FACET
(Forward-Aperture CMS ExTension)

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Search for long-lived particles at the LHC and beyond
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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 BSM.

- Generally, LLPs are naturally expected in models with small mass splitting between the adjacent states or with suppressed couplings to SM particles.

- In particular, 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

Motivation

- Searches for such particles in the TeV mass range continue at LHC, however the possibility that new particles may be relatively light ($\lesssim 25$ GeV), and yet have escaped detection so far.

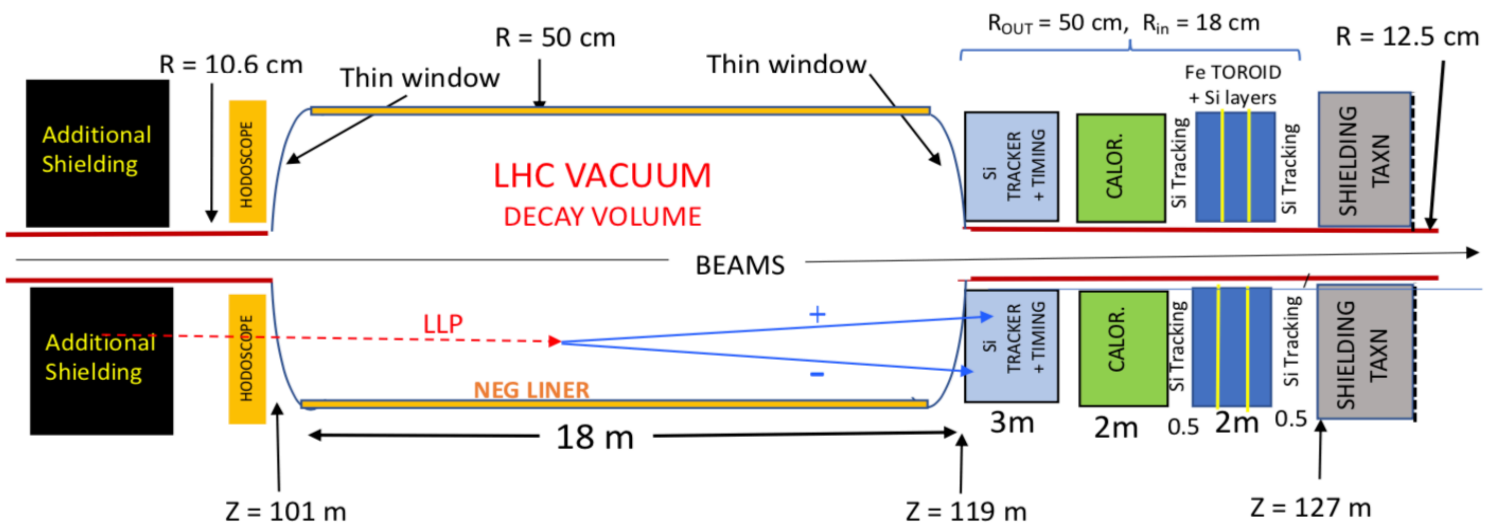
- FACET, can search for such LLPs, depending only on their forward production cross section, momentum, mass m_{χ^0}, and proper lifetime $c\tau$.
  - Direct path from IP to detectors is through 35m – 50m of iron absorber (magnets etc.)
  - covers a range of proper lifetimes $c\tau$ of ~0.1–100 m.
  - Full luminosity (HL) ~ 140/X and 3 ab^{-1}

- Aim is to have the precise reconstruction of decay vertices in the vacuum, to eliminate background from interactions.
  - have almost zero background even at HL-LHC era in many channels, in which case even a few events would be a discovery!

