The LDMX experiment

Bertrand Echenard
Caltech

MEPA 2023 – October 2023

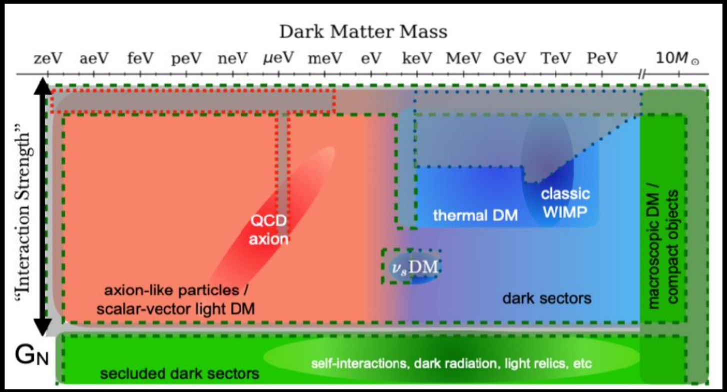
Dark matter – the question of our time

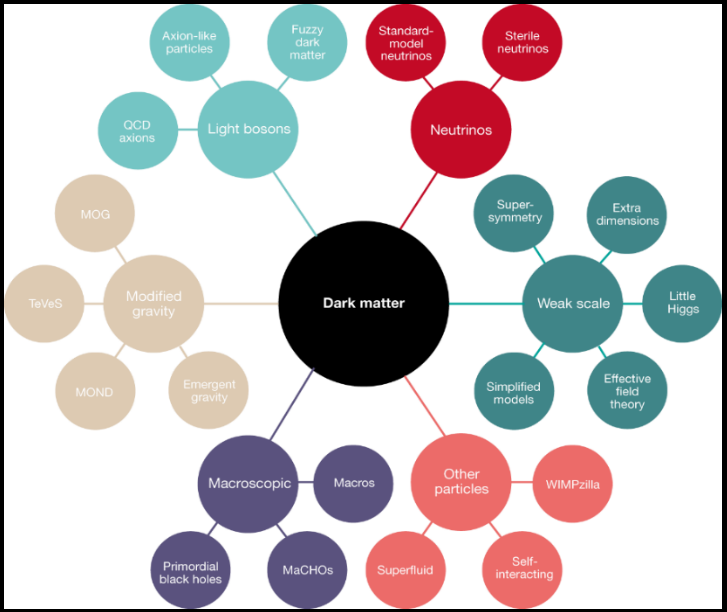
The question of our time, but we still know relatively little about it:

- **Abundance:** $\Omega_{DM} \sim 0.26$
- **Mass:** about 80 (60) orders of magnitude of mass range for bosons (fermions)
- **Interactions:** gravitational interaction, a self-interaction is possible if it is not too strong - other interactions with ordinary matter possible as long as they do not involve emission of photons

A vast range of possibilities

2211.09978



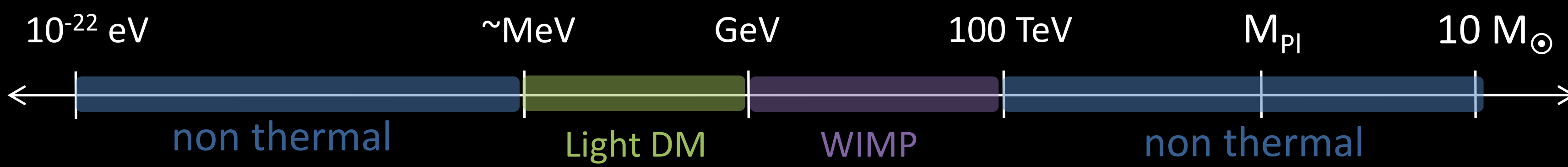


Bertone and Tait, Nature 562, 51–56 (2018)

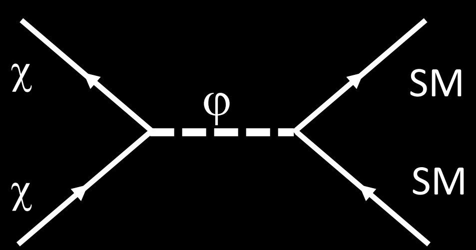
Light thermal dark matter

Thermal dark matter, originating as a relic in the early Universe, is arguably one of the most compelling paradigm. It is both generic – only requires a non-gravitational interaction between dark and familiar matter – and predictive.

The thermal paradigm greatly restricts the range of possible DM masses



Light DM – new light mediator needed to explain the DM abundance



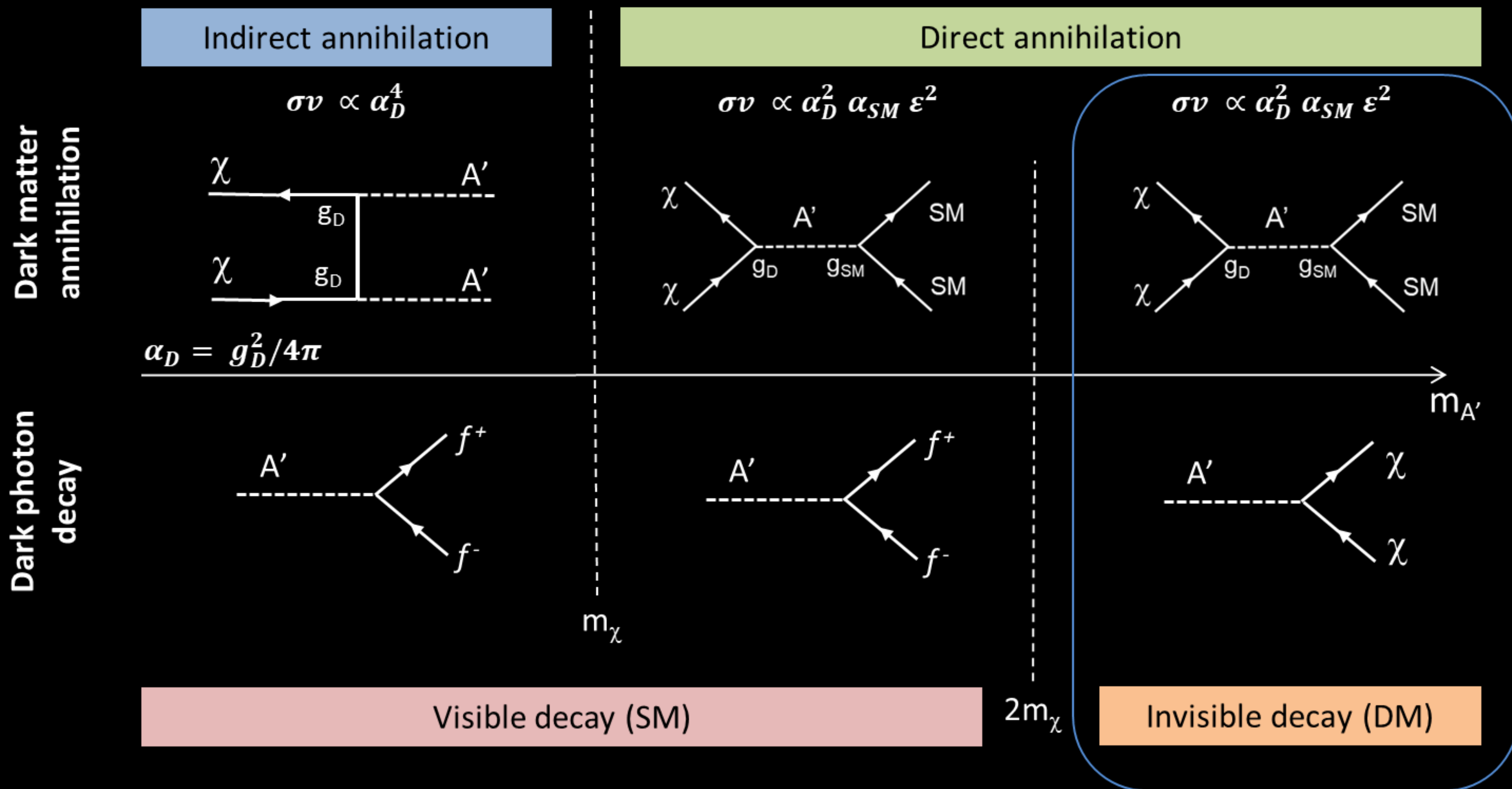
$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

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

New mediator must be neutral under the SM interactions.
Naturally realized in the context of hidden sectors

Light DM signatures

Hidden sector scenario with dark photon (A') and dark matter (χ) candidates



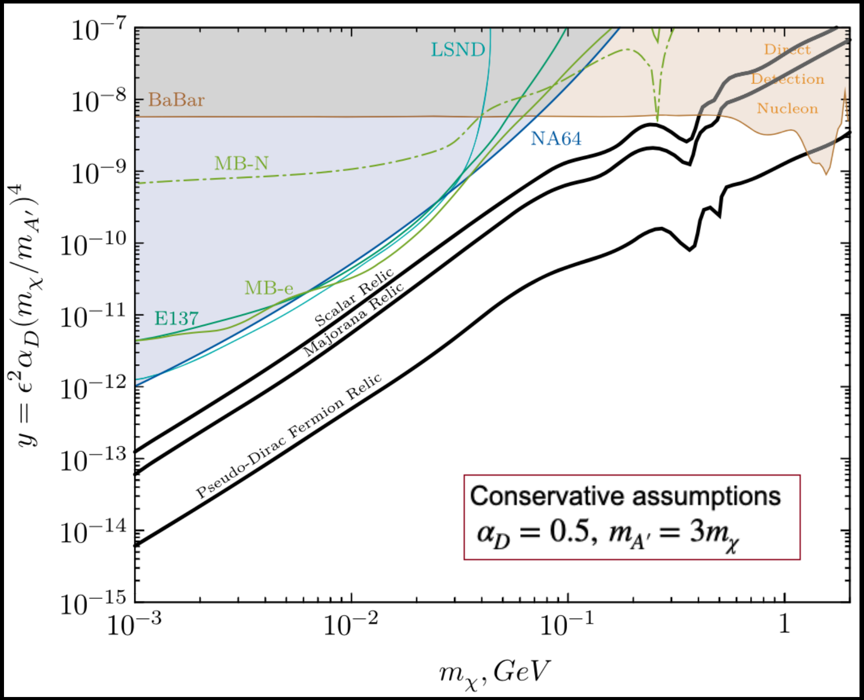
Hidden sector light dark matter

Benchmark scenario: light dark matter via vector portal

Very interestingly, the DM relic density for direct annihilation via the vector portal depends only on the mass, spin and dark sector couplings

$$< \sigma v > \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim y \frac{1}{m_x^2}$$

