The Light Dark Matter eXperiment

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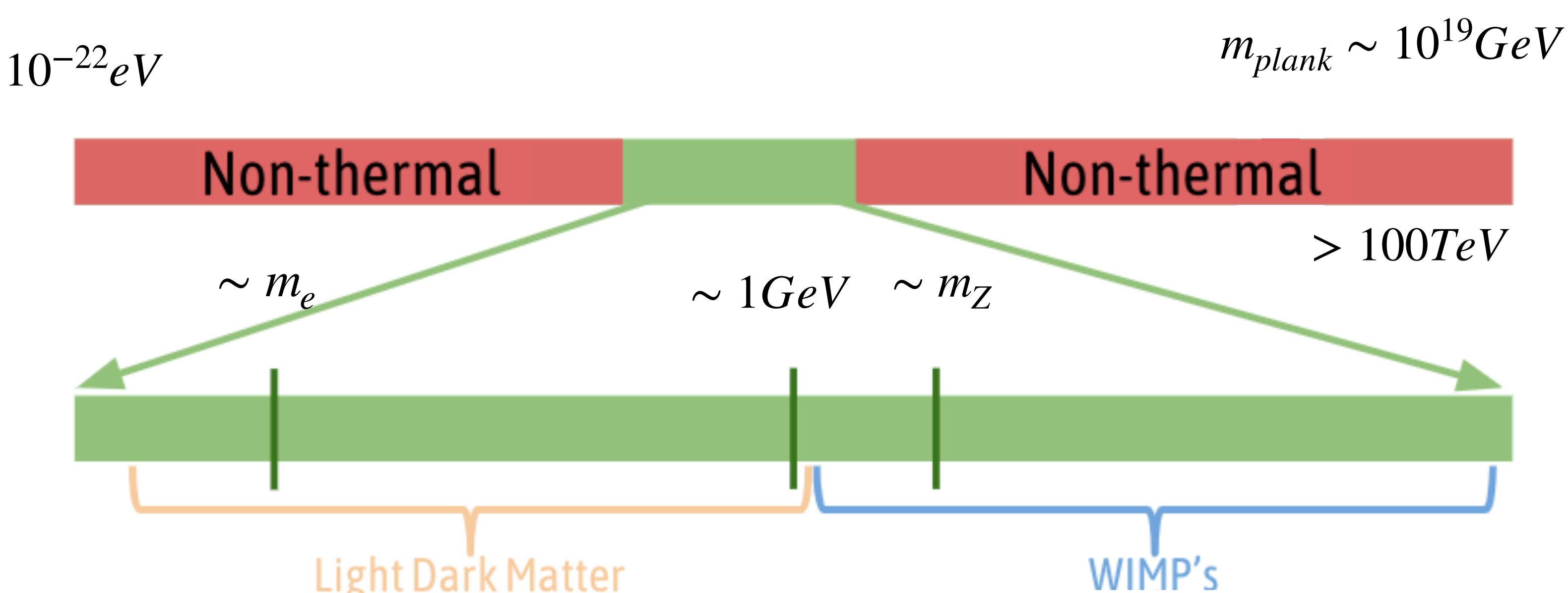
Thermal Dark Matter

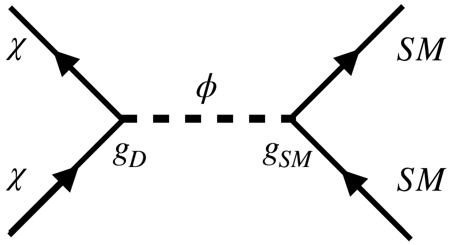
- Thermal Dark Matter (DM) originating as a relic of the hot early Universe is one of the most compelling paradigms.
- **Generic:** only non-gravitational interaction between DM and Standard Model (SM)
- **Predictive:** minimum annihilation rate $< \sigma v > \approx 10^{-26} cm^3 s^{-1}$



Thermal Contact implies a new mediator: Hidden sector light DM well-motivated model	Thermal freeze-out for weak scale masses. Major drive for DM search in the past years

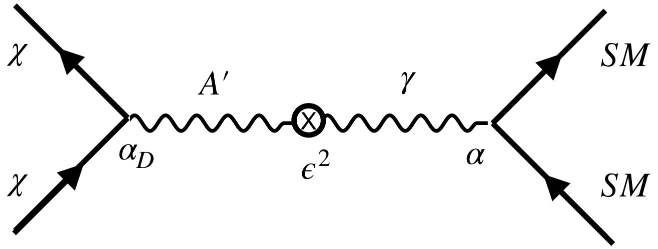
Light Thermal Dark Matter - Hidden sector

- 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 Standard Model (SM)
- Mutual interaction mediated by a massive gauge boson

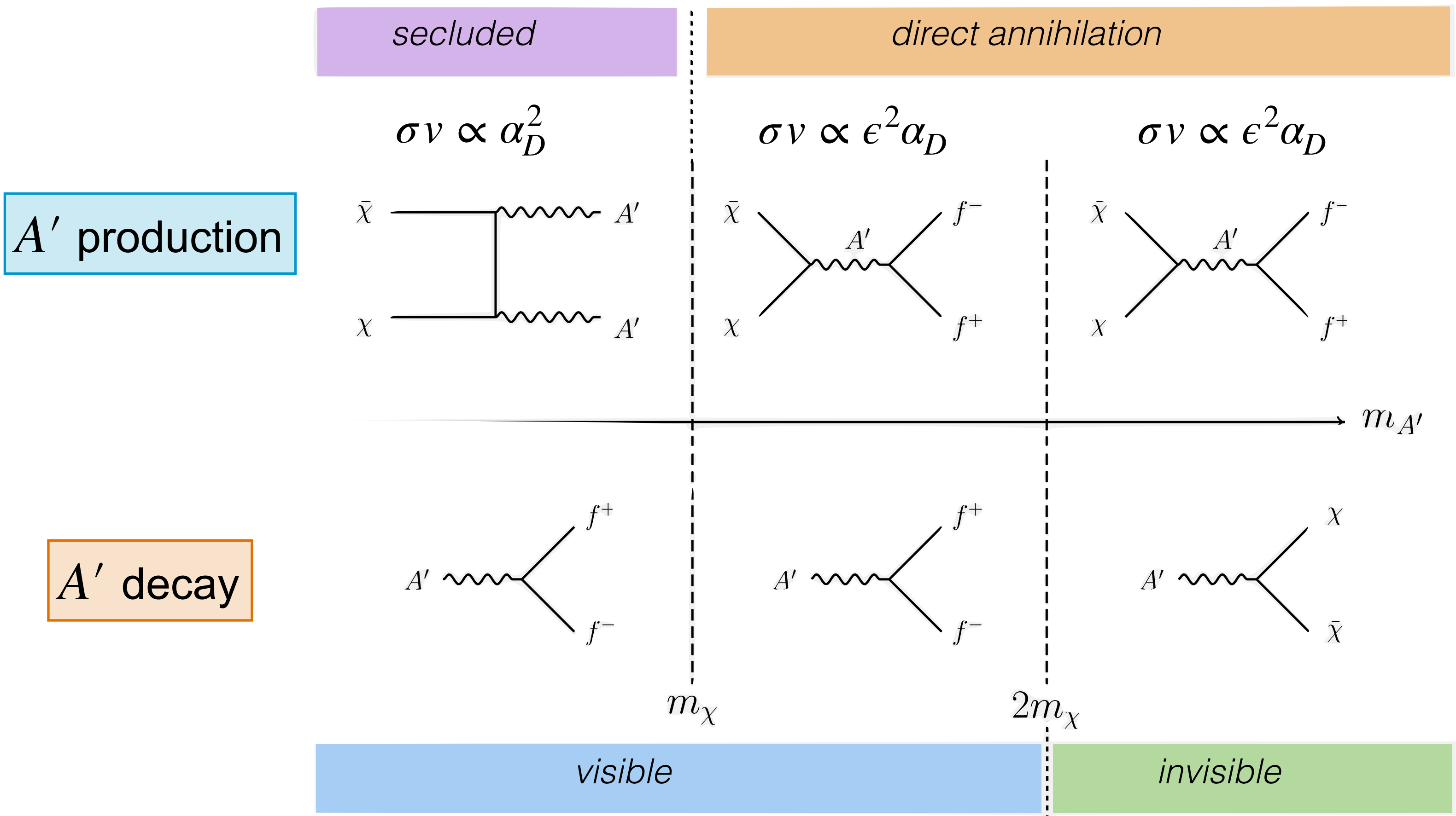


$$< \sigma v > \sim g_D g_{SM} \frac{m_\chi^2}{m_\phi^4}$$

- **Benchmark:** additional spin-one gauge boson ***"dark photon"*** A', neutral under SM, hidden $U(1)_D$ symmetry
- Kinetically mixing with SM $U(1)_\gamma$, (ϵ)



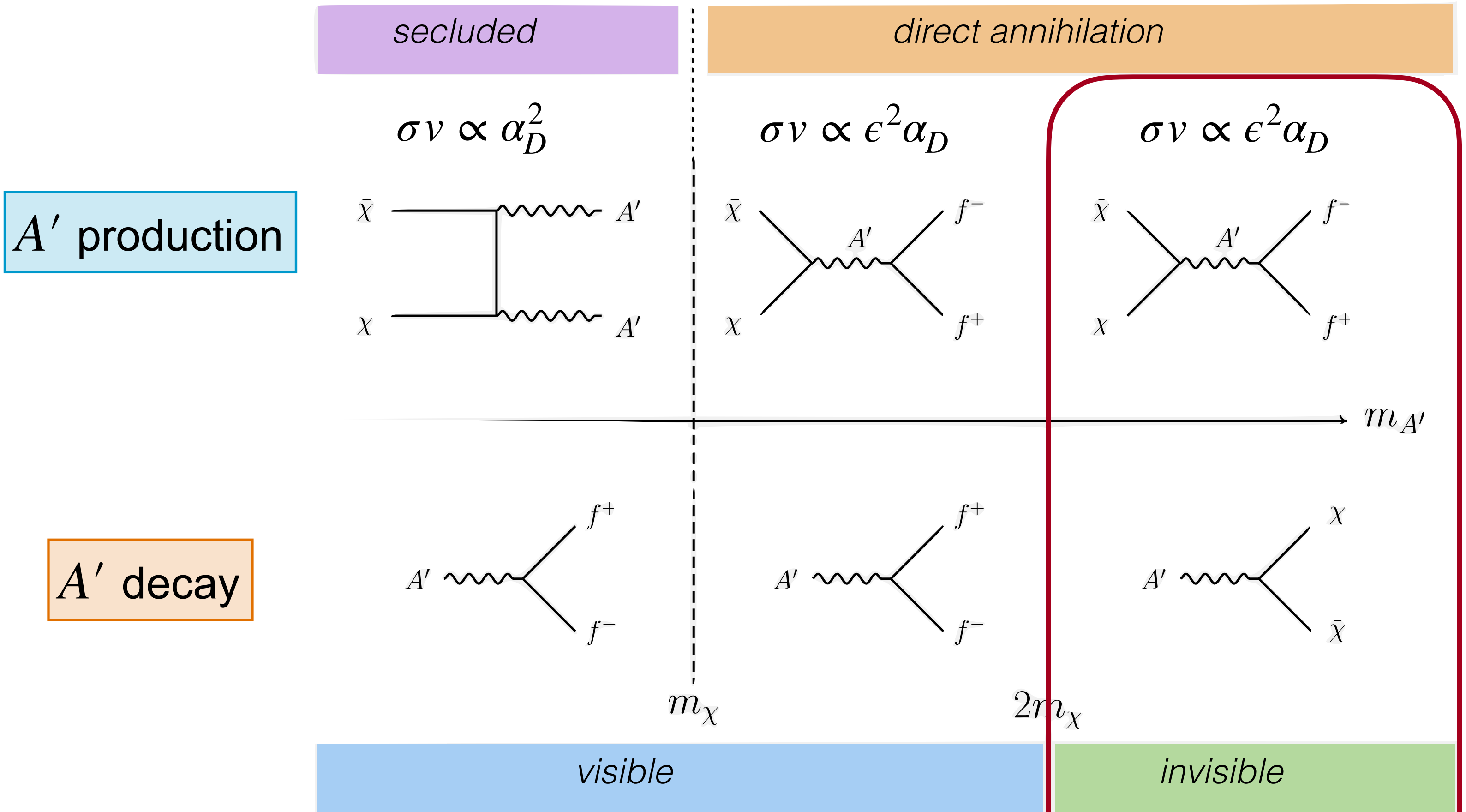
Possible dark photon signatures



Prompt decay (resonance feature)
Long-lived (displaced decay)

Missing …
…mass
…energy
…momentum

Possible dark photon signatures



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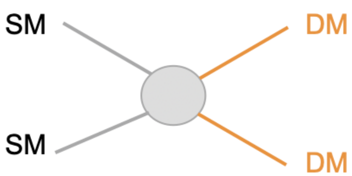
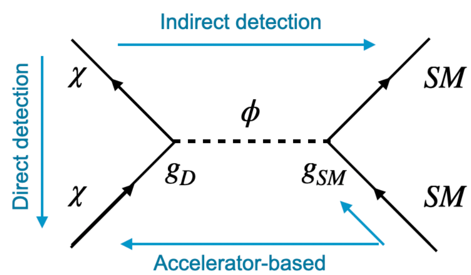
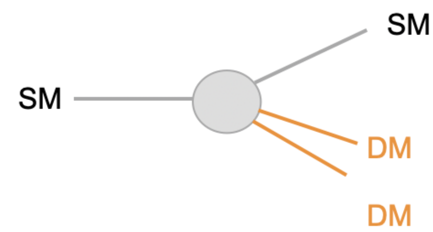
Light Dark Matter at accelerators

Thermal origin of Dark Matter → interaction between LDM and SM → production mechanism in accelerator-based experiments