FACET Layout

FACET (**F**orward-**A**perture **CMS** **E**x**T**ension)

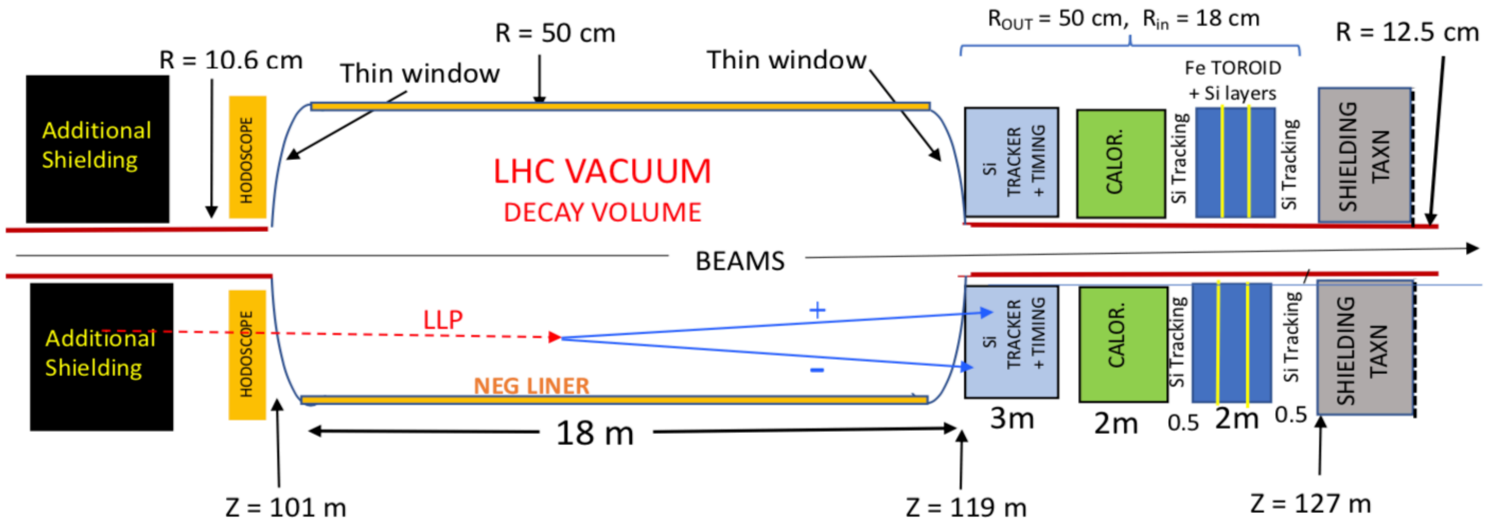
- is a new subsystem of the CMS experiment (not proposed to be a new experiment)
- will be sensitive to particles produced with polar angle $1 < \theta < 4$ mrad ($7.6 > \eta > 6.2$).
- has an 18 m long decay volume from z = 101 to 119 m on one side of the IP5 collision region
  - and another 8 m long region instrumented with various particle detectors.



FACET Layout

FACET (**F**orward-**A**perture **CMS** **E**x**T**ension)

