LDMX: The Light Dark Matter eXperiment

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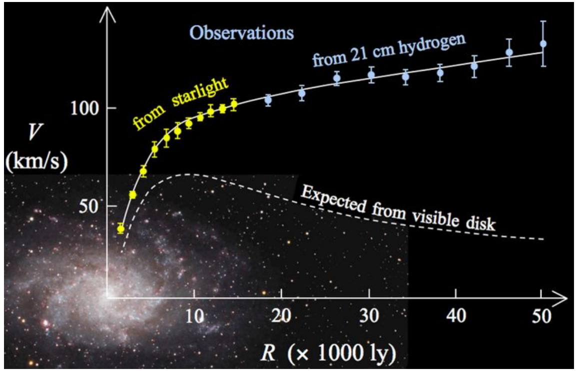
University of Wisconsin HEP Seminar

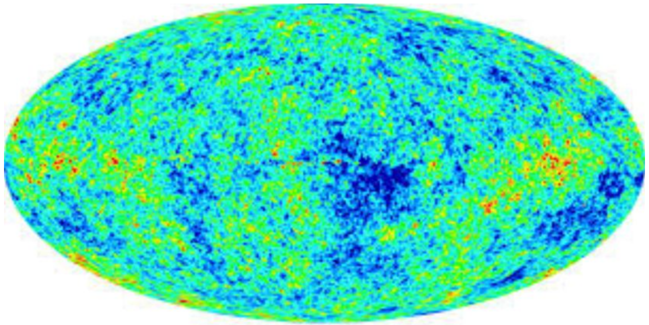
The Existence of Dark Matter

- There is clear evidence for the **existence of dark matter** (DM)
- The fundamental nature/origin of DM is a **central puzzle in particle physics**
- SM can't account for DM. What are some ideas for what DM could be?



Galactic Rotation Curves

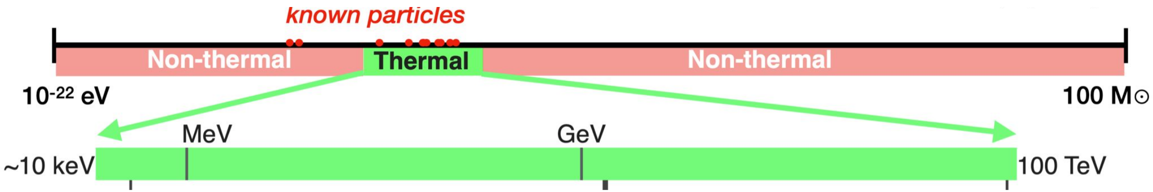
Gravitational Lensing



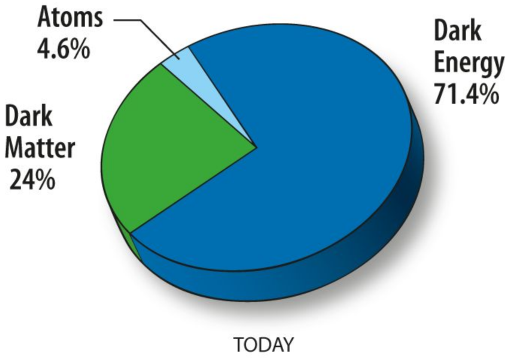
Cosmic Microwave Background

A Thermal Relic

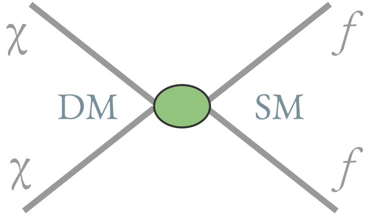
- Astrophysical evidence of DM does not constrain the mass scale very well
- **A thermal relic** - simple and predictive model of dark matter (DM)
- Thermal DM constrains DM mass to ~mass scale of SM particles and relates the annihilation cross-section to the observed relic abundance (~85%)



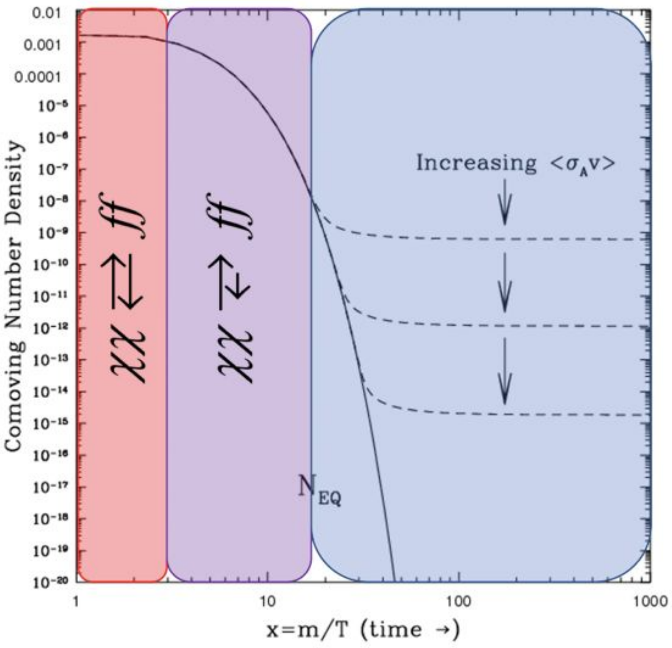
The range of (non-)thermal DM mass spans a range of ~(90)
7 orders of magnitude!



A Thermal Relic



arXiv:9506380

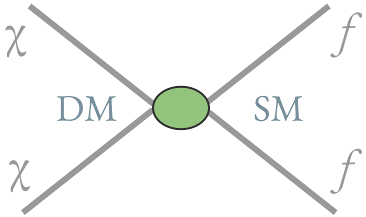


- What is a thermal origin of DM?
  - **1.** Assume DM was in thermal equilibrium with SM particles
  - **2.** The universe expands and cools such that DM pairs are no longer produced
  - **3.** The universe expands and cools such that DM annihilations cease
- The present DM density Ω_χ is related to the DM annihilation cross-section $\langle\sigma v\rangle$

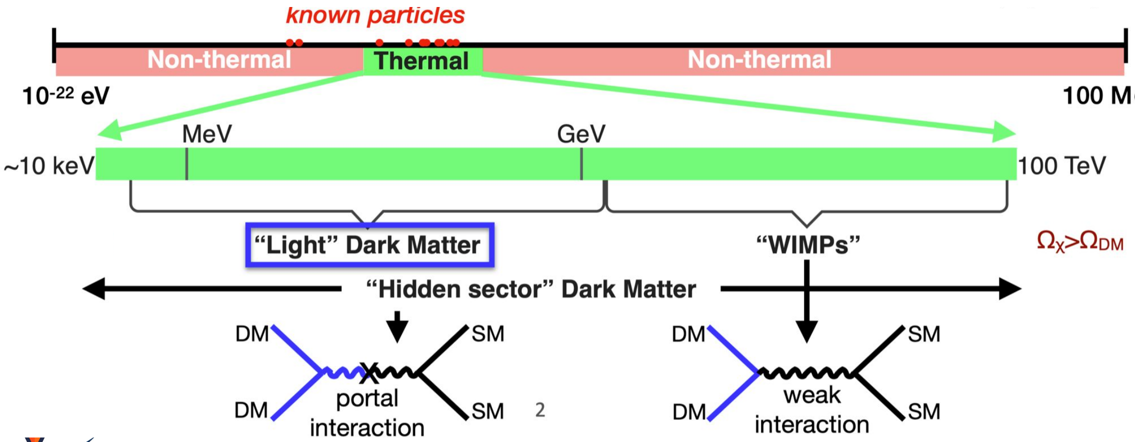
$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle} \longrightarrow \langle\sigma v\rangle = 3 \times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

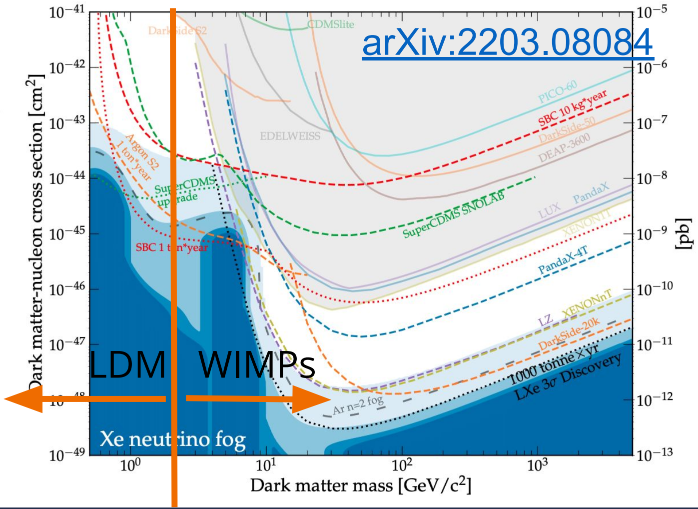
Any proposed mechanism must yield ≤ 85% DM!

A Thermal Relic - WIMPs and LDM



- WIMPs are well-motivated, but accessible parameter space is shrinking
- Increasing interest in expanding the thermal DM search to “Light” DM (LDM) in the MeV-GeV mass range
- LDM **requires non-SM “portal” interaction** due to the Lee-Weinberg Bound





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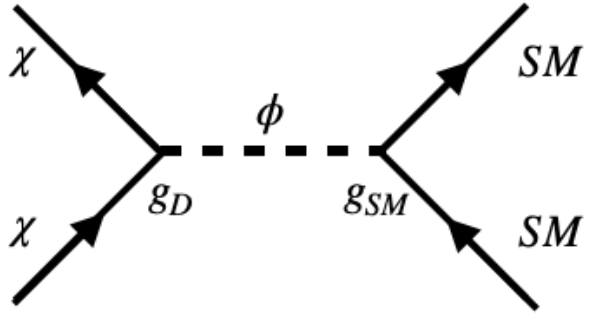
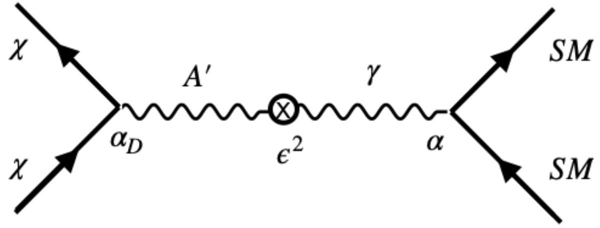
Light Thermal Dark Matter - Hidden Sector

- Hidden Sector Light Dark Matter
  - Sub-GeV DM requires an additional non-SM interaction for correct relic abundance
  - Why should the “dark sector” be any simpler than the SM sector?
  - Should we be looking for DM at the mass scale where we know stable SM particles exist?
- Simplest predictions involve a Dark Photon (A’)
  - Additional U’(1) symmetry with an additional massive spin-1 gauge boson, an A’
  - Kinetically mixes with SM U(1) with factor ε
  - Ubiquitous benchmark for the physics community

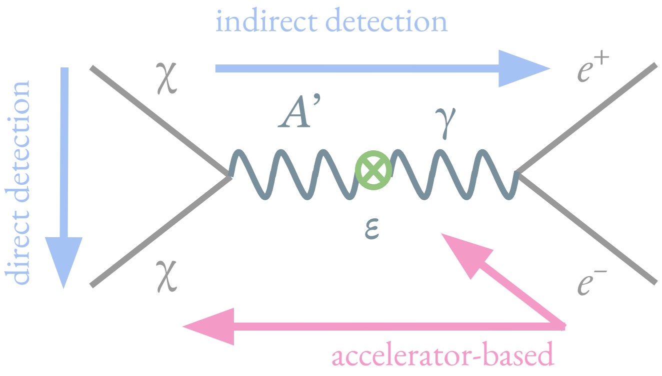




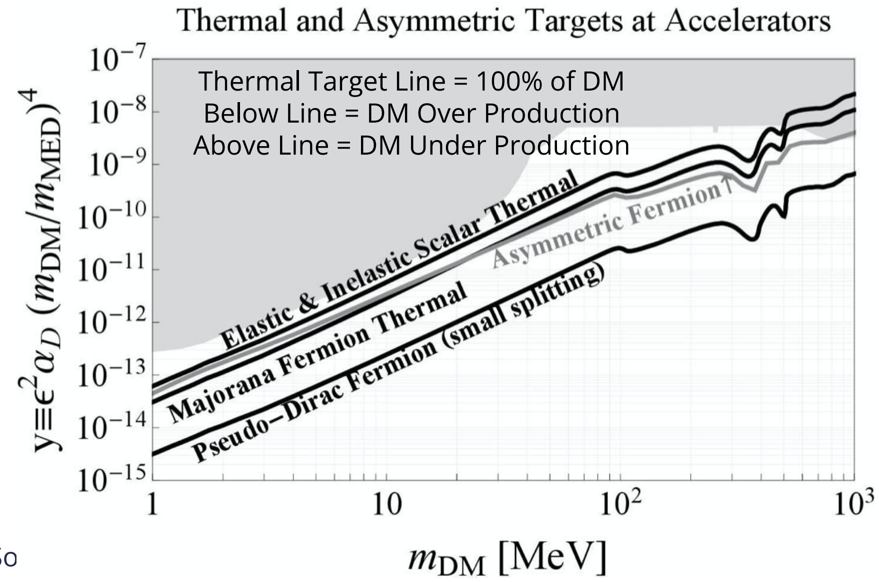
$$\epsilon F^{\mu\nu} F'_{\mu\nu}$$

Light Dark Matter at Accelerators

- Thermal Light DM models provide clear benchmarks for exclusion called "thermal targets" for a variety of types of experiments
- Thermal targets are **attainable with next generation accelerator experiments**