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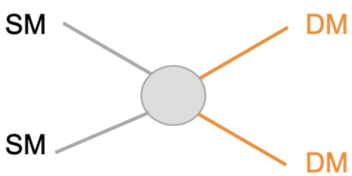
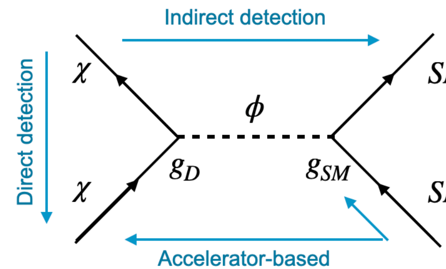
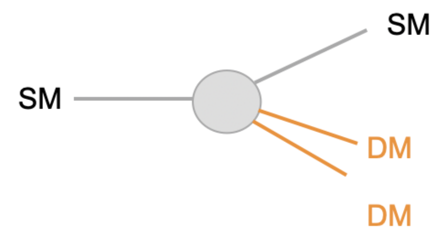
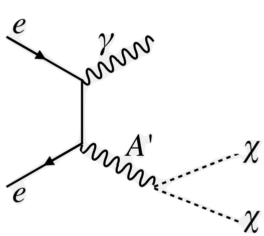
Thermal origin of Dark Matter → interaction between LDM and SM → production mechanism in accelerator-based experiments





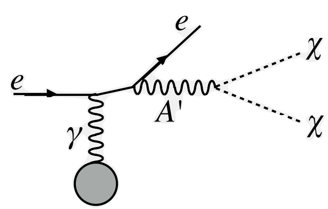


Collider



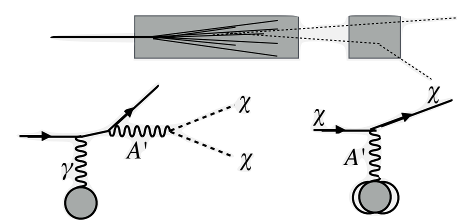
$\sigma_{coll} \propto \dfrac{\epsilon^2}{E^2_{com}}$ $<<$

Fixed target



$\sigma_{FT} \propto \dfrac{Z^2\epsilon^2}{m^2_{A'}}$ $\quad N \propto \epsilon^2$

Beam dump



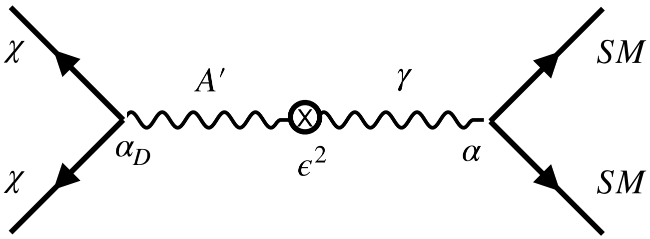
$>>$ $\quad N \propto \epsilon^4$ Direct detection

… and the most sensitive way is to search for this production using a primary e^- beam to produce DM on fixed-target collisions

Hidden Sector LDM with vector portal predictions …

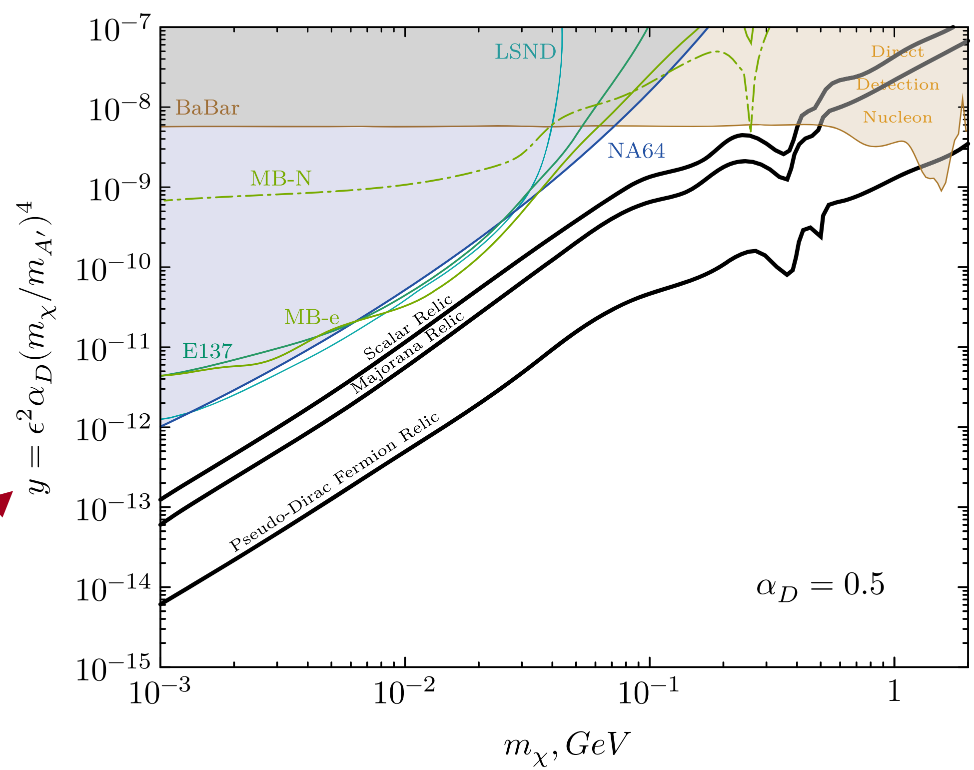
SLAC

PRL.123.121801



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

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



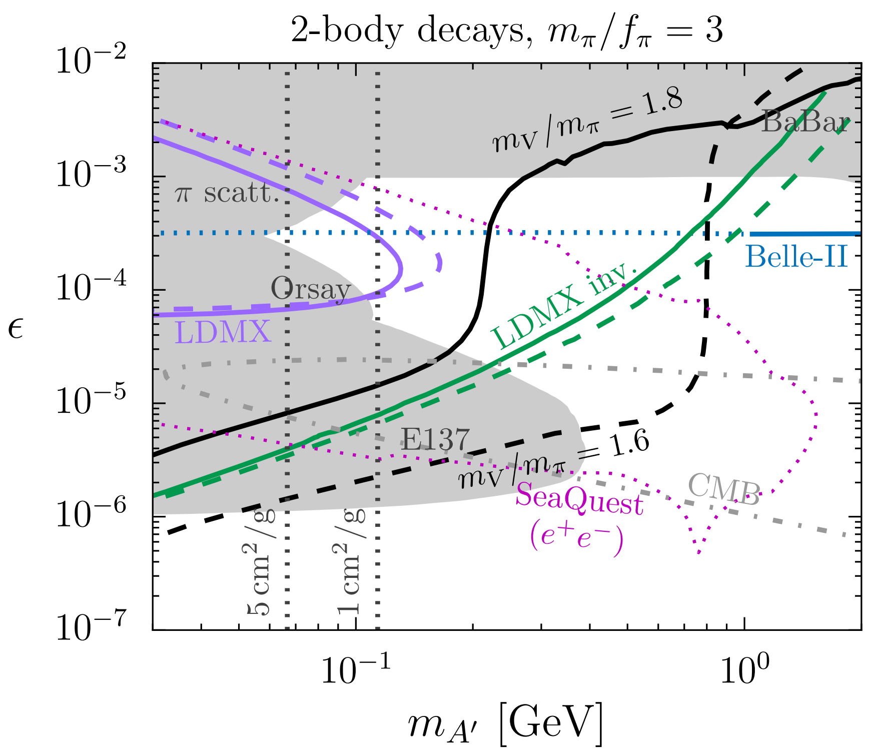
- **Clear predictions** as a function of m_χ and target particle type
- At accelerators: **all thermal targets in reach**

Conservative assumptions
$\alpha_D = 0.5, \; m_{A'} = 3 m_\chi$

… and more generally

- **Missing momentum/energy experiments sensitive to multiple BSM scenarios…**
  - Long-lived dark sector resonances
  - Strongly interacting DM
  - Freeze-in with heavy mediators
  - Millicharged dark sector particles
  - …
- And, in particular LDMX, could provide additional useful information for $e^{-}N$ scattering for future neutrino experiments

In this example:
$A' \to \pi_D \pi_D$ dark-pions



eN LOI Snowmass '21

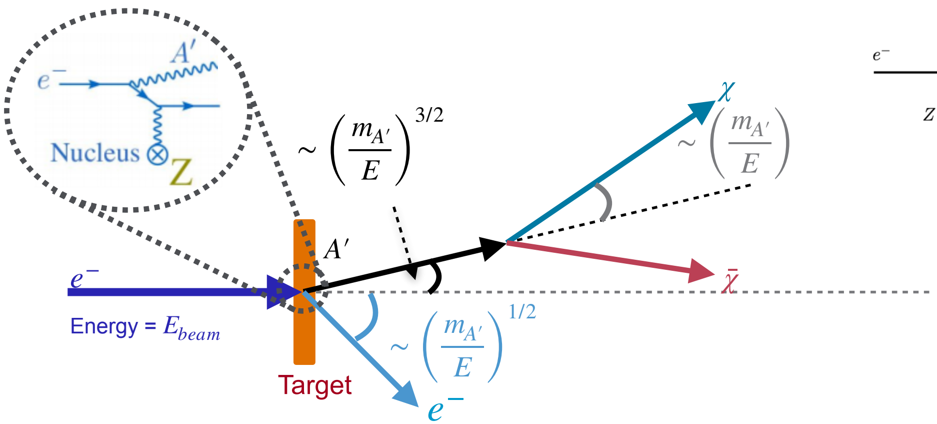
Whitepaper will be released March 15

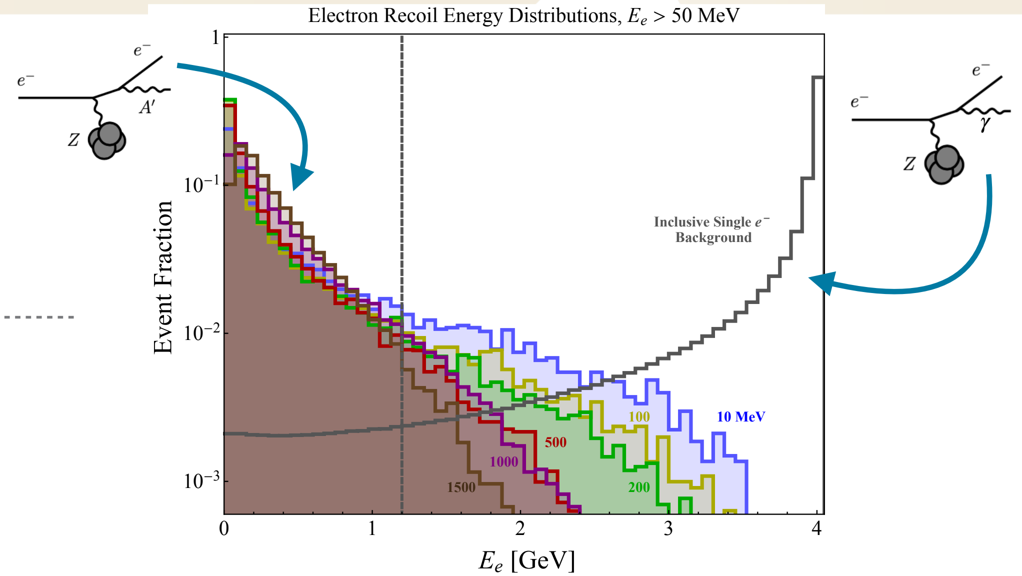
arXiv:1807.01730

arXiv:1801.05805

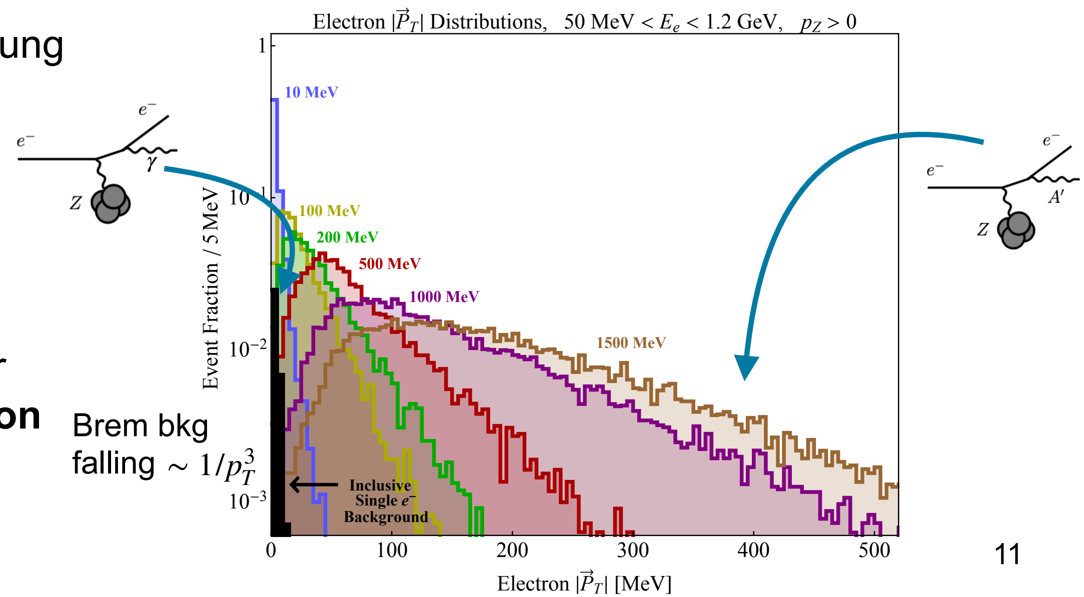
Missing momentum and LDMX

Missing momentum kinematics at a Fixed Target Experiment





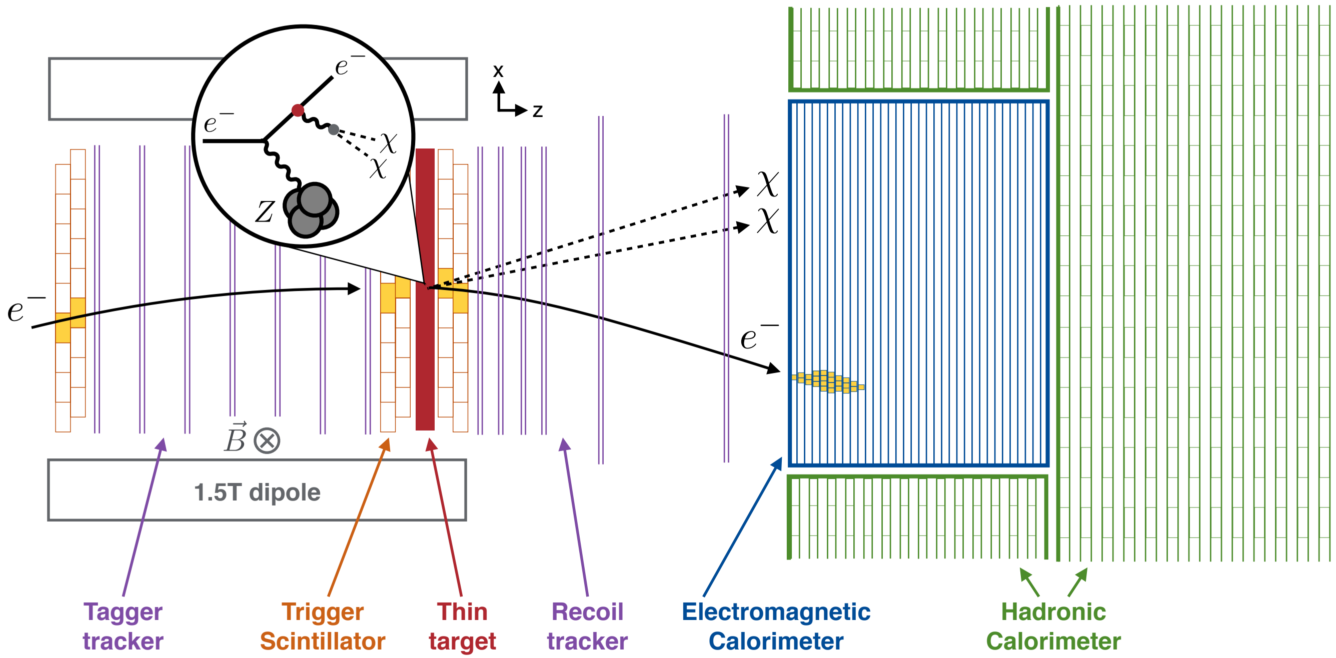
- $A' \to \chi\bar{\chi}$ carry away **most of the beam energy** and **escape undetected**
  - Opposite behavior for the bremsstrahlung emission



