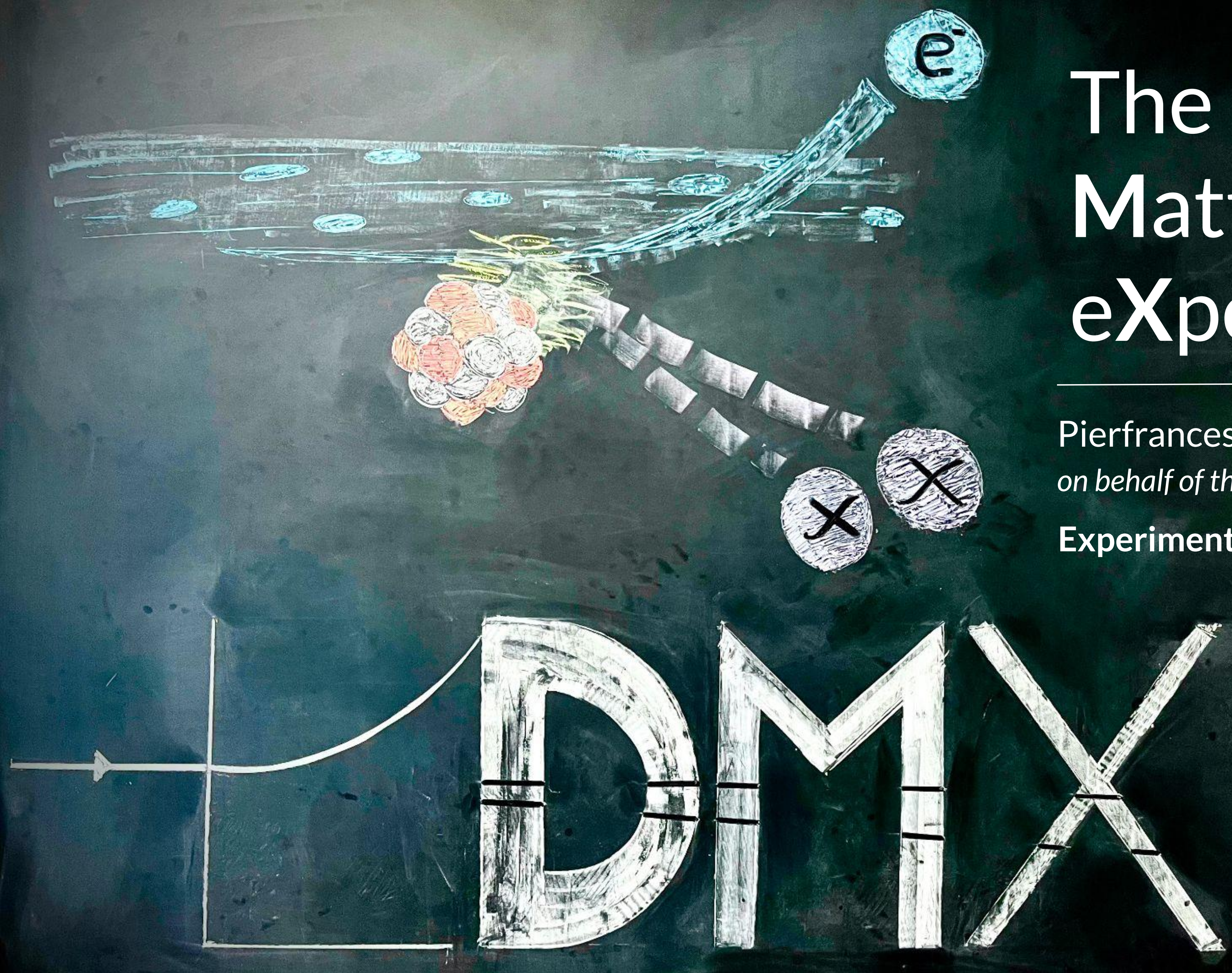
The Light Dark Matter eXperiment



Pierfrancesco Butti

on behalf of the LDMX Collaboration

Experimental Astro-Particle and Particle Physics Seminar

April 3rd, 2023

SLAC NATIONAL ACCELERATOR LABORATORY

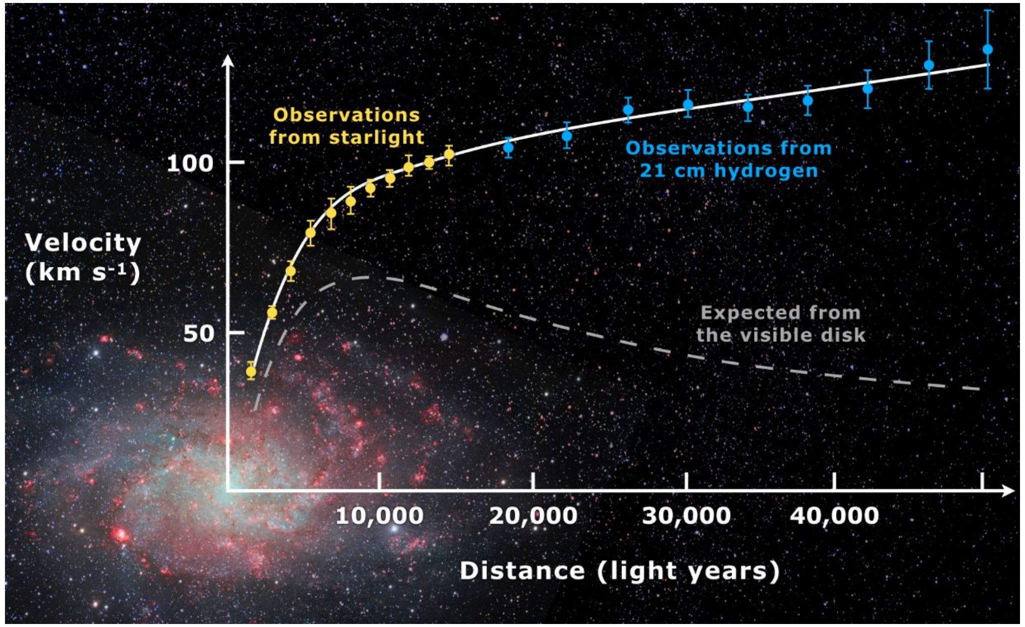
Stanford University

U.S. DEPARTMENT OF ENERGY

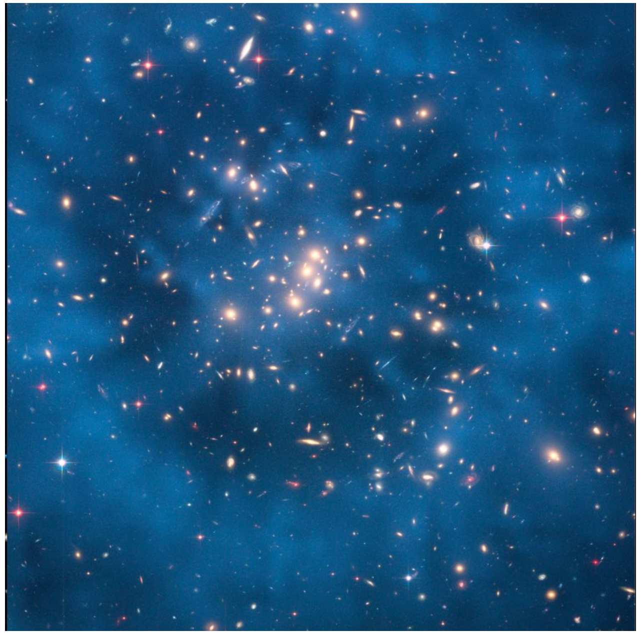
Evidence of Dark Matter in the Universe

- **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

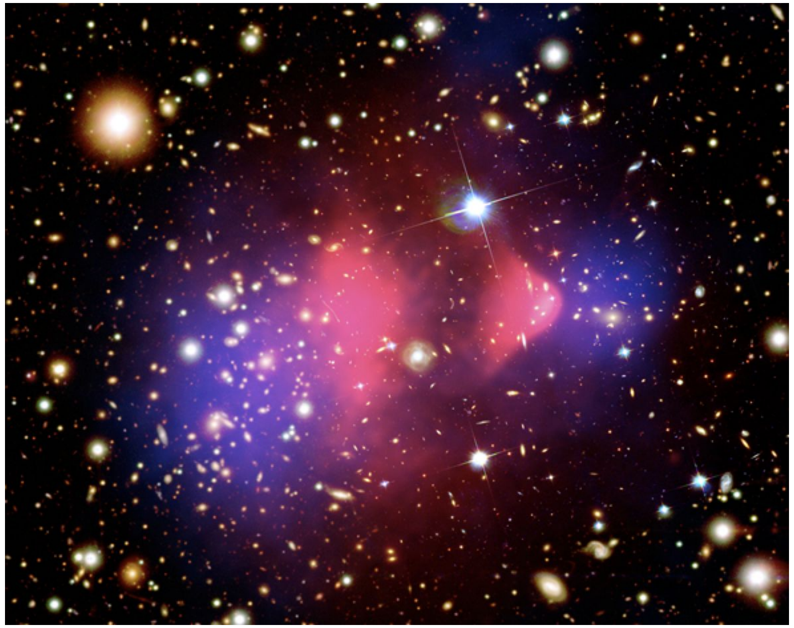
Messier 33 arXiv:9909252



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



The Bullet Cluster 1E 0657-56



Dark Matter Particle Candidates

Illustration by Sandbox Studio, Chicago with Ana Kova

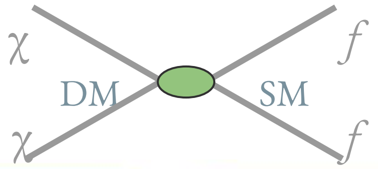
- **Dark Matter constitutes 85% of the matter in the Universe**
- Standard Model (SM) does not provide any particle candidate
- In the last decades, extensive worldwide research program has been built to understand the particle nature of DM in the universe
- Many scenarios have been proposed and the search for a DM particle candidates continues…

Thermal Dark Matter

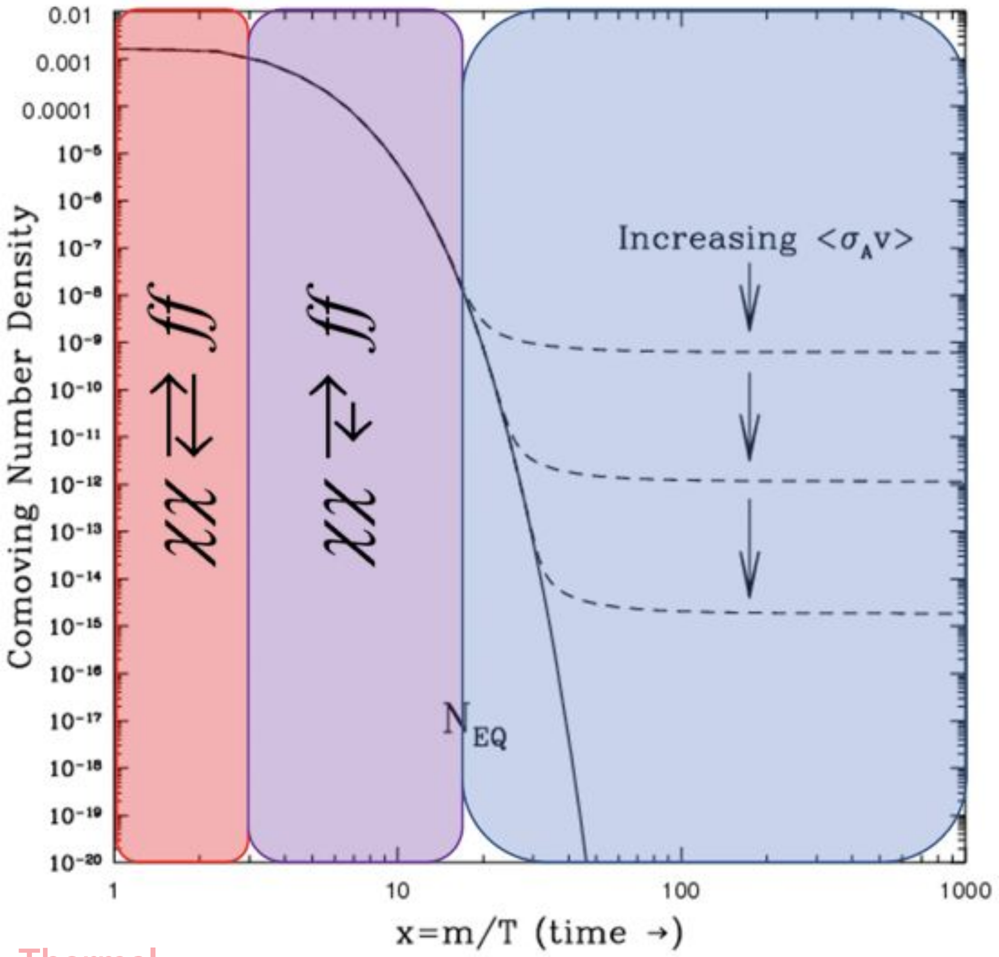
- **Assume DM in thermal equilibrium with SM in the very early universe**
- **Thermal DM as relic of the hot early Universe is one of the most compelling paradigms**
    - **Generic:** only non-gravitational interactions between DM and SM
    - **Predictive:** current relic density suggests interaction strength at accelerators

- The current relic density Ω_χ is related to the annihilation cross section

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



arXiv:9506380

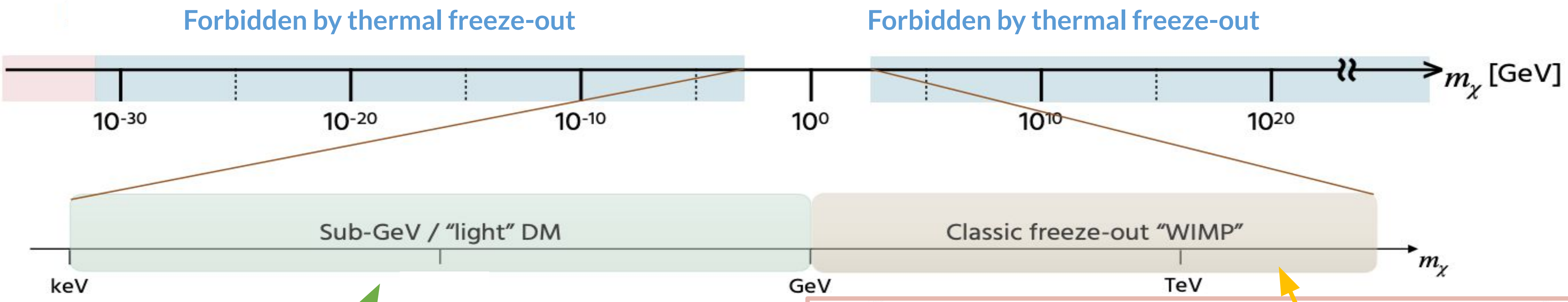


Thermal equilibrium

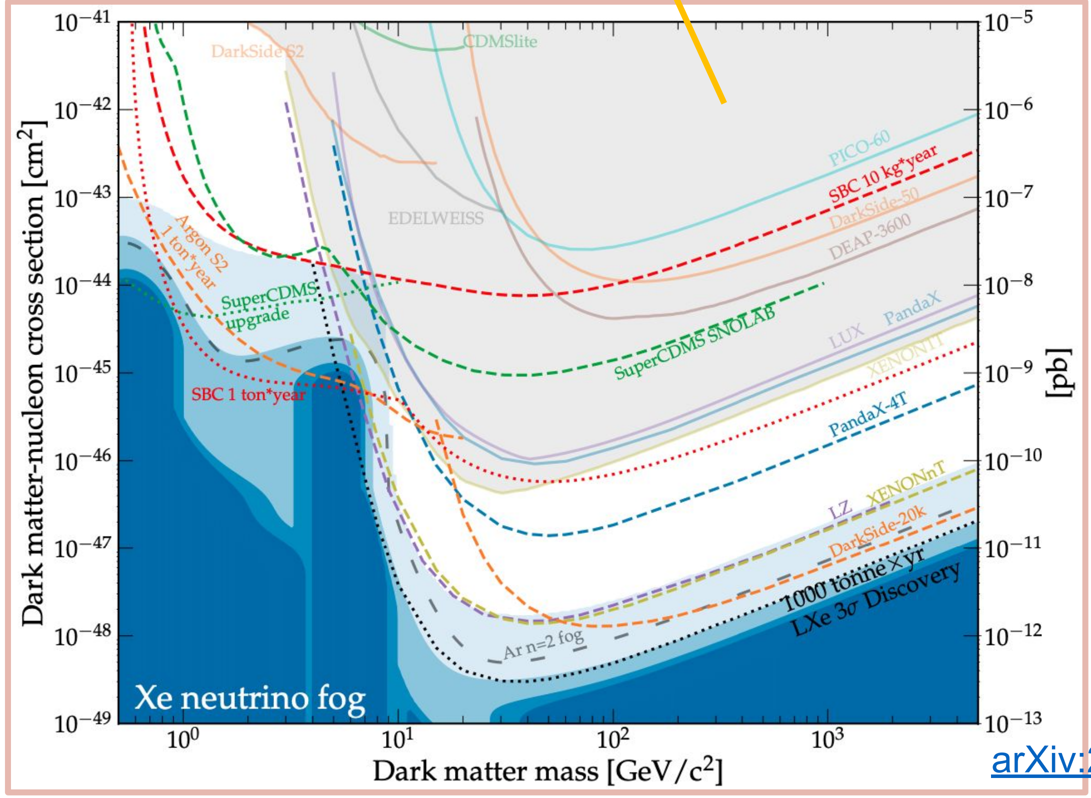
Cool down

Freeze-out

Thermal Dark Matter Mass Range

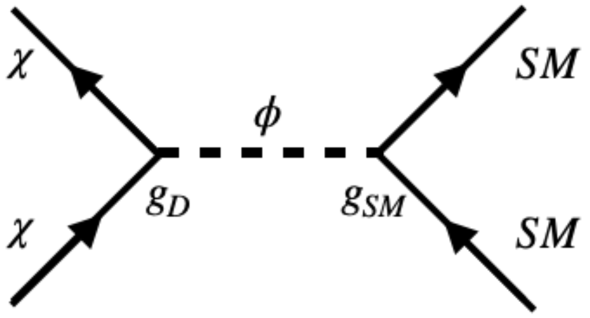


- Thermal Contact implies a new mediator
- Well motivated with hidden-sector models
- Largely unexplored



arXiv:2203.08084

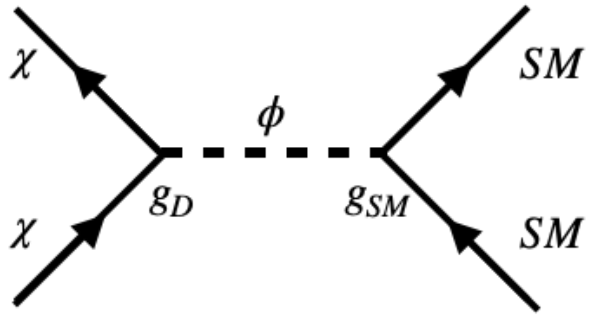
Light Thermal Dark Matter - Hidden Sector



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

- Freeze-out scenario with **Light Dark Matter (LDM)** requires **new light mediator** to provide the correct relic abundance
- Dark Matter can belong to a **“hidden sector”** secluded from the SM
- Mutual interaction mediated by a massive gauge boson

Light Thermal Dark Matter - Hidden Sector



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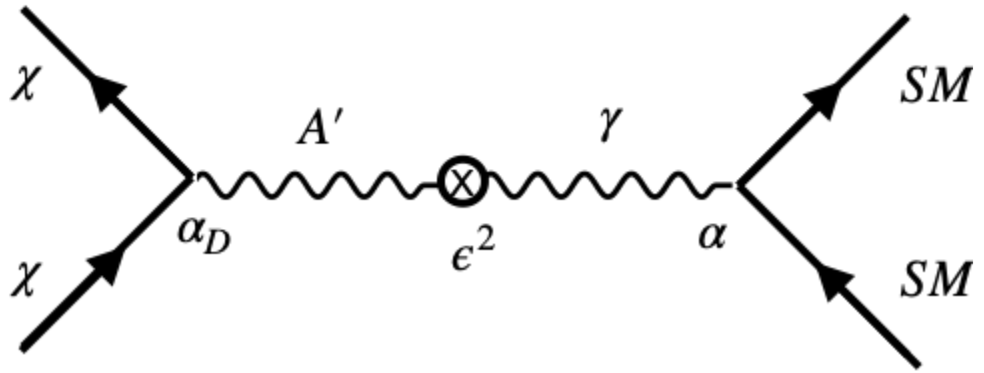
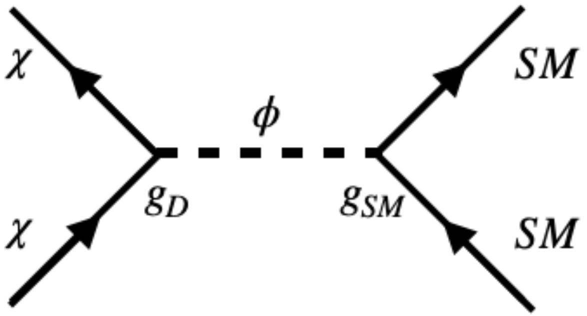
- Additional spin-one gauge boson "**dark photon *A'*** ", neutral under SM, hidden symmetry ***U(1)***$_D$
- Kinetically mixing with SM **U(1)**$_\gamma$ with factor ϵ
- Visible and invisible final states



Light Thermal Dark Matter - Hidden Sector



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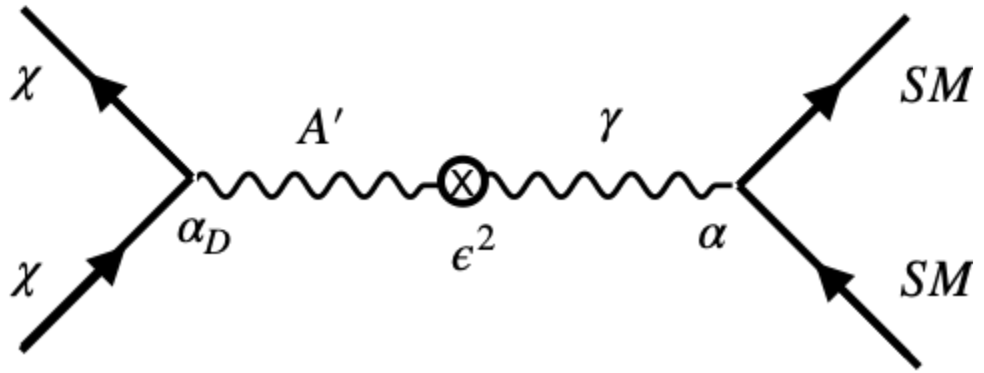
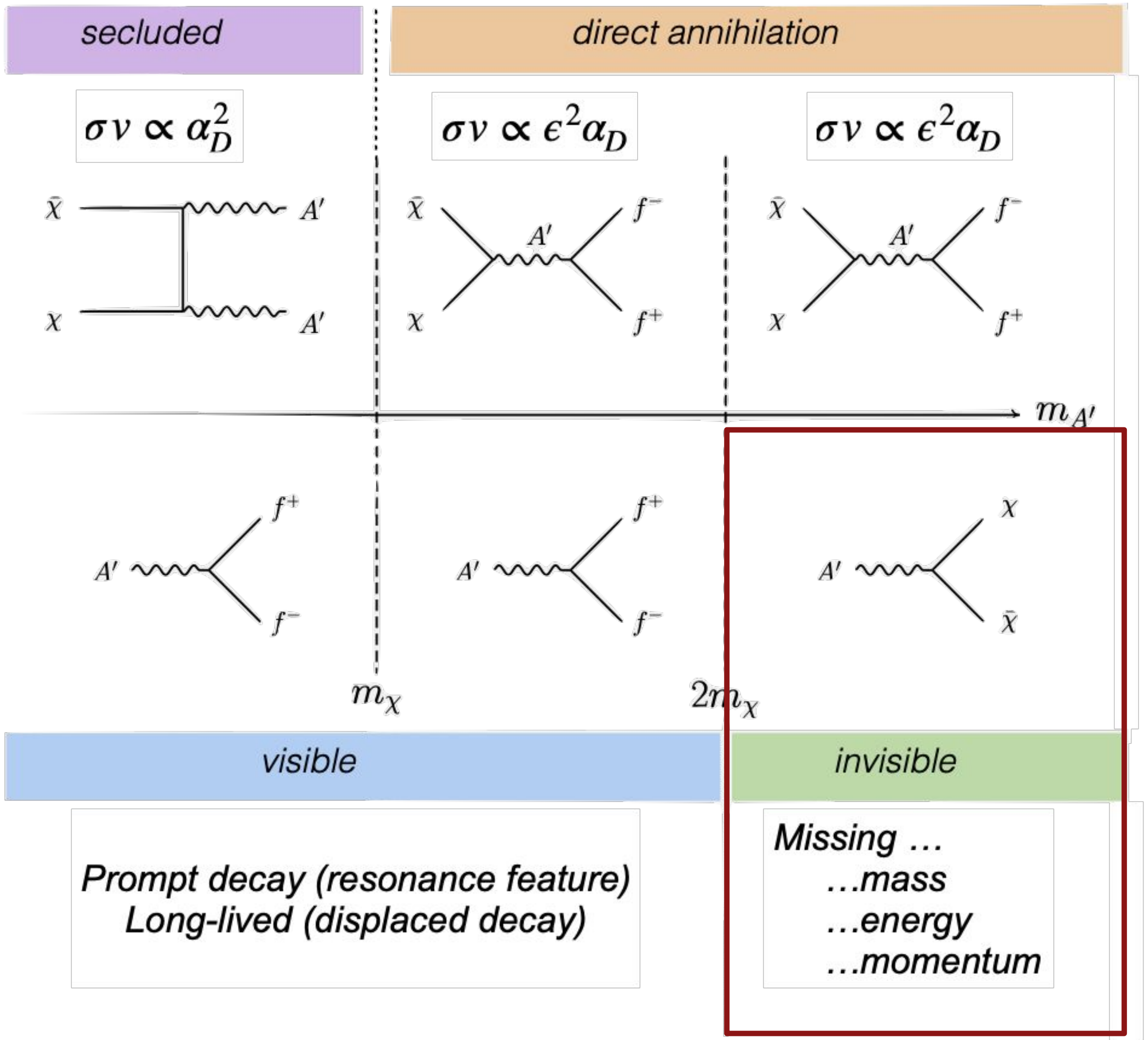


The minimal Dark Photon Dark Matter model is an ubiquitous benchmark for the physics community

