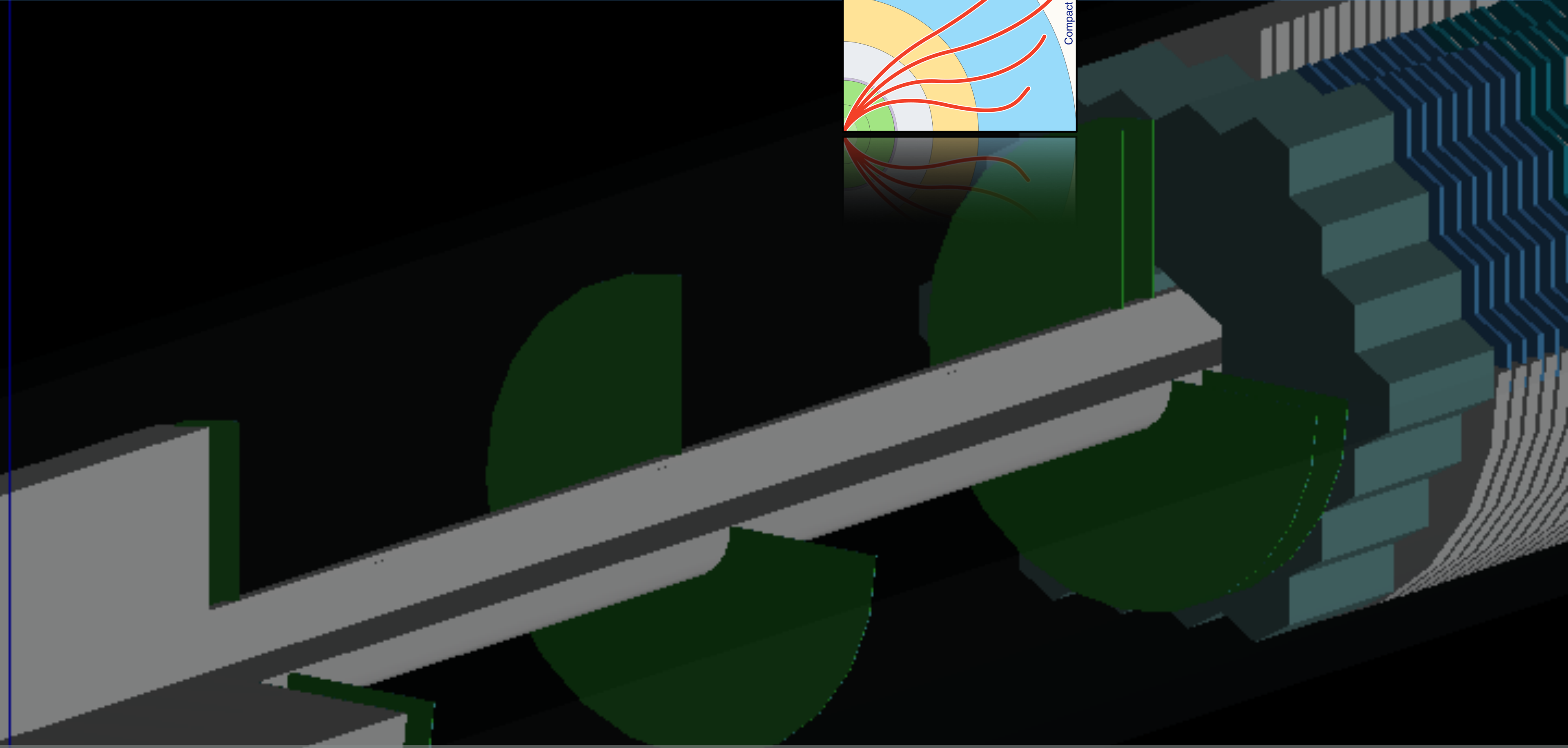
SEARCHES FOR NEW PHYSICS W/ FACET: FORWARD-APERTURE CMS ExTENSION



Greg Landsberg for the FMS Team ✧ 01/26/21

Fermilab LPC TOTW

Outline

- Physics Case for FACET
- Conceptual Outline
- Fluences and Backgrounds
- Physics Sensitivity Studies
- Detector Simulation
- Next Steps and Conclusions

Physics Case

- As more and more high-energy data are being collected and analyzed at the LHC, the high-mass reach becomes saturated
- Our best chance to discover new physics is therefore in the places that have not been explored before
- This typically means low masses and low couplings
  - ★ N.B. High masses and low couplings are also possible, but are unlikely to be accessible in Run 3
- Low couplings often imply long lifetimes (LLP)
- Low masses typically makes production peaking in the forward direction
- Thus, optimally one needs a precision spectrometer in the forward region of CMS, far upstream

Physics Case (cont'd)

- This, of course, has been realized by the HEP community at large and the LHC community in particular [cf., e.g., arXiv:1903.04497 White Paper] and resulted in a number of approved or proposed experiments:
  - ★ Beam dump experiments (NA62, SHiP, ...)
  - ★ Central remote detectors (CODEX-B, MATHUSLA, ...)
  - ★ Forward remote detectors (FASER, FASER-2, ...)
- We propose to significantly enhance the capabilities of the CMS experiment for LLP searches by installing FACET: Forward-Aperture CMS ExTension, a multi-particle spectrometer at z ~ +100 m from the IP (on one side of CMS)
- If approved, FACET will operate in Run 4 and beyond

FACET Advantages

- There are several major advantages of FACET w.r.t. the competition, most notably approved FASER and proposed FASER-2 HL LHC upgrade:
  - ★ FACET will be fully integrated in CMS and can be used either together with the central detector or as a standalone detector
  - ★ Unlike FASER, FACET is located around the LHC beam pipe, allowing to study unique physics processes not accessible to FASER, e.g., rare D meson decays
  - ★ Similar to the original SHiP proposal, FACET will have an LHC-quality vacuum decay volume ≈15 m long, which allows for an essentially background-free environment for the LLP searches
  - ★ FACET will be built based on the CMS Phase 2 Upgrade concept, combining silicon tracker, timing detector, HGCAL-type EM/HAD calorimeter, and GEM-type muon system in a compact design
    - ✤ We are not inventing any new detector concepts or infrastructure, but propose to benefit from and help with the present Phase 2 upgrade

Snowmass EoI

- **Submitted the conceptual design as a Snowmass EoI for EF08+09+10 groups**

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

Version 0.1

August 28, 2020

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), M.V.Garzelli (DESY), L.Bonechi (Univ, INFN Firenze), 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), R.Ulrich (KIT,tbc), D. Wright (LLNL), A.Skuja (Maryland), R.Rusack (Minnesota), H.Menjo (Nagoya), Zuowei Liu, Van Que Tran, Mingxuan Du (Nanjing), S.Malik (Puerto Rico).

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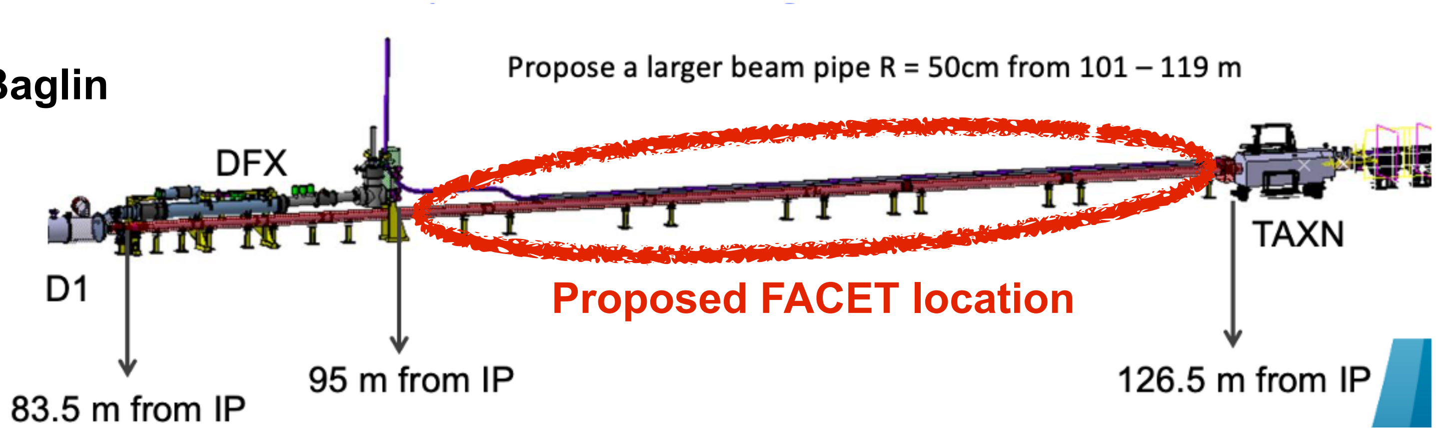
Abstract

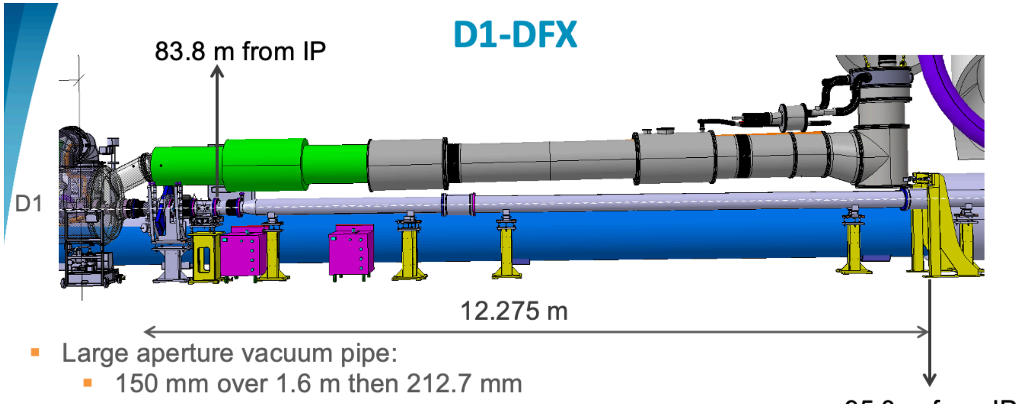
We intend to develop a proposal to search for BSM long-lived particles (LLPs) in the forward direction of IR5 (CMS), penetrating 35 m – 50 m of steel in the Q1 – Q3 quadrupoles and D1 dipole, and either decaying in a large vacuum pipe or interacting in an imaging calorimeter. Neutral LLPs with $|\eta|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

https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF9_EF8_ALBROW-111.pdf

HL-LHC Beamline

- Here are the schematics of Sectors 5-6, near the CMS IP





- Large aperture vacuum pipe:
  - 150 mm over 1.6 m then 212.7 mm
  - Flanges size DN200 and DN250

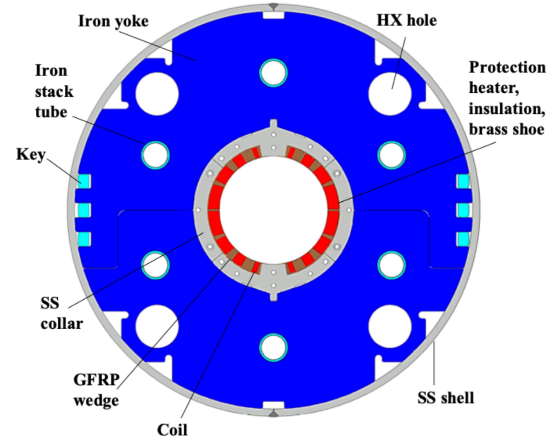


Fig. 4.1: Cross-section of the separation dipole.