- Recoil electron p_T spectrum of signal strongly depends on $m_{A'}$
  - Important for **signal identification** or extra handle for **background rejection**

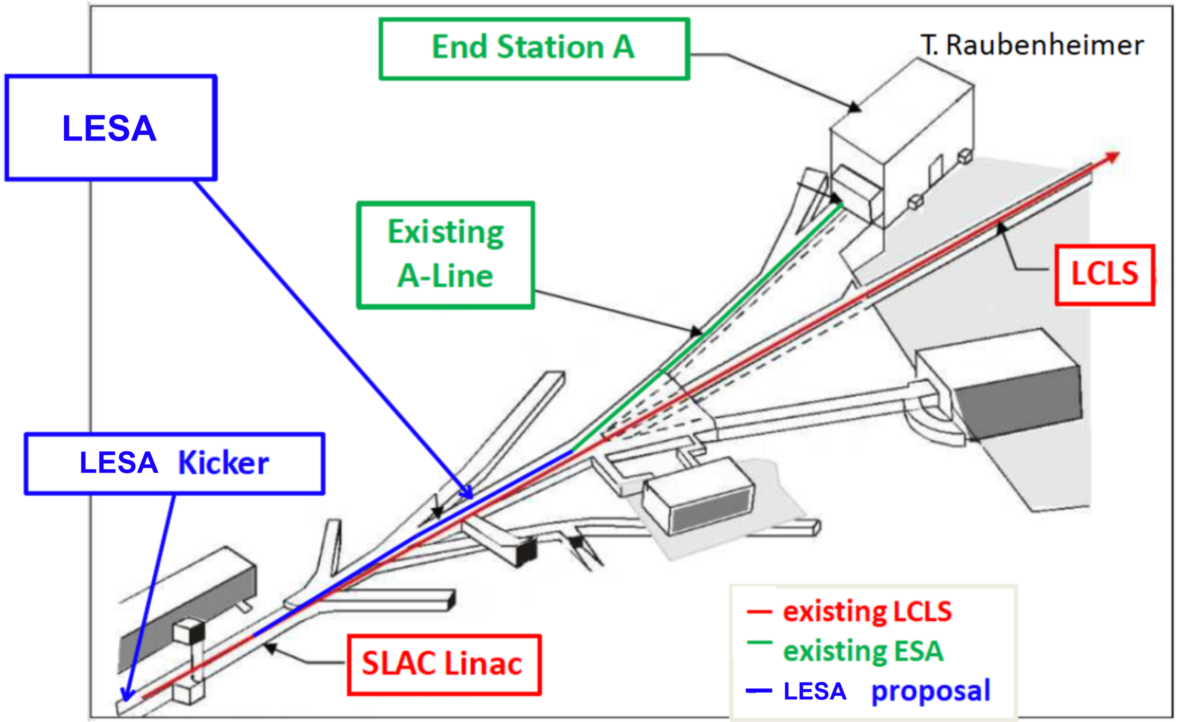
LDMX Experimental approach

- **Signal signature:**
  - **Recoiling electron** with energy much lower than beam and small but measurable transverse momentum
  - **Absence of any other activity** in the final state



- **Two main ingredients:**
  - Beam allowing for individual reconstruction of incident electrons
  - Detector technology with high radiation tolerance and high data rate

LDMX at SLAC: LCLS II Transfer Line

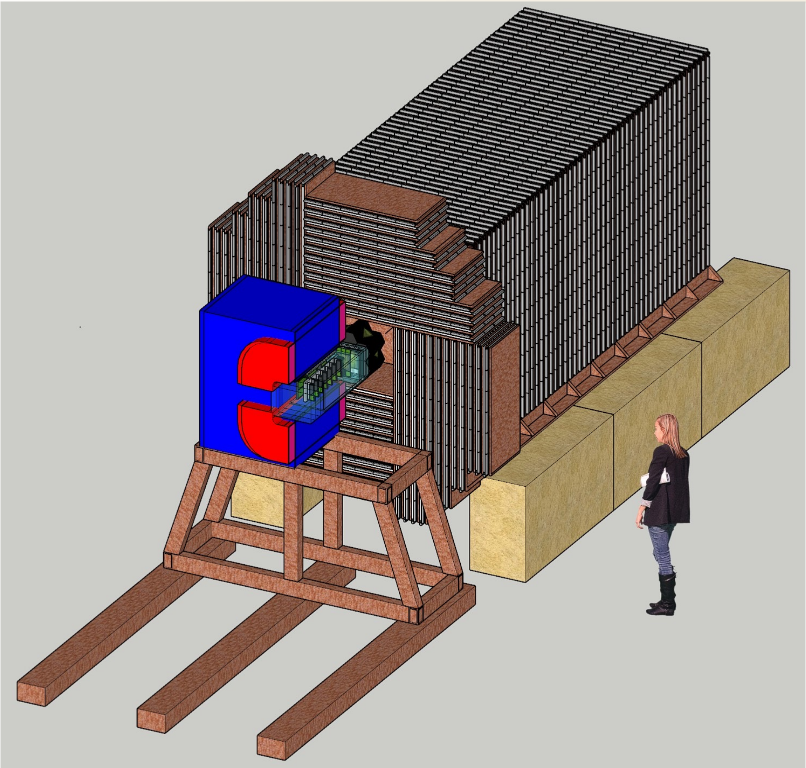


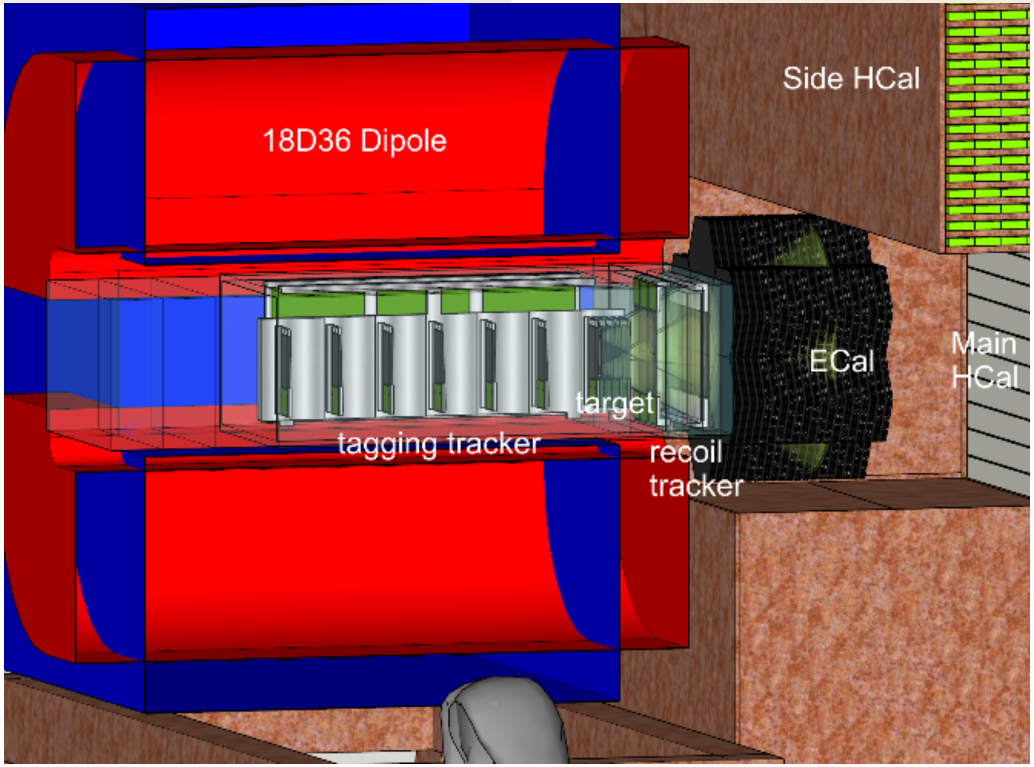
- **LCLS-2 beam at SLAC:**
  - e^- beam for photon science
  - Beam extraction using Linac to End Station A (LESA)
- **4 GeV beam energy**
  - phase-II upgrade at 8 GeV
- **Low-current**
  - Measure each incoming and outgoing electron
- **Fast repetition rate**
  - Expect 37.2 MHz bucket frequency
  - $\sim 10^{14} e^-$ electrons on target in 1-2 years

LDMX Baseline Schedule

2020	2023	2025	2027
Detector R&D	Construction	Phase I data taking	Phase II construction & operation

LDMX Detector Concept

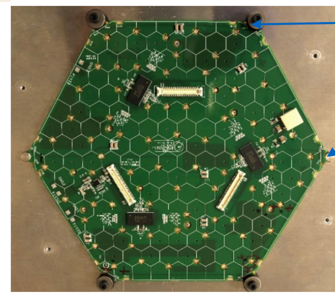


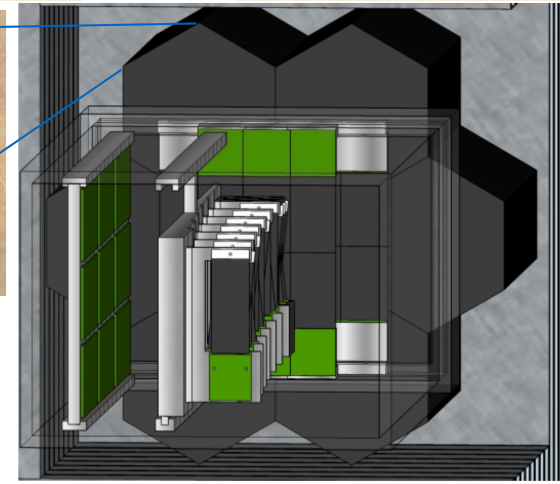


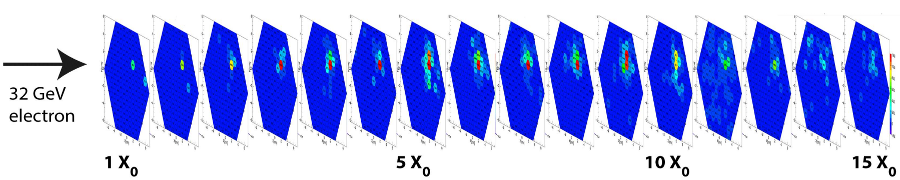
- Fast, low mass **tagger** and **recoil trackers**
- Fast, granular and radiation hard **electro-magnetic calorimeter** enclosed by hermetic **hadronic calorimeter**.
- **Trigger scintillator** for counting e^- / bunch

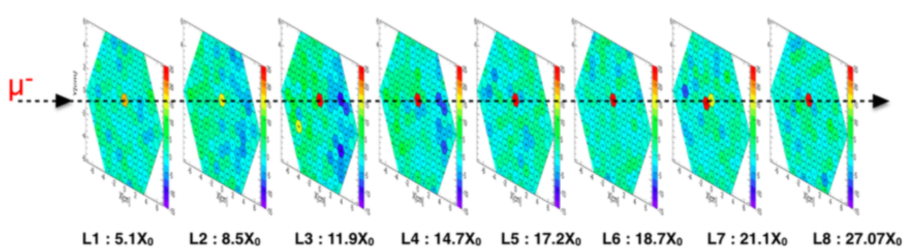
LDMX Electromagnetic Calorimeter (ECAL)

