Recent Progress Toward the Light Dark Matter eXperiment (LDMX)

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UVA High Energy Seminar
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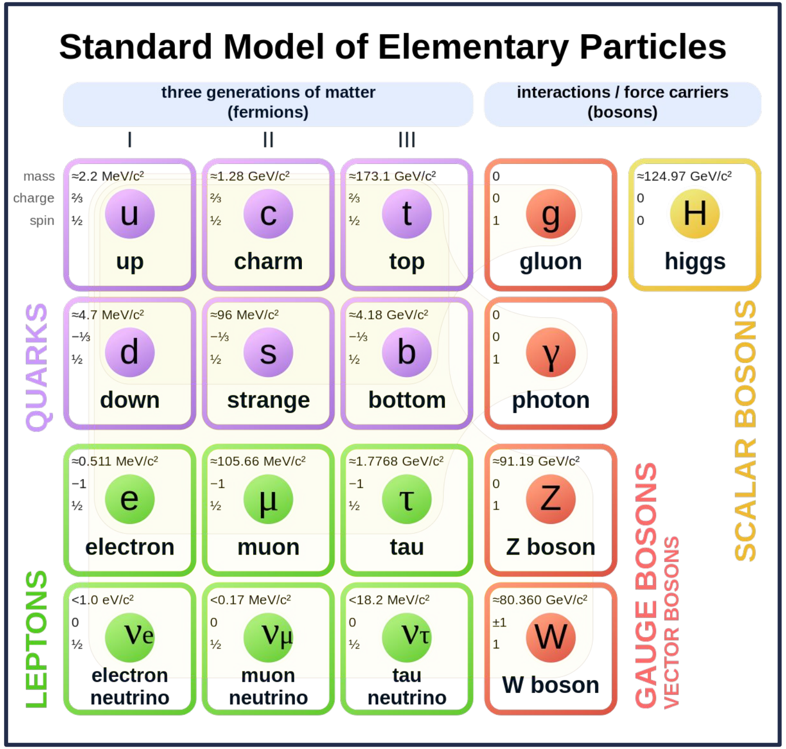
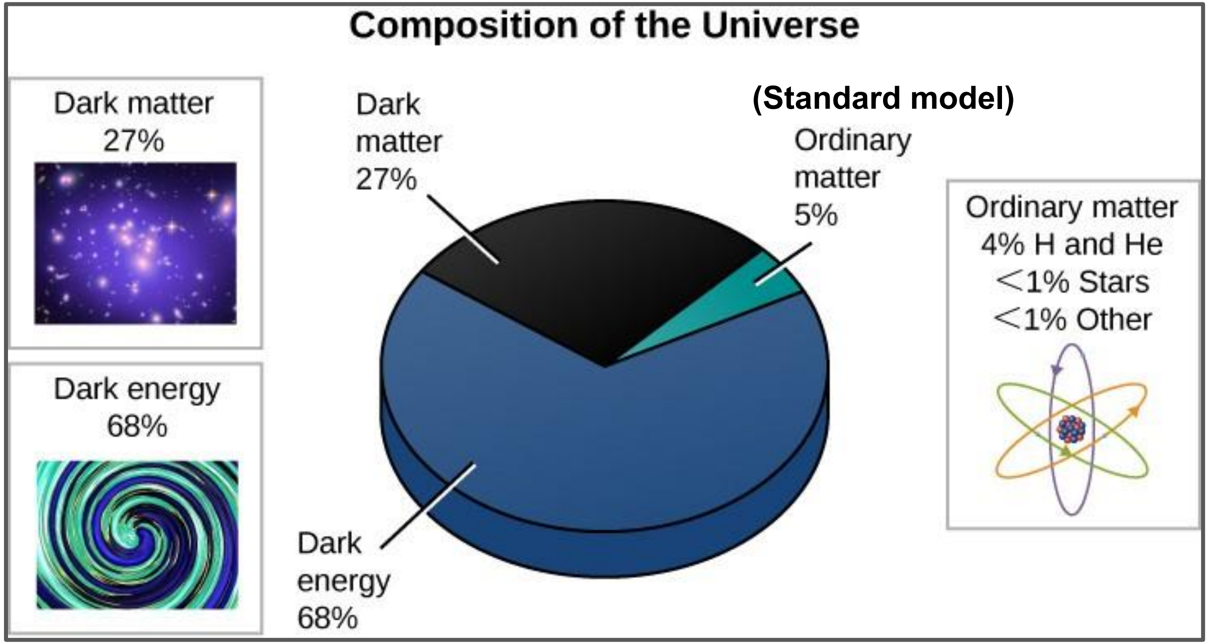
Standard Model of Particle Physics

- The biggest success of particle physics!
  - Has accurately explained almost all experimental results and precisely predicted other phenomena since the 1970s
- Each of these particles have been observed experimentally
  - All quarks, half of the leptons, and all bosons except for the photon were discovered using particle accelerators
- If we have the Standard Model (SM), and it works so well, why do we care about searching for dark matter?



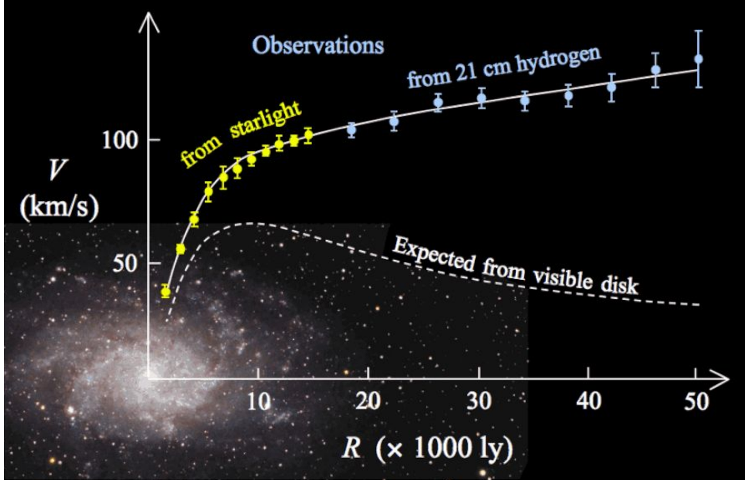
Why Dark Matter?

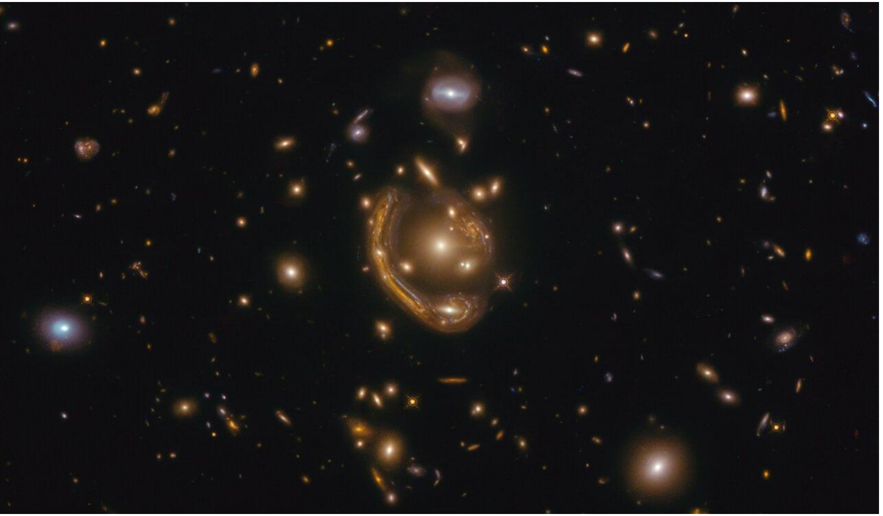


- We don't understand about 95% of the Universe's composition!
  - The current SM must not be complete
- Learning more about the nature of dark matter will (begin to) answer one of the foremost open questions in particle physics

Evidence for Dark Matter

- Strong case for the existence of dark matter (DM)
  - Galaxy rotation curves
  - Gravitational lensing
  - Cosmic Microwave Background anisotropy
  - Cluster collisions

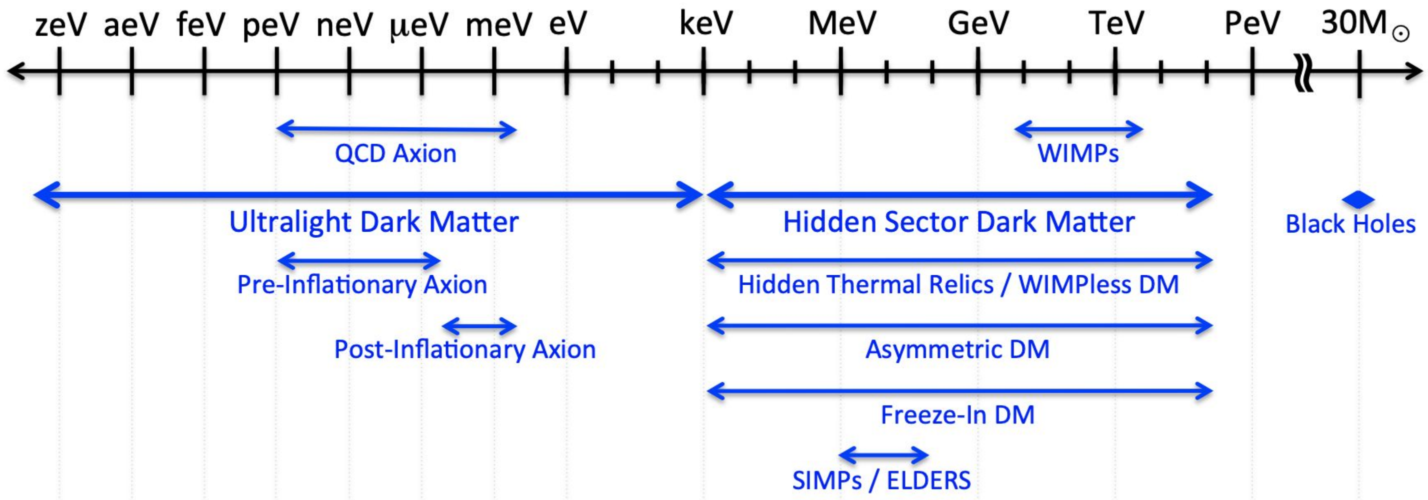




- No detection (yet!) - the origin and nature of DM is a key puzzle for particle physics
  - Standard model does not include dark matter
  - How do we narrow down a search region to determine what DM is?

Trying to Understand Dark Matter

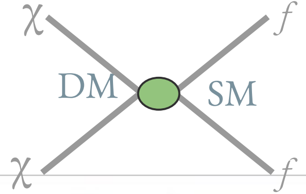
- What do we know?
  - Interacts gravitationally
  - Cosmological abundance
  - Limited interactions with known (SM) matter
- We don't know the mass of the DM



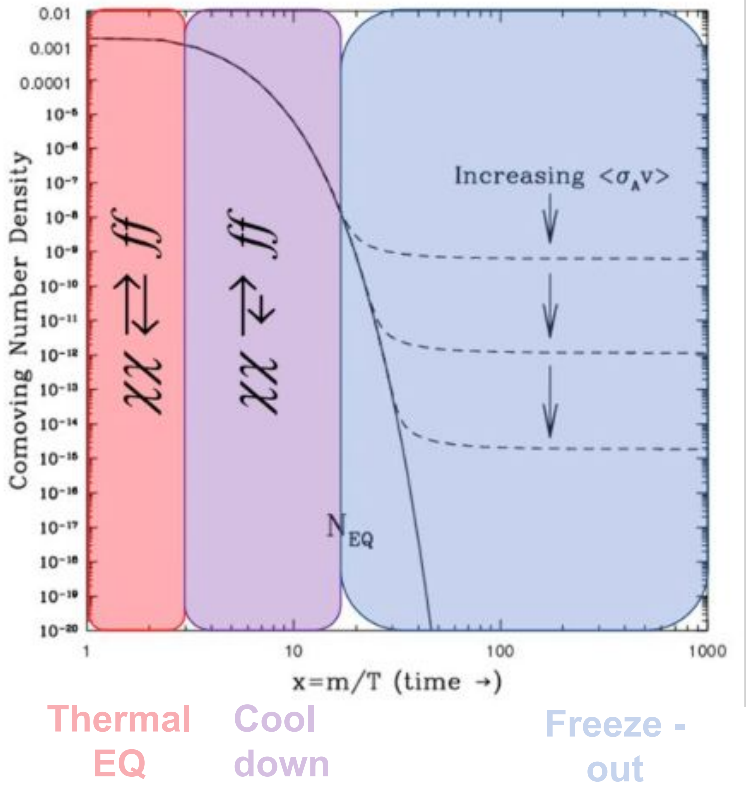
Thermal Dark Matter

- Assume we are dealing with ***particle-like DM***
- DM and SM particles in **thermal equilibrium** in the very early universe
- As universe cools and expands, **DM pairs are no longer in equilibrium**, resulting in decreasing amount of interactions
- Universe expands and cools enough such that DM is too dilute to interact → **freeze-out**
- The current relic density Ω_χ is related to the annihilation cross section $\langle \boldsymbol{\sigma v} \rangle$