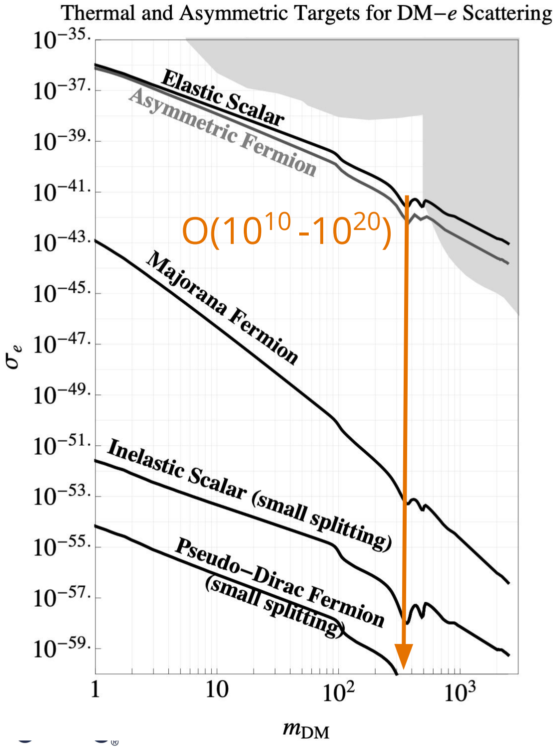


Kinetic Mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

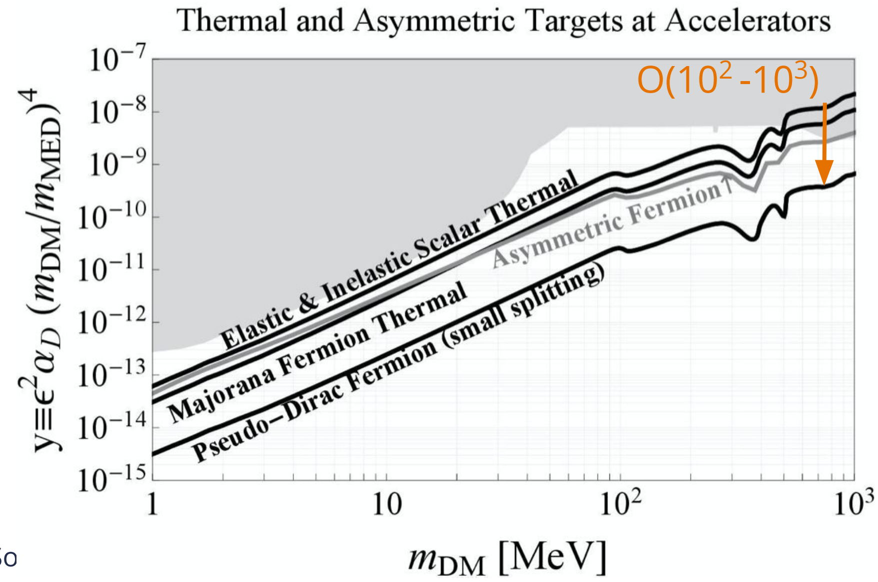


Advantage of DM Production at Accelerators

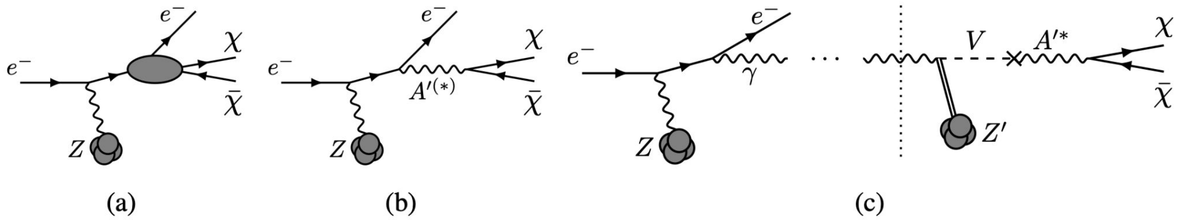
- LDM production at accelerators is fairly independent of specific DM model
- “Thermal targets” for sub-GeV dark matter models can be completely probed by LDMX!



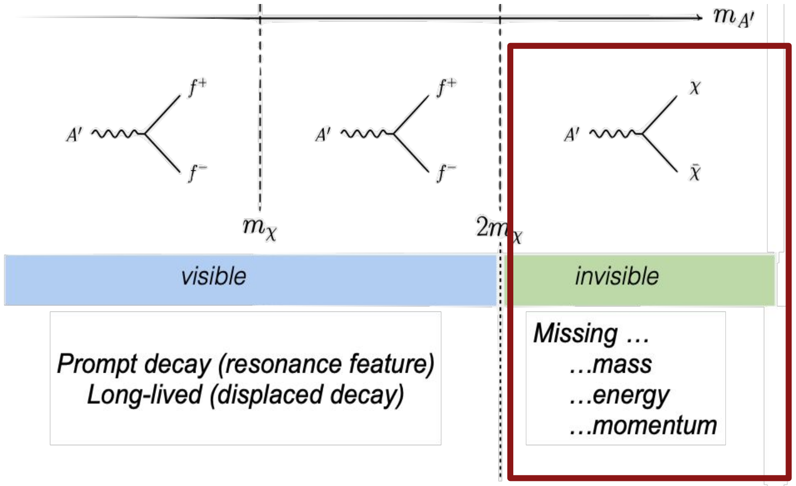
Non-relativistic vs semi-relativistic DM scattering



Dark Photon Signatures



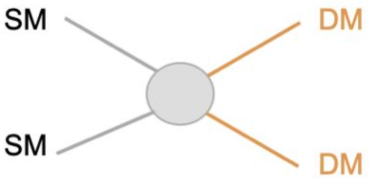
Dark Photon Production

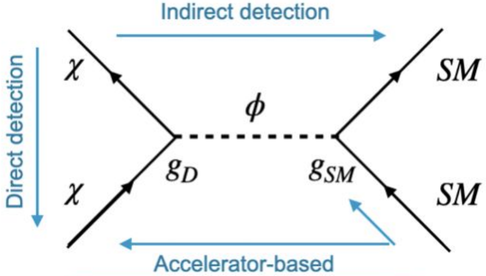


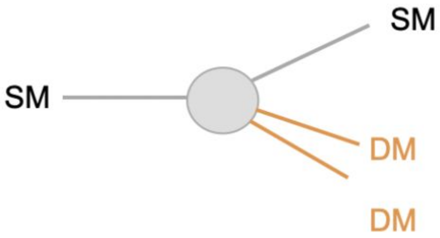
Dark Photon Decay

Both visible and **invisible** final states are allowed depending on the mass hierarchy

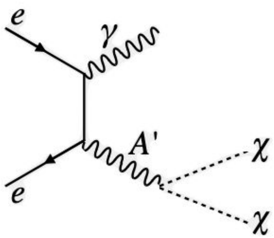
Advantage of Fixed Target Missing Momentum Search





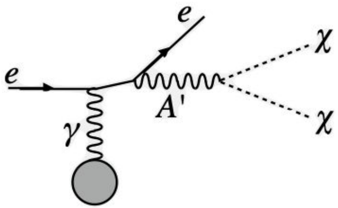


Collider



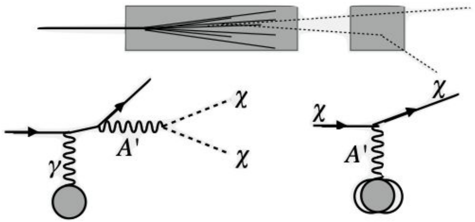
$\sigma_{coll} \propto \frac{\epsilon^2}{E_{com}^2}$ <<

Missing Momentum



$\sigma_{FT} \propto \frac{Z^2\epsilon^2}{m_{A'}^2}$ $N \propto \epsilon^2$

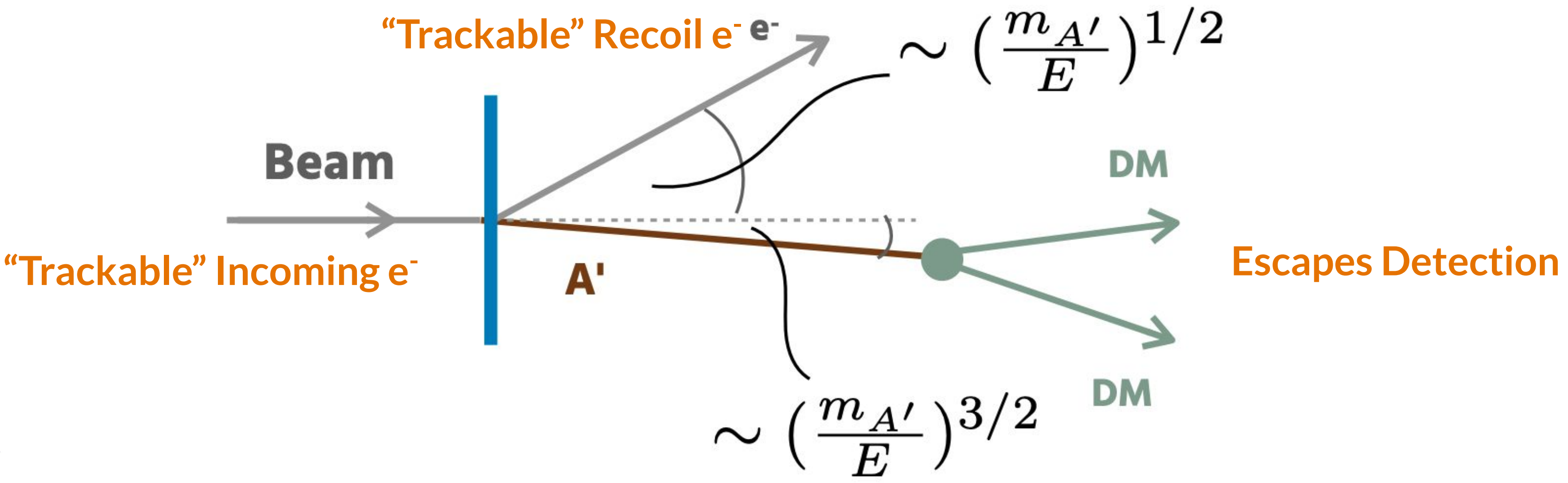
Beam dump



>> $N \propto \epsilon^4$ Direct detection

Dark Photon with a Fixed Target

- Fixed Target Signal Characteristics:
    - Dark bremsstrahlung A’ production, invisible decay
    - **A’s take most of the beam energy; only visible final state particle is a soft recoil electron**



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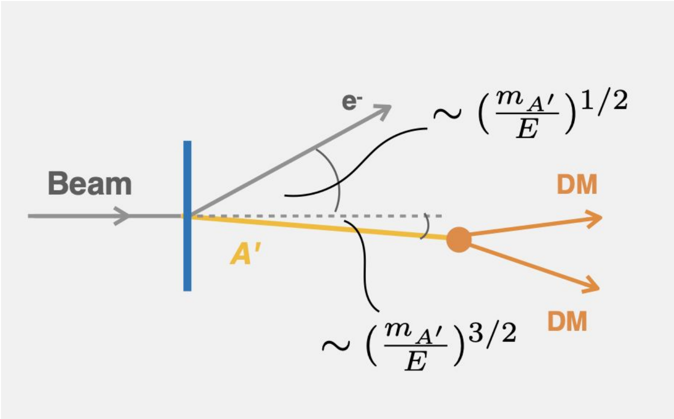
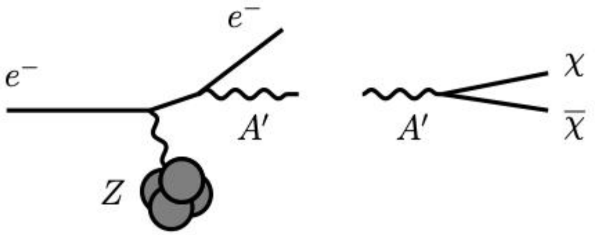
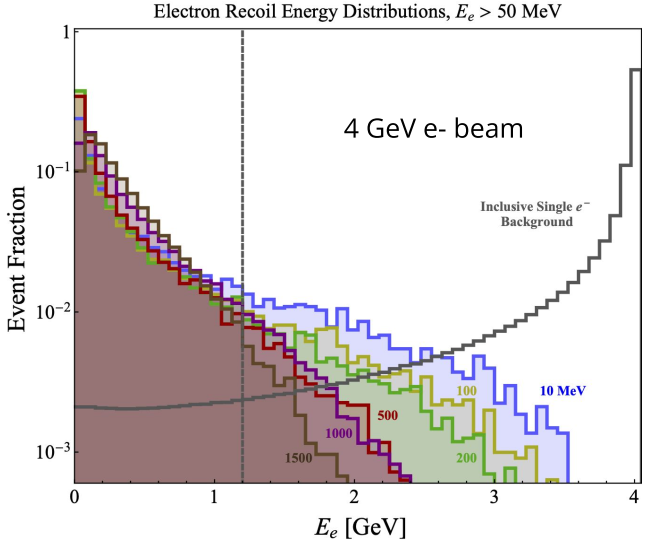


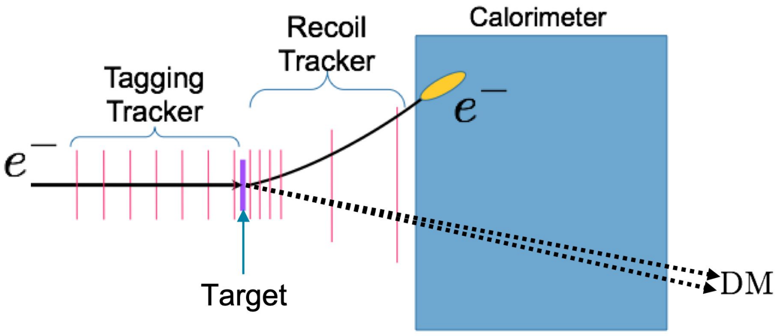




- Can probe this mechanism through a missing momentum search. We need…
  - High momentum resolution
  - High veto efficiency of SM backgrounds

LDMX Concept

- Missing momentum and energy approach
  - DM production identified by missing energy/momentum in detector
  - Equipped for particle ID e/gamma
  - Recoil pT used as discriminator/identifier



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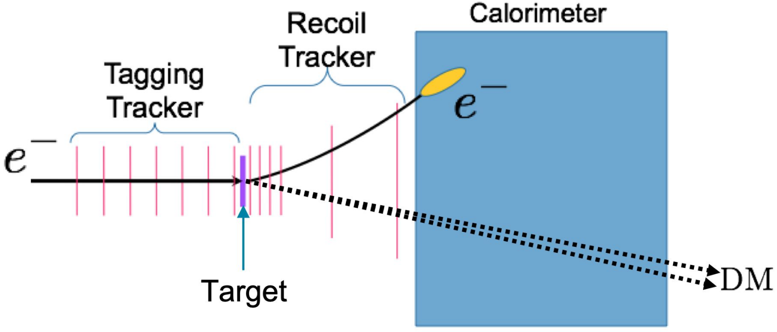
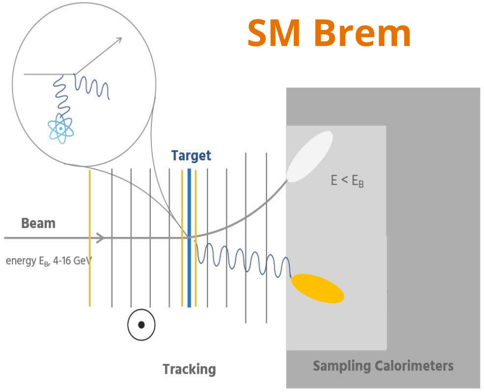
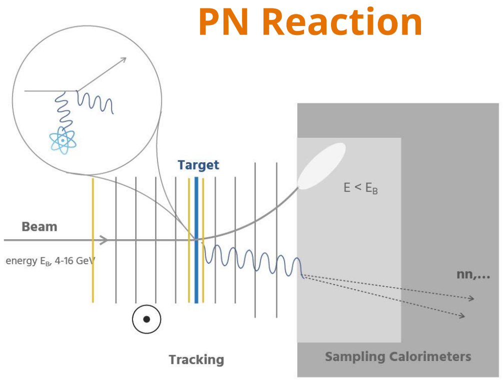


