Status and future prospects of the Light Dark Matter eXperiment

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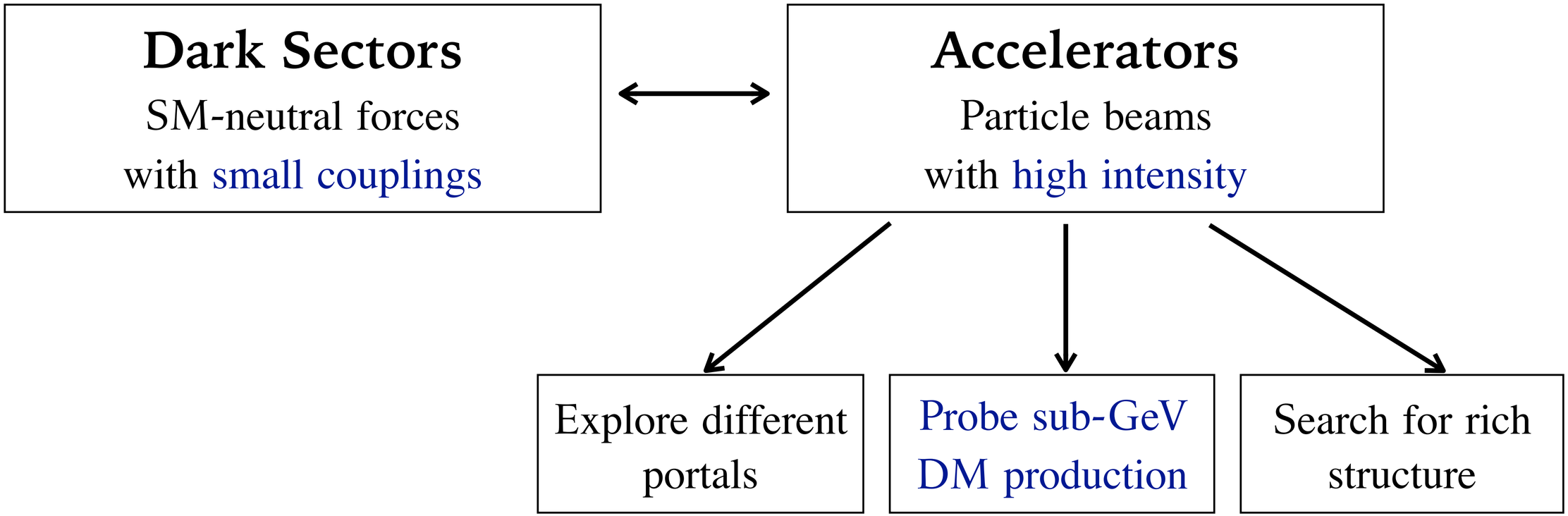
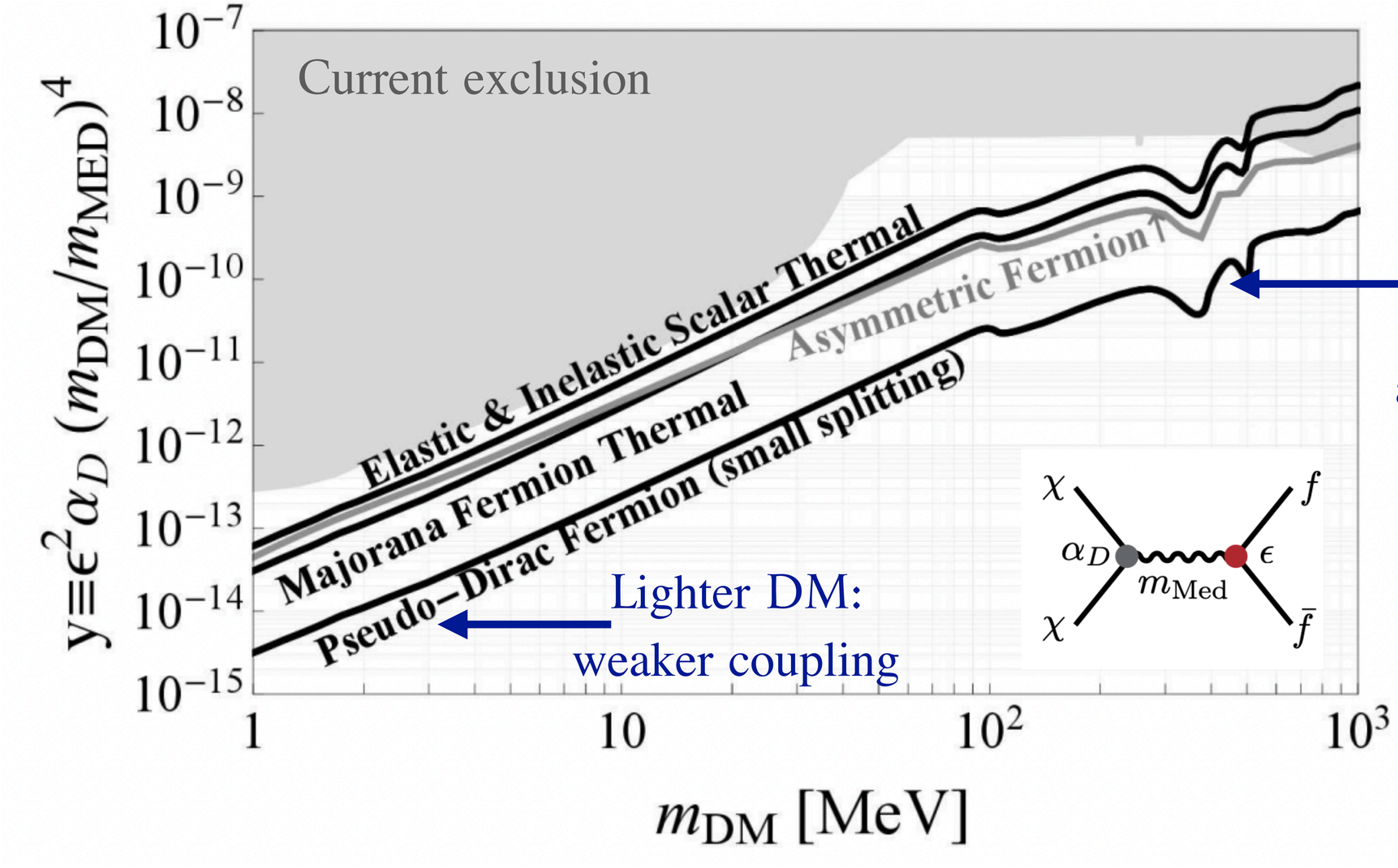
Aspen Center for Physics
March 28th, 2023

Fermilab

Accelerators: A powerful and essential probe of dark sectors



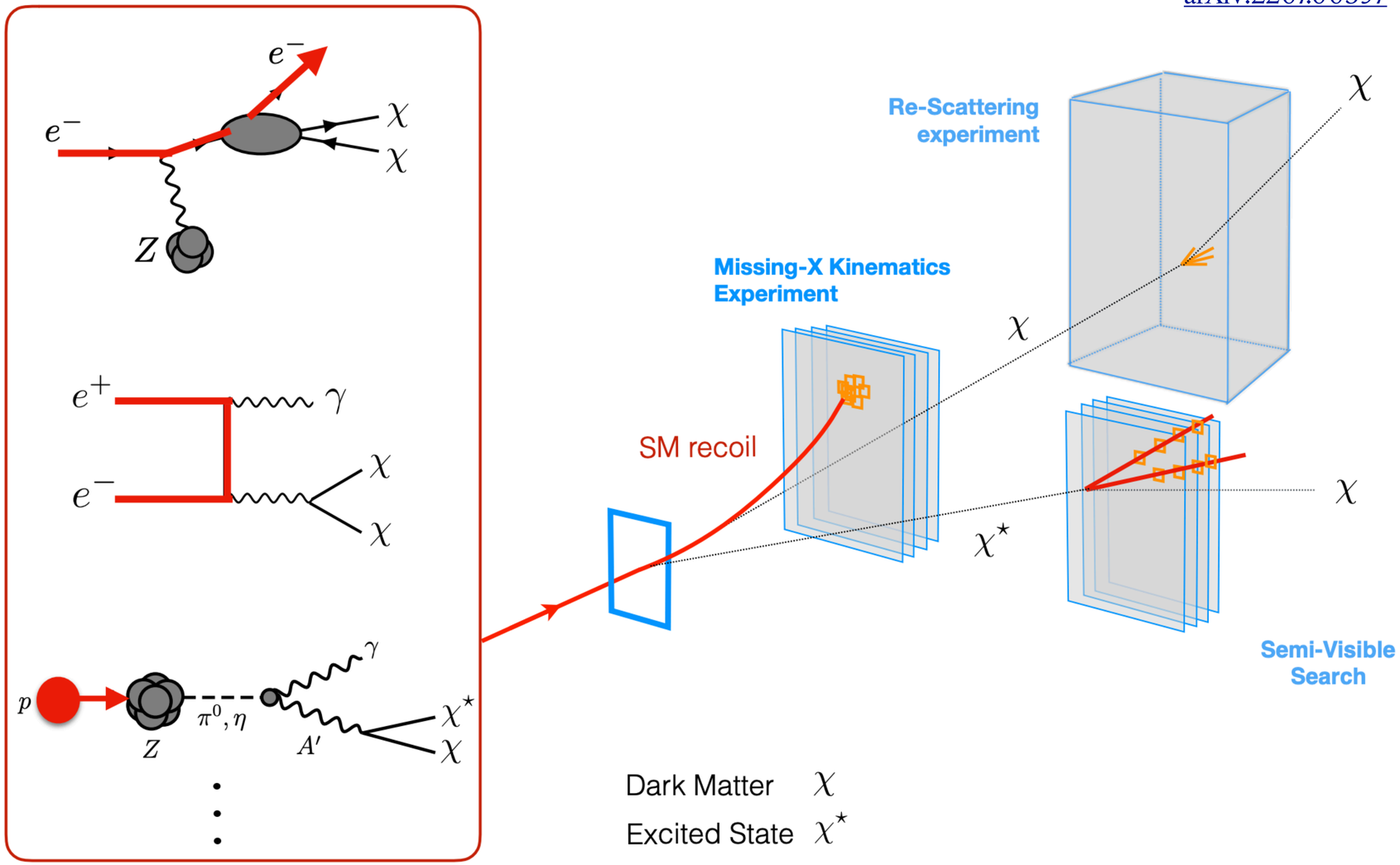
Thermal dark matter production: clear milestones in mass and coupling



Thermal targets in accelerators

Complementary accelerator approaches for detecting dark matter production

arXiv:2207.00597



Complementary accelerator approaches for detecting dark matter production

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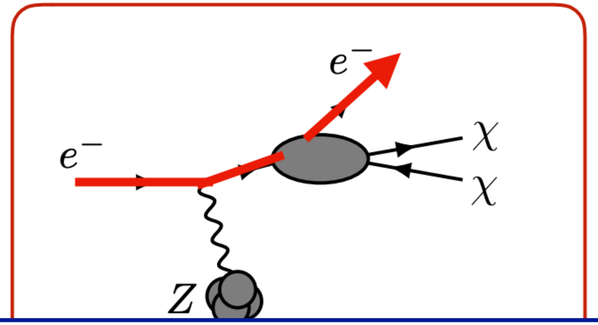
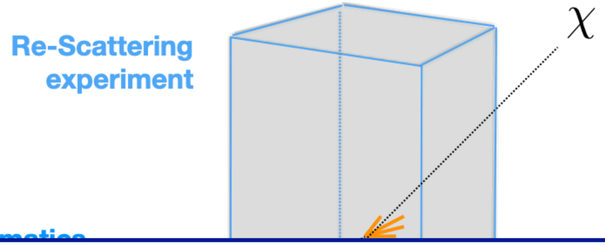
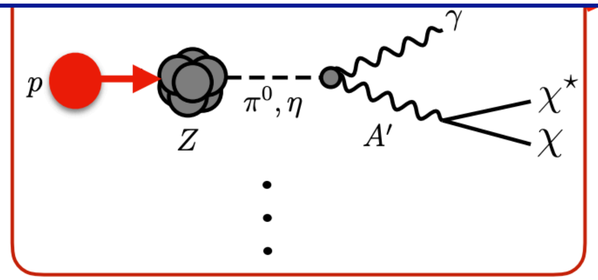




LMDX: Missing X kinematics experiment

- Cross section scales as ϵ^2 (instead of ϵ^4)
- Uses missing momentum technique: handle to reject backgrounds
- Can FULLY explore all thermal targets @ MeV-GeV

