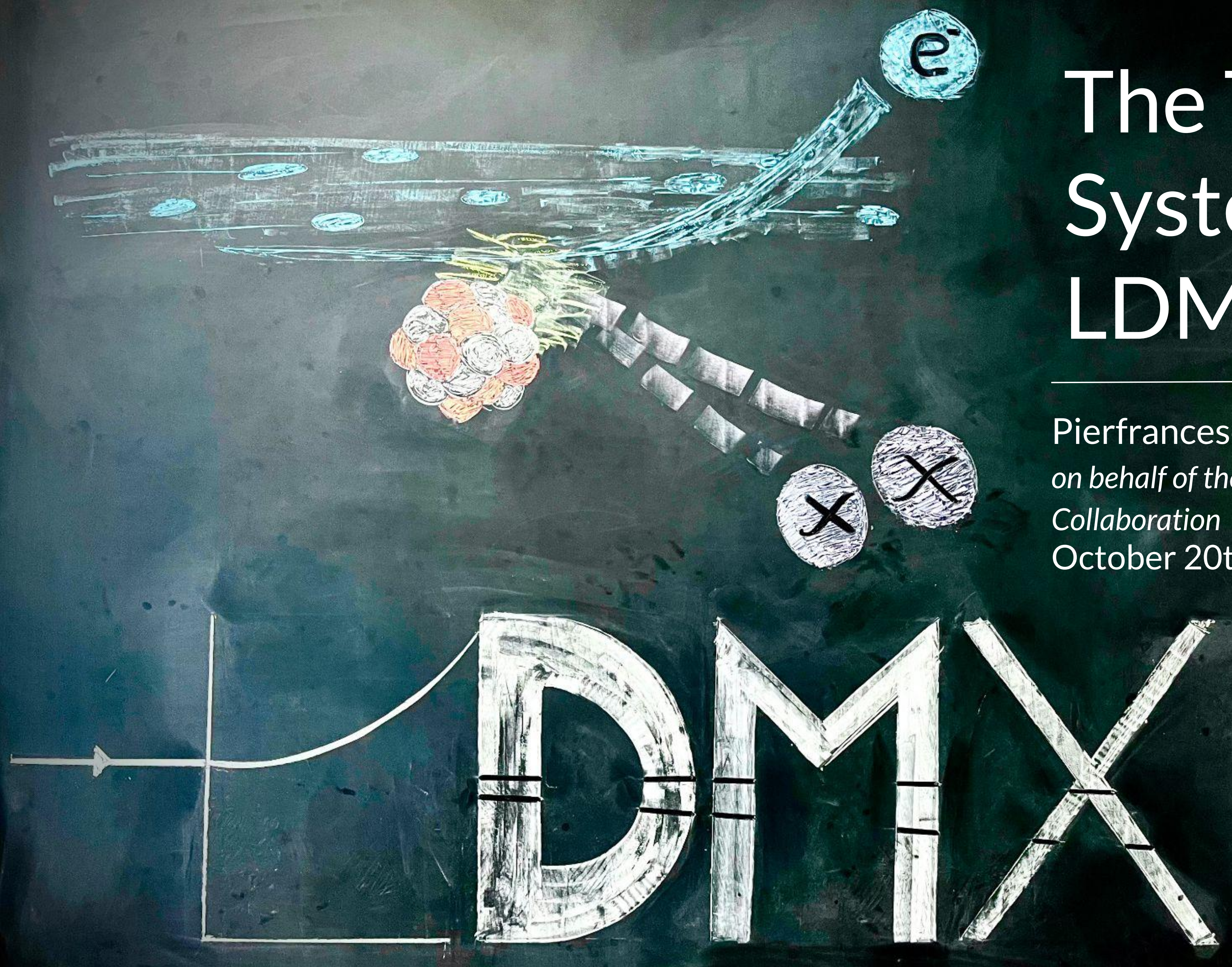


The Tracker System of LDMX

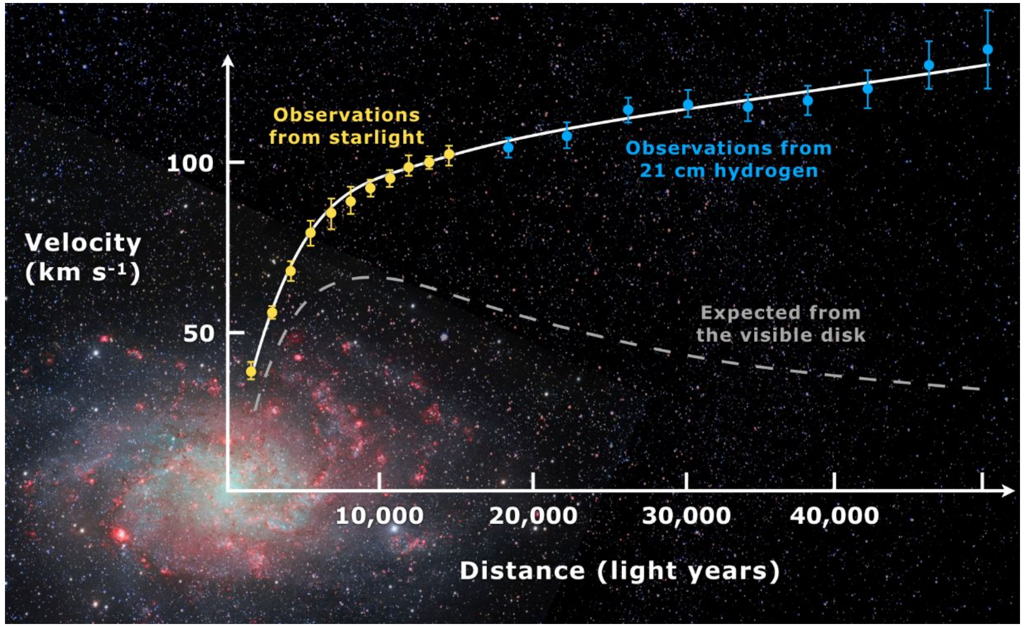
Pierfrancesco Butti
on behalf of the Light Dark Matter eXperiment Collaboration
October 20th, Vertex 2023

SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University
U.S. DEPARTMENT OF ENERGY

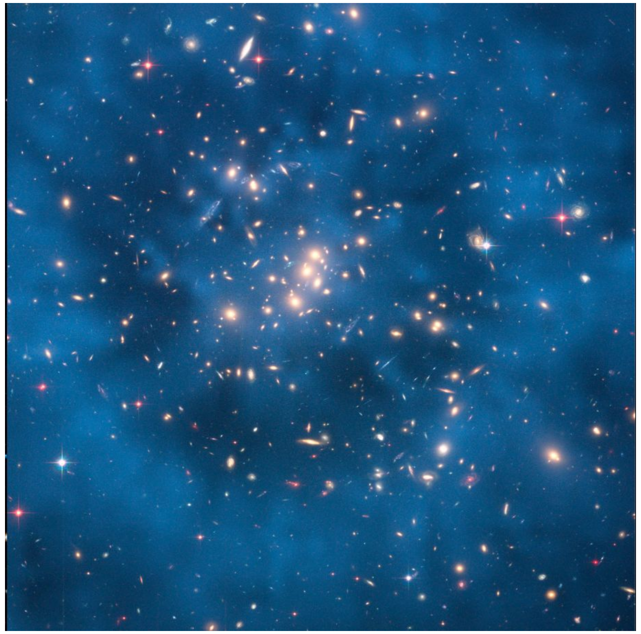
Evidence of Dark Matter in the Universe

- **There is clear evidence for the existence of Dark Matter (DM) in the Universe**
  - **Observation of the rotation speed of spiral galaxies**
  - **Gravitational lensing**
  - The Bullet Cluster
  - Cosmic microwave background

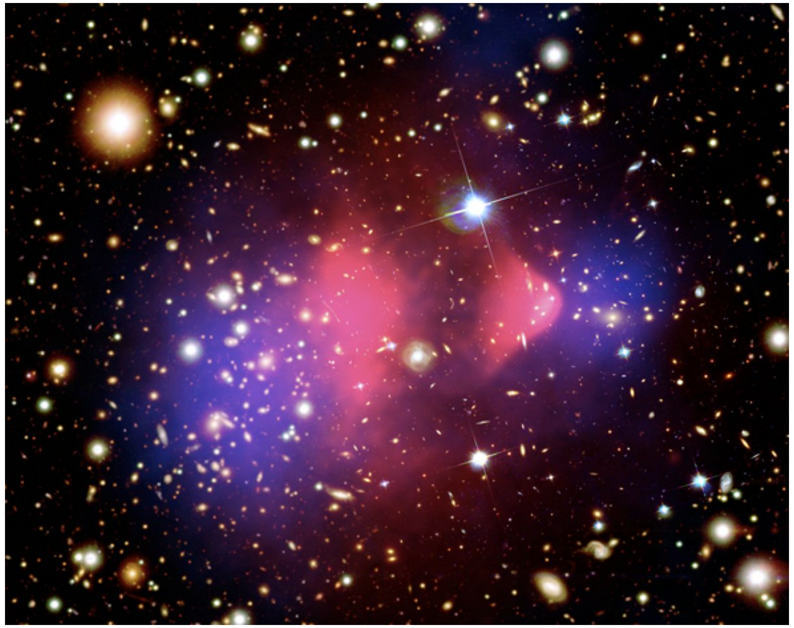
Messier 33 arXiv:9909252



NASA, ESA, M.J. Jee and H. Ford

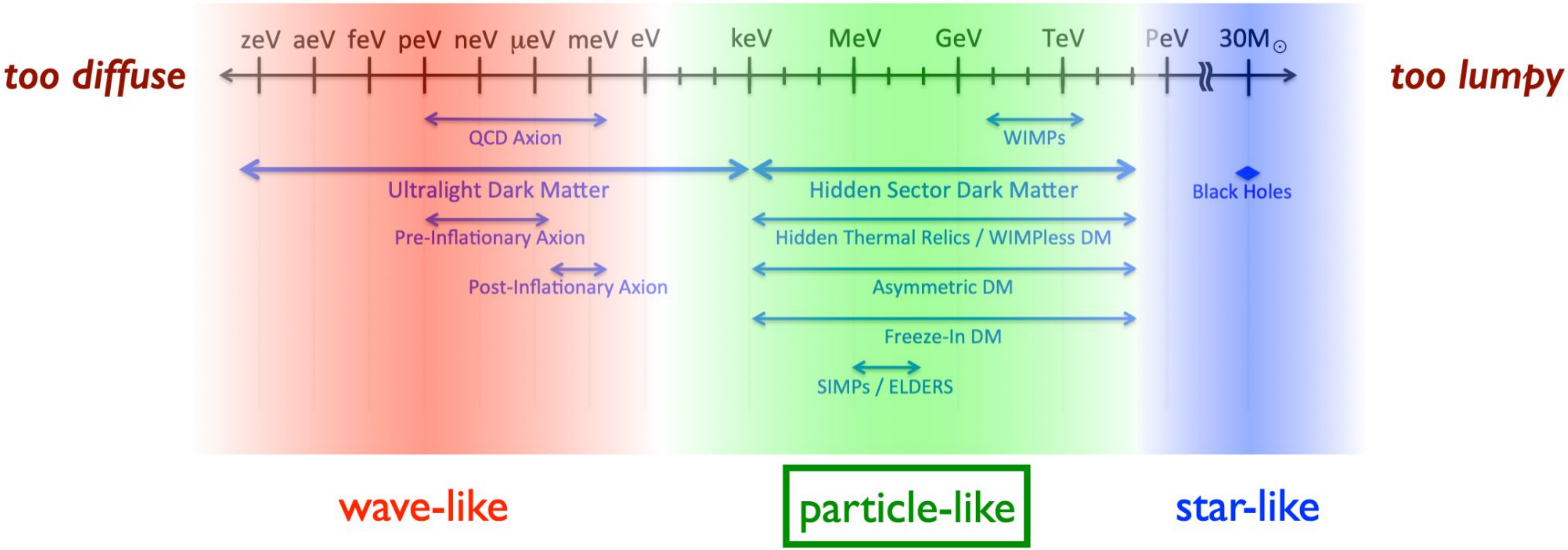


The Bullet Cluster 1E 0657-56



Thermal Dark Matter Mass Range

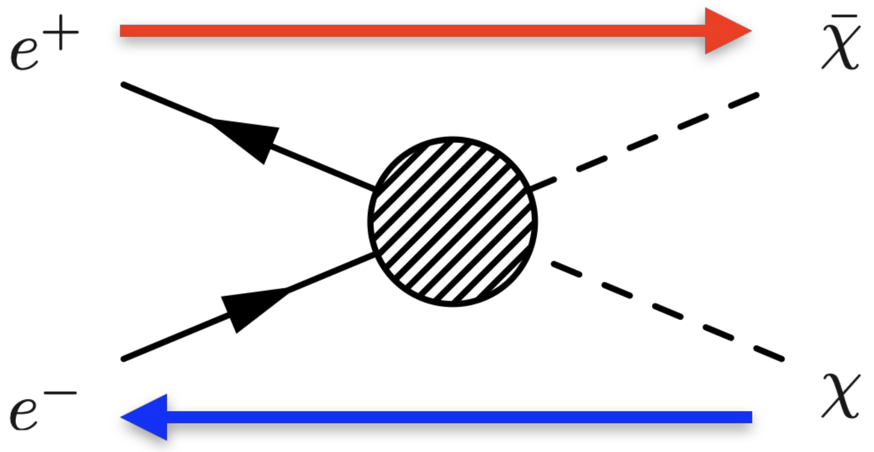
arXiv:1707.04591 [hep-ph]

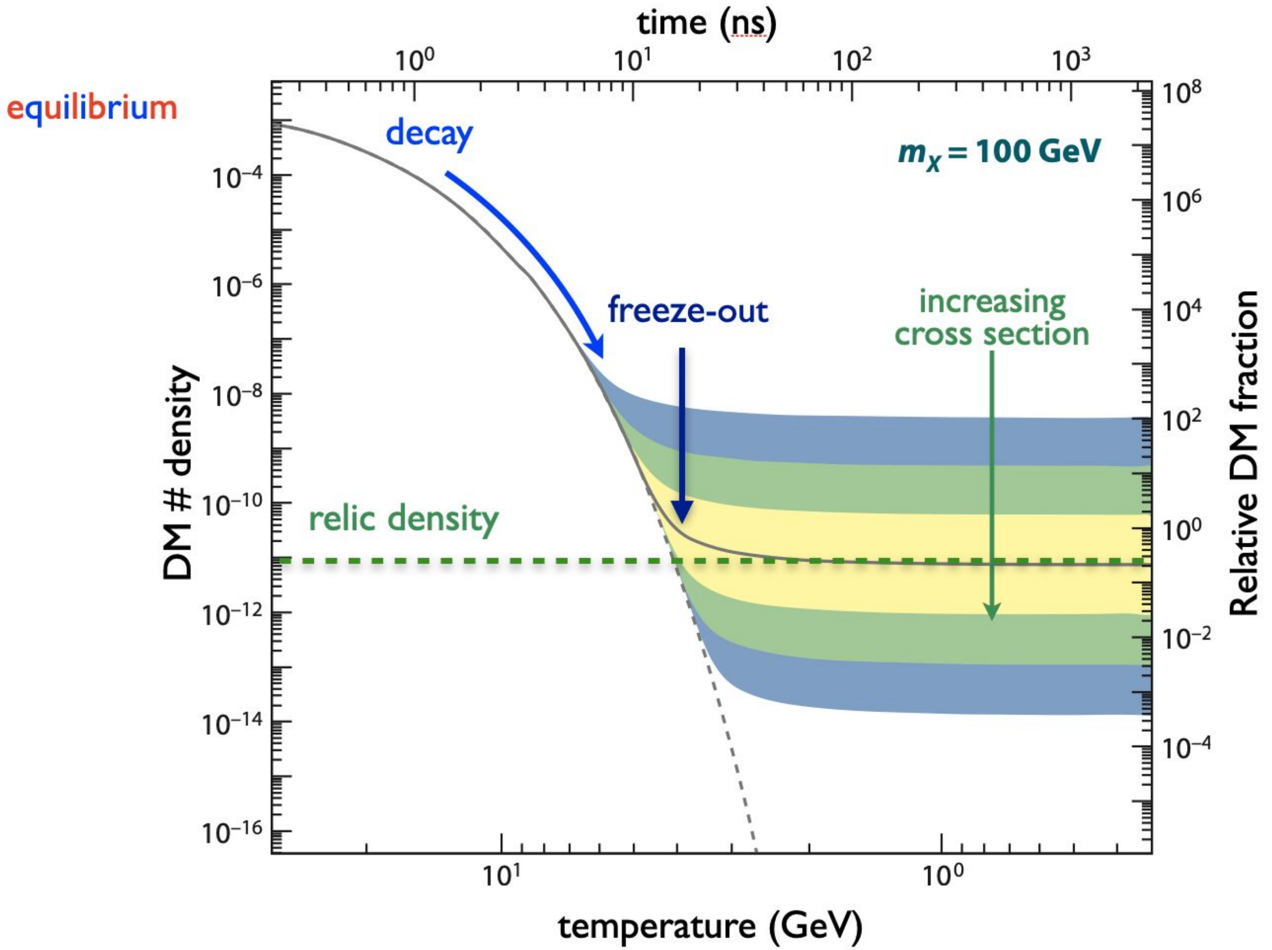


Thermal relics are an important class of dark matter where sub-GeV region is still relatively unexplored.

arXiv:9506380

Thermal Dark Matter





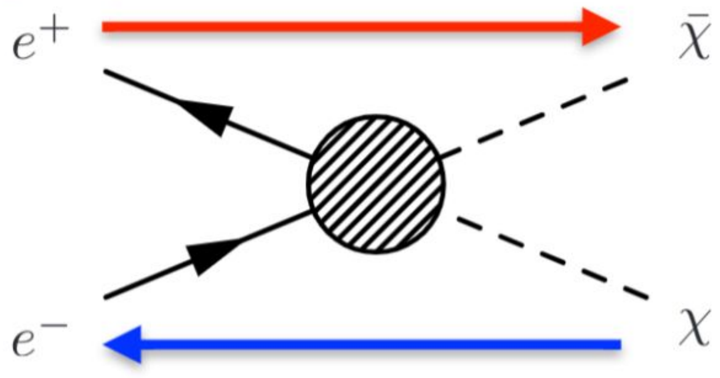
- Assume DM in thermal equilibrium with SM in the very early universe
- Thermal DM as relic of the hot early Universe is one the most compelling paradigms
  - Generic and Predictive

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

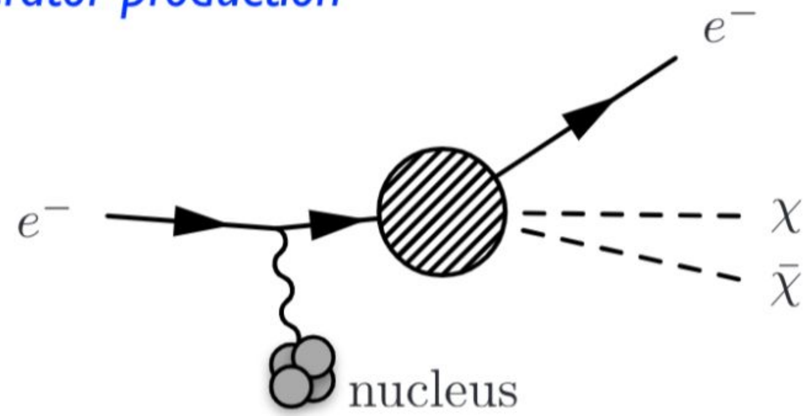
arXiv:9506380

Thermal Dark Matter

cosmological production



accelerator production



$$\sigma v = \frac{1}{16\pi^2}\frac{\bar{\mathcal{M}}(s)}{s}$$

at freeze-out:

$$s_{fo} \approx (2m_\chi)^2$$
$$\sigma v = 3 \cdot 10^{-26}\text{cm}^3/s$$

$$\Rightarrow |\bar{\mathcal{M}}(s_{fo})|^2 = 10^{-6} m_\chi^2/\text{GeV}^2$$

for production at $s \approx s_{fo}$:

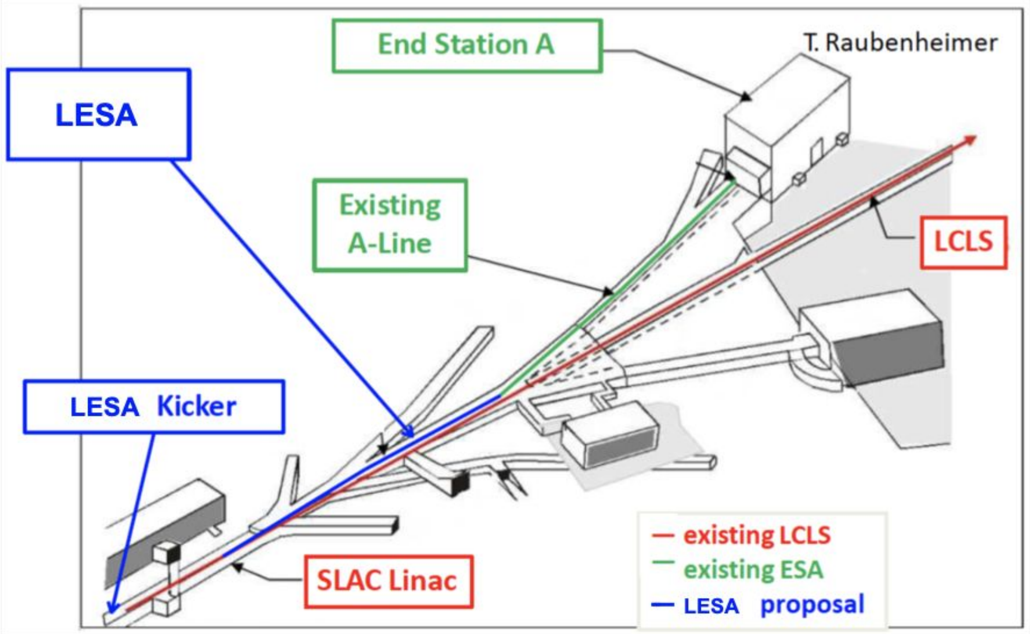
$$\frac{\sigma_{\chi\bar{\chi}}}{\sigma_{brem}} \approx \frac{|\mathcal{M}|^2}{e^2}\frac{1}{48\pi^2}\frac{(2m_\chi)^{-2}}{m_e^{-2}} f_{coh} \approx 2 \cdot 10^{-15} f_{coh}$$

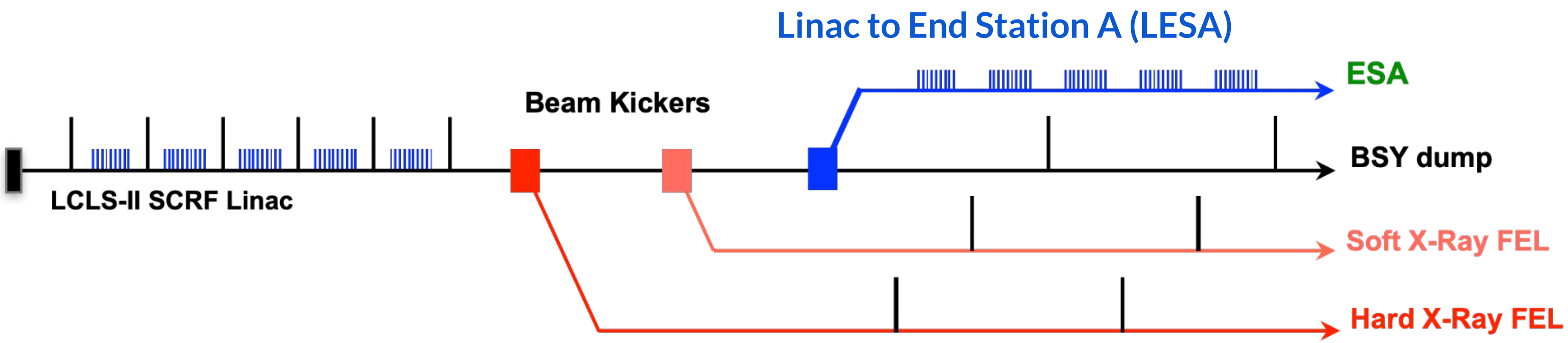
where f_{coh} is $\mathcal{O}(1)$ for $m_\chi \lesssim 100$ MeV

Since smaller cross sections result in DM overabundance, an accelerator experiment with ~10^{16} electrons has generic ability to produce sub-GeV freeze-out thermal relics.

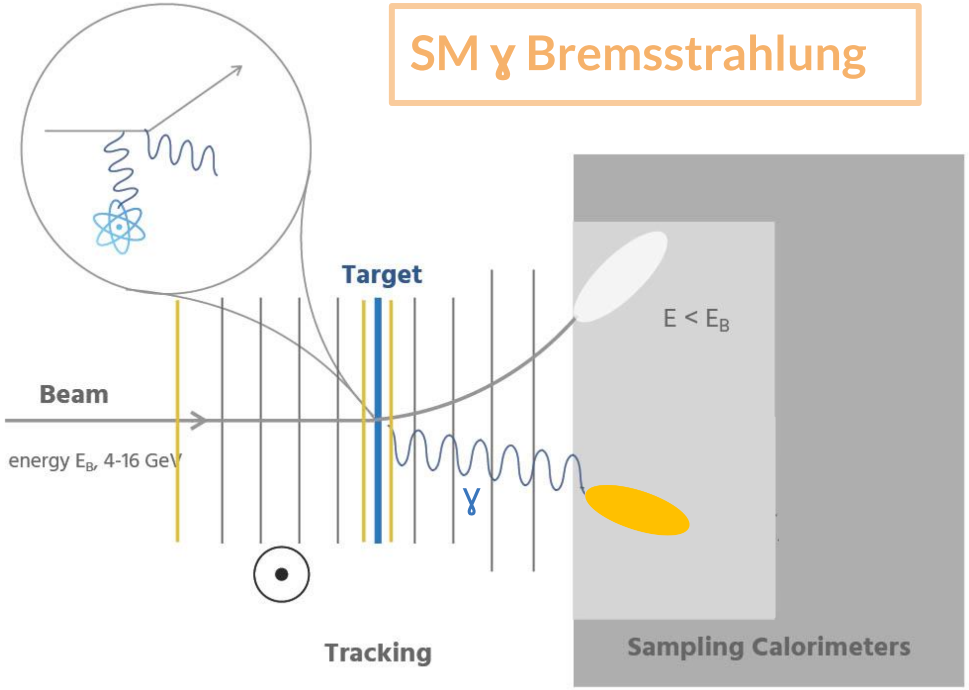
The Beamline: Linac to End Station A (LESA) at SLAC

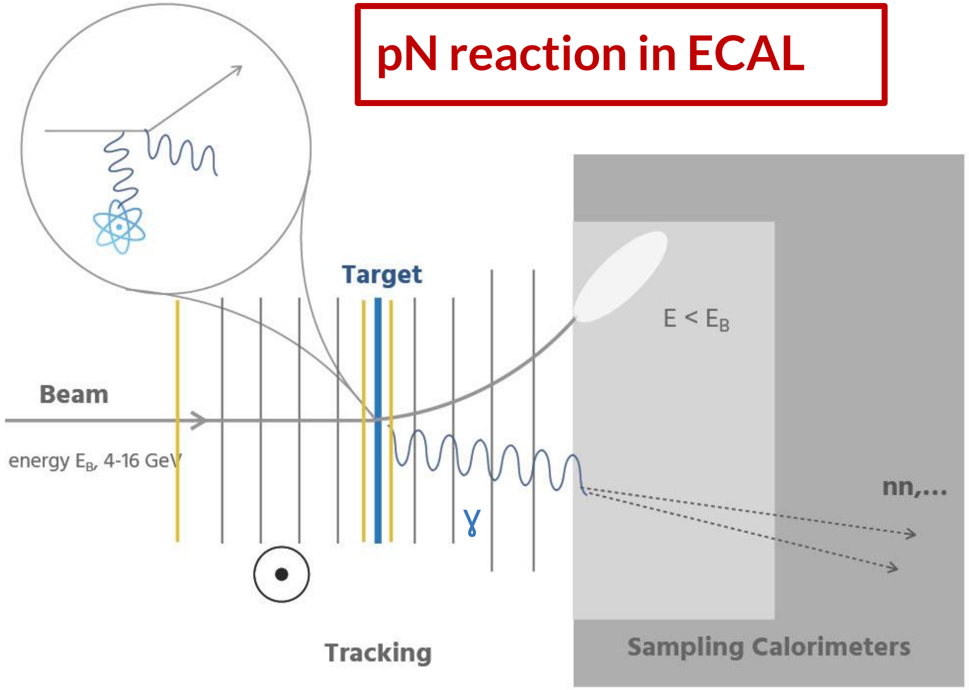
- **Low-intensity, multi-GeV electron beam (up to 10^{16} e- on target (EOT))**
  - **Single electron on target per event**
  - **Large beamspot (~20cm^2) and high-repetition rate**
- **LCLS-II beam at SLAC:**
  - Accelerates 186 MHz bunches
  - ~5k hours /year operation for photon science at ~930kHz: **99% of bunches to dump**
- Sector 30 Transfer Line (S30XL) drives ~60% of unused low-charge bunches to LESA **with LDMX as primary user**





