LDMX: A Search for Dark Matter Using a High Intensity Electron Beam

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(on behalf of the LDMX collaboration)

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Frontier Physics Group
University of Virginia

Planning the Future of Particle Physics

Last summer about a thousand particle physicists gathered together in Seattle (& virtually) to plan the future of particle physics in the USA for the next decade.

Community Summer Study

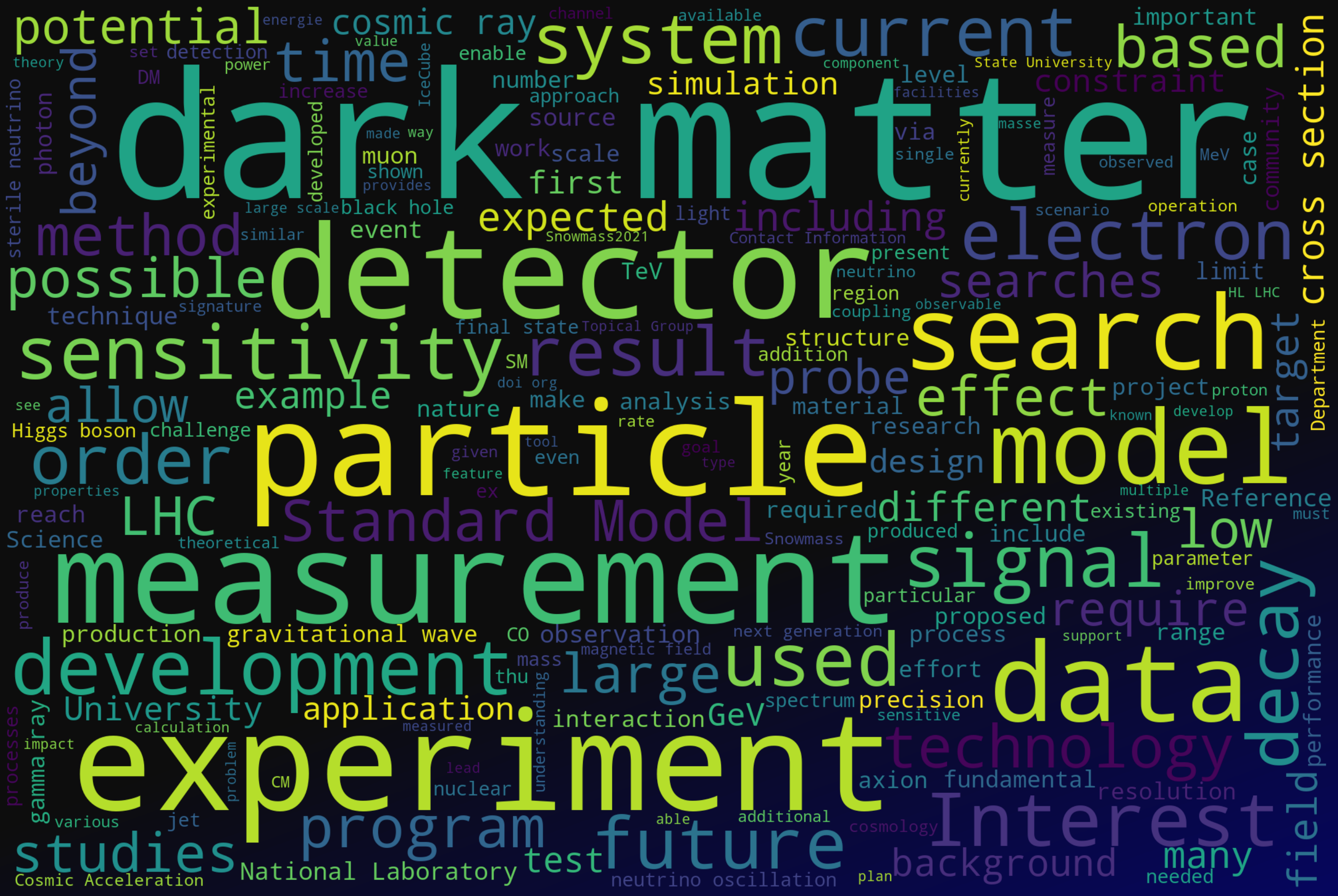
SNOWMASS

July 17-26 2022, Seattle

Sergei Supinsky (AFP)

Dark Matter is Hot: Snowmass 2022 Letters of Intents

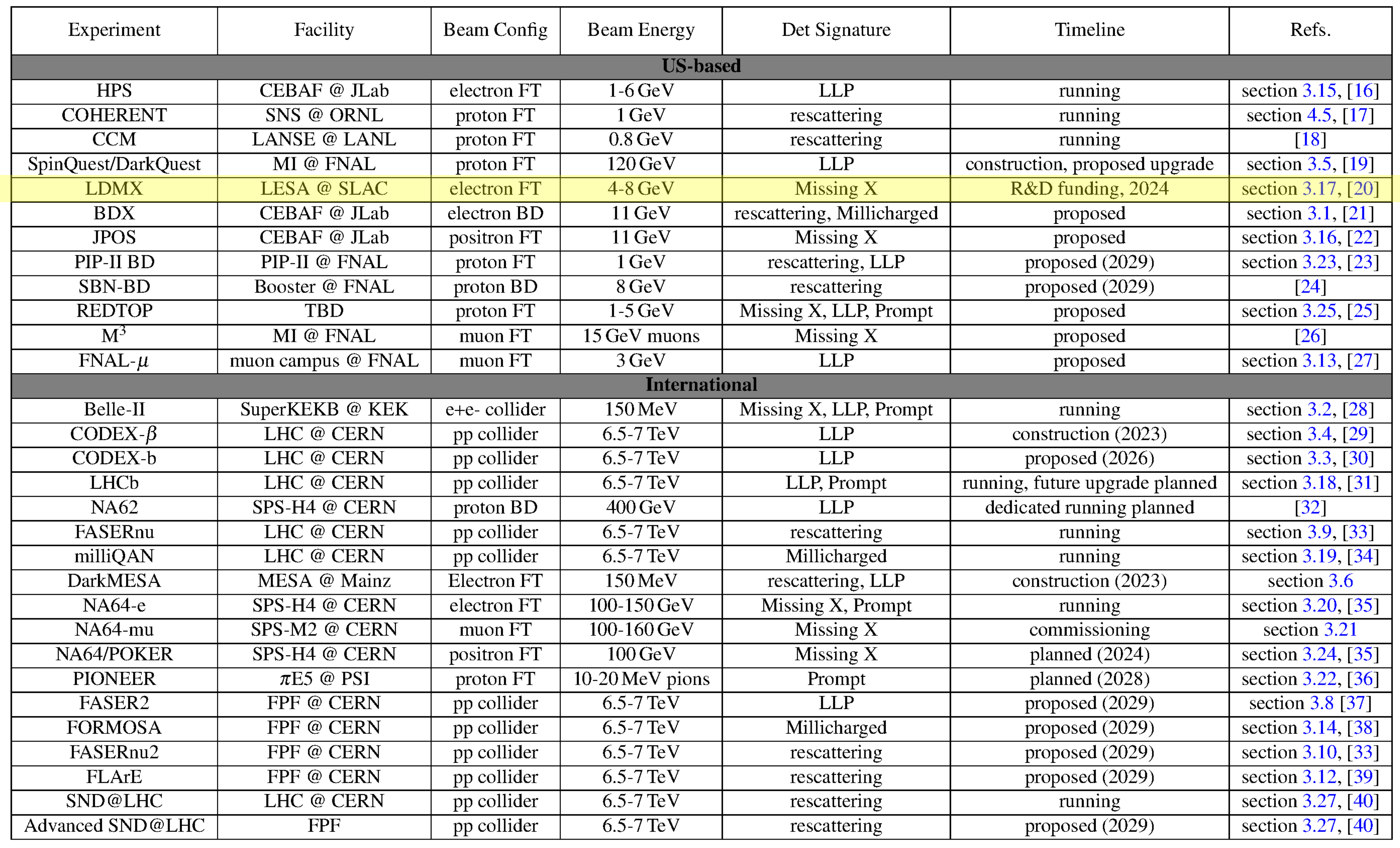
Word clouds from 522 Letter of Intents submitted for the USA decadal planning study (Snowmass 2022) for elementary particle physics, which was help this July



Identifying the nature of this exotic matter is the outstanding particle physics goal of our time

Dark Matter: Accelerator Searches Landscape Keeps Growing

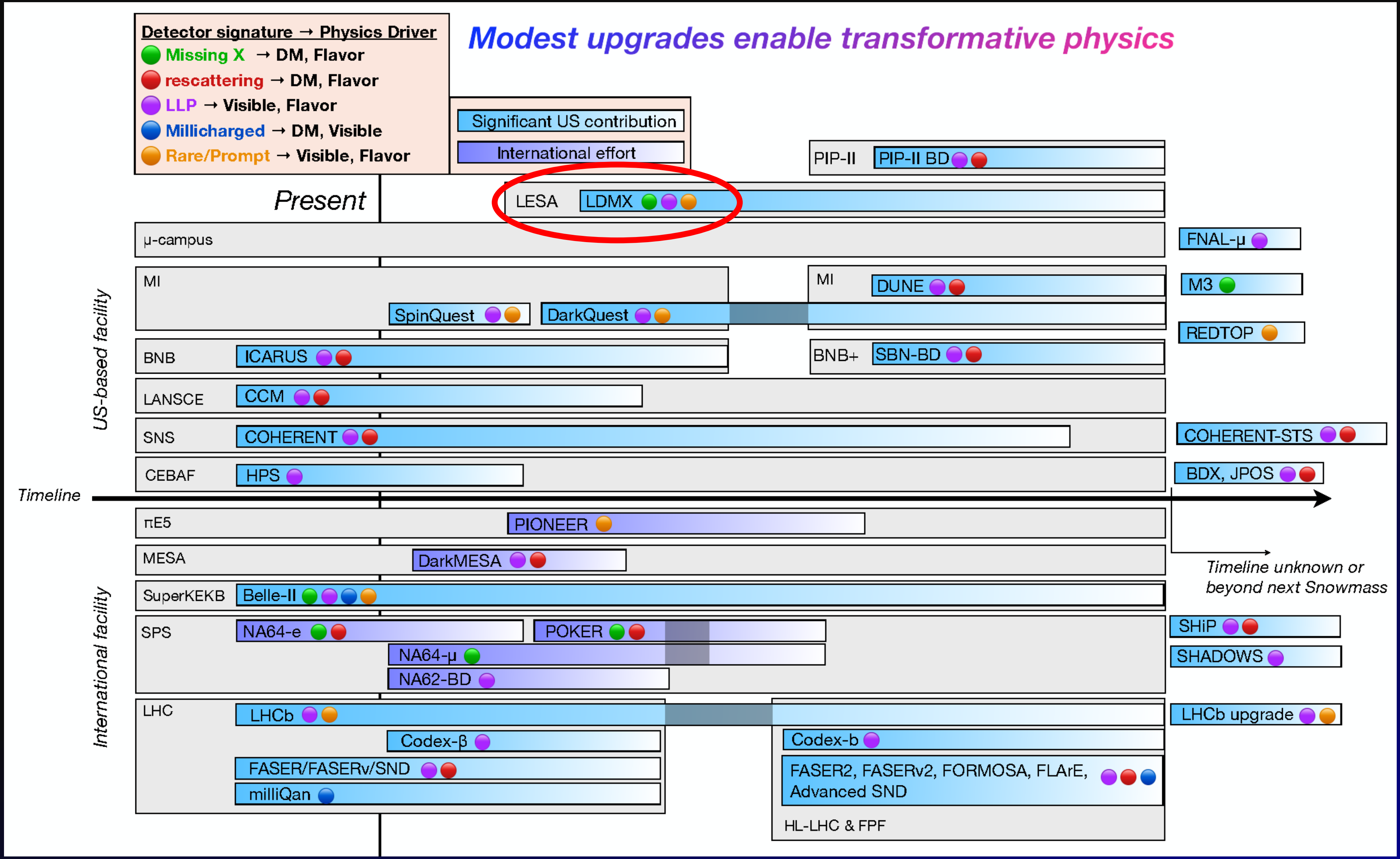
Experiments and Facilities for Accelerator-Based Dark Sector Searches (arXiv.2206.0422)



Experiment	Facility	Beam Config	Beam Energy	Det Signature	Timeline	Refs.
US-based						
HPS	CEBAF @ JLab	electron FT	1-6 GeV	LLP	running	section 3.15, [16]
COHERENT	SNS @ ORNL	proton FT	1 GeV	rescattering	running	section 4.5, [17]
CCM	LANSE @ LANL	proton FT	0.8 GeV	rescattering	running	[18]
SpinQuest/DarkQuest	MI @ FNAL	proton FT	120 GeV	LLP	construction, proposed upgrade	section 3.5, [19]
LDMX	LESA @ SLAC	electron FT	4-8 GeV	Missing X	R&D funding, 2024	section 3.17, [20]
BDX	CEBAF @ JLab	electron BD	11 GeV	rescattering, Millicharged	proposed	section 3.1, [21]
JPOS	CEBAF @ JLab	positron FT	11 GeV	Missing X	proposed	section 3.16, [22]
PIP-II BD	PIP-II @ FNAL	proton FT	1 GeV	rescattering, LLP	proposed (2029)	section 3.23, [23]
SBN-BD	Booster @ FNAL	proton BD	8 GeV	rescattering	proposed (2029)	[24]
REDTOP	TBD	proton FT	1-5 GeV	Missing X, LLP, Prompt	proposed	section 3.25, [25]
M^3	MI @ FNAL	muon FT	15 GeV muons	Missing X	proposed	[26]
FNAL-μ	muon campus @ FNAL	muon FT	3 GeV	LLP	proposed	section 3.13, [27]
International						
Belle-II	SuperKEKB @ KEK	e+e- collider	150 MeV	Missing X, LLP, Prompt	running	section 3.2, [28]
CODEX-β	LHC @ CERN	pp collider	6.5-7 TeV	LLP	construction (2023)	section 3.4, [29]
CODEX-b	LHC @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2026)	section 3.3, [30]
LHCb	LHC @ CERN	pp collider	6.5-7 TeV	LLP, Prompt	running, future upgrade planned	section 3.18, [31]
NA62	SPS-H4 @ CERN	proton BD	400 GeV	LLP	dedicated running planned	[32]
FASERnu	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.9, [33]
milliQAN	LHC @ CERN	pp collider	6.5-7 TeV	Millicharged	running	section 3.19, [34]
DarkMESA	MESA @ Mainz	Electron FT	150 MeV	rescattering, LLP	construction (2023)	section 3.6
NA64-e	SPS-H4 @ CERN	electron FT	100-150 GeV	Missing X, Prompt	running	section 3.20, [35]
NA64-mu	SPS-M2 @ CERN	muon FT	100-160 GeV	Missing X	commissioning	section 3.21
NA64/POKER	SPS-H4 @ CERN	positron FT	100 GeV	Missing X	planned (2024)	section 3.24, [35]
PIONEER	πE5 @ PSI	proton FT	10-20 MeV pions	Prompt	planned (2028)	section 3.22, [36]
FASER2	FPF @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2029)	section 3.8 [37]
FORMOSA	FPF @ CERN	pp collider	6.5-7 TeV	Millicharged	proposed (2029)	section 3.14, [38]
FASERnu2	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.10, [33]
FLArE	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.12, [39]
SND@LHC	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.27, [40]
Advanced SND@LHC	FPF	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.27, [40]

Dark Matter: Accelerator Searches Landscape

Experiments and Facilities for Accelerator-Based Dark Sector Searches (arXiv.2206.0422)