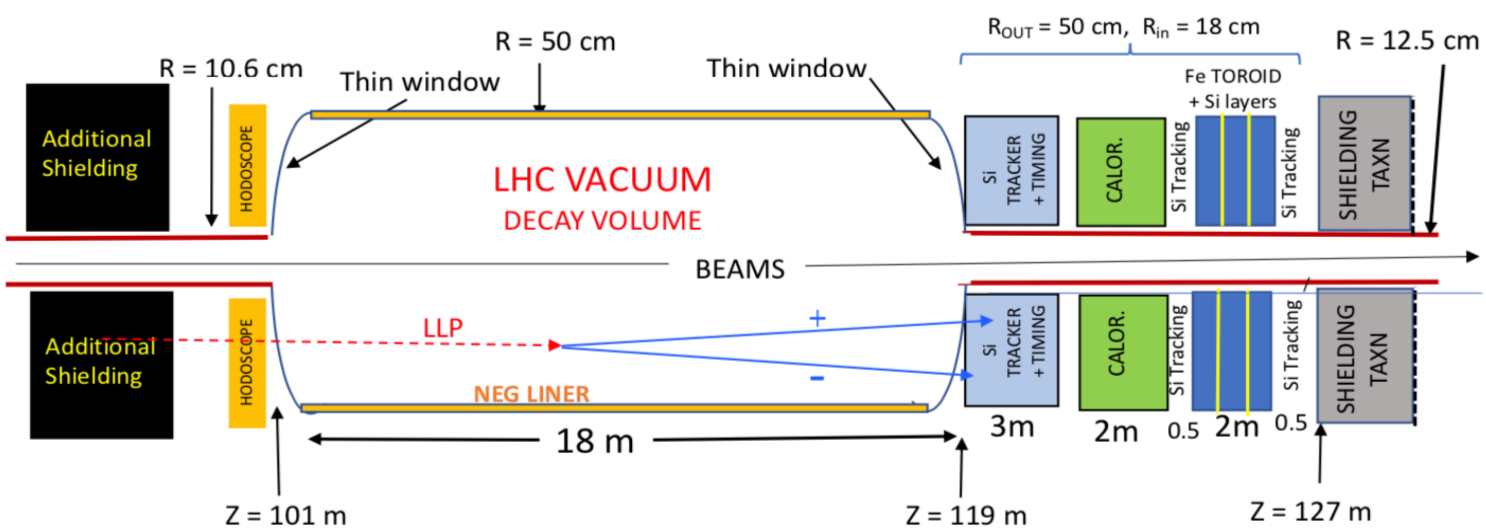
- Additional shielding will be placed upstream of the first detector, which is a two-layer counter hodoscope made of radiation-hard quartz blocks.
- On both ends of the enlarged beam pipe, (from R = 50 to 12.5 cm), there are thin (~2 mm) aluminum hemispherical caps
  - to minimize multiple scattering of the charged particles
  - mitigate the impedance mismatch



FACET Layout

FACET (**F**orward-**A**perture **CMS** **E**x**T**ension)

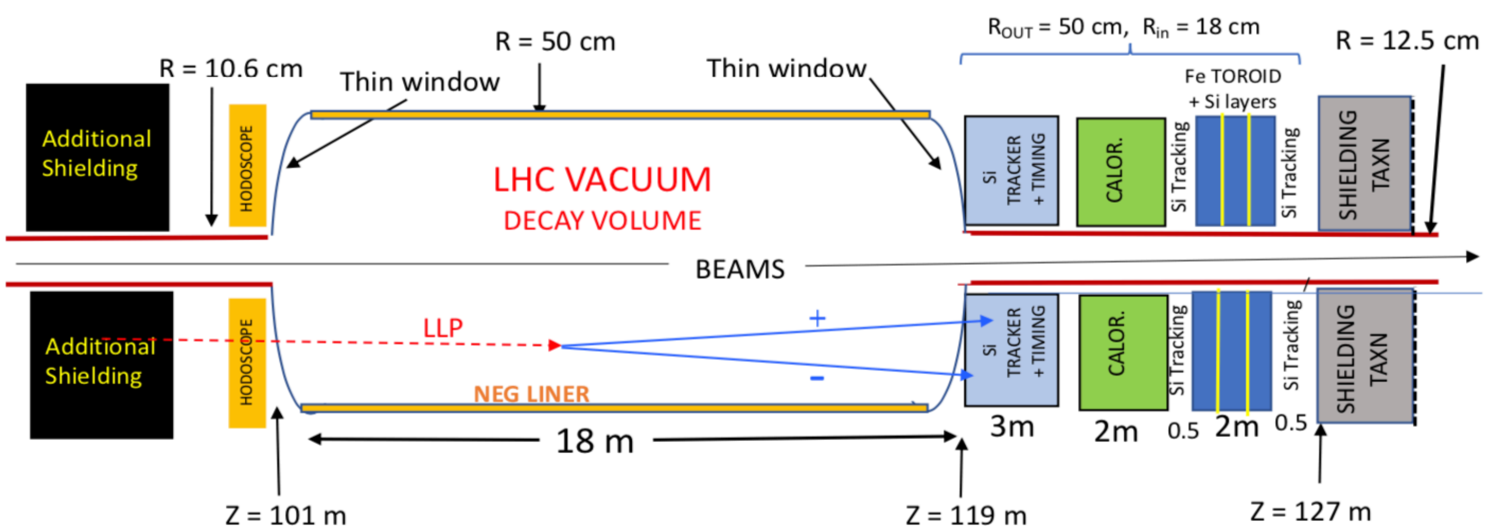
- Precision tracking
  - Silicon tracking detectors measure charged particle tracks, followed by an EM and Hadron calorimeter to measure the energies of electrons, photons and hadrons.
- Iron toroid (B ~ 1.75 T) instrumented with additional silicon tracking
  - measures the charge of muons and allows an approximate measurement of the muon momentum and the dimuon mass for any muon pairs.