Dimensionless variable $$y = \alpha_D \, \varepsilon^2 \frac{m_x^4}{m_A^4}$$

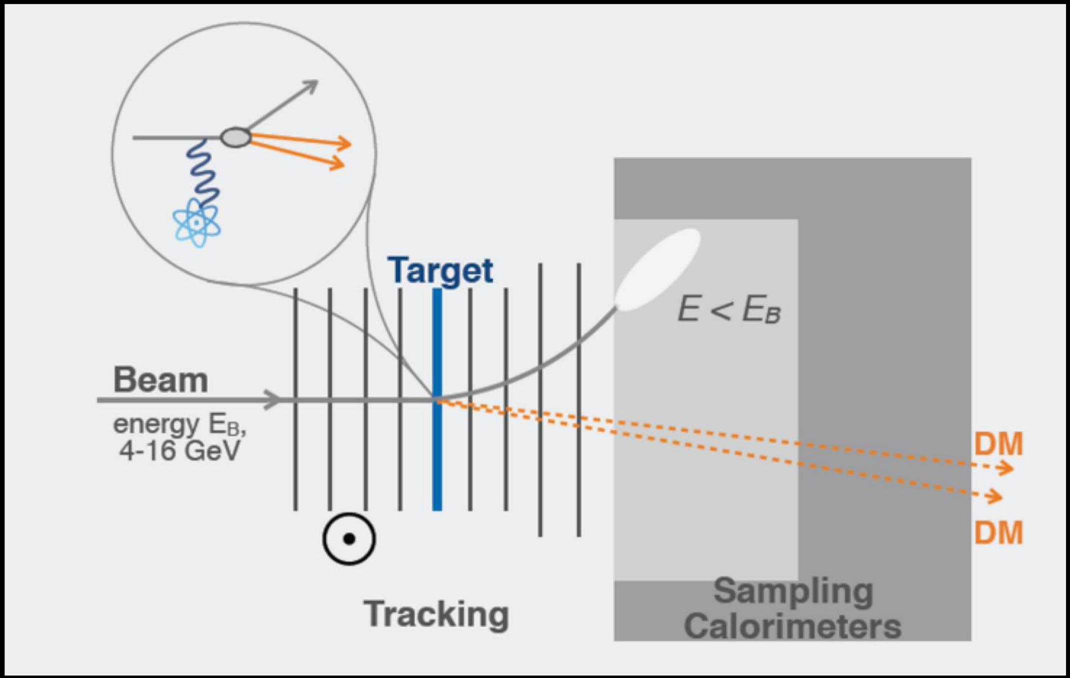


Hidden sector light DM defines sharp targets, accessible in laboratory

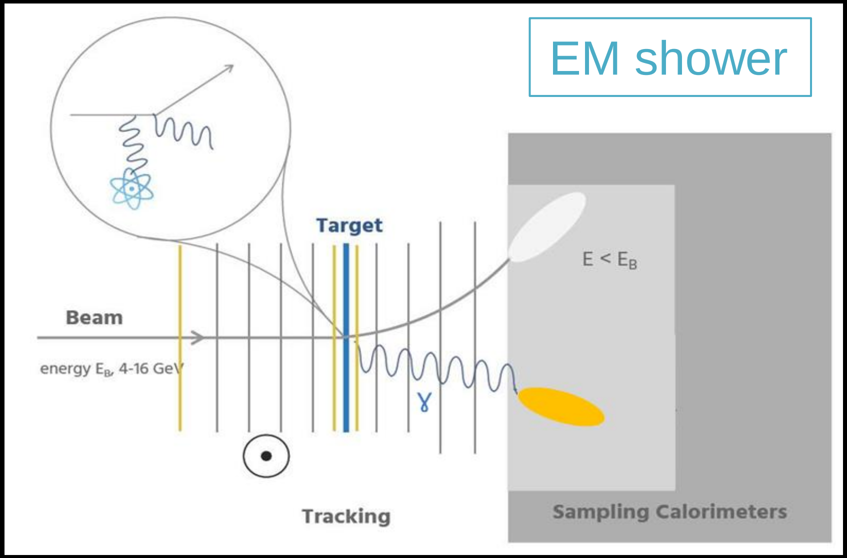
LDMX concept

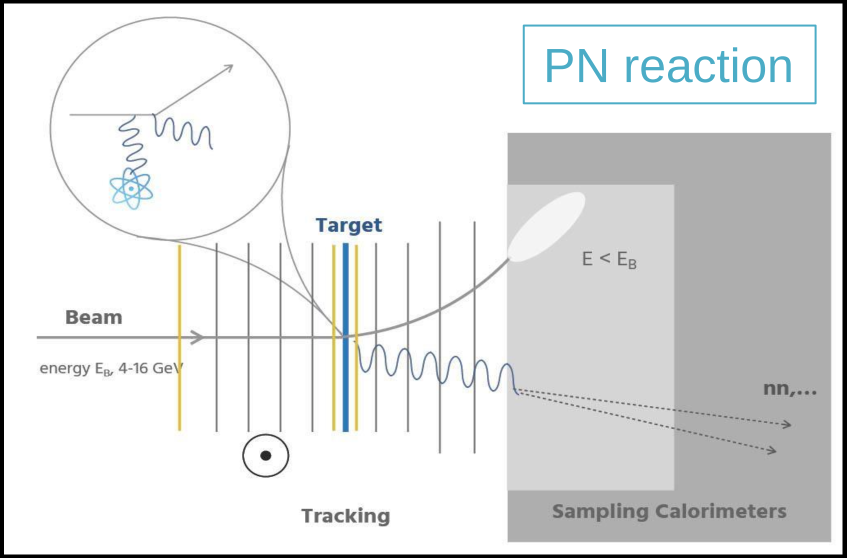
LDMX (Light Dark Matter eXperiment) proposes to produce DM in electron-nucleus interactions and use the “missing momentum” approach to identify this process with unique capability to probe the thermal targets in the sub-GeV region.

Individually measure electron scatterings on a thin target. Signal is identified as a deflected electron and nothing else in the detector to balance the transverse momentum (similar to missing energy but with additional information about direction)



Background processes





Major background:

- Radiated photon produces an electromagnetic shower in the calorimeter
- Very large rate, vetoed by measuring the total energy in the calorimeter

Challenging background:

- Radiated photon induced photo-nuclear interaction producing a few neutral particles
- Small rate, but difficult to identify (require large hadronic calorimeter to detect the neutrals)

LESA @ SLAC

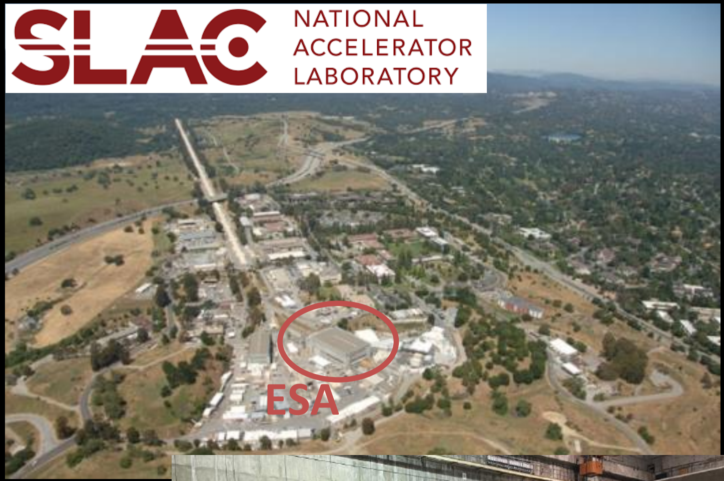
LCLS-II beam at SLAC:

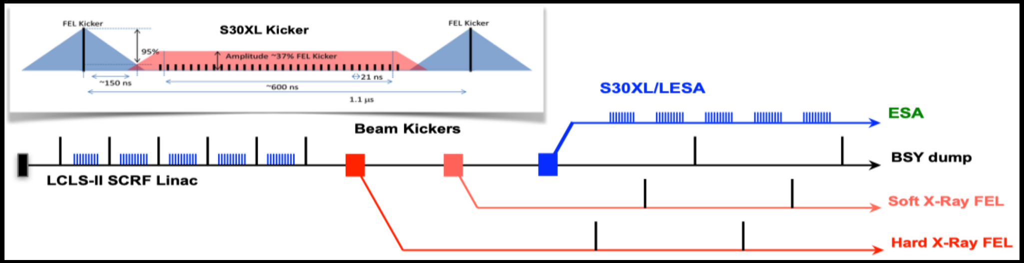
- Linac Coherent Light Source, a free electron laser producing femtoseconds X-ray pulses for multi-purpose science (material, biology, chemistry, optics,…)
- **~ 99% of electrons are unused**

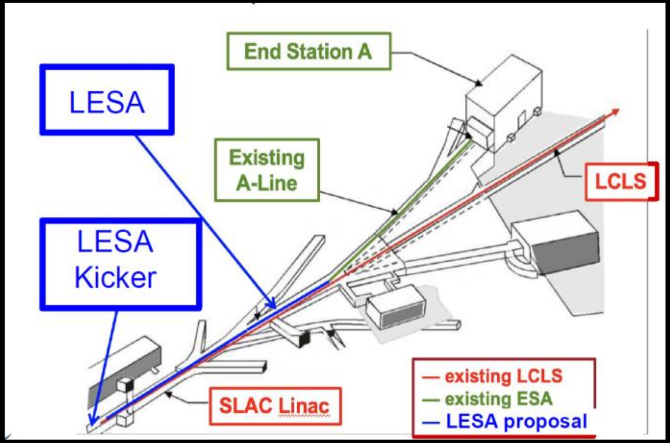
LESA: new beamline to drive ~60% of unused low-charge bunches to End Station A – **completely parasitic to LCLS operation**

LESA beamline installation and commissioning is on-going (FY24-25)

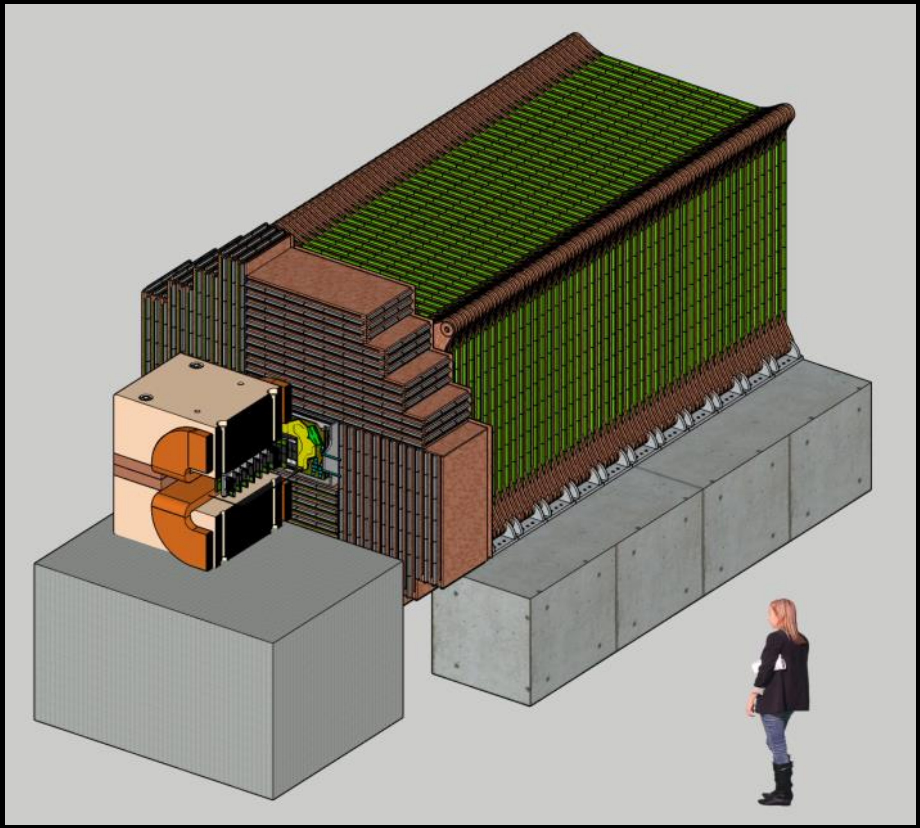
- LCLS-II upgrade to 8 GeV in FY27-28

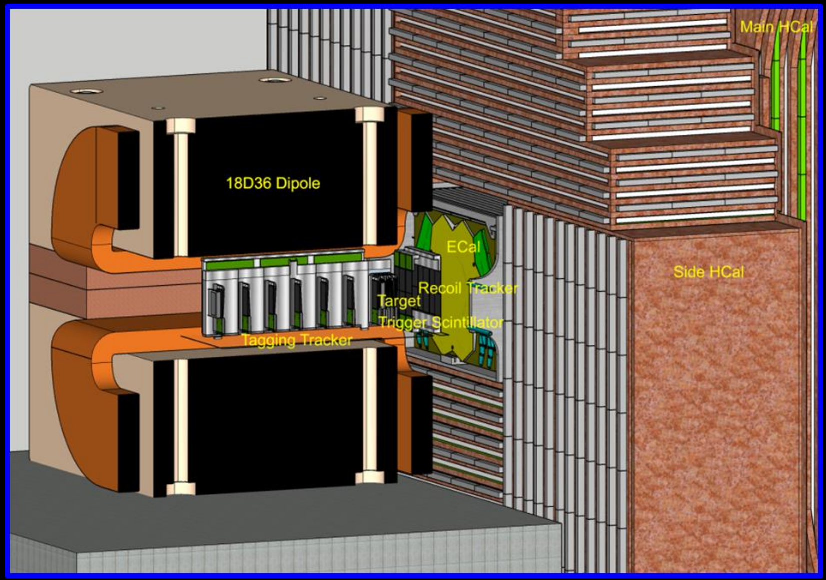






LDMX experiment





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

Detector concept

- **Tagger Tracker** with low acceptance and high resolution at beam energy
- **Recoil Tracker** with large acceptance and high resolution at low particle momenta
- **Trigger scintillator** for fast electrons-per-bunch counting
- **Electromagnetic calorimeter** with fine granularity for EM/Had shower shapes and MIP tracking
- **Hadronic calorimeter** with very low energy veto threshold for neutral hadrons

