass. We base these studies on a total integrated luminosity of 3 $\mathrm{ab}^{-1}$ of proton-proton collisions at a center-of-mass energy $\sqrt{s} = 14$ TeV, with either 3 or 5 candidate events, assuming no background and that FACET can detect all penetrating neutral particle decays to $\geq 2$ charged particles or photons occurring between $101 < z < 119$ m with the decay products within $18 < R < 50$ cm at $z = 120$ m.

## 3.1 Dark Photons

Massive dark photons $A'$ are neutral gauge bosons, which are not directly charged under SM gauge groups. However, they can interact with SM particles via mixing with photons. A recent review can be found in Ref. [5]. A massive virtual photon produced by any process in a hadron-hadron collision has some probability of conversion to an $A'$, governeed by the kinetic mixing parameter $\epsilon$. If $m_{A'} \lesssim 1$ GeV, the most prolific source will be decays of $\pi^0$, $\eta$, and $\eta'$ mesons. The fluxes of these particles are highest at small polar angles.

Fig. 2 shows limits calculated using FORESEE [27] without assuming any other BSM sources of dark photons, such as a heavy $Z'$ bosons, which can extend the mass range and require the energy of the LHC.

For $m_{A'} > 1$ GeV the main production mechanisms are: $q+\bar{q} \to A'+X$; Drell–Yan: $q+\bar{q} \to A'$; bremsstrahlung: $p \to A' + p$ and $q \to A' + q$; and heavy-quark decays: $c \to A' + X$, $b \to A' + X$. The decay modes to SM particles of a minimal dark photon are the same as the final states in $e^+e^- \to \gamma^*$ at $\sqrt{s} = m_{A'}$.

A comparison of the FACET and other experiments dark photon reach for all final states in the model of Ref. [43] is given in Fig. 3 (left). In this model, the main production mechanism of dark photons is via radiation in a rather rich hidden sector, which contains a Dirac fermion $\psi$ and two gauge bosons, which mix with the SM weak hypercharge field $B_\mu$. FACET covers a unique region of the mixing parameter $\epsilon_1$ vs. mass (or alternatively lifetime vs. mass) phase space. Figure 3 (right) shows the number of events as a function of lifetime $c\tau$ for three $A'$ masses for the model parameters corresponding to the reach shown in Fig. 3 (left).

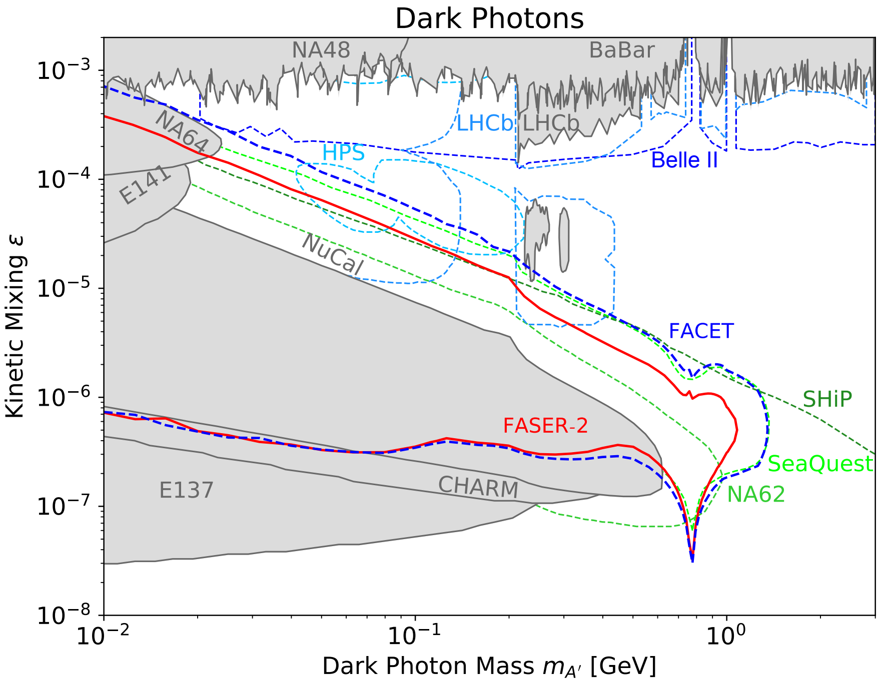

Figure 2: FACET reach for dark photons in a generic model with no BSM sources, as calculated with FORESEE [27]. Existing bounds (gray shaded regions) are taken from CHARM (following Ref. [28]), BaBar [28], E137 [29], E141 [30], LHCb [31], NA48/2 [32], NA64 [33], and NuCal [34], along with the prospective limits taken from studies performed for Belle II [35], HPS [36, 37], LHCb [38, 39], NA62 [40], SeaQuest [41], FASER-2 [27], and SHiP [42].