FACET Layout

FACET (**F**orward-**A**perture **CMS** **E**x**T**ension)

- A layer of fast timing with low-gain avalanche detectors will be included.
  - This high-resolution timing, with σ_t ~ 30 ps, will provide vertex positioning in 4D (x,y,z,t) and a time-of-flight measurement for charged particles
- High-granularity electromagnetic and hadron calorimetry,
  - identical technology to the CMS HGCAL are also included.



LLP at FACET

FACET (**F**orward-**A**perture **CMS** **E**x**T**ension)

- The reach in LLP parameter space has been calculated for
  - dark photons,
  - heavy neutral leptons,
  - axion-like particles,
  - dark Higgs bosons in several benchmark scenarios.

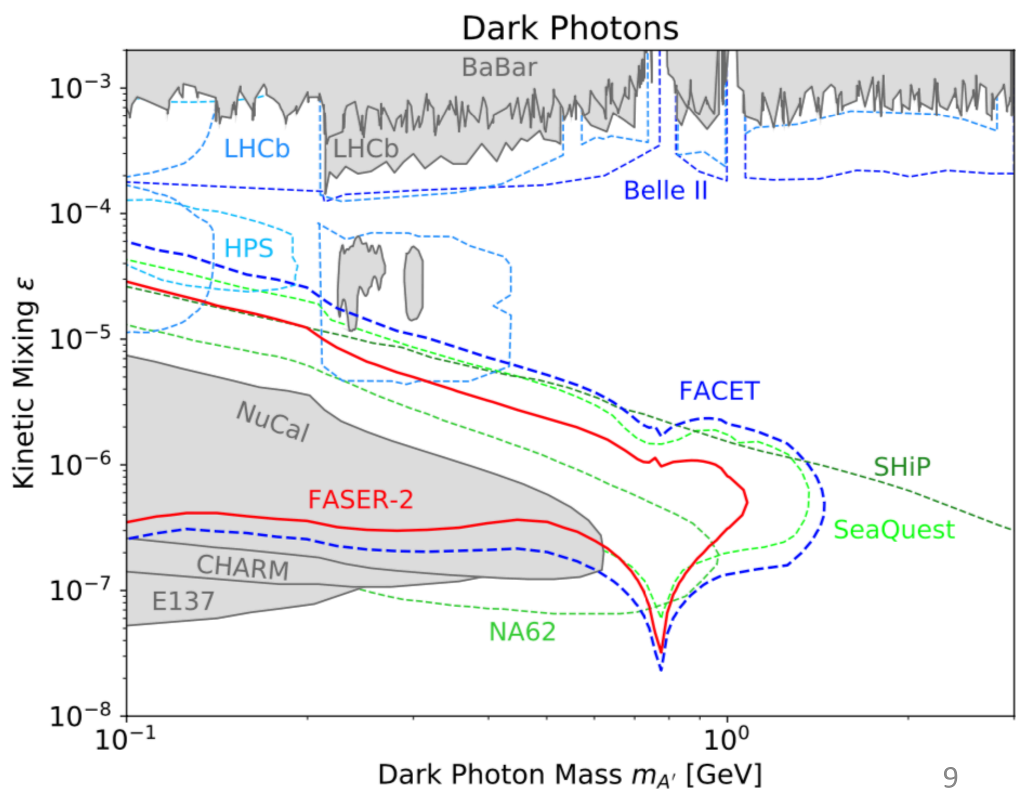
- Predictions are generally model dependent, and some also depend on the nature of other BSM particles