Possible Dark photon signatures

A' production

A' decay



Dark Matter at Accelerators

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

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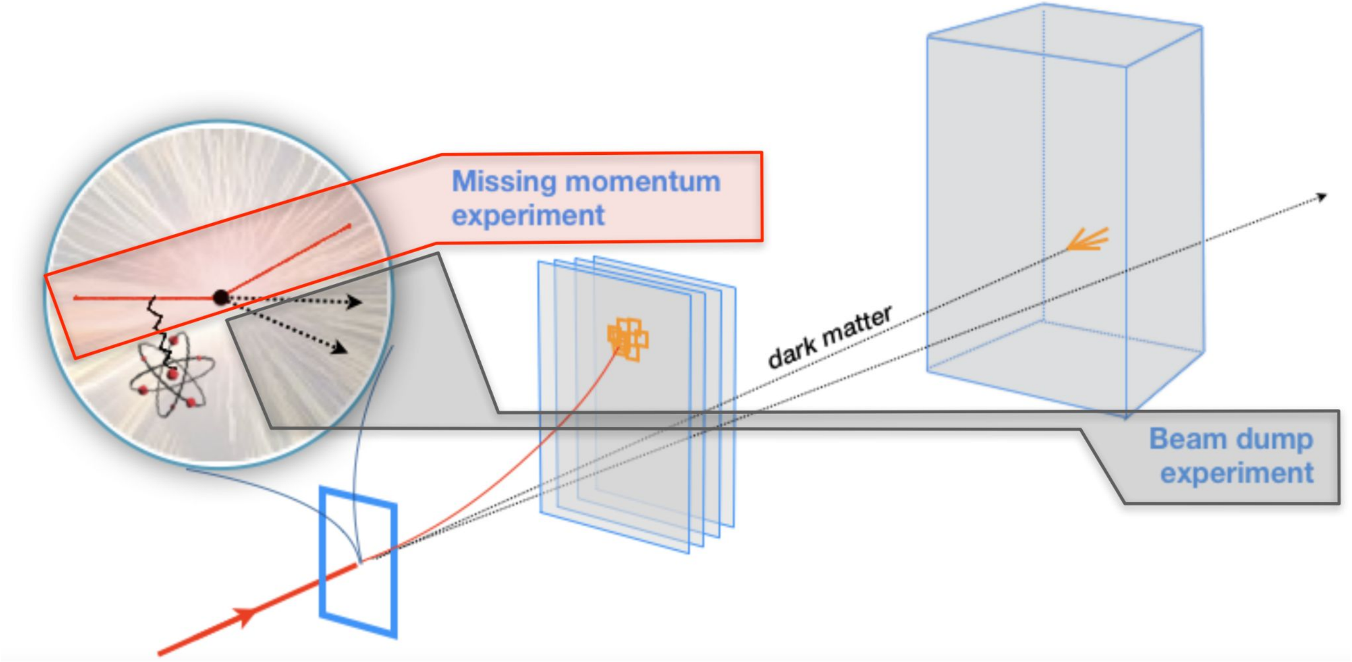
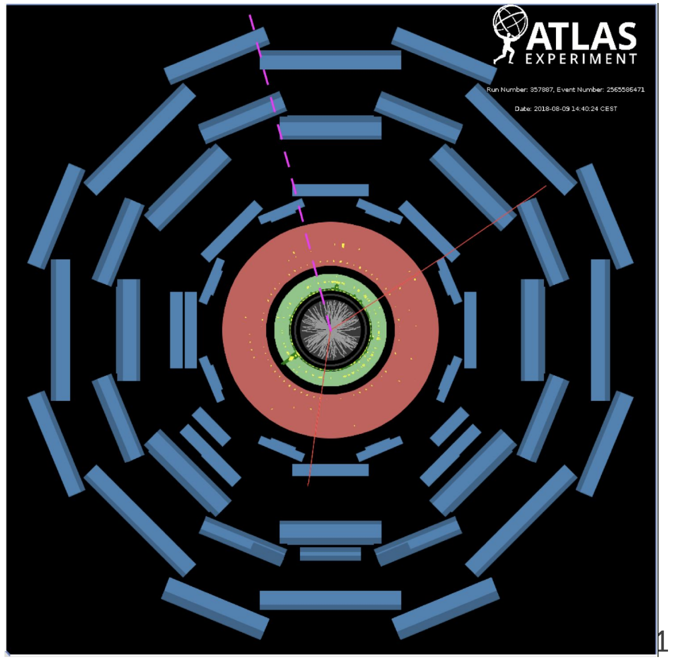
RECREATING BIG BANG DARK MATTER PRODUCTION AT ACCELERATORS

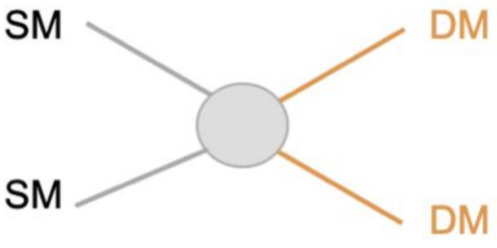
At beam-on-target facilities…

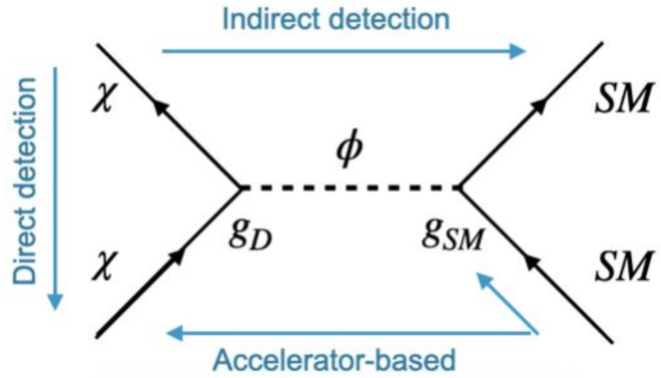


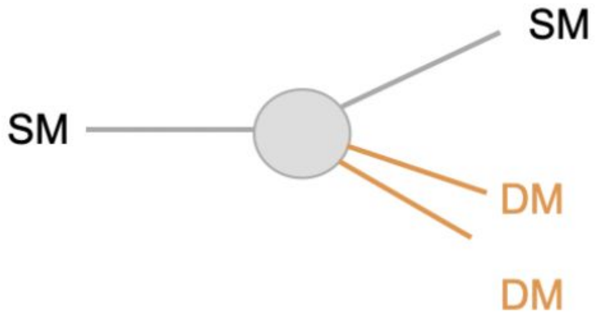
…or colliders



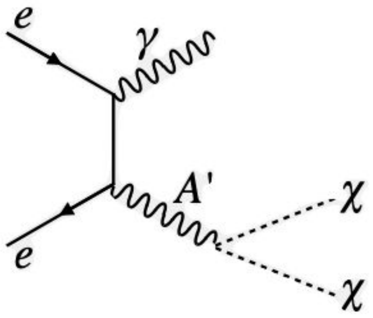
Dark Matter at Accelerators: scenarios





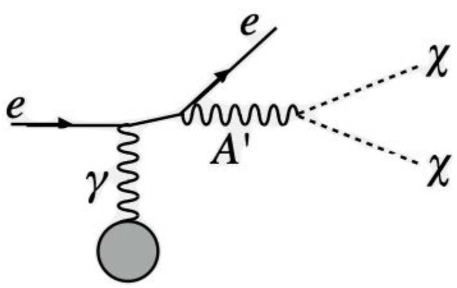


Collider



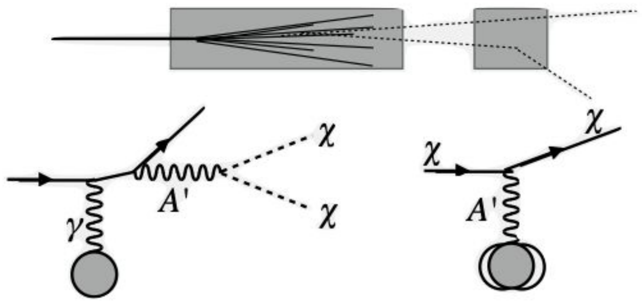
$\sigma_{coll} \propto \frac{\epsilon^2}{E_{com}^2}$ <<

Missing Momentum



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

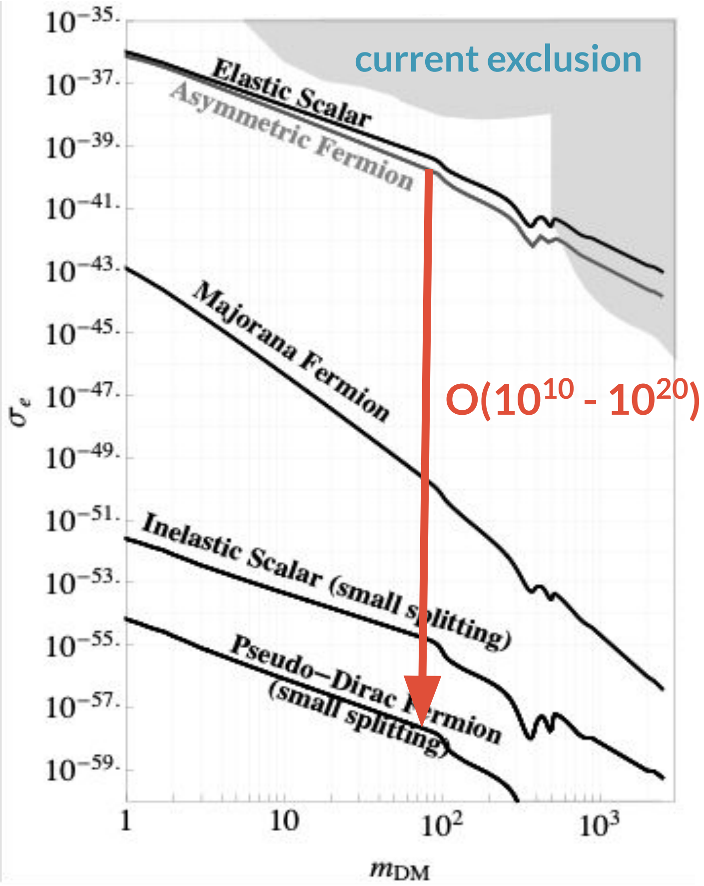
Beam dump



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

Dark Matter at accelerators: advantages

- **Direct Detection**
  - Strong velocity / spin dependence of scattering spreads out direct detection cross sections



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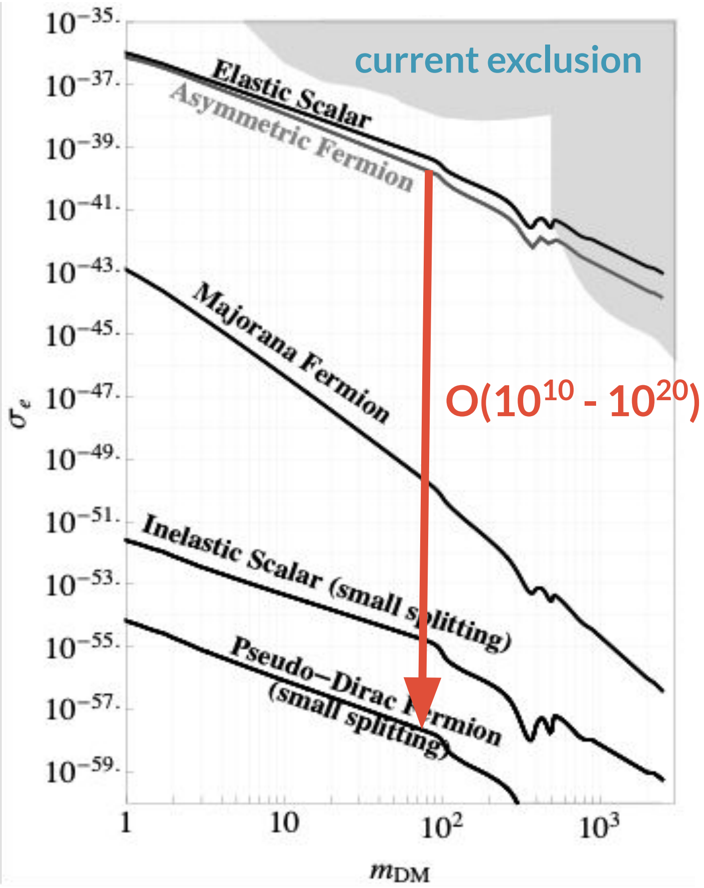
$$< \sigma v > \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim y \frac{1}{m_\chi^2}$$

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



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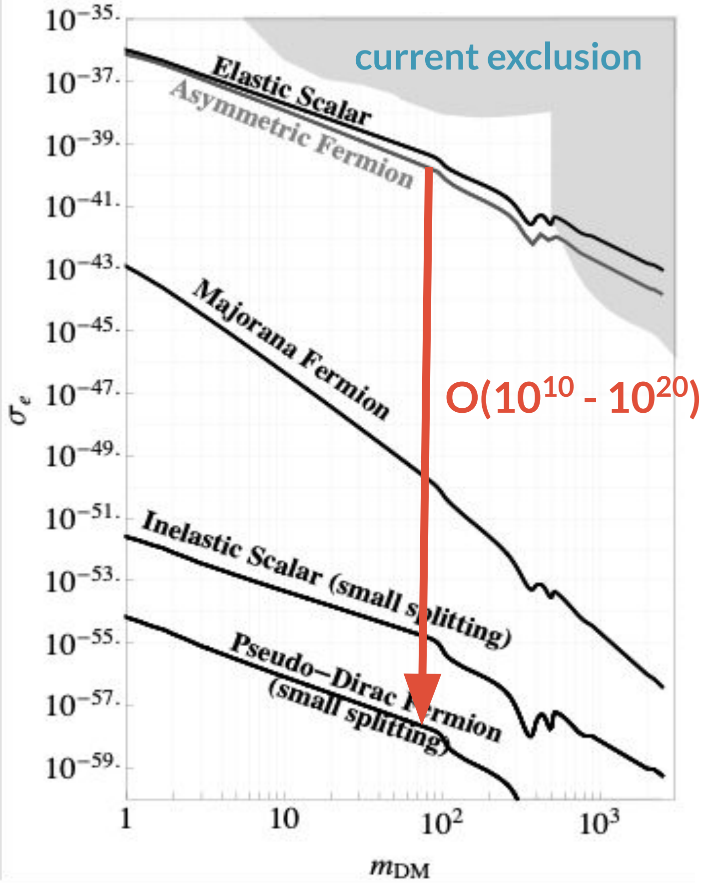
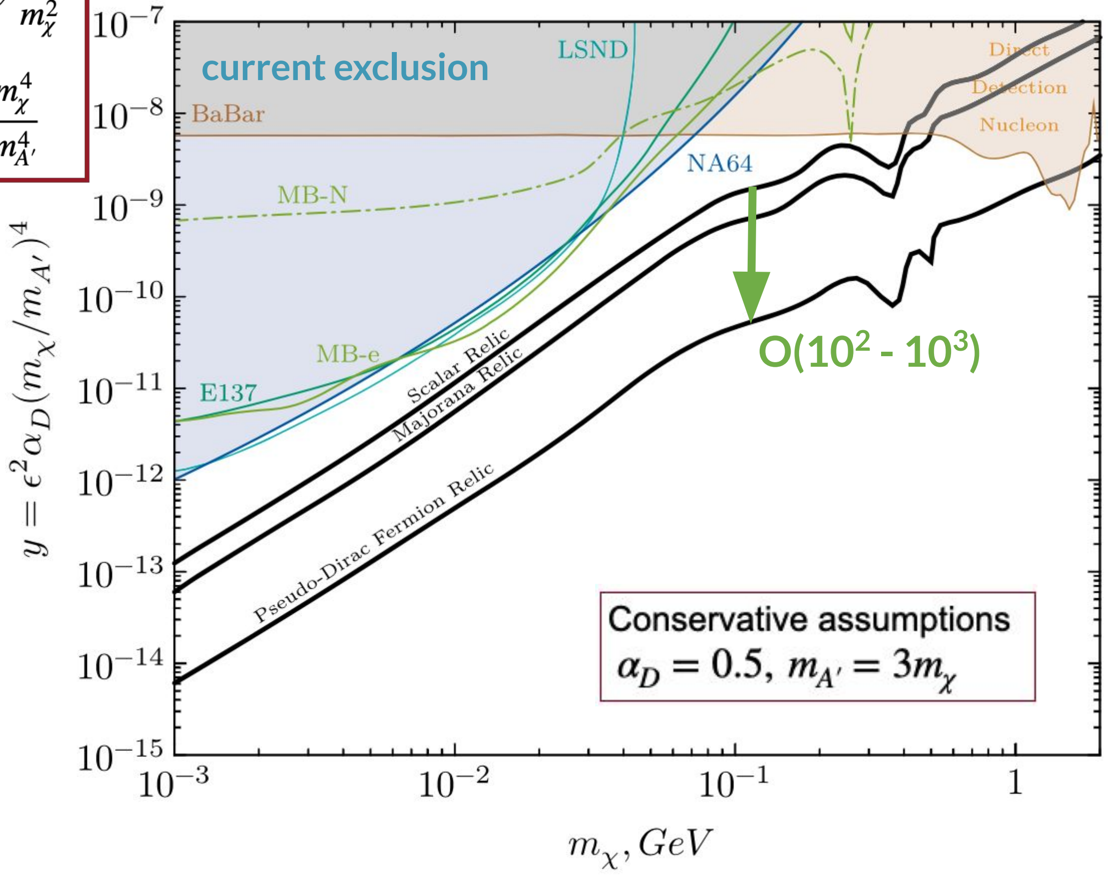
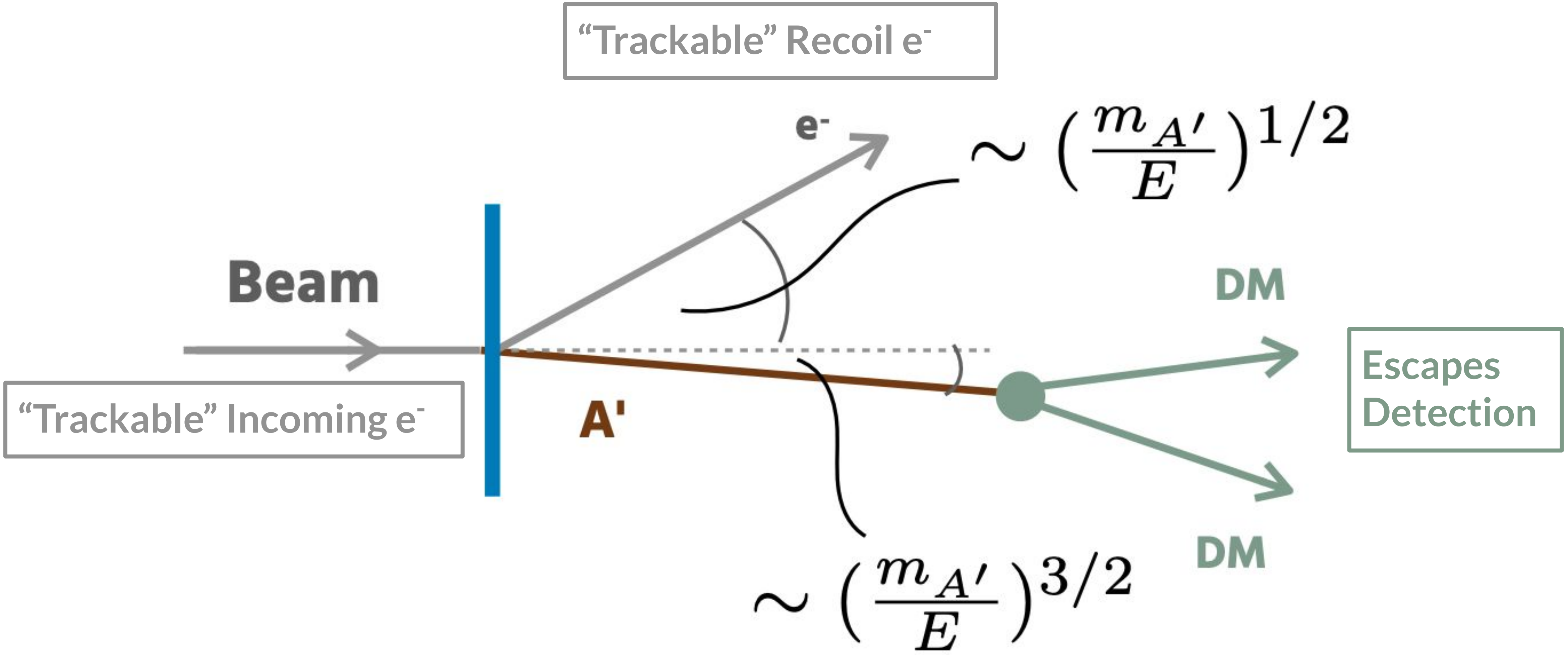


- **Accelerator Production:**
  - Range of freeze-out interaction strengths much more compact
  - All thermal targets within reach



Dark Photon kinematics at a Fixed Target Experiment



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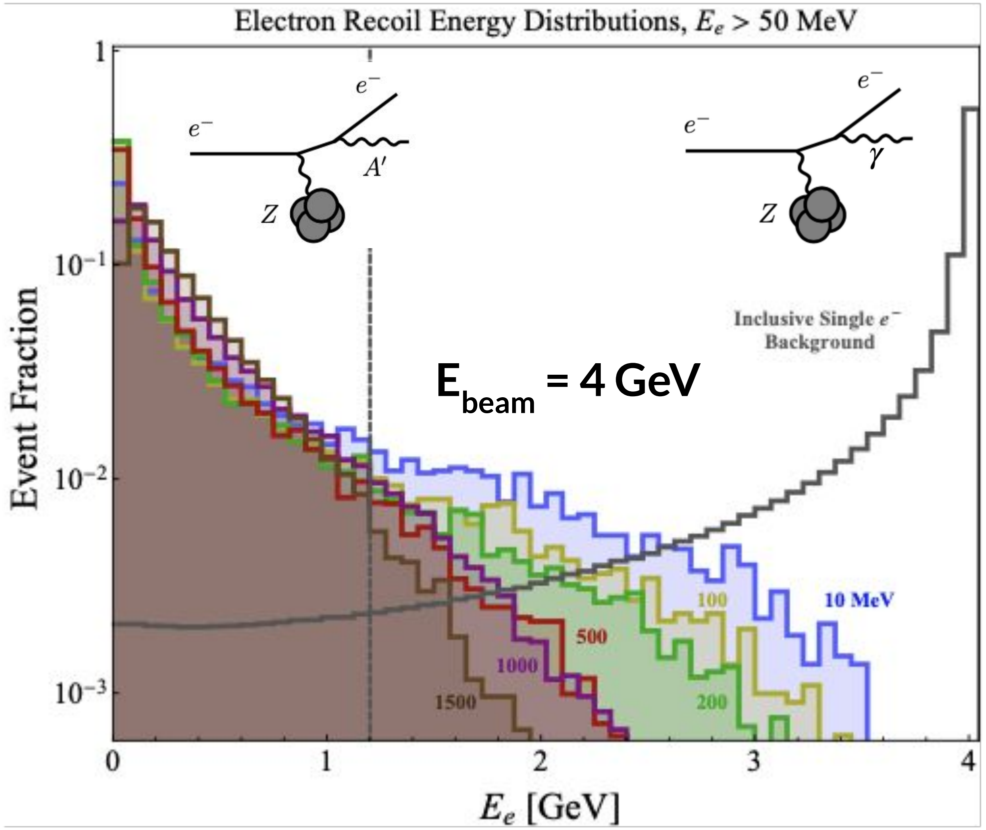
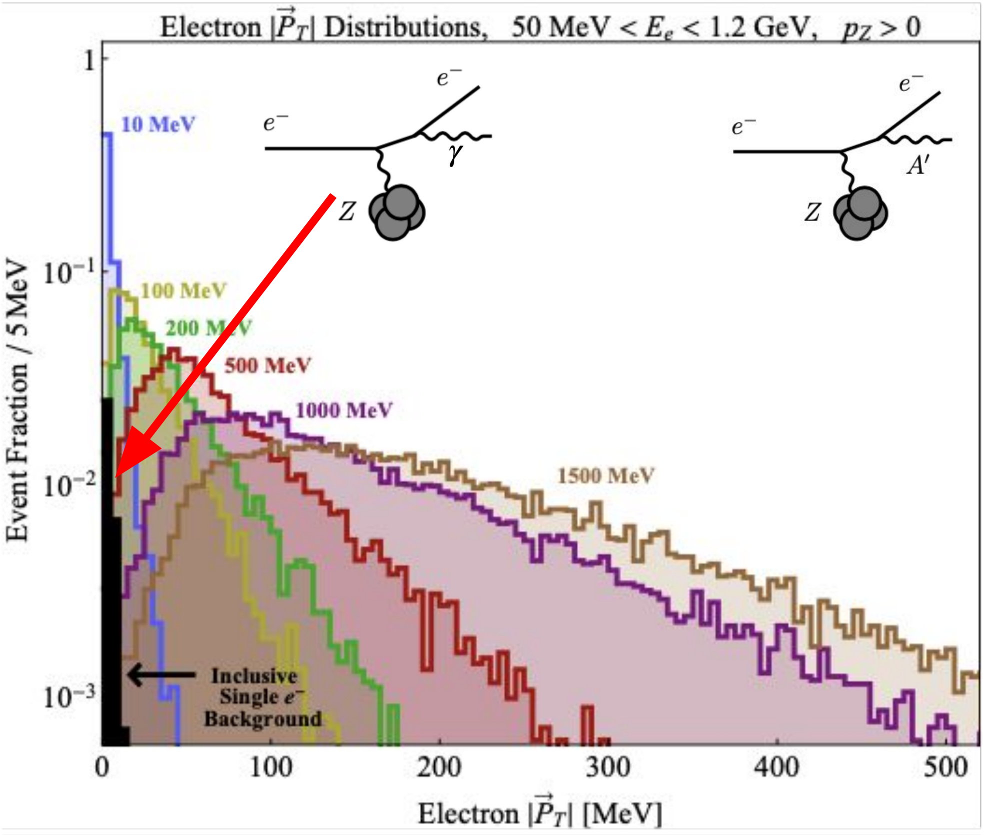
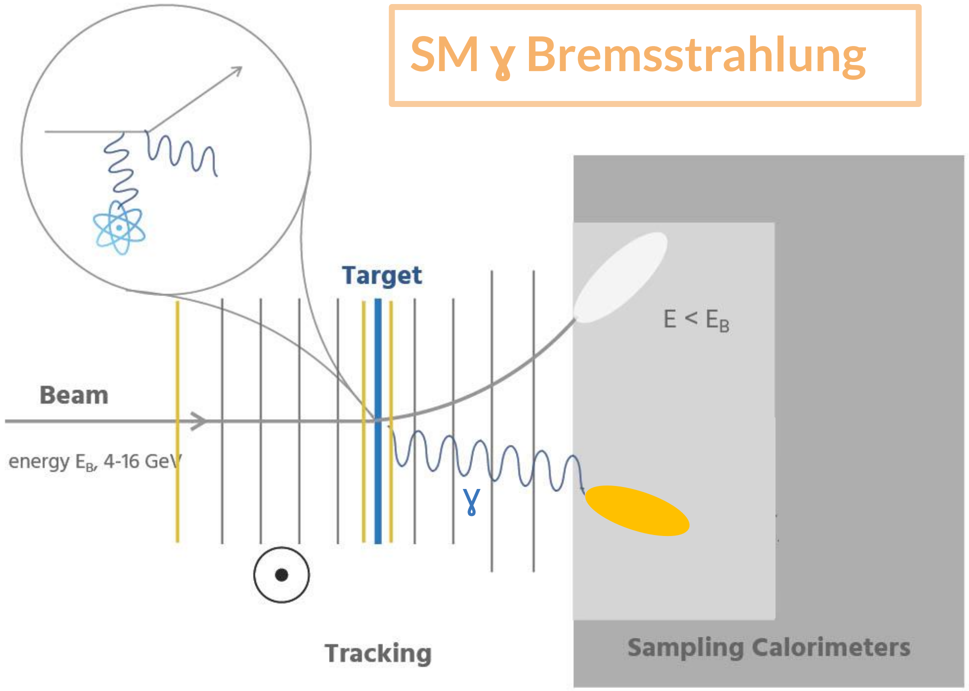




