FACET

Forward-Aperture CMS ExTension

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Workshop on Feebly-Interacting Particles

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CERN

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Motivation

- The existence of long-lived particles (LLPs), i.e., particles with the proper lifetime $c\tau$ in a macroscopic range, is predicted in many models of physics beyond the standard model (BSM).

LLPs are often present in particle dark matter (DM) models, where they serve as portals between the DM and SM particles.

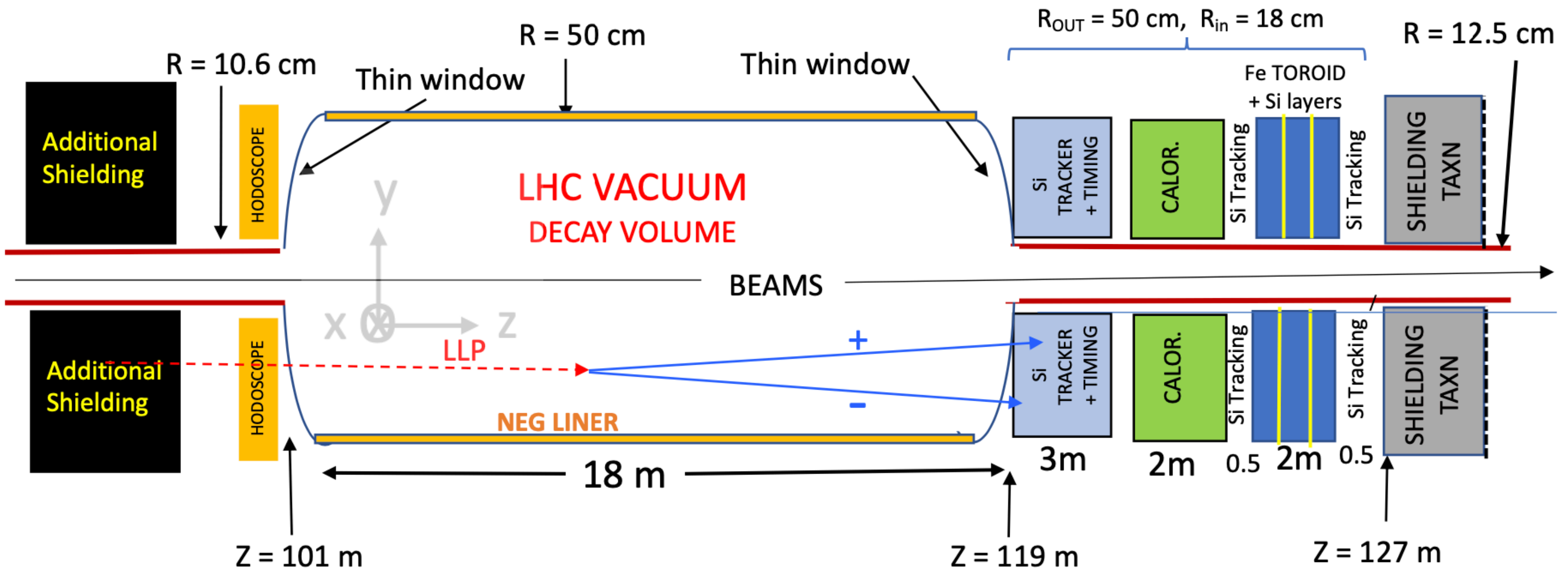
dark photons	heavy neutral leptons
axion-like particles	scalars or dark Higgs particles

- While searches for such particles in the TeV mass range continue at the CERN 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 SM particles.

Motivation

- The proposed new CMS subsystem, FACET can search for many such LLPs depending only on their forward production cross section, momentum, mass m_{X^0} and proper lifetime $c\tau$.
- Longer lifetimes can be probed in the LHC Run 3
- There are several ongoing searches proposals for HL-LHC

