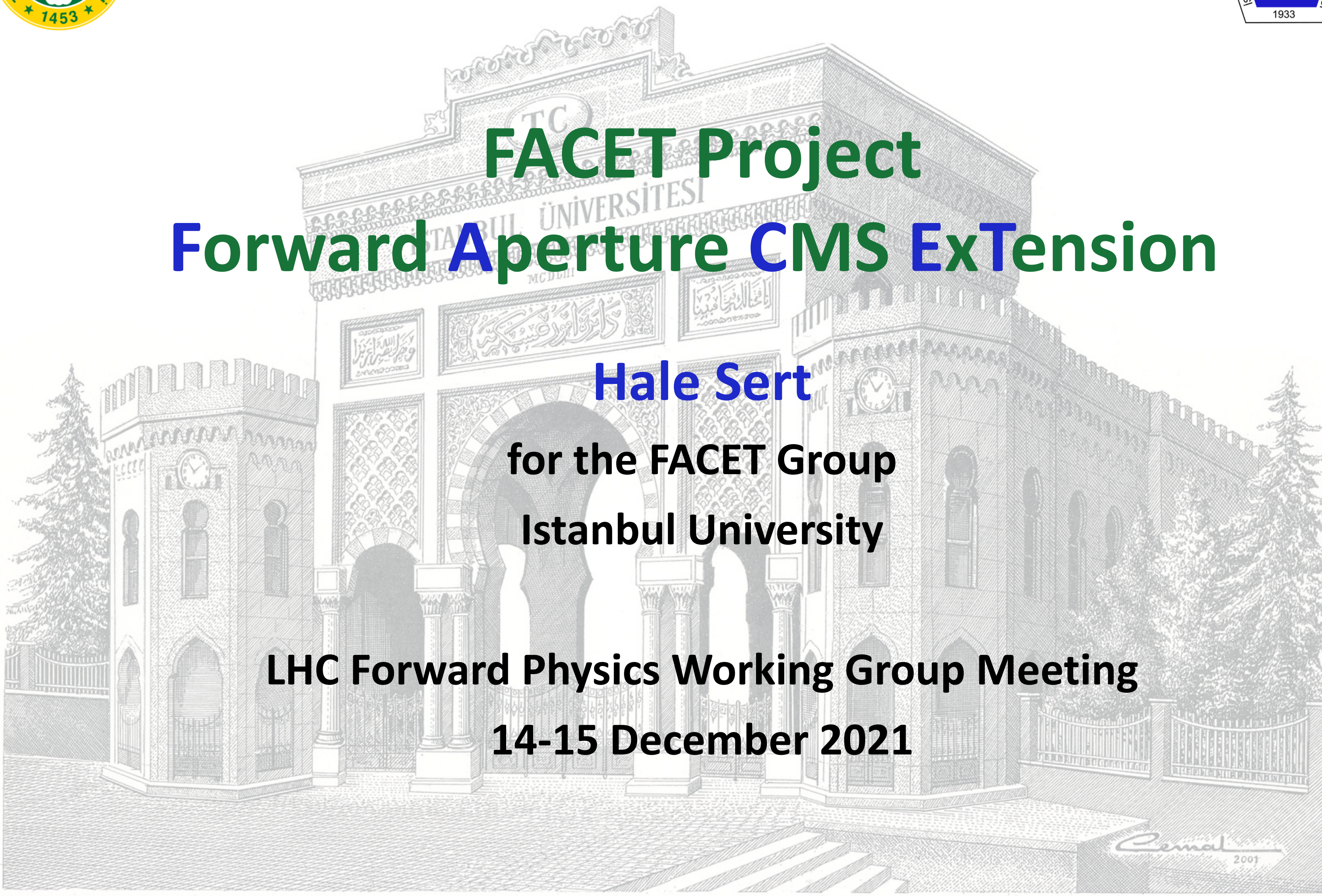


FACET Project

Forward Aperture CMS ExTension

Hale Sert

for the FACET Group

Istanbul University

LHC Forward Physics Working Group Meeting

14-15 December 2021

What is FACET?

- It is a new detector proposed to be built as a subsystem of the CMS
  - for the HL-LHC data taking period, $3\ \mathrm{ab}^{-1}$
- It is a detector designed to be built in the very forward region
  - η coverage: $6.2 < \eta < 7.6$, i.e polar angle: $1 < \theta < 4$ mrad
- It will search for the physics beyond the SM, long lived particles (LLPs).

What is FACET?

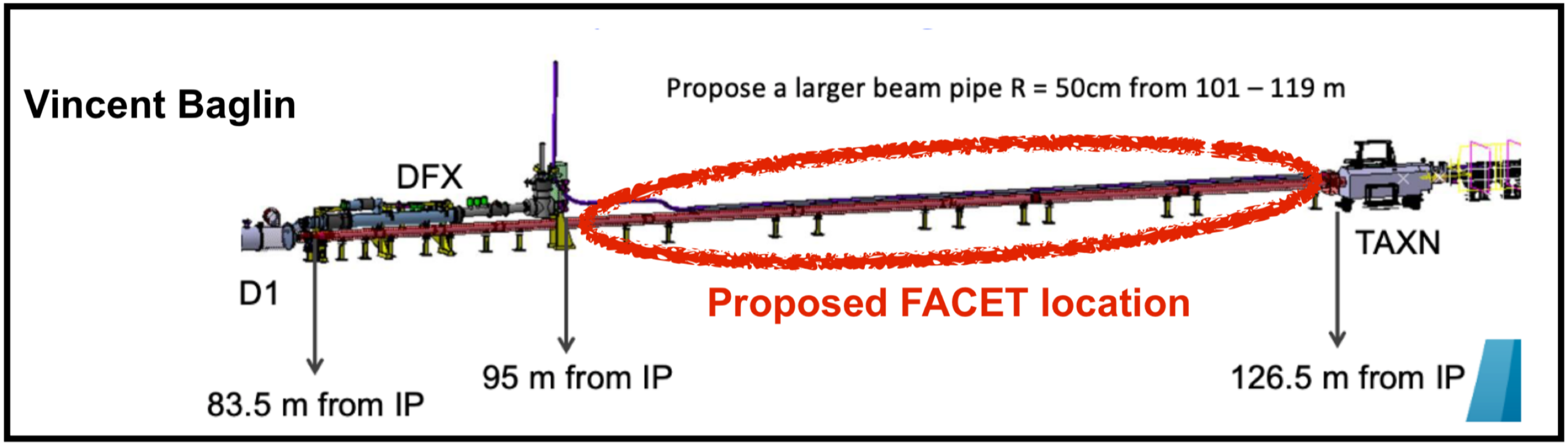
- It is a new detector proposed to be built as a subsystem of the CMS
  - for the HL-LHC data taking period, $3\ \mathrm{ab}^{-1}$
- It is a detector designed to be built in the very forward region
  - η coverage: $6.2 < \eta < 7.6$, i.e polar angle: $1 < \theta < 4$ mrad
- It will search for the physics beyond the SM, long lived particles (LLPs).