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

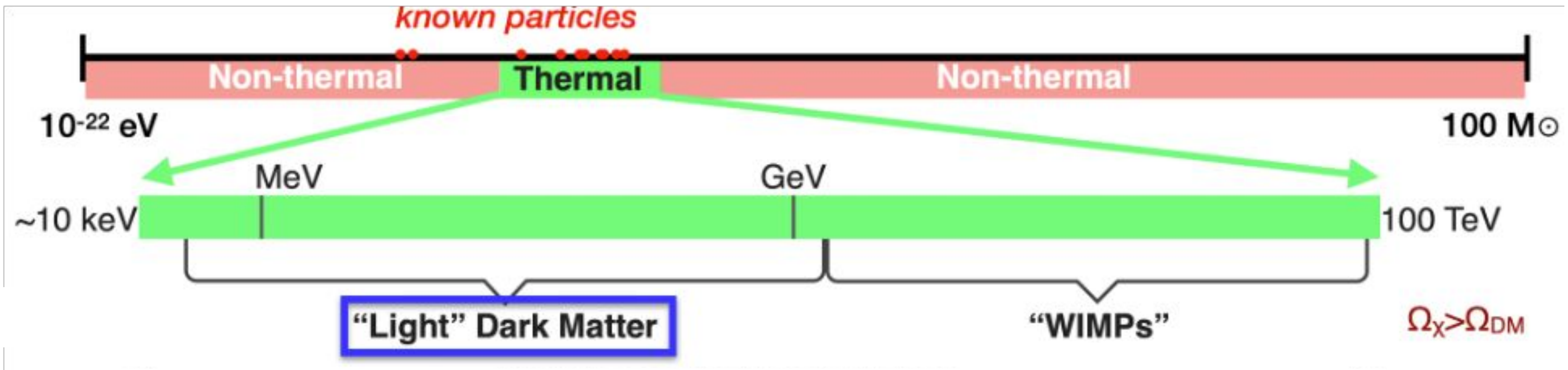


arXiv:9506380

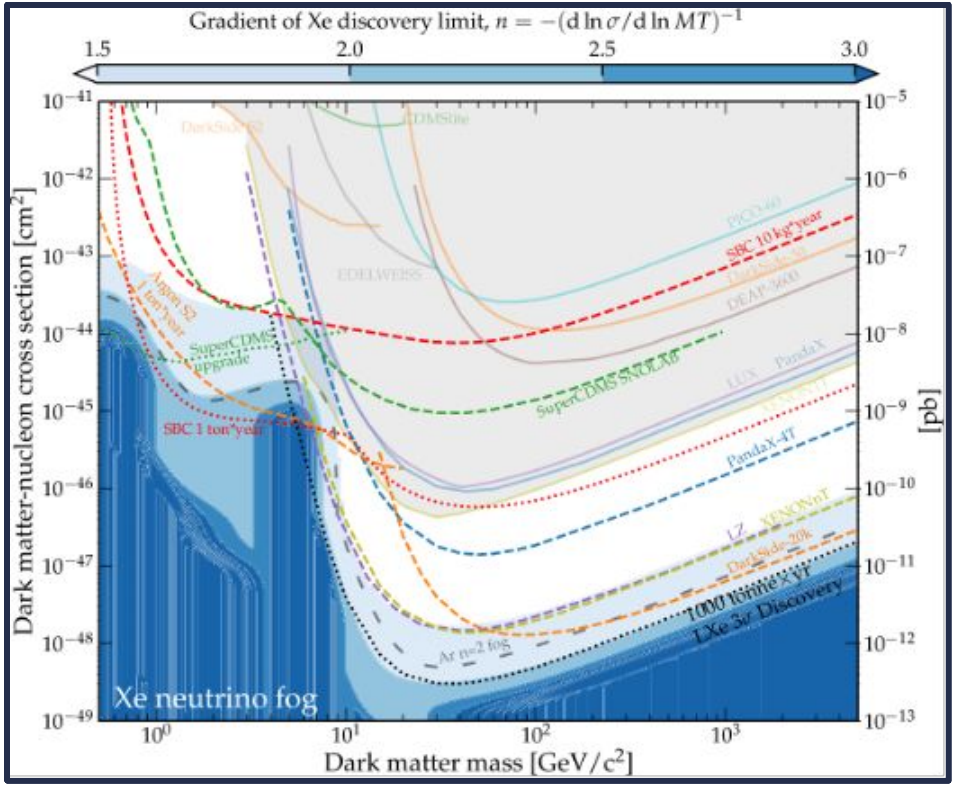


Thermal Dark Matter - LDM and WIMPs

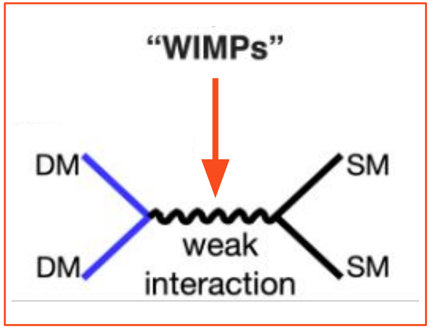
These assumptions/observations greatly narrow down our mass range!



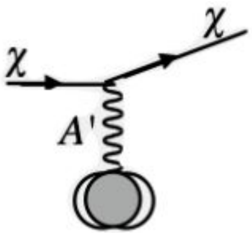
Thermal Dark Matter - WIMP Direct Detection Limits



arXiv:2203.08084

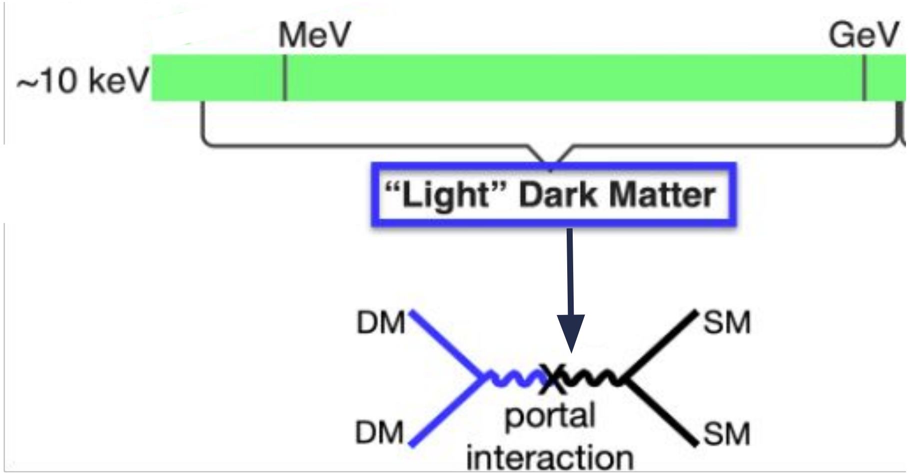


WIMPs are well-motivated, but accessible parameter space is shrinking



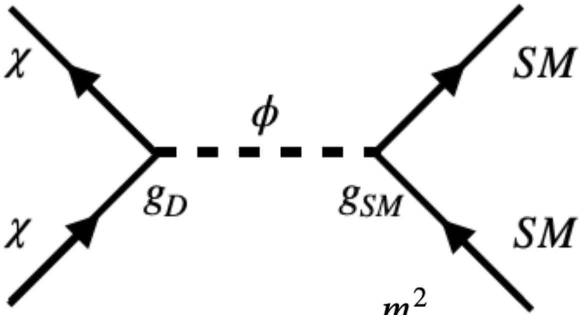
Thermal Dark Matter - Light Dark Matter

- Natural extension to search other area of thermal dark matter - light dark matter (LDM)
- Still at the mass scale where SM particles exist, so it is important to explore!
- Need a new non-SM interaction for this coupling of DM to SM matter



Light Thermal Dark Matter - Hidden Sector

- DM could belong to some "hidden sector" that is secluded from the SM
- Sub-GeV DM requires an additional non-SM interaction to maintain the correct relic abundance
  - Mediated by new massive gauge boson



$$< \sigma v > \sim g_D g_{SM} \frac{m_\chi^2}{m_\phi^4}$$

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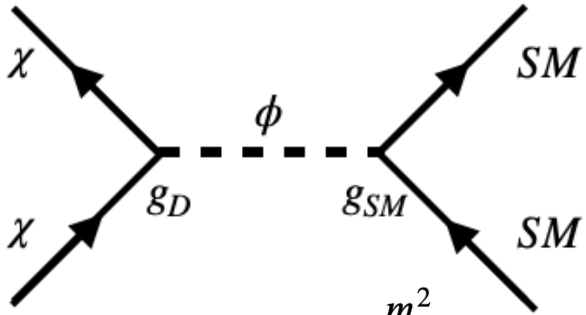

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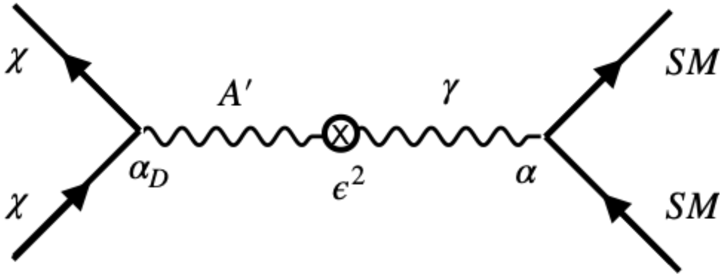


$$\alpha_D = \frac{g_D^2}{4\pi}$$

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

- Additional spin-one gauge boson (**dark photon** or **A’**)
  - neutral under SM
  - Hidden, broken symmetry ***U(1)***$_D$
- Kinetically mixing with SM **U(1)**$_\gamma$ with factor ϵ
- Visible and invisible final states

Light Thermal Dark Matter - Hidden Sector

- DM could belong to some "hidden sector" that is secluded from the SM

The minimal Dark Photon model is an ubiquitous benchmark for the physics community

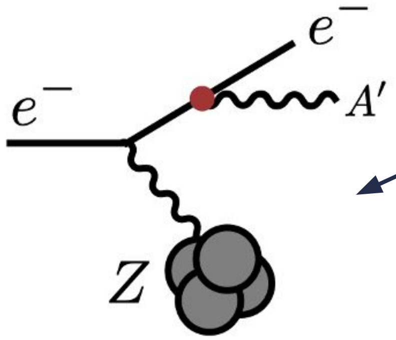
- Kinetically mixing with SM **U(1)$_Y$** with factor ϵ
- Visible and invisible final states

$$\alpha_D = \frac{g_D^2}{4\pi}$$

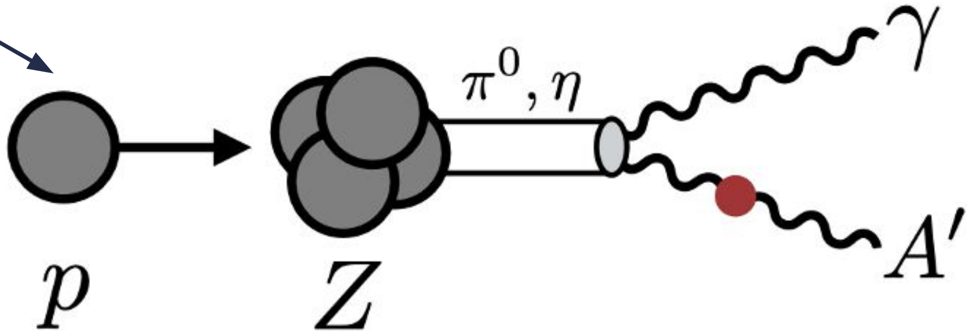
$$\epsilon F^{\mu\nu} F'_{\mu\nu}$$

Dark Photon Production at Accelerators

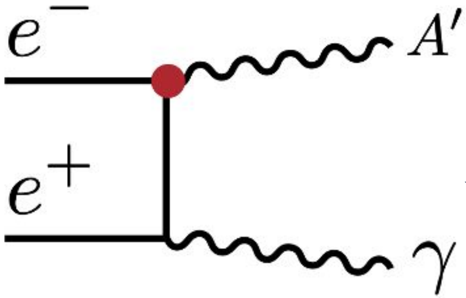
Fixed Target Experiments



Bremsstrahlung (*e*,*p*)



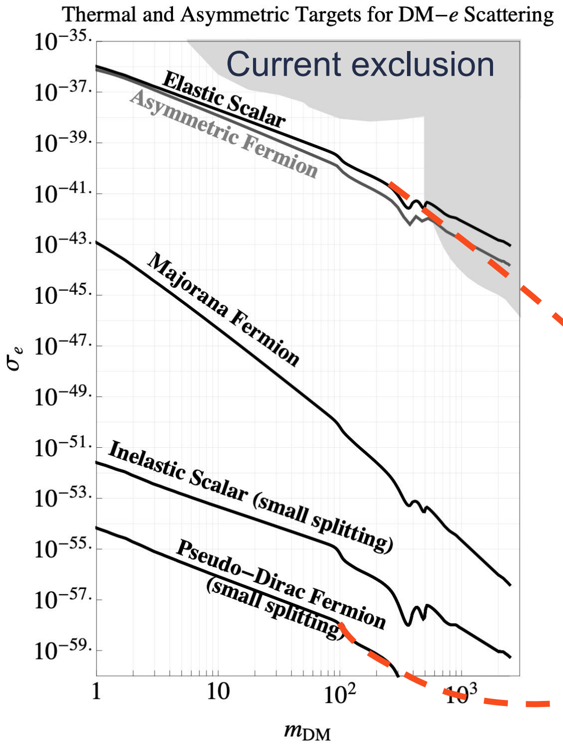
Decay of pseudoscalar mesons



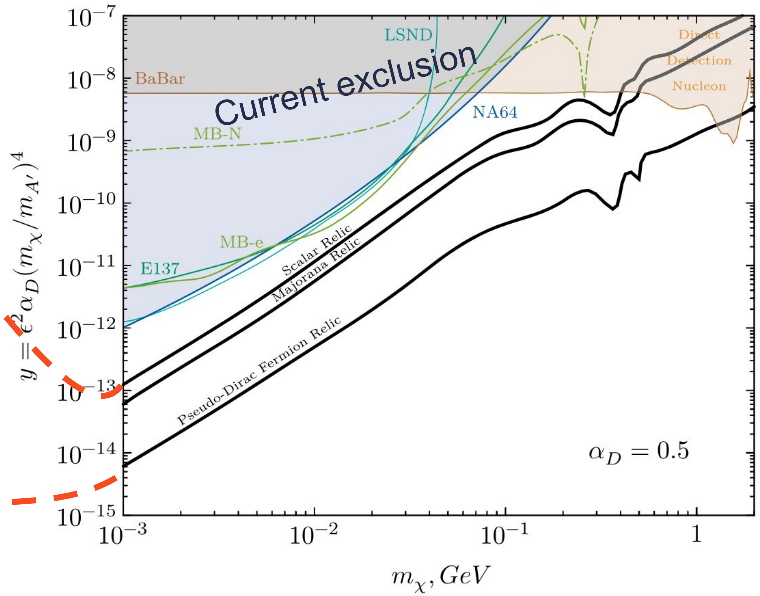
Colliding beams (*e*,*p*)

Collider Experiments

Advantage of DM Production at Accelerators



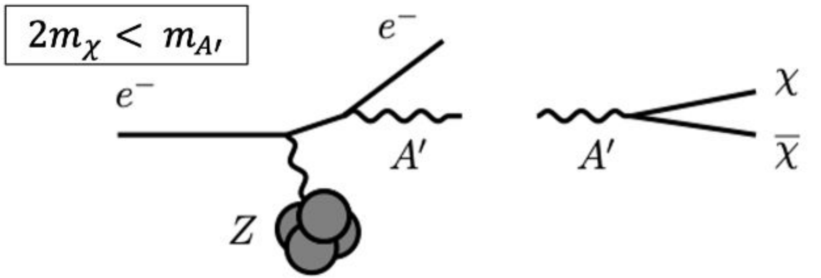
- LDM production at accelerators is fairly independent of the DM model, especially when compared to direct detection
  - ALL "thermal targets" for sub-GeV dark matter models are much more accessible for accelerator experiments