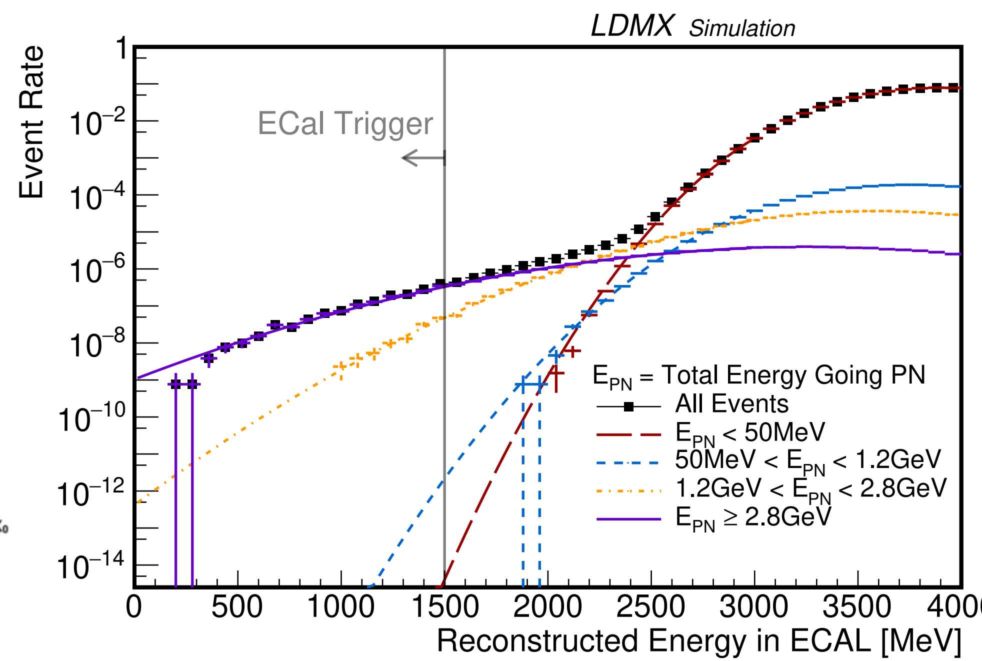
- Si-W sampling calorimeter
- 32 Si layers, $\sim 40X_0$ deep for extraordinary shower containment
- **High-granularity**
  - Transverse and longitudinal shower shapes
- **MIP sensitivity**
  - Tracking of isolated charged hadrons
- **Missing Energy Trigger**
  - In conjunction with the Trigger Scintillator







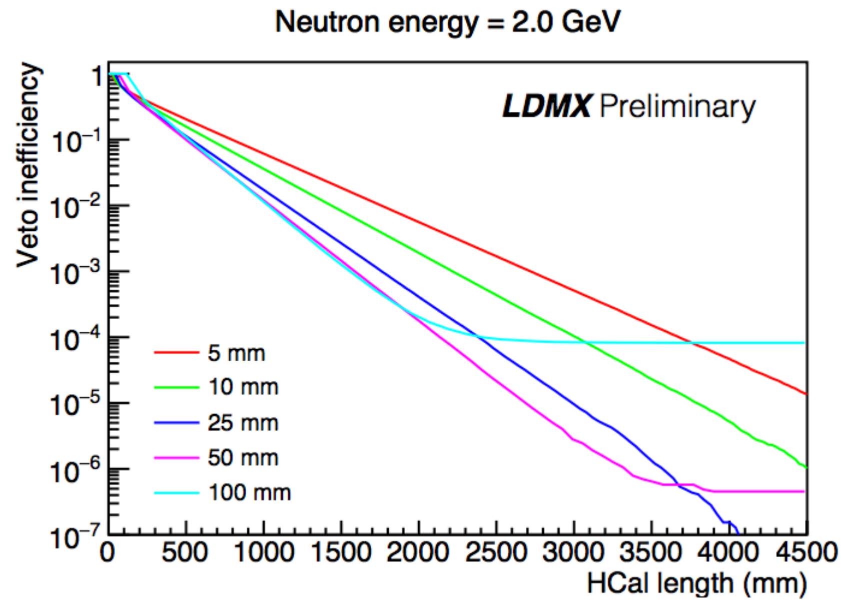


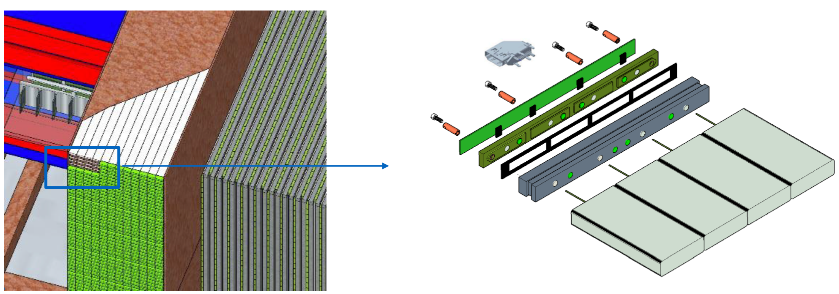


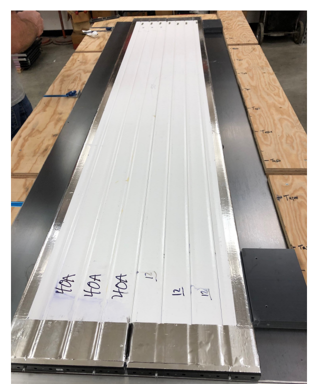
Gonzales, Calor18 arXiv:1708.08234

LDMX Hadron Calorimeter (HCAL)

- Scintillator based sampling calorimeter, similar technology of Mu2E cosmic ray veto (CRV)
- Readout adapted from ECAL HGCROC
- Alternating x/y orientation
  - **Sensitive to EM showers** escaping ECAL
  - **Detect neutral hadrons with high efficiency** in 0.1-10 GeV range
  - **MIP sensitivity**
- Two components, depth optimized using single neutrons:
  - **Main HCAL**: ~90 layers, 25 mm absorber / 20mm scintillator (~15λ_A)
  - **Side HCAL**: ~32 layers, ~3λ_A







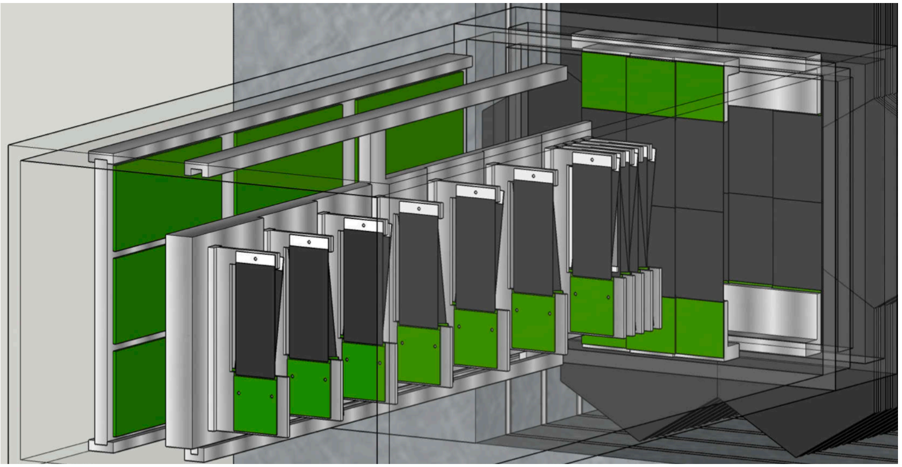
HCAL Prototype designed and commissioned for LDMX CERN testbeam (Oct ’21)
Currently preparing for a 2nd testbeam in April

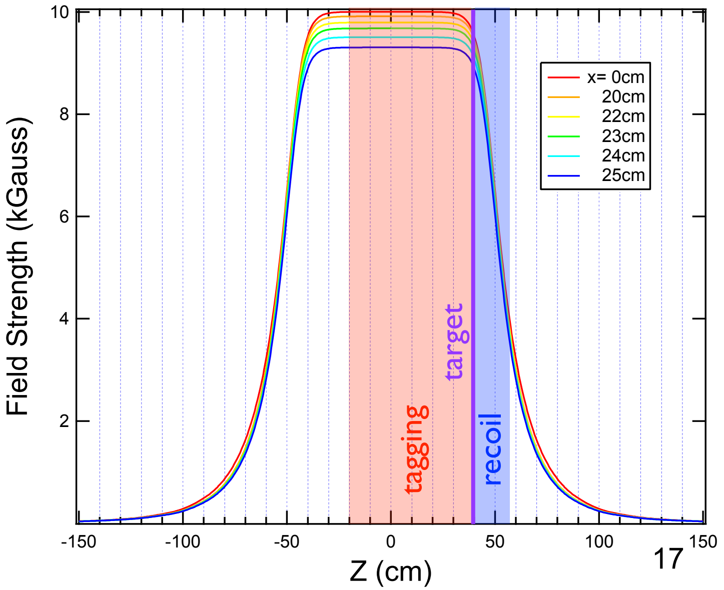
LDMX Tagger and Recoil Trackers

- **Tagger Tracker** - **Magnet Bore**
  - 7 double-sided low mass silicon strip modules ($\sim 0.7X_0$)
    - $10cm$ spacing, $\pm 100mrad$ stereo $\sigma_{r\phi} \sim 6\mu m,\ \sigma_z \sim\ 60\mu m$

- **Recoil Tracker** - **Fringe Field**
  - 4 stereo layers + 2 single-sided vertically oriented axial layers
  - Compact, low mass
  - Efficient reconstruction of 50MeV - 1.2 GeV recoil e^{-}

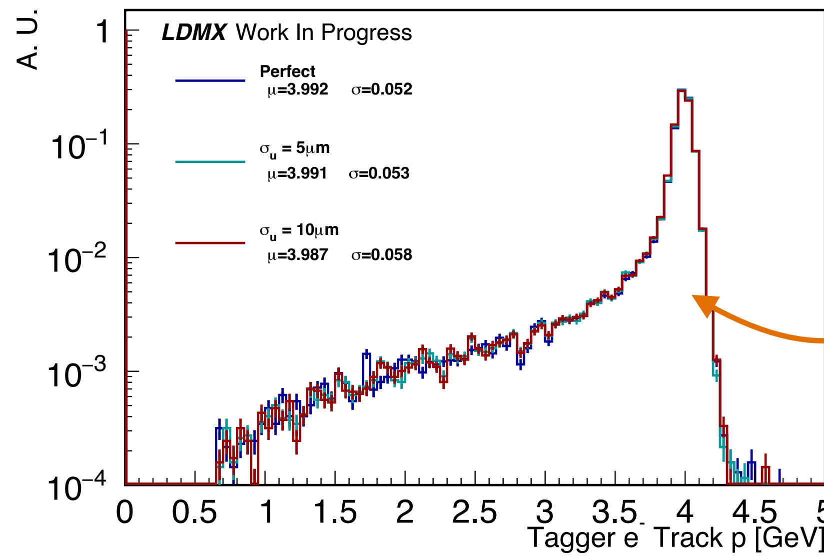
- **Tungsten Target**
  - $\sim 0.1X_0$: high signal rate, keep momentum resolution
  - Scintillator pads in the front/back



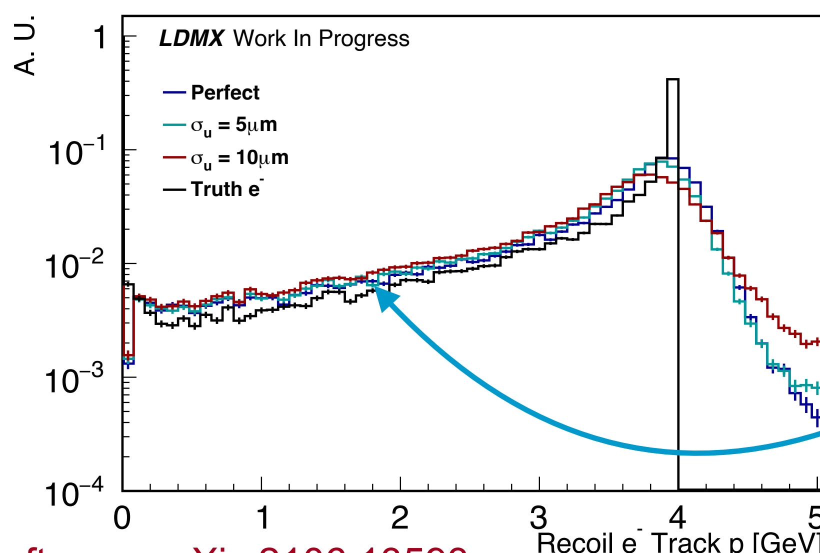


LDMX Track reconstruction

- LDMX search requires high precision tracking
- **Tagger**:
  - Off-energy beam rejection
- **Recoil**:
  - **Low** particle **momentum** regime in a **strongly non uniform** $\vec{B}$
- Interfaced to **ACTS**, modern toolkit based on **well-tested reconstruction code** from LHC experiments
- **Algorithms tuning** in LDMX phase space for ultimate physics performance



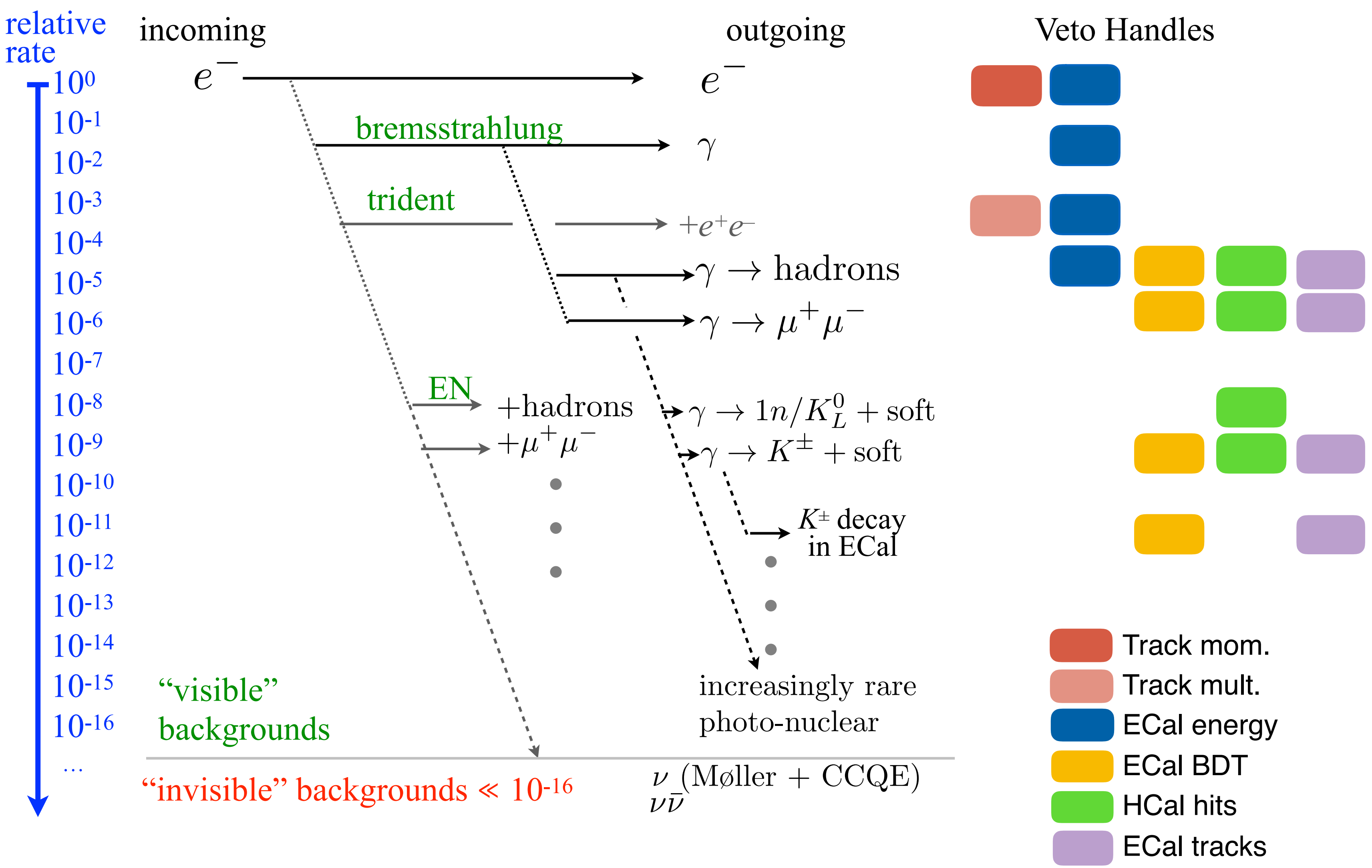
Precise beam e^- momentum reconstruction