FACET Layout

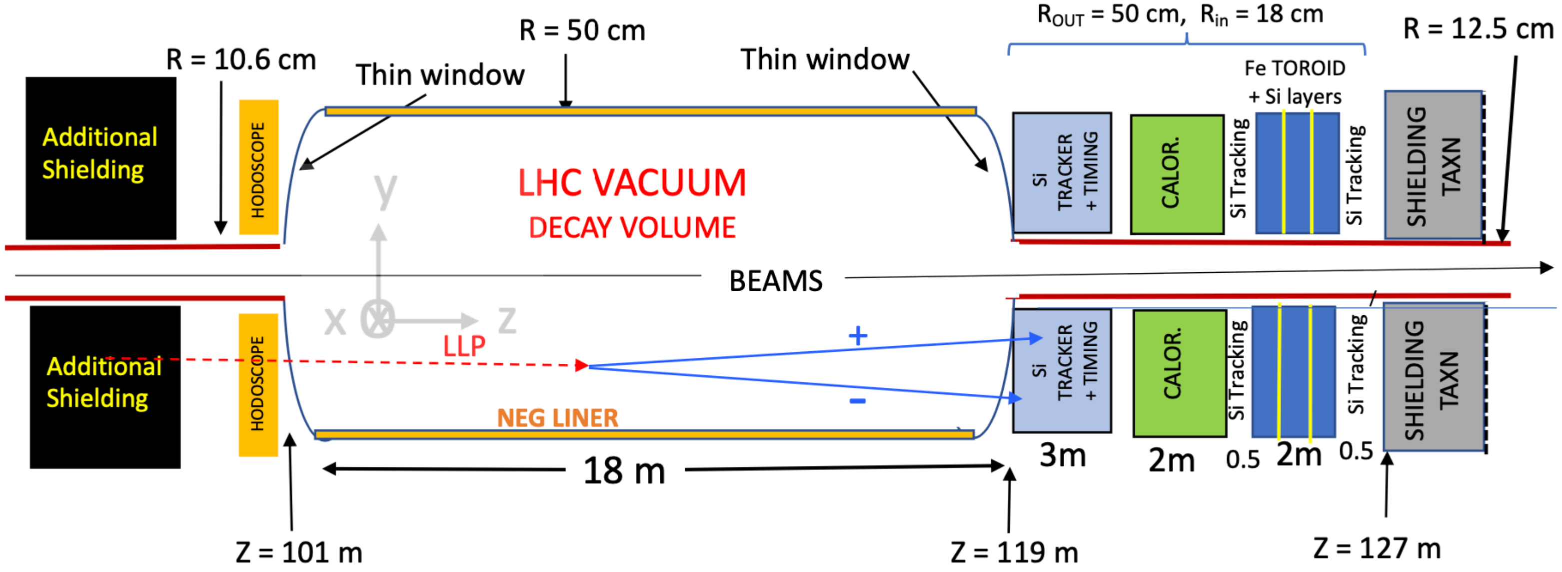


- sensitive to particles produced with polar angle $1 < \theta < 4$ mrad $7.6 > \eta > 6.2$
- LLPs penetrate 50 m iron in LHC magnet, + Additional shielding
- 18 m long decay volume from $z = 101$ to 119 m

  8 m long region instrumented with various particle detectors.
- There are thin ($\sim$2 mm) aluminum convex caps

  — to minimize multiple scattering of the charged particles.

FACET Layout



- precision tracking + high-resolution timing $\sigma_t \sim 30$ ps
- Calorimeter (High-Granularity)
- an iron toroid + silicon tracking

  $B \sim 1.75$ T

LLPs

- In several benchmark scenarios the reach in LLP parameter space has been calculated for