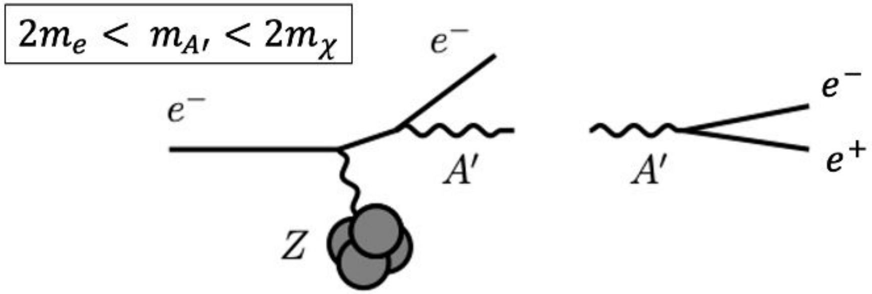


Key difference is the non-relativistic (DM-e) vs relativistic (accel.) DM scattering

$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle}$$

Dark Photon Signatures

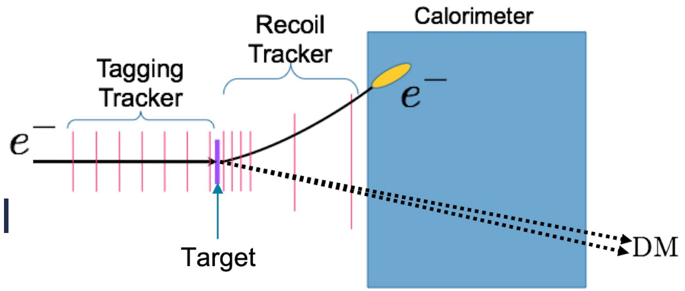




- Invisible decay
  - Decays into DM particles that don't interact with detector
- For LDMX, characterized by some missing energy/momentum in the detector as a whole

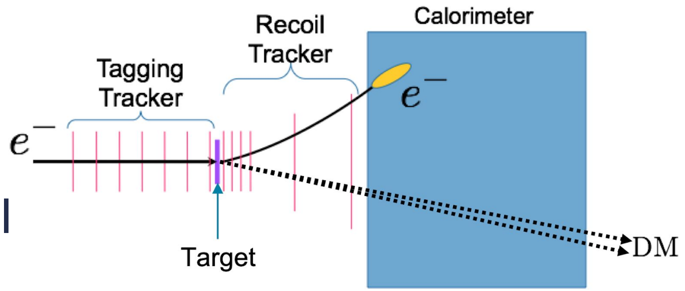
- Visible decay
  - Decays into SM particles
  - Long-lived
- For LDMX, characterized by a displaced, sudden appearance of energy deposited in some downstream part of the detector

LDMX Concept



- Look for missing momentum (and energy) in recoil electron
  - Also use detectors to identify the missing momentum & energy → DM production!
  - Particle ID
  - Transverse momentum of recoil e^- used as discriminator/identifier

LDMX Concept



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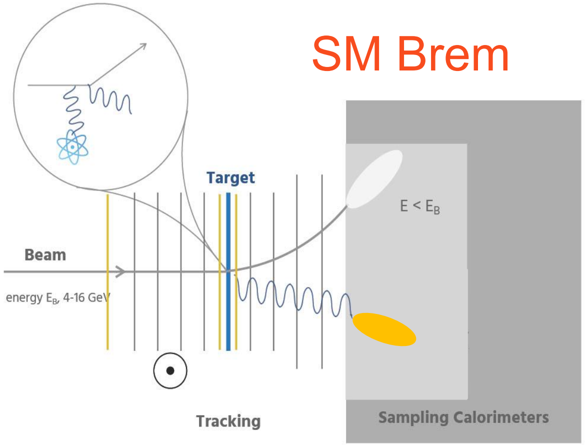
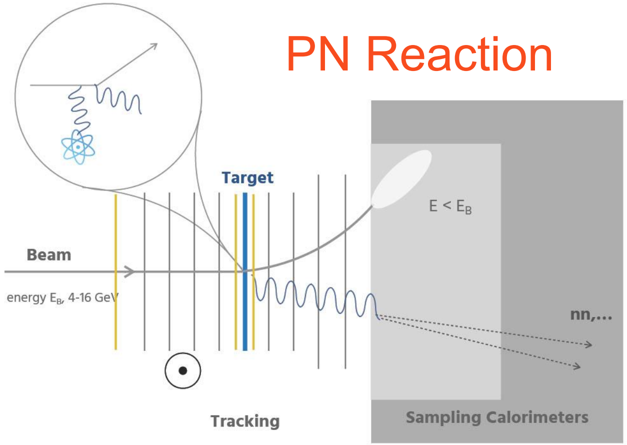
SM Brem



PN Reaction



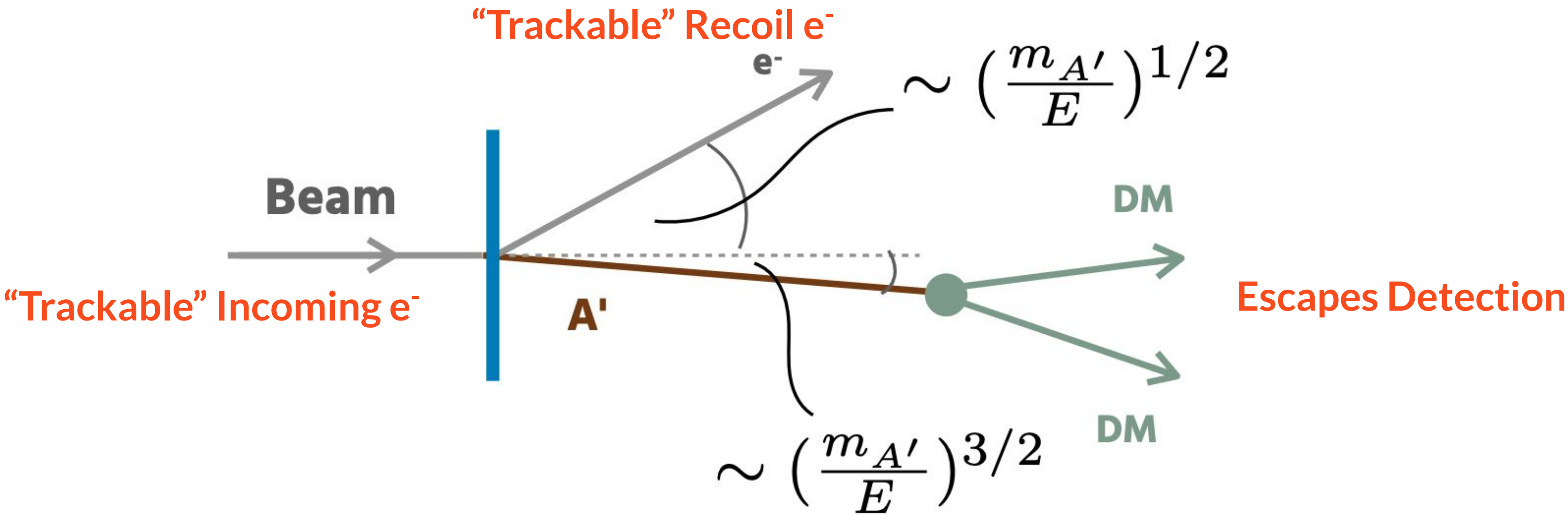
- Must mitigate SM background
  - Main background is SM bremsstrahlung
  - Most challenging background is photo-nuclear (PN) reactions

Dark Photon Kinematics at a Fixed Target Experiment

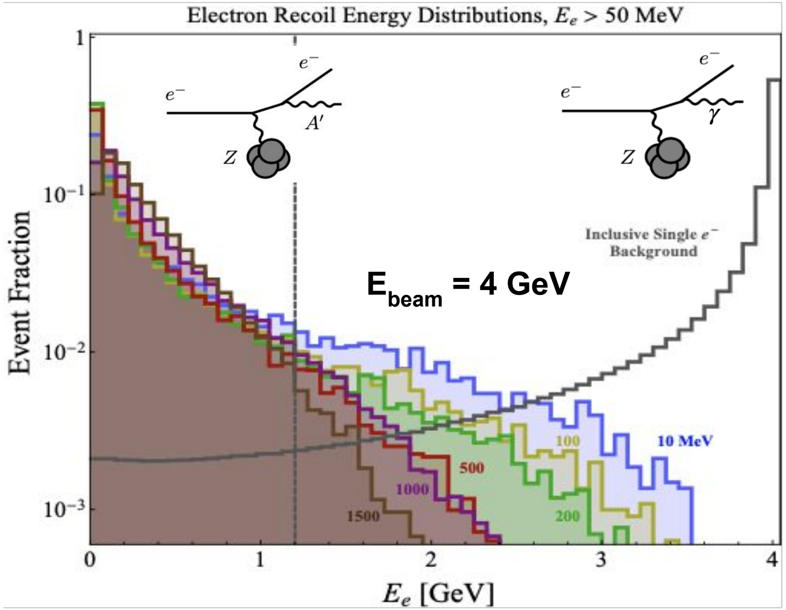
Fixed target signal characteristics:

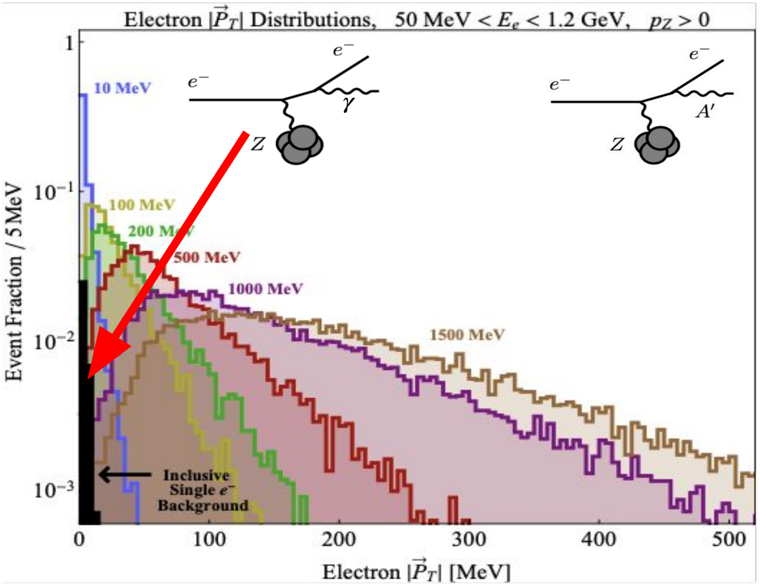
→ Dark bremsstrahlung A' production (invisible decay)

→ **A's take most of the beam energy; only visible final state particle is a soft recoil electron**



Dark Photon Kinematics at a Fixed Target Experiment

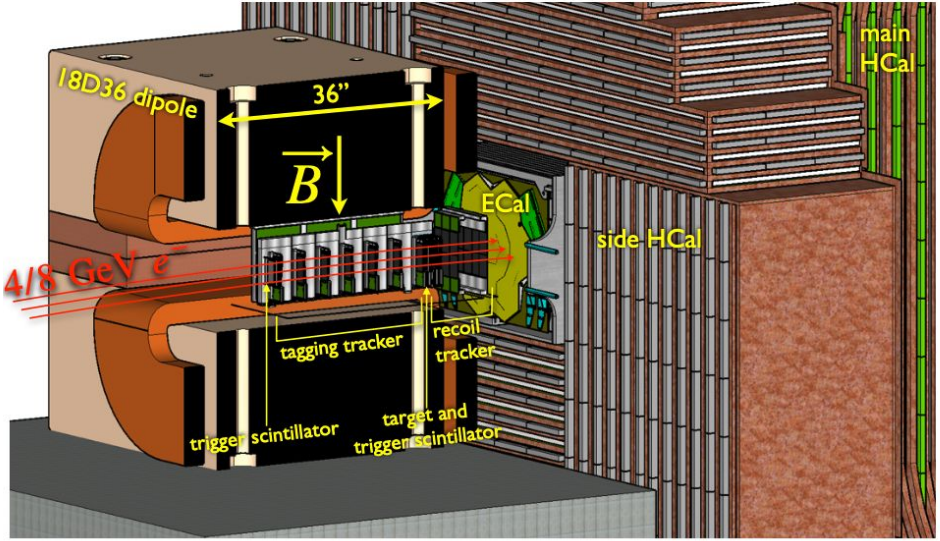


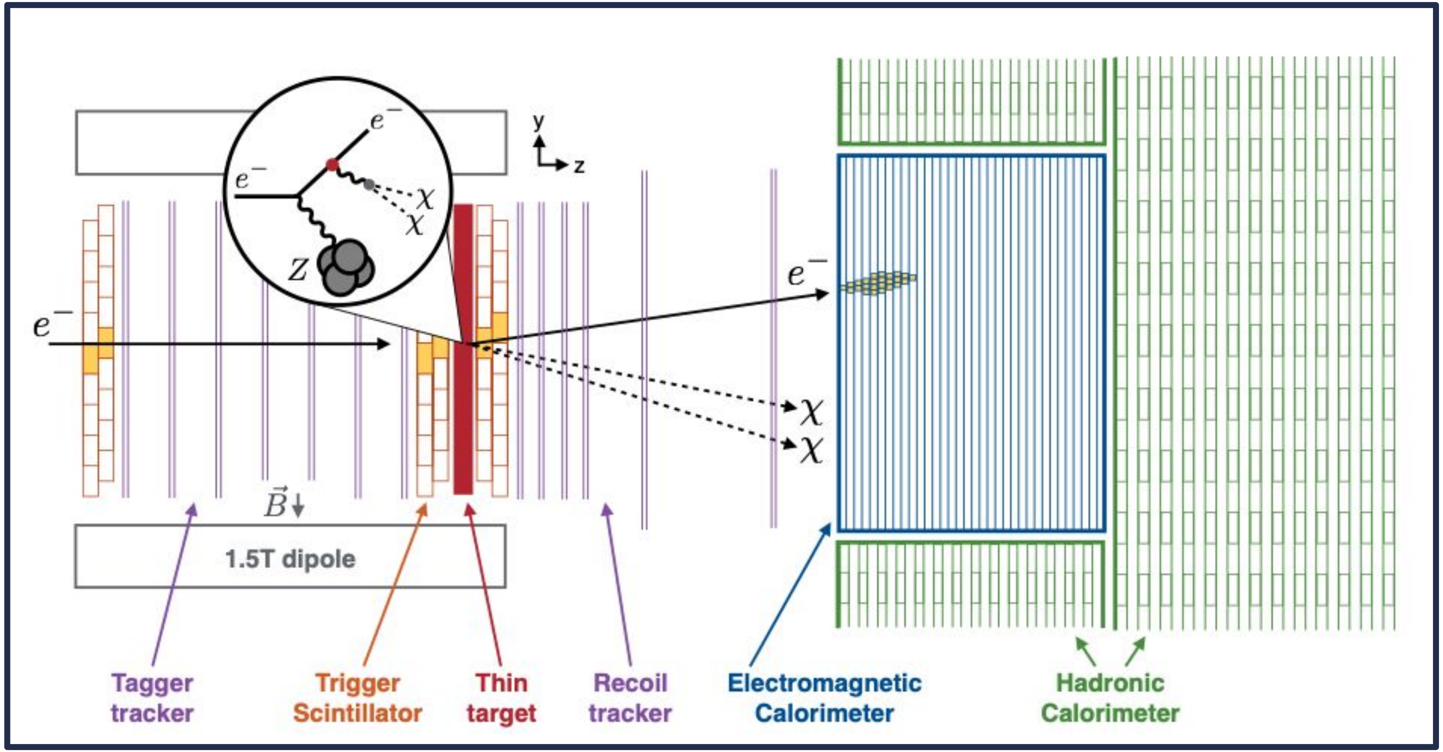


- **A'→χχ carry away most of the beam energy and escape undetected**
  - Opposite behavior for the bremsstrahlung emission
- **Recoil electron p_T spectrum depends strongly on $m_{A'}$ for signal**
  - Signal identification or extra handle for background rejection