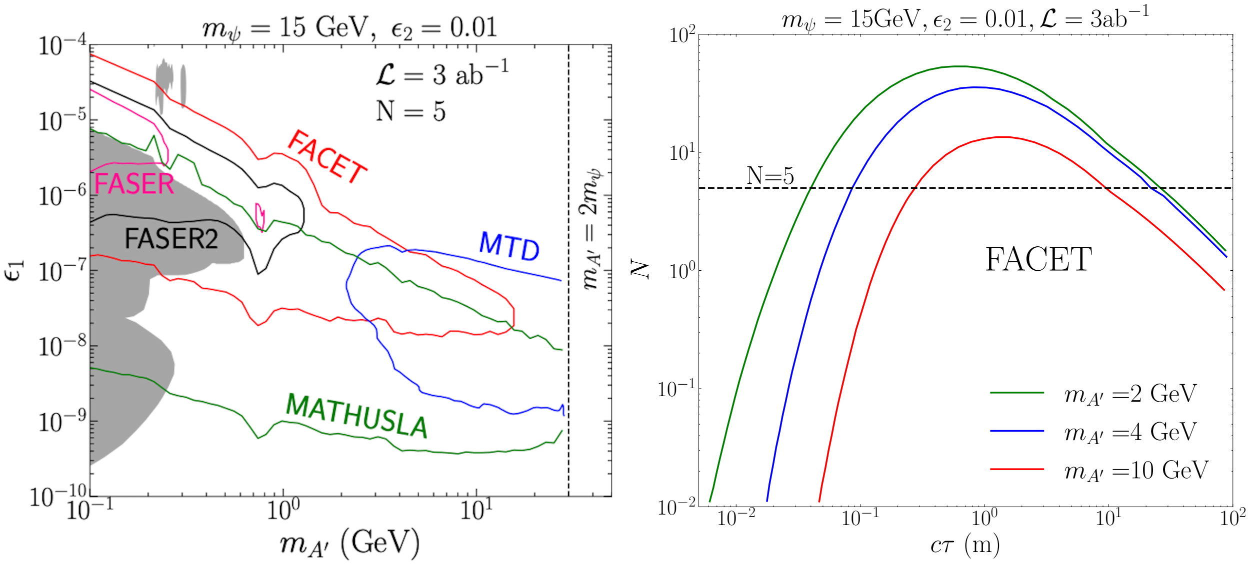

Figure 3: Left: FACET reach for dark photons (5 event contours) in the parameter space of coupling $\epsilon_1$ and mass $m_{A'}$ in the model of Ref. [43]. Of the other projects shown, only FASER and MTD, the CMS Phase-2 MIP Timing Detector, are currently approved. Right: Number of dark photon events as a function of $c\tau$ for $m_{A'} = 2$, 4, and 10 GeV in this model.

## 3.2 Heavy Neutral Leptons

Many extensions of the SM involve heavy right-handed neutrinos or heavy neutral leptons $N_i$ (where the subscript $i$ indicates flavor), which may explain the light neutrino masses through the seesaw mechanism [8,44,45]. They may be produced in any kinematically allowed SM weak leptonic decay, e.g., of $s$, $c$, $b$, $t$ quarks, or $W$ or $Z$ bosons. We consider a specific extension of the SM model [46], with a $Z'$ boson (which can be light and yet have escaped detection due to the small coupling to SM particles) and three heavy right-handed Majorana neutrinos $N_i$. In this model, the decay $Z' \to N_i N_i$ is allowed, and the $N_i$ can be long-lived and decay to SM particles, e.g., a lepton of the same flavor and a virtual $W^*$ or $Z^*$ boson. For the $Z'$ masses in the 10–100 GeV range, most interesting in this model, the branching fraction of the $Z' \to N_i N_i$ decays amounts to about 20%, i.e., rather large and similar to that for the $Z$ boson decays into SM neutrinos.

