The FACET PROJECT

Mike Albrow (Fermilab, CMS)

LoI to CMS under development
Run 4 (2028+) and beyond

FACET = **F**orward **A**perture **C**MS **E**x**T**ension;
formerly Forward Multiparticle Spectrometer (FMS)

New subsystem for CMS in region **between S/C dipole D1** (z = 80m) **and TAXN** (z = 127m)
Enlarge beam pipe from z = 101m to 119m (L = 18m) from R =12.5 cm to R = 50 cm
→ **BIG VACUUM TANK** (LHC quality) + CMS Upgrade quality tracking + EM+HAD calo + μ's

TWO MOTIVATIONS:

PRIMARY

1) Search for new **BSM Long-Lived Particles** penetrating 35-50m iron & decaying in vacuum
M(X) up to ~ 25 GeV (multiparticle decays) with long lifetimes $c\tau$ = 0.1 m – 100 m
Full luminosity (HL) ~ 140/X and 3 ab^{-1}

THIS COMES TOO: Unexplored phase space region:

2) Standard model physics: charged particles through D1 aperture (35 Tm bend) (η > ~ 7.5)
e/h/μ measured (and pairs). (π/K/p ID would require transition radiators)
E.g. γ^* , J/ψ → $\mu^+\mu^-$ and ^{3}He and anti-^{3}He at high luminosity
Also: K^0_s and Λ^0 and $D^0 \rightarrow K^\pm \pi^\mp$ in any **low pileup pp runs and ion runs (p+O, O+O)**

New Beyond Standard Model particles

Must exist if dark matter is **particles** – do they interact with SM particles (other than gravity)?
High mass searches at LHC – nothing yet
May be light (< 20 GeV) but with small coupling to SM particles – weak or not-so-weak

Many theoretically motivated possibilities:

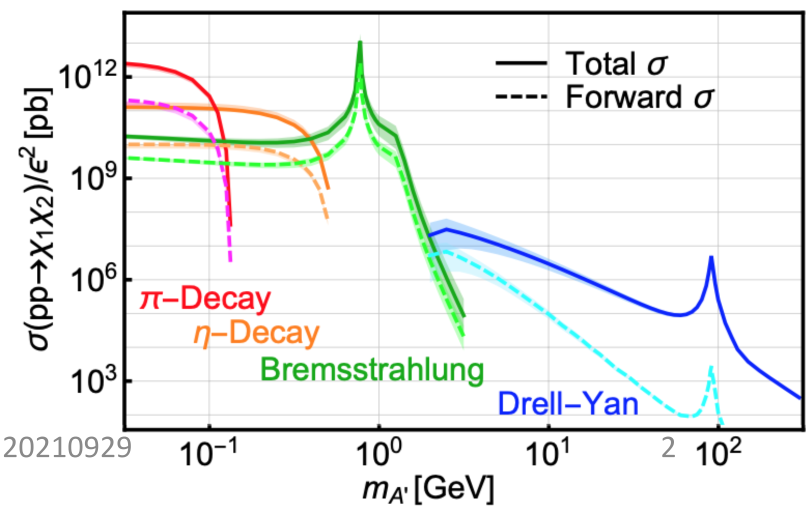
Vector J = 1 : Z' or dark photon **A'** that mixes with photon γ^*
Fermion J = ½ : Heavy neutral lepton **HNL**
Scalar J = 0 : **dark Higgs**, dark pseudoscalars (π'), axion-like particles (**ALP**s)

Not dark matter if they decay, but can be **PORTALs** to dark world if they couple to SM&DM
FACET: Inclusive search for **anything** penetrating then decaying - must be BSM!

Production:
A': Any source of photons e.g. $\pi^0 + \eta^0 + \eta'$ decays if M(A') < 1 GeV
Bremsstrahlung $p \to p + \gamma^*$ & $q \to q + \gamma^*$
Drell-Yan q-$\bar{q}$ annihilation
QCD: **$q\, g \to q\, \gamma^*$**

Dark Higgs **ϕ** from c, b decays & decay → c, b
Mixing H – **ϕ**

Berlin & Kling arXiv:1810.01879



RUN 4 – HL LHC (2028+)

CMS
CENTRAL

IR5

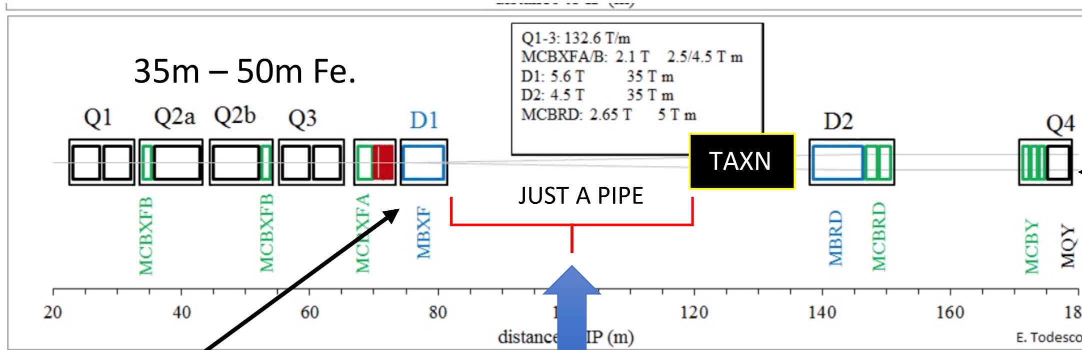


Fig. 2.1: The lay-out of the LHC interaction region (upper part) and of the HL-LHC interation region (lower par

BEAMS

Dipole section

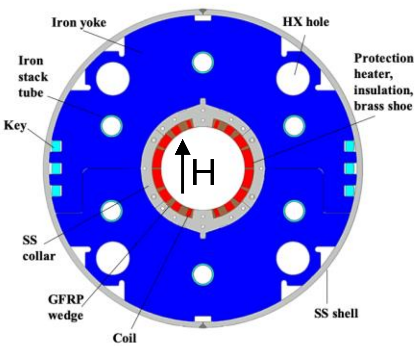
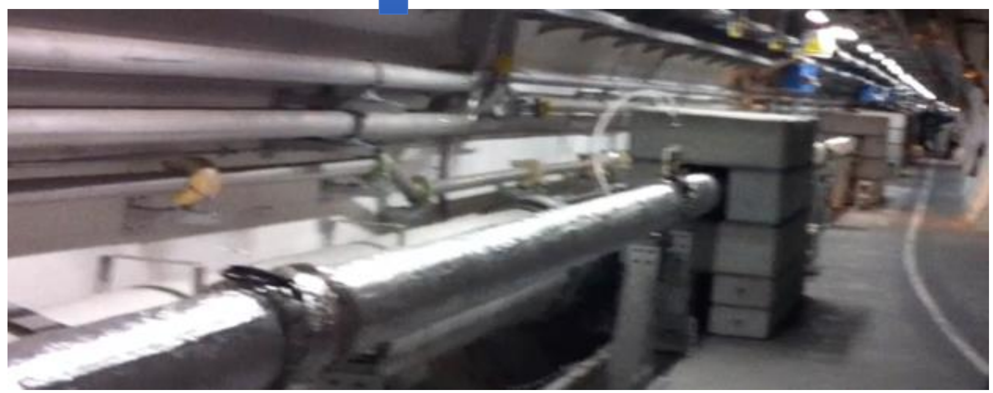


Fig. 4.1: Cross-section of the separation dipole.



We had Forward Shower Counters (rapidity gaps) in 2012 – low luminosity

~46m bare pipe (as now), R ~ 12 cm

Separation dipole D1 (new, S/C)
140 mm aperture,
Outer diameter 57 cm
35 Tm integrated field

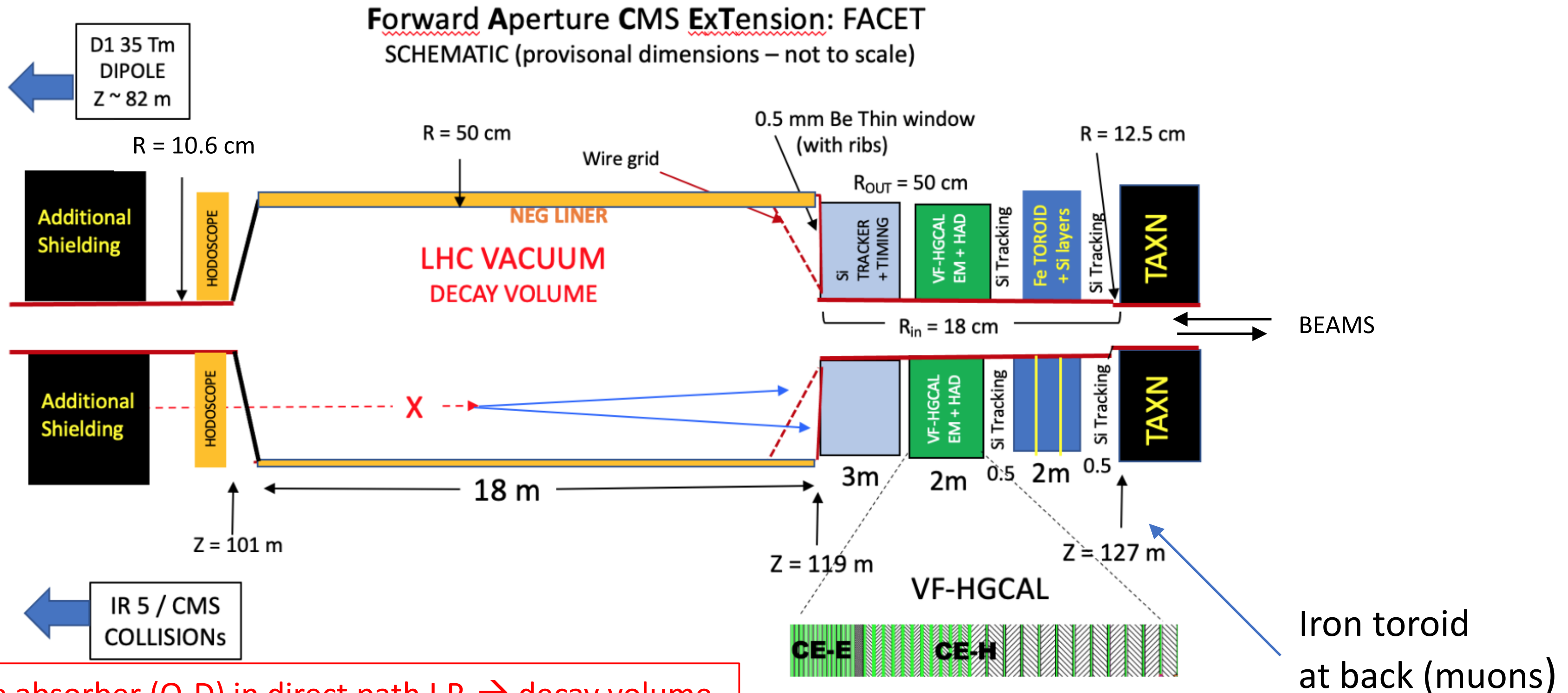
Propose to replace with larger vac pipe R = 50 cm, L = 18 m (z =101-119 m)

