The Light Dark Matter eXperiment

Omar Moreno SLAC on behalf of the LDMX Collaboration

Fermilab UCSB SLAC Caltech SCIPP Santa Cruz Institute for Particle Physics LUND UNIVERSITY

ICHEP2018 SEOUL
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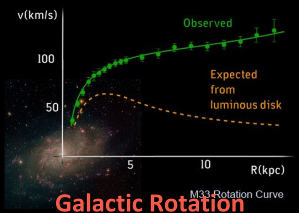
SLAC

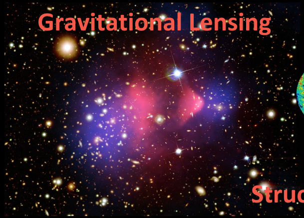
The Search for Dark Matter

LDMX

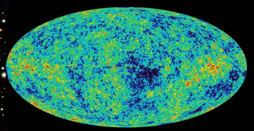
There is strong evidence for the existence of Dark Matter, but it's nature continues to elude us!



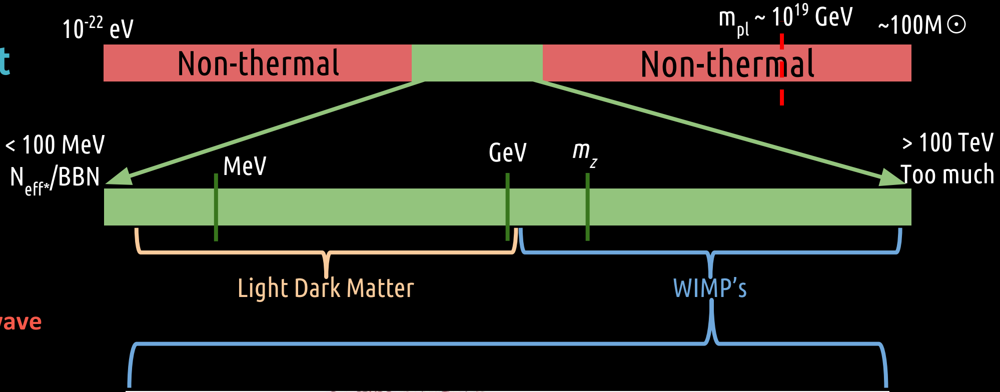
Galactic Rotation Curves



Gravitational Lensing

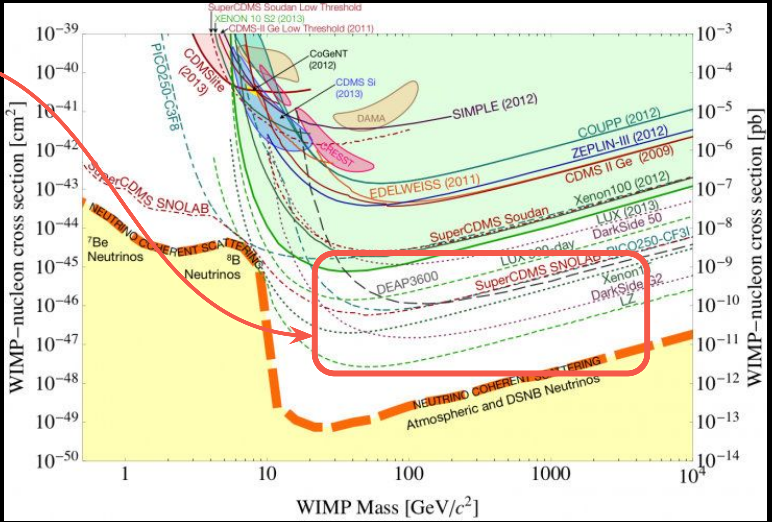


Structure of Cosmic Microwave Background



Broad and impressive program has been built to understand ~GeV - TeV (WIMP) Dark Matter, but searches for them in the most favorable areas have yielded nothing … will be ruled out or found in the coming years by next gen experiments (e.g. SuperCDMS, LZ or LHC)

What about light (< 1 GeV) thermal DM?



Searching For Light Dark Matter

Light Dark Matter in the broad vicinity of the weak scale is a natural and simple generalization of WIMPs. **Light thermal dark matter requires a new force** to achieve the correct thermal relic (WIMP's limited by Lee-Weinberg Bound to 2 GeV). Phys. Rev. Lett. 39, 165

Given the complex structure of the Standard Model, a **"Dark Sector"** where dark matter interacts via a light mediator is an obvious scenario to test. It has been the focus of a broad array of searches and experiments for many years now.

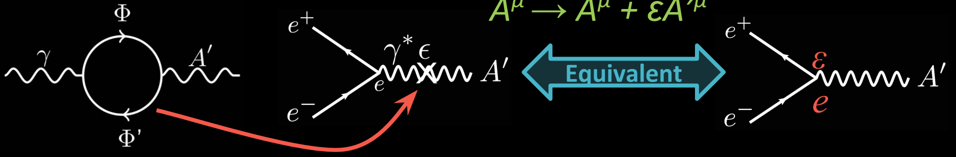
Let's focus on the simplest scenario where DM interacts via a vector mediator (dark photon, A')

kinetic mixing between SM photon and the dark photon

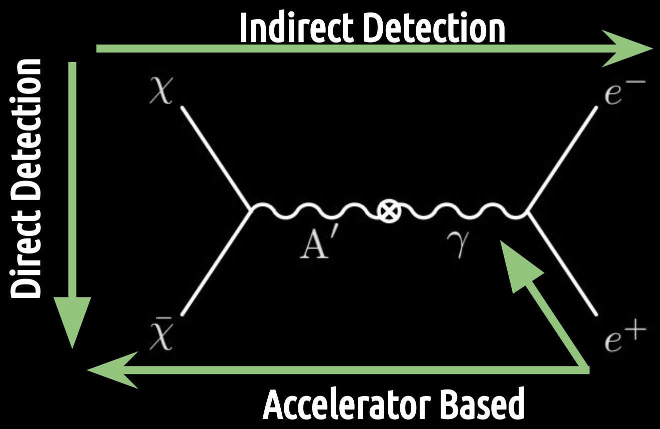
→ induces weak coupling to electric charge

$$\frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

$A^\mu \longrightarrow A^\mu + \varepsilon A'^\mu$

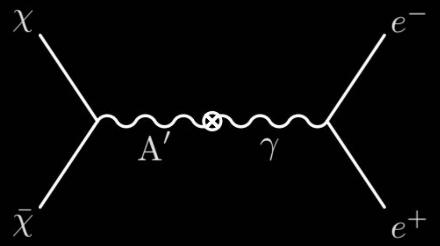


If $m_{A'} > 2m_\chi$



Electron accelerators can play a major role in testing models of light dark matter!

Thermal DM Targets at Accelerators

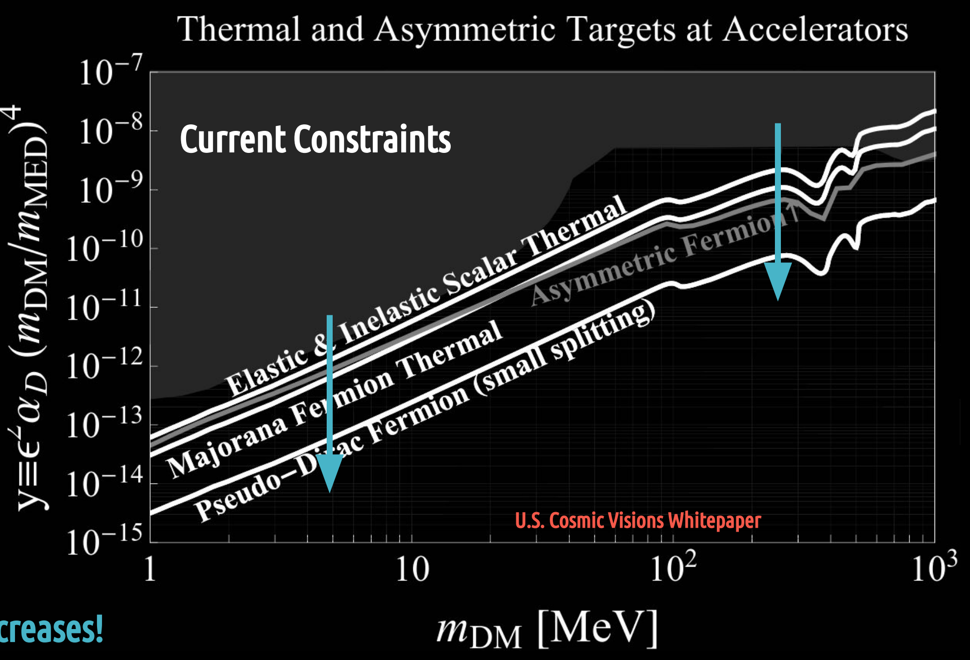


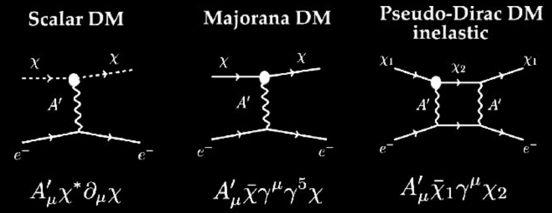
Need a way to estimate the reach of searches $\longrightarrow$ Introduce dimensionless interaction strength, y

$$\sigma v(\chi\chi \to A'^* \to f f) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Uses **conservative** values for $\alpha_D (= .5)$ and $m_\chi / m_{A'}$ $(m_{A'} = 3m_\chi)$

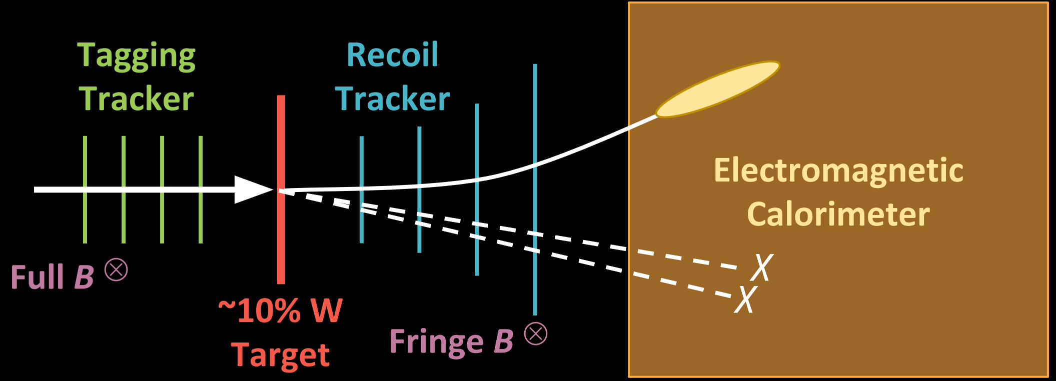
As α_D or $m_\chi / m_{A'}$ decreases, **the sensitivity of an experiment increases!**



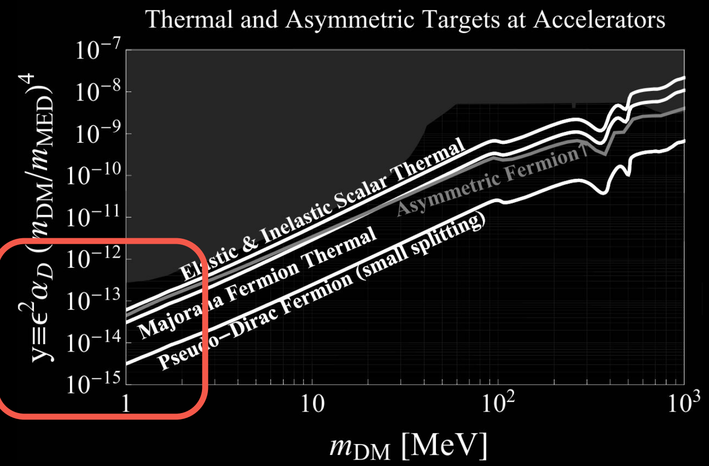


The Light Dark Matter eXperiment

The Light Dark Matter eXperiment is a e^- fixed target missing momentum search for light dark matter



$$\sigma \propto \epsilon^2 \rightarrow N_{signal} \simeq N_{e-} \times y|_{1\ \mathrm{MeV}}$$



A zero background experiment can test all thermal targets over most of the MeV-GeV range (with 10^{16} e^- on target)!