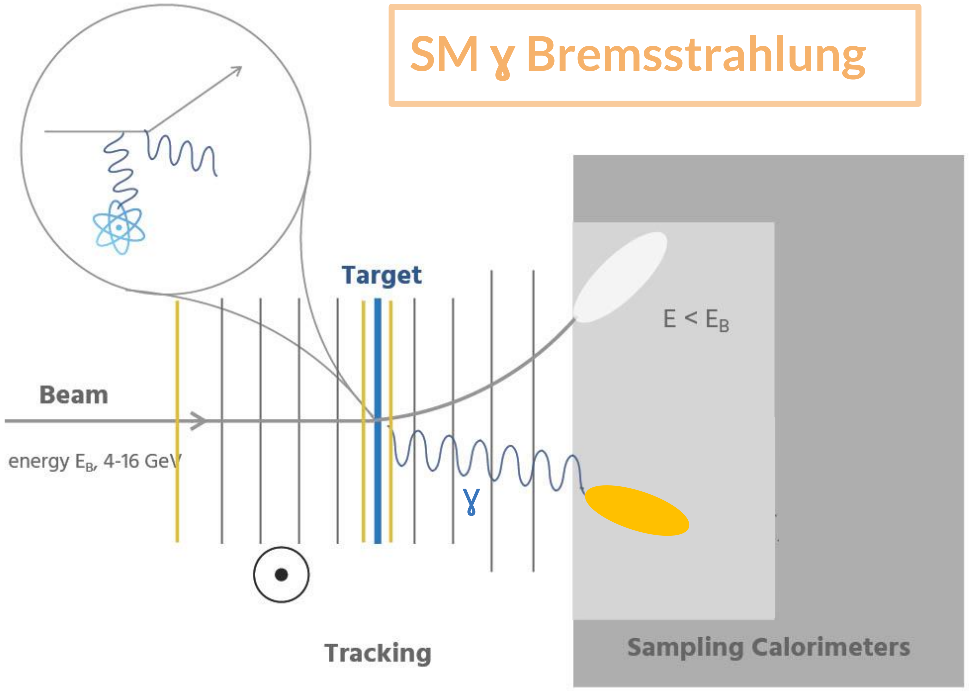
- **A'→χχ carry away most of the beam energy and escape undetected**
  - Opposite behaviour for the bremsstrahlung emission
- **Recoil electron p_T spectrum depends strongly on m_A for signal**
  - Signal identification or extra-handle for background rejection

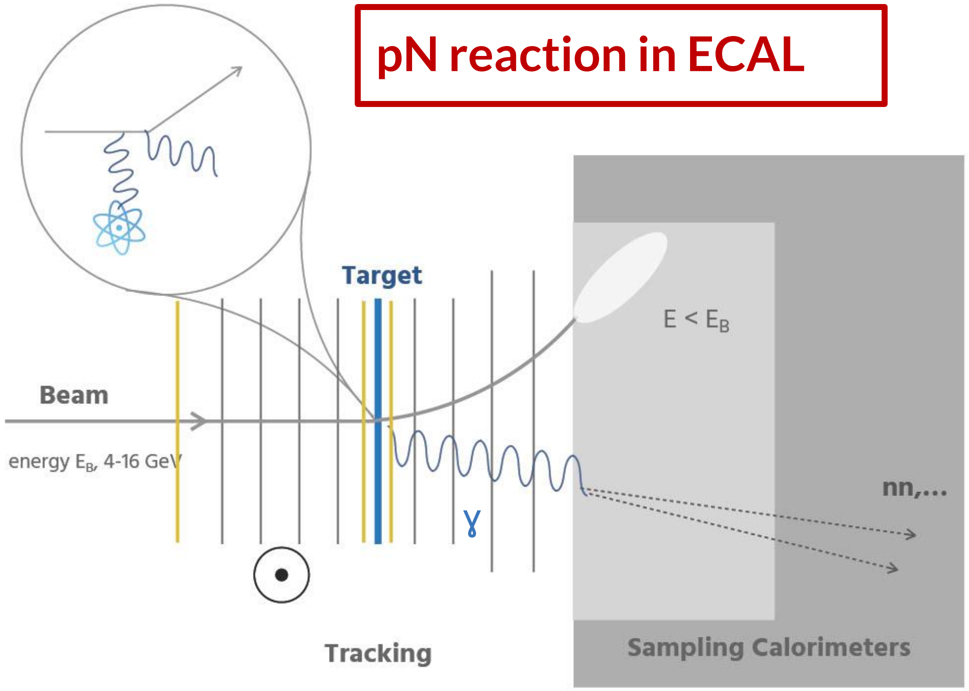
Background processes



- **Main background:**
  - **SM ɣ Bremsstrahlung**
  - Vetoed by energy deposit in an electromagnetic calorimeter
  - Precise incoming electron momentum measurement

Background processes

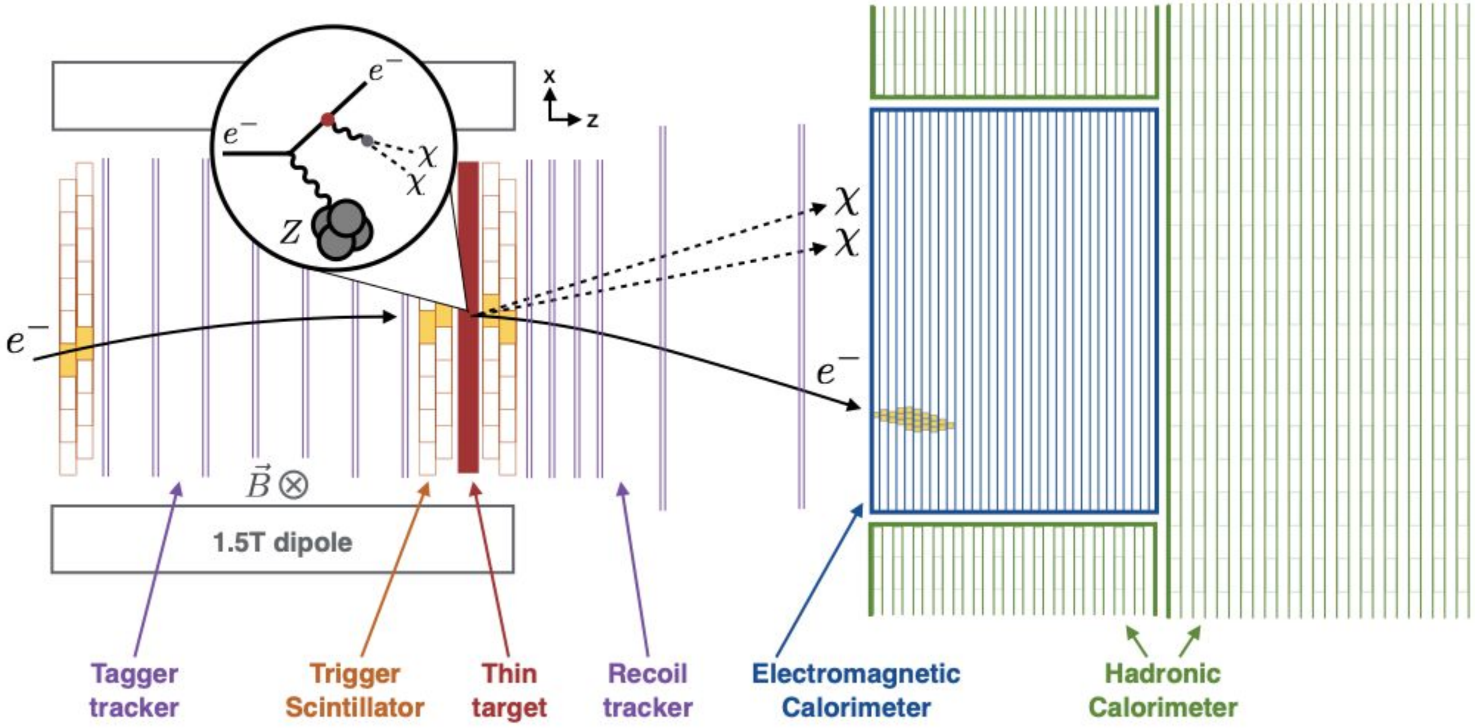




- **Main background:**
  - **SM ɣ Bremsstrahlung**
  - Vetoed by energy deposit in an electromagnetic calorimeter
  - Precise incoming electron momentum measurement

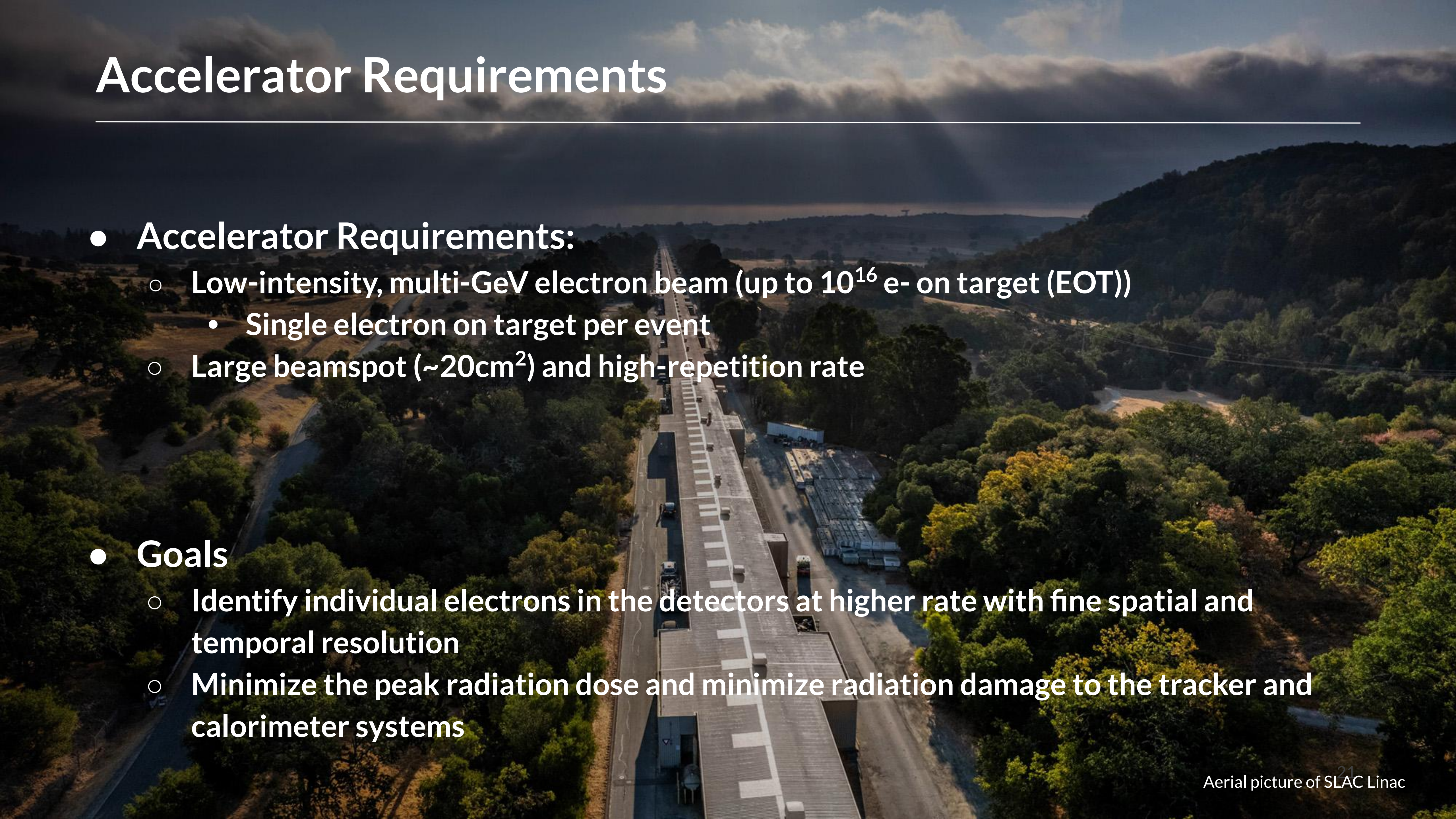
- **Challenging background:**
  - **Photo-Nuclear reactions producing neutral final states**
  - Rare reaction where photon leads to low deposited energy in the calorimeters
  - Relative rate with respect to Bremsstrahlung ~10^{-8} - 10^{-11}

LDMX: Detector Design Drivers



- **Flagship objective: missing momentum signatures**
  - **Recoil electron** with energy much lower than beam and transverse momentum kick across the target.
  - **Absence of any other particle** with significant energy **in the final state**

Accelerator Requirements



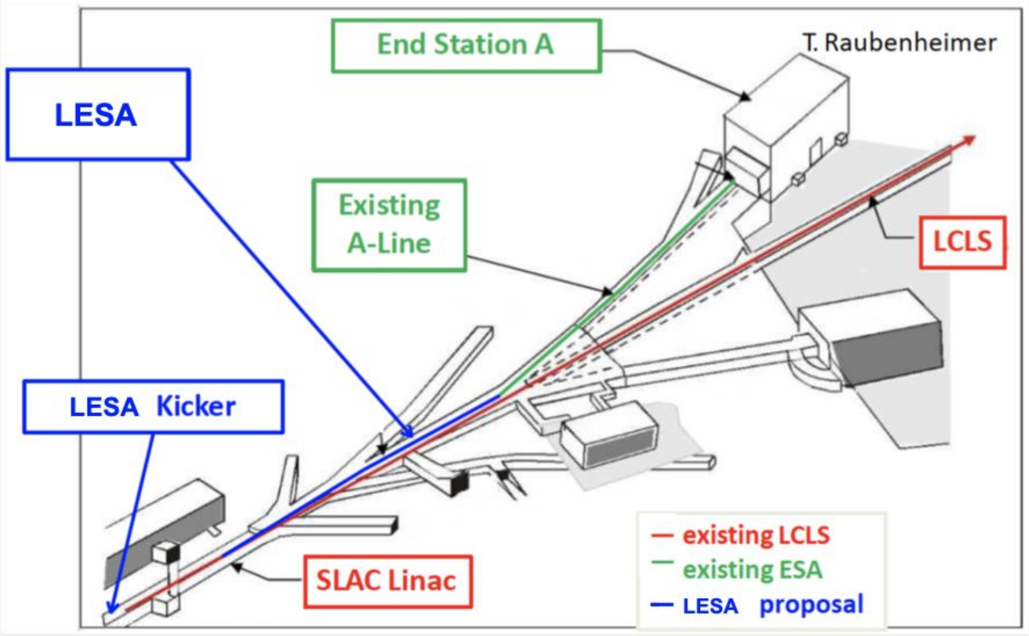
- Accelerator Requirements:
  - Low-intensity, multi-GeV electron beam (up to 10^{16} e- on target (EOT))
    - Single electron on target per event
  - Large beamspot (~$20cm^2$) and high-repetition rate

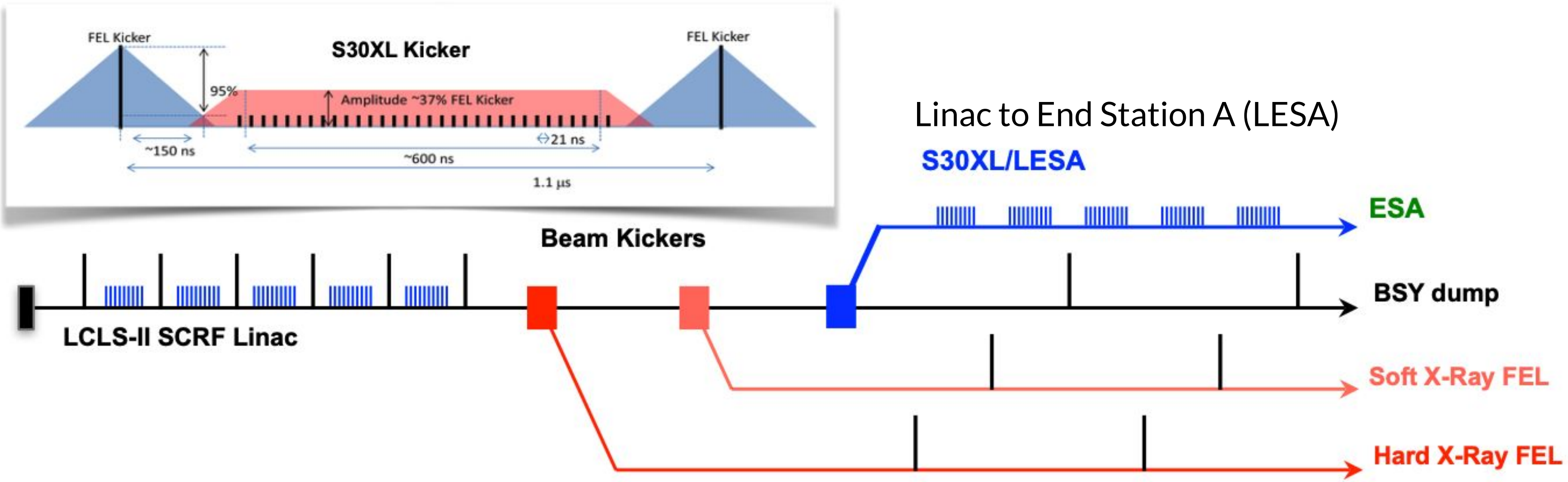
- Goals
  - Identify individual electrons in the detectors at higher rate with fine spatial and temporal resolution
  - Minimize the peak radiation dose and minimize radiation damage to the tracker and calorimeter systems

Aerial picture of SLAC Linac

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





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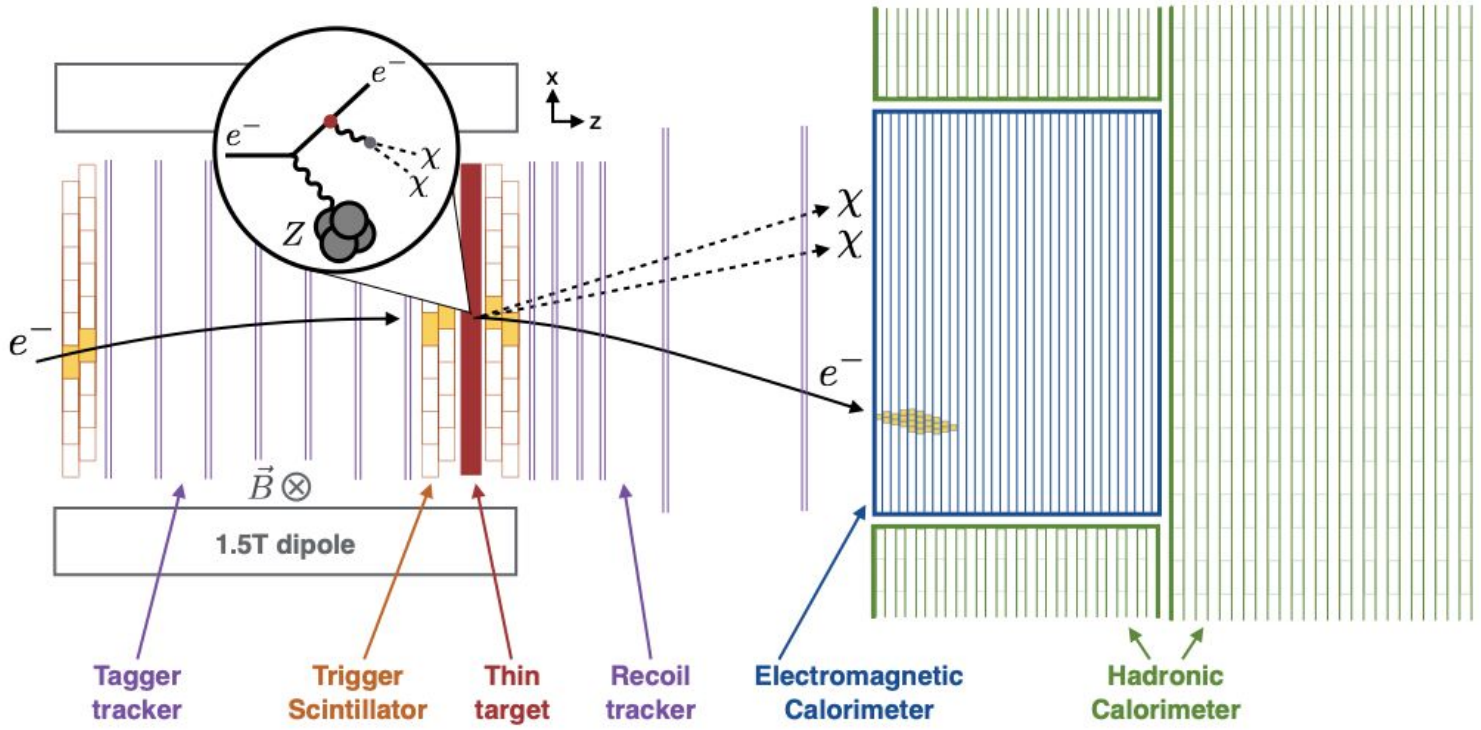
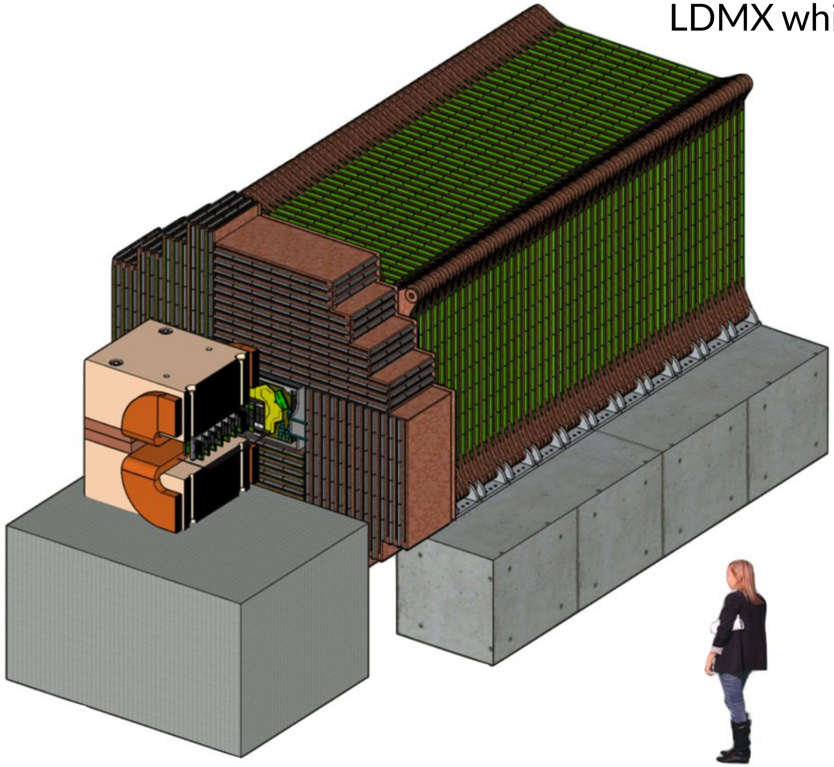
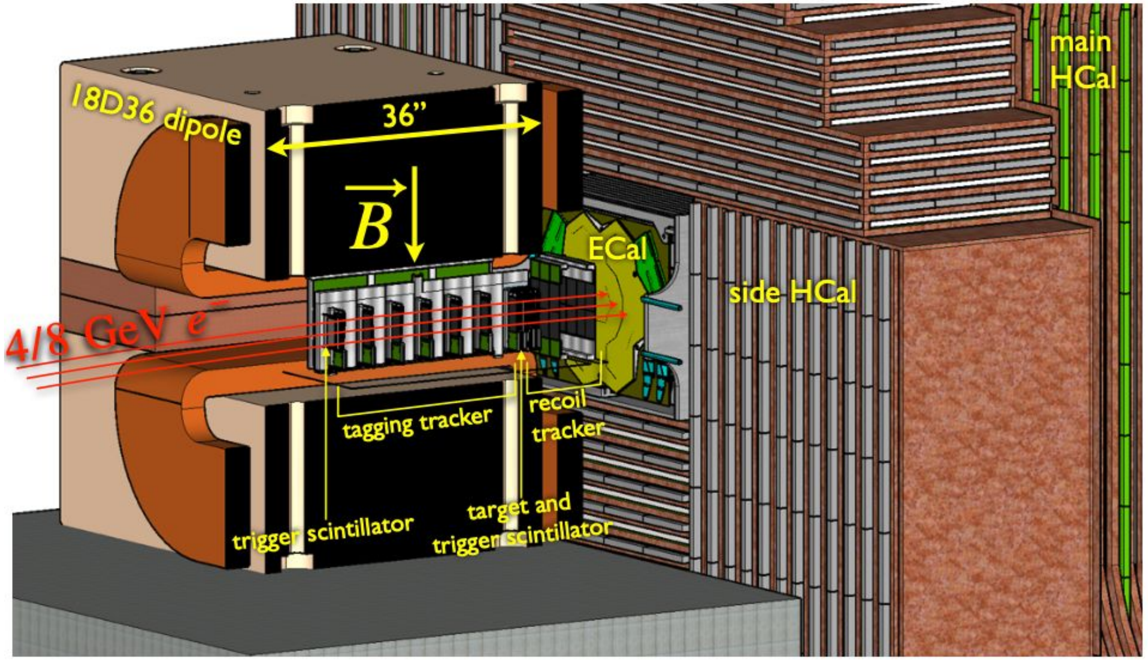


- Flagship objective: missing momentum signatures
  - **Recoil electron** with energy much lower than beam and transverse momentum kick across the target.
  - **Absence of any other particle** with significant energy **in the final state**
- **High efficiency SM background veto**
  - **Resolve** recoil electron energy and momentum to separate from bremsstrahlung events
  - **Eliminate** rare neutral background events originating from pN reactions in the calorimeters

The LDMX Detector Concept

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

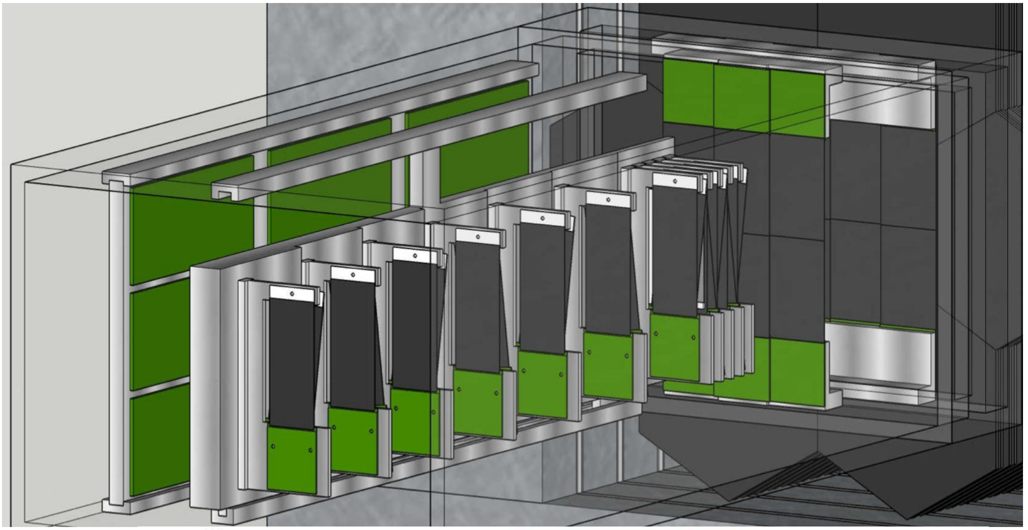


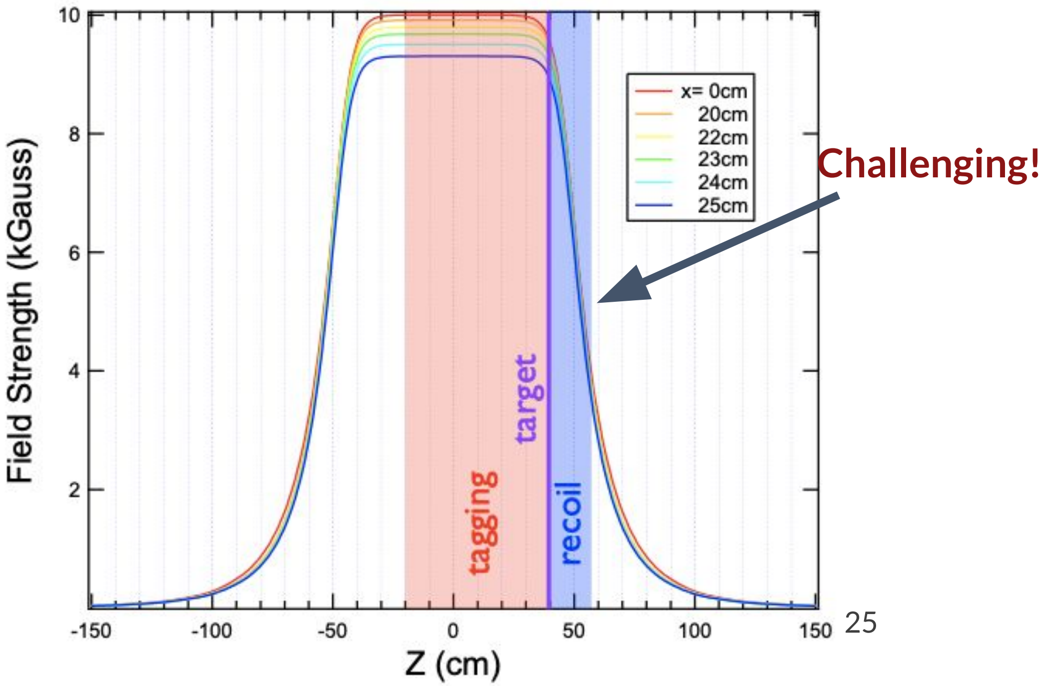


- **Detector Design**
  - **Tagger Tracker** with low acceptance and high resolution at beam energy
  - **Recoil Tracker** with large acceptance and high resolution at low particle momenta
  - **Electromagnetic calorimeter** with excellent sensitivity and granularity for EM/Had shower shapes determination and Minimum Ionizing Particles (MIP) tracking capability and for Missing Energy trigger
  - **Hadronic calorimeter** with good segmentation and very low energy veto threshold for neutral hadrons
  - **Trigger scintillator** for fast electrons-per-bunch counting

The Magnet and Tracker System

- **Beamline**
  - **Dipole** magnet up to 1.5 T
- **Trigger Scintillator**
  - Arrays of scintillator bars for fast electron counting
- **Tracker System design**
  - Leverage experience, facilities and equipment from Heavy Photon Search SVT tracker built at SLAC
- **Tagger Tracker**:
  7 double-strip layers, high p-resolution (σ_u~6 um σ_v~ 60um)
  Recoil Tracker:
  4 double-strip layers + 2 axial-only for increased acceptance.