Outline

- In which part of the CMS/HL-LHC will it be built?
- What will be the design of the FACET?
- What are the physics motivations of proposing such a detector?
- What is the status of the project?

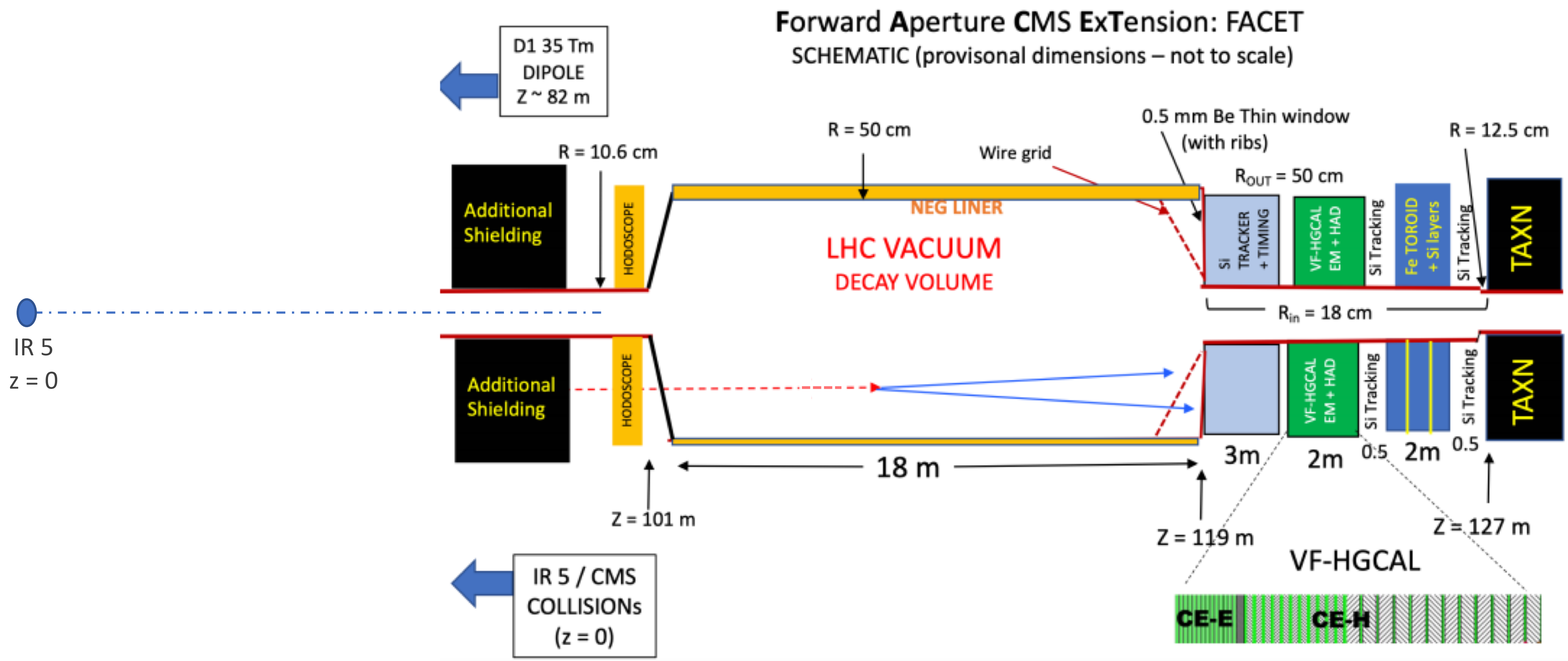
FACET Location

- It will be built +100 m away from the interaction point, IP5 (on one side of CMS)
- New subsystem for CMS in region
  - between **dipole D1 magnet** and **TAXN**
- FACET will have L = 18 m long decay volume
  - from z = 101m to 119m
  - followed by an 8 m region instrumented with various particle detectors.



FACET Design

- Enlarging beam pipe from R =10.6 cm to R = 50 cm within 101 < z < 119 cm
- Shielding by about 30-50 m (300 λ_{int}) of iron from HL-LHC magnets
- Hodoscope: a multi-layer radiation-hard scintillation counter(tag charged particles)
- High resolution tracking ($\sigma_{x,y} \approx$ 30 μm over 2 m) with timing ($\sigma_t \approx$ 30 ps) information
- High Granularity Calorimeters HGCAL will be used with timing information



Motivations

Search for new Beyond the Standard Model particles, **Long-Lived Particles (LLPs)**

- The LLPs should penetrate 35-50 m iron & decay in vacuum
  - Masses up to ~ 25 GeV can be searched for (multiparticle decays)
  - Long lifetimes: unboosted lifetimes up to $c\tau$ = 0.1 m – 10 m can be studied
  - Full luminosity (HL) ~ 140/X and 3 ab^{-1}

- A key feature of this proposal is the precise reconstruction of decay vertices in the vacuum, to eliminate background from interactions.

- The goal is to have almost zero background even at HL-LHC era in many channels, in which case even a few events would be a discovery!

Physics Reach of the FACET

New Beyond Standard Model particles

- High mass searches at LHC – nothing found yet
- Might be light (< 50 GeV) but with small coupling to SM particles (neutral particles coupling to the SM and DM particles)
    - dark photons,
    - heavy neutral leptons,
    - axion-like particles, and
    - scalars or dark Higgs particles

- **Small couplings** => **long lifetimes :** searches for LLPs that can manifest as displaced vertices

LLPs can be probed by experiments:

- FASER (Run 3) in the beam direction at a distance z = 480 m from the IP
- MATHUSLA (proposed exp. For HL-LHC)
- CODEX-b (proposed exp. For HL-LHC) (?)
- FASER-2 (proposed exp. For HL-LHC)
- NA62 (fixed target experiment at the CERN SPS)

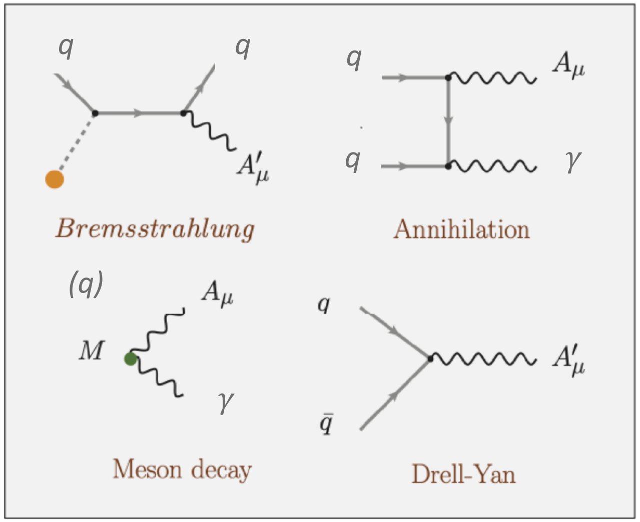
Dark Photons, A'

- $\boldsymbol{A'}$:massive, new neutral gauge bosons that do not have SM interactions.
  - However, they can mix kinetically with the SM photons.
- A massive virtual photon produced in pp collisions has some probability of conversion to an $\boldsymbol{A'}$.