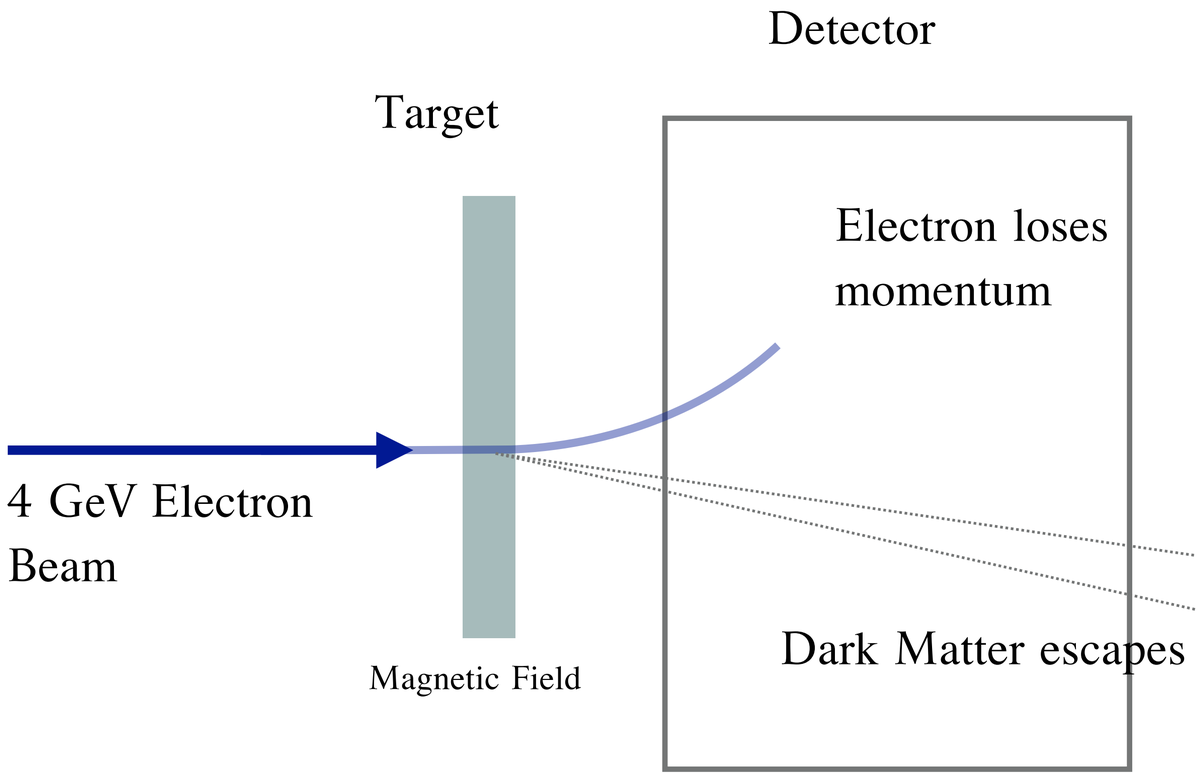


Semi-Visible Search

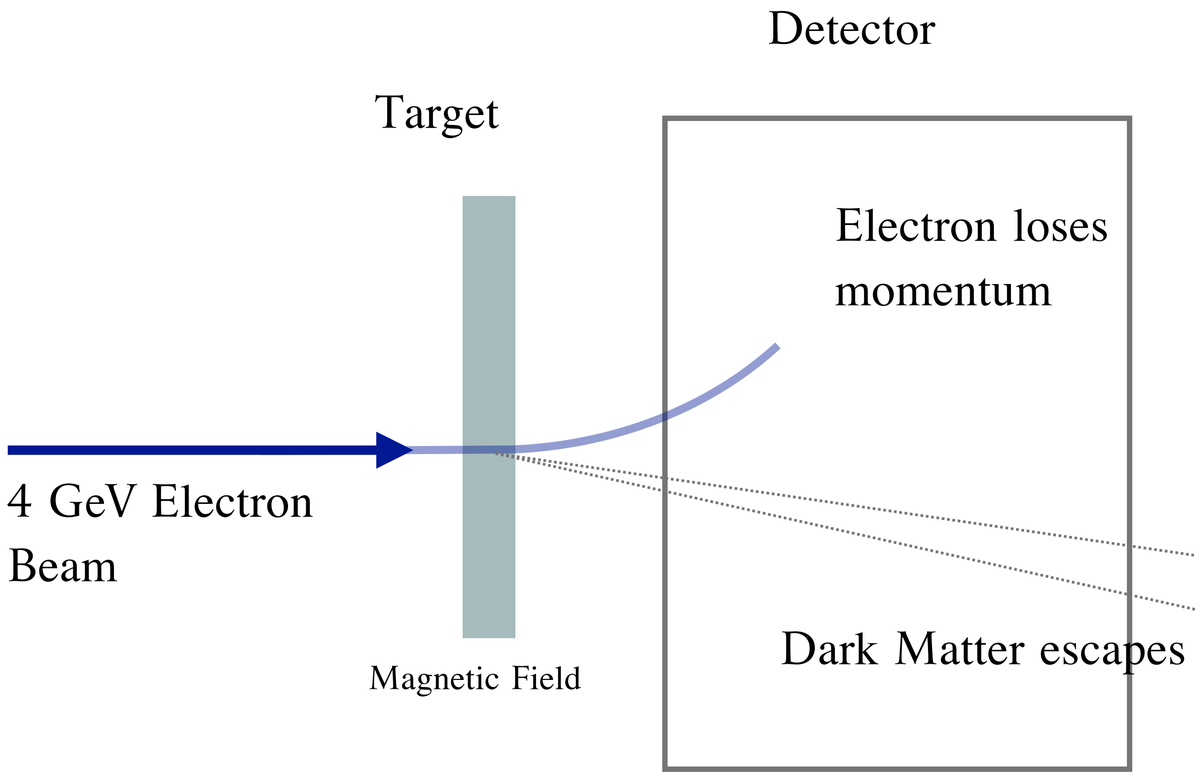
Dark Matter χ

Excited State $\chi^\star$

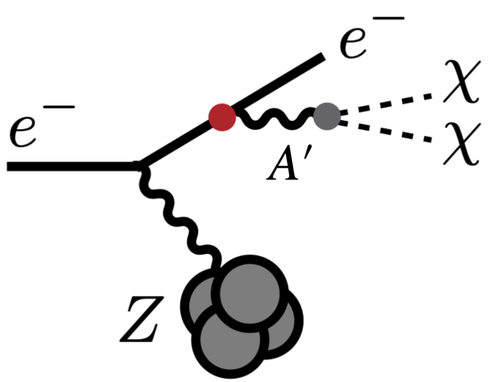
Detecting dark matter with missing momentum



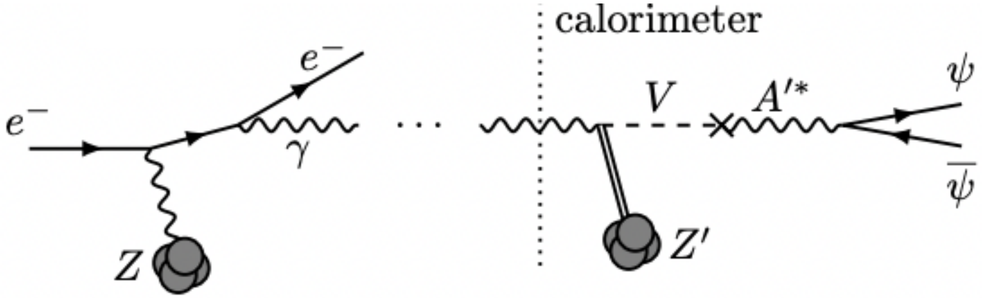
Detecting dark matter with missing momentum



Dark-Bremsstrahlung



Meson-production



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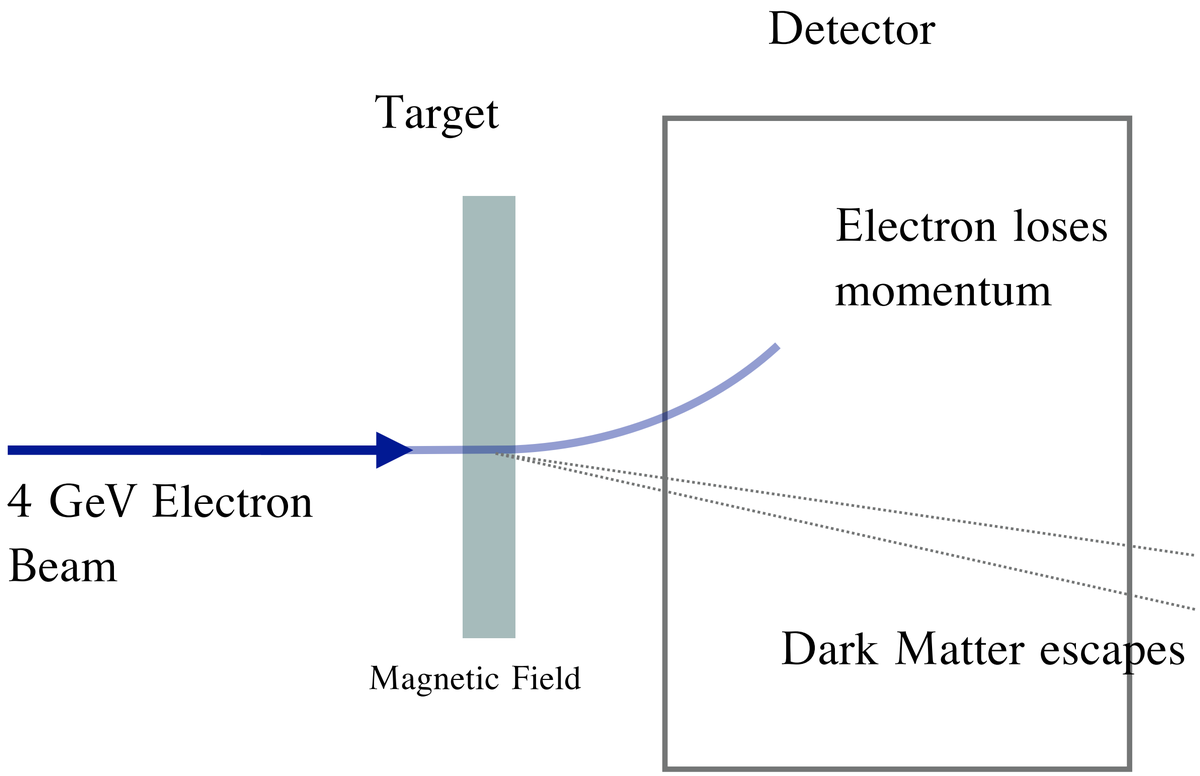
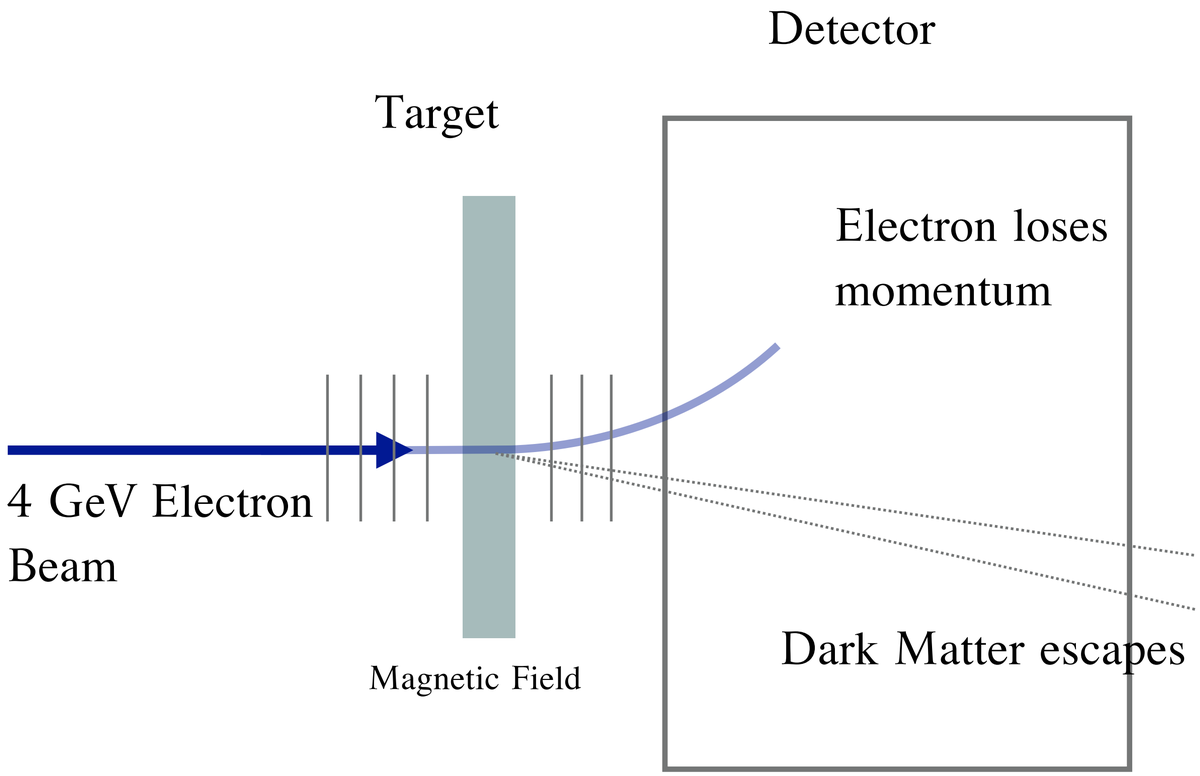
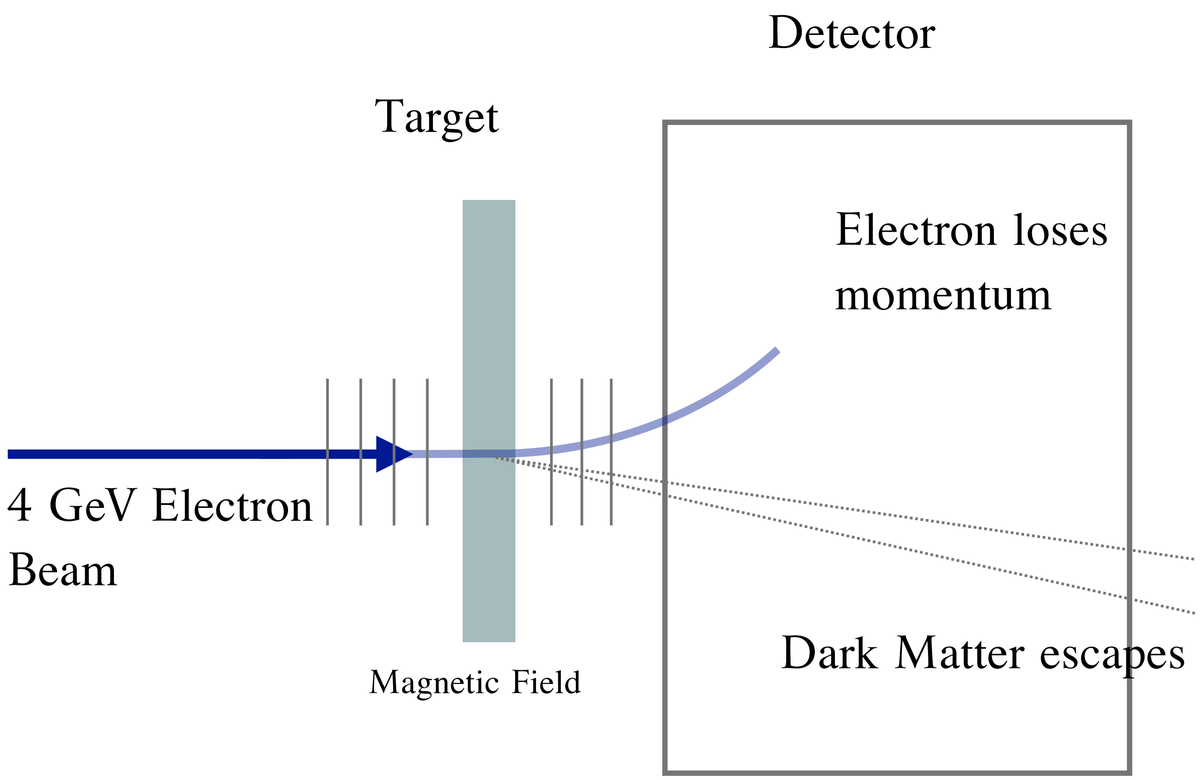


Detecting dark matter with missing momentum

Identify individual electrons (+ momenta) → Need low current beam (+ tracker)



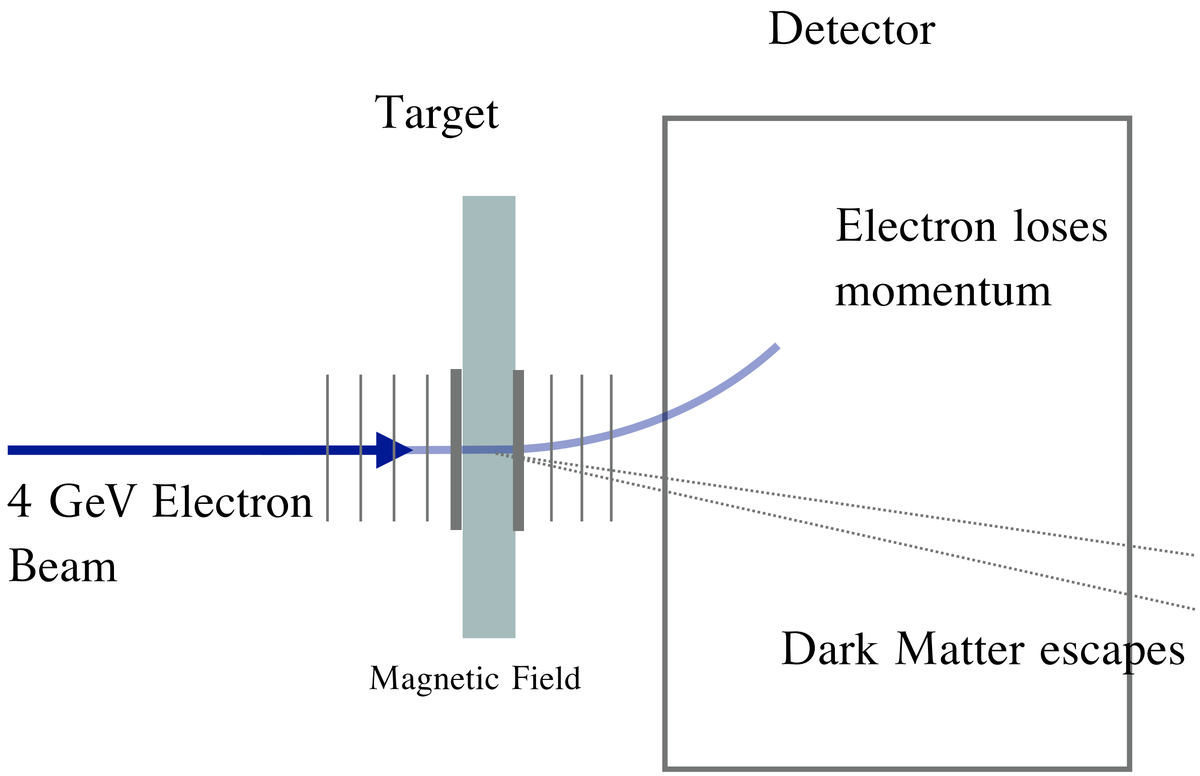
Detecting dark matter with missing momentum



Identify individual electrons (+ momenta) → Need low current beam (+ tracker)