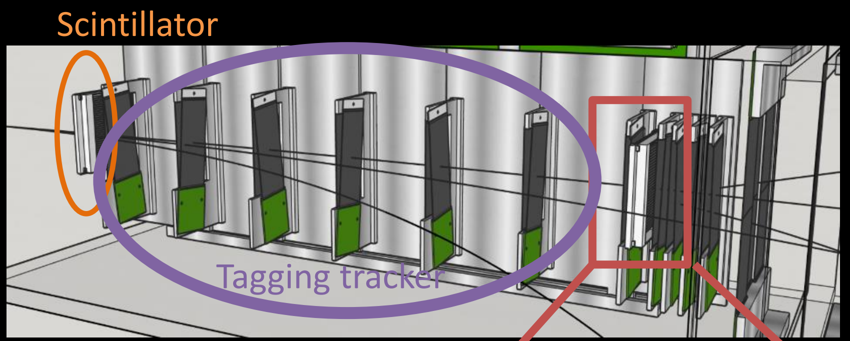
Tracking and target system

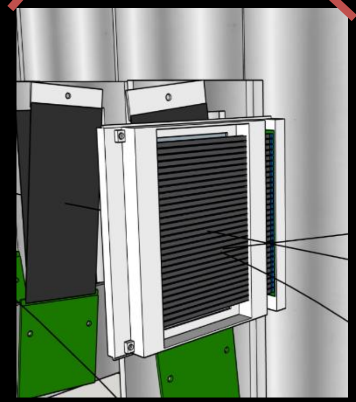
Tracking system

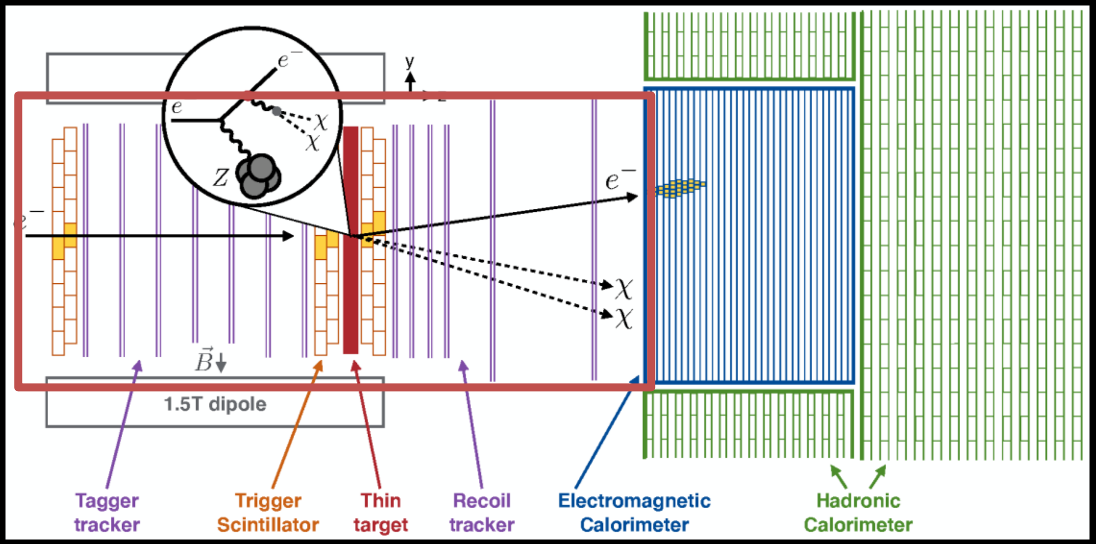
- Tagging tracker to measure incoming e-
- Recoil tracker to measure scattered e-
- Silicon tracker similar to HPS SVT
- Fast (2ns hit time) and radiation hard

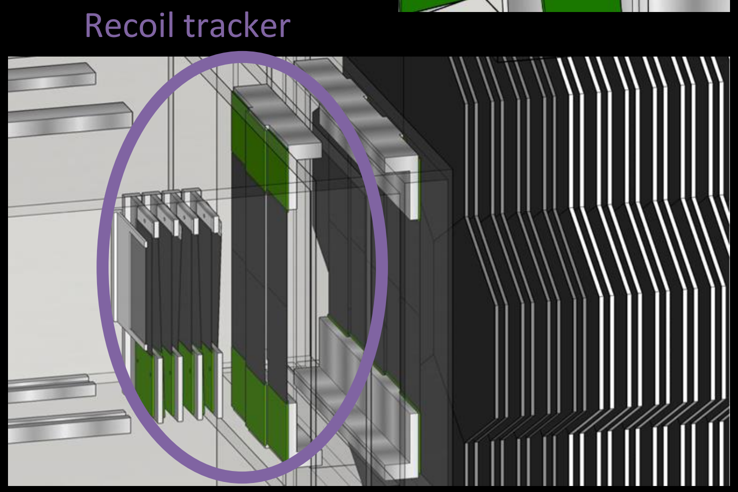
Tungsten target and scintillator planes

- Scintillator pads to count # incoming electrons
- Thin target to balance between signal rate and momentum resolution, potentially active target

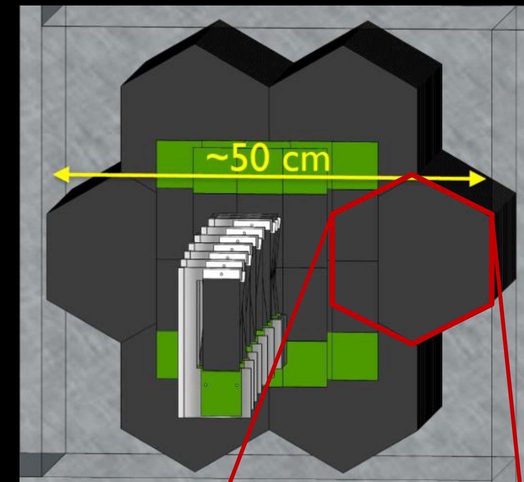






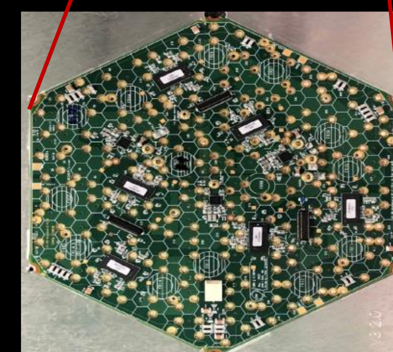


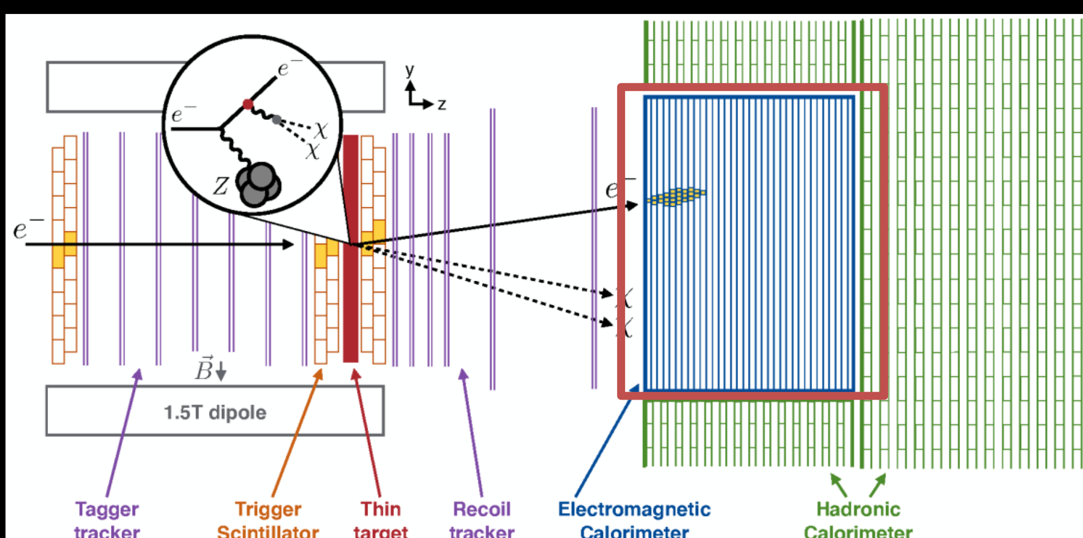
Electromagnetic calorimeter

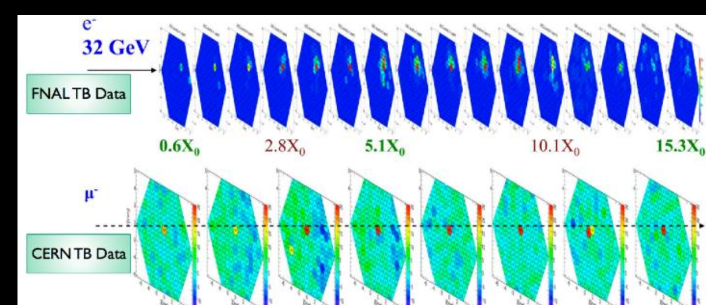


Electromagnetic calorimeter

- Based on CMS Phase-II forward high granularity calorimeter (HGC) upgrade
- Tungsten-Silicon sampling calorimeter: $\sigma(E)/E \sim 20\%/\sqrt{E}$
- High granularity enables track reconstruction
- Significant depth: 40 X_0
- Radiation hard
- Provides a fast energy trigger: E < 1.2 GeV