Two scenarios based on the mass of $\boldsymbol{A'}$:

- **For $\boldsymbol{M(A') \leq 1}$ GeV,** the most dominant sources
  - decays of π^0, η^0or η' mesons.

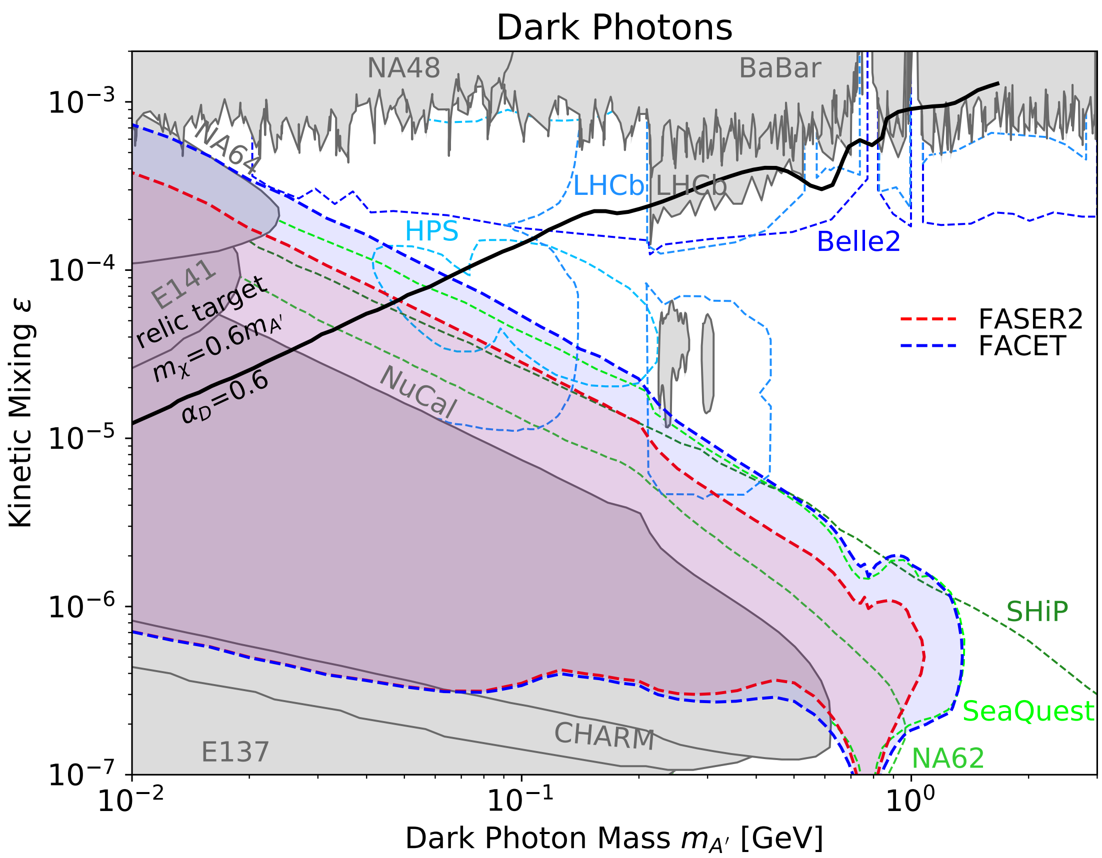
  (The fluxes are highest at small polar angles)
- **For $\boldsymbol{M(A') > 1}$ GeV,** the main sources are:
  - $q + \bar{q} \rightarrow A' + X$
  - Drell-Yan : $q + \bar{q} \rightarrow A'$
  - Bremsstrahlung (q → q + A' & p → p + A')
  - Heavy quark decay :$c/b \rightarrow A' + X$



Adapted from Fabbrichesi, Gabrielli, Lafranchi
Dark Photon Review arXiv:2005.01515 [hep-ph]

Dark Photons, A'

- An inclusive study with the mentioned production and decay processes



$M(A') <$ a few GeV

Generated using "FORESEE"
arXiv:2105.07077 [hep-ph]

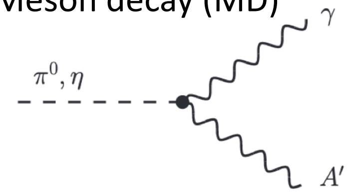
- FACET sensitivity competes with the fixed target experiments at low mass!

Dark Photons, A':

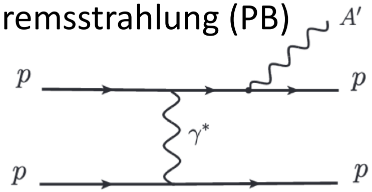
arXiv:2111.15503v1 [hep-ph]
M. Du, R. Fang, Z. Liu and V. Q. Tran

- New vector boson $\mathbf{Z'}$ + dark photon $\boldsymbol{A'}$ + hidden sector fermion $\boldsymbol{\psi}$ – dark matter candidate
- In the considered model, dark photon can be produced in 3 main processes:

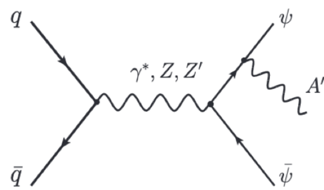
Meson decay (MD)



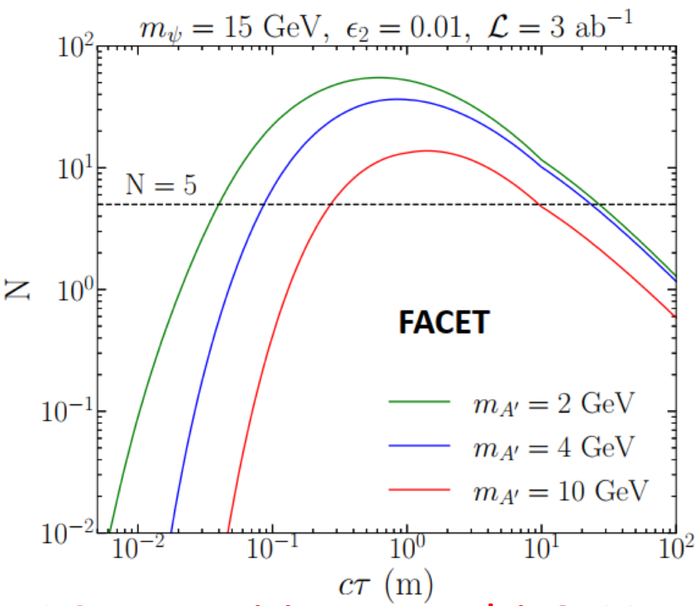
Proton bremsstrahlung (PB)