SLAC

Dark Bremsstrahlung Kinematics

LDMX

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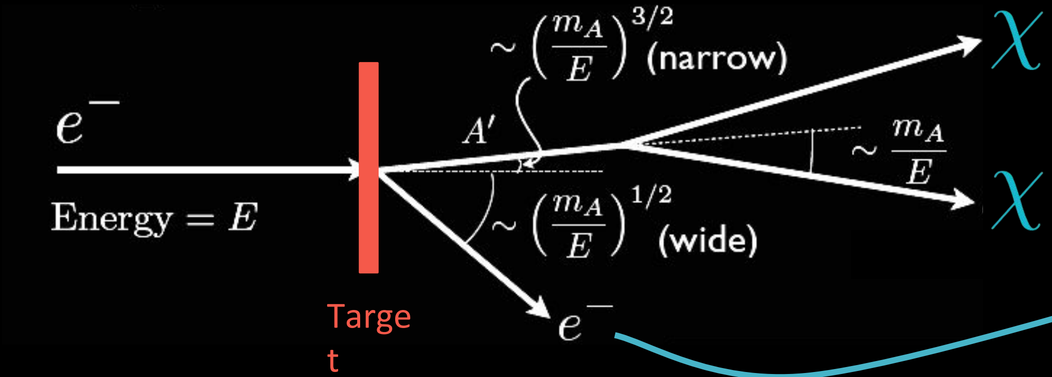
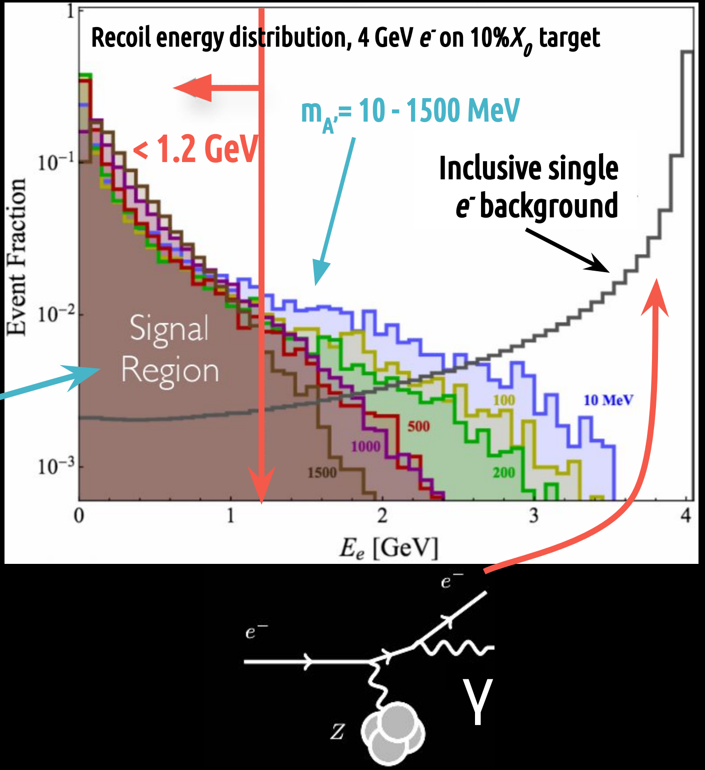
Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets



but with different rates and kinematics

- Production is sharply peaked at x ≈ 1 ⟶ A' takes most of the beam energy
- Recoil is produced very soft and at wide angles ⟶ Large missing momentum

Recoil kinematics allow efficient signal definition providing a factor of 30 background rejection!



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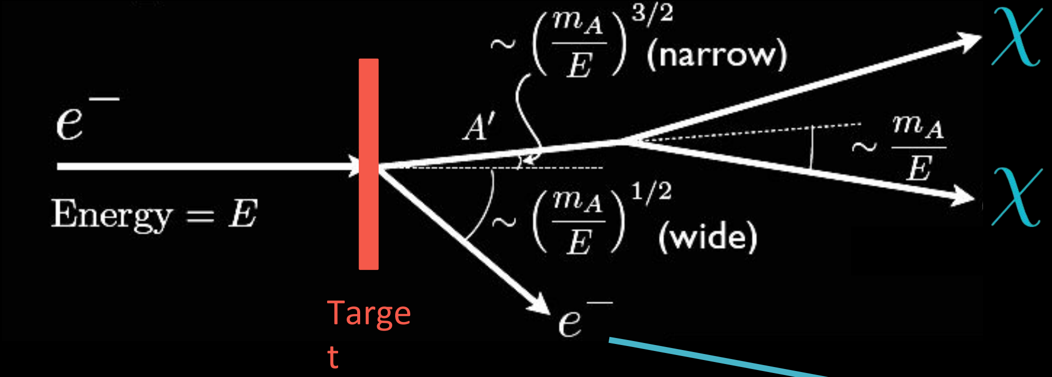

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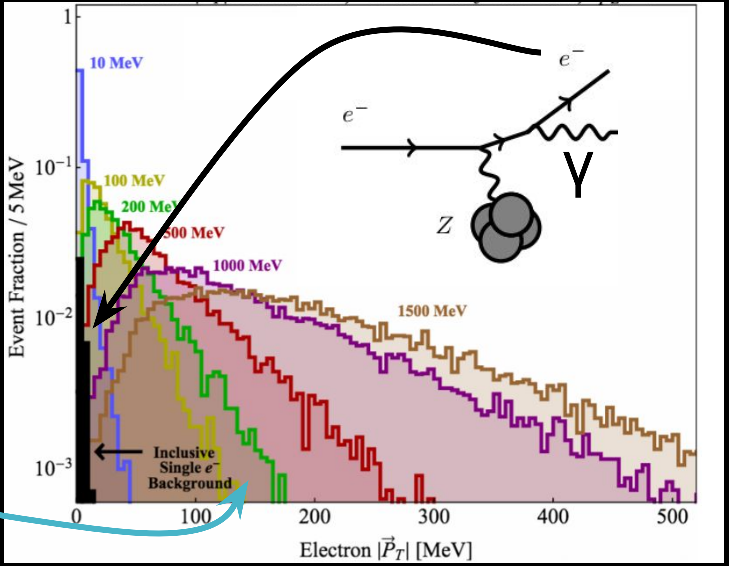
p_t is also an important experimental handle as it depends on the mass of the A'



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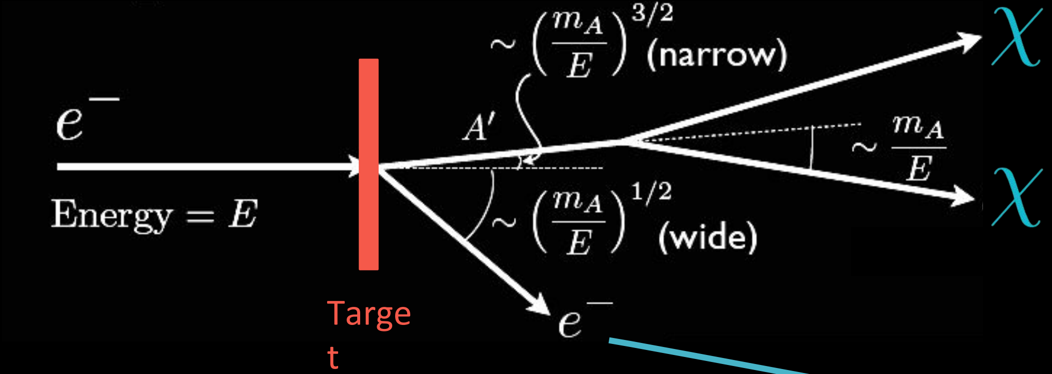