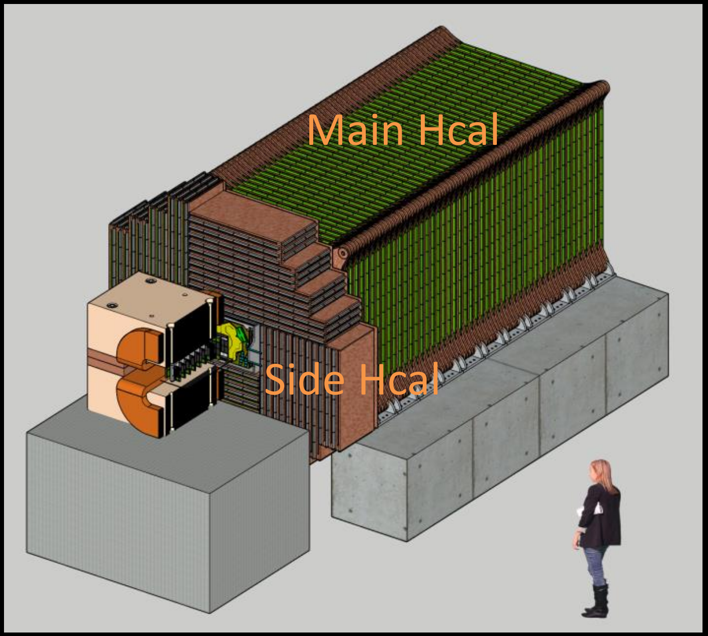


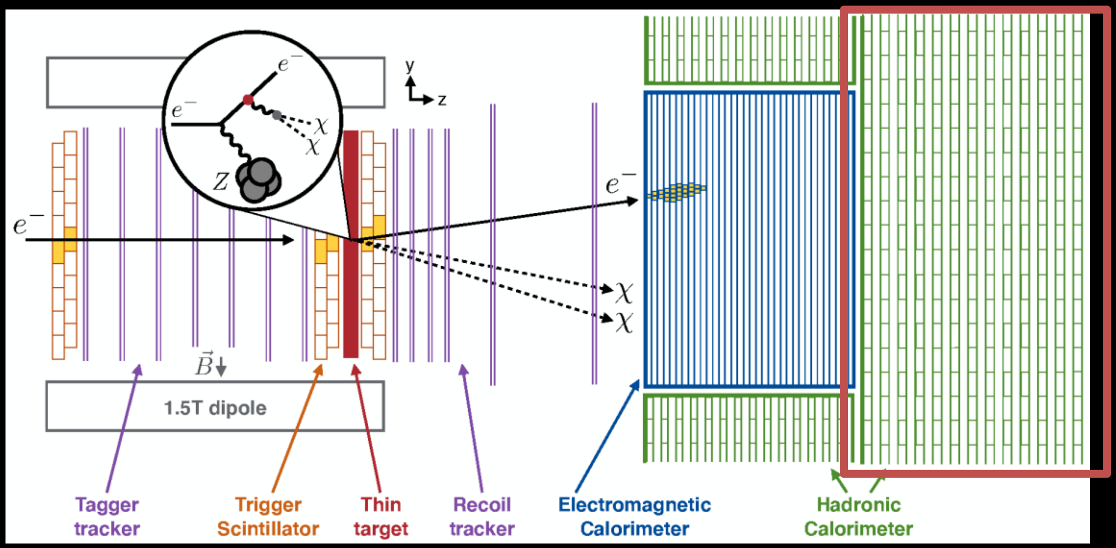


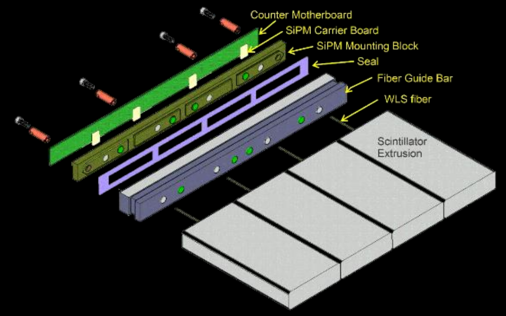
Hadronic calorimeter

Hadronic calorimeter

- Detects neutral hadrons (mostly K_L,n) produced in photonuclear reactions, EM showers escaping ECal, and MIPs (muons)
- Iron-scintillator sampling calorimeter: 96 layers of 20/25 mm polystyrene / Fe
- Extruded 5x2 cm^2 scintillator bars with inserted wavelength-shifting fibers, read out with Silicon Photomultipliers - developed for Mu2e cosmic ray veto

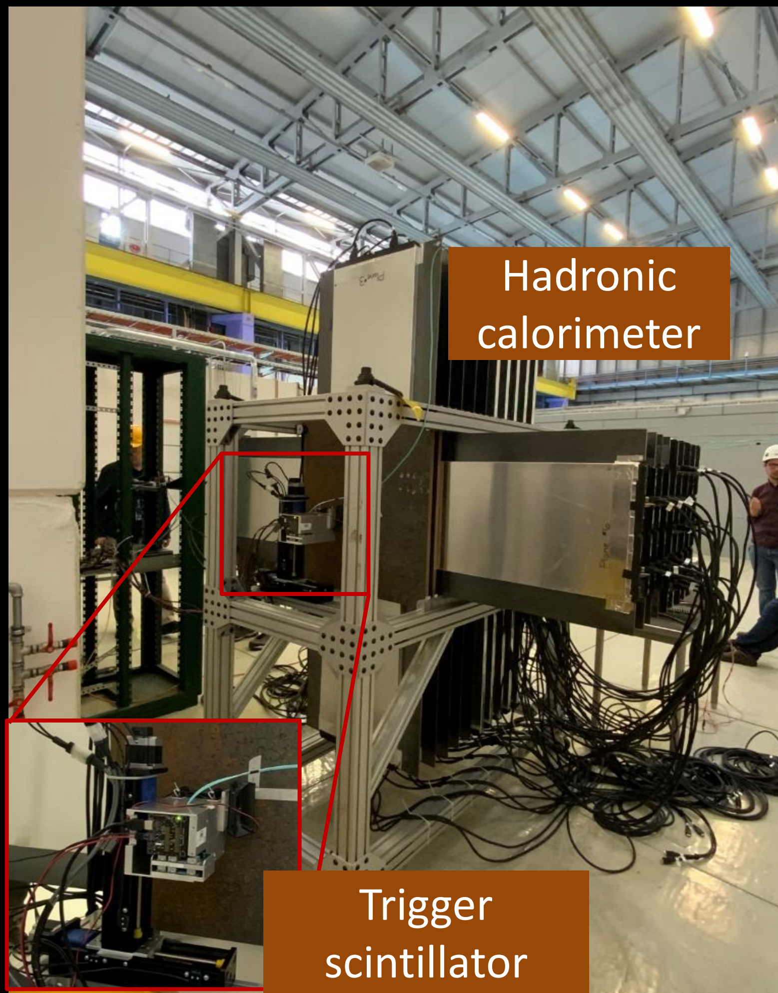




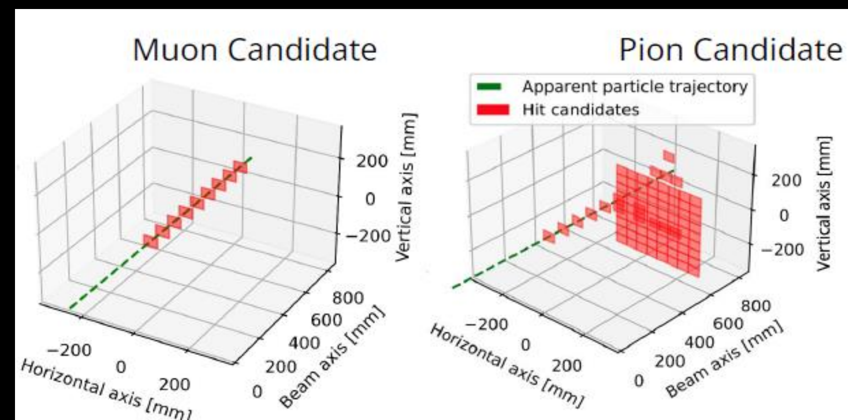


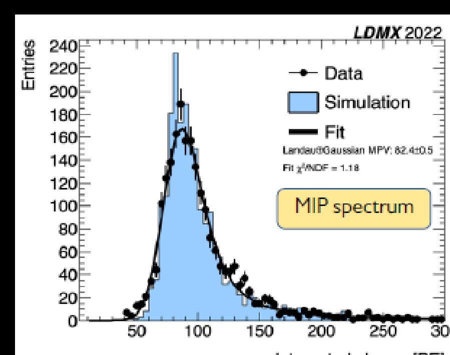
Prototype / test beam at CERN

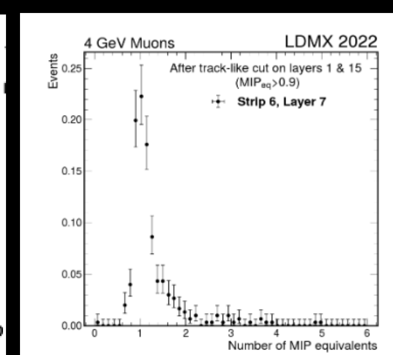
Hadronic calorimeter and trigger scintillator prototypes have been tested at the CERN T9 beam line.



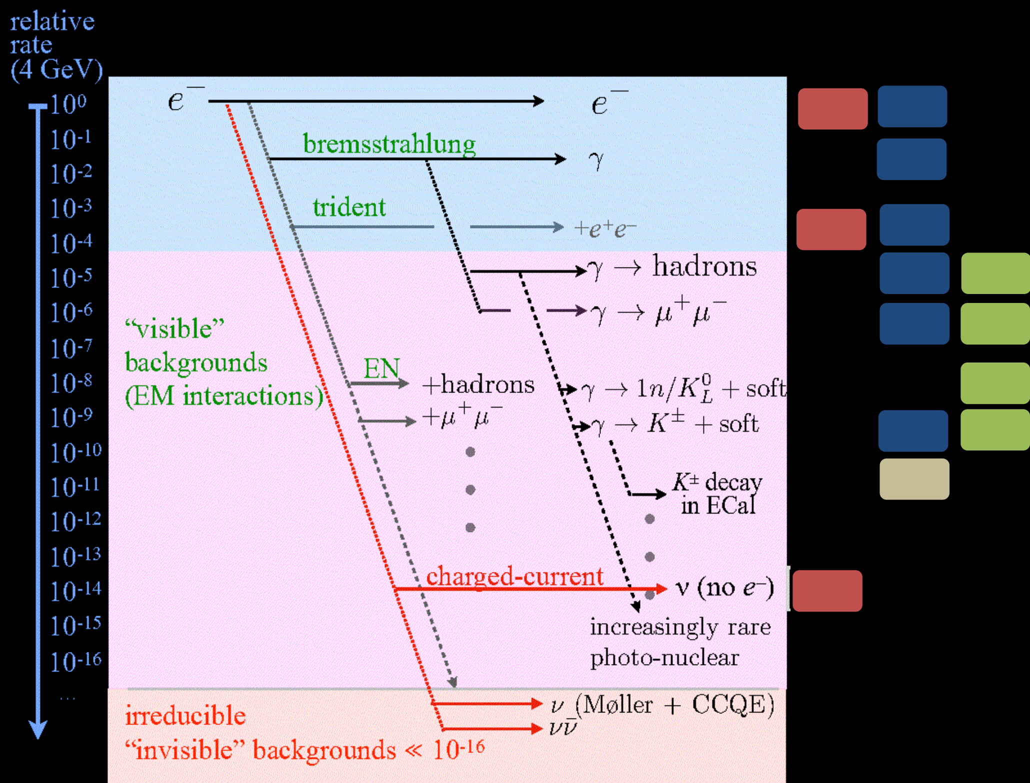
Very successful data taking campaign - on-going data analysis







Background and vetoes - 4 GeV



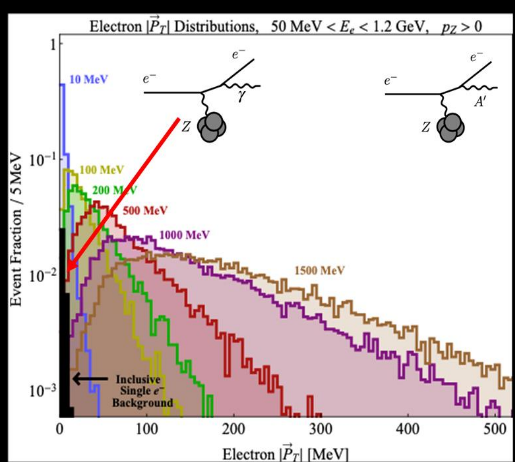
Recoil tracker – exactly one track
Remove electro-nuclear & rare invisible ν processes

