

# The Light Dark Matter Experiment

Omar Moreno **SLAC** on behalf of the LDMX Collaboration

**Fermilab**

**UCSB**



**SLAC**

**Caltech**

**SCIPP**

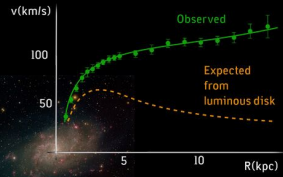
Santa Cruz Institute for Particle Physics



**LUND**  
UNIVERSITY

Thirteenth Conference on the Intersections of Particle and Nuclear Physics  
May 29 - June 3, 2018  
Palm Springs, California

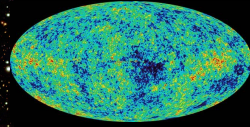
There is strong evidence for the existence of Dark Matter, but it continues to elude us!



Galactic Rotation Curves



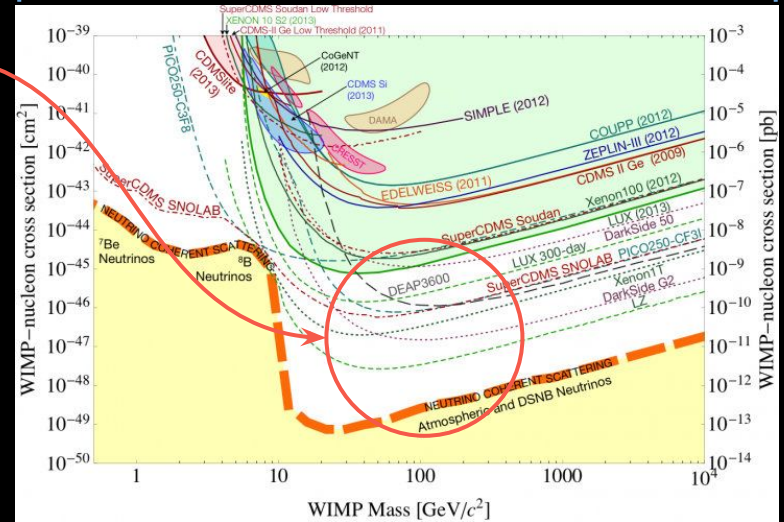
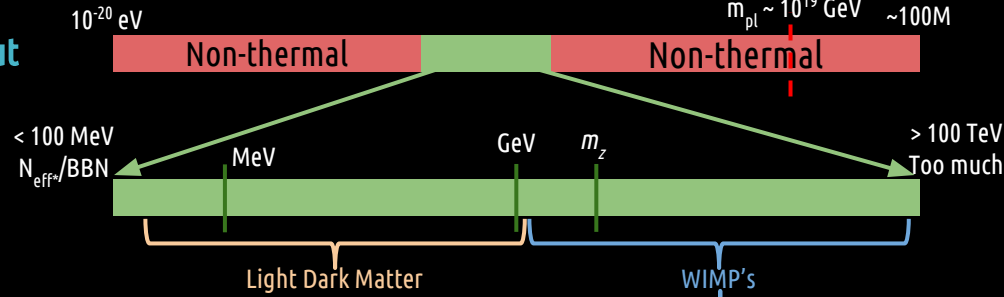
Gravitational Lensing



Structure of Cosmic Microwave Background

Broad and impressive program has been built to understand Weakly Interacting Massive Particle (WIMP) Dark Matter, but searches for them in the most favorable areas have yielded nothing ... will be ruled out or found by **SuperCDMS, LZ** or **LHC** in the coming years.

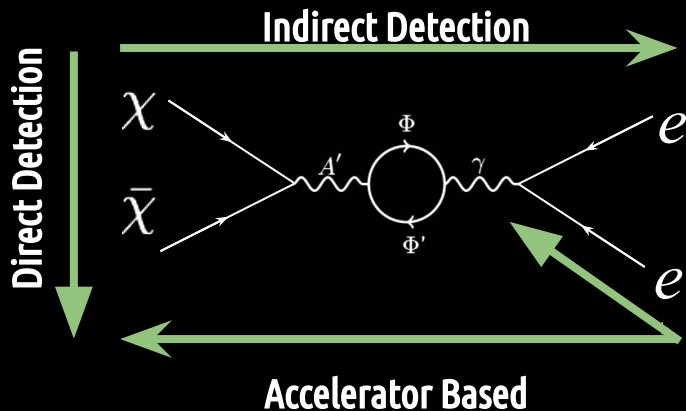
What about light ( $< 1$  GeV) thermal DM? Parameter space remains largely unexplored.



**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](#)

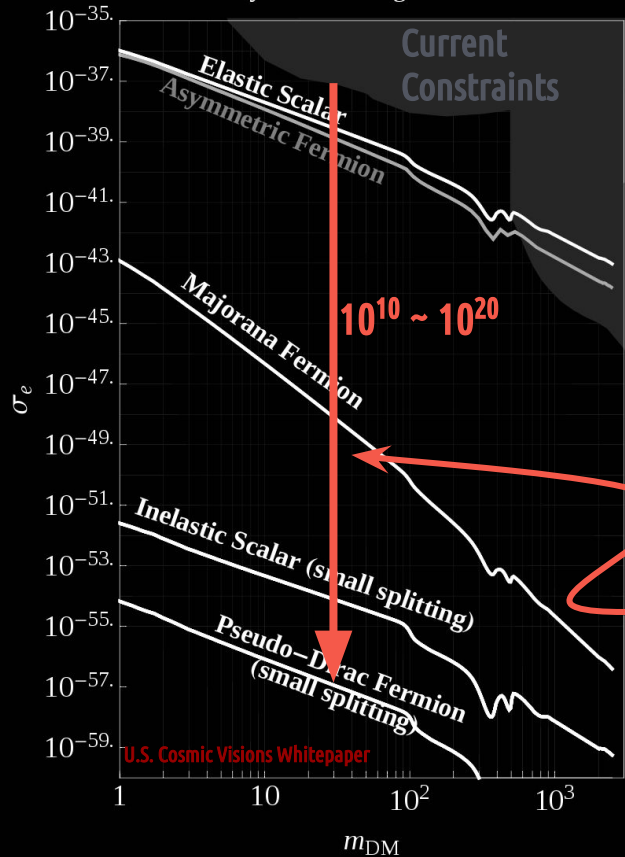
Given the complex structure of the Standard Model, a "Dark Sector" where dark matter interacts via a light mediator is an obvious scenario to test. It has been the focus of a broad array of searches and experiments for many years now.