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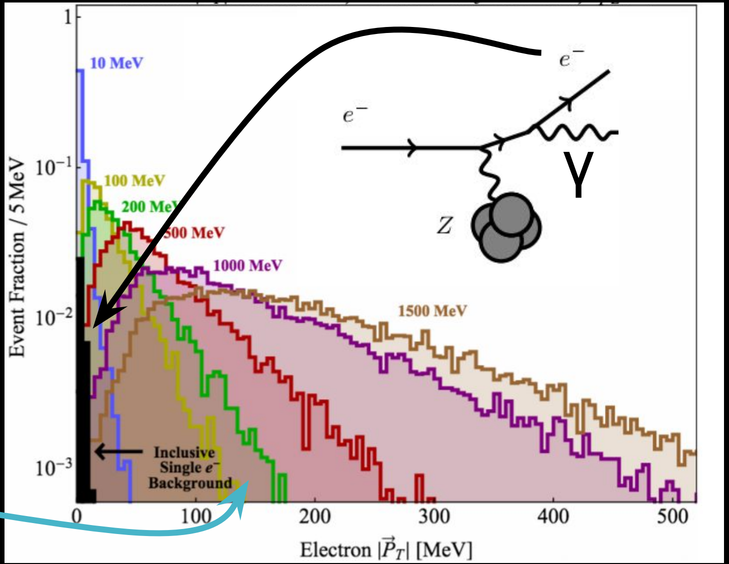
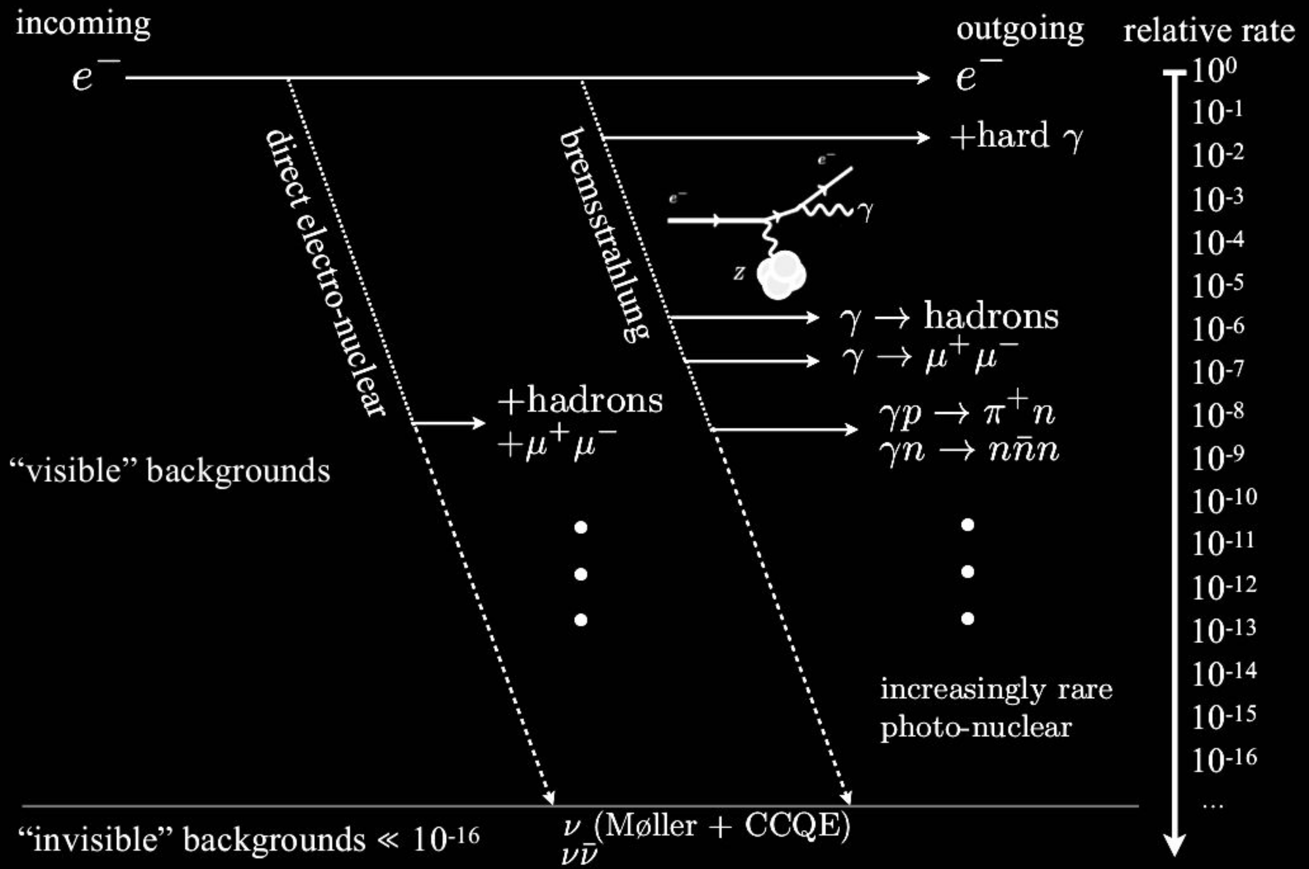
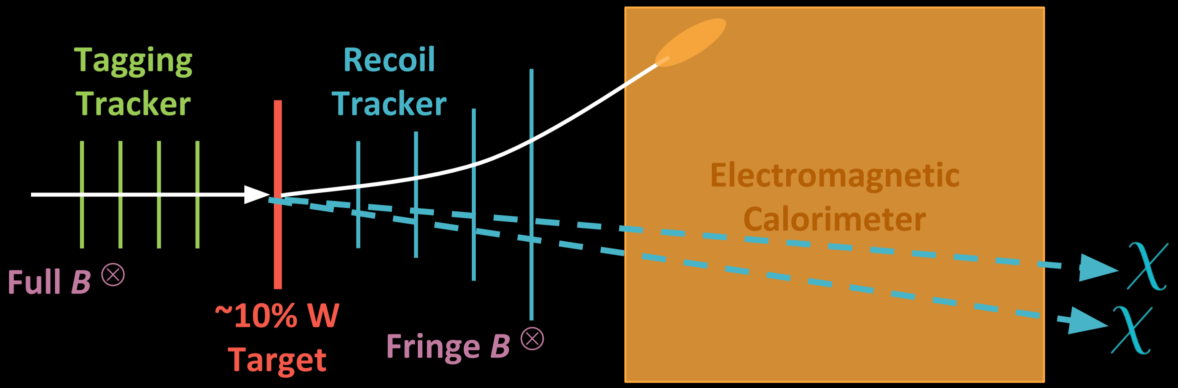


Goal: achieve zero background without using p_T as a signal discriminator

Missing Momentum Backgrounds



LDMX Design Considerations



Beam that allows individual tagging and reconstruction of 10^{16} incident e^-

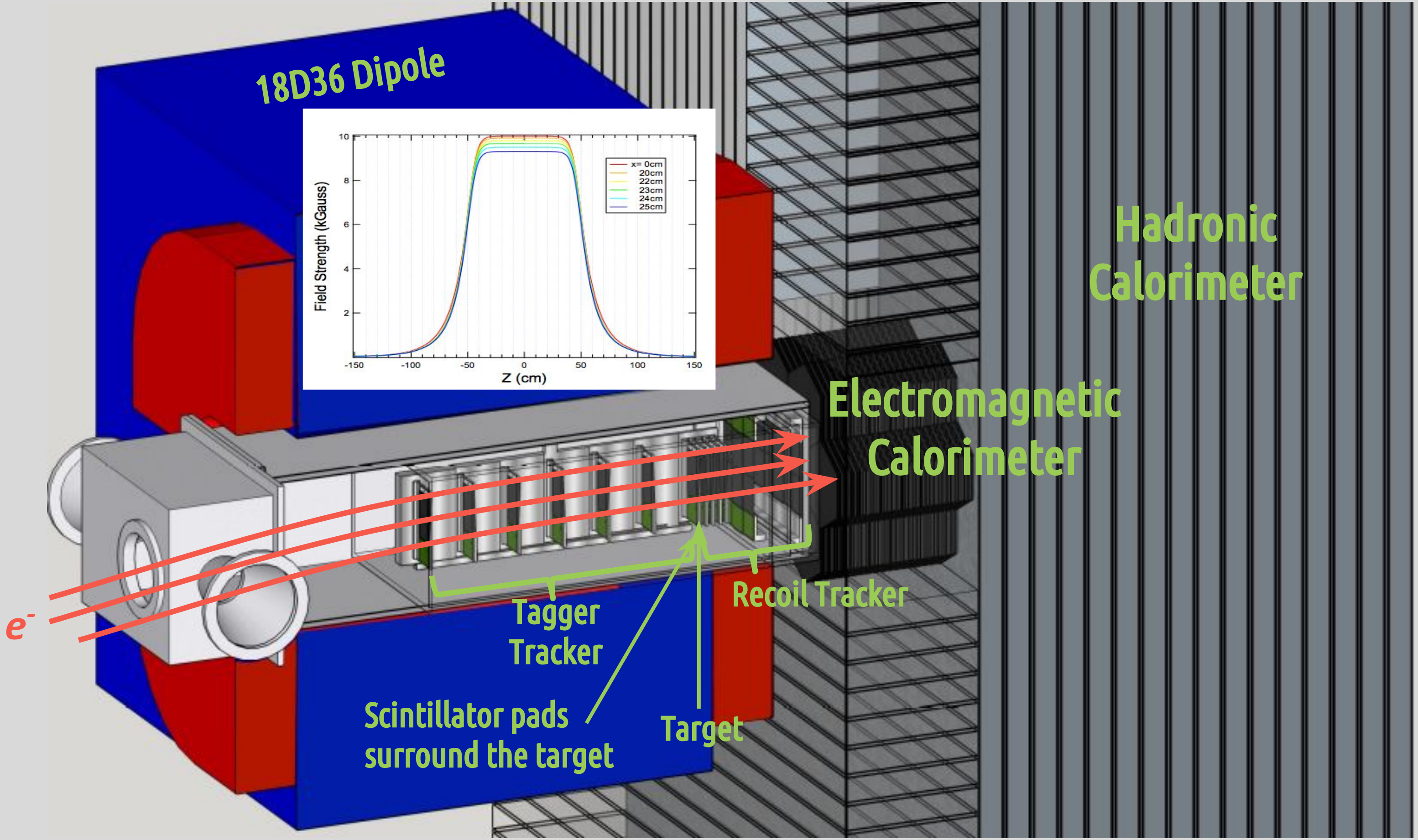
- A low-current, multi-GeV, e^- beam with high repetition rate (10^{16}/year ≈ 1 e^-/3 ns).
  - The possibilities are DASEL @ SLAC (4/8 GeV) and CERN and CEBAF @ JLab (< 11 GeV)
- large beamspot (~10 cm^2) to spread out otherwise extreme rates and radiation doses

Tracking and calorimetry capable of high rates and radiation tolerance

- High resolution, low mass tagging/recoil trackers
- High energy resolution EM calorimeters

Requirements for 10^{16} experiment close to limits of available technologies ➡ Two-stage approach to LDMX: $4{\times}10^{14}$ "Phase I" (1 e^-/25 ns @ 4 GeV) followed by 10^{16} "Phase II" (O(1 e^-/ns) @ >8 GeV)

LDMX Phase I Detector Concept



Tagger and Recoil Trackers

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Silicon strip trackers will be similar to the HPS Silicon Vertex Tracker

- Fast (2 ns time resolution)
- Meets radiation tolerance requirements

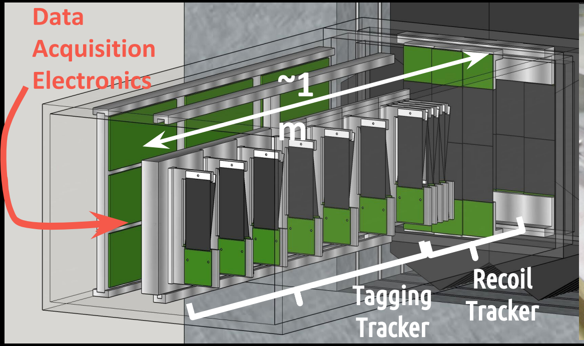
Tagging tracker ⟶ 7 measurement stations composed of two sensors at small angle stereo