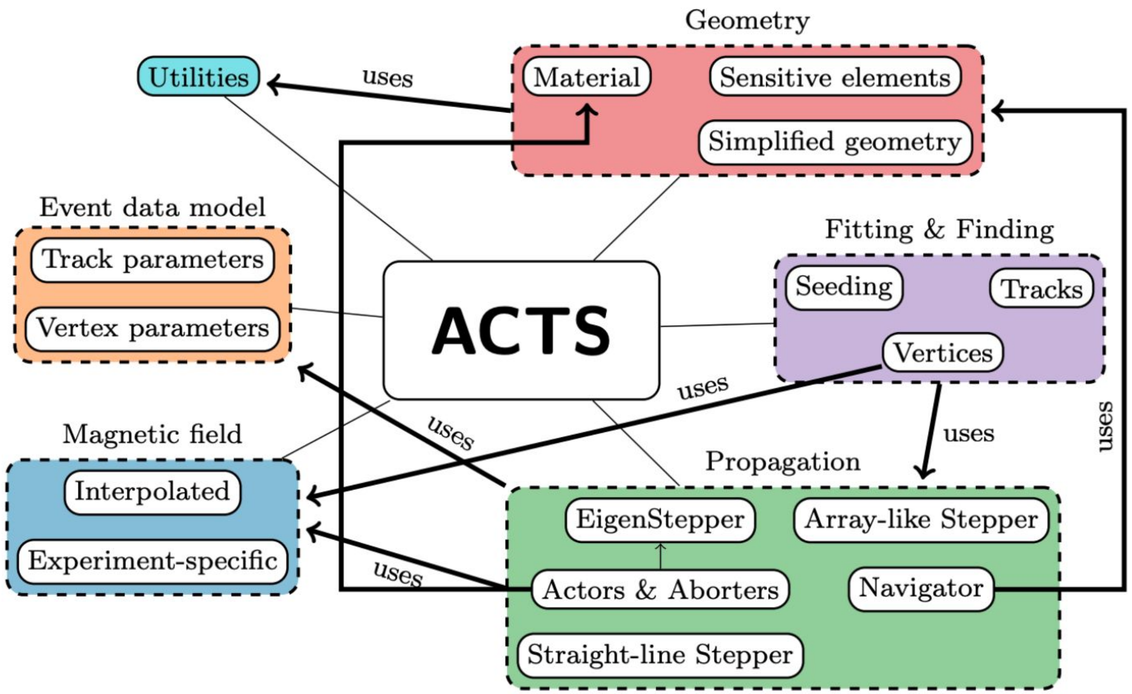


Track Reconstruction - A community effort

- **LDMX search requires high precision tracking**
- **Tagger:**
  - Off-energy beam rejection
- **Recoil:**
  - Low particle momentum regime in a strongly non uniform B-field

arxiv:2106.13593

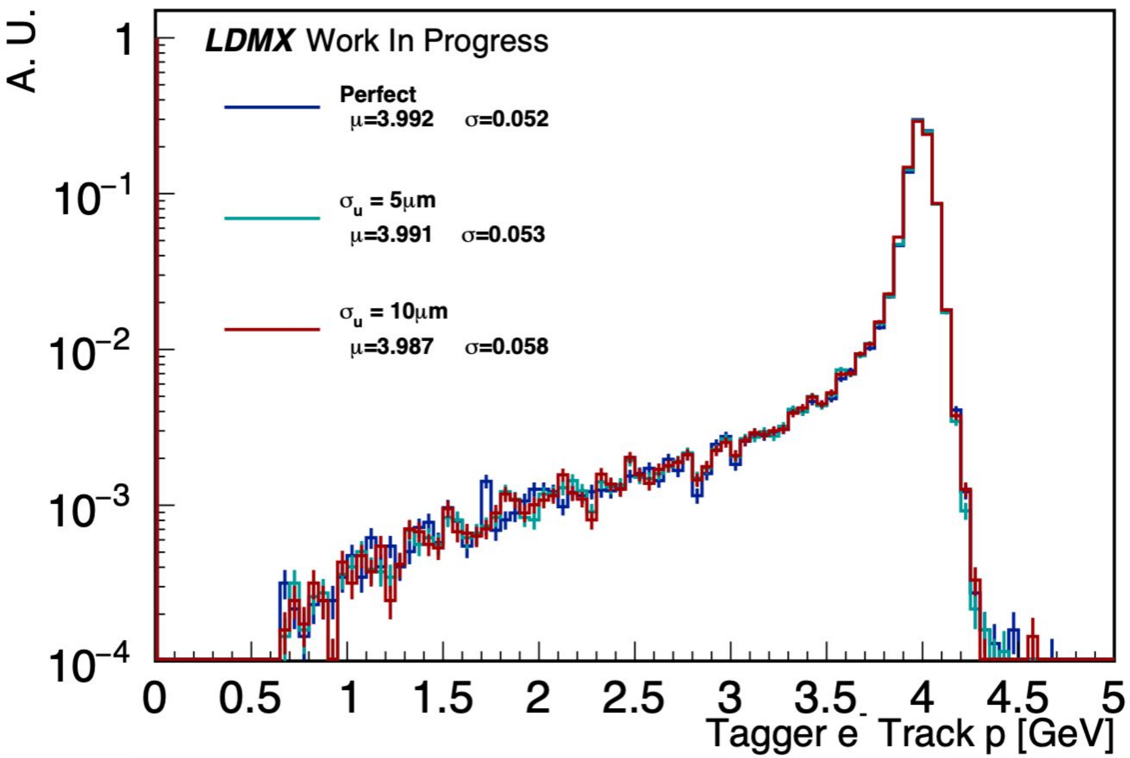
- **LDMX leverages ACTS, modern library based on well-tested reconstruction from LHC experiments**
  - Ties LDMX to the larger tracking community
  - As a small experiment → focus on physics goals using well supported tools



- **Fully implemented in the LDMX reconstruction**

Tracking - Main figures of merit

- Tagger Tracker offers **very precise incoming e$^-$ momentum** determination (σ_p ~ 50 MeV @ E_{beam} = 4 GeV)



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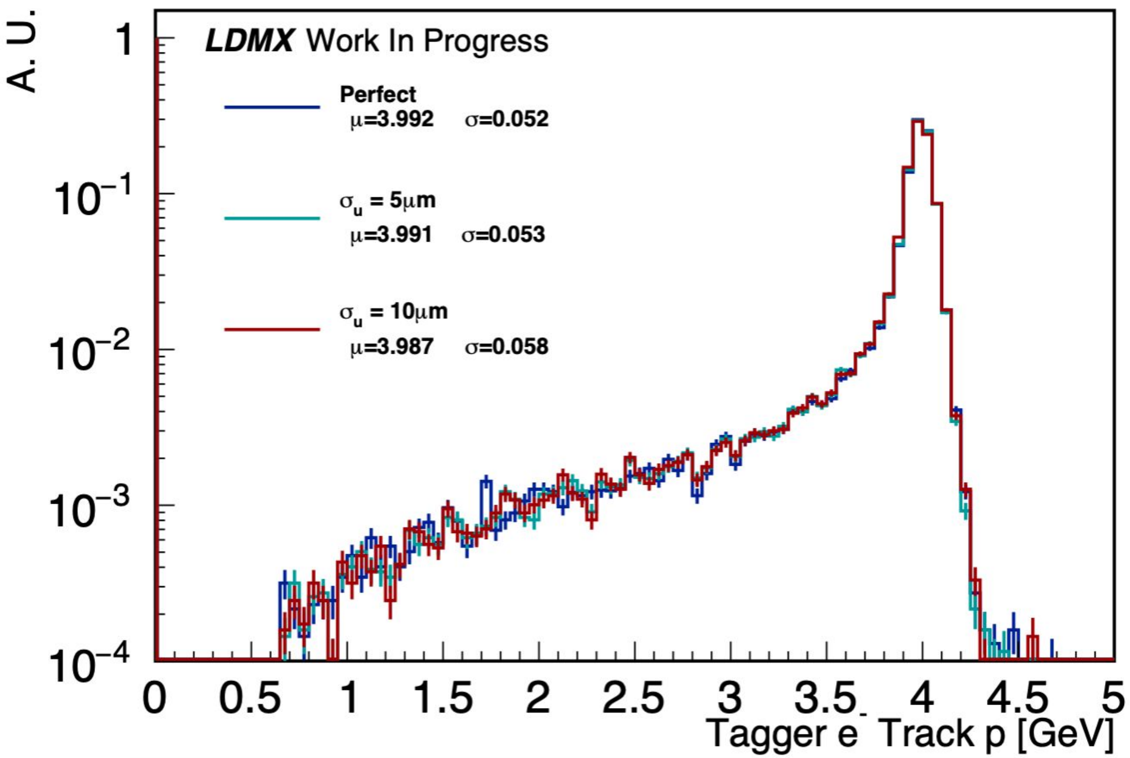
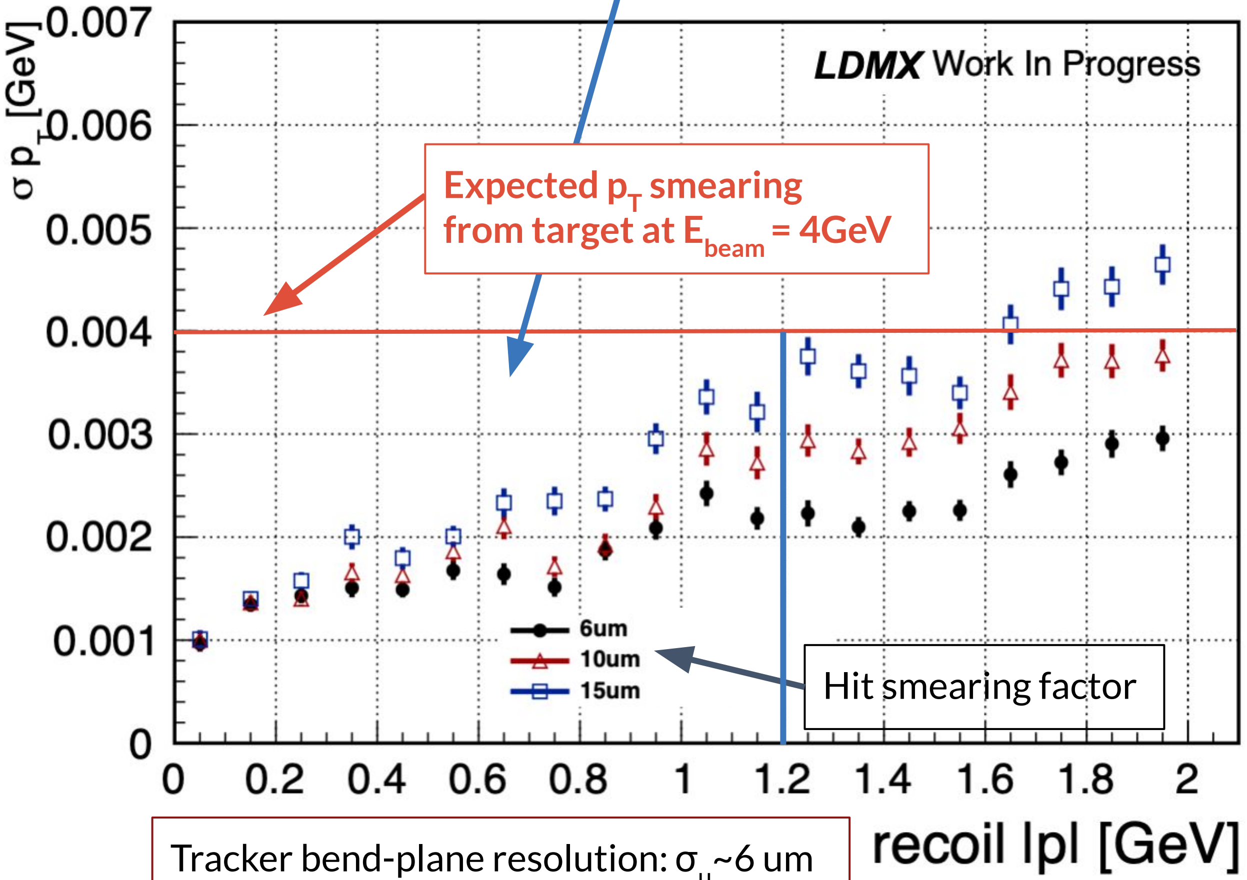


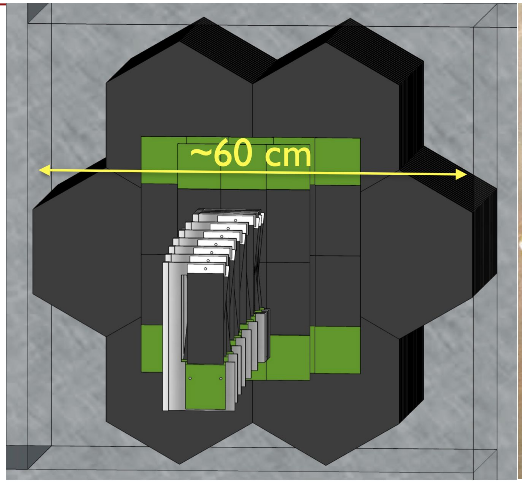
- Recoil tracker p_T resolution expected to **meet the design requirement**
  - Region of interest: p_T < 1.2 GeV

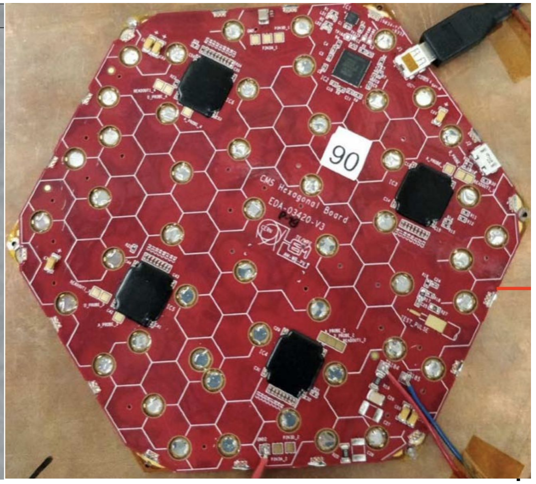


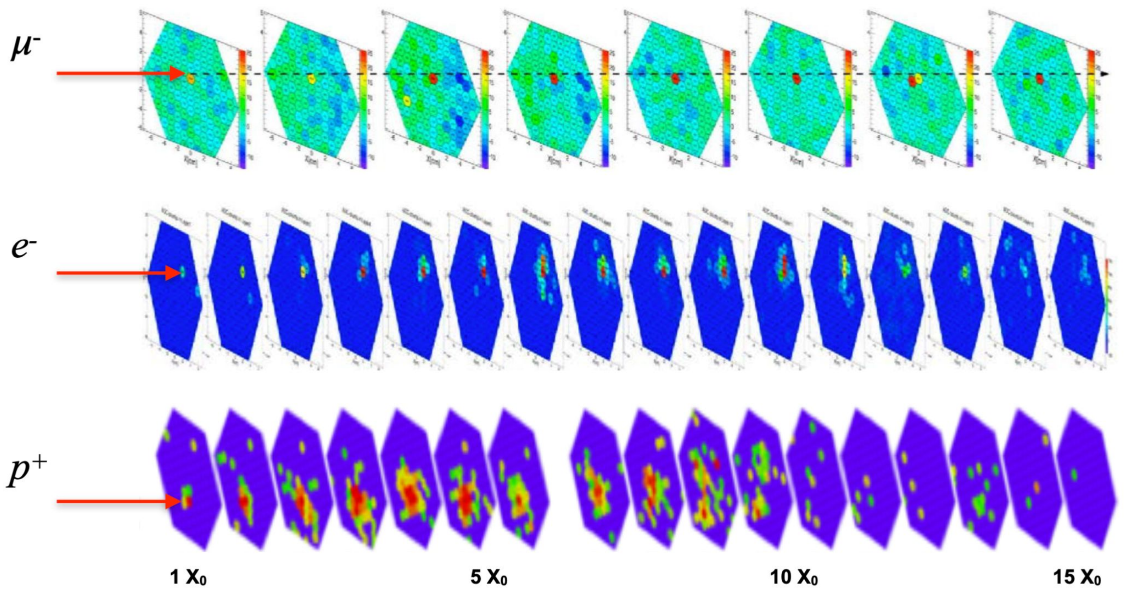
Tracker bend-plane resolution: σ_u~6 um

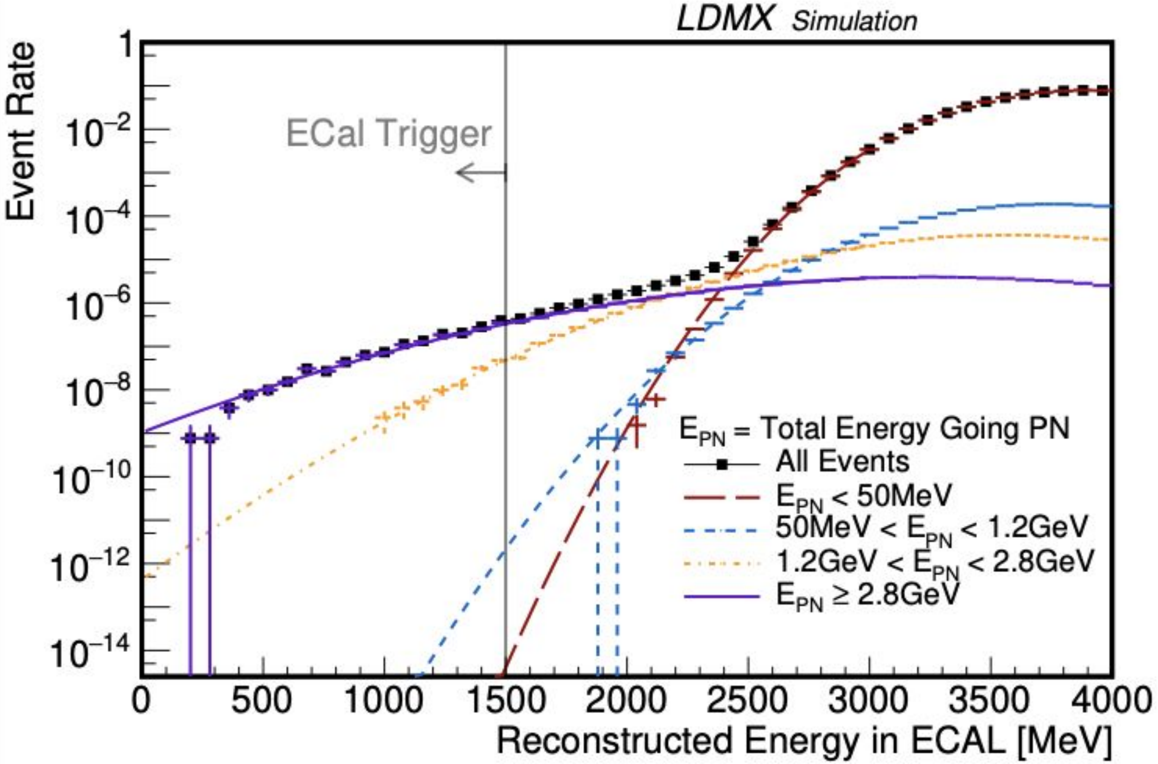
The Electromagnetic Calorimeter

- **Si-W sampling calorimeter, from CMS HGCal**
  - 32 Si Layers, ~40 X_0 depth for extraordinary shower containment
- **High-Granularity**: shower discrimination and MIP tracking to reject rare bkg, e.g $\gamma \rightarrow \mu^+\mu^-$
- **Fast Missing Energy Trigger**