As an example, let's focus on the case where DM interacts via a vector mediator

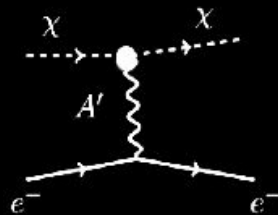


**Electron accelerators can play a major role in testing models of light dark matter!**

Thermal and Asymmetric Targets for DM–e Scattering

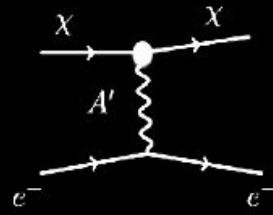


Scalar DM



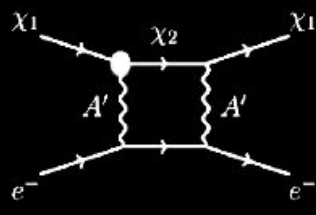
$$A'_{\mu} \chi^* \partial_{\mu} \chi$$

Majorana DM



$$A'_{\mu} \bar{\chi} \gamma^{\mu} \gamma^5 \chi$$

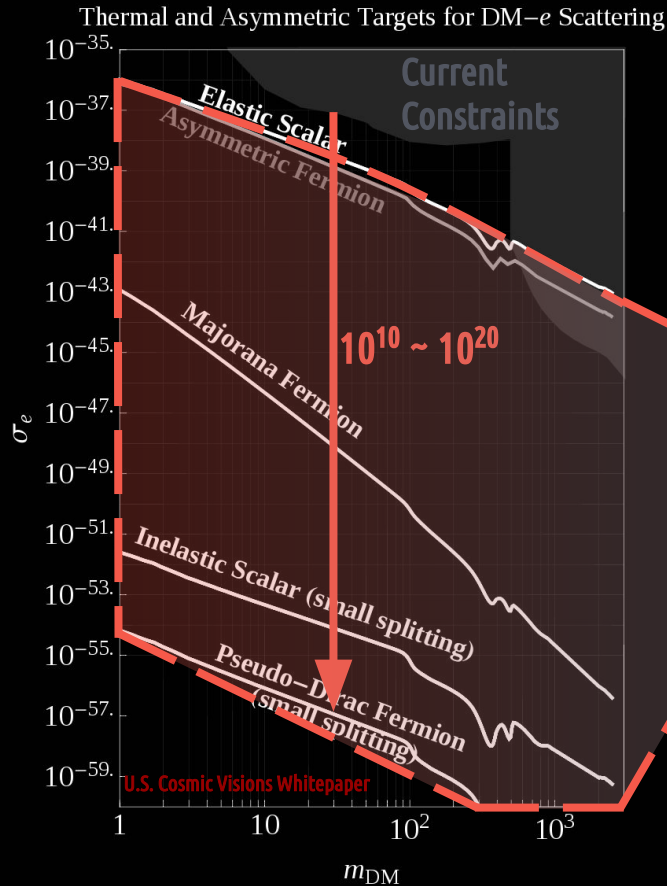
Pseudo-Dirac DM inelastic



$$A'_{\mu} \bar{\chi}_1 \gamma^{\mu} \chi_2$$

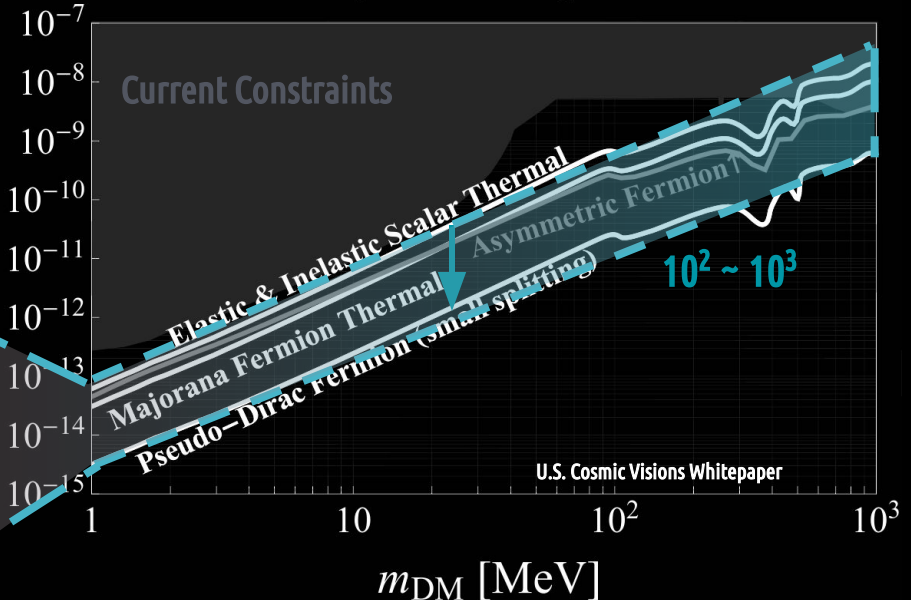
There is a strong dependence of the direct detection (DD) cross-section on the DM halo velocity that leaves several thermal targets out of the reach of current DD experiments.

U.S. Cosmic Visions Whitepaper



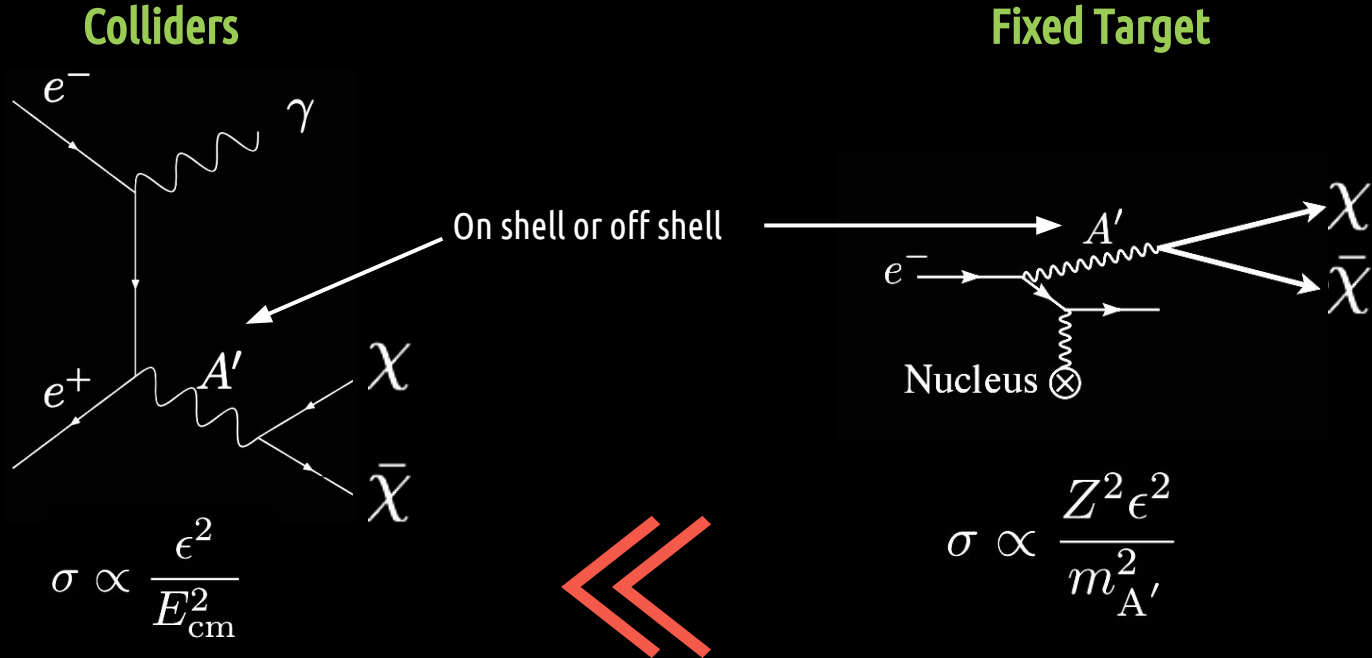
$$y \equiv \epsilon^2 \alpha_D^4 (m_{DM}/m_{MED})^4$$

Thermal and Asymmetric Targets at Accelerators



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**

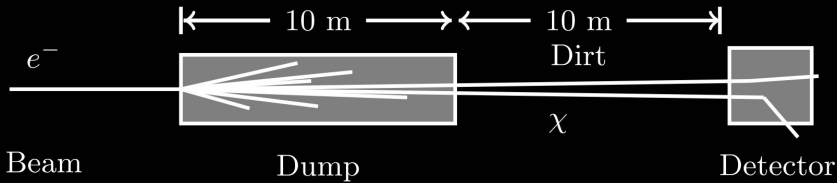
Maximize dark mediator ( $A'$ ) production  $\rightarrow$  Greater LDM yields



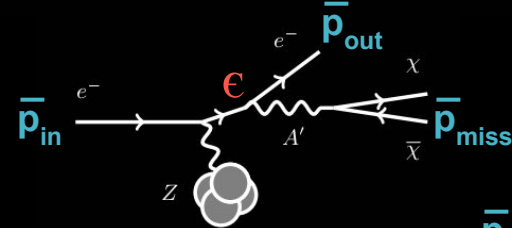
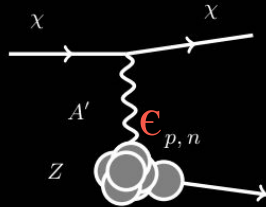
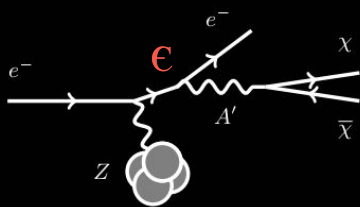
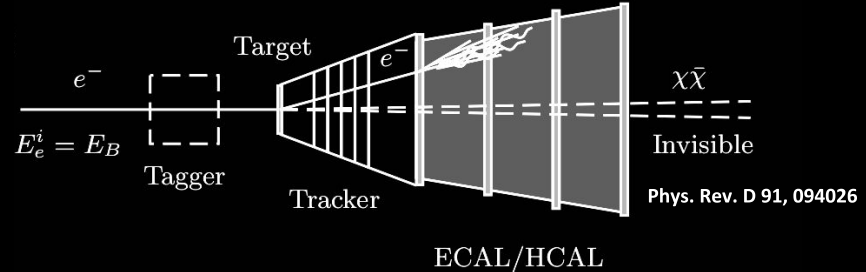
Dark bremsstrahlung allows large yield of light DM to be generated!

arXiv:1607.01390

## Beam Dump



## Missing Momentum



$$N \propto \epsilon^4$$

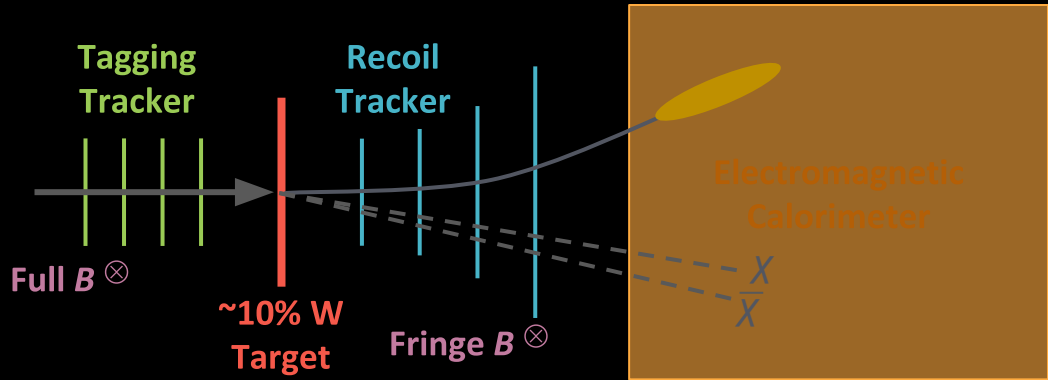


$$N \propto \epsilon^2(1-\epsilon^2) \approx \epsilon^2$$

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

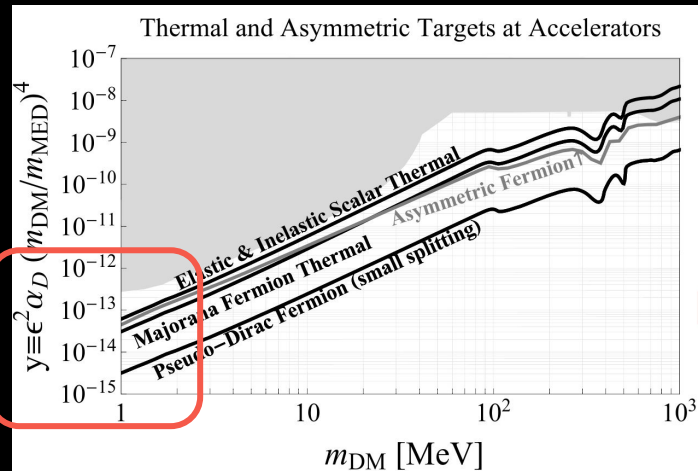
Missing momentum approach results in the highest signal yields!

