The FACET PROJECT

Mike Albrow (Fermilab, CMS)

LoI to CMS under development
Run 4 (2027+) and beyond

FACET = **F**orward **A**perture **C**MS **Ex**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 steel & decaying in vacuum
M(X) up to ~ 25 GeV (multiparticle decays) with long lifetimes $c\tau$ = 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 – eventually?)
E.g. γ^* , J/ψ → $\mu^+\mu^-$ and ^{3}He and anti-^{3}He at high luminosity Rare LFV $D_s \rightarrow \mu+\mu+\pi-$? < 10^{-7}
Also: K^0_s and Λ^0 and $D^0 \rightarrow K^{\pm}\pi^{\mp}$ in **low pileup pp runs and ion runs (p+O, O+O)** if they come.

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:

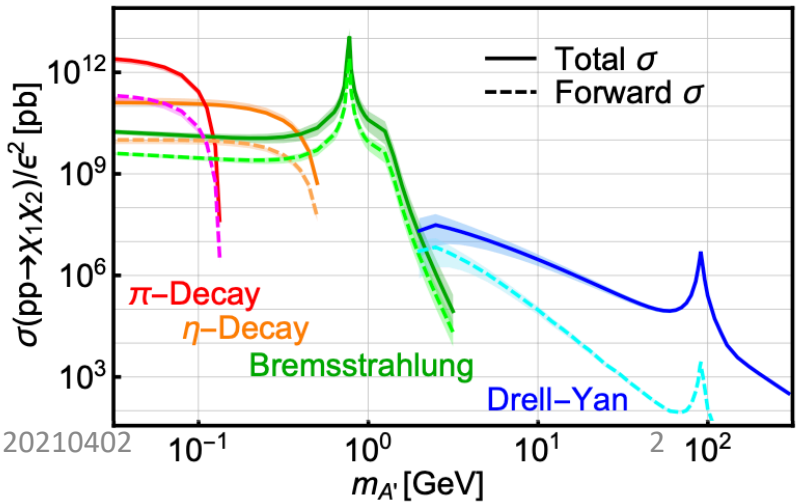
Vector J = 1 : Z' or dark photon **A'** that mixes with photon γ^*
Spinor J = ½ : Heavy neutral lepton **HNL**
Scalar J = 0 : **dark Higgs**, dark pseudoscalars (π'), axion-like particles (**ALP**s)

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 $p \rightarrow p + \gamma^*$ & $q \rightarrow q + \gamma^*$
Drell-Yan q-$\bar{q}$ annihilation
QCD: **q g → q γ^***

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

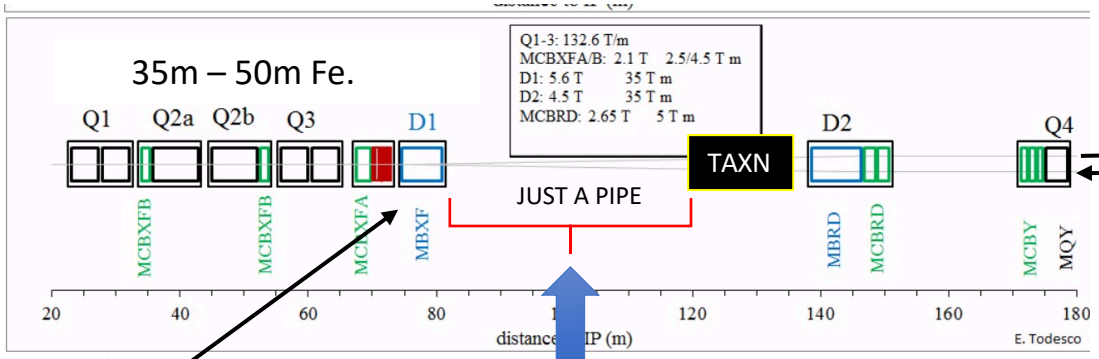
Berlin & Kling arXiv:1810.01879



RUN 4 – HL LHC

CMS CENTRAL

IR5



BEAMS

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

Dipole section

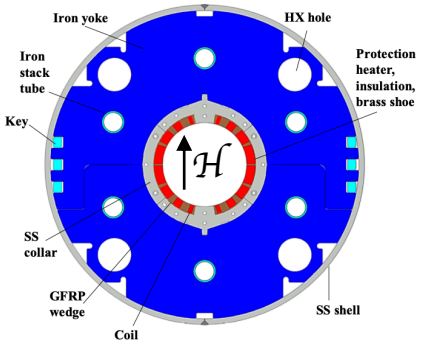


Fig. 4.1: Cross-section of the separation dipole.

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

~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

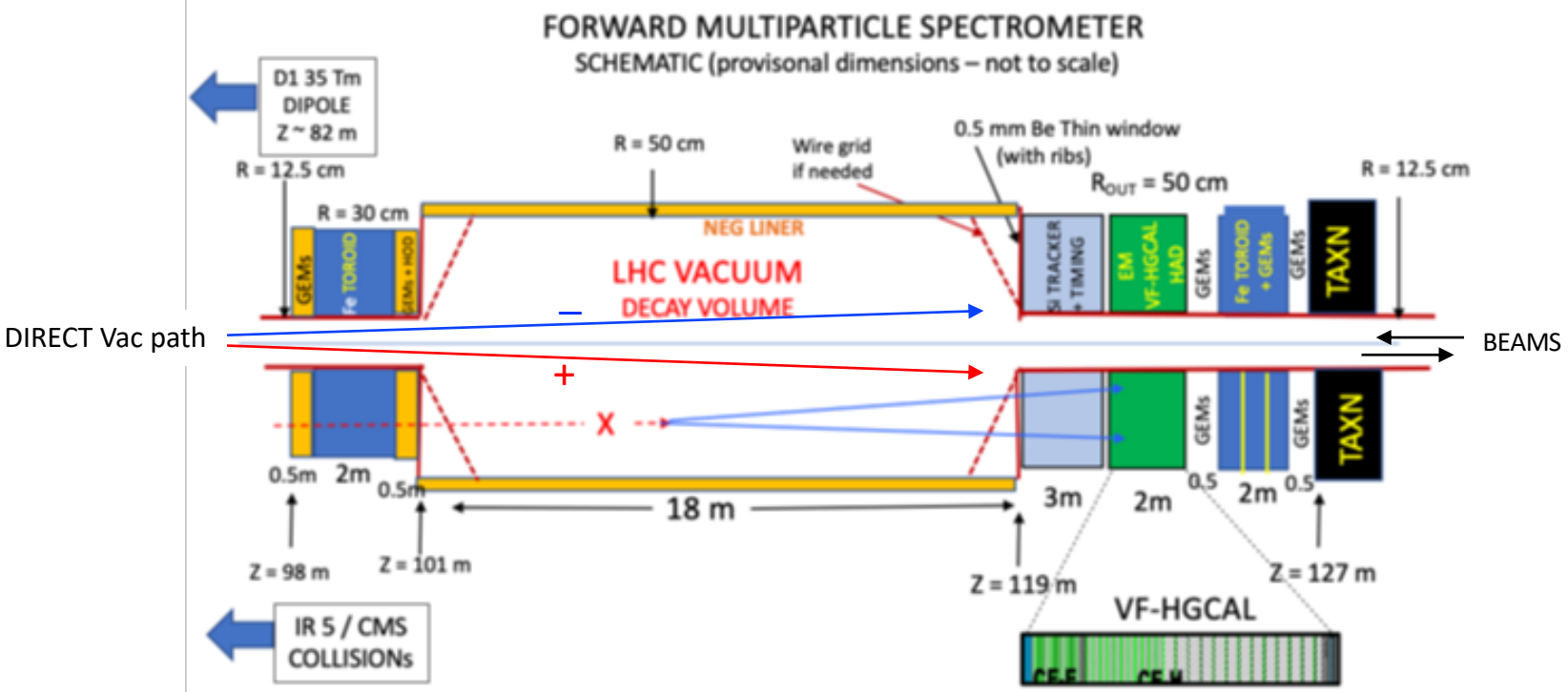
Propose to replace with larger vac pipe R = 50 cm, L = 18 m (z =101-119 m)

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

LHC: "Provisionally OK, subject to detailed study"

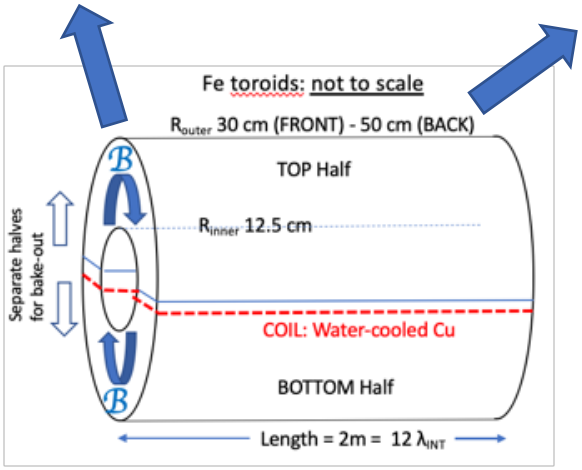
No special running conditions required.