Detector signature → Physics Driver
- 🟢 Missing X → DM, Flavor
- 🔴 rescattering → DM, Flavor
- 🟣 LLP → Visible, Flavor
- 🔵 Millicharged → DM, Visible
- 🟠 Rare/Prompt → Visible, Flavor

Modest upgrades enable transformative physics

Significant US contribution

International effort

Present

US-based facility

PIP-II: PIP-II BD 🟣🔴

LESA: LDMX 🟢🟣🟠

μ-campus

FNAL-μ 🟣

MI: SpinQuest 🟣🟠, DarkQuest 🟣🟠

MI: DUNE 🟣🔴

M3 🟢

REDTOP 🟠

BNB: ICARUS 🟣🔴

BNB+: SBN-BD 🟣🔴

LANSCE: CCM 🟣🔴

SNS: COHERENT 🟣🔴

COHERENT-STS 🟣🔴

CEBAF: HPS 🟣

BDX, JPOS 🟣🔴

Timeline

International facility

πE5: PIONEER 🟠

MESA: DarkMESA 🟣🔴

Timeline unknown or beyond next Snowmass

SuperKEKB: Belle-II 🟢🟣🔵🟠

SPS: NA64-e 🟢🔴, POKER 🟢🔴, NA64-μ 🟢, NA62-BD 🟣

SHiP 🟣🔴

SHADOWS 🟣

LHC: LHCb 🟣🟠, Codex-β 🟣, FASER/FASERν/SND 🟣🔴, milliQan 🔵

HL-LHC & FPF: Codex-b 🟣, FASER2, FASERν2, FORMOSA, FLArE, Advanced SND 🟣🔴🔵

LHCb upgrade 🟣🟠

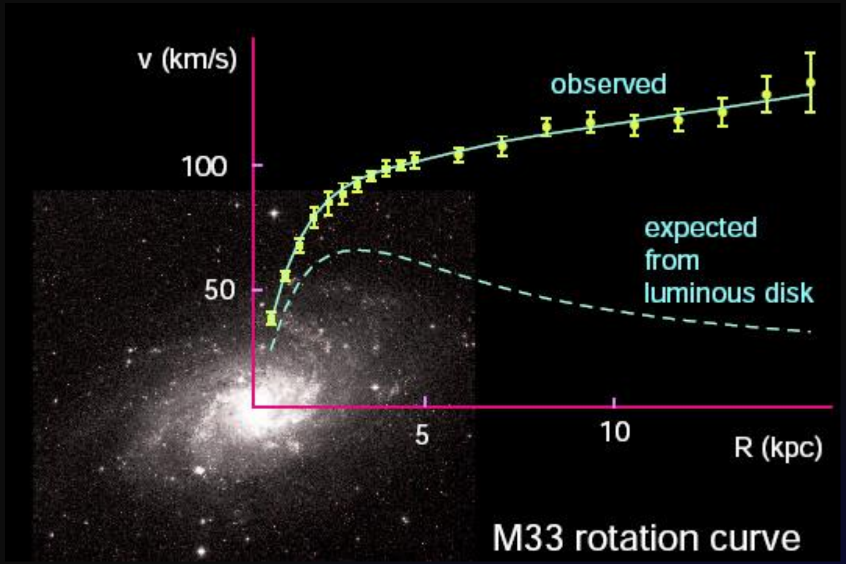
Dark Matter Exists: Gravitational Evidence

Four sources on vastly different scales: galactic to universal

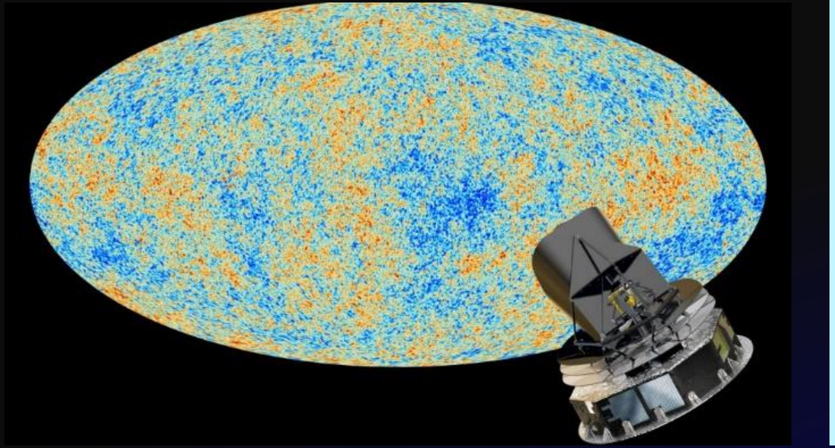
- Galactic rotation curves
- Gravitational lensing
- Large scale structure of universe
- Microwave background radiation

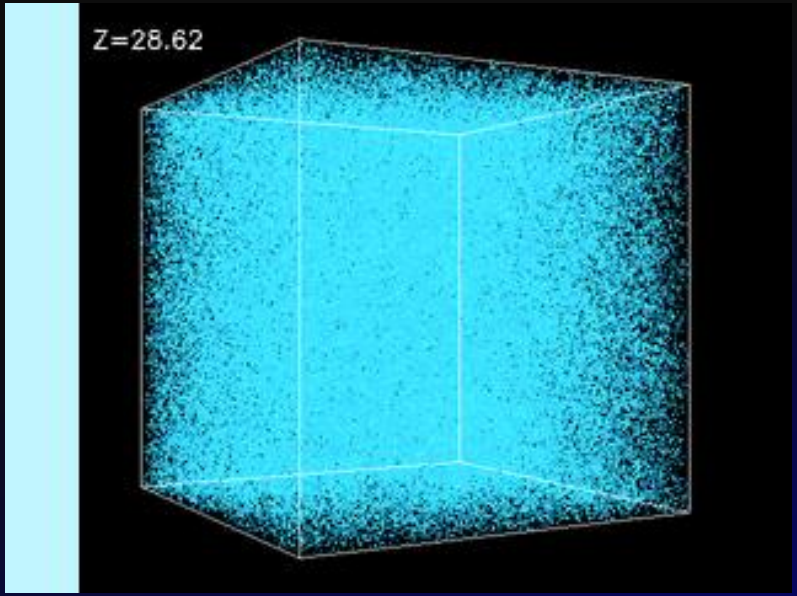
Best estimate: 85% of the mass of the universe is dark matter

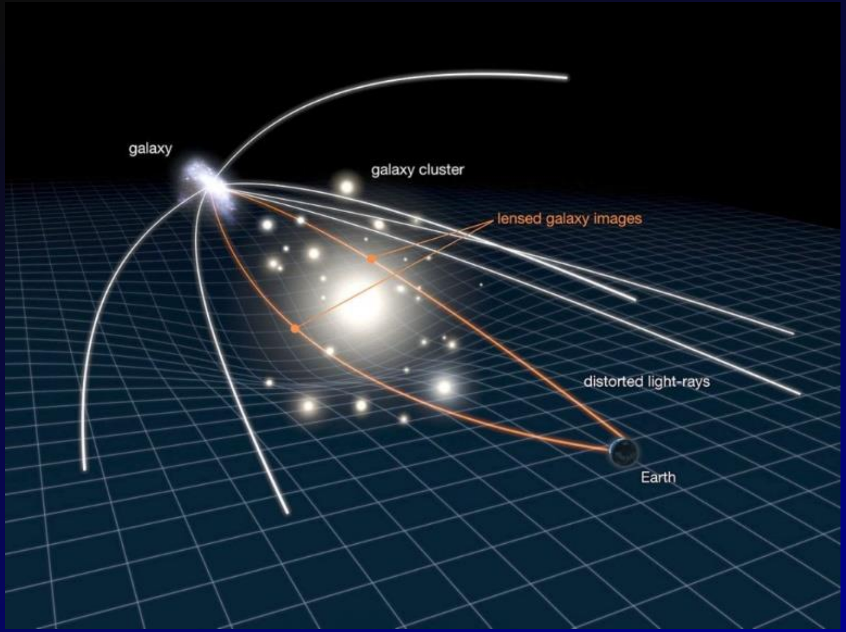
Dark matter was present at the beginning of the universe



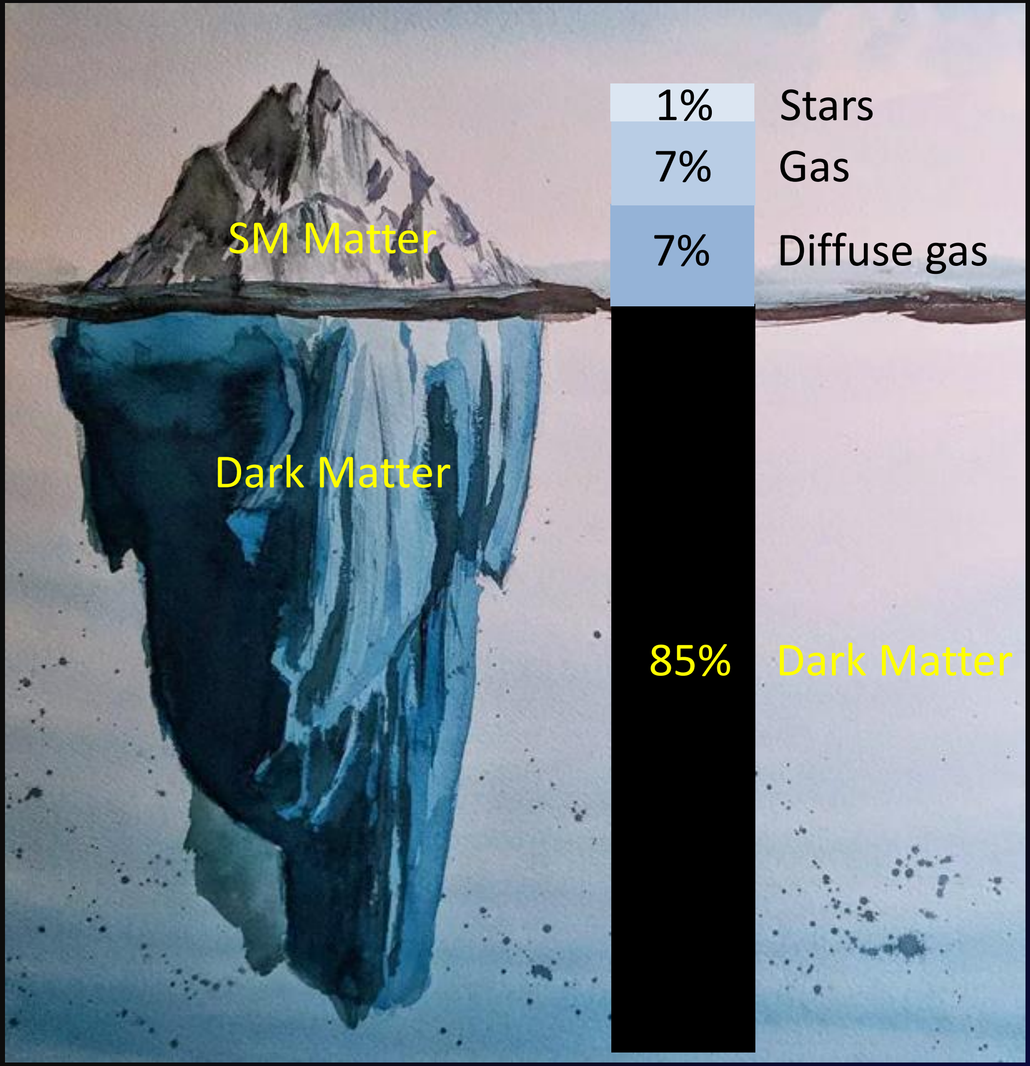
M33 rotation curve







Composition of Matter in Universe



DM density: ~0.3 GeV/cm

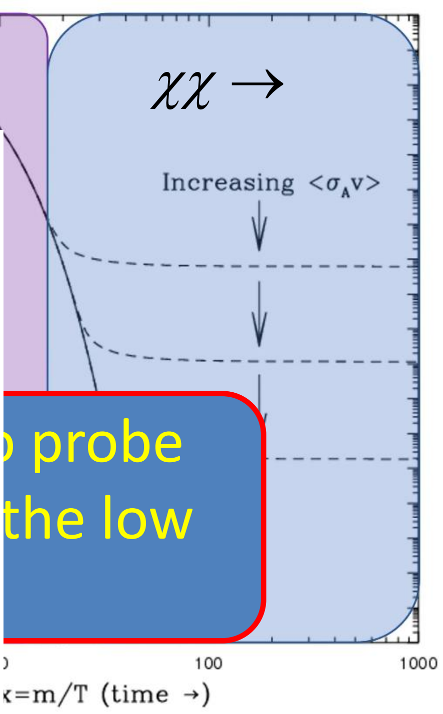
Flux: ~30,000/s·cm^2 @100 km/s (if mass is 100 GeV)

We know the DM was present in the early universe

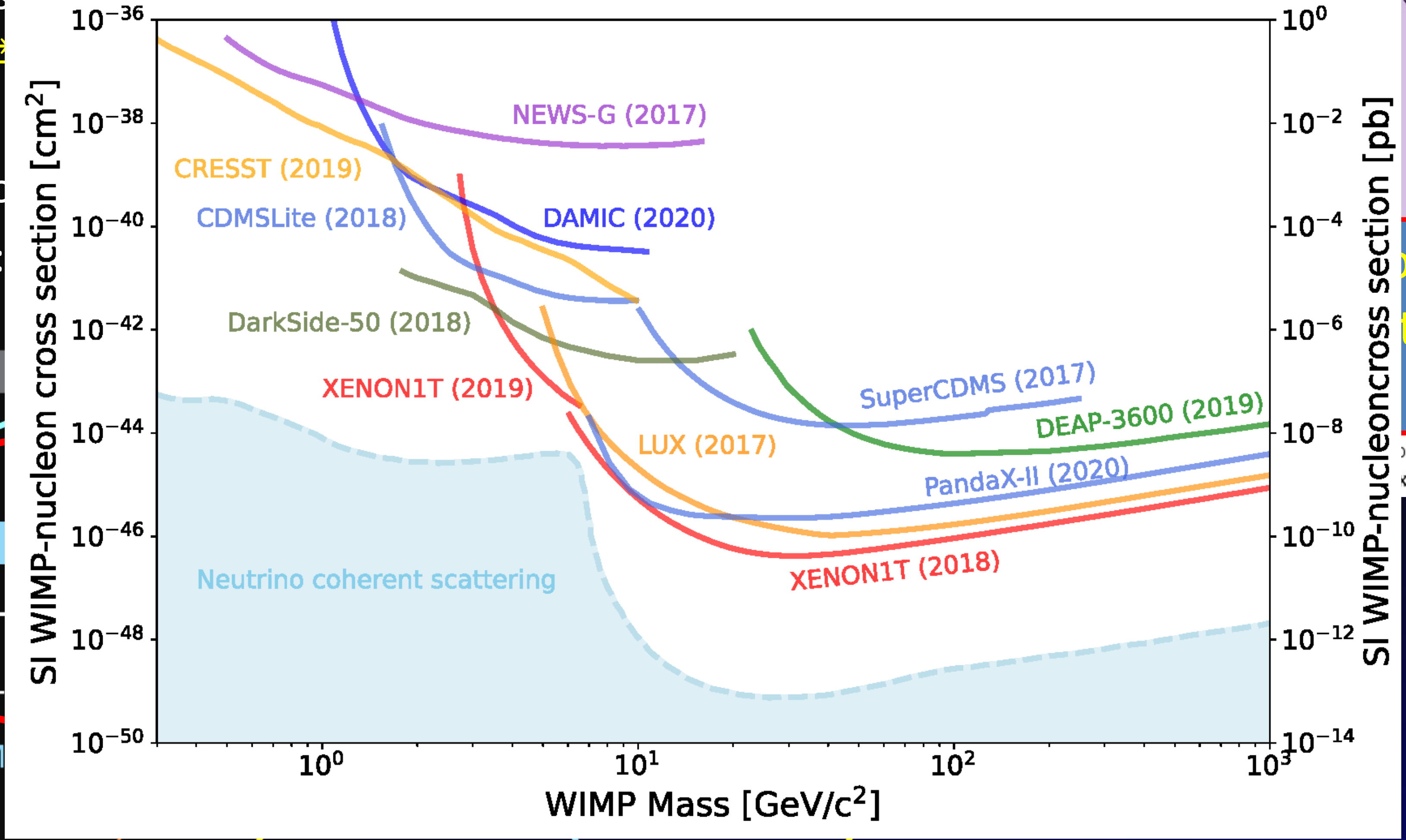
The fact that the densities of DM and SM are roughly the same suggest that they were perhaps coupled in the early universe