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



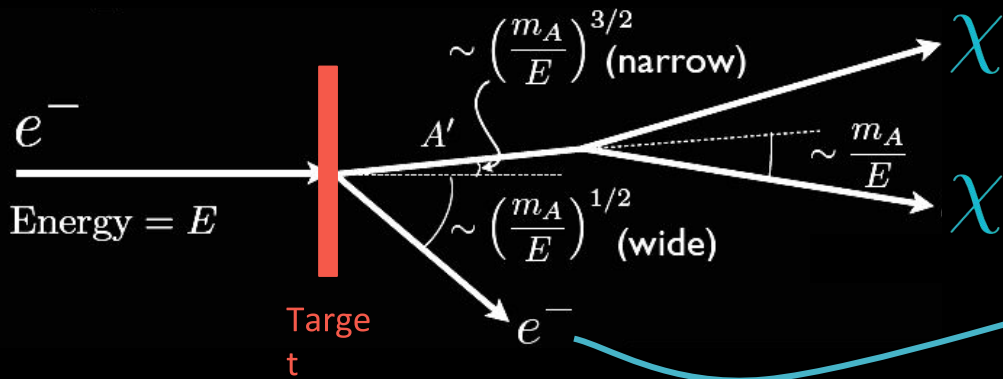
$$\sigma \propto e^2 \rightarrow N_{\text{signal}} \simeq N_{e^-} \times y|_{1 \text{ MeV}}$$

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





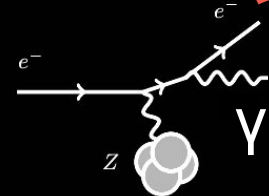
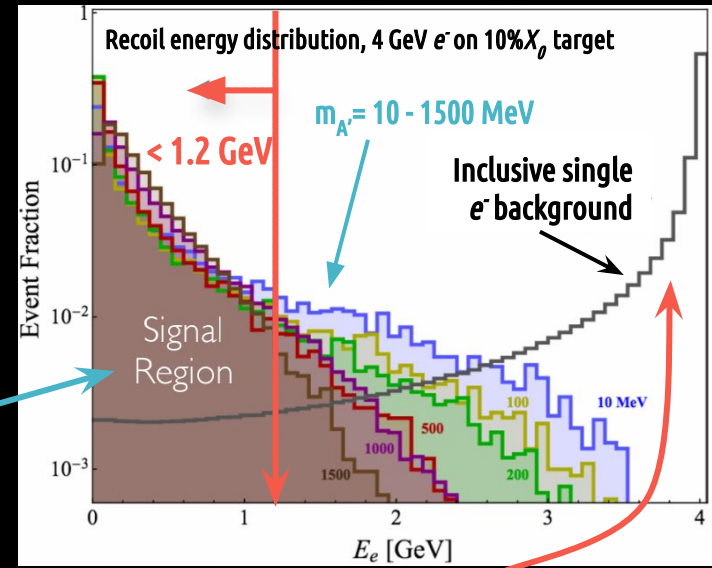
Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets



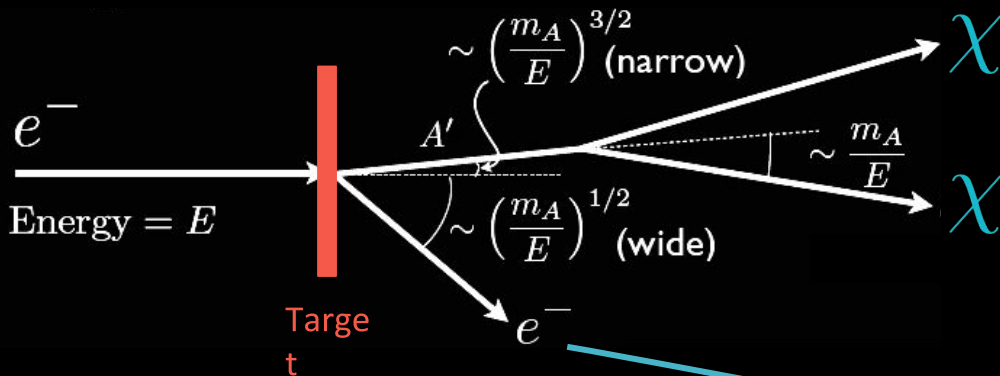
but with different rates and kinematics

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

Recoil kinematics allow efficient signal definition providing  $\sim 30\times$  background rejection!



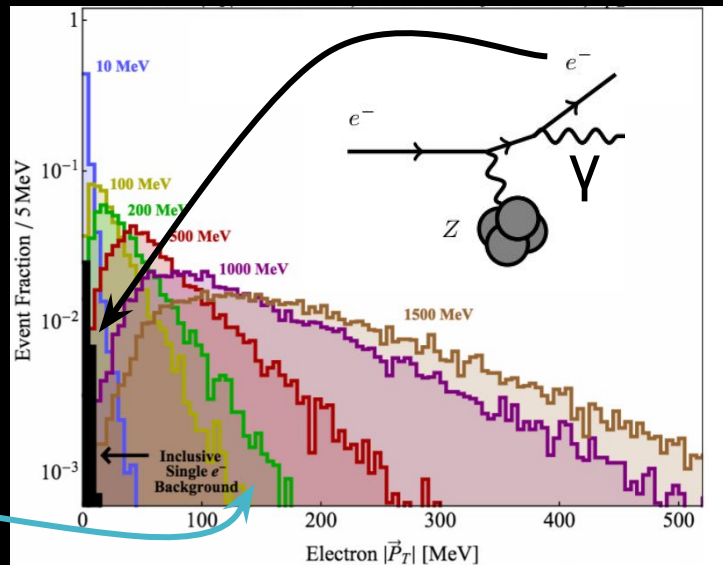
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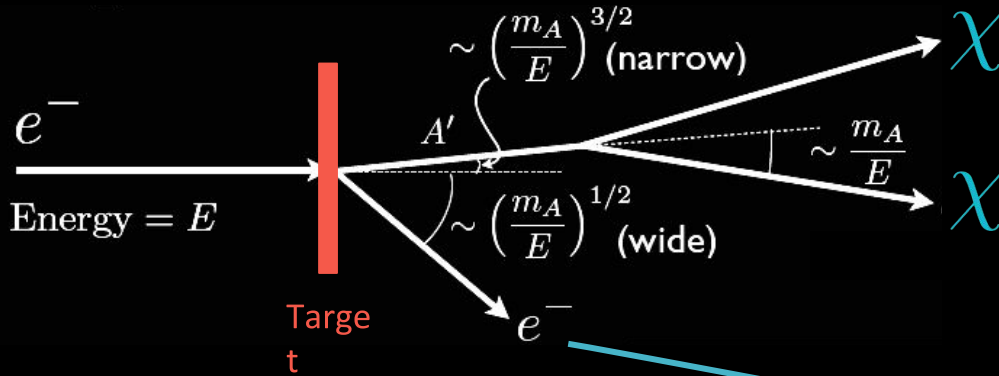
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$p_t$  is also an important experimental handle as it depends on the mass of the  $A'$