LDMX Design

- Basically dumping the beam onto our detector!
    - Need hermetic, radiation tolerant detector designed for high beam rates
- **Tagging tracker**: low acceptance and high resolution at beam energy
- **Recoil tracker**: large acceptance and high resolution at low particle momenta
- **Electromagnetic calorimeter**: fast, good energy resolution, and high granularity
- **Hadronic calorimeter**: high veto efficiency of neutral hadrons
- **Trigger Scintillator**: scintillator bars provide fast, accurate count of incoming electrons





Tagging and Recoil Tracker
Simplified version of Silicon Vertex Tracker from HPS at JLab (visible dark photon search)

Trigger Scintillator
Small, simple plastic scintillator arrays with SiPM readout

Electromagnetic Calorimeter
Draws on design of CMS Si-W HGCal

Hadronic Calorimeter
Will be built at UVA! Inspired by Mu2e Cosmic Ray Veto

Tracking and Target System

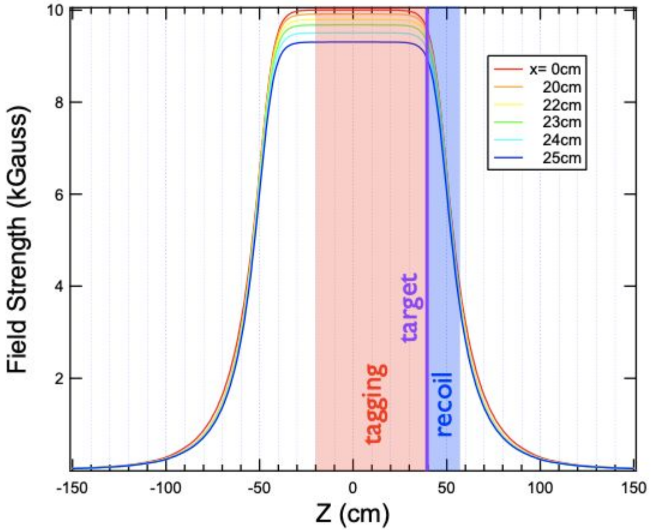
Tracking system

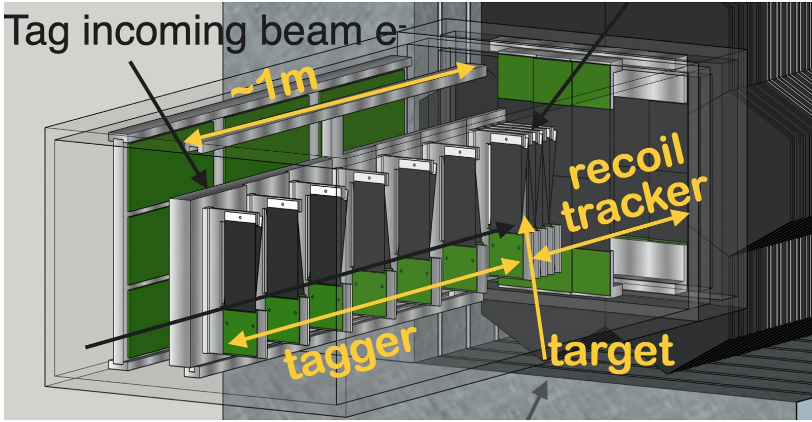
arXiv:2212.10629v2

- Silicon tracker - reuses HPS designs for detector modules and readout
- Tagging tracker in central dipole field, measures incoming electron
- Recoil tracker in fringe field, measures recoil electron and vetoes extra particles

Thin Target

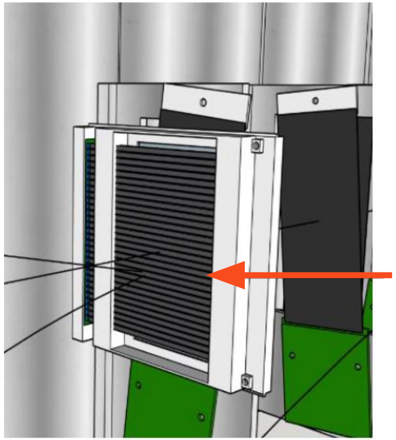
- Balance signal rate vs momentum resolution
- $0.1X_0$ Tungsten target, considering an active target





Trigger Scintillator (TS)

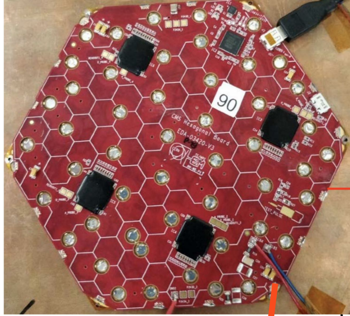
- Arrays of scintillator bars able to count number of incoming electrons in each beam pulse
- Primary input to missing energy trigger system!
- Read out through SiPMs, though the associated electronics will be different than the Hadronic Calorimeter



Scintillator pads around target

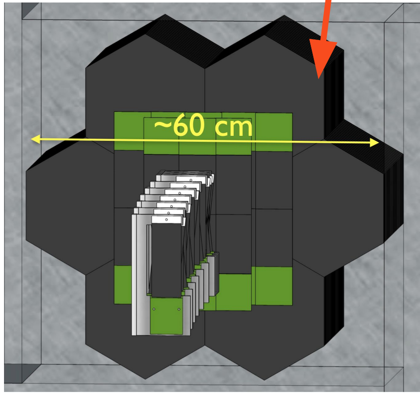
TS Prototype from CERN testbeam

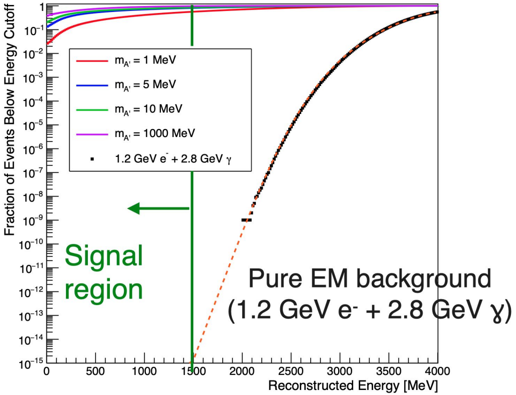
Electromagnetic Calorimeter (Ecal)

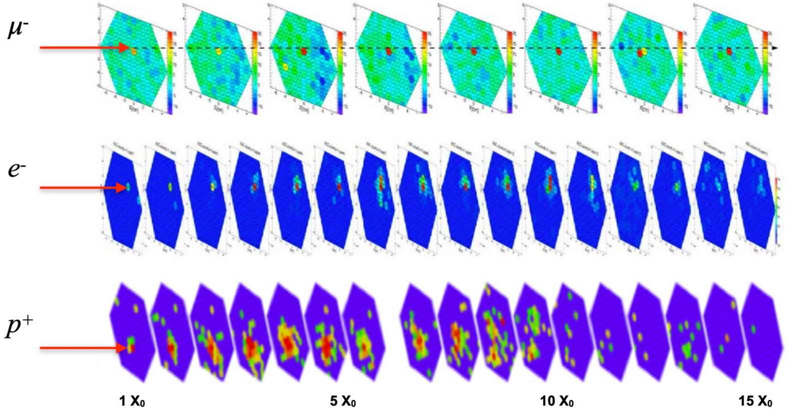


10.17181/CERN.IV8M.1JY2

- Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - ~ 40 X_0 depth (34 Si layers) for extraordinary shower containment
- Provides fast missing energy trigger (E < 1.5 GeV)
- High granularity - transverse and longitudinal shower shapes can be exploited to reject backgrounds
- Capable of MIP tracking to further improve background rejection

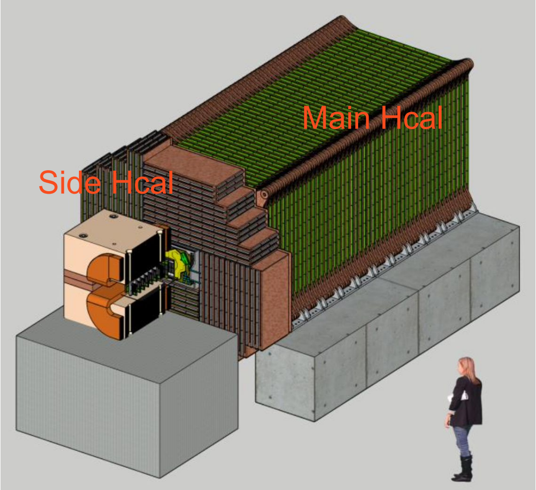


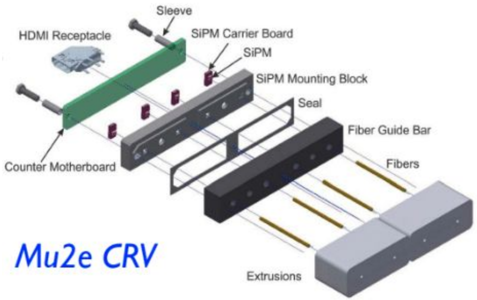


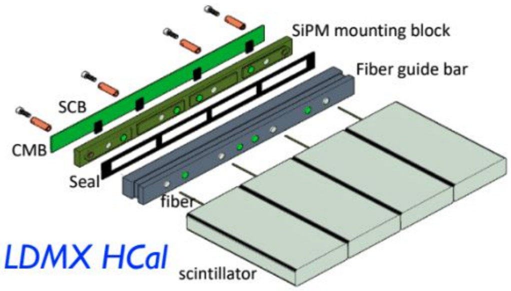


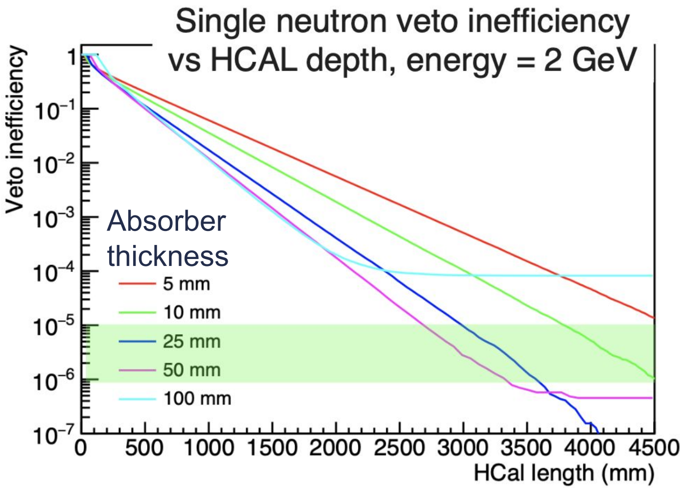
Hadronic Calorimeter (Hcal)

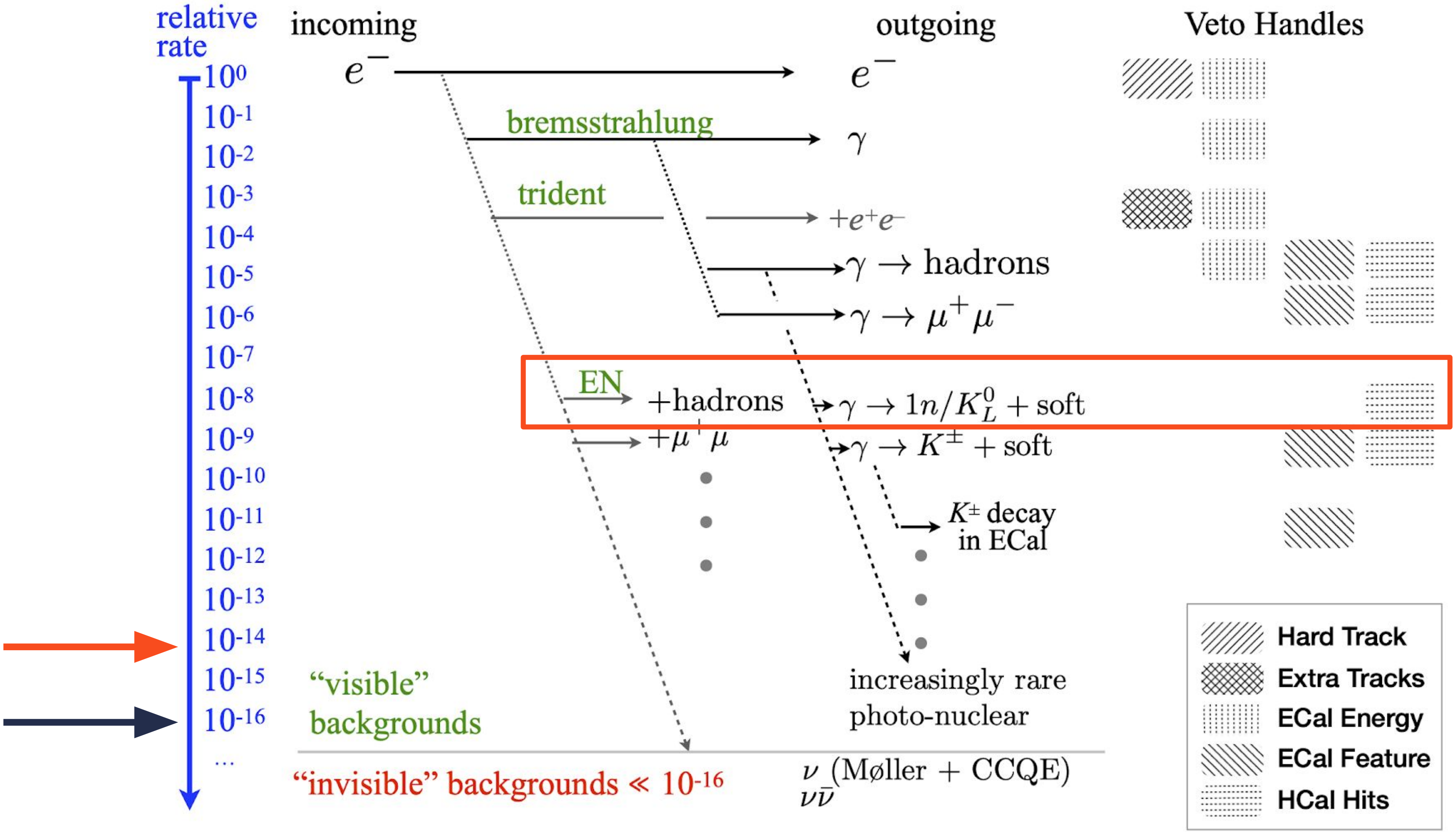
- Segmented scintillator/steel sampling calorimeter
  - 96 layers of 20 (25) mm of polystyrene (Fe) → ~17λ
- Detects neutral hadrons (mostly K_L,n) produced in photonuclear reactions, and MIPs
- Extruded scintillator bars with inserted wavelength-shifting fibers, read out with SiPMs
  - developed for Mu2e Cosmic Ray Veto - I worked on this!
- Side HCal rejects wide angle brem and γ→μ+μ-