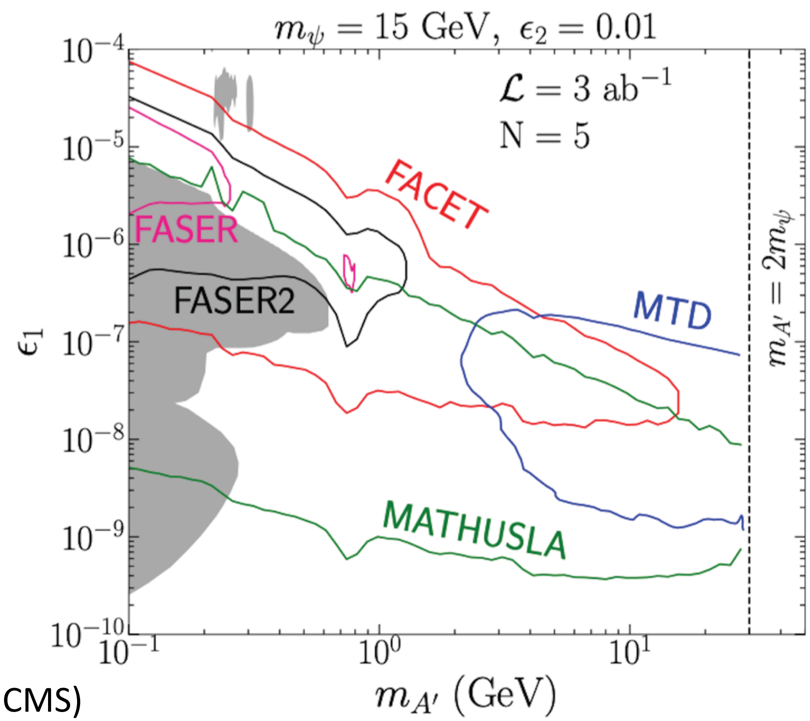


Hidden sector radiation (HR)



- $\boldsymbol{A'}$ decays to
  - leptons, l^+l^- (e, μ, τ) or
  - hadrons





- FACET sensitive to multi-GeV mass region

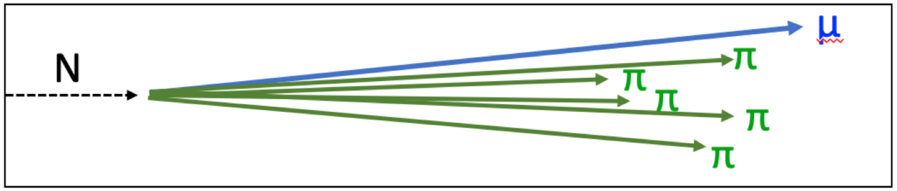
between FASER2 and MTD (MTD: MIP Timing Detector in CMS)

Heavy Neutral Leptons (HNL or N_i)

- Extensions of the SM involving heavy right handed neutrinos (N_i) or HNLs
  - may explain the light neutrino masses through the seesaw mechanism
- In the studied model, $U(1)_{B-L,}$ there is a Z' boson and 3 additional RH neutrinos
  - $Z' \rightarrow N_i N_i$

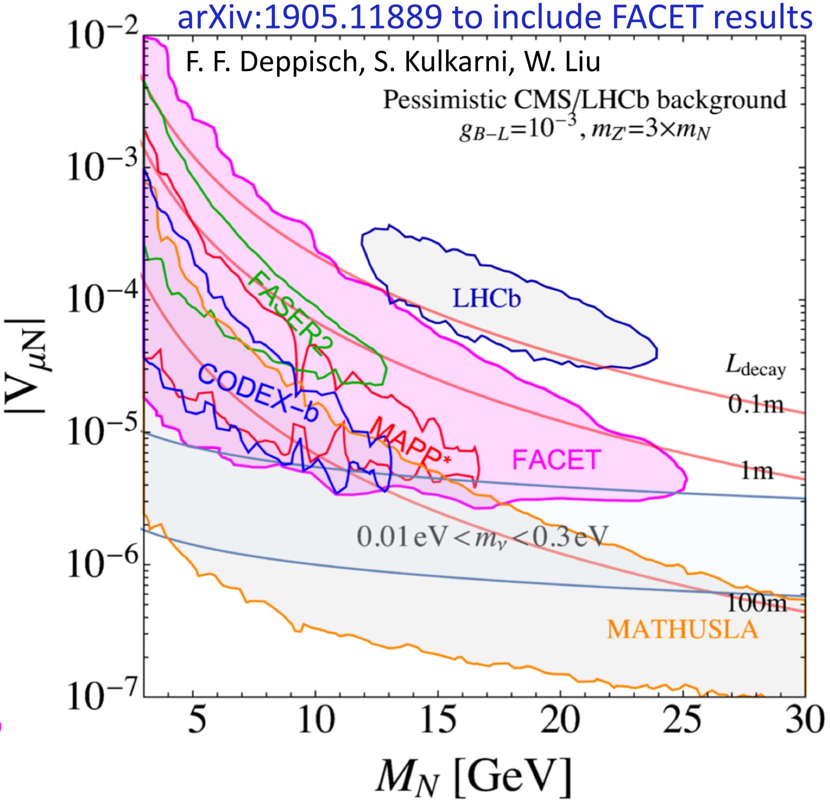
where

$N \rightarrow l^{\pm} q\bar{q}$ and $N \rightarrow l^{+} l^{-} \nu_l$ via $W^{\pm(*)}, Z^{(*)}$,
with $l = e, \mu, \tau$



- Such a 6-prong event would have no background. The contours correspond to 3 events in 3 ab^{-1}.
- Comparison of HNL reach with other experiments (only LHCb is approved now)
- FACET shows a discovery reach up to ~25 GeV

