The Light Dark Matter eXperiment

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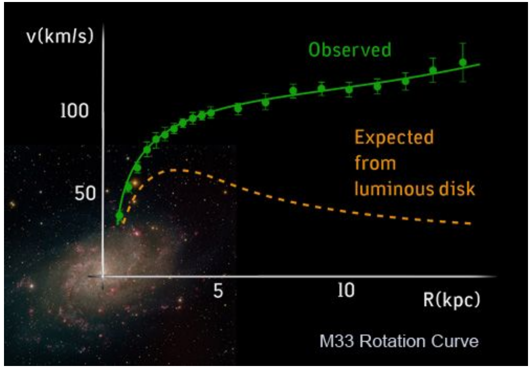
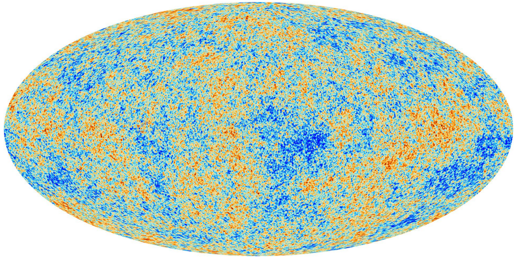
The Evidence for Dark Matter

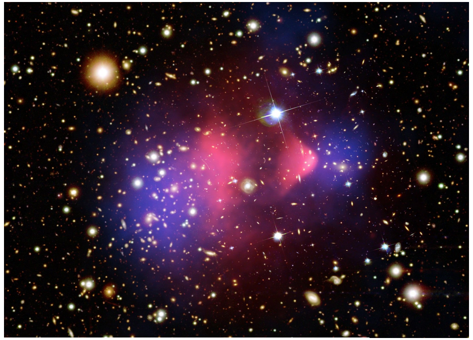
Galactic Rotation Curves



Structure of Cosmic Microwave Background

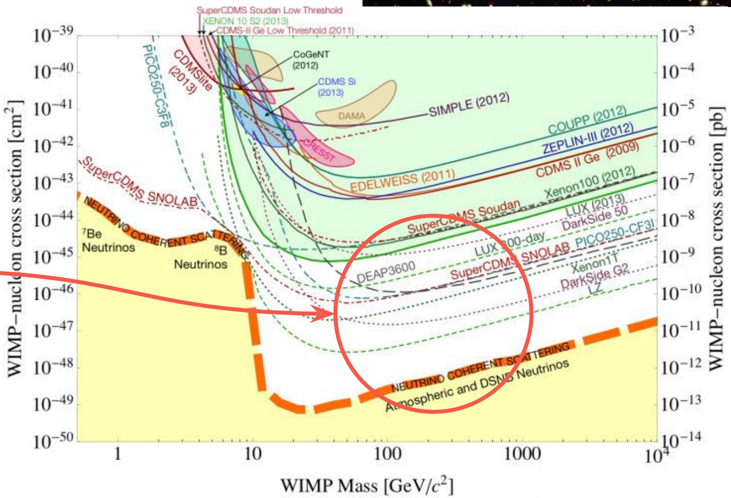


Gravitational Lensing



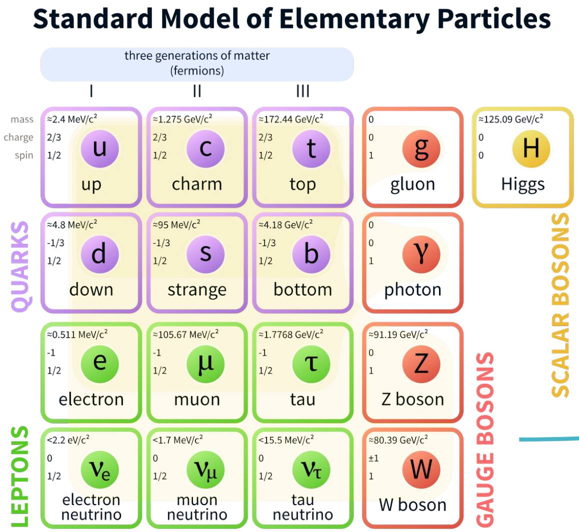
There is strong evidence for the existence of Dark Matter, but it remains undetected.

Weakly Interacting Massive Particle (WIMP) Dark Matter are a motivated candidate 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.



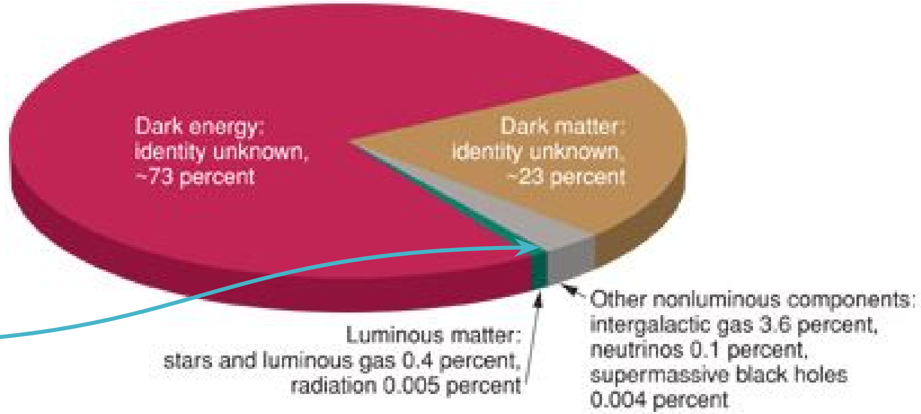
Light Dark Matter

Light Dark Matter (i.e. DM sub-GeV range) 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