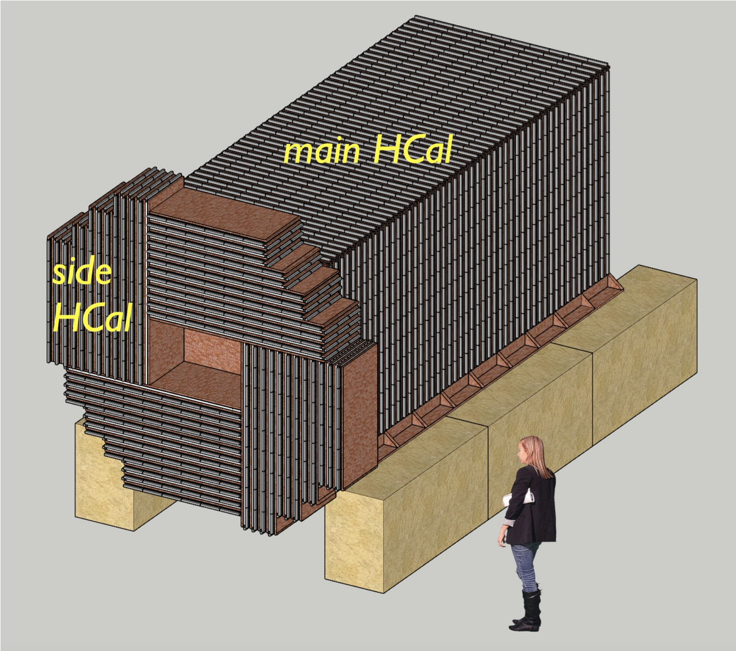


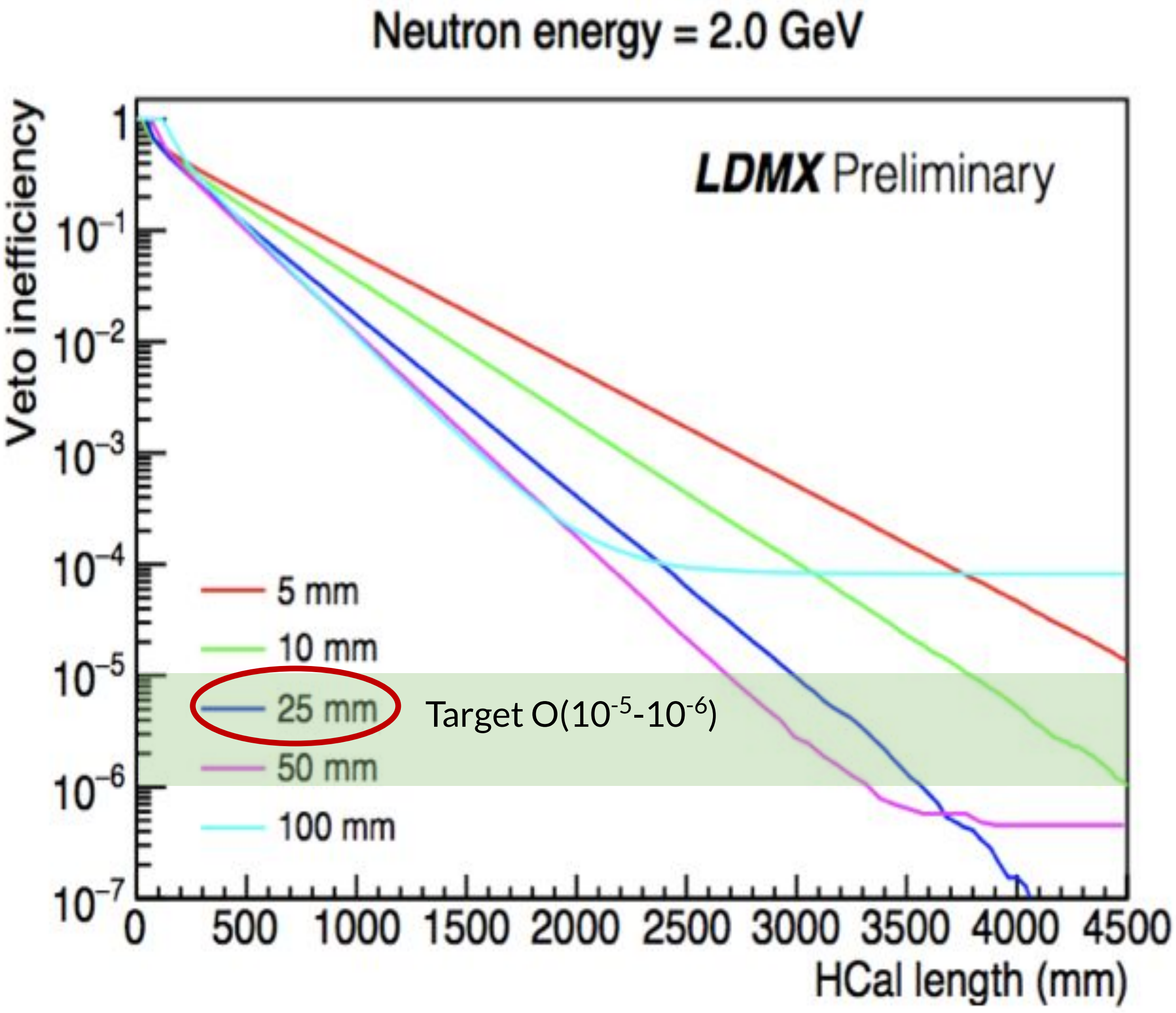




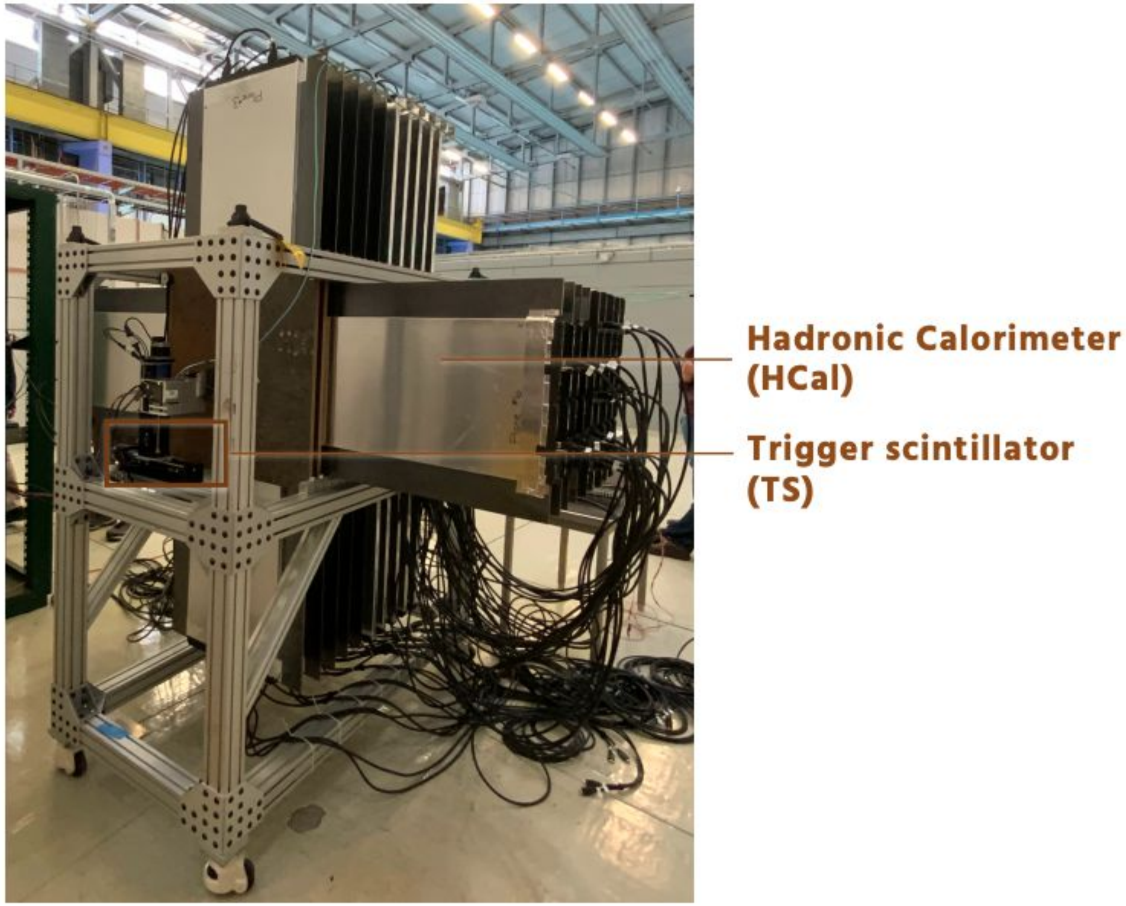
The Hadronic Calorimeter

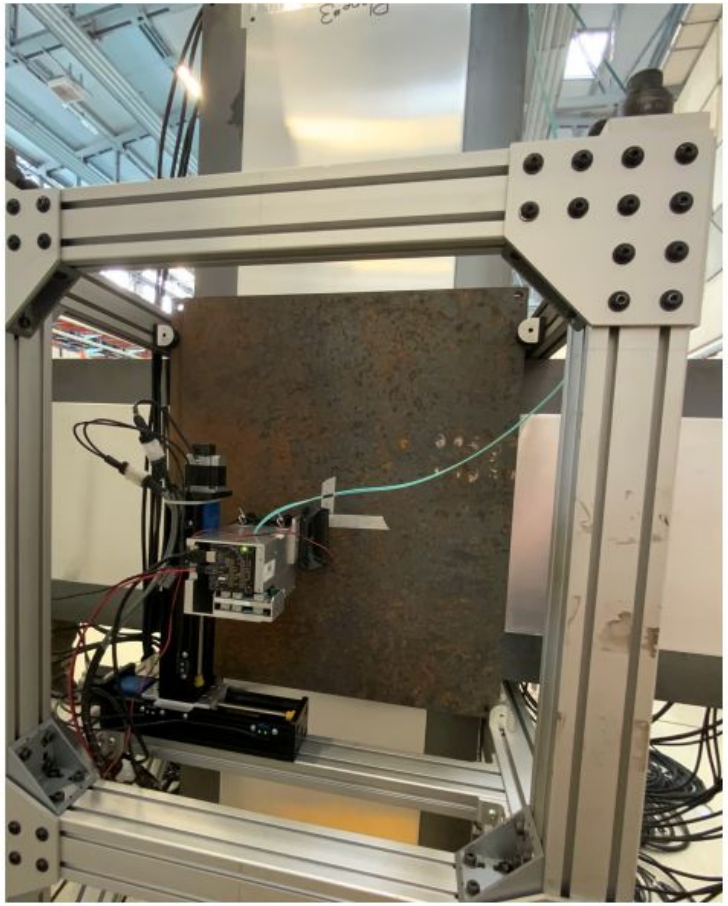
- Scintillator based sampling calorimeter, t**echnology from Mu2e Cosmic Ray Veto**
- Alternating x/y orientation
  - **High efficiency in detecting neutrons in the 0.1-10 GeV range**
  - MIP Sensitivity
- **Side HCAL design optimized for high-multiplicity final state and wide angle bremsstrahlung**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





The LDMX Testbeam at CERN - Prototypes

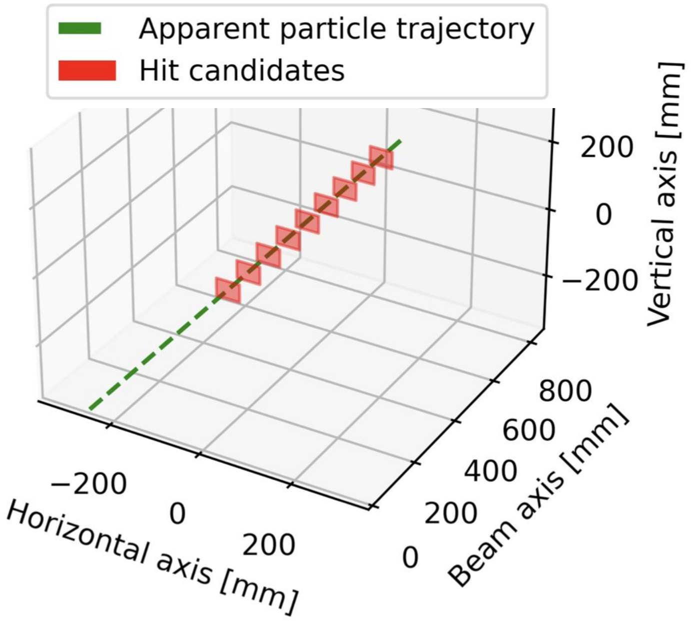


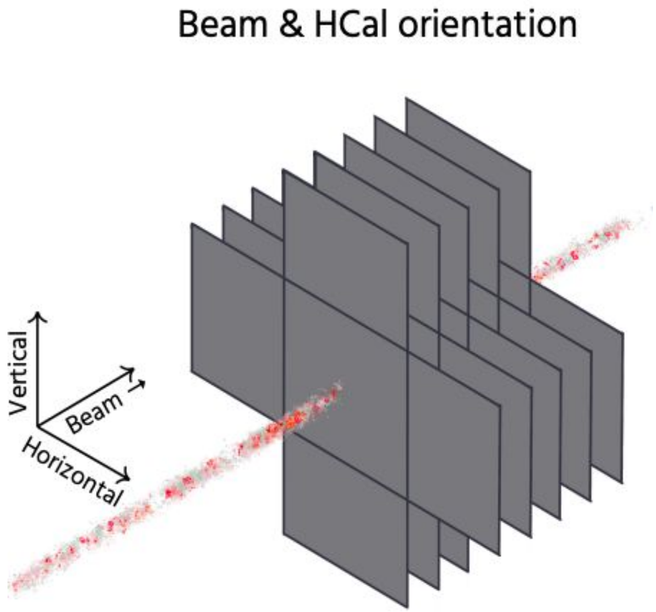


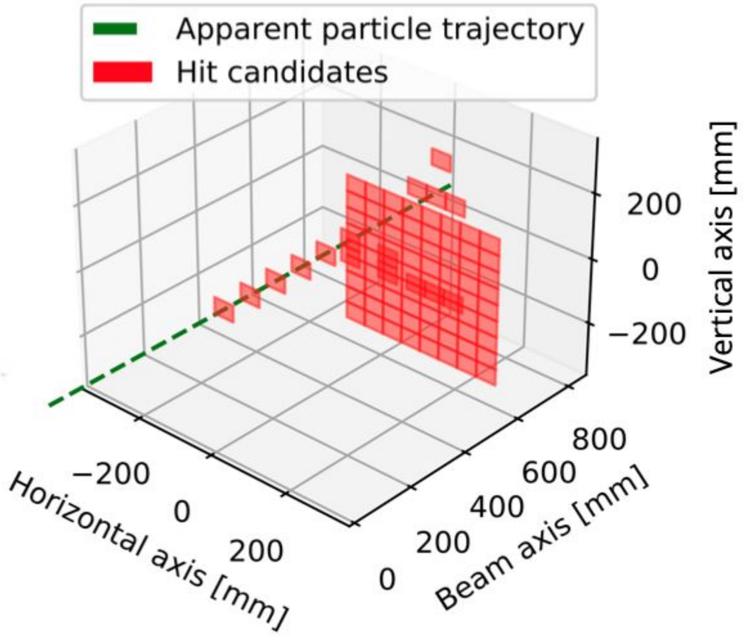
- **Prototypes of all HCAL components constructed and integrated successfully into testbeam (CERN April '22)**
  - Comparison to Geant4 simulated response
  - Development of reconstruction algorithms

The LDMX Testbeam at CERN - Event Display

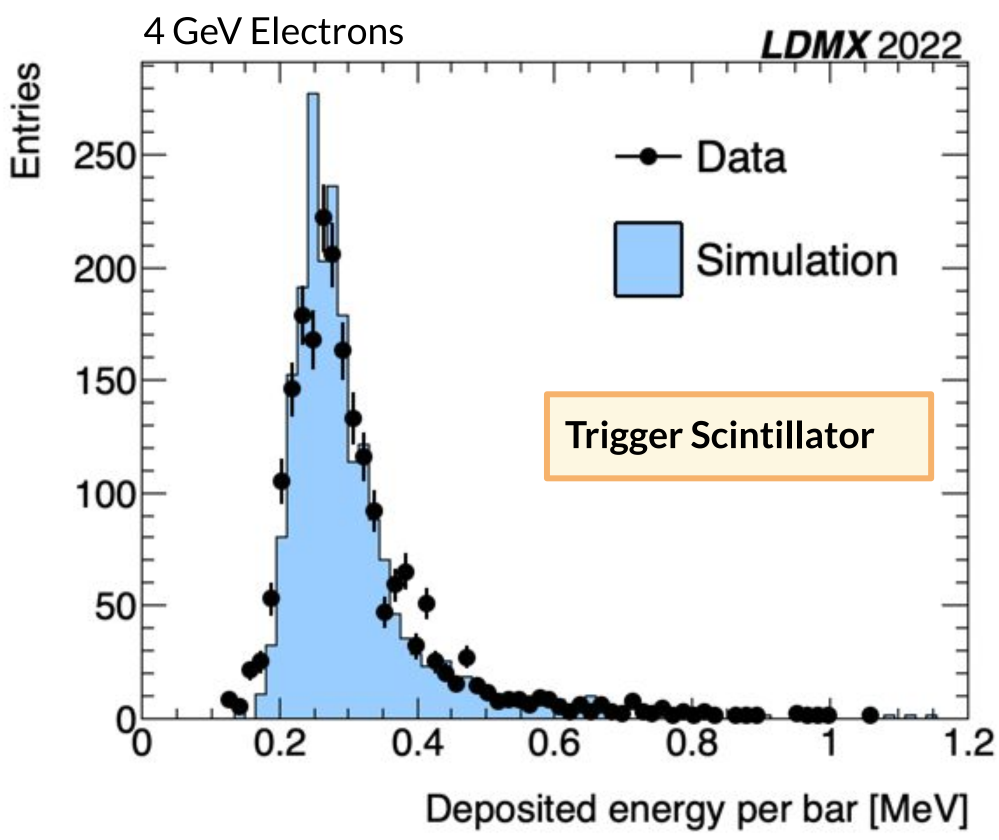
- **Muon Candidate**
  - Crisp signature in HCal
- **Pion Candidate**
  - MIP-like deposits followed by cloud of hits

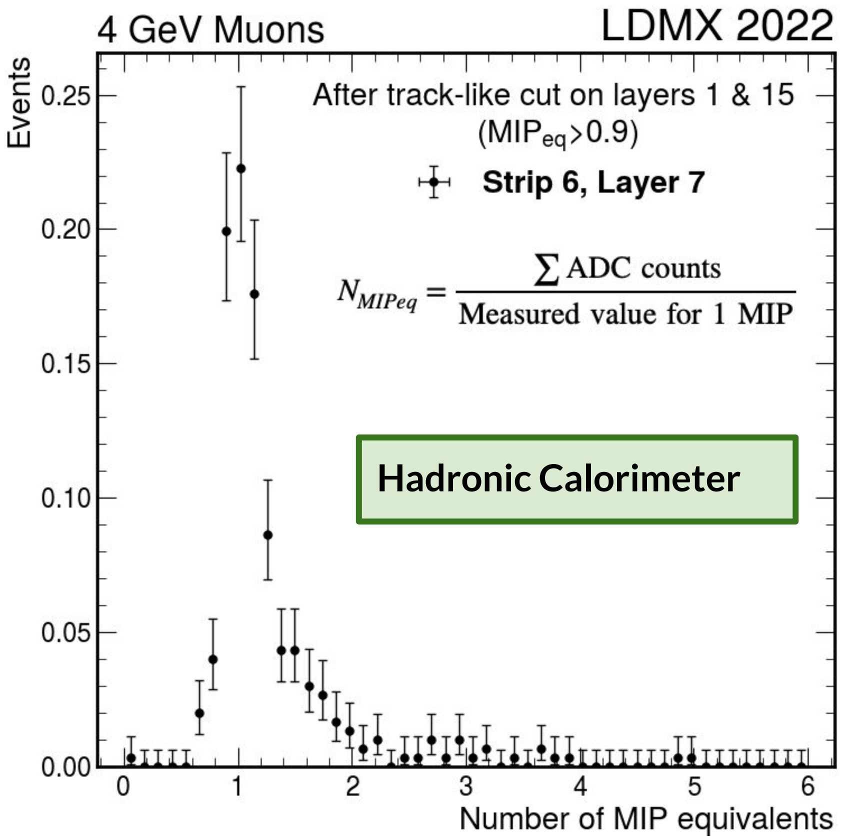






The LDMX Testbeam at CERN - Additions and Motivations

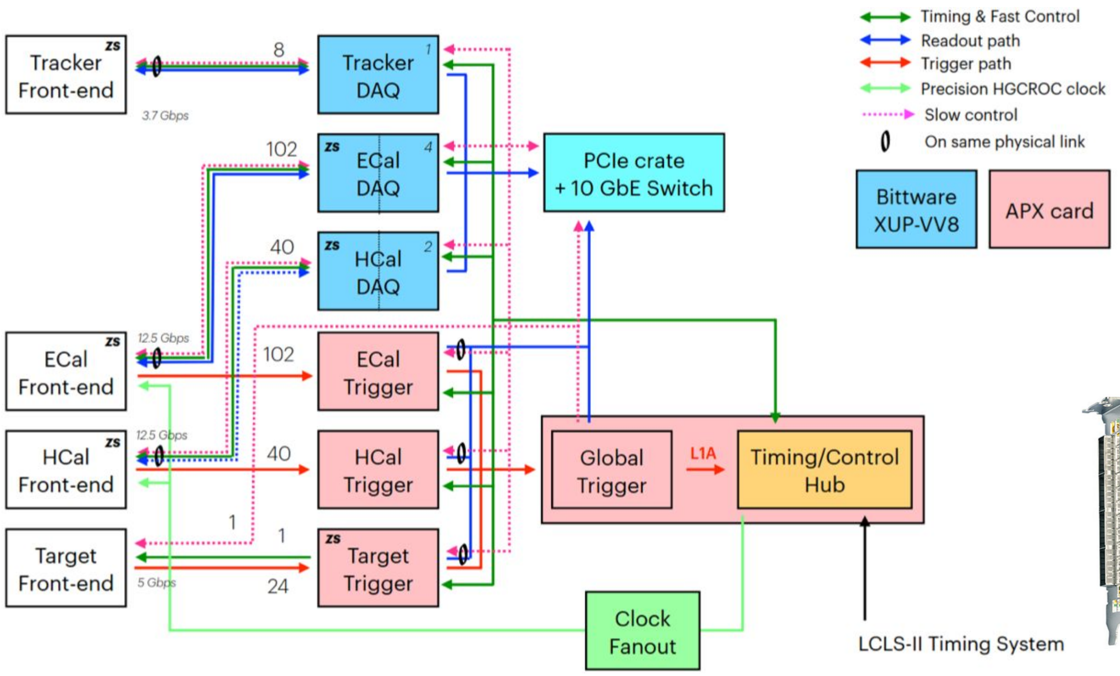




- **Successful test-beam to demonstrate Trigger Scintillator and HCAL response**
  - **TS response well modelled by Geant4 MC simulation**
  - **Excellent HCAL MIP identification capability**

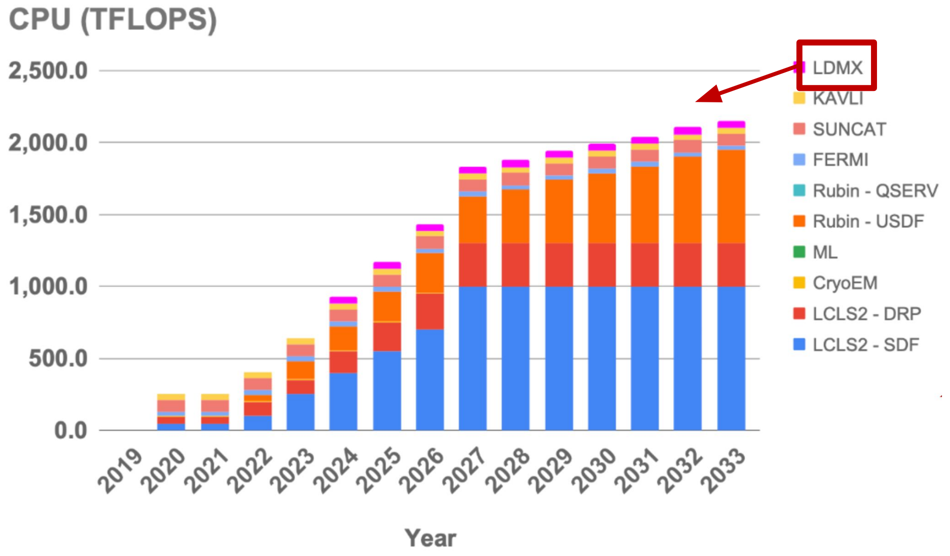
Data Acquisition (DAQ) Design and computing facilities

- **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**



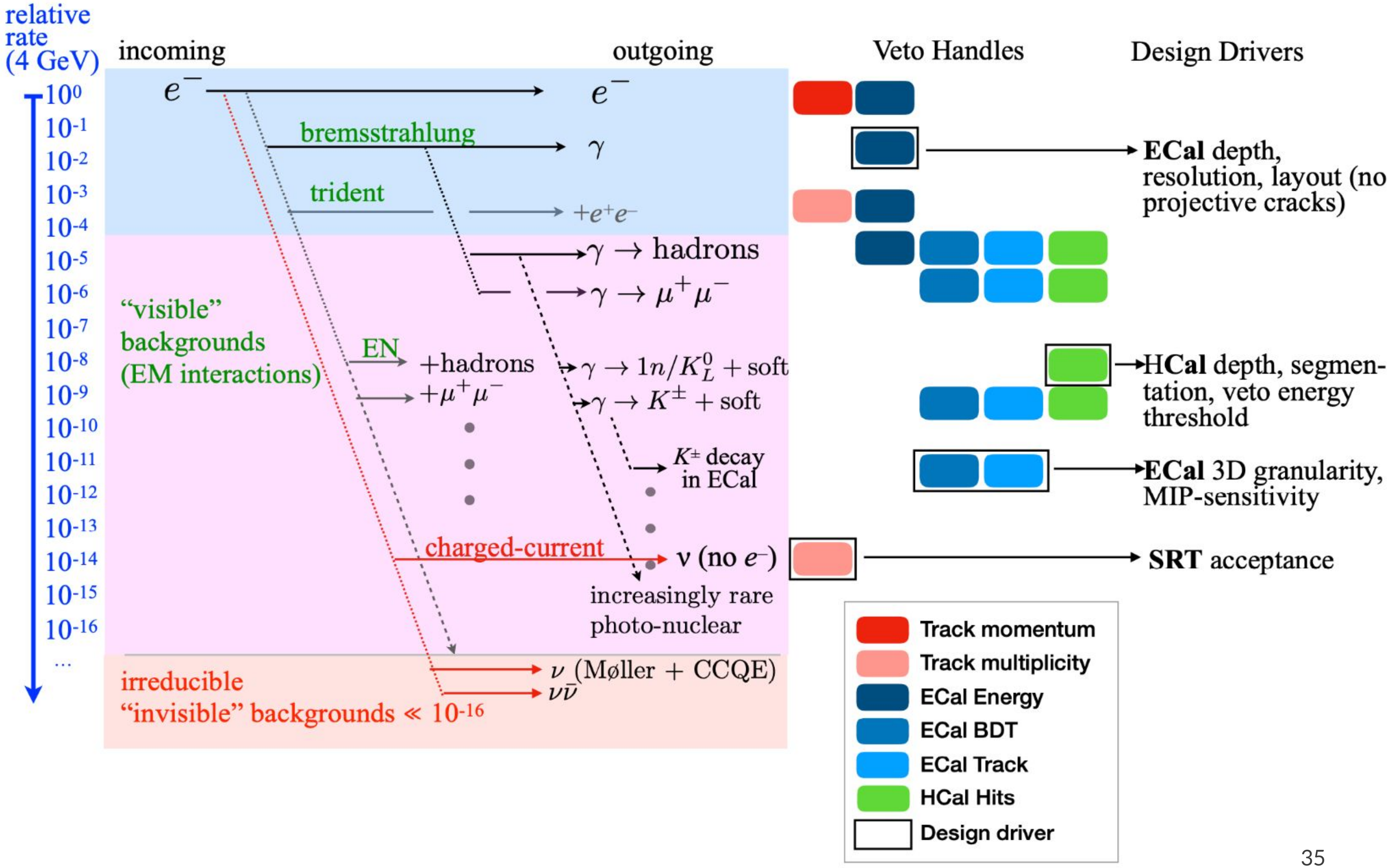
- **Computing model for LDMX leverages**
  - **SLAC Shared Scientific Data facility (SDF)**
  - Lightweight distributed computing System (LDCS)
    [arxiv:2105.02977](#)

Backgrounds Overview and Dedicated Vetoes

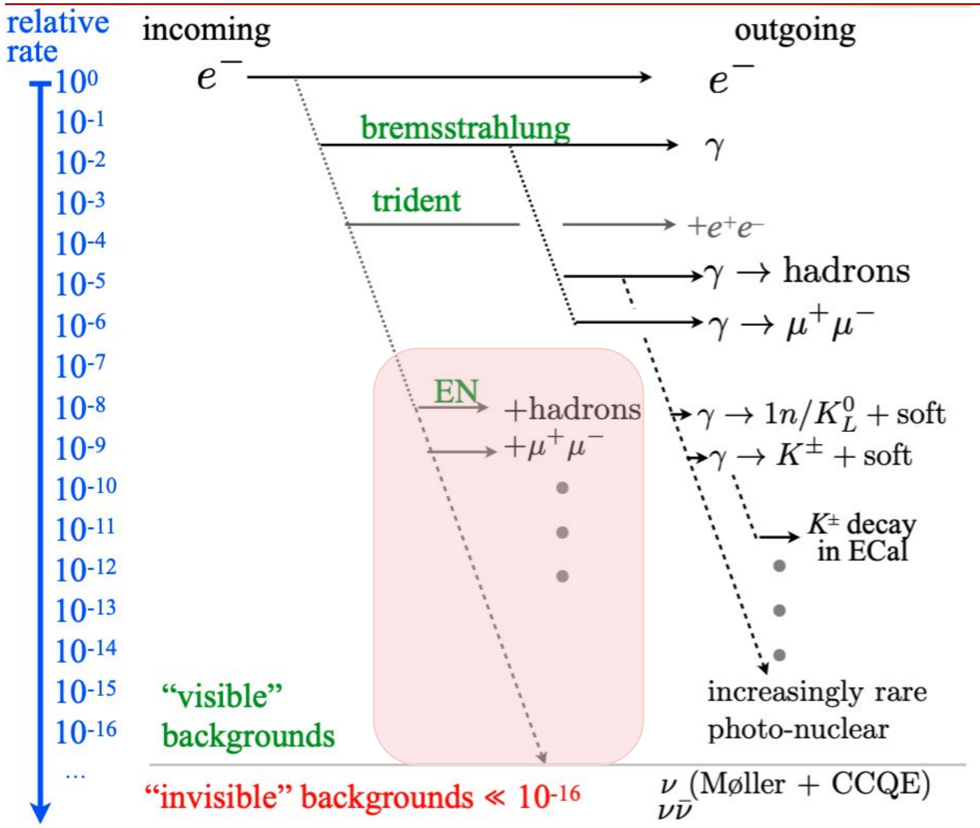
Gaussian energy fluctuations

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

Irreducible prompt $\not{E}$

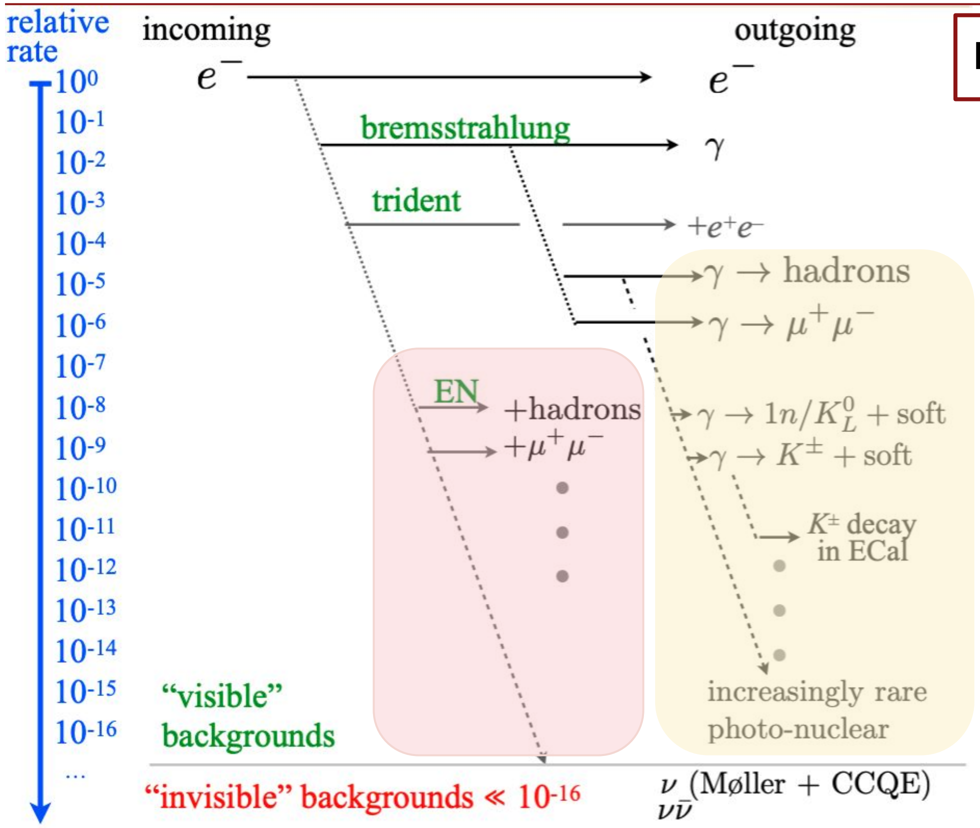


Rare Background rejection

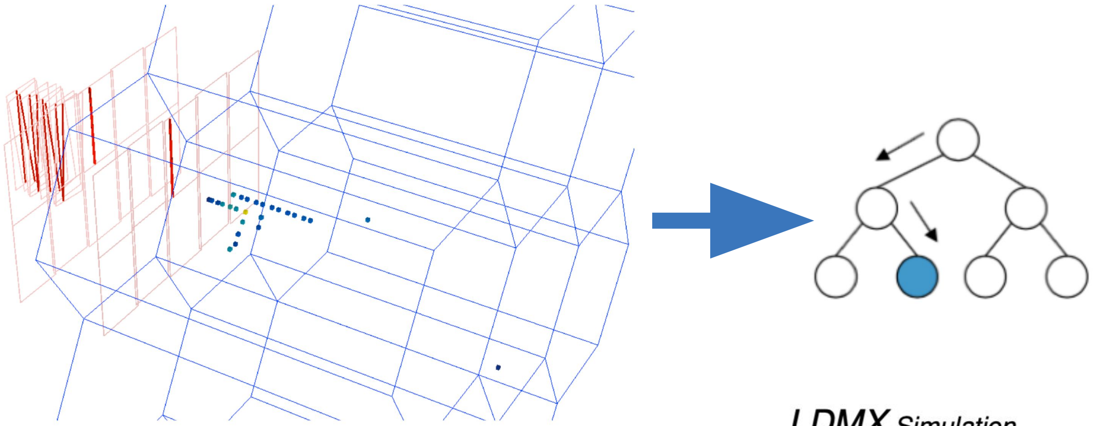


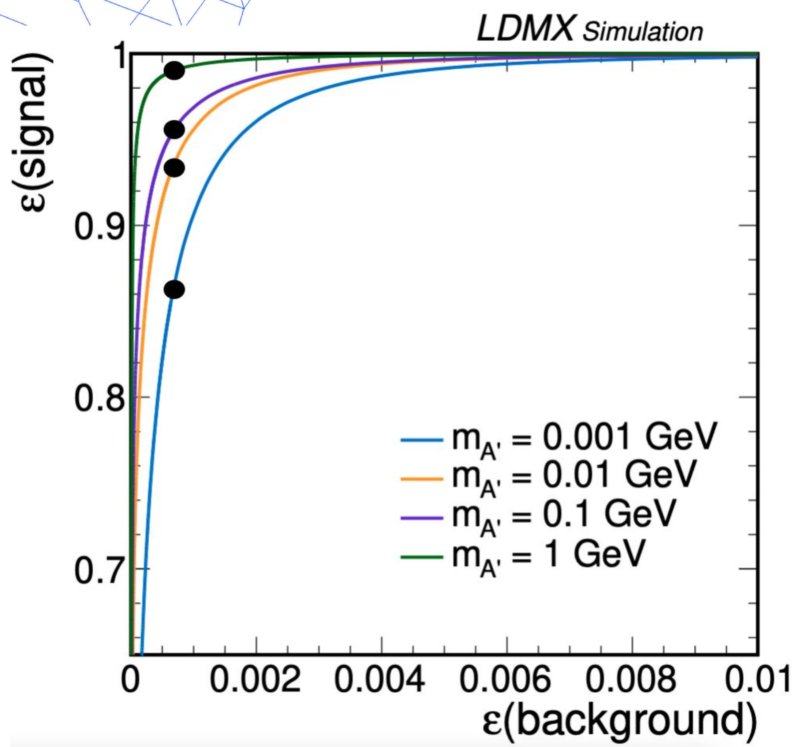
- **Exactly one e$^-$ track in the recoil tracker**
  - Removes electro-nuclear (eN) bkg & rare invisible ν processes