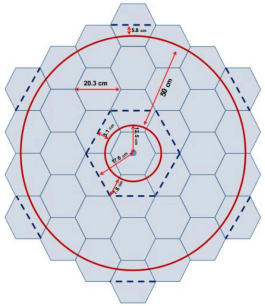
FACET



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

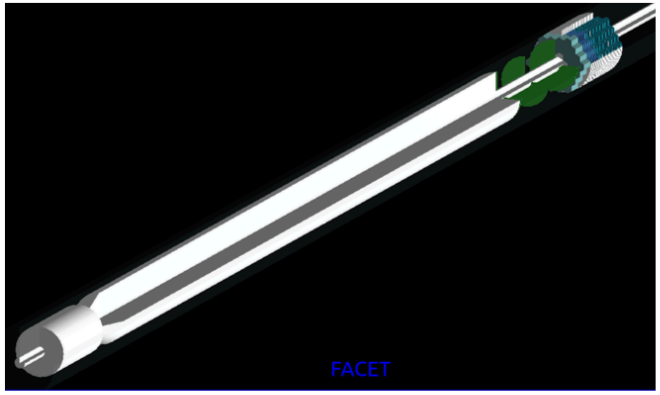
Iron toroids at Front and back

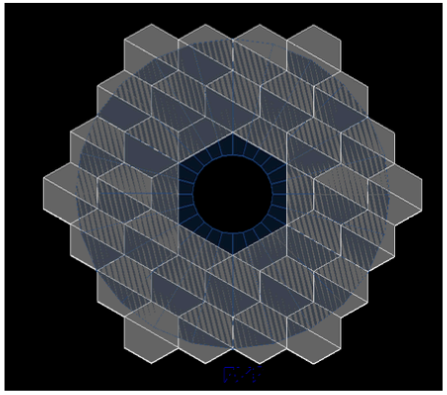


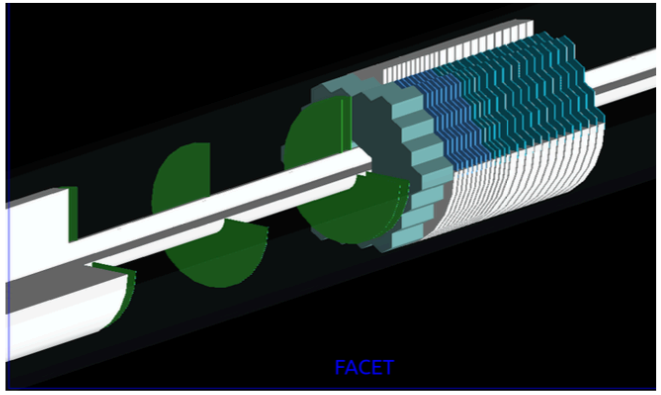


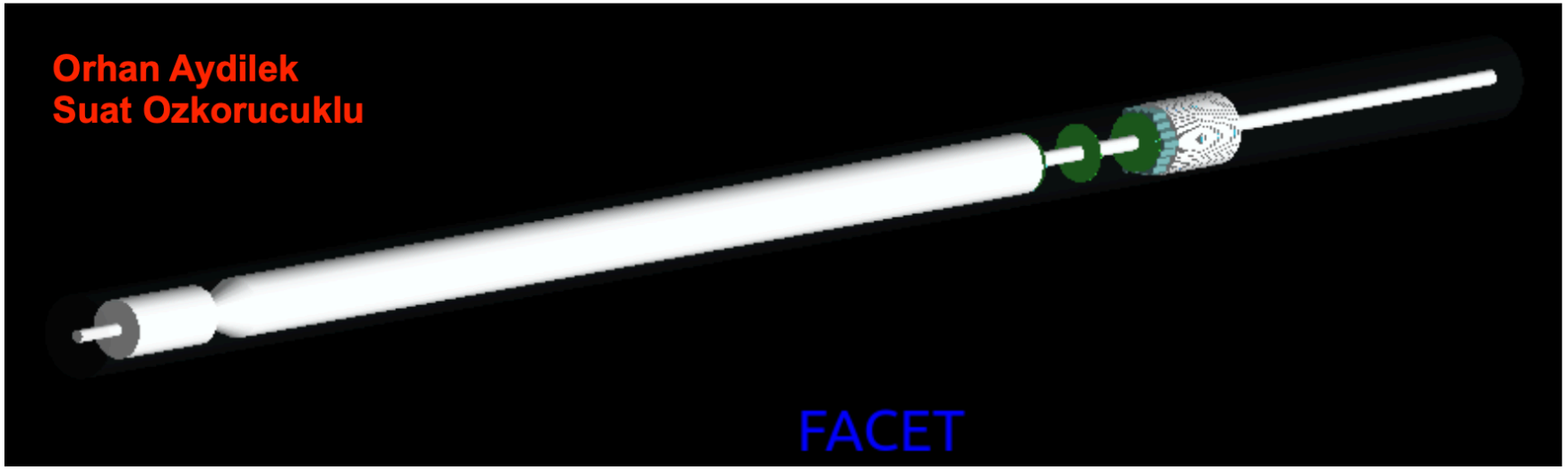
Plan to use only detectors planned for CMS at HL
~ + 5% is sufficient (0.7 m^2)

GEANT Simulations (& DELPHES) being developed (Istanbul Group)
Use hexagonal or half-hexagonal silicon wafers as Endcap