  Dark Photons **Heavy Neutral Leptons**

  Axion-Like Particles **Dark Higgs Bosons**

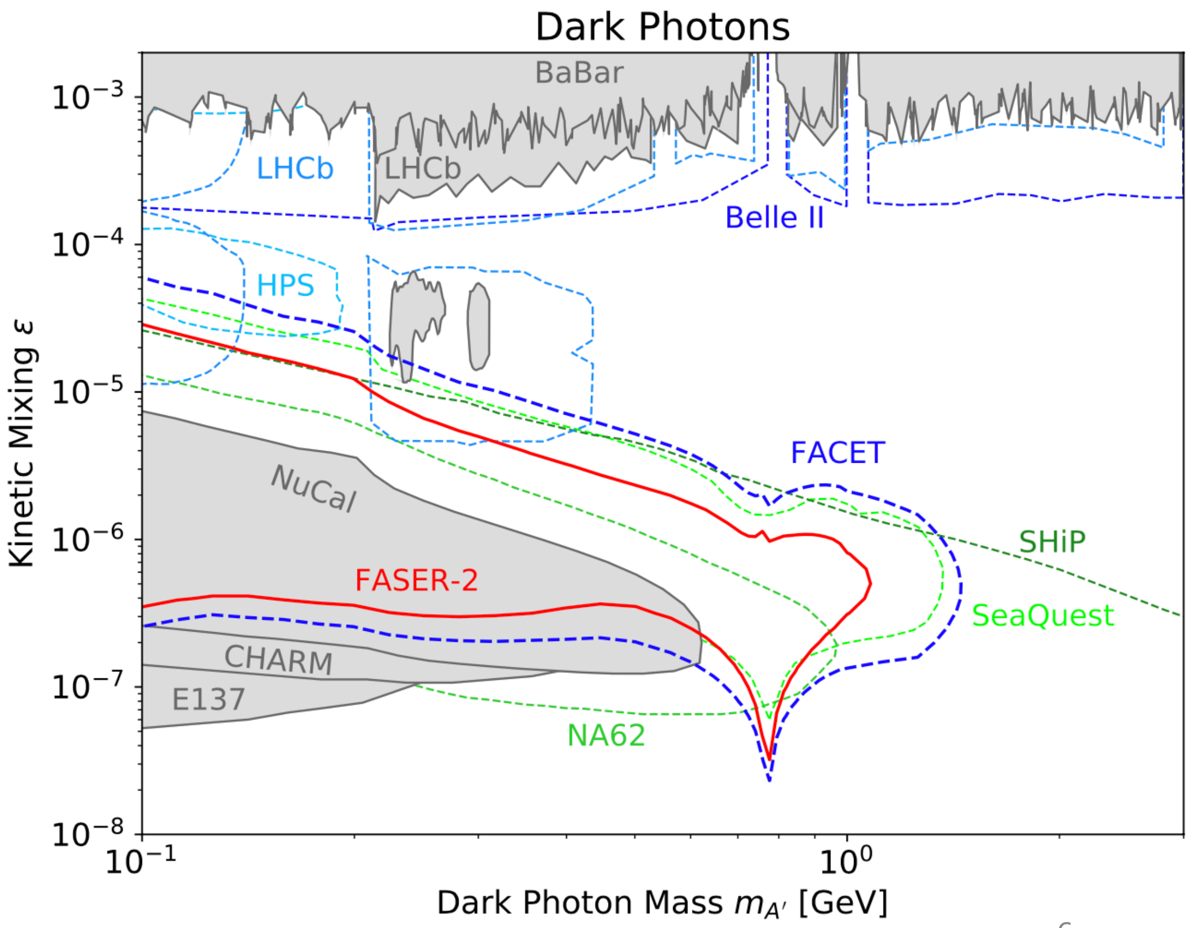
- Predictions
  - generally model dependent
  - depend on the nature of other BSM particles

- Proton - proton collisions at a center-of-mass energy $\sqrt{s} = 14$ TeV
  - total integrated luminosity of 3 ab^{-1}
  - either 3 or 5 candidate events assuming no background and that FACET can detect all penetrating neutral particle decays to ≥ 2 charged particles or photons occurring between $101 < z < 119$ m with the decay products within $18 < R < 50$ cm at $z = 120$ m