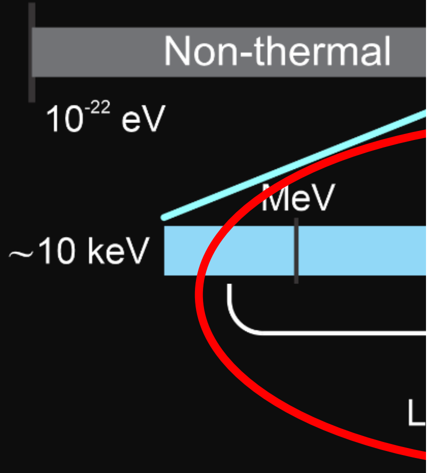
Dark Matter: Thermal Relic Production

- Assume DM was in thermal equilibrium with SM in the very early universe: $\chi\chi \rightleftarrows$
- Universe cooled
- Universe kept co
- Present density:



probe
the low

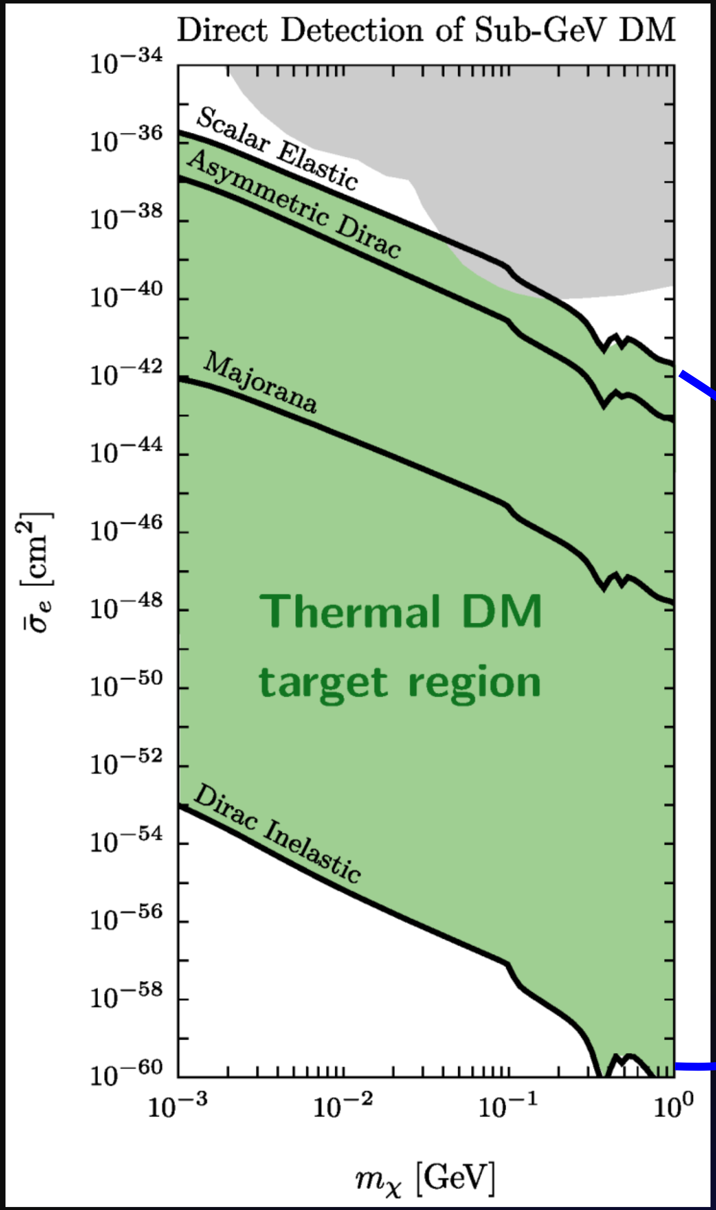




Sub-GeV DM:
M_χ < 10 MeV: early
BBN problems
comparatively
under-explored

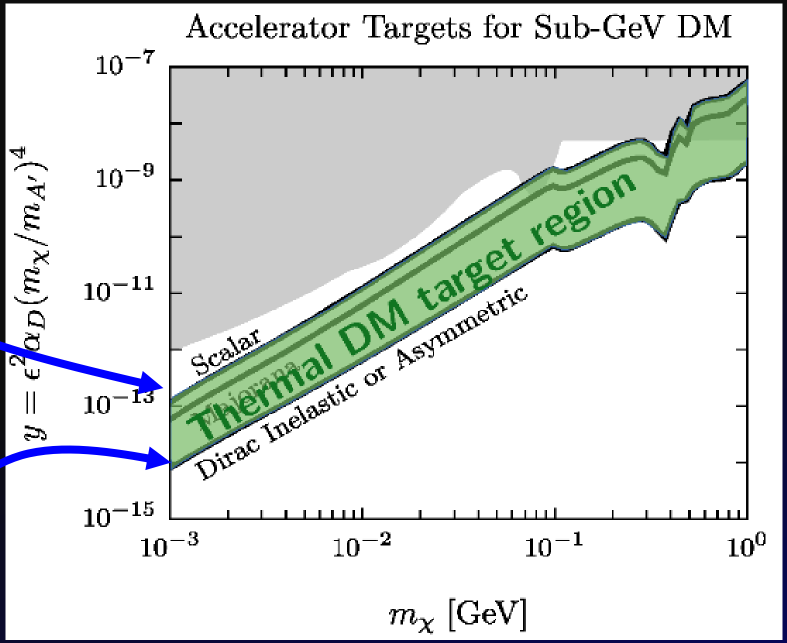
M_χ < 2 GeV: early freeze out,
too much DM
Region is being well explored

Accelerator Production of Sub-GeV Dark Matter: Advantages



Direct Detection:

Strong velocity/spin dependence of scattering spreads out direct detection cross sections over many orders of magnitude



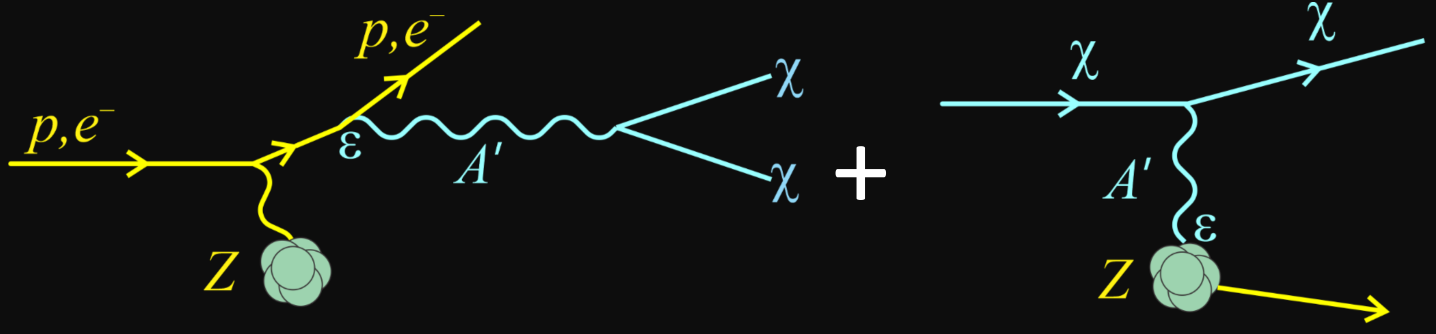
Accelerator Production:

Range of freeze-out interaction strengths much more compact: spans factor of ~ 30 for a given DM mass

All of these thermal targets are within reach

Searching for Dark Matter with Fixed-Target Experiments

Beam dump

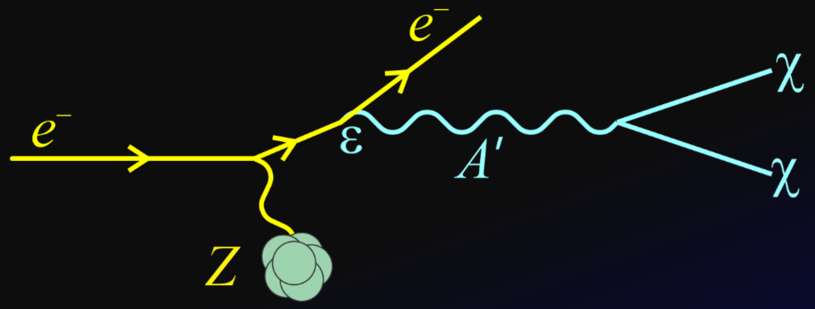


$$N \propto \varepsilon^4$$

Probes dark sector coupling

Suppressed by ε^4

Missing energy / momentum



$$N \propto \varepsilon^2$$

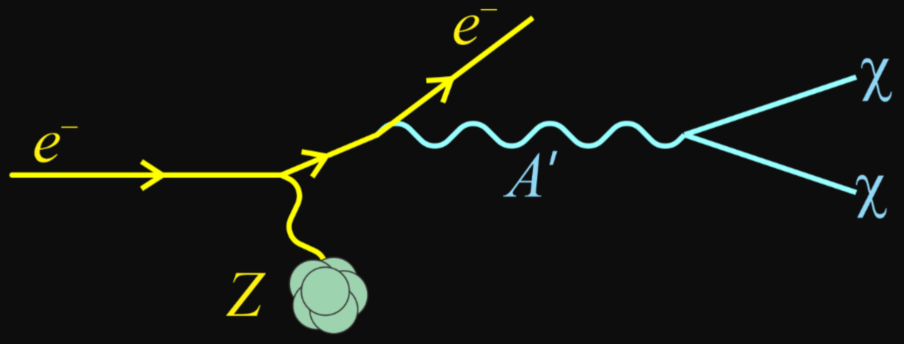
Large yield, particularly for low mediator masses

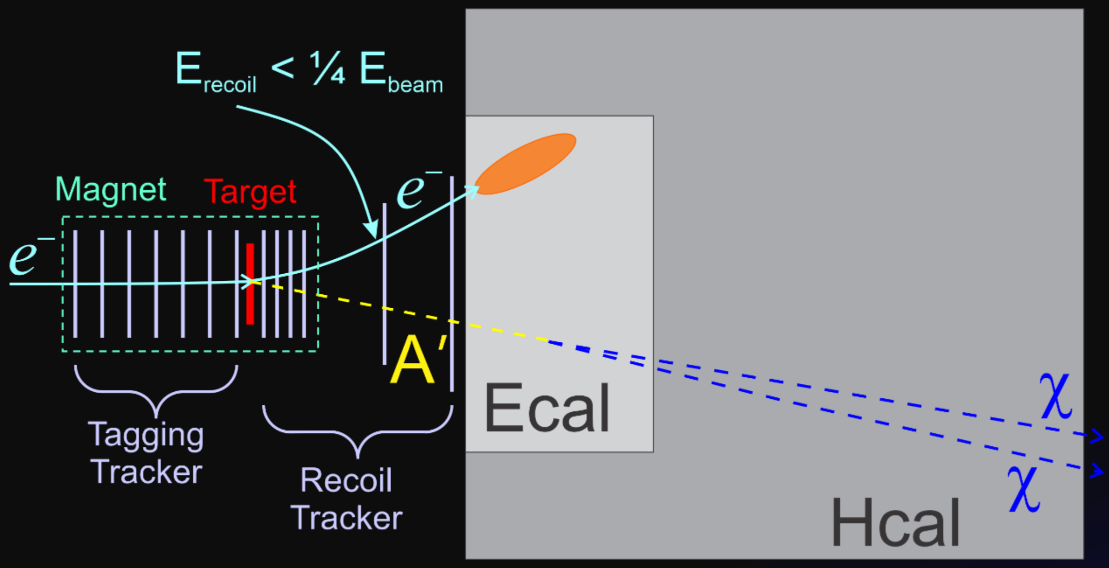
No DM detection penalty

LDMX has chosen this path

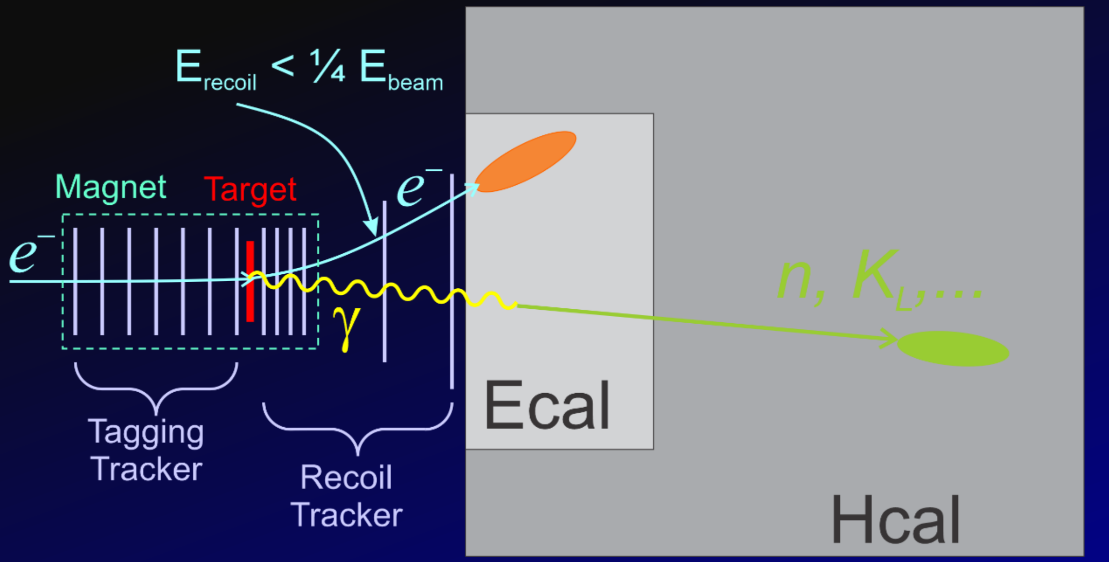
Experimental Technique in a Nutshell

LDMX uses missing momentum technique





Signal



Background

Beam:

- Parasitically use the SLAC LCLS II beam (4/8 GeV): ~40 MHz e^-

Signal:

- Substantial energy loss by the 4/8 GeV beam electron
- Large recoil electron p_T
- Absence of any additional visible final-state particles