This is only change required of LHC – ALICE has a similar big pipe

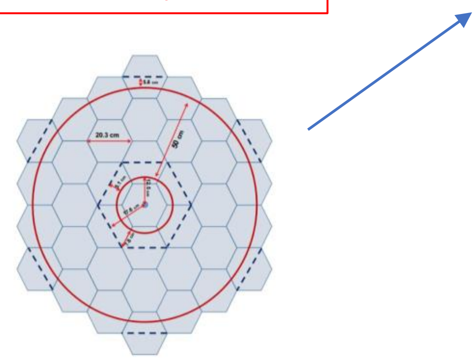
LHC: "Provisionally OK, subject to detailed study"

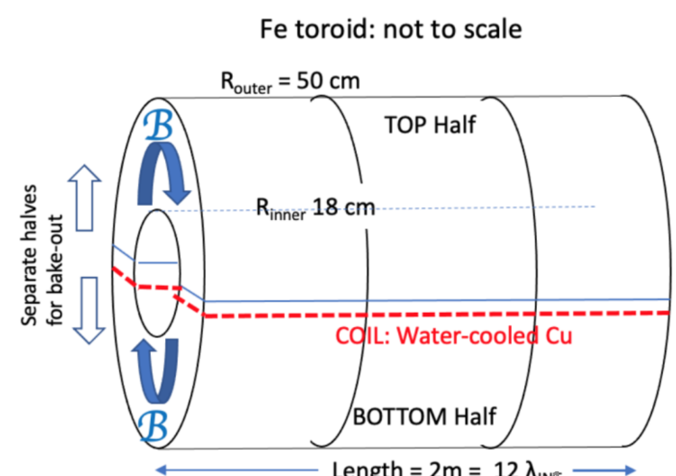
No special running conditions required.

FACET



35m – 50m Fe absorber (Q,D) in direct path I.P. → decay volume





Plan to use only detectors planned for CMS at HL

~ + 5% is sufficient (0.7 m^2)

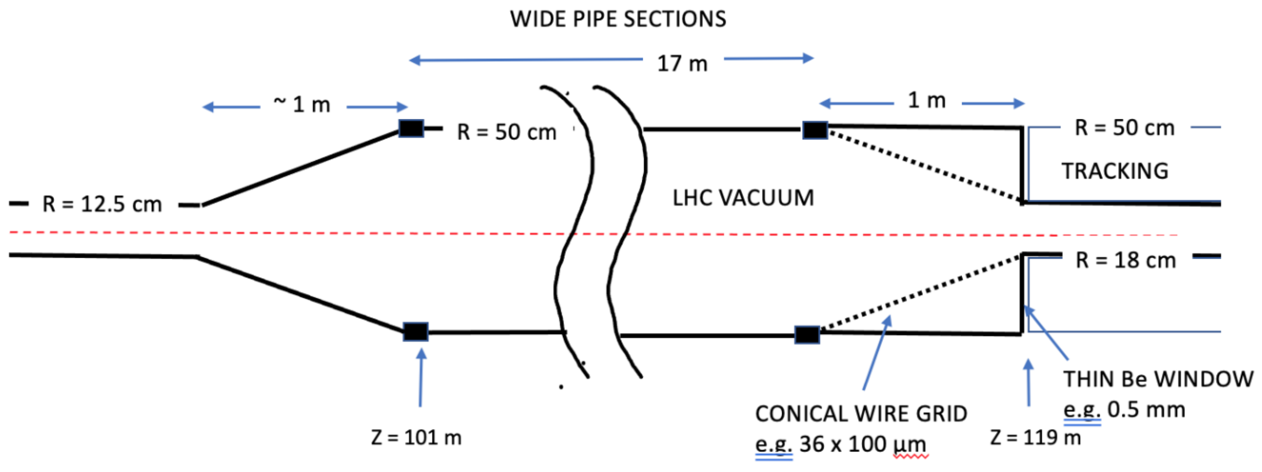
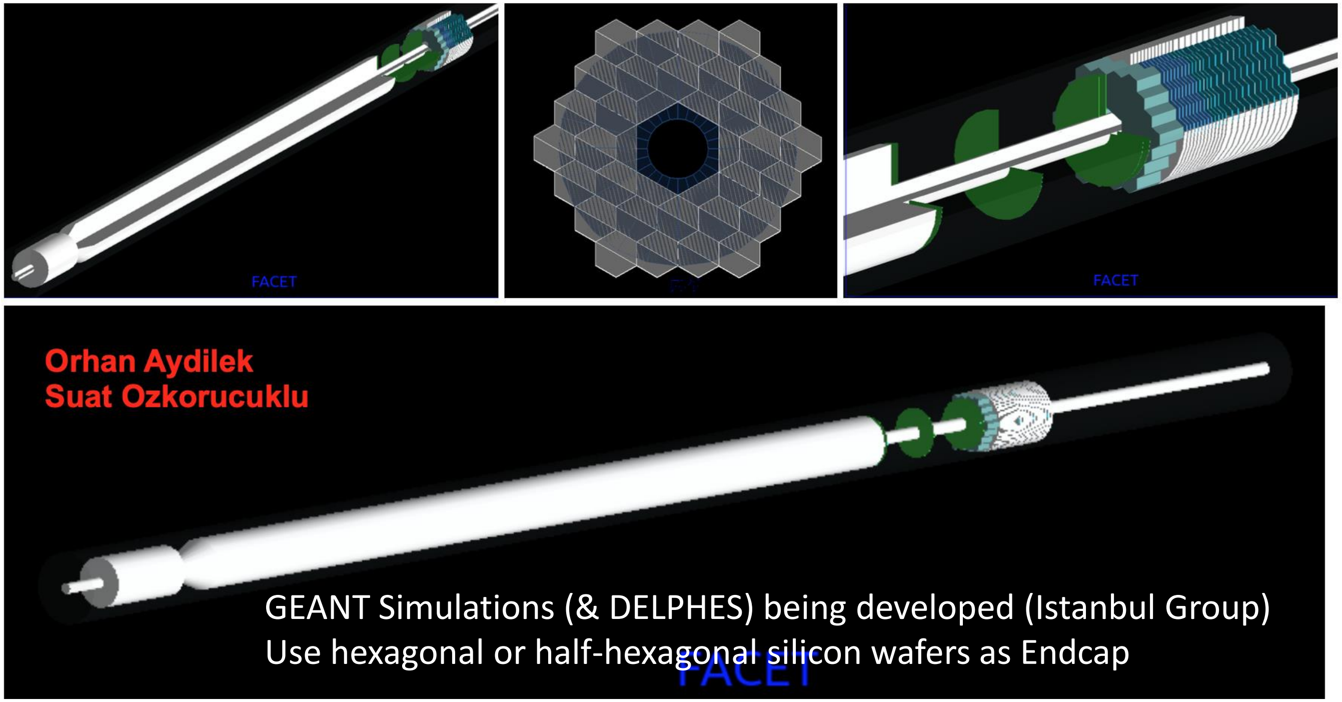


Figure 4: Pipe sections with wire grid concept.

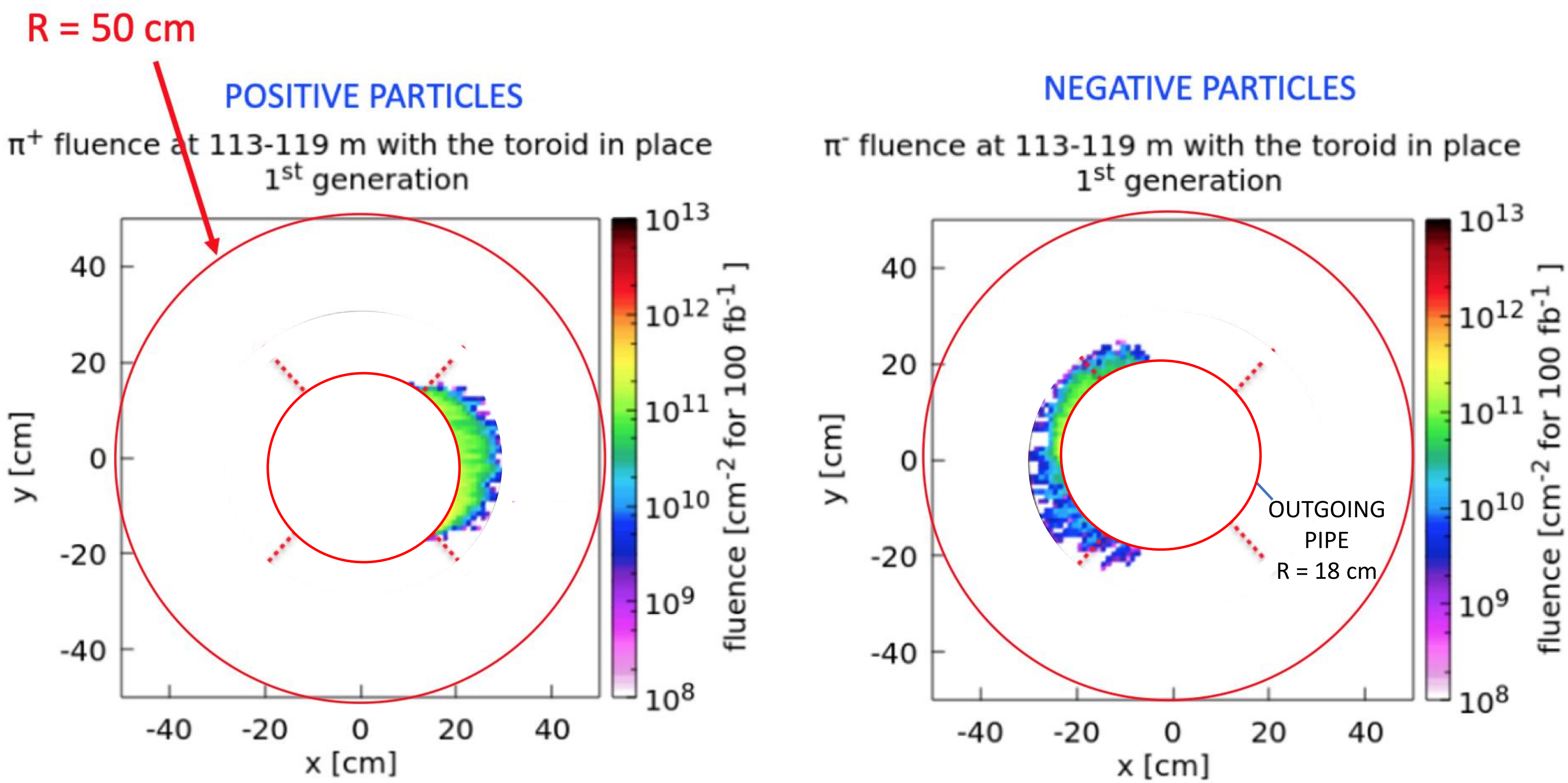


Charged particles through vacuum pipe & D1 aperture (deflected)

Cover small areas L (-) and R (+).