Dark Photons

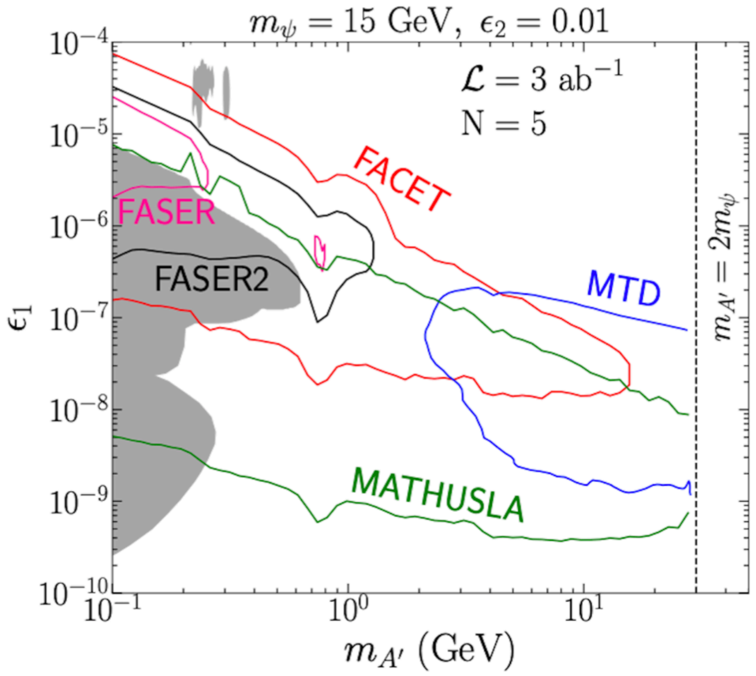
- A massive virtual photon produced by any process in a hadron-hadron collision has some probability of mixing with an A', governed by the kinetic mixing parameter ϵ.

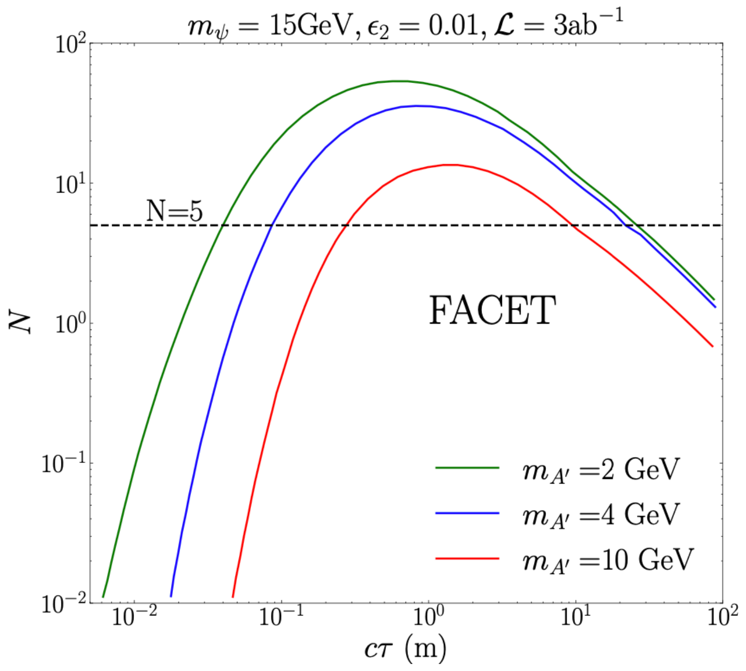
- $m_{A'} \lesssim 1$ GeV
  - The most prolific source will be decays of π^0, η, and η' mesons
  - The fluxes of these particles are highest at small polar angles.
  - FACET reach for dark photons in a generic model with no BSM sources, as calculated with FORESEE



Dark Photons

- The main production mechanisms $m_{A'} > 1$ GeV
  - $q+\bar{q} \to A' + X$
  - bremsstrahlung: $p \to A' + p$ and $q \to A' + q$
  - Drell–Yan: $q+\bar{q} \to A'$
  - heavy-quark decays: $c \to A' + X$, $b \to A' + X$
- A comparison of the FACET and other experiments dark photon reach for all final states in the model of M. Du et al.
  - Figure (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 (left)





Heavy Neutral Leptons

- The most important reason to add heavy neutral leptons to the SM is to explain the neutrino oscillations since they provide an elegant way to generate nonzero neutrino masses via the seesaw mechanism