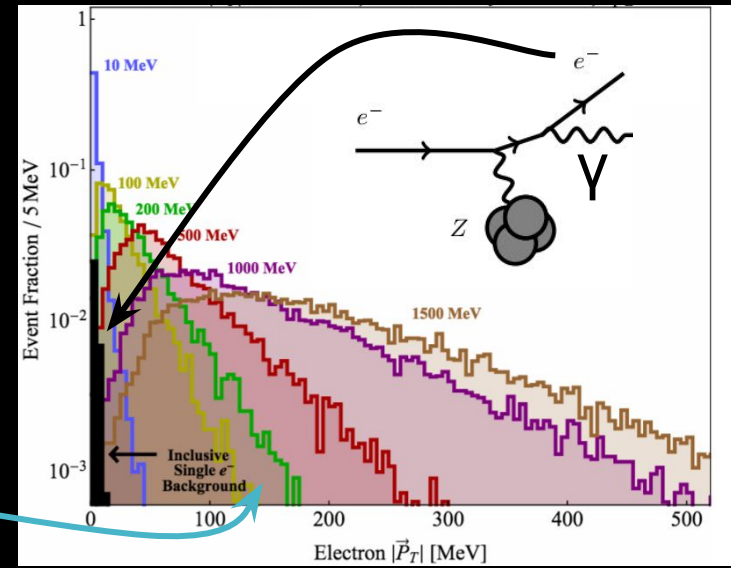
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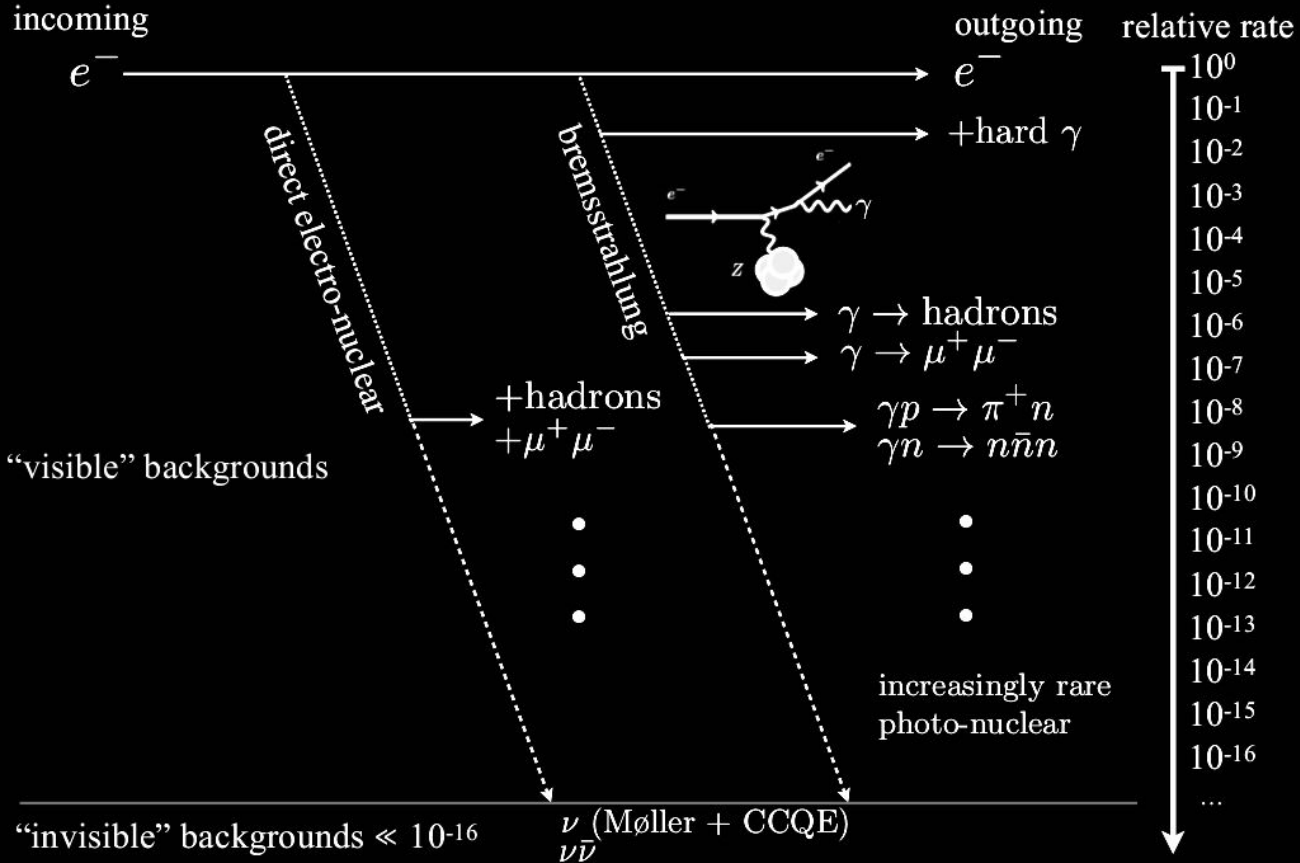
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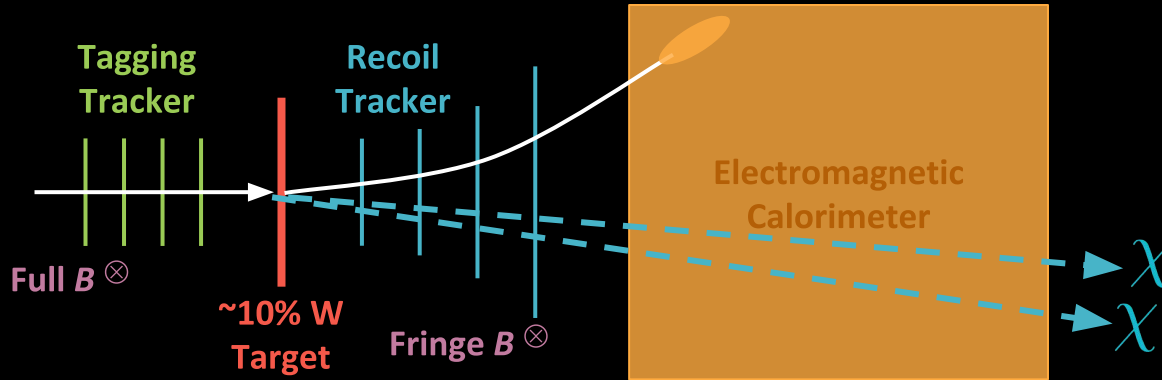
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**Goal: achieve zero background without using  $p_T$  as a signal discriminator**

# Missing Momentum Backgrounds





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

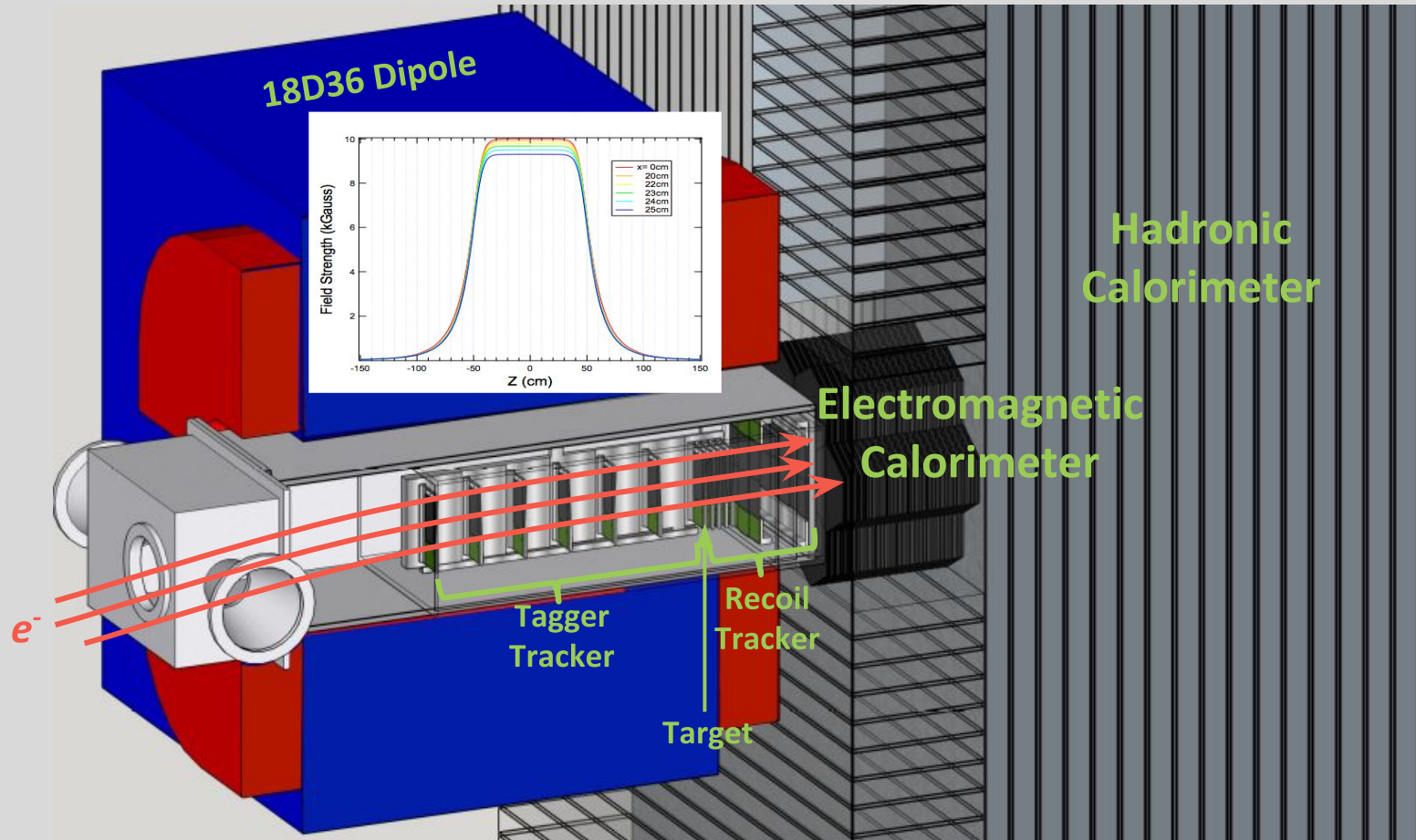
- ☛ A low-current, multi-GeV,  $e^-$  beam with high repetition rate ( $10^{16}/\text{year} \approx 1 e^-/3 \text{ ns}$ ).
- ☛ The possibilities are DASEL @ SLAC (4/8 GeV) and CERN and CEBAF @ JLab ( $< 11 \text{ GeV}$ )
- ☛ large beamspot ( $\sim 10 \text{ cm}^2$ ) to spread out otherwise extreme rates 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  $\Rightarrow$  Two-stage approach to LDMX:  $4 \times 10^{14}$  "Phase I" ( $1 e^-/25 \text{ ns @ } 4 \text{ GeV}$ ) followed by  $10^{16}$  "Phase II" ( $O(1 e^-/\text{ns}) @ >8 \text{ GeV}$ )