Good brem tail modeling

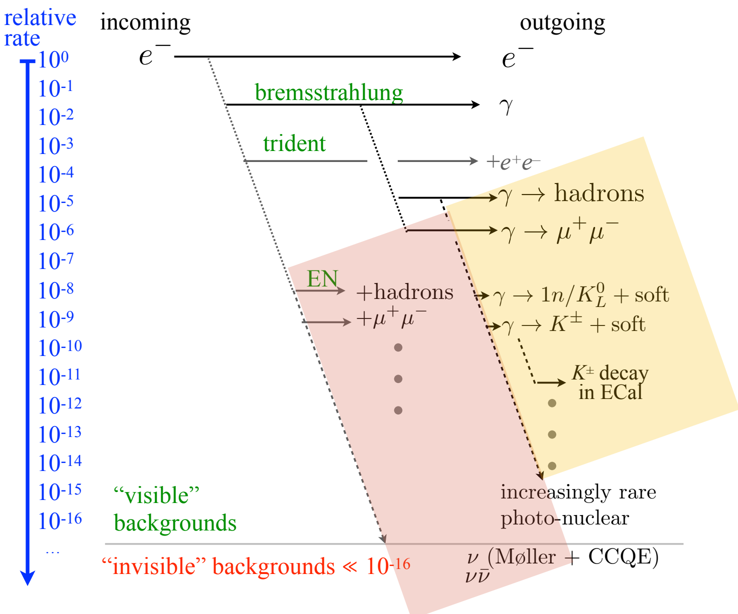
A Common Tracking Software, arXiv:2106.13593

LDMX Bremsstrahlung Background



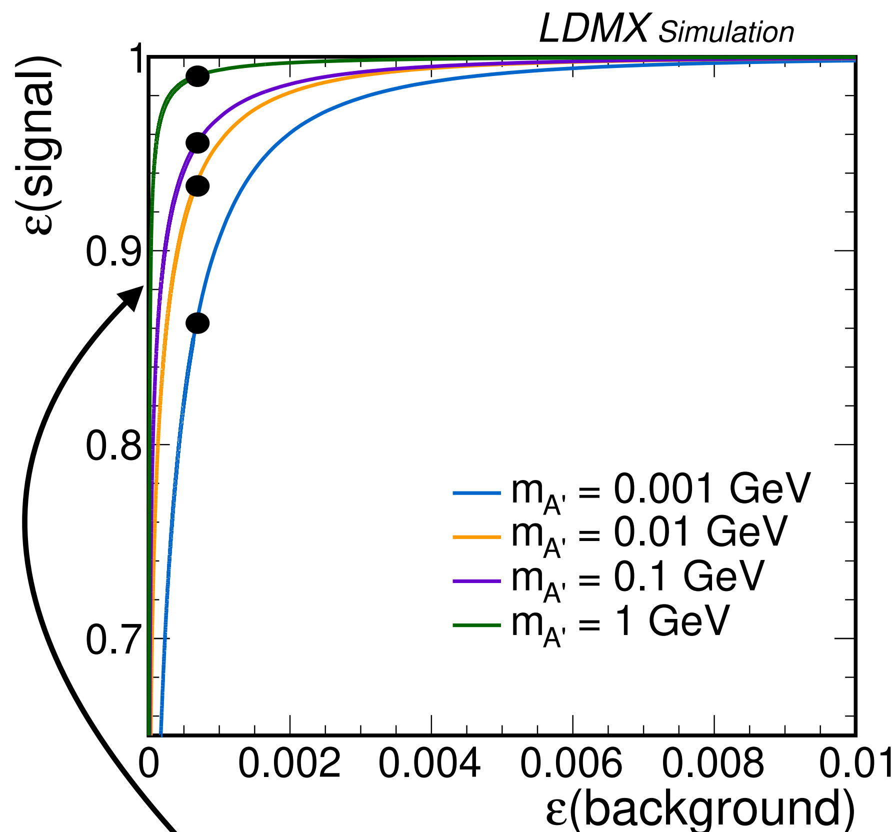
LDMX Bremsstrahlung Background

JHEP04(2020)003



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

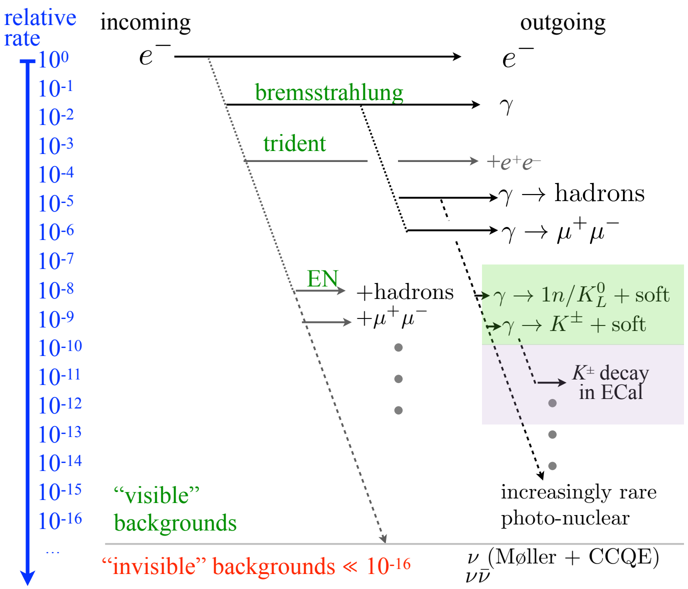
- **ECal Based BDT Veto**
  - ***Global ECAL features***
  - ***EM Shower features in containment regions*** *around* the e^- and the inferred γ directions

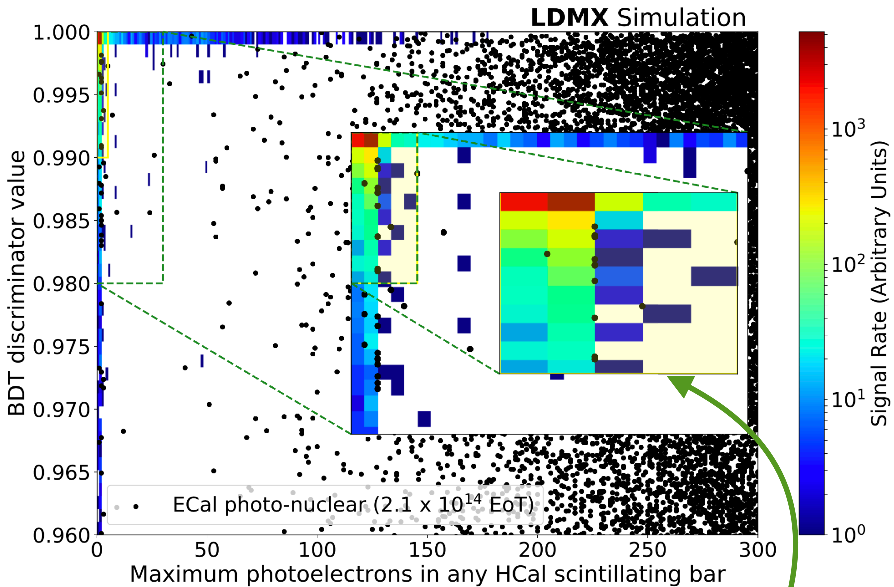


BDT score > 0.99, WP @99.9% bkg rejection / 85-99% efficiency

LDMX Bremsstrahlung Background

JHEP04(2020)003

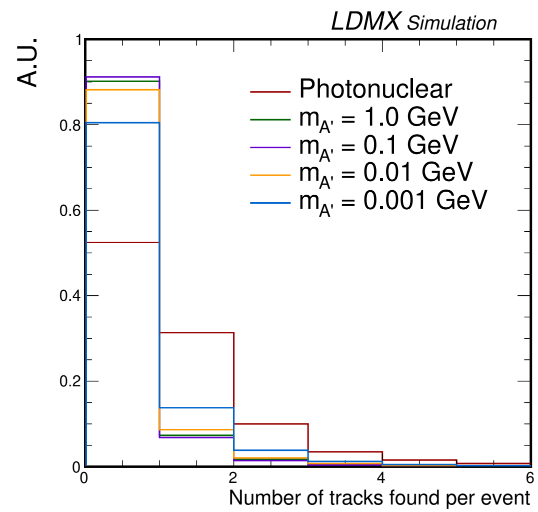




ECAL BDT + HCAL VETO Signal Region

- **HCAL hit Veto**
  - Single scintillator bar with **5 Photoelectron (PE) hits** in time with beam e^-
  - Targets events with soft product escaping ECAL acceptance and PN reactions leading to $1n/K_L^0$

- **MIP Tracking in ECAL**
  - Veto on reconstructed single isolated tracks around γ direction
  - Targets events with single $K^{+/-}$ decaying in the ECAL



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

Results and Sensitivity

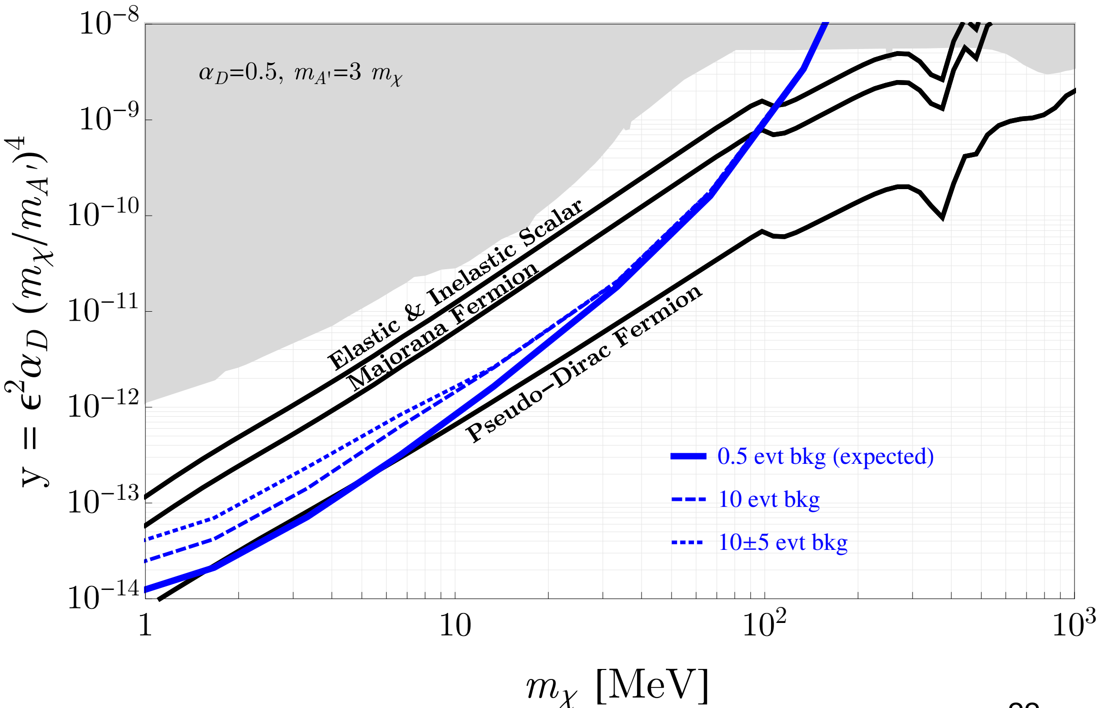
SLAC

JHEP04(2020)003

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

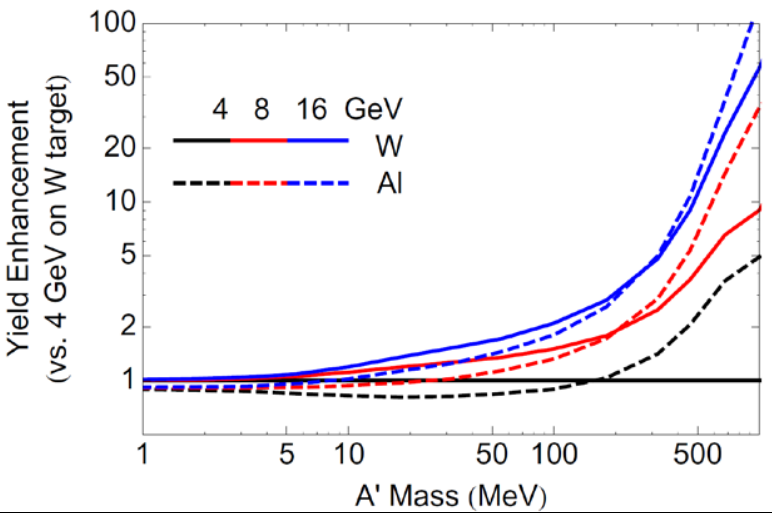
- **Outstanding sensitivity** in a mass range up to $m_\chi < 100MeV$