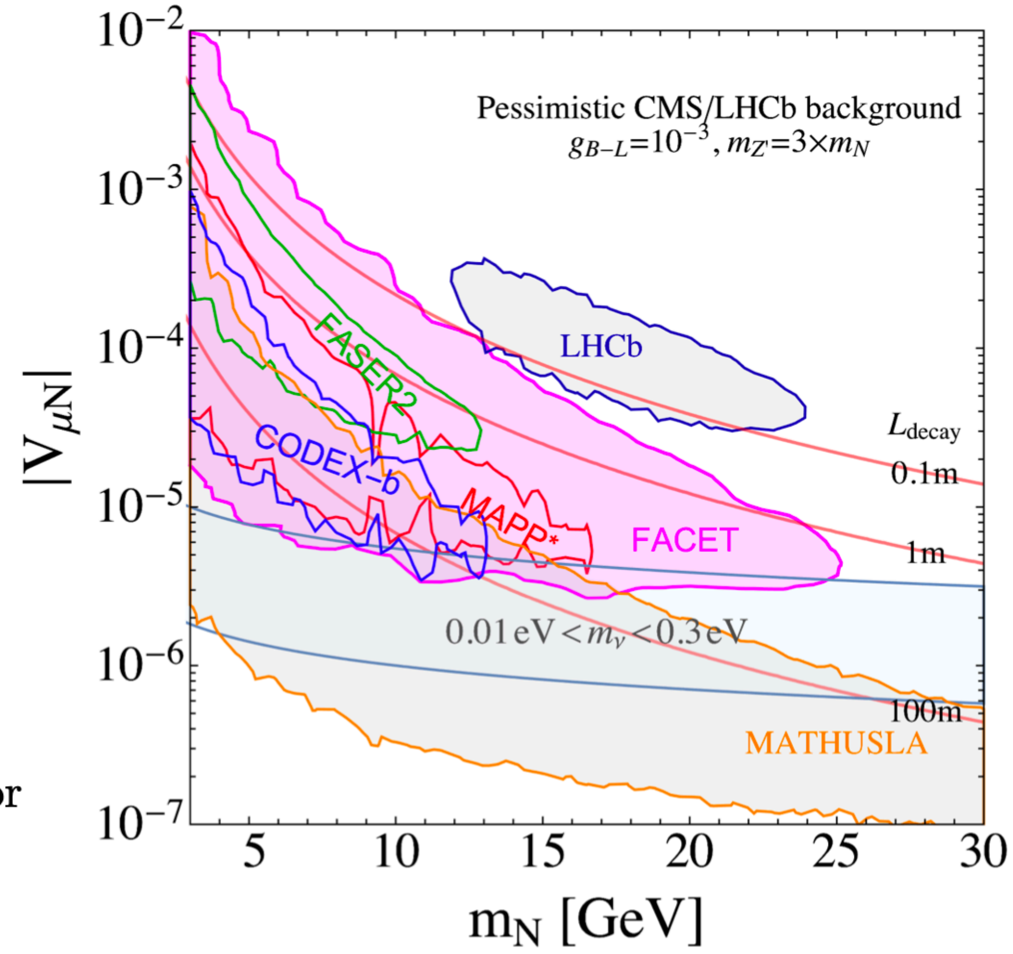
- Many extensions of the SM involve heavy right-handed neutrinos or heavy neutral leptons N_i may explain the light neutrino masses

- a specific extension of the SM with a Z' boson and three heavy right-handed Majorana neutrinos N_i is considered

$$Z' \to N_i N_i$$

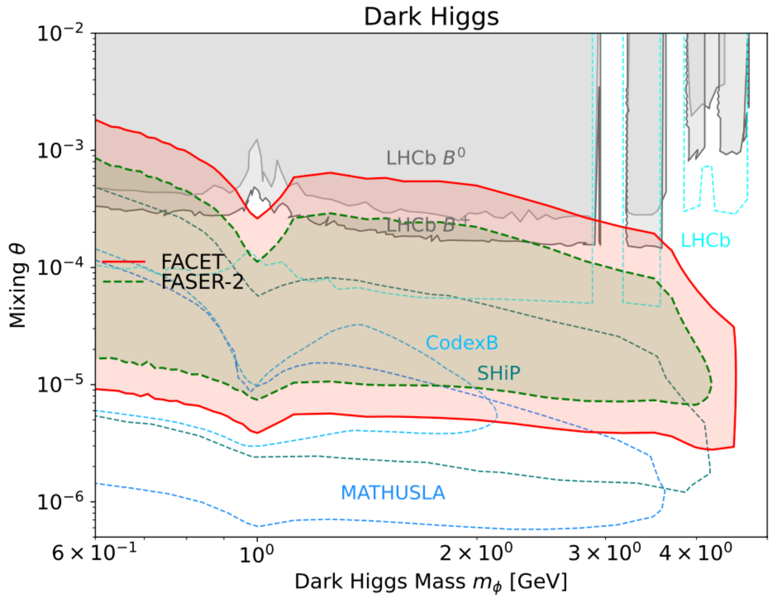
- Figure shows the coverage in the mixing parameter $|V_{\mu N}|$ vs. m_N plane in the case of a single Majorana neutrino N mixed with a muon neutrino.