Rare Background rejection



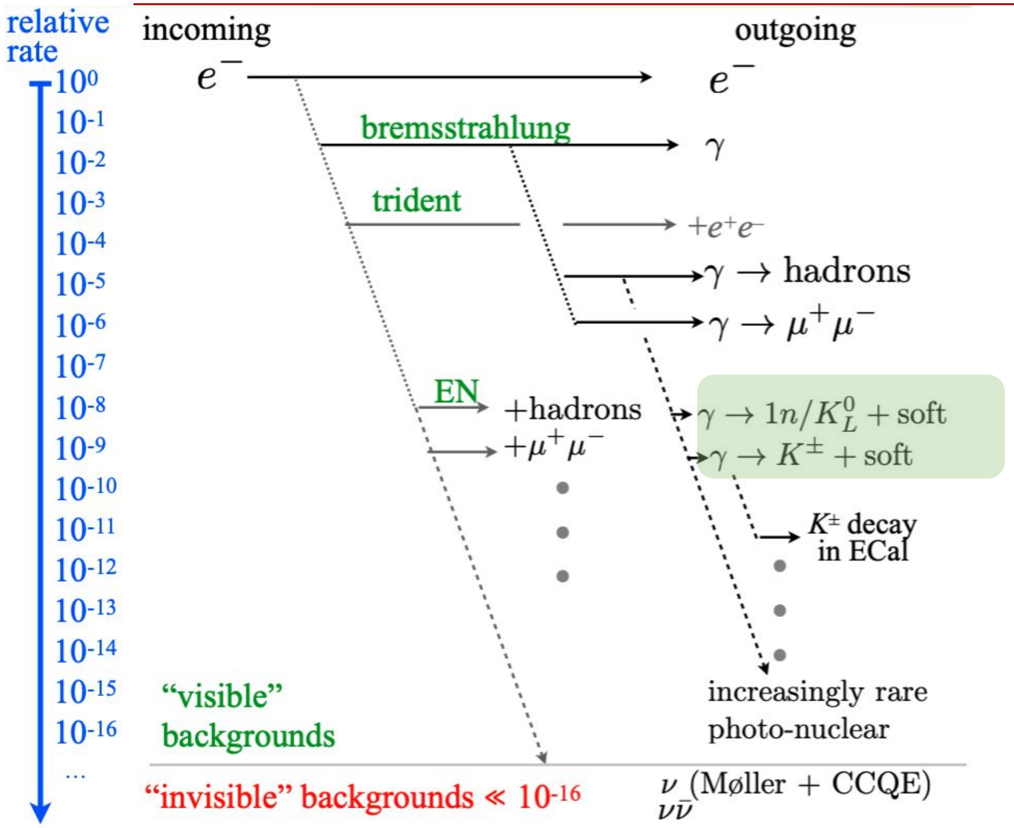
ECAL veto based on boosted decision tree (BDT) optimized vs ECAL pN bkg

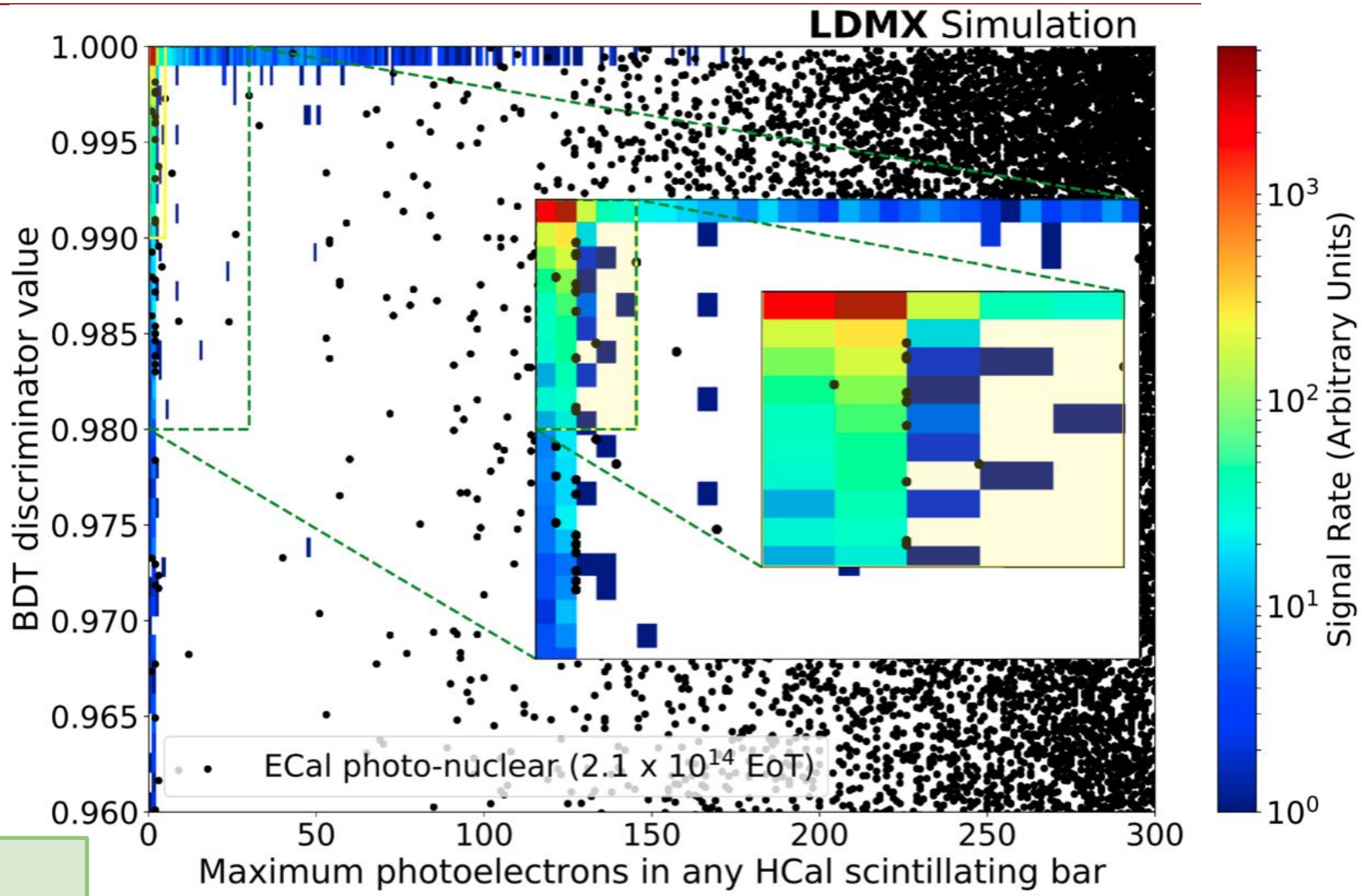




- **Exactly one e^- track in the recoil tracker**
  - Removes electro-nuclear (eN) bkg & rare invisible ν processes
- **ECAL BDT Veto**
  - Global ECAL Features
  - EM Shower features leveraging ECAL granularity

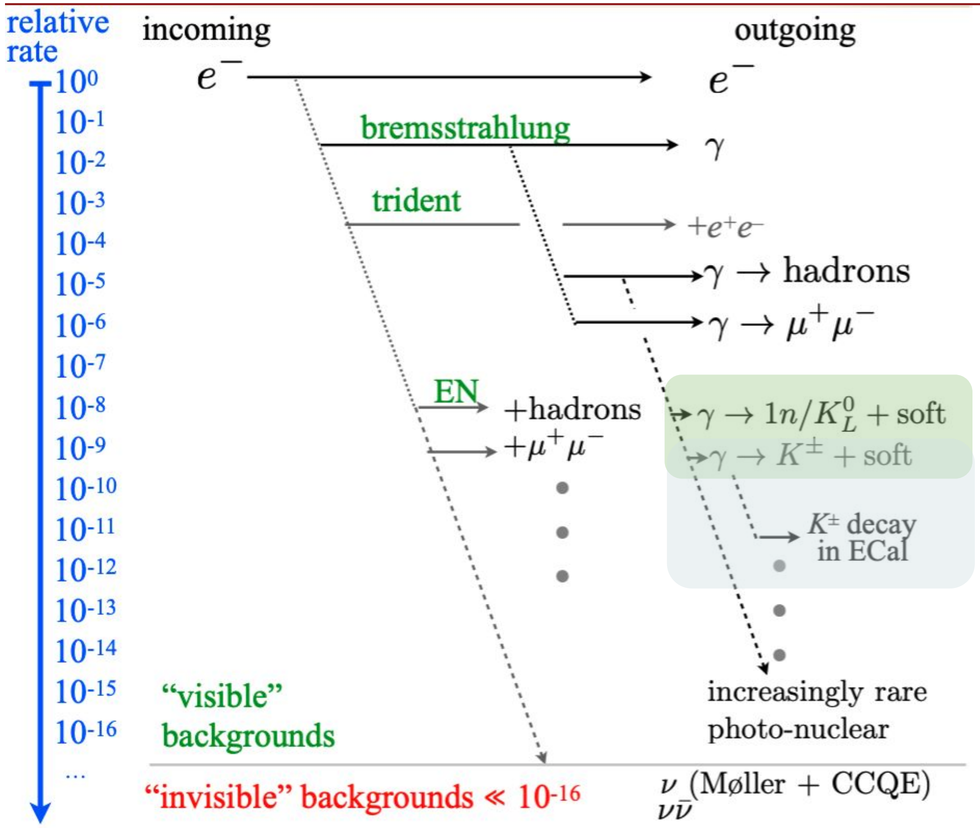
Rare Background rejection

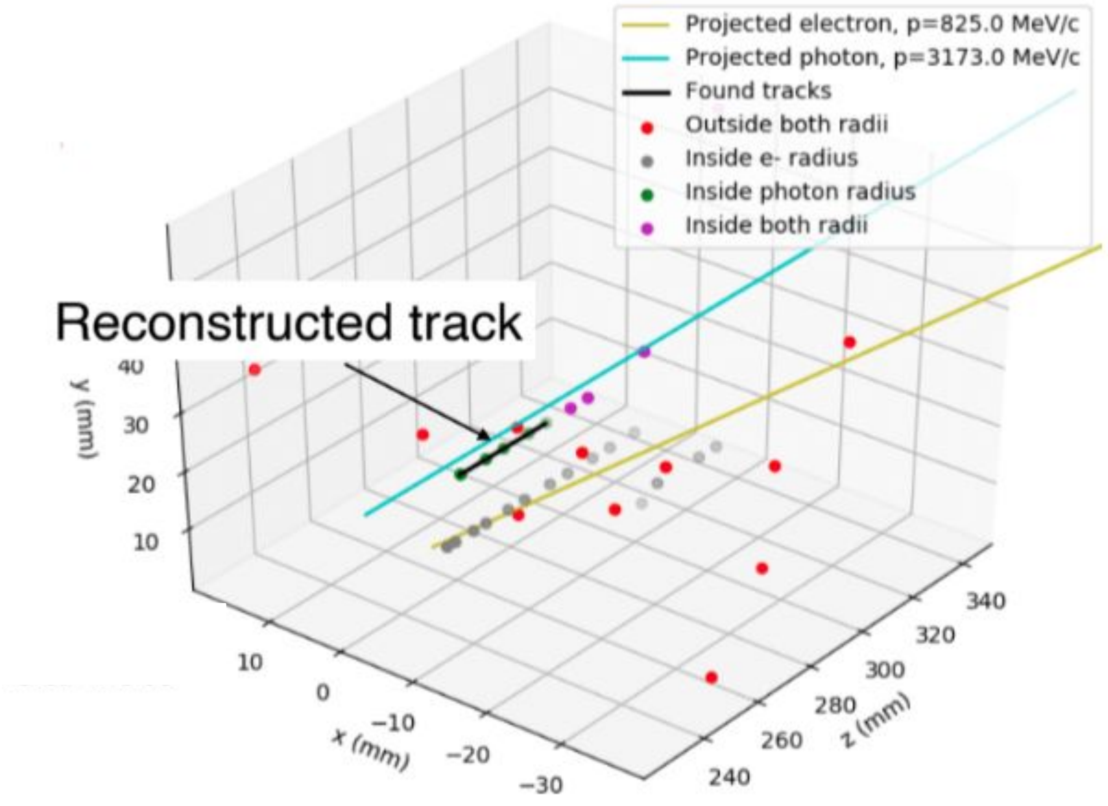




- **HCAL hit Veto**
  - Single scintillator bar with **< 5 photoelectrons hits**
  - Targets neutral particles and soft products escaping ECAL

Rare Background rejection





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

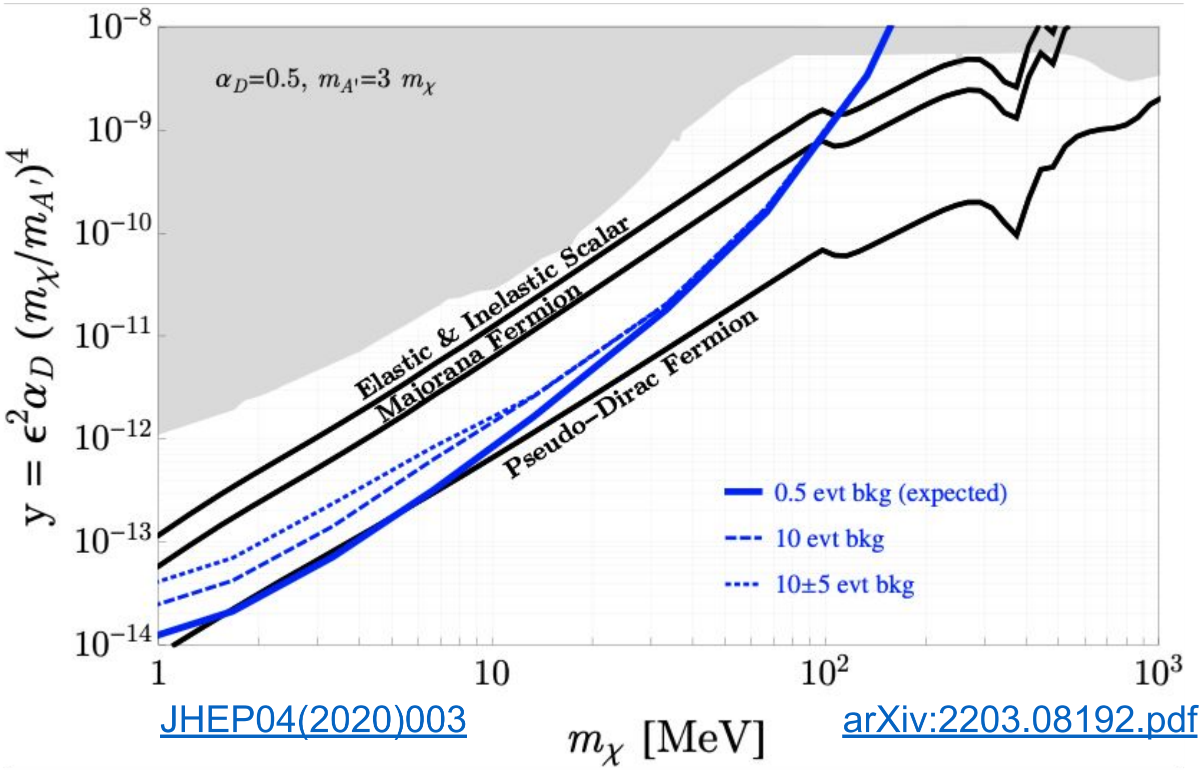
- **MIP Tracking in ECAL**
  - Veto on reconstructed single isolated track around γ direction

Results

- Expected **background free search** with $4\text{x}10^{14}$ electrons on target and E_{beam} = *4 GeV*

	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}	4.7×10^{11}	6.3×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.6×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.3×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.3×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks $= 0$	< 1	< 1	< 1	< 1

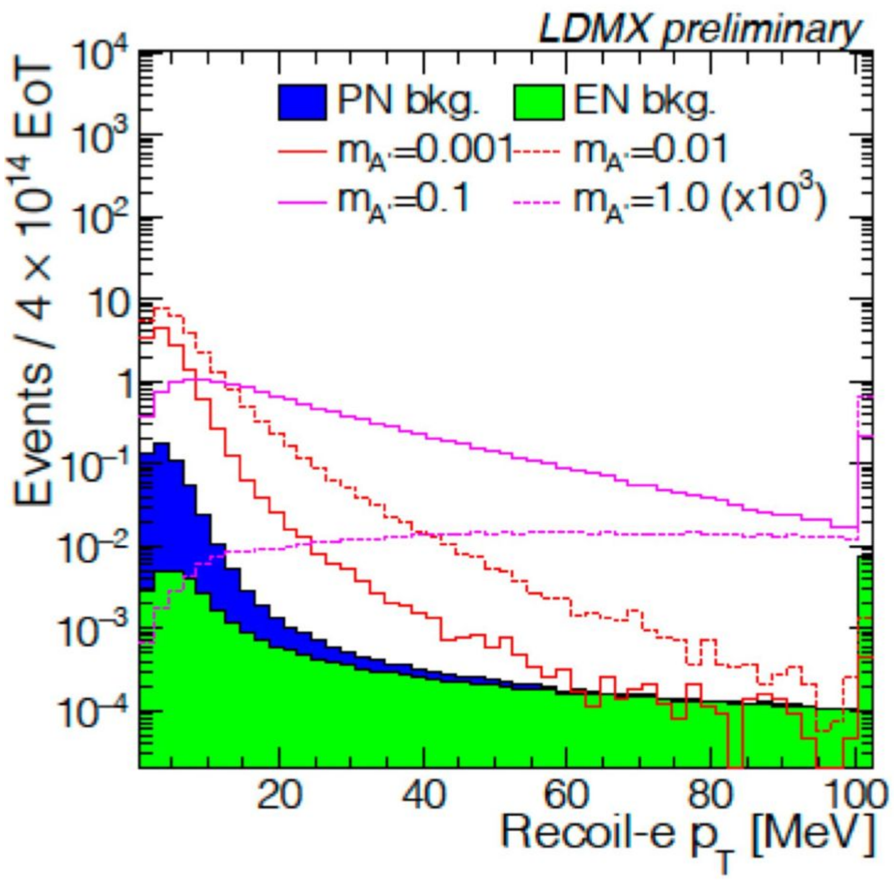
- **Outstanding sensitivity** in a mass range up to $m_\chi <$ *100 MeV*

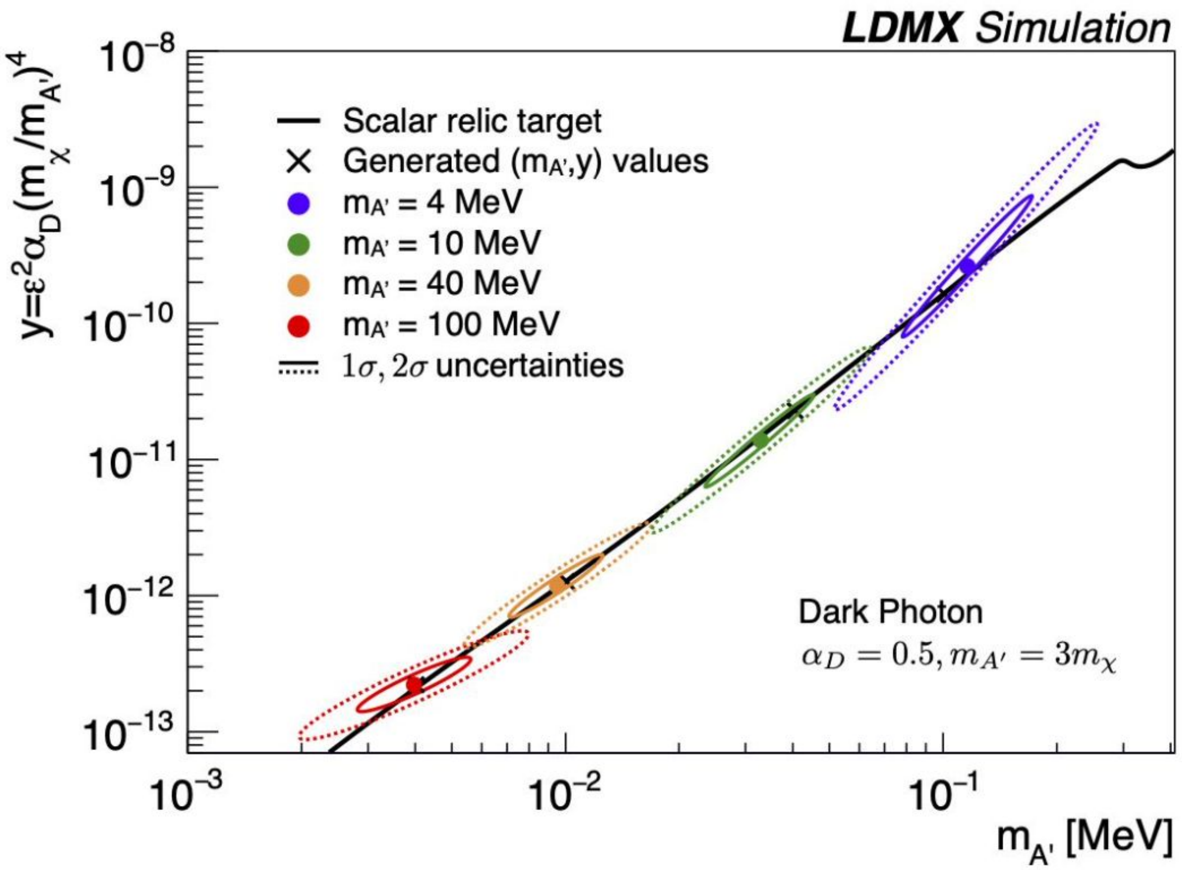


JHEP04(2020)003

arXiv:2203.08192.pdf

Determination of LDM signal mass scale





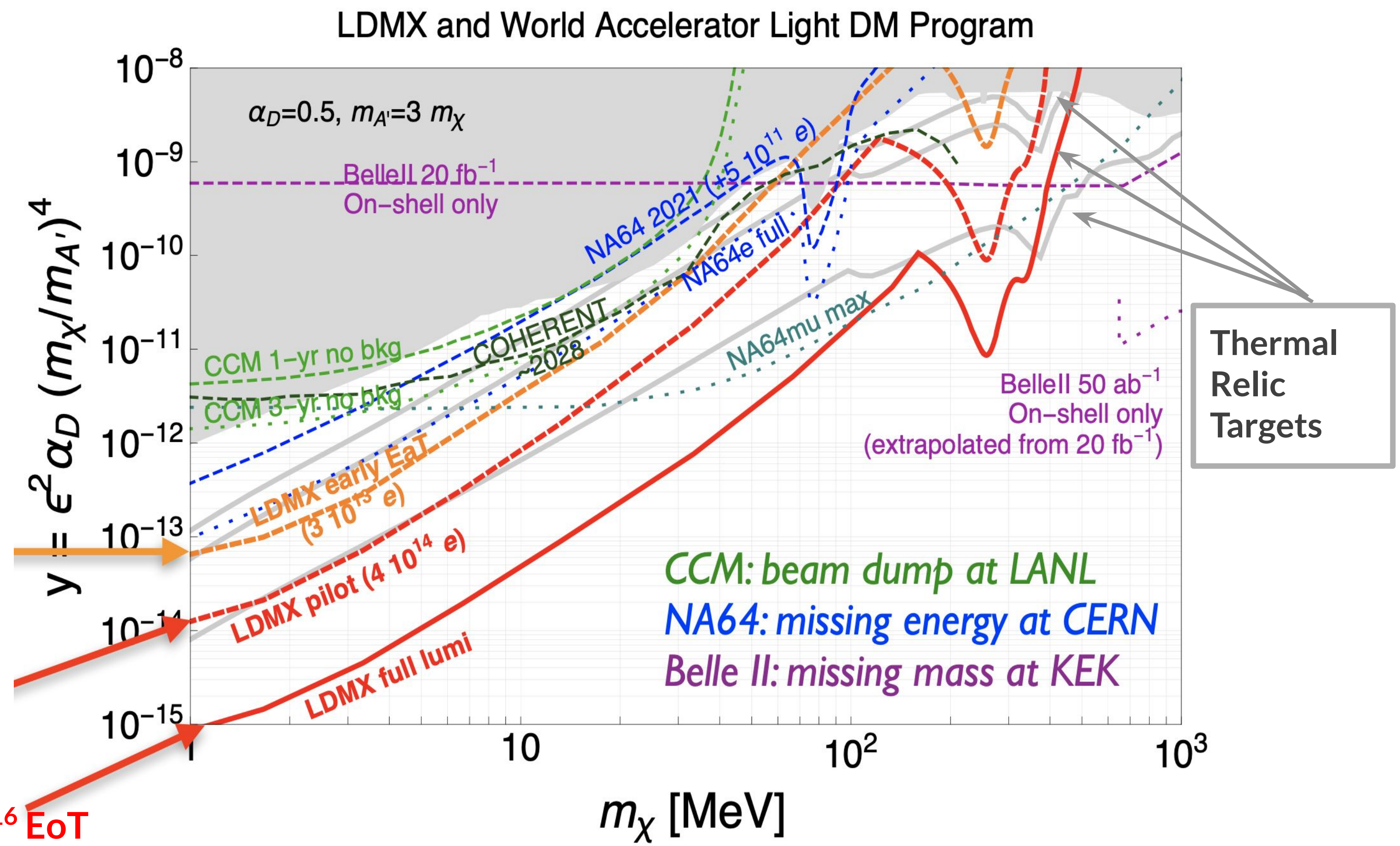
- **Recoil electron transverse momentum key final measurement**
  - Not used in the other veto handles
  - Gives confidence in signal estimate of DM mass scale