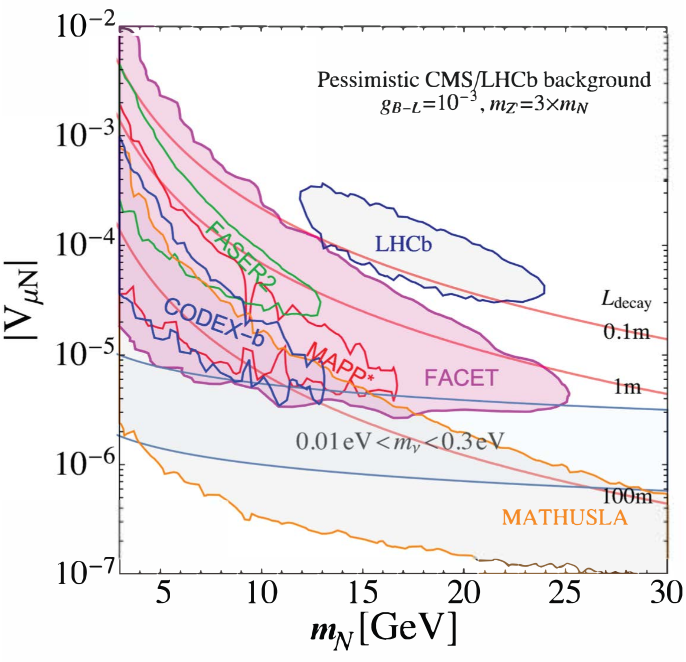

Figure 4: FACET reach in the mixing parameter vs. mass plane for a heavy neutral lepton, along with projections for other proposed experiments, as well as for MAPP and the upgraded LHCb detectors [46].

Fig. 4 shows the coverage in the mixing parameter $|V_{\mu N}|$ vs. $m_N$ plane in the case of a single Majorana neutrino $N$ mixed with a muon neutrino. In this case, FACET has a unique sensitivity at high masses, above ~15 GeV for lifetimes $c\tau$ between ~0.1 and ~100 m.

## 3.3 Axion-Like Particles

Pseudoscalar particles, such as extremely light axions, were initially proposed to solve the strong $CP$-problem of QCD. More massive axion-like particles (ALPs, $a$) may exist, and if produced at the LHC [11,47], they may decay with long lifetimes into photon pairs (or $\gamma e^+ e^-$) or lepton pairs, after penetrating thick absorbers. FACET will be well-placed to discover such ALPs in certain regions of their mass and the coupling to SM gauge bosons. An overview of the FACET reach for ALPs is given in Fig. 5 in a specific $W$-dominance ALP model [48,49], as a function of the ALP mass and the coupling to $W$ bosons, $g_{aWW}$.