- FACET has a unique sensitivity at high masses, above ~15 GeV for lifetimes $c\tau$ between ~0.1 and ~100 m.

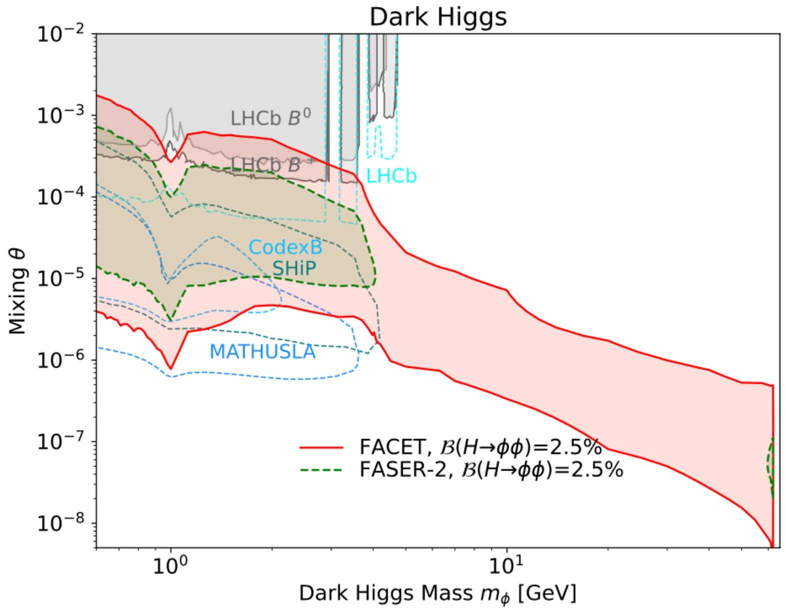


Dark Higgs Boson

- A dark Higgs field provides a simple mechanism to give mass to the dark photon A'.
- The dark Higgs boson can be very long-lived due to its suppressed couplings to the accessible light SM states.
- The reach of FACET for a dark Higgs boson decaying to a detectable final state is given in Fig.
- 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



B meson decays



$H(125)\to\phi\phi$ decay

Backgrounds

- FACET is unique among all LHC LLP search proposals in having a very large volume of LHC-quality vacuum for decays.
- Our goal is to have no background events even with 3 ab^{-1} of integrated luminosity in many decay channels
- The direct path from the collision region to the decay volume has 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.
- Neutral hadrons (K^0 and Λ^0) 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 region and using the decay position information will reduce this neutral hadron background

Backgrounds

- 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 λ_{int} of iron absorber in LHC magnets
  - the vacuum decay volume
  - high precision tracking
  - a high-granularity calorimeter
  - and muon momentum measurement in the toroidal spectrometer.

Triggers

- 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 FACET trigger could also be run in a standalone mode
  - with only FACET information saved, and without correlating with the central CMS detector.
- For any low-pileup LHC runs, with proton, as well as with ion beams, a different set of triggers will be prepared.

Summary

- FACET is proposed as a new subsystem for CMS in the high-luminosity LHC era.
  - a 30-50 m magnetic iron shielding
    - which reduces almost all charged SM backgrounds
  - a "tagger" a multi-layer radiation-hard scintillation / quartz hodoscope,
    - to tag charged particles that would help to reject them in the trigger
  - a big vacuum tank with the LHC quality, (18 m long and 1 m diameter pipe)
    - no interaction background
    - A high quality vacuum will be crucial for background reduction by requiring a decay vertex in the LHC quality vacuum
  - a CMS upgrade quality tracking including timing information
  - a high granularity calorimetry for electromagnetic and hadronic showers
  - a magnetic toroid muon spectrometer with silicon tracking

Conclusion

- The main purpose is to search for BSM LLP decaying in a large vacuum volume, during the high-luminosity LHC phase, corresponding to an integrated luminosity of about 3 ab^{-1} of pp collisions at $\sqrt{s} = 14$ TeV.