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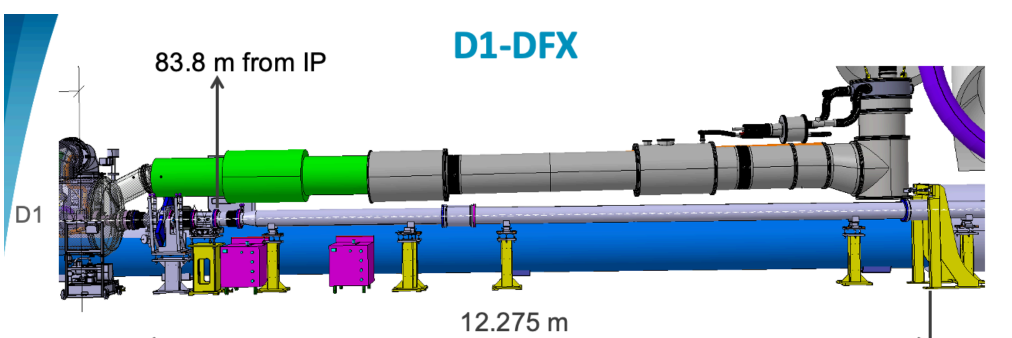
Vincent Baglin



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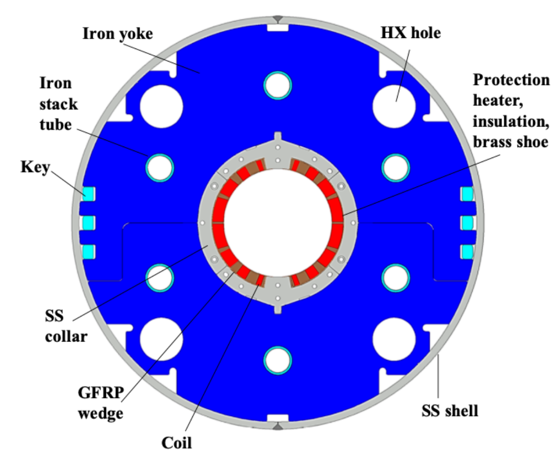
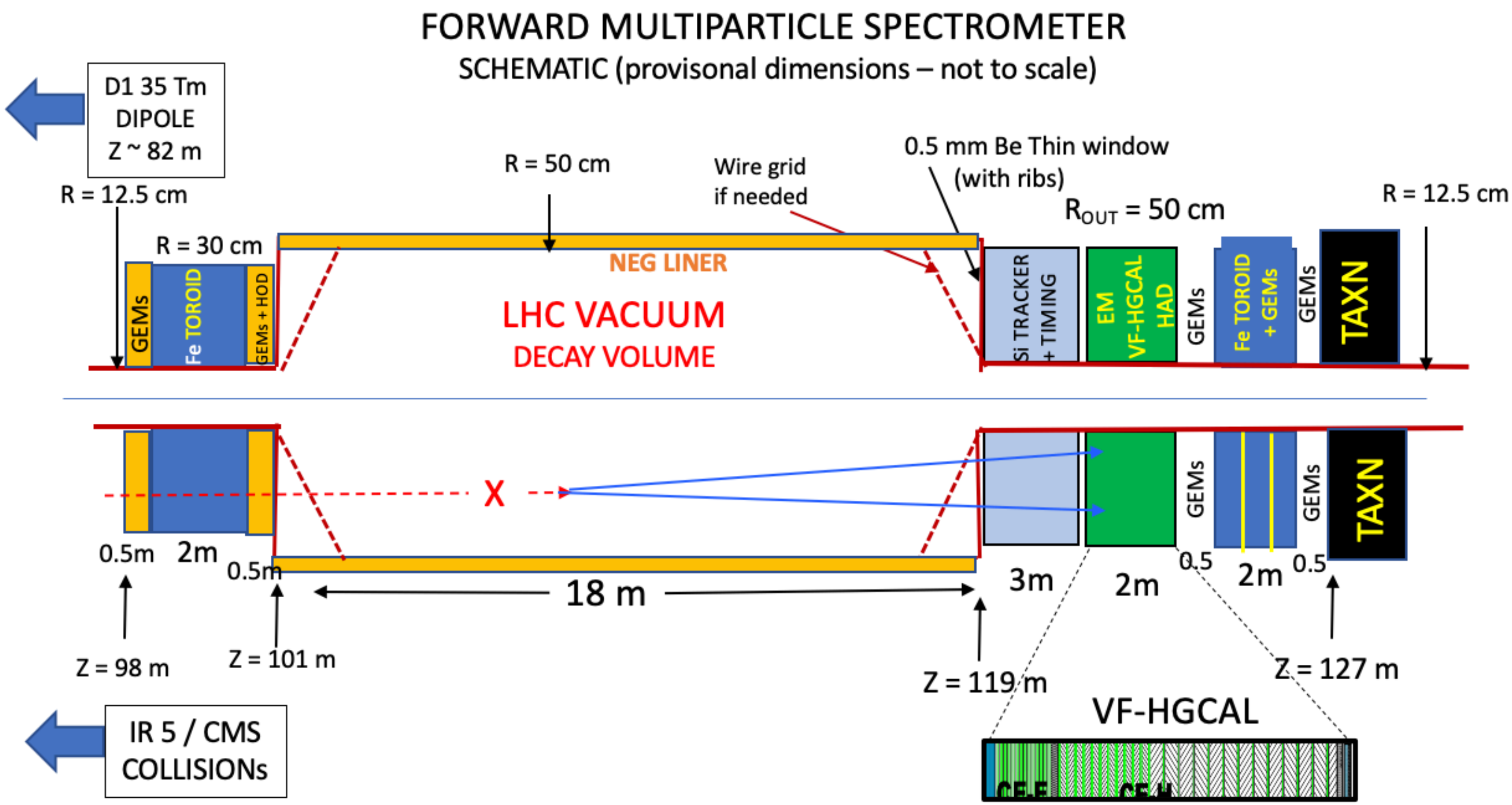


Fig. 4.1: Cross-section of the separation dipole.

Conceptual Design

- Take advantage of presently sparsely instrumented gap at 95 < z < 127 meters on the positive side of CMS
  - ★ The detector design is evolving; here is the latest snapshot
  - ★ R = 50 cm beam-pipe idea was run by the LHC accelerator experts and it is possible, provided the impedance match via a wire grid



Solid Angle Coverage

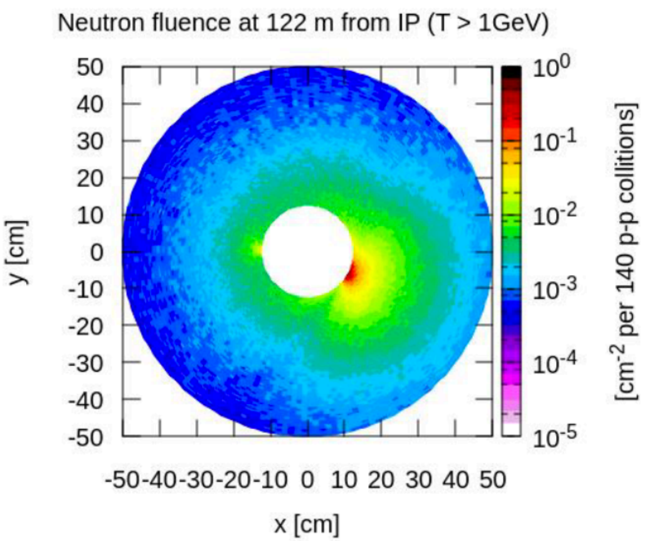
- The detector will have a radius of ~50 cm, at ~100 m from the IP, corresponding to θ < 5 mrad and the pseudorapidity coverage between 6 < η < 8
  - ★ Technically, there is no upper pseudorapidity cutoff for the decaying LLP's, beyond the kinematics, but the R = 12.5 cm LHC beam pipe at the entrance to the neutral particle absorbers (TAXN), effectively limits the acceptance of the LLP decays beyond that, as there is no detector coverage possible below this radius
  - ★ If it's feasible to reduce this aperture, despite beams being separated at this point, the acceptance could further increase
- The θ coverage is an order of magnitude better than for FASER and is similar to that of the proposed FASER-2 upgrade
- The detector is shielded by about 30-50 m of steel in front of it, which corresponds to 190-300 interaction lengths
  - ★ This is better than FASER that has ~100 m of concrete/rock

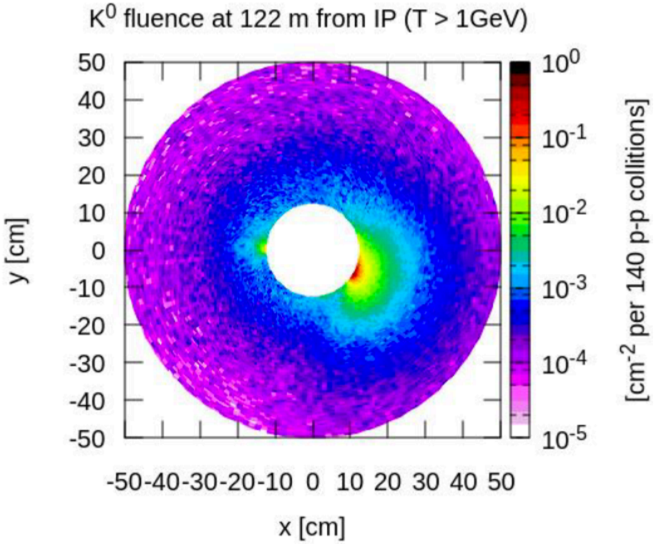
Detector Design

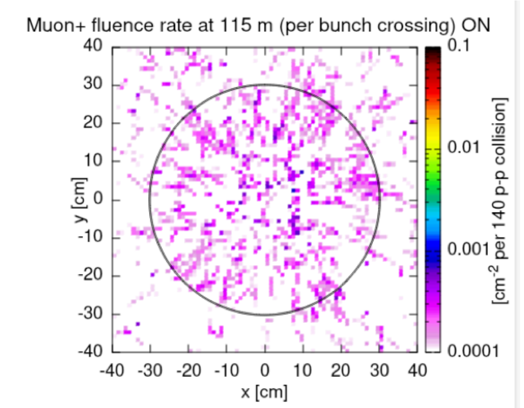
- Given very low background, the FACET concept is to have a multi-particle spectrometer capable of identifying e, μ, τ, ɣ, and hadrons from LLP decay
- A 4- or 5-plane 0T silicon strip detector followed by a compact, HGCAL-type calorimeter, and ~3 GEM muon detector planes inside a toroidal magnetic fieldwould enable these capabilities
- An addition of precision MIP timing (either using silicon detectors or with a LYSO hodoscope) would allow to further suppress the backgrounds and perform the LLP mass measurement
- While the detailed design is in progress, we believe that the detector cost could be kept at about 5 MCHF, which is about twice as expensive as FASER, but some 5 times cheaper than FASER-2 upgrade cost

Radiation Environment

- **Extensive FLUKA simulation of particle fluences expected at the FACET location during the HL LHC operations is available**
  - ★ **The azimuthal asymmetry is because of the dipole bending plane**
  - ★ **Typical fluence is 10^{-2} cm^{-2} per bunch crossing, which corresponds to ~ 10^{12} n/cm^2 in 10 years of the HL LHC operations, or about 1 Mrad integrated dose**
  - ★ **This is less than the exposure of the outer part of the HGCAL**