- A total integrated luminosity of 3 ab^{-1} of pp collisions at a $\sqrt{s} = 14$ TeV
  - with either 3 or 5 candidate events, assuming no background and that FACET can detect all penetrating neutral particle decays to ≥ 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'

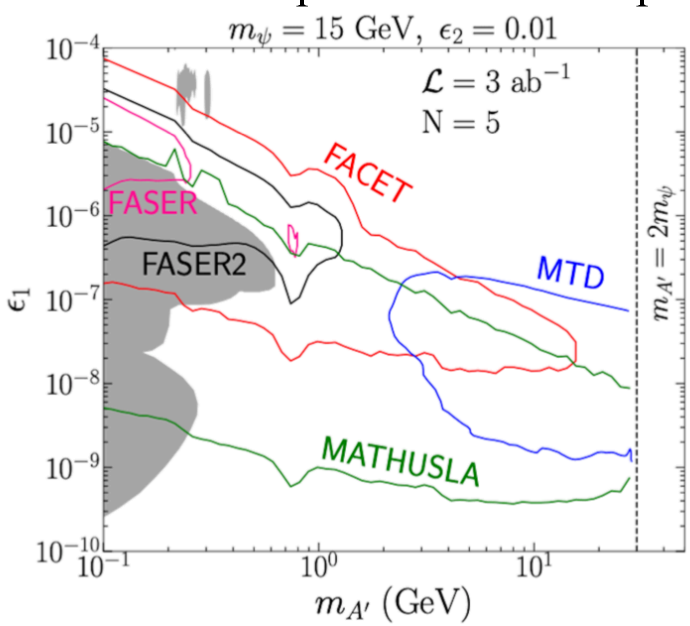
- Massive dark photons A′ are neutral gauge bosons can interact with SM particles via mixing with photons.
- A massive virtual photon produced by any process in a hadron-hadron collision has some probability of conversion to an A′.

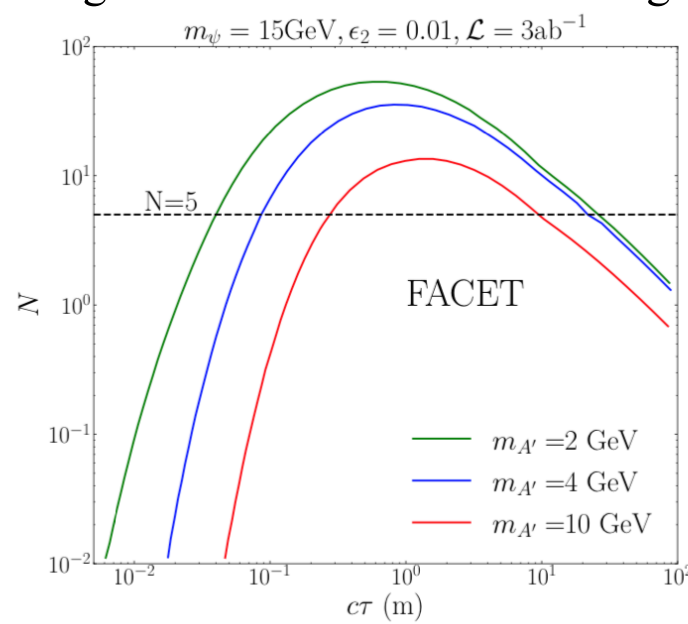
- If $\mathbf{m_{A'}} \lesssim$ **1 GeV**, the most dominant source will be decays of $\boldsymbol{\pi^0}$**, η,** and **η′ mesons**.
    - The fluxes of these particles are highest at small polar angles.
- Right figure shows limits calculated using `FORESEE` without assuming any other BSM sources of dark photons