- 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 searches can be background-free in many channels, especially for LLPs with mass > 0.8 GeV

- FACET will explore a unique area in the parameter space of mass and couplings, largely complementary to other existing and proposed searches.

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

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thanks

FOR ATTENTION

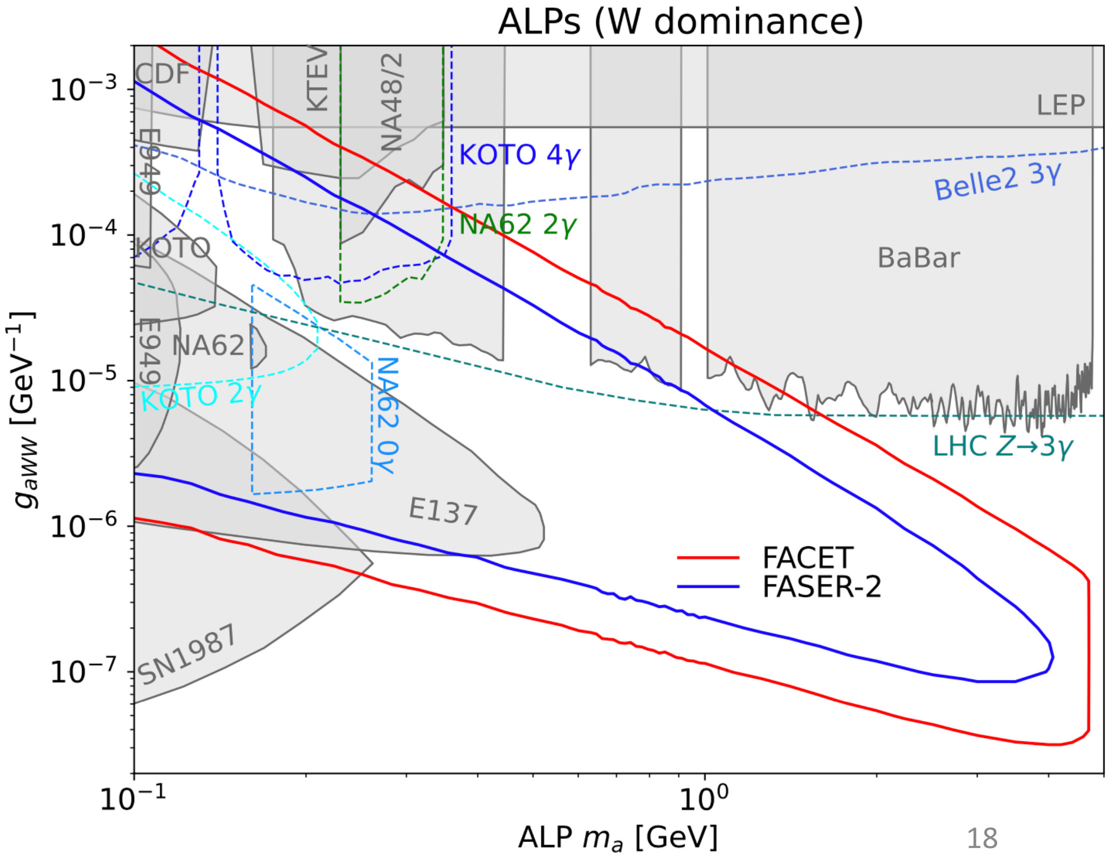
BACK UP

Axion-Like Particles

- Axion-like particles (ALPs) are hypothetical pseudoscalar bosons that appear naturally in many extensions of the SM More massive ALPs may exist
  - if produced at the LHC they may decay with long lifetimes into photon pairs 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.

- FACET reach for ALPs is given in Fig. in a specific W-dominance ALP model as a function of the ALP mass and the coupling to W bosons.



Backgrounds

- 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.
  - This background will be eliminated by charged-particle tagging in the upstream hodoscope, and precision vertexing.

- 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 π^0, η, and η' meson decays, as well as from $K_S^0 \to \pi^0\pi^0$ decays.
  - The electromagnetic section of the calorimeter measures both the shower directions and the distance of closest approach of the two photons.
  - 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