Apparatus

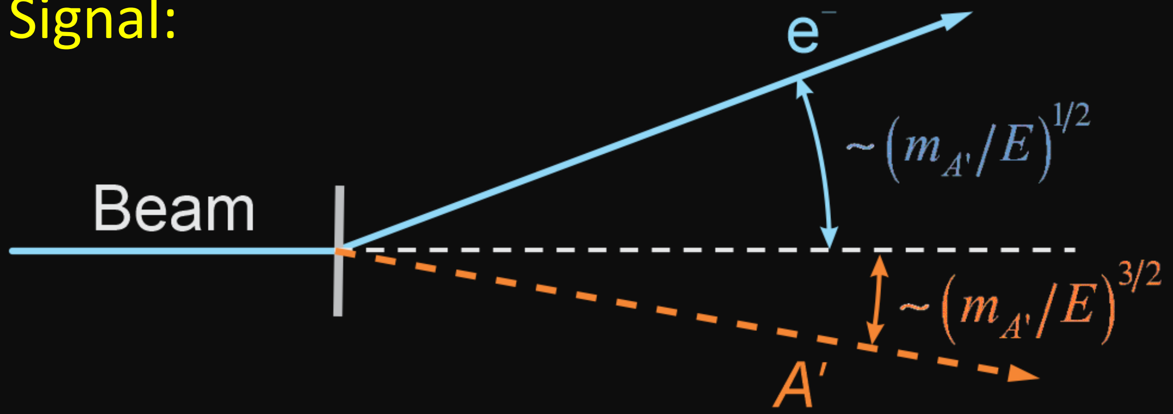
- Thin production target to produce DM bremsstrahlung
- Precision tracking of the electron before/after target
- Excellent EM and Hadronic calorimetry to capture background gammas & neutrons produced by photo-nuclear and electro-nuclear processes, as well as other backgrounds

Electron Parameters: Signal & Background

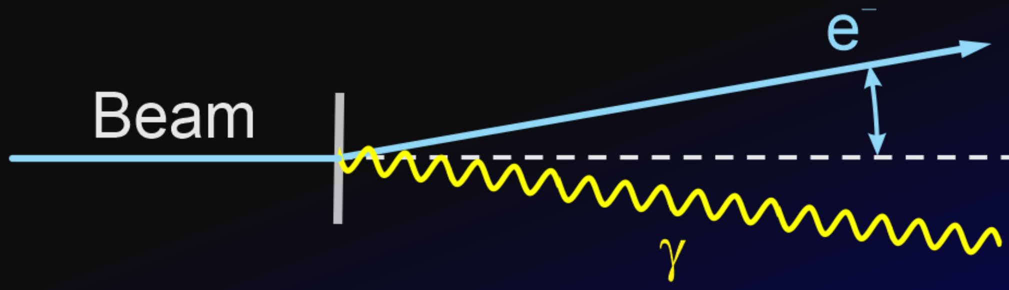
Difference between SM and Dark A’ bremsstrahlung is the latter carries away much more of the beam energy and transverse momentum than SM bremsstrahlung

Larger the A’ mass, the greater the difference from SM bremsstrahlung

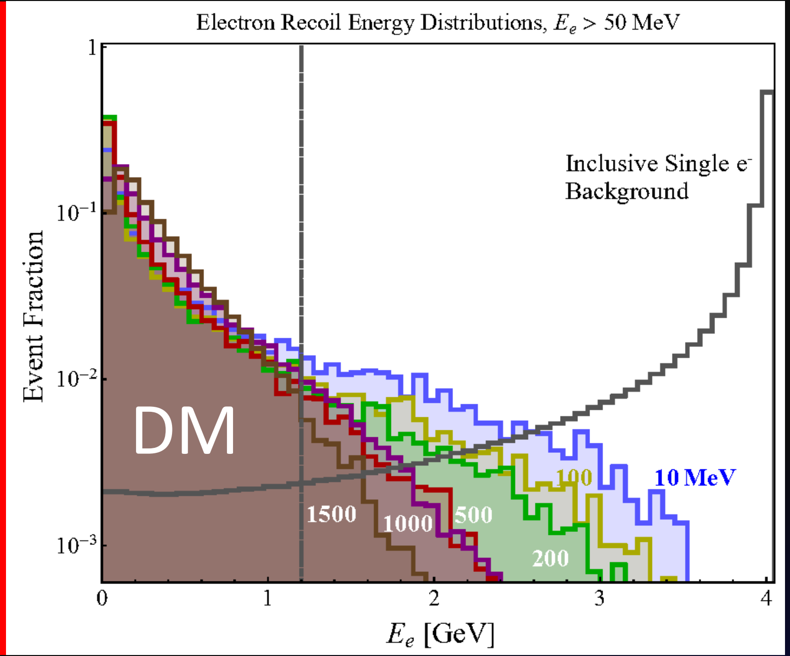
Signal:



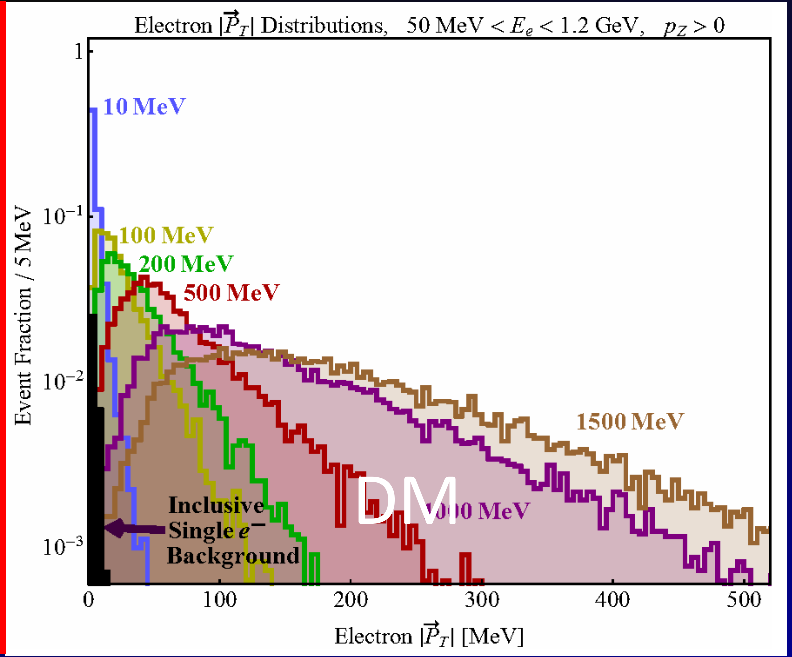
Background:



Recoil Electron Energy

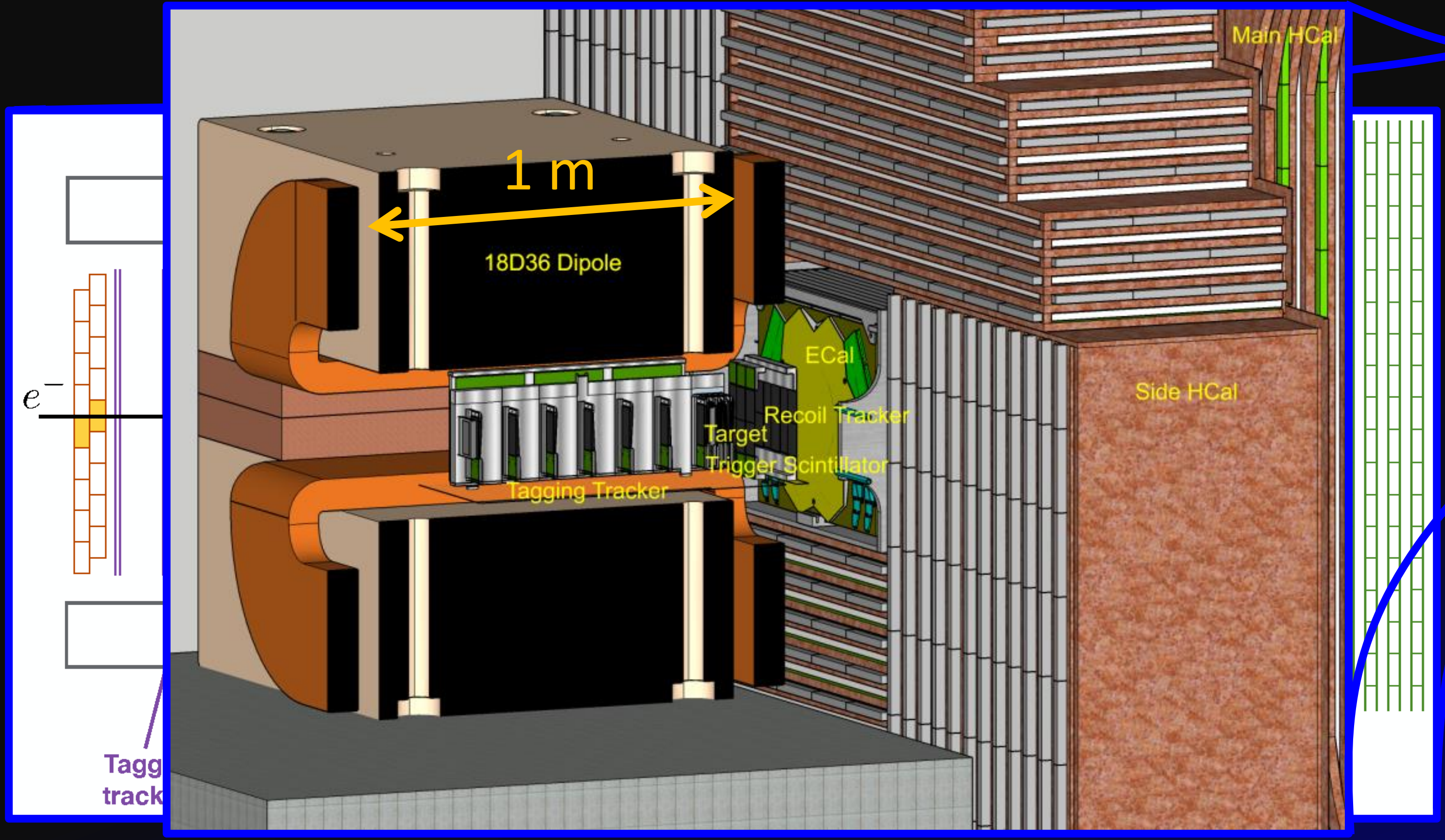


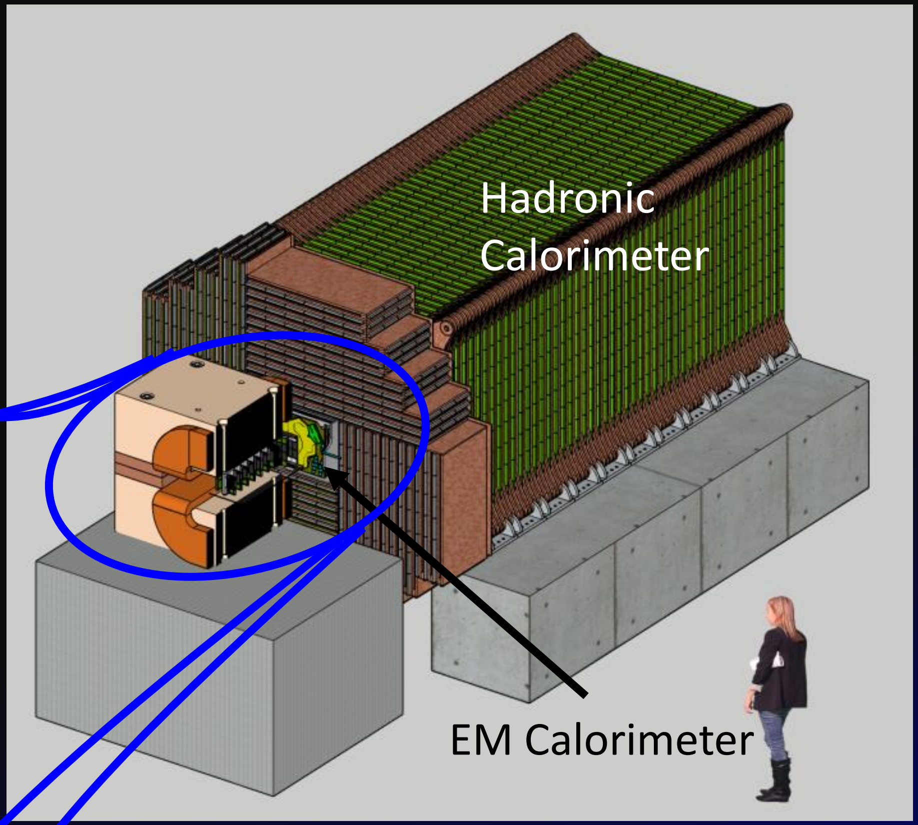
Recoil Electron p_T



Apparatus

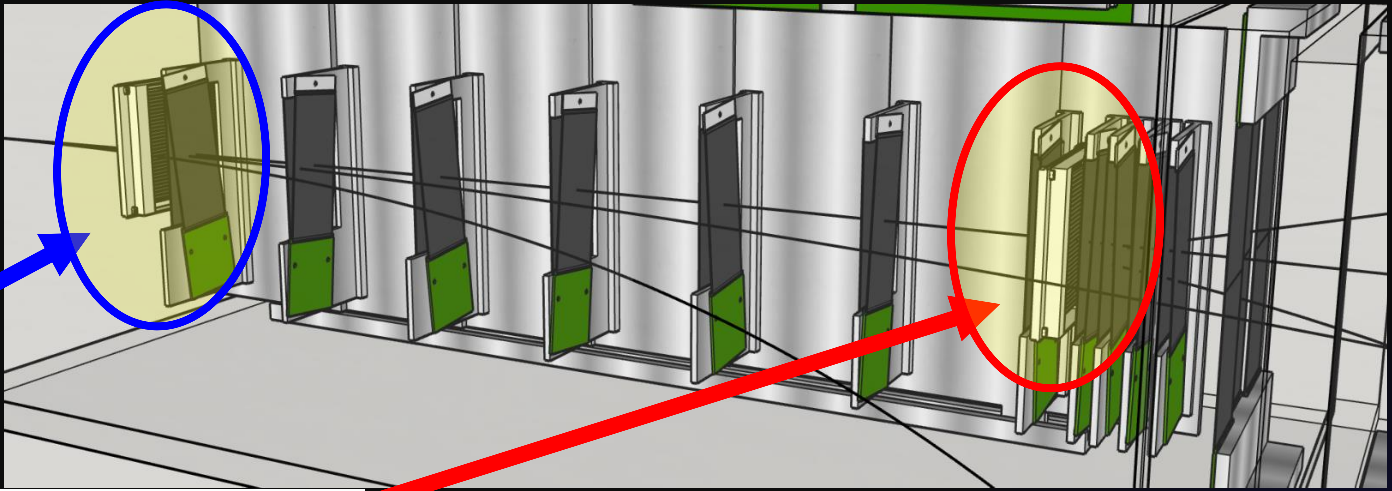
- Tagged beam dump experiment: tag and measure each incoming electron
- Use existing detector technologies that have been designed for high rate / high radiation environments: (1) to keep costs down, and (2) to allow the apparatus to be fabricated quickly