Everywhere else (95%) only penetrating neutrals, (+ backgrounds from interactions in pipe etc)

Instrument for decays in High Luminosity running.



Simulations with DPMJET + FLUKA – M. Sabate-Gilarte & F. Cerutti

Search for highly penetrating X^0 decaying in vacuum to:

Studies in progress with simulations

$\gamma\gamma$ (no tracks - or conversion - to high granularity EM calorimeter)

e^+e^- if M(X) > 2 MeV (track pair and high granularity EM calorimeter)

$e^\pm\mu^\mp$ if M(X) > 108 MeV (Muon through calo & muon chambers) not from $\tau^+\tau^-$

$\mu^+\mu^-$ if M(X) > 212 MeV (Muon pair through calo & muon chambers)

Fixed target "beam dump" advantage if M(X) < 1 GeV

$\tau^+\tau^-$ if M(X) > 3.6 GeV (e^+e^- or $\mu^+\mu^-$ or $e^\pm\mu^\mp$ or e/μ + hhh ?)

$q\bar{q}$ + $c\bar{c}$ if M(X) > ~ 4 GeV (== e^+e^- charm factory event boosted to TeV!)

$b\bar{b}$ if M(X) >~ 10 GeV

LHC advantage: Backgrounds very low (~ zero?) with >= 4 tracks on vertex in vac.

Possibly: Dark Matter not decaying but interacting in calorimeter (very good imaging, timing!) ?
Probably neutron and K^0_L background overwhelming for DM. Some ν interactions expected (cf FASERν)

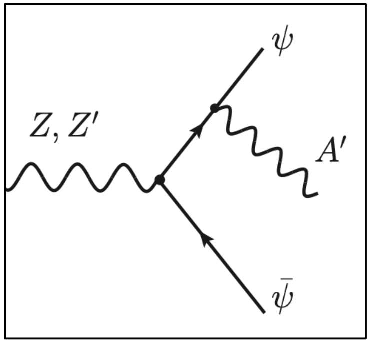
Distinct "classes" of LLP : (A) involving massive states (>~ 100 GeV: H, Z') in production
Large solid angle central detector coverage favored – high p_T
(B) only involving light states (< ~ 20 GeV) in production
Low-p_T, forward production favored, Δy . Δφ rather than ΔΩ

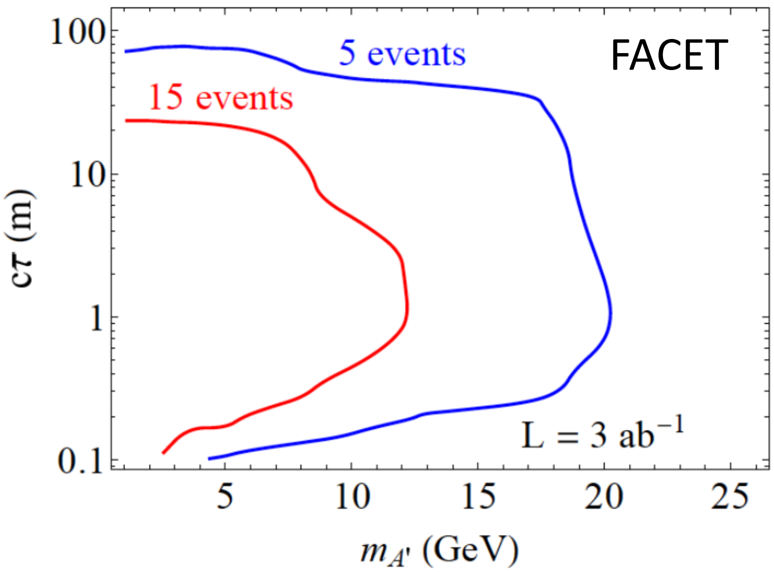
One example of Class A in FACET: arXiv:1912.00422 [hep-ph]

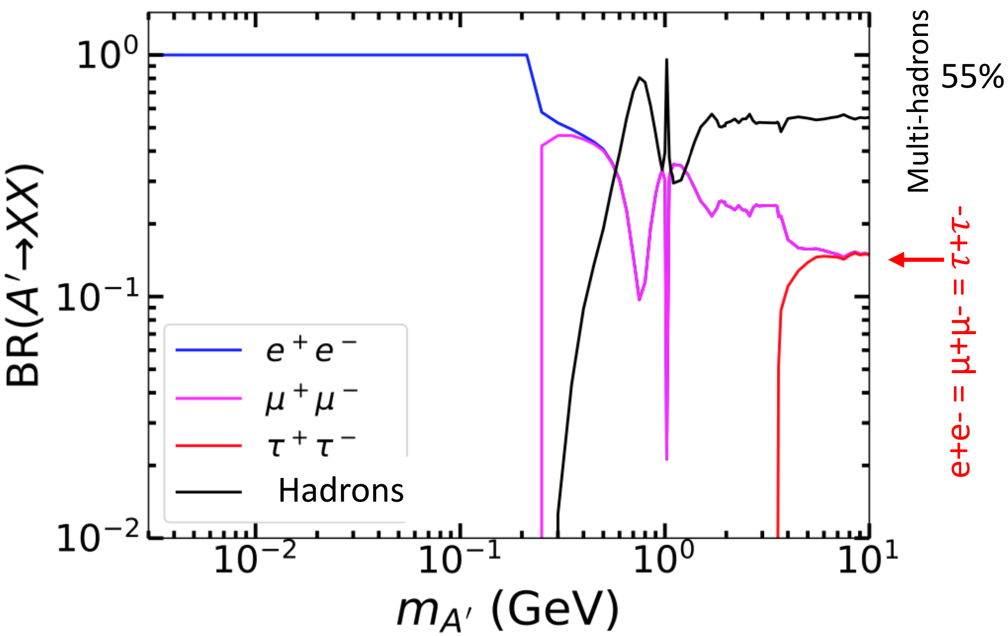
Enhanced Long-Lived Dark Photon Signals at the LHC

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

Involves new Z'(700 GeV) and heavy "hidden" fermion ψ



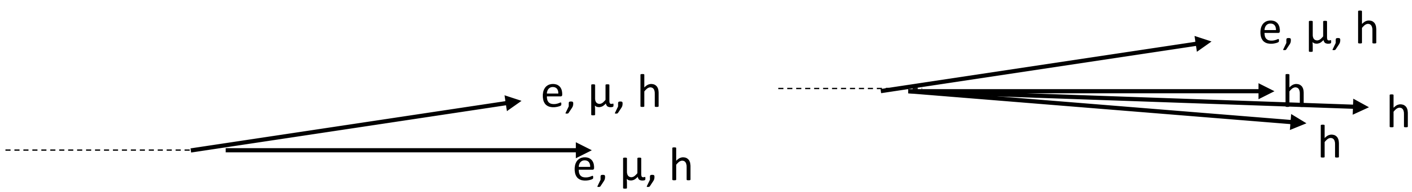




Class A: some coverage **if background-free,**
- but central favored

$X^0 \rightarrow \tau + \tau$

$M(\tau)$ = 1776.86 MeV → M(X) > ~ 3600 MeV
Main decays: μ ν ν & e ν ν each about 0.175 so μ μ, e e 3% each, e μ = 6%
Non-pointing because neutrinos missing.
BR (h ν) = 0.115 (mostly π).
BR (h + ≥ 1 neutrals) 37%
BR (h h h + ≥ 0 neutrals - 3 prong) 15%



$X^0 \rightarrow c + \bar{c}, b + \bar{b}$

Like e+e- events above open charm threshold 2 x $M(D^0)$ = 3730 MeV
Boosted to high p_z (acceptance?) and decaying in pipe

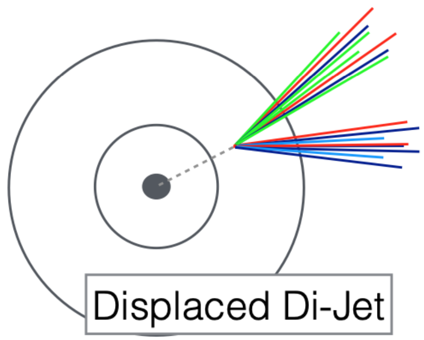
Full simulations in progress

$X^0 \rightarrow q + \bar{q} \rightarrow$ Jet + Jet

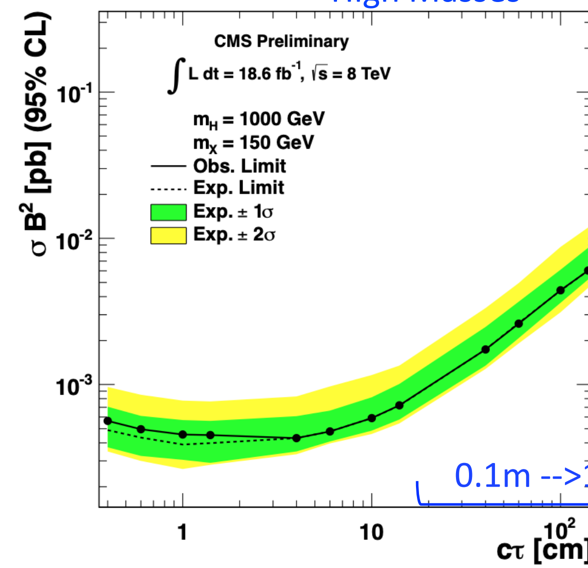
Emerging Jets with much longer c.τ than central detectors