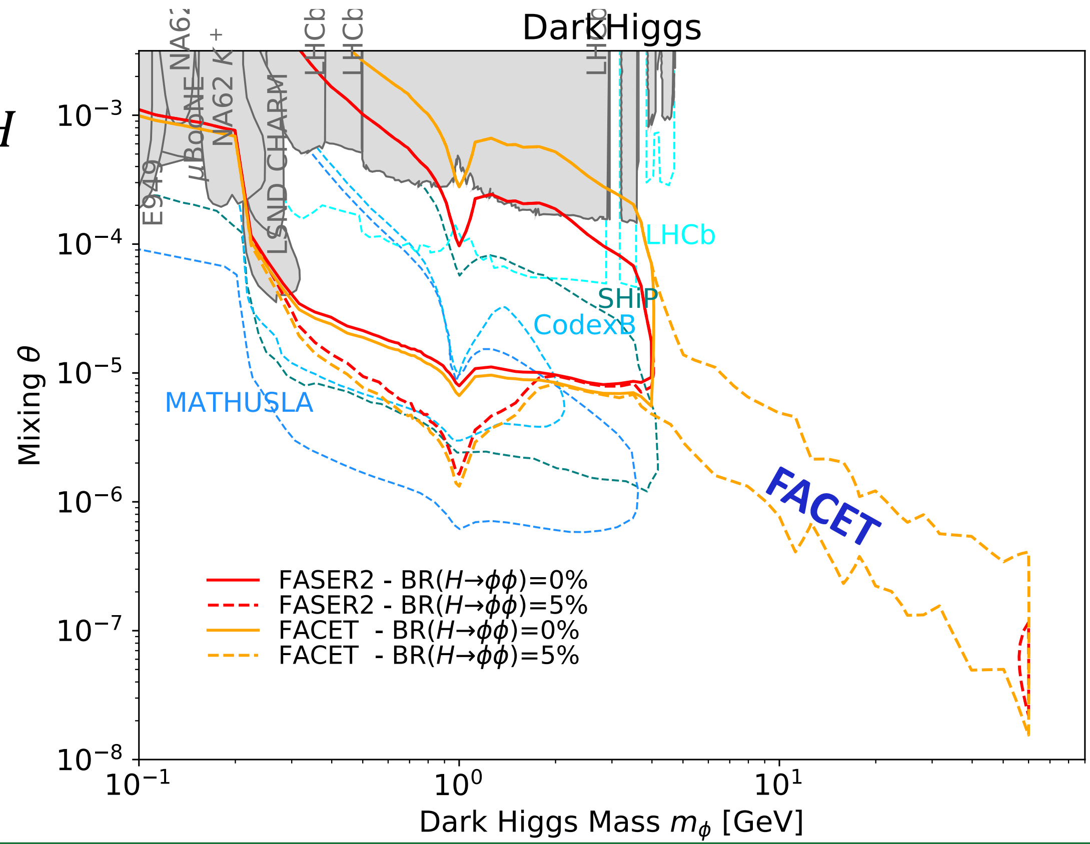
Suchita Kulkarni modified based on arXiv:1905.11889 to include FACET results



Dark Higgs Boson, ϕ

- A dark sector partner ϕ of the 125 GeV Higgs boson, H(125)
- It can be produced in the decay of Higgs boson (125 GeV)
  - $H \rightarrow \phi\phi$

The reach of FACET for a dark Higgs:



In the model:

- a non-zero trilinear coupling $\phi\phi H$
- Resulting in a 5% BF of $H \rightarrow \phi\phi$. which is within the limits set on invisible H width

- FACET has a unique sensitivity up to half the Higgs mass.

Signal Topology

Signal Topology: Highly penetrating LLP decaying in vacuum to:

- $\gamma\gamma$ no tracks or conversion
- $e^{+}e^{-}$ if M(LLP) > 2 MeV
- $e^{\pm}\mu^{\mp}$ if M(LLP) > 108 MeV
- $\mu^{+}\mu^{-}$ if M(LLP) > 212 MeV

Fixed target experiments have the advantage of higher luminosity for

M(LLP) < 1 GeV

- $\tau^{+}\tau^{-}$ if M(LLP) > 3.6 GeV
- $q\bar{q} + c\bar{c}$ if M(LLP) > ~ 4 GeV
- $b\bar{b}$ if M(LLP) >~ 10 GeV

LHC experiments becomes advantageous!

Backgrounds very low with a few tracks in the vacuum

M(LLP) > 1 GeV

Backgrounds: Reducible Backgrounds

Direct SM processes

- All SM particles, except ν's are subtracted by the shielding before the hodoscope

For LLP→ l^+l^- processes:

- Pileup with two muons or electrons from different collision in the same BX
  - eliminated by tagging the charged particle in the hodoscope and precise vertexing
  - as well as using the distance of closest approach of the tracks

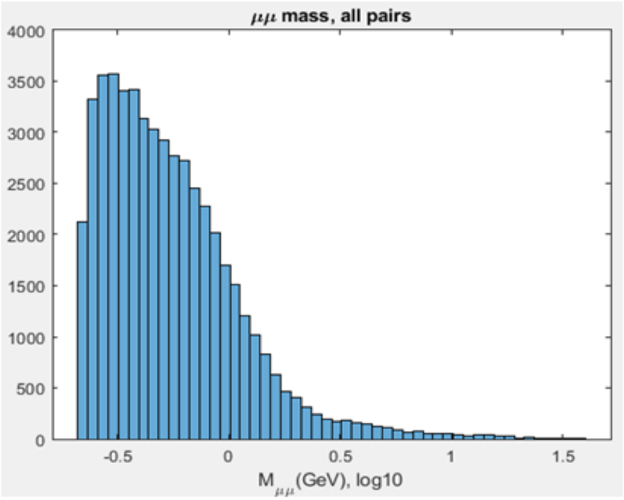
For LLP→ $4\ \mathrm{hadrons}$ processes:

- Some 4-body K^0 decays will be background in M(LLP) ~ 500 MeV/c, not at higher mass.
- Pileup of two unrelated hadronic K_S^0 decay ($\pi^+\pi^-$ 69%)
  - Superimposed in x,y,z consistent in time
  - Mass constraints and pointing back to IR requirements supresses the background

Backgrounds: Challenging Backgrounds

Indirect SM particles from interaction in the beam pipe and LHC components (p, n, π)

- Simulation predicts about **one neutral hadron** and ~ 1.9 **muons** entering the vacuum decay volume at R > 10.6 cm per BX
  - **Neutral hadrons:** K_S^0, K_L^0, Λ^0 and Ξ^0
    - HGCAL enables to reconstruct the invariant mass of hadrons
    - Requiring hadrons to point back to IR, they can be reduced
    - But may still be *overwhelming* for $LLP \rightarrow h^+h^-$ with $M(LLP) \leq 1\ GeV$
  - **Muons**: $LLP \rightarrow \mu^+\mu^-$
    - Are produced in various sources
    - It is dominant for $M(\mu^+\mu^-) < 1$ GeV



What is unique for FACET?

FACET will have

- 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 and ignore them in the trigger and analysis
- 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 granular calorimeters** for electromagnetic, hadronic calorimeters
- a muon detector

Status of the FACET Project

- A short physics reach paper is about to be submitted in arXiv.