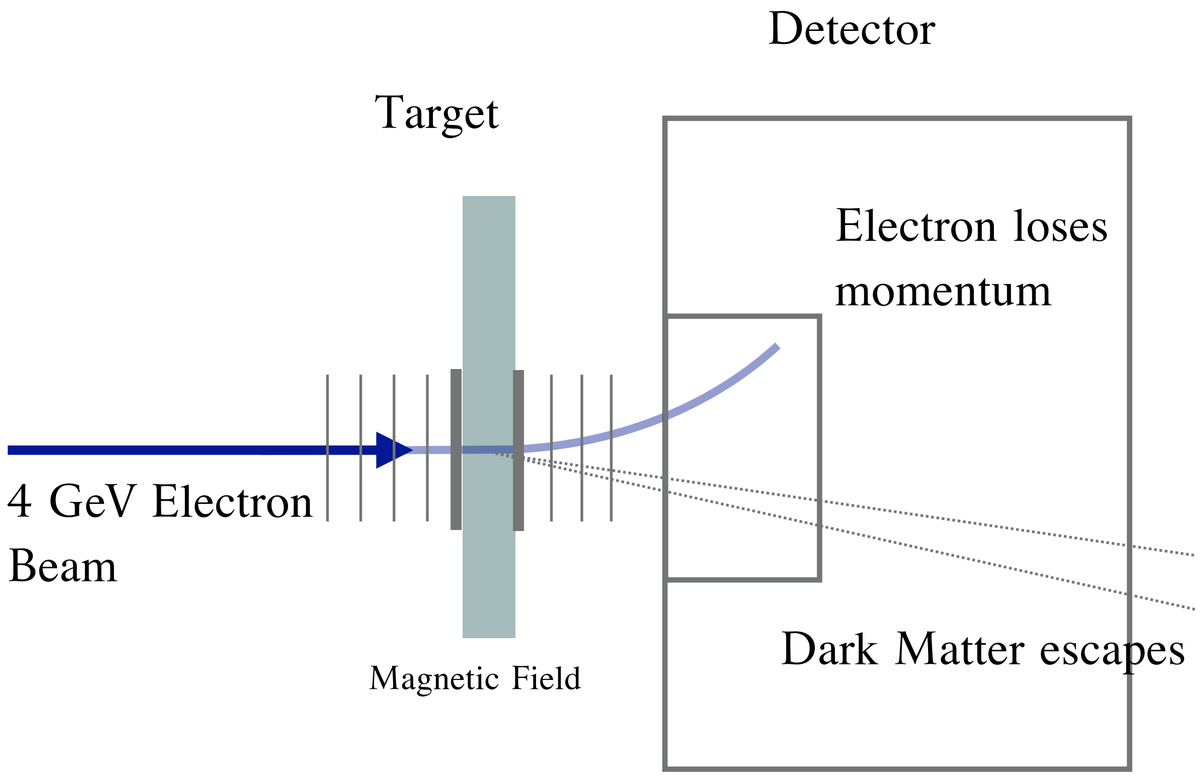
Operate with a LOT of electrons (10^{14}) → Radiation-hardness

Detecting dark matter with missing momentum



Identify individual electrons (+ momenta)	→	Need low current beam (+ tracker)
Operate with a LOT of electrons (10^{14})	→	Radiation-hardness
Select on missing energy (fast)	→	Trigger every ~25 ns: LHC-like readout

Detecting dark matter with missing momentum

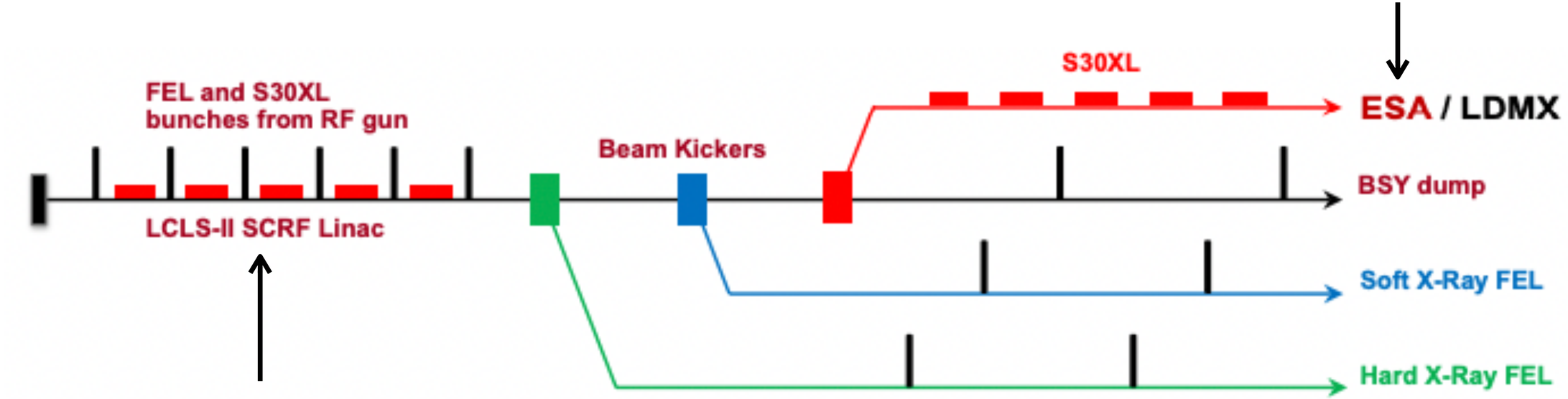


Identify individual electrons (+ momenta)	→	Need low current beam (+ tracker)
Operate with a LOT of electrons (10^{14})	→	Radiation-hardness
Select on missing energy (fast)	→	Trigger every ~25 ns: LHC-like readout
Characterize rare backgrounds	→	Calorimeters with fast readout

High precision electron source: LDMX beamline @ FY2025

4 GeV Electron beam @ SLAC

27 ns bunches w/ $\langle n_e \rangle \sim 1$



Parasitic use of LCLS-II:

~60% of unused low-charge bunches

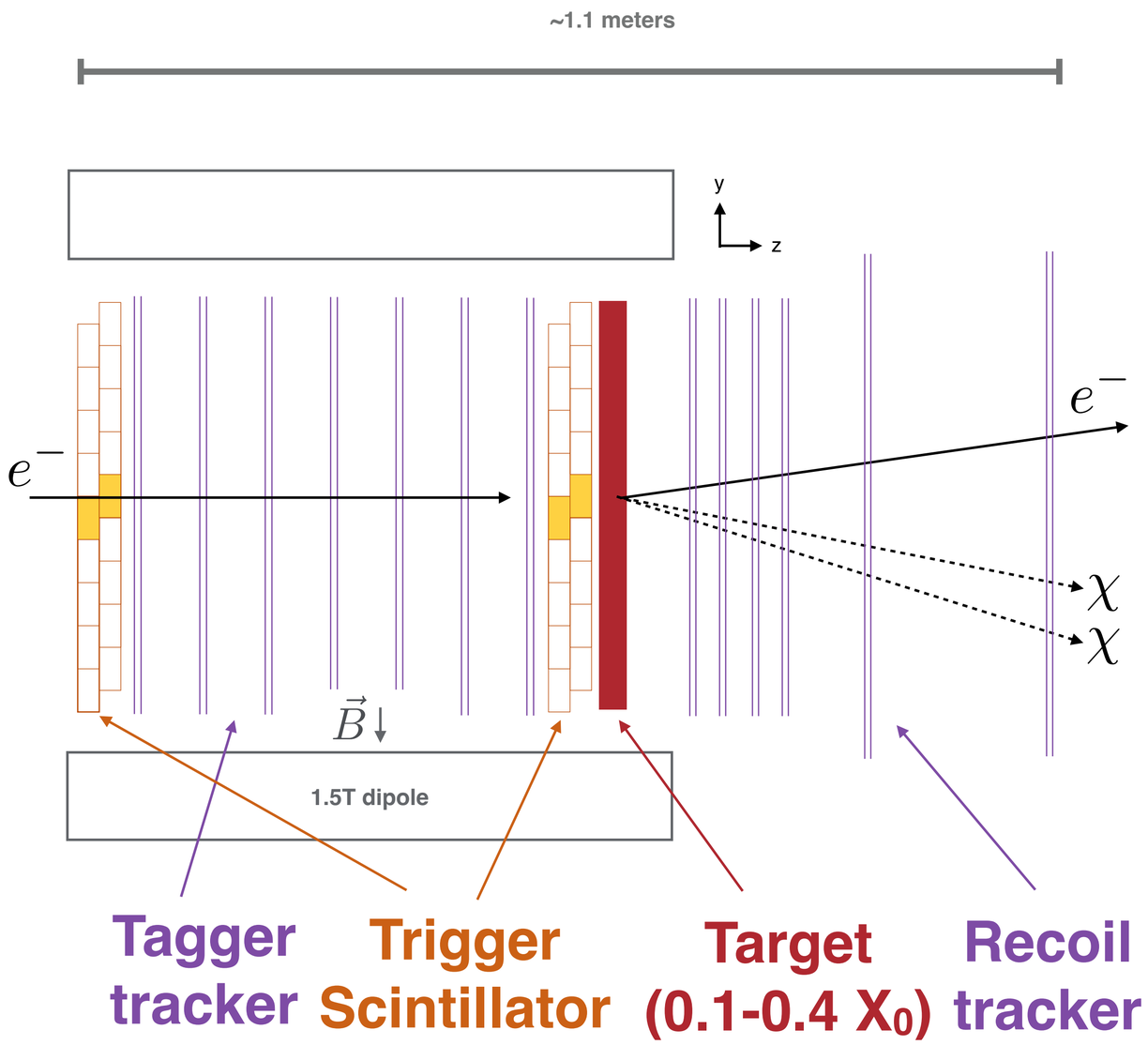
(To **E**nd-**S**tation-**A**)

Beamspot: ~ 20cm^2, Rate: 10^8 EOT/s

4×10^{14} Electrons on Target (EOT) in 1-2 years

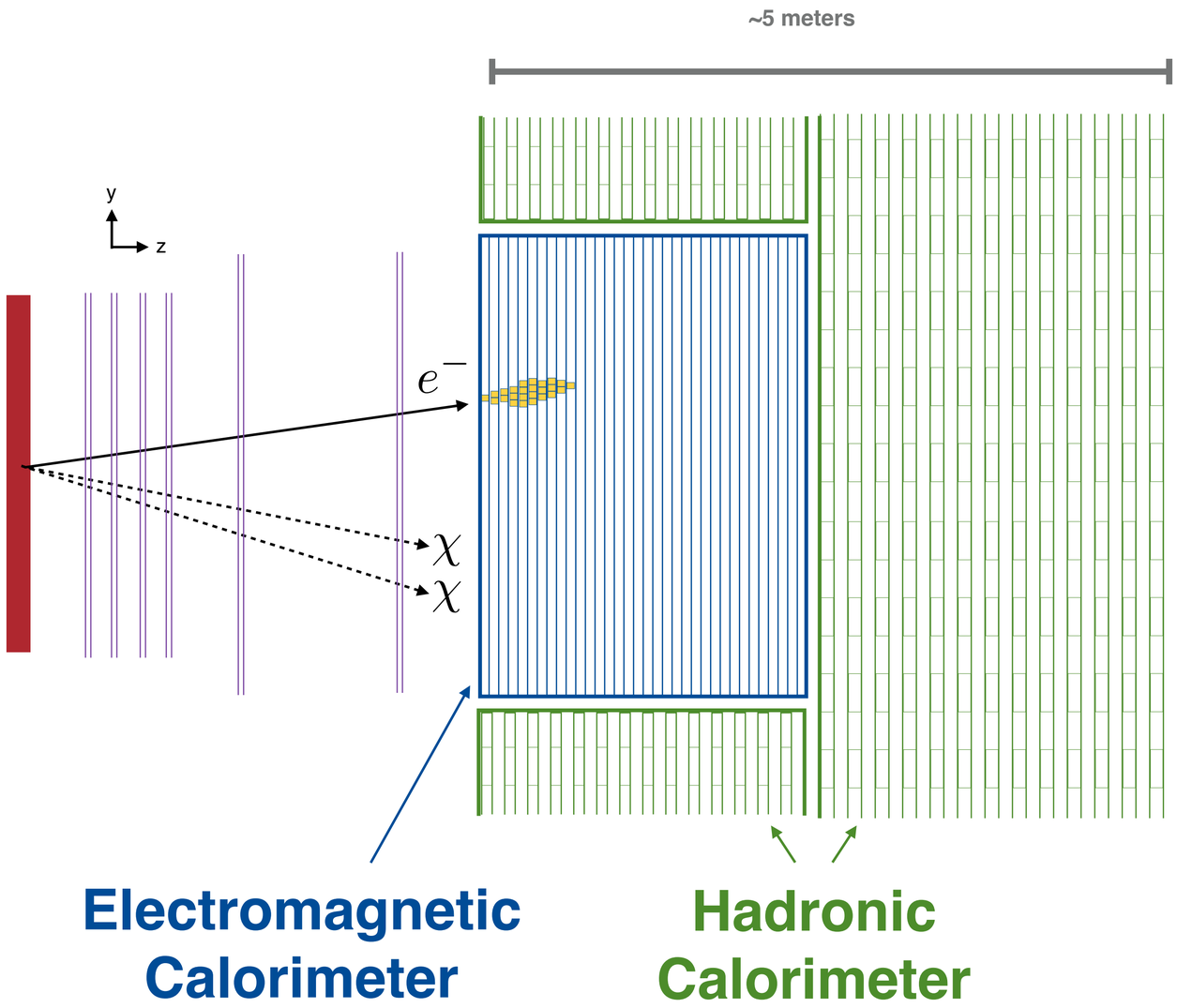
After upgrade: 8 GeV beam (Total 10^{16} EOT)

Tagging individual electrons



- Tag filled bunches:
  missing energy trigger < 1 kHz
  arrays of 48 scintillator bars
- Precise electron tagging:
  σ_p~50 MeV @ E = 4 GeV
  7 double-strip layers
- Measure recoil p_T:
  σ_{pT}~1-4 MeV @ p_T < 1.2 GeV
  4 double-strip layers + 2 axial-only

Fast calorimeter for signal and background characterization



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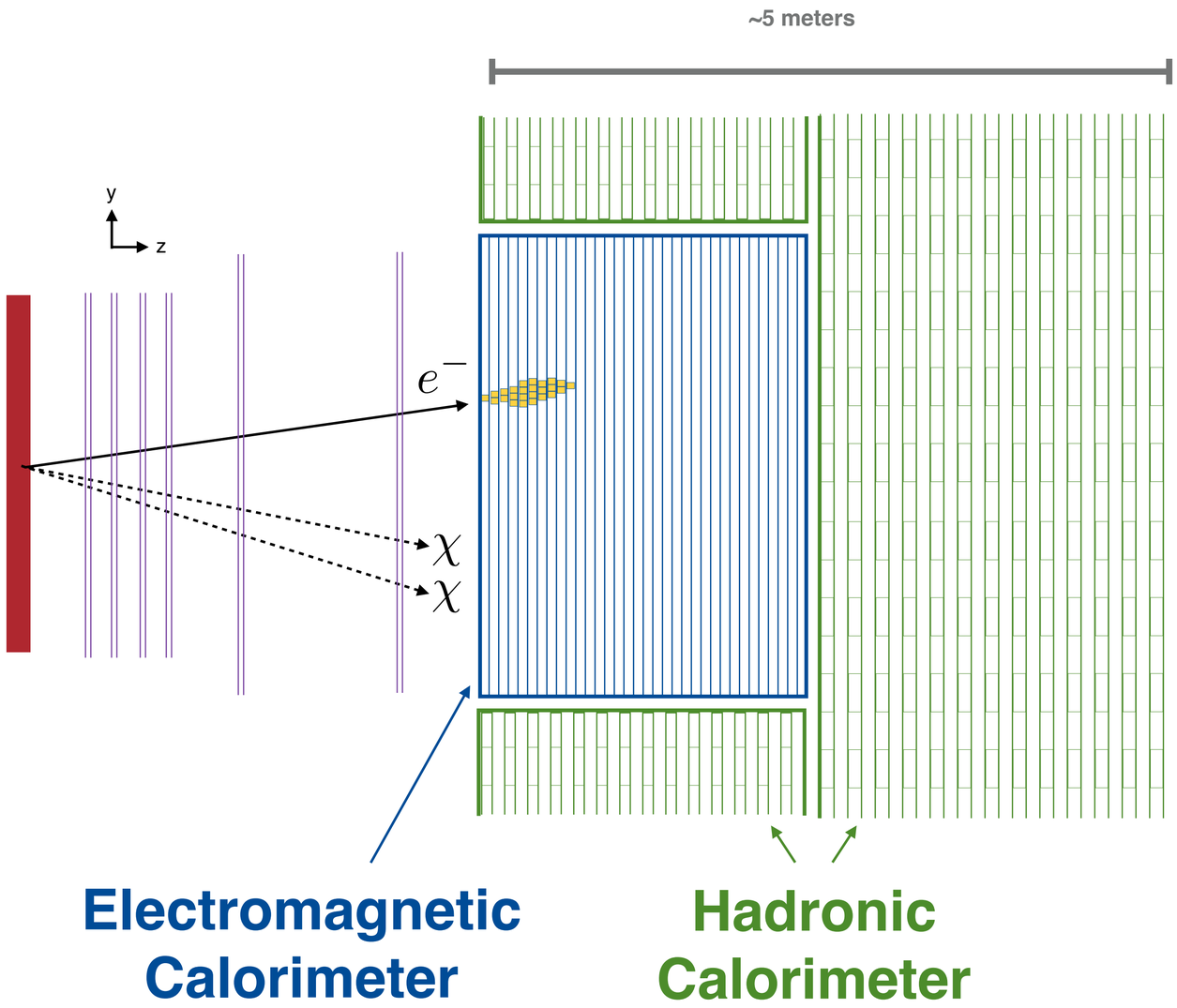