Background processes

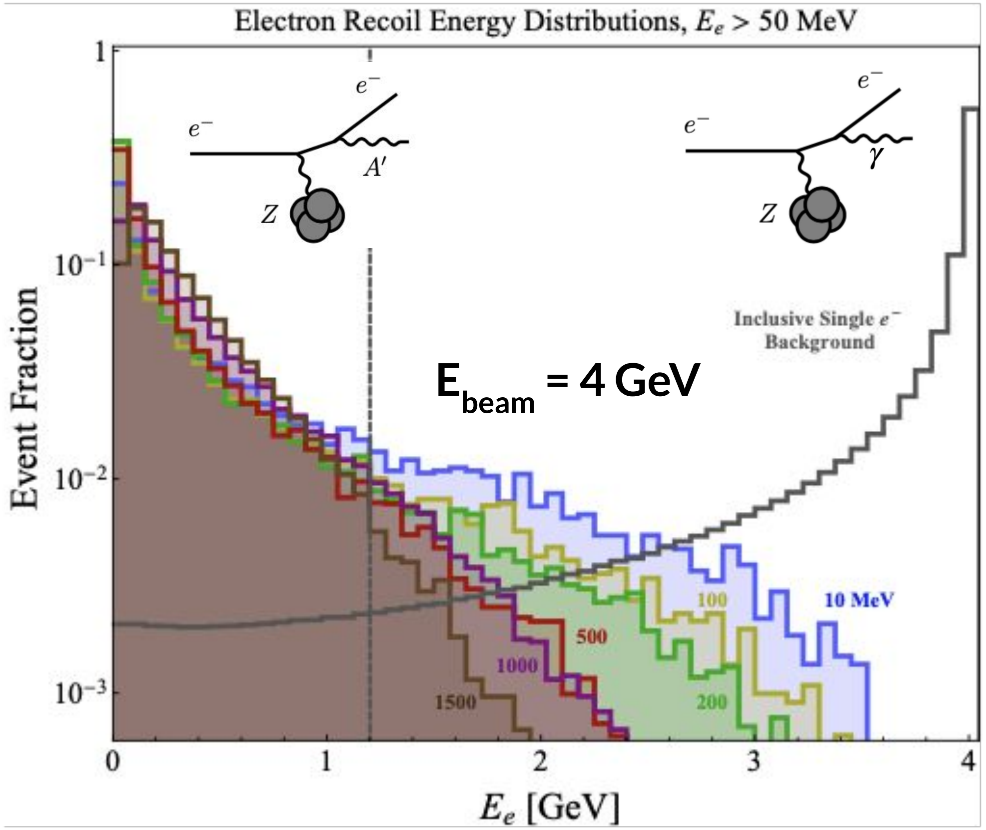


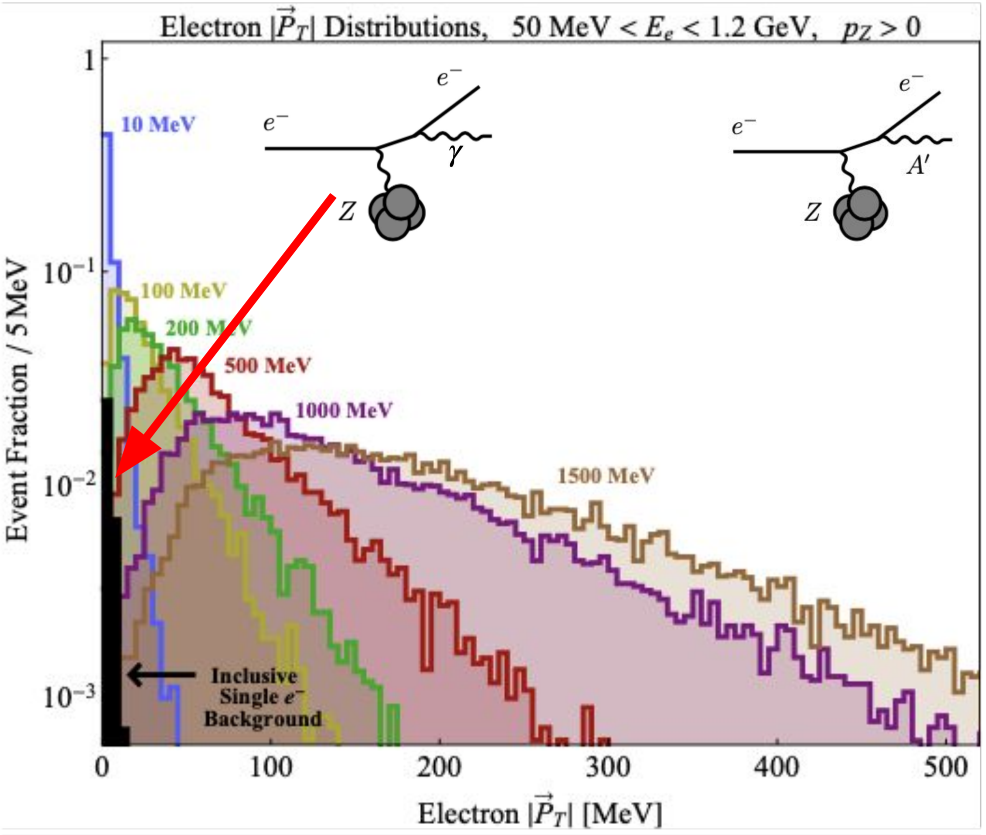


- **Main background:**
  - **SM ɣ Bremsstrahlung**
  - Vetoed by energy deposit in an electromagnetic calorimeter

- **Challenging background:**
  - **Photo-Nuclear reactions producing neutral final states**
  - Relative rate with respect to Bremsstrahlung ~10^{-8} - 10^{-11}

Kinematics at a Fixed Target Experiment





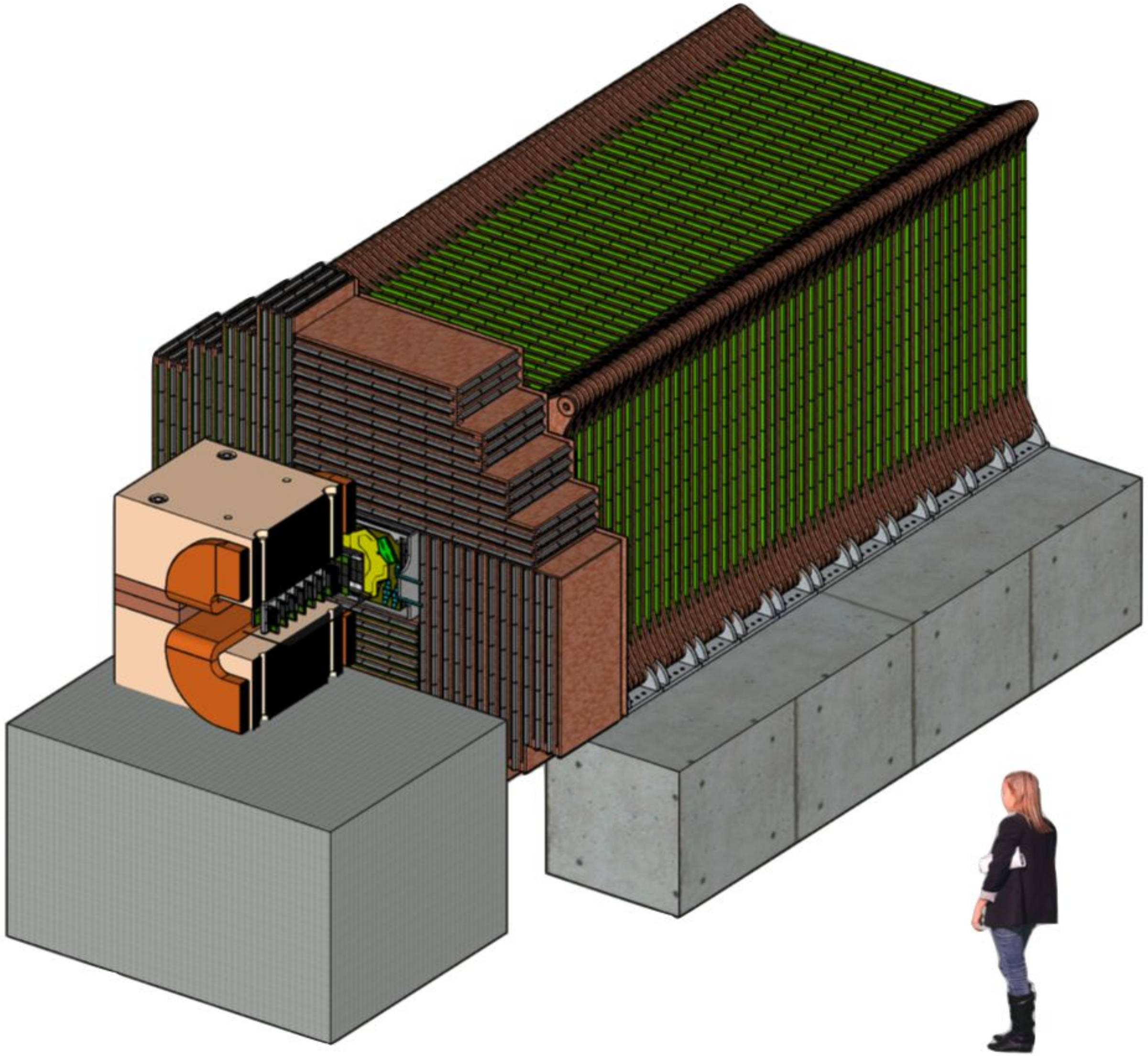
- **A'→χχ carry away most of the beam energy and escape undetected**
  - Opposite behaviour for the bremsstrahlung emission

- **Recoil electron p_T spectrum depends strongly on m_A for signal**
  - Signal identification or extra-handle for background rejection

The LDMX Detector Concept

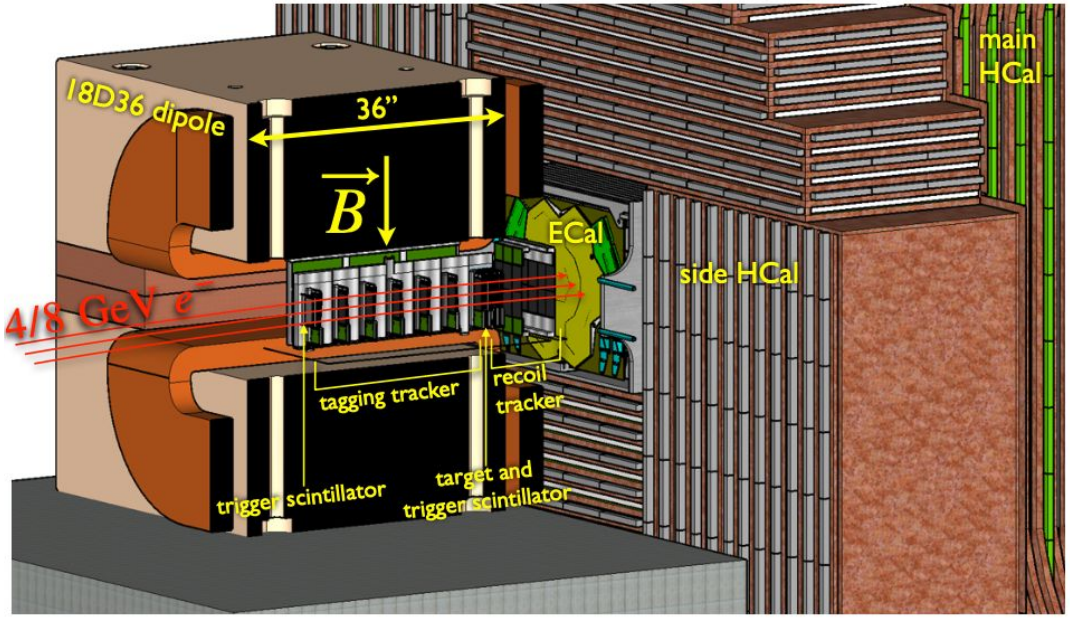
LDMX whitepaper: https://arxiv.org/abs/1808.05219

- **Detector Design**
  - **Tagger Tracker** with low acceptance and high resolution at beam energy
  - **Recoil Tracker** with large acceptance and high resolution at low particle momenta
  - **Electromagnetic calorimeter** with excellent sensitivity and granularity
  - **Hadronic calorimeter** with good segmentation and very low energy veto threshold for neutral hadrons
  - **Trigger scintillator** for fast electrons-per-bunch counting

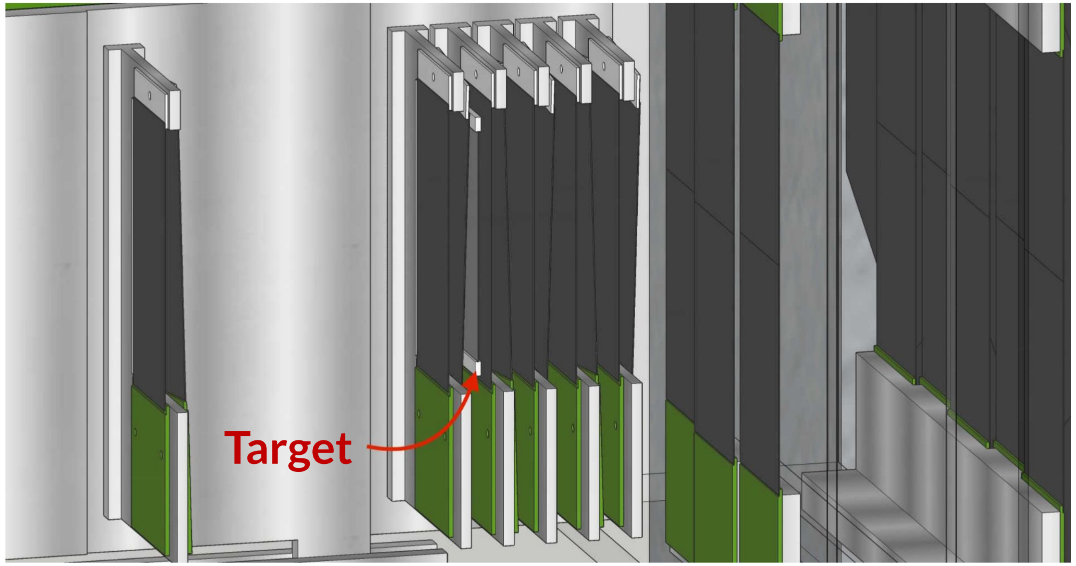


LDMX Tracker System Requirements

- **Detector Design**
  - **Tagger Tracker**
    precisely reconstruct the incoming electron momentum, rejecting off-energy ones
    Located before the target

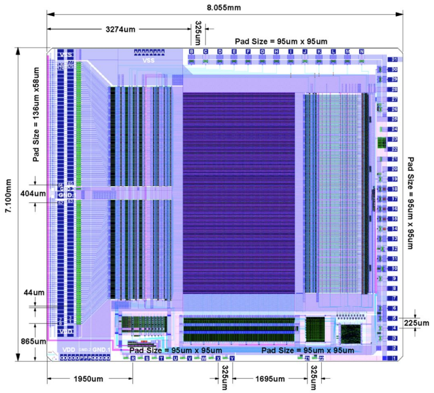


  - **Recoil Tracker**
    reconstruct recoil electron (or eN products) with high acceptance and good resolution at low momentum
    Located after the target

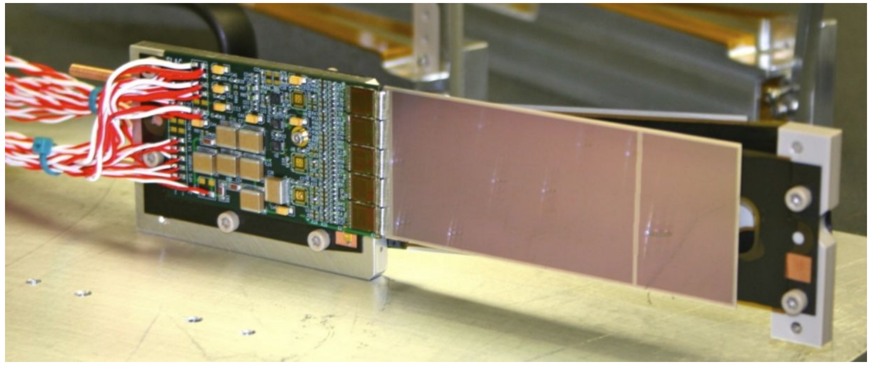


The LDMX Tracker System: Modules

- **Tracker System design**
  - Leverage experience, facilities and equipment from Heavy Photon Search SVT tracker built at SLAC
- **Modules identical to the HPS SVT**
  - p-in-n$^+$ type silicon microstrip
  - 30 (60um) sensor (readout) pitch
  - up to 350 V bias
  - ~4 x 10 cm sensors, glued back to back
- **Low material budget**
  - Each sensor ~ 0.7% X_0
- **CMS APV25 ASICs**
  - Multi peak mode: 2ns time resolution
  - for LDMX 3 sample readout: up to ~100 kHz trigger rate
  - 5 (6) chips per sensor



APV 25 Chip

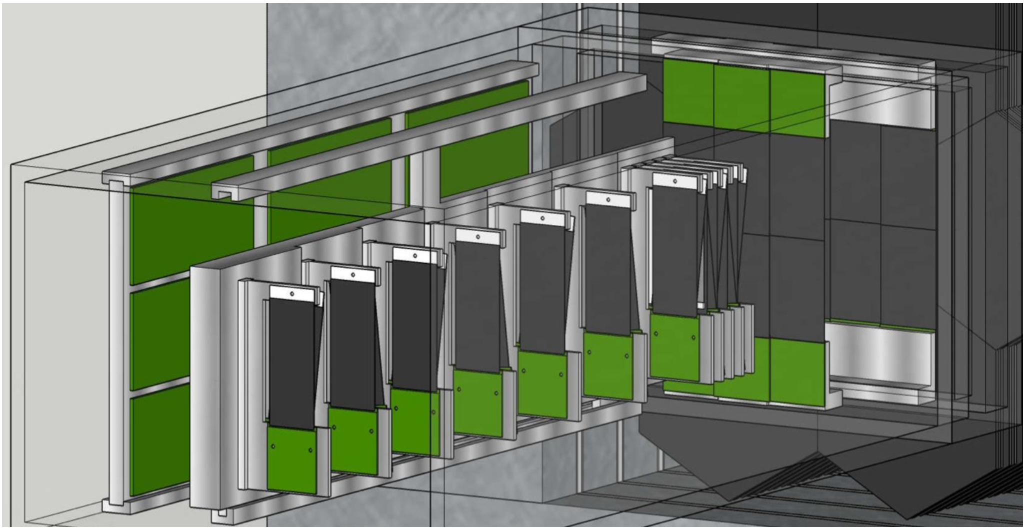


HPS SVT module

The LDMX Tracker System: Trackers

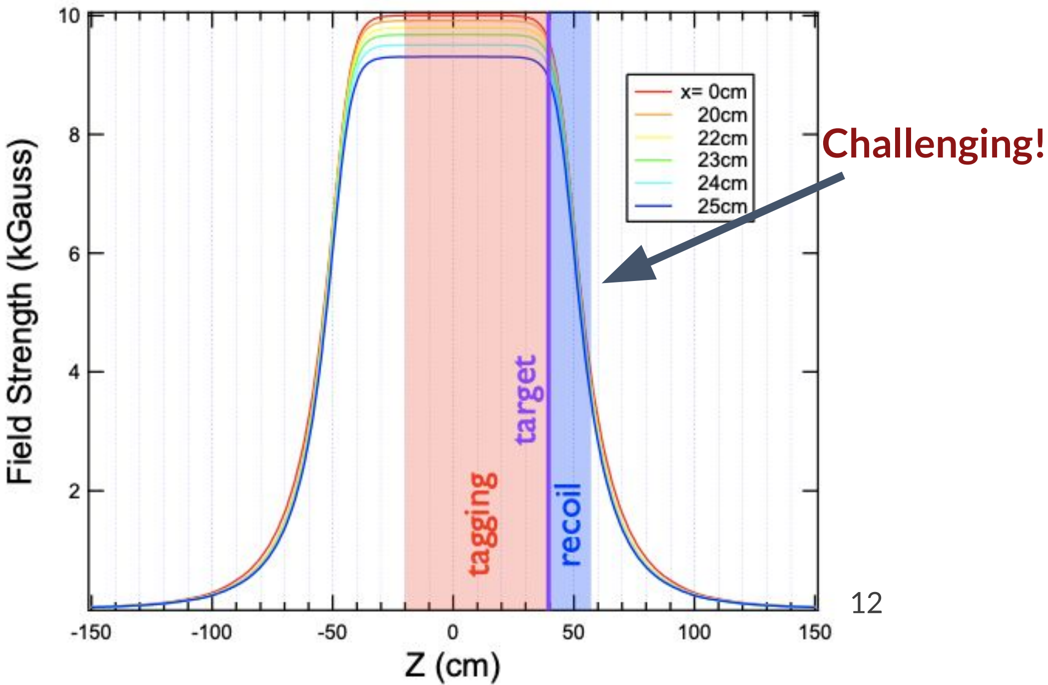
- **Tagger Tracker**:
  - 7 double-strip layers, high p-resolution **(σ_u~6 um σ_v~ 60um)**
  - 98.3 x 38.3 mm, 60um pitch, 639 ch, 5 APV25 chips

Layer	1	2	3	4	5	6	7
z-position, relative to target (mm)	-607.5	-507.5	-407.5	-307.5	-207.5	-107.5	-7.5
Stereo Angle (mrad)	-100	100	-100	100	-100	100	-100
Bend plane (horizontal) resolution (μm)	~6	~6	~6	~6	~6	~6	~6
Non-bend (vertical) resolution (μm)	~60	~60	~60	~60	~60	~60	~60



- **Recoil Tracker:**
  - 4 double-strip layers + 2 axial-only for increased acceptance.
  - Back layers feature modules 78x48 mm^2, 62.5 um pitch -> 768 ch, 6 APV chips
  - **Dipole Fringe Field**

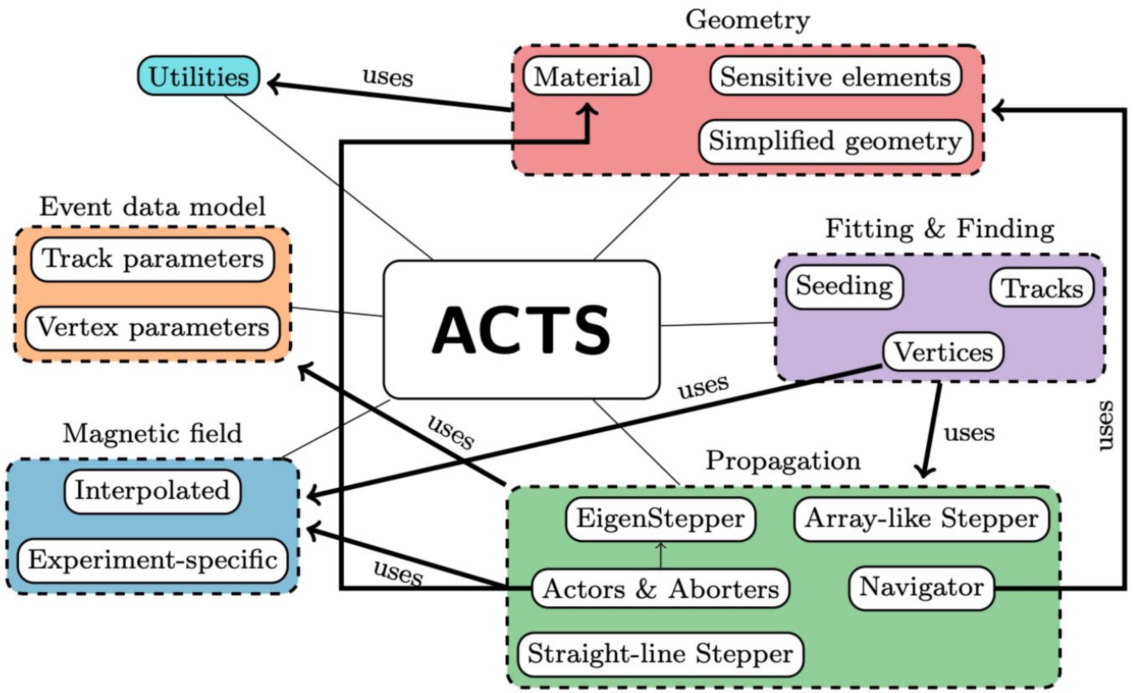
Layer	1	2	3	4	5	6
z-position, relative to target (mm)	+7.5	+22.5	+37.5	+52.5	+90	+180
Stereo Angle (mrad)	100	-100	100	-100	-	-
Bend plane (horizontal) resolution (μm)	≈6	≈6	≈6	≈6	≈6	≈6
Non-bend (vertical) resolution (μm)	≈60	≈60	≈60	≈60	-	-



Track Reconstruction - A common Tracking Software

- **LDMX search requires high precision tracking**
- **LDMX leverages ACTS, modern library based on well-tested reconstruction from LHC experiments**
  - Ties LDMX to the larger tracking community
  - As a small experiment → focus on physics goals using well supported tools

arxiv:2106.13593



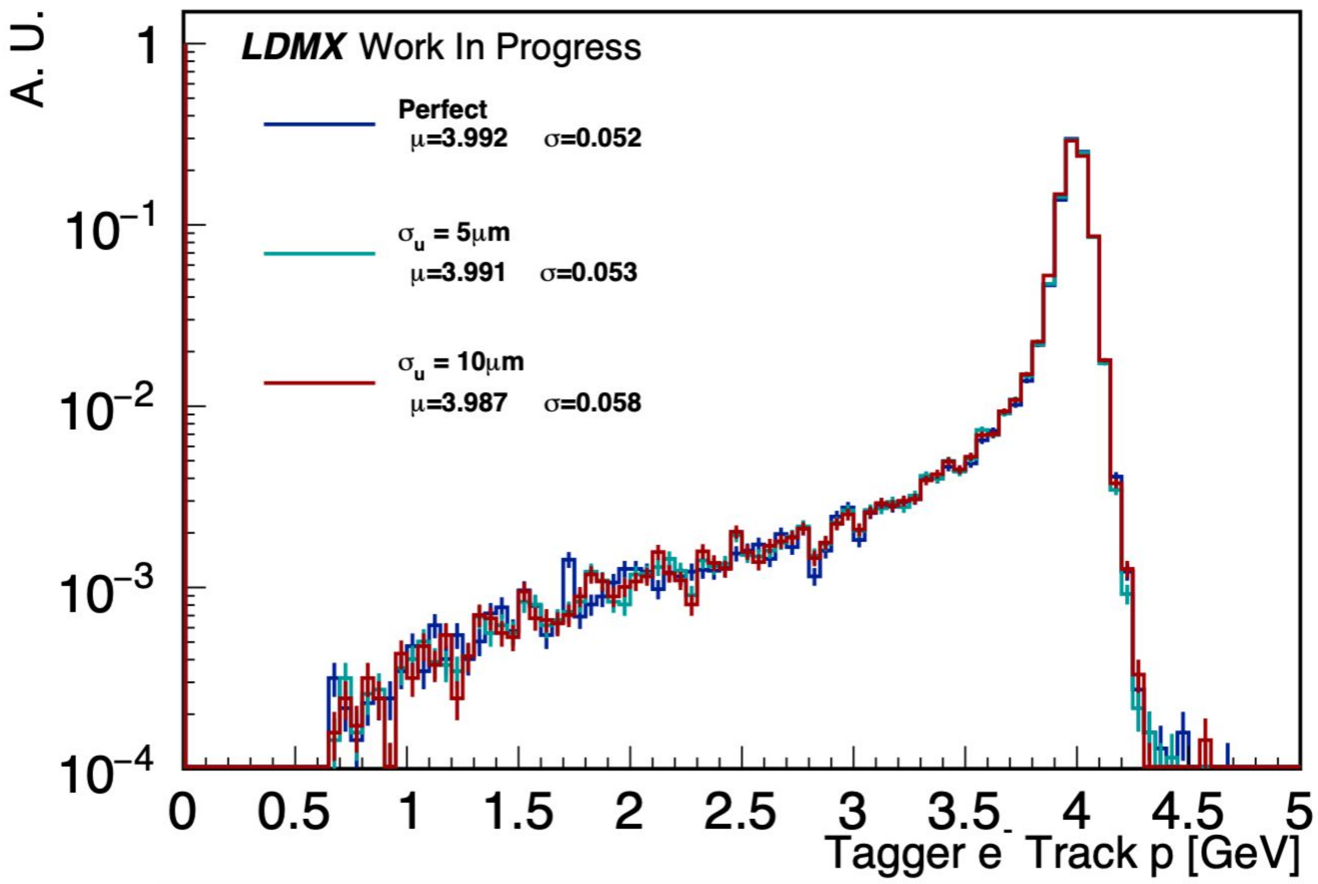
Space point formation

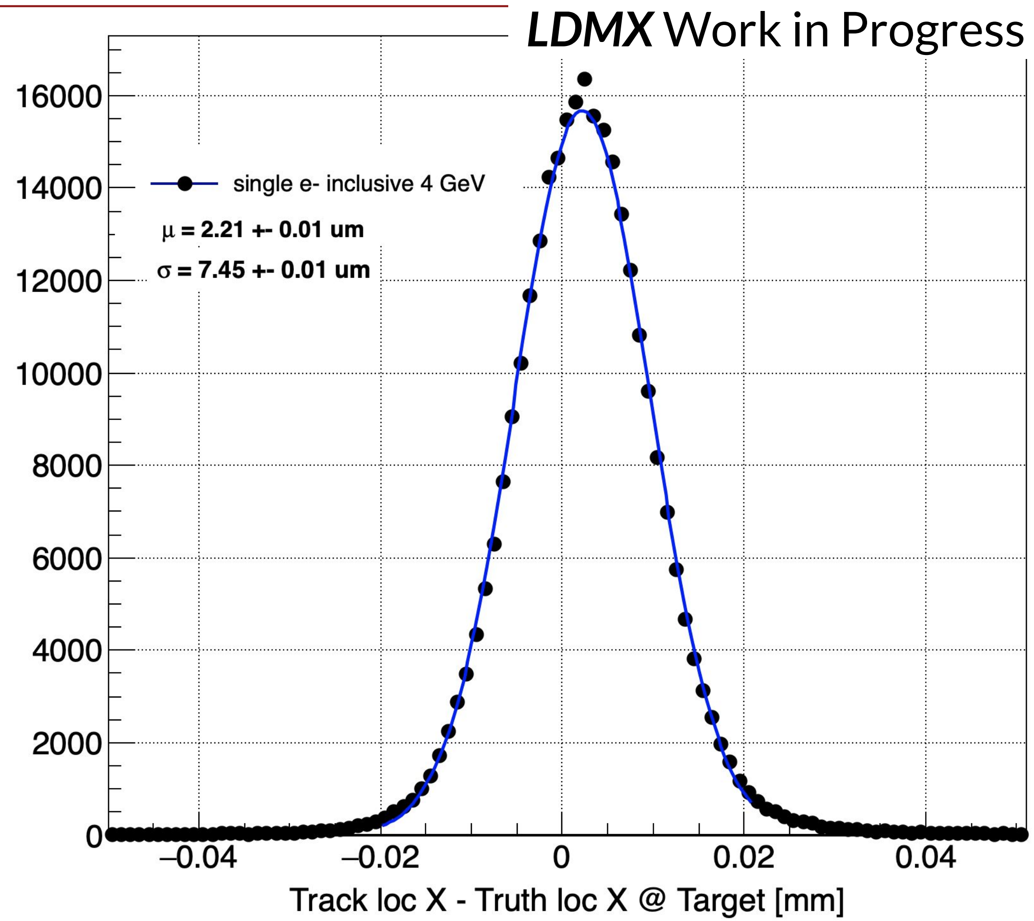
Seed finding

Track candidates
(Combinatorial Kalman Filter)