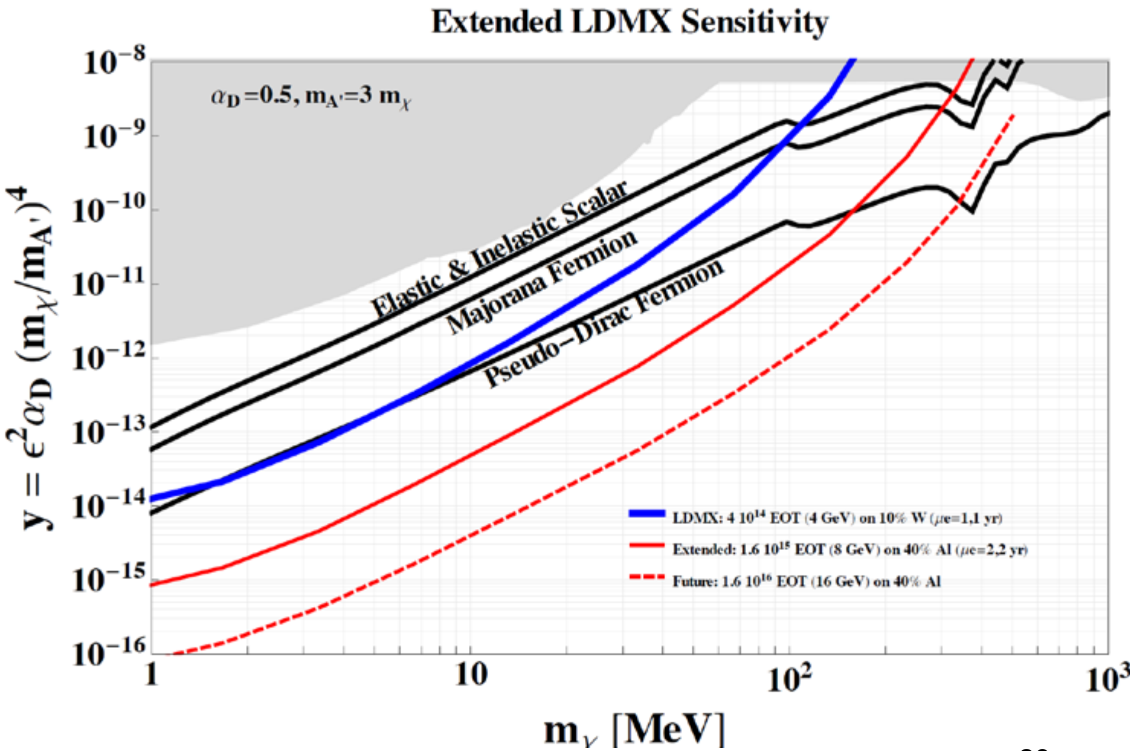
	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.7×10^{11}	6.3×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.6×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$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



Phase-II upgrade

- **Strategies to increase Phase-I reach**
  - Change target density / thickness
  - Increase beam energy
- **Future runs at higher energy** are able to explore the phase space **up to** $m_\chi < 300 MeV$





arXiv:1905.07657.pdf

Summary

- **Thermal-relic models offer predictive and compelling explanation for Dark Matter existence**

- **LDMX** is an electron beam on target experiment designed to probe the **sub-GeV mass range for thermal-relic Dark Matter**
  - Focus on invisible signature
  - Signal identification using missing momentum technique

- **Sensitivity beyond invisible search**:
  - General exploration of hidden sector physics, e.g. displaced vertex signatures
  - Electronuclear measurements in a unique forward phase space to support neutrino experiments

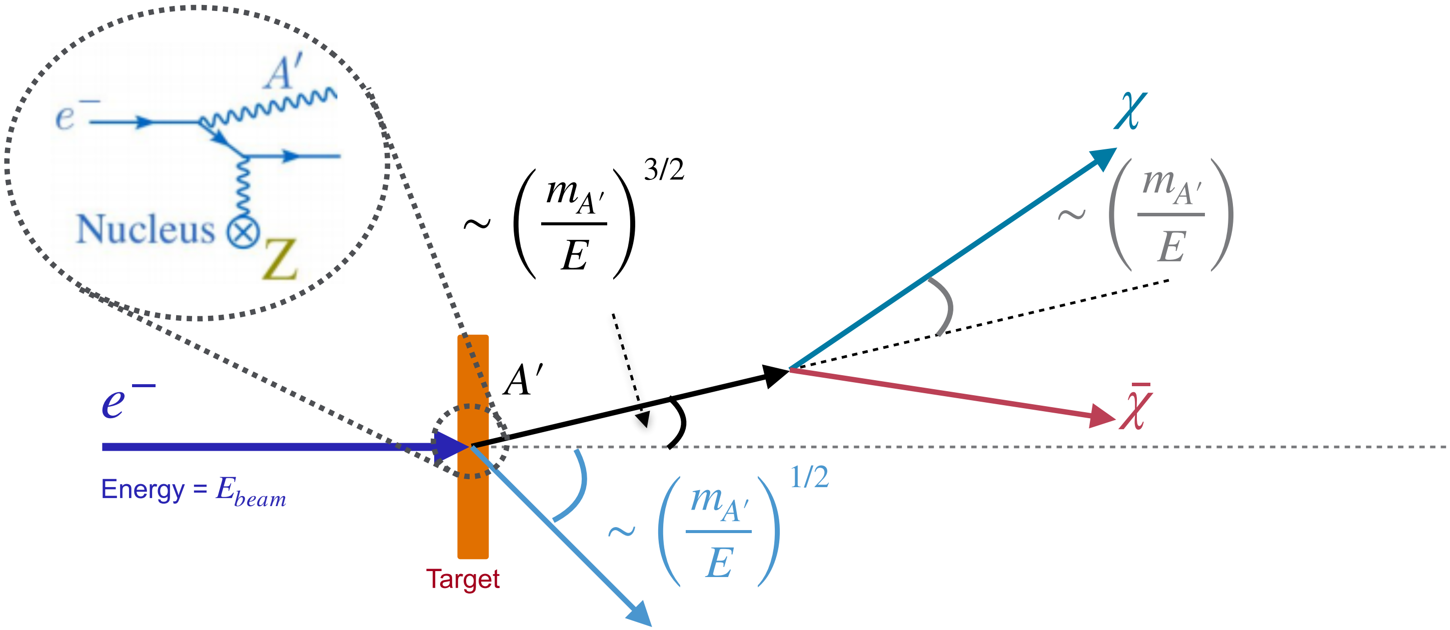
- **Exciting times ahead as the experiment is moving from concept design to creation**

BACKUP SLIDES

Advantages of Missing Momentum measurements

- Missing Mass:
  - i.e. Babar, Padme
  - Relies on reconstructing the full final state, only practical in e+/e- collisions, lower luminosity
- DM re-scattering:
  - i.e. BDX, MiniBoone
  - High intensity beams but Low probability of DM scattering (scales as the SM-DM coupling to the fourth power)
- Missing Energy
  - i.e NA64
  - Fewer kinematic handles wrt missing momentum
  - Lack of electron/photon discrimination, bkg from neutrinos

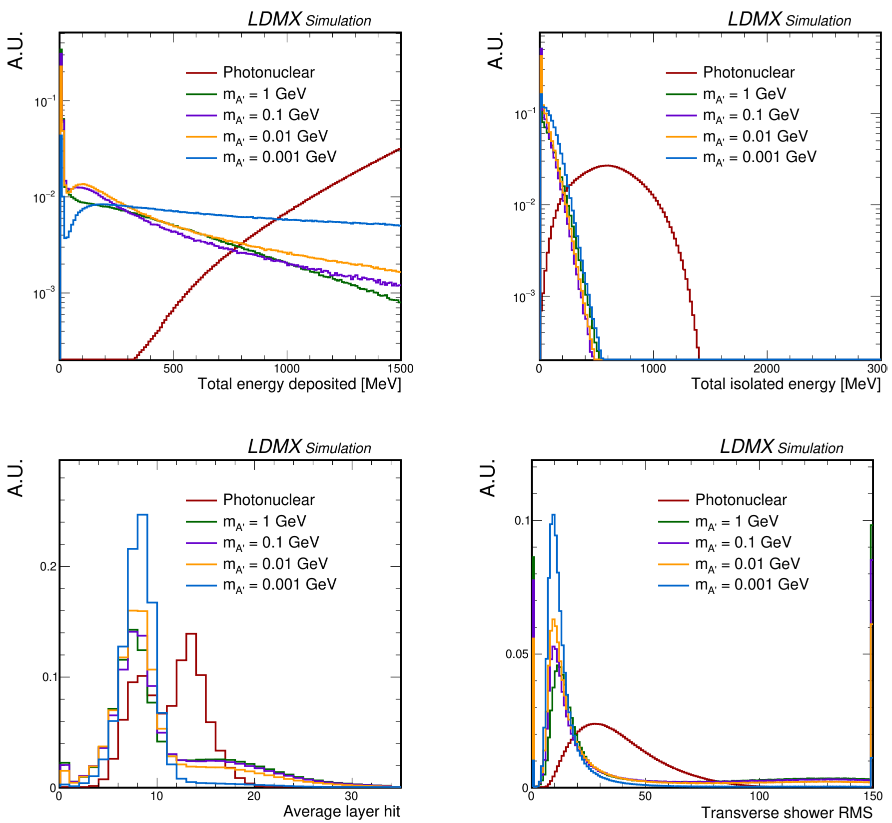
Kinematics sketch



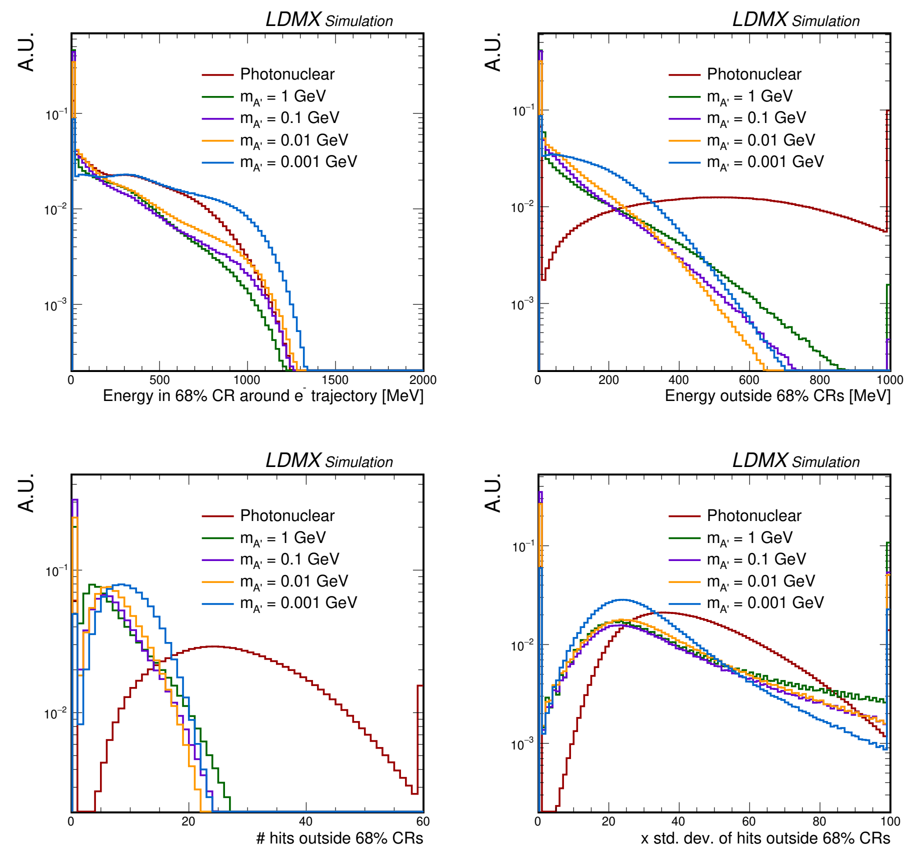
ECAL BDT

- Example distributions of some of the variables used as input for the ECAL BDT based PN veto
- The variables are classified as "global", which take into account averages over the whole ECAL detector and "shower shape", which characterize the ECAL shower in the hypothesis of background event with a hard photon.