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

S.Cerci†, D.Sunar Cerci† (Adiyaman Univ.), D.Lazic (Boston Univ.),
G.Landsberg* (Brown Univ.), M.G.Albrow*, J.Berryhill, D.R.Green,
J.Hirschauer (Fermilab), F.Cerutti, M.Sabaté-Gilarte (CERN),
J.E.Brücken (Helsinki Inst. Phys.), S.Kulkarni (Univ. Graz),
L.Emediato, A.Mestvirishvili, J.Nachtman, Y.Onel, A.Penzo (Univ. Iowa),
O.Aydilek, B.Hacisahinoglu, S.Ozkorucuklu*, H.Sert, C.Simsek, C.Zorbilmez (Istanbul Univ.),
I.Hos† (Istanbul-Cerrahpasa Univ.), B.Isildak† (Ozyegin University),
N.Hadley, A.Skuja (Univ. Maryland), M.Du, Z.Liu, R.Fang (Univ. Nanjing),
V.Q.Tran (Tsung-Dao Lee Inst., Shanghai)

*Contacts: albrow@fnal.gov, Greg.Landsberg@cern.ch, Suat.Ozkorucuklu@cern.ch

†Also at Istanbul University

December 13, 2021

Status of the FACET Project

- "Enhanced long-lived dark photon signals at lifetime frontier detectors"
  - by *M. Du, R. Fang, Z. Liu and V.Q. Tran* published recently to **arxiv:2111.15503v1**
  - **that includes the FACET physics reach!**

- Letter of Intent to CMS is under development!
  - Proposed for Run4 (~2028)

- The studies for the detailed detector layout as well as physics simulations establishing FACET reach during the HL-LHC period has been ongoing

Summary

- FACET is proposed as **a new subsystem for CMS** in the high-luminosity LHC era.
  - FACET is planned to operate in Run 4 and beyond.
- FACET is designed to have **discovery potential up to LLP masses ~ 25 GeV**
- It requires an enlarged beam pipe, followed by high-precision tracking and calorimeter modules using **identical technology to the planned CMS upgrades.**
- With the features of FACET, like shielding, existence of charged particle tagger and a large vacuum volume for decays, we **aim** to have **almost zero background in many channels.**
- FACET covers a region of parameter space not accessible to other experiments
  - which makes it a project **complementary to other searches.**

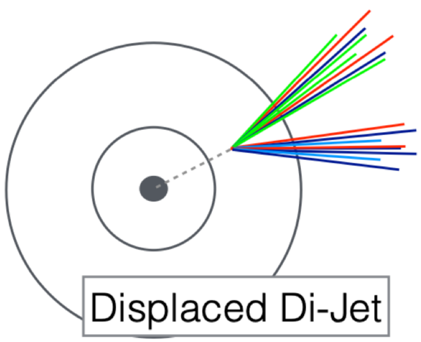
Thanks for your attention!

Backup

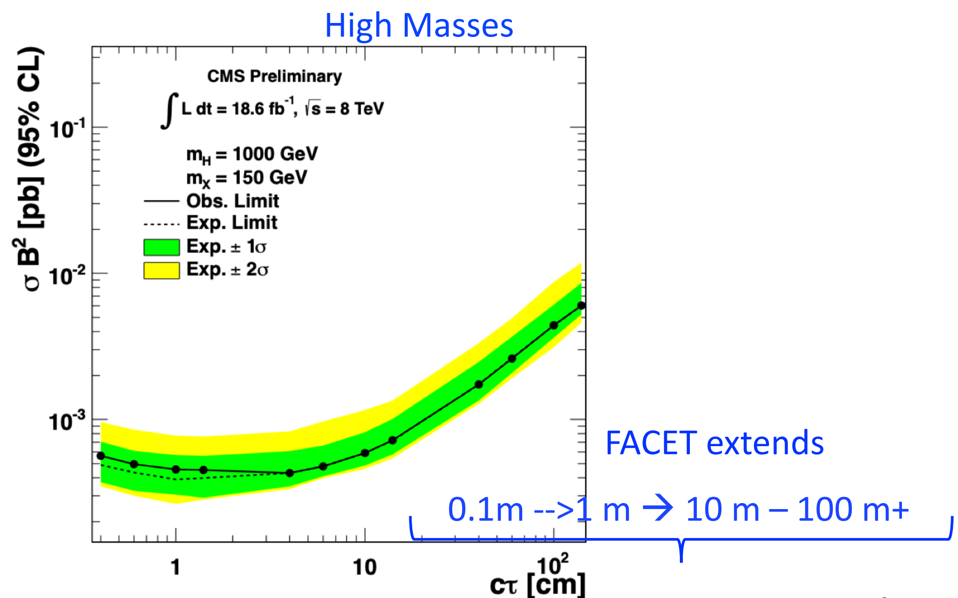
LLP → q + q →Jet + Jet (Heavy Dark Photon)

Emerging Jets with much longer c.τ than central detectors

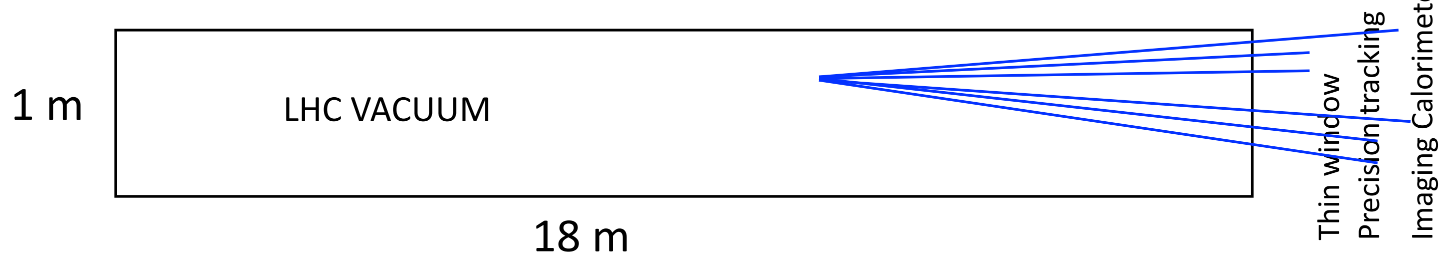
CMS Central
Transverse view



CMS Collaboration, Phys.Rev.D.91, 012017 (2015) [arXiv:1411.6530].