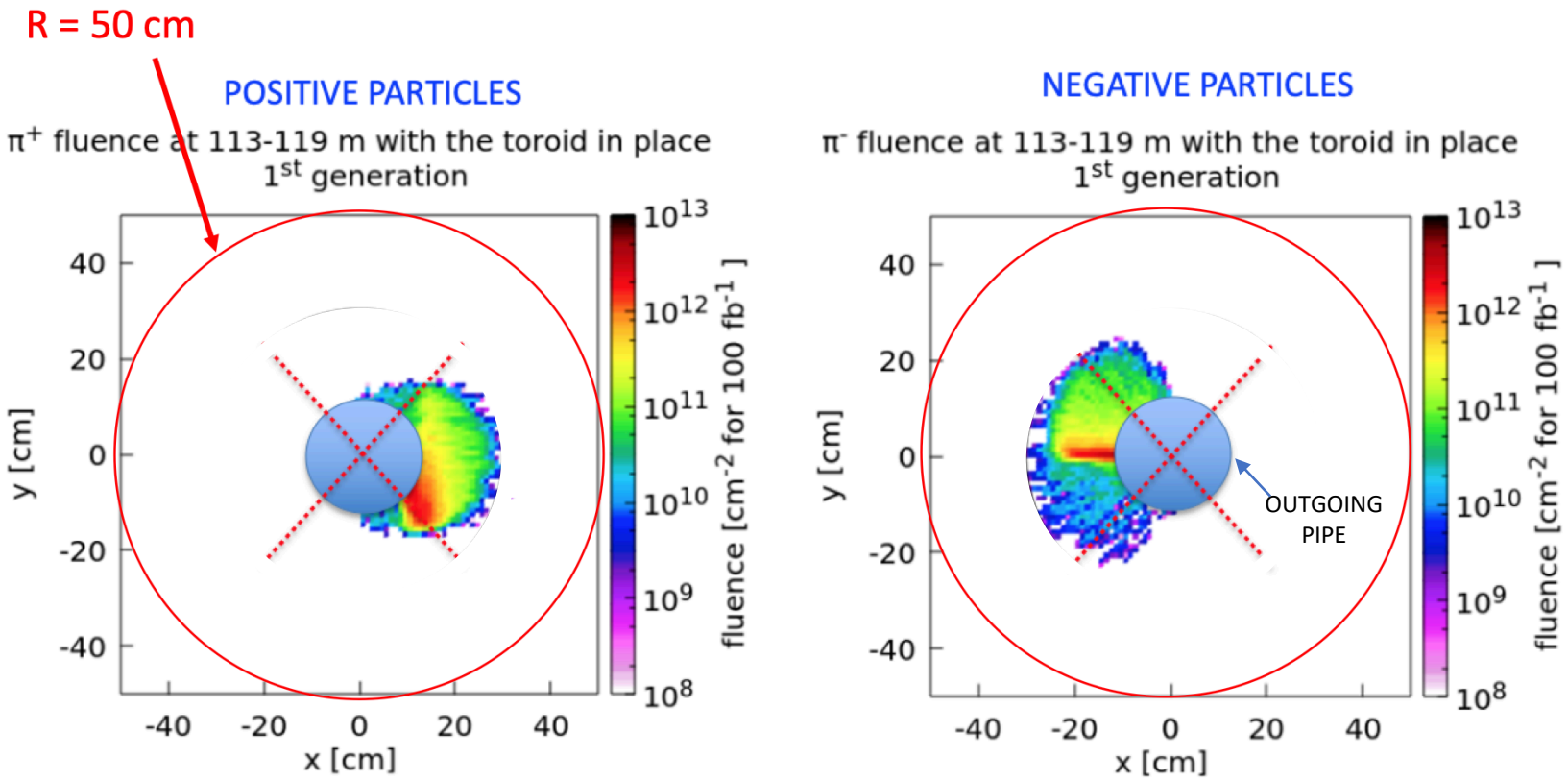




Charged particles through vacuum pipe & D1 aperture (deflected) and Toroid hole

Cover small areas L (-) and R (+). Eventually?: Instrument these areas with TRD for π/K/p/d

Everywhere else (95%) only penetrating neutrals, instrument for decays at High Luminosity



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

- Vertical crossing angle + Quadrupole fields → Up/Down asymmetry

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 (< ~ 10 GeV) in production

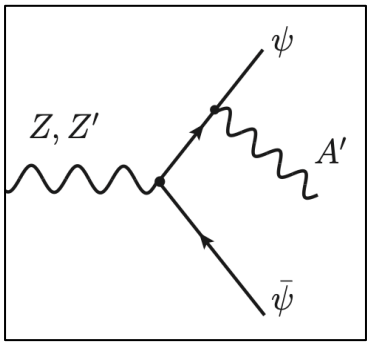
Low-p_T, forward production favored, Δy . Δφ rather than ΔΩ

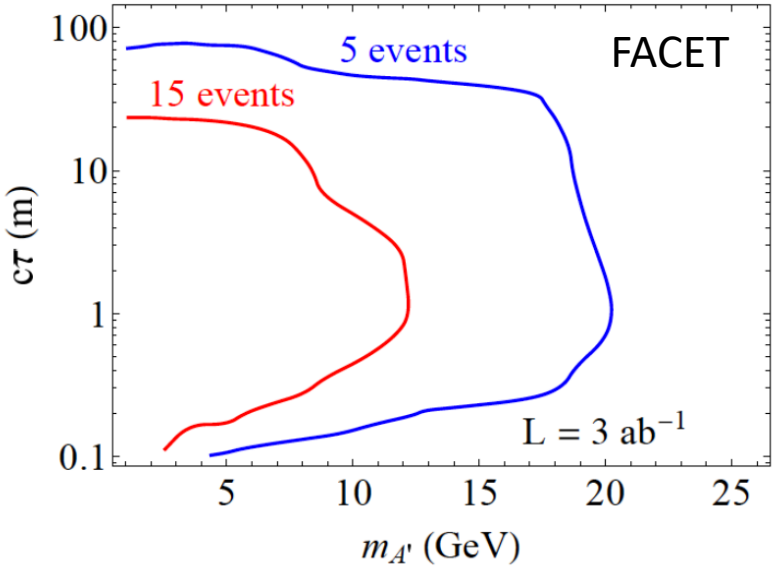
One example of Class A in FMS: arXiv:1912.00422 [hep-ph]

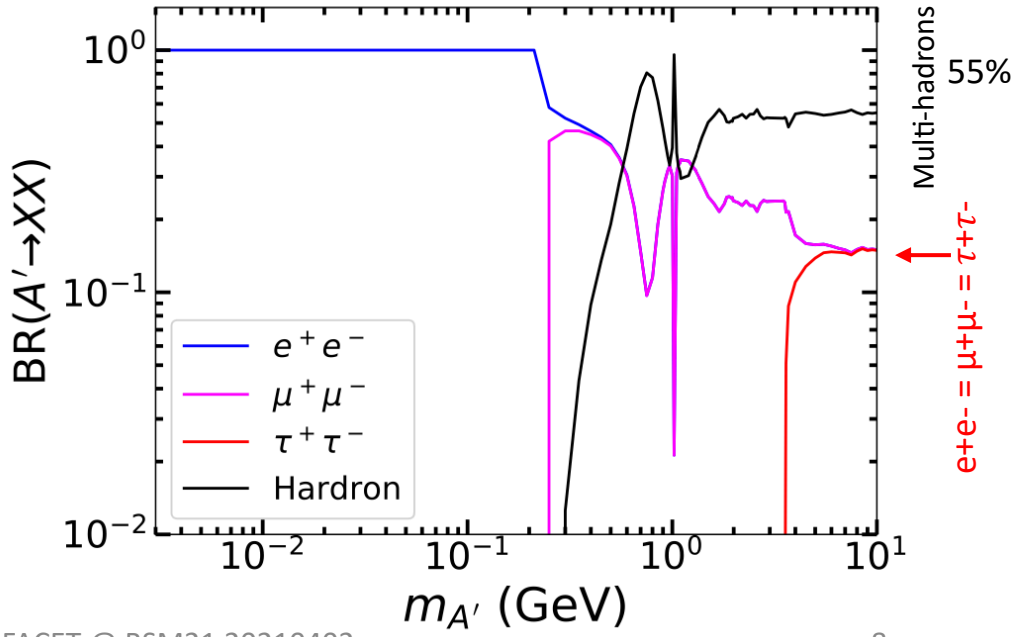
Enhanced Long-Lived Dark Photon Signals at the LHC

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

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







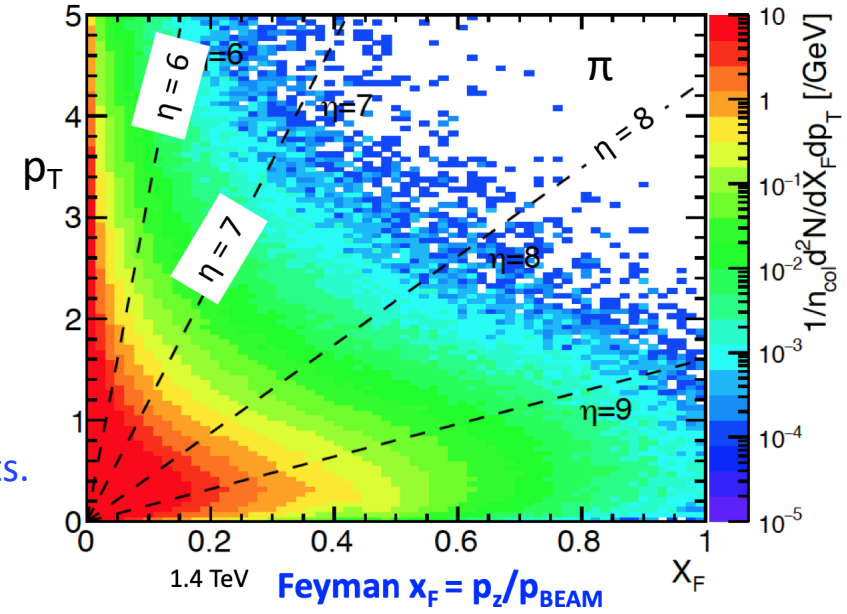
Class A: some coverage **if background-free,**

- but central favored

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

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

EPOS-LHC (H.Menjo)



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 - ~ 10 GeV

LHC increasingly favored over Fixed Target experiments.