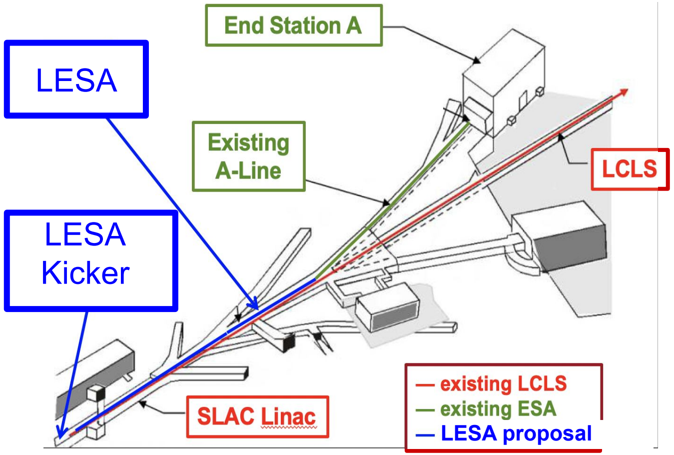




- Must mitigate SM background
  - Main background is SM bremsstrahlung
  - Most challenging background is photo-nuclear (PN) reactions

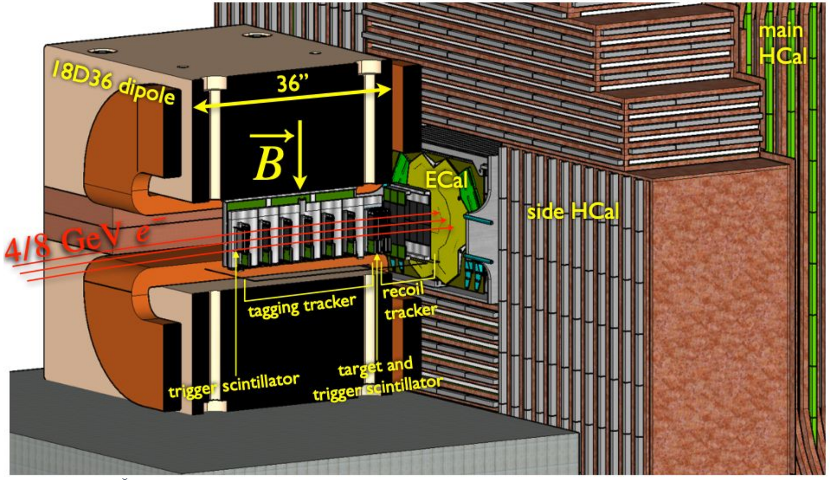
LDMX Beamline

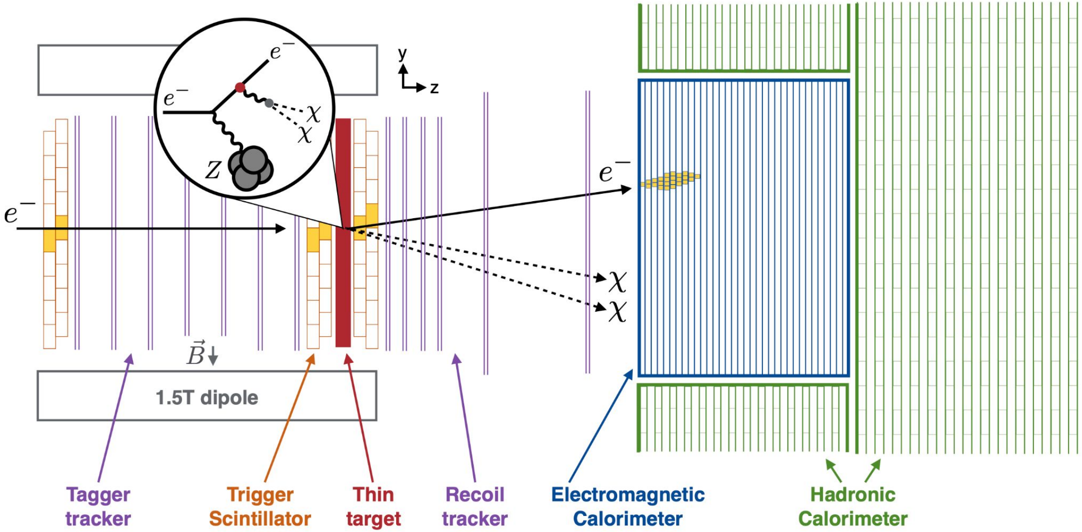
- 4 and 8 GeV e- beam provide by SLAC
  - **Parasitically** use the LCLS-II beam with a dedicated transfer line (LESA)
  - **Individual tagging** and reconstruction of up to 10^{16} e-
  - Low current, high repetition rate **37 MHz, μ = 1**
  - Currently under construction, early commissioning in FY 24-25 with 4 GeV and LCLS-II 8 GeV upgrade in ~FY 27-28



LDMX Design

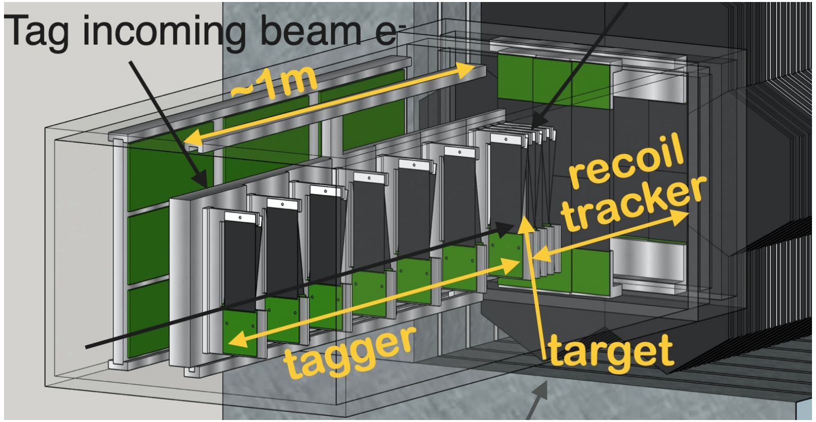
- Need hermetic, radiation tolerant detector designed for high beam rates
  - **Tagging/recoil tracker**: fast with high momentum resolution and large acceptance
  - **Electromagnetic calorimeter**: fast, good energy resolution, and high granularity
  - **Hadronic calorimeter**: high veto efficiency of neutral hadrons
  - **Trigger Scintillator**: scintillator bars provide fast count of incoming electrons

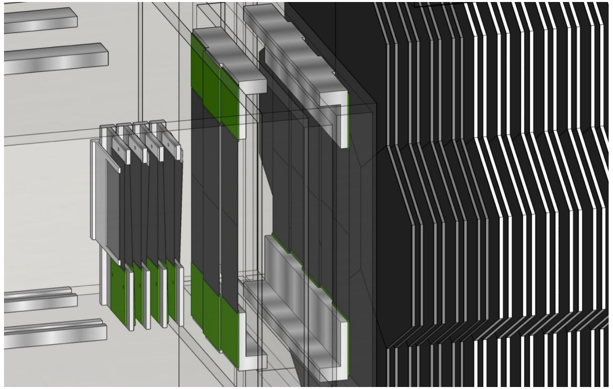




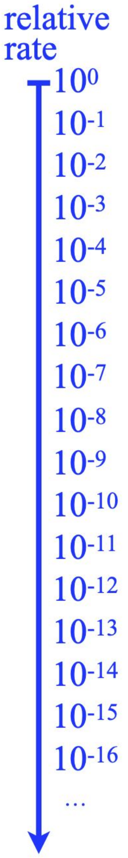
Tracker and Trigger Scintillator

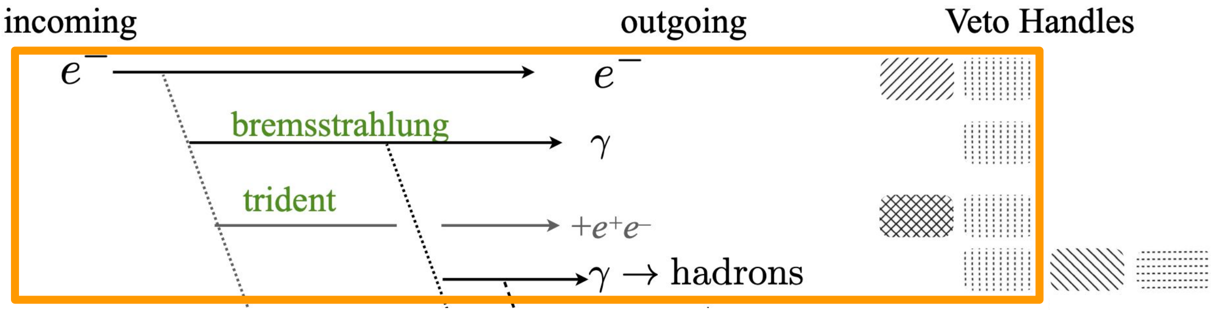
- Tagging tracker
  - Measures incoming beam electron
- Recoil tracker (based on Heavy Photon Search design) arXiv:2212.10629v2
  - Measures recoil electron and vetoes extra particles
- Trigger Scintillator
  - Arrays of scintillator bars provide fast count of incoming electrons
  - Used an input to the missing energy trigger

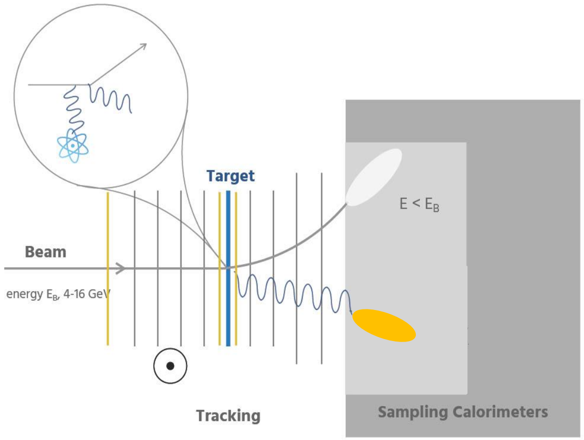


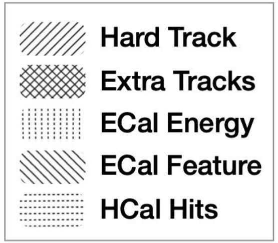


Backgrounds

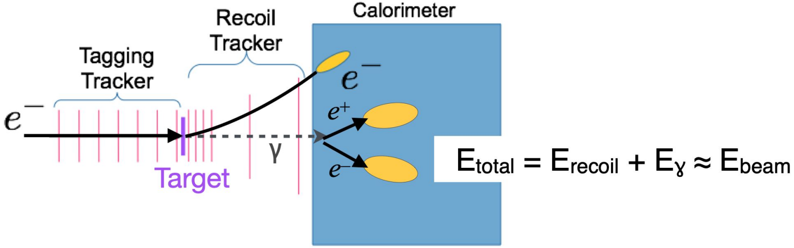






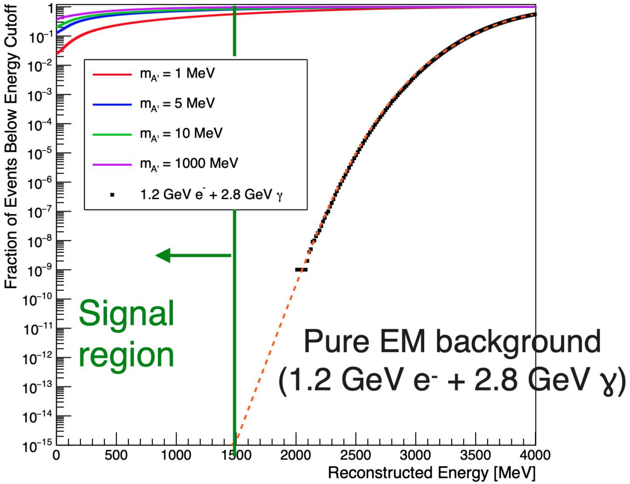


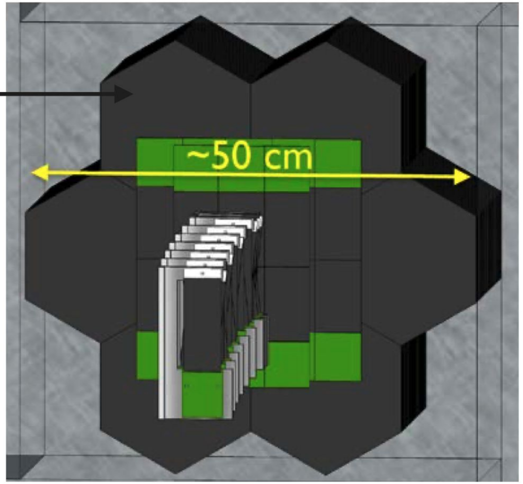
Electromagnetic Calorimeter



- 40 X_0 Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - Provides fast missing energy trigger
  - Dense, radiation hard, full shower containment, and high granularity