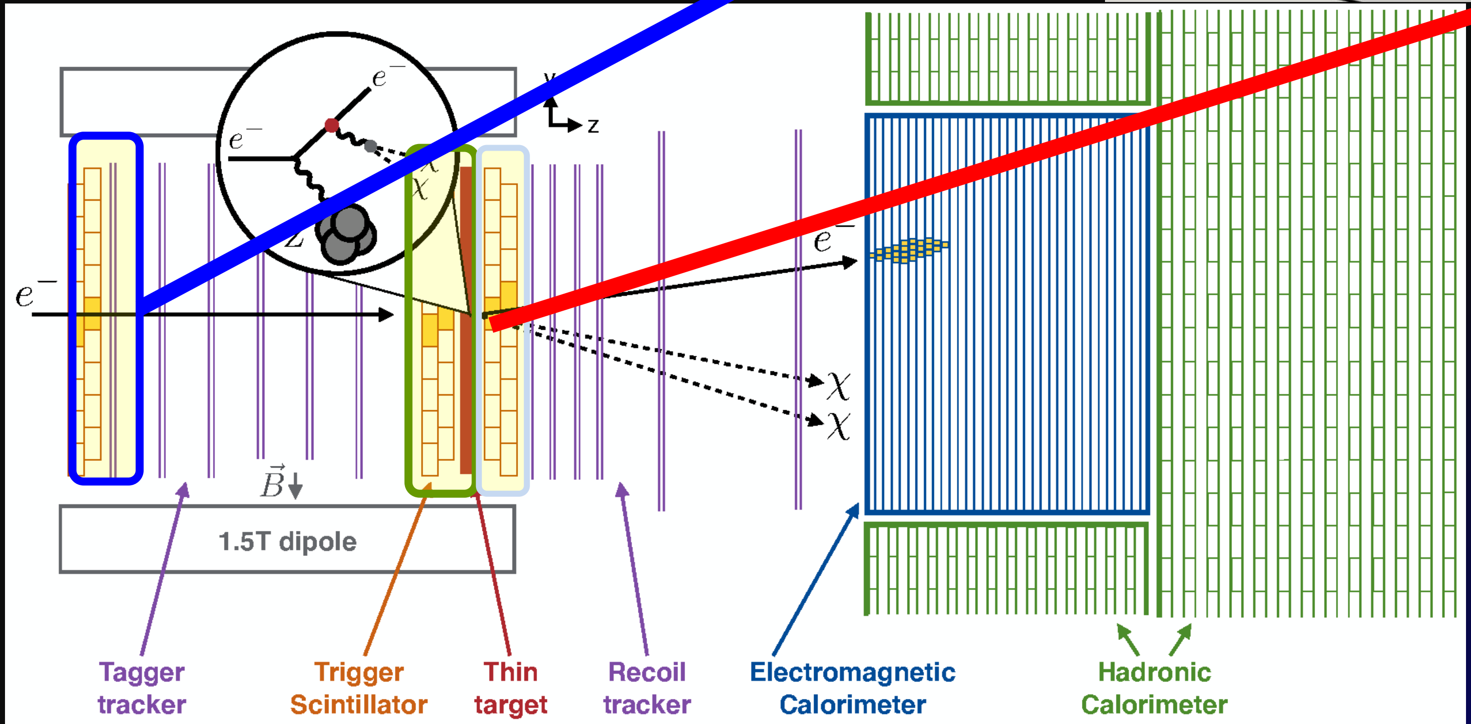


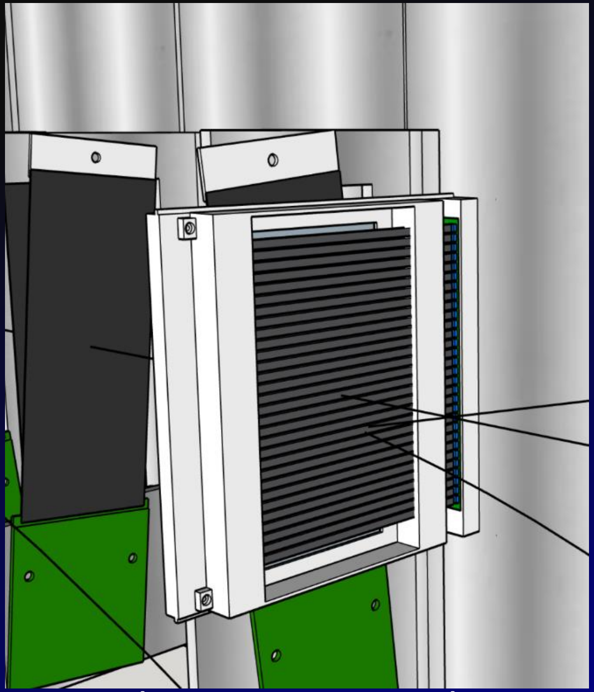


Apparatus: Trigger Scintillator

- Low-energy ECal trigger requires knowledge of #e^-/pulse: average ~1 e^-/25 ns pulse
- Thin segmented scintillator:
  - 2 offset layers/station: 48 total counters
  - 3 mm pitch
- Note: 40 MHz e^- beam spot is large: ~20 cm^2



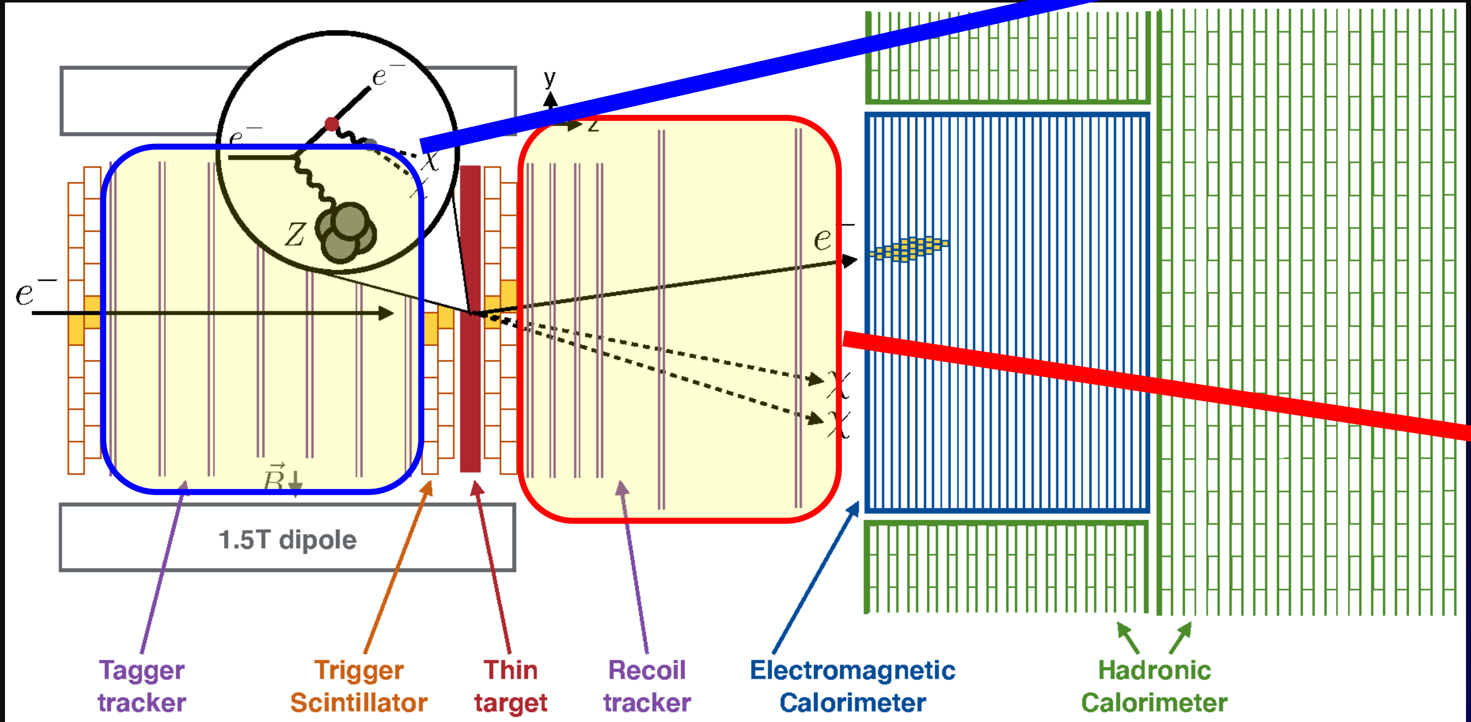


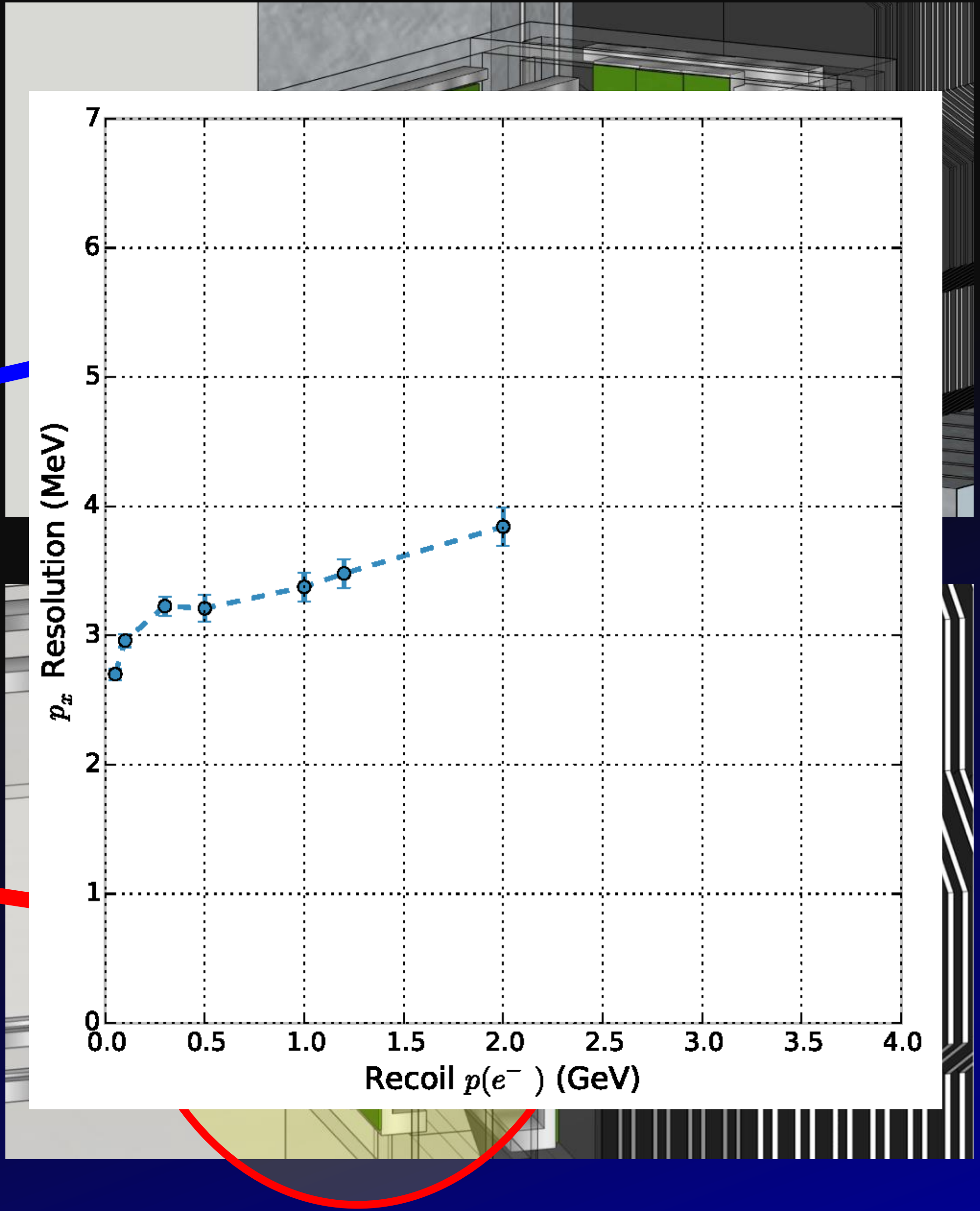


2 mm deep x 3 mm wide strips

LDMX Apparatus: Tagger & Recoil Tracker

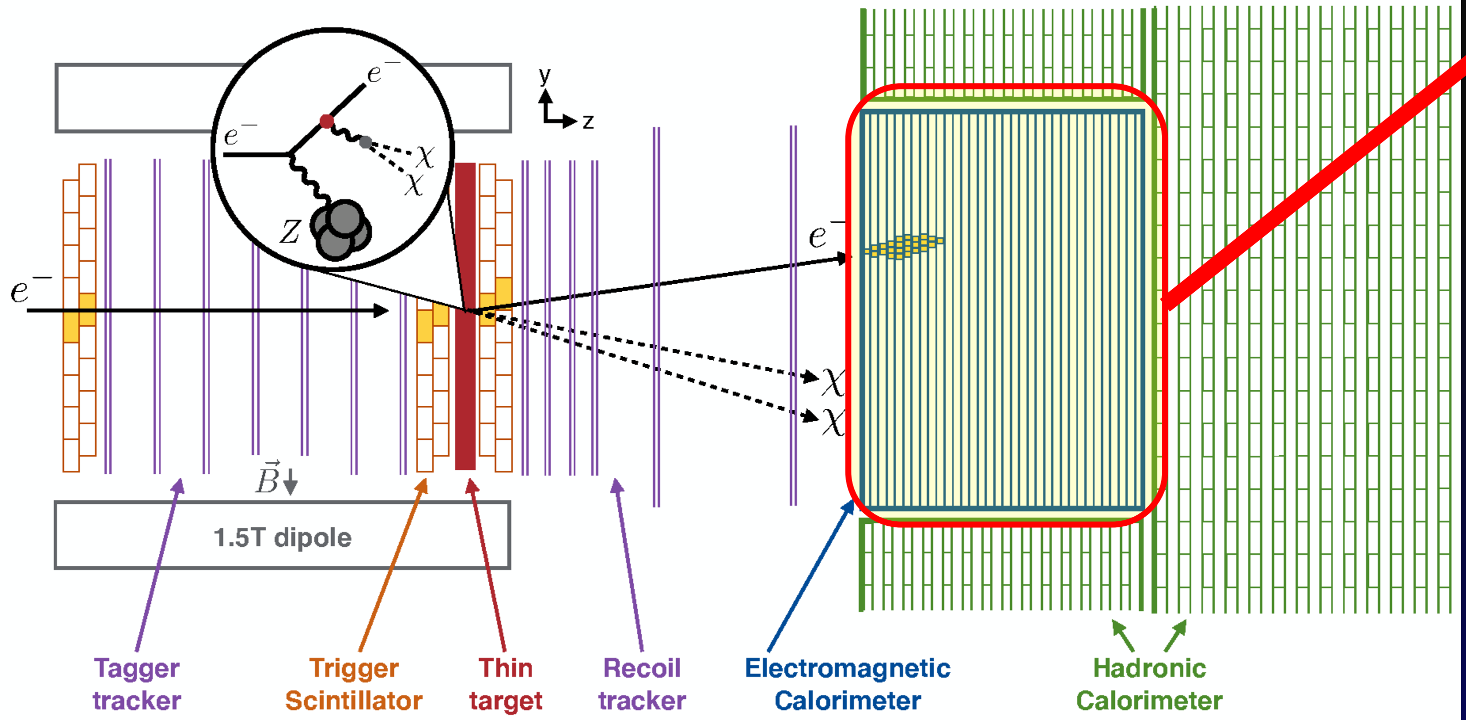
- Tagger / Recoil tracker inside 1.5 T dipole field / fringe field measure momentum of incoming / recoil e⁻ to <1%
- Double-sided silicon, Based on Vtx Tracker for HPS expt (JLab)
- 4 MHz/mm^2 rate capability
- 0.7% X_0 per 3d hit
- 6 (60) µm hor (ver) resolution; ~2 ns timing resolution