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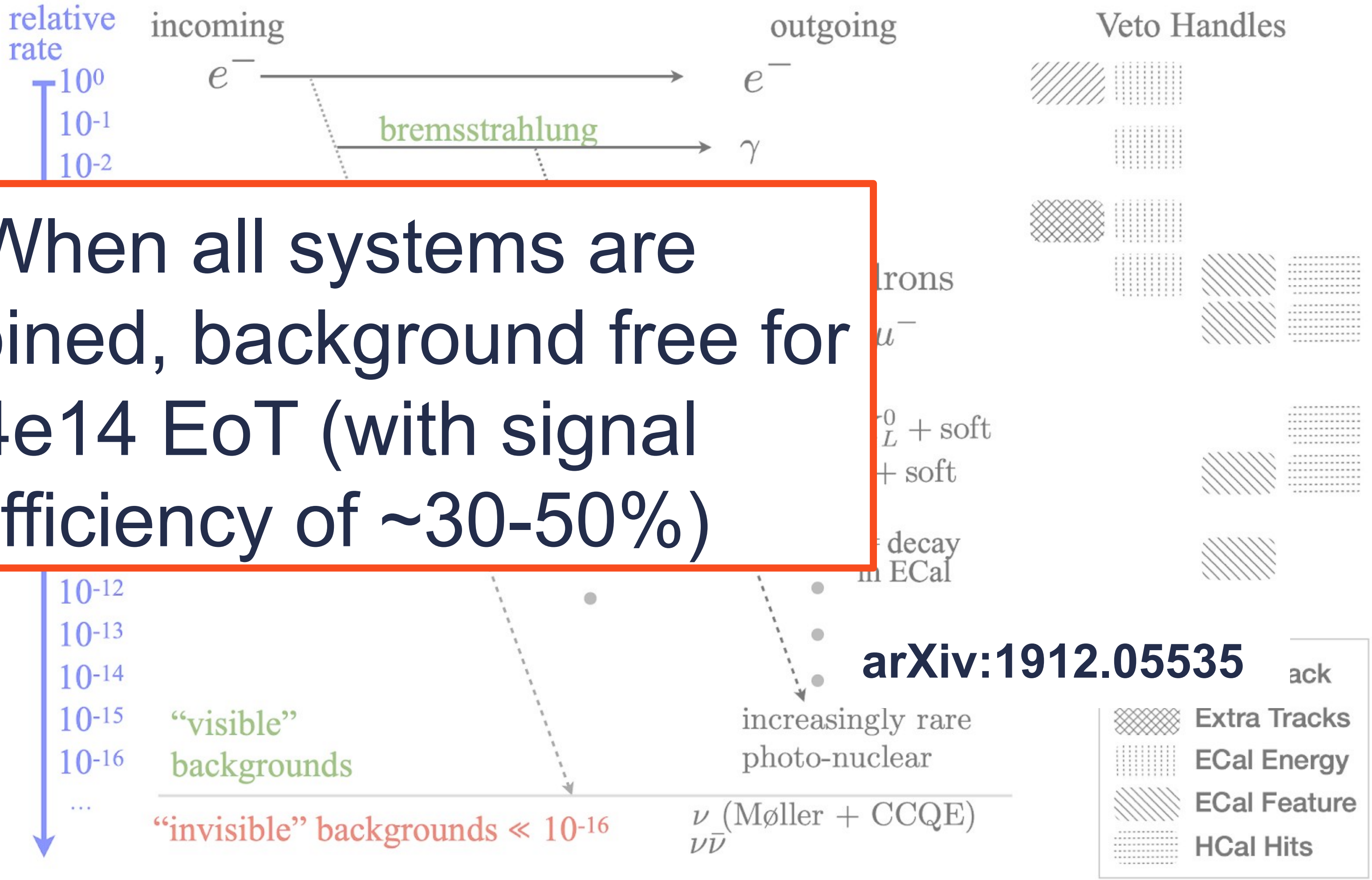
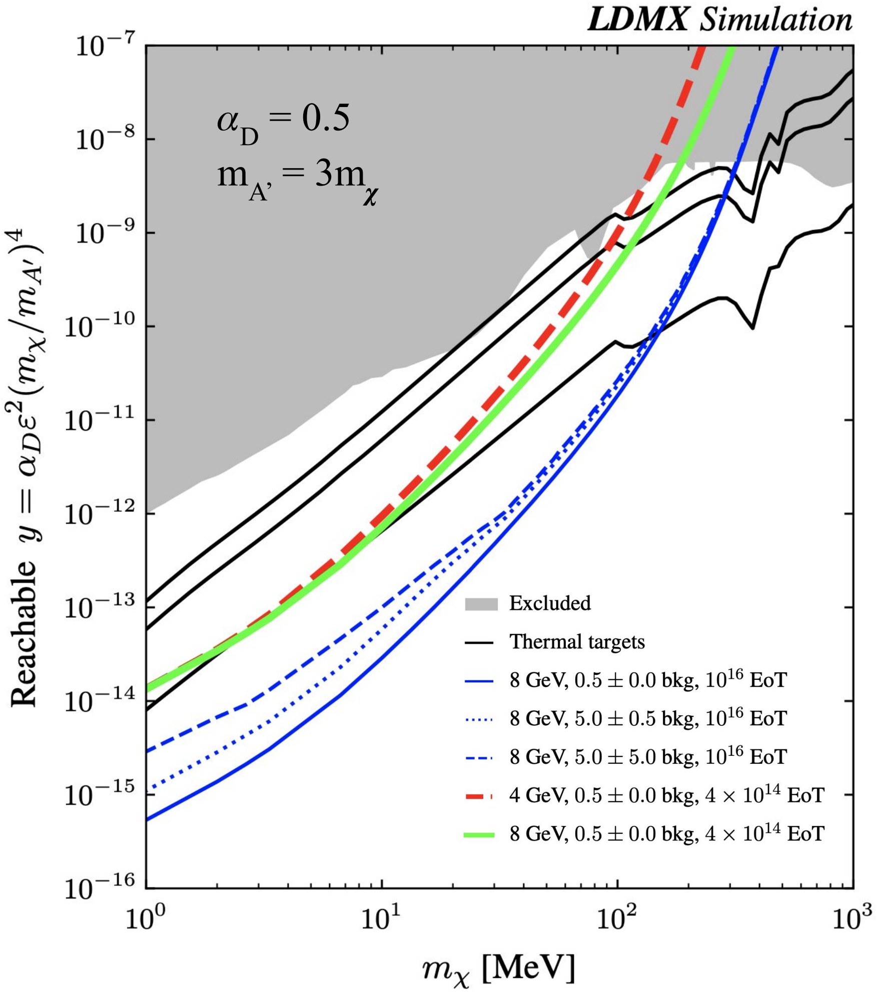


When all systems are combined, background free for 4e14 EoT (with signal efficiency of ~30-50%)

arXiv:1912.05535

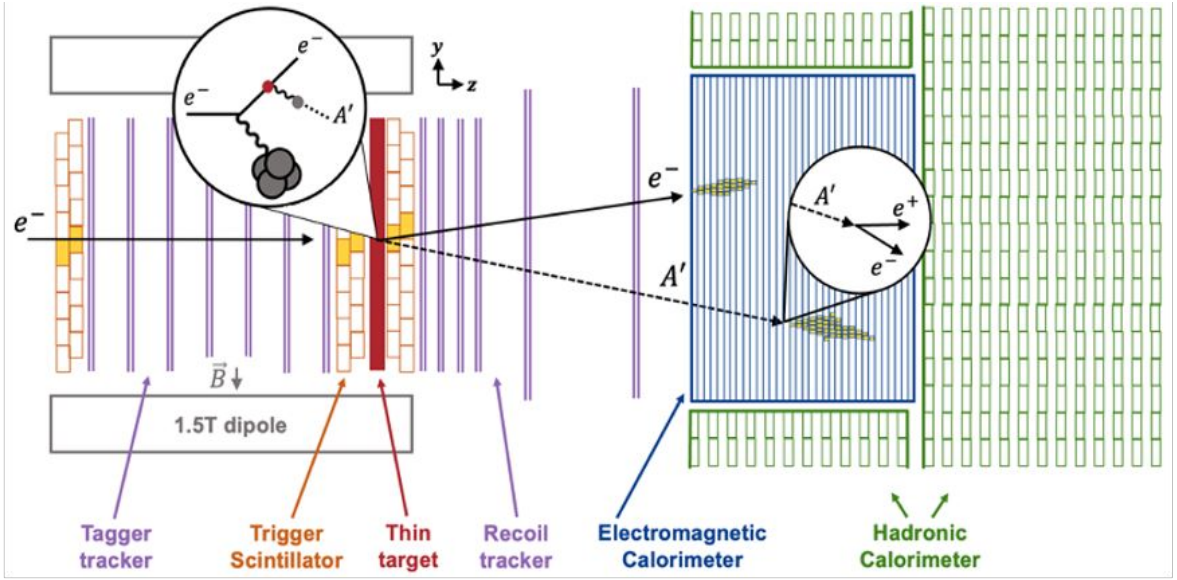
Projected Sensitivity

- LDMX is able to reach ALL thermal targets!
  - Even with some background included for the 8 GeV run, clearly pass all the benchmark models, so we will be able to exclude all of them
- **y** is just a measure of the interaction strength, and is a dimensionless variable often used

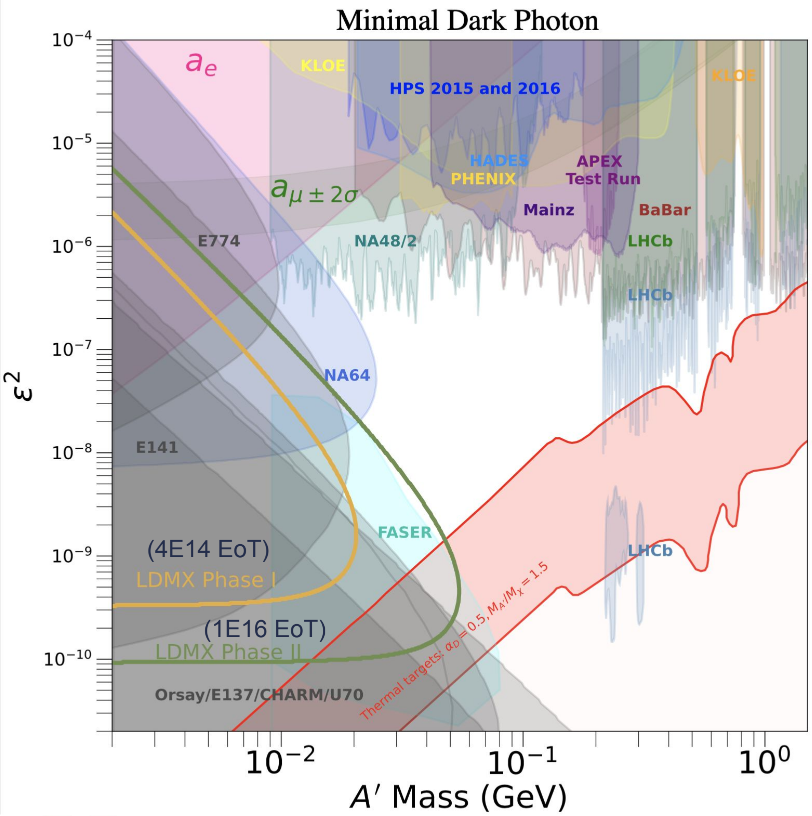


Additional Physics - Visible Signatures

- Complementary to main search, LDMX can also look for A’ decays into SM particles (visible decay channel)
  - $2m_e < m_{A'} < 2m_\chi$
- Many models could be tested (minimal dark photon, ALPs, SIMPS, etc.)



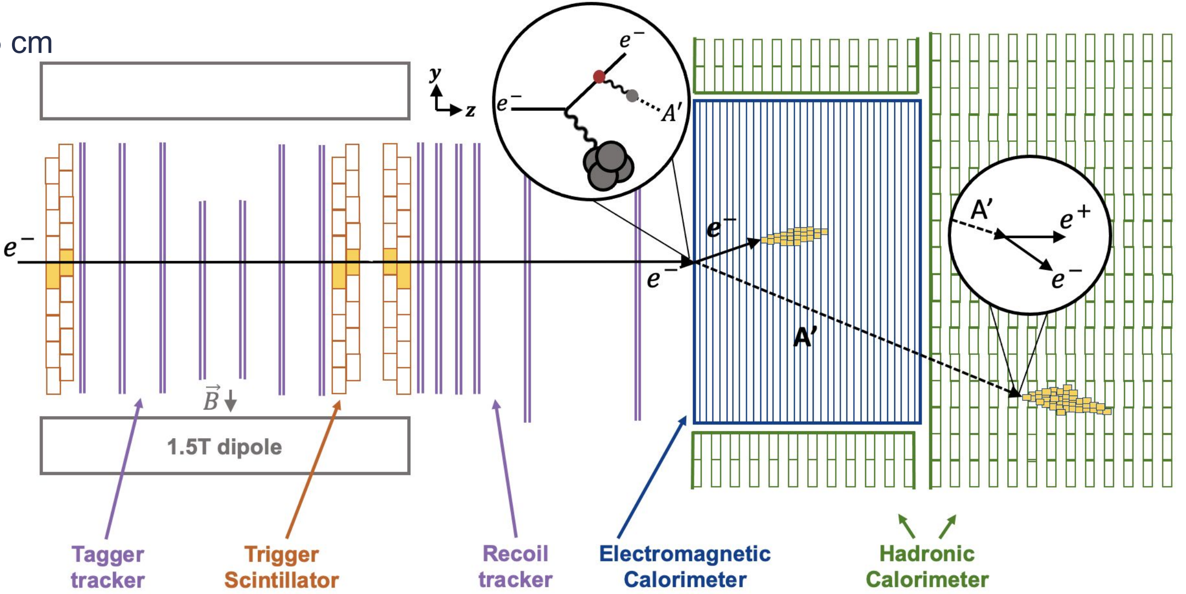
Visibles Sensitivity



- UVA group has been focusing on minimal dark photon model
- Successfully developed new trigger and trained new BDT to reject backgrounds
  - Not expected to be background-free, unlike the main search
- Work is ongoing (but almost complete!) for 4 GeV study, internal note almost ready for review by physics committee
  - Next step is to do full 8 GeV study

Ecal as Target (EaT) Visibles Search

- To be able to probe additional untouched areas of parameter space, need to increases the reach to larger epsilon, which means decreasing the baseline
- Could attempt to do an short run where the beam is shot directly at the front face of the Ecal, without a target in-between
    - Would reduce the baseline by ~ 25 cm



Where are we?