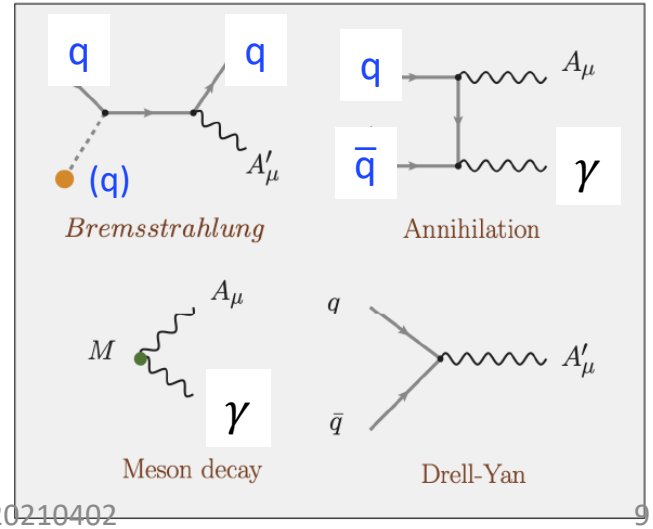
Forward region favored over central (fluxes)

A' production processes Light or medium classes →

Also proton bremsstrahlung p → p γ^*

Adapted from Fabbrichesi, Gabrrielli, Lafranchi

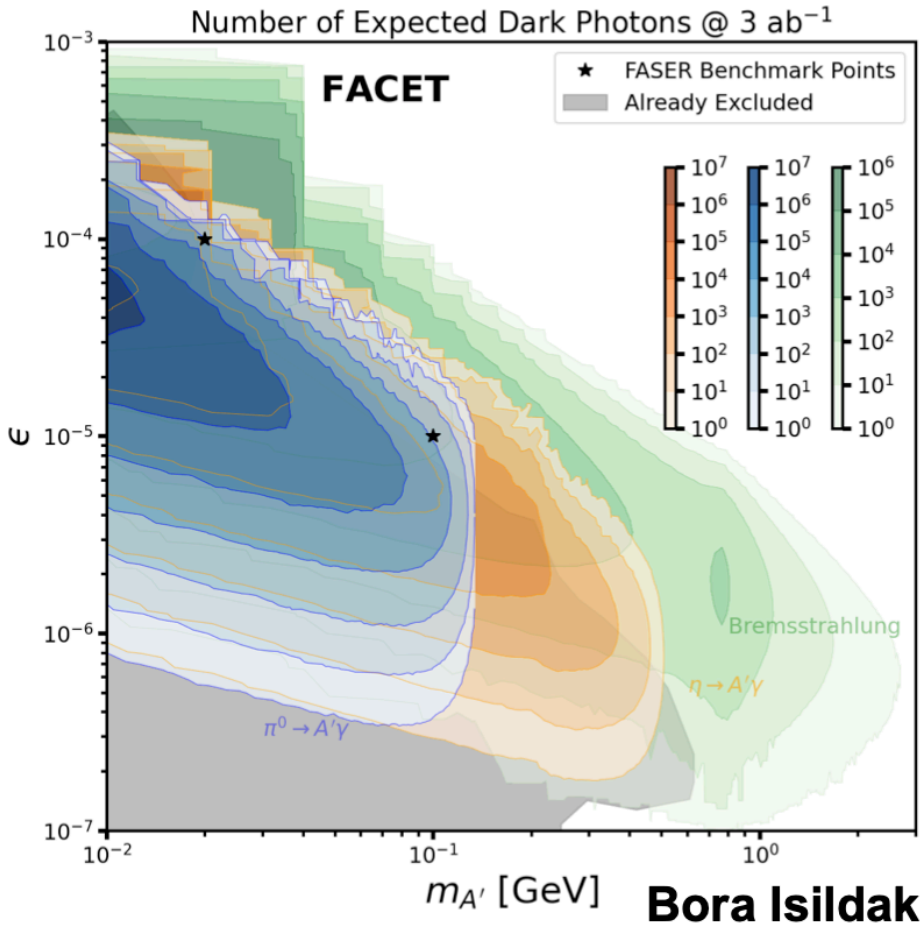
Dark Photon Review arXiv:2005.01515 [hep-ph] 2020



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".

Simulations with EPOS of expected reach in mass x coupling plane



Preliminary

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

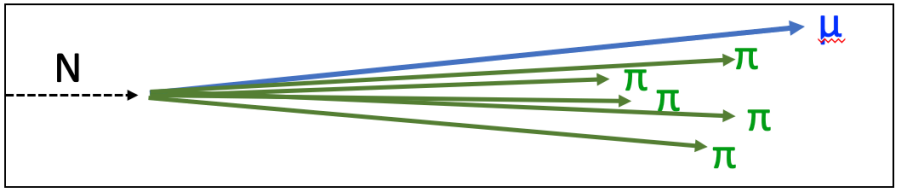
E.g. Frank F. Deppisch, Suchita Kulkarni, Wei Liu arXiv:1905.11889v2 [hep-ph]

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!):

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

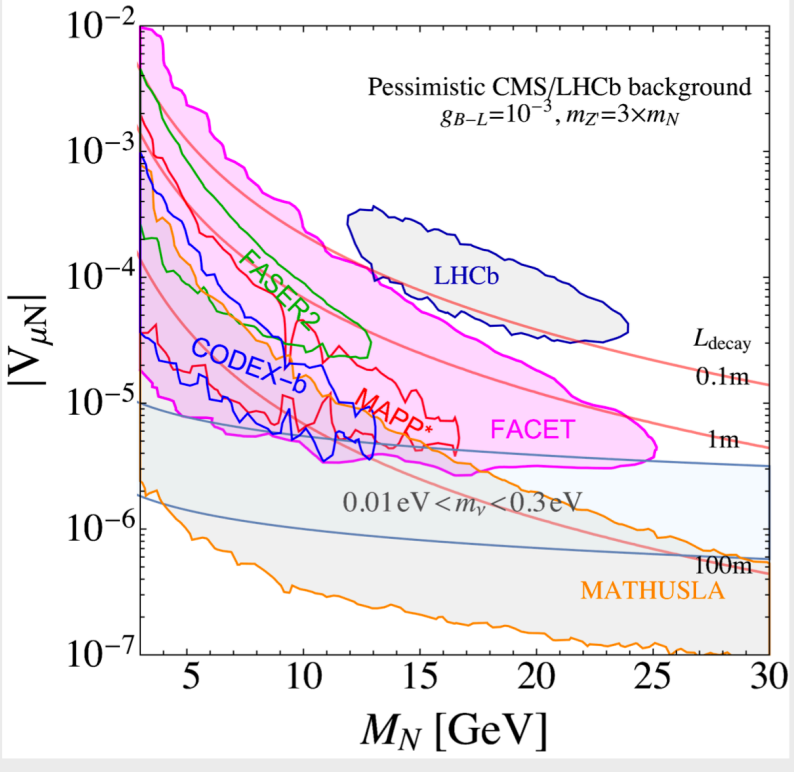


Comparison of HNL reach with other experiments:
Of these, only LHCb is approved now &
their background may be reducible)

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

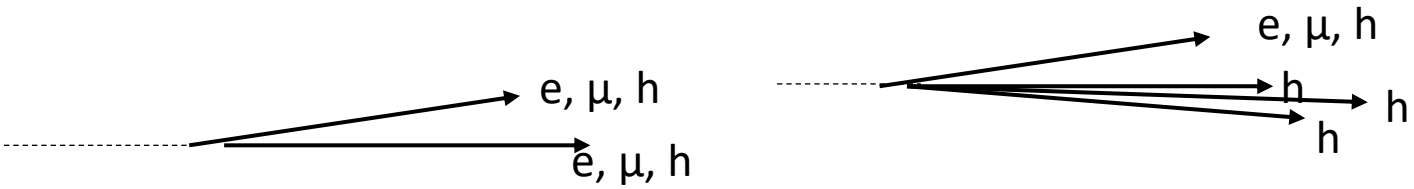
Note:
in areas of overlap # events can be very different!

(Thanks to Suchita Kulkarni for FACET study)



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

M(τ) = 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%



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

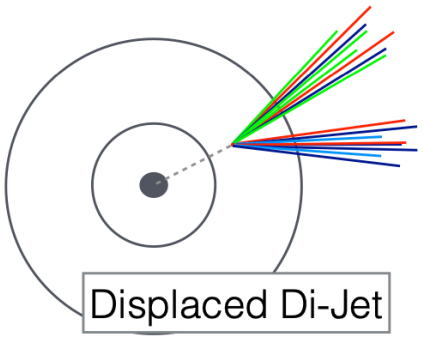
Consider e+e- events above open charm threshold 2 x M(D^0) = 3730 MeV
Boosted to high p_z (acceptance?) and decaying in pipe

All need full simulations – in progress

$X^0 \rightarrow q + q \rightarrow$ Jet + Jet?