Tagger - Recoil matching

Tagger Tracker Performance



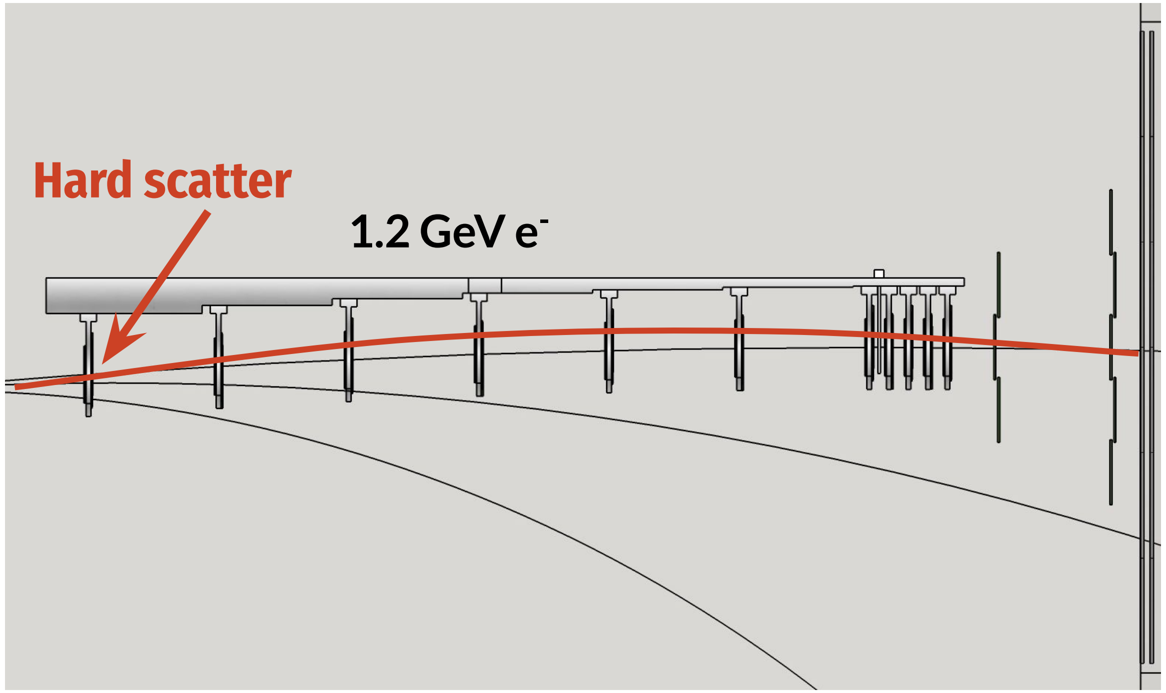


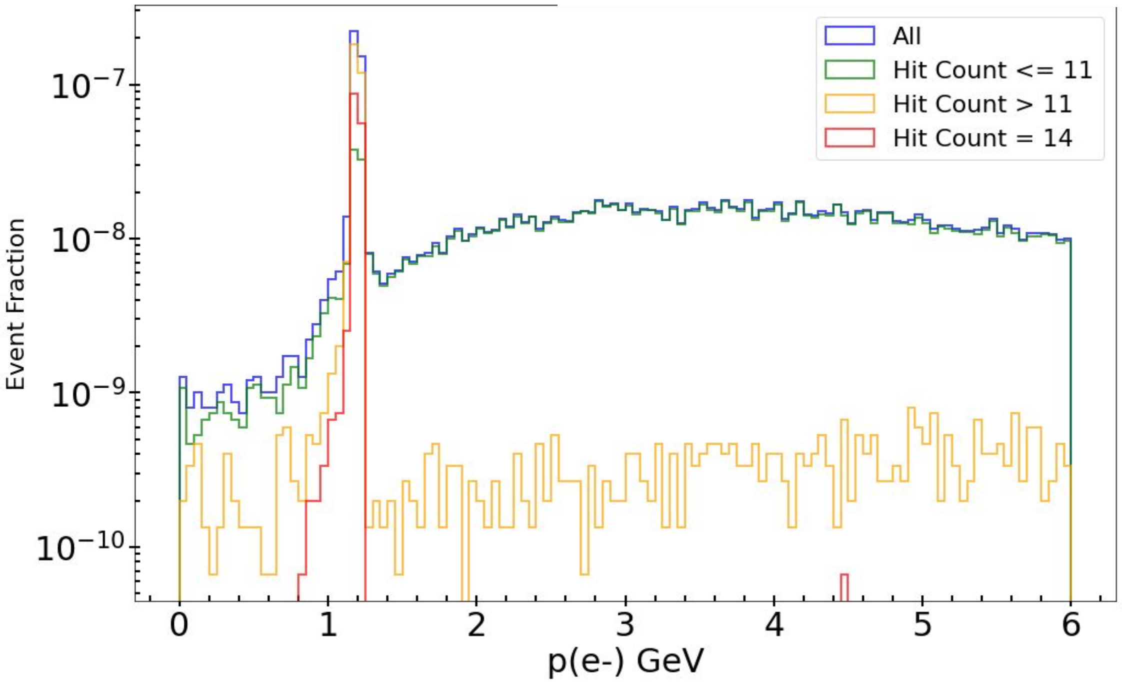
- Tagger Tracker offers **very precise incoming e$^-$ momentum** determination (σ_p ~ 50 MeV @ E_{beam} = 4 GeV, ~1%)
- Momentum expected to improve with deployment of GSF refitter, current under validation

- Extrapolation on target:
  - σ_X ~ 7 um σ_Y ~ 90 um

Tagger Tracker - Off-energy electrons

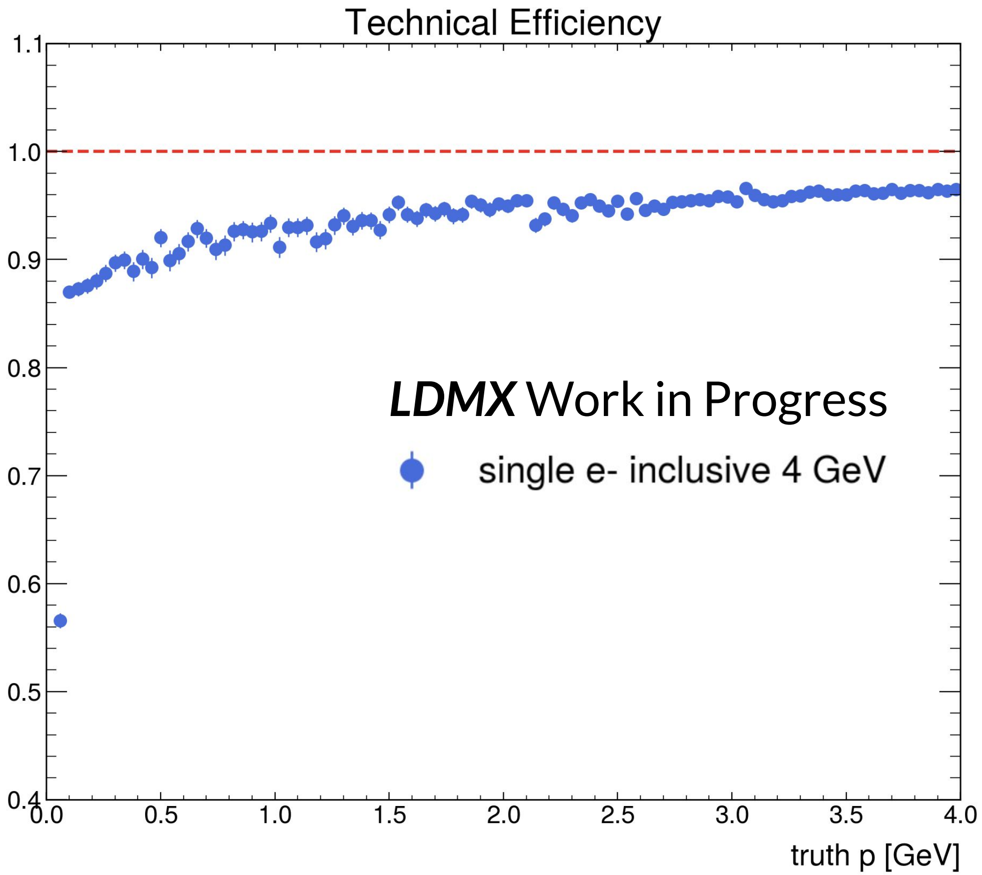
- **Estimated 10^{11} off-energy electrons in the Tagger Tracker due to beam quality**
- Most off-energy electrons bent out before reaching target
- Key importance remove off-energy electrons that mimic a 4 GeV electron trajectory

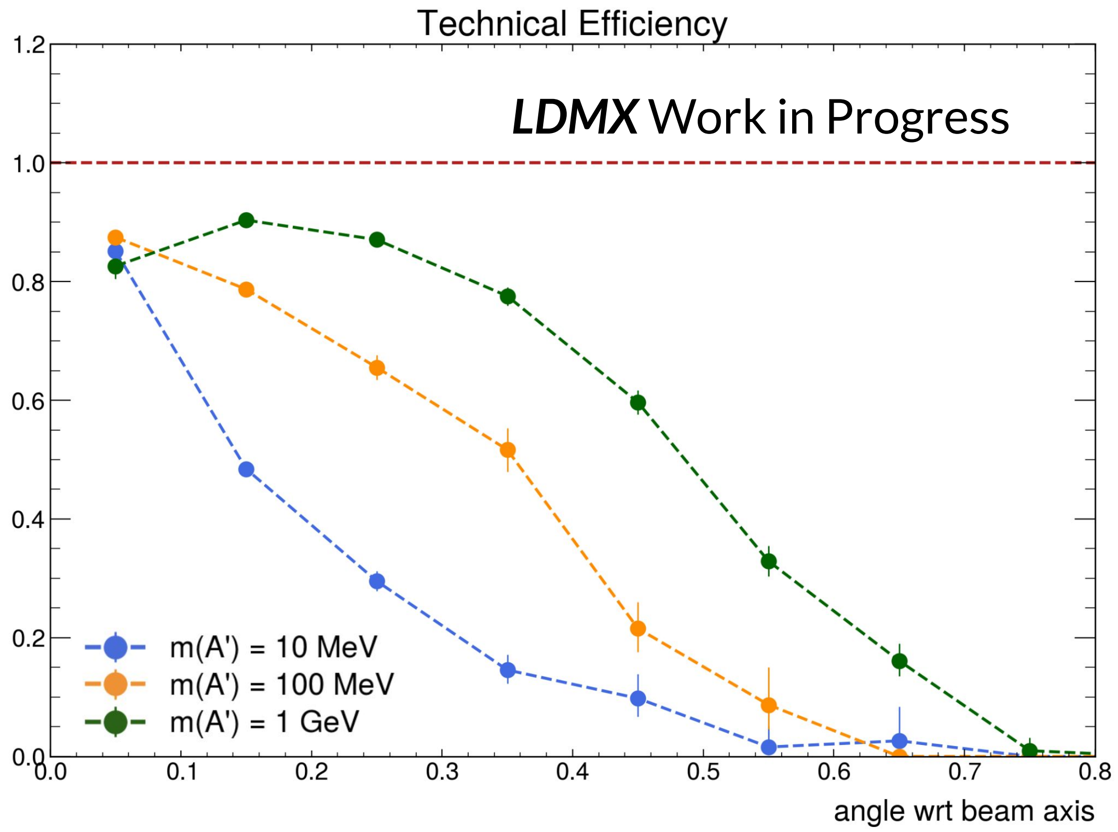




- High quality tracks with additional rectangular cuts show < 6 x 10^{-10} mis-reconstruction rate

Recoil Tracker - Performance



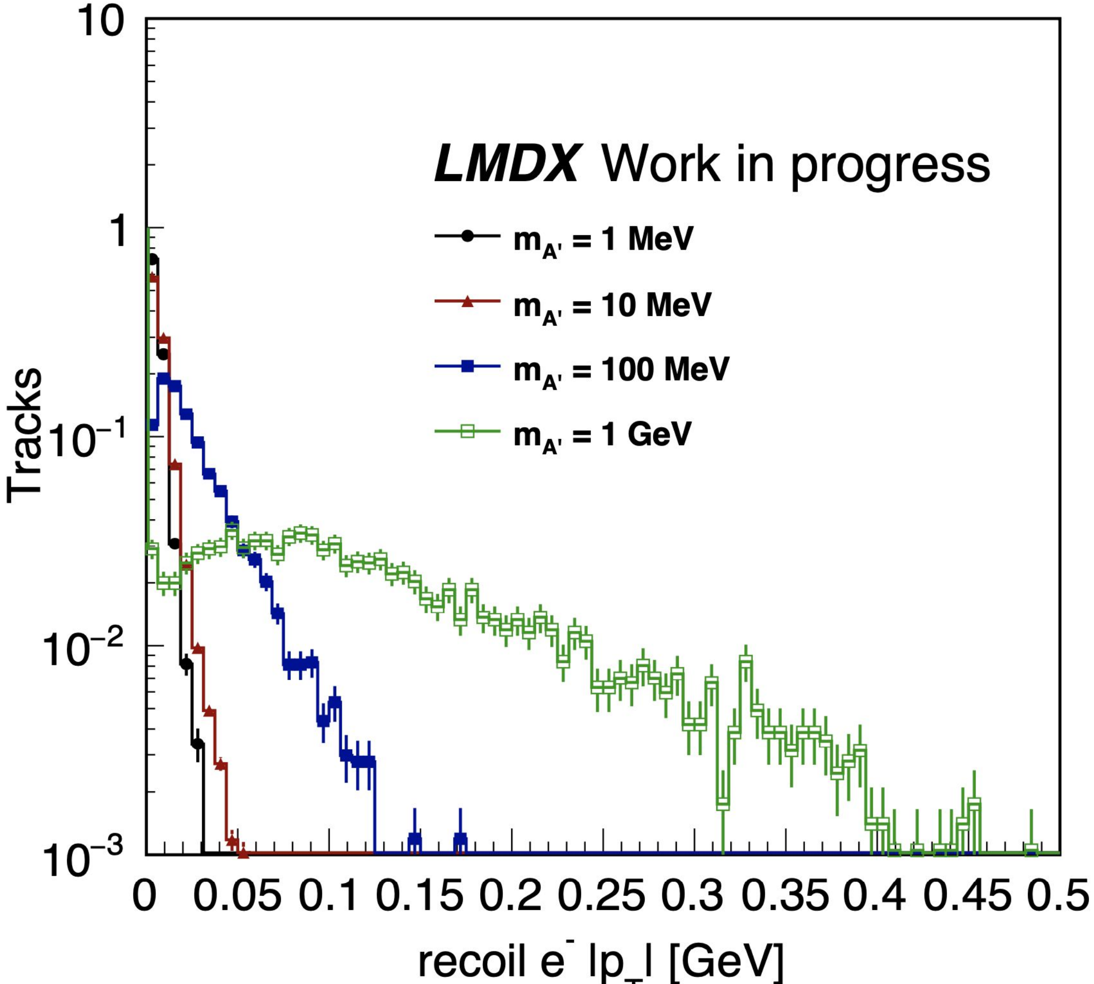


- **Technical Efficiency = Reconstructible vs reconstructed particles**
- >90% single e- efficiency down to ~100MeV
- Track finding under investigation to improve low pT electron efficiencies

- Recoil e- efficiency dependent on signal kinematics
- Extends up to 45deg for higher masses

Recoil Tracker - Performance

- Track p_T provides signal discrimination handle



Recoil Tracker - Performance

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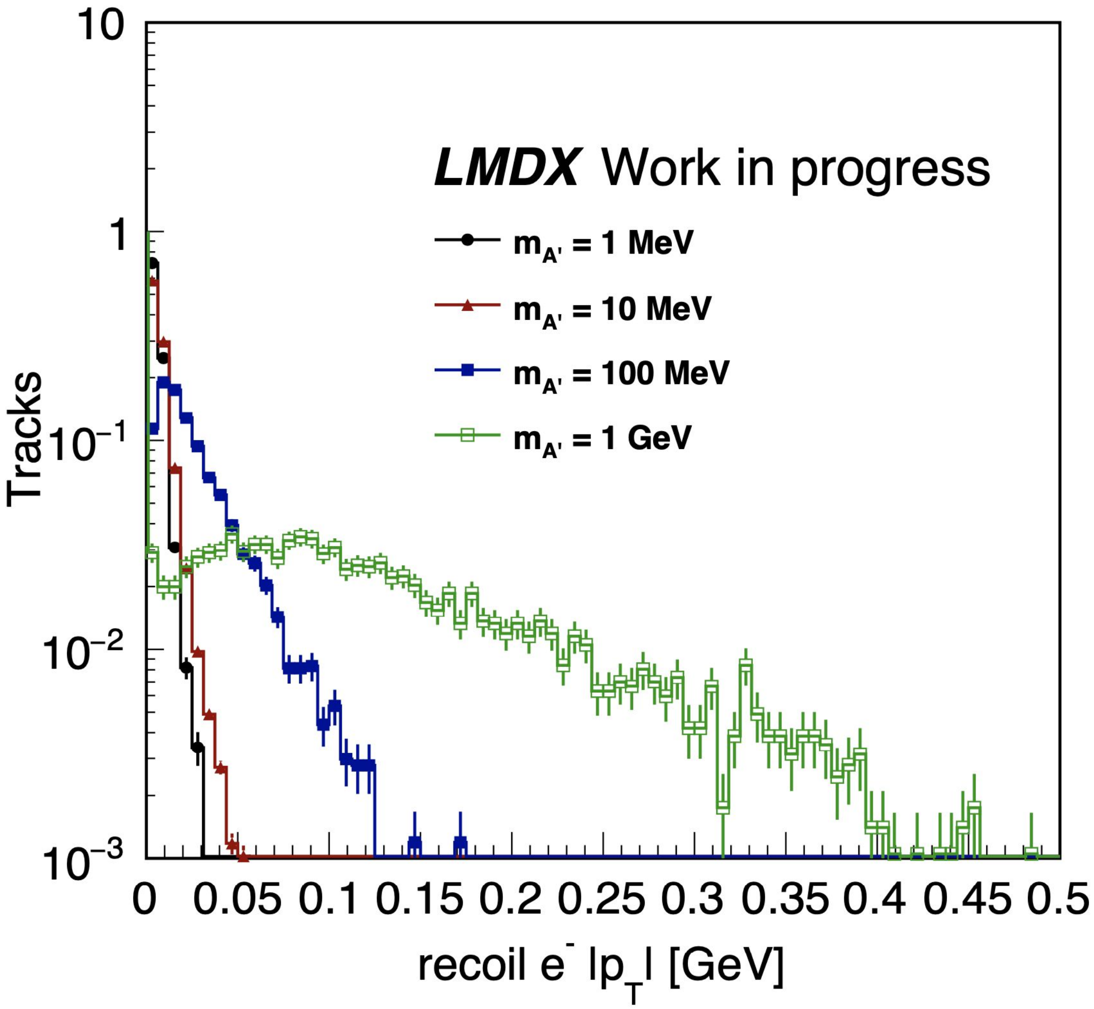
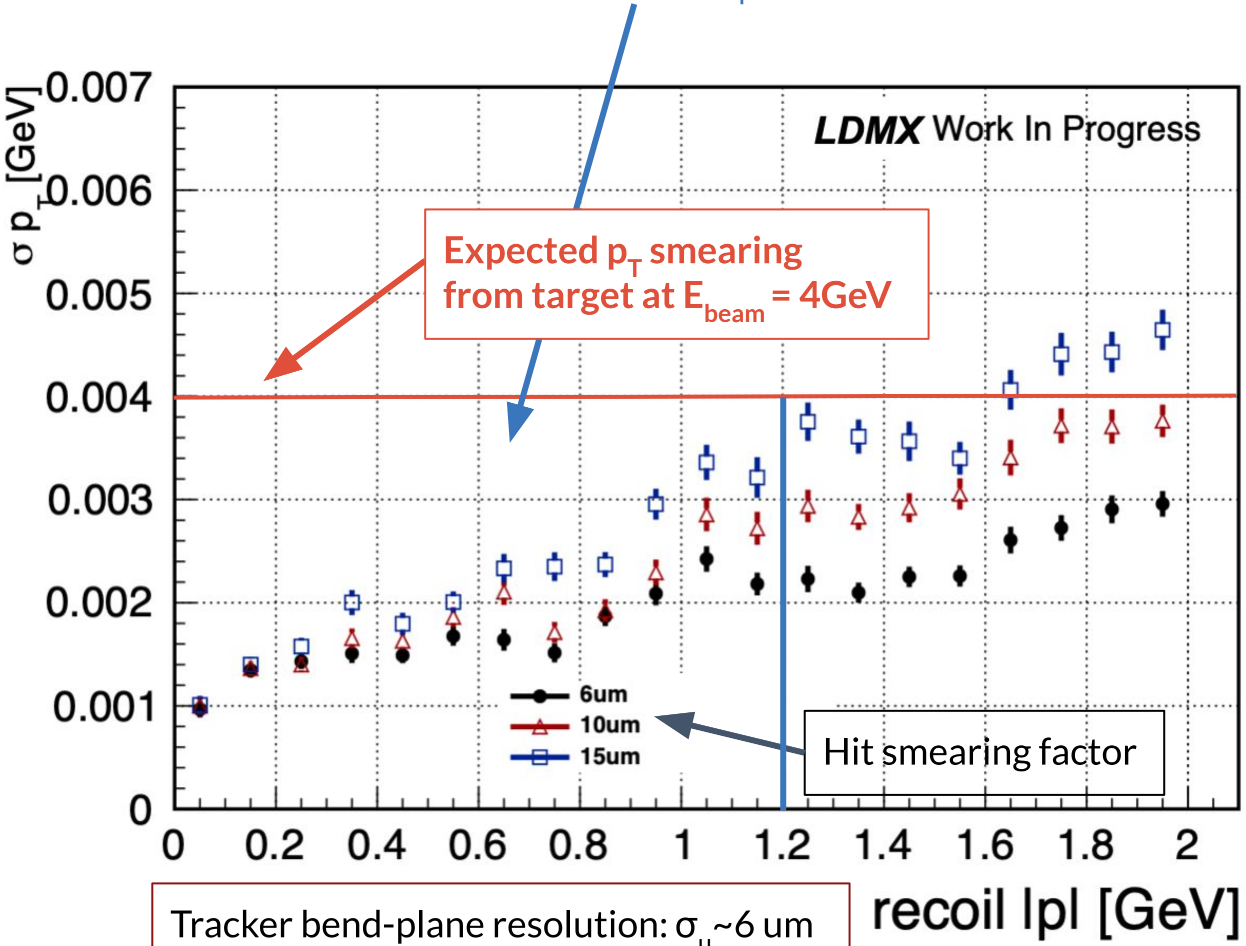
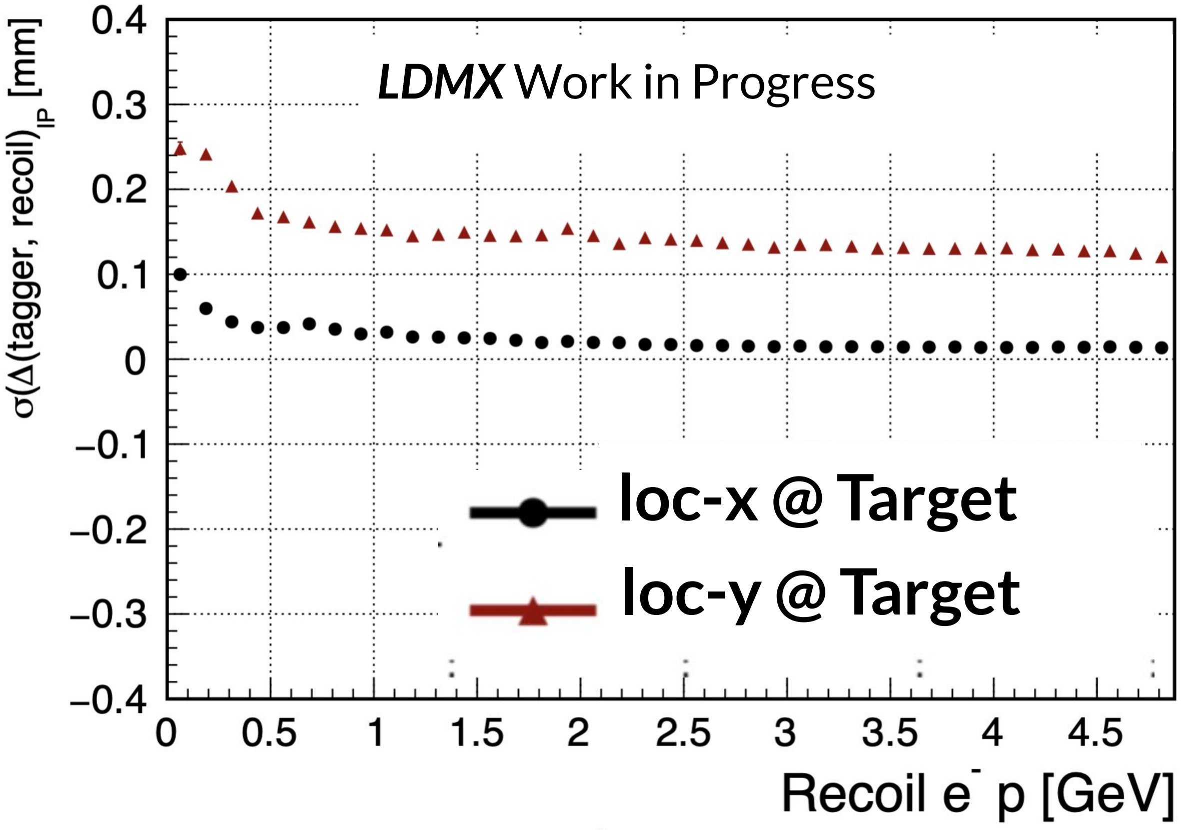


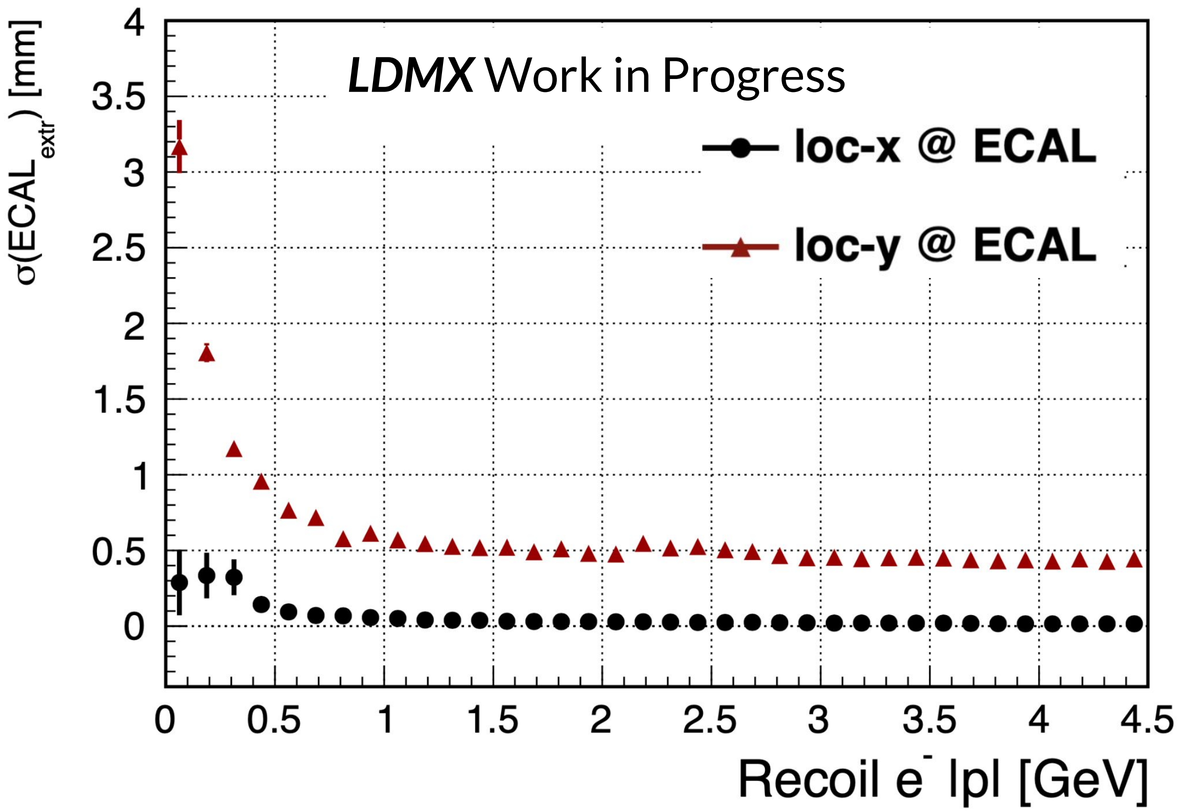
- Recoil tracker p_T resolution expected to **meet the design requirement**
  - Region of interest: p_T < 1.2 GeV



Tracker bend-plane resolution: σ_u~6 um

Tagger-Recoil Matching and ECAL Extrapolation





- **Track matching between tagger and recoil tracks**
  - Combined σ_x (σ_y) of ~ 20um (~150 um)
- Possible to use tagger track hit on target as constraint