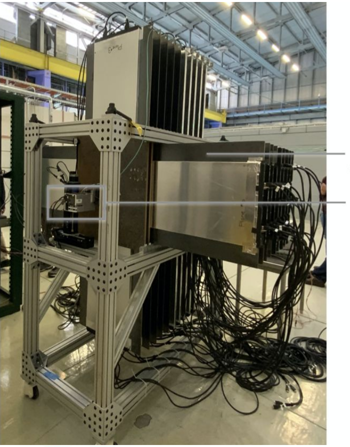
- 2020-present: DOE Dark Matter New Initiatives (DMNI) Funding
- 2027 (TBC/funding dependent): Begin construction!
- 2029 (TBC): Begin data taking!

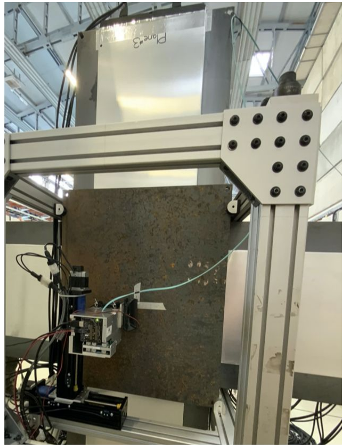
With DMNI R&D Funding

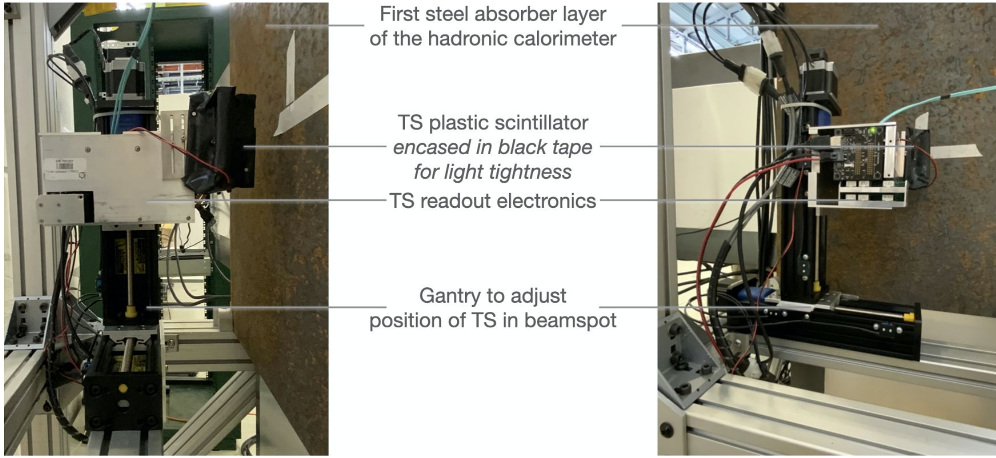
- Spring 2022: CERN testbeam with (partial) Hcal and TS prototypes
- Fall 2024: S30XL Beam Commissioning using TS prototype
- 2025 (TBC): testbeam at SLAC

LDMX Testbeam at CERN

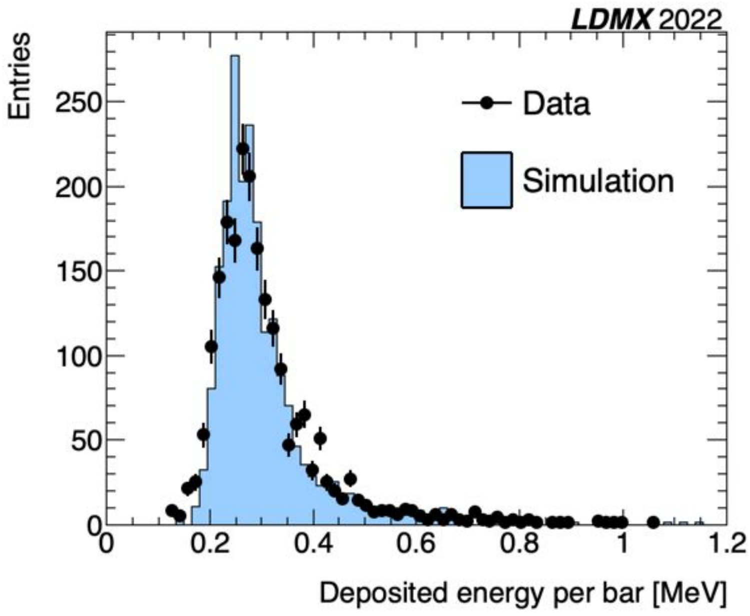
- Successful testbeam at CERN PS in April 2022
  - Hcal and TS prototypes
- Demonstrated successful operations, readout & electronics, and basic physics capabilities of two subsystems
- Analysis work/internal note ongoing

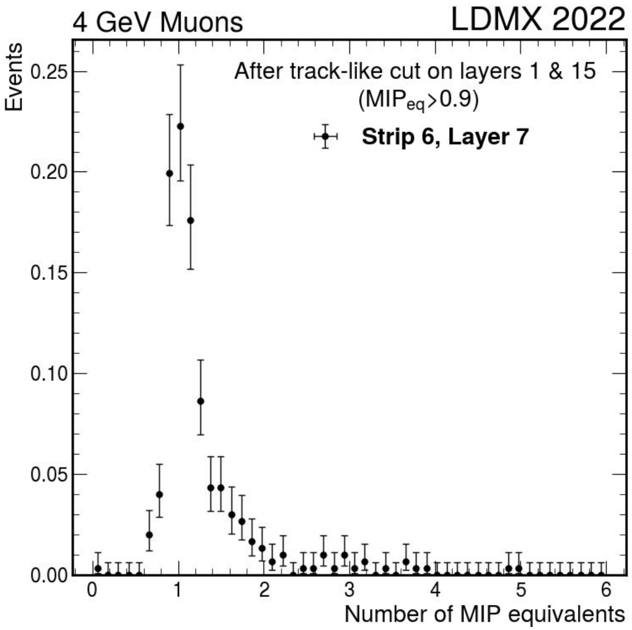






LDMX Testbeam at CERN - Preliminary Results





- TS response well modeled by Geant4 MC simulation
- Excellent Hcal MIP identification capability

Accelerator Requirements for LDMX

- Low-intensity, multi-GeV electron beam (up to 10^{16} electrons on target (EoT))
  - Average of a single electron on target per event
- Large beamspot (~$20 cm^2$) and high-repetition rate

Goals

- Identify individual electrons in the detectors at higher rate with fine spatial and temporal resolution
- Minimize the peak radiation dose and minimize radiation damage to the tracker and calorimeter systems

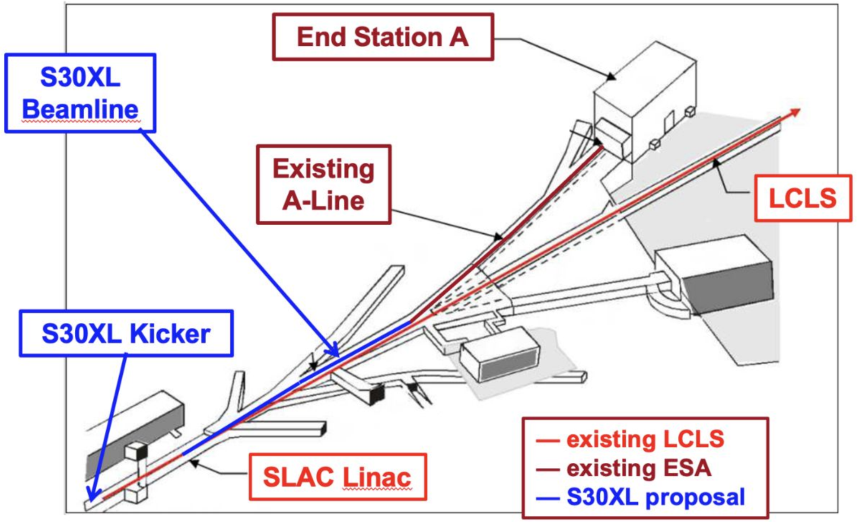
Beam for LDMX

LCLS-II (Linac Coherent Light Source) **beam at SLAC**

- Free electron laser producing femtosecond X-ray pulses for multipurpose science
- 99% of electron bunches are unused!

S30XL/LESA

- New beamline to drive 60% of unused low-charge bunches to End Station A
- Able to run in a mode that is completely parasitic to LCLS-II operation
- LCLS-II beam upgrade from 4 to 8 GeV in FY27-28
- S30XL/LESA beamline installation and commissioning is ongoing (FY24-25)



S30XL Commissioning

- LDMX has been given the opportunity to help commission S30XL this summer/fall
  - Put the TS prototype from CERN testbeam in the beam
- Through the DOE SCGSR grant, I will be resident at SLAC over the summer to help with this effort!

Goals

- Measure beam parameters of the dark current in S30XL
- Demonstrate that the system can run parasitically to LCLS-II in Dark Current mode without any adverse impacts

Additional Future Testbeam at SLAC

- May be able to put the Hcal and TS prototypes (from CERN testbeam), along with an Ecal module in End Station A
    - Some time 2025?
- Invaluable chance to test area where LDMX will eventually reside, along with testing proper beam timing and structure

Conclusions

- Thermal DM is a simple and compelling scenario, and MeV-GeV scale is a logical place to look - extension of WIMPs!
- LDMX will be able to provide world-leading sensitivity to sub-GeV DM and is able to test many LDM scenarios along the way
- Past and future testbeam efforts help to strengthen the design of LDMX
  - I will be going to SLAC this summer to join in S30XL testbeam/commissioning!!

Caltech

Fermilab

LUNDS UNIVERSITET

UNIVERSITY OF MINNESOTA

UCSB
UNIVERSITY OF CALIFORNIA SANTA BARBARA

Carnegie Mellon University

SLAC NATIONAL ACCELERATOR LABORATORY

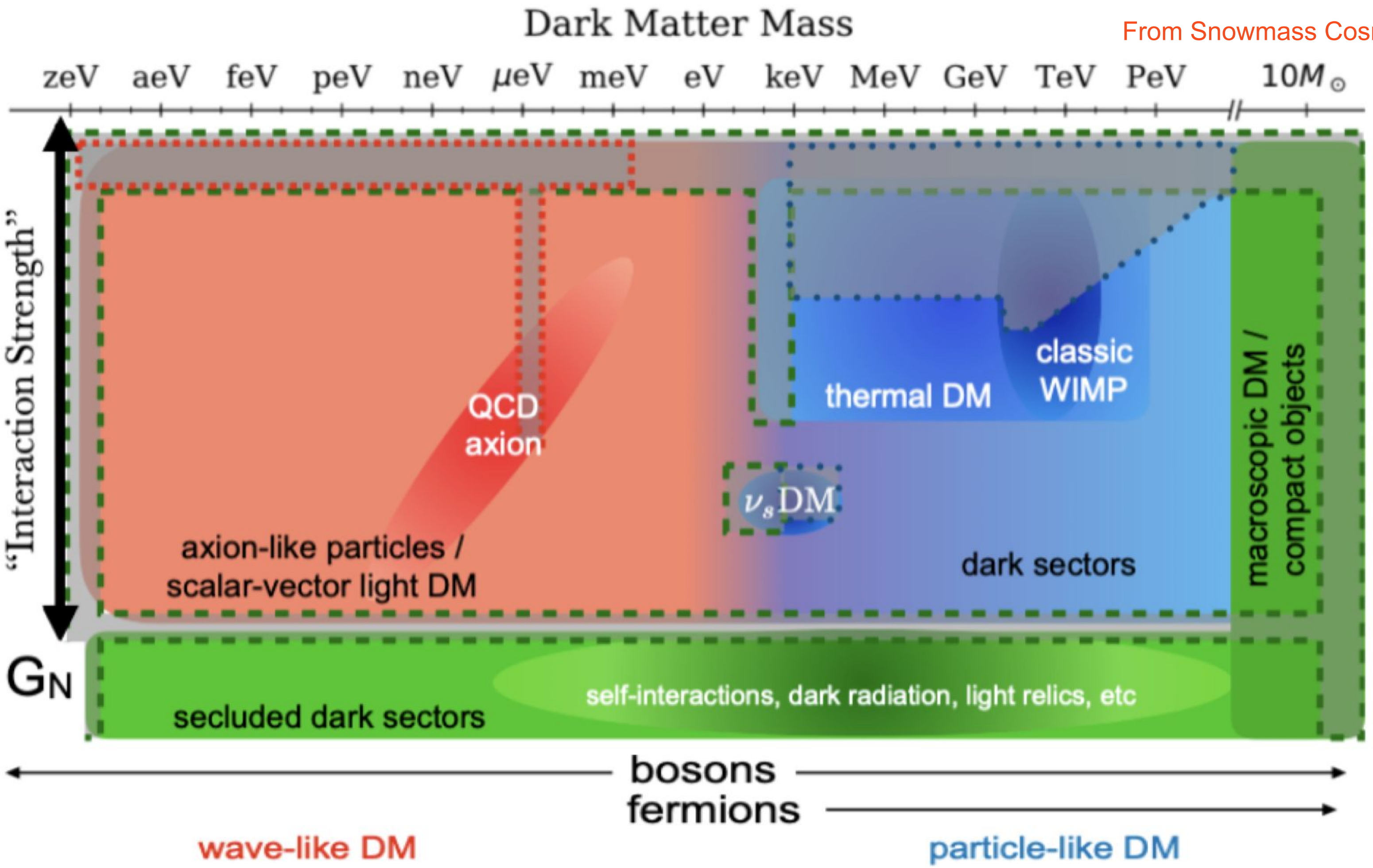
STANFORD UNIVERSITY

TEXAS TECH UNIVERSITY.