FACET Big Pipe

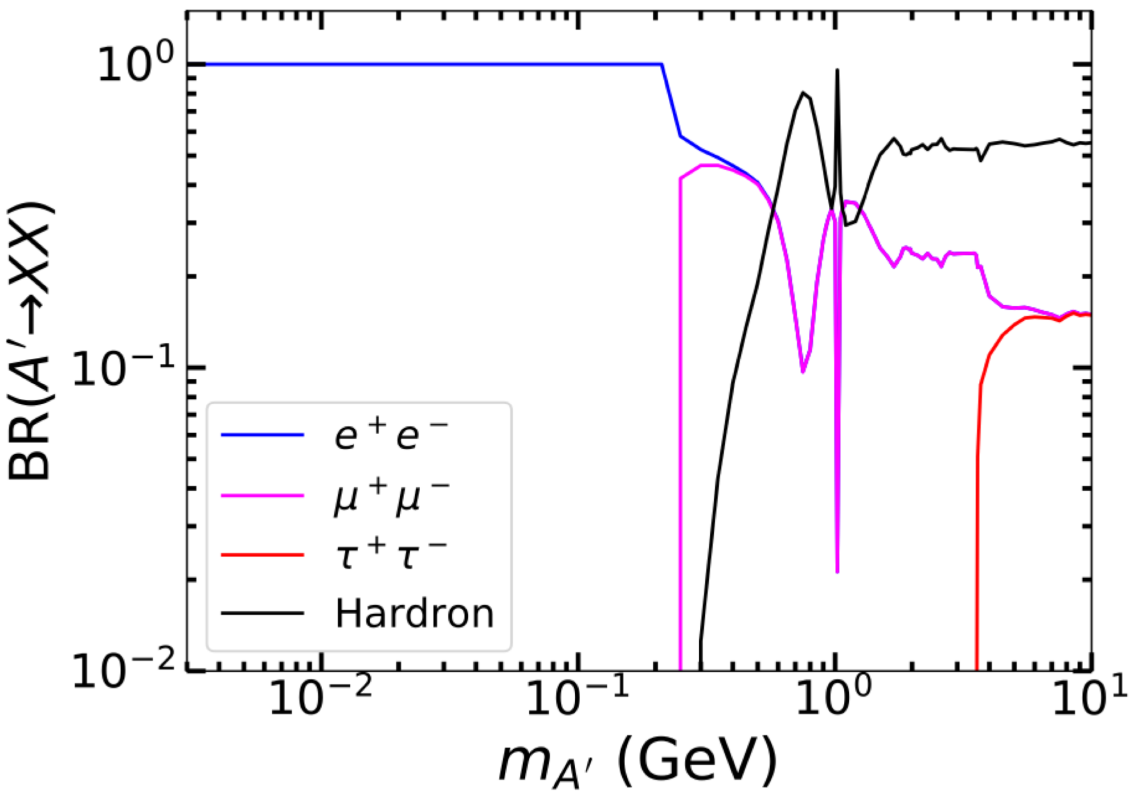


Dark Photon

One example of Class A in FACET: arXiv:1912.00422 [hep-ph]

Enhanced Long-Lived Dark Photon Signals at the LHC

Mingxuan Du,[1] Zuowei Liu,[1,2,3,*] and Van Que Tran[1]



LLP→ $\gamma + \gamma$ -- ALPs etc.

Critical issue is shower pointing (π^0, η decays prompt)

<u>$\gamma\gamma$ vertex resolution</u>, X^0 trajectory and opening angle

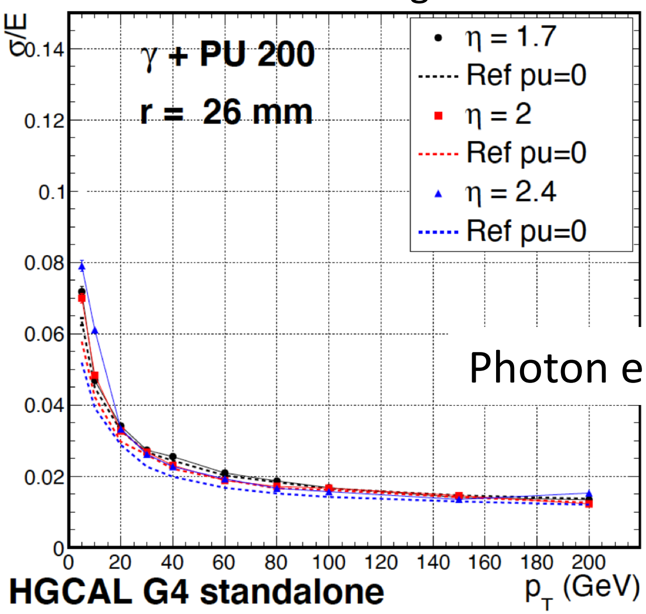
Single shower position resolution ~ 1mm

Angle resolution < 7 mrad (25 GeV showers)

σ(M) ~ < ~ few %

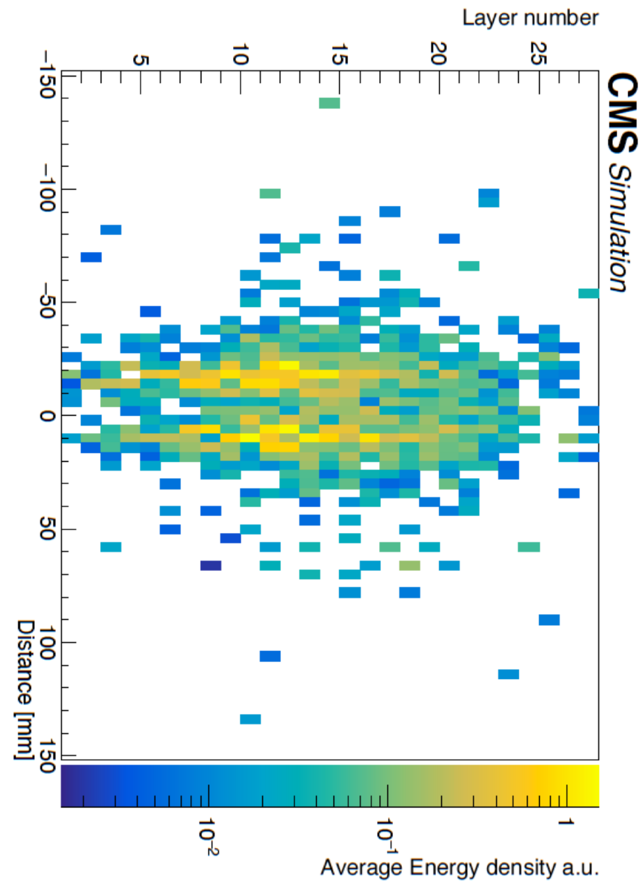
Simulation being done – π^0 π^0 pileup background?