# LDMX Phase I Detector Concept

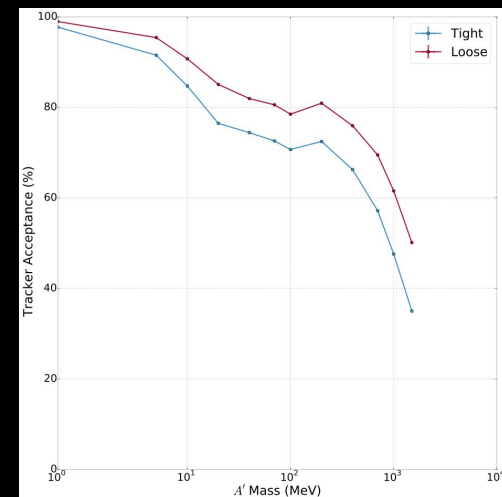
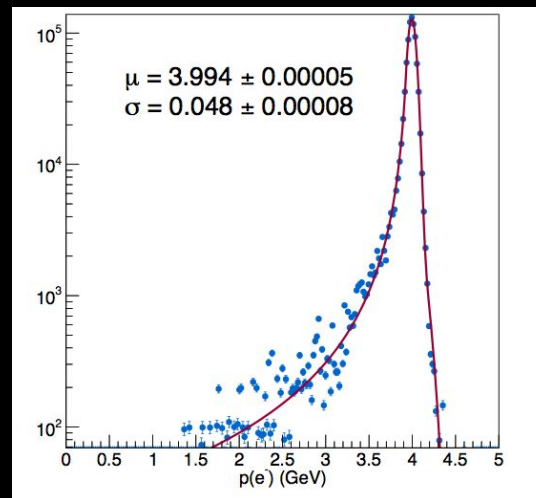
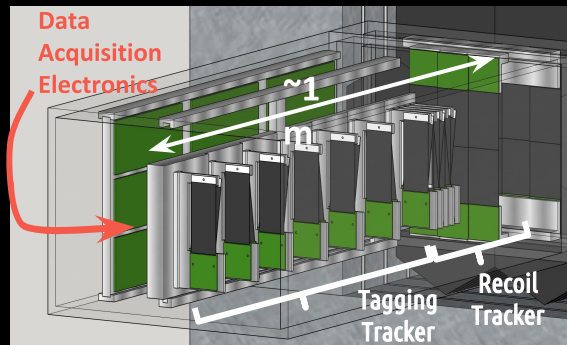


Silicon strip trackers will be similar to the HPS Silicon Vertex Tracker

- ☸ 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

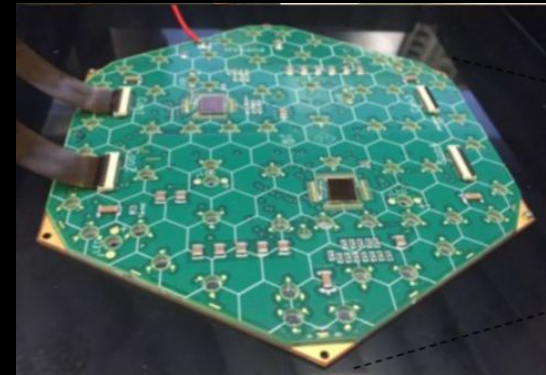
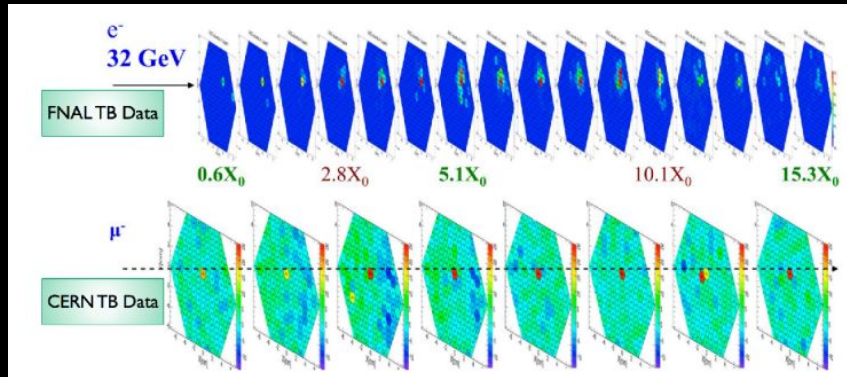
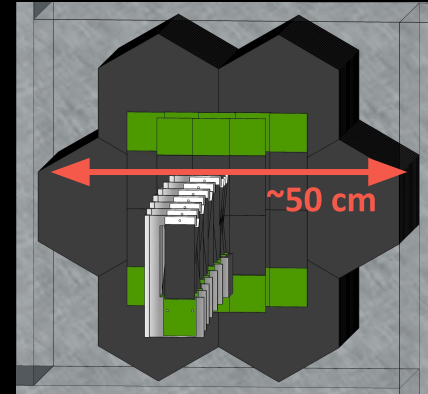


Si-W calorimeter developed for CMS upgrade

- 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 ( $\sim 3 \mu s$ )
- Is capable of MIP tracking which will help with background rejection.

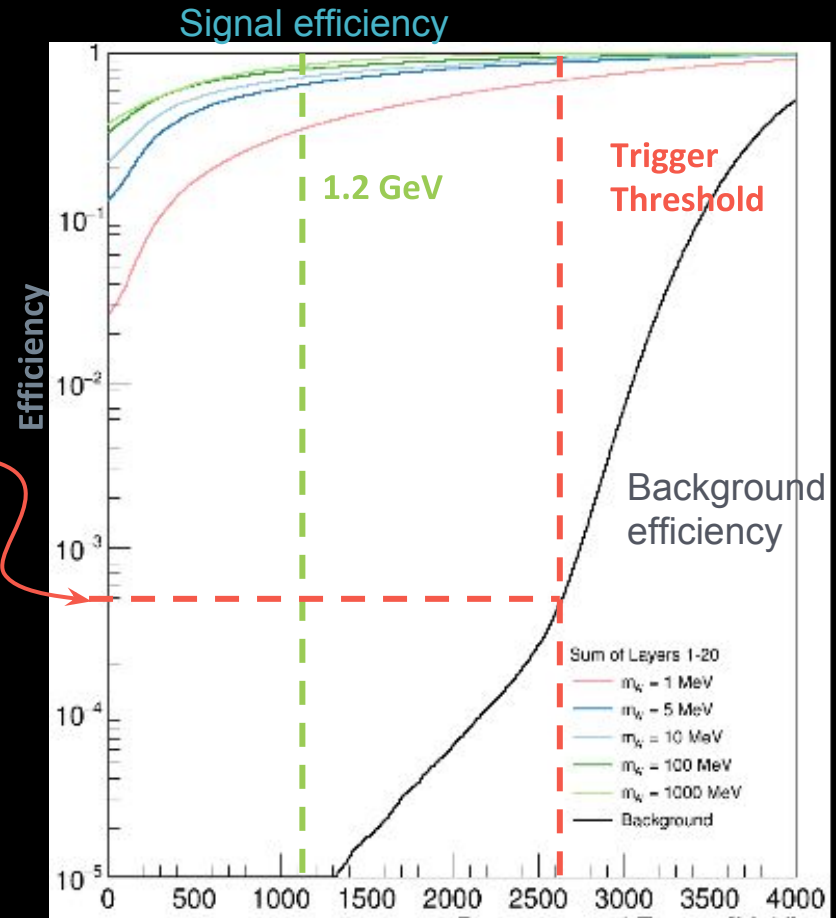
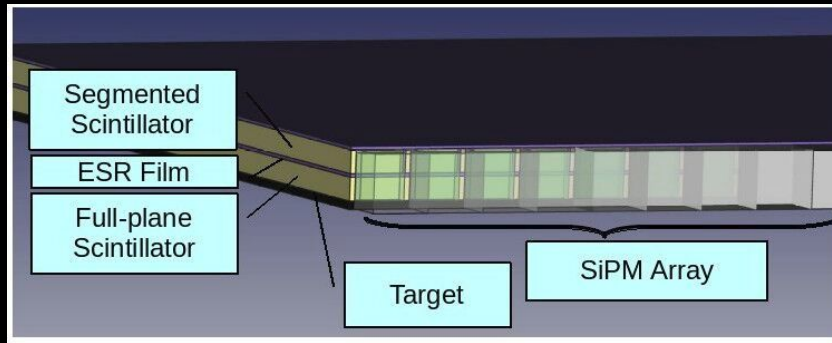




Trigger makes use of Ecal and trigger scintillator pad downstream of the target to reject beam backgrounds

- 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

$3 \times 10^{-4}$  background rejection!

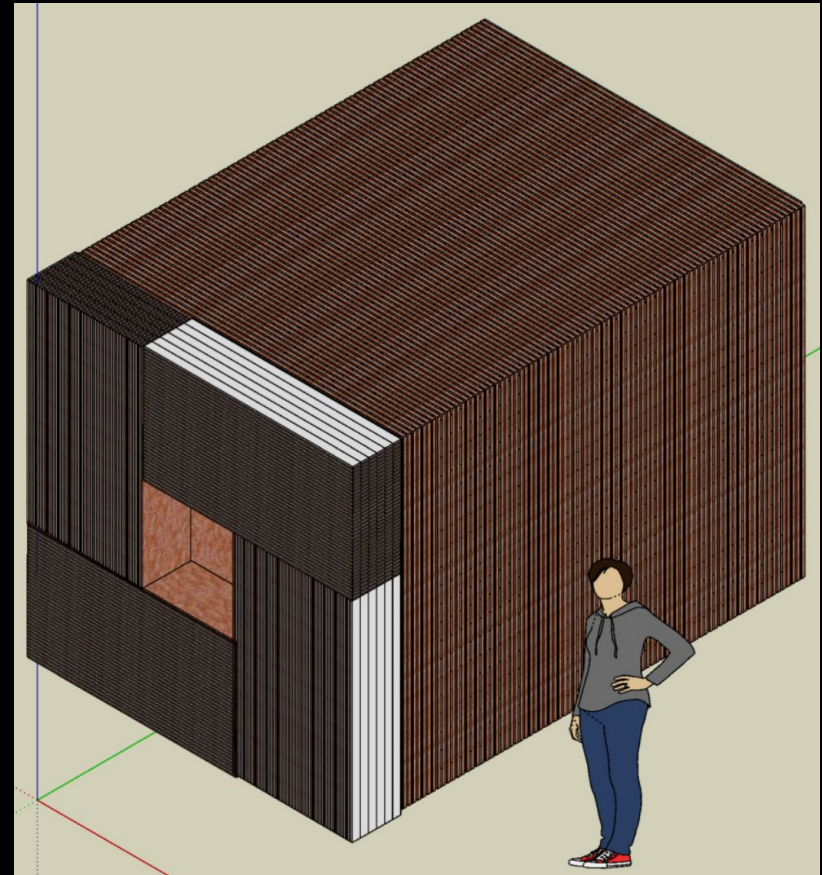
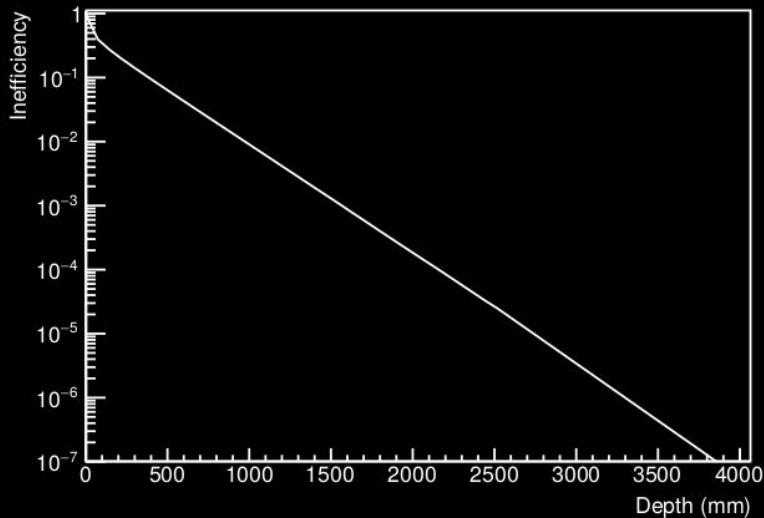