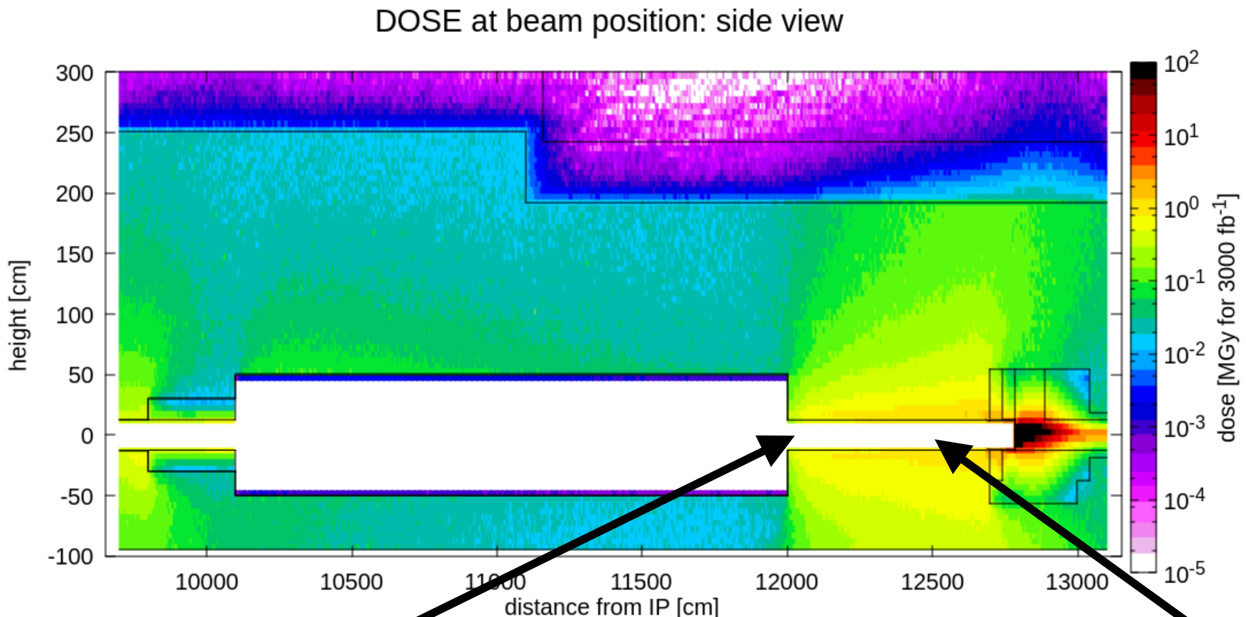


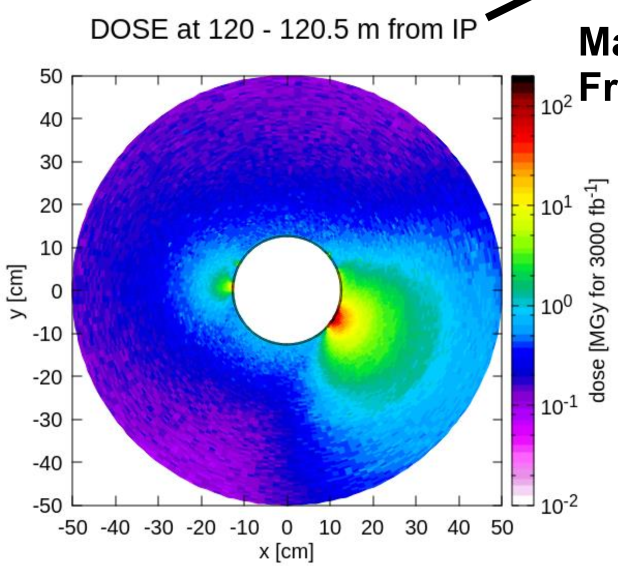




Marta Sabaté-Gilarte
Francesco Cerutti

Exposure Simulations





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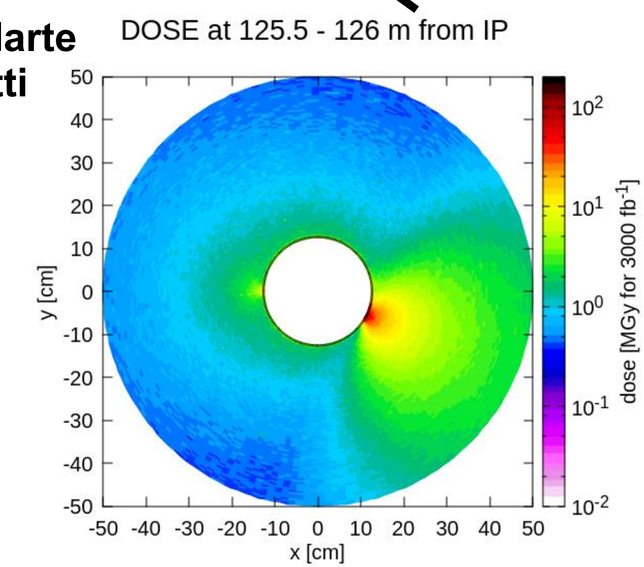
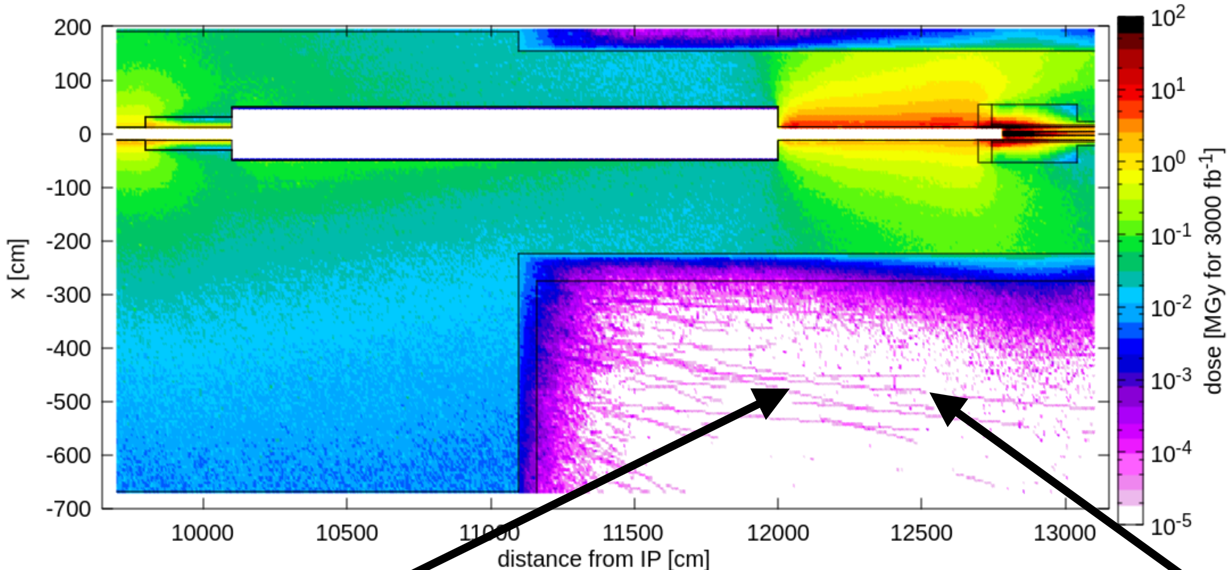
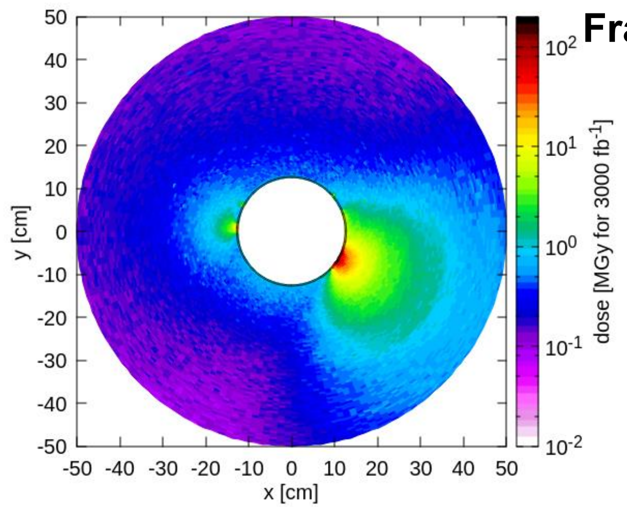


Exposure Simulations

DOSE at beam height: top view



DOSE at 120 - 120.5 m from IP



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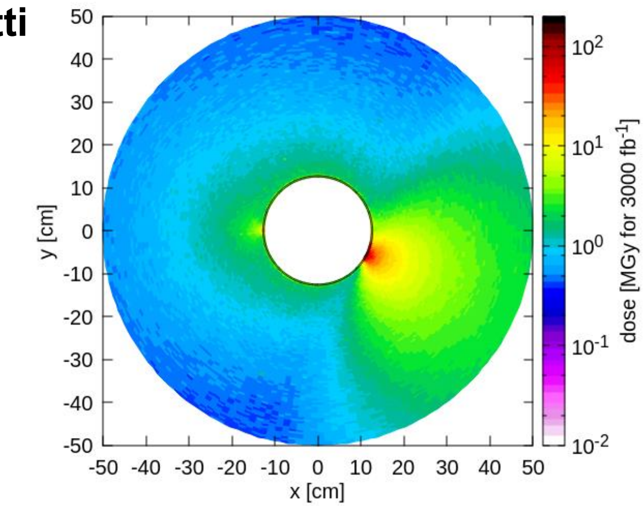
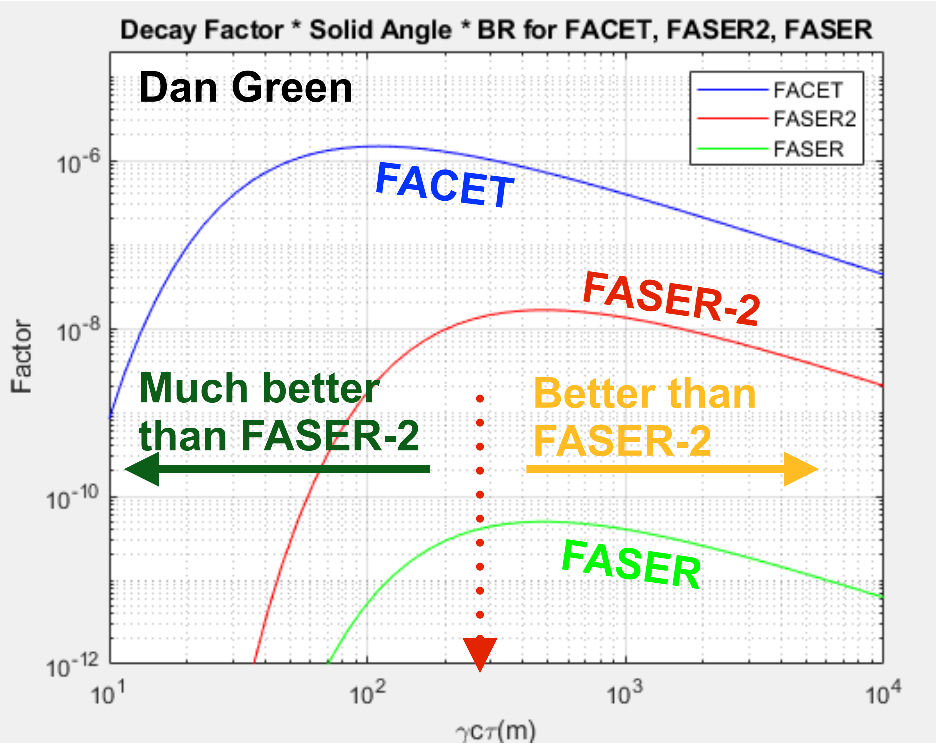
DOSE at 125.5 - 126 m from IP



Physics Reach vs. Lifetime

- For LLPs decaying within the FACET vacuum volume, the figure of merit (e.g., 5 signal events expected) depends primarily on $\gamma c\tau$
- Here is how FACET compares with FASER and FASER-2
- FASER-2 sensitivity is expected to be 2 orders of magnitude higher, but it is still short of that for FACET for $\gamma c\tau$ > 1 km
- Additionally, FACET will have a unique coverage for $\gamma c\tau$ < 100 m