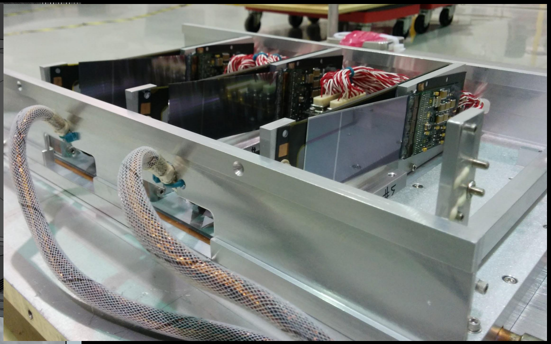
- Used to select against off-energy e^-

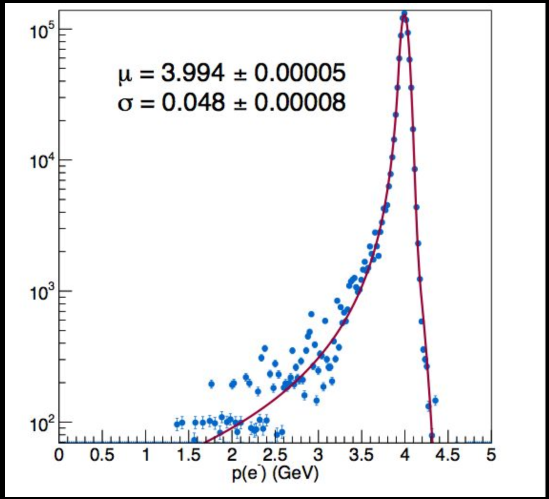
Recoil tracker ⟶ 4 stations composed of sensor pairs at small angle stereo + 'axial only' layers

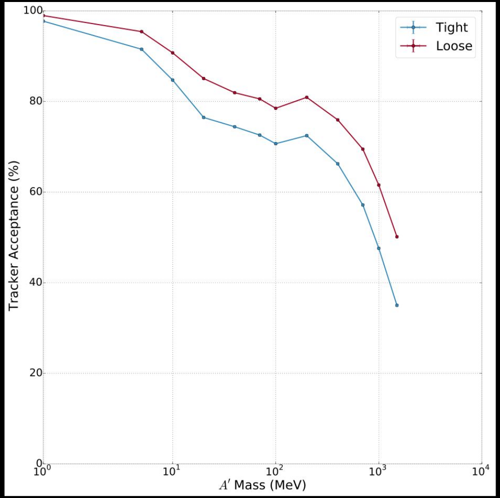
Single 18D36 dipole magnet ⟶ Two field regions

- Tagging tracker in central 1.5T field
- Recoil Tracker in fringe field





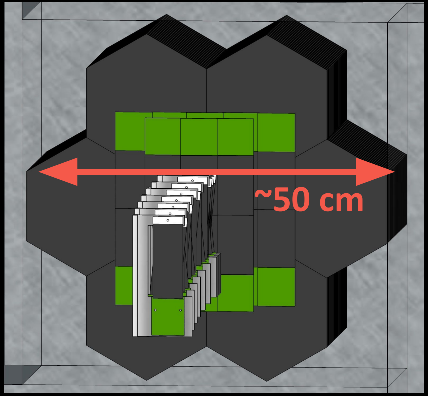




Electromagnetic Calorimeter

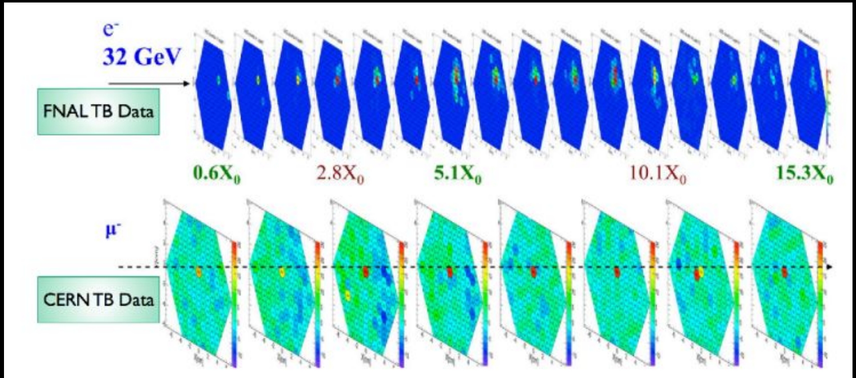
Si-W calorimeter developed for CMS upgrade

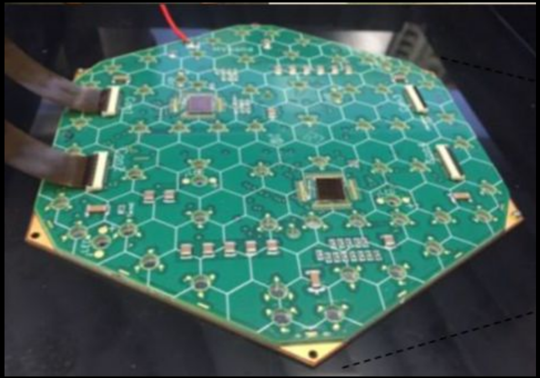
- Fast, dense, granular for high occupancies ⟶ Allows for exploitation of both longitudinal and transverse shower shapes
- Deep (40 X_0) for extraordinary EM containment



For LDMX

- Easily withstands the effective fluence of 10^{13} n/cm^2 caused by 10^{14} e^-'s on target
- Can provide fast trigger for trackers (~3 μs)
- Is capable of MIP tracking which will help with background rejection.



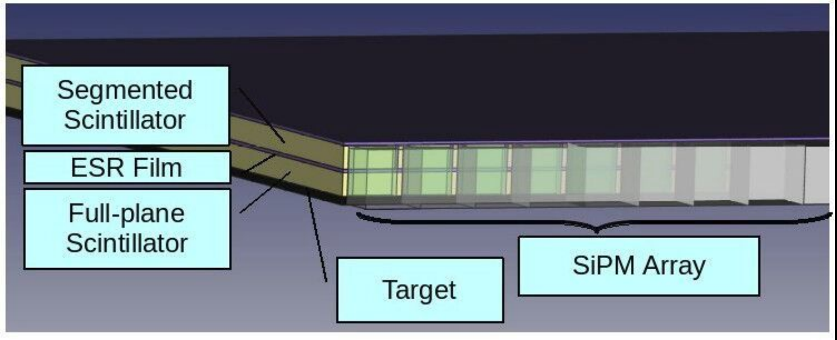


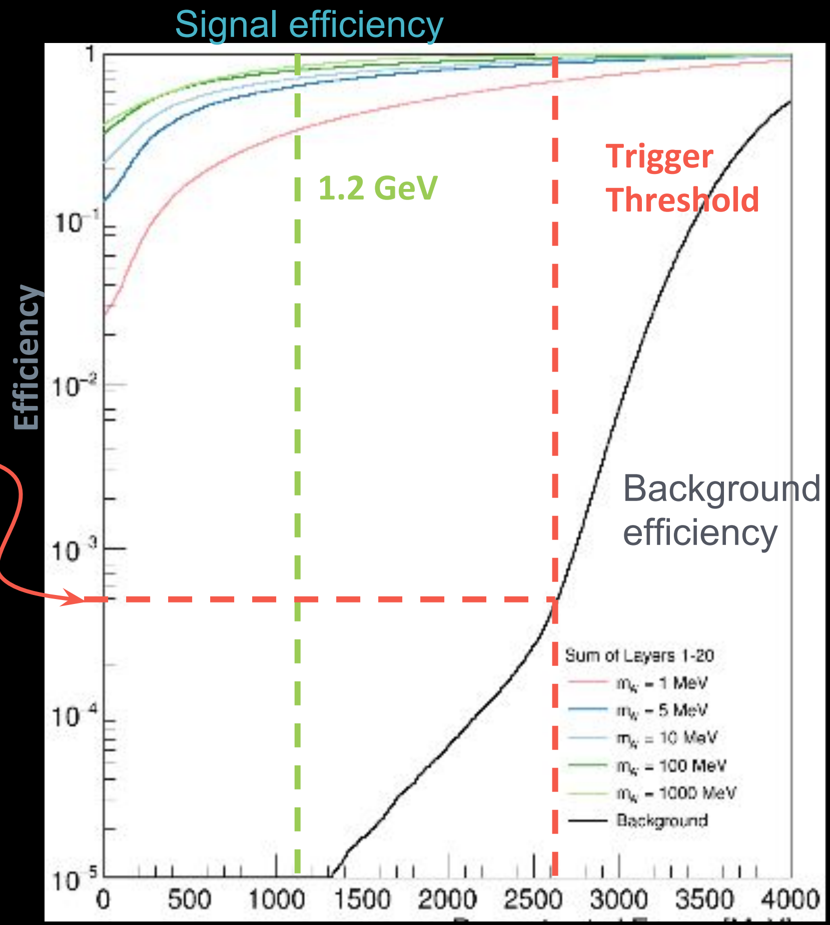
Trigger

Trigger makes use of Ecal and trigger scintillator pad downstream of the target to reject beam backgrounds

- Apply a cut on the sum of the first 20 Ecal layers
- Scintillator pad used to count the number of incident electrons ⟶ Allows setting of trigger threshold

3×10^{-4} background rejection!

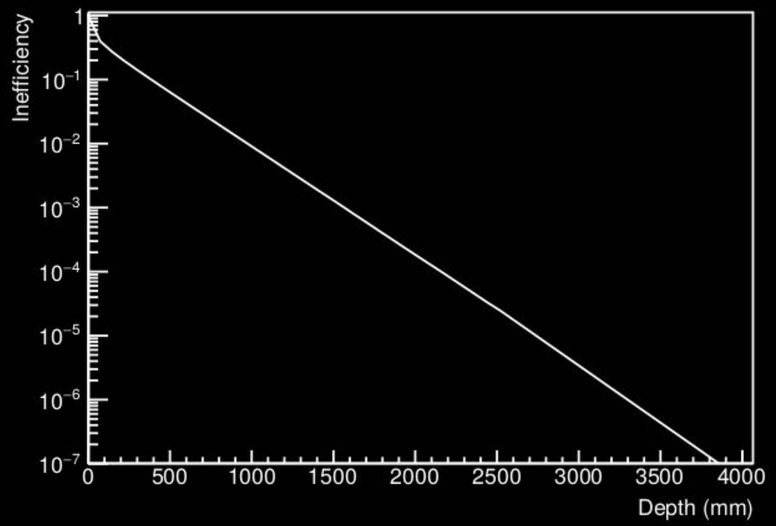


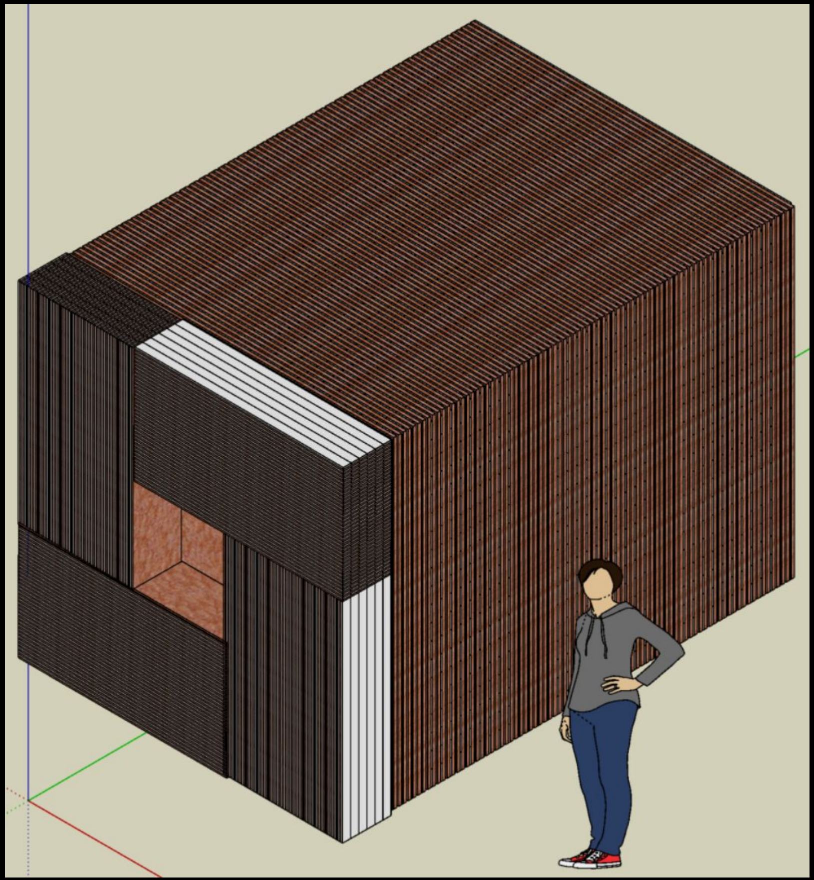


Hadronic Calorimeter

Makes use of CMS upgrade hardware
- Steel absorber/plastic scintillator
- SiPM readout via WLS fibers

Surround ECal as much as possible
- Many PN events have a high multiplicity of soft neutral hadrons
- Also catches wide-angle brems (≳ 25 deg.)