ECAL Veto
BDT using shower features leveraging ECal granularity

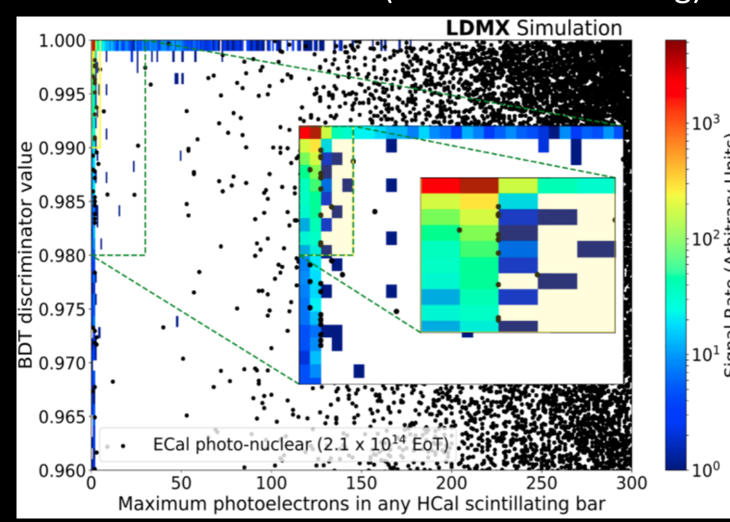
HCAL Veto
Remove event with neutral escaping the ECal

MIP Tracking in ECAL
Veto isolated track around photon direction

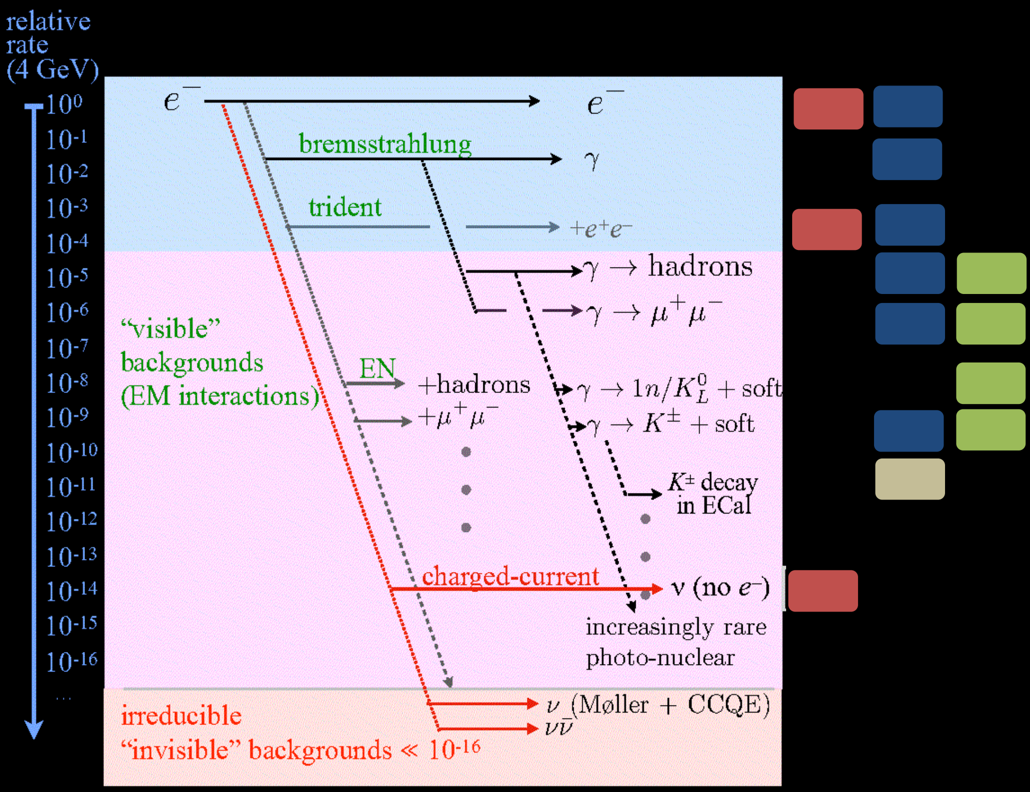
Electron P_T
Unused, additional handle in case of unexpected bkg



Ecal and HCal veto (before MIP tracking)



Background and vetoes - 4 GeV



Recoil tracker – exactly one track
Remove electro-nuclear & rare invisible ν processes

ECAL Veto
BDT using shower features leveraging ECal granularity

HCAL Veto
Remove event with neutral escaping the ECal

MIP Tracking in ECAL
Veto isolated track around photon direction

Electron P_T
Unused, additional handle in case of unexpected bkg

Extensive simulation studies show that the search remains **background free** up to 4x10^{14} EOT

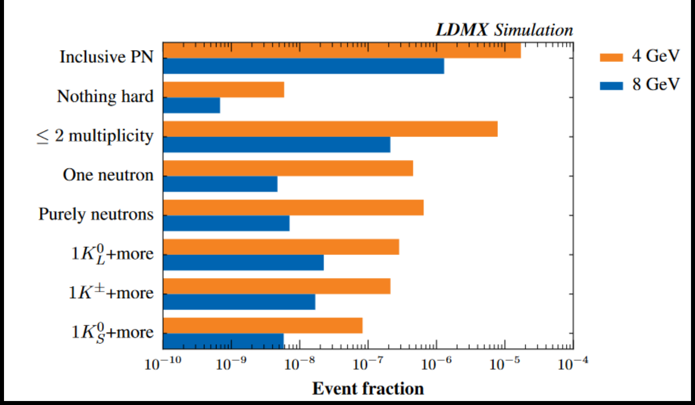
	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.7×10^{11}	6.3×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.6×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ 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

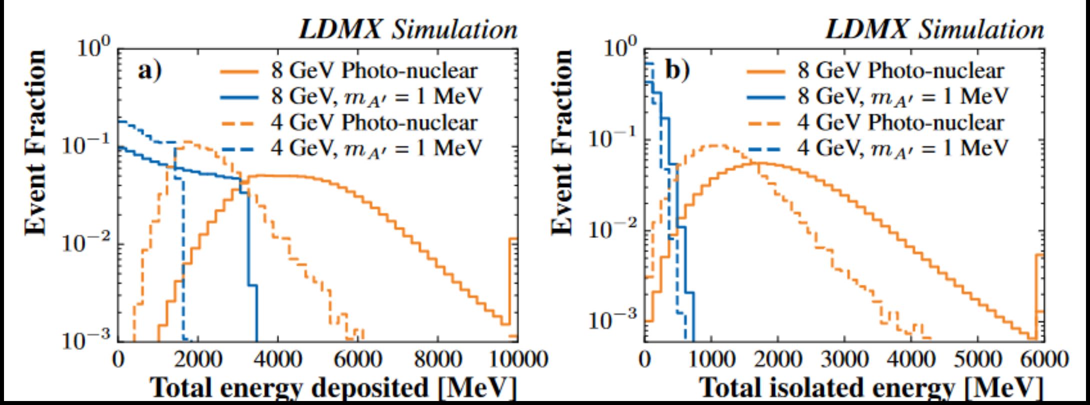
JHEP04(2020)003 and 2203.08192

Background and vetoes - 8 GeV

The majority of the data will be taken at 8 GeV, which offers several advantages

Higher multiplicity in photo-nuclear events





arxiv:2308.15173

Higher signal cross-section

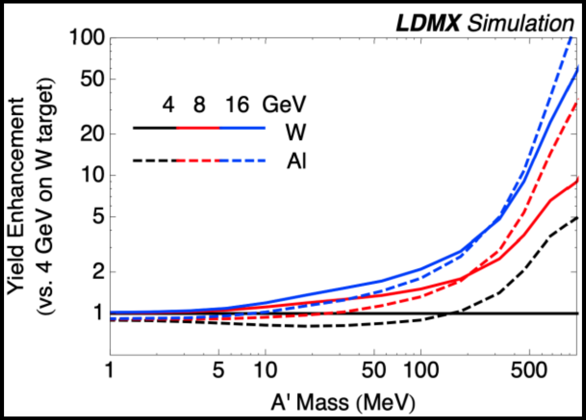
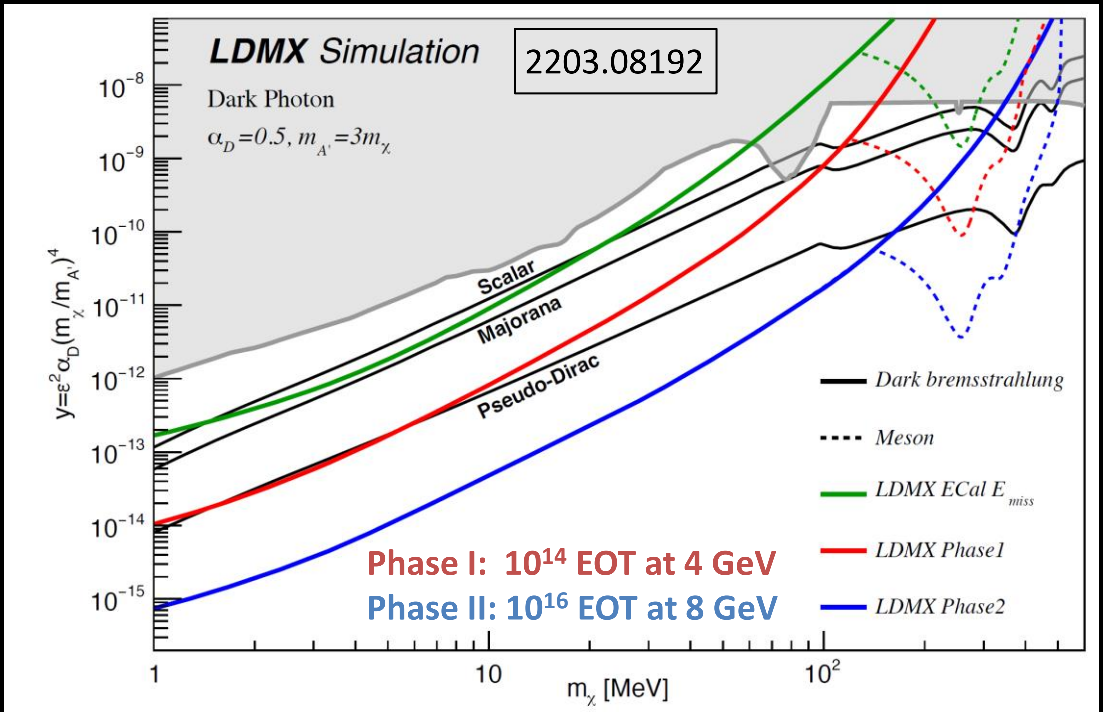
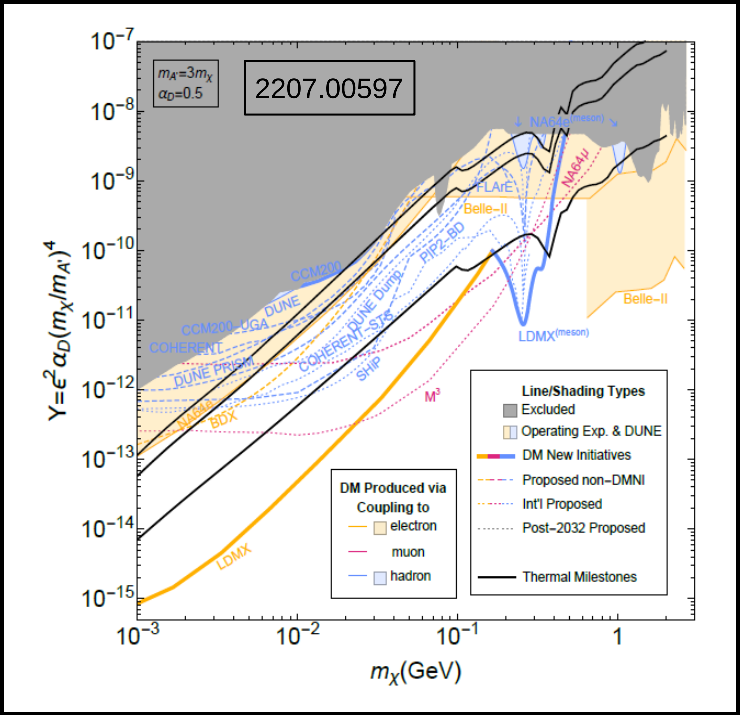