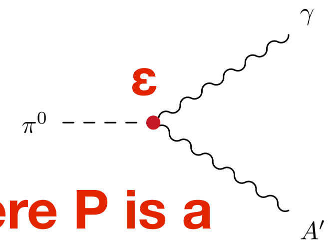


FACET Physics Landscape

- The main long-lived particle models we can probe are similar to those of FASER(-2), but enhanced via accessibility to hadronic and tau decay modes
- There are several classes of models we could explore [for more details, cf. FASER "Physics Book" arXiv:1811.12522]:
  - Dark Vectors (Dark Photons and Z' Bosons)
  - Dark Higgs and Dark Pseudoscalars
  - Heavy Neutral Leptons
  - Axion-Like Particles (ALPS)
- In addition, FACET physics program can be enriched via:
  - Rare D meson decays (e.g., LFV decays)
  - Strongly Interacting Dark Matter (SIMP)
  - Standard model physics topics: hadron production in the forward region
  - He and anti-$He^{3,4}$ production measurement - relevant for astrophysics

Indirect LLP Production

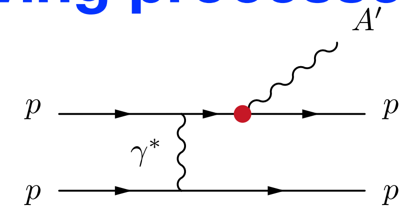
- Given the η range of FACET, the main production mechanisms for light LLPs are expected to be meson decays
- Typical examples:
  - ★ π^0, $\eta \rightarrow \gamma\gamma_D$ via kinetic mixing parameter ε
  - ★ For higher masses, decays of $J/\Psi \rightarrow P\gamma_D$ (where P is a pseudoscalar meson) are relevant as well, but unfortunately, production cross section is too small to be of interest
  - ★ $b \rightarrow s\phi_D(\phi_D)$ for dark Higgs bosons, e.g., $B^\pm \rightarrow K^\pm\phi_D(\phi_D)$ - depending on the model, the decay with either single Higgs boson or a pair of Higgs bosons dominates
  - ★ $D \rightarrow K\ell N$, $D \rightarrow \ell N$, and $B \rightarrow D\ell N$ for HNLs (depending on the mass); also τ decays for HNLs mixed with ν_τ



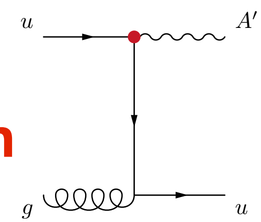
- In all these cases, we only care about the LLP part of the decay chain and need it to subsequently decay within the FACET decay volume to be detectable w/ low background

Direct LLP Production

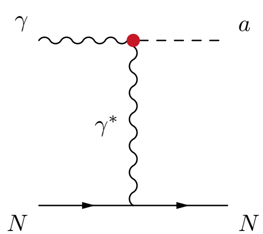
- **In addition to these processes, LLPs can also be produced directly in the forward region via the following processes:**
  - ★ **Dark bremsstrahlung via coherent emission from a proton**



  - ★ **Direct dark photon production**

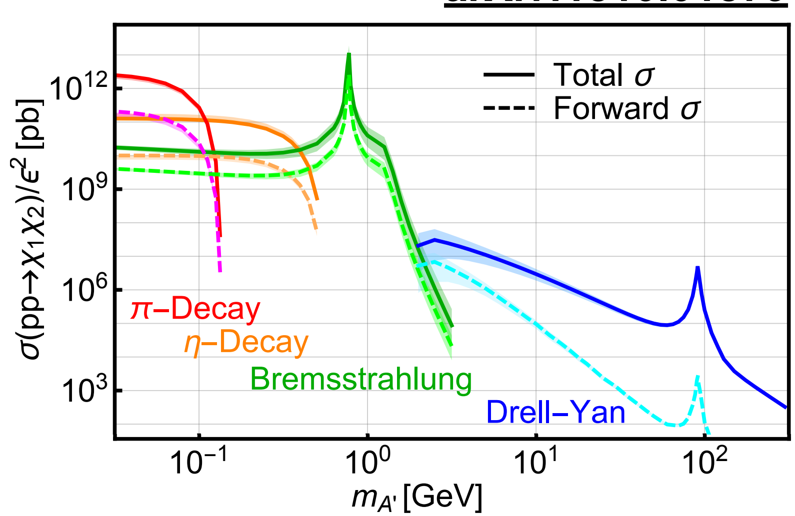


  - ★ **Primakoff production of ALPs**



  - ★ **Drell-Yan production at higher masses, although it's hard to compete with LHCb and ATLAS/CMS central detectors**

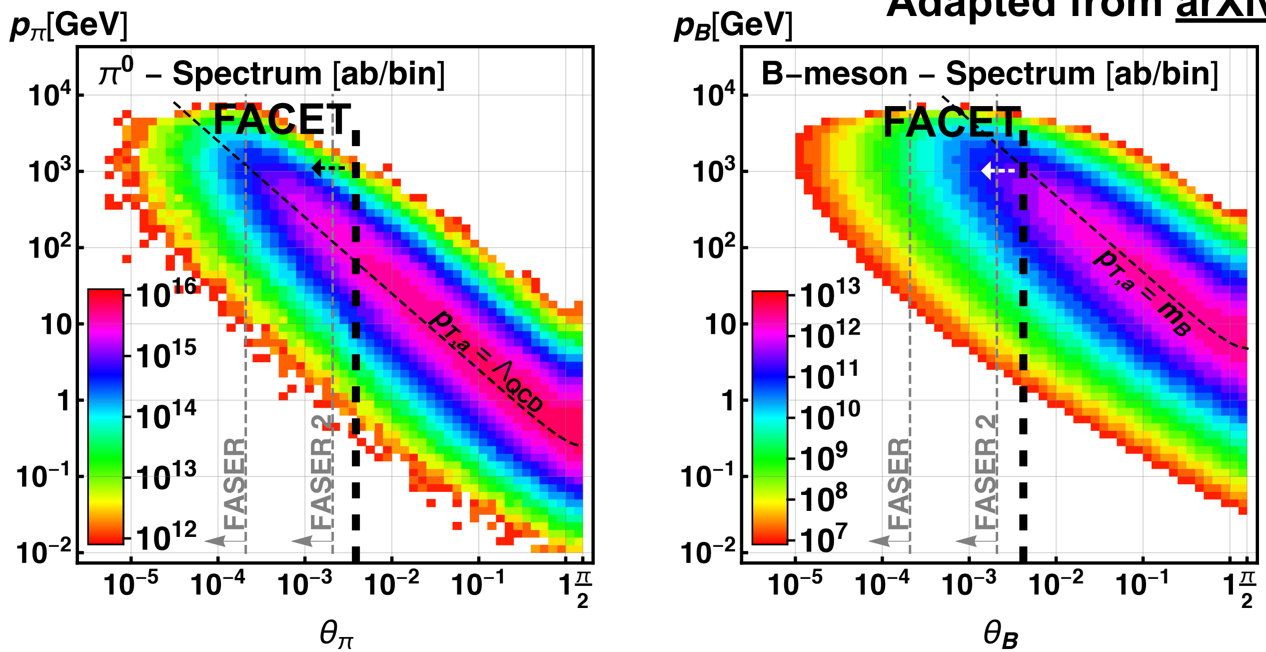
arXiv:1810.01879



Estimating Physics Reach

- Initial studies of the physics reach of FACET for these processes
- Using the same approach as FASER: generating forward meson production (EPOS-LHC for light mesons; FONLL for D and B mesons), map the mesons in θ and p and use these maps to generate decays we are interested in to estimate the acceptance
    - ★ Many thanks to Felix Kling for providing us with the FASER maps for initial studies

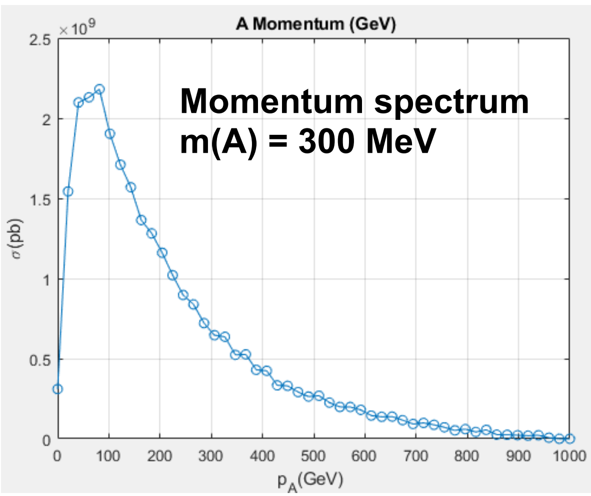
Adapted from arXiv:1811.12522

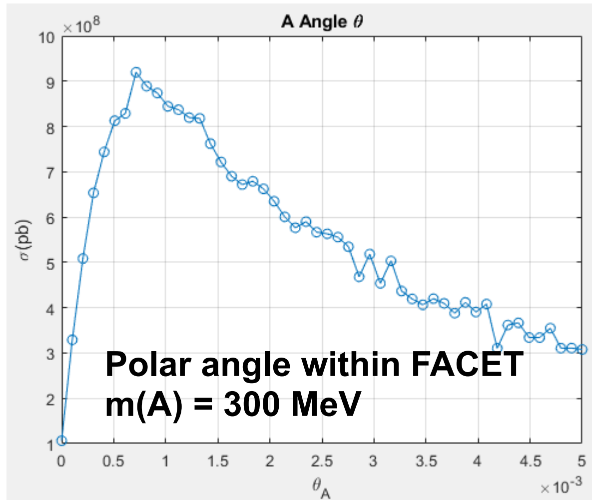


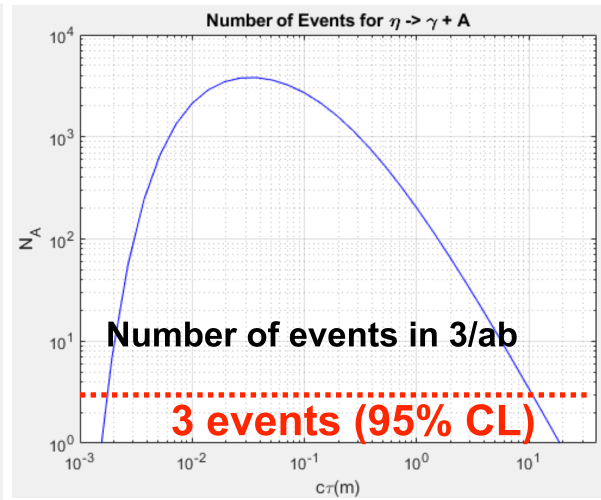
Example of Simulations

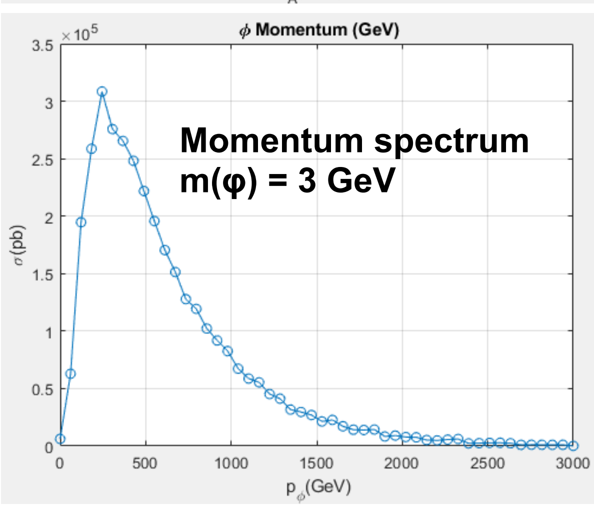
- So far looked at dark photons and dark Higgs bosons in 2-body η and B meson decays, respectively