10.17181/CERN.IV8M.1JY2





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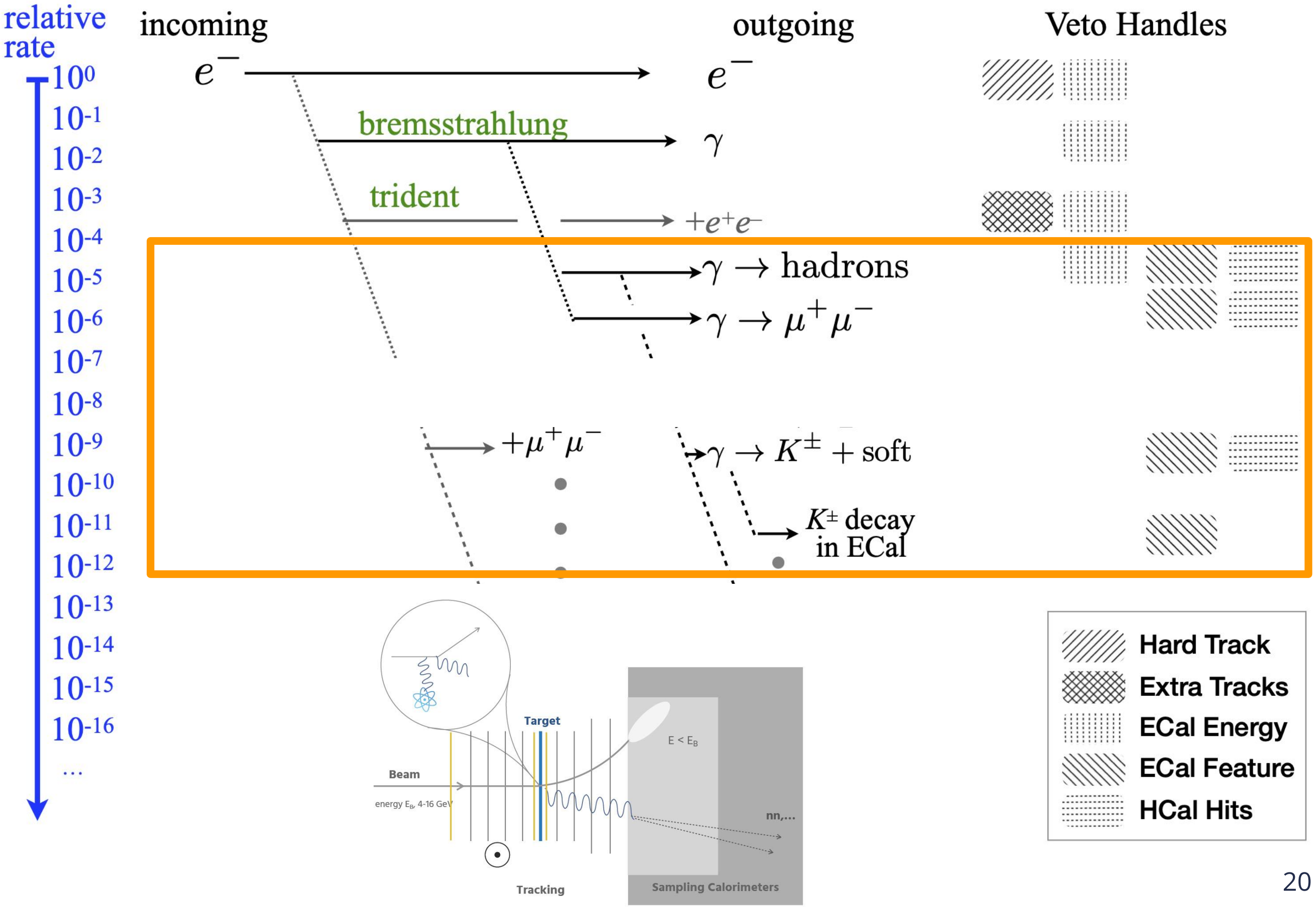
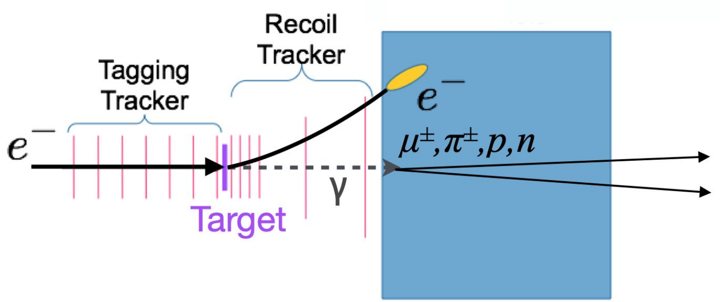
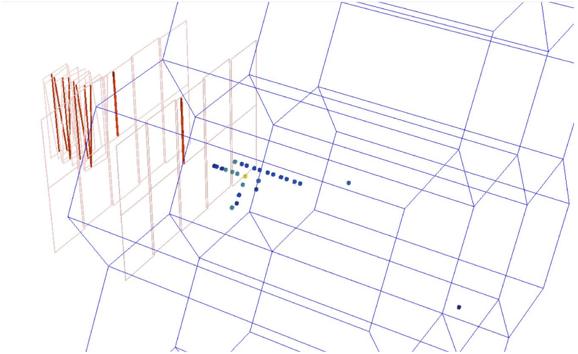
Backgrounds

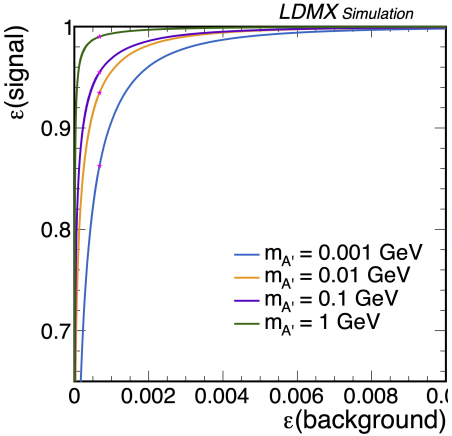


Ecal Veto

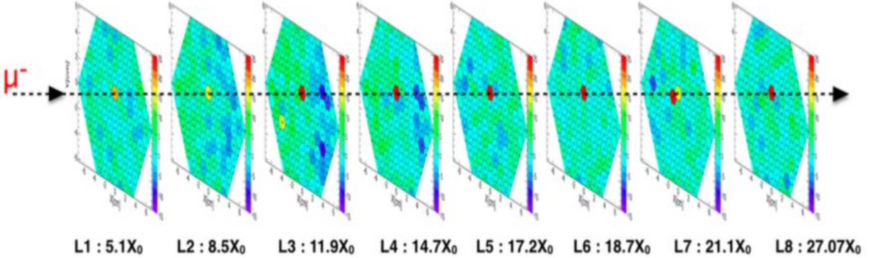
- More difficult to veto: Rare photon reactions that deposit low energy in the Ecal
  - Exploit longitudinal/transverse shower shapes and train a boosted decision tree (BDT)
  - High granularity Ecal enables MIP tracking







A.Martelli on behalf of CMS, arXiv:1708.08234



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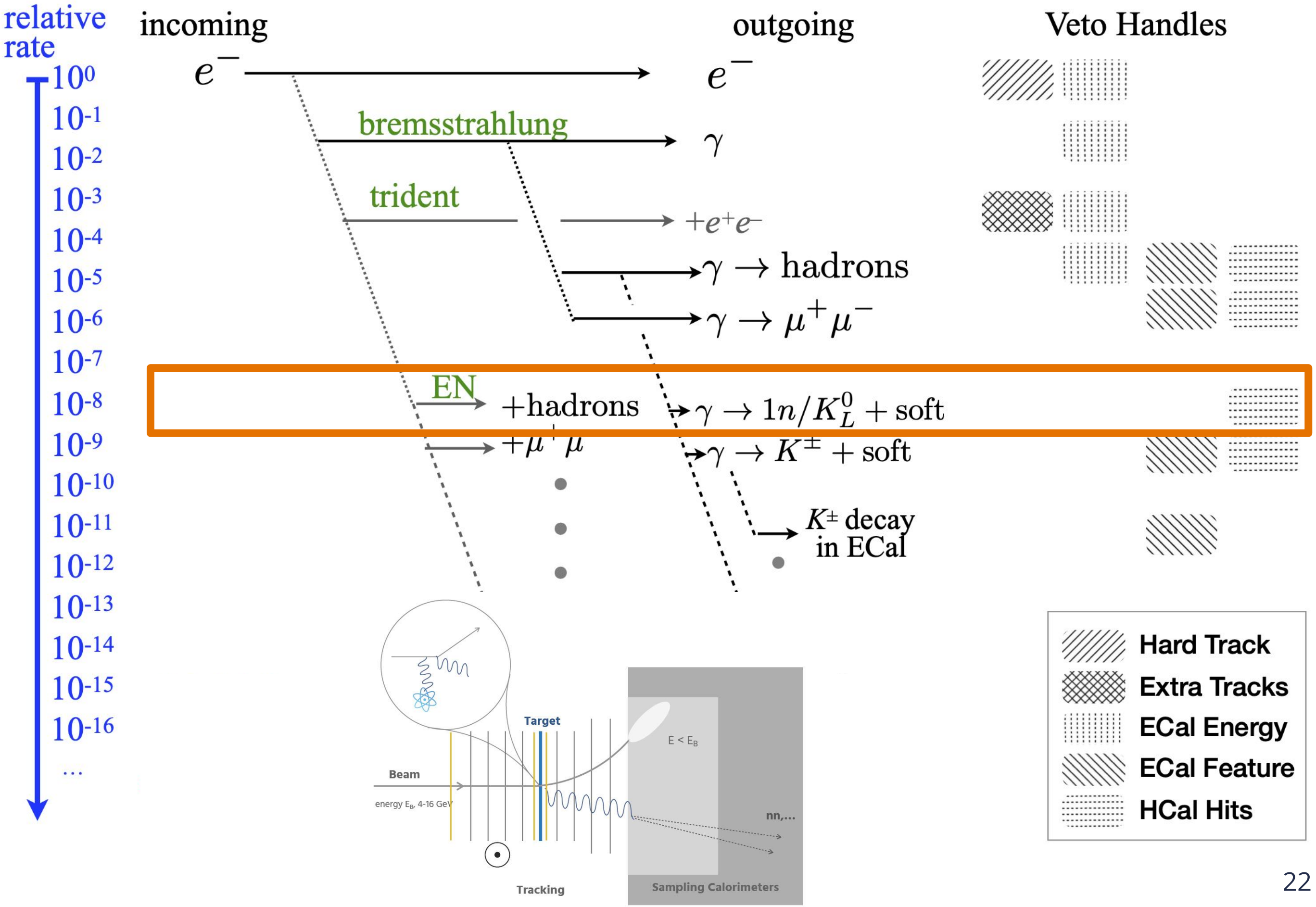
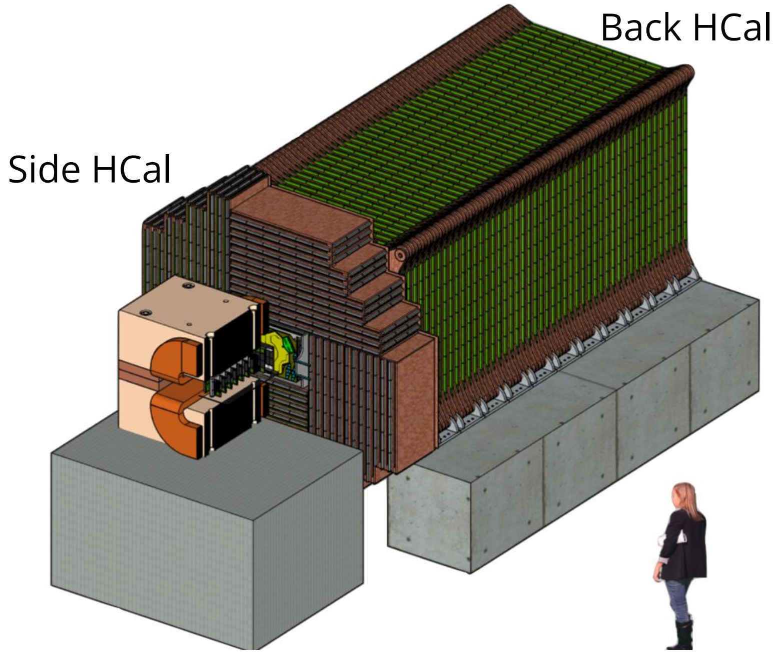
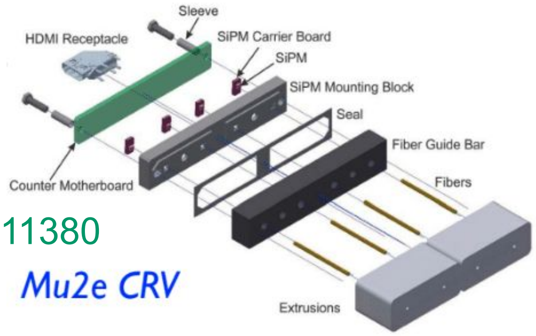
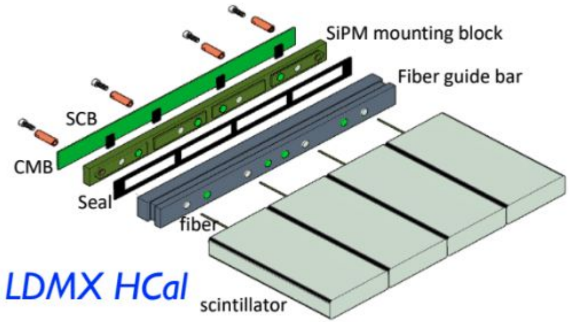


Hadronic Calorimeter



- Sampling calorimeter with segmented plastic/steel
  - Readout by wavelength shifting fibers and SiPMs (based on the Mu2e Cosmic Ray Veto design)
  - Highly efficient veto for Photo-Nuclear (PN) processes that produce neutral hadrons. Desire 1e-6 rejection
  - Side HCal rejects wide angle brem and $\gamma \rightarrow \mu^+\mu^-$