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p <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

So far so good, on-going studies with more statistics

LDMX sensitivity



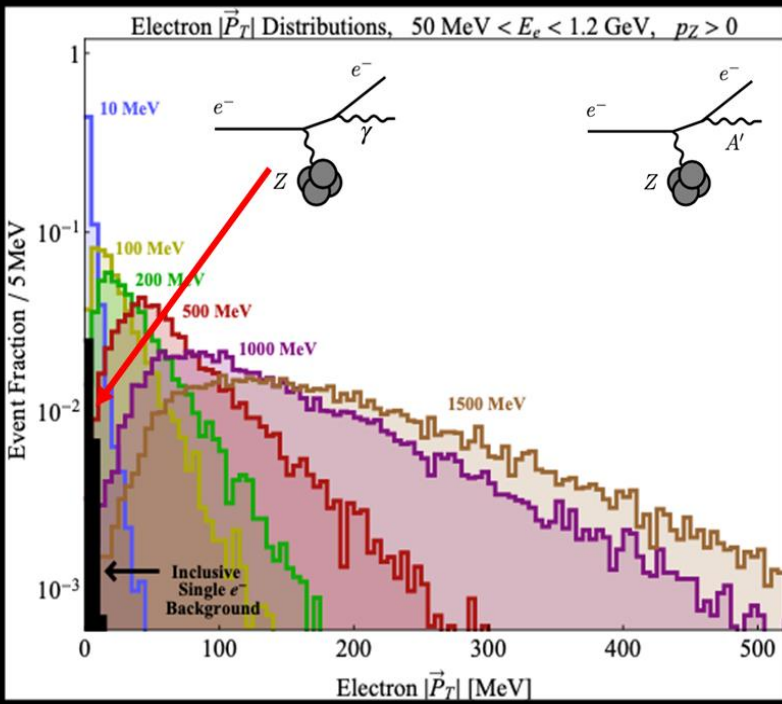


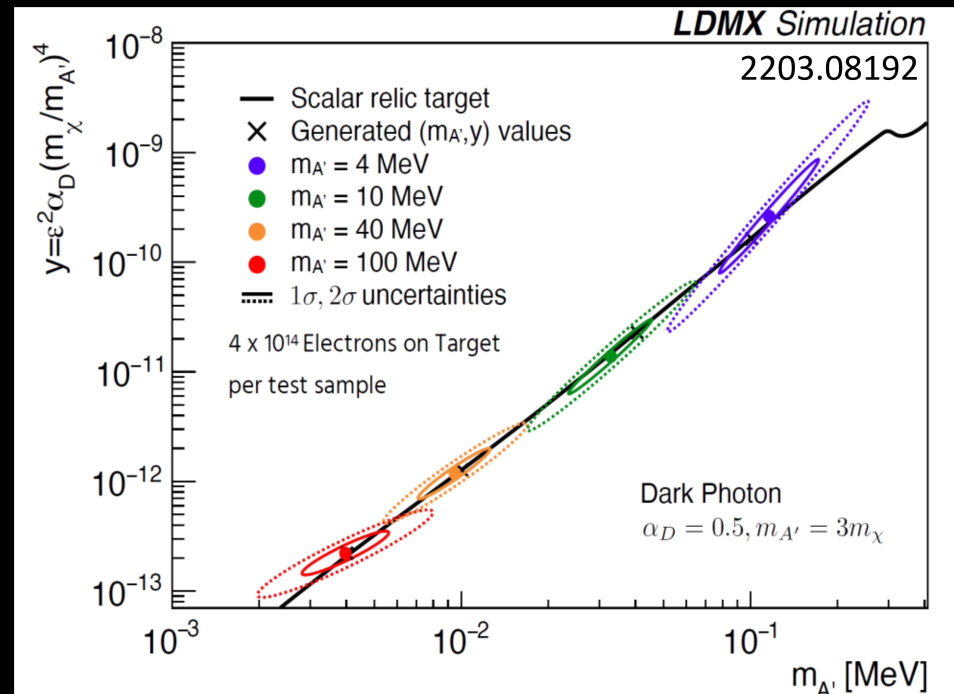
LDMX can probe all thermal targets up to a few hundreds of MeV

Unparalleled sensitivity in the low mass region - missing energy approach becomes limited by rare ν background

LDMX sensitivity

Estimate DM mass from electron p_T spectrum





LDMX can provide information about the DM mass and coupling in case of an observation – unique capability of missing momentum approach

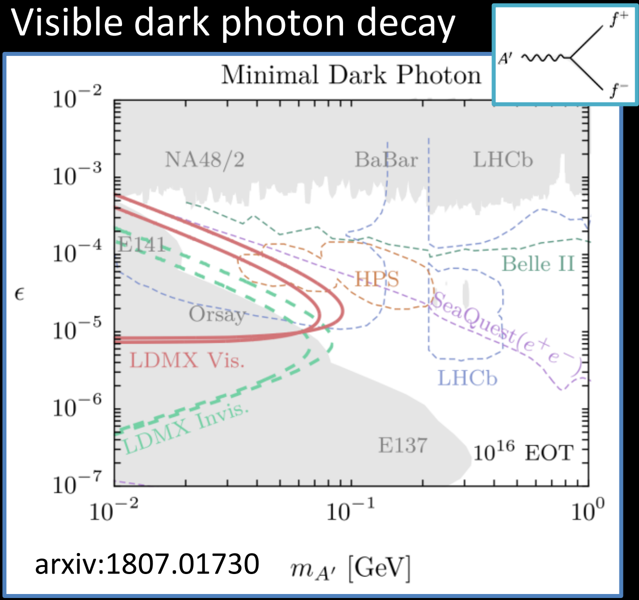
More generally

LDMX would also be sensitive to many other BSM physics scenarios, such as:

- New force carriers coupling to electrons, decaying visibly or invisibly
- Quasi-thermal DM, such as asymmetric DM and ELDER DM
- New long-lived resonances produced in the dark sector (SIMP)
- Freeze-in models with heavy mediators
- Axion-like particles
- Milli-charged dark sector particles

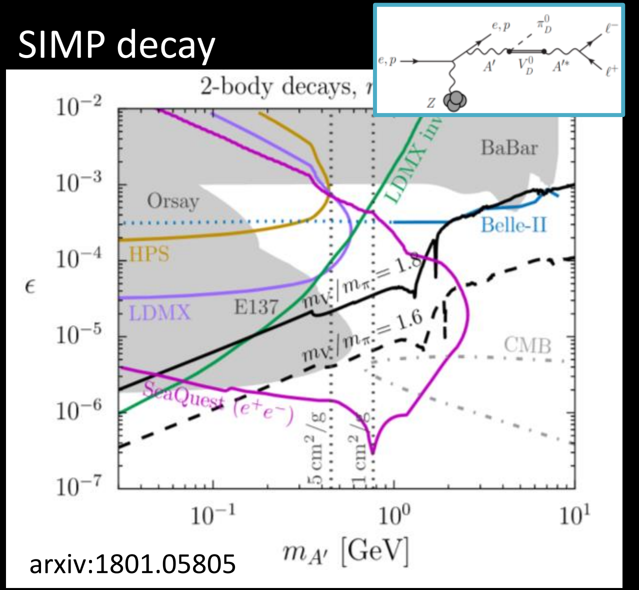
LDMX could explore a vast array of sub-GeV physics with unique sensitivity

Visible dark photon decay



arxiv:1807.01730

SIMP decay



arxiv:1801.05805

Electro-nuclear interactions and neutrino physics

Electro-nuclear measurements (eN) can be related to neutrino-nuclear interactions (νN) and constrain nuclear models

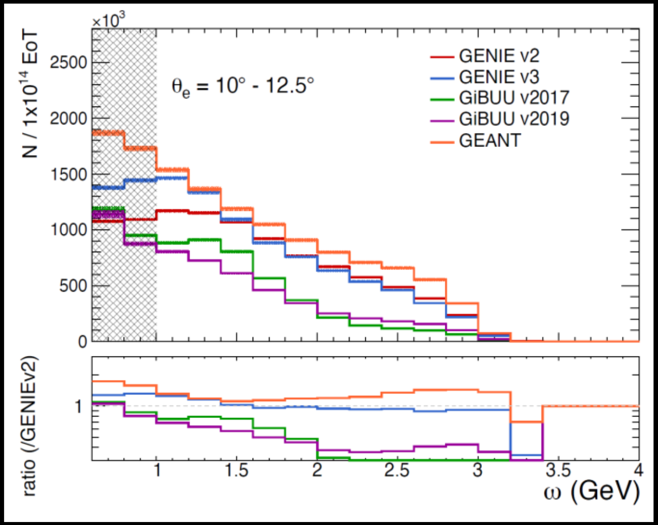
Current generators predictions for neutrino interactions disagree widely over phase space covered by LDMX.

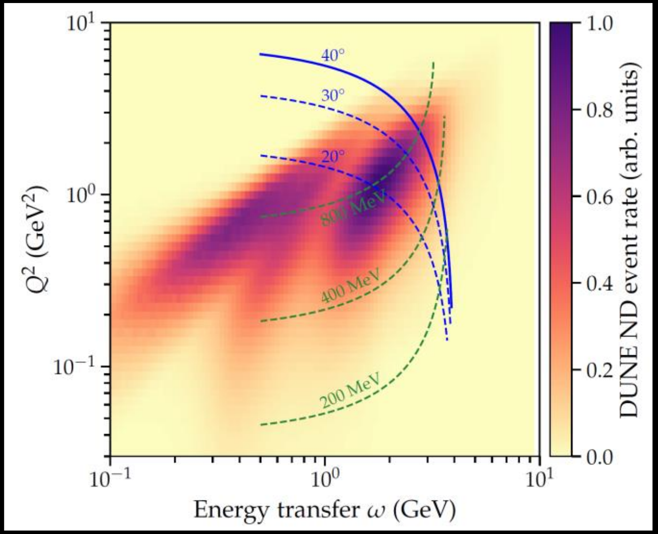
LDMX measurements would constrain lepton-nucleon interaction models in the same phase space

- Full forward acceptance, nearly hermetic
- Fully reconstructed initial and final state
- Excellent neutron detection efficiency

LDMX could also provide useful information for neutrino experiments

Event distribution as a function of electron energy transfer





PhysRevD.101.053004

Conclusion

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 world-leading sensitivity to sub-GeV DM and can test many predictive light DM scenarios

LDMX has also impressive sensitivity to:

- Visible signatures of mediators and dark sector particles
- Broad range of new physics models with missing momentum signatures
- Important electron scattering measurements to constrain neutrino cross-section uncertainties for DUNE

The experiment is ready to move forward with the construction phase

- Dark Matter New Initiatives R&D funding has been very productive
- LESA Beamline construction is underway at SLAC
- A test-beam run at CERN has validated key detector developments