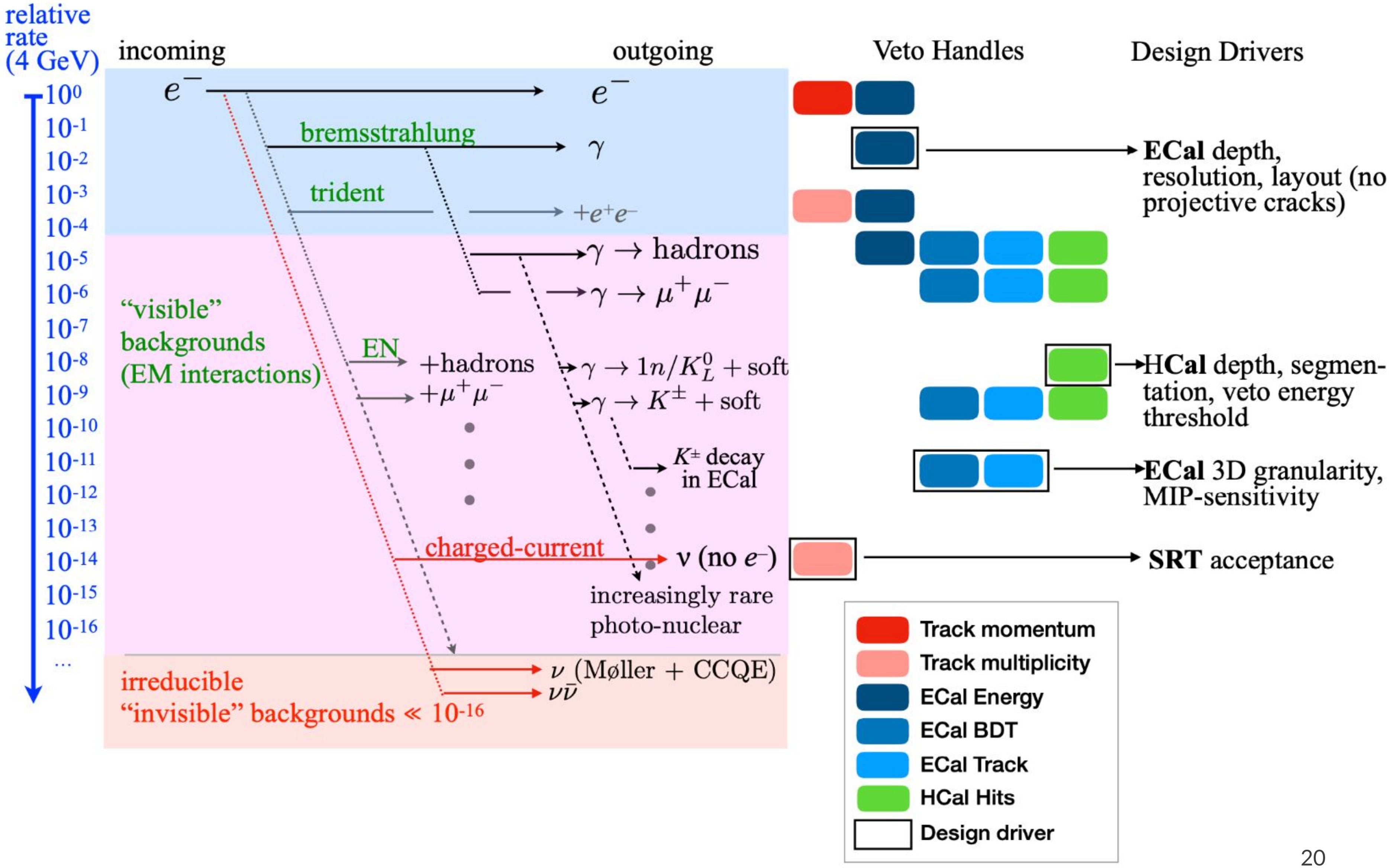
- **Extrapolation to ECAL**
  - σ_x (σ_y) of ~ 50um (~500 um) > 1 GeV

Backgrounds Overview and Dedicated Vetoes

Gaussian energy fluctuations

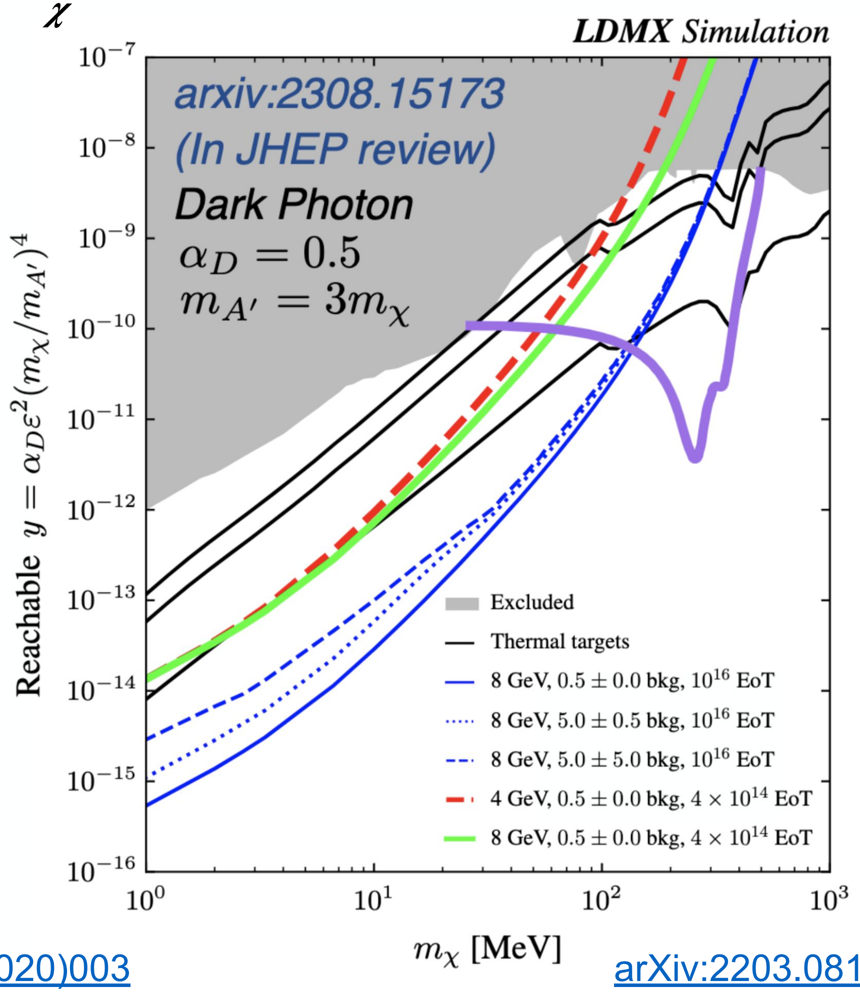
Rare reactions → products escape ECal and/or anomalous energy deposition

Irreducible prompt $\not{E}$



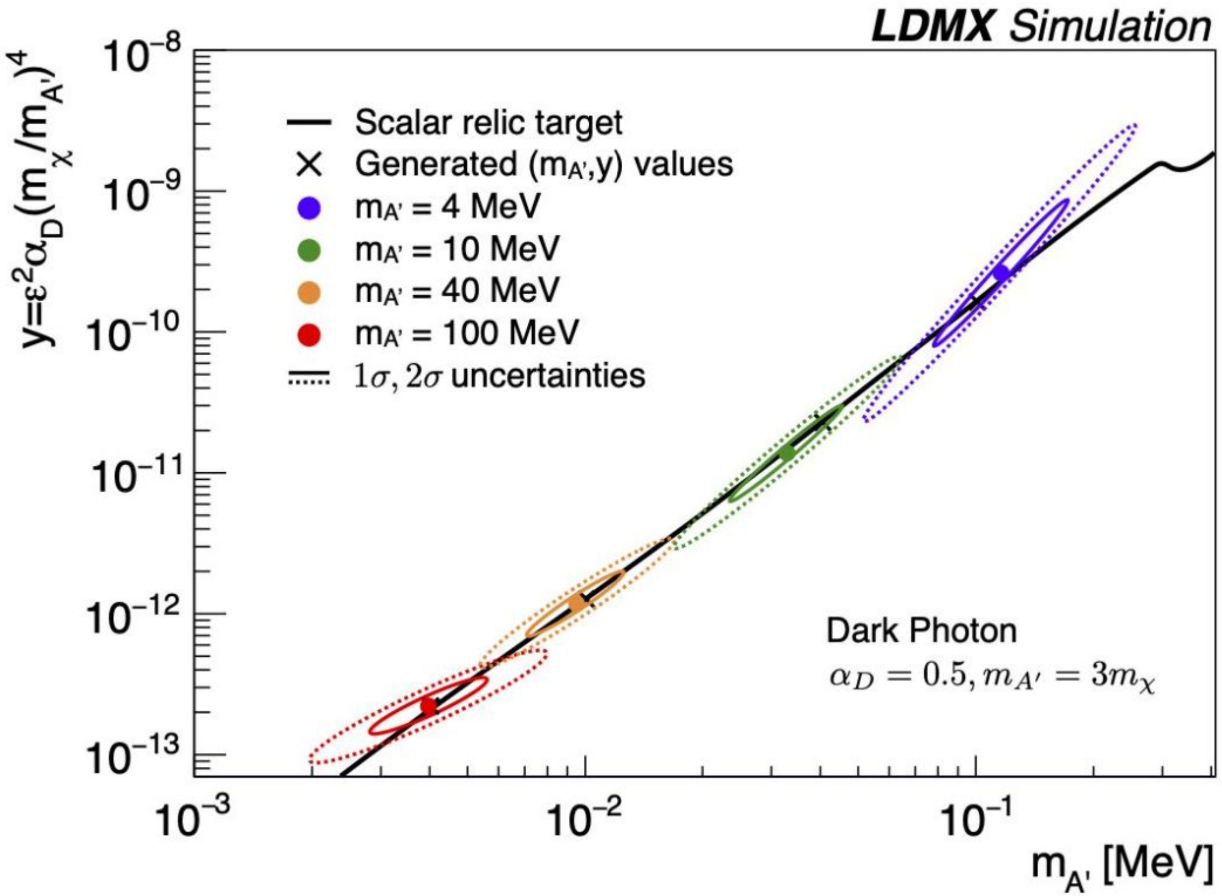
Results

- **Outstanding sensitivity** in a mass range up to $m_\chi < 100\ MeV$



JHEP04(2020)003 arXiv:2203.08192.pdf

- **Recoil electron transverse momentum key final measurement**



Physics Potential and guaranteed deliverables

- **L**DMX has a **broad discovery potential** in both invisibile and visible signatures of light dark matter production at an electron-beam facility
- However, the physics potential is enriched by fundamental **guaranteed deliverables**:
    - Measurement of electron-nucleon (eN) scattering in the forward region

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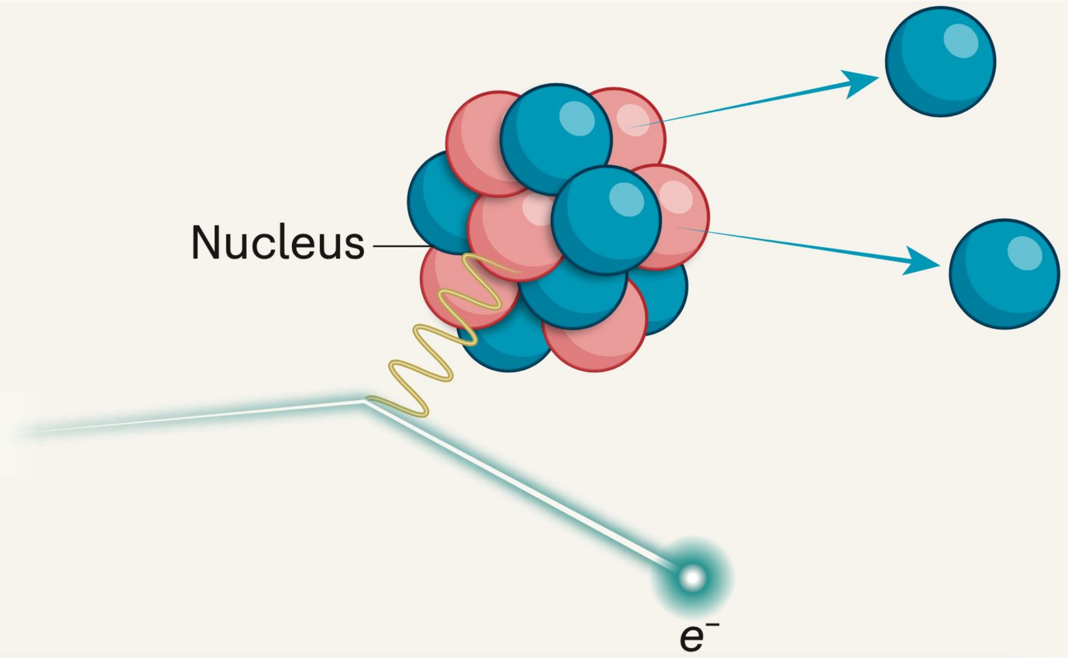
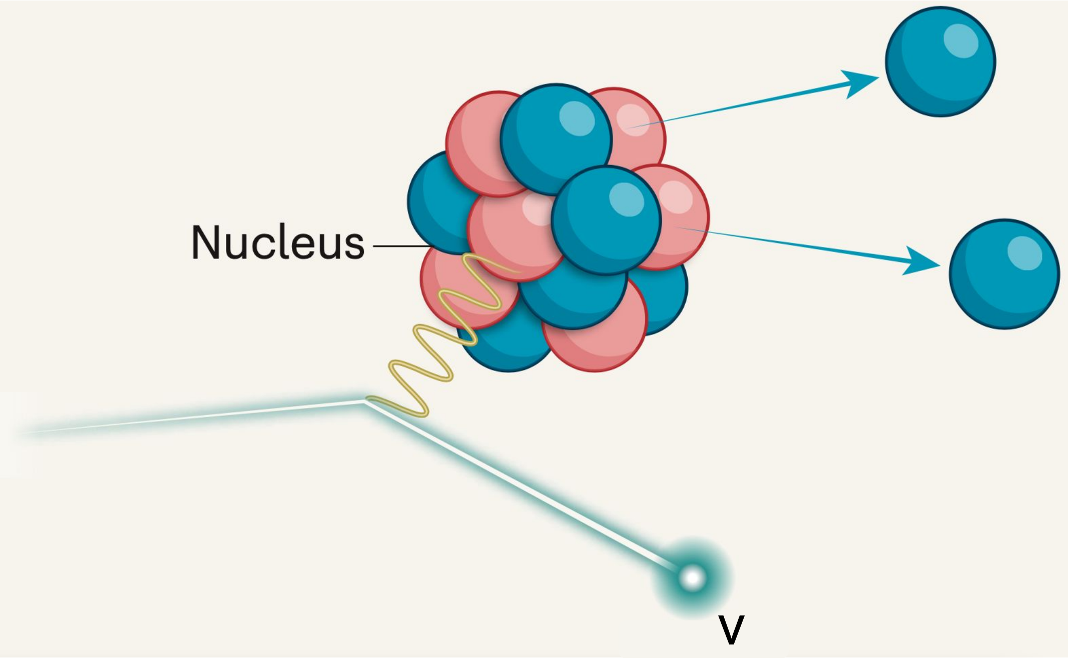
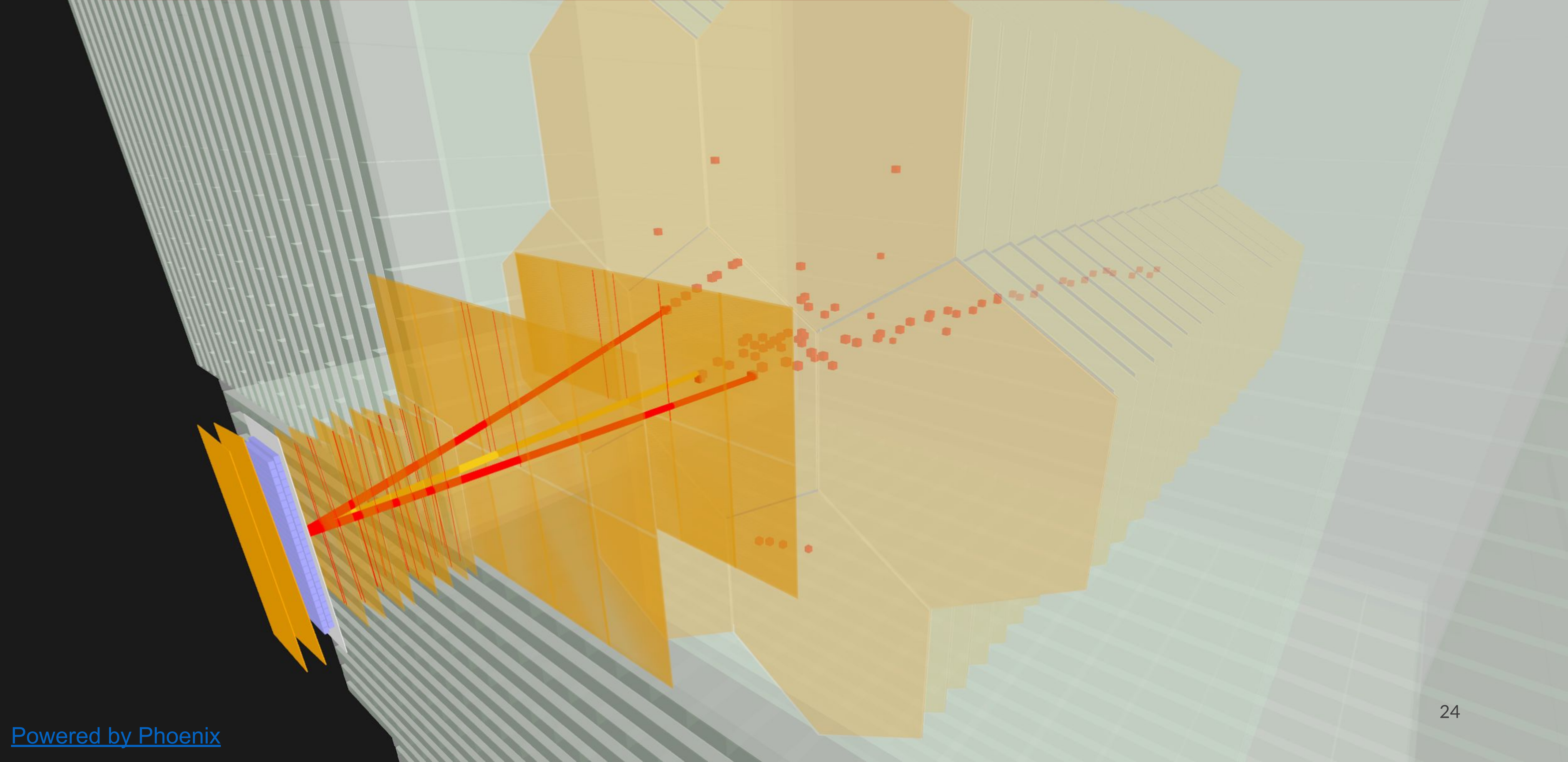




- **eN scattering as a probe for vN scattering**
- **Strong force nuclear effects are the main source of uncertainty → identical** between the two scattering processes

Electronuclear Simulated Event Display



Powered by Phoenix

Summary

- **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

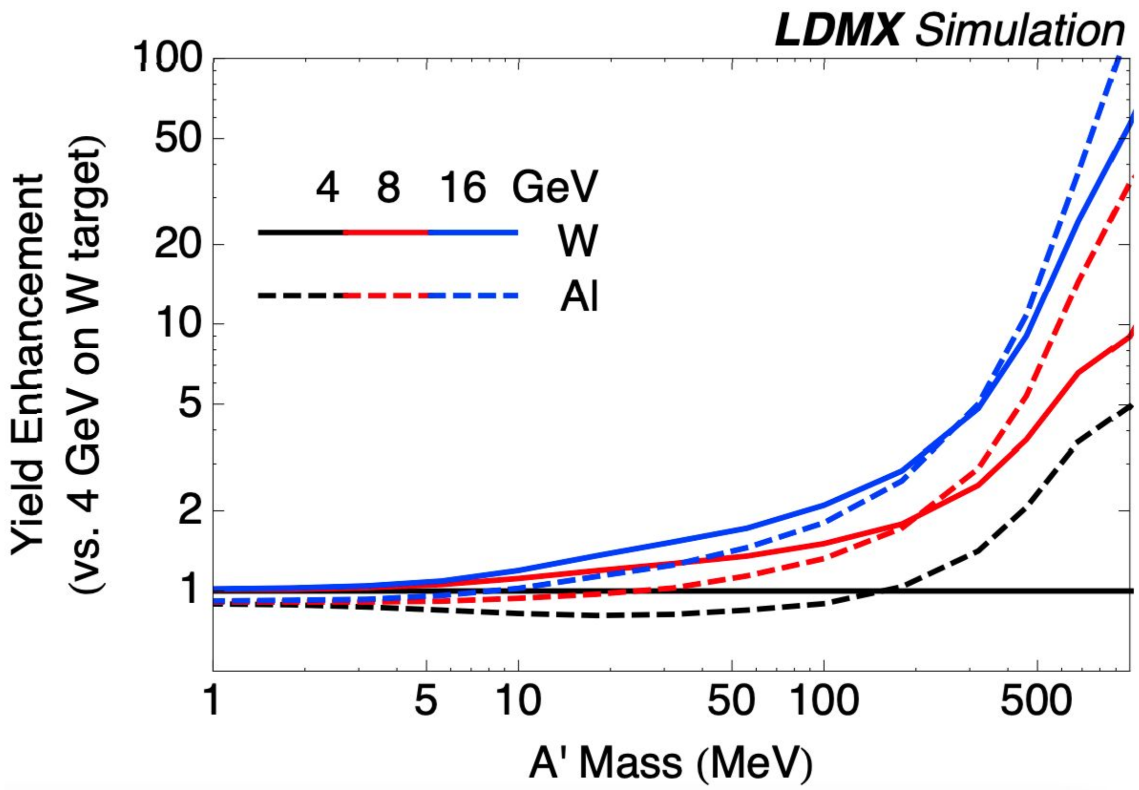
- LDMX has impressive **physics discovery potential and guaranteed deliverables**

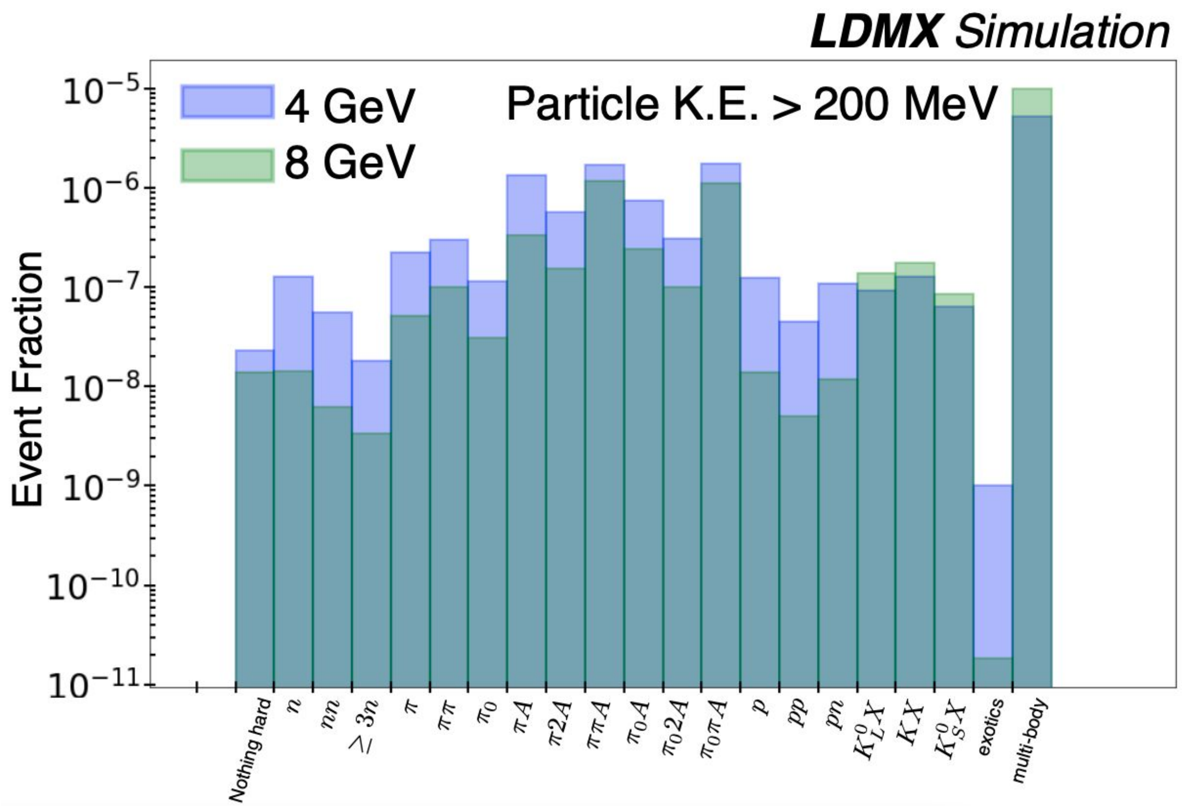
- The experiment requires a specific tracker design and precise track reconstruction for its physics case

- Current studies show the tracker performance passes the key requirements and a track reconstruction framework is in place