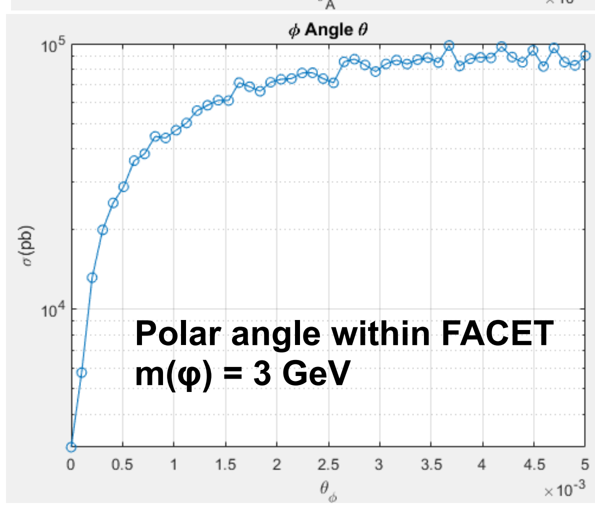
Dan Green

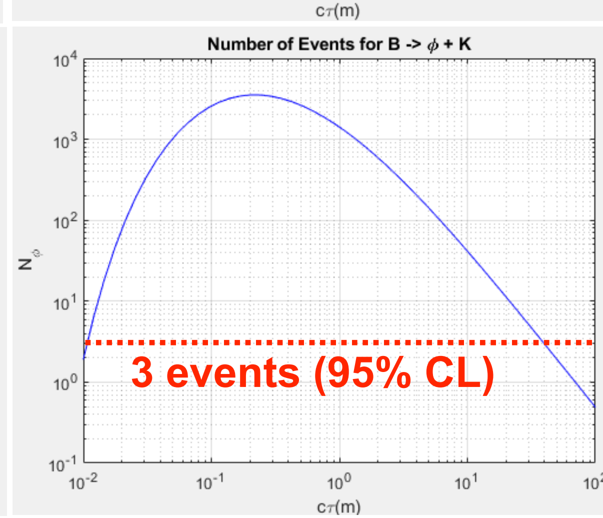












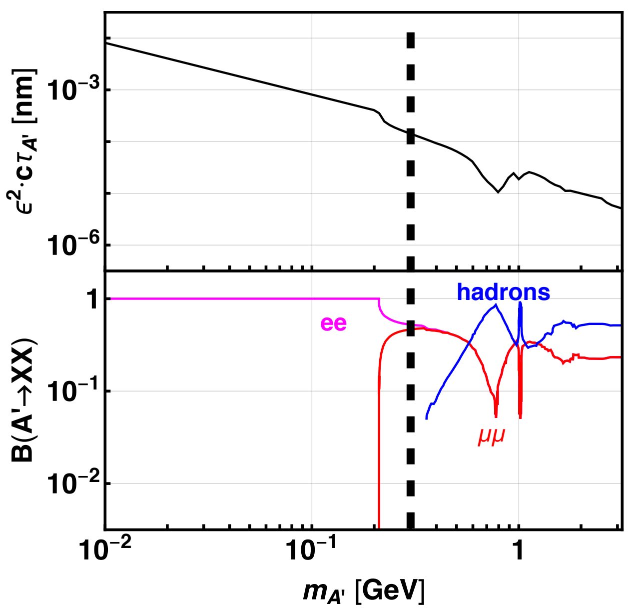
Dark Photon Reach

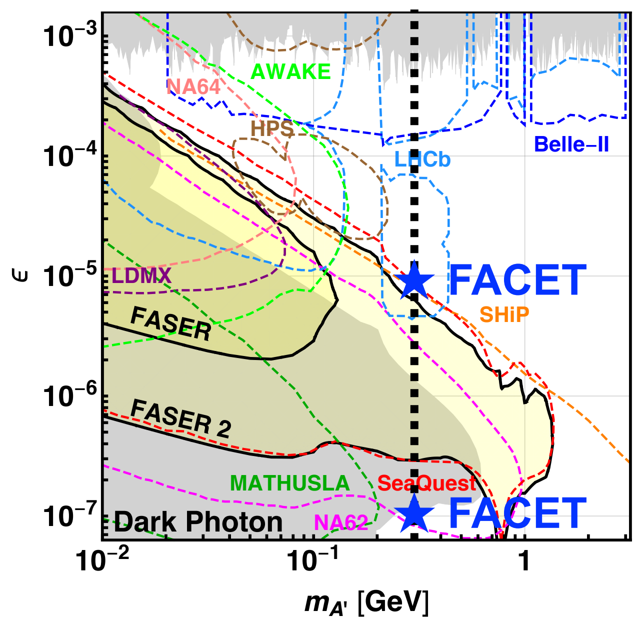
- We can translate these numbers in the exclusion plot, a la the ones found in the FASER Physics Book
- The branching fraction of the P → γA decay is given by [arXiv:1803.05466]:

$$\mathcal{B}(P \to \gamma A) = 2\varepsilon^2 \left[1 - \left(\frac{M_A}{M_P}\right)^2\right]^3 \mathcal{B}(P \to \gamma\gamma)$$

  - ★ In the case of η → γA, $\mathscr{B} = 0.26\varepsilon^2$ for m_A = 300 MeV
- The lifetime in this case is $c\tau \approx 10^{-4}/\varepsilon^2$ nm = $10^{-13}/\varepsilon^2$ m
- The 3 event 95% CL limits reach is expected at cτ ≈ 1.5 mm and 10 m ⇒ $\varepsilon \approx 8 \times 10^{-6}$ and 1×10^{-7}, beyond FASER-2 for both lower and upper limits

Adapted from arXiv:1811.12522





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Kin. mixing x 2 photons — Phase space — SM branching fr.

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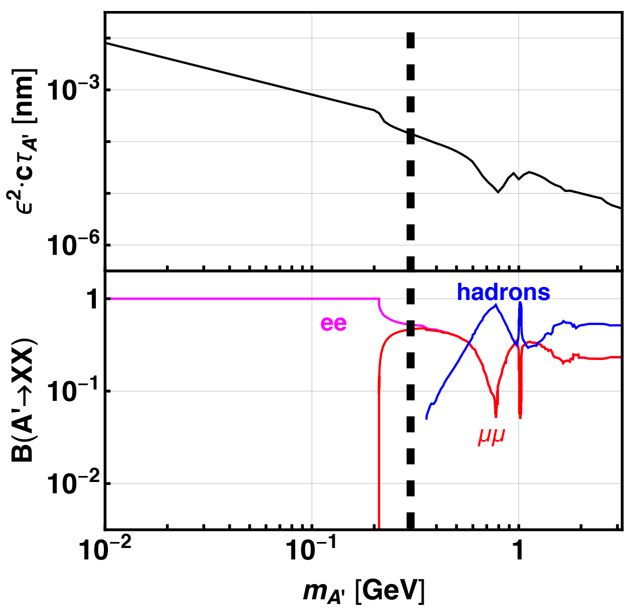
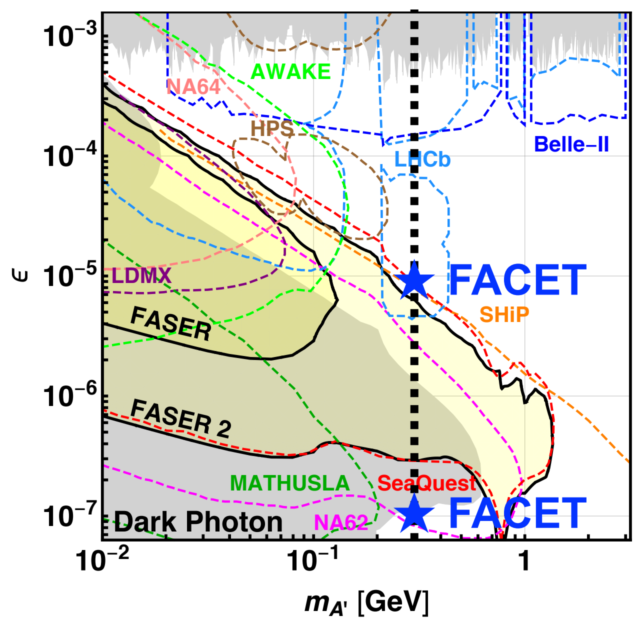




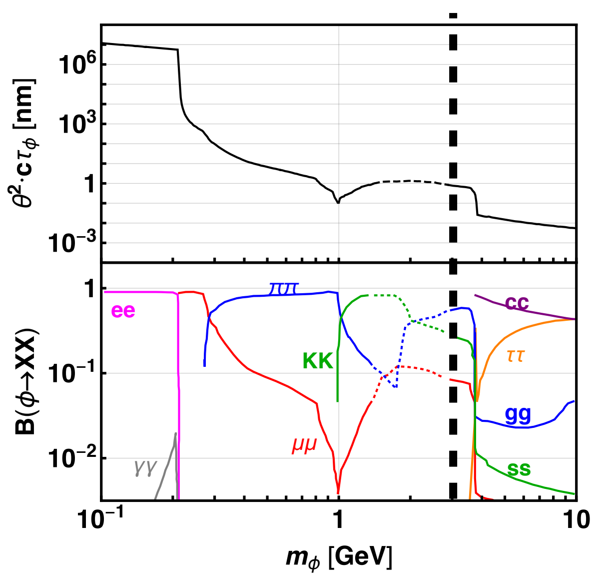
Dark Higgs Reach

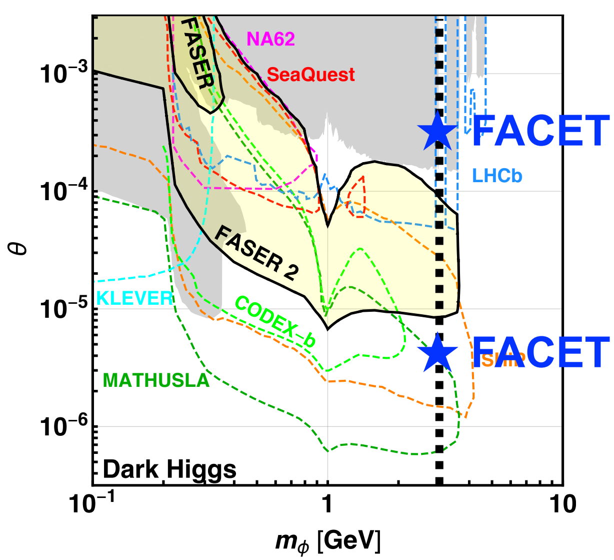
- **Similar exercise can be made for a dark Higgs ϕ**
- **The branching fraction of the B → Kϕ decay is given by [arXiv:1710.09387]:**

$$\mathcal{B}(B \to X_s \phi) = 5.7\theta^2 \left[1 - \left(\frac{M_\phi}{M_b}\right)^2\right]^2$$

  - ★ **Here θ is the ϕ-H mixing angle**
  - ★ **In the case of B → Kϕ, $\mathscr{B}$ = 2.1θ^2 for m_ϕ = 3 GeV**
- **The lifetime in this case is cτ ≈ 0.9/θ^2 nm = 9 x $10^{-10}/\theta^2$ m**
- **The 3 event 95% CL limit reach is expected at cτ ≈ 1cm and 40 m ⇒ θ ≈ 3 x 10^{-4} and 4 x 10^{-6}, significantly better than FASER-2 for both upper and lower limit**