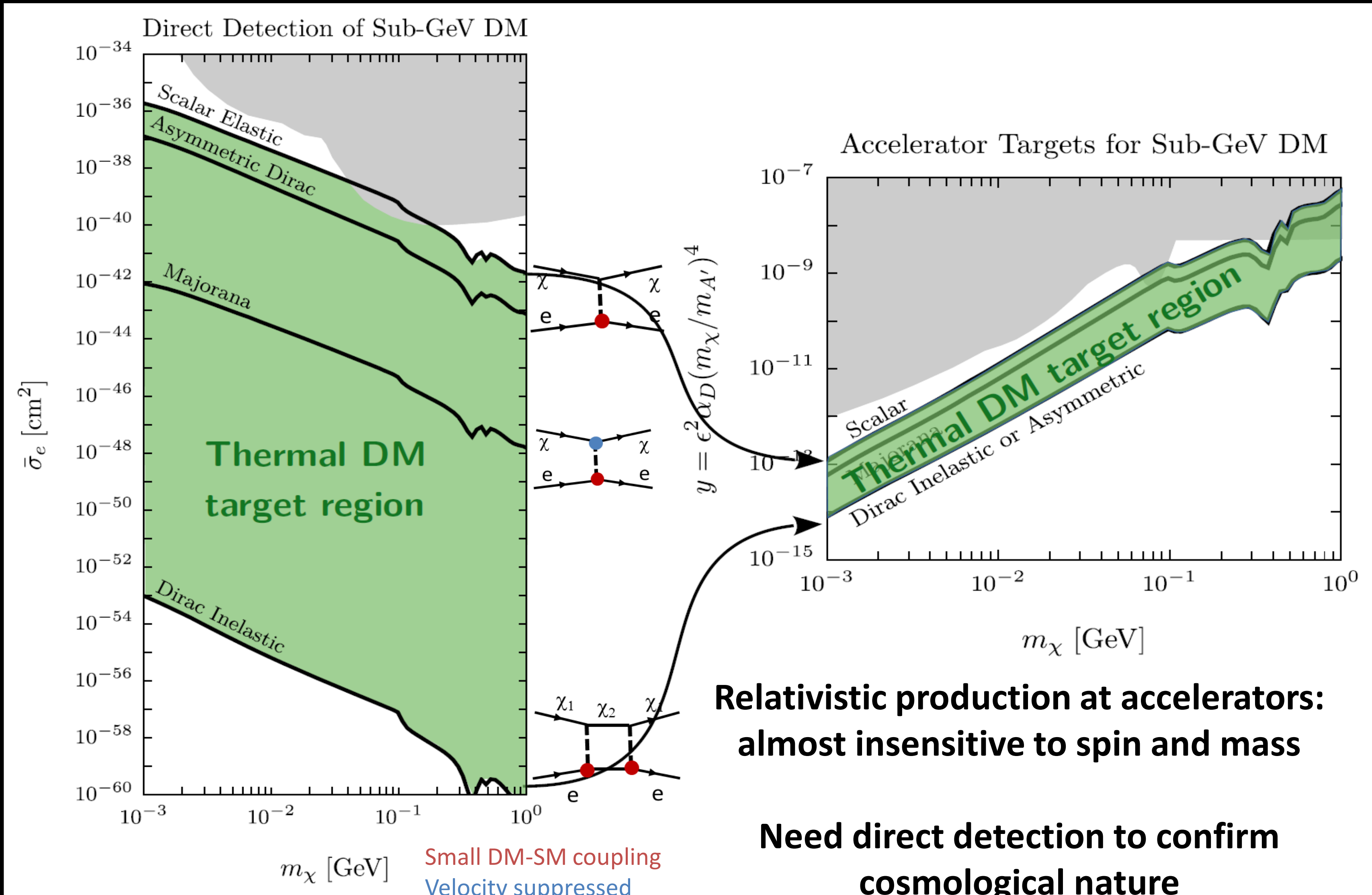
LDMX could be taking data in 2-3 years after establishing the funding profile, and potentially make a groundbreaking discovery shortly thereafter

Thank you for your attention

@ C. Group and son

Extra Material

Why accelerators?



Relativistic production at accelerators: almost insensitive to spin and mass

Need direct detection to confirm cosmological nature

Signal kinematics

The recoil electron kinematics is very different between the signal and background processes.

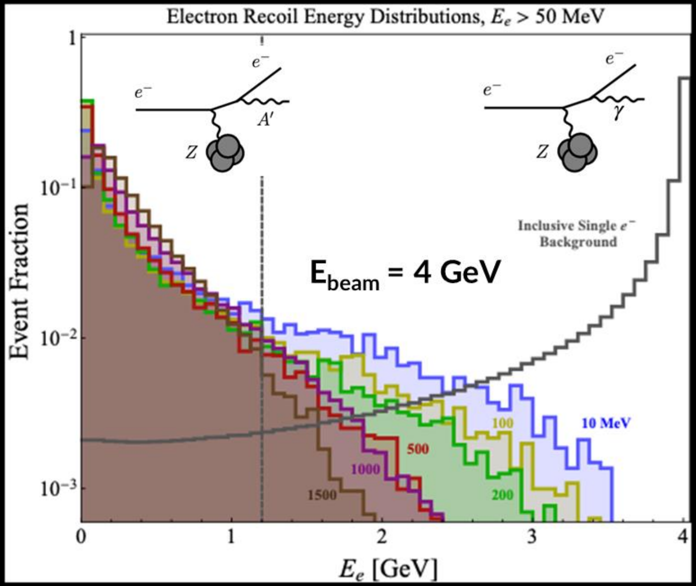
The A' is emitted at low angle and carries most of the energy:

- large missing energy, soft recoil electron
- large missing p_T, large angle recoil electron

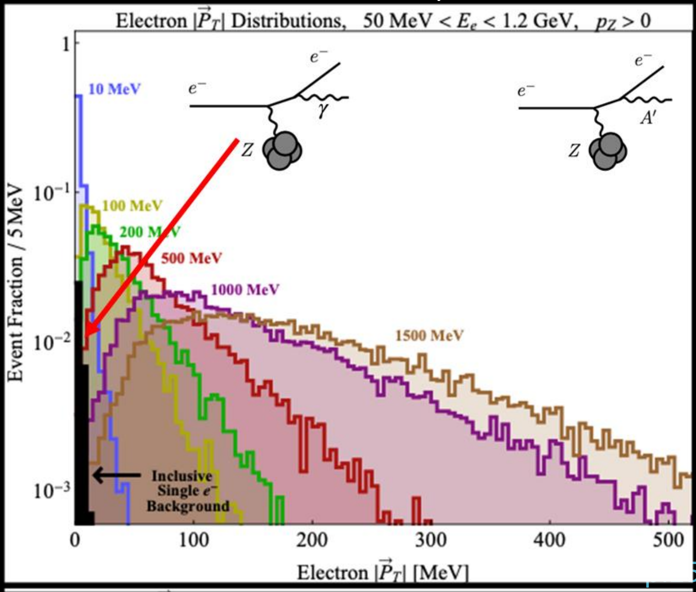
The electron recoil momentum offers additional handle to reject backgrounds or to measure the signal properties

- Clear advantage over missing energy measurement

Recoil energy

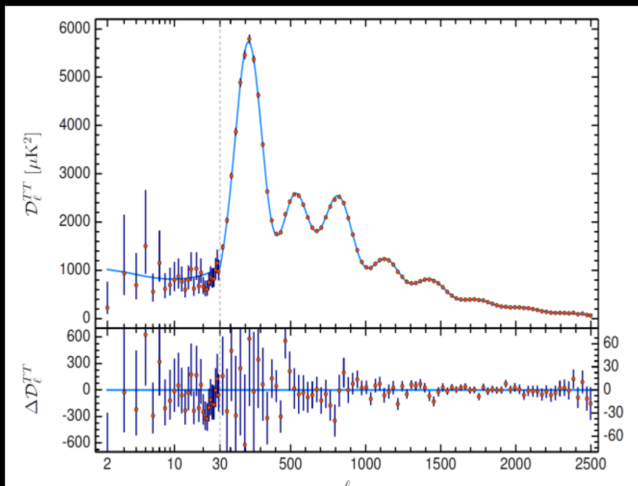


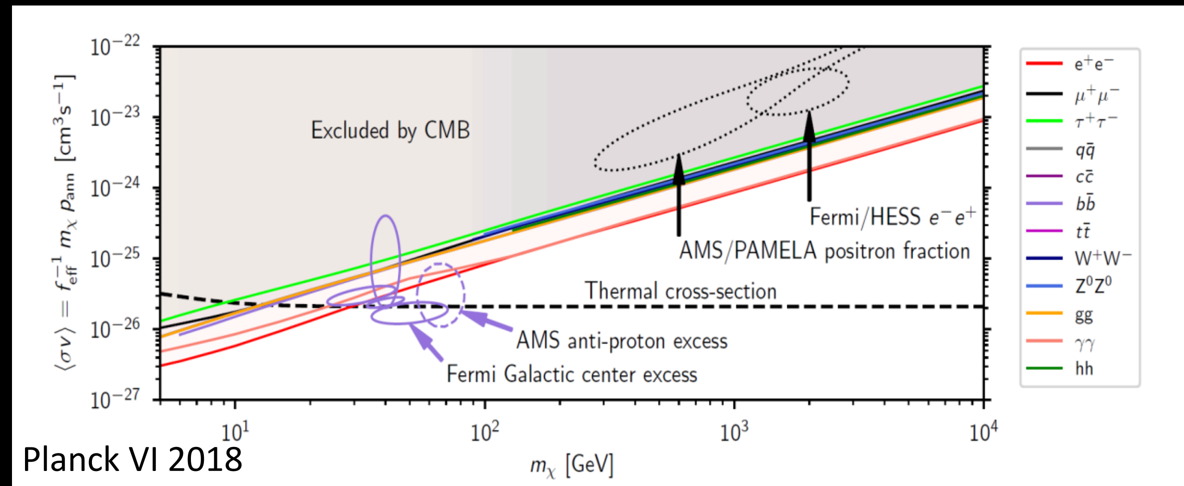
Recoil p_T



Cosmological constraints

Primordial DM annihilation injects energy in the CMB → distorts spectrum





Planck VI 2018

Rules out DM masses below ~10 GeV but probe temperatures << freeze-out temperature