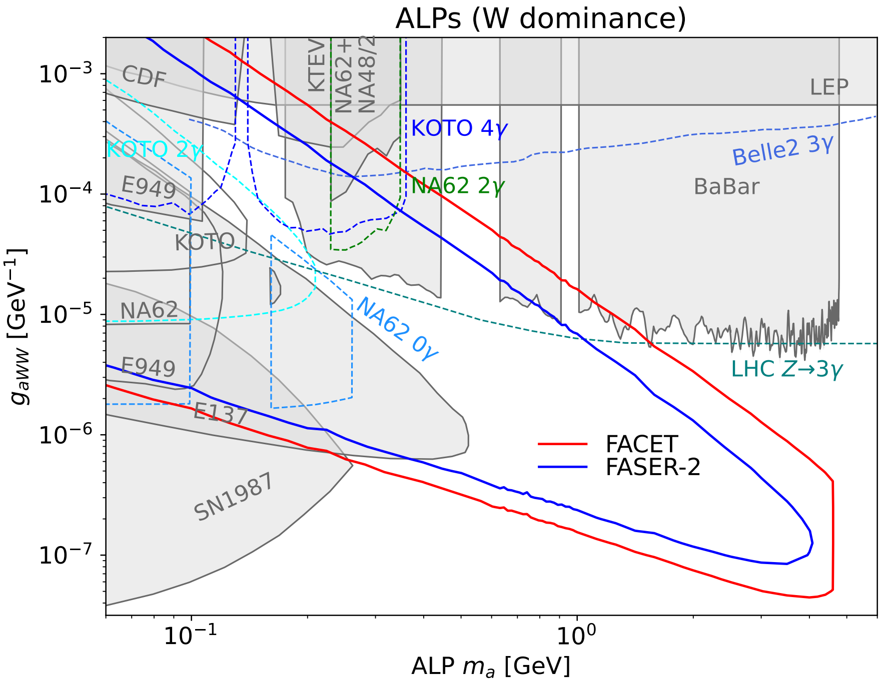

Figure 5: FACET sensitivity to ALPs in the $W$-dominance model, as a function of mass and coupling, as calculated with Foresee [27]. The gray-shaded regions are excluded by current bounds, while dashed lines correspond to projected sensitivity of various experiments, as calculated in Refs. [48, 49]. The BaBar limits are from Ref. [50]. More details can be found in Refs. [51, 52] and references therein.

### 3.4 Dark Higgs Bosons

The possible existence of a dark sector partner $\phi$ of the 125 GeV Higgs boson has attracted attention, as discussed, e.g., in Refs. [12, 13, 63]. A dark Higgs field provides a simple mechanism to give mass to the dark photon $A'$. The corresponding dark Higgs boson $\phi$ may be the lightest dark sector state and can decay into SM particles via mixing with the Higgs boson, governed by the mixing angle $\theta$. Unitarity and perturbativity suggest that the dark Higgs boson cannot be much heavier than the dark gauge boson $A'$, while it can be significantly lighter. The dark Higgs boson can be very long-lived due to its suppressed couplings to the accessible light SM states.

For mass ranges below ∼5 GeV the dominant production mechanism is through $B$ meson decays, e.g., $B \to K + \phi$, with $\phi$ decaying to pairs of most massive SM fermions accessible kinematically, e.g., to a pair of muons for light $\phi$, or to a pair of $\tau$ leptons or charm quarks for a heavier $\phi$. A heavier $\phi$ may also decay to another pair of new scalars, $s$, which may in turn be LLPs.

The reach of FACET for a dark Higgs boson decaying to a detectable final state is given in Fig. 6. In addition to the production via $B$ meson decays (left plot), we also consider the case of a small, non-zero trilinear coupling $\phi\phi H$ between the SM Higgs and dark Higgs bosons, resulting in a 2.5% branching fraction of the $H(125) \to \phi\phi$ decay (right plot). This value is lower than the projected limits on the BSM Higgs boson decay branching fraction at the high-luminosity LHC [64]. In this case, the low-mass reach is slightly improved compared to the case with no trilinear coupling, as a new decay mode $b \to s\phi\phi$, where $b$ and $s$ is are the bottom and strange quarks, respectively, is present due to a virtual Higgs boson exchange [13]. However, the most striking feature in this model