Dark Photons, A'

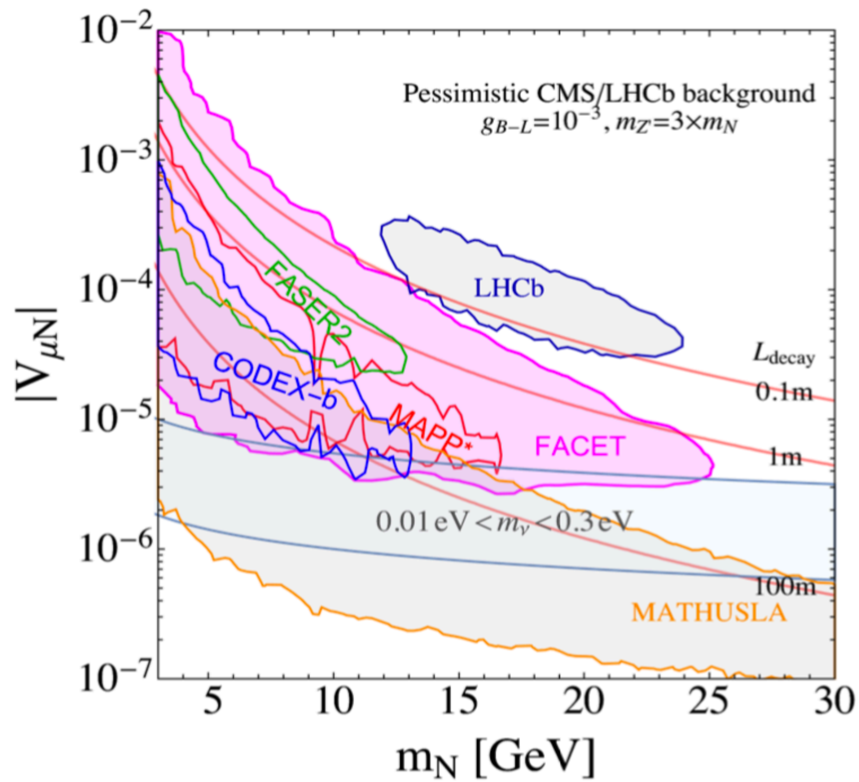
- For $\mathbf{m_{A'} > 1GeV}$ the main production mechanisms are:
  - $q + \bar{q} \rightarrow A' + X$
  - Drell–Yan: $q + \bar{q} \rightarrow A'$
  - bremsstrahlung: $p \rightarrow A' + p$ and $q \rightarrow A' + q$
  - heavy-quark decays: $c \rightarrow A' + X$, $b \rightarrow A' + X$
- A comparison of the FACET and other experiments dark photon reach in a specific model with a heavy Z' (Model of Du, Fang, Liu)
  - Right figure 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 left figure.





Heavy Neutral Leptons

- Many extensions of the SM involve heavy right-handed neutrinos or heavy neutral leptons N_i – may explain the light neutrino masses through the seesaw mechanism.
- A specific extension of the SM, with a Z' boson and three heavy right-handed Majorana neutrinos N_i, is considered. (Model of Deppisch, Kulkarni, Liu)
  - $Z' \to N_i N_i$