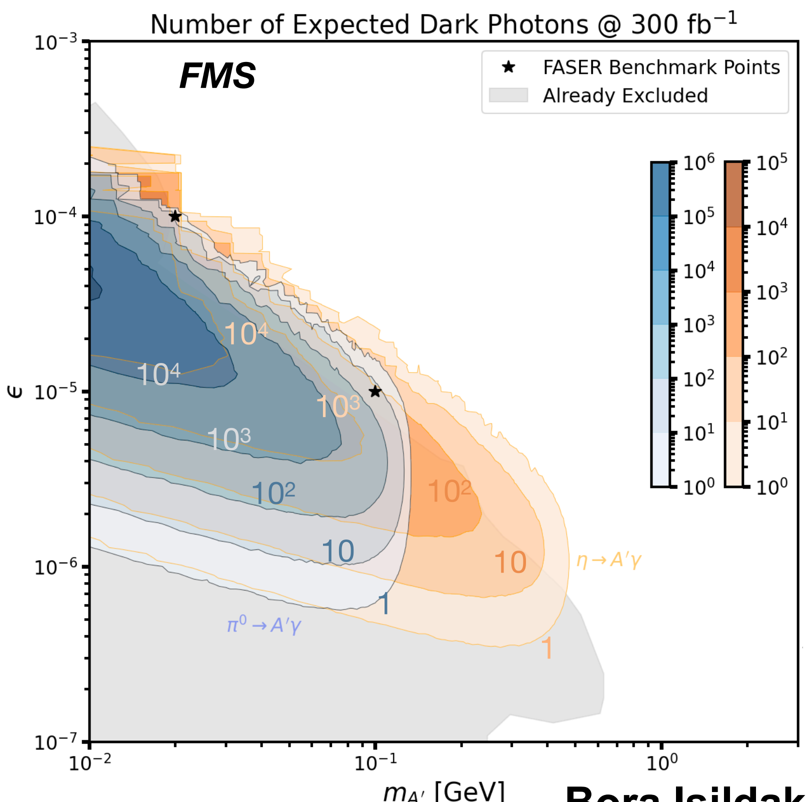
Adapted from arXiv:1811.12522





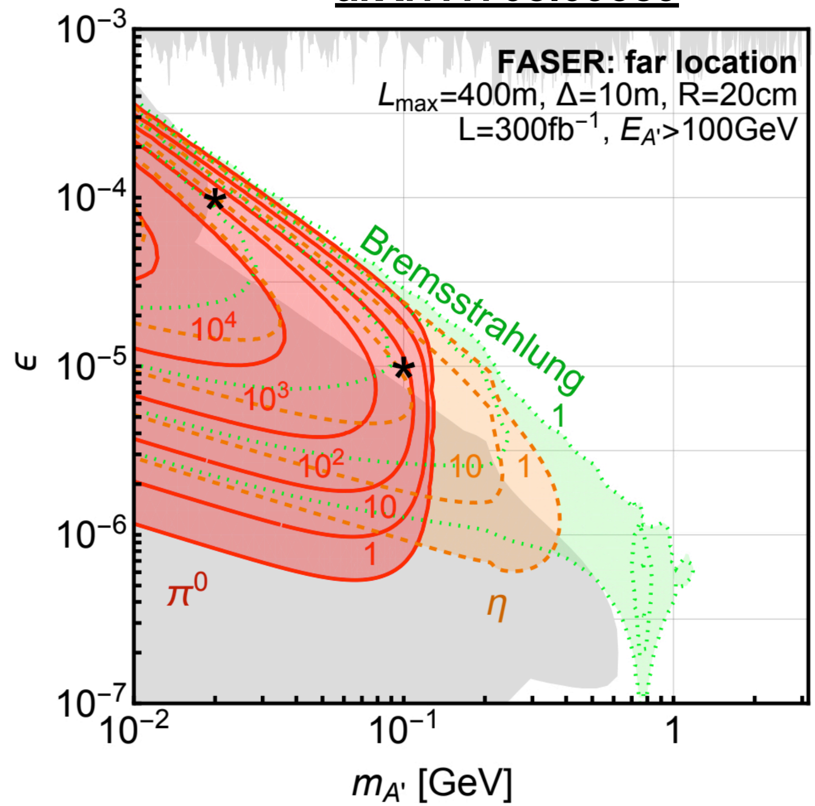
Complete Simulation

- **First complete simulation starting from scratch (EPOS), with a full reach plot for dark photons!**
  - ★ **N.B. The plot is done for 300 fb^{-1} to enable comparison with FASER study; the bremsstrahlung production is not included**



Bora Isildak

arXiv:1708.09389



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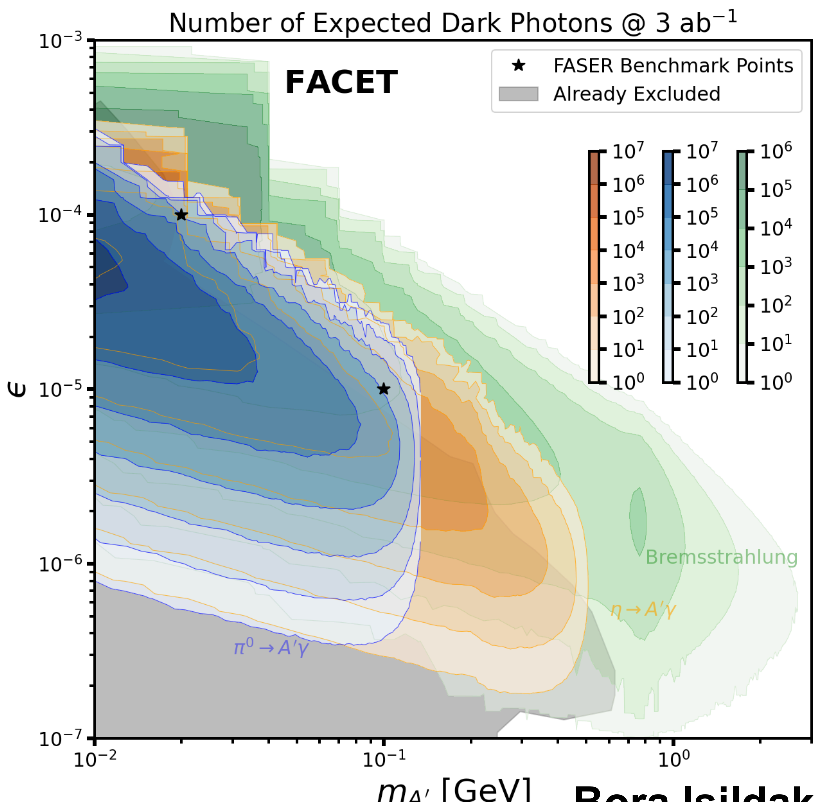
  - ★ N.B. The plot is done for 300 fb^{-1} to enable comparison with FASER study; the bremsstrahlung production is not included
  - ★ And here is a 3 ab^{-1} sensitivity plot with bremsstrahlung included!



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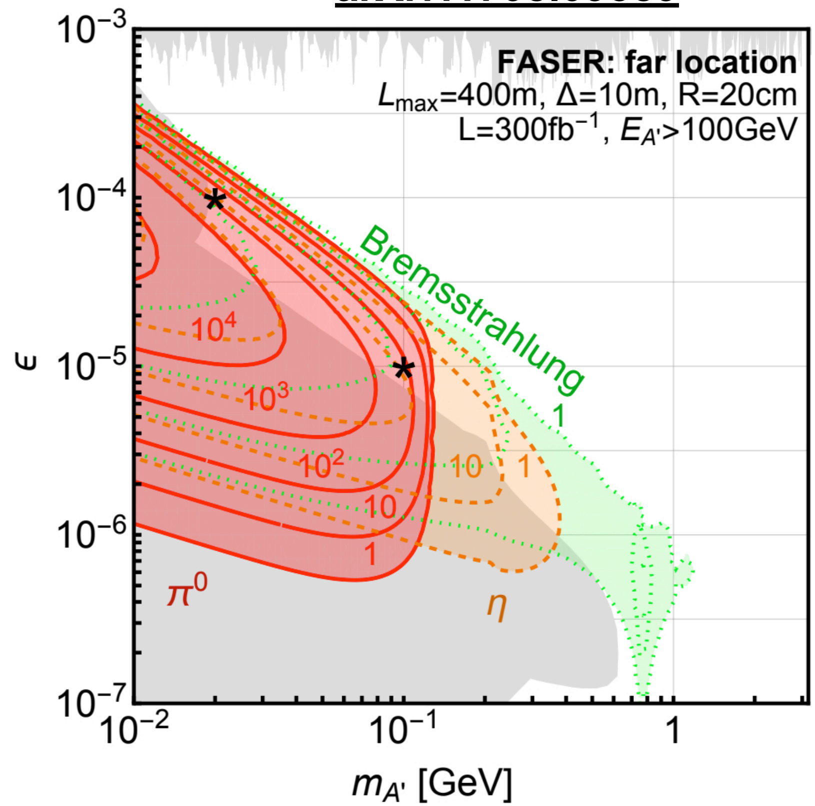
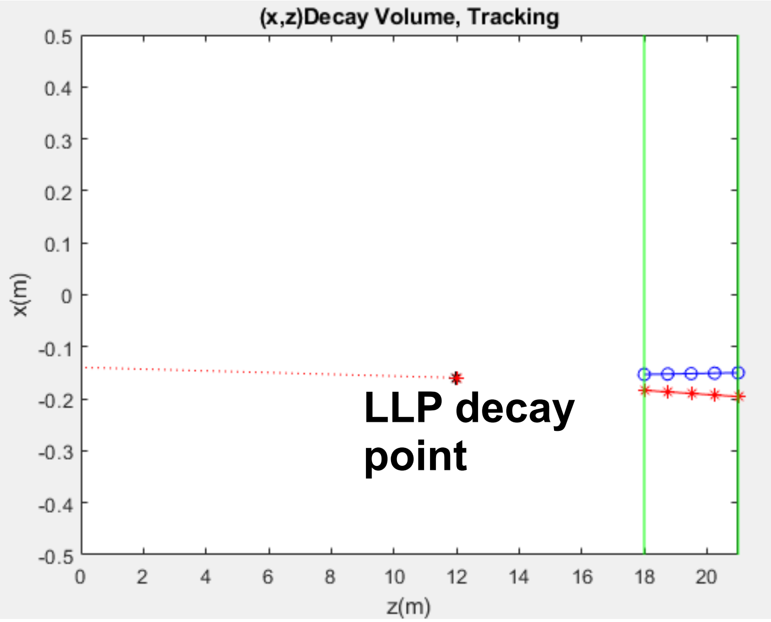
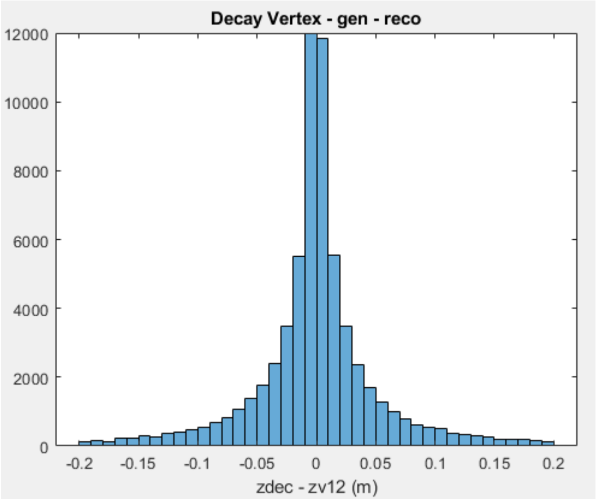
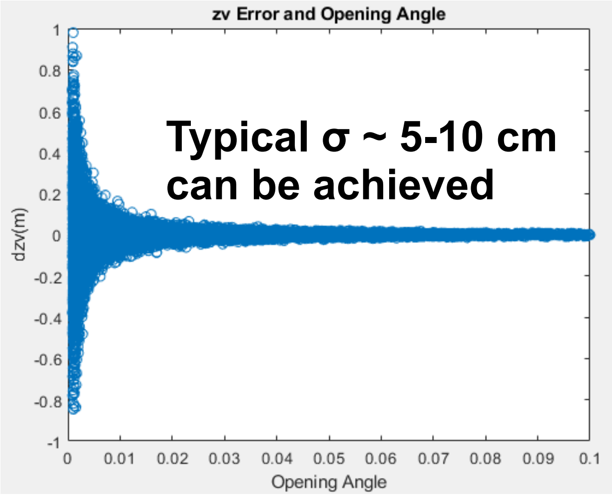


Reconstructing Events

- Typical configuration we would like to reconstruct is a pair of tracks forming a common vertex within the decay volume
- Pointing resolution in z has been estimated assuming 5 tracking planes with 30 μm hit resolution each (~100 μm strips)