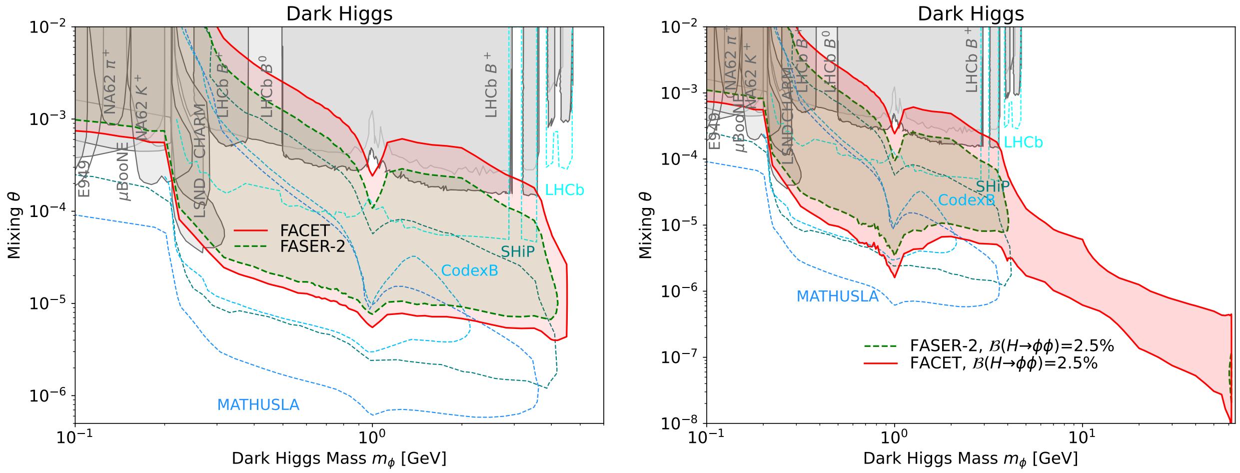

Figure 6: Reach of FACET and other existing and proposed experiments for a dark Higgs boson $\phi$ with the assumption of either 0% (left) or 2.5% (right) branching fraction for the $H(125) \to \phi\phi$ decays. In the second scenario, FACET offers a unique coverage all the way to half $m_H$ for a range of mixing angles. FACET and FASER-2 contours are calculated with FORESEE [27]. Current exclusions from NA62 [53], BNL-E949 [54], LHCb [55,56], CHARM [57], LSND [58], MicroBooNE [59] are shown as gray shaded regions. Also, sensitivity from studies for MATHUSLA [60], CODEX-b [61], LHCb upgrade [61], and SHiP [62] are shown.

is that FACET offers a unique sensitivity for the dark Higgs boson masses up to the kinematic limit of $m_H/2$ due to a large number of Higgs bosons that are produced at the high-luminosity LHC with a significant longitudinal boost, resulting in at least one of the two dark Higgs bosons decaying within the FACET detector acceptance [14].

# 4 Triggers

As a part of the CMS Phase-2 Upgrade at the high-luminosity LHC, the Level-1 (L1) trigger system will be upgraded, with a latency increased to 12.5 $\mu$s and output rate to the High-Level Trigger (HLT) increased to 750 kHz. The HLT will analyse the data with close to off-line performance, sending data to long-term storage at a rate of about 7.5 kHz. FACET will provide an additional external trigger to the CMS L1 Global Trigger, built from the hodoscope, tracking, calorimeter, and muon detector information, and using the same hardware and code to be used in the upgraded CMS detectors.

The L1 triggers will be formed from, among others:

1. $\geq 2$ tracks with a small distance of closest approach inside a decay volume;
2. $\geq 2$ muon tracks through the toroidal spectrometer;
3. $\geq 1$ cluster of energy in the electromagnetic calorimeter above some threshold and with a direction requirement based on the tracker and/or the calorimeter;
4. $\geq 1$ cluster of energy in the hadron calorimeter above some threshold and with a direction requirement based on the tracker.

To achieve maximum sensitivity for the LLP search, FACET will be exposed to all bunch crossings. The goal of the trigger is to select all candidates for $X^0 \to \geq 2$ charged tracks or two photons (even if merged), while excluding decays of the SM particles, such as $K^0$ and $\Lambda$.

The FLUKA [24, 25] code, regularly used for LHC background calculations, predicts that there will be about 30 charged particles with the momentum above 1 GeV (mostly protons, $\pi^\pm$, and $e^\pm$, with $\sim$1.9 $\mu^\pm$) entering the tracker at $R > 18$ cm per bunch crossing (with a pileup of 140). These are all background tracks, and will be tagged as such by the front hodoscope and ignored. The L1 track trigger will form tracks (at $119 < z < 121$ m) and calculate the position of candidate vertices inside the decay volume, as well as confirm that the decay signature is consistent with an LLP originating at IP5.

Since the planned rate of L1 triggers for CMS is 750 kHz, FACET triggers at a L1 rate of a few kHz is a goal, which should be achievable by tuning thresholds. The HLT can apply selections close to the offline analysis to reduce the rate to long-term storage to $\lesssim$100 Hz out of 7.5 KHz total rate-to-tape for CMS. The FACET-triggered events will include the full CMS data, and the FACET information will be included in all CMS triggered events. The FACET data will be $\ll 1\%$ of the full CMS data. The FACET trigger could also be run in a standalone mode, with only FACET information saved, and without correlating with the central CMS detector.