Makes use of CMS upgrade hardware

- 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 ( $\gtrsim 25$  deg.)

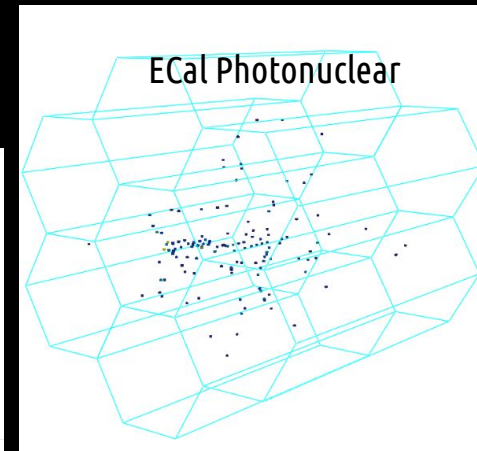
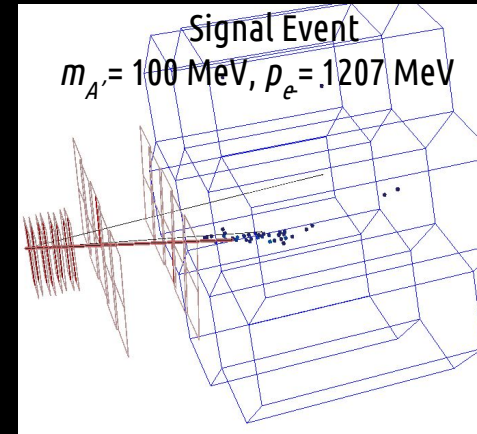
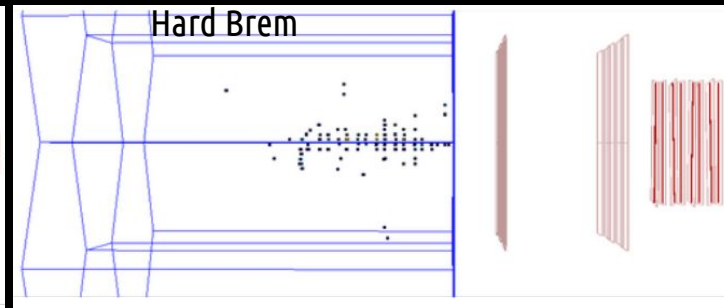
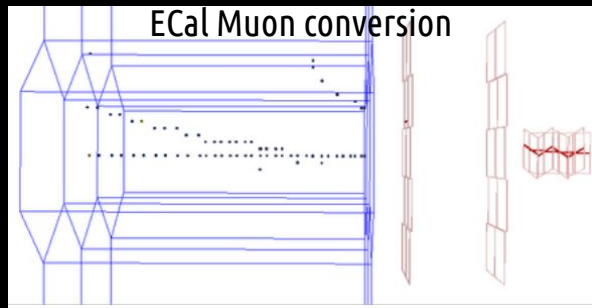


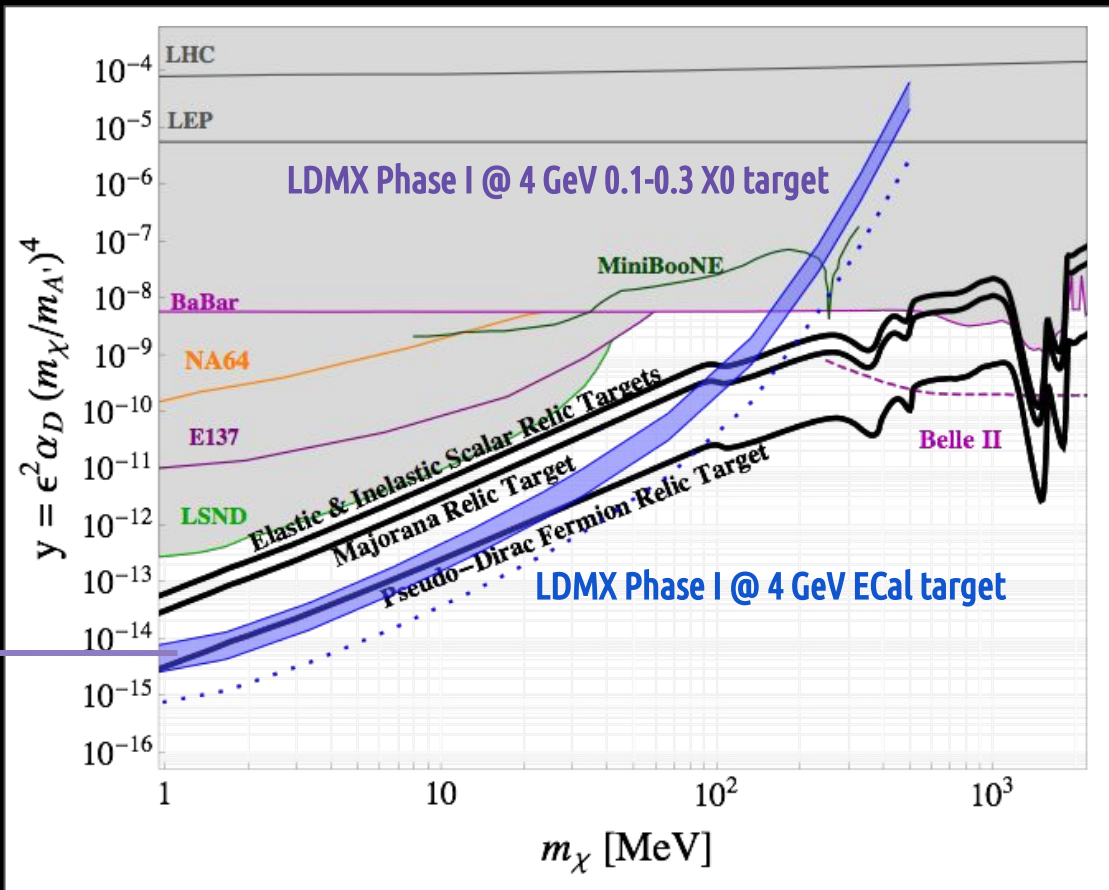
Photo/electronuclear as well as muon conversion backgrounds can occur in the target, recoil tracker or Ecal

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

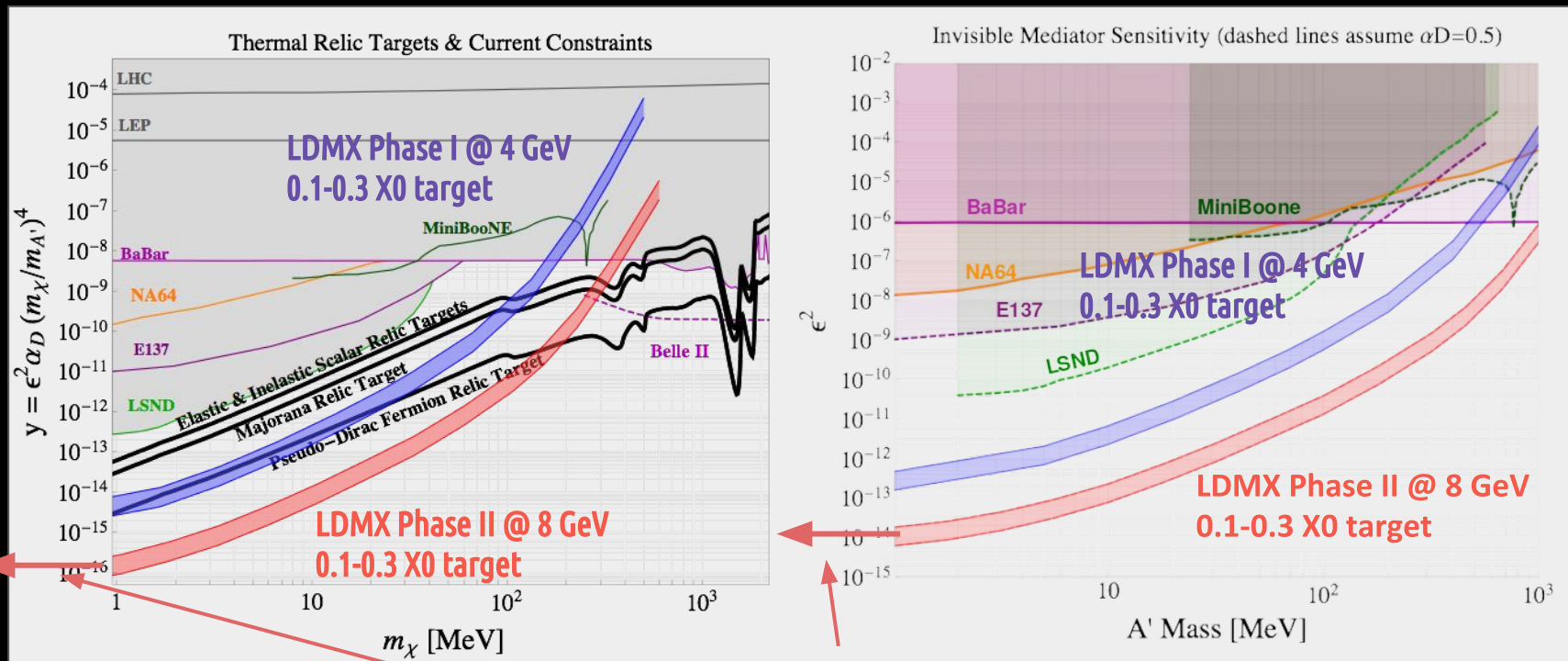
Initial studies using a veto making use of information from each subsystem was able to eliminate all but a few photonuclear events from a sample equivalent to  $10^{14} e^-$  on target!