- Fully contain EM showers:
  - Trigger on missing energy
  - Veto Brem. photons / e^+e^-
  - 32 Si/W Layers ~ 40 X_0 absorber depth

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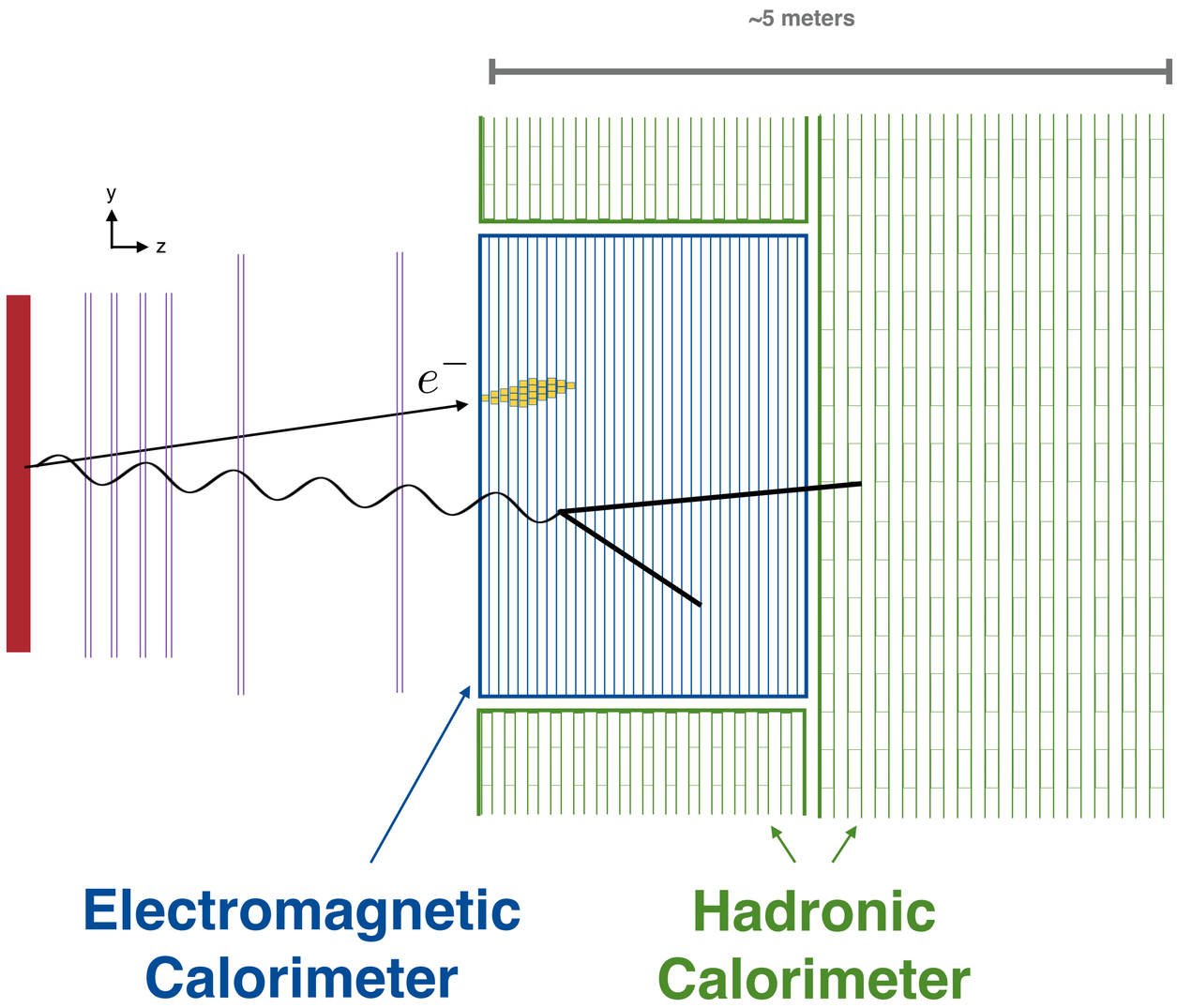

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  - Rate: 1 in 10^5 - 10^6 incident electrons
  - High Granularity with large dynamic range

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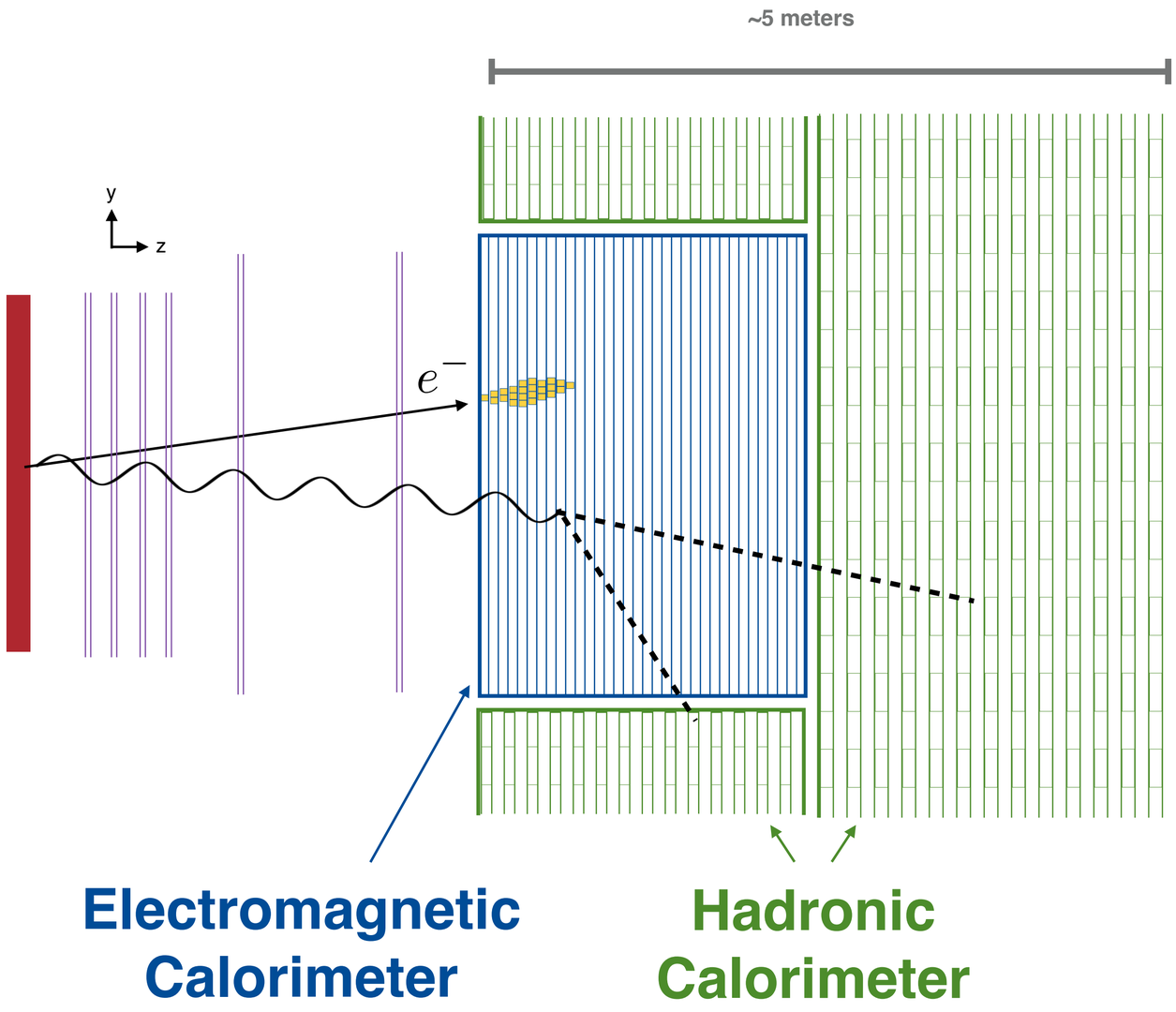

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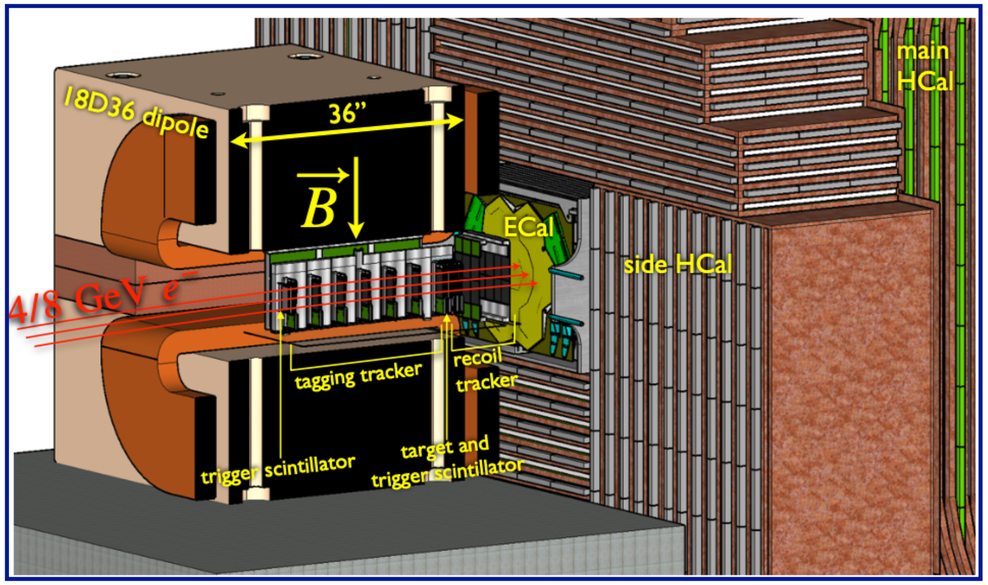
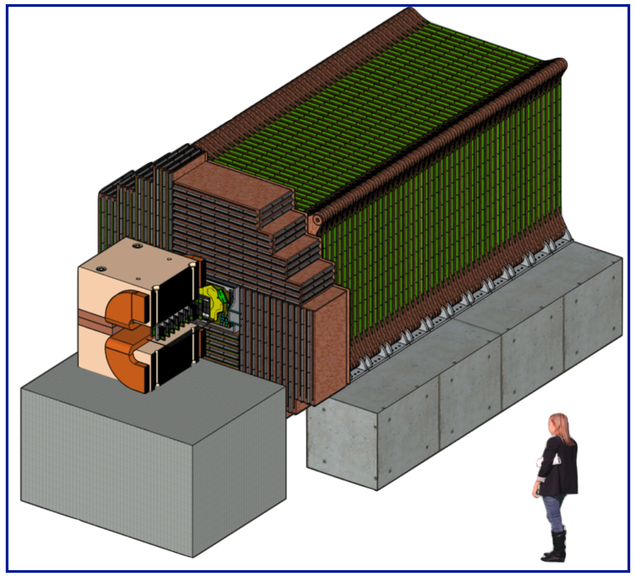
  - Rate: 1 in 10^5 - 10^6 incident electrons
  - High Granularity with large dynamic range
- Veto rare showers: escape Ecal and/or anomalous energy deposits
  - Rate: 1 in 10^8 - 10^{11} incident electrons
  - Ecal Shower Features + Hcal depth
  - Neutron ID: 0.1 - 10 GeV

The LDMX experimental design and status



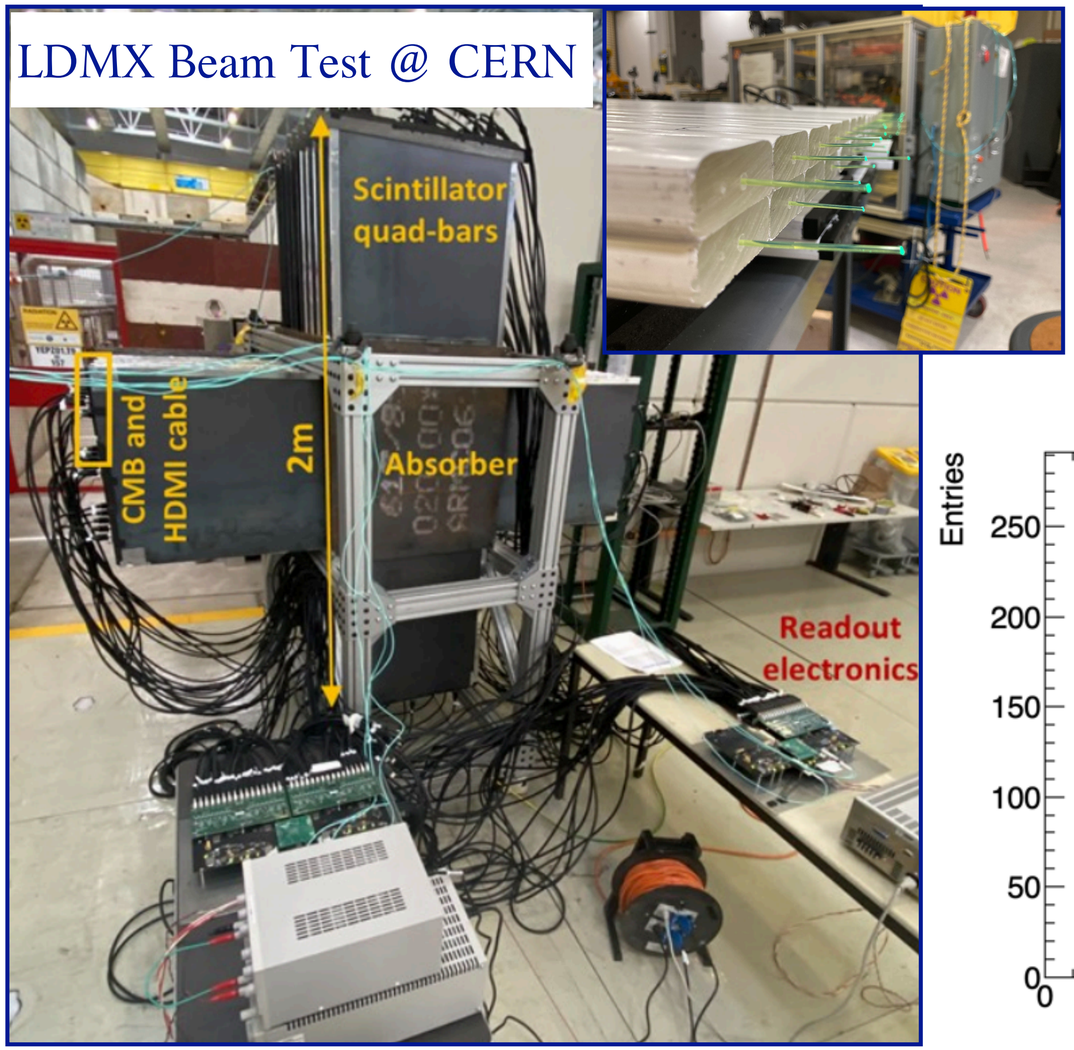


R&D funding
from DOE DMNI
Magnet @ SLAC
to be refurbished

Synergy from existent technologies:

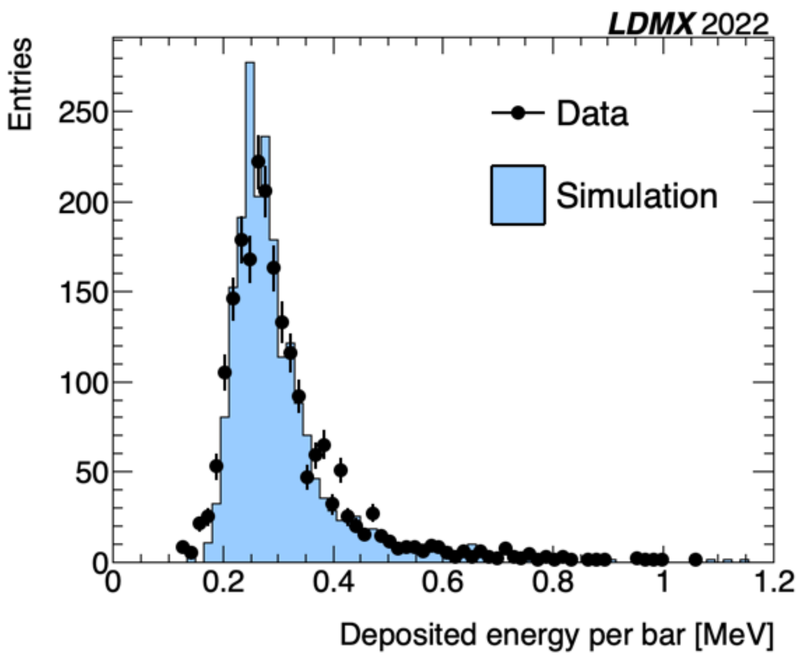
- Tracker modules (HPS Silicon Tracker)
- Hcal scintillators (Mu2e Cosmic Ray Veto)
- ECal (CMS HGCAL)
- ECal + HCal readout (CMS HGROC)

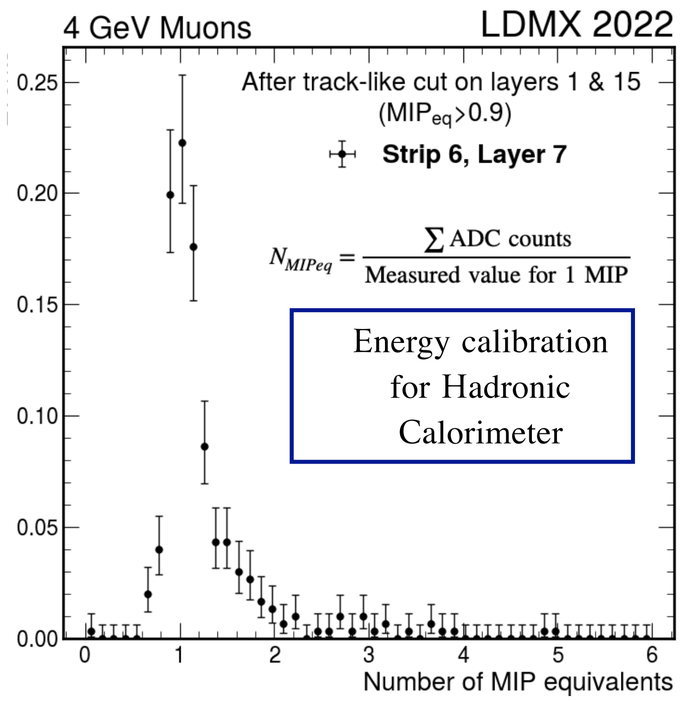
Sub-detector prototypes beam test



First beam test data with 2 sub-detector prototypes

- ➤ TS response well modeled by Geant4 MC simulation
- ➤ HCal response to MIP / noise validated with data





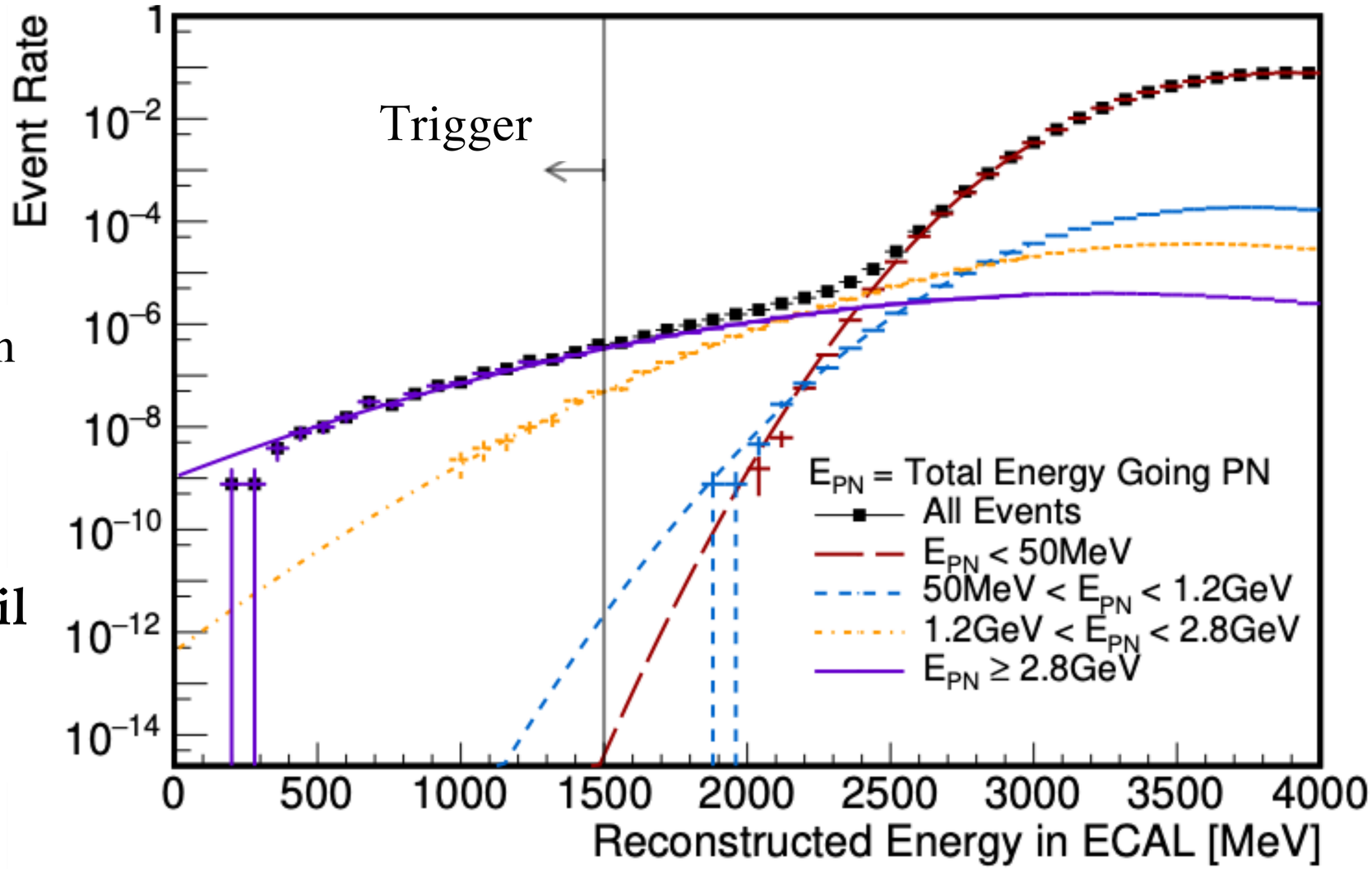
More results to come…

(1) Missing energy trigger: electron loses 62.5% of its energy

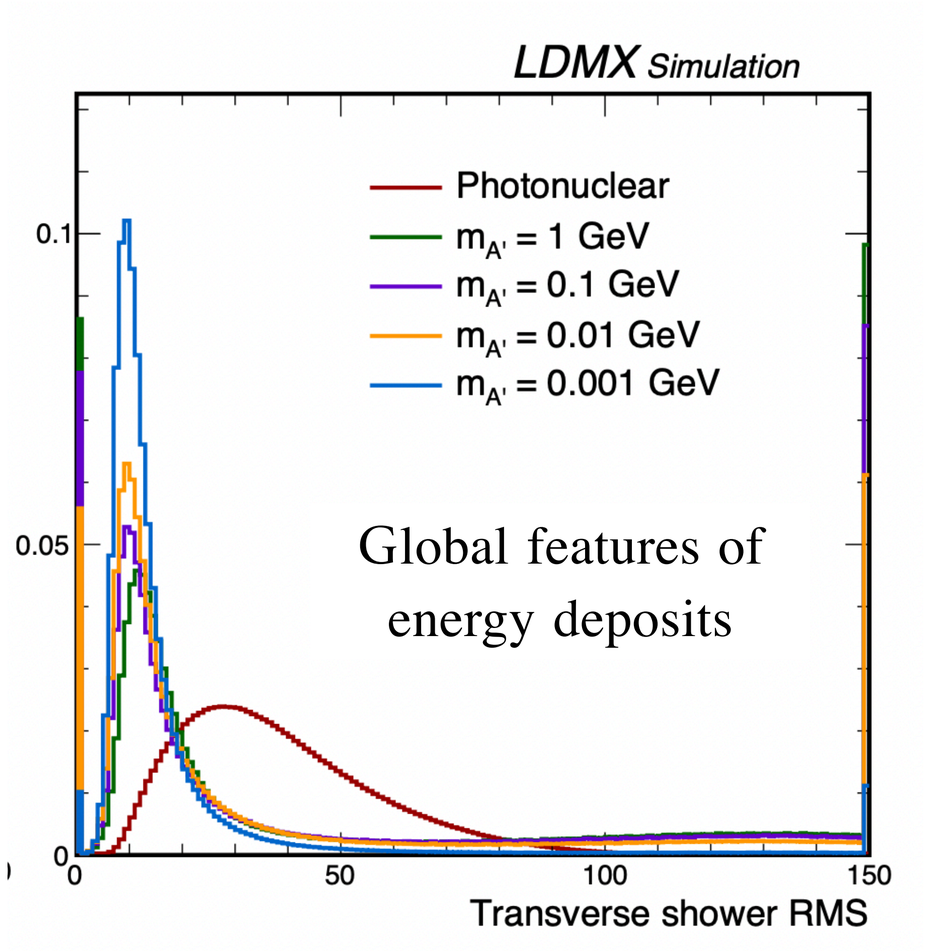
Leading PN contribution with E > 2.8 GeV

↓

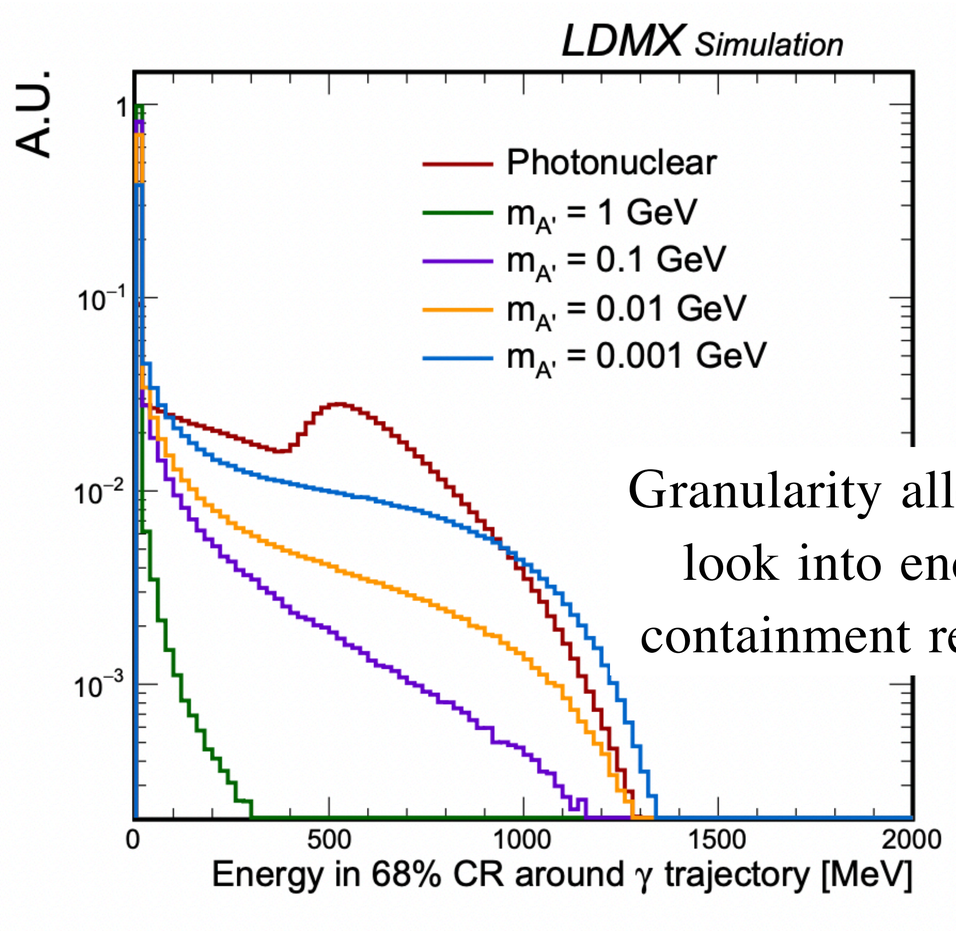
+ requiring **single recoil track** p < 1.2 GeV (reduces bkg. by 1/10)