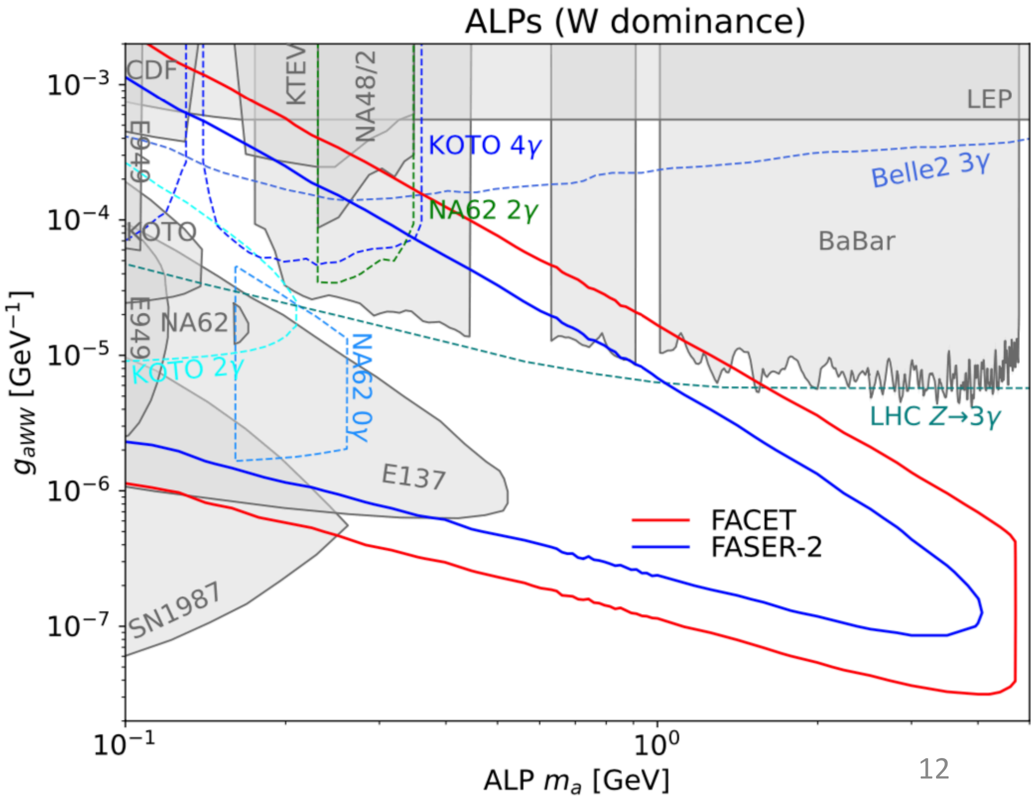
- Right figure shows the coverage in the mixing parameter $|V_{\mu N}|$ vs. m_N plane in the case of a single Majorana neutrino N mixed with a muon neutrino.
- **FACET** has a **unique sensitivity** at high masses, above ~15 GeV for **lifetimes $c\tau$ between ~0.1 and ~100 m**

Axion-Like Particles

- More massive axion-like particles (ALPs, a) may exist
  - if produced at the LHC, they may decay with long lifetimes into photon pairs or lepton pairs, after penetrating thick absorbers.
  - EM part of HGCAL has high granularity and measures the direction of photon showers, but vertexing much worse than for charged tracks

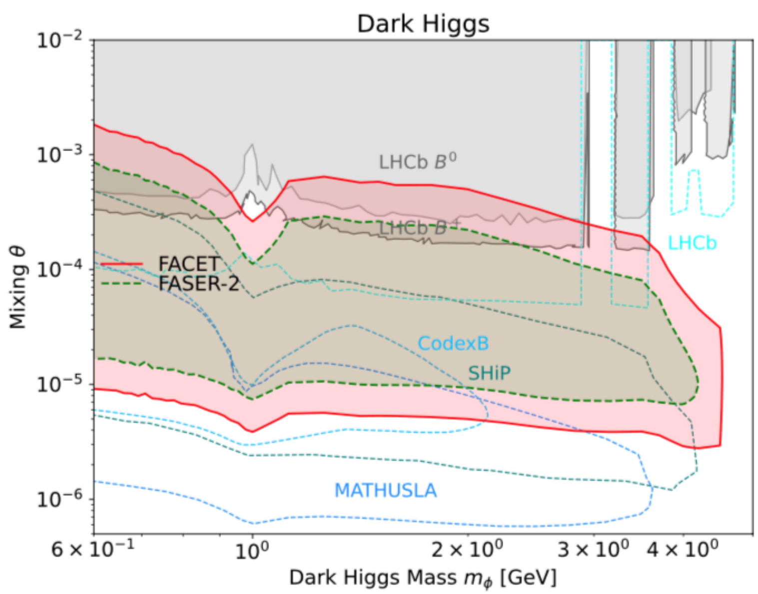
- <u>FACET will be well-placed to discover such ALPs</u> in certain regions of their mass and the coupling to SM gauge bosons.