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



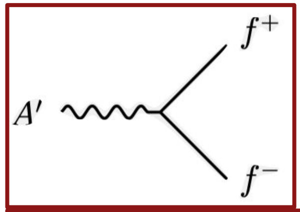
10 days (1 e-/25 ns)
ECal as Target (EaT)

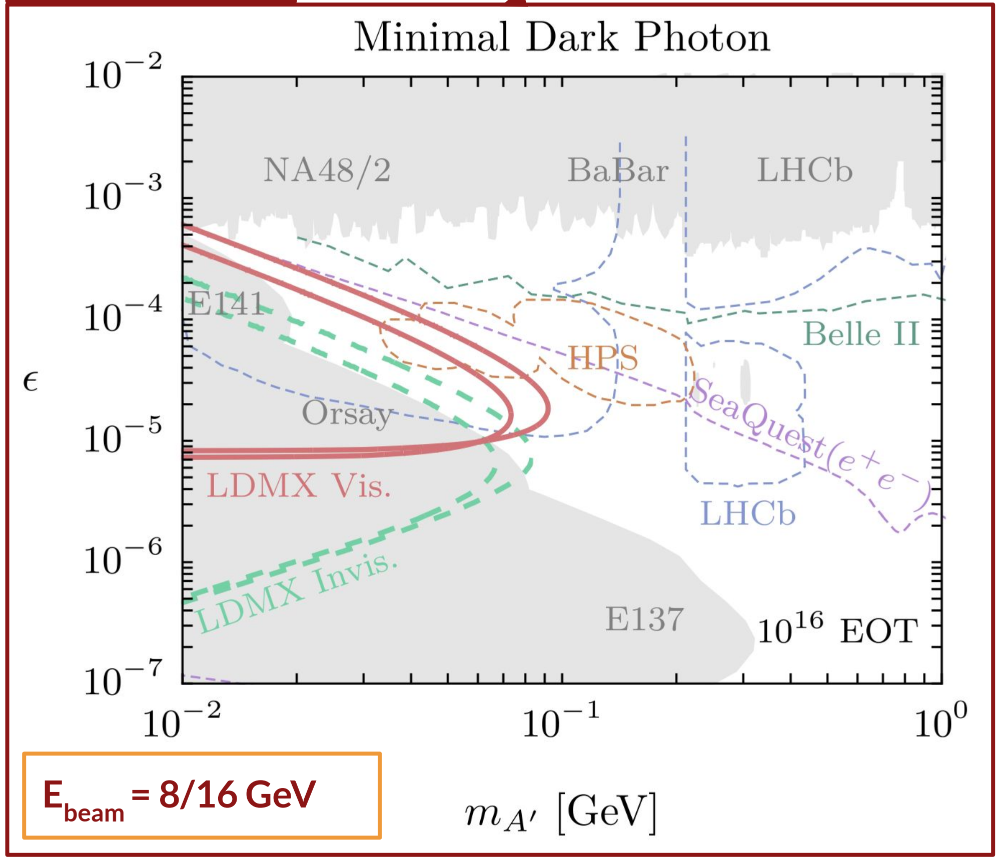
135 days (1 e-/25 ns)
(10% X_0 tungsten)

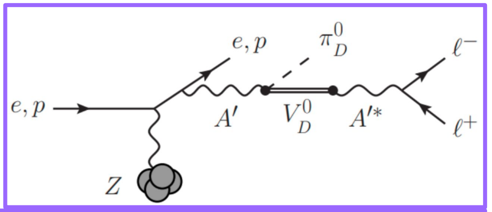
500 days (2 e-/25 ns)
(thicker target) 1.6x10^{16} EoT

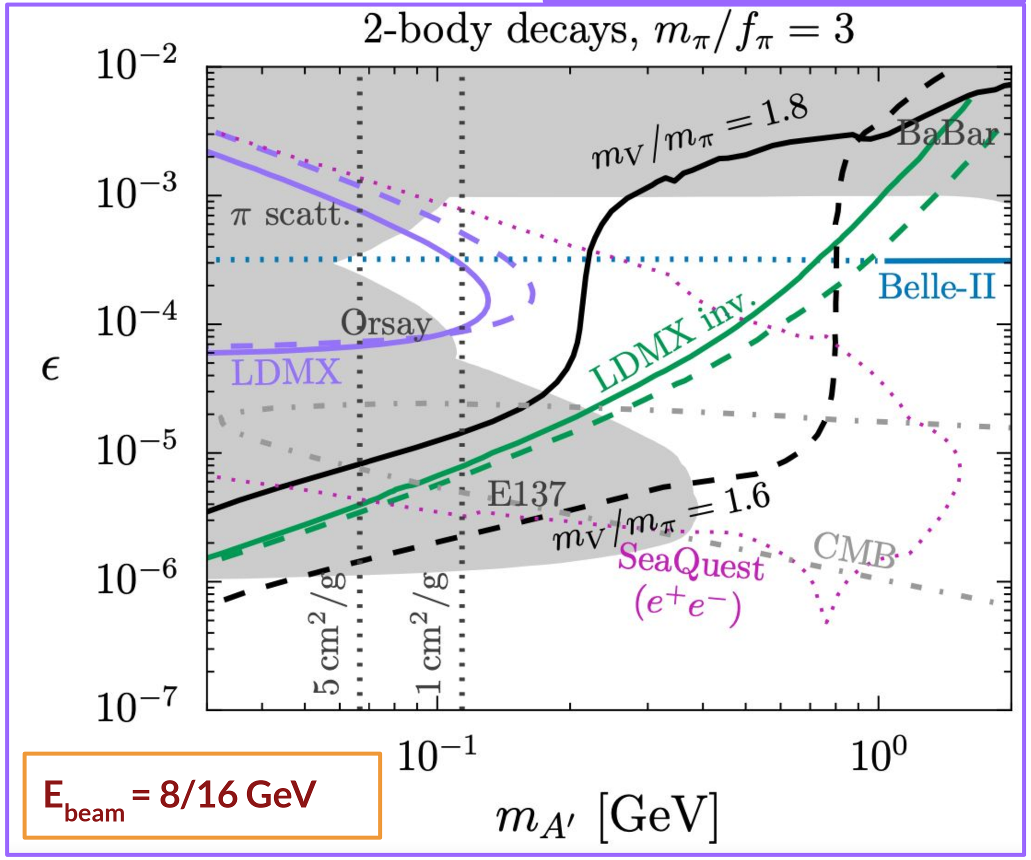
Physics Potential - Visible signatures

- Broad sensitivity to unstable dark sector particles beyond LDM:
  - **Visible decaying Dark-photons**, Axion-Like particles, **SIMPs**









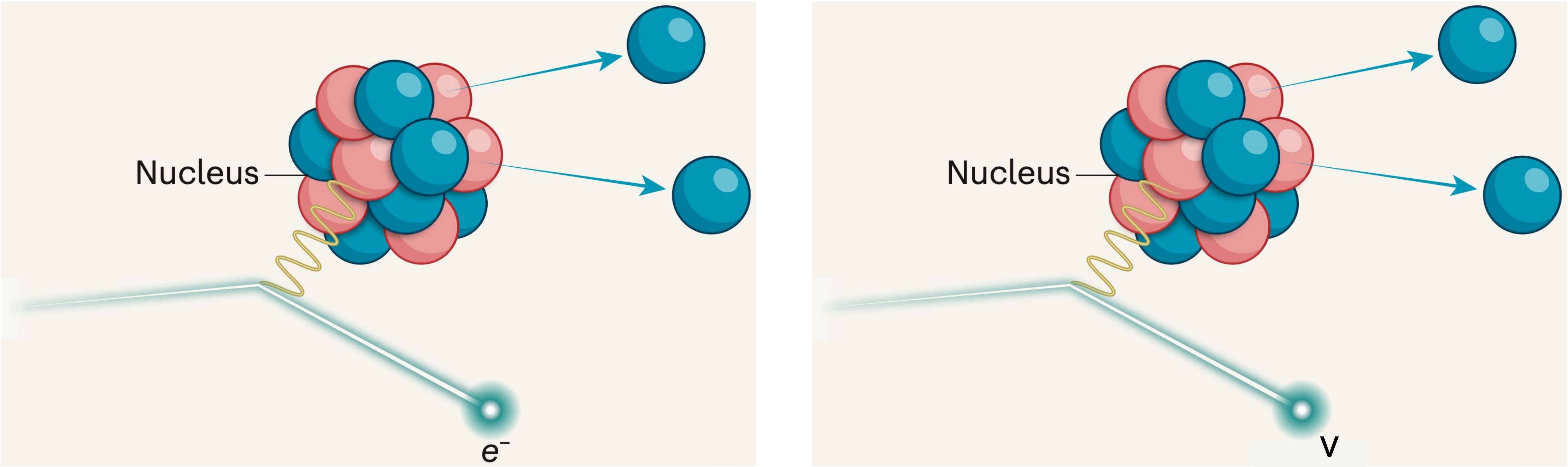
arxiv 1807.01730 Phys. Rev., D97(5):055033, 2018

Physics Potential: 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

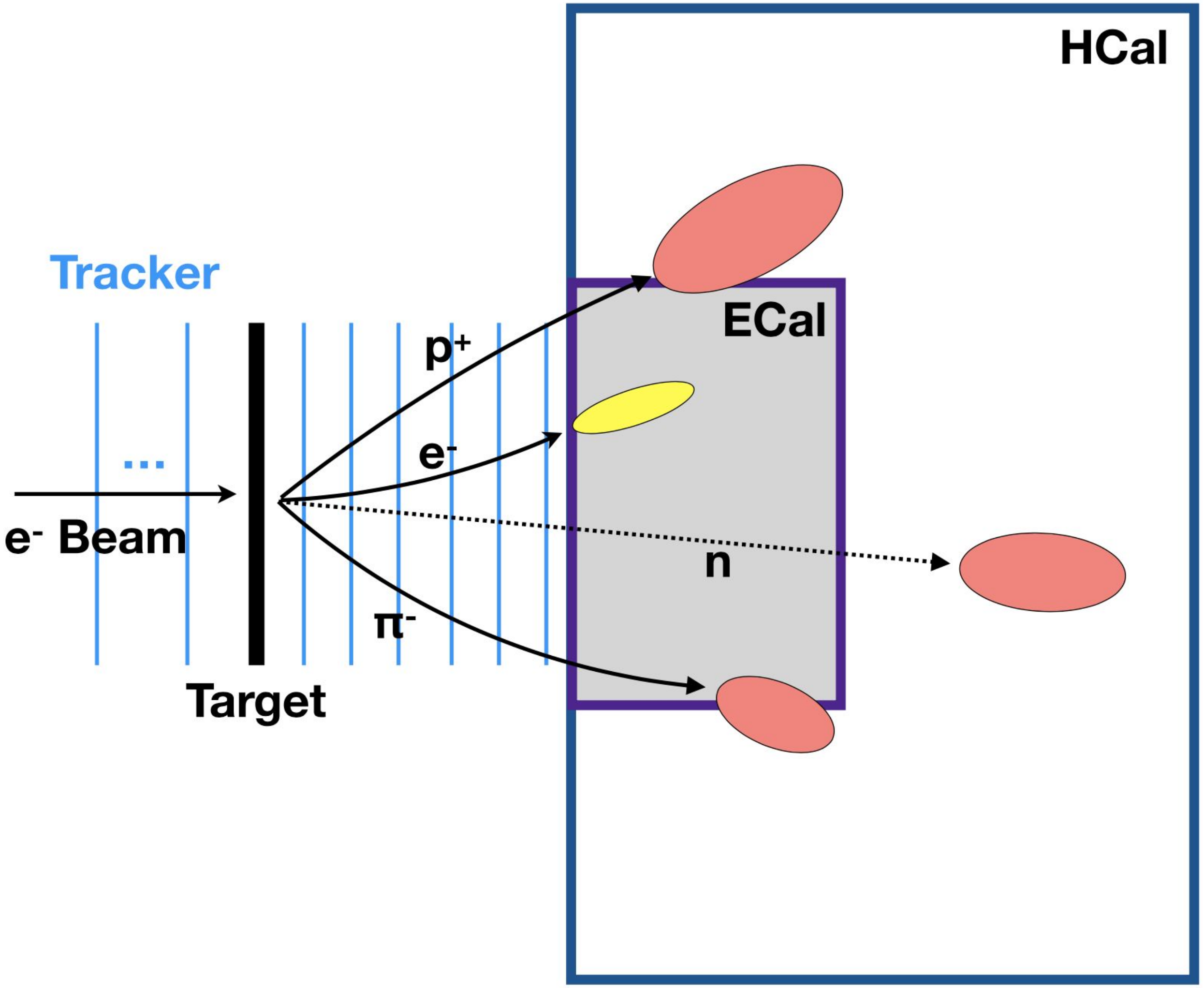
- However, the physics potential is enriched by fundamental **guaranteed deliverables**:
    - Measurement of electron-nucleon (eN) scattering in the forward region

Physics Potential: forward eN scattering measurements



- **eN scattering as a probe for νN scattering**
  - Known differences can be corrected given a complete reconstruction of the final state
- **Strong force nuclear effects are the main source of uncertainty** → **identical** between the two scattering processes

Physics Potential - Electron Nucleon Measurements

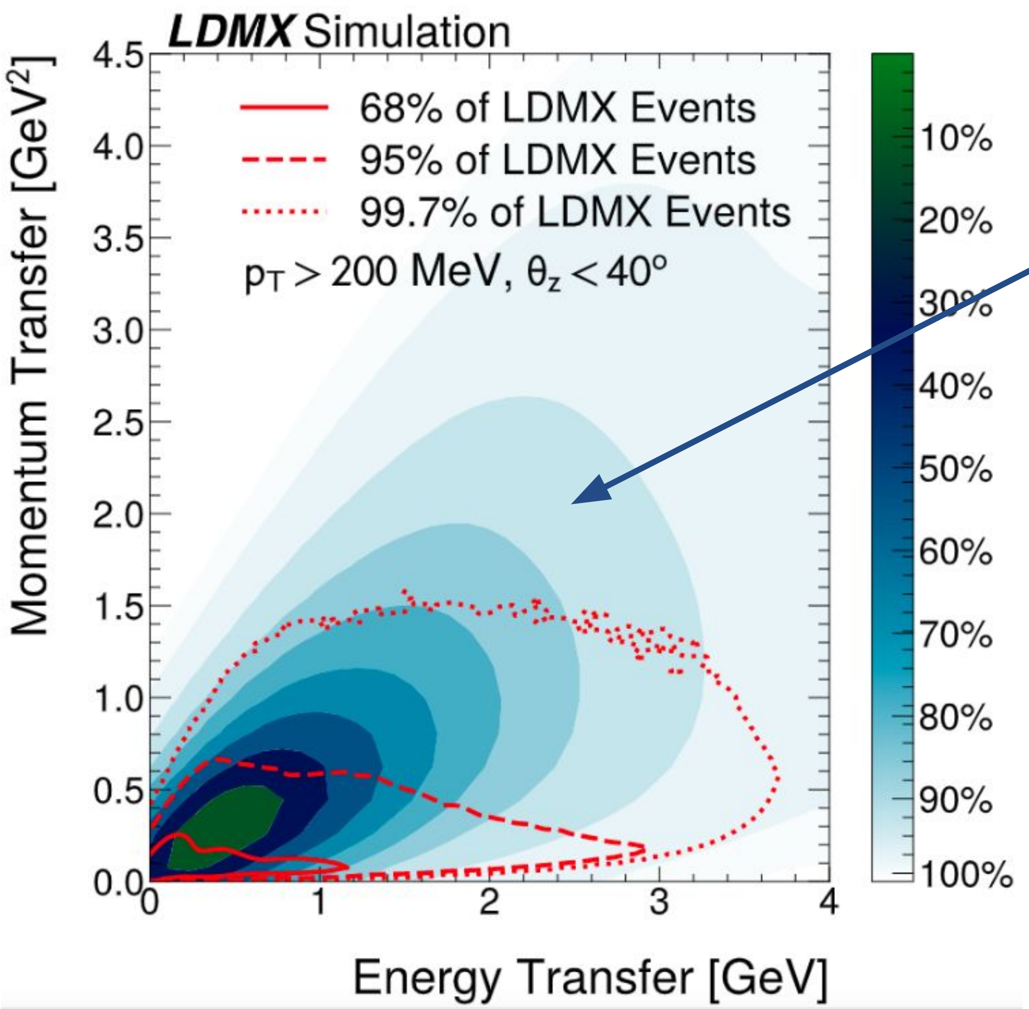


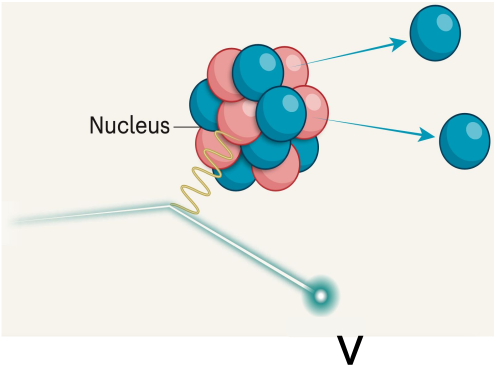
- **LDMX design offers**:
  - **Full forward acceptance**, nearly hermetic
  - **Fully reconstructed initial and final state**
  - **Excellent neutron detection efficiency of the HCAL** → Challenge in ν experiments

PhysRevD.101.053004

Physics Potential - Electron Nucleon Measurements

PhysRevD.101.053004

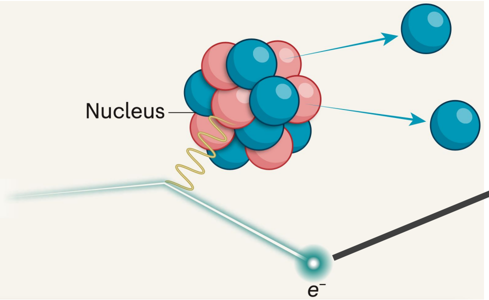




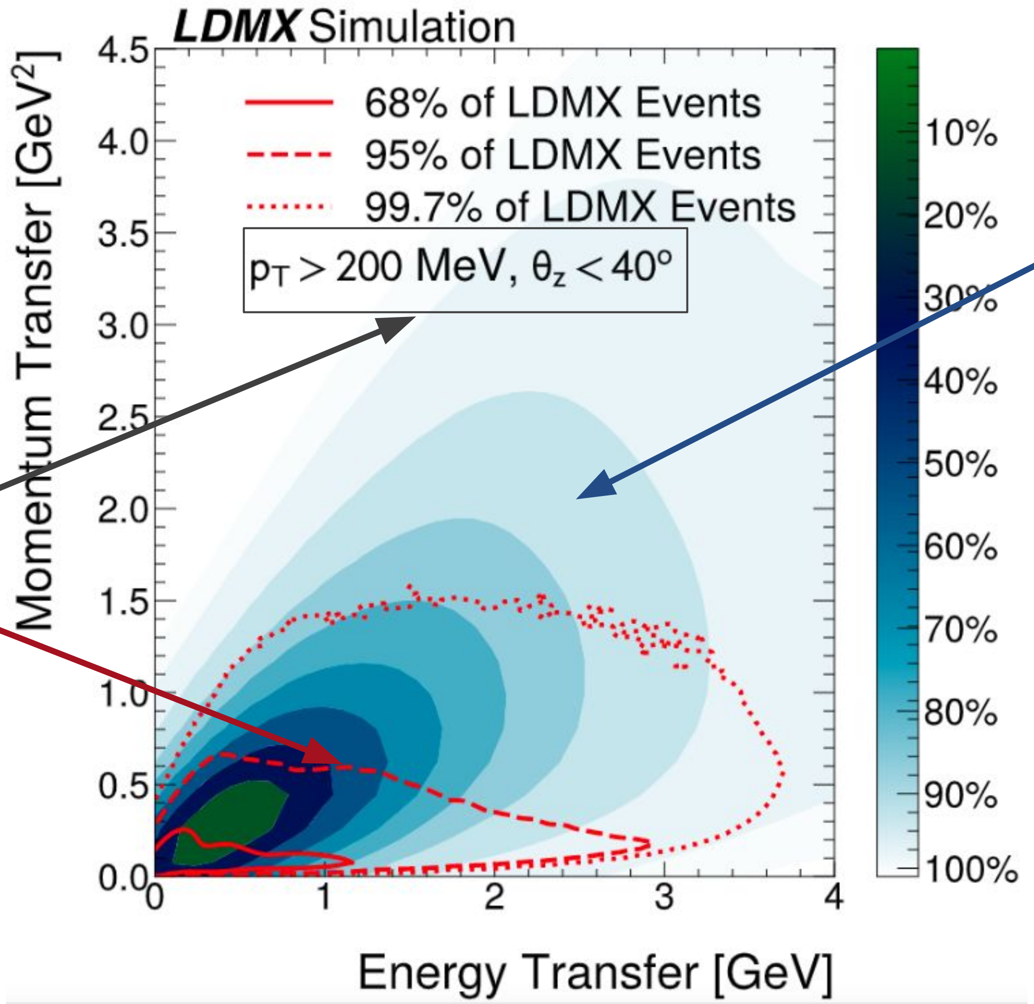
Simulated DUNE Events in LAr

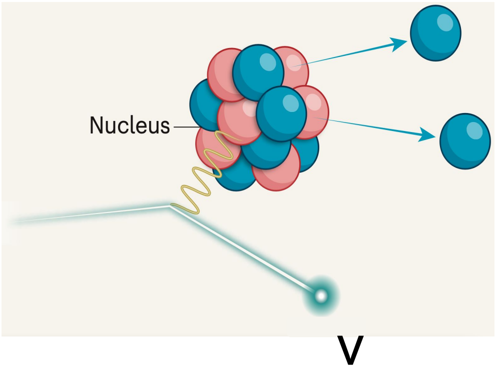
Physics Potential - Electron Nucleon Measurements

PhysRevD.101.053004



LDMX recoil e⁻ p_T and polar angle θ_z





Simulated DUNE Events in LAr

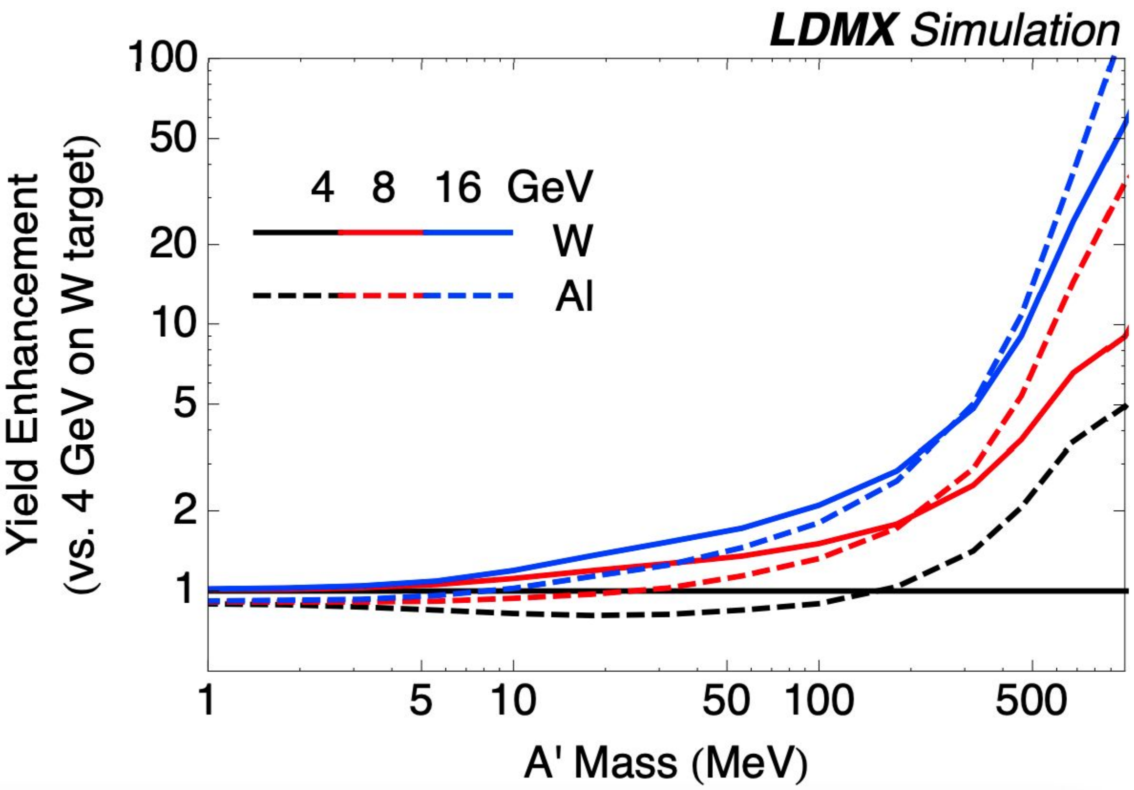
- **LDMX has unique capability** to inform neutrino interaction models in the regions most relevant to DUNE