Sensitivity extends to lower masses

O. Moreno (SLAC National Accelerator Laboratory) Thirteenth Conference on the Intersections of Particle and Nuclear Physics May 29 - June 3, 2018



Sensitivity extends to lower masses

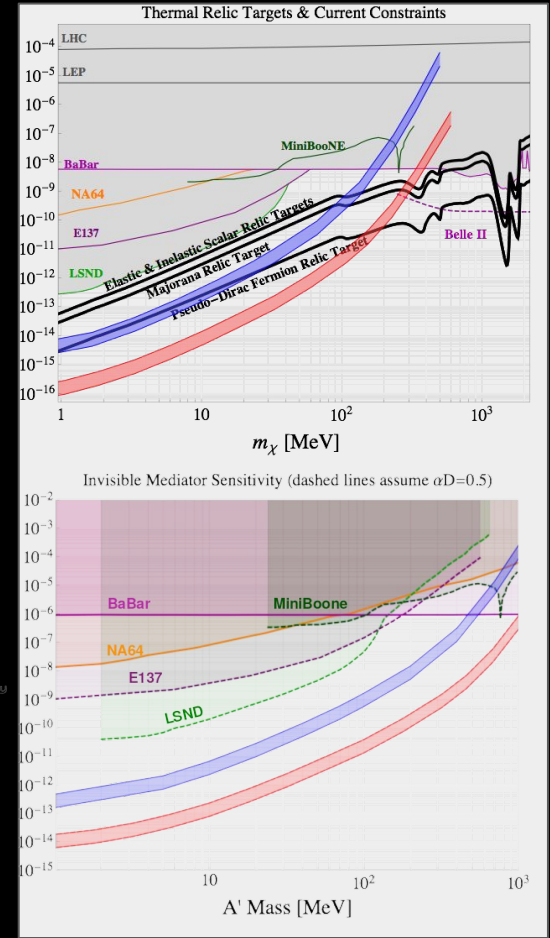
Accelerator-based DM searches have unique sensitivity in the MeV-GeV range.

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

“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

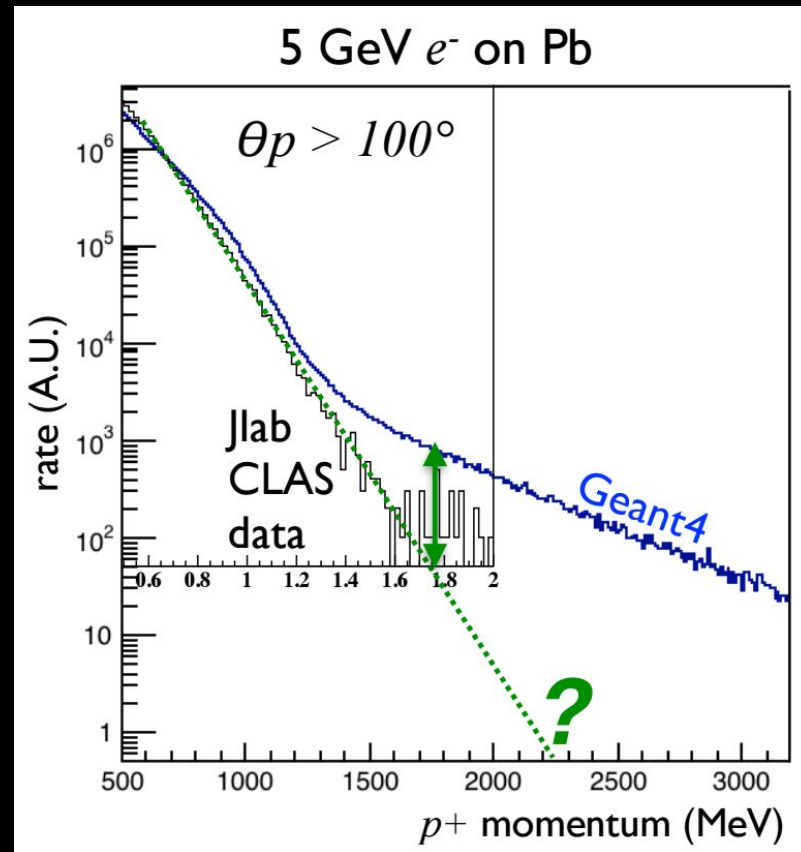
Marco Battaglieri (SAC co-chair),<sup>1</sup> Alberto Belloni (Coordinator),<sup>2</sup> Aaron Chou (WG2 Convener),<sup>3</sup> Priscilla Cushman (Coordinator),<sup>4</sup> Bertrand Echenard (WG3 Convener),<sup>5</sup> Rouven Essig (WG1 Convener),<sup>6</sup> Juan Estrada (WG1 Convener),<sup>3</sup>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



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.



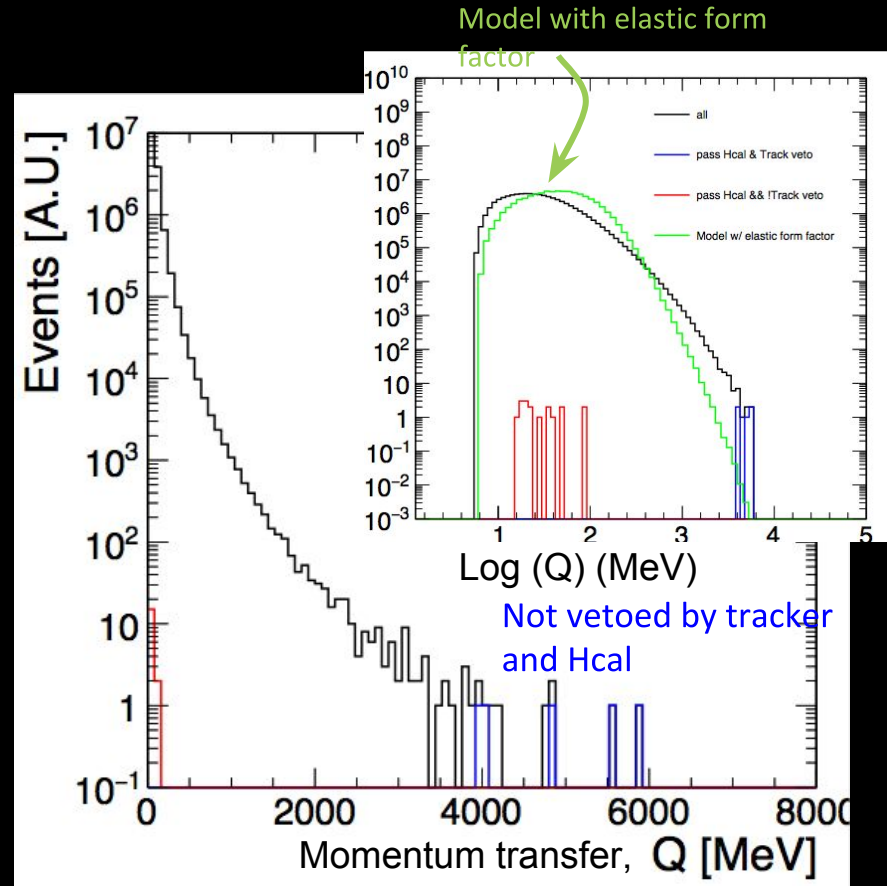
Di-muon backgrounds can occur in the target, recoil tracker or Ecal

Have several handles that can be used to veto these backgrounds

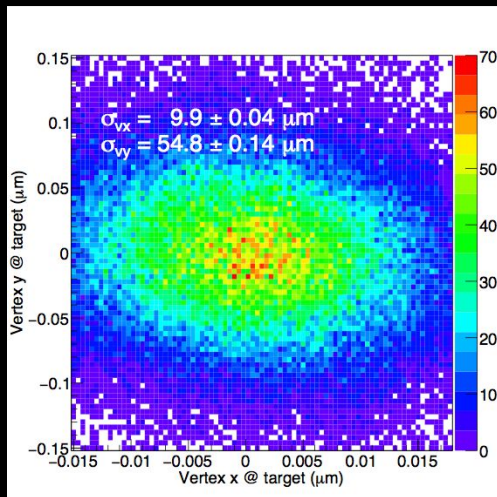
- Recoil tracker → (for  $\gamma \rightarrow \mu + \mu^-$  in target & recoil tracker)
- Ecal
- Hcal

An initial veto using only tracker and HCal eliminates all but a few events where both muons are emitted at  $\geq 90^\circ$  for  $\sim 10^{14}$  EOT.