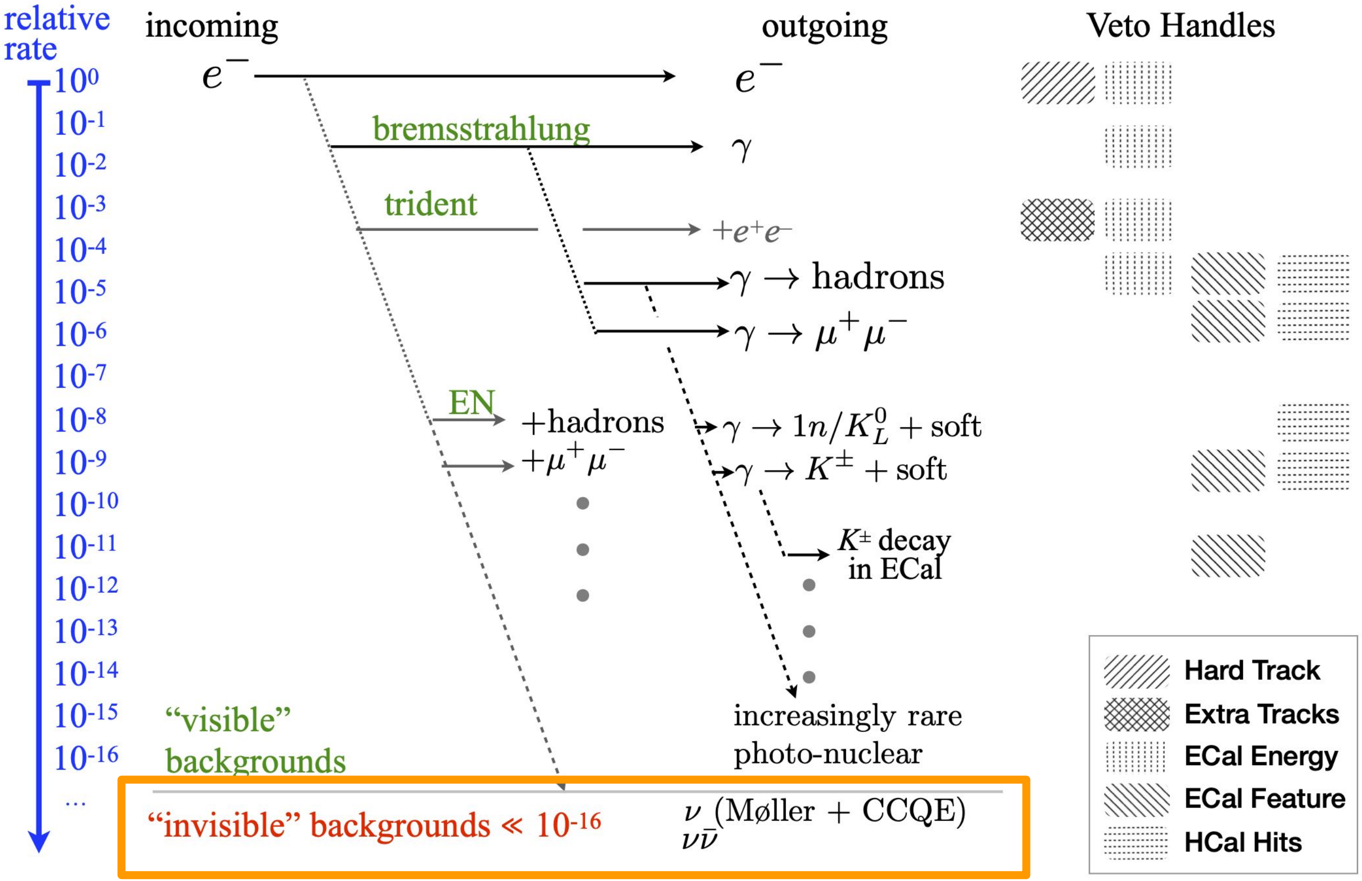




arXiv:2210.11380

Backgrounds

- Irreducible SM backgrounds << 10^{-16}
- Goal is background-free experiment for 10^{16} EoT
- Multiple veto handles for most backgrounds



Event Selection

- Require single low momentum track
- Require Ecal BDT > 0.99 & Hcal Max PE > 5
- Remaining background is eliminated by Ecal MIP tracking

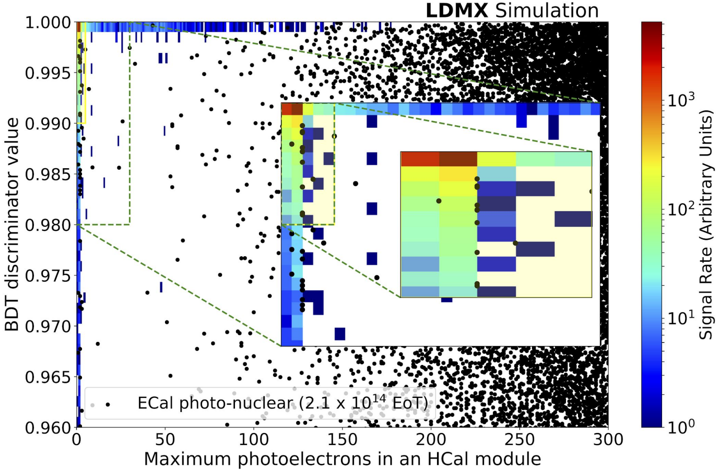
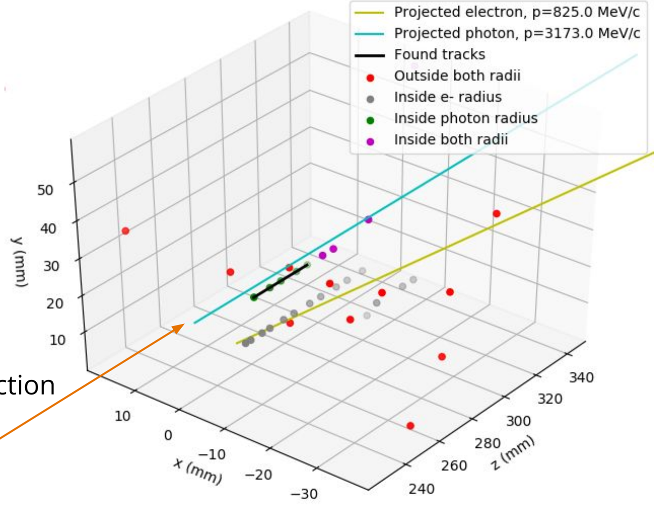


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1



Beam Direction

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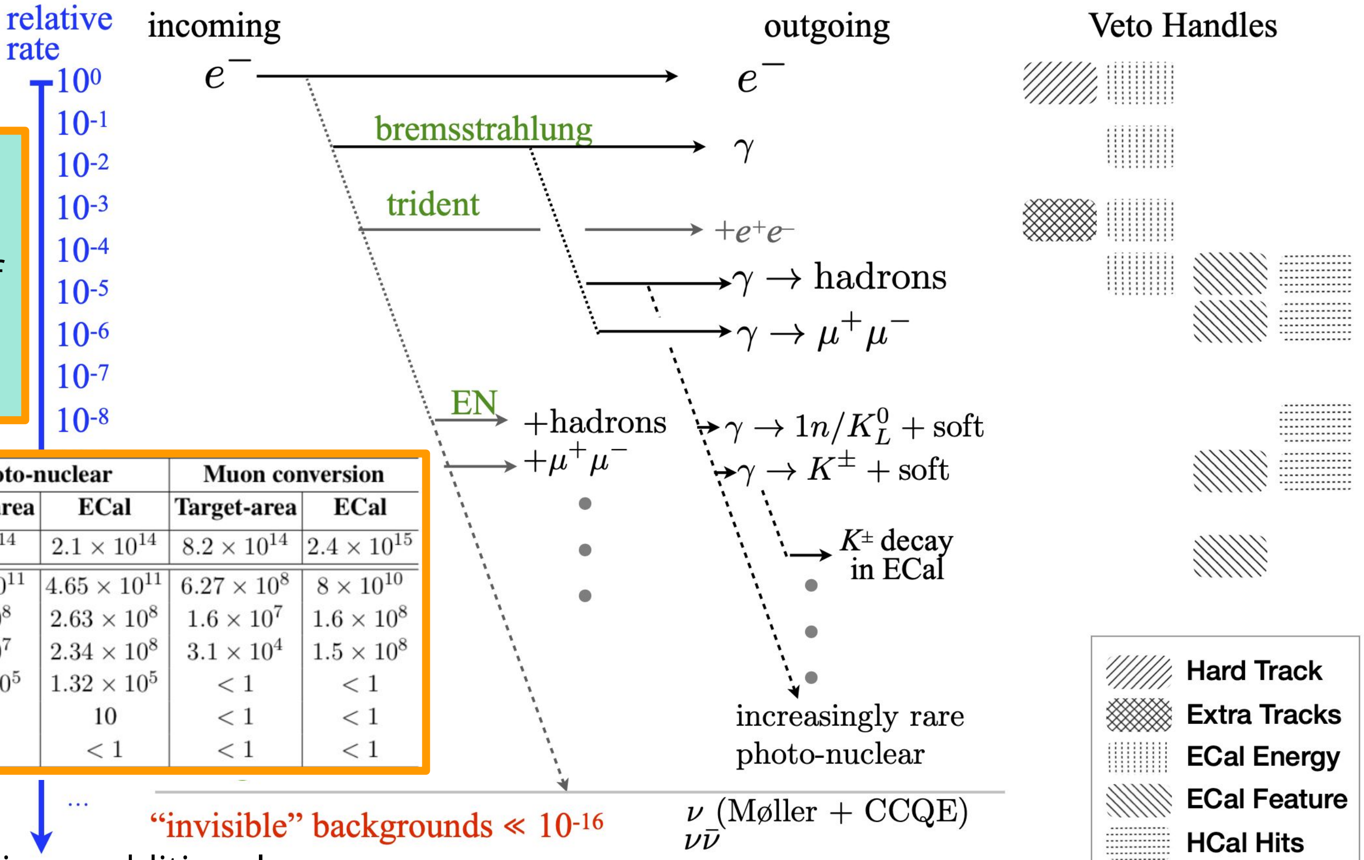
Backgrounds

All systems combined: < 1 background event with signal efficiency of ~30-50% for O(1e14) EoT!



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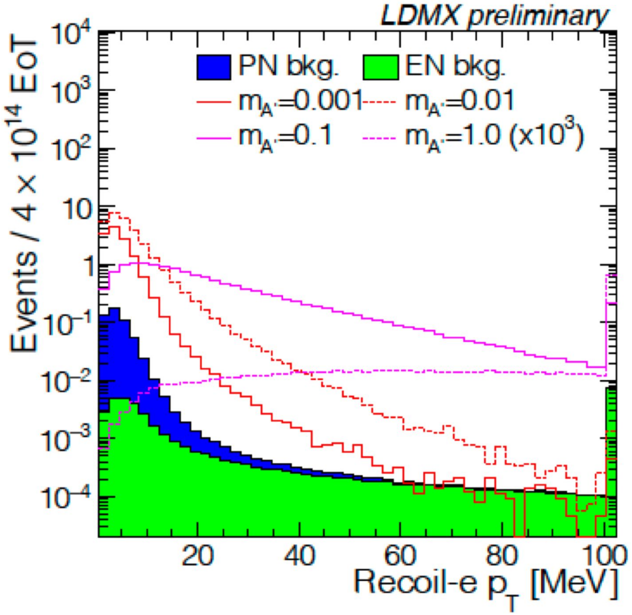
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

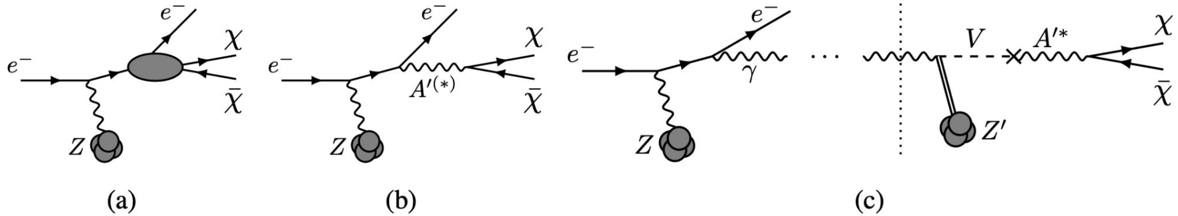
Recoil e- pT is an additional discriminator on backgrounds

arXiv:1912.05535

Signal vs. Background Kinematics

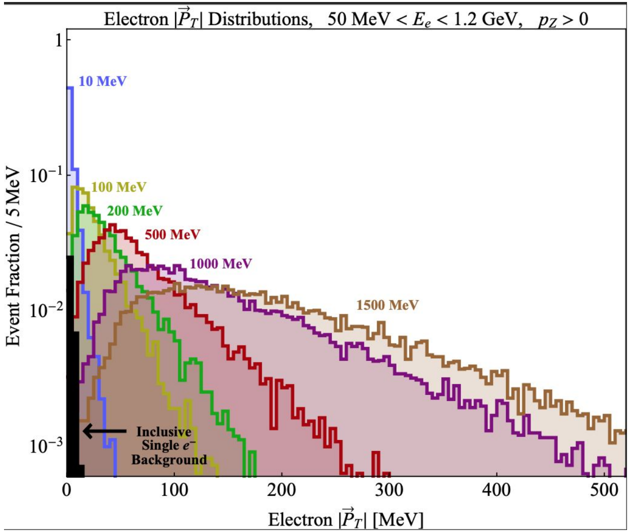
- Transverse momentum of recoil election is the last veto handle
- Currently not used in veto efficiency estimates, but as a backup discriminator in the case of unexpected background
- Larger mass signal -> larger recoil e- pT

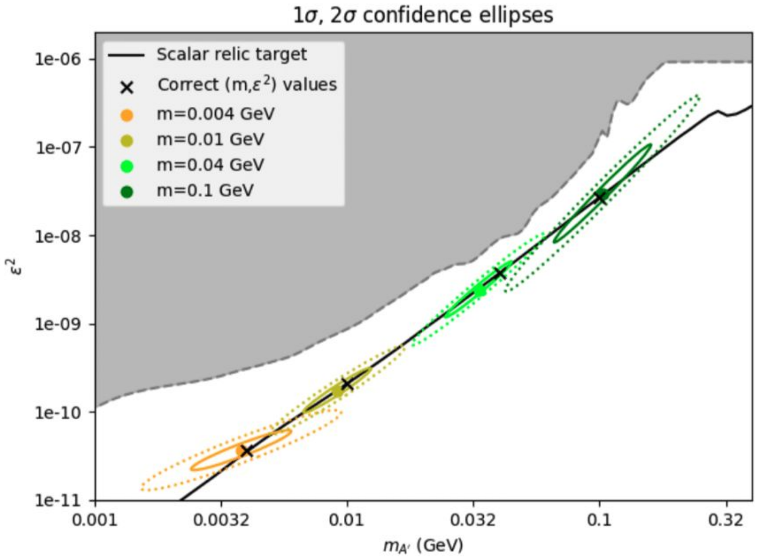




Signal Kinematics

- Recoil electron transverse momentum can also be used to estimate and constrain DM mass scale
- Signal rate constrains the scale of the "y" parameter