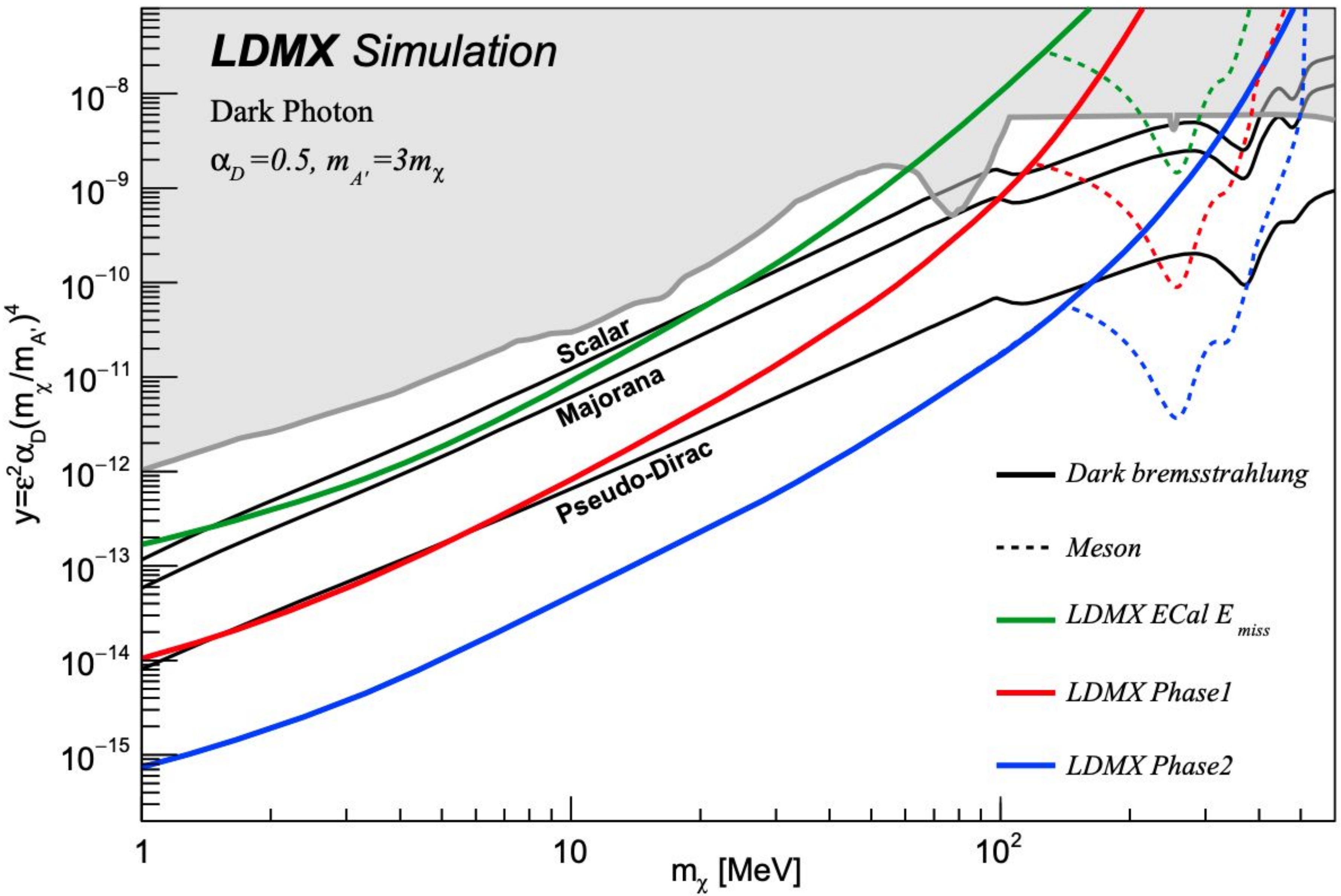
Backup

Phase II Prospects

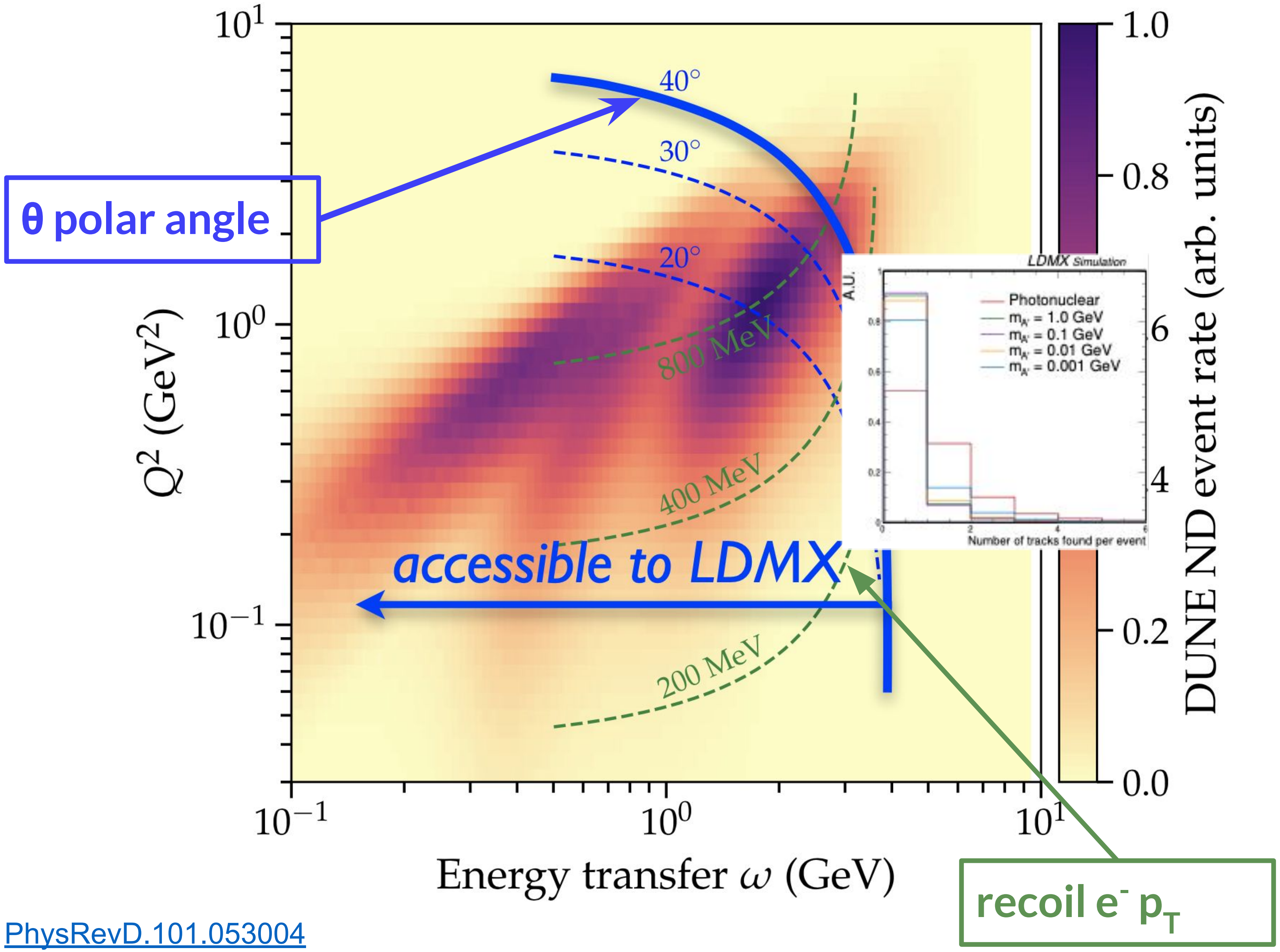




Phase II Prospects



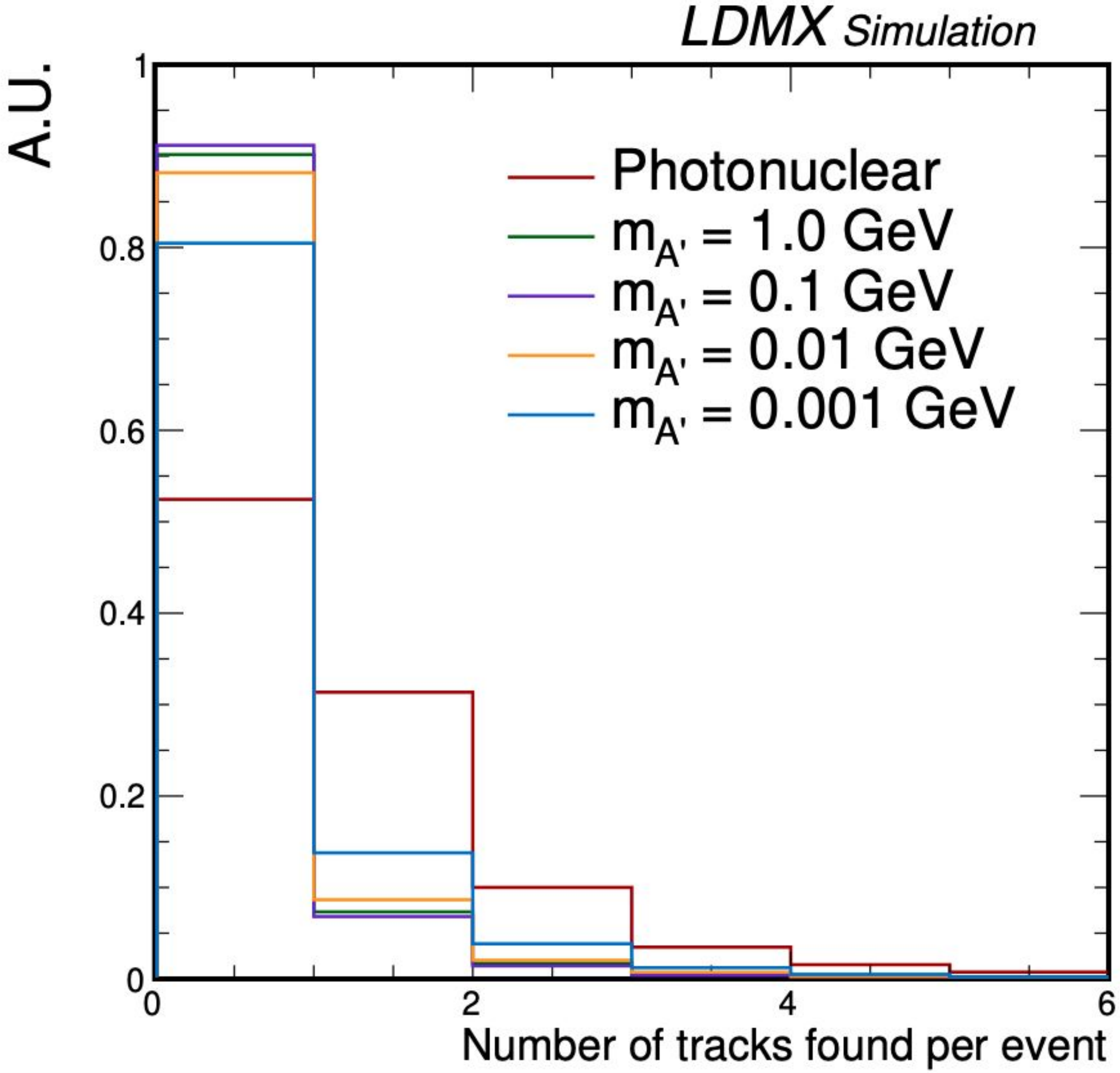
Physics Potential - Electron Nucleon Measurements



PhysRevD.101.053004

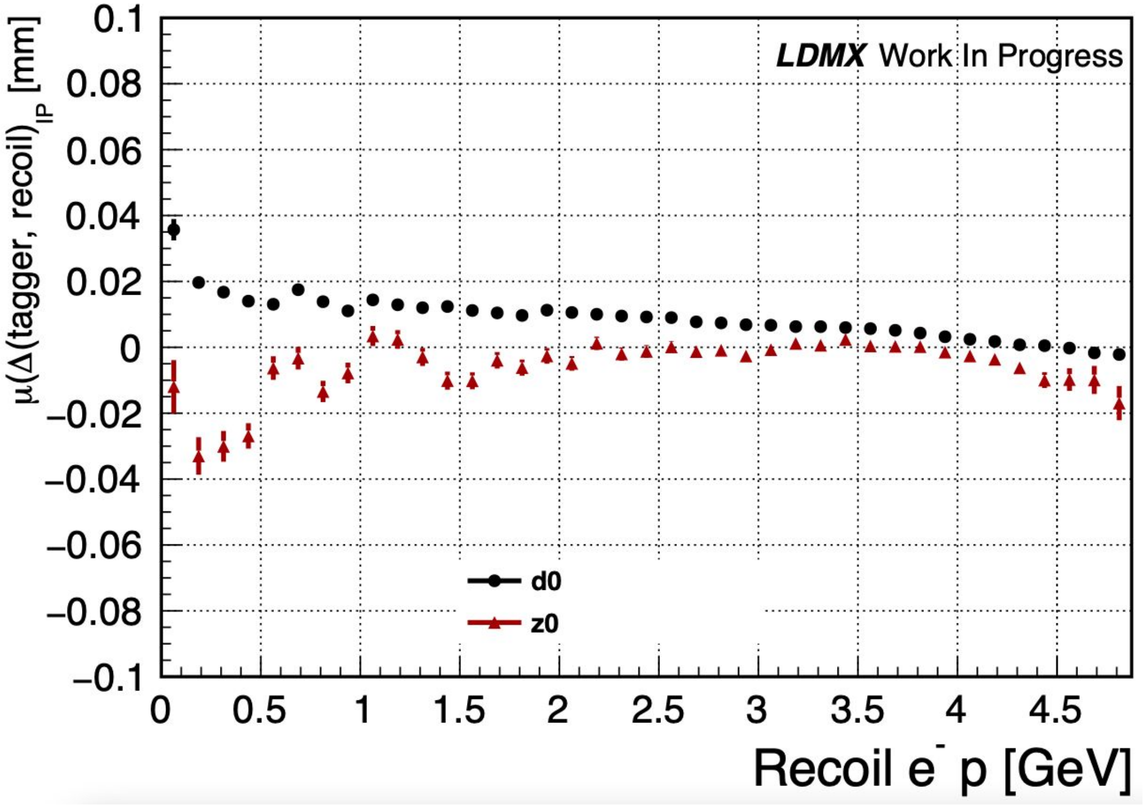
- **LDMX can access**
  - Important phase space relevant for DUNE
  - Can extend to recoil electron acceptance up to
    - Polar angle θ = 40°
    - p_T > 200 MeV

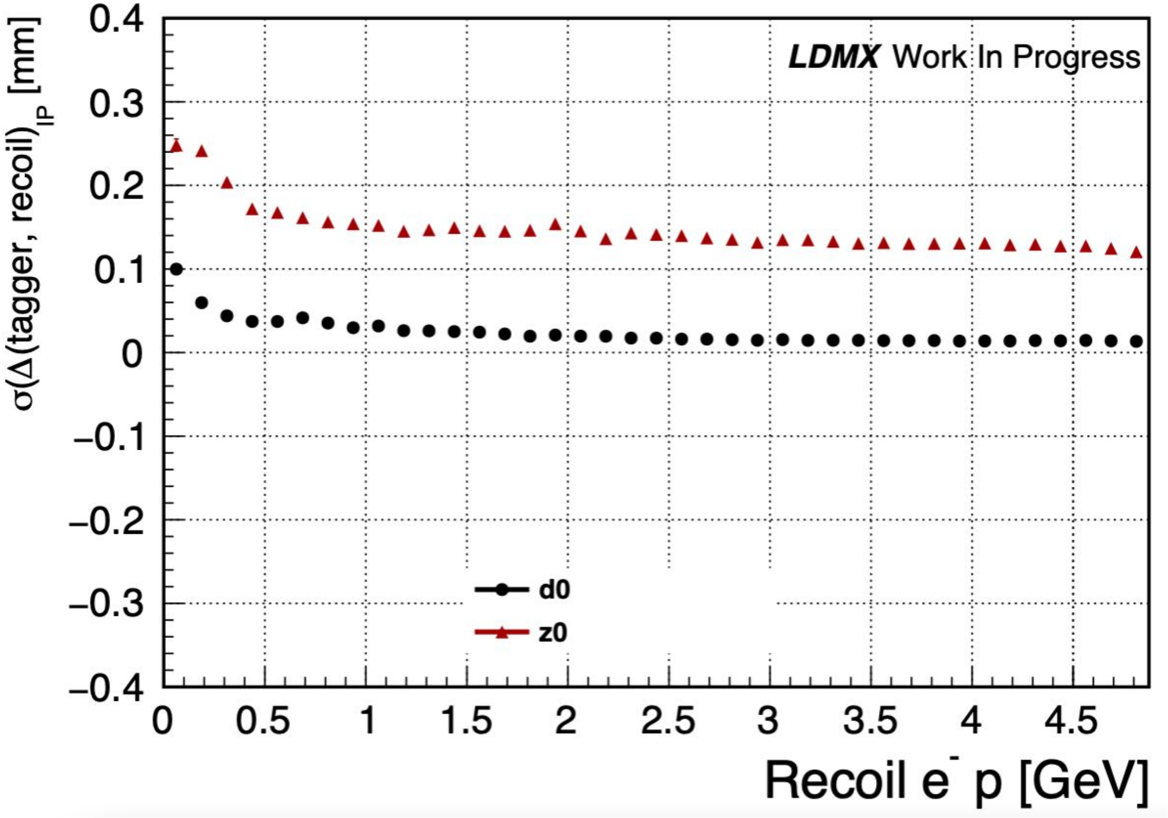
MIP Tracking in ECAL



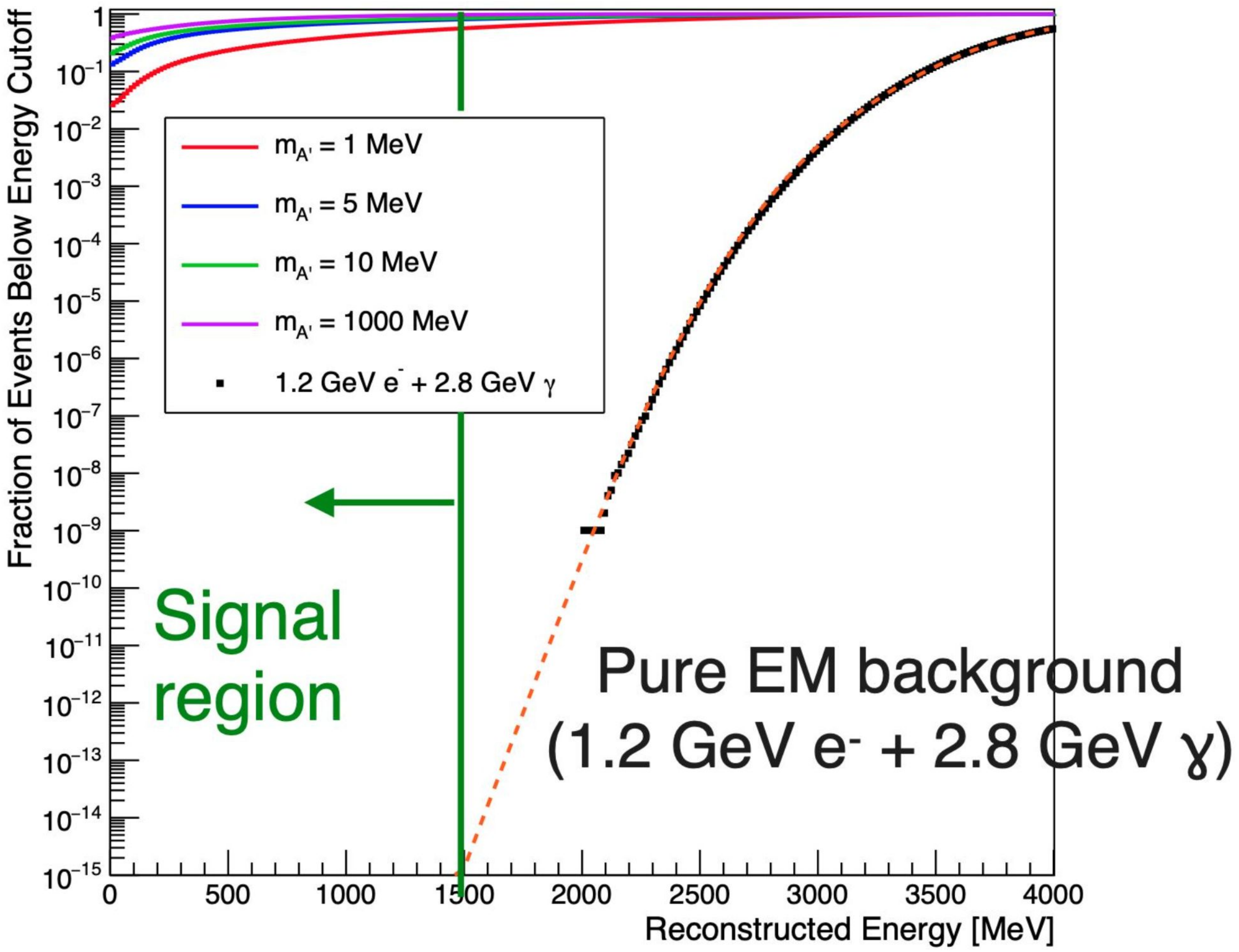
MIP Tracking rejects surviving PN events keeping >80% efficiency on signal

Tracking - Impact parameters at the target



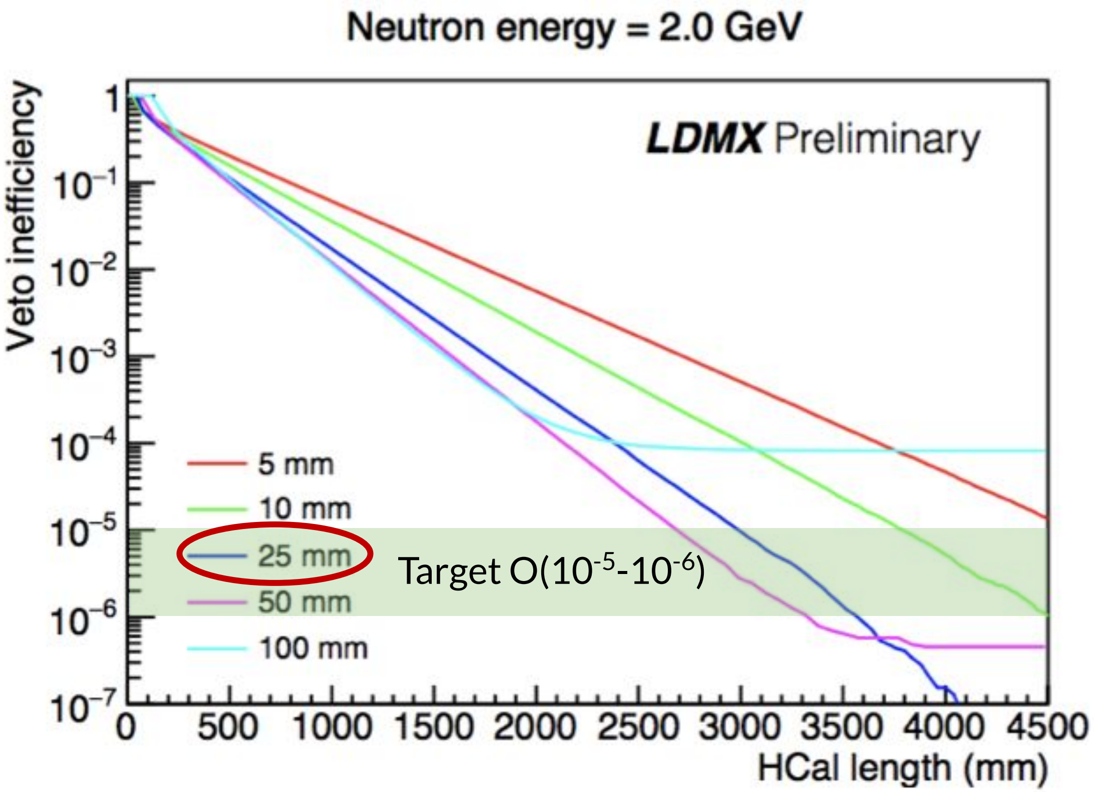


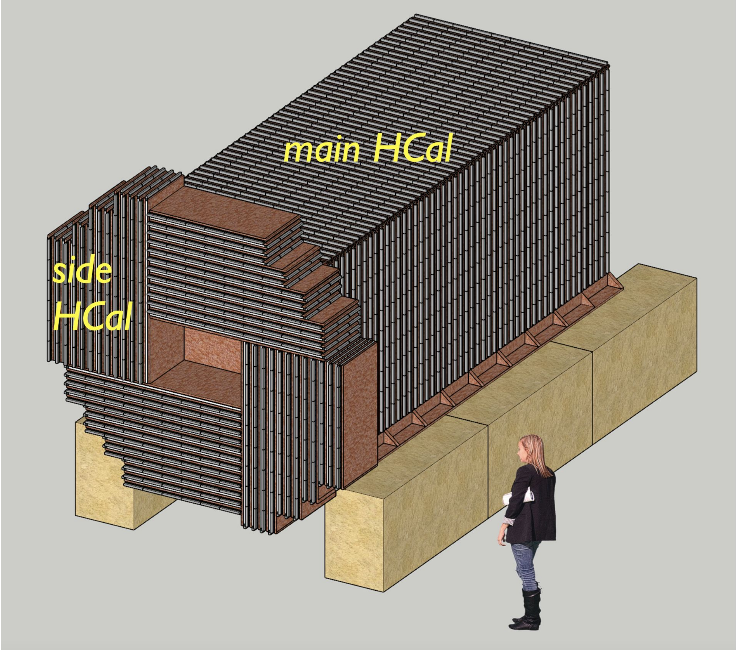
Trigger - LDM

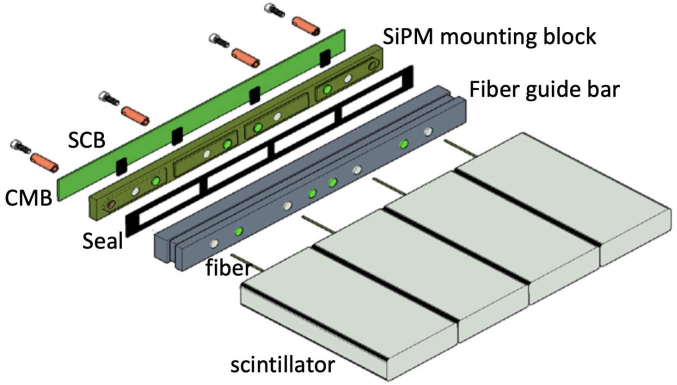

Fraction of Events Below Energy Cutoff
Reconstructed Energy [MeV]
$m_{A'}$ = 1 MeV
$m_{A'}$ = 5 MeV
$m_{A'}$ = 10 MeV
$m_{A'}$ = 1000 MeV
1.2 GeV e^- + 2.8 GeV γ
Signal region
Pure EM background
(1.2 GeV e^- + 2.8 GeV γ)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
0
500
1000
1500
2000
2500
3000
3500
4000

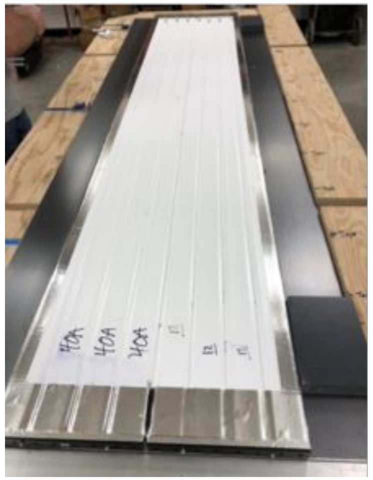
The Hadronic Calorimeter

- Scintillator based sampling calorimeter, **technology from Mu2e Cosmic Ray Veto**
- Alternating x/y orientation
  - **High efficiency in detecting neutrons in the 0.1-10 GeV range**
  - MIP Sensitivity
- **Side HCAL design optimized for high-multiplicity final state and wide angle bremsstrahlung**
- **Readout adapted from ECAL HGROC**



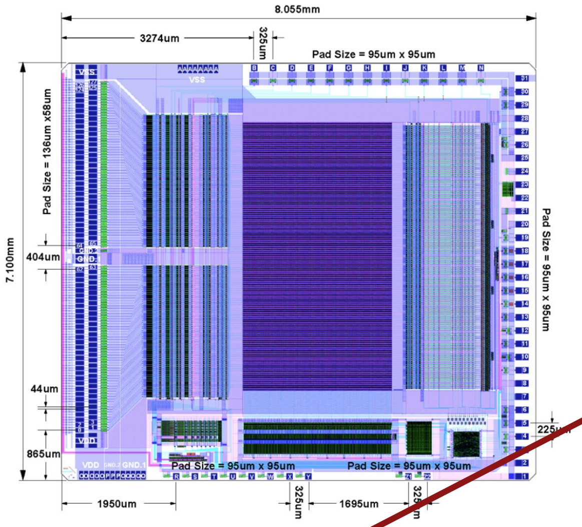


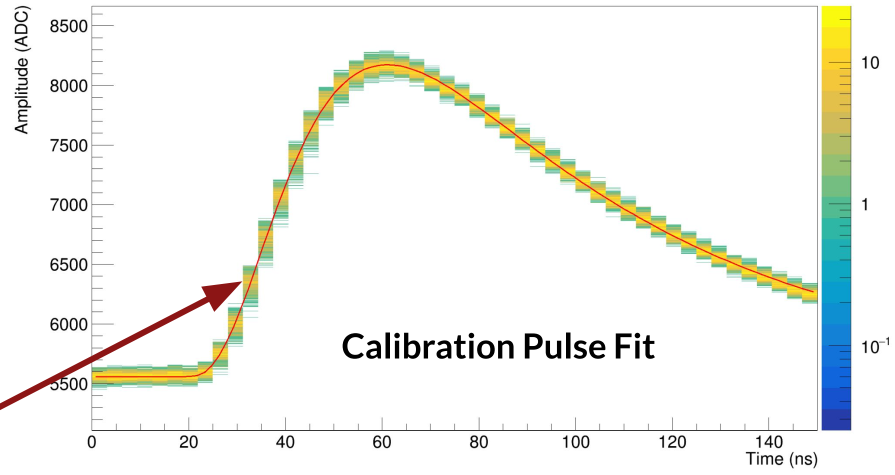




The HPS SVT System - APV25 Readout

- Developed for CMS
- Radiation Hard:
  - Fast front-end shaping time 35ns
  - Readout sampling time 25ns
  - Low noise S/N > 25
- Timing information
  - Pile-up rejection
  - High-precision hit reconstruction
  - **Essential for HPS and other experiments with Continuous Wave beam and high-pileup**

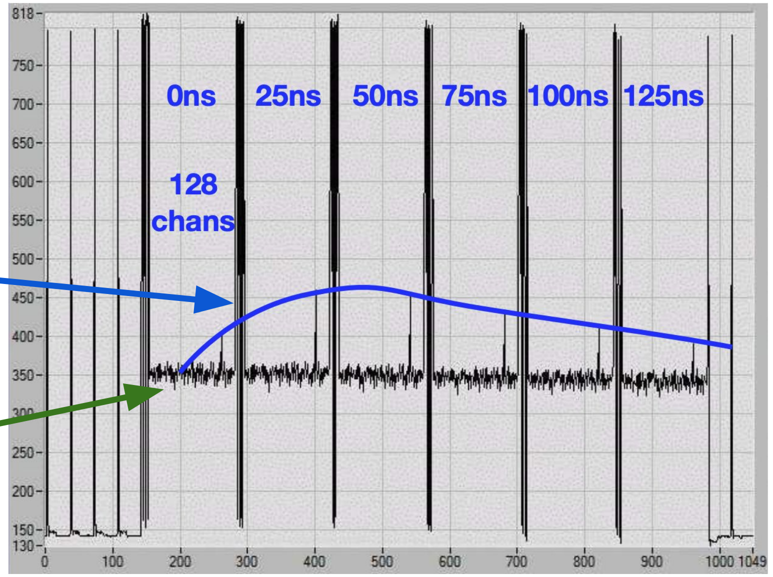




Extract per-channel pulse shape parameters

Apply shape to readout signal

ToA from baseline intercept
$\sigma(t_0) \sim 2ns$

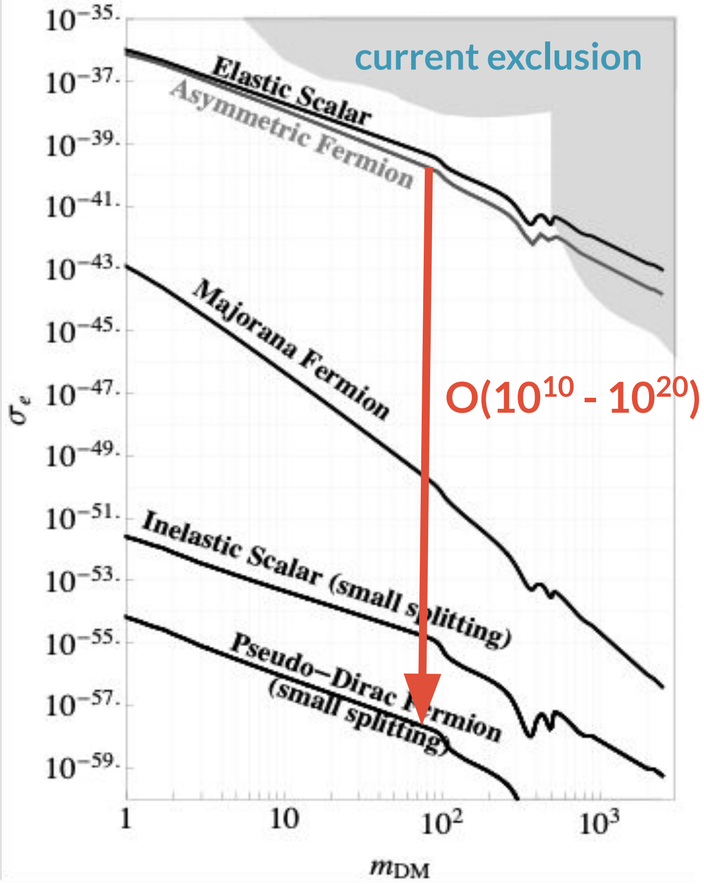


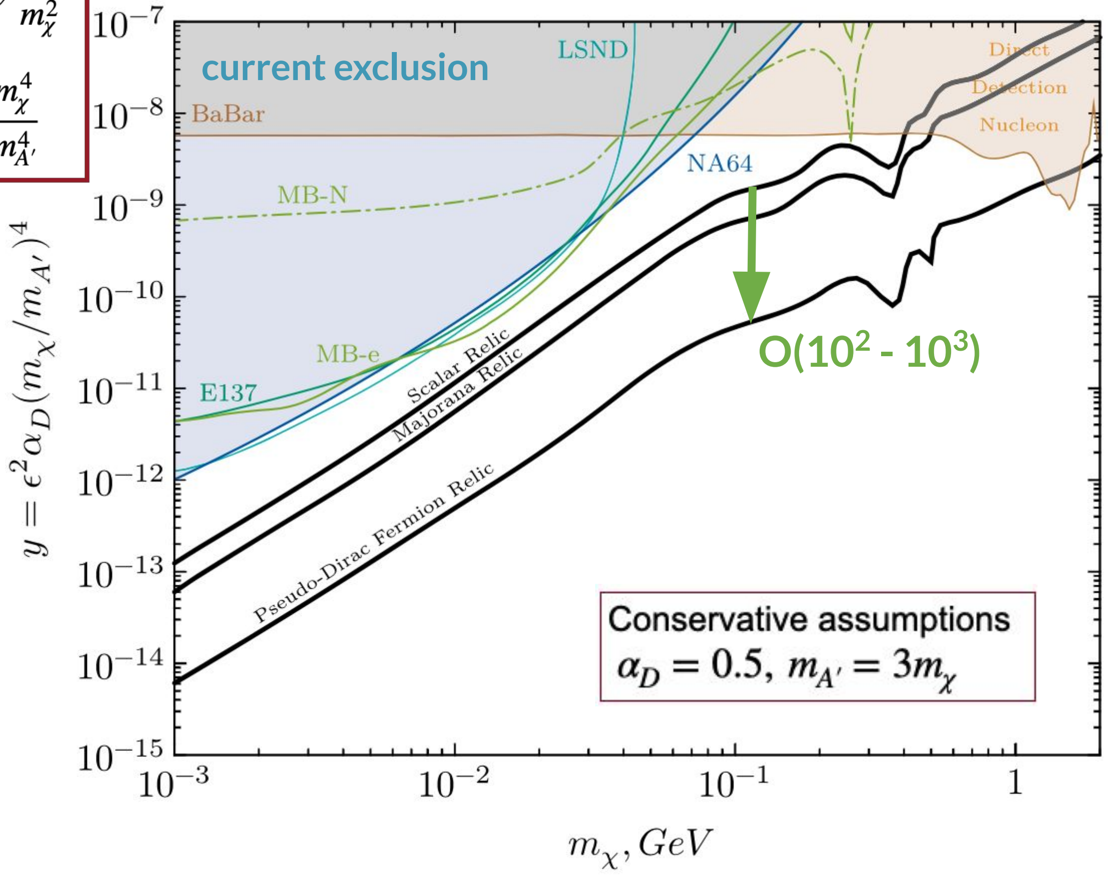
Dark Matter at accelerators: advantages

- **Direct Detection**
  - Strong velocity / spin dependence of scattering spreads out direct detection cross sections
- **Accelerator Production:**
  - Range of freeze-out interaction strengths much more compact
  - All thermal targets within reach