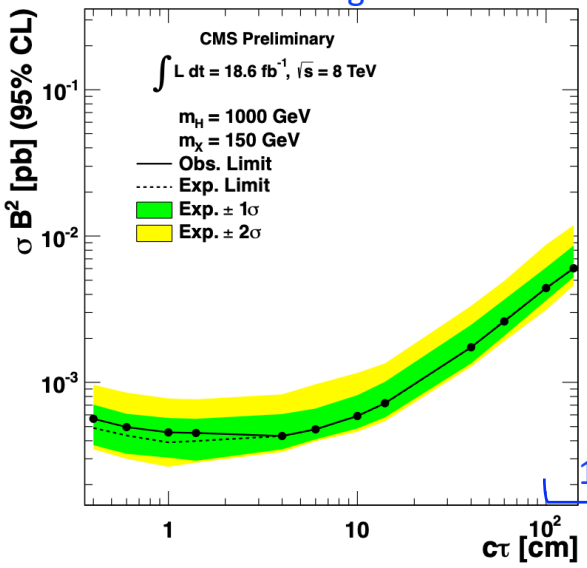
Emerging Jets with much longer c.τ than central detectors

CMS Central
Transverse view



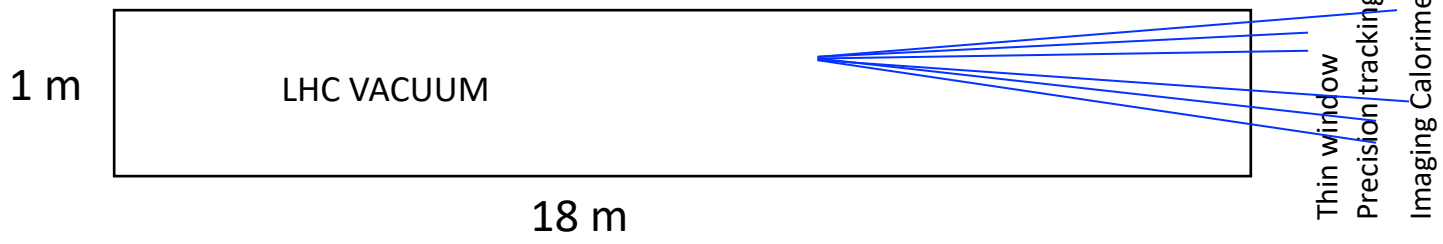
CMS Collaboration, Phys.Rev.D.91, 012017 (2015) [arXiv:1411.6530].

High Masses



1 m → 10 m – 100 m+

FMS



"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)

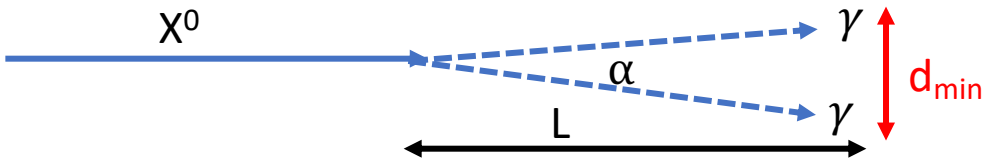
$\gamma\gamma$ vertex resolution, X^0 trajectory and opening angle

Single shower position resolution ~ 1mm

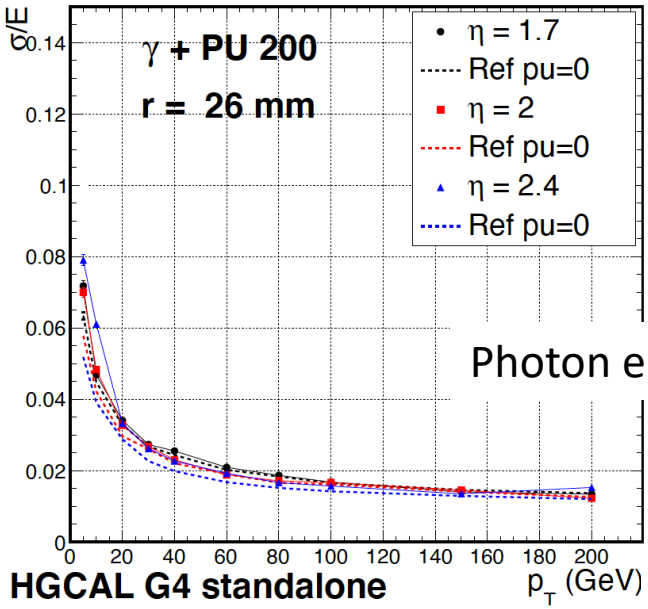
Angle resolution < 7 mrad (25 GeV showers)

$\sigma(M)$ ~ < ~ few %

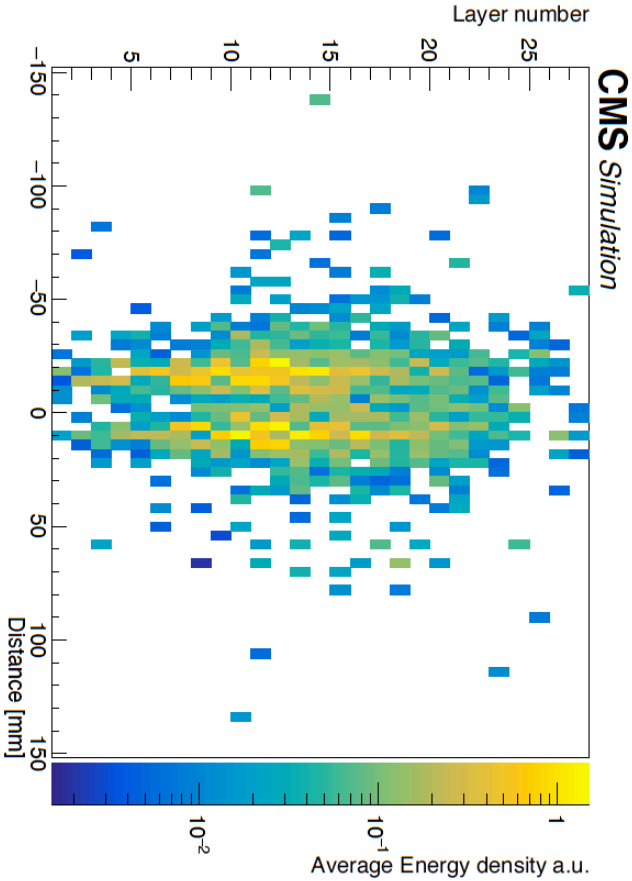
Simulation being done – π^0 π^0 pileup background?