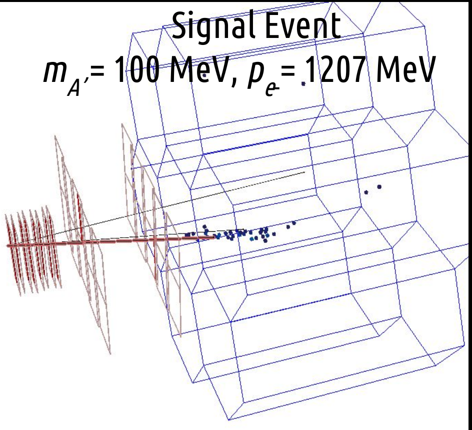
Rejecting Backgrounds

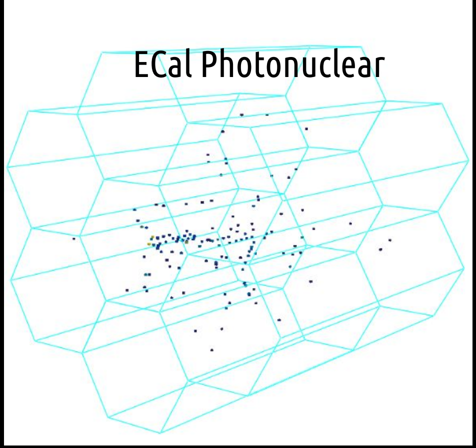
Photo/electronuclear as well as muon conversion backgrounds can occur in the target, recoil tracker or Ecal

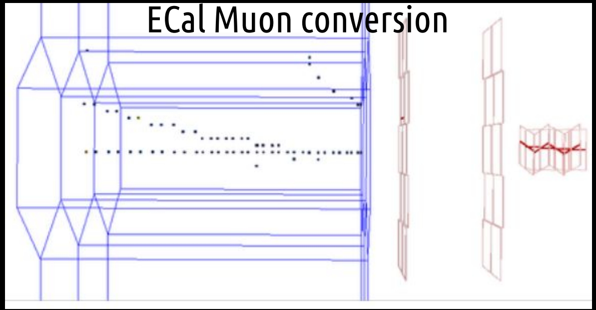
Have several handles that can be used to veto these backgrounds

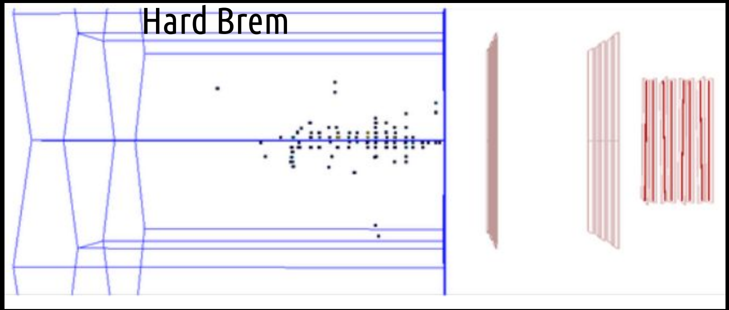
- Last layers of Tagger tracker → used to reject PN/EN from the target
- Recoil tracker → used to reject PN/EN and muon conversions that occur the target and recoil tracker
- Ecal - Use boosted decision tree to reject both target PN/EN and Ecal PN → Ecal EN is not a concern
- Hcal can be used to reject all backgrounds types

Initial studies using a veto making use of information from each subsystem was able to eliminate all photonuclear events from a sample equivalent to 10^{14} e^- on target!