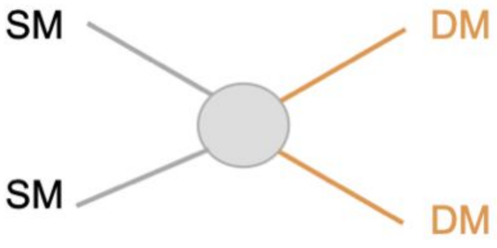
$$< \sigma v > \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim y \frac{1}{m_\chi^2}$$

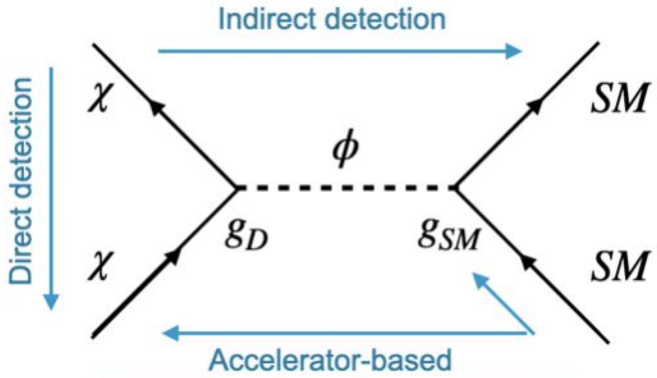
$$y = \alpha_D \, \epsilon^2 \frac{m_\chi^4}{m_{A'}^4}$$

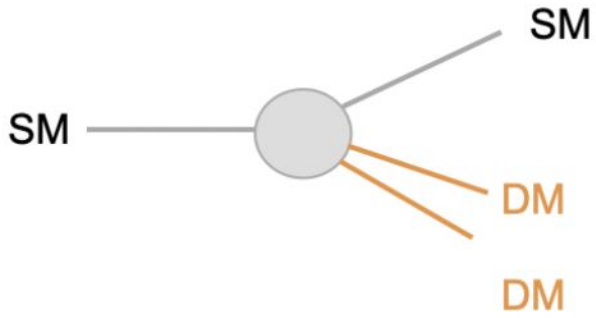




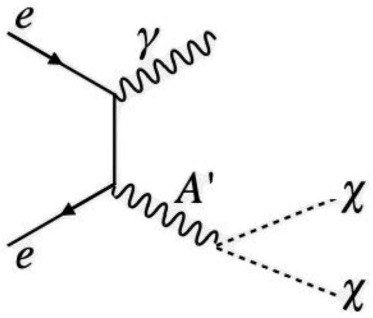
Dark Matter at Accelerators: scenarios





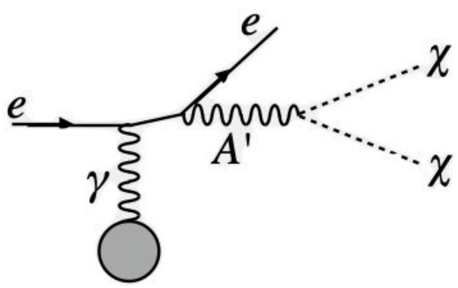


Collider



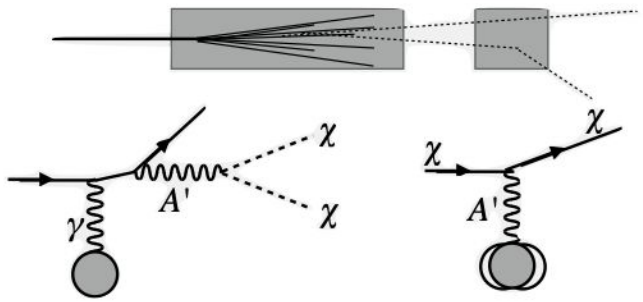
$\sigma_{coll} \propto \frac{\epsilon^2}{E_{com}^2}$ < <

Missing Momentum



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

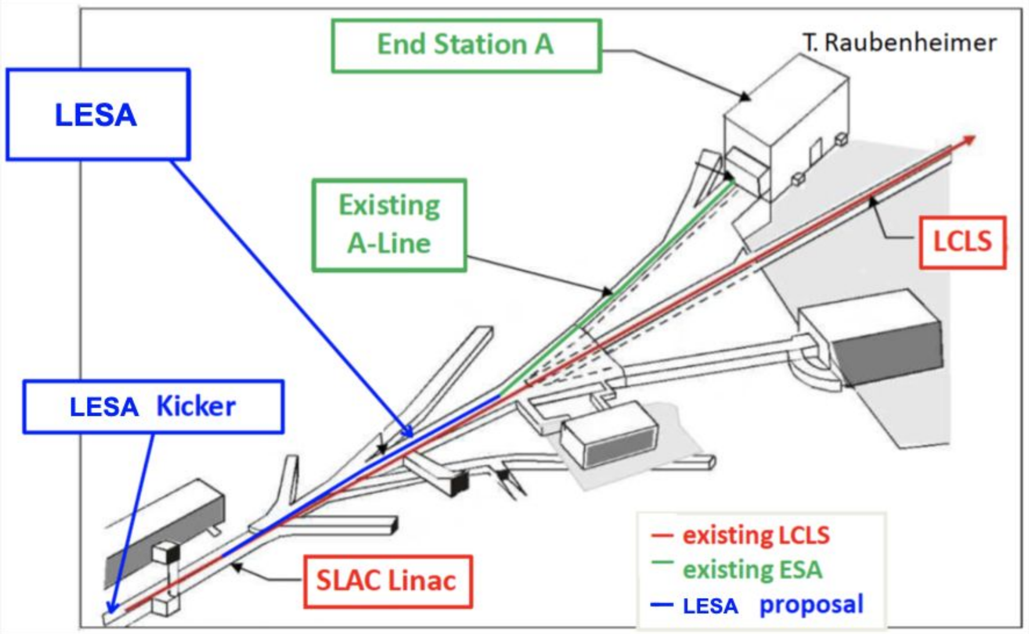
Beam dump

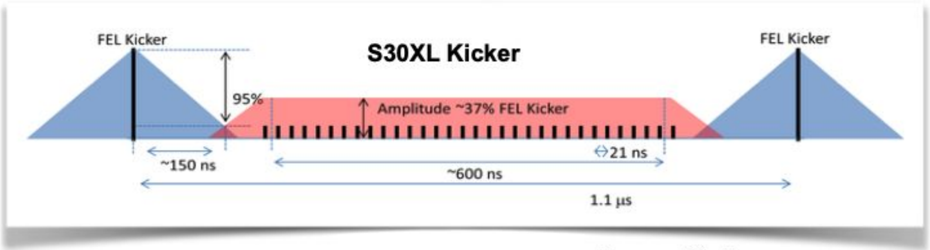


> > $N \propto \epsilon^4$ Direct detection

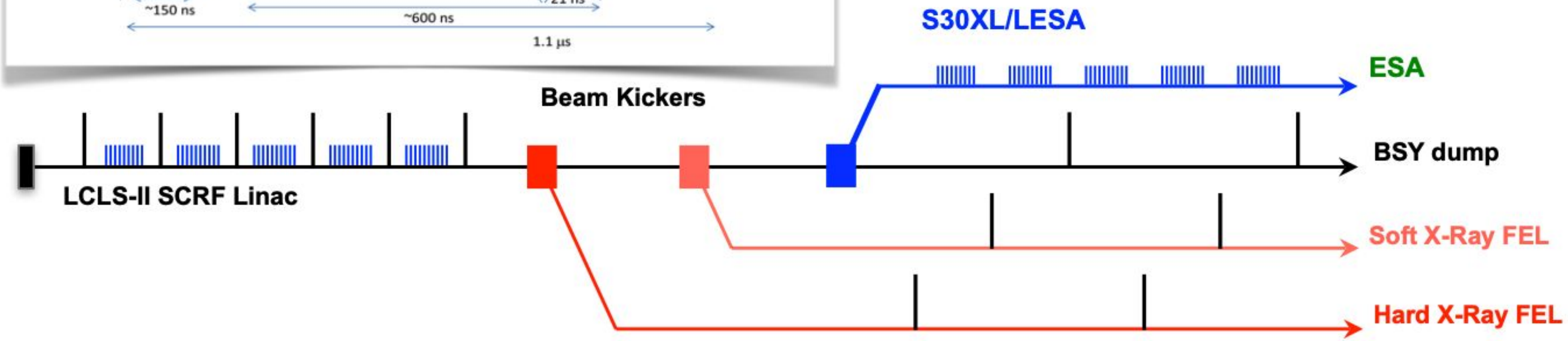
The Beamline: Linac to End Station A (LESA) at SLAC

- **LCLS-II 4-GeV beam at SLAC:**
  - Accelerates 186 MHz bunches
  - ~5k hours /year operation for photon science at ~930kHz: **99% of bunches to dump**
- Sector 30 Transfer Line (S30XL) drives ~60% of unused low-charge bunches to LESA **with LDMX as primary user**
  - LESA beamline installation and commissioning is planned for FY24-25
  - Early commissioning of LDMX with low-current CW in FY25
  - LCLS-II upgrade to 8 GeV in ~FY27-28





Linac to End Station A (LESA)



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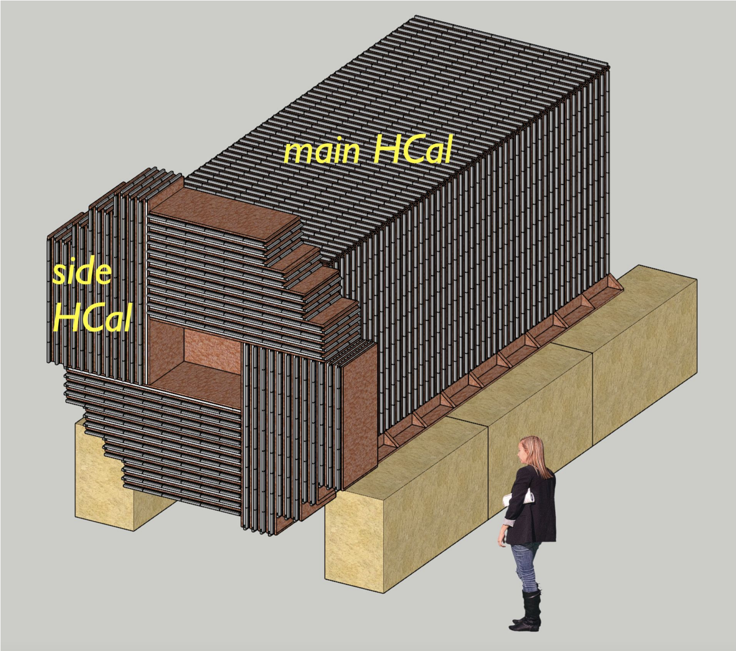
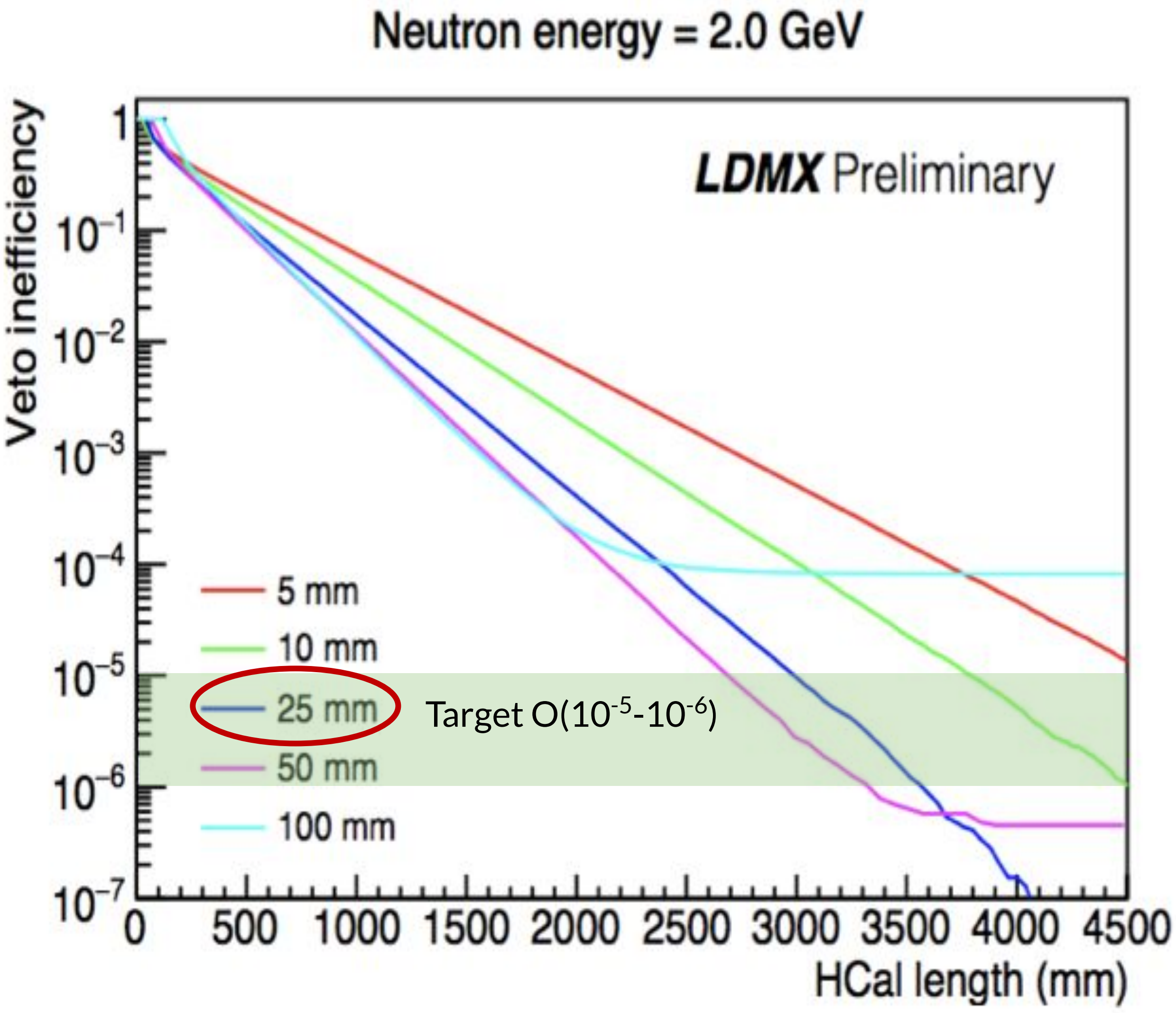
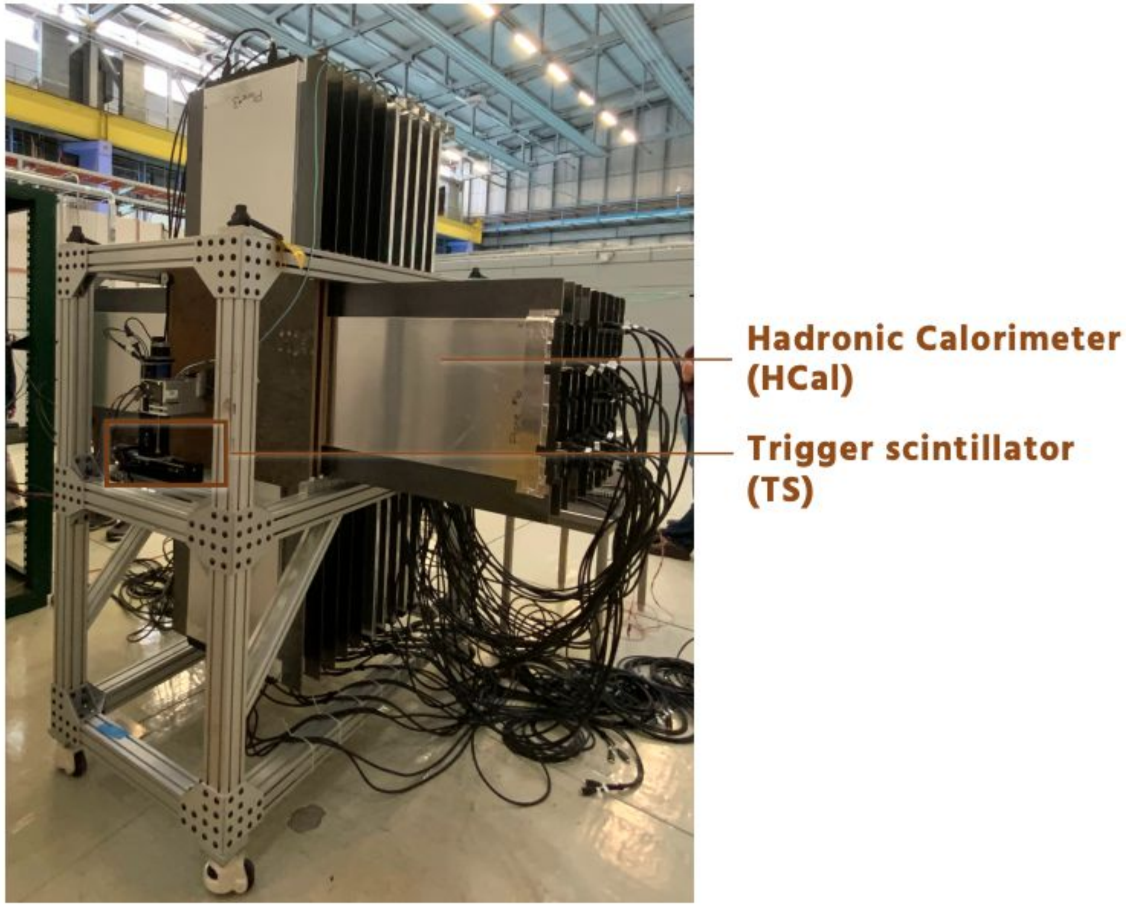
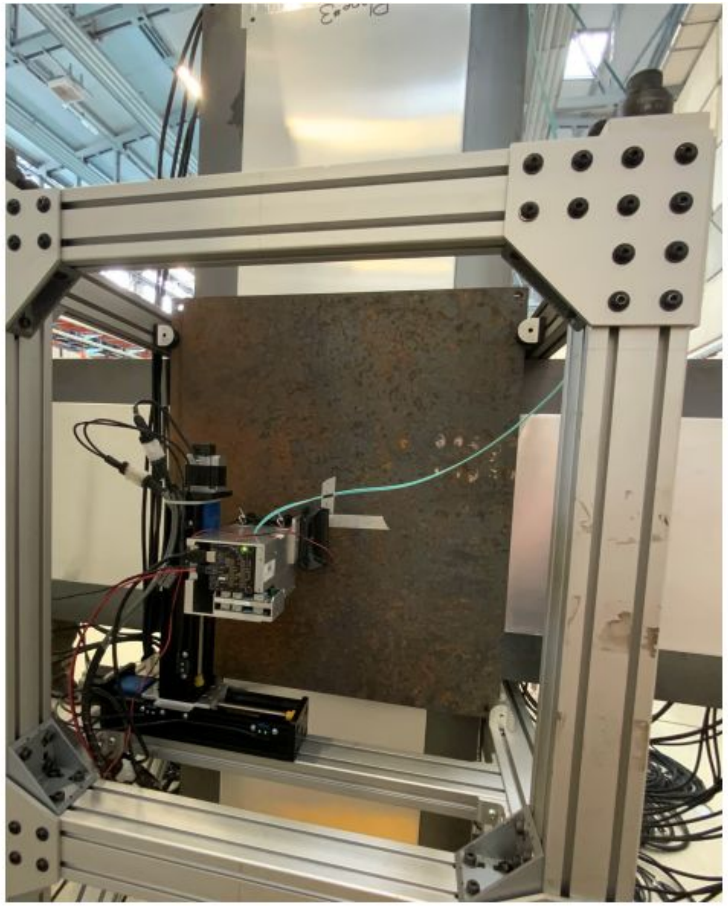




The LDMX Testbeam at CERN - Prototypes



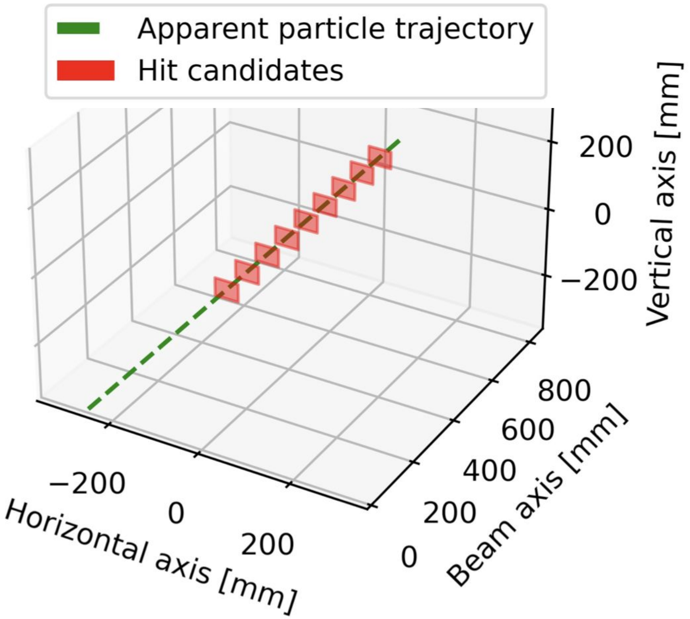


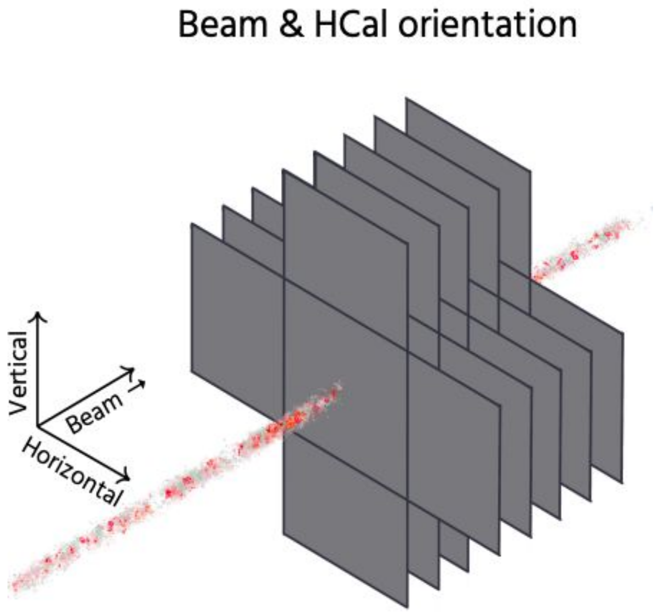
- **Prototypes of all HCAL components constructed and integrated successfully into testbeam (CERN April '22)**
  - Comparison to Geant4 simulated response
  - Development of reconstruction algorithms

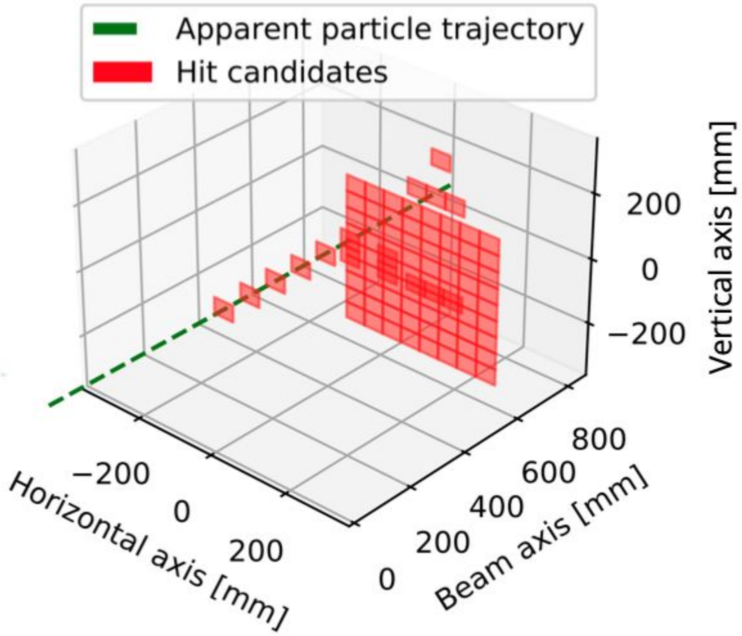
The LDMX Testbeam at CERN - Event Display

- **Muon Candidate**
  - Crisp signature in HCal

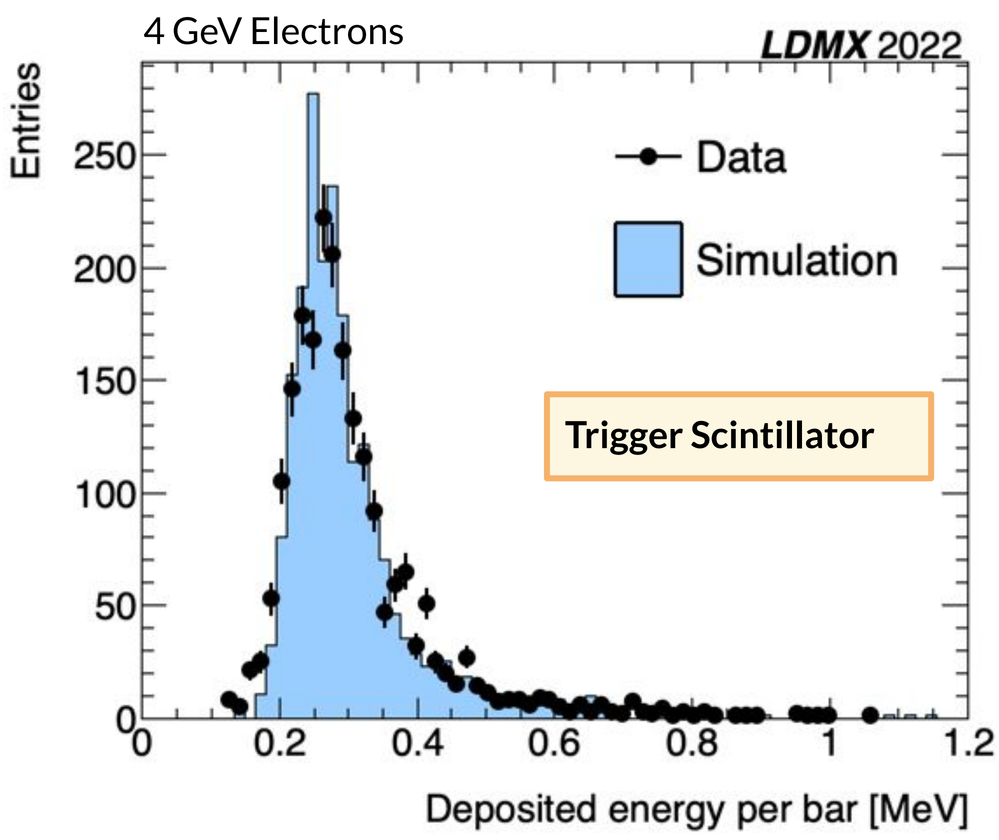
- **Pion Candidate**
  - MIP-like deposits followed by cloud of hits