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

CMS Central
Transverse view



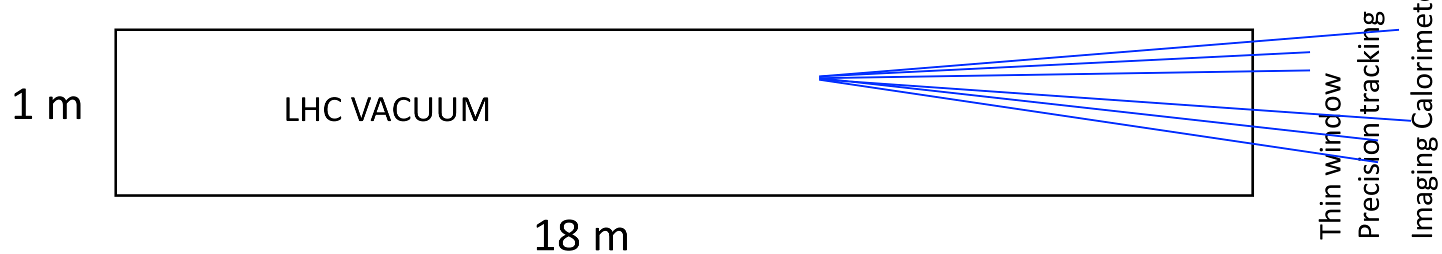
High Masses



FACET extends

0.1m -->1 m → 10 m – 100 m+

FACET Big Pipe

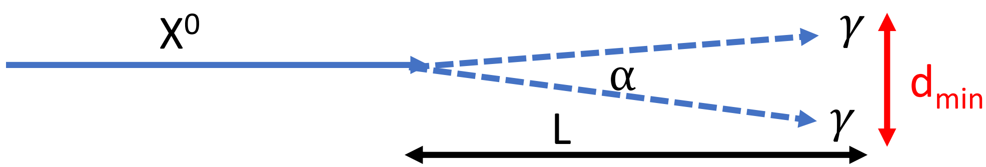


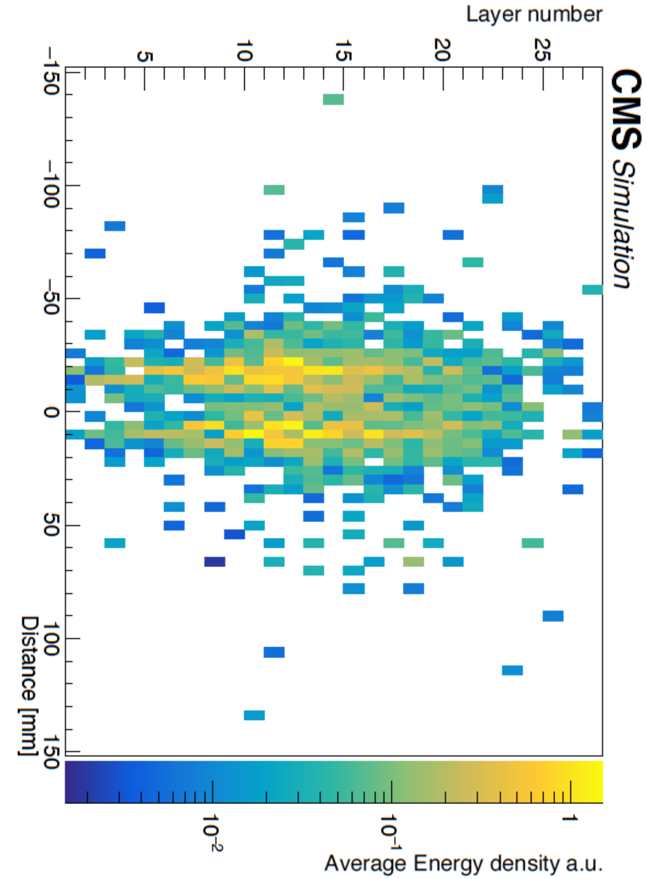
"NISO" = Nothing In Something Out (with vertex, directionality and timing to reject B/G)

$X^0 \rightarrow \gamma + \gamma$ -- ALPs etc.

Critical issue is shower pointing (π^0, η decays prompt)
$\gamma\gamma$ vertex resolution, X^0 trajectory and opening angle
Single shower position resolution ~ 1mm
Angle resolution < 7 mrad (25 GeV showers)

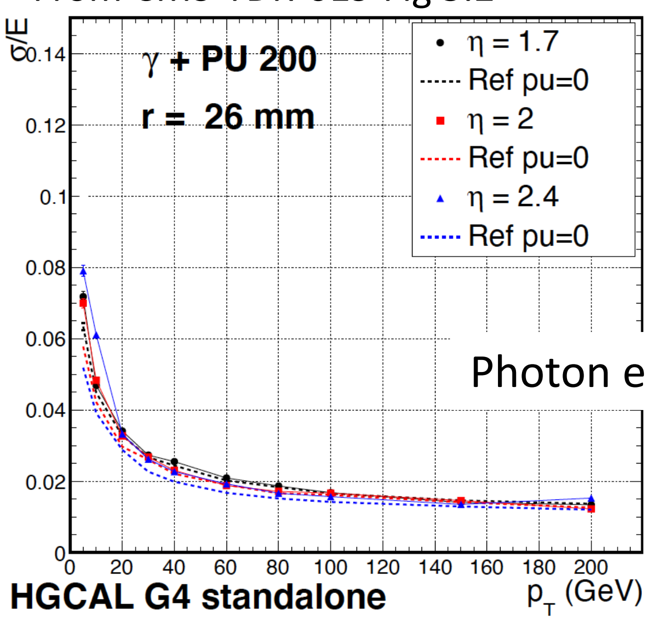
$\sigma(M)$ ~ < ~ few %
Simulation being done – π^0 π^0 pileup background?





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

From CMS-TDR-019 Fig 5.2

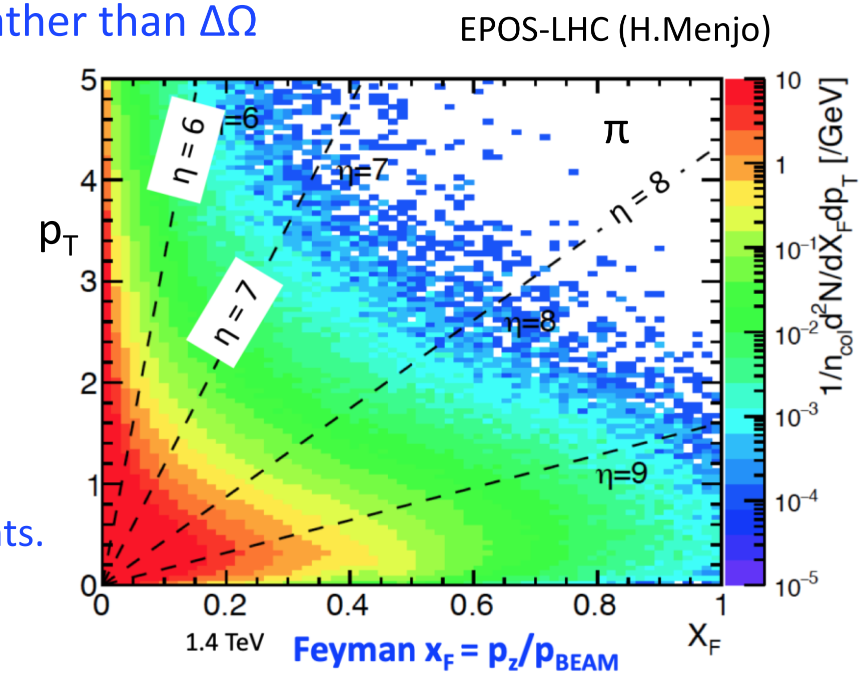


Photon energy resolution

~ E(X)/2 at θ ~ mrad in FACET

Class (B) only involving light states (< ~ 10 GeV) in production

Low-p_T, forward production favored, Δy . Δφ rather than ΔΩ

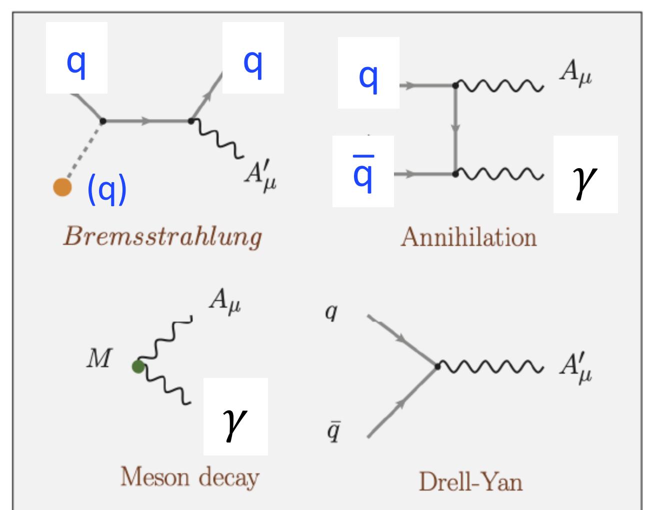


1) Light: m < m(η) 548 MeV), m(η') 958 MeV)

Note:
Beam dump experiments (e.g. NA62) have higher fluxes

2) m > 1 GeV - ~ 20 GeV
LHC increasingly favored over Fixed Target experiments.
Forward region favored over central (fluxes)

A' production processes Light or medium classes →
Also proton bremsstrahlung p → p γ*
Adapted from Fabbrichesi, Gabrrielli, Lafranchi
Dark Photon Review arXiv:2005.01515 [hep-ph] 2020



Note: Production not only in primary collisions but also in secondaries hitting Endcap, collimators, magnets etc.
"Amplifier" for lowish mass region.
-- Fixed target production but with some ~ TeV "beams".

Example of model where **FACET has unique coverage for dark photons**:

Multi-GeV mass region between FASER2 and MTD (MIP Timing Detector in CMS)

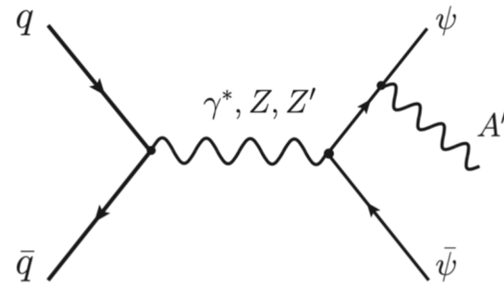
New vector boson **Z'** + dark photon **A'** + stable millicharged fermion **ψ** – dark matter candidate

Masses and couplings in ranges allowed by existing experiments and cosmology.