From CMS-TDR-019 Fig 5.2

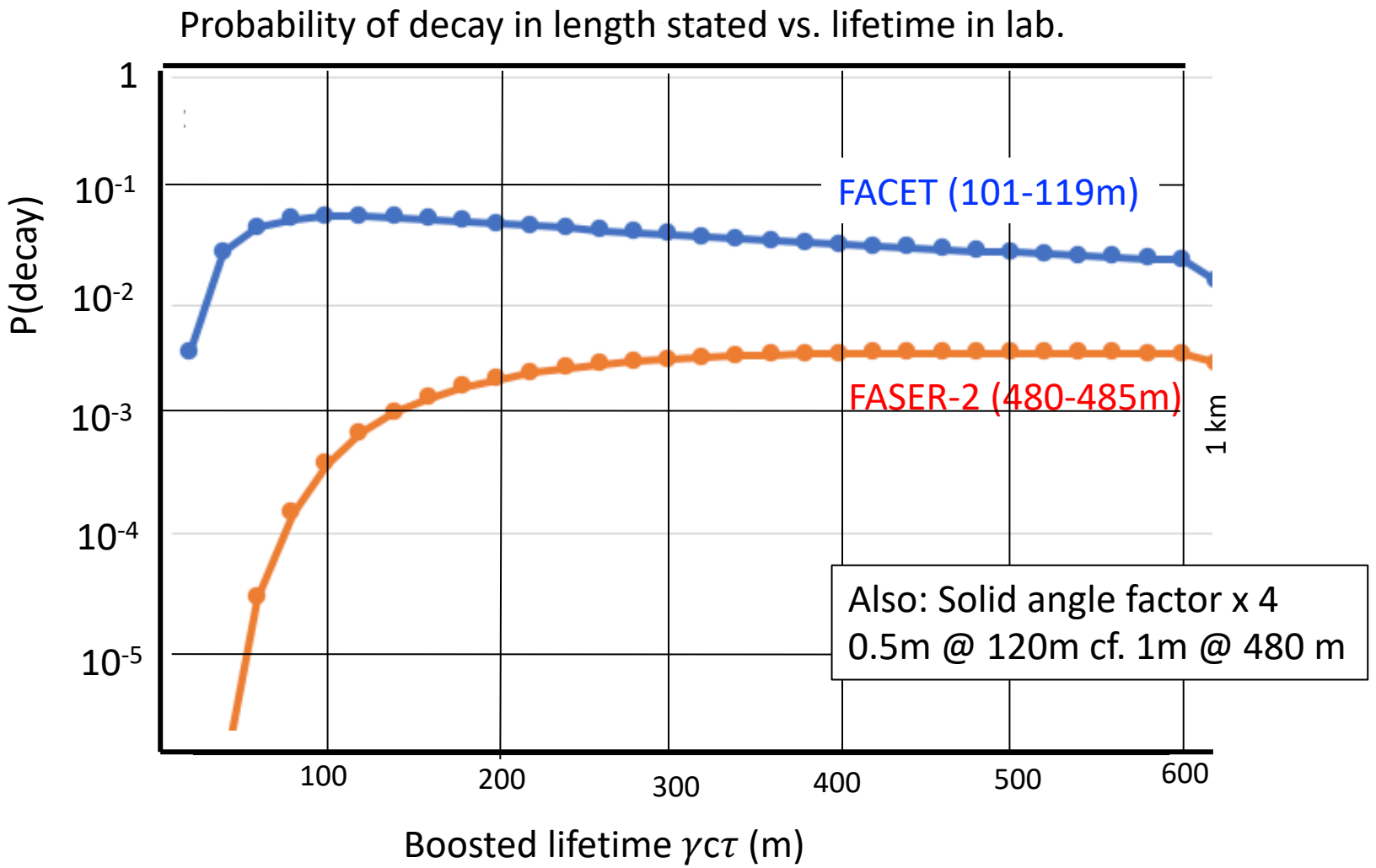


Photon energy resolution



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

~ E(X)/2 at θ ~ mrad in FACET



For $c\tau$ divide by γ = E/m e.g. m = 5 GeV, E = 50 GeV divide by 10, so $c\tau$ > 100 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

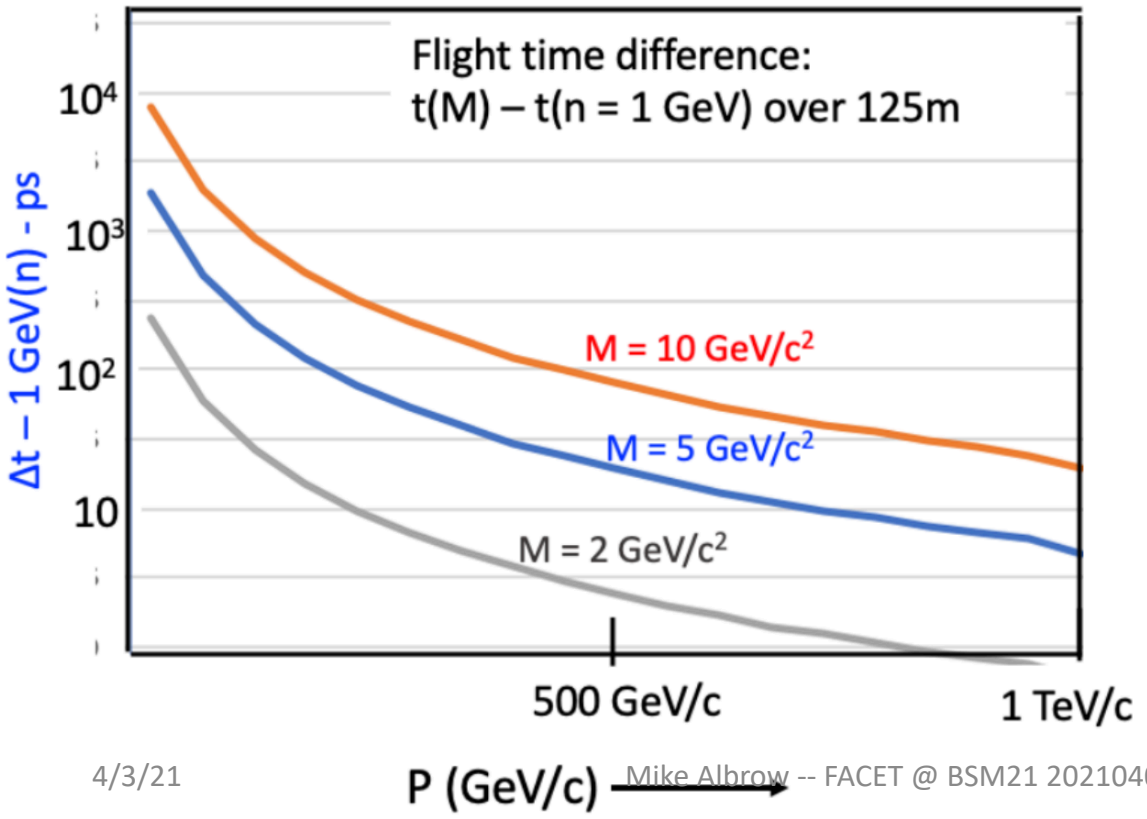
Two different reasons:

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

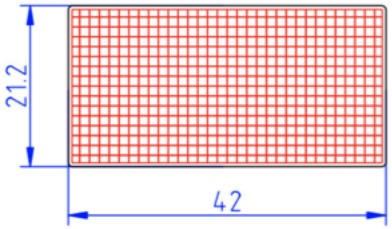
σ(t) interactions in BX ~ 200 ps

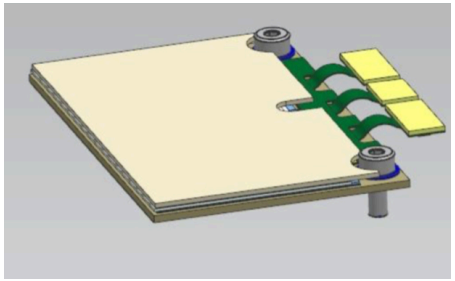
Time of flight → constraint on M(X) if M(X)/p(X) low enough

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



1.3mm x 1.3mm pads from 6" wafers



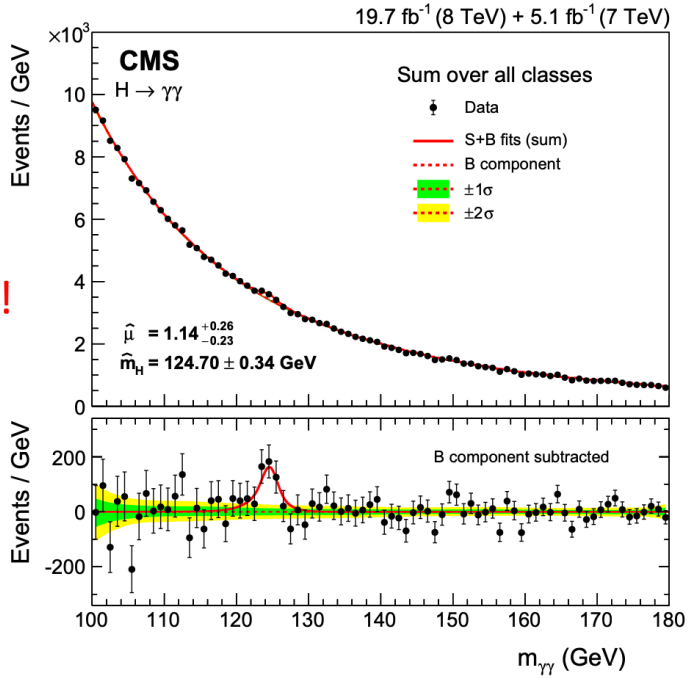


Erik Brucken (Helsinki Inst. Phys.)

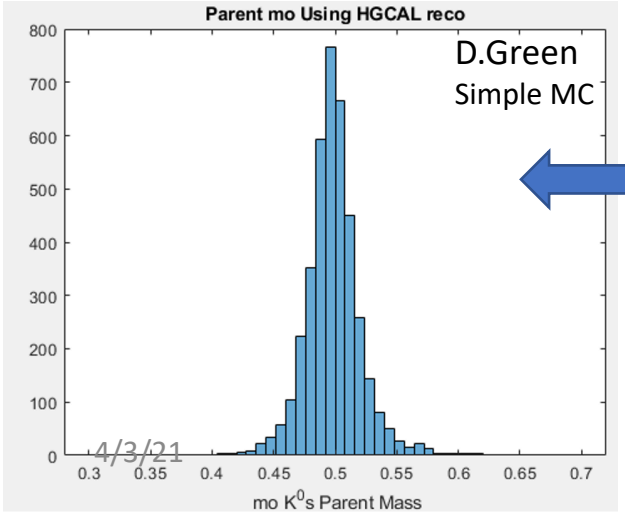
ZERO BACKGROUND? Is it possible? Studies underway