(2) Discriminating EM showers: signal vs photo-nuclear production



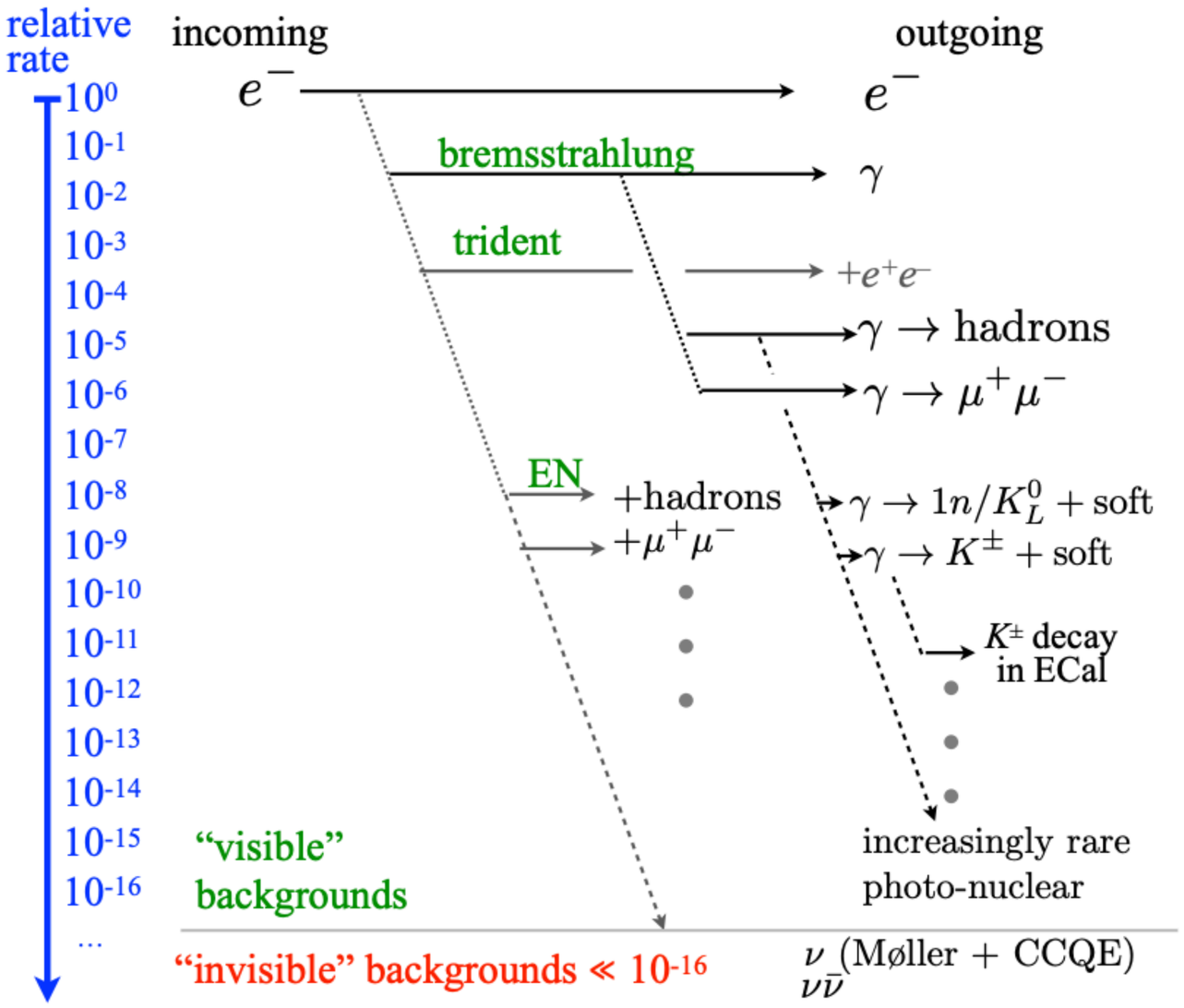
Global features of energy deposits



Granularity allows to look into energy containment regions

Reject 99.9% PN events with 85-99% signal efficiency

(3) Veto on rare processes: near zero-background



Bremsstrahlung + energy fluctuations

Rare reactions

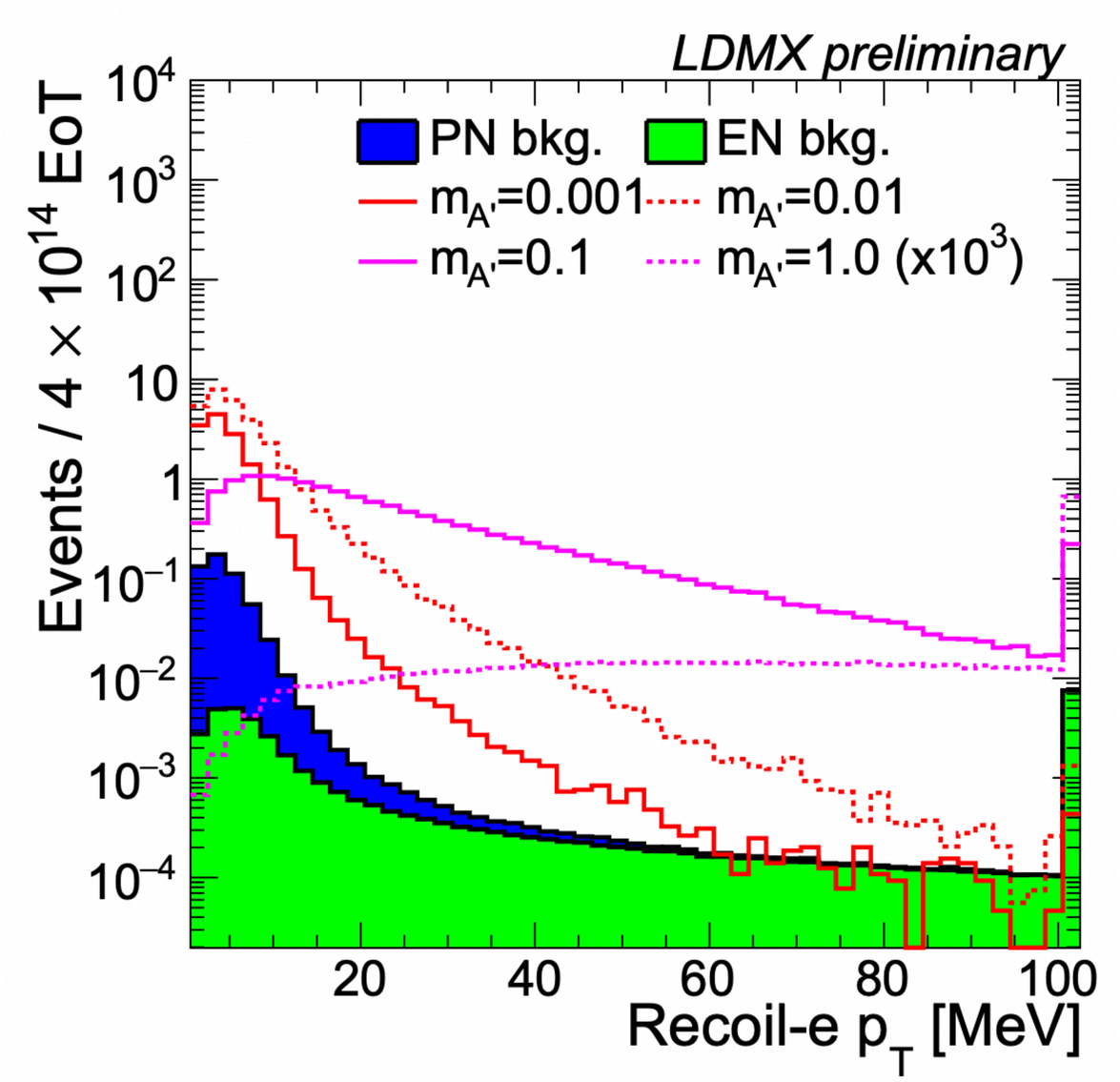
Irreducible missing energy

(3) Veto on rare processes: near zero-background

	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

Background-free with 30-50% signal efficiency@ 4×10^{14} EOT

(4) Sensitivity to dark matter mass scale

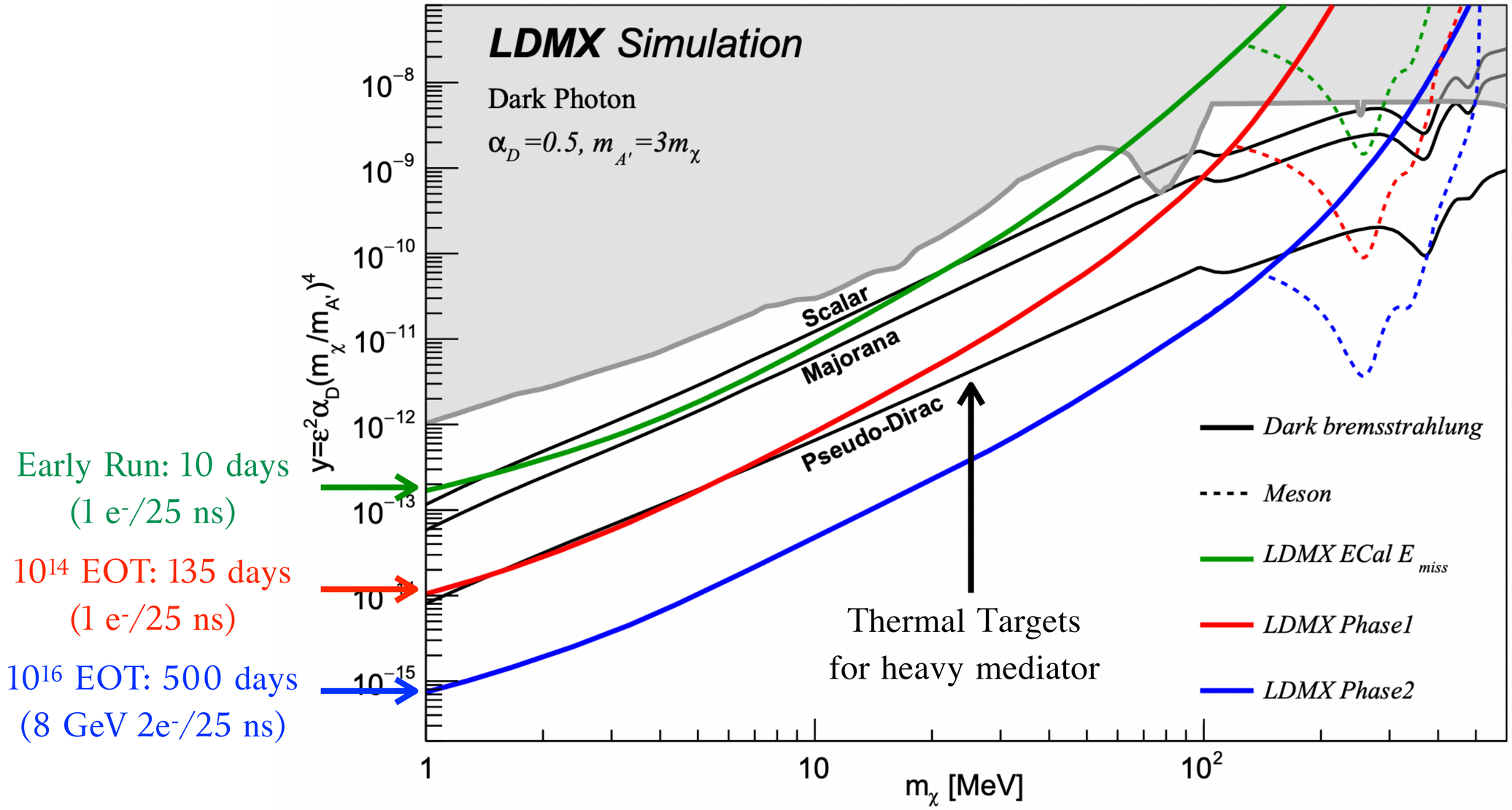


Final handle: e^- p_T measurement

- Used for extra background discrimination
- OR, to set DM mass scale within a factor of 2 at 95% CL.

LDMX is uniquely sensitive to MeV-GeV DM production

arXiv:2203.08192



Sensitivity assuming: 0.5 background events

LDMX is uniquely sensitive to MeV-GeV DM production

arXiv:2203.08192

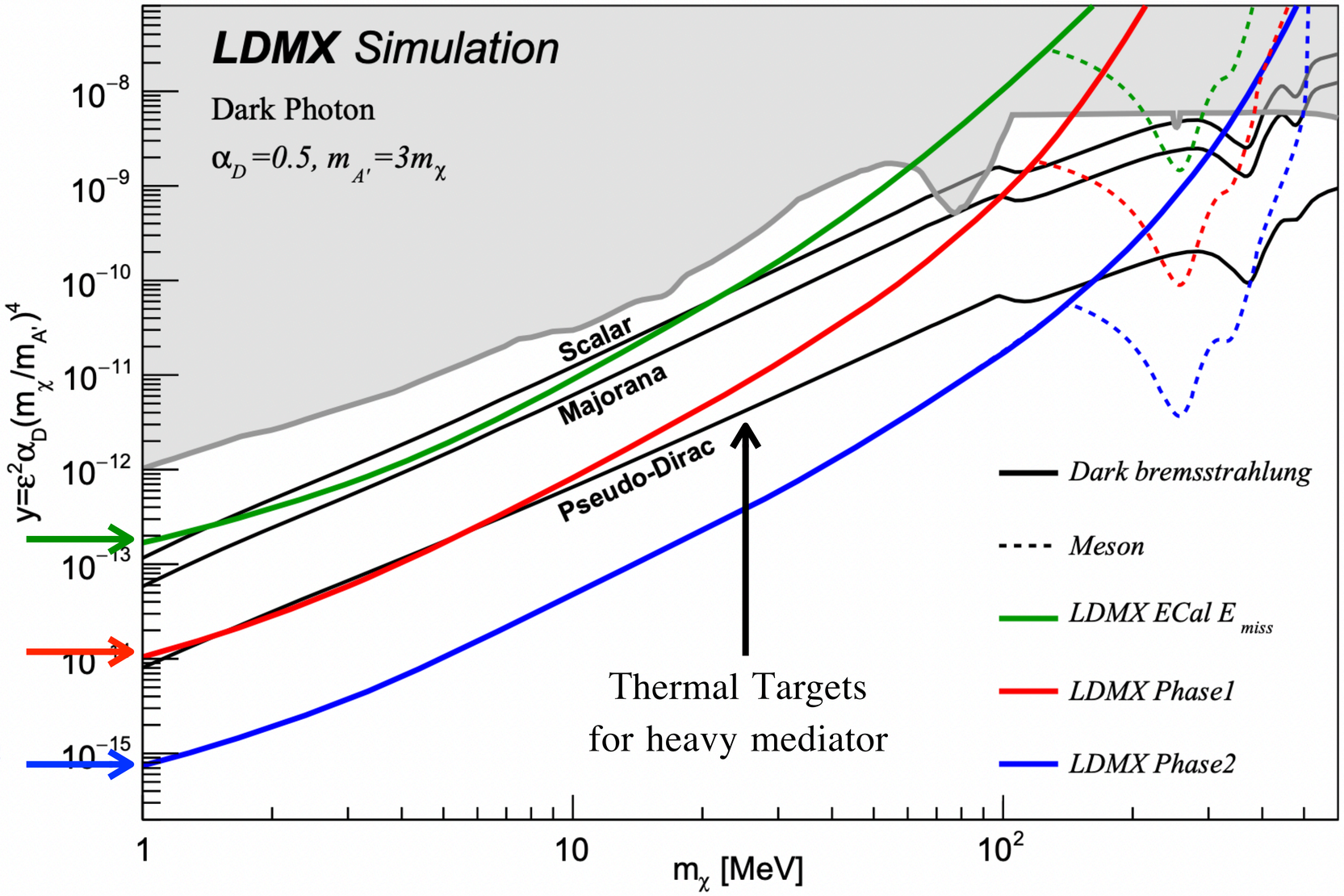
Timeline

2023 Construction ?

2025 Early Run: 10 days (1 e⁻/25 ns)

2027 10^{14} EOT: 135 days (1 e⁻/25 ns)

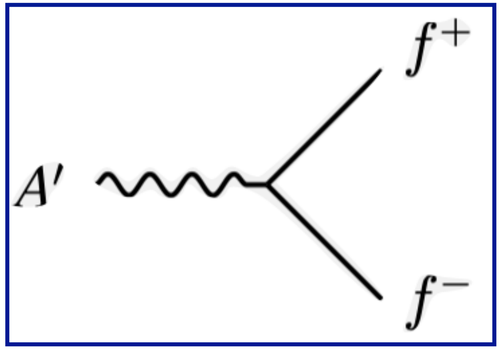
>2028 10^{16} EOT: 500 days (8 GeV 2e⁻/25 ns)



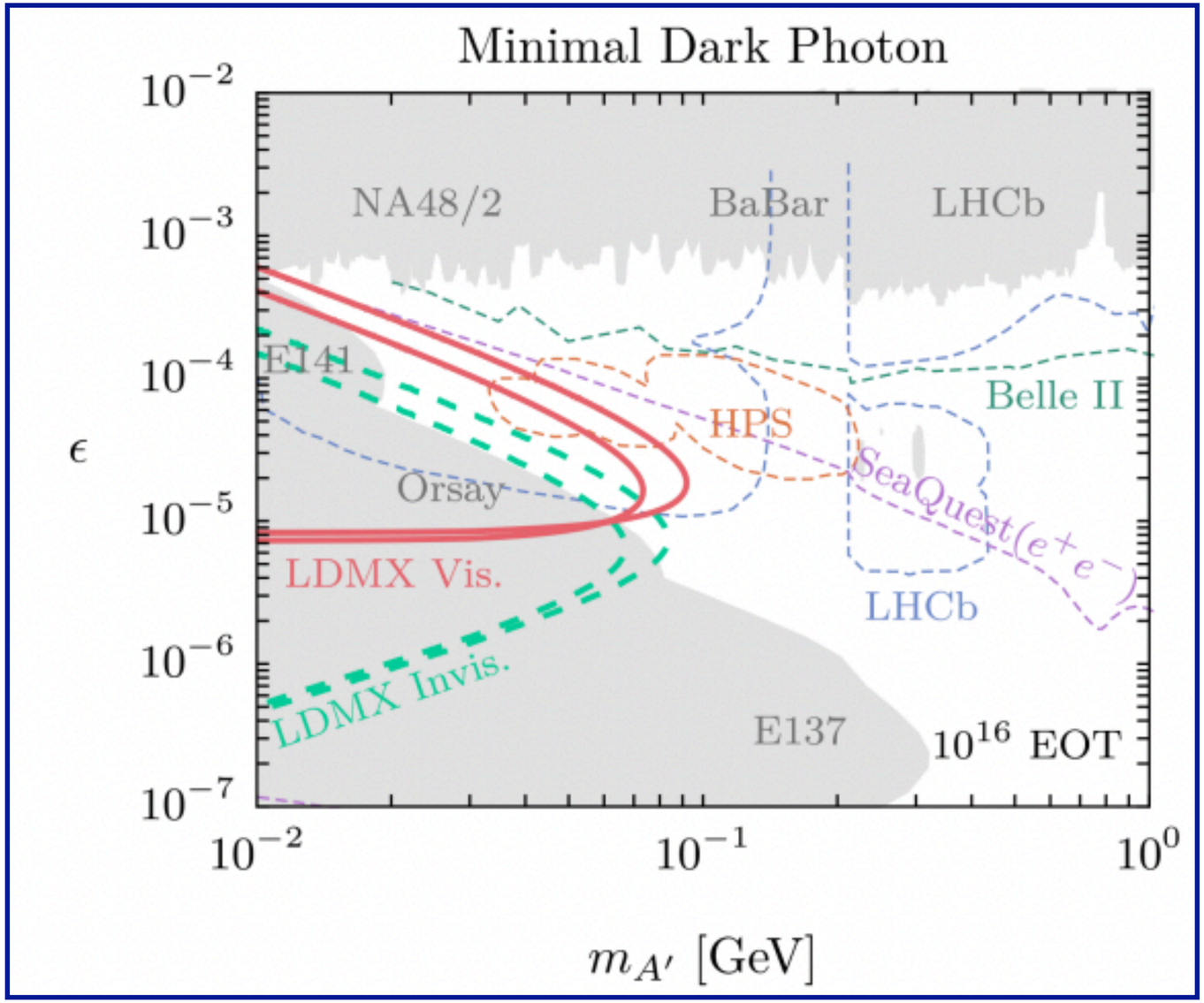
Sensitivity assuming: 0.5 background events