From CMS-TDR-019 Fig 5.2



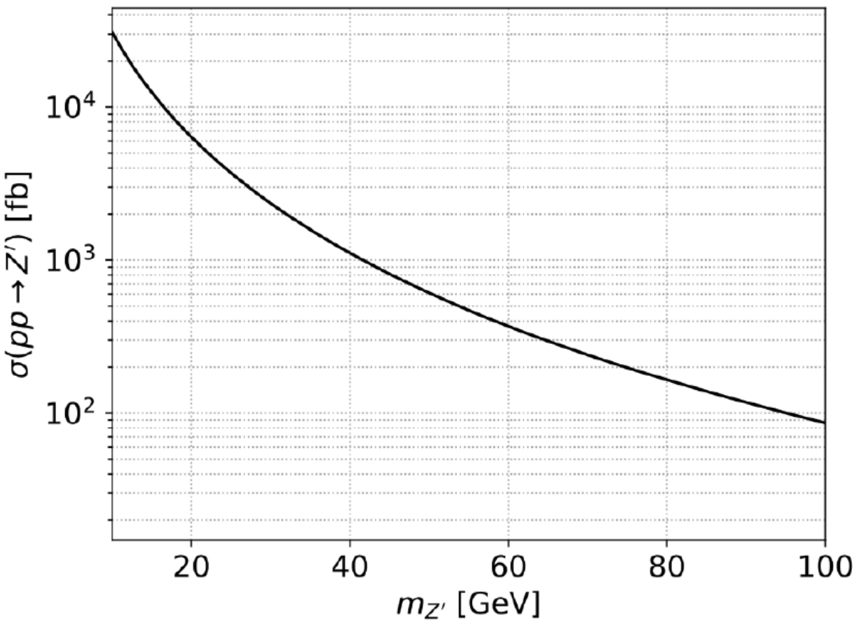
Photon energy resolution

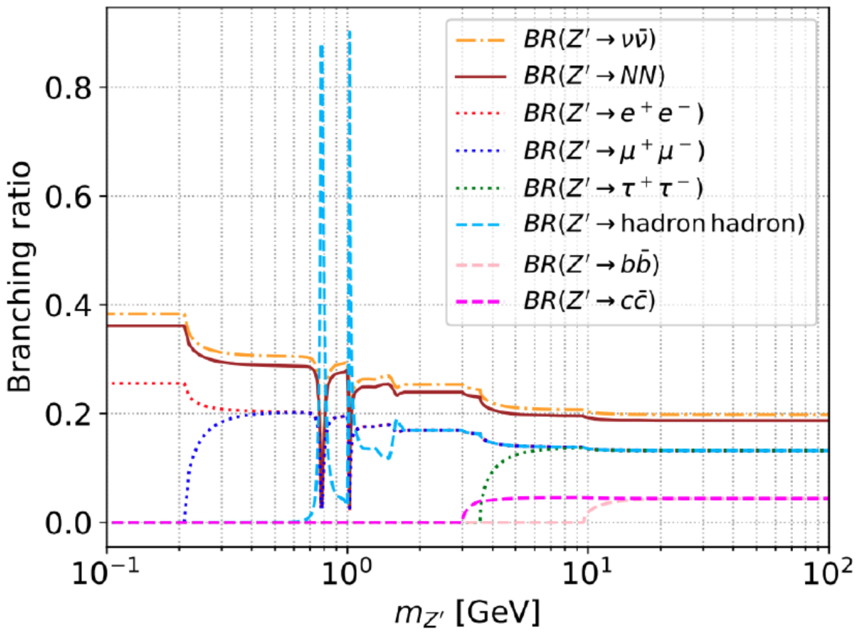
~ E(X)/2 at θ ~ mrad in FACET



Simulation two 80 GeV parallel photons separated by 30 mm.
From CMS-TDR-019 Fig 5.1

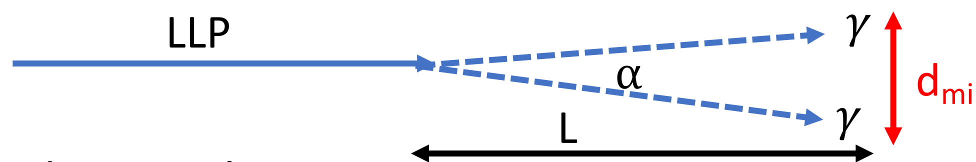
Heavy Neutral Leptons





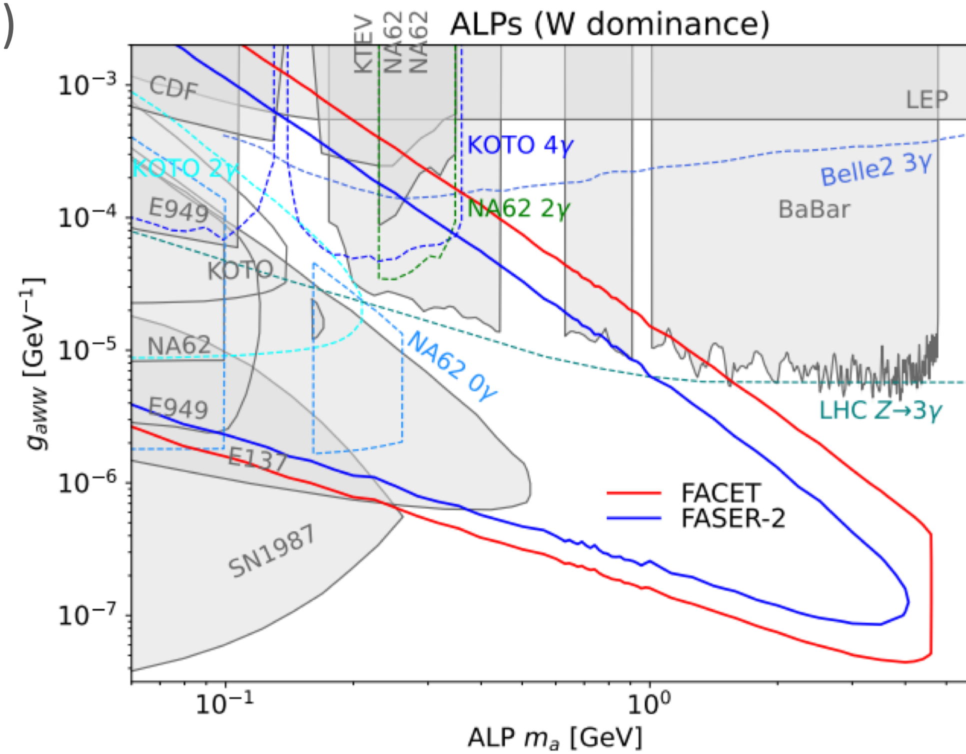
Axion-Like Particles, ALPs

- Massive axion-like particles (ALPs) may exist, and if produced at the LHC they may decay with long lifetimes into photon pairs or lepton pairs after penetrating thick absorbers.



- Shower pointing should be determined precisely
  - $\gamma\gamma$ vertex resolution (under study)
  - LLP trajectory
  - Opening angle

- An overview for the FACET axion-like particle reach in a specific model



- FACET can extend physics reach to smaller coupling and larger masses

Triggers

- CMS triggers will be upgraded for HL-LHC
  - L1 output rate increased from 100 kHz to 750 kHz
  - HLT rate increased to 7.5 kHz from 1 kHz
- FACET will provide an additional external trigger to the L1 Global Trigger,
  - built from the tracking, hodoscope, calorimeter and muon information
- The goal of the trigger is to select all candidates for X^0 >= 2 charged tracks or merged two photons while excluding SM particles such as K^0 and Λ^0.

Sources of Muon Background

The major source is

- Hadronic showers in the shielding

The remaining ones:

- True $K_L^0 \rightarrow \mu^+\mu^-$ decays in the vacuum volume for $BR = 7 \times 10^{-9}$
- $K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$ and $\pi^\pm \mu^\mp \nu_e$ $=>$ a misidentified $\pi^\pm$ as lepton
  - Missing neutrino smears the pointing from the IR for M(LLP) < 0.5 GeV
- $K_L^0 \rightarrow \pi^+\pi^-$ => two misidentified $\pi^\pm$ as leptons/muons $BR < 10^{-8}$