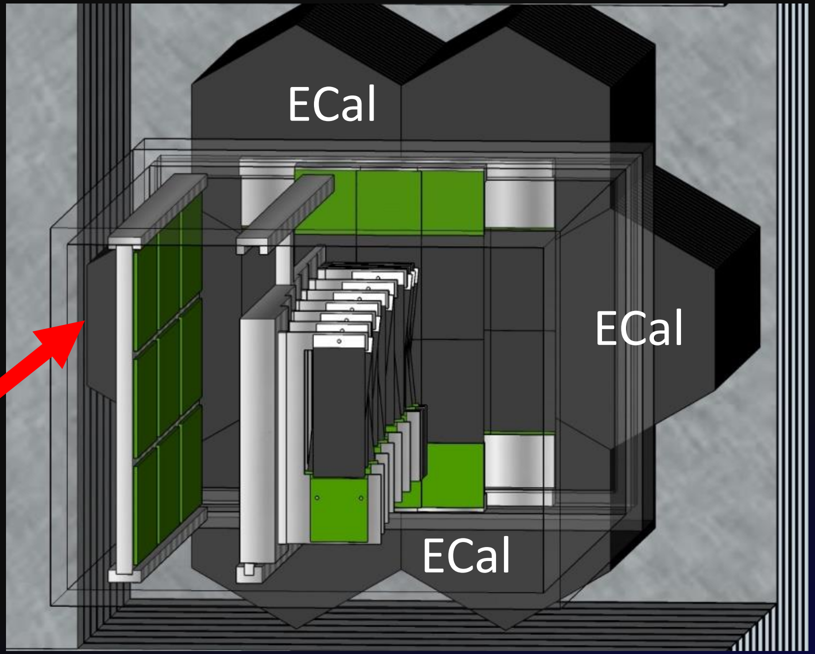


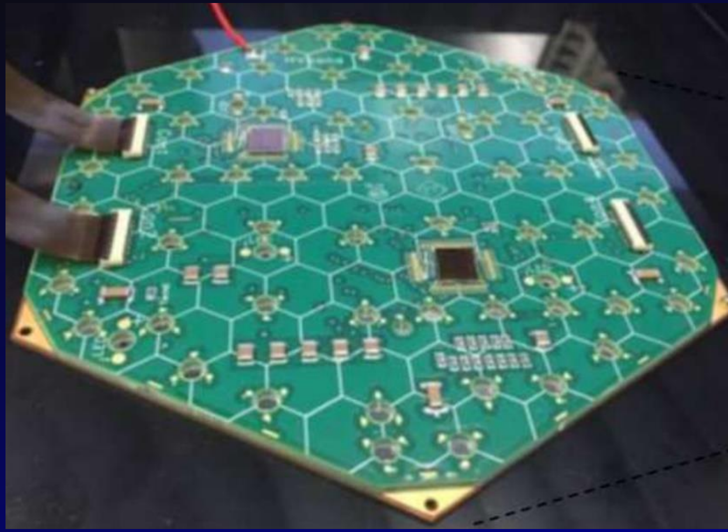


LDMX Apparatus: Electromagnetic Calorimeter

- Tungsten-Silicon sampling calorimeter: $\sigma(E)/E \sim 20\%/\sqrt{E}$
- Based on CMS Phase-II forward calorimeter (HGC) upgrade
- High granularity (0.56 cm^2 pad area): 68% of EM shower <1 cm 1st 15 layers
- Can track MIPs
- Deep: 40 X_0 & radiation hard: max dose for LDMX is 3 x 10^{13} n/cm^2
- Provides a fast energy trigger: E < 1.5 GeV

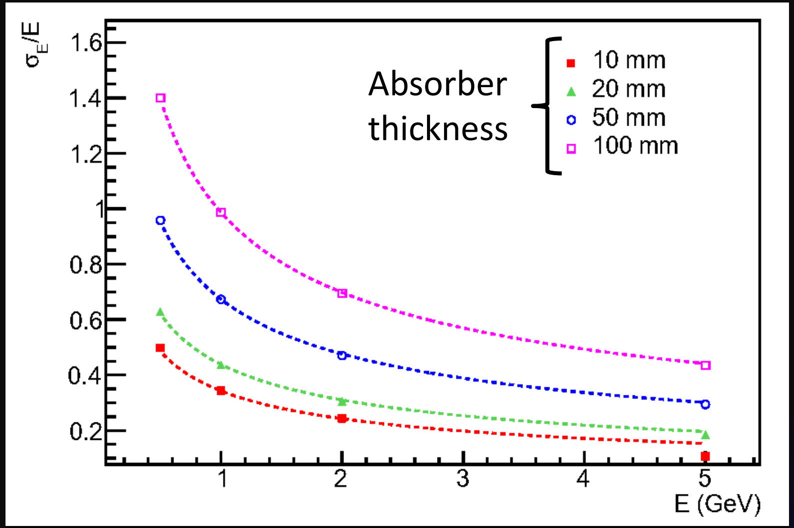




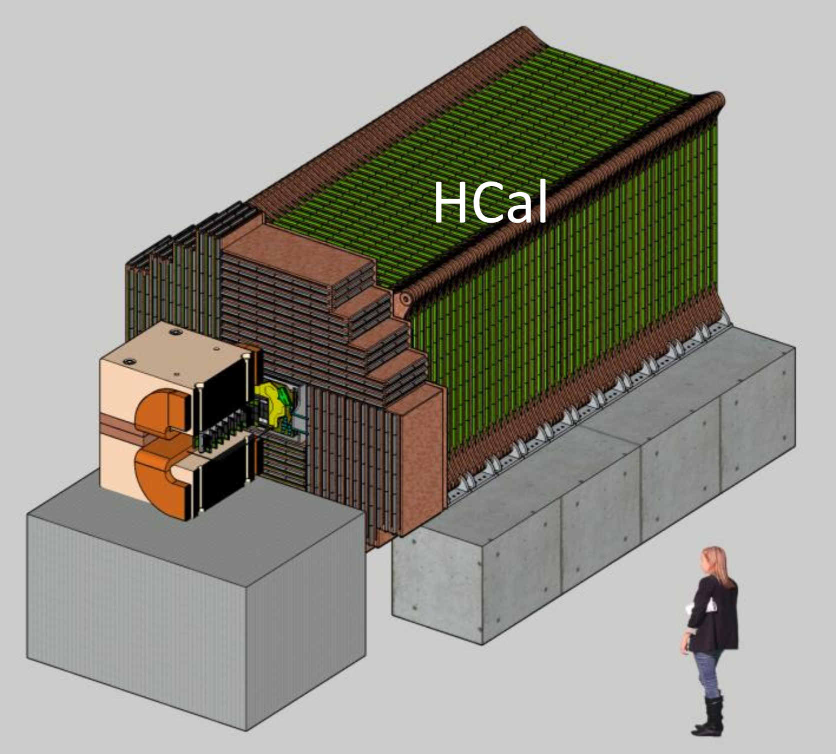


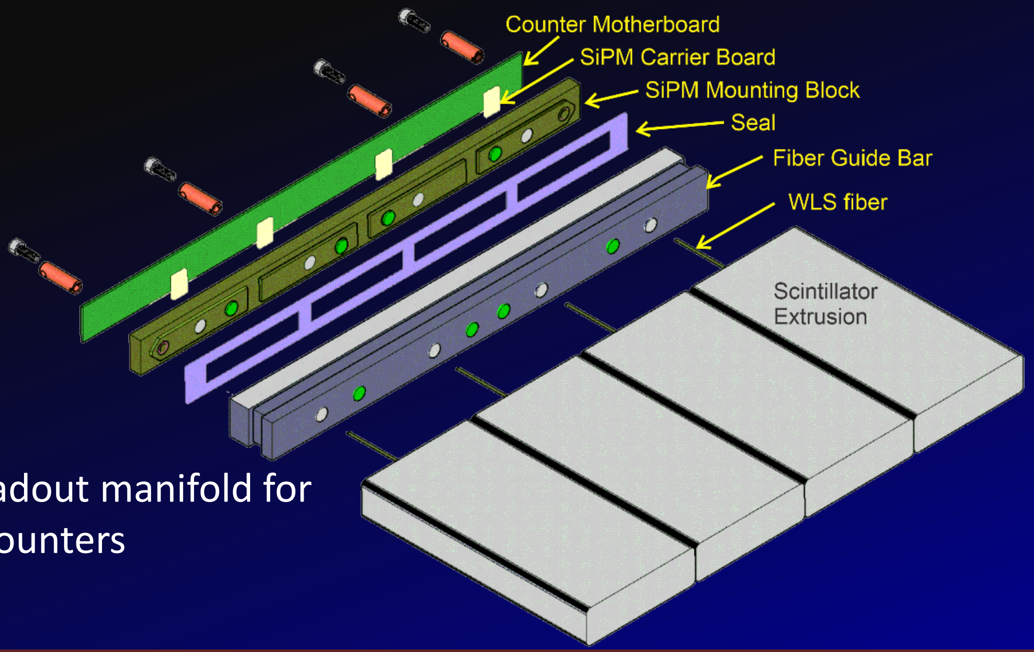
LDMX Apparatus: Hadronic Calorimeter

- Detects neutral hadrons/neutrons produced in photonuclear reactions in ECal/target with high eff., EM showers escaping ECal, and MIPs (muons)
- Iron-scintillator sampling calorimeter: 96 layers of 20/25 mm PS/Fe: 17λ
- Extruded 50x20 mm^2 scintillator bars with inserted wavelength-shifting fibers, read out with Silicon Photomultipliers (SiPMs)
- Active element based on the Mu2e Cosmic Ray Veto detector



Energy resolution for neutrons





Readout manifold for 4 counters

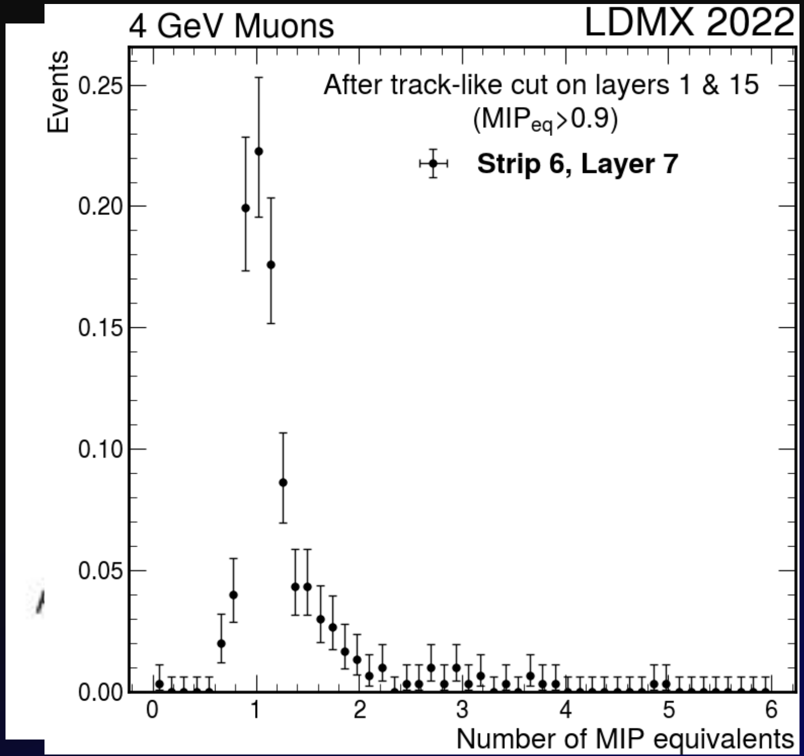
CERN Test Beam Run

Prototype HCAL and Trigger scintillator detectors fabricated and tested

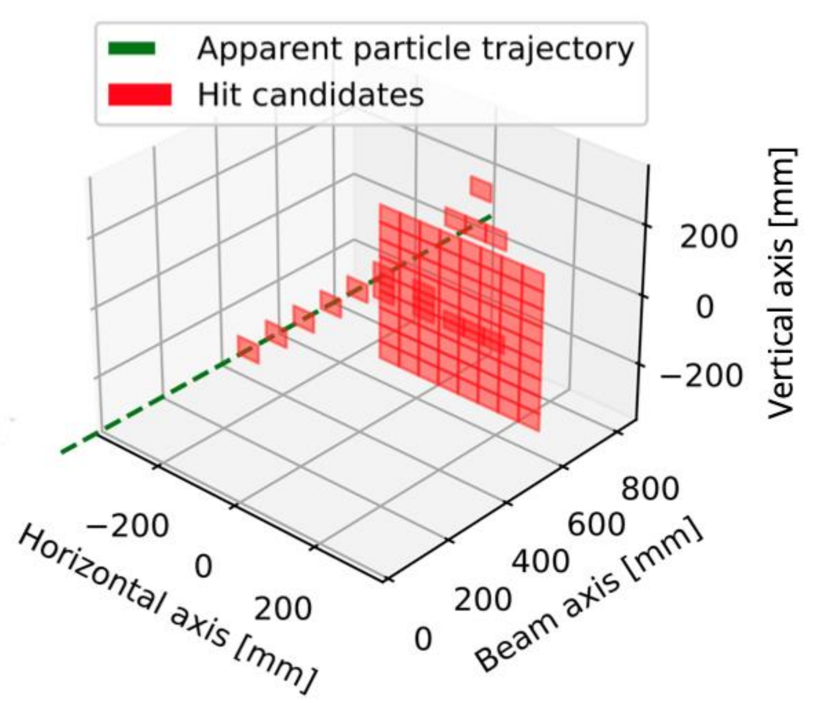
April 2022 at CERN

Demonstrated successful operation of the readout and of physics capabilities of the detectors

Incident Muon



Incident Charged Pion



LDMX Mounted at SLAC Linac Coherent Light Source

LDMX will use new beamline (LESA) being built for the upgraded SLAC Light Source (LCLS-II) being commissioned (2023-2024)

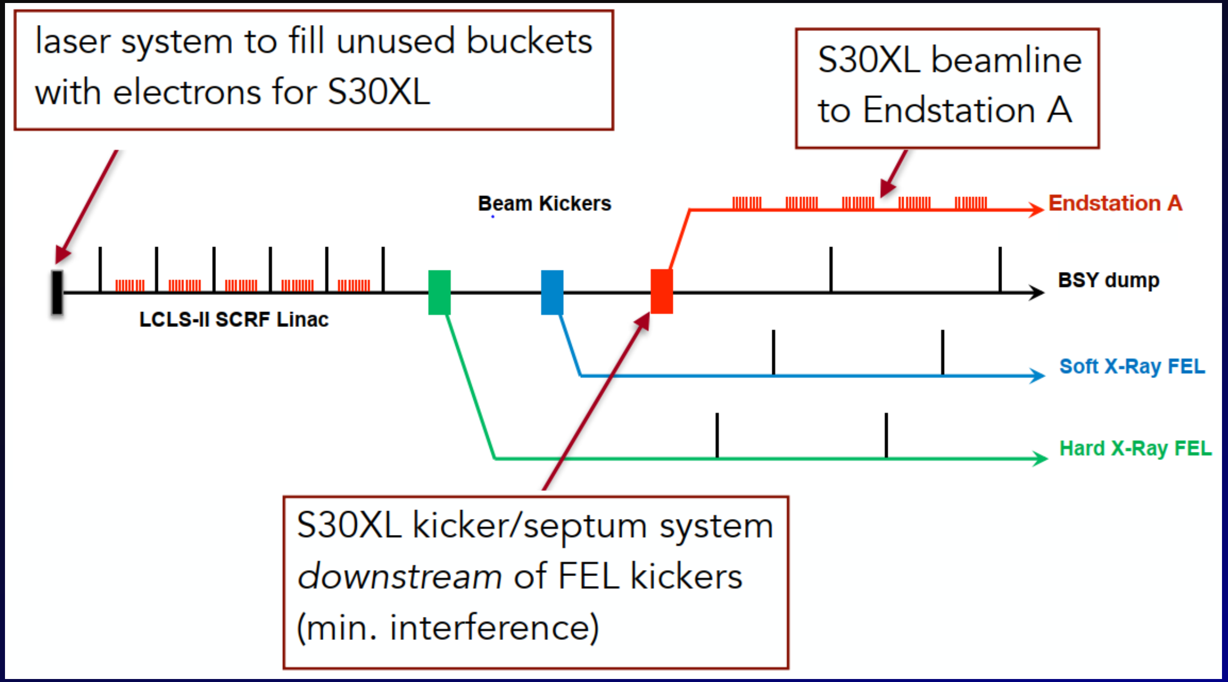
Parasitic: Use unused LCLS-II beam bunches