LDMX physics reach to other dark sectors

Berlin et. al. PRD 99, 075001 (2019)



Short baseline for
visible displaced decays
of dark photons
(requires new trigger)



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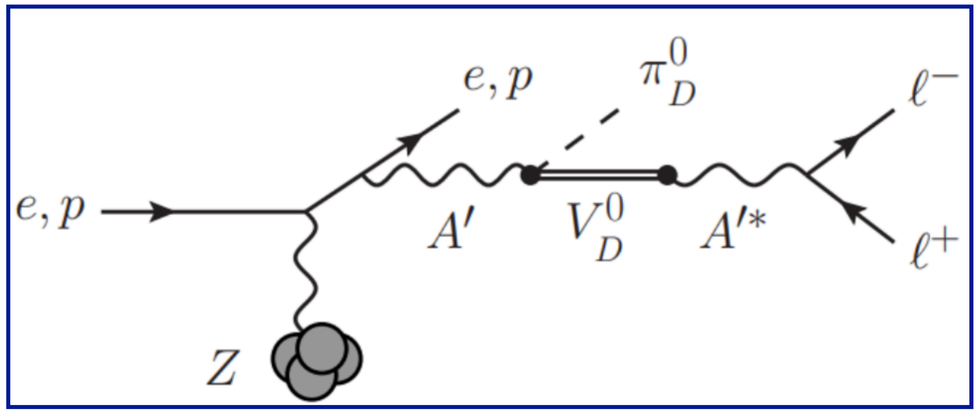
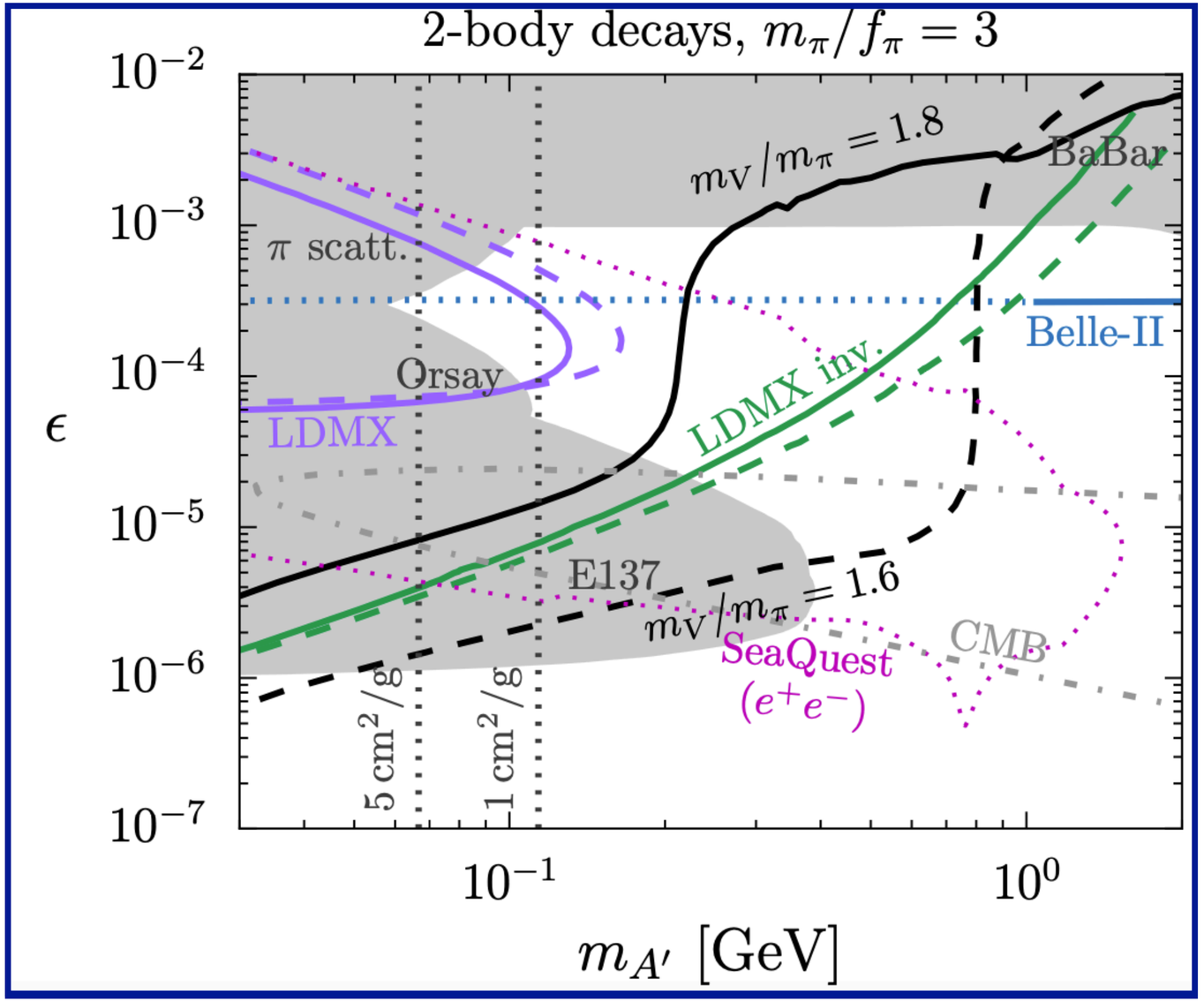
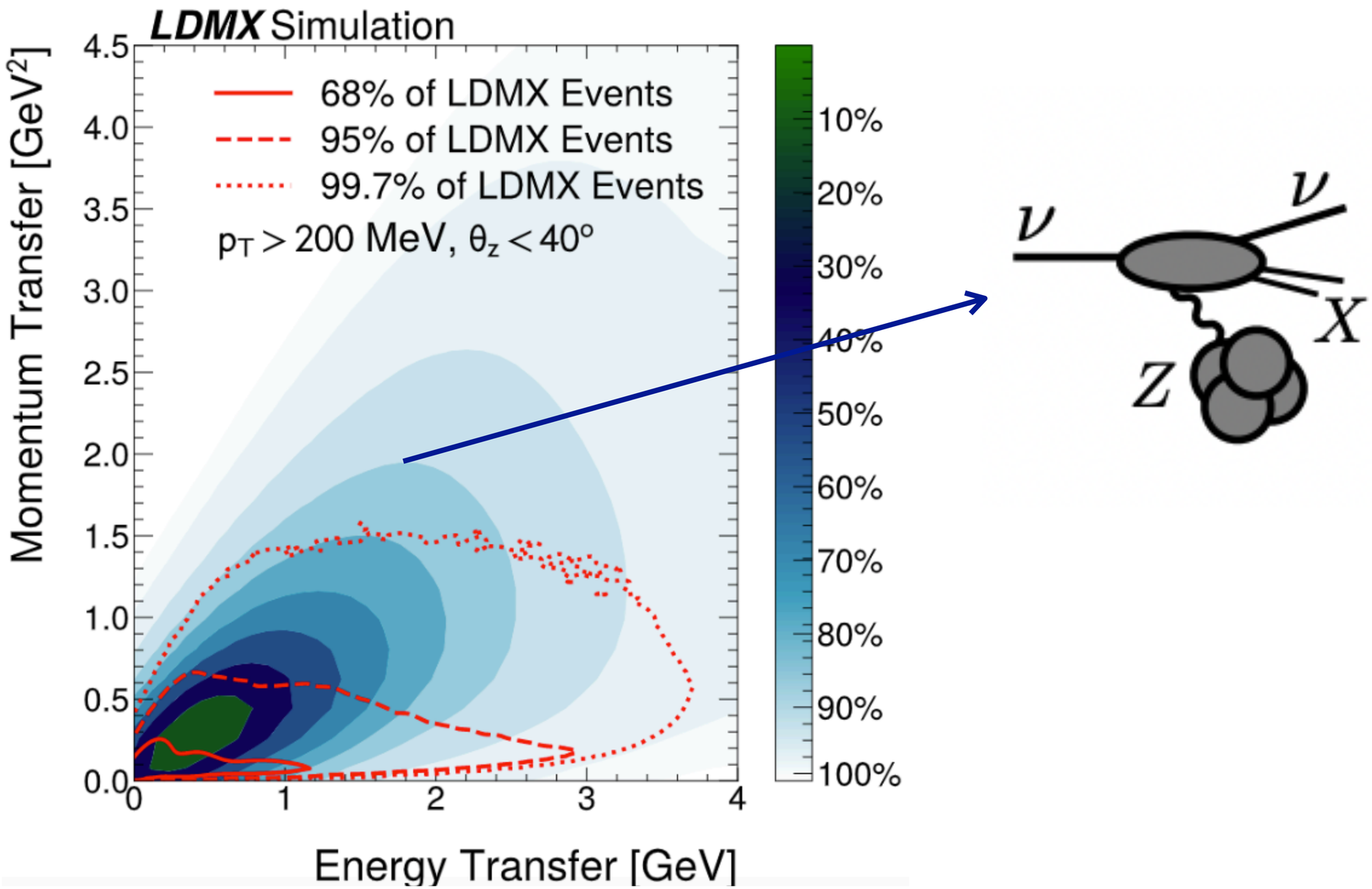


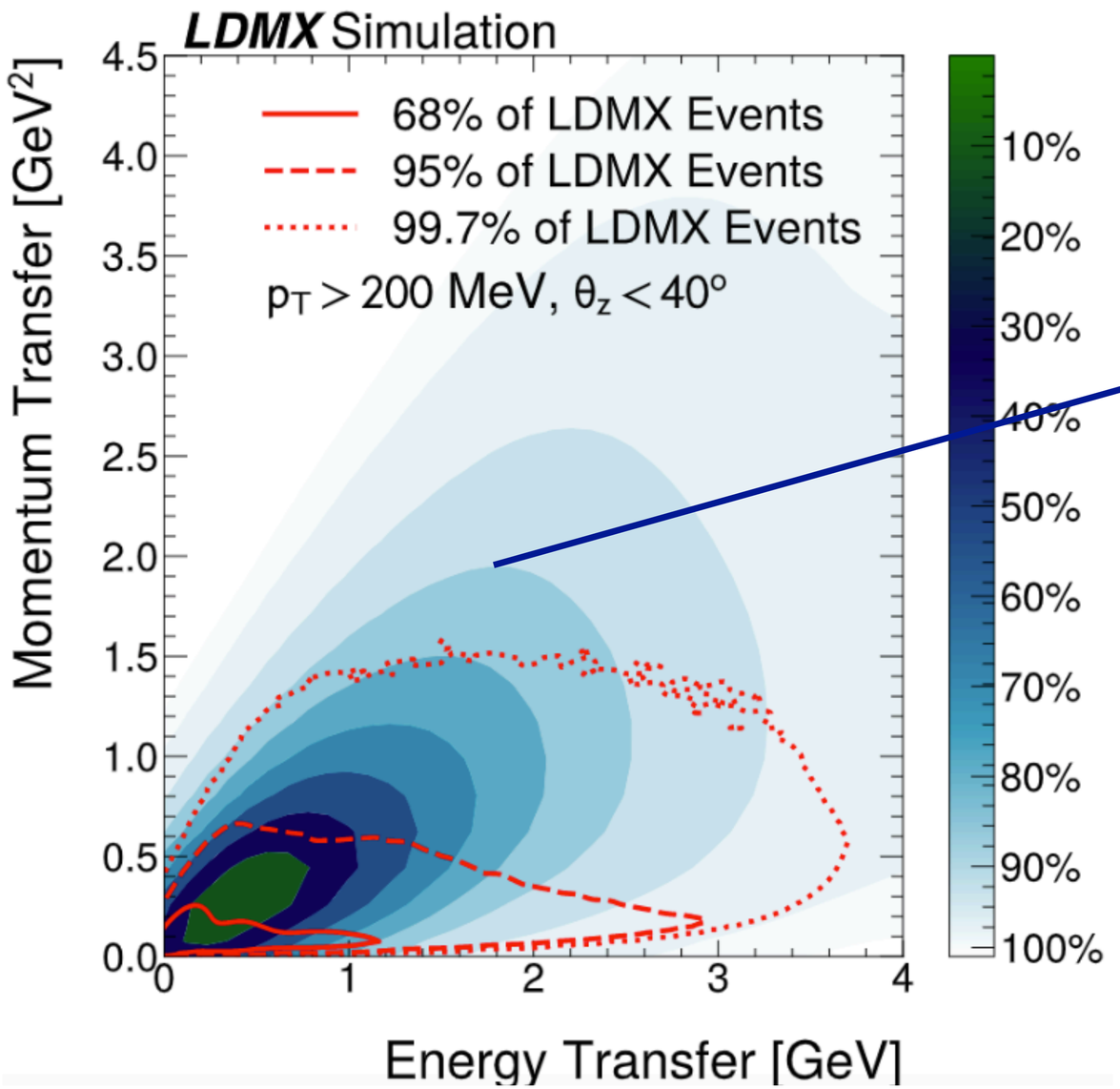
Long lived decay of dark mesons benefits from similar missing momentum strategy (+ visible decays)