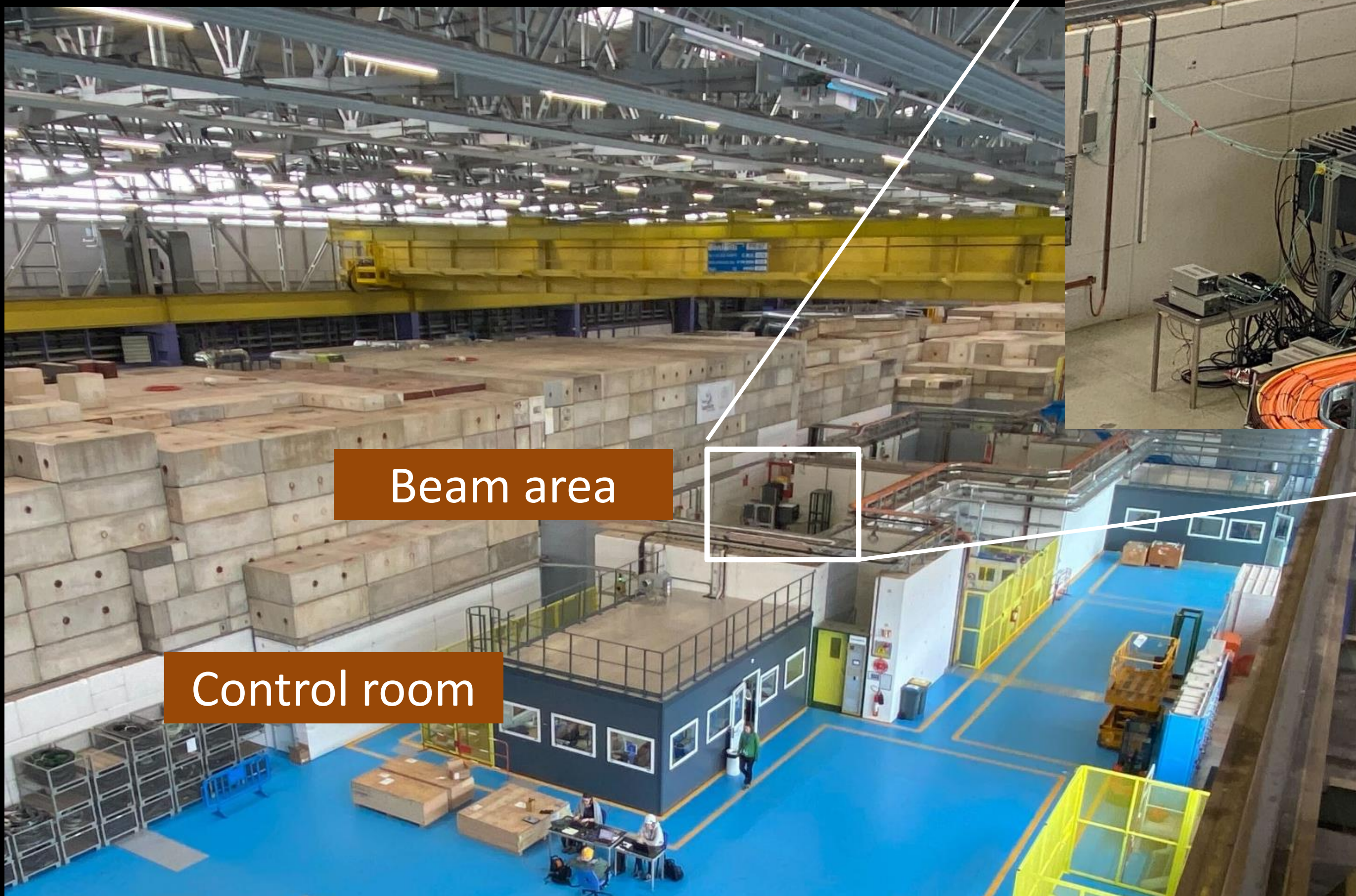
Allow models where annihilation rates decrease at low temperatures:

- p-wave annihilation – velocity suppressed (scalar and Majorana fermion DM)
- Inelastic co-annihilation – two states split by Δ mass, shuts off before CMB since heavy state has decayed (inelastic scalar or pseudo-Dirac fermion DM)

Exclude s-wave annihilation – no velocity suppression (Dirac fermion DM)

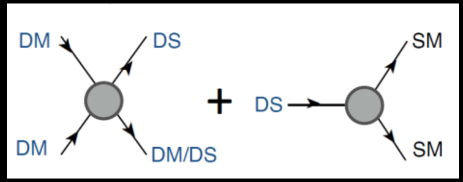
Prototype and test beam at CERN

Hadronic calorimeter and trigger scintillator prototypes have been tested at the CERN T9 beam line



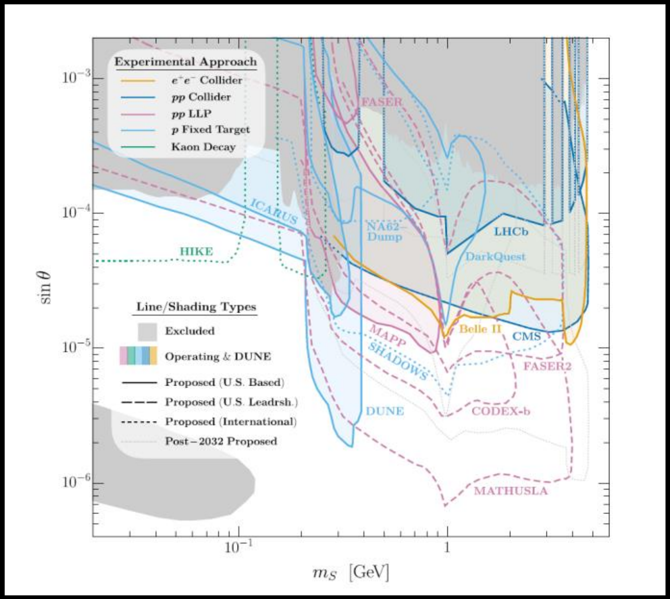
Secluded dark matter

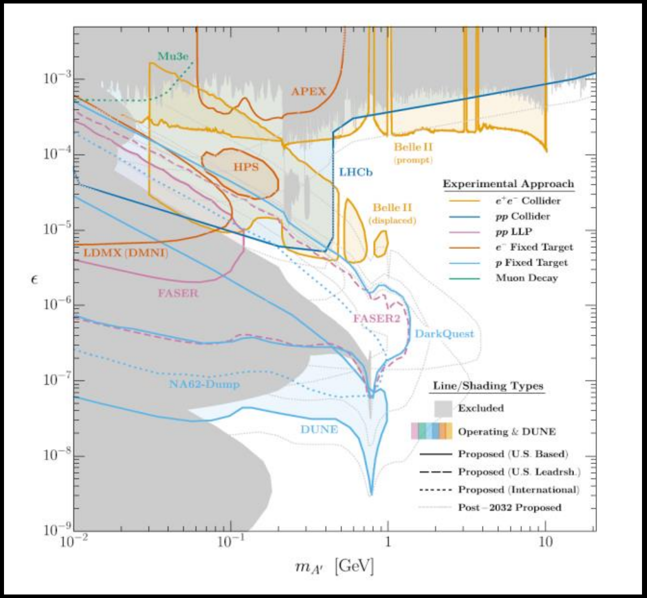
Dark matter annihilates into pair of mediators when $m_{DM} > m_{MED}$, followed by mediator decay to SM particles.



Annihilation cross-section depends only on dark sector physics, but thermal equilibrium requires a minimal DM-SM coupling

$\rightarrow$ broad region of parameter space compatible with light DM hypothesis





B. Batell et al., 2207.06905

Freeze-in DM

DM abundance initially vanishes and slowly builds up over time via feeble DM-SM coupling

- DM produced in thermal era but never in thermal equilibrium

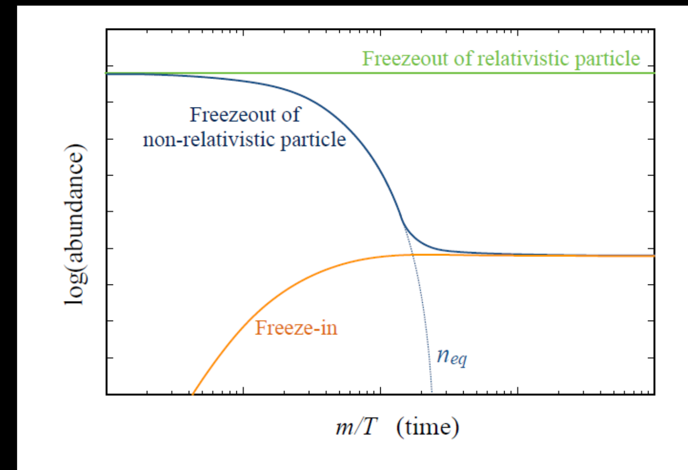
Dark sector realization requires extremely small couplings

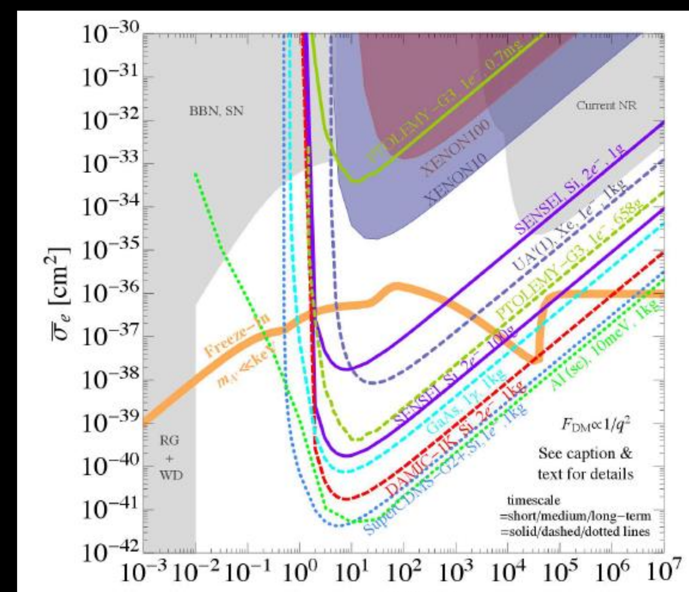
- typically at a level unobservable for any experiment

But for $m_{DM} < 1$ MeV, freeze-in also require mediator mass < 10^{-10} eV

- Small mediator mass and low momentum transfer boosts the electron-DM scattering cross-section $\rightarrow$ potentially detectable process

T. Lin 1904.07915



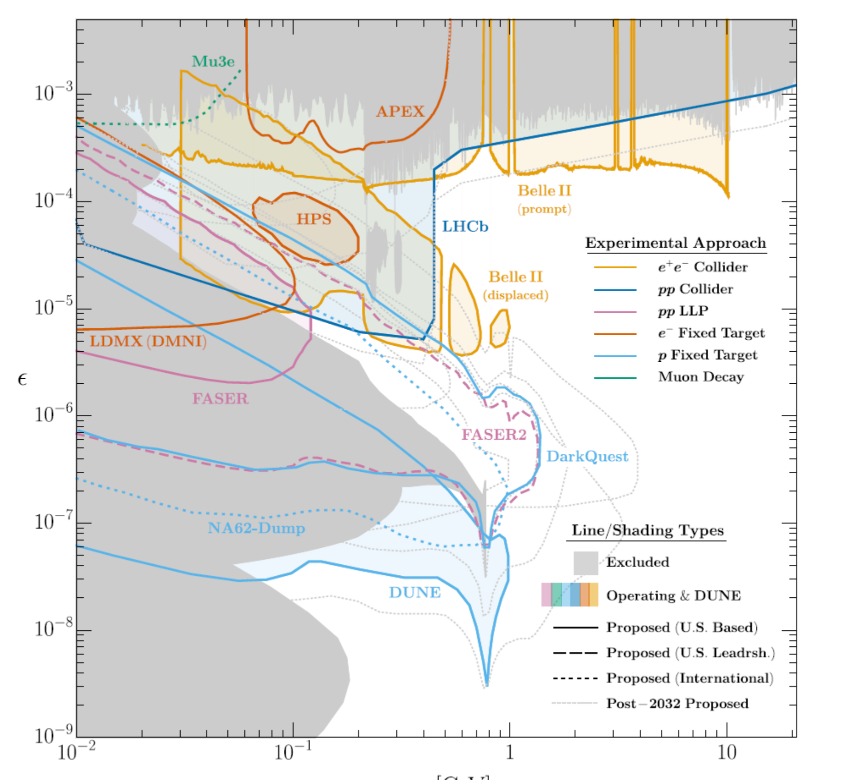


1707.04591

Visible dark photon decays

Non-minimal models motivate generic search for visible mediator decays

Constraints on kinetic mixing



2207.06905

Collider typically probe parameter space "from the top" – larger coupling and wide range of masses

Beam dump / fixed target probe longer lifetimes → lower masses and couplings

Region below ~1 GeV will be significantly constrained by upcoming experiments (both colliders and beam dump / fixed target)