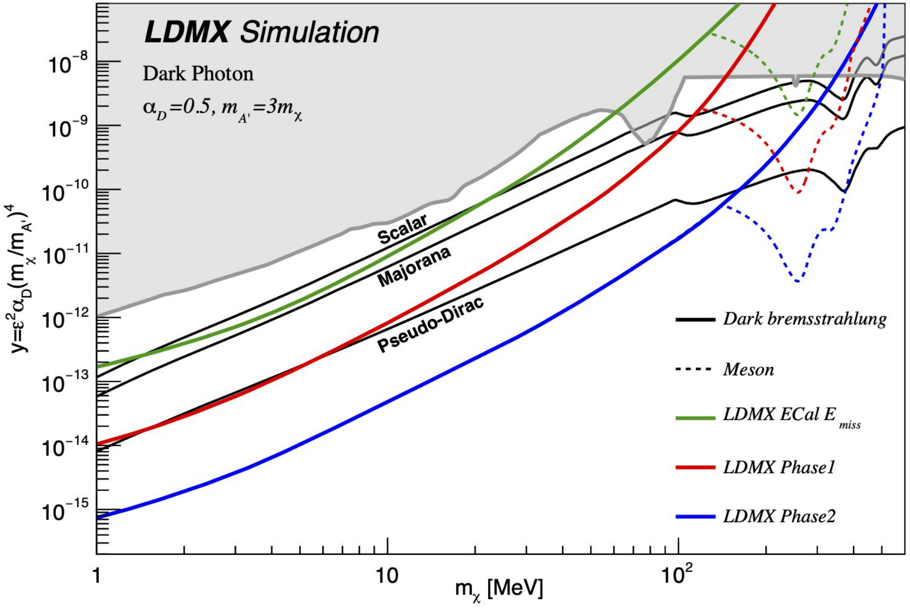


LDMX Sensitivity

$$2m_{DM} < m_{A'}$$

Phase 1: 4 GeV, 10^{14} electrons
Phase 2: 8 GeV, 10^{16} electrons

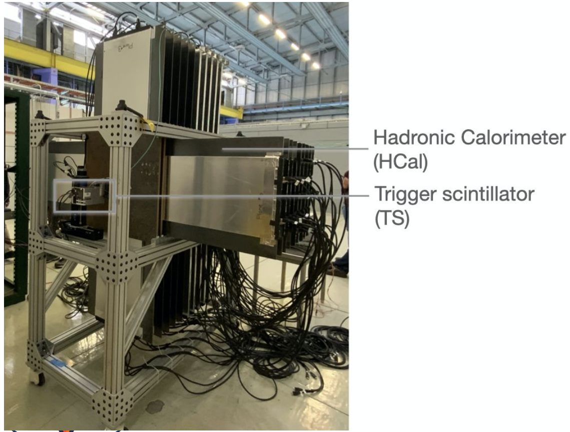
arXiv:1808.05219

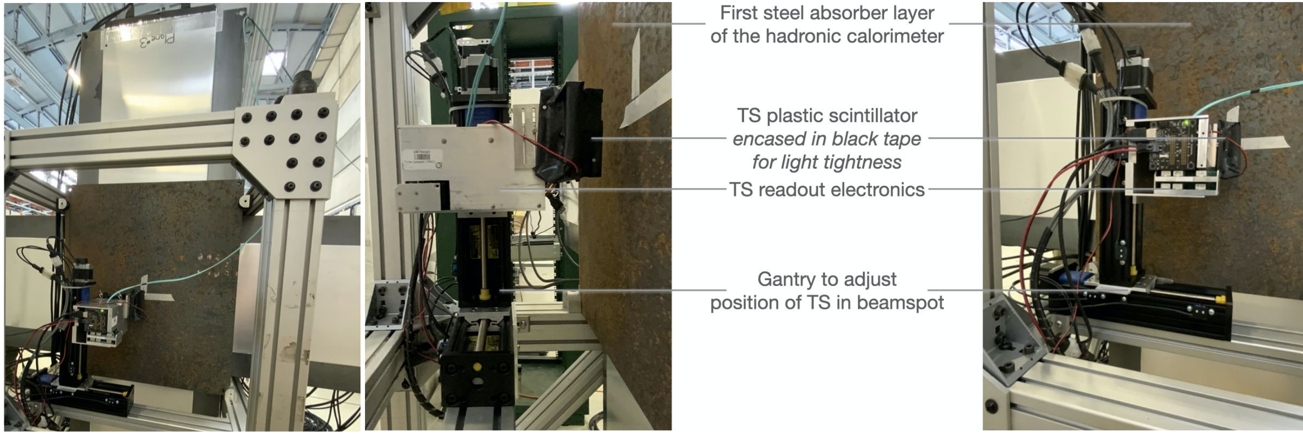


LDMX is based on existing technology from other experiments
We are “shovel ready” to build LDMX

CERN Test Beam

- Recent successful test beam at CERN PS in April 2022 with Hcal and trigger scintillator (TS) prototypes
- Demonstrated successful operations, readout & electronics, and basic physics capabilities of two subsystems

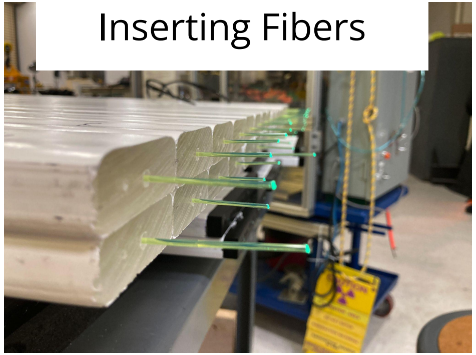




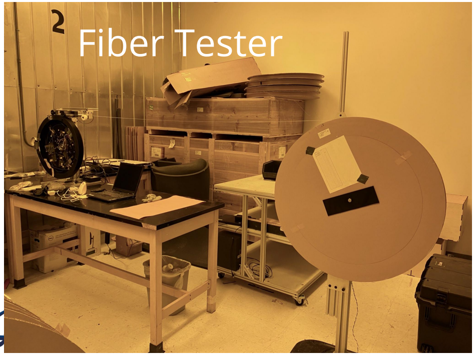
CERN Test Beam - Quad-bar Fabrication

Mu2e Cosmic Ray Veto (CRV) module factory at the **University of Virginia** used for Hcal quad-bar fabrication

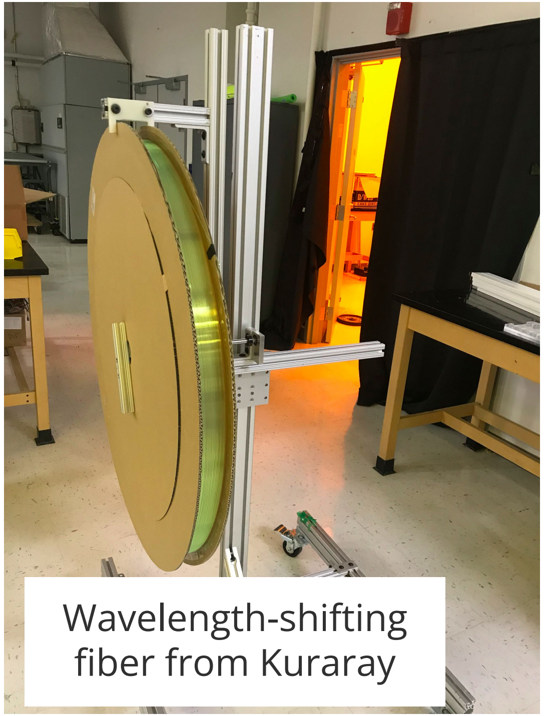
arXiv:2302.09172


Inserting Fibers


Forming Quad-bars


Fiber Tester


Hcal Quad-bar

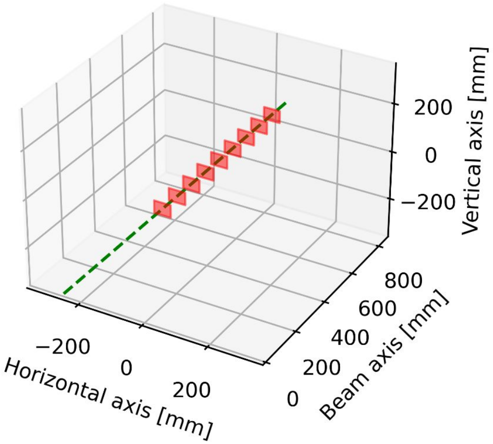

Wavelength-shifting fiber from Kuraray

CERN Test Beam

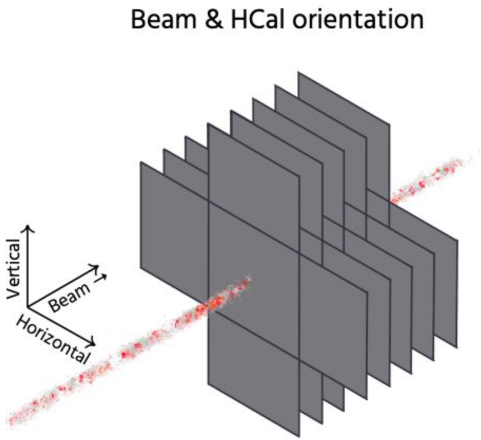
CERN PS T9 Beamline

CERN Test Beam - Analysis

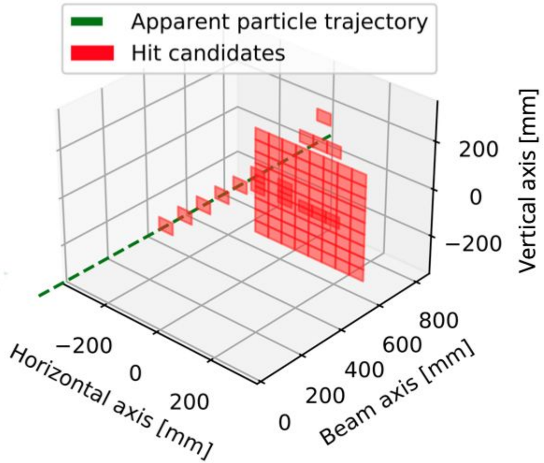
Muon Candidate



Beam & HCal orientation

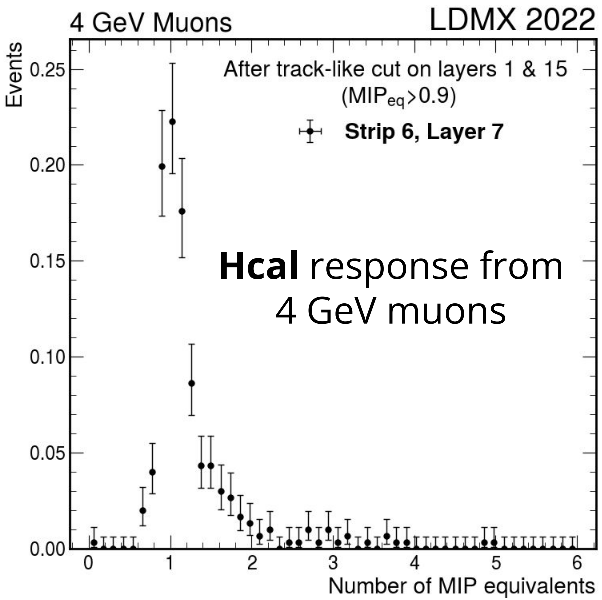


Pion Candidate

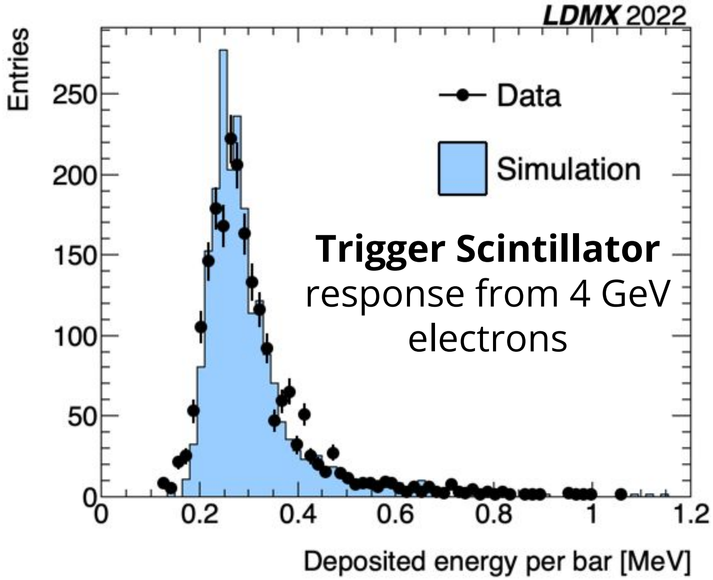


Preliminary results, data analysis is ongoing

CERN Test Beam - Analysis



Hcal response from 4 GeV muons

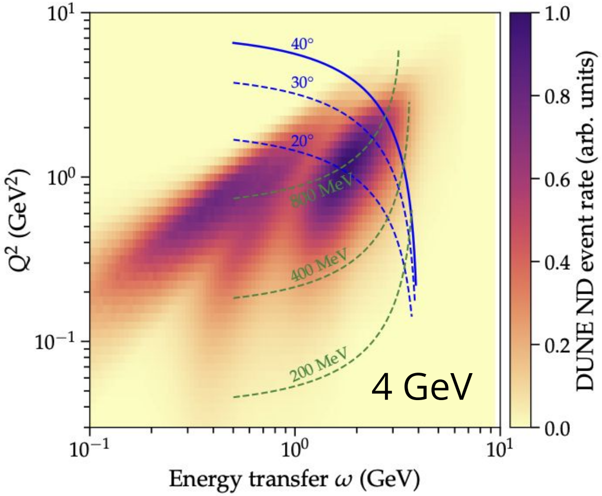


Trigger Scintillator response from 4 GeV electrons

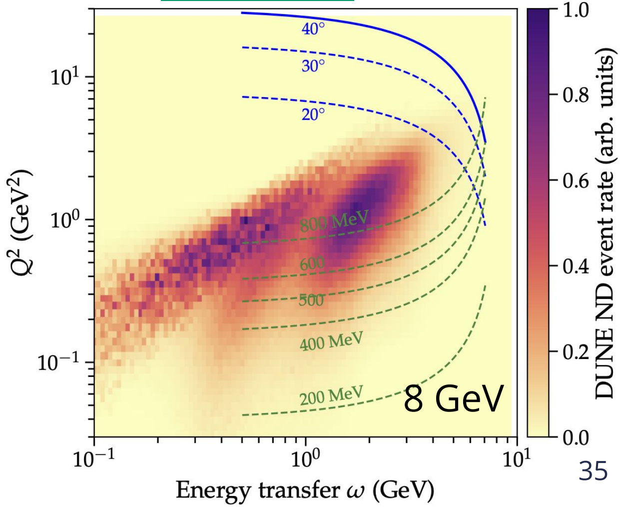
Preliminary results, data analysis is ongoing

LDMX - Additional Physics Program

- LDMX offers a broader physics program beyond a missing momentum search for LDM
- Small angle acceptance (nearly hermetic) and fully reconstructing final and initial states allows for several unique measurements
  - Electro-nuclear scattering measurements of interest to neutrino experiments such as DUNE (right), can constrain neutrino production cross-sections
  - Searching for visibly decaying long-lived particles (next slide)