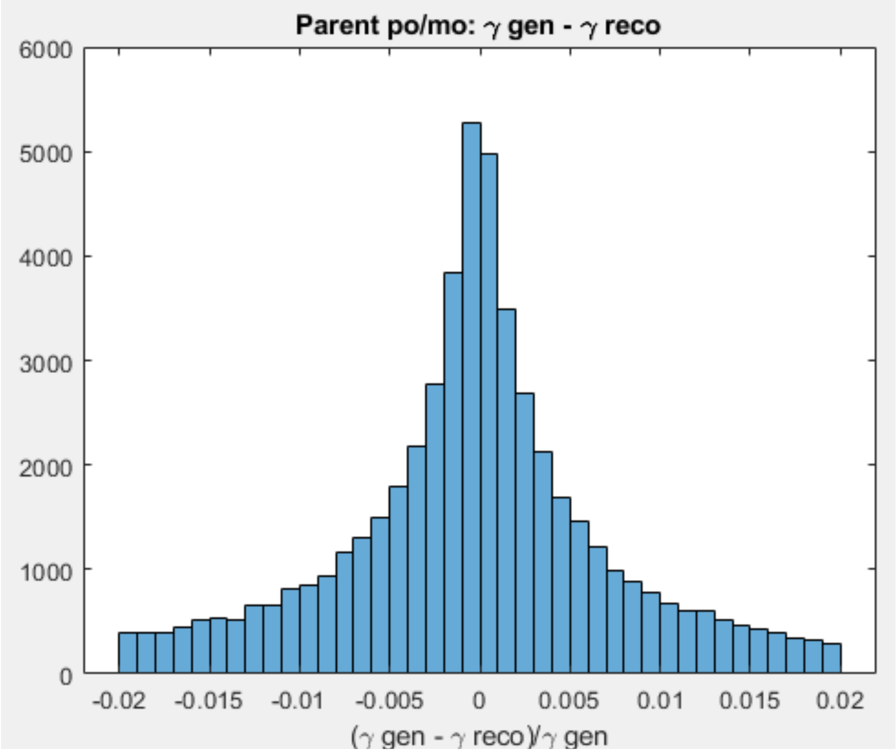


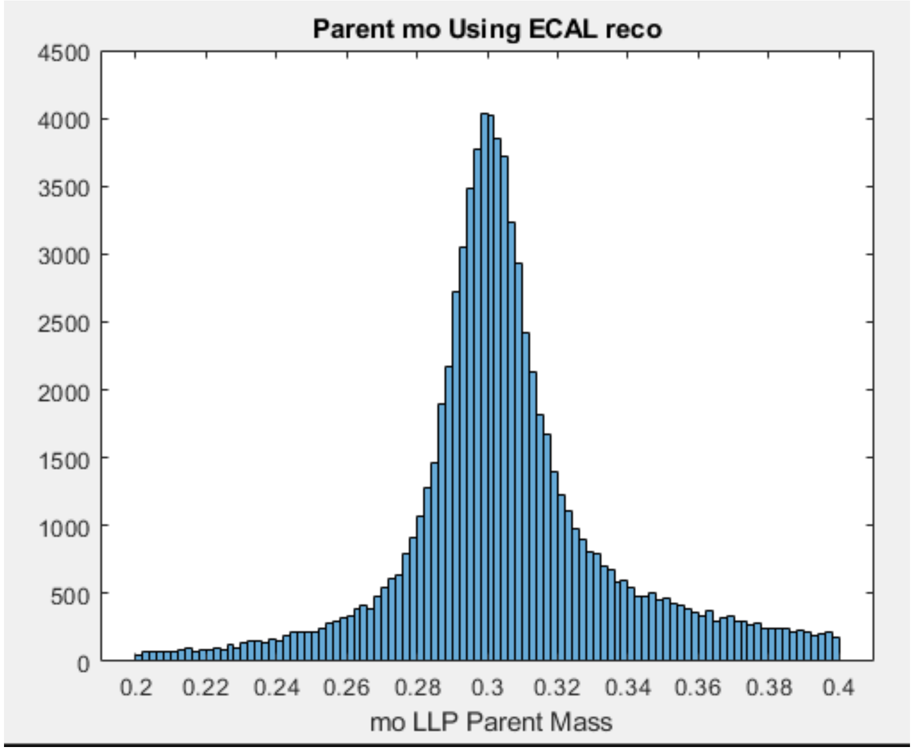


Dan Green

Using Calorimetry

- For decays into electrons (dark photons, ALPs), we can further get E from the calorimetry and the directions of the electrons from the tracker, which allows to estimate the LLP γ-factor with a precision ~5 x 10^{-3} and, hence, the LLP mass, as illustrated for a 300 MeV dark photon decaying to e^+e^- with the mass resolution ~7%





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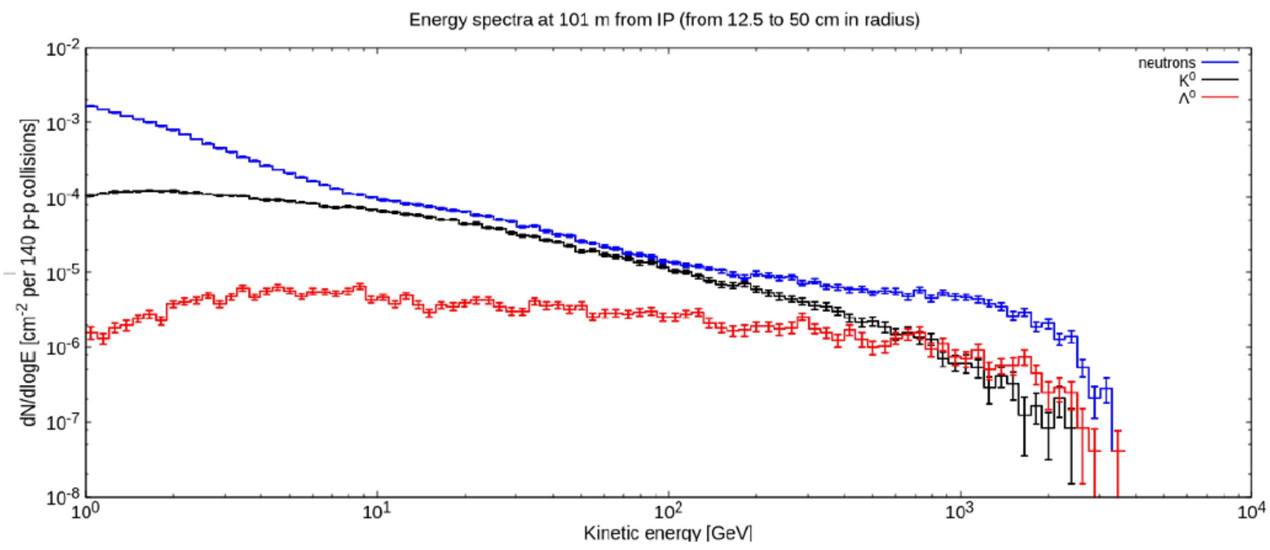
Backgrounds

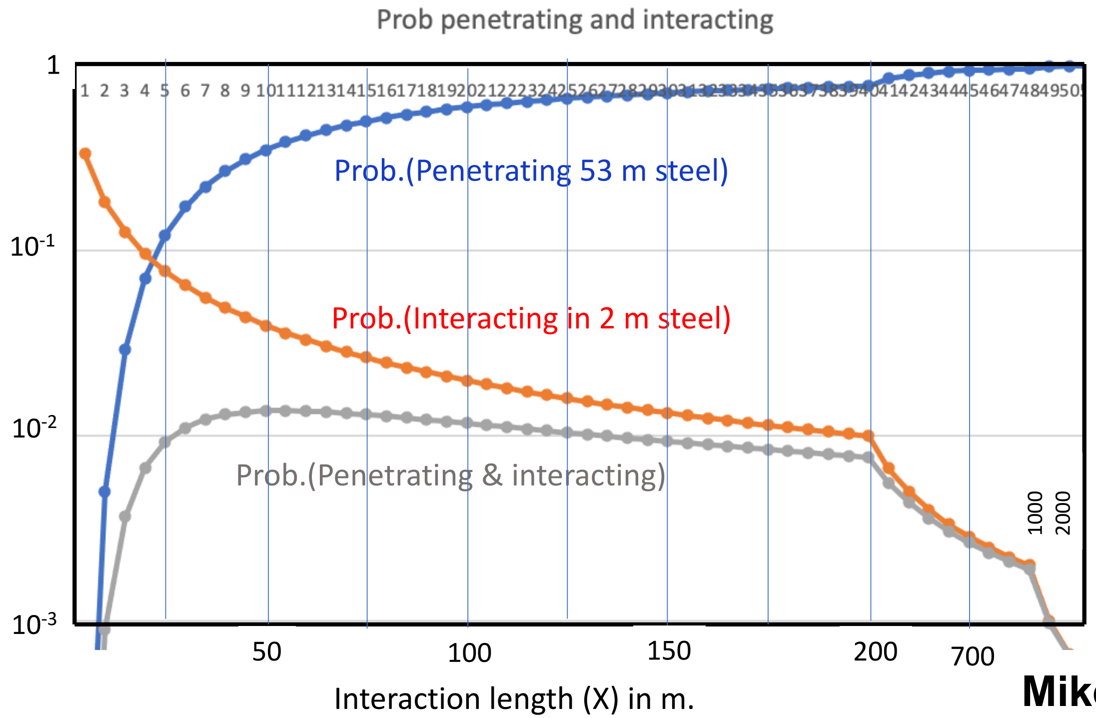
- FASER studies assumed background-free situation, enabled by veto counters
- in FACET we not only have those, but also the vacuum decay volume, which should be extremely powerful in reducing backgrounds
- The only ones that originate within the decay volume are decays of K^0_L and Λ produced not so far upstream
- FLUKA simulations show that the K^0 flux is ~10^{-3}/event; the Λ flux is ~2 orders of magnitude smaller
  - ★ ct(Λ) ~ 3 cm; need a γ factor ~ 100 to decay within the decay volume - not many will survive
  - ★ ct(K^0_L) ~ 16 m; decay within the vacuum volume is uniform; decay into neutrals are most problematic - will be a background for, e.g., ALP searches
- The charged decays are easily removable via mass constraints; need to estimate the neutral decay contribution, which would require more detailed simulation
  - ★ Mainly affect very low-mass LLP searches < 0.5 GeV, which is not the main goal
- FASER claims that this background is negligible for them; hope to demonstrate this for FACET as well



Marta Sabaté-Gilarte
Francesco Cerutti

Toward SIMP Detection

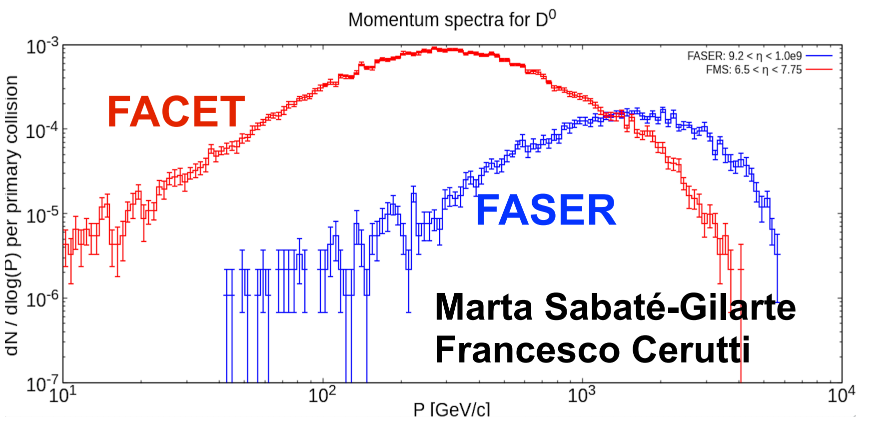
- Potentially have sensitivity to SIMPs interacting or decaying late (in the FACET calorimeter)
- SIMP must NOT interact in the material upstream and instead interact (or decay) within the 2 m of the calorimeter volume
- ~1% acceptance can be reached in a large range of SIMP interactions lengths (in Fe) between 25 and 200 m, which corresponds to the interaction strength between 1% and 1 per mil of the strong interaction