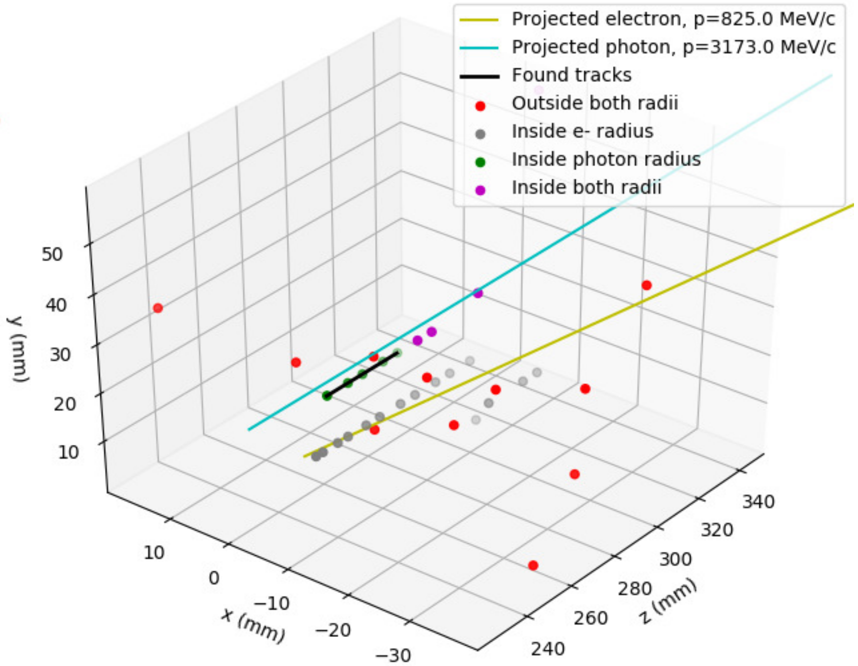
Global ECAL Variables

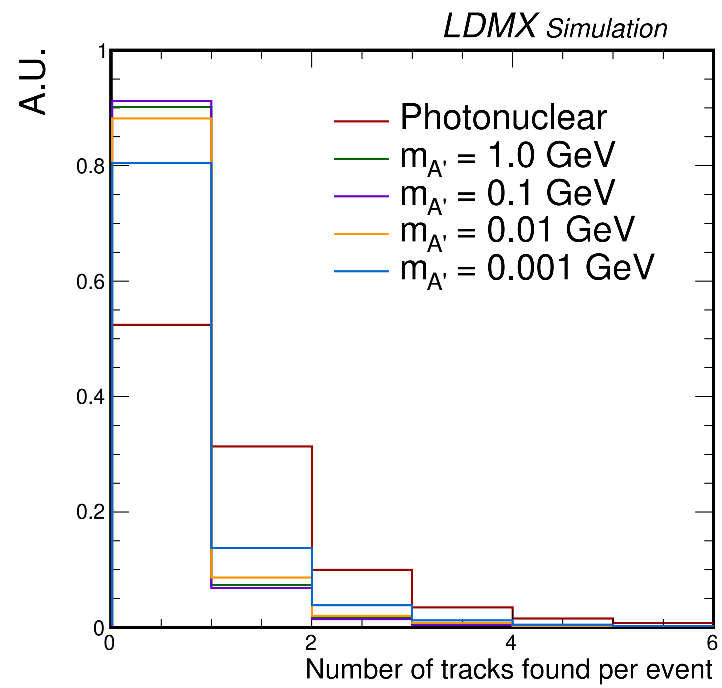


Shower Shape Variables



MIP Tracking in the ECAL

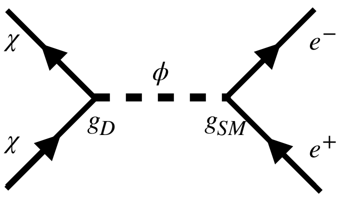




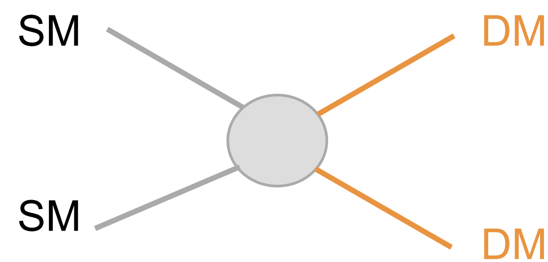
LDMX Concept

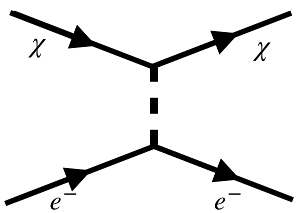
- High-luminosity measurement of missing momentum in multi-GeV fixed target electron collisions
  - Sensitive to dark matter production directly and via a mediator
  - Extend N64 sensitivity
- Low current ~pA with high bunch repetition ~40MHz electron (~10^8 e/second electrons on target [50Me-/s Phase I, 1Ge / s Phase II]) beam with 4-16 GeV energy.
  - Target sub-GeV DM search with below threshold to generate neutrinos => irreducible bkg
  - Proposed SLAC 4-8 GeV, 11 GeV jLab, 3.5-16 GeV SpS (which one has been finally accepted? SLAC?)
- With upgrade of trigger and daq LDMX can provide improved data on final states in eN scattering in multiGeV region, which is of interest to the neutrino scattering community

Rotated Feynman diagrams



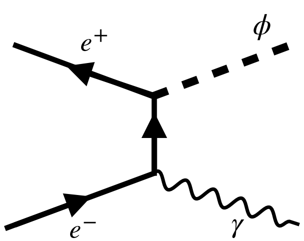
Direct annihilation

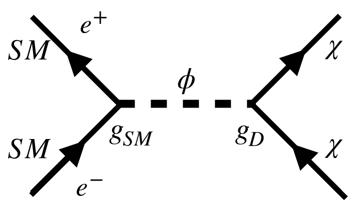


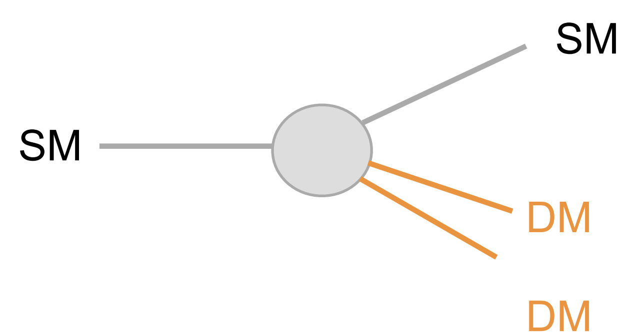


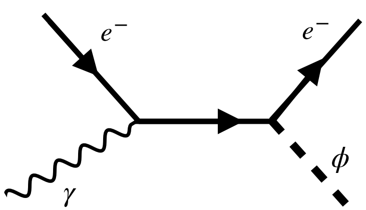
Direct detection

Direct production





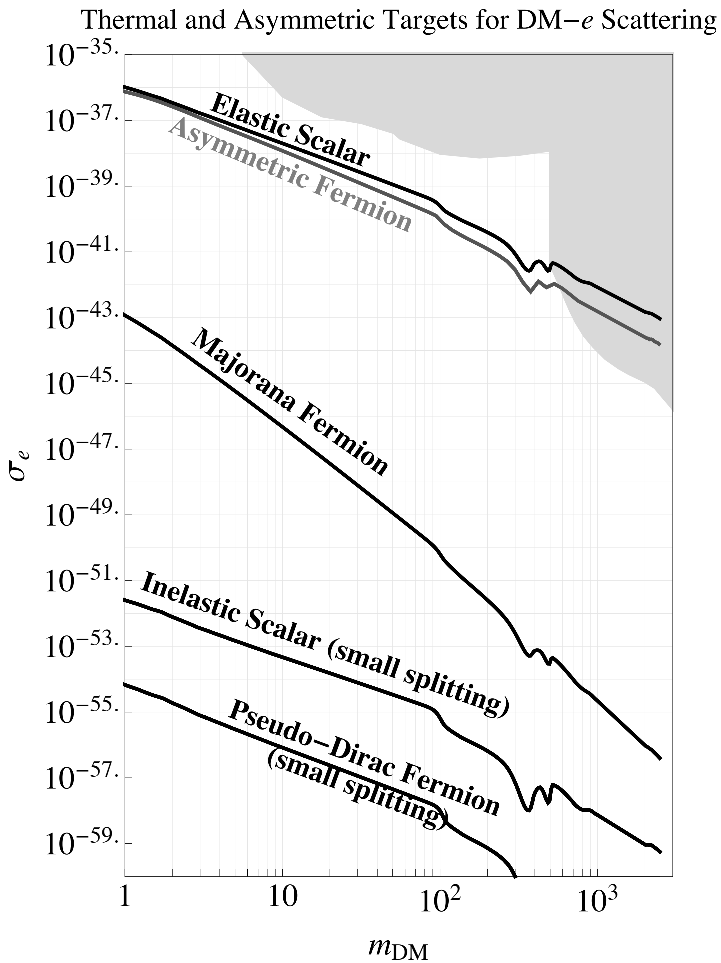




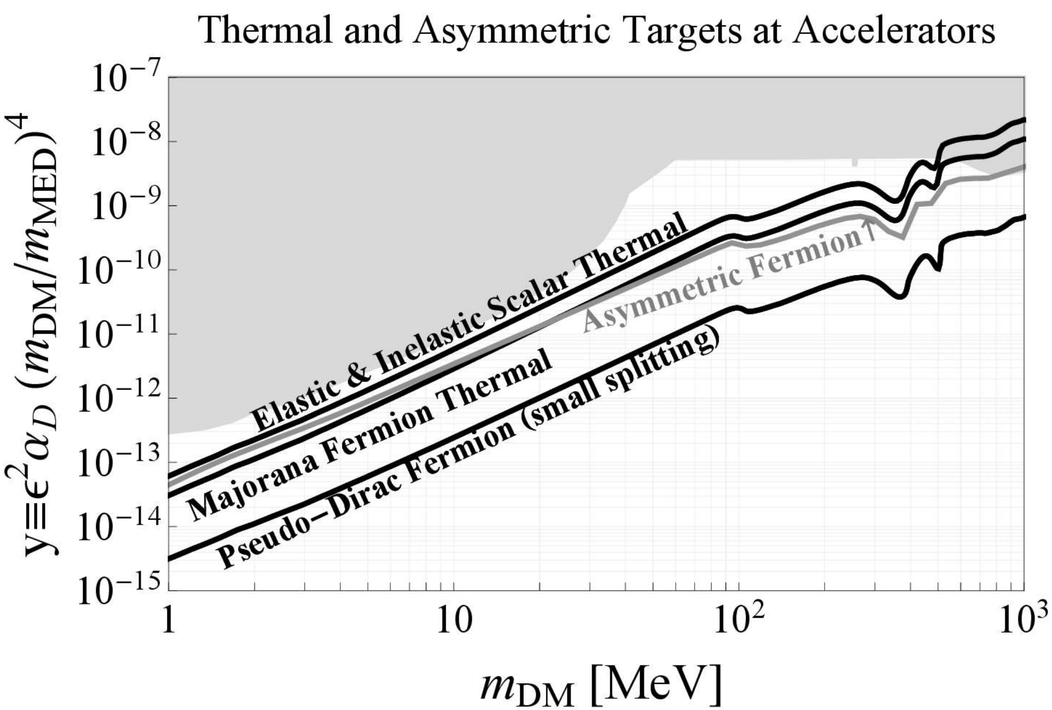
Darksstrahlung

Motivations for Accelerator searches for DM

Direct detection:
Strong spin/velocity dependence



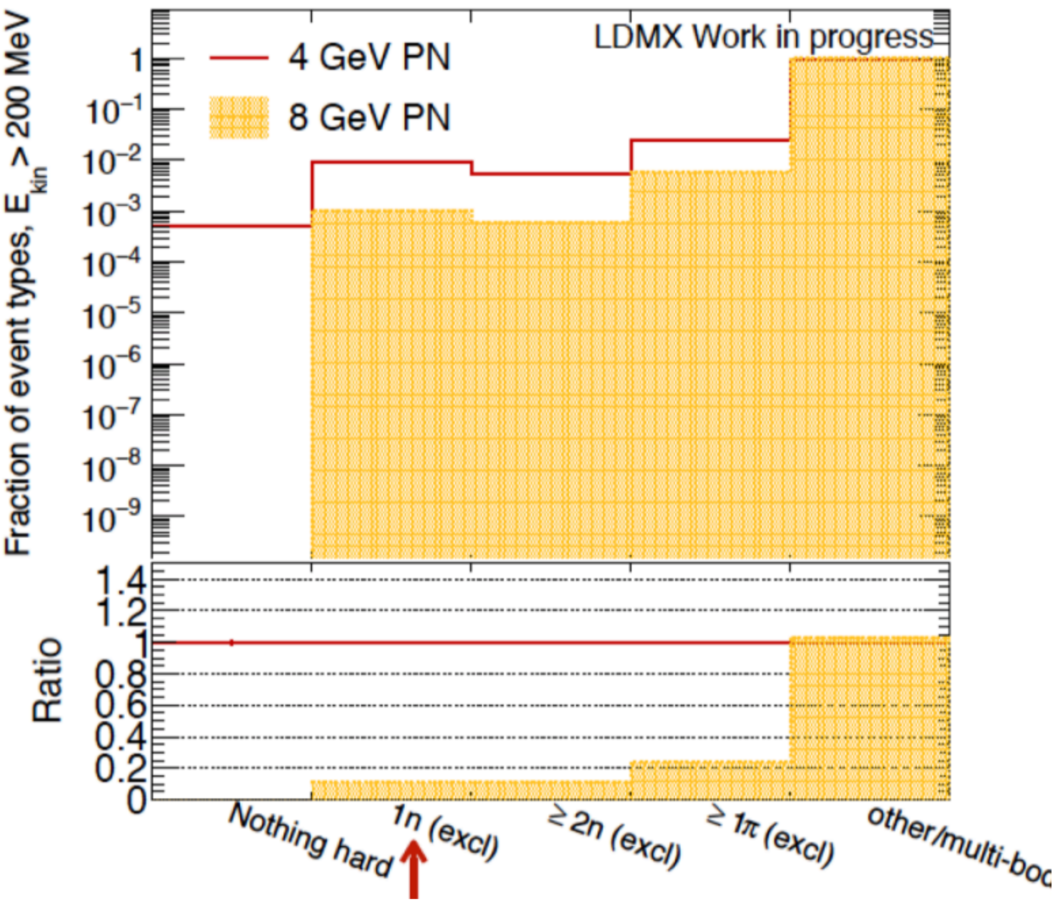
At accelerator: relativistic production
Spin/velocity dependence reduced and all relic targets in reach



https://arxiv.org/pdf/1807.01730.pdf

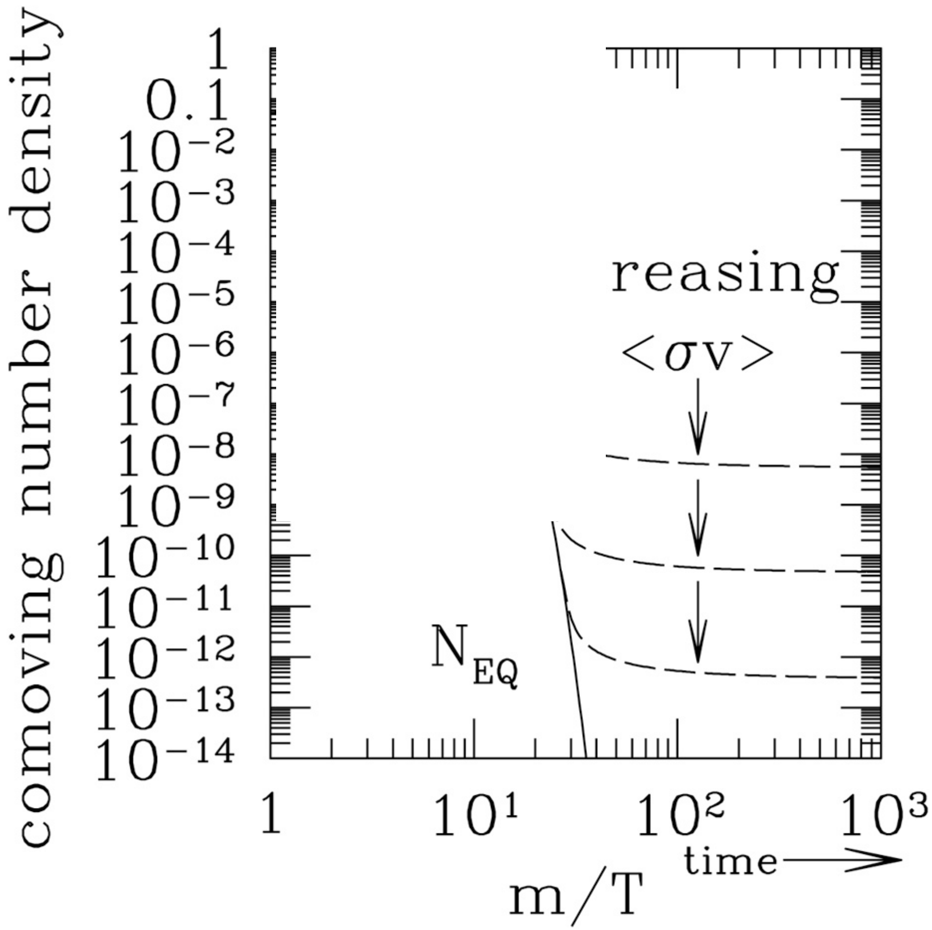
Higher energy

- Improved background rejection possibility
- Invisible background with ν still negligible with 10^{16} EOT
- Reduced 1n Photonuclear background, particularly critical for the analysis