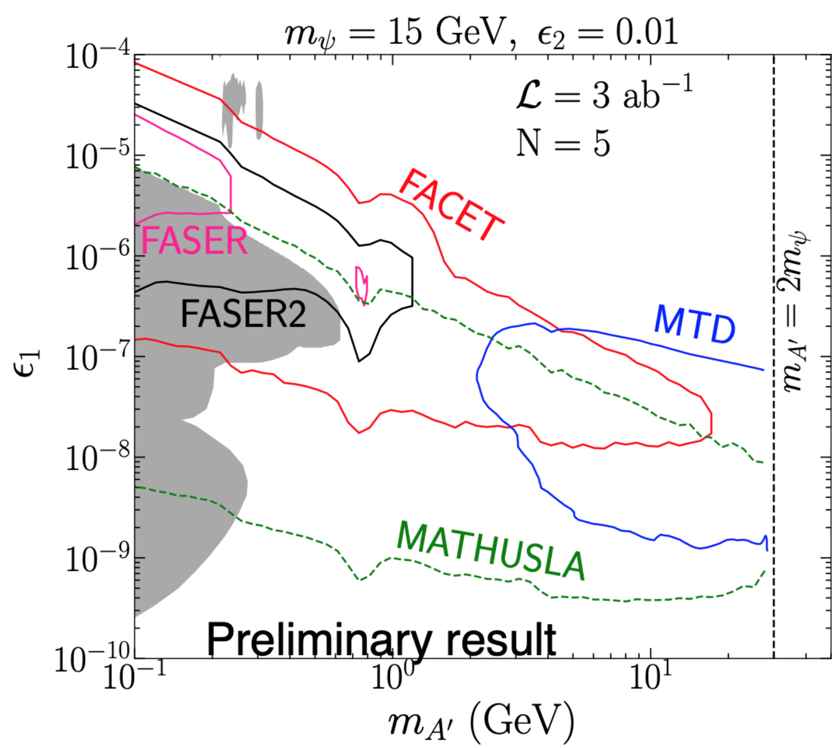
- Pair of ψ particle produced at pp collision via Z, Z', γ exchange
- ψ particle radiates off dark photon A' (analogs to QED radiation)

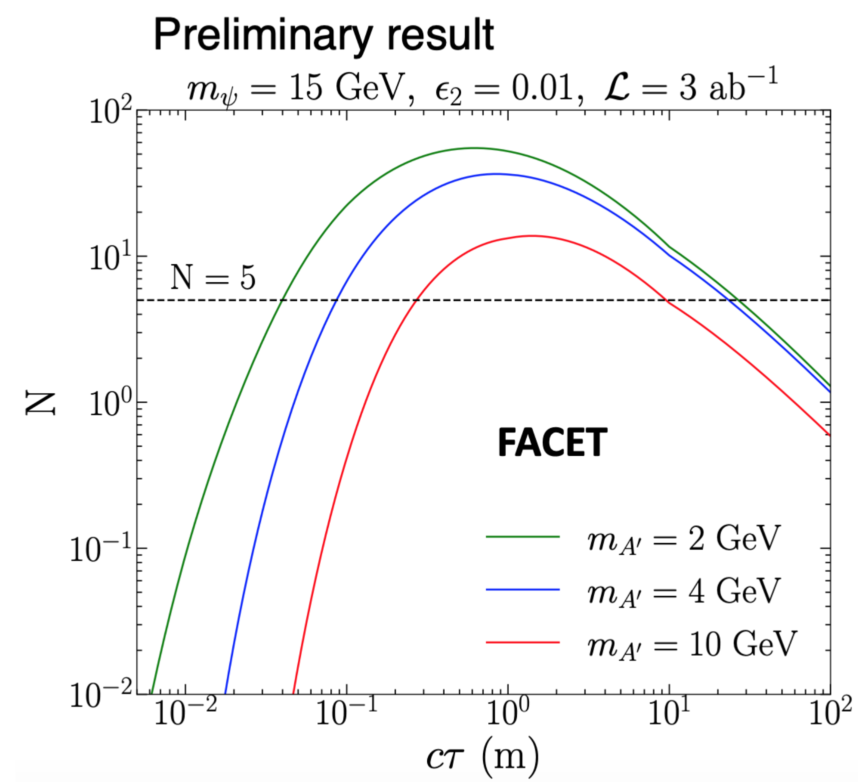
arXiv:1912.00422v1 [hep-ph]

M. Du, R.Fang, Z. Liu and Van Que Tran

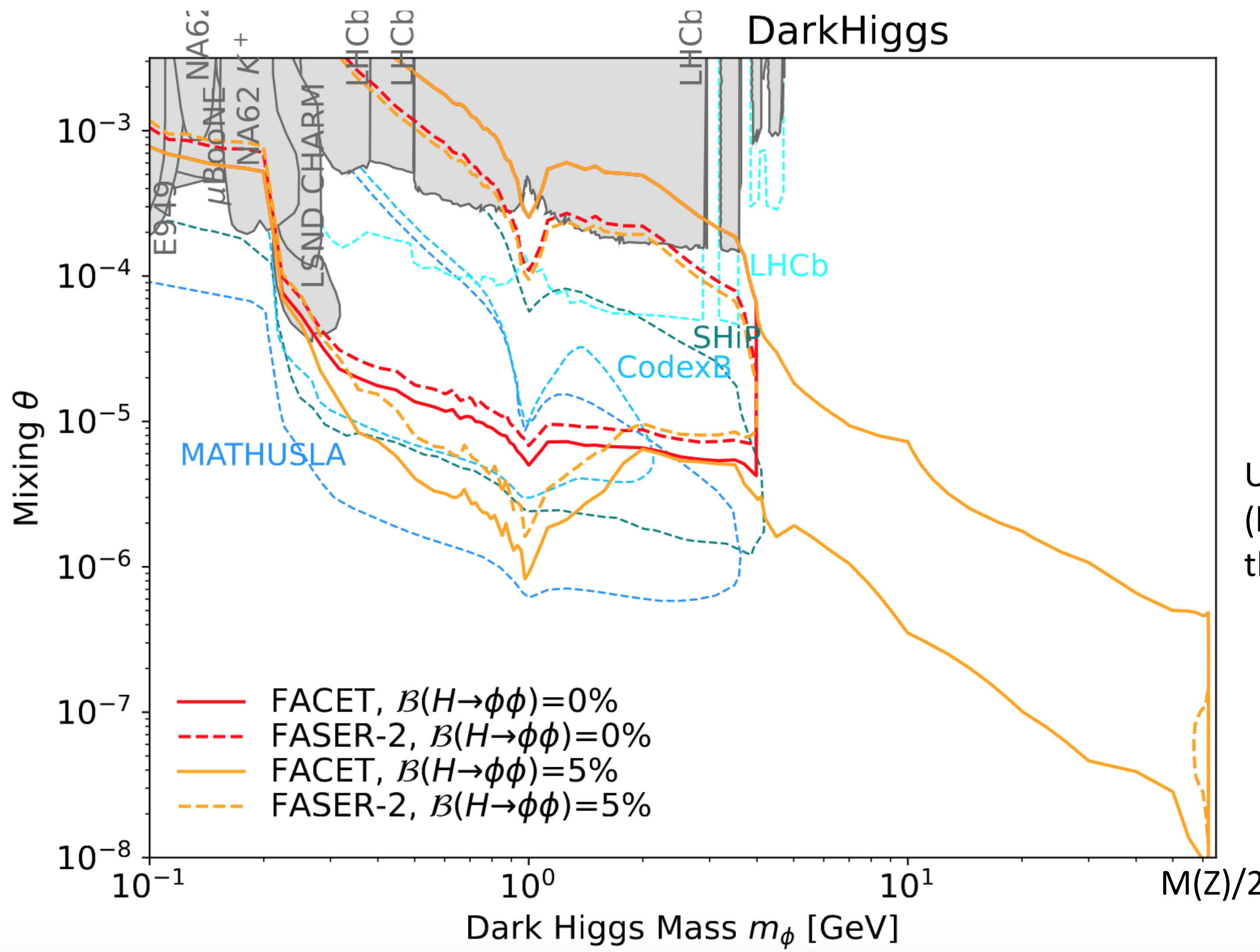


HR = Hidden Sector Radiation





Dark Higgs: Can be light, e.g. lighter than b-quark or Z and produced in its decays & decay to two new scalars h --> $\phi\phi$



Unique extra coverage (larger $\boldsymbol{\theta}$ and closer to IP than FASER-2

Heavy Neutral Leptons ("heavy neutrino") via Z' --> NN (Gauged B - L)

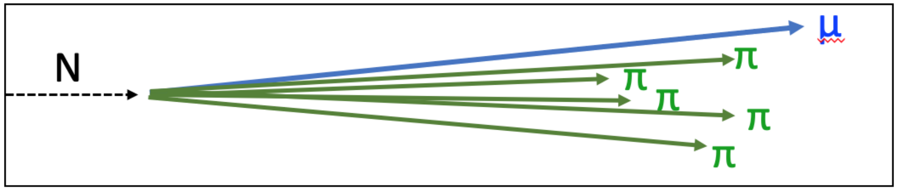
E.g. Frank F. Deppisch, Suchita Kulkarni, Wei Liu arXiv:1905.11889v2 [hep-ph]

For a particular case, choice of parameters

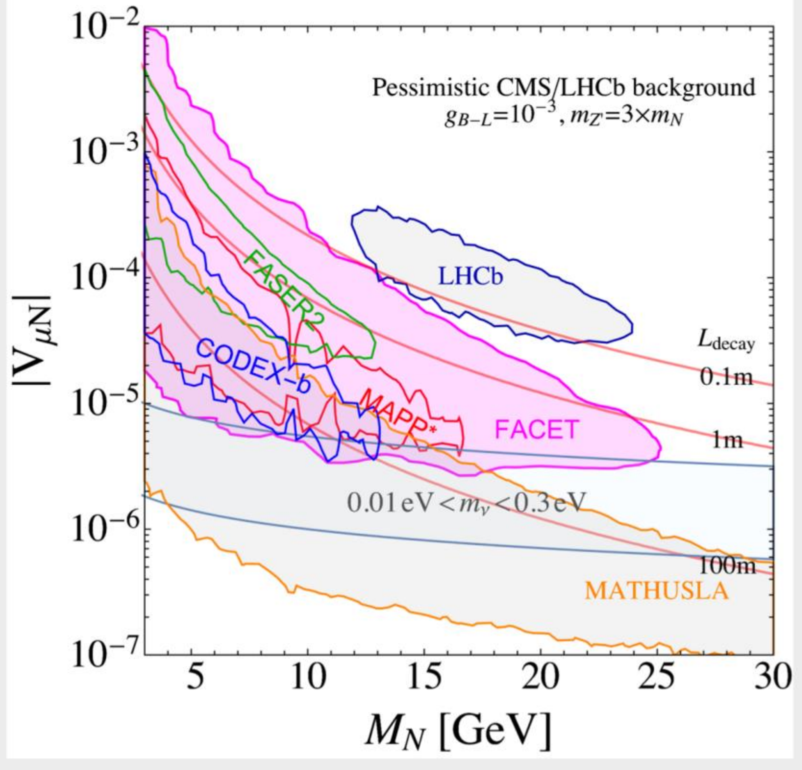
N can be long-lived if m_N small, coupling $V_{\mu N}$ small: $L_N \approx 0.025\ \mathrm{m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100\ \mathrm{GeV}}{m_N}\right)^5$