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

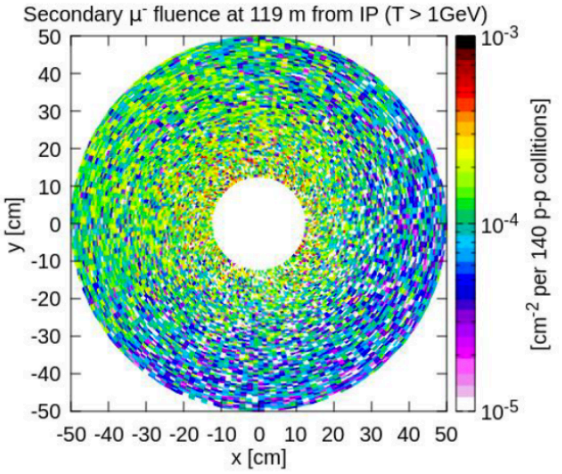


Both charged tracks well measured (over 3m, σ = 30 μm)
+ Calorimeter energy → mass: exclude 0.4 – 0.6 GeV
Muon momenta measured in back toroid.
Also have lifetime distribution **($c\tau$ (K_S) = 2.7 cm)**

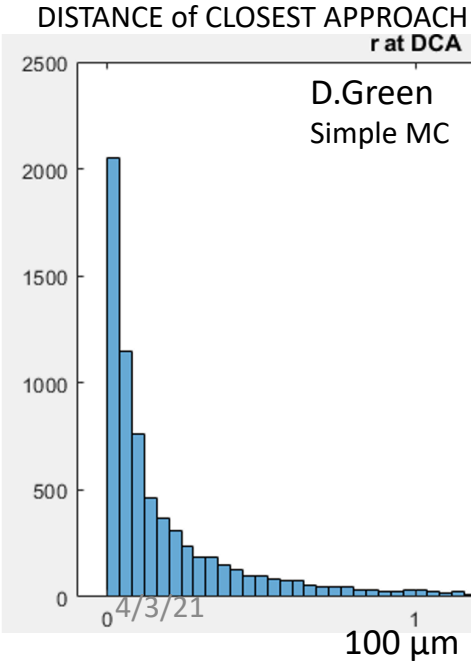
4-track vertex B/G: 2 overlapping K^0 decays?
Vertexing in space & time: x,y,z,t - **good (30 ps) timing helps**

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 Toroid GEMs: Error circle ~ 50 μm
Tag and discard entering muons. Want efficiency > 99.99%
> Excellent input hodoscope/tracker (few mm² 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.)



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

Integration with CMS plan

FACET: New subsystem of CMS, integrated.

All detectors are identical to planned CMS Upgrade detectors, only ~ 6% 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.

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

But important with low-pileup pp data and p+O, O+O - if it happens.

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)

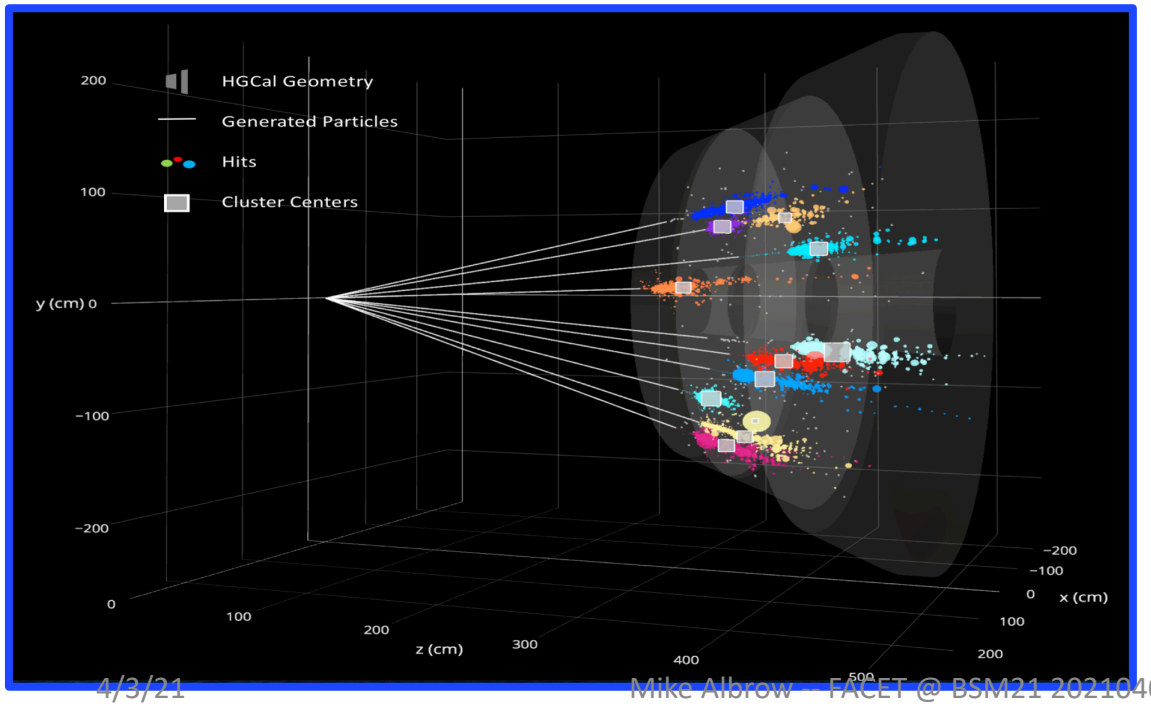
Bi-weekly meetings: simulations, **developing "Letter of Intent" to CMS**

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

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

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 $\tau\,\tau$, c-cbar, jet+jet** with **no background - ??**



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

SUMMARY:

FACET: Forward Multiparticle Spectrometer for CMS Run 4

Under development → Letter of Intent to CMS summer 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.

Thank you

Back-ups →

A Long-Lived Particle and Dark Matter Search at the LHC at z = 80 - 127 m. (Expression of Interest: Snowmass EF08+09+10)

Are we looking in the wrong direction?
Let's look FORWARD to it! (I know, FASER will be)

A new subsystem for CMS Run 4 (HL-LHC)

82– 126m downstream of IR-5

D.Cerci, S.Cerci (Adiyaman), G.Landsberg (Brown), M.G.Albrow*, D.R.Green, J.Hirschauer, V.Kashikhin, G.Krnjaic, N.Mokhov, I.Rakhno (Fermilab), M.Paulini (Carnegie-Mellon), A.De Roeck (CERN), L.Bonechi (Univ, INFN Firenze), D.Acosta (Florida), M.V.Garzelli (Hamburg), J.E.Brücken (Helsinki Inst. Phys.), L.Emediato, J.Nachtman, Y.Onel, A.Penzo (Iowa), O.Aydilek, B.Hacisahinoglu, B.Isildak, S.Ozkorucuklu, C.Simsek (Istanbul), C.Royon (Kansas), D. Wright (LLNL), A.Skuja (Maryland), R.Rusack (Minnesota), M.Klute (MIT), H.Menjo (Nagoya), Z. Liu, V. Tran, M. Du (Nanjing), C.Hill (Ohio State), S.Malik (Puerto Rico).
*Contact: albrow@fnal.gov

Abstract

We intend to develop a proposal to search for BSM long-lived particles (LLPs), such as dark photons with $m_{A'} \lesssim 20$ GeV, in the forward direction of IR5 (CMS), penetrating 35 m – 50 m of steel in the Q1 – Q3 quadrupoles and D1 dipole, and either decaying in a large vacuum pipe or interacting in an imaging calorimeter. Neutral LLPs with $|\eta| > 8$ decaying after traversing 83 m of vacuum may also be detected if their mass is several GeV.