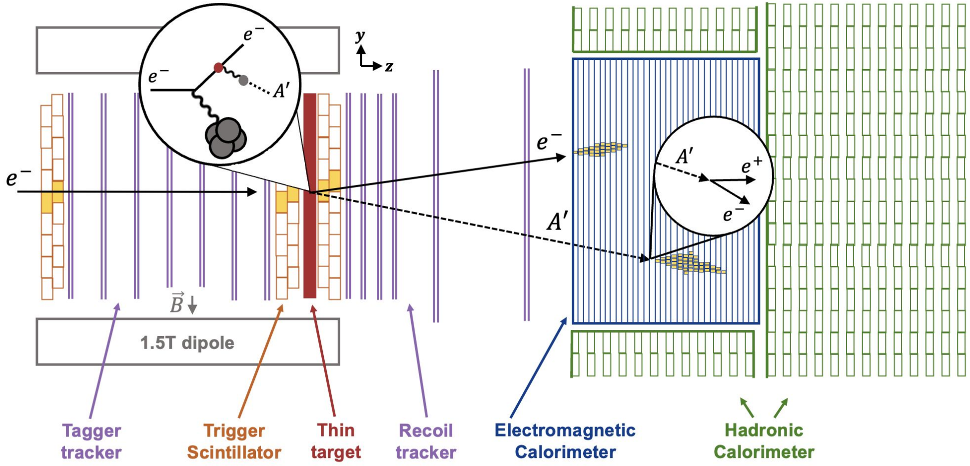


arXiv:1912.06140



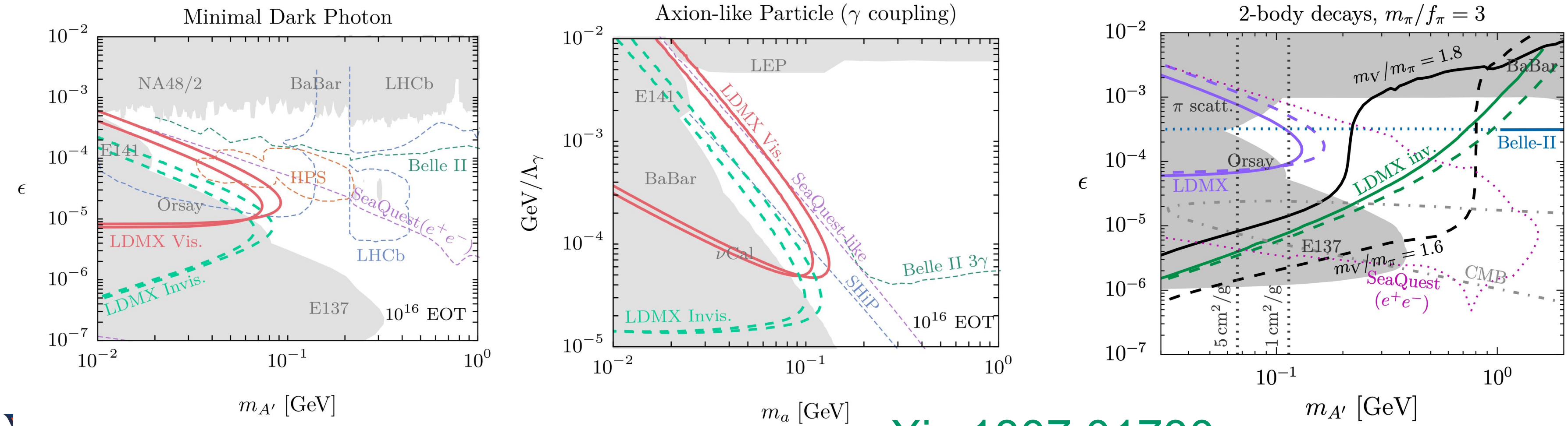
LDMX Visible Signatures

- LDMX is effectively an active beam dump; ideal for long-lived particles
- Possible to probe a sudden “appearance” of SM particles in Ecal/Hcal
    - Needs modified missing energy trigger
    - Mitigation of PN backgrounds (much like the standard missing momentum search)
    - Mitigation of brem conversions that penetrate deeply into the Ecal



LDMX Visible Signatures

- LDMX has competitive sensitivity for several models of interest to DM - minimal dark photon, ALPs, SIMPs, etc.
- Updated projections with full simulation are nearing completion



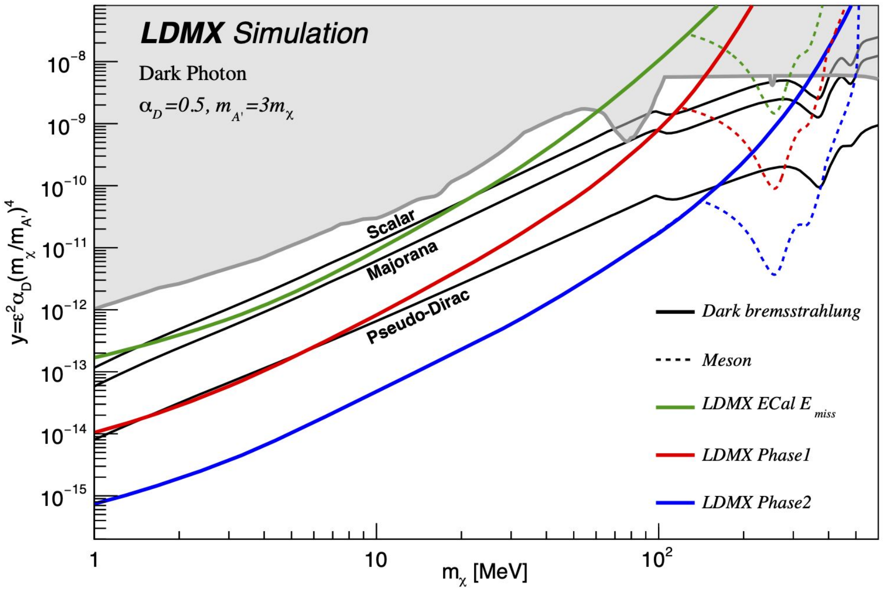
Projections are for 8 GeV and 16 GeV beams

arXiv:1807.01730

Strongly Interacting Massive Particles

Conclusion

- **Thermal Dark Matter is a simple and compelling scenario**, and the MeV-GeV scale is a good place to explore - logical extension of WIMP
- **LDMX provides a world-leading sensitivity to sub-GeV DM** and can test many predictive LDM scenarios
- LDMX has impressive **physics discovery potential and guaranteed deliverables**
- **The experiment is ready to move forward with the construction phase**
- **LDMX could be taking data in 2-3 years** after establishing the funding profile and make a major discovery shortly thereafter



Thank You!