N decays (+ same with $e^{\pm}$ and $\tau^{\pm}$ for other N flavors - 3 particles to discover!):

$$N \to \mu^{\pm} q\bar{q} \text{ and } N \to \mu^{+}\mu^{-}\nu_{\mu} \text{ via } W^{\pm(*)}, Z^{(*)}$$



(Thanks to Suchita Kulkarni for FACET study)

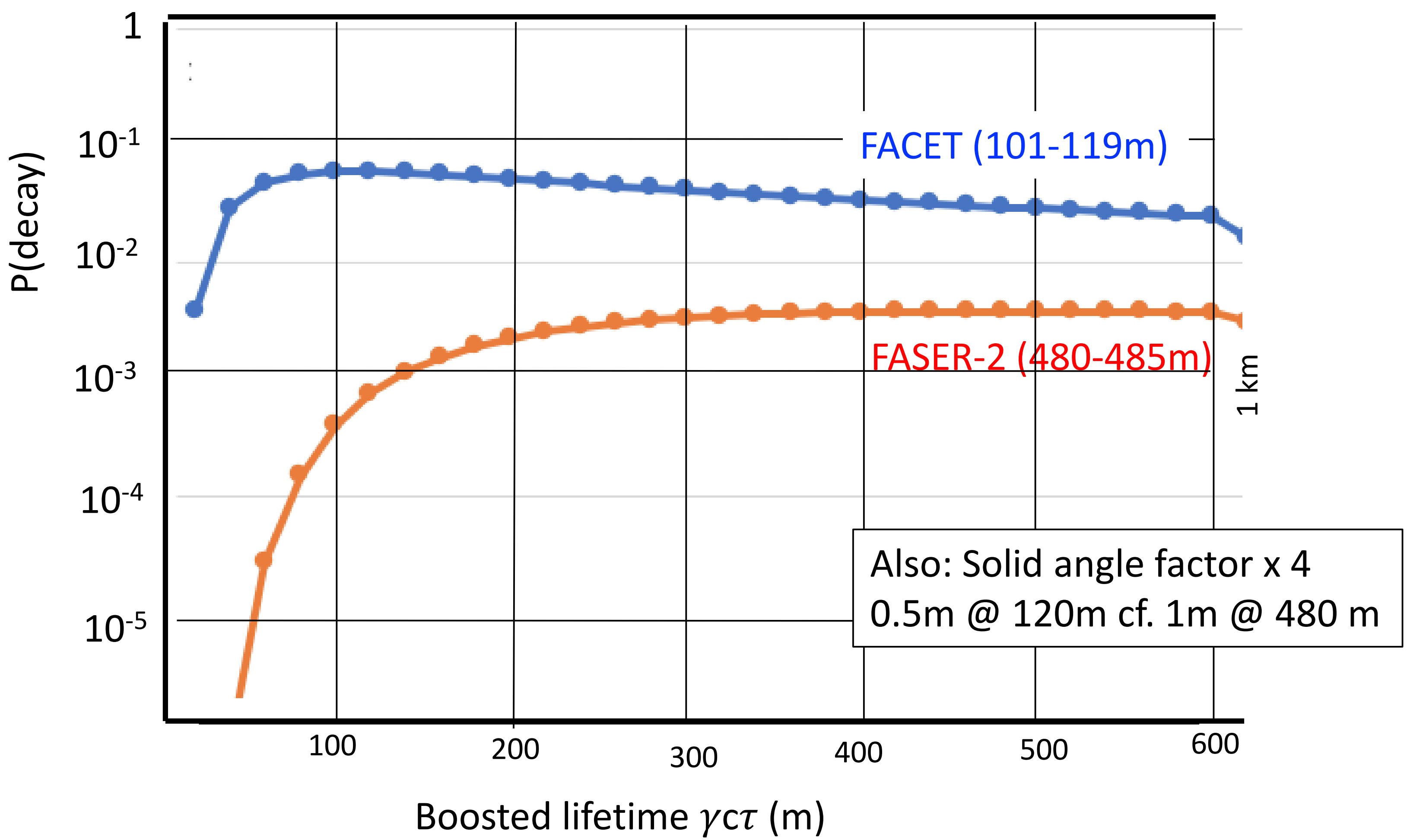


Comparison of HNL reach with other experiments:
Of these, only LHCb is approved now &
their background may be reducible)

FACET's larger decay volume at z = 100m : unique

Note:
in areas of overlap # events can be very different!

Probability of decay in length stated vs. lifetime in lab.



For $c\tau$ divide by γ = E/m e.g. m = 5 GeV, E = 50 GeV divide by 10, so $c\tau$ > 10 m is OK
Coverage in $c\tau$ - m plane depends on momentum spectra – model dependent

Precision timing (< ~ 30 ps on tracks) with MIP Timing Detector MTD (LGAD) layer

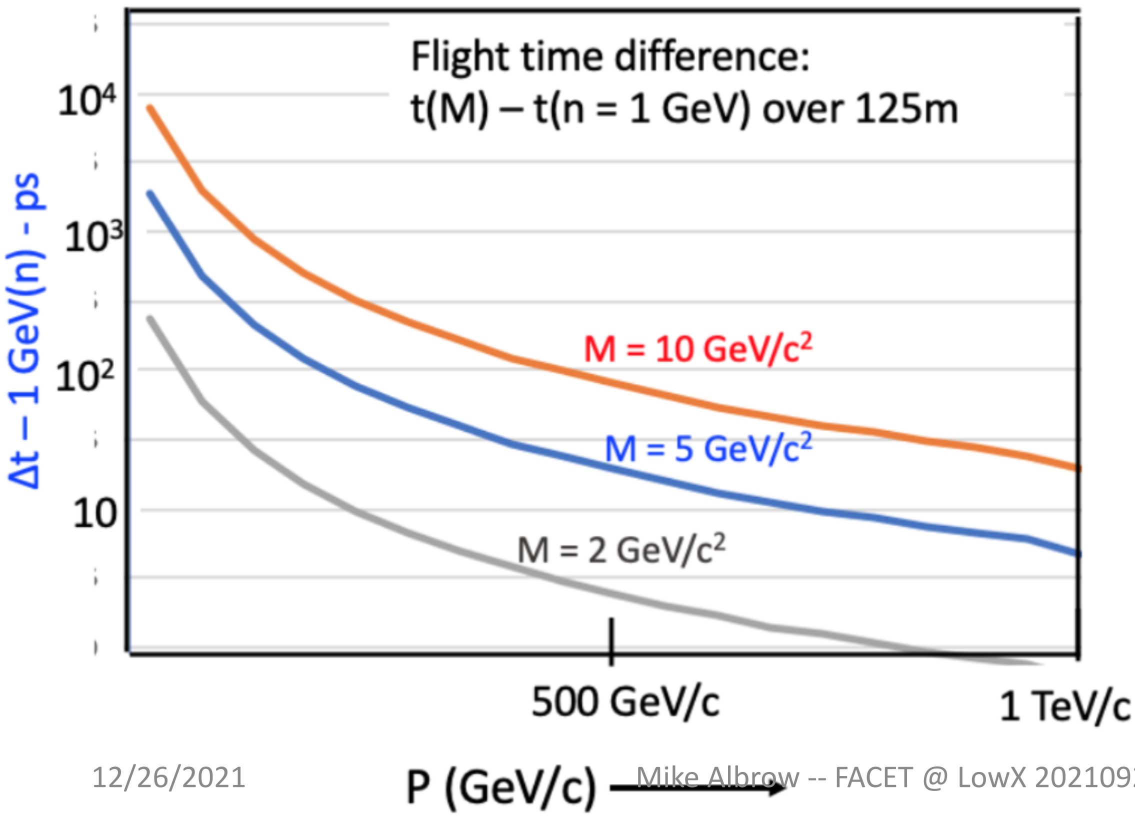
Two different reasons:

Background reduction: Vertex in x,y,z,t.

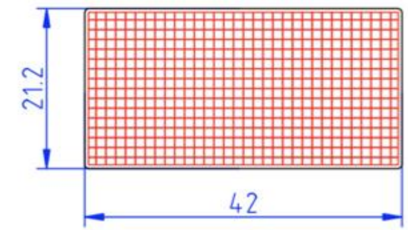
σ(t) interactions in BX ~ 200 ps

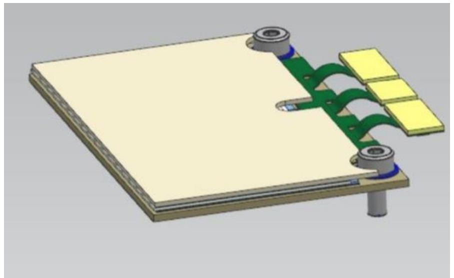
Time of flight → constraint on M(X) if M(X)/p(X) low enough

Example. … M(X) = 5 GeV & p(X) = 100 GeV/c Δt(5-1) = 420 ps



1.3mm x 1.3mm pads from 6” wafers





Integration with CMS plan

FACET: New subsystem of CMS, integrated.

All detectors are identical to planned CMS Upgrade detectors, only ~ 5% area
→ No separate R&D needed, DAQ same. Increase “spares” in purchasing?