CMS People presently active. Boxes show most active –
Biweekly meetings – want to join? Contact Deniz.sunar.Cerci@cern.ch

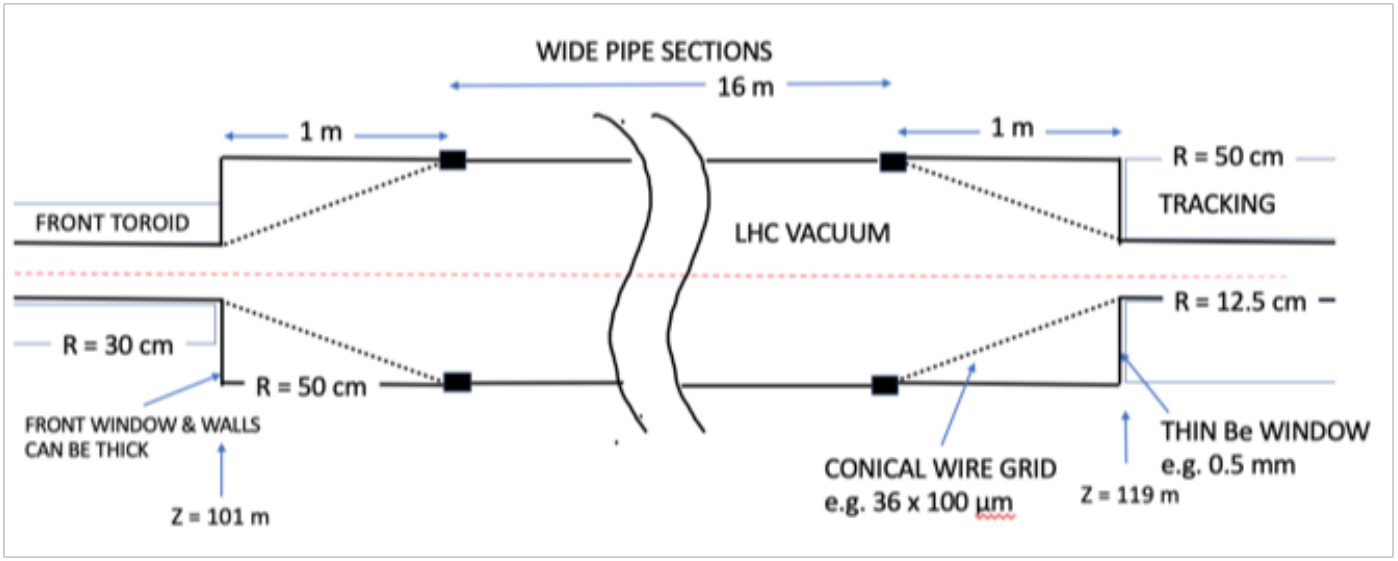
Adiyaman University, Turkey: D. Cerci, S. Cerci
Brown University, USA: G. Landsberg
Carnegie-Mellon University, USA: M. Paulini
CERN: A. De Roeck
Fermilab, USA : M.G. Albrow, D.R. Green, J. Hirschauer, ++?
Firenze, Univ. and INFN, Italy: L. Bonechi
Helsinki Inst. Phys., Finland: J.E. Brucken

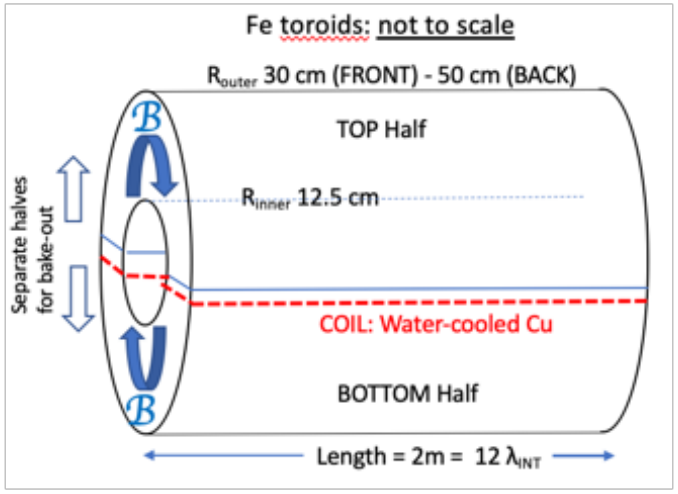
Univ. Iowa, USA: L. Emediato, A. Meshvirishvili, J. Nachtman, Y. Onel, A. Penzo
Univ. Istanbul, Turkey: O.Aydilek, B. Isildak, B. Hacisahinoglu, S. Ozkorucuklu, C. Simsek
Kansas University, USA: C. Royon,
Karlsruhe Institute of Technology, Germany: R. Engel, T. Pierog, R. Ulrich,...

Lawrence Livermore National Lab., USA: D. Wright
Univ.Maryland, USA: N. Hadley, A. Skuja

& non-CMS
CERN: V. Baglin, F. Cerutti, P. Fessia, M. Sabate-Gilate
Fermilab, USA: V. Kashikhin, G. Krnjiac, N. Mokhov, I. Rahkno
Louisiana State University, USA: M.L. Cherry

Suggested scheme for enlarged pipe (not yet confirmed/detailed by LHC)





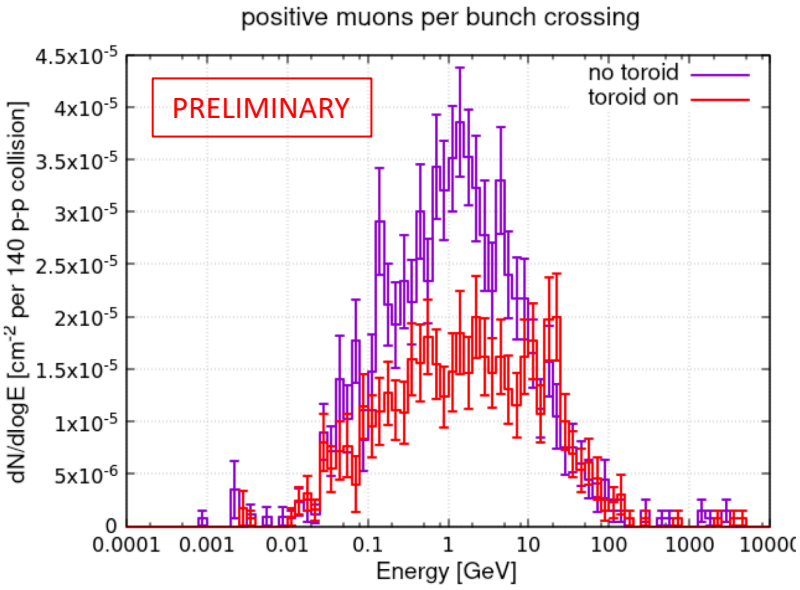
FRONT TOROID: Deflect low momentum muons **IN & OUT** + VETO hodoscope behind.
Mainly for LLP search – charged hadrons through hole

BACK TOROID: Muon chambers in front & behind
Measure Q = +/- and approximate p(μ) for M(μ+ μ-)

FLUKA calculations of particles emerging from back of Q1-Q3 + D1 + FT steel.

F. Cerutti & M. Sabate-Gilarte

MUON SPECTRUM

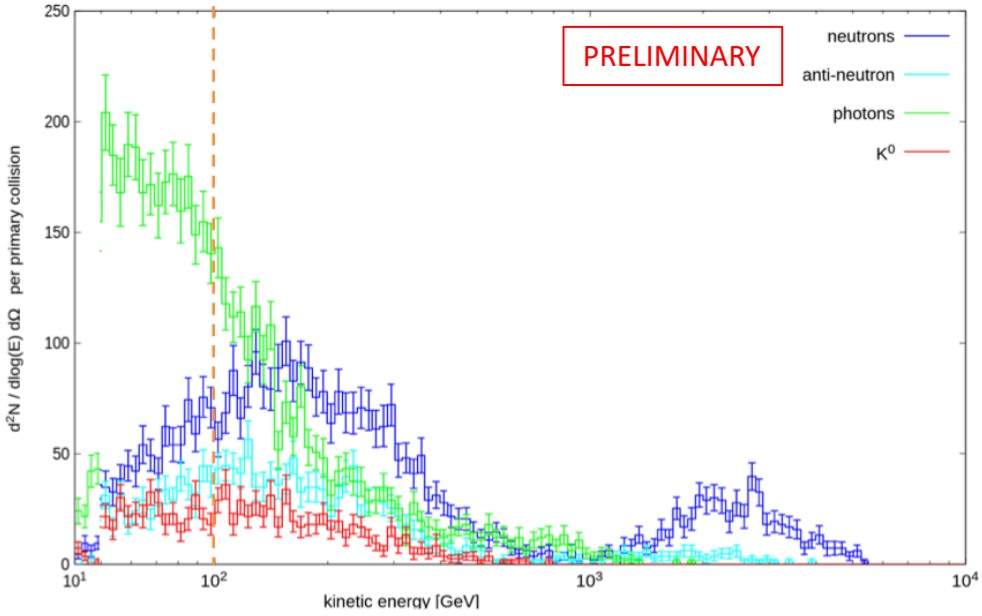


BACKGROUNDS SUBJECT TO FURTHER STUDY

Toroid on: 0.3 μ^+ & 0.35 μ^- / 140 X
Most below 10 GeV
To be updated with new geometry

Neutral hadrons & photons behind steel absorbers – only K^0 and Λ^0 decay -

& O(1) charged hadron through D1 and hole in toroid – swept L & R by fields, then straight to tracker.
Measure h^+ and h^- in 1 – 3 TeV region
SM physics – anti-^{3}He and ^{4}He (Q = 2)



Note: This is per unit solid angle. $d\Omega = 5 \times 10^{-5}$
> ~ 10^{-1} / bunch crossing (140 int.) above ~ 600 GeV