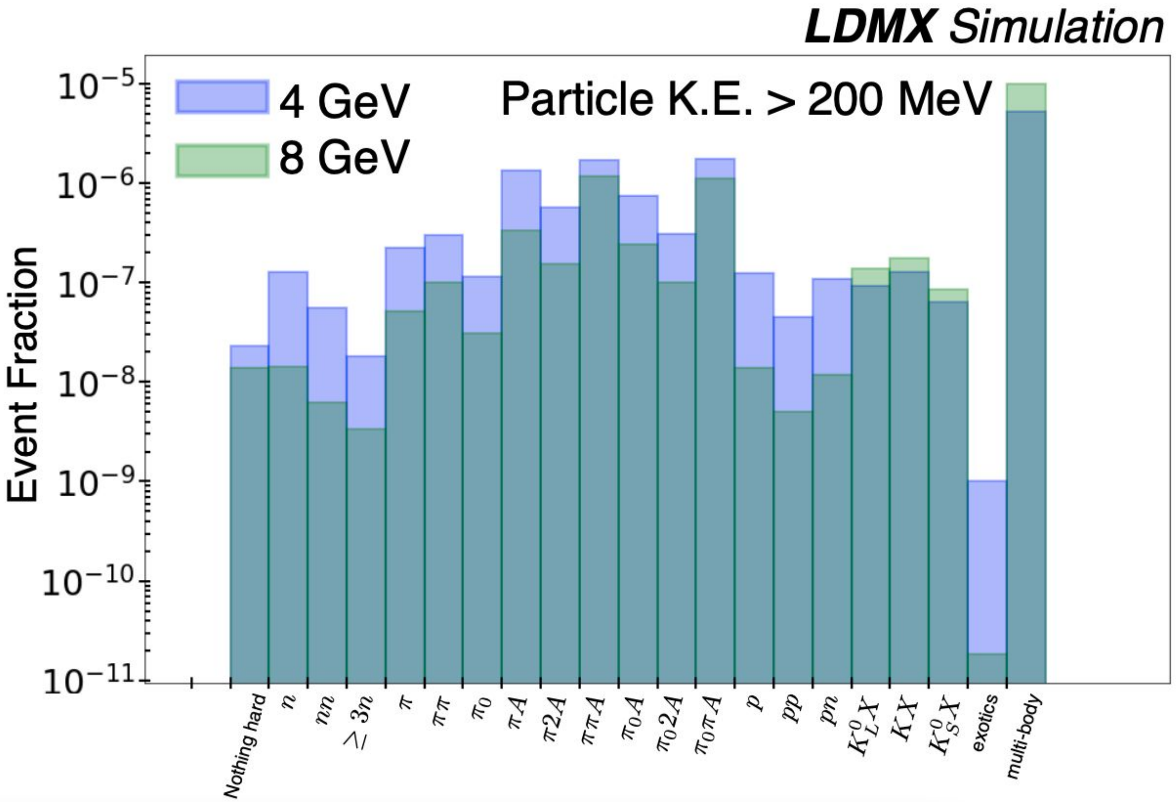
Summary

- **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 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

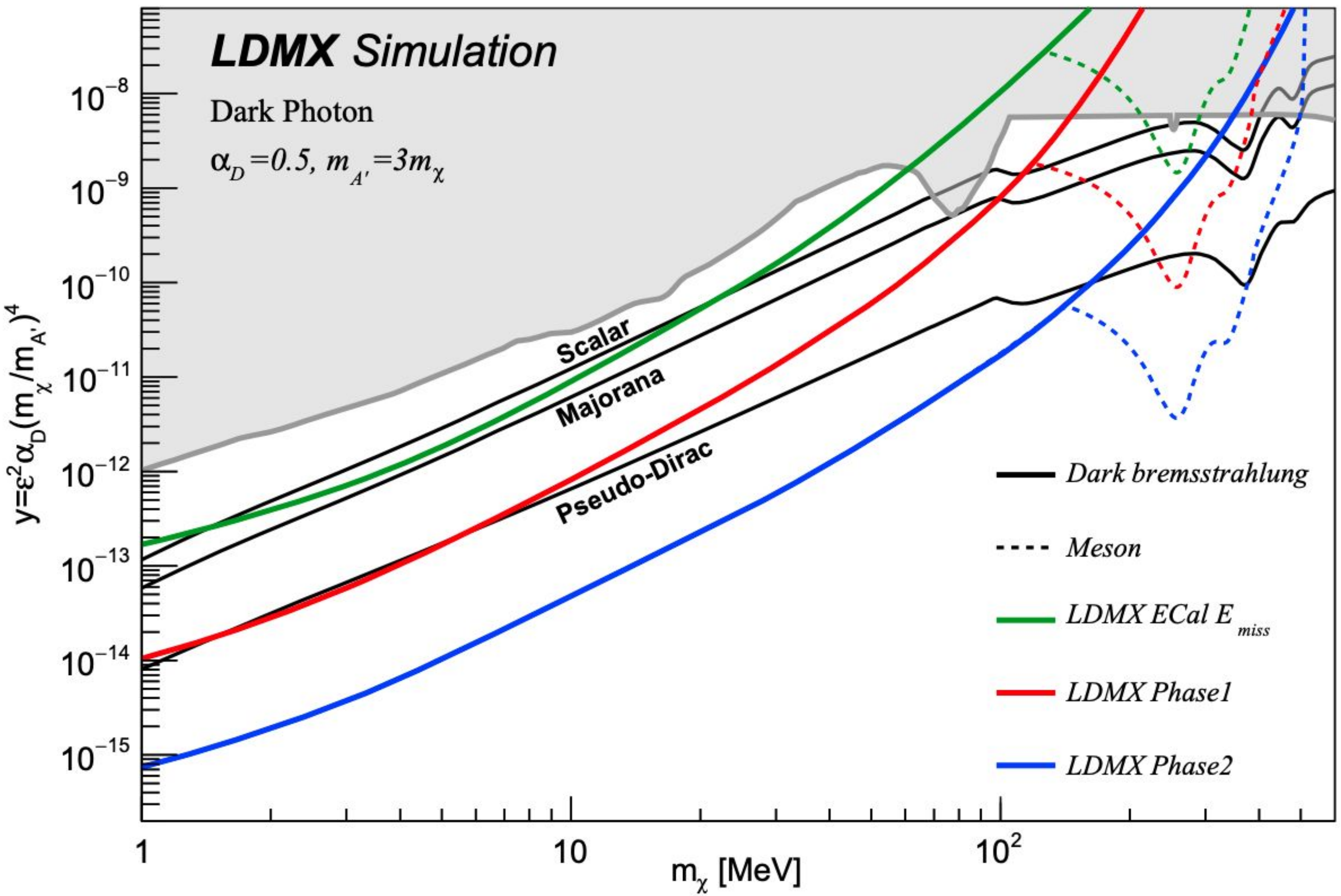
Backup

Phase II Prospects

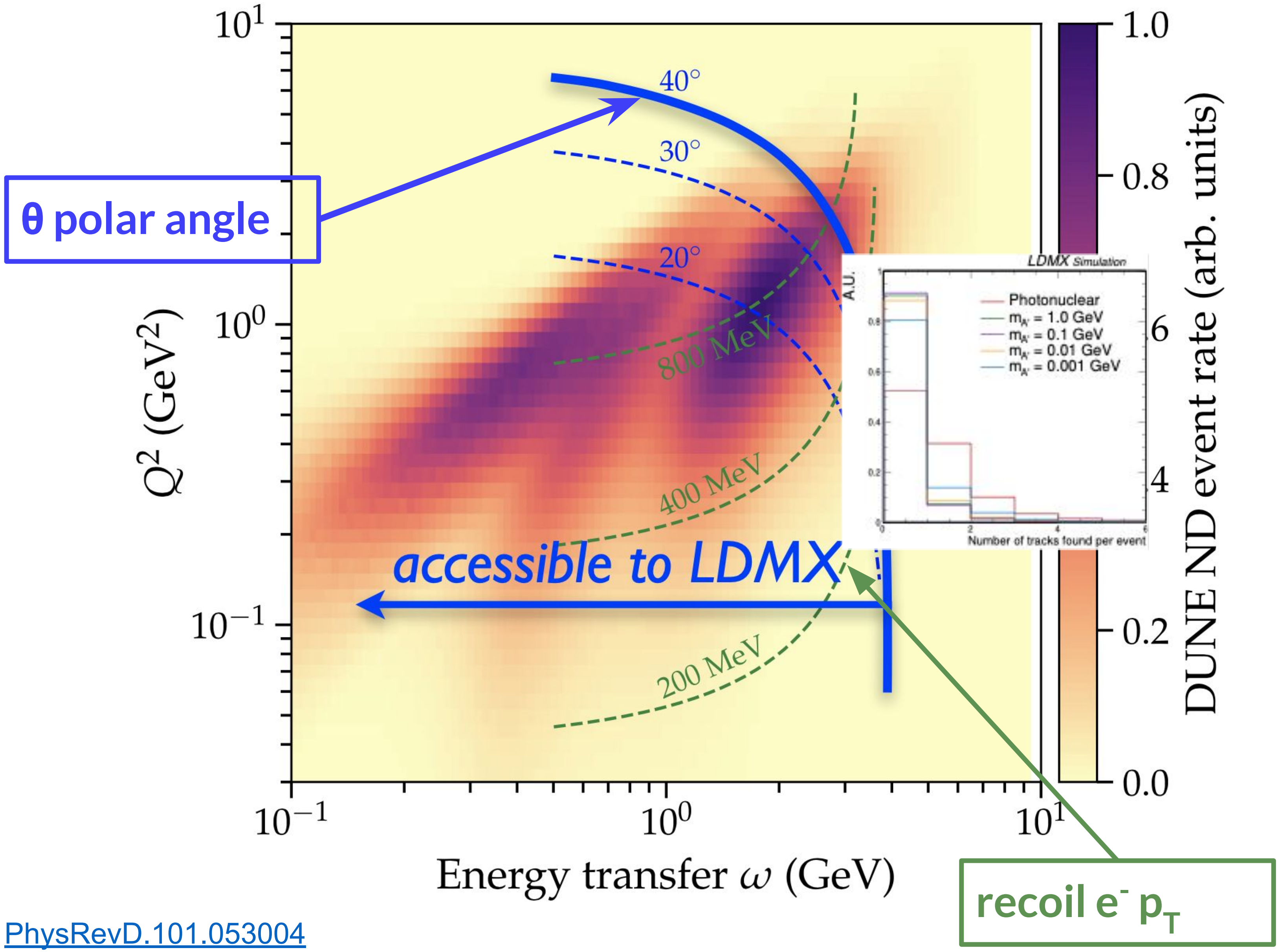




Phase II Prospects



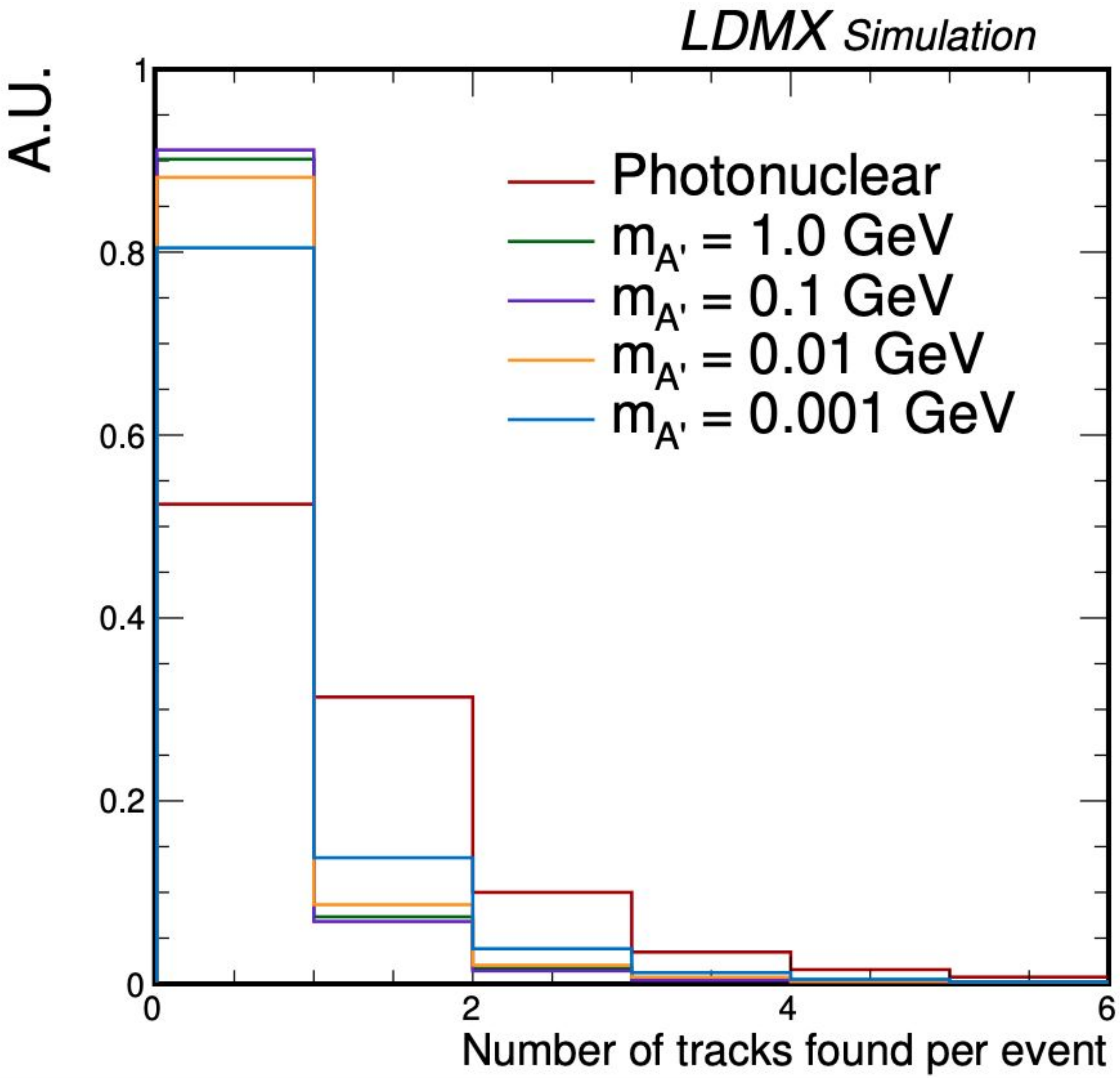
Physics Potential - Electron Nucleon Measurements



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 - Trackers resolution

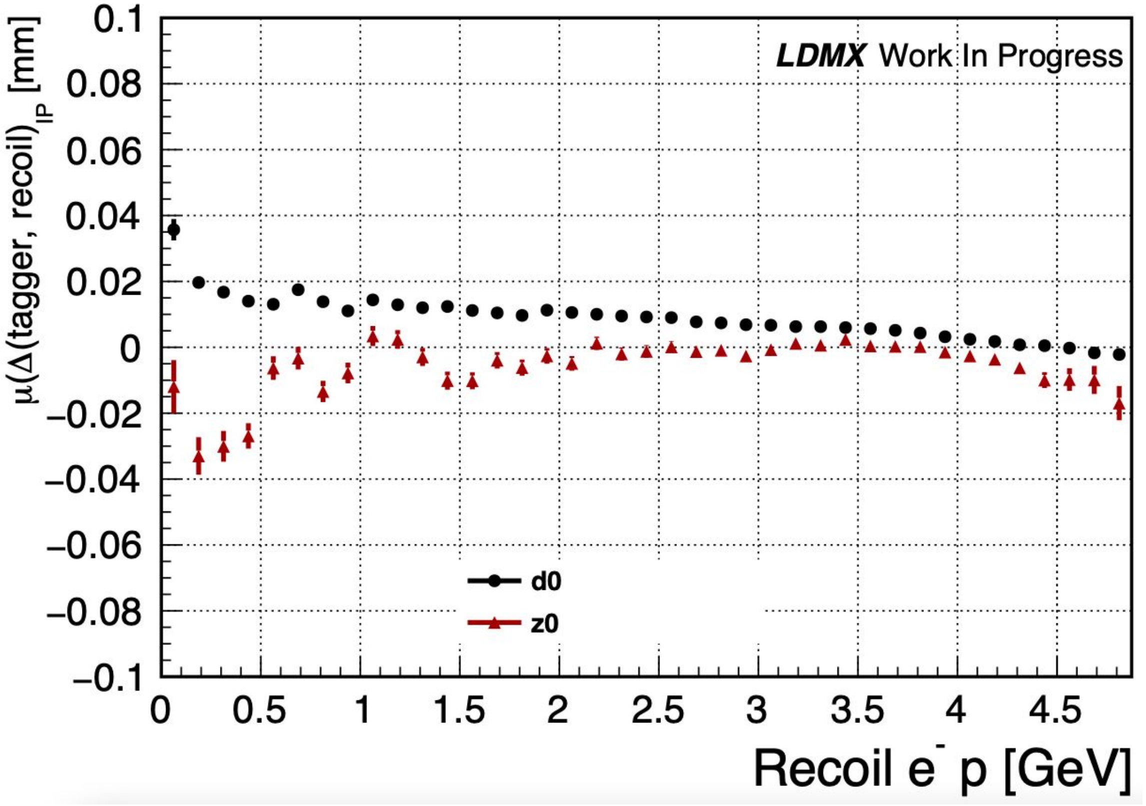
TABLE I: The layout and resolution of the tagging tracker.

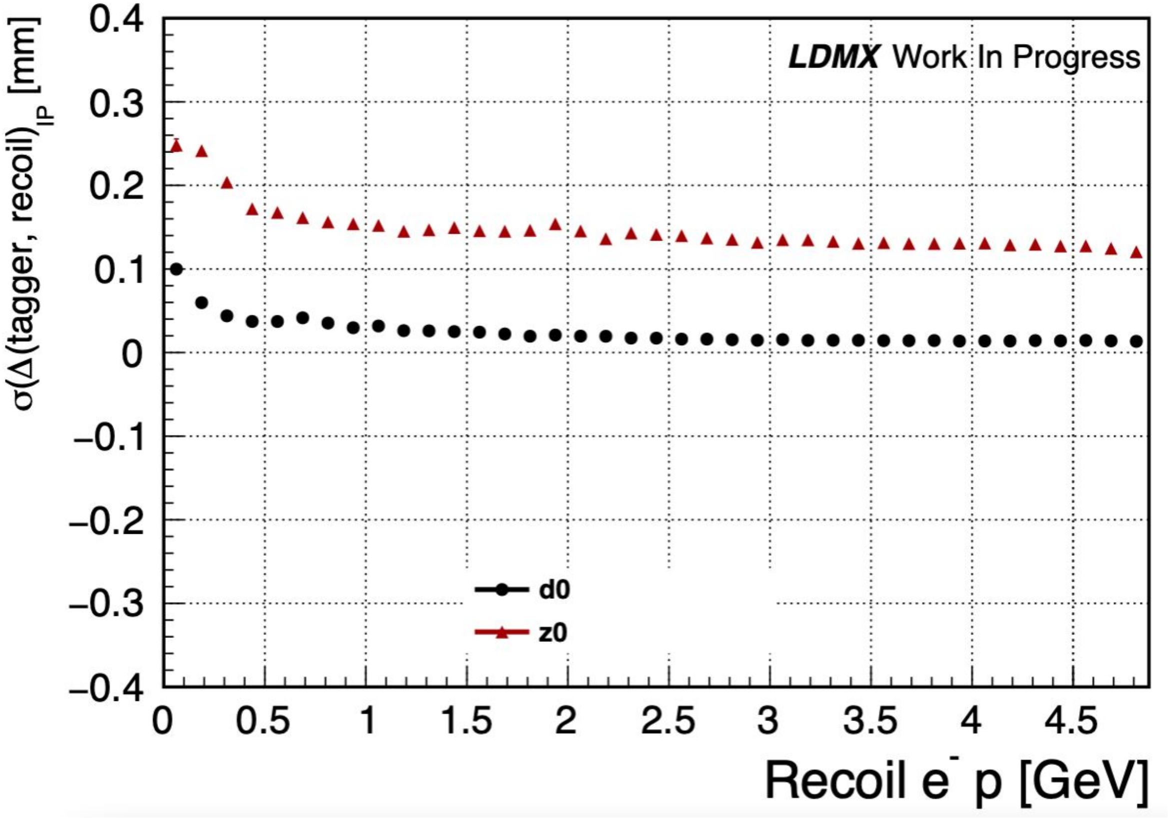
Layer	1	2	3	4	5	6	7
z-position, relative to target (mm)	-607.5	-507.5	-407.5	-307.5	-207.5	-107.5	-7.5
Stereo Angle (mrad)	-100	100	-100	100	-100	100	-100
Bend plane (horizontal) resolution (μm)	$\sim$6	$\sim$6	$\sim$6	$\sim$6	$\sim$6	$\sim$6	$\sim$6
Non-bend (vertical) resolution (μm)	$\sim$60	$\sim$60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

TABLE II: The layout and resolution of the recoil tracker.

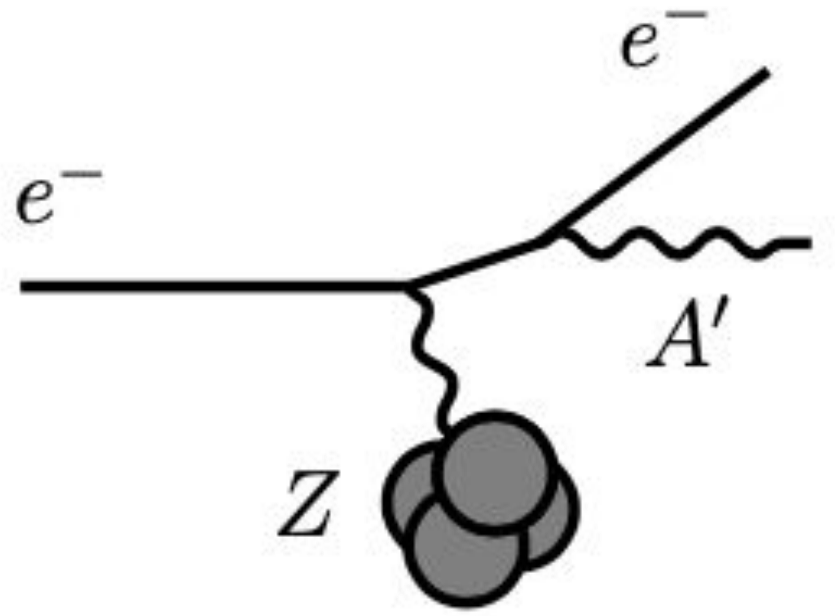
Layer	1	2	3	4	5	6
z-position, relative to target (mm)	+7.5	+22.5	+37.5	+52.5	+90	+180
Stereo Angle (mrad)	100	-100	100	-100	-	-
Bend plane (horizontal) resolution (μm)	$\approx$6	$\approx$6	$\approx$6	$\approx$6	$\approx$6	$\approx$6
Non-bend (vertical) resolution (μm)	$\approx$60	$\approx$60	$\approx$60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

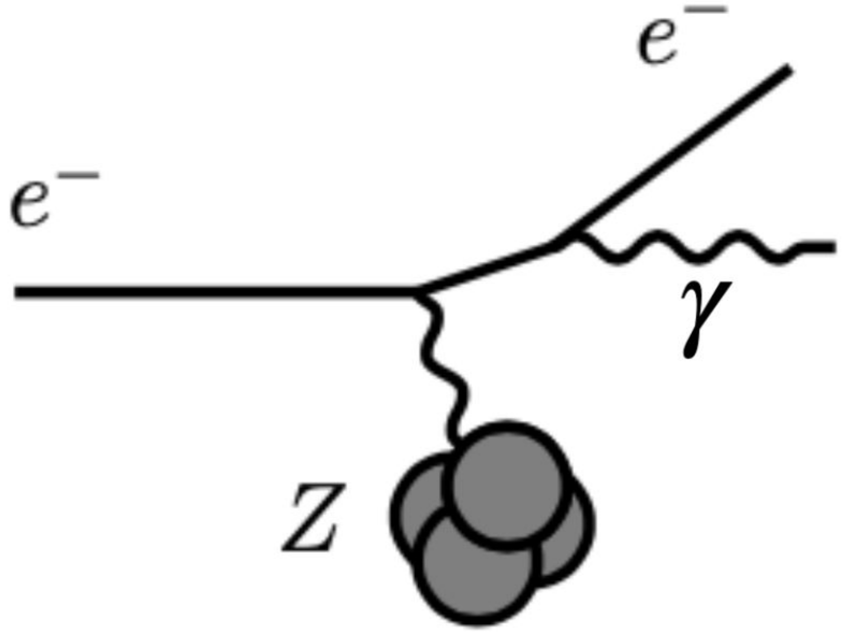
Tracking - Impact parameters at the target





Dark Photon kinematics at a Fixed Target Experiment

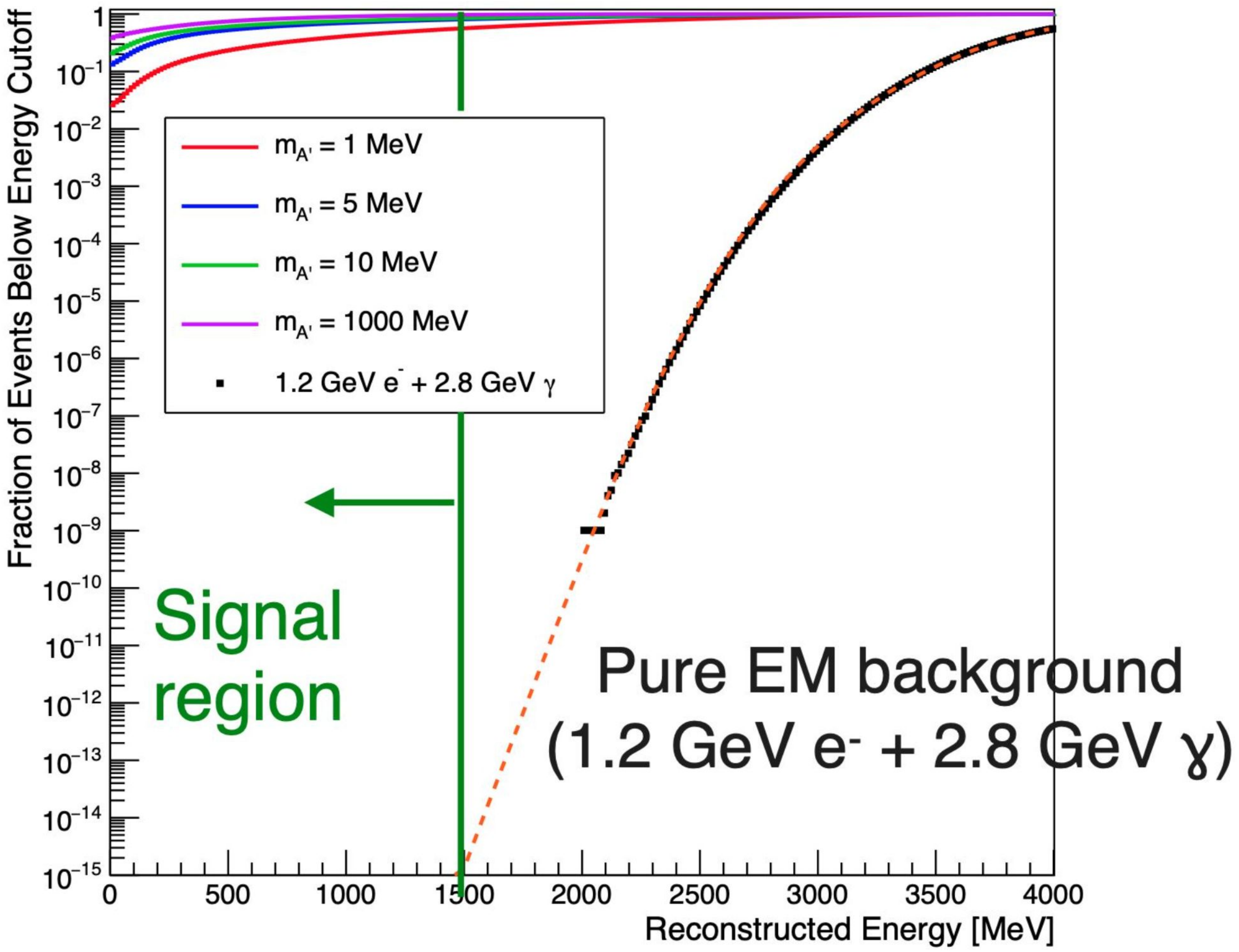




Summary

- **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 also impressive sensitivity to**:
  - Visible signatures of mediators and Dark Sectors particles
  - Broad range of new physics scenarios with missing energy/momentum signatures
  - Important eN scattering measurements to constrain neutrino cross-section uncertainties for DUNE
- **The experiment is ready to move forward with the construction phase**
  - Dark Matter New Initiative R&D funding has been very productive
  - LESA Beamline construction is underway at SLAC
  - Detector technologies have been proven by other HEP experiments
  - Test-beam at CERN validated key detector developments
- **LDMX could be taking data in 2-3 years after establishing the funding profile and make a major discovery shortly thereafter**

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)

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**