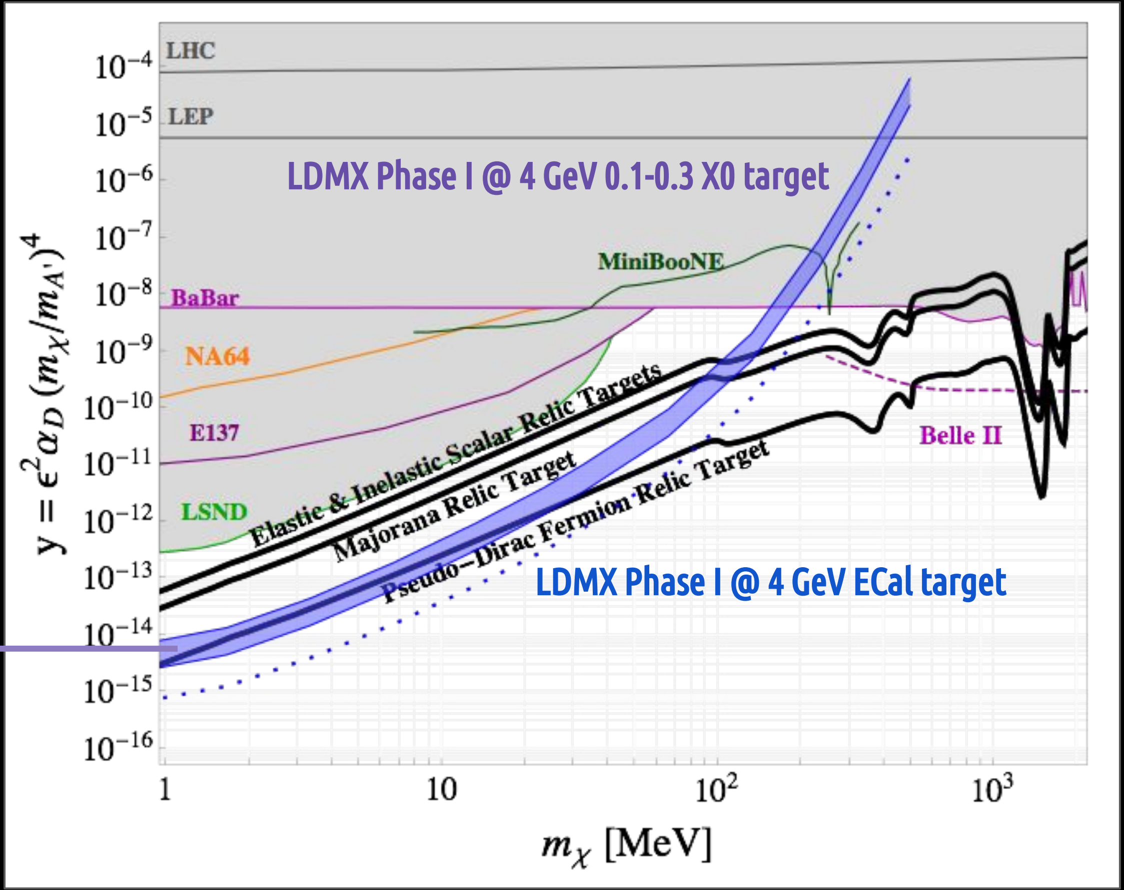






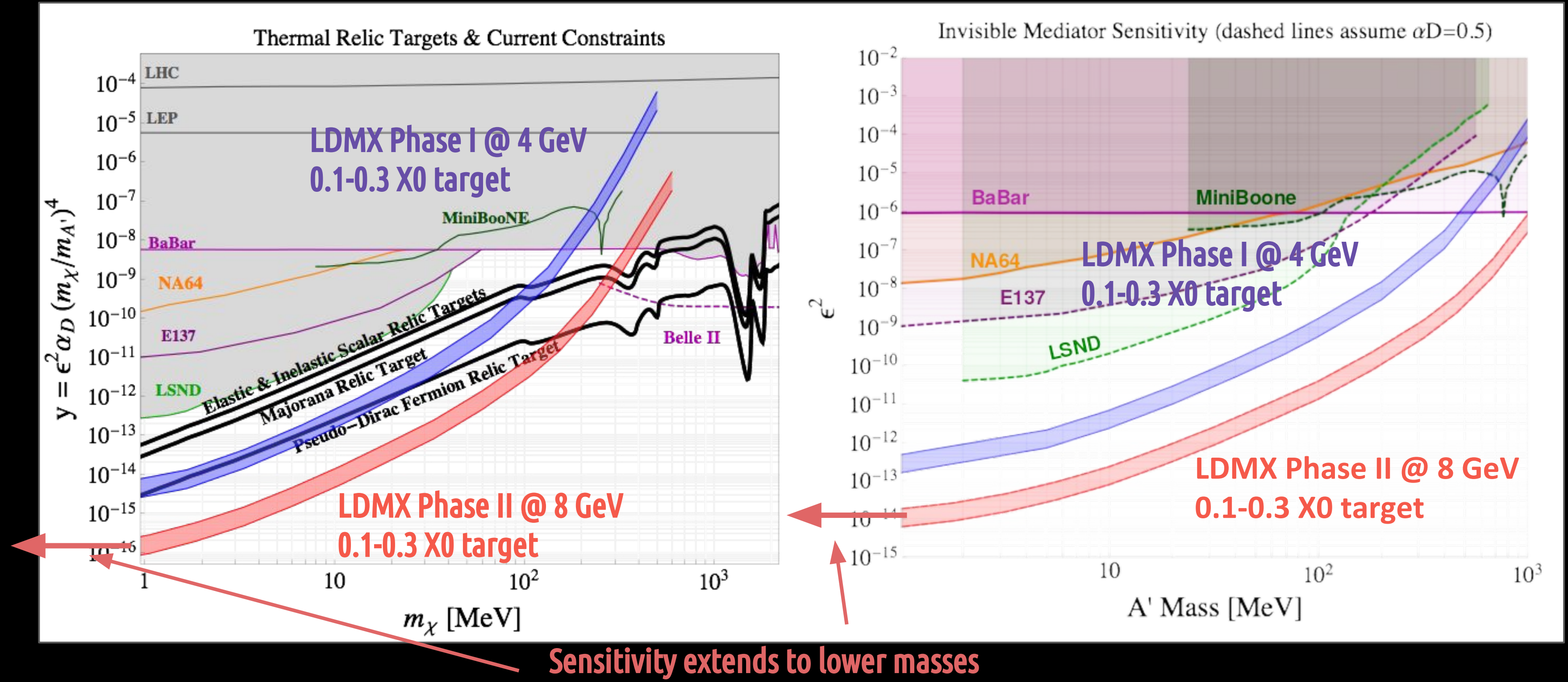


LDMX Phase I Reach



Sensitivity extends to lower masses

LDMX Phase II Reach



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Summary and Outlook

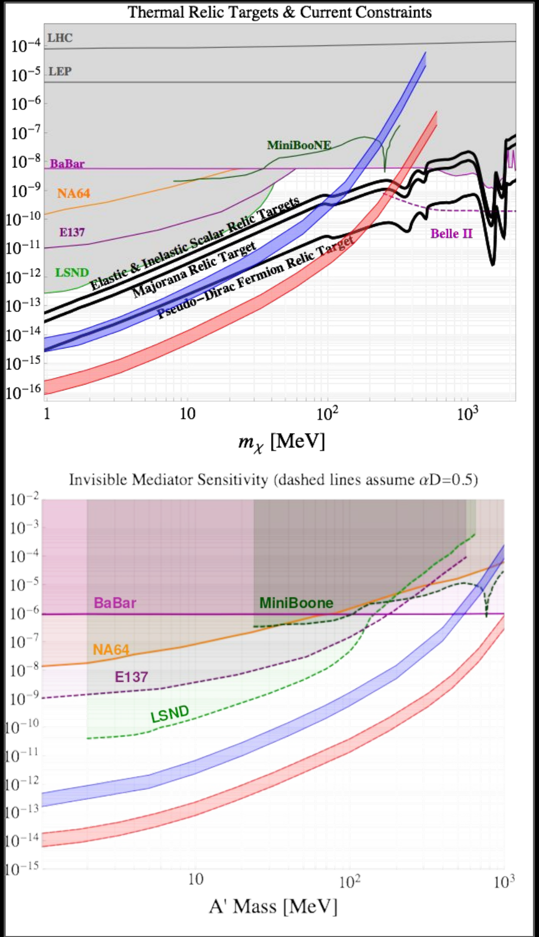
Accelerator-based DM searches have unique sensitivity in the MeV-GeV range.

Missing Momentum experiments provide best sensitivity per luminosity.

LDMX can robustly reach all thermal targets over most of the MeV-GeV range and probe other physics models.

Broad physics potential: LDMX can probe sub-GeV dark sectors that couple weakly to electrons, and the physics of photo- and electro-nuclear collisions.

- **Sub-GeV dark matter production**
- **Sub-GeV invisibly decaying mediators**
- Displaced vertex signatures that arise from visibly decaying mediators
- Displaced electron-positron showers that arise from 'DM co-annihilation' models
- Sub-GeV axion-like particles
- Milli-charge particles
- Dark Vectors decaying to neutrinos
- Photonuclear and electronuclear measurements of interest for neutrino experiments --> drive to understand nuclear final state interactions



Backup

U.S. Cosmic Visions New Ideas in Dark Matter

"A workshop focusing on potential new small-scale projects in the U.S. Dark Matter search program"

https://indico.fnal.gov/conferenceDisplay.py?confId=13702

Whitepaper (> 200 authors) coming soon … stay tuned!

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

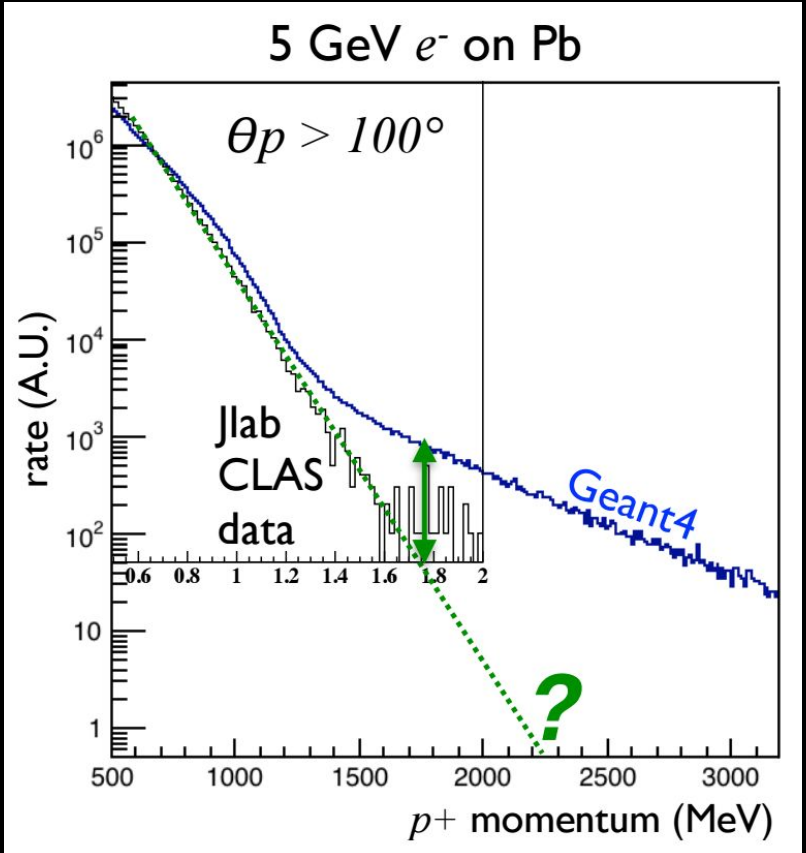
Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,10] Joseph Incandela (Coordinator),[11] Eder Izaguirre (WG3 Convener),[12] Daniel McKinsey (WG1 Convener),[13] Matthew Pyle (SAC member),[13] Natalie Roe (Coordinator),[14] Gray Rybka (SAC member),[15] Pierre Sikivie (SAC member),[16] Tim M.P. Tait (SAC member),[7] Natalia Toro (SAC co-chair),[9,17]

Photonuclear Events in Geant4

Geant4 produces surprising number of events with enormous momentum transfer to recoiling nucleus.

- With high energy secondaries emitted at large angles, these are very difficult events to veto.
- Geant4 is not tuned to data in this regime, which is sparse in the literature.
- Energy/angle spectra from data provide evidence for a universal exponential fall-off, suggesting that Geant4 rates in this regime are overestimated by orders of magnitude.

The validity of all simulations is questionable, so we are working to identify data we can use as a reference point to tune the MC and validate our photonuclear rejection performance.



Rejecting Muon Conversions

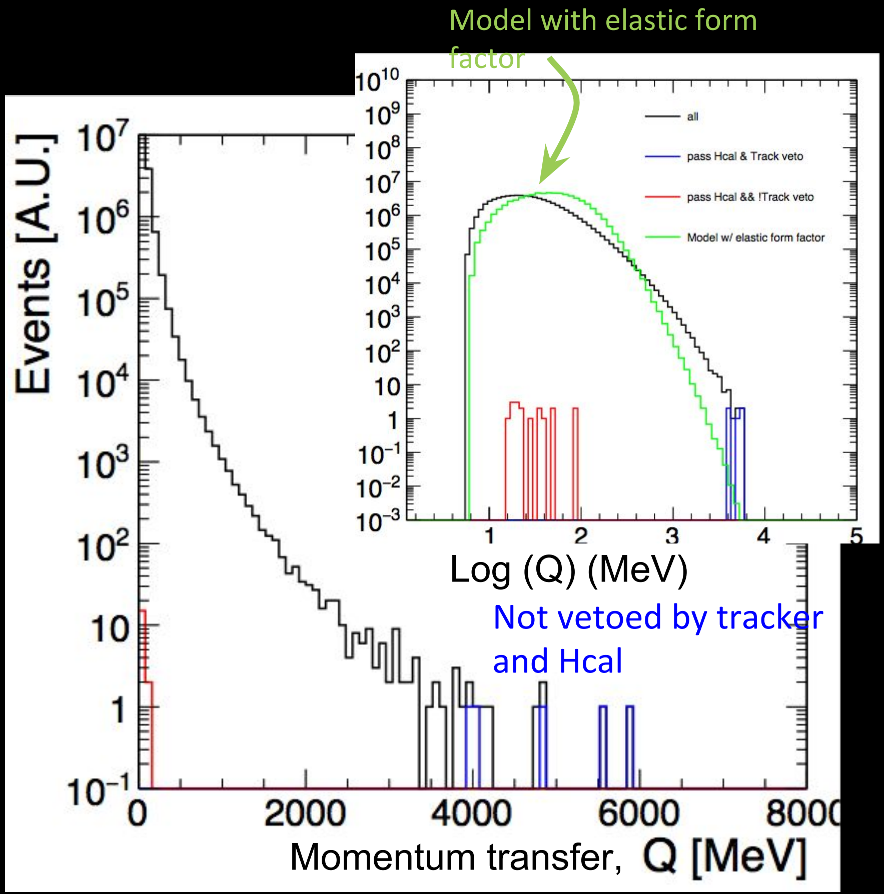
Di-muon backgrounds can occur in the target, recoil tracker or Ecal

Have several handles that can be used to veto these backgrounds

- Recoil tracker → (for $\gamma \to \mu+\mu-$ in target & recoil tracker)
- Ecal
- Hcal

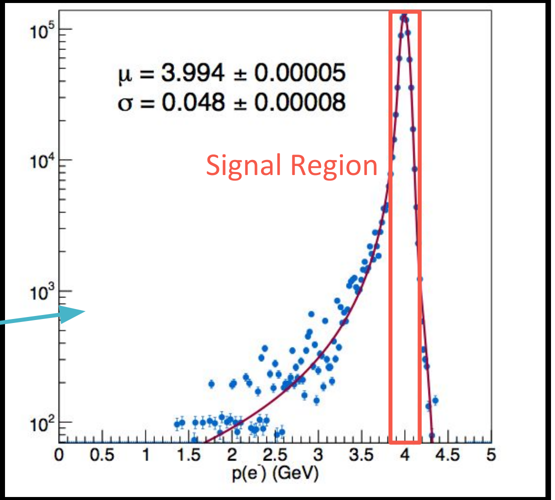
An initial veto using only tracker and HCal eliminates all but a few events where both muons are emitted at ≳90° for ~10^{14} EOT.

Geant4 also grossly overestimates rate of $\gamma \to \mu+\mu-$ events with extremely high q^2.