55% duty factor (600 ns/1100 ns)

Phase I: 4 GeV bean @ 40 MHz → O(10^{14}) e^- in a 1 year run

Phase II: 8 GeV beam (LCLS-II-HE) → O(10^{16}) e^- in a 3 year run

Future: eSPS (16 GeV) at CERN?



laser system to fill unused buckets with electrons for S30XL

S30XL beamline to Endstation A

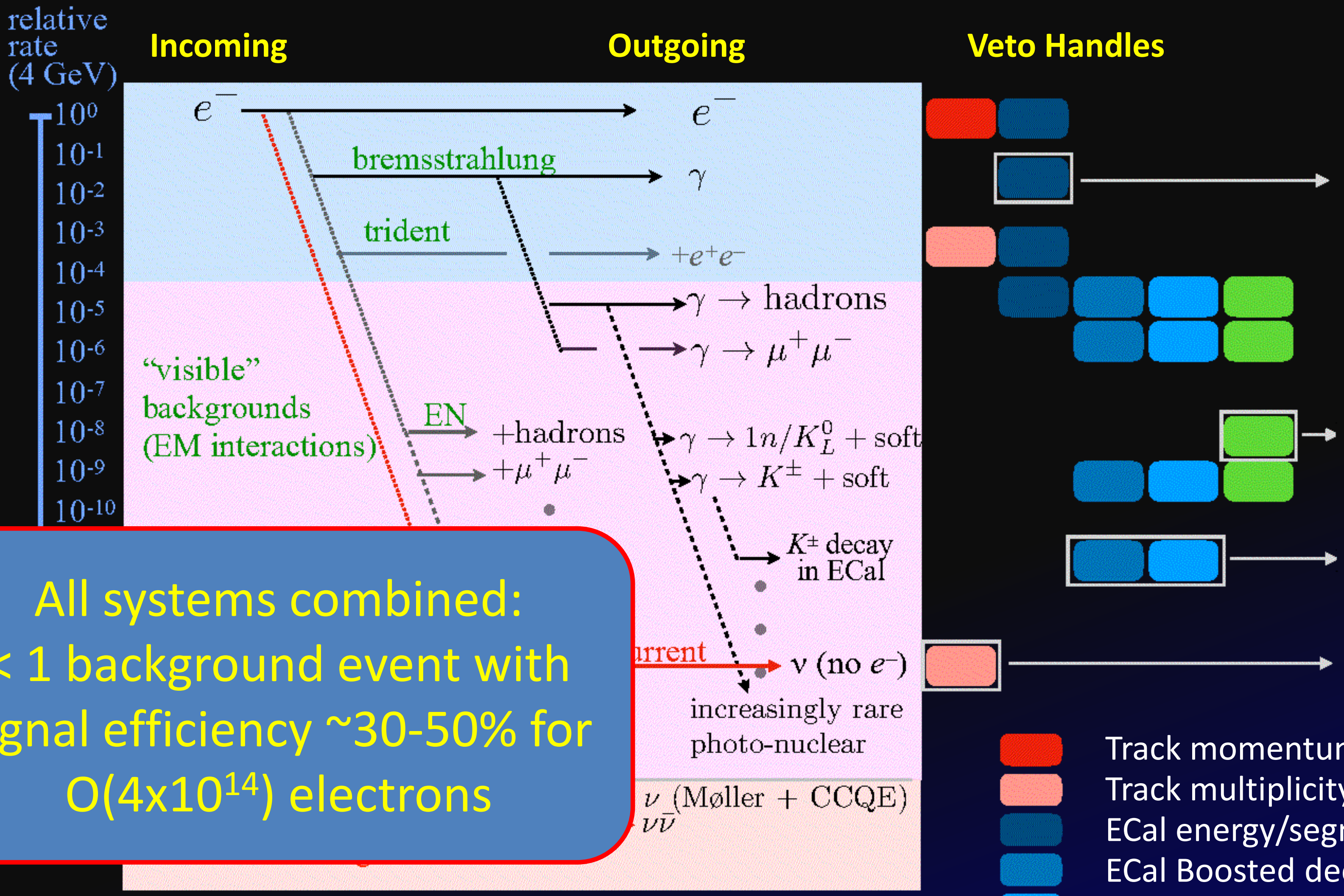
S30XL kicker/septum system *downstream* of FEL kickers (min. interference)

Backgrounds, Backgrounds, Backgrounds . . .

Gaussian energy fluctuations

Rare reactions: products escape HCal and/or anomalous energy deposition

Neutrino “floo



All systems combined:
< 1 background event with signal efficiency ~30-50% for $O(4\times10^{14})$ electrons

Åkesson et al, JHEP04 (2020) 003.

Design Drivers

ECal depth, resolution, hermiticity

HCal depth, segmentation, hermiticity

ECal 3D granularity, MIP-sensitivity

Recoil Tracker acceptance

- 🟥 Track momentum
- 🟧 Track multiplicity
- 🟦 ECal energy/segmentation
- 🟦 ECal Boosted decision tree
- 🟦 ECal trackng

Tools

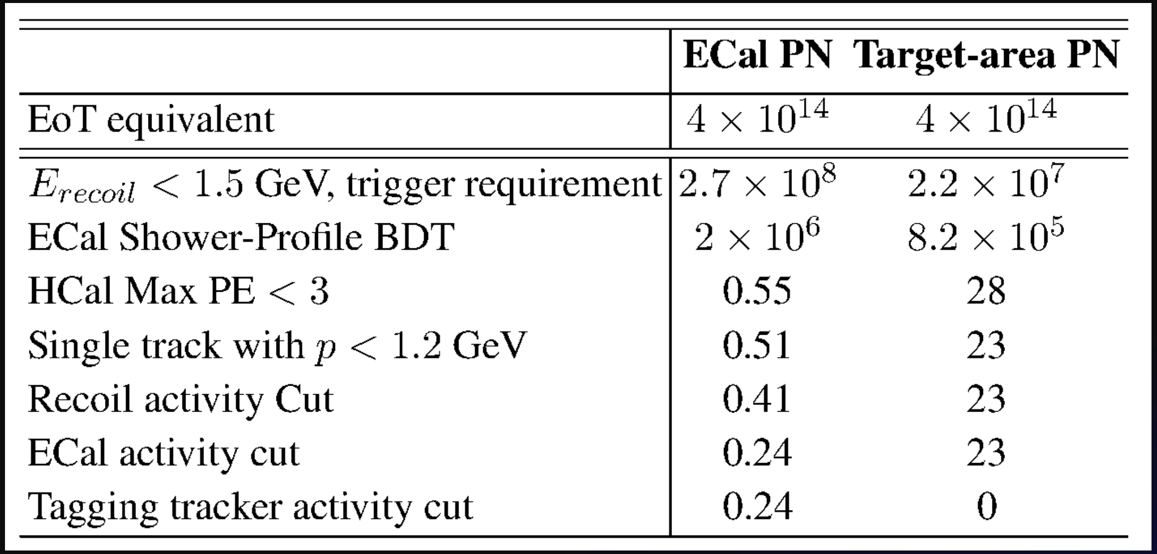
Note: transverse momentum not used as a discriminant in these studies

Backgrounds: Photo-Nuclear

The most difficult background to reject

Tools:

1. E_{recoil} < 1.2 GeV
2. ECal shower profile differences (with a BDT)



	ECal PN	**Target-area PN**
EoT equivalent	4×10^{14}	4×10^{14}
$E_{recoil} < 1.5$ GeV, trigger requirement	2.7×10^{8}	2.2×10^{7}
ECal Shower-Profile BDT	2×10^{6}	8.2×10^{5}
HCal Max PE < 3	0.55	28
Single track with $p < 1.2$ GeV	0.51	23
Recoil activity Cut	0.41	23
ECal activity cut	0.24	23
Tagging tracker activity cut	0.24	0

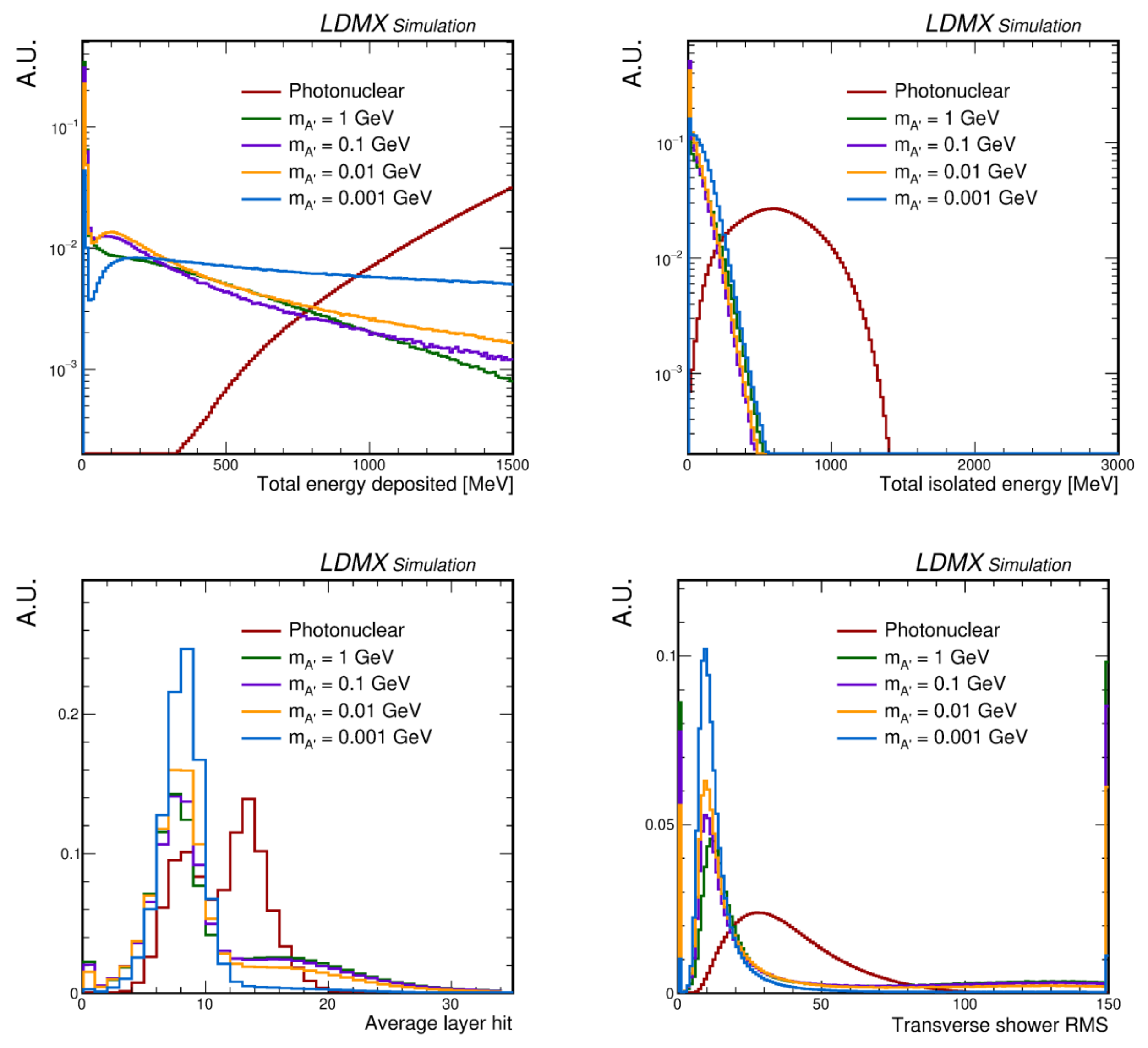


Photo-nuclear vs signal energy profile differences

Putting it all Together: LDMX Dark Matter Reach

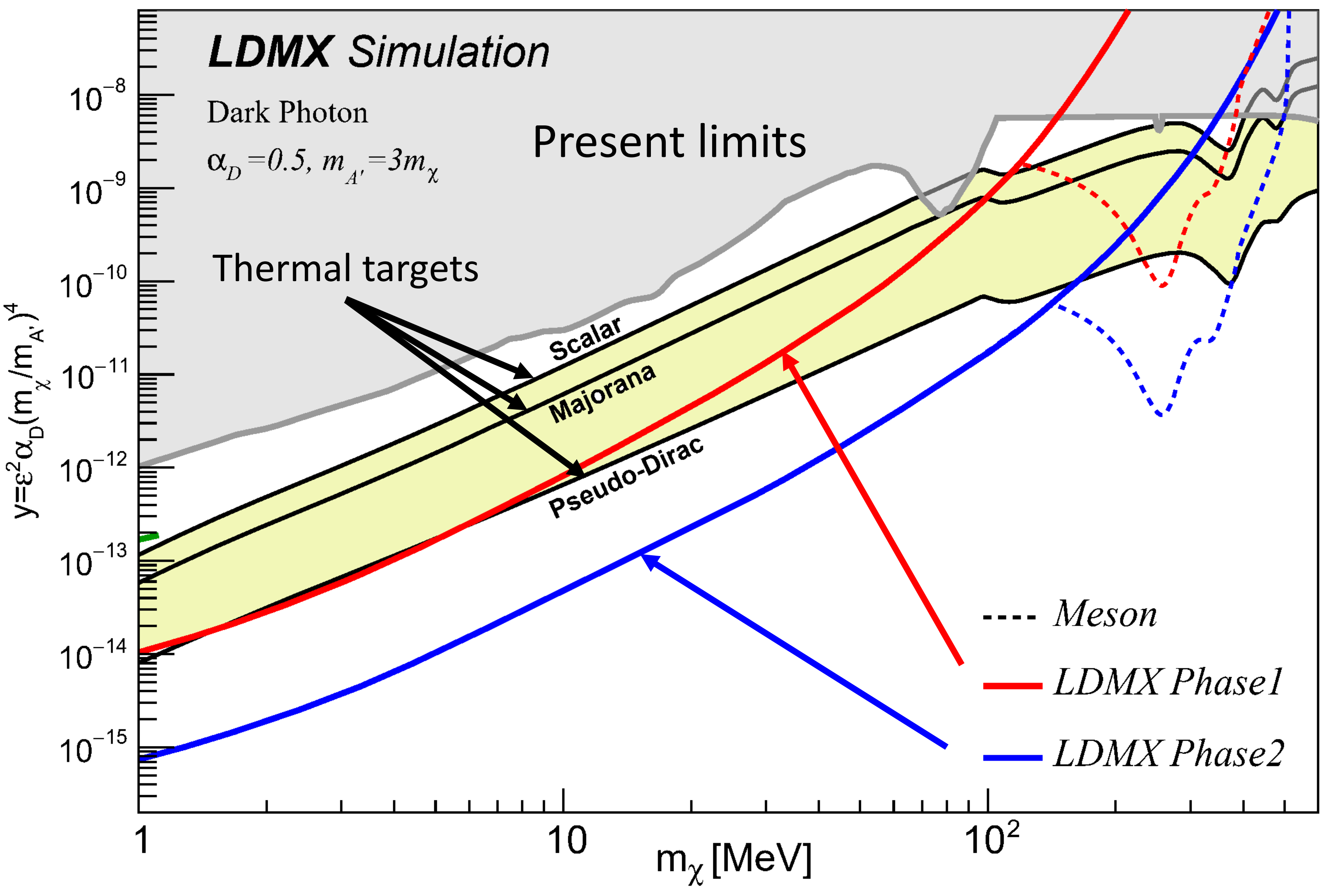
We are sensitive to a broad range of the m_χ parameter space for a wide range of thermal targets, assuming a Dark Photon portal