For charged particles with $\theta < 1$ mrad that come through the dipole D1 aperture, the rates will be high, but some SM channels, e.g., $e^+e^-$ and $\mu^+\mu^-$, are interesting and special triggers for those can be included. Such triggers will be prescaled, but the data will be useful for checks throughout the LHC running.

For any low-pileup LHC runs, with proton, as well as with ion beams, a different set of triggers will be prepared. Since many bunch crossings will then have only a single interaction, correlations between leading charged hadrons and the central event can be studied.

## 5 Backgrounds

FACET is unique among all LHC LLP search proposals in having a very large volume of LHC-quality vacuum for decays. Vertices with $R > 15$ cm inside a fiducial volume with two or more associated tracks cannot have come from interactions; they must be due to decays[2]. Our goal is to have no background events even with 3 ab$^{-1}$ of integrated luminosity in many decay channels; in which case even a few signal candidate events can mark a discovery.

The direct path from the collision region to the decay volume has 200–300 $\lambda_{\text{int}}$ (depending on $\theta$) of magnetized iron, effectively eliminating all SM particles, except neutrinos. Therefore the only SM particles entering the decay volume are indirect, from interactions in the beam pipe and LHC components. Most are at large enough polar angle $\theta$ to miss the tracker, nevertheless the FLUKA code predicts that there will be about $\sim$30 charged particles with the momentum above 1 GeV entering the tracker at $R > 18$ cm per bunch crossing. There is a significantly larger flux of lower momentum charged particles entering the hodoscope, most of which have large enough polar angles to miss the downstream tracker. This drives the need for at least one layer of $\sim$1 cm$^2$ pads in the hodoscope.

Neutral hadrons of concern are $K^0_S$, $K^0_L$, $\Lambda$, and $\Xi^0$, with about one entering the decay volume per bunch crossing. Their decay tracks will be well measured and their energies determined in the calorimeter. A Monte Carlo simulation shows that the parent mass and the direction can be reconstructed with this information. Requiring the parent track to point back to the IP5 interaction

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[2] Interactions of beam bunches with residual gas molecules in the LHC during the high-luminosity LHC operations are actively being studied [65], but such vertices would be close to the outgoing beams with $R < 10$ cm.

region and using the decay position information (flat in $z$ for an LLP) will reduce this neutral hadron background, that may still be overwhelming for $X^0 \to h^+h^-$ with $m_{X^0} \lesssim 0.8$ GeV.

The situation is much better for lepton pairs. Only $K^0$ decays can contribute; for $K^0_S$ either through both charged pions being misidentified as electrons or as muons, or by genuine dilepton decays, all of which have very small branching fractions $< 10^{-8}$. The $K^0_L$ meson has common semileptonic decays to $\pi^\pm e^\mp \nu_e$ and $\pi^\pm \mu^\mp \nu_e$, so only one $\pi^\pm$ has to be misidentified as a lepton. The missing neutrino smears the pointing from the IP5, the reconstructed mass is a continuum with $m_{X^0} < 500$ MeV, and the $z$ distribution of the vertex is not nearly uniform as it would be for an LLP.

In $2\times10^{15}$ bunch crossings (3 ab$^{-1}$) we expect several thousand true $K^0_L \to \mu^+\mu^-$ decays in the vacuum volume given the branching fraction of $7 \times 10^{-9}$. The $\mu^+\mu^-$ mass is reconstructed and, if compatible with $m_{K^0}$, the momentum, the decay time $c\tau$ and the total momentum are known. While it would be interesting (and an excellent control measurement) to observe these rare $K^0$ dilepton decays, they will not be a background to $X^0 \to l^+l^-$ decays for $m_{X^0} \gtrsim 0.6$ GeV.