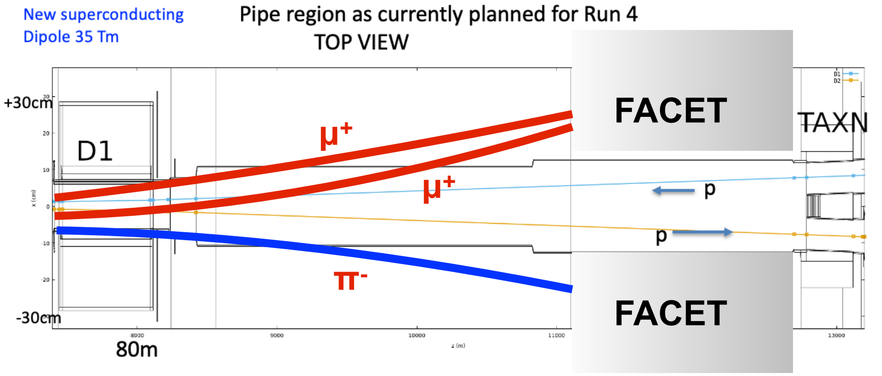


Mike Albrow

D Meson Rare Decays

- The flux of D mesons is very large, and much larger than in FASER
- Even at high γ, they will decay very close to the CMS IP
- Can look for the decay products that enter the D1 dipole aperture (~1 mrad) and then swept into the FACET detector by the dipole magnetic field

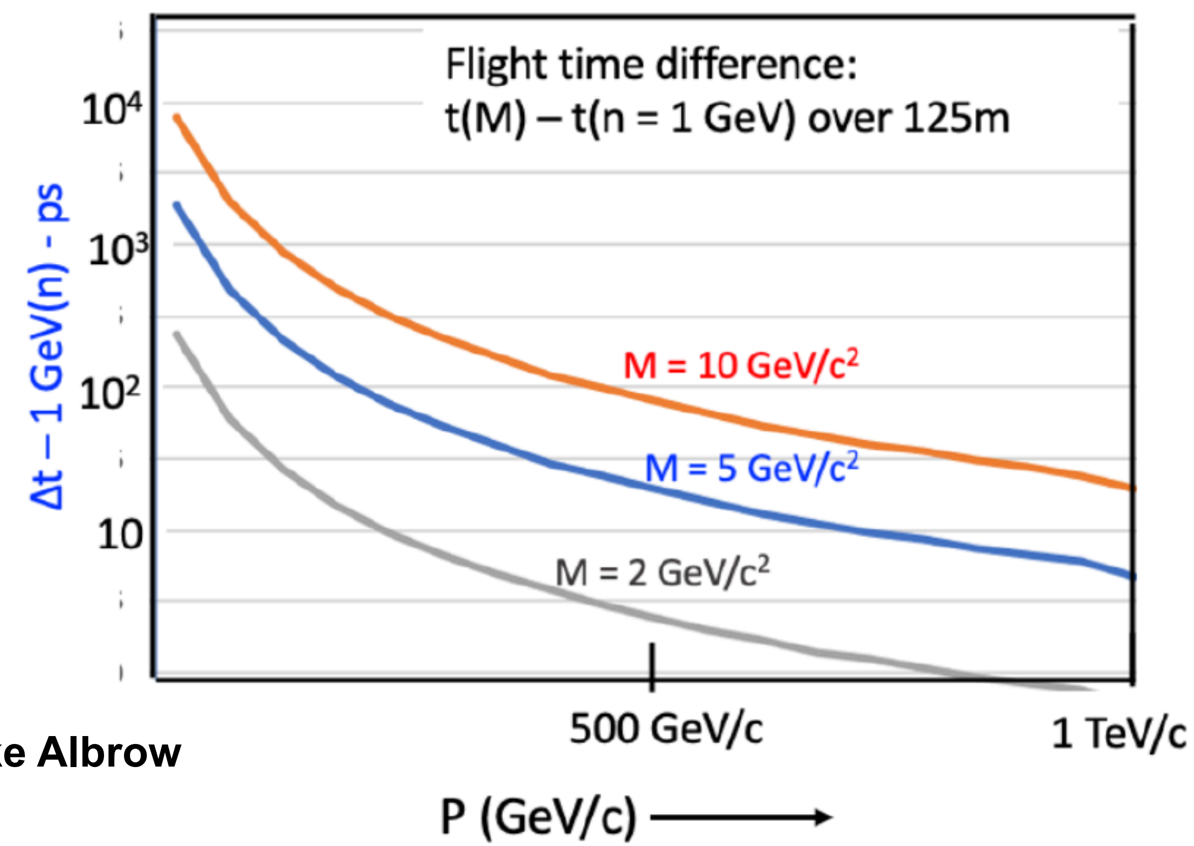




- Need detailed simulation to estimate the fraction, but expect ~10^{12} D meson decays in 3/ab
- An interesting example to study: $D_{(s)}^+ \rightarrow \mu^+\mu^+\pi^-$ - the "golden" SHiP LFV decay

Time-of-Flight

- ~20 ps TOF would allow us to estimate the mass from the known momentum for ɣ factors of up to ~100
- This also gives an additional handle against backgrounds that often do not come following a straight line from the IP



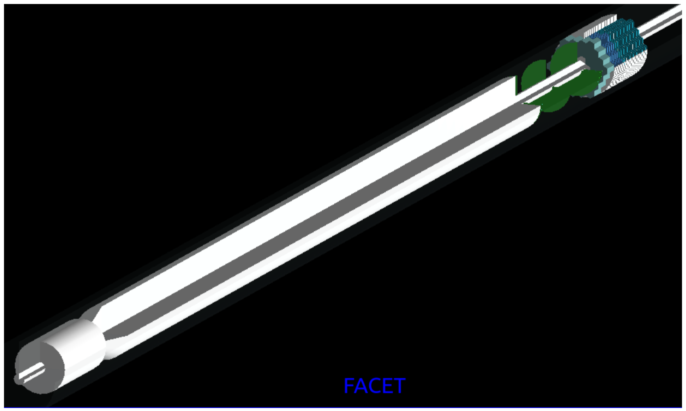
Mike Albrow

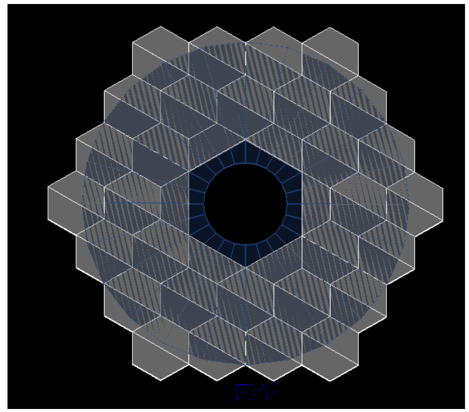
Other Physics Topics

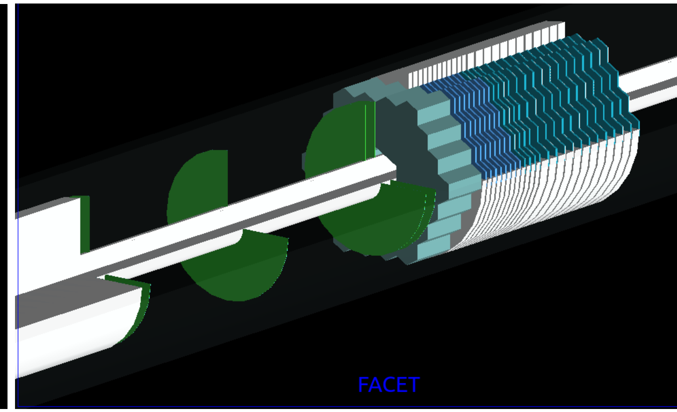
- A number of other physics topics should be accessible with FACET, perhaps with some detector modifications
  - ★ Have to be mindful of several hard constraints, such as space (prohibits magnetic tracker), cost (limits the number of detector planes), beam backgrounds (prohibits neutrino physics via emulsions)
- Can explore simultaneous triggering by CMS and FACET in low-luminosity environment (e.g., heavy-ion running)
- Can look for millicharged particles (cf. FORMOSA, arXiv:2010.07941
- Can do some SM physics (forward meson production with D1 as a spectrometer, etc.)

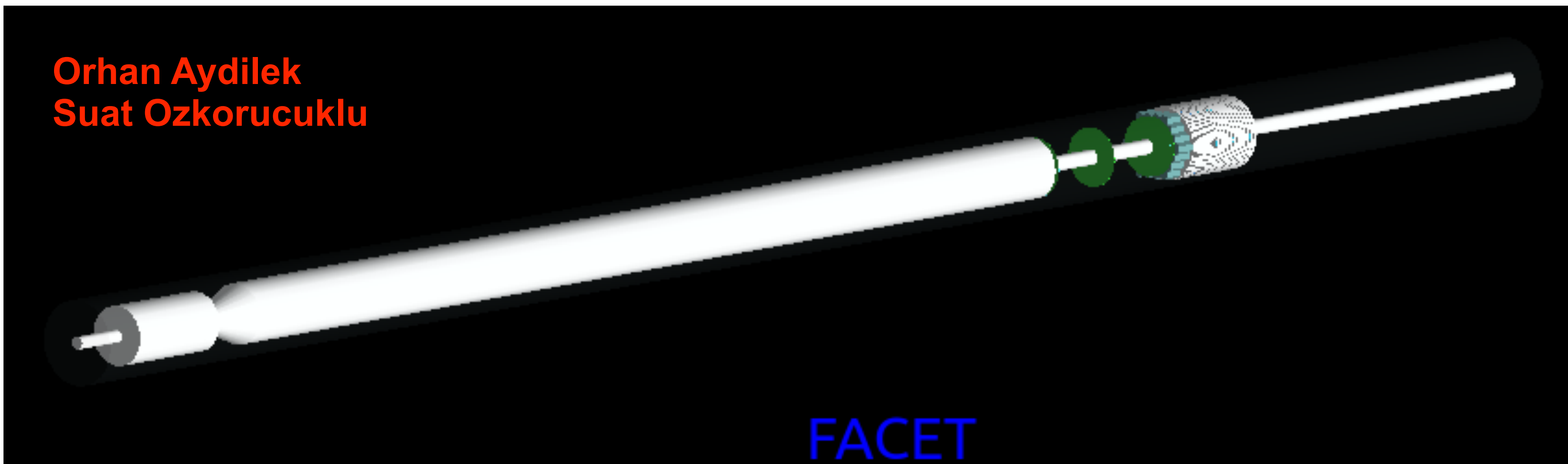
Towards Full Simulation

- Significant progress has been made on incorporating FACET into GEANT4
- Also working on the DELPHES simulation for optimization and benchmarks









Conclusions

- FACET proposal will enhance significantly the capabilities of the Phase 2 CMS upgrade in detecting long-lived particles with the masses ~1-10 GeV
- FACET is based on the same detector technologies as being pursued by CMS as a part of Phase 2 upgrade
- FACET sensitivity rivals that of the proposed FASER-2 upgrade and is unprecedented for the lifetimes $\gamma c\tau$ ~ 100 m
- The detailed detector layout is being worked on, as well as physics simulations establishing FACET reach during the HL-LHC running
- We plan to submit an LoI to CMS before summer; if approved, we plan to start raising external funding
- We have a core group of ~10 people actively involved in this work now and about 30 people who expressed interest to join this project
- We welcome new collaborators to join us in this exciting quest for new physics at HL-LHC
- You can join our e-group cms-fms-llp@cern.ch or contact us directly at albrow@fnal.gov, dgreen@fnal.gov, and Greg.Landsberg@cern.ch