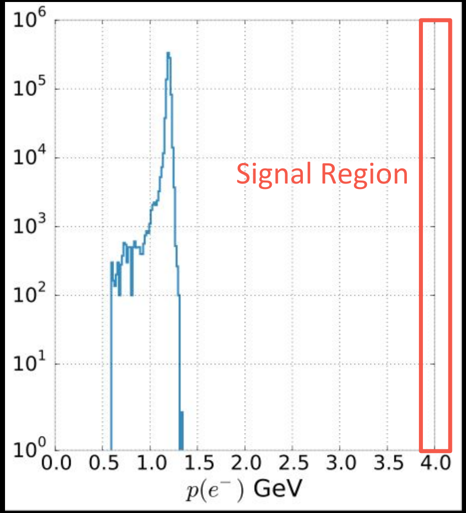


Tagging Tracker Performance

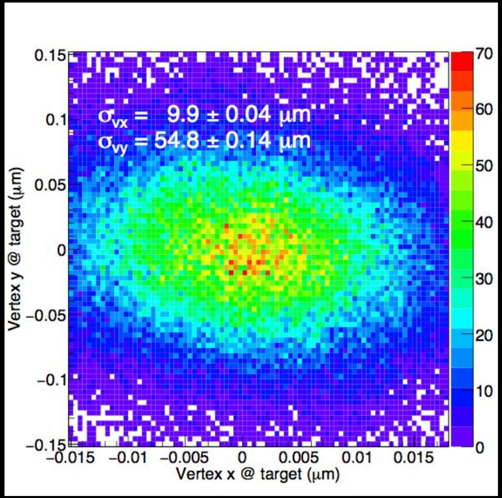
4.0 GeV e^- on 10% X0



1.2 GeV e^- worse case scenario



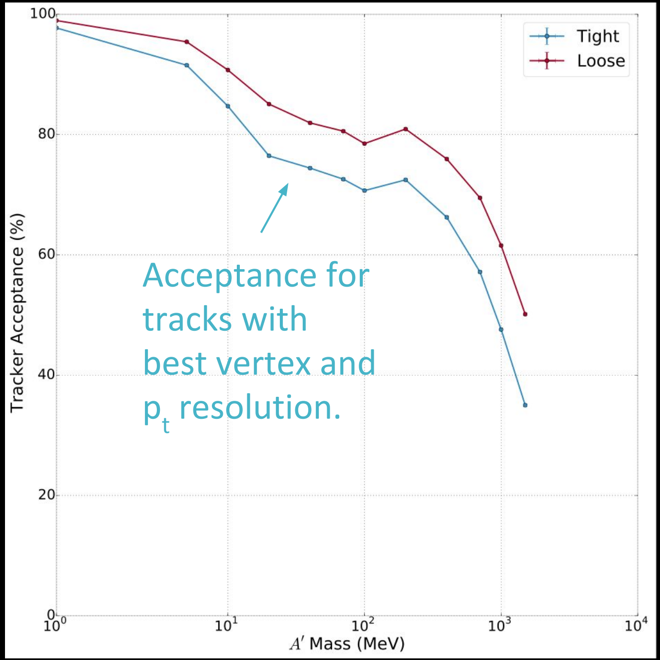
Momentum resolution of ~1% allows **rejection of off-energy components in beam**



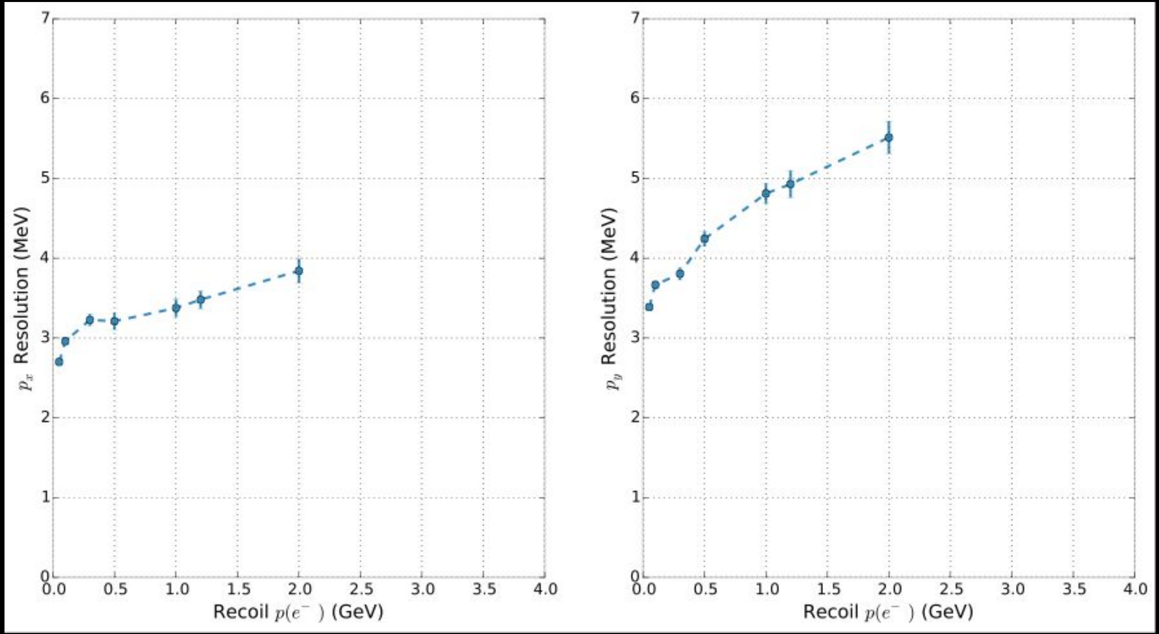
Momentum Resolution at target is small compared to 4 MeV smearing from multiple scattering in 10% X0 target ⟶ **Good p_T resolution**

Recoil Tracker Performance

Good acceptance over a wide range of A′ masses



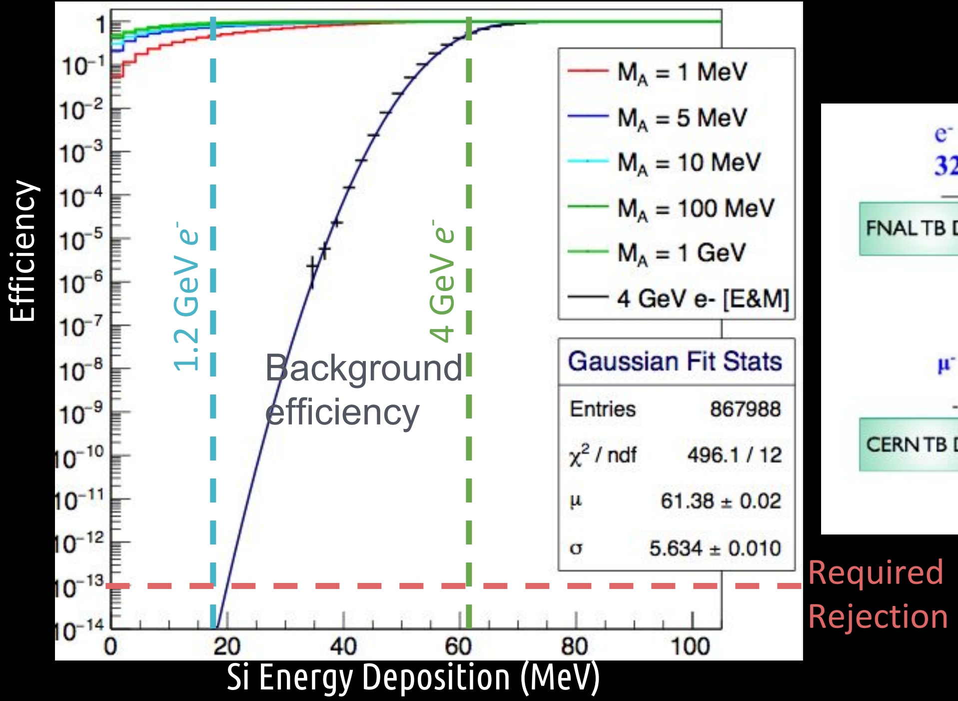
Acceptance for tracks with best vertex and p_t resolution.



Delivers best possible resolution for p_T

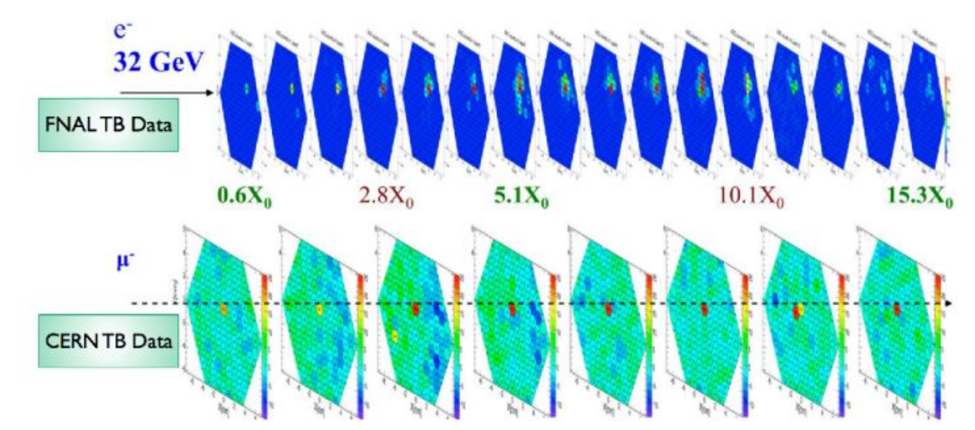
Ecal Performance

Ecal can distinguish EM showering backgrounds from signal (<1.2 GeV e^-) for Phase I



ECal can track minimum ionizing particles (MIPs), important for rejection of $\gamma \to \mu+\mu-$ and $\gamma \to$ photonuclear events.