LDMX
Phase 1: 4 GeV
O(10^{14}) electrons
Phase 2: 8 GeV
O(10^{16}) electrons

$$\sigma v \approx \alpha_D \varepsilon^2 \frac{m_\chi^2}{m_{A'}^4}$$

$$\approx \alpha_D \varepsilon^2 \frac{m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2}$$

$$\approx y \frac{1}{m_\chi^2}$$



Effect of Beam Energy on Dark Matter Yield

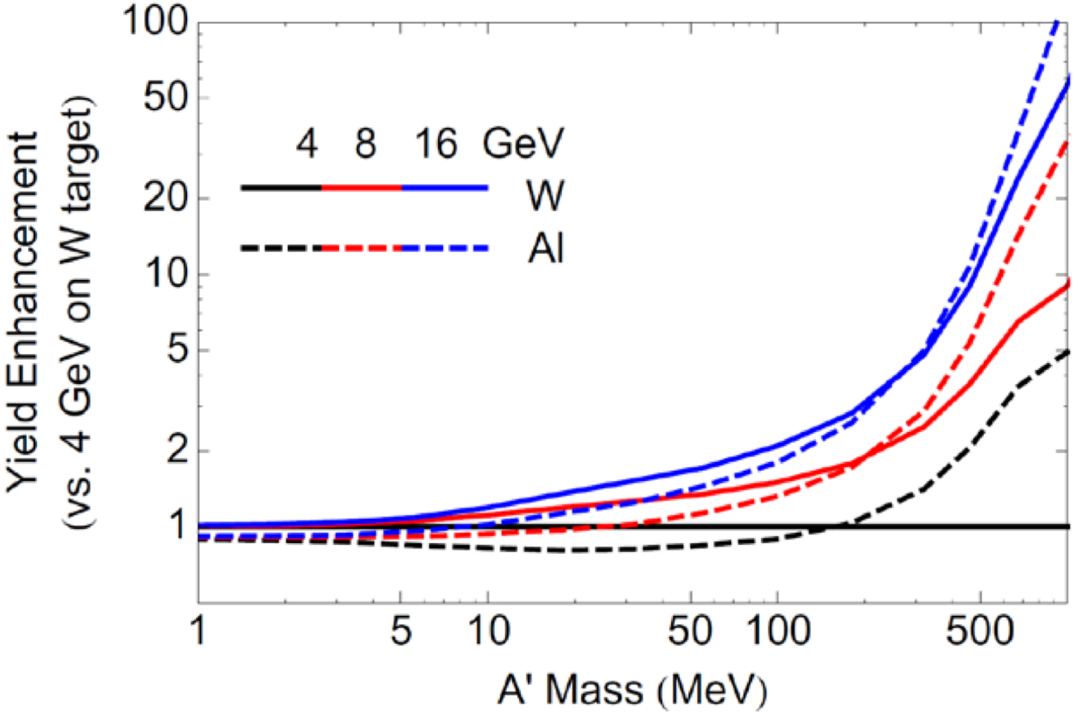
Phase II LDMX:

- 8 GeV
- 50X more statistics than Phase I

Large yield enhancement at large dark photon (A’) masses

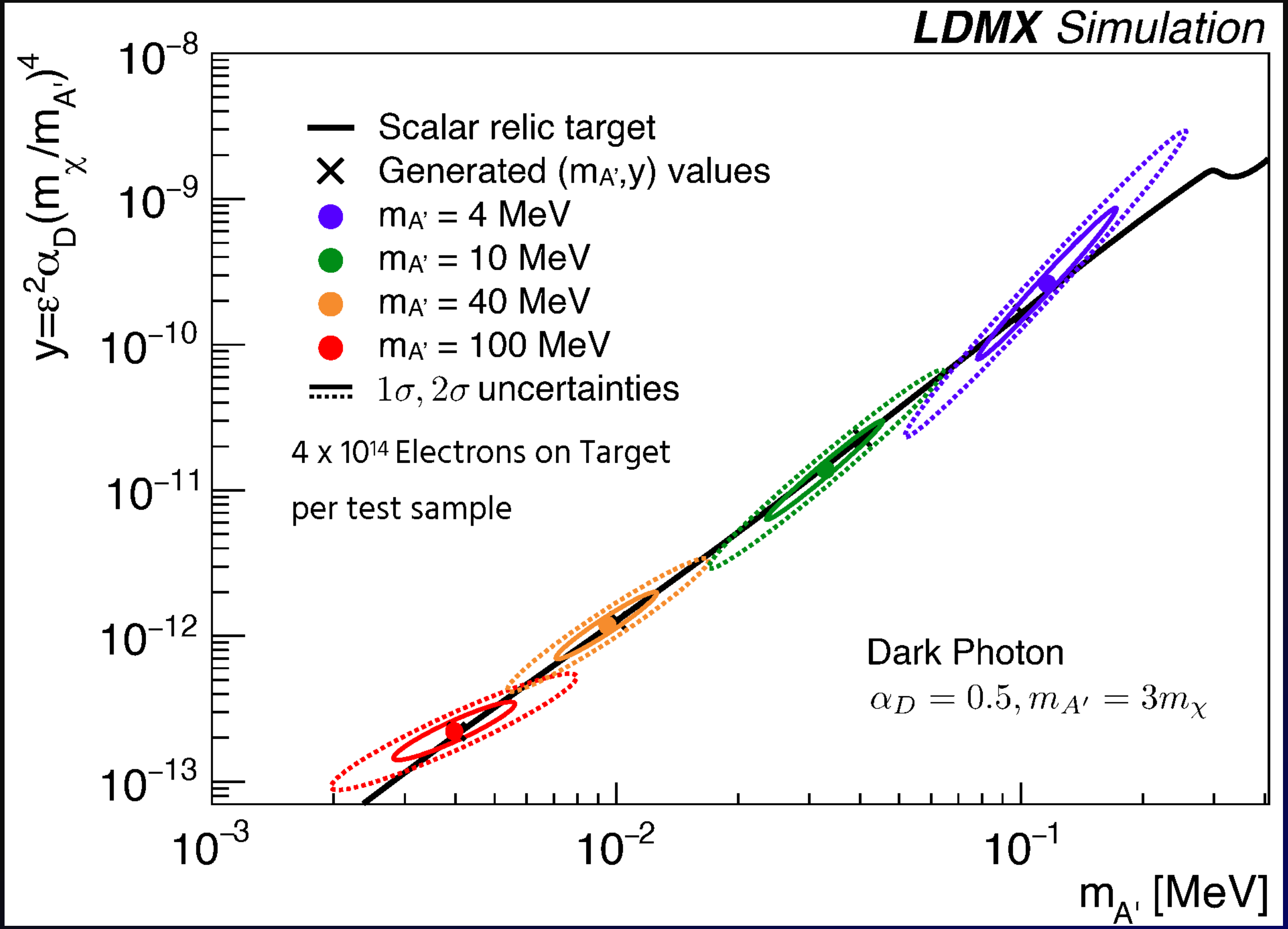
Backgrounds easier to handle:

- ECal veto alone rejects at least 10 – 20X more background at 8 GeV than 4 GeV.
- HCal-only veto efficiencies also improve, while signal efficiencies are kept at the same level.
- Why?:
  - More energetic final-state particles
  - Cross-sections for two-body photonuclear reactions, the most challenging to reject, fall as $1/E^3$
  - Decay-in-flight backgrounds are further suppressed when the decaying meson is boosted.



Knowing Transverse Momentum and Energy give Clue to A’ Mass

Combining recoil electron E and p_T spectrum gives us a handle on the mediator mass

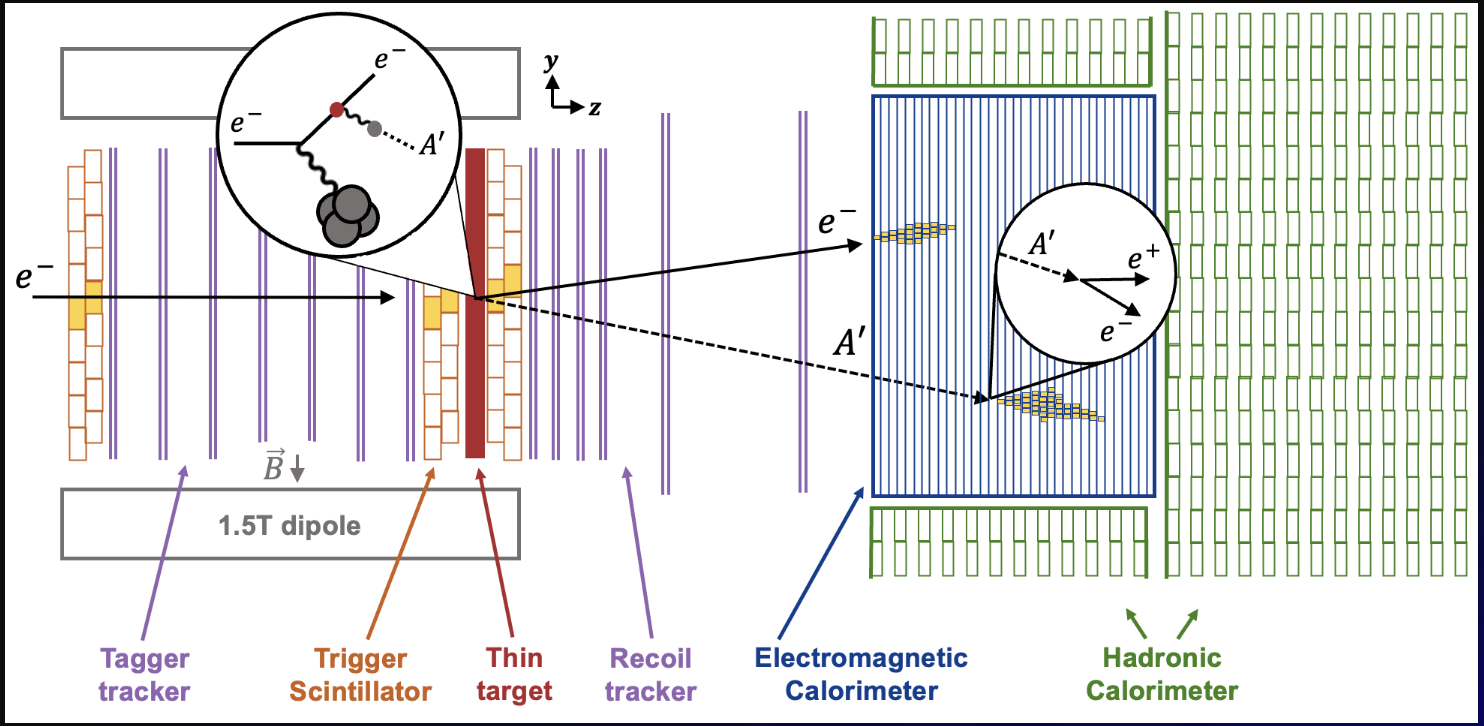


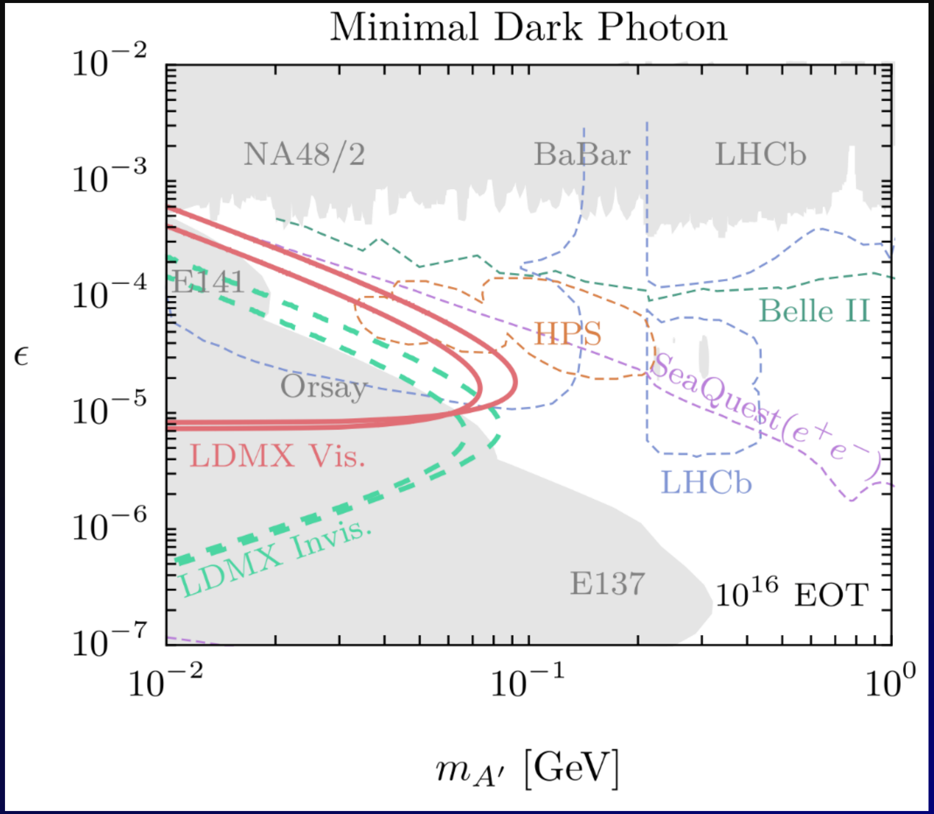
Visible Signatures

Possible to search for “appearance” of SM particles in Ecal/Hcal

LDMX has competitive sensitivity for several models of interest: minimal dark photon, ALPs, SIMPs, etc.

Work in progress: projections with full background studies are nearing completion





Timeline

Past

2009 Bjorken, Essig, Schuster, and Toro: “New Fixed-Target Experiments to Search for Dark Gauge Forces”; PRD 80 (2009) 075018

2015 Izaguirre, Krnjaic, Schuster, and Toro explore possibilities of a missing momentum experiment; PRL 115, 251301 (2015)

2015 Dark Sectors Workshop: LDMX at SLAC

2018 Detailed initial design study completed (arXiv:1808.05219)

2019 Collaboration formed

2021 LDMX received prototype funding in FY22 as part of the DOE Dark Matter New Initiatives project

2022 Successful test-beam run at CERN

Future

2023 Beamline (LESA) commissioning

2025 Fabrication starts (?)

2026-2028 8 GeV upgrade (LCLS-II-HE)

2028 First beam LDMX Phase-II

We are ready to build the experiment now!

LDMX Collaboration

“Small” collaboration by modern HEP standards

Strong set of collaborating institutions

Strong support from the funding agencies, in USA and in Europe

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

And finally: apologies for leaving out other physics topics that will be addressed by LDMX: such as: Axion-like particles, milli-charged particles, electron-nucleus scattering measurements

Backup Slides

HCal Photonuclear Background Discrimination

Distribution of ECal BDT discriminator value versus the maximum number of PEs in an HCal scintillating bar 2.1×10^{14} EoT equivalent ECal-photonuclear sample (black points) and a signal sample with an A’ mass of 100 MeV (heat map).

The shaded yellow box indicates the signal region.

Colored squares are signal events

Background events in signal box are rejected by other criteria