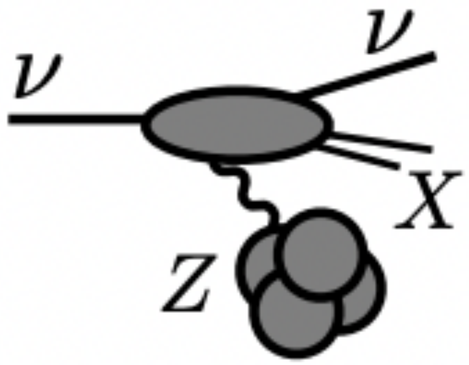


LDMX physics reach beyond dark sectors



LDMX physics reach beyond dark sectors

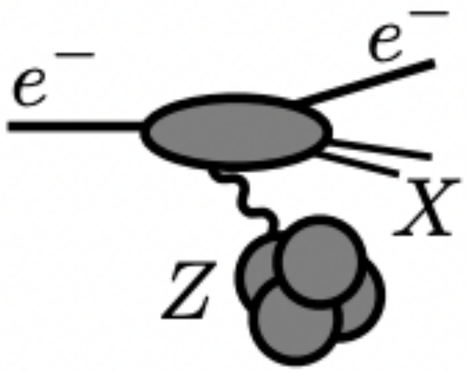


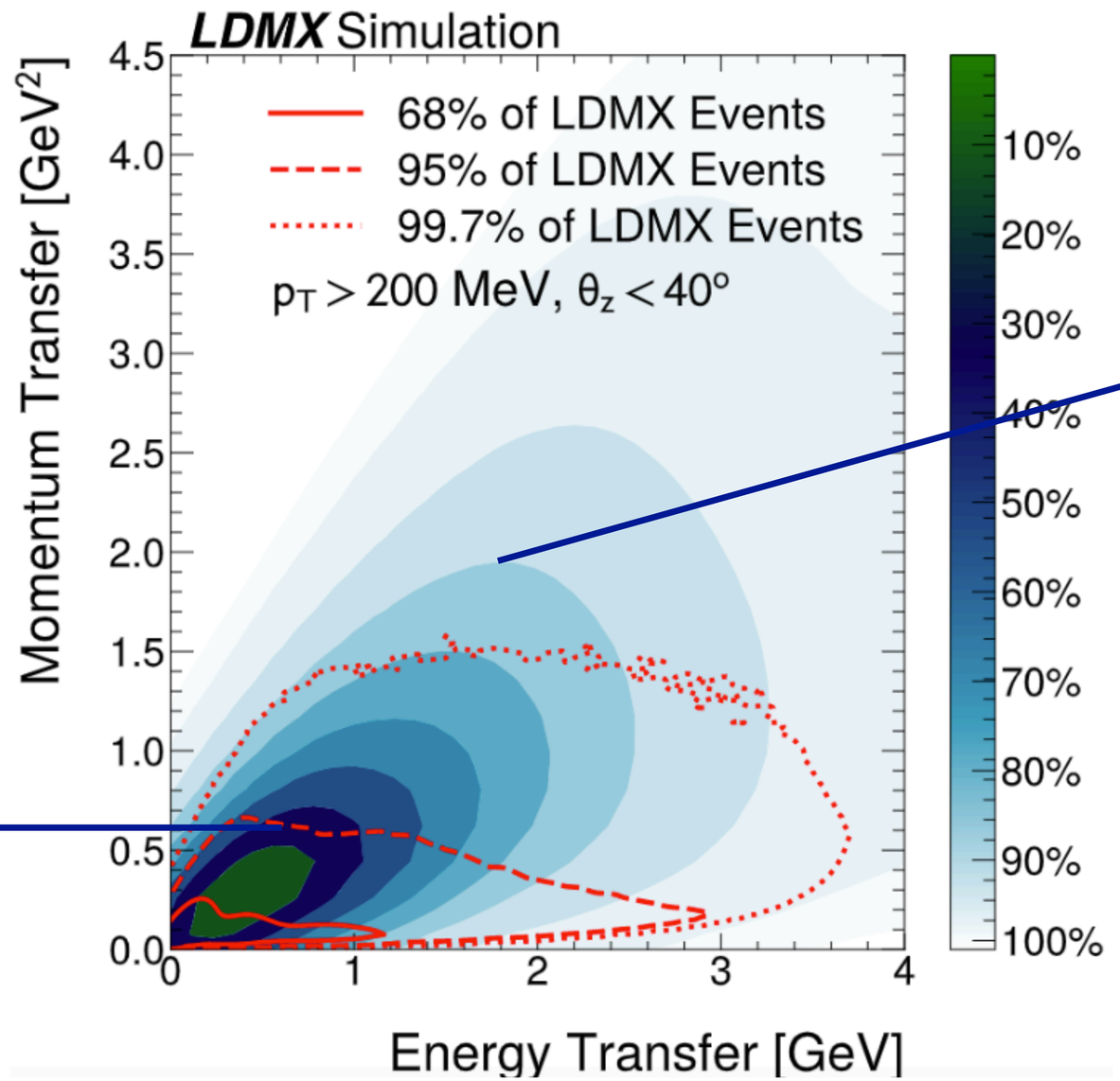


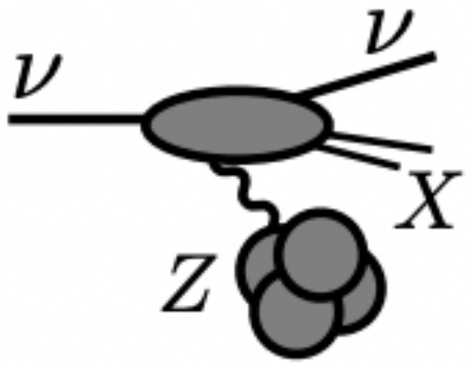
Simulated LAr νN events (DUNE)

LDMX physics reach beyond dark sectors

LDMX recoil e⁻ p_T and polar angle θ_Z





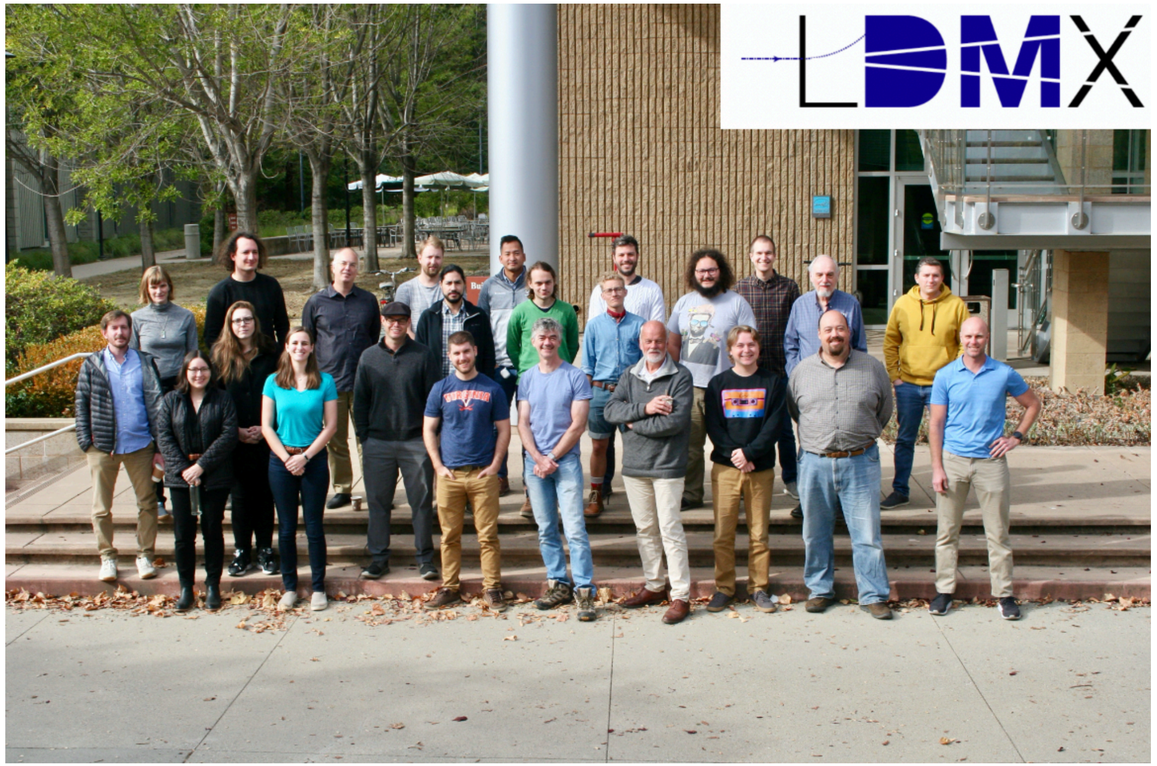


Simulated LAr νN events (DUNE)

Conclusions

- LDMX is a neat and simple idea: electron recoils against dark matter, measure electron p_T.
  - ✓ clean and intense electron beam: LESA construction underway at SLAC
  - ✓ detector technologies proven by other HEP experiments
- LDMX will deliver world-leading sensitivity to sub-GeV DM.
- The experiment is ready to build!
- LDMX could be taking data in 2-3 years after establishing the funding profile.

Thanks!

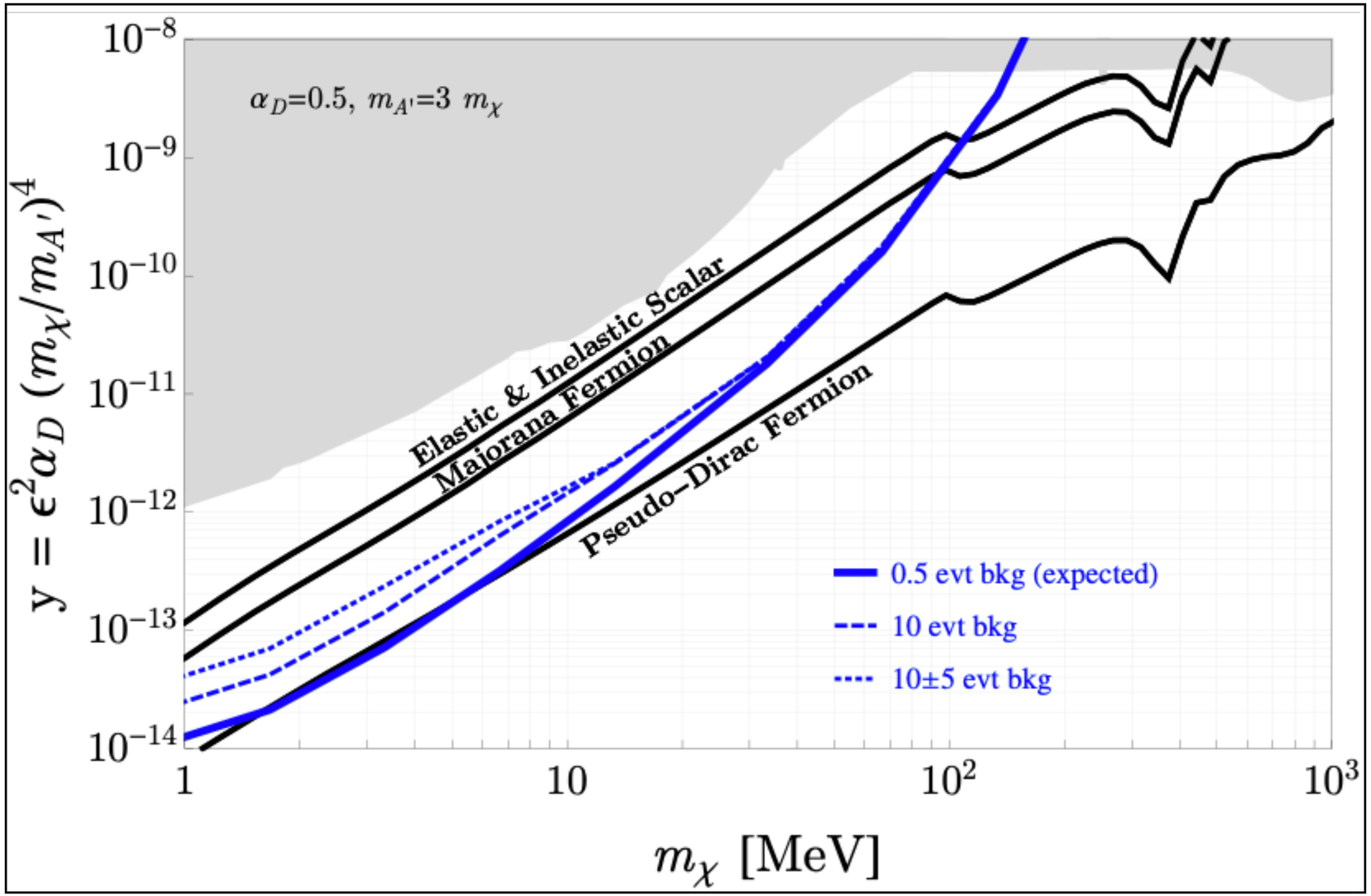


References:

- Light Dark Matter eXperiment (LDMX) (1808.05219)
- Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX (1807.01730)
- A High Efficiency Photon Veto for the Light Dark Matter eXperiment (1912.05535)
- Lepton-Nucleus Cross Section Measurements for DUNE with the LDMX Detector (1912.06140)
- Characterizing Dark Matter Signals with Missing Momentum Experiments (2010.03577)

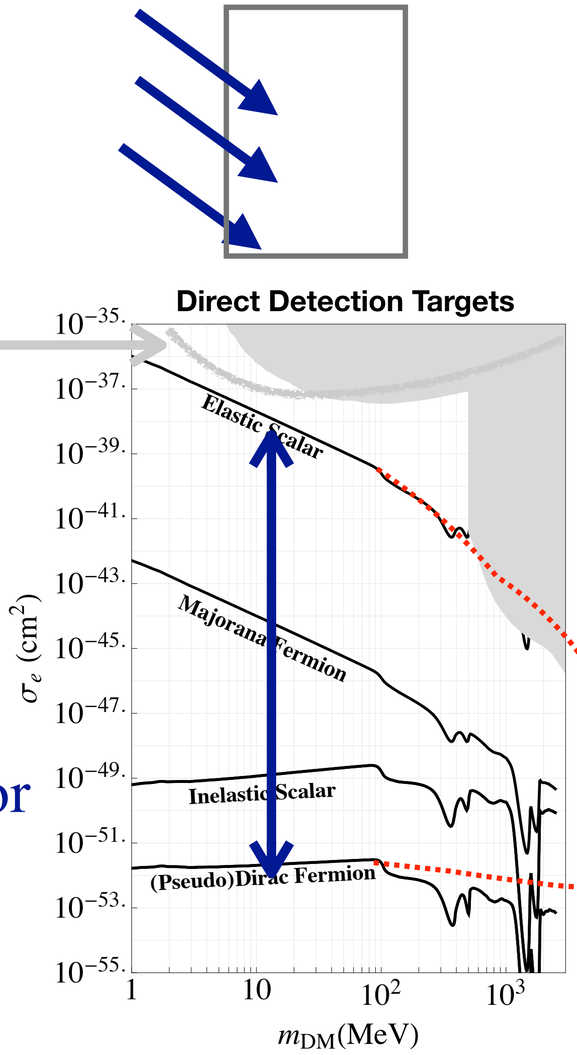
Backup

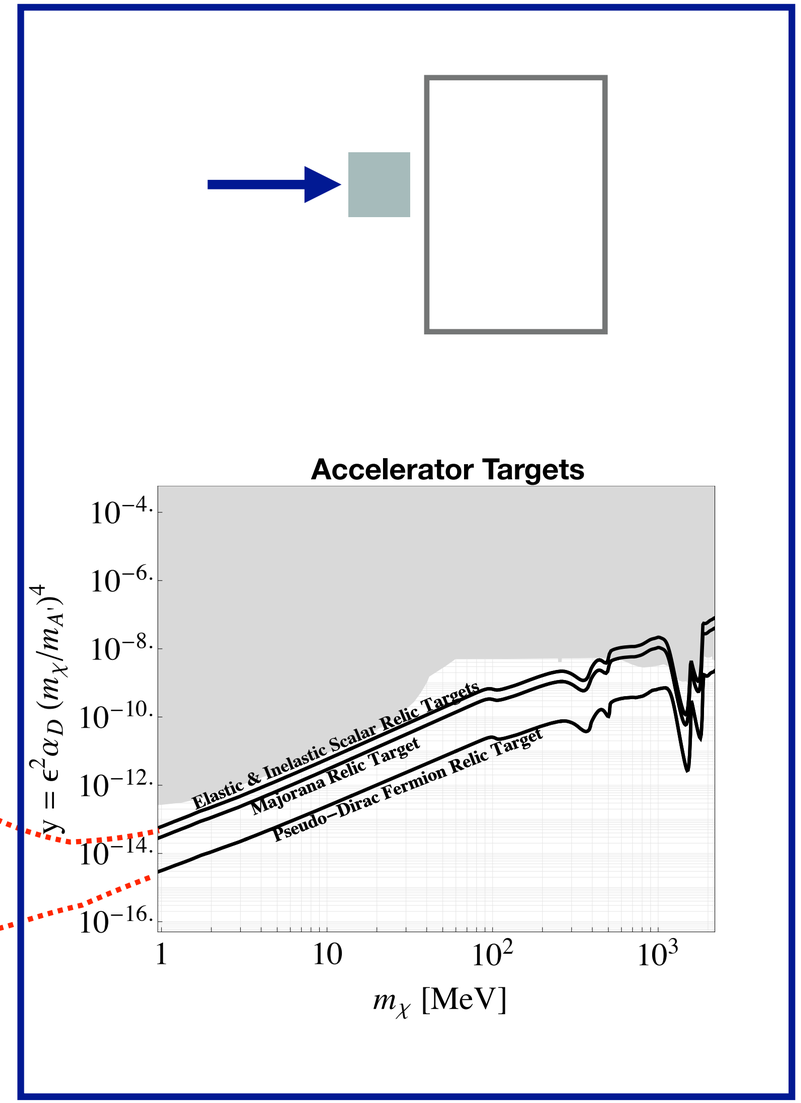
10^14 sensitivity



Accelerators can access all thermal targets

Good news!
Explored
very soon





Strong velocity or spin dependence $O(10^{10}\text{-}10^{20})$

Compact range for exploring relativistic DM production! $O(10^2)$