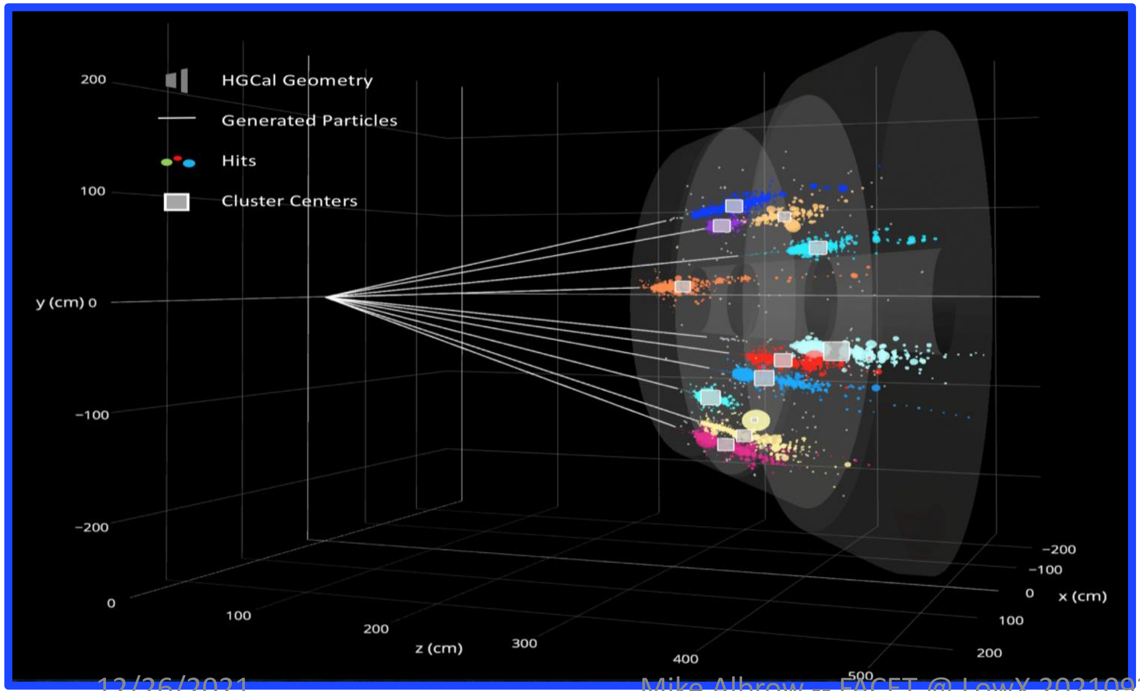
FACET detectors read out with all CMS events.
Separate L1 trigger from FACET, e.g.
>=2 tracks from vertex in vacuum without incoming charged particles in line
HLT refines selection with full reconstruction as usual.

Can also send **FACET-only data to separate stream** (small events)
With 140/BX not clear if correlation between Central CMS & FACET is useful

But correlations important with any low-pileup pp data and p+O, O+O .

Strengths of FACET for Long-Lived Particle Search

Large volume of vacuum for decays : 1m diameter and 18 m long
High precision tracking and imaging calorimeter ("HGCAL") to reconstruct decays in vacuum
35m – 50m shielding in direct path from IR for penetrating LLPs
No direct charged particles over most of area (swept aside by Q1-Q3 and D1)
Boosted lifetimes up to km, unboosted **c.τ 1 m – 100 m** to reach 120 m
Masses ~ 1 GeV – 20 GeV+ especially
Ability to reconstruct **multiparticle decays τ τ , c-cbar, jet+jet** with **no background - ?**



FACET:
Complementary to all LHC central detector searches
& other search experiments
fixed target & LHC

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

Paper in preparation, prior to LoI/EoI to CMS & CERN LHCC

September 13, 2021

S.Cerci[†], D.Sunar Cerci[†] (Adiyaman Univ.), G.Landsberg[*] (Univ. Brown), M.G.Albrow[*], J.Berryhill, D.R.Green, J.Hirschauer, V.Kashikhin, N.Mokhov, I.Rakhno (Fermilab), M.Paulini (Carnegie-Mellon Univ.), F.Cerruti, D.Lazic, M.Sabate-Gilarte (CERN), J.E.Brücken (Helsinki Inst. Phys.), L.Emediato, J.Nachtman, Y.Onel, A.Penzo (Univ. Iowa), O.Aydilek, B.Hacisahinoglu, I.Hos, B.Isildak, S.Ozkorucuklu[*], H.Sert, C.Simsek, C.Zorbilmez (Istanbul Univ.), N.Hadley, A.Skuja (Univ. Maryland), R.Rusack (Univ. Minnesota), M.Klute (MIT), Z.Liu, V.Q.Tran, M.Du (Nanjing)

[*]Contacts: albrow@fnal.gov, Greg.Landsberg@cern.ch, Suat.Ozkorucuklu@cern.ch
[†]Also at Istanbul University

Biweekly meetings – a CMS member now or potentially & want to join?
Contact Deniz.sunar.Cerci@cern.ch or above contacts

SUMMARY:

FACET: Forward Multiparticle Spectrometer for CMS Run 4

Under development → Letter of Intent to CMS Fall 2021

Unique LLP discovery potential at HL (3 ab^{-1}) + SM hadron physics at low lumi pp, pO, OO

LHC magnets (quads + dipole) 35-50m Fe absorber for LLP, spectrometer for SM
Large 18m x 1m ϕ vacuum tank as decay volume, very low backgrounds
Thin back window + 3m tracking + 2m EM+HAD calorimeter + 3m muon spectrometer
All clones of CMS Endcap upgrade detectors but ~ 5% of area.

Many opportunities to participate for theorists, phenomenologists, CMS members

Special thanks to LHC Colleagues: Francesco Cerutti, Marta Sabate-Gilarte, Vincent Baglin et al.

Forward Hadron Spectrometer project

QCD not LLPs – Low pileup running

Snowmass White Paper to be prepared for March 2022

Similar large beam pipe downstream of any intersection:

ALICE (has one to be modified), ATLAS, CMS, LHCb ??

Larger upstream pipe --> Increase acceptance for throughgoing hadrons

Hadron (π, K, p) identification with Transition Radiation Detectors (3m – 4m)

PHYSICS:

Forward hadron production spectra (including charm, e.g. D^0 --> K π)

Intrinsic heavy flavor a la Brodsky

Needed to understand VHE cosmic ray showers

Needed to know forward neutrino spectra and composition (incl. $\boldsymbol{\nu}_\tau$)

++

With correlations to full event in central detectors

Also in heavy ion collisions.

Such measurements should be done at LHC before it ends!

Please see me albrow@fnal.gov and help prepare this White Paper

Thank you

Back-ups →

Progress in 2020 (earlier talks on hadron spectra)

Two dedicated workshops in 2020:

April 16+17 https://indico.cern.ch/event/868473/
Forward Spectrometer Meeting (one day LLP + one day Hadron spectra)

October 1st https://indico.cern.ch/event/959035/
FMS-LLP search General Meeting

November 16th talk (MGA) at Eighth Workshop on Long-Lived Particles at LHC

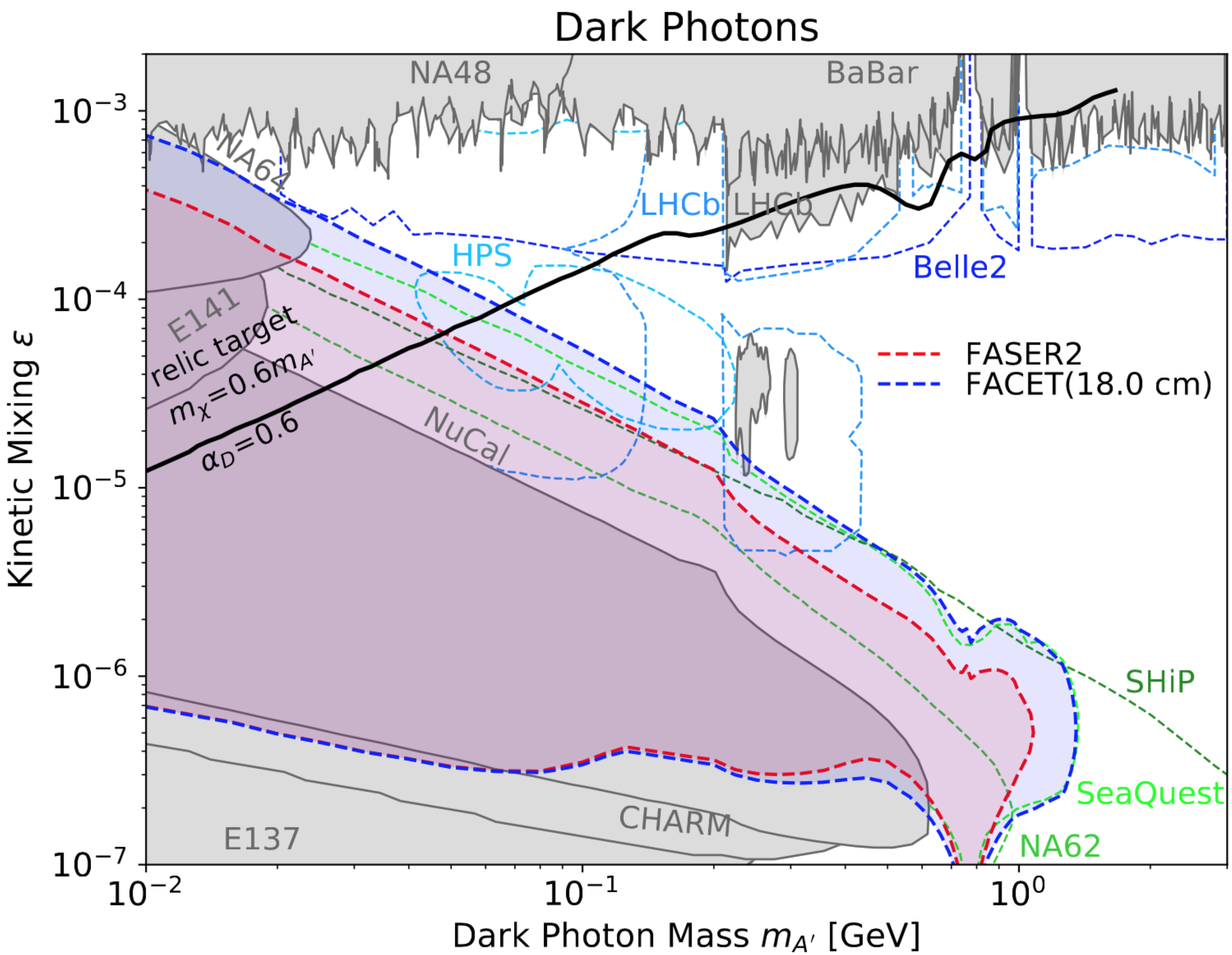
Two Snowmass2021 Expressions of Interest (EXO, HAD)