UNIVERSITY of VIRGINIA

Backup

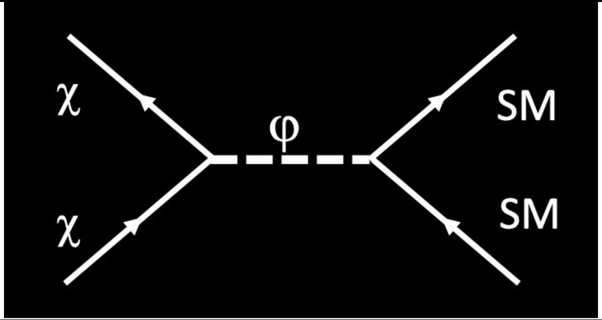
From Snowmass Cosmic Frontier Report



Annihilation Cross Section Dependence

$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

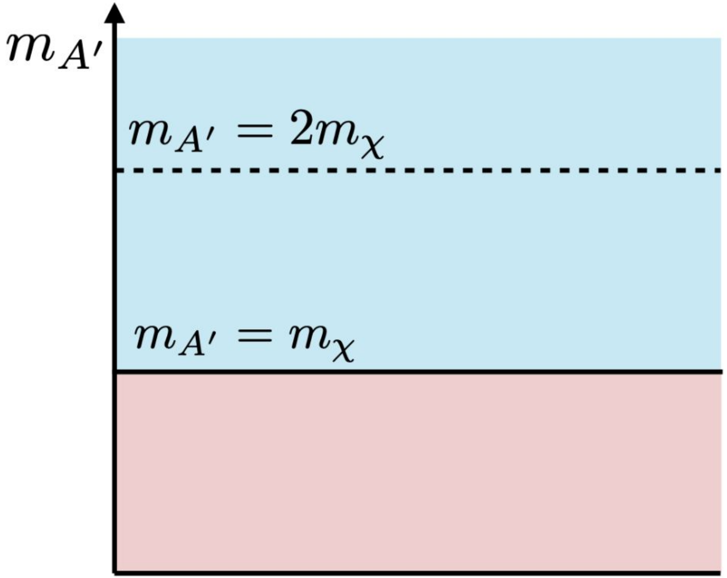
$$m_\varphi^4 < \sigma v > \sim g_D^2\, g_{SM}^2\, m_x^2 \leq m_x^2 \qquad \text{since } g \leq O(1)$$



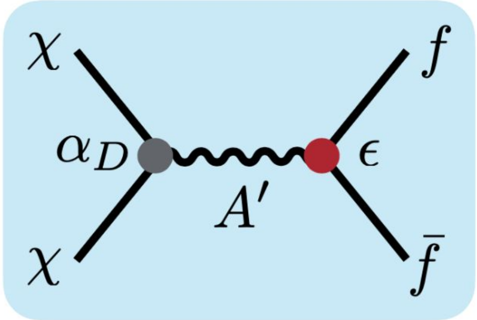
$$< \sigma v > \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim y \frac{1}{m_\chi^2}$$

$$y = \alpha_D\, \epsilon^2\, \frac{m_\chi^4}{m_{A'}^4}$$

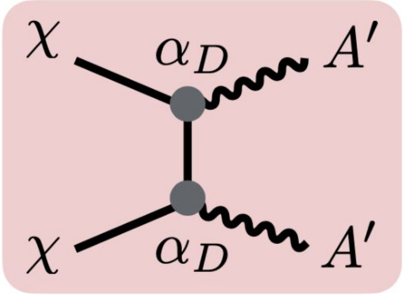
DM Mass Ordering



Mass ordering drives phenomenology.



DM annihilates to SM pairs.
$\sigma \sim \varepsilon^2$ gives a relic target.

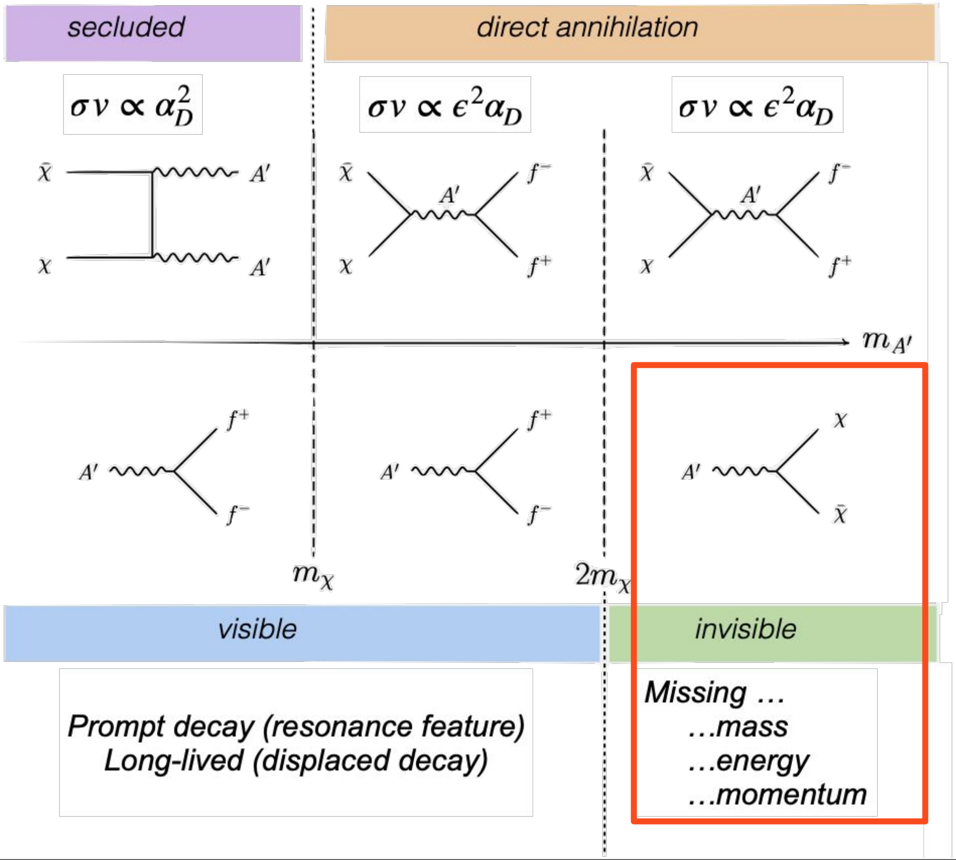


DM annihilates to A' pairs. $\sigma \sim g_D^2$.
'Secluded annihilation': no relic target.

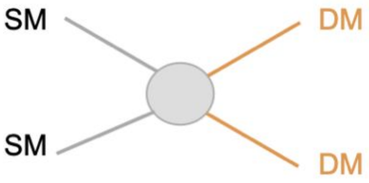
Possible Dark Photon Signatures

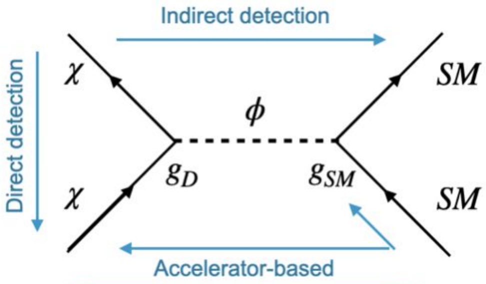
A' production

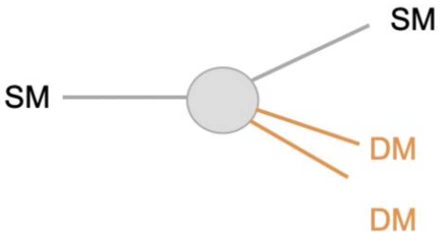
A' decay



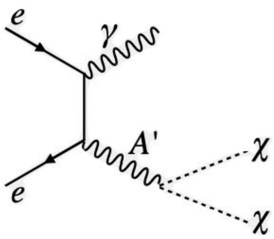
Advantage of Fixed Target Missing Momentum Search





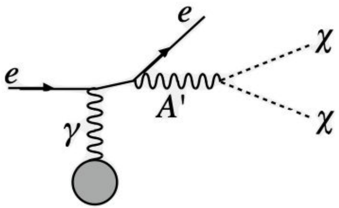


Collider



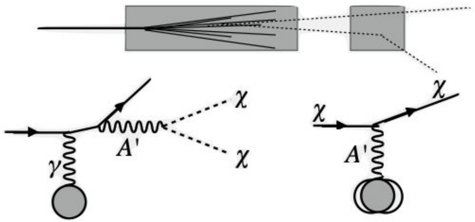
$\sigma_{coll} \propto \frac{\epsilon^2}{E_{com}^2}$ <<

Missing Momentum



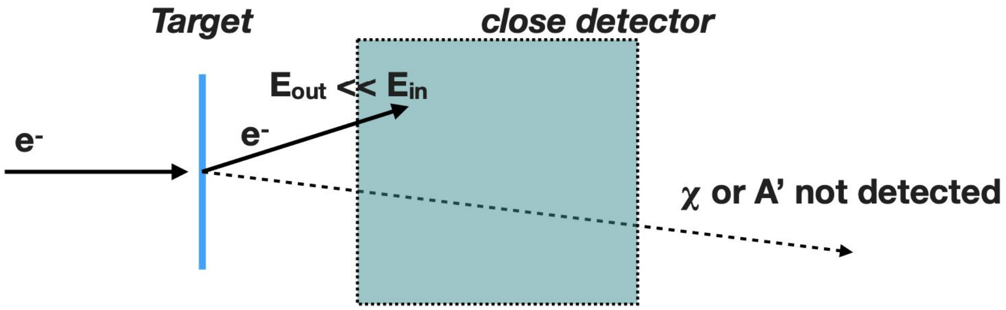
$\sigma_{FT} \propto \frac{Z^2\epsilon^2}{m_{A'}^2}$ $N \propto \epsilon^2$

Beam dump



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

Fixed Target Missing Momentum Search Concept

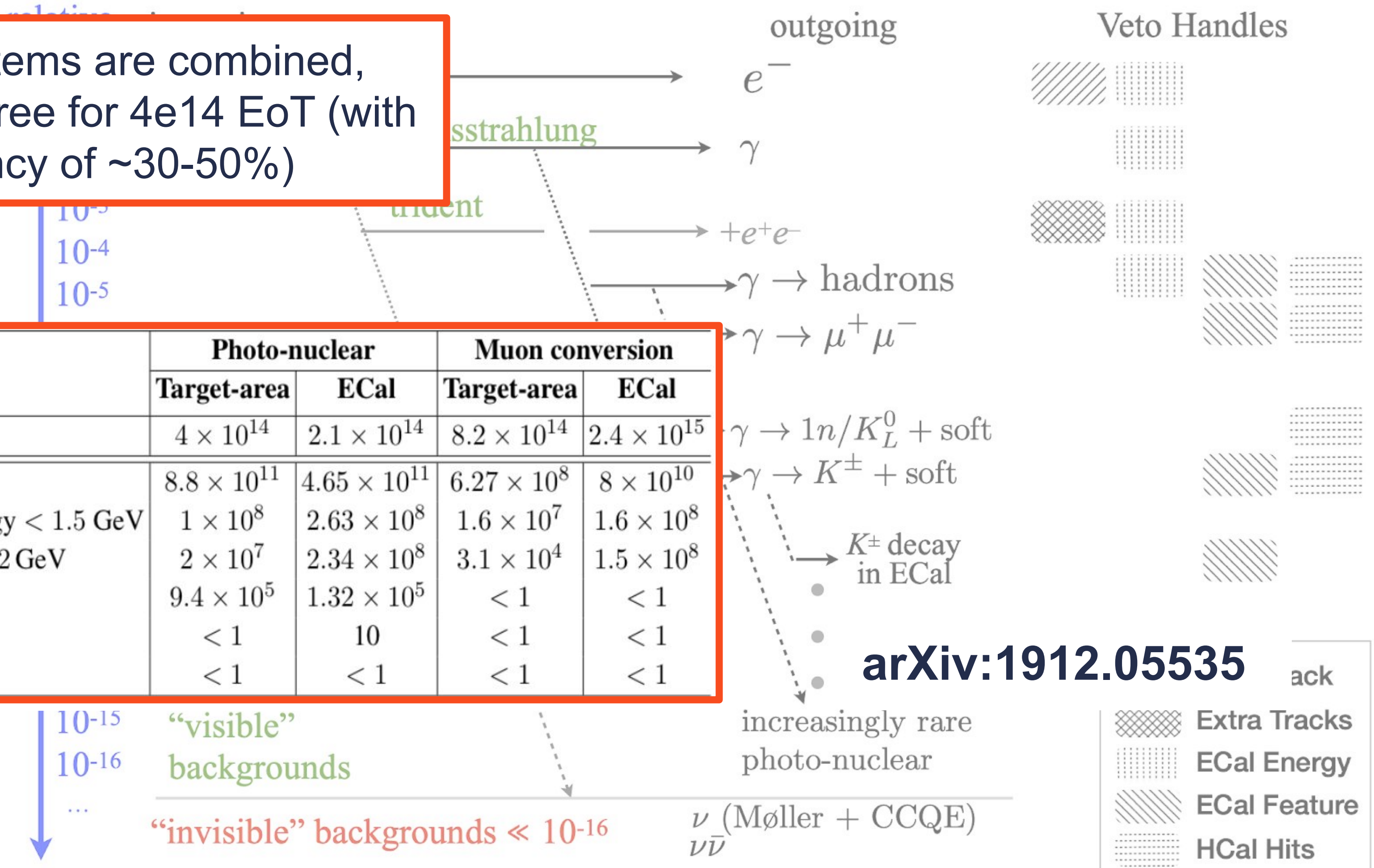


- Larger yield than beam-dump experiments
  - no additional ε^2 DM detection penalty
- DM production identified via missing momentum and energy in detector

Feasible to cover all thermal targets with this approach!!