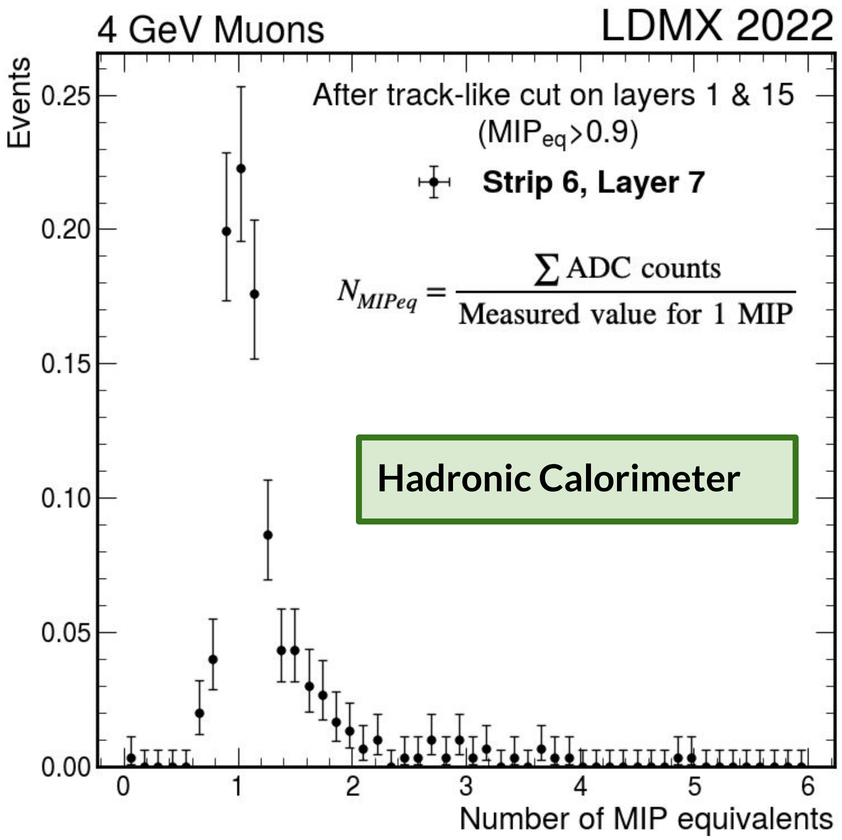






The LDMX Testbeam at CERN - Additions and Motivations

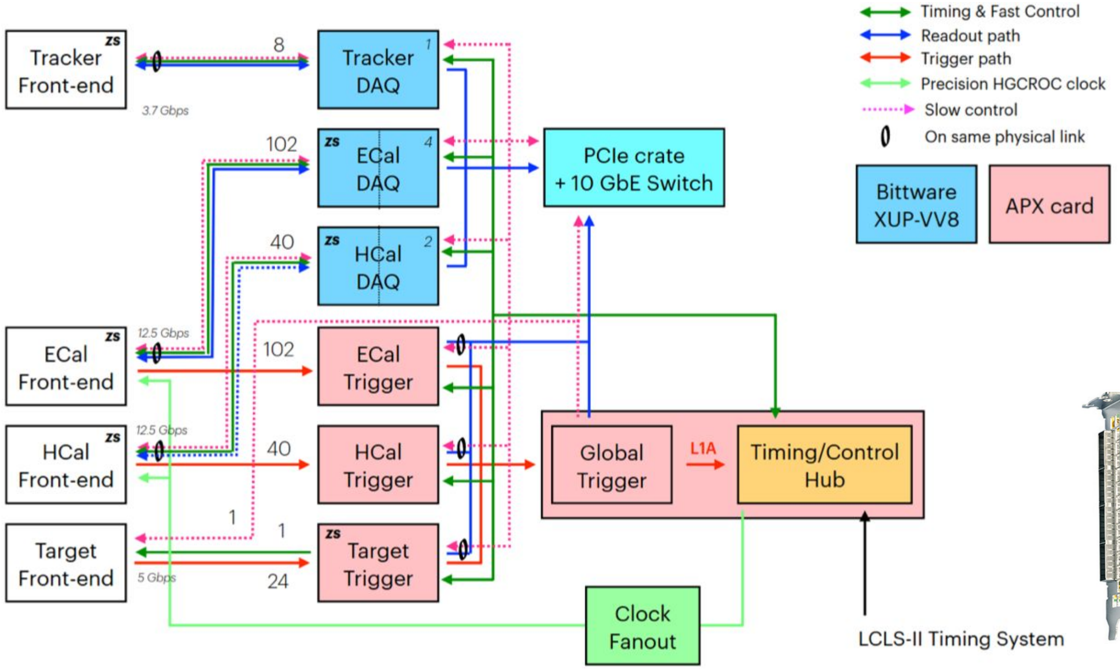




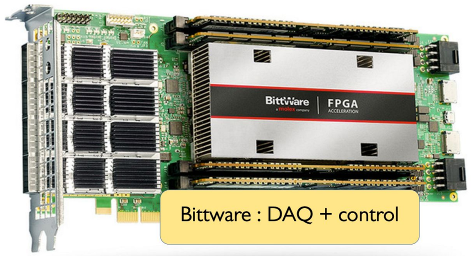
- **Successful test-beam to demonstrate Trigger Scintillator and HCAL response**
  - **TS response well modelled by Geant4 MC simulation**
  - **Excellent HCAL MIP identification capability**

Data Acquisition (DAQ) Design and computing facilities

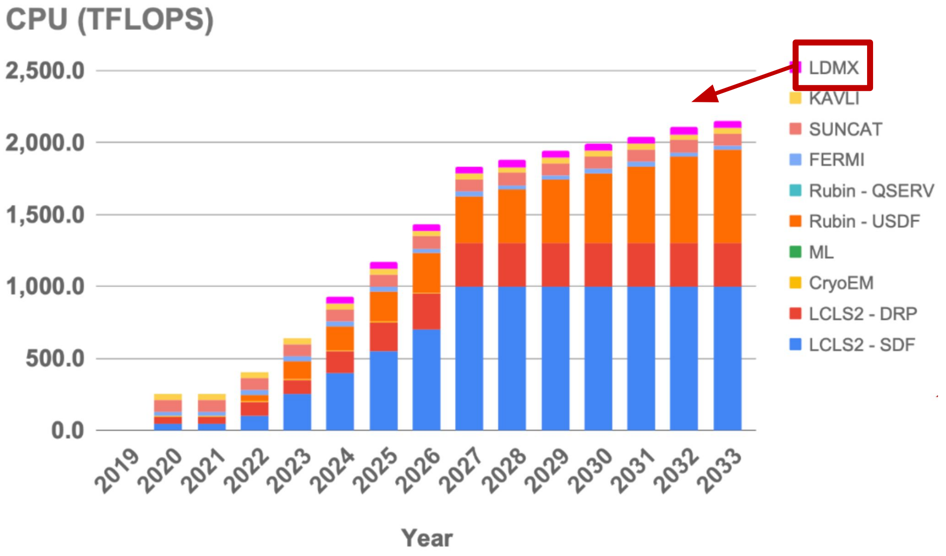
- **LDMX is leveraging independent development of a new DAQ system**
  - Based on commercial FPGA PCIe hardware



[bittware fpga xup-vv8]()

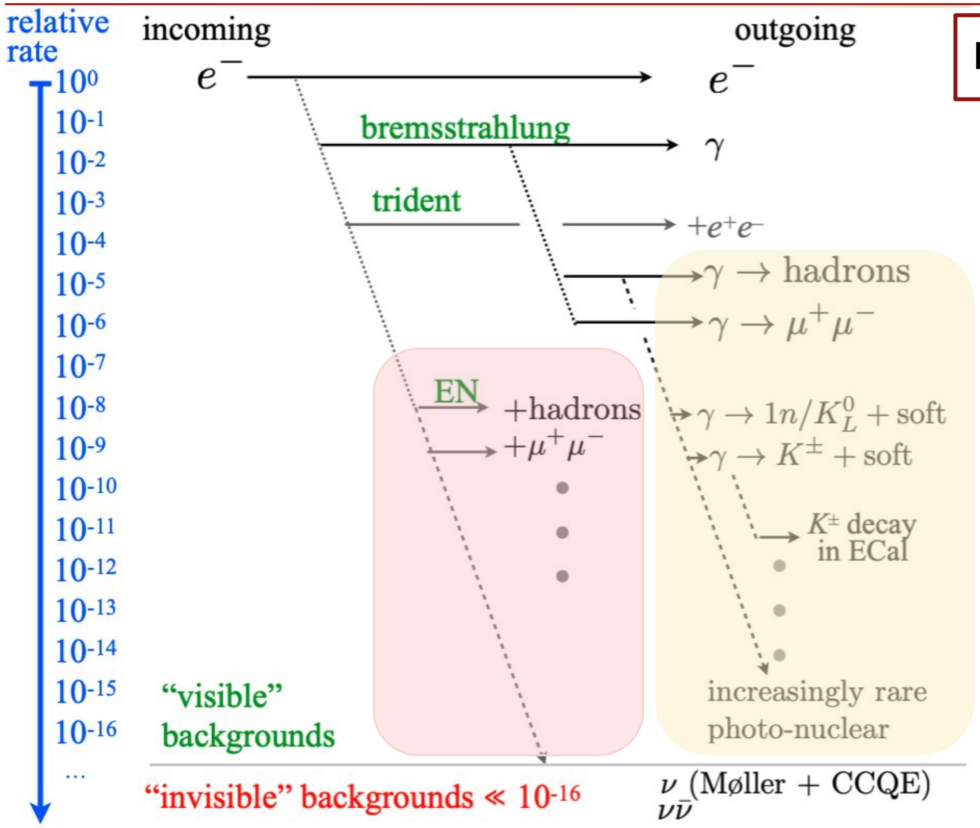


- **Next generation of lightweight DAQ solution for small experiments**
  - **Currently under test using Heavy Photon Search test-stand at SLAC**

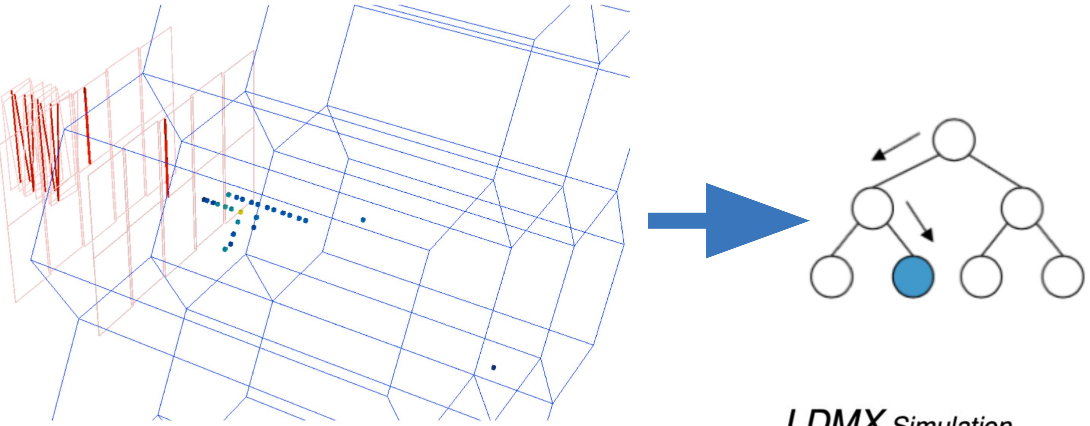


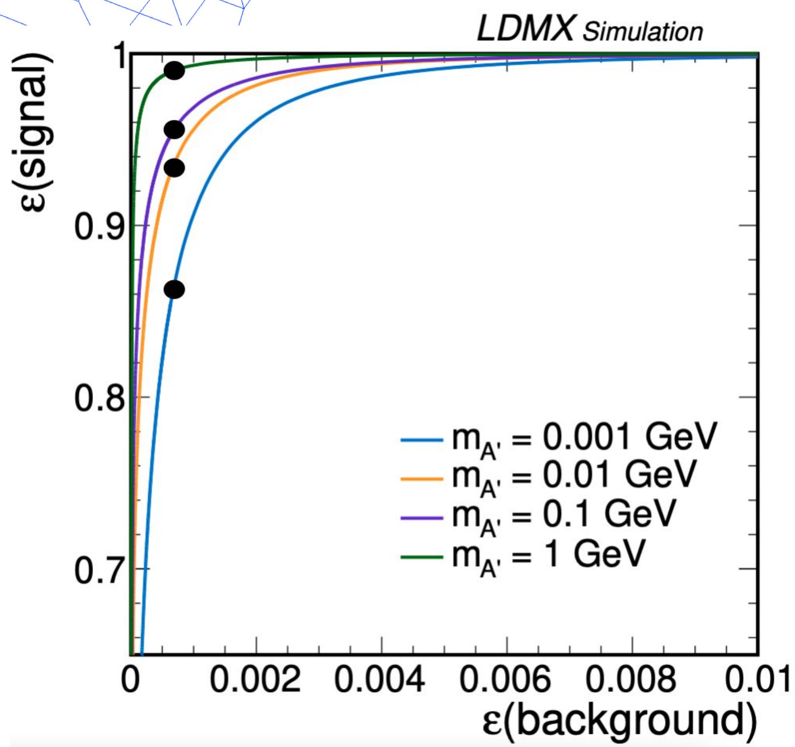
- **Computing model for LDMX leverages**
  - **SLAC Shared Scientific Data facility (SDF)**
  - Lightweight distributed computing System (LDCS) [arxiv:2105.02977]()

Rare Background rejection



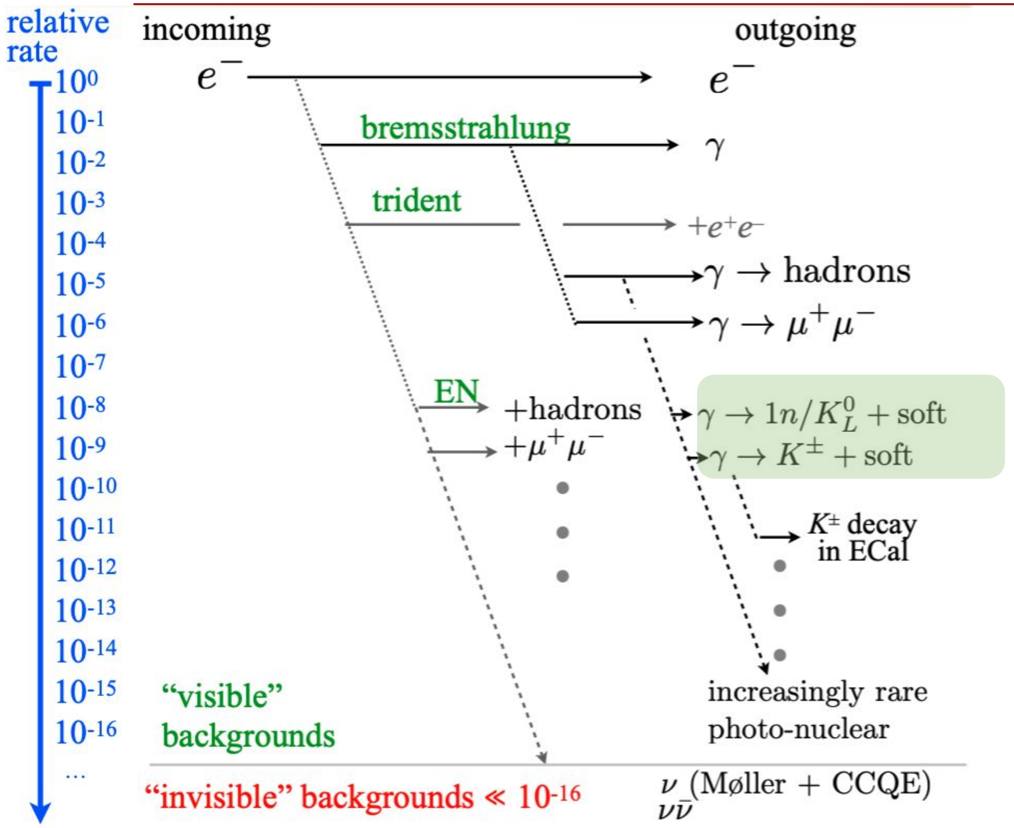
ECAL veto based on boosted decision tree (BDT) optimized vs ECAL pN bkg

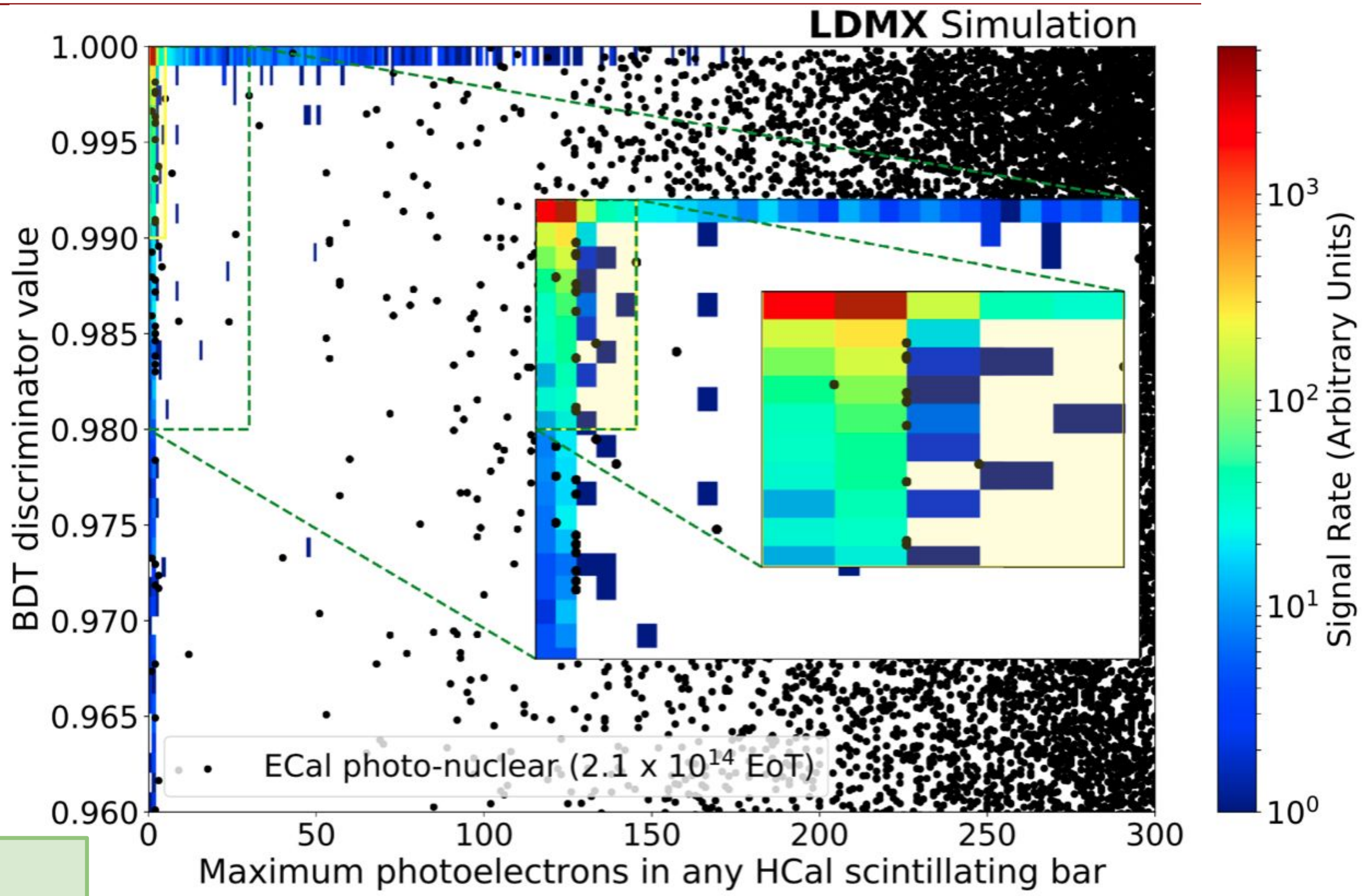




- **Exactly one e^- track in the recoil tracker**
  - Removes electro-nuclear (eN) bkg & rare invisible ν processes
- **ECAL BDT Veto**
  - Global ECAL Features
  - EM Shower features leveraging ECAL granularity

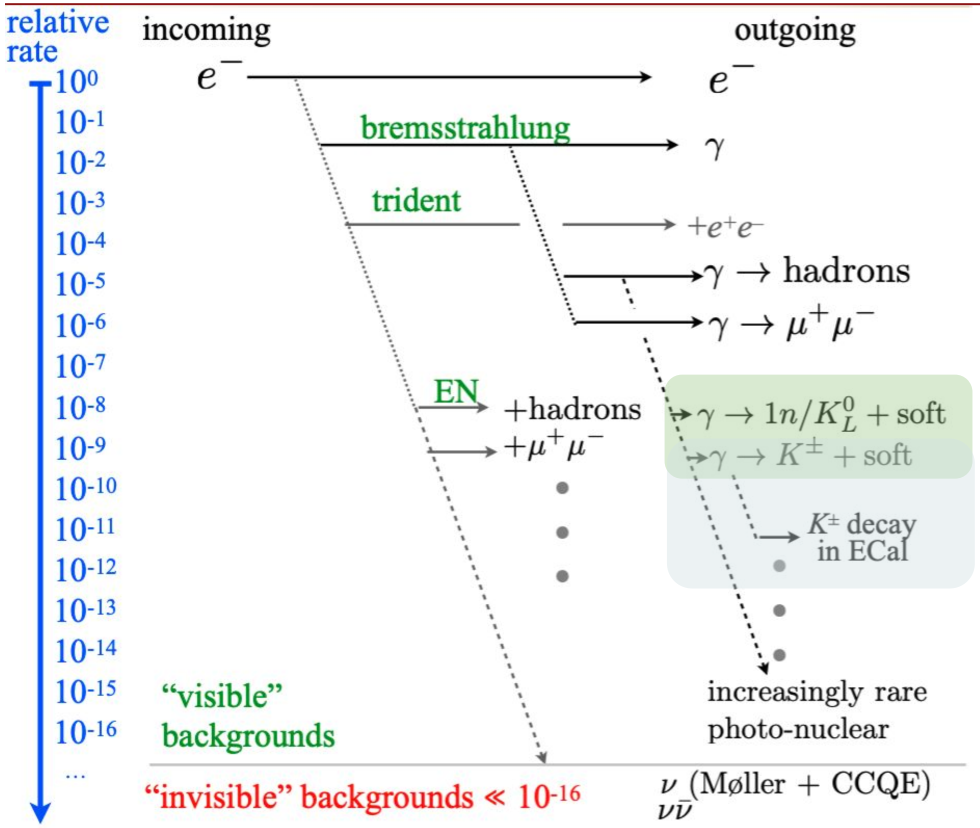
Rare Background rejection

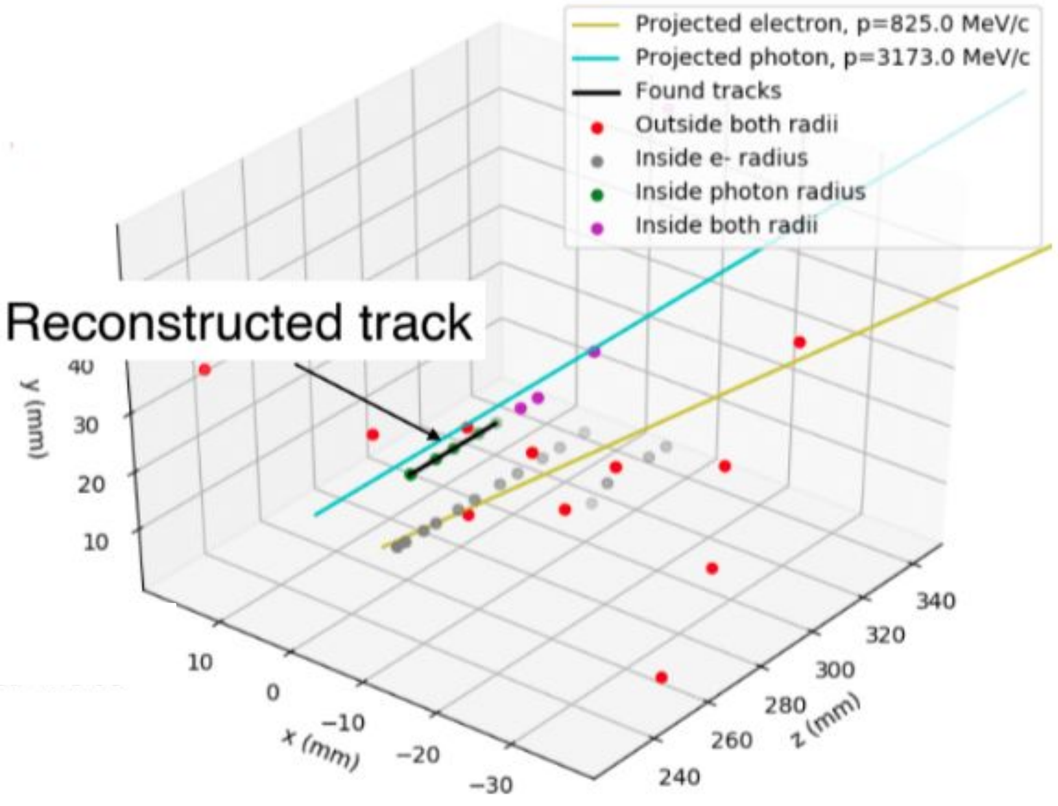




- **HCAL hit Veto**
  - Single scintillator bar with **< 5 photoelectrons hits**
  - Targets neutral particles and soft products escaping ECAL

Rare Background rejection



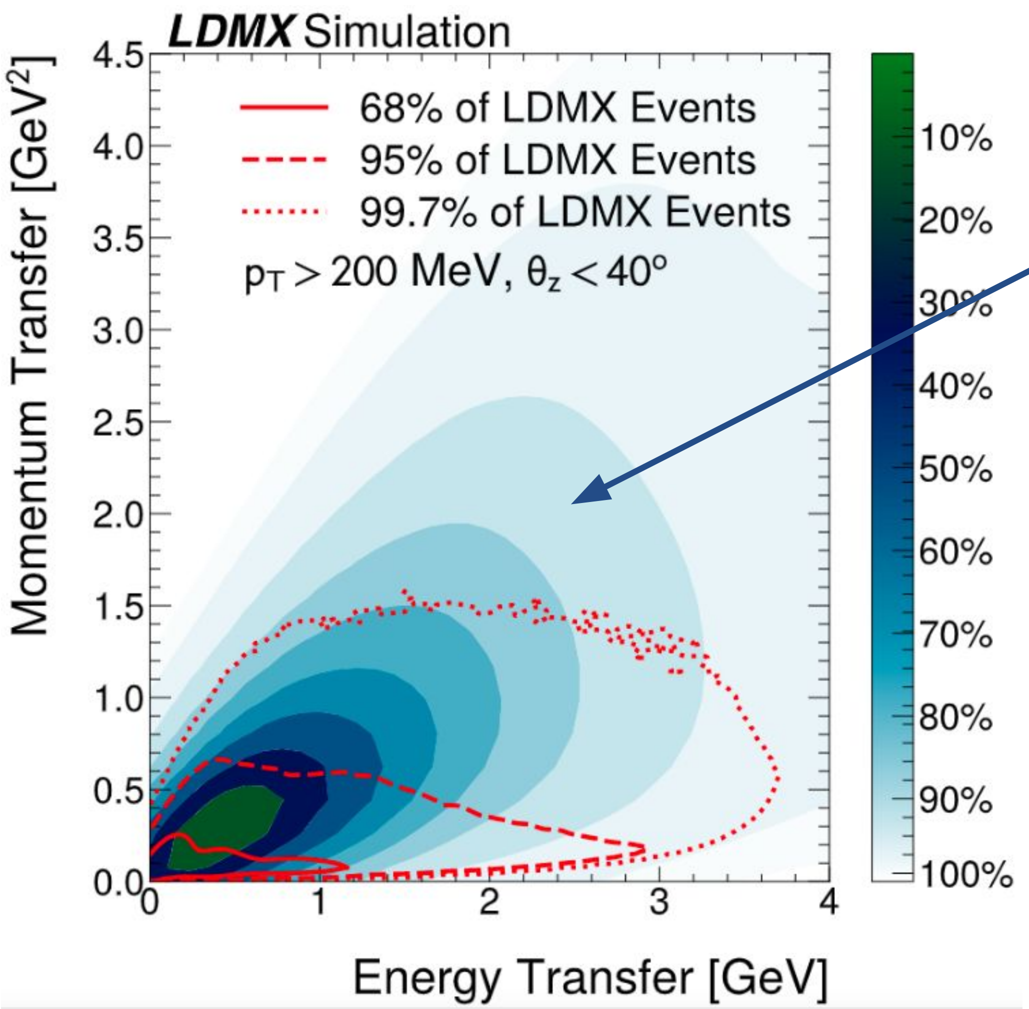


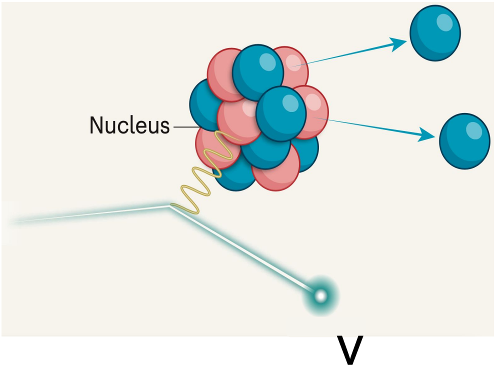
- **HCAL hit Veto**
  - Single scintillator bar with **< 5 photoelectrons hits**
  - Targets neutral particles and soft products escaping ECAL

- **MIP Tracking in ECAL**
  - Veto on reconstructed single isolated track around γ direction

Physics Potential - Electron Nucleon Measurements

PhysRevD.101.053004





Simulated DUNE Events in LAr

Physics Potential - Electron Nucleon Measurements

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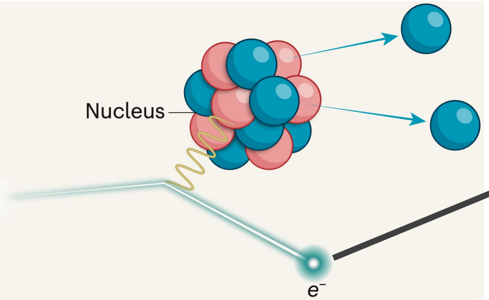
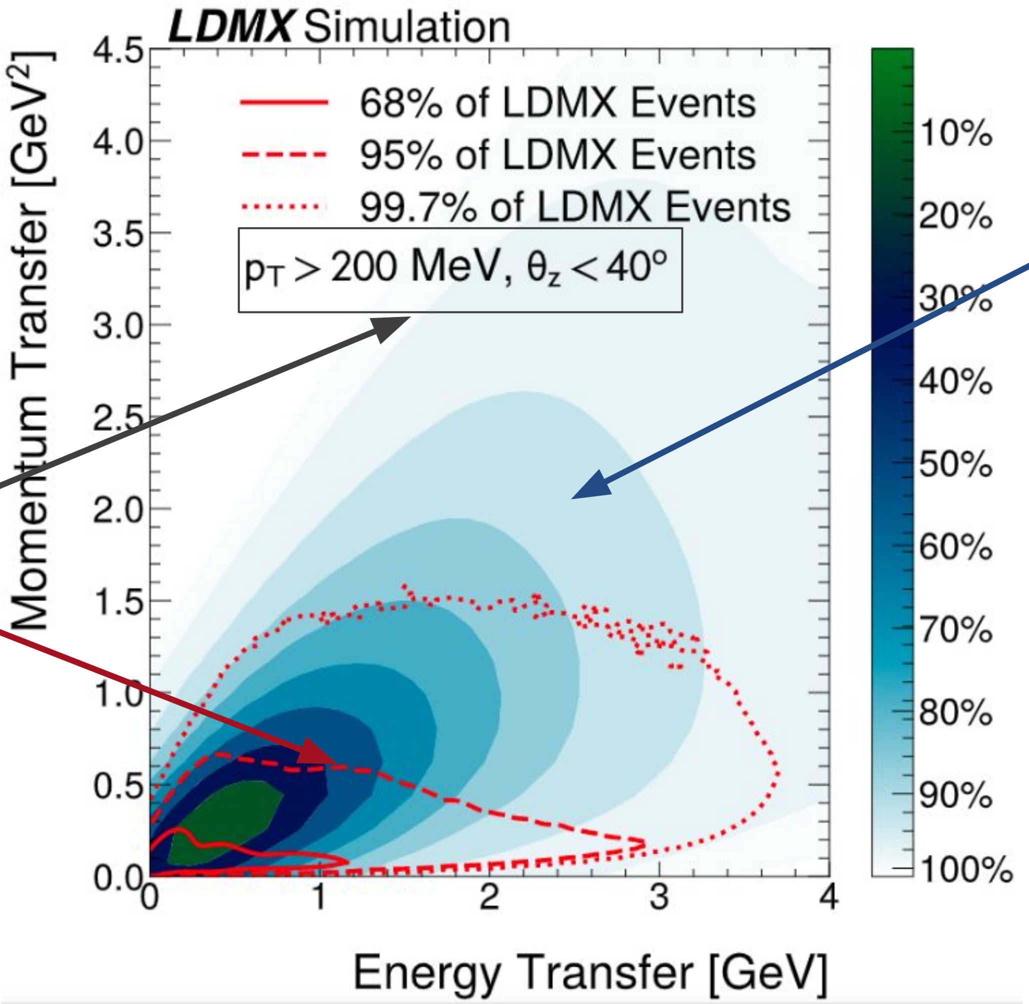
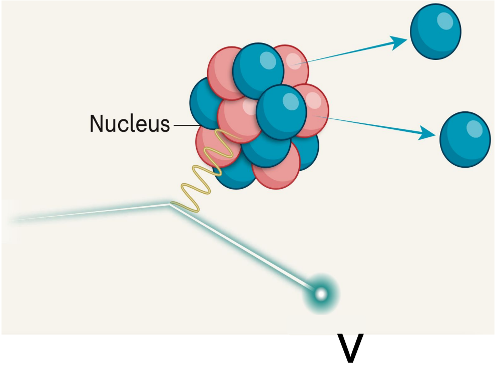