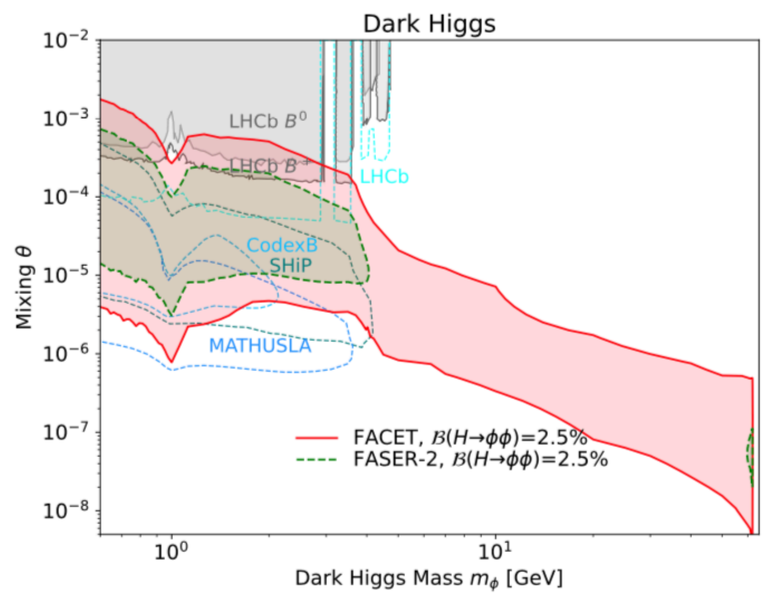
- FACET reach for ALPs is given in the right figure in a specific W-dominance ALP model, as a function of the ALP mass and the coupling to W bosons



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 below figure.
  - B meson decays (left plot) & the H(125) → $\phi\phi$ decay (right plot)
- FACET offers a unique sensitivity for the dark Higgs boson masses up to the kinematic limit of $m_H/2$





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 the iron absorber,
  - the vacuum decay volume,
  - high precision tracking,
  - a high-granularity calorimeter,
  - muon momentum measurement in the toroidal spectrometer.

Conclusion

FACET (**F**orward-**A**perture **CMS** **E**x**T**ension)

- 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” hodoscope, a multi-layer radiation-hard scintillation counter
    - 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, hadronic calorimeters
  - a magnetic toroid muon spectrometer with silicon tracking

Conclusion

FACET (**F**orward-**A**perture **CMS** **E**x**T**ension)

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

Conclusion

Paper has been accepted for publication in JHEP!

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

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Conclusion

- Theorists and phenomenologists: Please include the FACET physics reach in your publications.
- Letter of Intent to CMS is under development!
  - to be built by Run4 (2028)
- The studies for the detailed detector layout as well as physics simulations establishing FACET reach during the HL-LHC period are ongoing
- Interested members of CMS – and theorists – are welcome to join in!
  - We have biweekly meetings on Wednesdays at 19:00 CERN-time.

Thank you for your attention!

Backup

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.
- Since many bunch crossings will then have only a single interaction, correlations between leading charged hadrons and the central event can be studied.

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, Λ^0) from showers in absorbers 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 their decay tracks measurements and their energies.
  - 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

- A potential background in the $X^0 \rightarrow l^+l^-$ 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 $X^0 \rightarrow \gamma\gamma$, 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.
  - 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.