CERN and FNAL Test Beam Data



LDMX Collaboration

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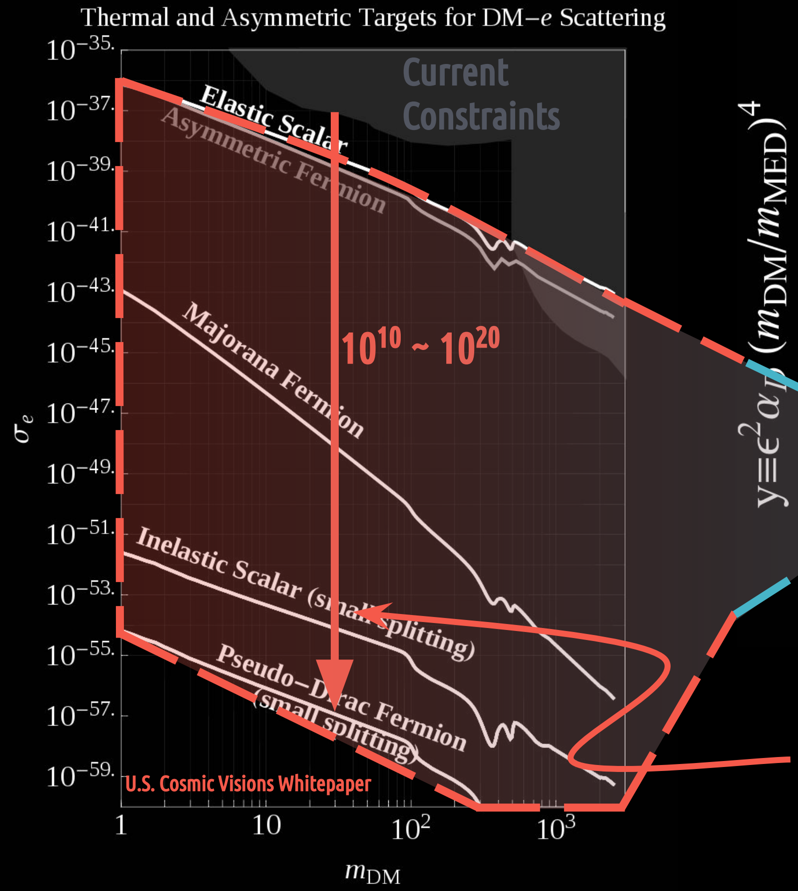
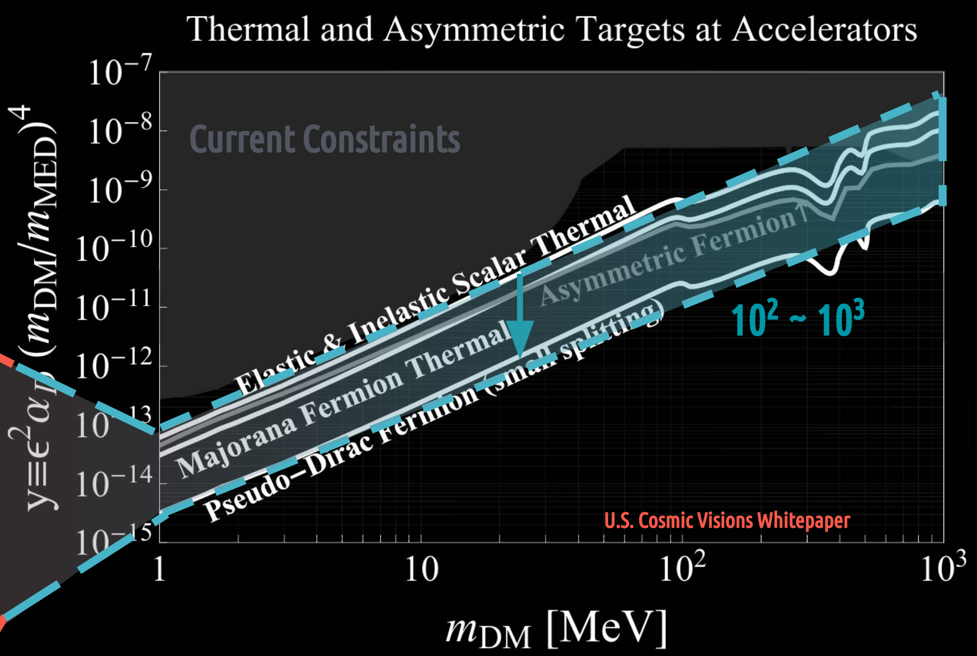
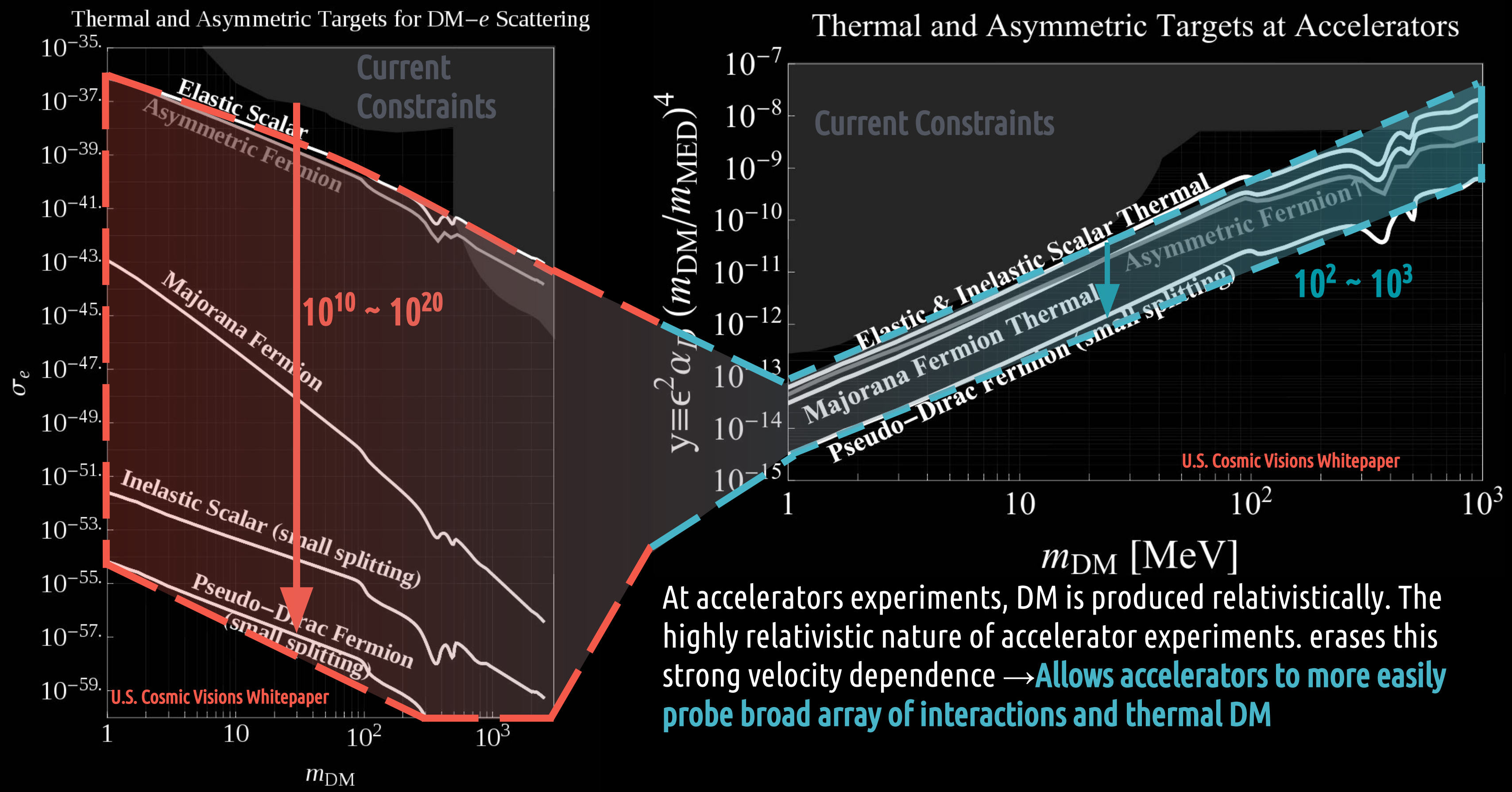
Comparison to Direct Detection





There is a strong dependence of the direct detection (DD) cross-section on the DM halo velocity that leaves several thermal targets out of the reach of current DD experiments.

Comparison to Direct Detection

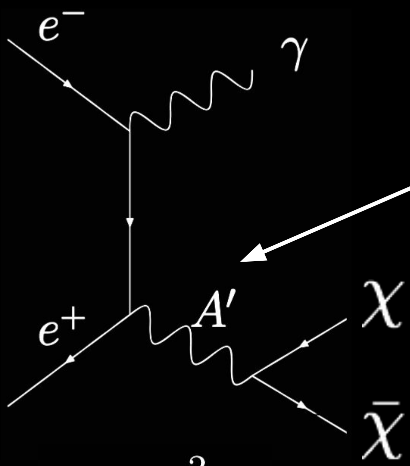


At accelerators experiments, DM is produced relativistically. The highly relativistic nature of accelerator experiments. erases this strong velocity dependence →**Allows accelerators to more easily probe broad array of interactions and thermal DM**

Accelerator Based Searches

Maximize dark mediator (A') production $\longrightarrow$ Greater LDM yields

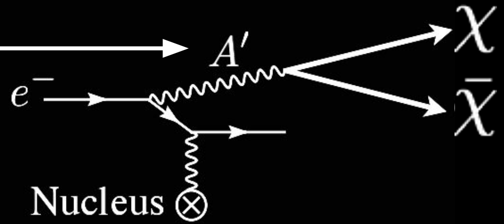
Colliders



$$\sigma \propto \frac{\epsilon^2}{E_{\mathrm{cm}}^2}$$

On shell or off shell

Fixed Target



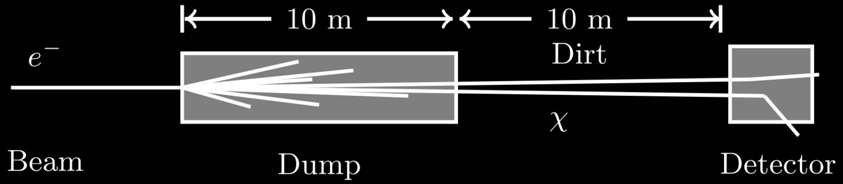
$$\sigma \propto \frac{Z^2\epsilon^2}{m_{\mathrm{A'}}^2}$$

Dark bremsstrahlung allows large yield of light DM to be generated!

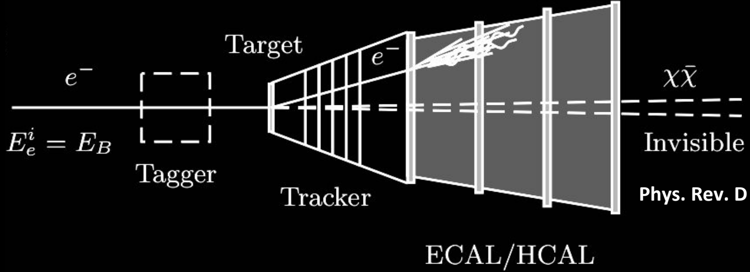
Fixed Target: Beam Dump vs Missing Momentum

Beam Dump

arXiv:1607.01390



Missing Momentum



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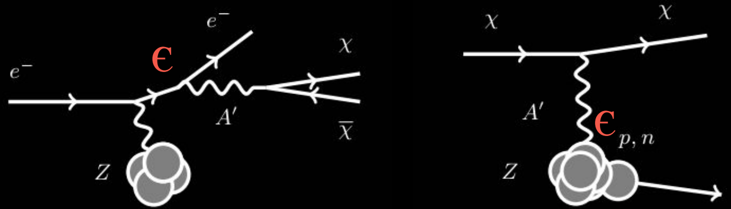

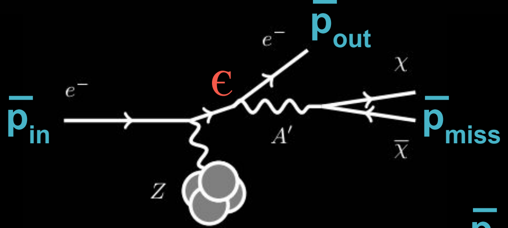

$\bar{p}_{in} = \bar{p}_{out} + \bar{p}_{miss}$

$N \propto \epsilon^4$ ≪ $N \propto \epsilon^2(1-\epsilon^2) \approx \epsilon^2$

Missing momentum approach results in the highest signal yields!