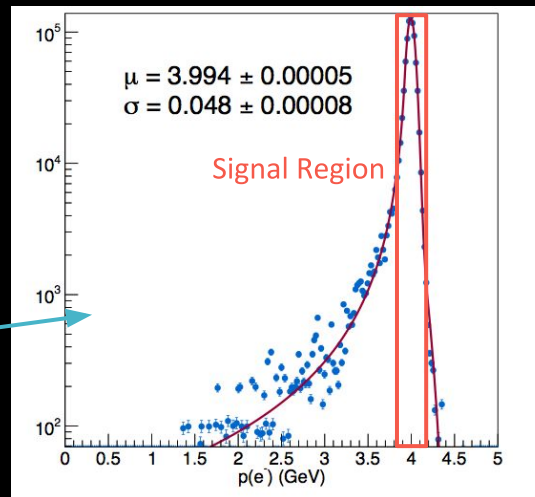
Geant4 also grossly overestimates rate of  $\gamma \rightarrow \mu + \mu^-$  events with extremely high  $q^2$ .



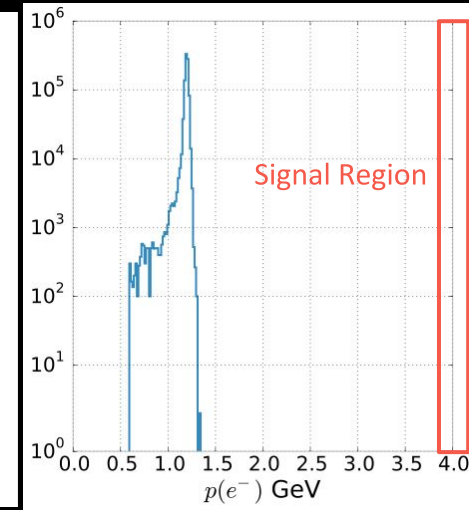
Momentum resolution of  $\sim 1\%$  allows rejection of off-energy components in beam



4.0 GeV  $e^-$  on 10% X0

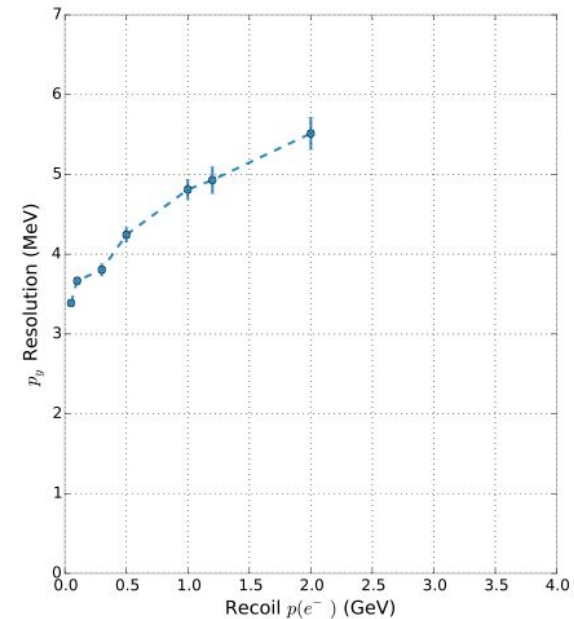
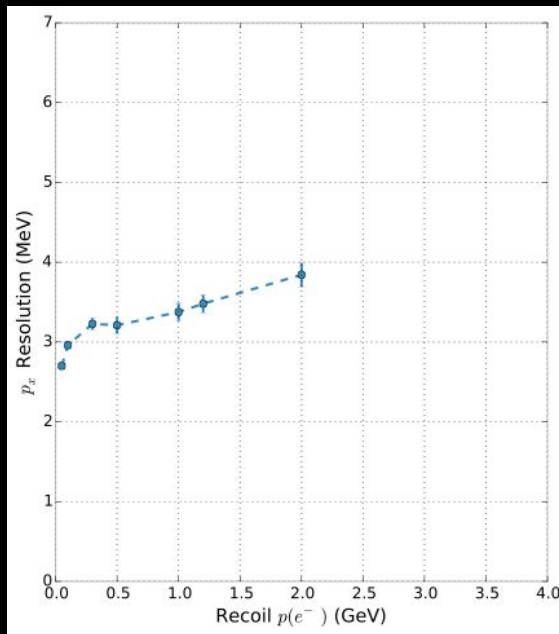
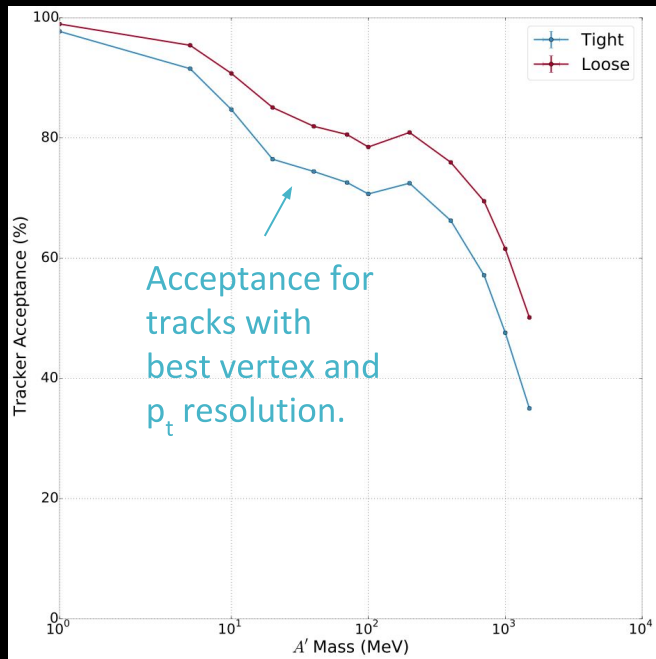


1.2 GeV  $e^-$  worse case scenario



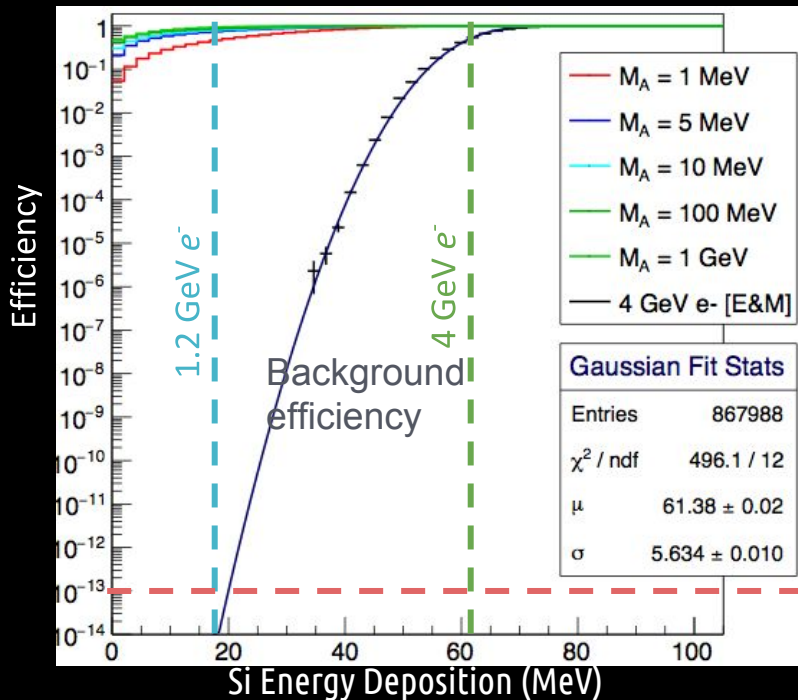
Momentum Resolution at target is small compared to 4 MeV smearing from multiple scattering in 10% X0 target  $\rightarrow$  **Good  $p_T$  resolution**

Good acceptance over a wide range of  $A'$  masses



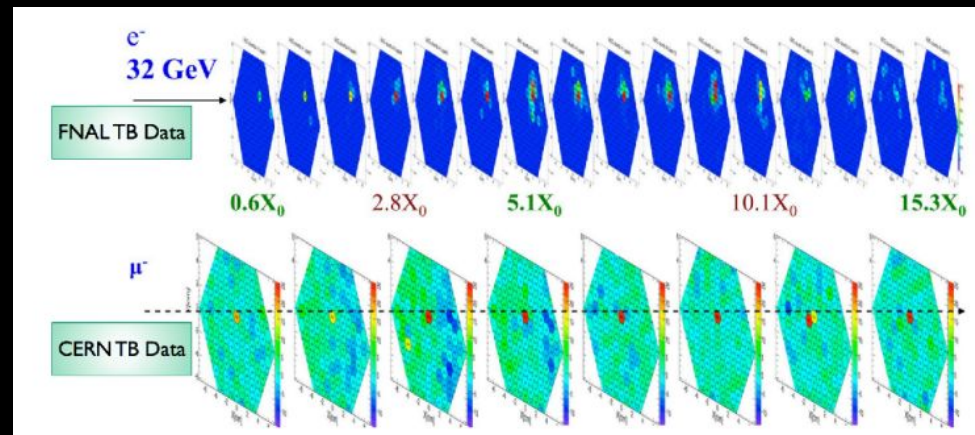
Delivers best possible resolution for  $p_T$

Ecal can distinguish EM showering backgrounds from signal ( $<1.2 \text{ GeV } e^-$ ) for Phase I



Ecal can track minimum ionizing particles (MIPs), important for rejection of  $\gamma \rightarrow \mu^+ \mu^-$  and  $\gamma \rightarrow \text{photonuclear}$  events.

CERN and FNAL Test Beam Data



Required Rejection



UNIVERSITY OF MINNESOTA



Caltech



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