Caltech

Fermilab

Lunds Universitet

University of Minnesota

UCSB University of California Santa Barbara

Carnegie Mellon University

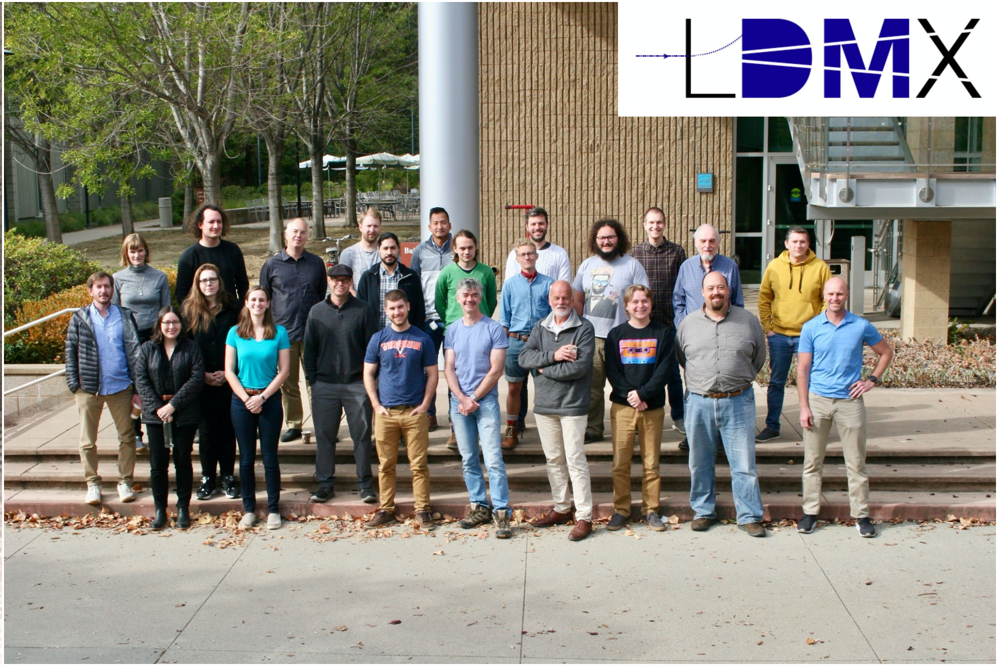
SLAC National Accelerator Laboratory

Stanford University

Texas Tech University

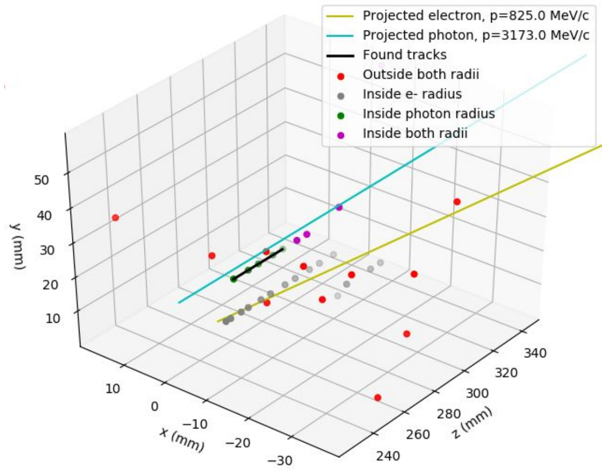
University of Virginia

Craig Group + Son

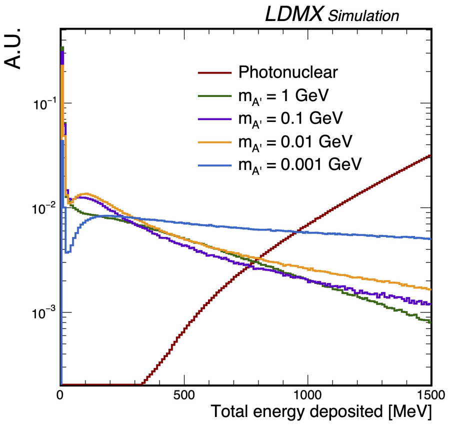


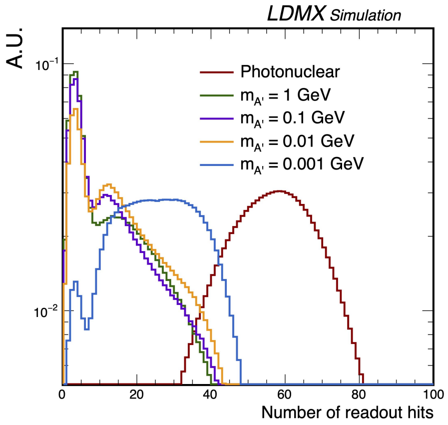
LDMX

Ecal BDT

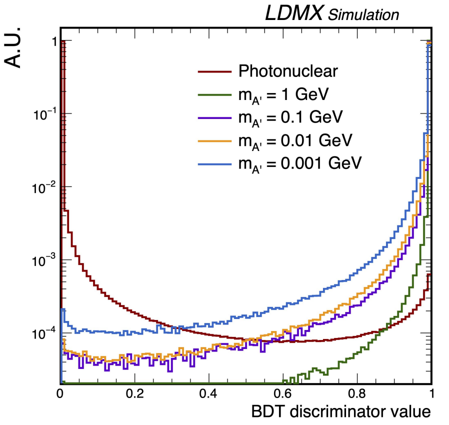


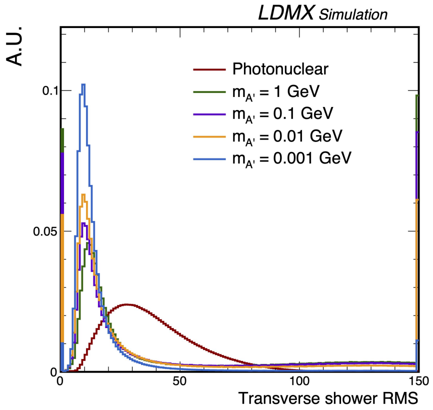
MIP Tracking



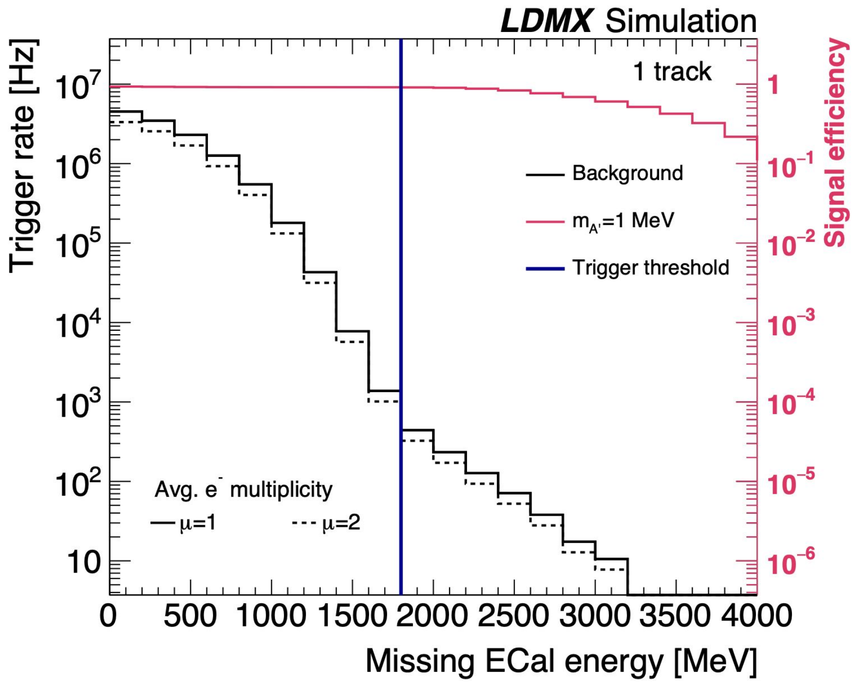


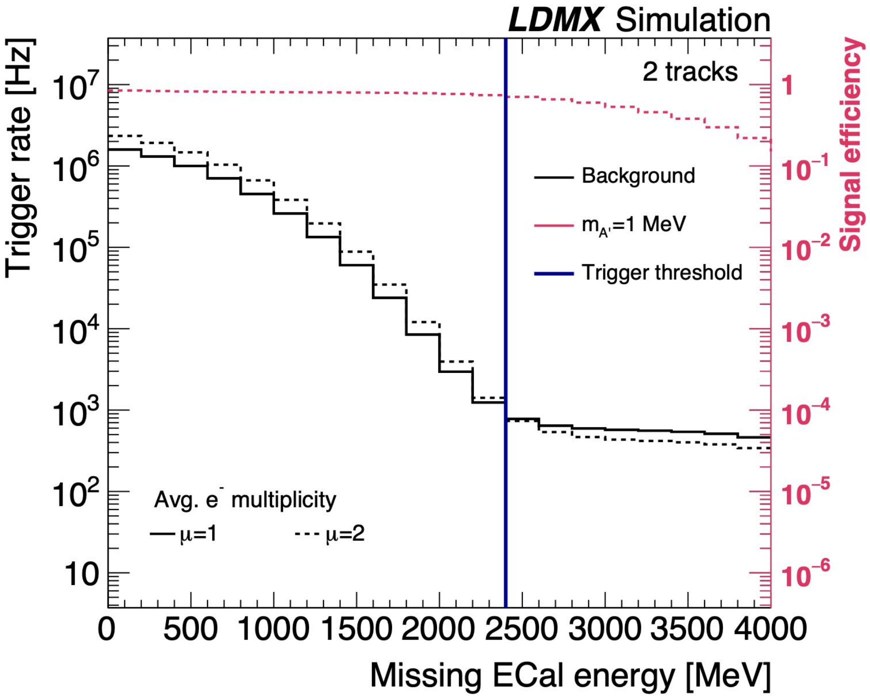
BDT Variables



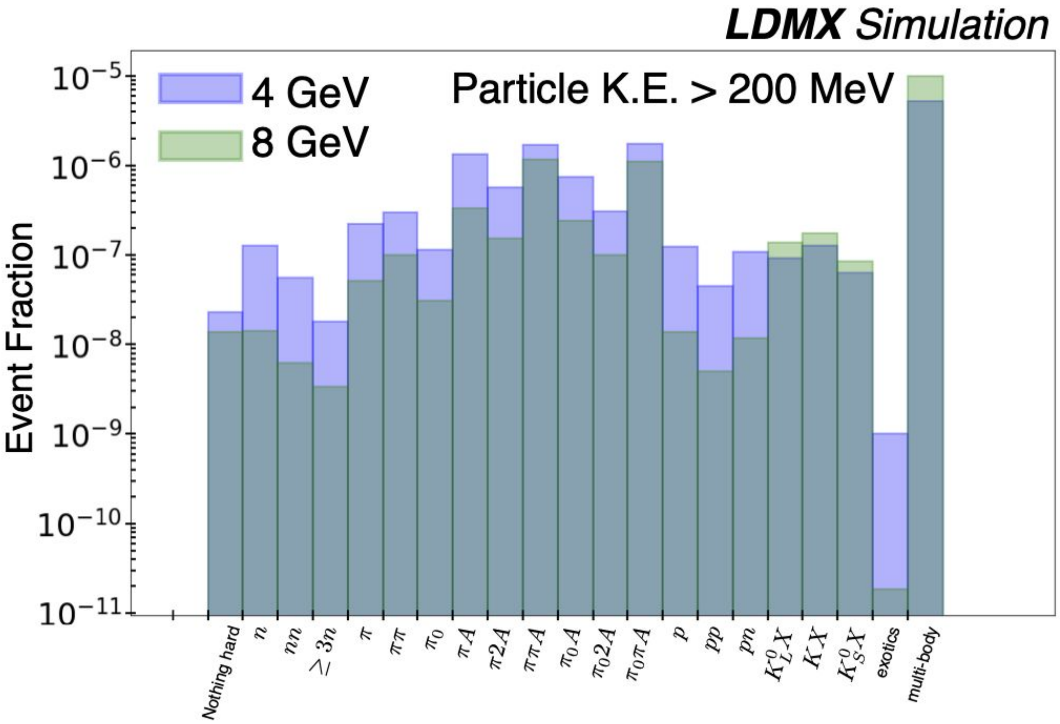


Trigger Multi-Electron Bunches

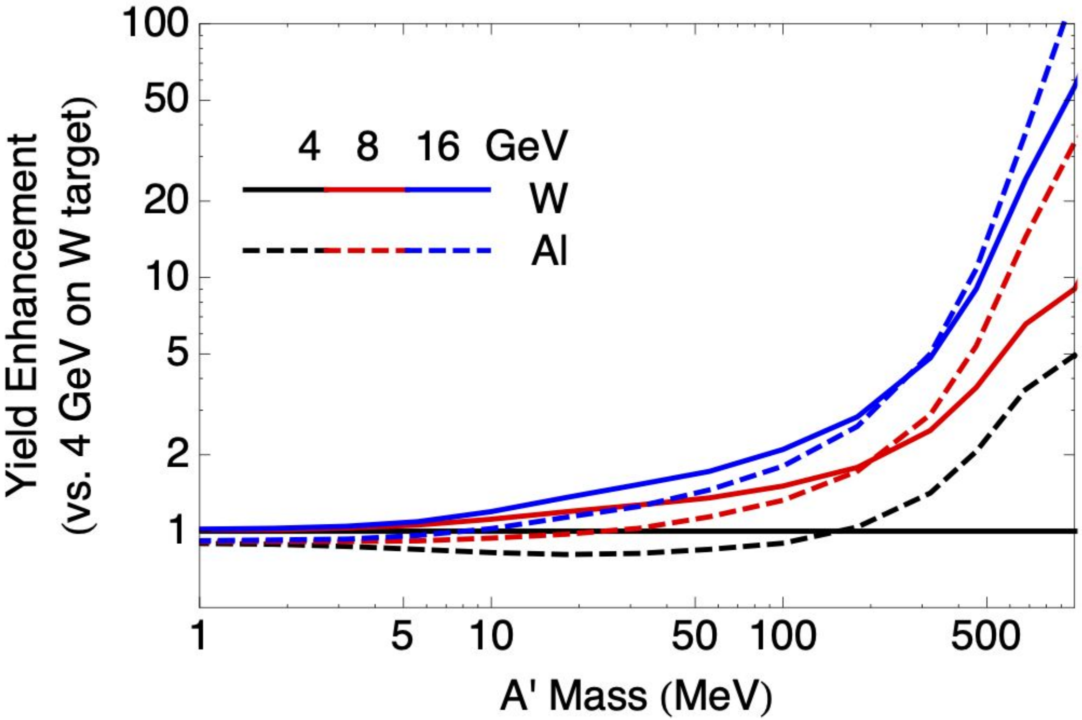




PN Background Final State



Fixed Target Choices

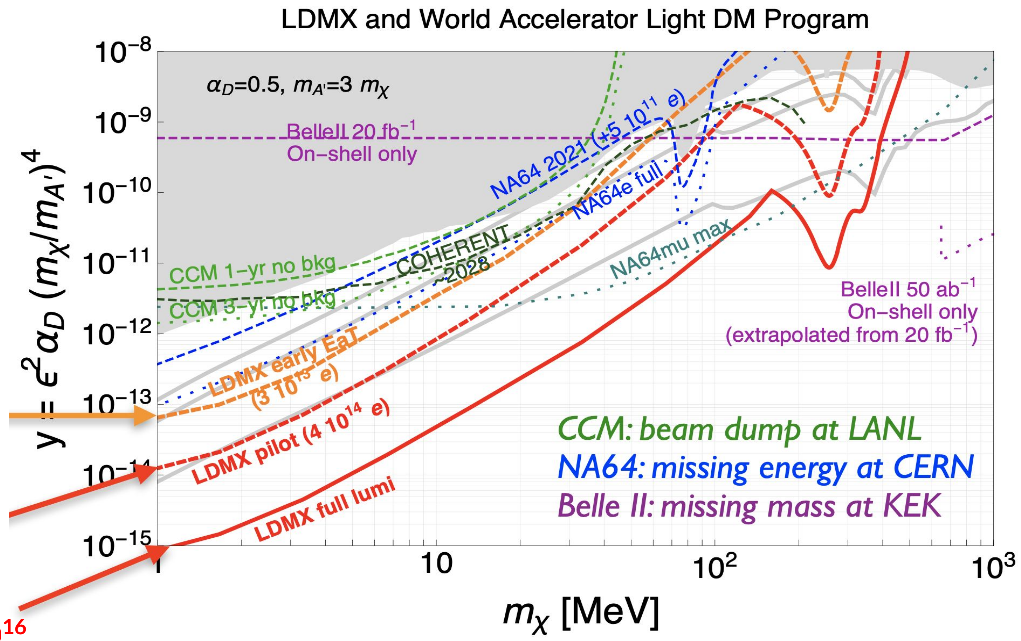


LDMX Projections Detailed

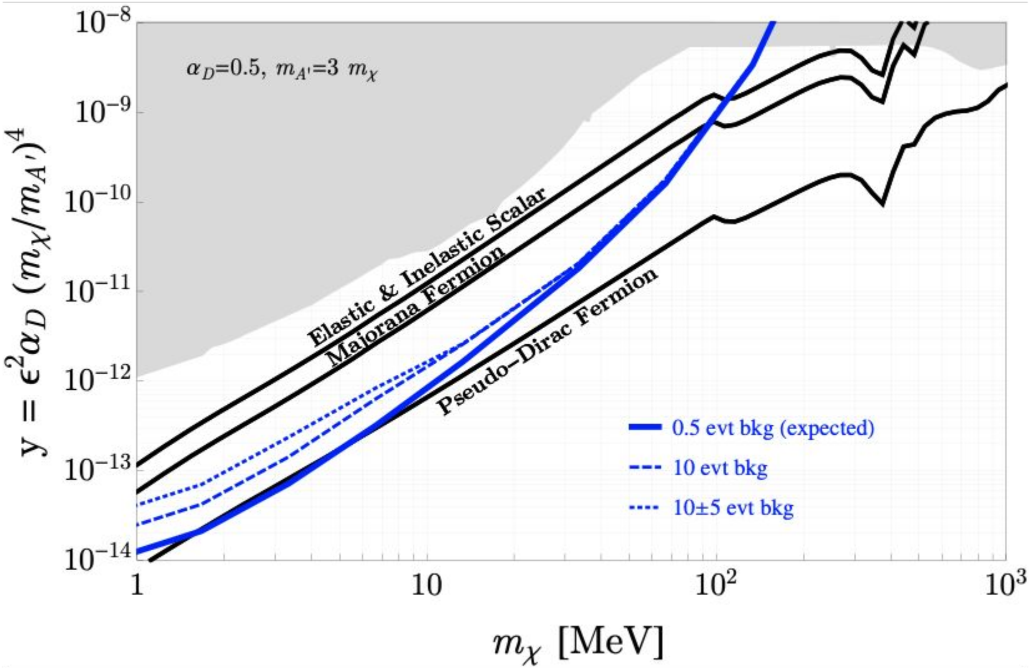
10 days (1 e-/25 ns)
ECal as Target (EaT)

135 days (1 e-/25 ns)
(10% X_0 tungsten)

500 days (2 e-/25 ns)
(thicker target) 1.6×10^{16}
EoT



LDMX Projections with Background



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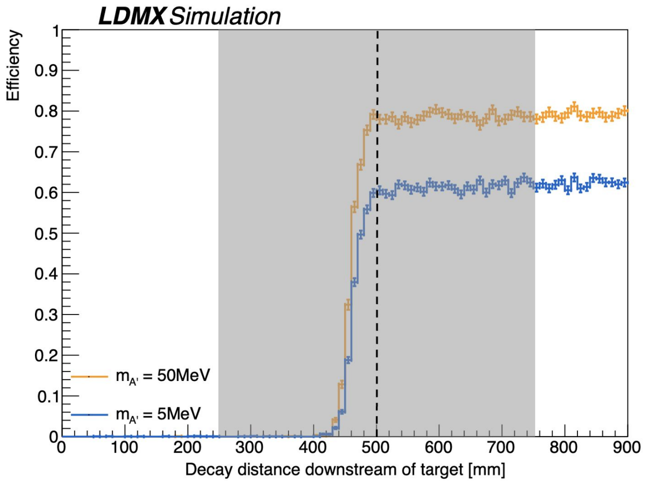
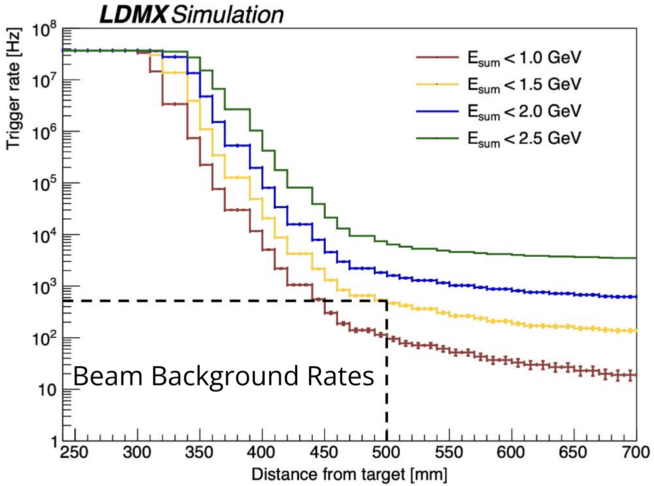
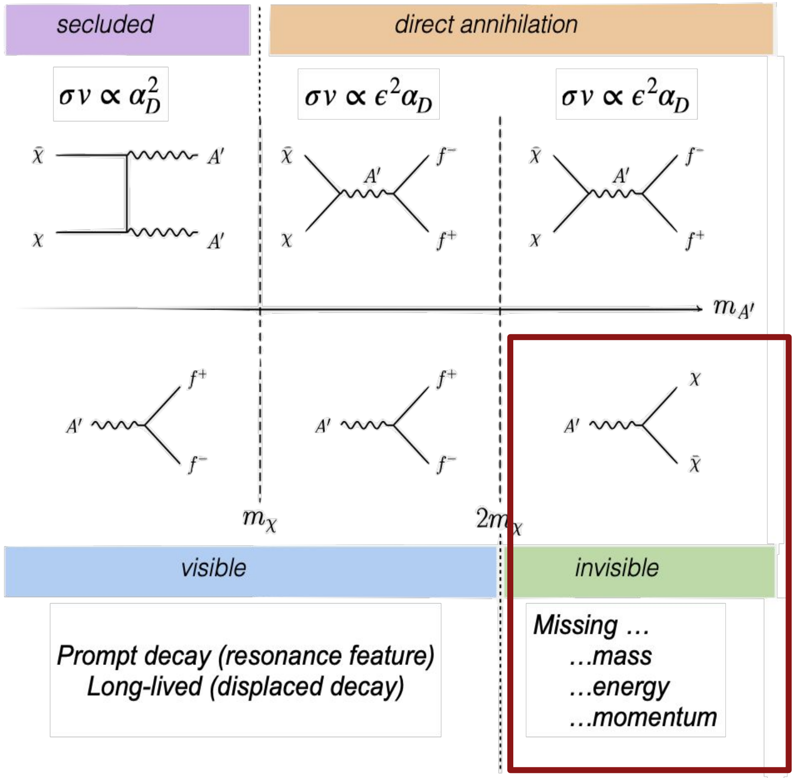




Dark Photon Signatures



Dark Photon Production

Dark Photon Decay

Both visible and **invisible** final states are allowed depending on the mass hierarchy