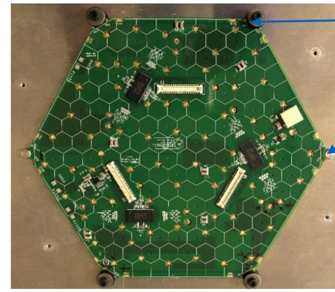
Dark Matter as Thermal Relic

al relic

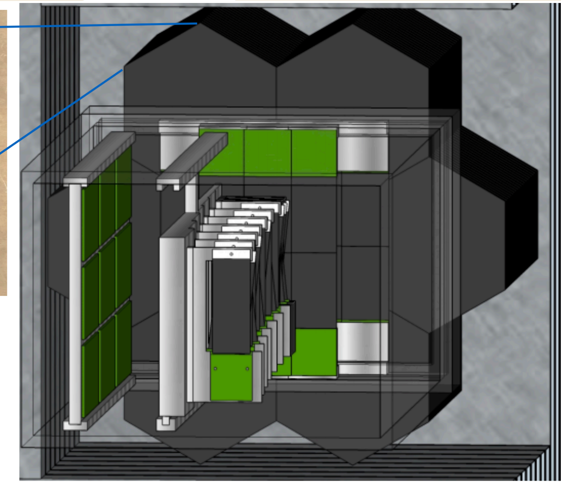


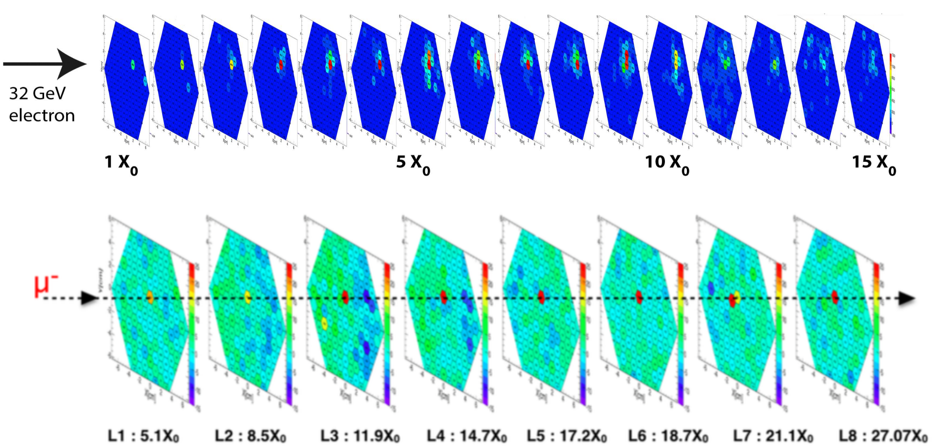
LDMX Electromagnetic Calorimeter (ECAL)

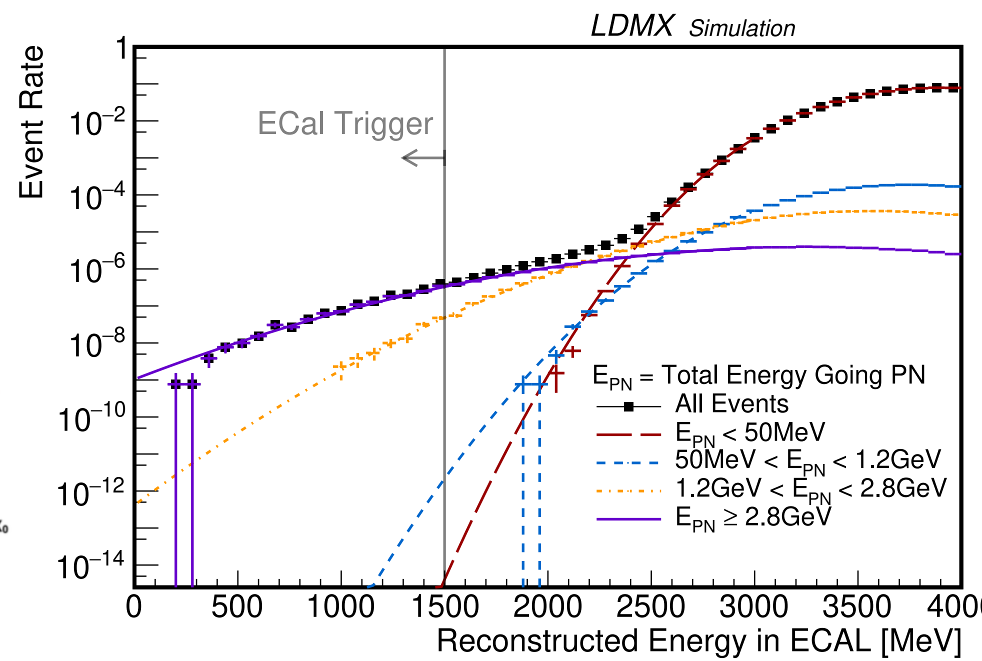
- Si-W sampling calorimeter
- 32 Si layers, $\sim 40X_0$ deep for extraordinary shower containment
  - 30cm depth x 50 cm width
- **High-granularity**
  - Transverse and longitudinal shower shapes for Photo-Nuclear (PN) events rejection
- **MIP sensitivity**
  - Tracking of isolated charged hadrons for PN bkg rejection
- **Missing Energy Trigger**
  - In conjunction with the Trigger Scintillator



300(500) μm thick sensors







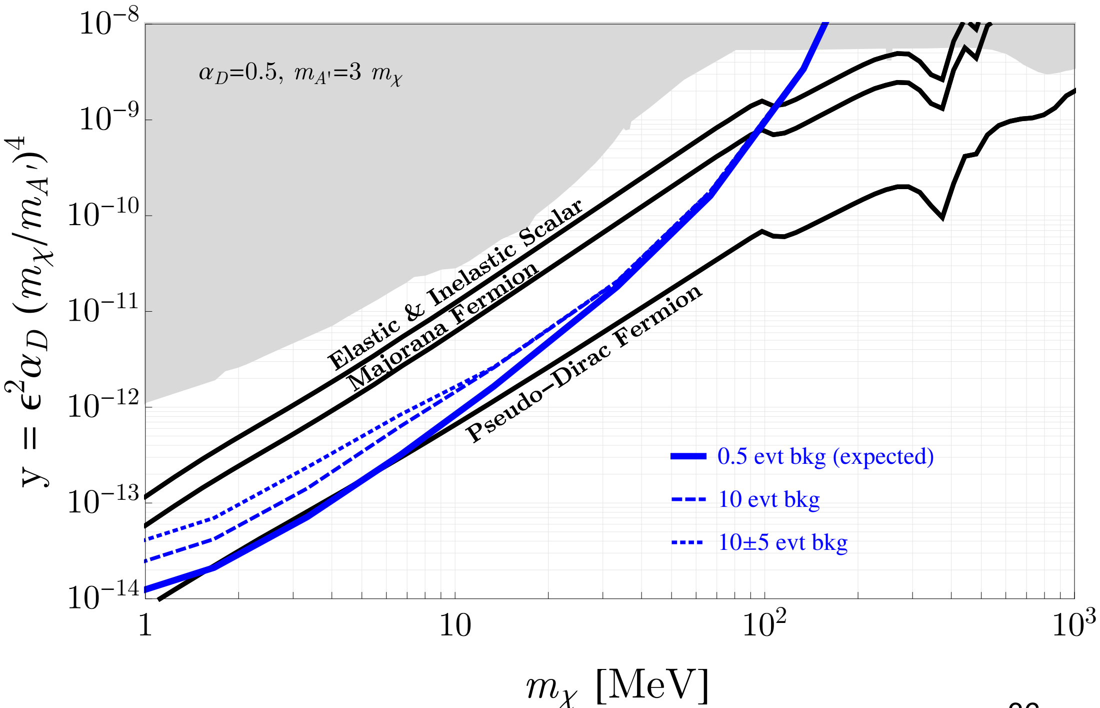
Gonzales, Calor18 arXiv:1708.08234

Results and Sensitivity

- Rejection factor of 10^{-13} is achieved for photons with $2.8\ GeV < E_\gamma < 4\ GeV$
- Expected **background free search** with 4×10^{14} electrons on target and $E_{beam} = 4GeV$
- **Outstanding sensitivity** to a variety of thermal targets in a mass range **up to** $m_\chi < 100MeV$

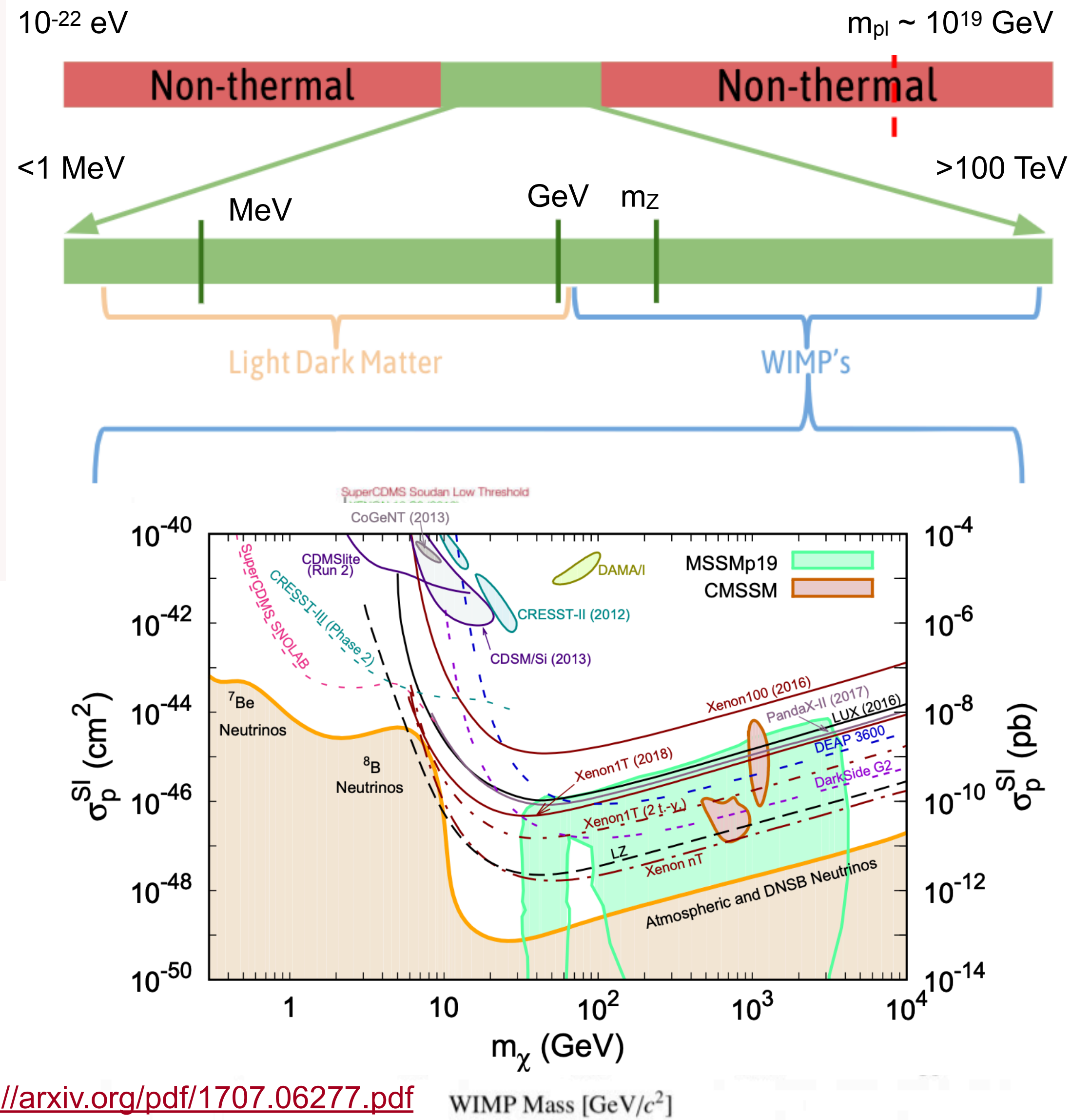
JHEP04(2020)003

	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 $< 1.5\,\mathrm{GeV}$	1×10^{8}	2.6×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2\,\mathrm{GeV}$	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



Search for Dark Matter

Illustration by Sandbox Studio, Chicago with Ana Kova



- In the last decades, extensive worldwide research program has been built to understand the particle nature of Dark Matter (DM) in the universe
- Searches for WIMP DM in the most natural areas in mass have found no signal so far

https://arxiv.org/pdf/1707.06277.pdf