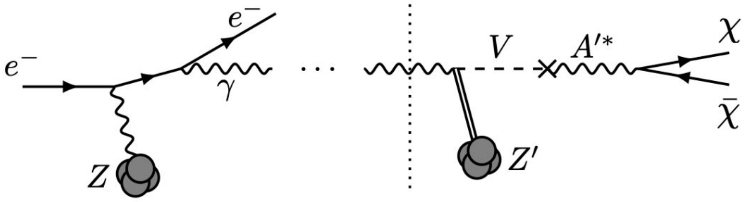
When all systems are combined, background free for 4e14 EoT (with signal efficiency of ~30-50%)

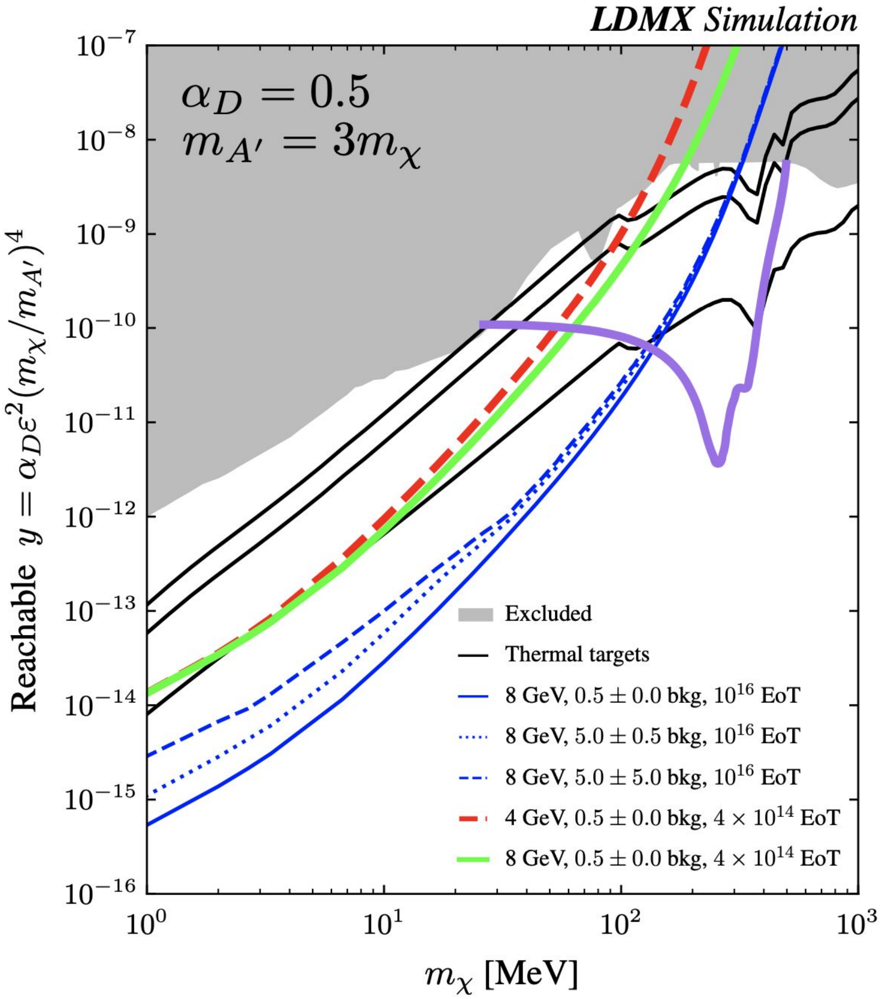
	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ 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



arXiv:1912.05535

Gain additional sensitivity from invisible meson decay channel

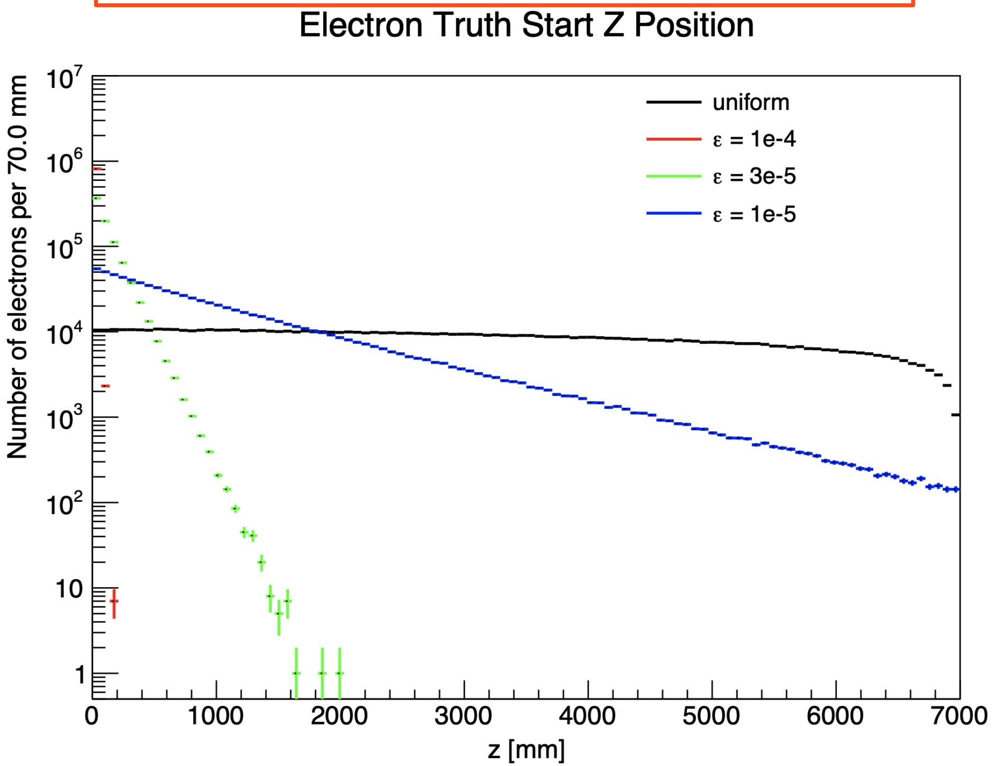




Relationship between ε and A’ Lifetime

- As epsilon gets larger, the proper lifetime of the A’ decreases
- To be able to probe untouched areas of parameter space, need to increases the reach to larger epsilon, which means decreasing the baseline

$$\gamma c \tau_{A'} = 32.5\ \text{cm} \left(\frac{E_{A'}}{4\ \text{GeV}}\right) \times \left(\frac{10^{-5}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2$$

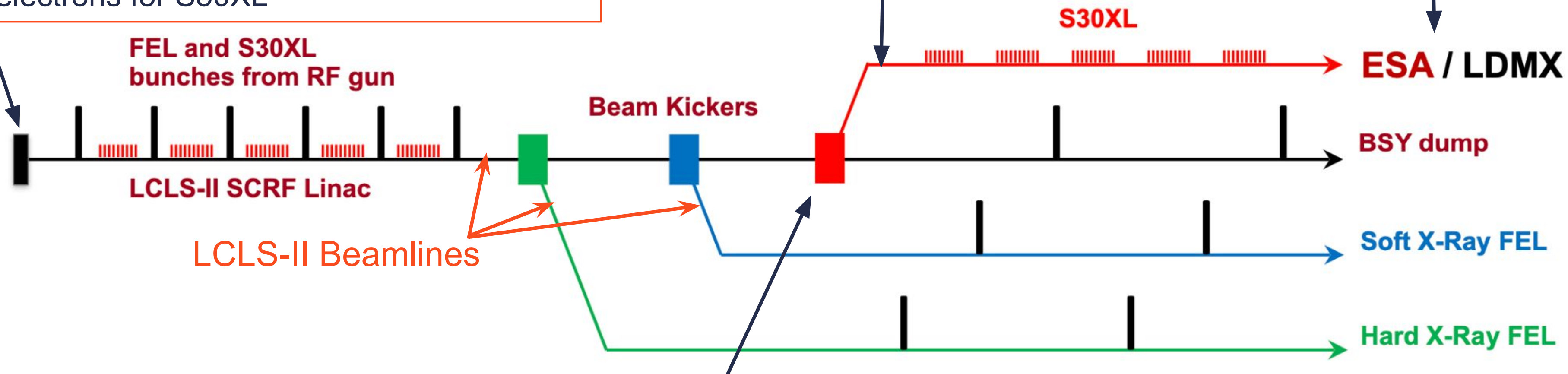


Beam for LDMX

Experimental Facilities
→ Small upgrades to ESA systems & A-Line

S30XL+LESA Beamline connecting to ESA line
→ 3 dipoles & 14 quads (all refurbished)

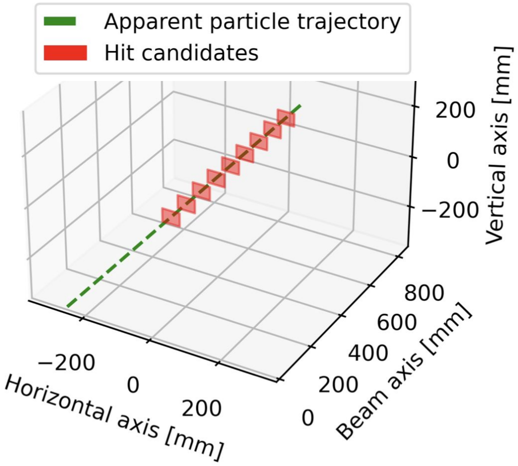
Laser system to fill "unused" buckets with electrons for S30XL

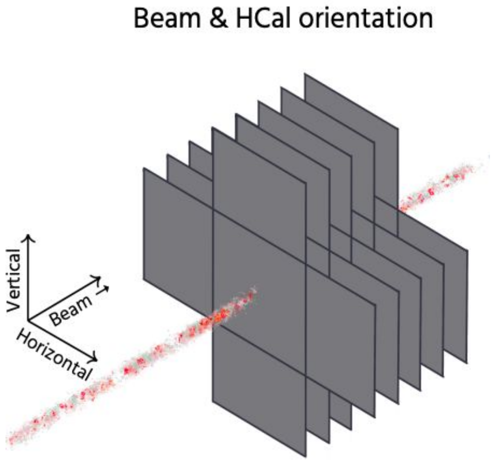


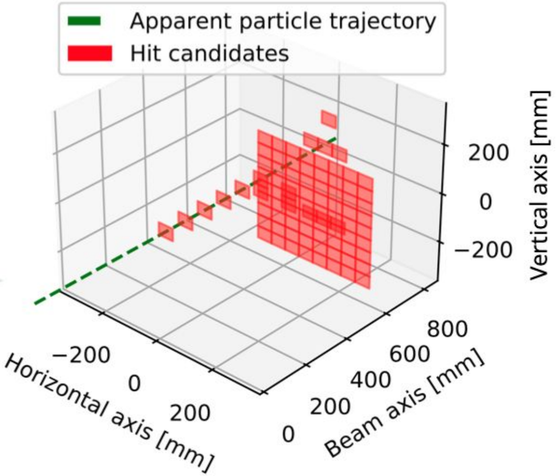
S30XL kicker/septum system downstream of FEL kickers to eliminate interference
→ Based on LCLS-II design

LDMX Testbeam at CERN - Preliminary Results

- Muon Candidate
  - Clear, crisp MIP signature in Hcal
- Pion Candidate
  - MIP-like deposits followed by a cloud of hits

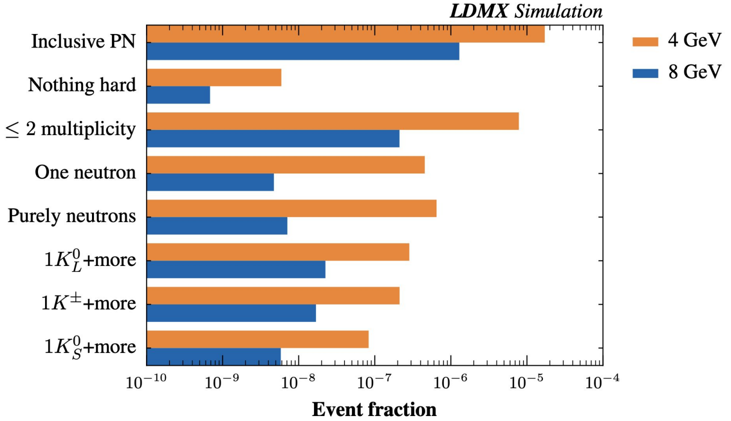


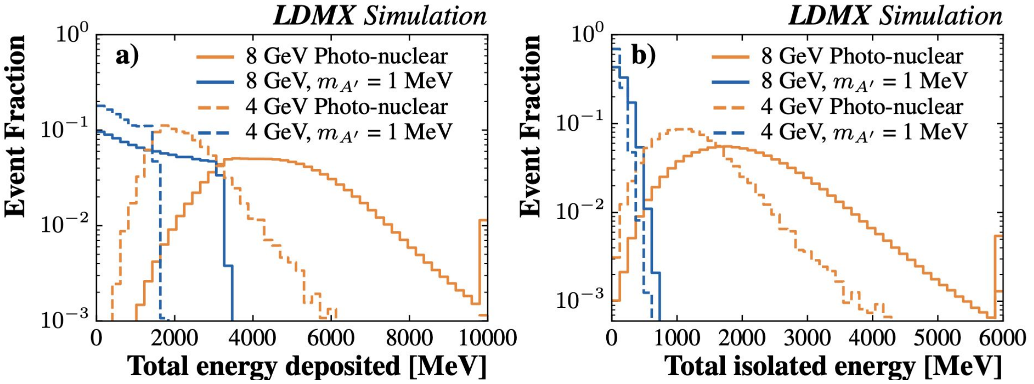




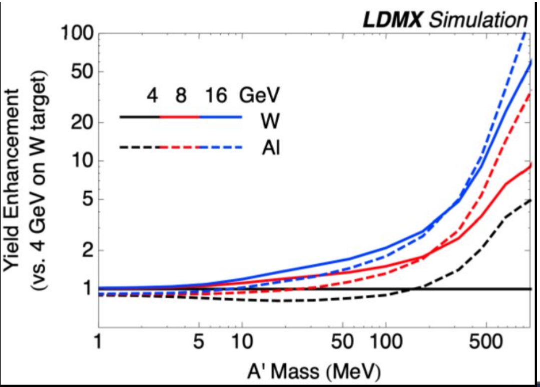
Advantages of 8 GeV Beam

arxiv:2308.15173





Overall reduction of PN events that pass the trigger and higher multiplicity



Higher signal cross-section

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT Equivalent	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}
Trigger (front ECal energy < 3160 MeV)	7.57×10^{7}	4.43×10^{8}	2.37×10^{7}	8.12×10^{7}
Total ECal energy < 3160 MeV	2.73×10^{7}	7.27×10^{7}	1.76×10^{7}	6.06×10^{7}
Single track with p < 2400 MeV/c	3.03×10^{6}	6.64×10^{7}	5.32×10^{4}	5.69×10^{7}
ECal BDT (85% eff. $m_{A'} = 1$ MeV)	1.50×10^{5}	1.04×10^{5}	< 1	< 1
HCal max PE < 8	< 1	2.02	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1