LDMX recoil e^- p_T and polar angle θ_z

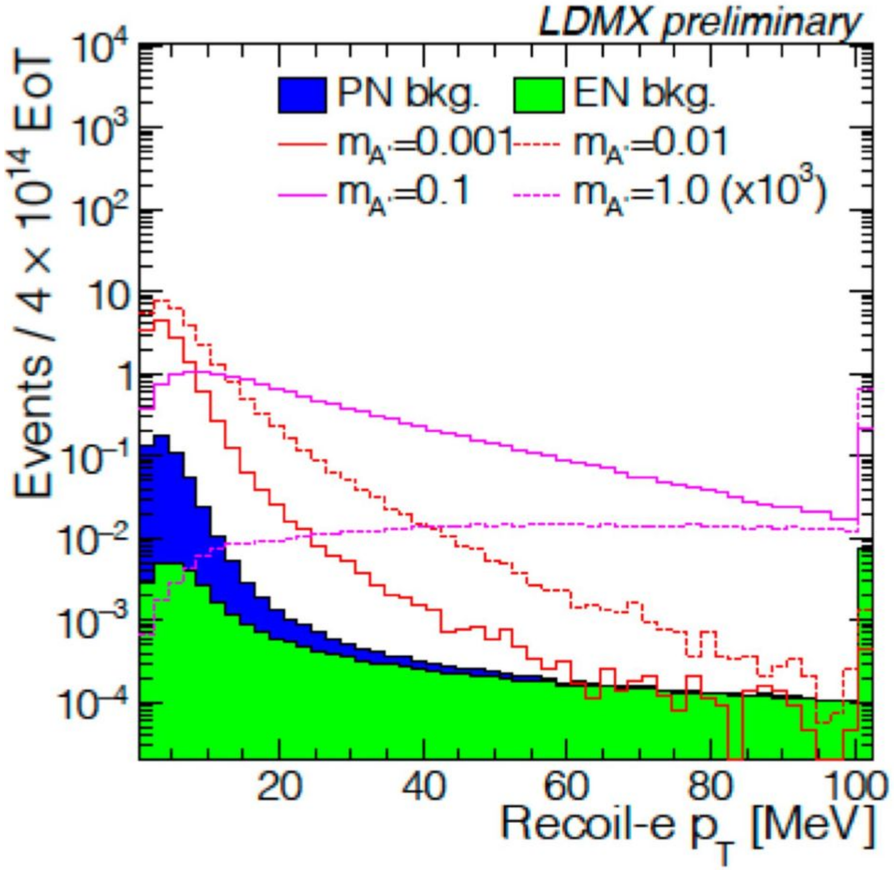




Simulated DUNE Events in LAr

- **LDMX has unique capability** to inform neutrino interaction models in the regions most relevant to DUNE

Determination of LDM signal mass scale



Future Runs - Phase II

- **Strategies to increase Phase-I reach**
  - Change target density / thickness
  - Increase beam energy
- **Future runs at higher energy will explore the phase space up to m_{χ} < 300 MeV**

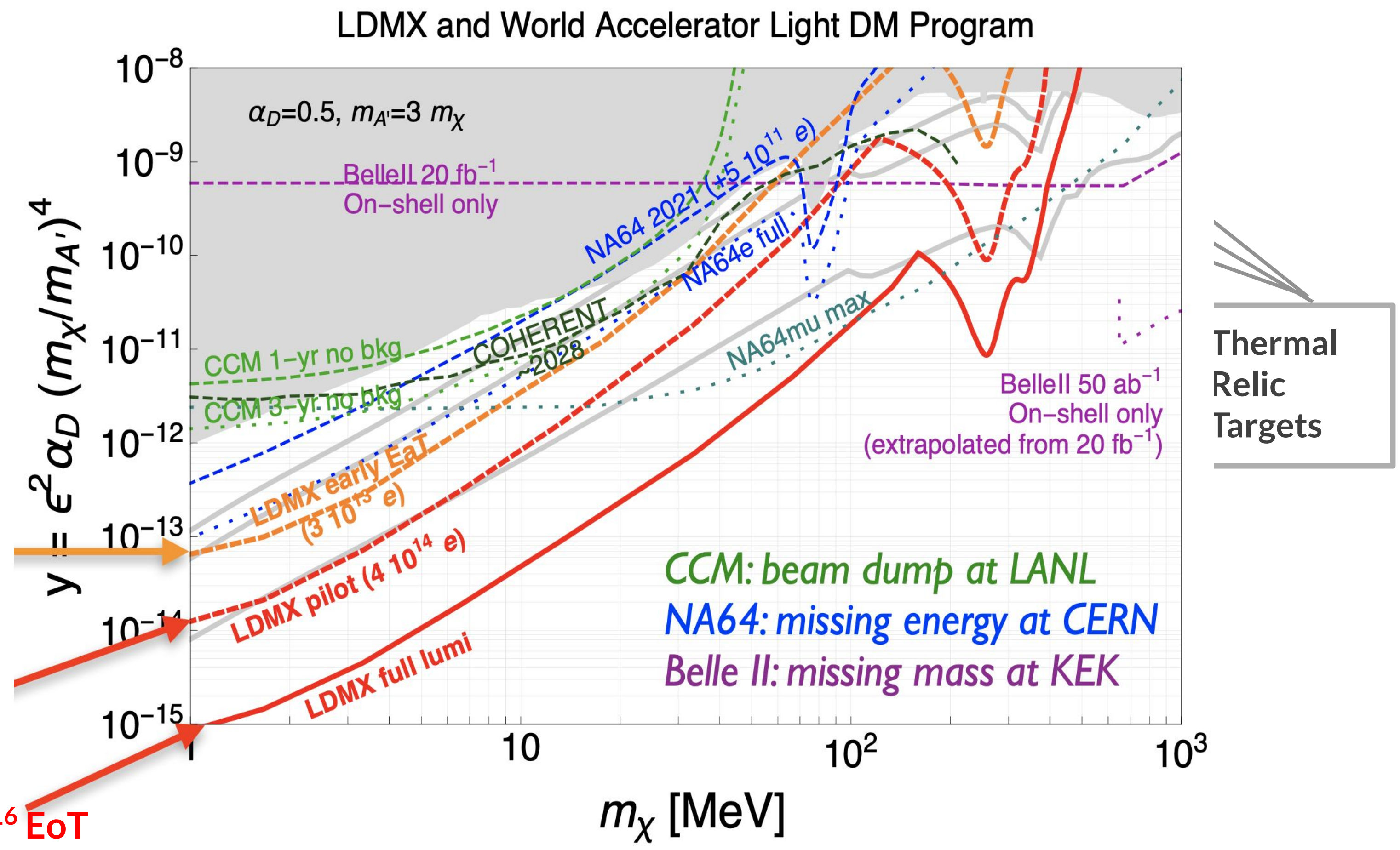
arXiv:2203.08192.pdf

arXiv:1905.07657

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

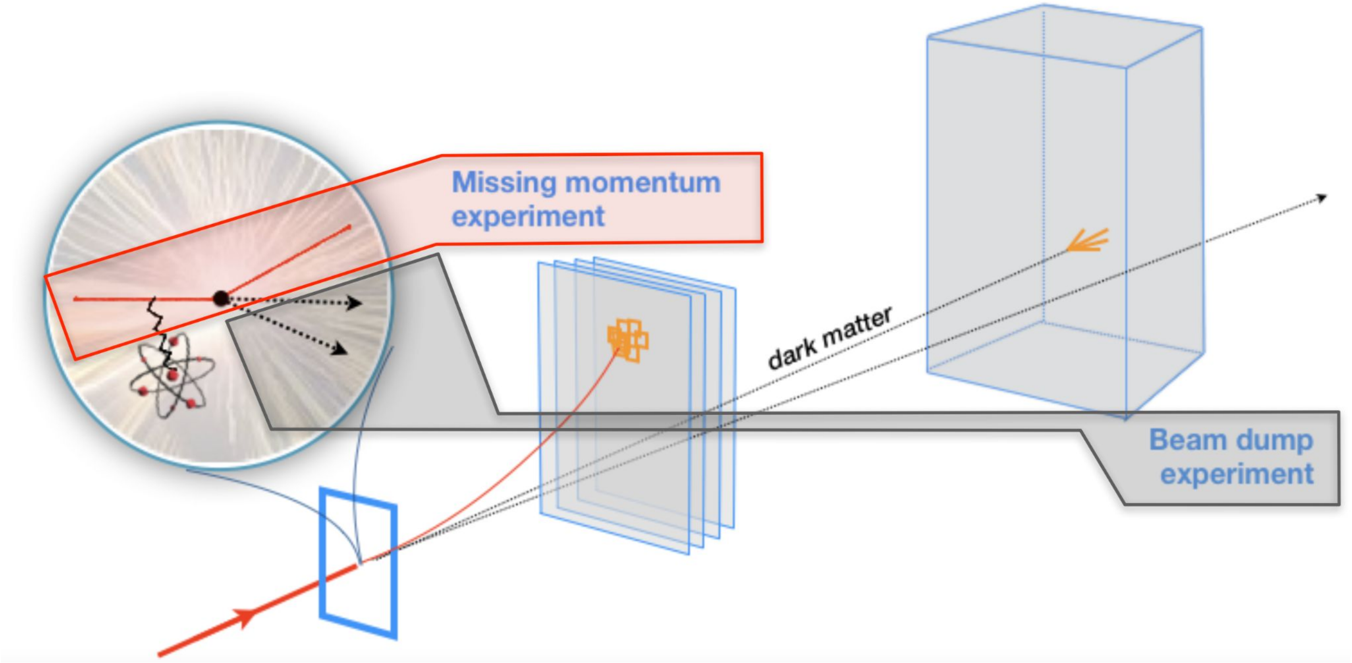


Dark Matter at Accelerators

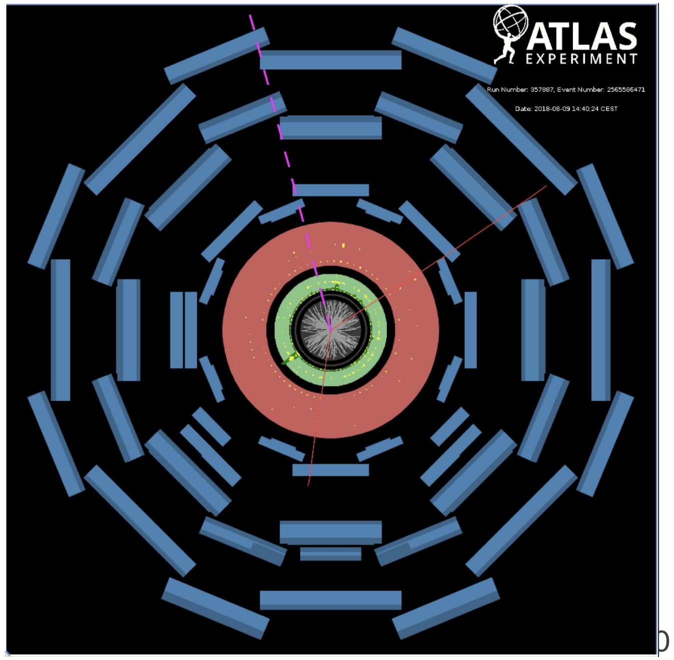
Thermal Origin of Dark Matter → **Interaction between DM and SM** → **Production mechanism at accelerator-based experiments**

Recreating Big Bang Dark Matter Production at Accelerators

At beam-on-target facilities…

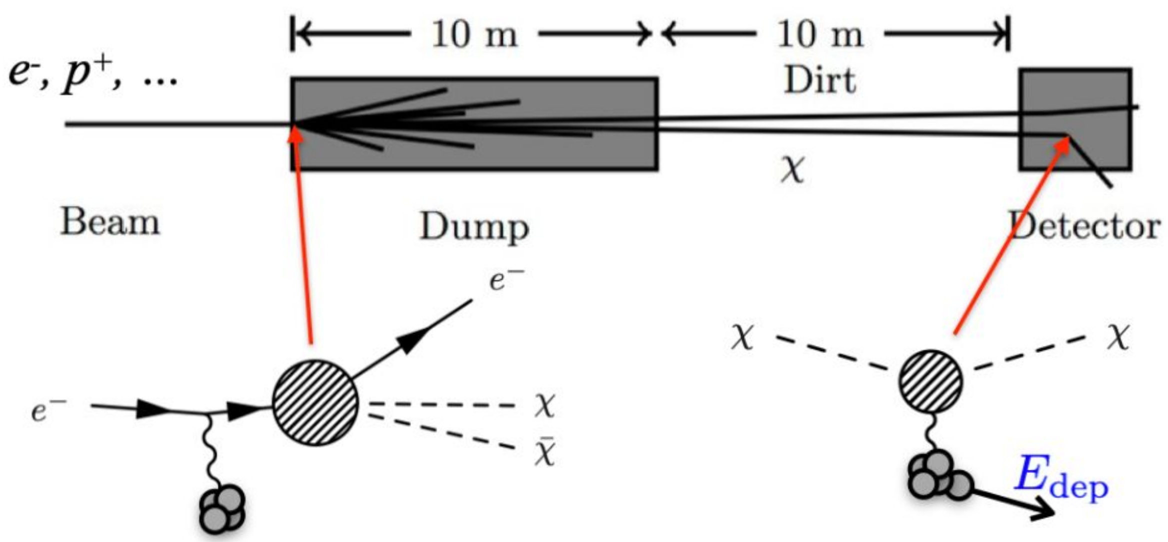


…or colliders



Experimental Approaches

Beam Dumps: Produce and re-scatter DM

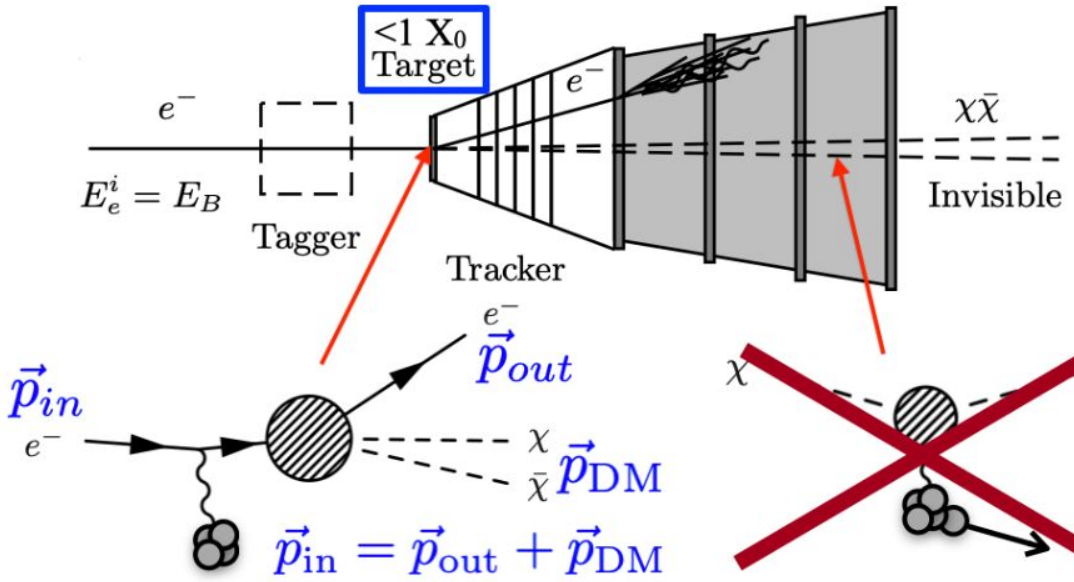


- new sensitivity with ~10^{21} particles
- covers thermal targets with ~10^{28} particles

Requirements:

- most powerful and energetic beam available
- most massive detector available
- (key background: neutrinos)

Missing Momentum: Detect DM production



- new sensitivity for ~10^{12} electrons
- covers thermal targets for ~10^{16} electrons

Requirements:

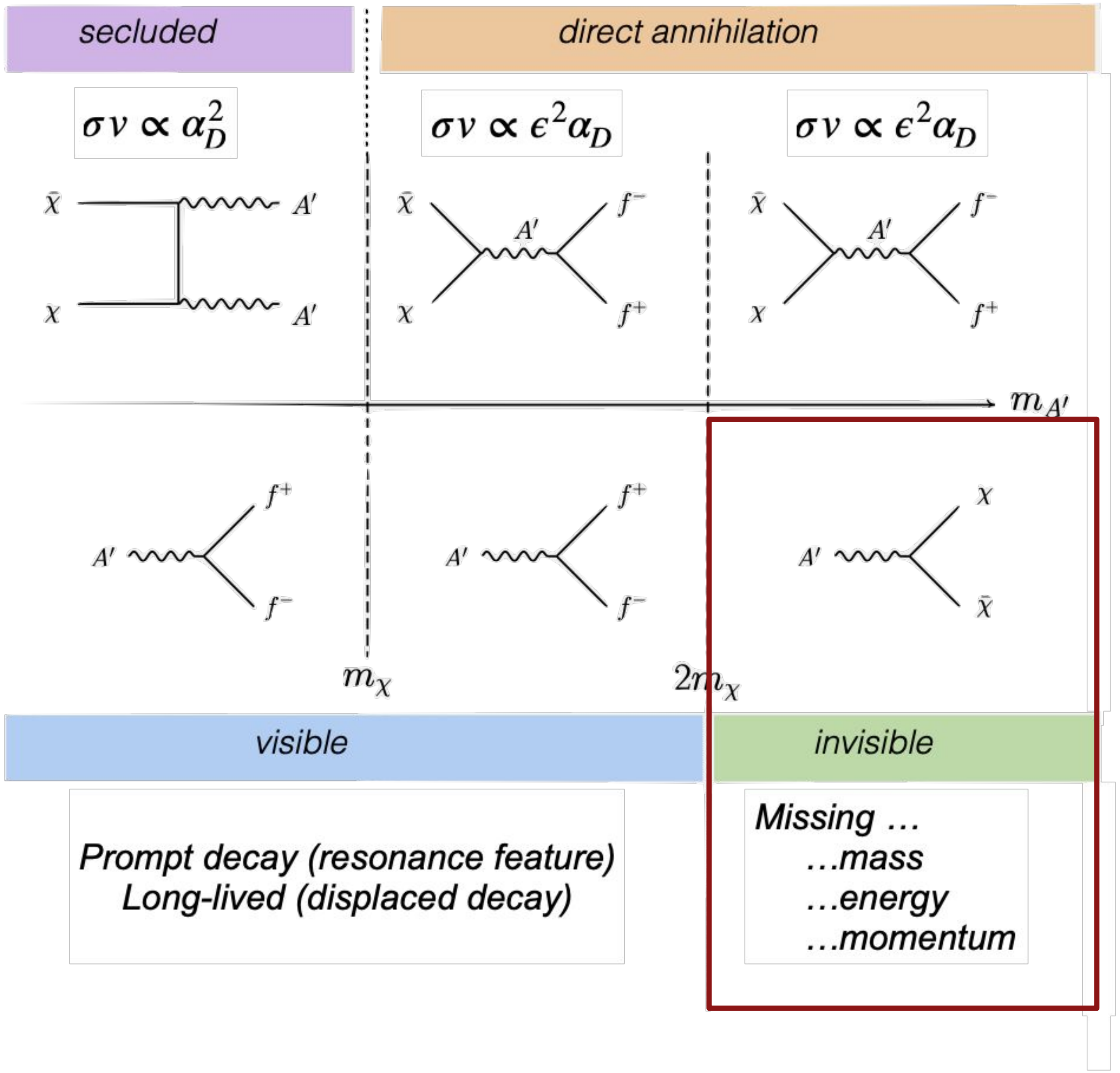
- high rate beam at ~1e^-/bunch (1 year = 3×10^{16} ns)
- fast, sensitive, detector systems
  (key backgrounds: $e^- \to e^- + \gamma$, $\gamma N \to$ hadrons)

Both approaches work, but only missing momentum feasibly covers all thermal targets

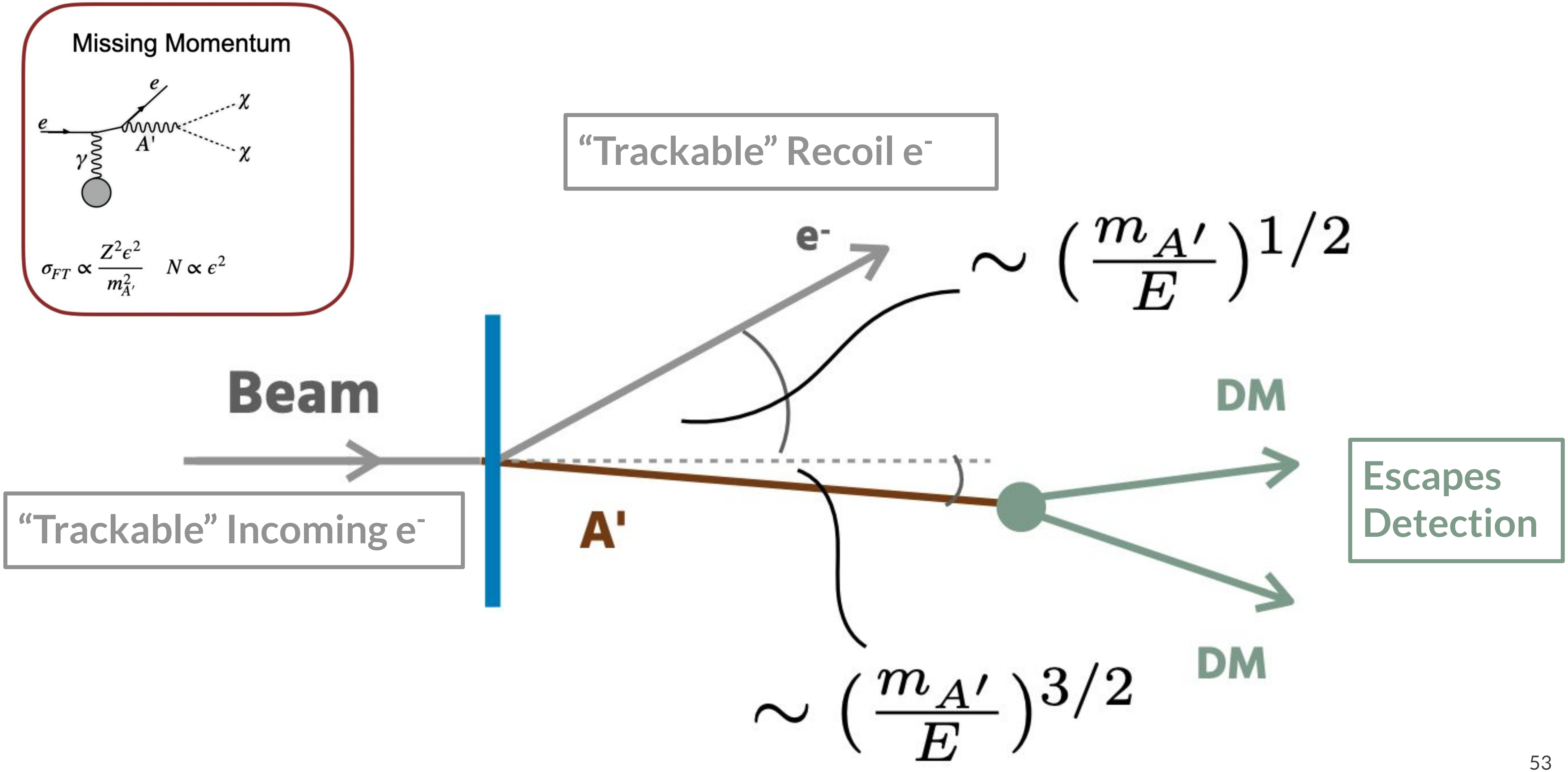
Possible Dark photon signatures

A' production

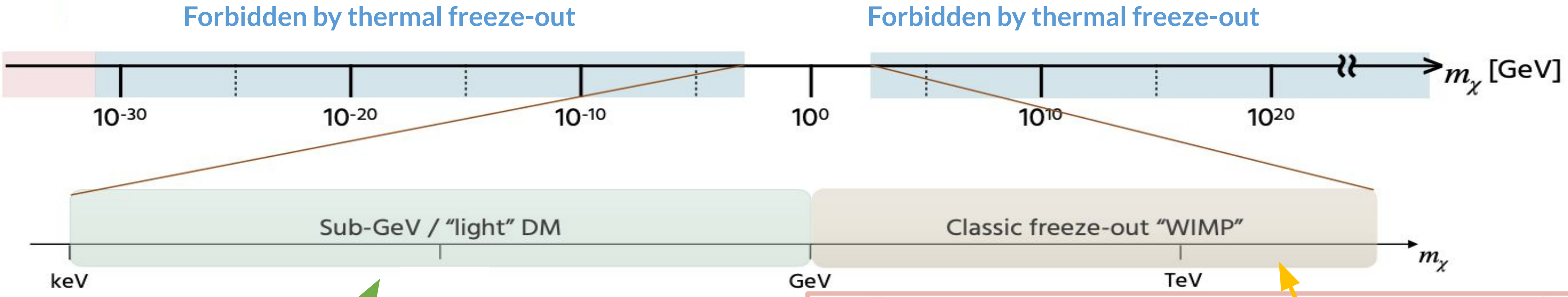
A' decay



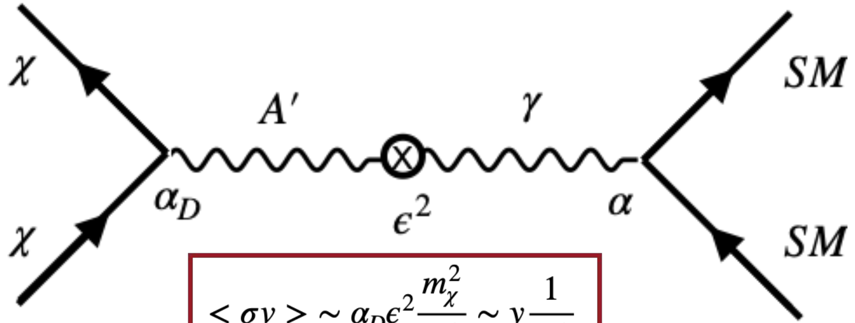
Dark Photon kinematics at a Fixed Target Experiment



Thermal Dark Matter Mass Range



- Thermal Contact implies a new mediator
- Well motivated with hidden-sector models
- Largely unexplored



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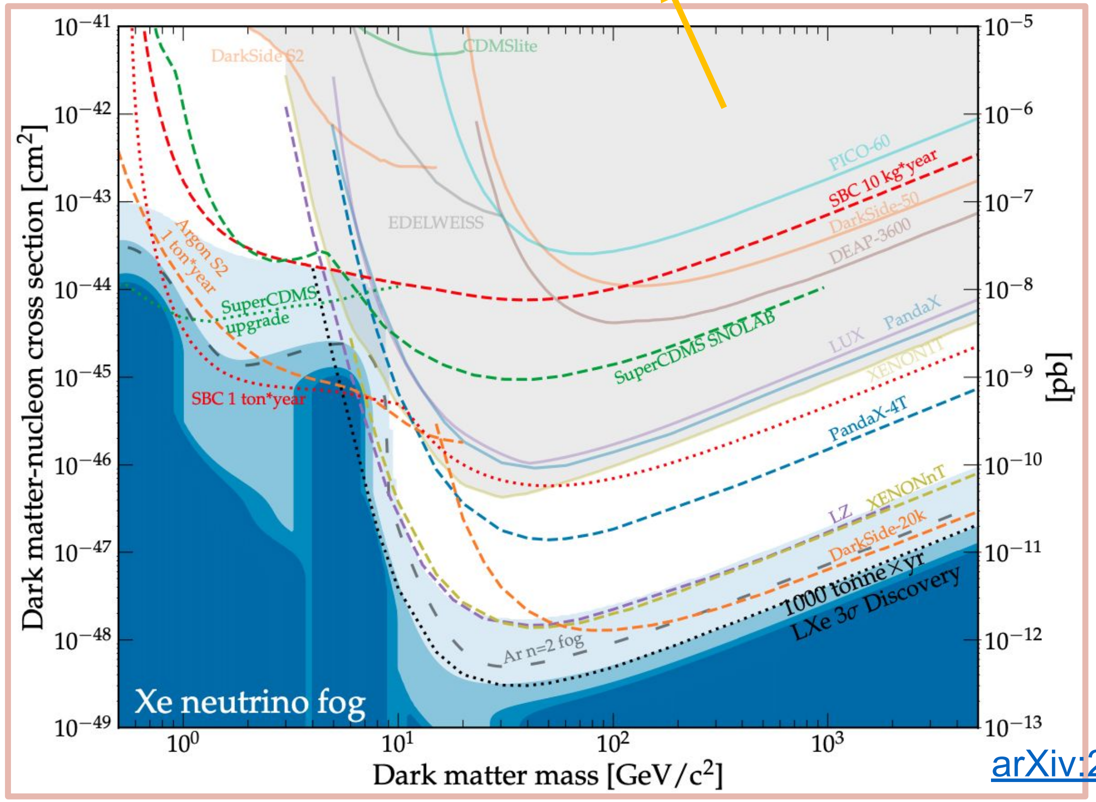

arXiv:2203.08084