Bi-weekly meetings: simulations, **developing "Letter of Intent" to CMS**

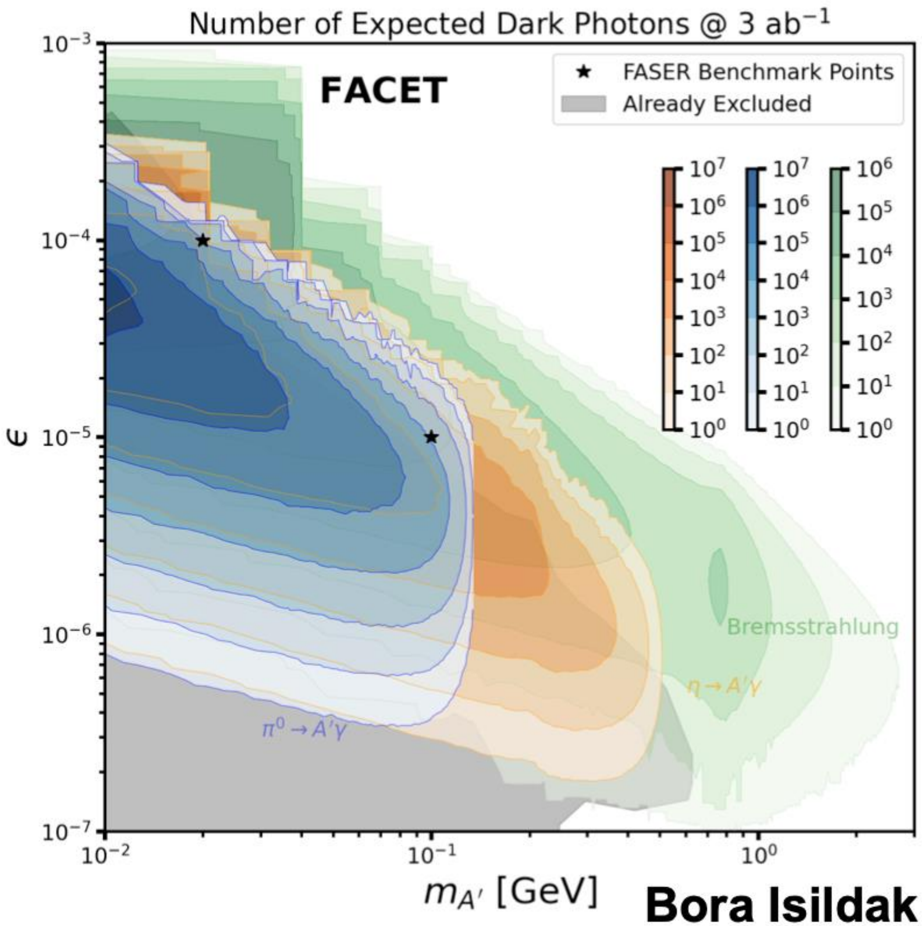
If in CMS & interested contact Deniz.Sunar.Cerci@cern.ch

Presentation to **CMS Plenary Dec 1st by Greg Landsberg (Brown Univ)**

For $M(A_\mu) > 1$ GeV the main sources are (1) annihilation: $q\bar{q} \to A_\mu + \gamma$, (2) Drell-Yan: $q\bar{q} \to A_\mu$, (3) quark bremsstrahlung: $q \to q + A_\mu$, and (4) (c- or b-) meson decays: e.g. $D \to A_\mu + X$.



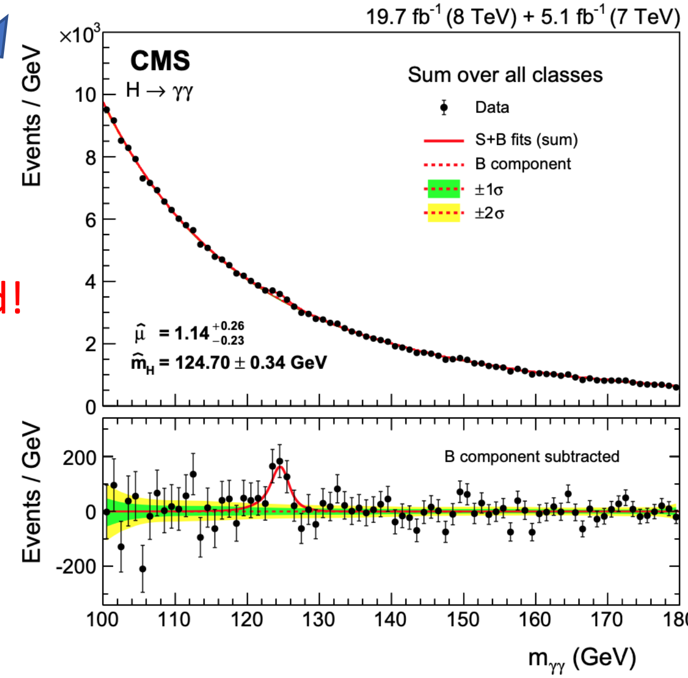
Simulations with EPOS of expected reach in mass x coupling plane



Preliminary

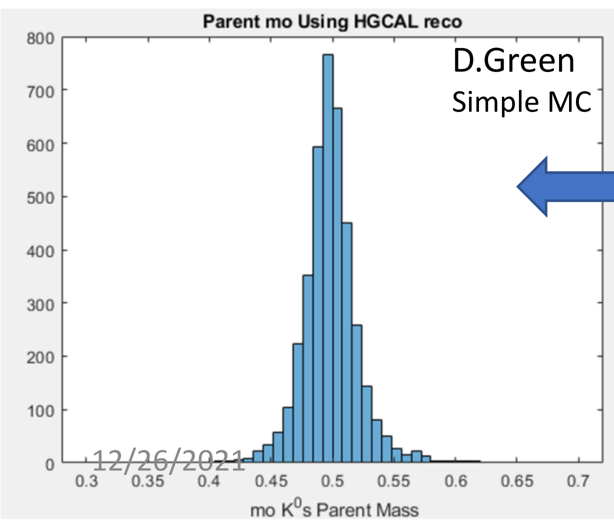
ZERO BACKGROUND? Is it possible? Studies underway

CONTRAST W & Z discoveries: 6 and 4 candidates, negligible background, expected particles.
H discovery in $\gamma\gamma$ … S/B = 1/20 in peak 1 GeV mass bin (σ = 1.35 GeV)



A few clean events with "0" background – discovery
HL Run = 3 ab^{-1} = 2 x 10^{15} bunch crossings (140/X)
Strategy: identify & simulate all possible backgrounds.
Aim to kill them → influences detector design.
VACUUM tank: vertex inside – no interaction background!

Example 1: X → μ+μ-
Only SM: ~ 5 x 10^{15} K^0 entering pipe→ μ+μ- (BR < 10^{-9})
π+ π- with both tagged as muons: **μ/π separation!**
K^0_L →πμν with one fake μ, etc. M < 0.5 GeV

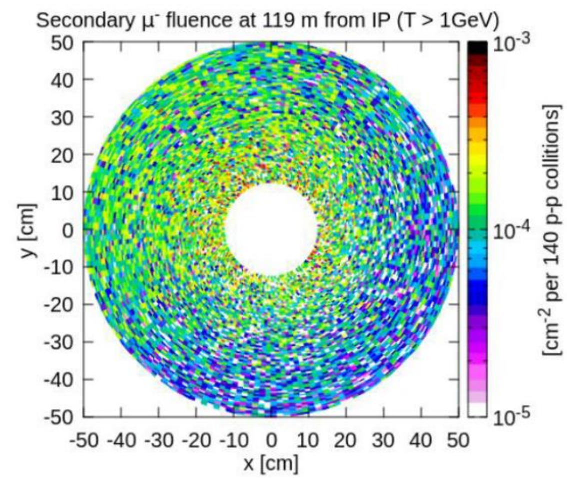


Both charged tracks well measured (over 3m, σ = 30 μm)
+ Calorimeter energy → mass: exclude 0.4 – 0.6 GeV
Muon momenta measured in back toroid.
Also have lifetime distribution **($c\tau$ (K_S) = 2.7 cm)**

4-track vertex B/G: 2 overlapping K^0 decays?
Vertexing in space & time: x,y,z,t - **good (30 ps) timing helps**

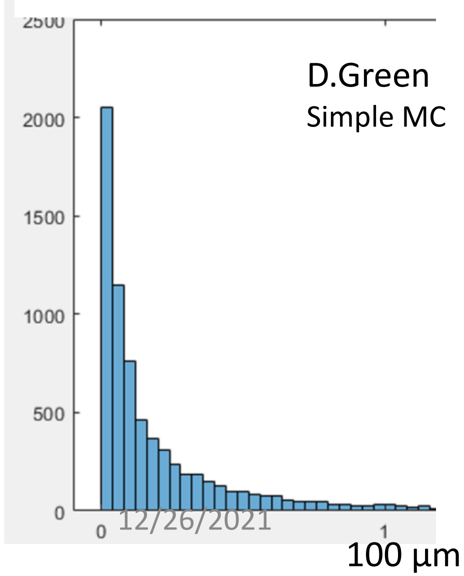
ZERO BACKGROUND? Is it possible - continued?

Another background to X → μ+ μ- to consider:
Two independent muons, different collisions in same BX, crossing in space!
Have ~ 1.4 μ / BX (secondaries from interactions)
Distributed over area (FLUKA simulation):



Project track to Front Hodoscope: Error circle ~ 50 μm
Possible: six layers of rad hard scintillator strips uvwuvw at 60°
Tag and discard entering muons. Want inefficiency < 10^{-6}
> Excellent input hodoscope/tracker (few mm^2 segmentation)
Still have ~ **10^7 BX** with two uncorrelated muons entering tank
Calculate **dca = distance of closest approach**, cut at 50 μm
> Excellent tracking resolution (and thin back window, no m.s.)

DISTANCE of CLOSEST APPROACH



VERY preliminary estimate ~ 150 μμ in 3 ab^{-1} with a random crossing pair
50% are ++ or - - background
Time spread σ(coll/BX) ~ 200 ps cf σ(track) ~ 30 ps
> Time resolution on tracks wanted!
"Parent" pointing back to IR ?
Any remnant fake pairs? M(μ+μ-) look for peaks.
Background/bin is relevant :
> **Good p(μ) resolution → M(μ+μ-) resolution**
Studies in progress but **ZBG*** may be possible IFF detectors ****
Higher M(X) cleaner, e.g. multi-hadrons. *Zero BackGround