A potential background in the $X^0 \to l^+l^-$ channel is from pileup, with two muons or electrons from different collisions in the same bunch crossing appearing to come from a common vertex in the decay volume. Studies done with FLUKA show that the transverse distribution of muons is approximately proportional to $1/R$, the density ranging from $2 \times 10^{-4}$ to $8 \times 10^{-5}$ cm$^{-2}$. The total is an average of 1.9 muons (both charges) per bunch crossing within $18 < R < 50$ cm. This background will be eliminated by charged-particle tagging in the upstream hodoscope, and precision vertexing. If the inefficiency of the hodoscope is $10^{-4}$ ($10^{-5}$) there will be $\sim 10^7$ ($\sim 10^5$) bunch crossings in 3 ab$^{-1}$ with two or more untagged muons entering the decay volume. A Monte Carlo study of pairs of uncorrelated muons was used to determine the probability that any pair has a distance of closest approach $< 60$ $\mu$m; the prediction is 150 (1.5) two-track vertices from pileup, which is further reduced by a factor of two by the opposite-sign track requirement. Further requiring the vector sum of the muon momenta to point back to the IP5 collision region eliminates this background.

A search for $X^0 \to \gamma\gamma$, e.g., for an axion-like particle, having no charged tracks and less precise vertex location, will be challenging, with a large background from photons from $\pi^0, \eta$, and $\eta'$ meson decays, as well as from $K^0_S \to \pi^0\pi^0$ decays. The electromagnetic section of the calorimeter measures both the shower directions and the distance of closest approach of the two photons, albeit without the high precision which is achieved for tracks. Requiring matching in $x,y,z,t$ using position and timing information and that the momentum of the diphoton pair points back to IP5 will suppress these backgrounds, especially for $m_{\gamma\gamma} \gtrsim 1$ GeV. Studies based on full detector simulation are under way to determine whether this background could be controlled.

Many BSM particles with masses above about 1 GeV have decay modes to more than two charged particles. The only SM hadrons that can decay to four charged particles inside the FACET decay volume are $K^0$, via the following decays: $K^0_S \to e^+e^-\pi^+\pi^-$ , $K^0_L \to e^+e^-\pi^+\pi^-$ , $K^0_L \to e^+e^-e^+e^-$, and $K^0_L \to \mu^+\mu^-e^+e^-$. With the expected $K^0$ fluxes FACET will detect such decays, but they will not constitute a background for 4-body decays with $m_{X^0} \gtrsim 0.6$ GeV.

We have also considered pileup of two unrelated neutral-hadron (e.g., $K^0_S$, $\Lambda$) decays, but to be a background to $X^0 \to 4$ hadrons these decays must be superimposed in $x,y,z$, consistent in time, and the apparent "parent" must point back to IP5. In addition, for some of the signals we may veto pair masses compatible with that of a neutral $K^0$ or $\Lambda$. These requirements eliminate the background from pileup.

To summarize, while decays of neutral hadrons inside the vacuum volume will be a major source of background for hadronic decays of LLPs with $m_{X^0} \lesssim 0.8$ GeV, decays to leptons and multihadrons at higher masses should have vanishing backgrounds even in 3 ab$^{-1}$, thanks to 200–

300 $\lambda_{\text{int}}$ of the iron absorber, the vacuum decay volume, high precision tracking, a high-granularity calorimeter, and muon momentum measurement in the toroidal spectrometer.

## 6 Summary

FACET is proposed as a new subsystem for CMS in the high-luminosity LHC era. The primary objective is to search for beyond the standard model long-lived particles decaying in a large vacuum volume, during the high-luminosity LHC phase, corresponding to an integrated luminosity of about 3 $\text{ab}^{-1}$ of proton-proton collisions at $\sqrt{s} = 14$ TeV. The FACET detector requires an enlarged beam pipe section between $z = 101$ and 119 m, followed by high-precision tracking and calorimeter modules using identical technology to the CMS Phase-2 upgrade. These are designed for the high radiation environment expected in the high-lminosity LHC era. The searches can be background-free in many channels, especially for neutral long-lived particles with masses $\gtrsim$1 GeV. FACET will make an inclusive search for dark photons, heavy neutral leptons, axion-like particles, and dark Higgs bosons with a sensitivity defined by their masses and couplings to standard model particles. The couplings must be large enough to give a detectable production cross section in the forward direction, and for the particles to decay to visible states, while small enough for the particles to traverse 35–50 m of iron upstream of the decay volume. FACET will explore a unique area in the parameter space of mass and couplings, largely complementary to other exsiting and proposed searches, yet with some overlap ensuring seamless coverage.

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