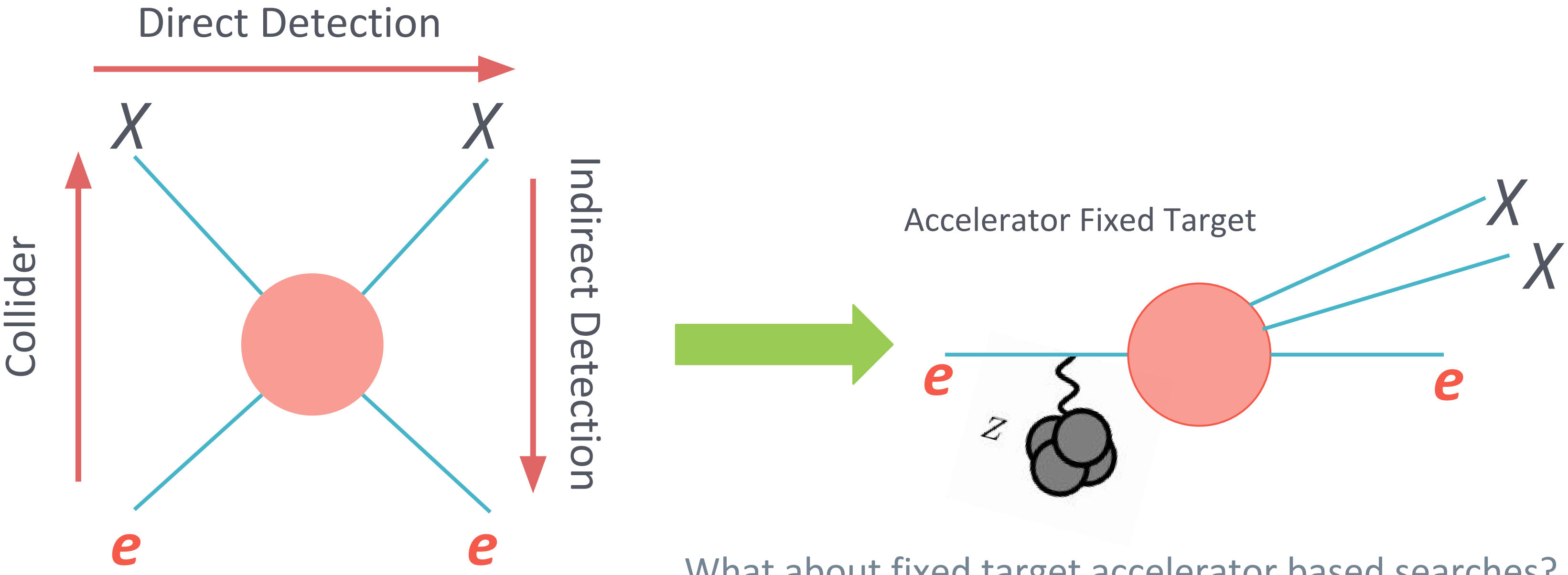
Standard Model of Elementary Particles

	three generations of matter (fermions) I	II	III			
mass charge spin QUARKS	≈2.4 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈172.44 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs	SCALAR BOSONS
	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
LEPTONS	≈0.511 MeV/c^2 -1 1/2 e electron	≈105.67 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson		GAUGE BOSONS
	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson		



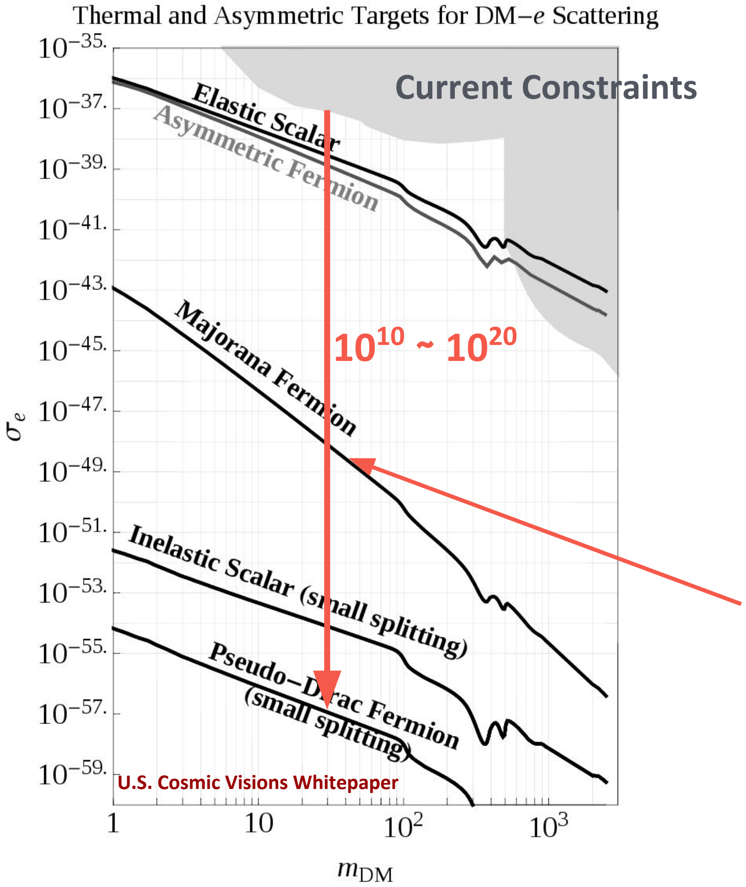
Given the complex structure of the Standard Model, a "Dark Sector" where dark matter interacts via a light mediator is an obvious scenario to test. It has been the focus of a broad array of searches and experiments for many years now.

Searching For Light Dark Matter



What about fixed target accelerator based searches?
What advantages do they offer over other approaches?

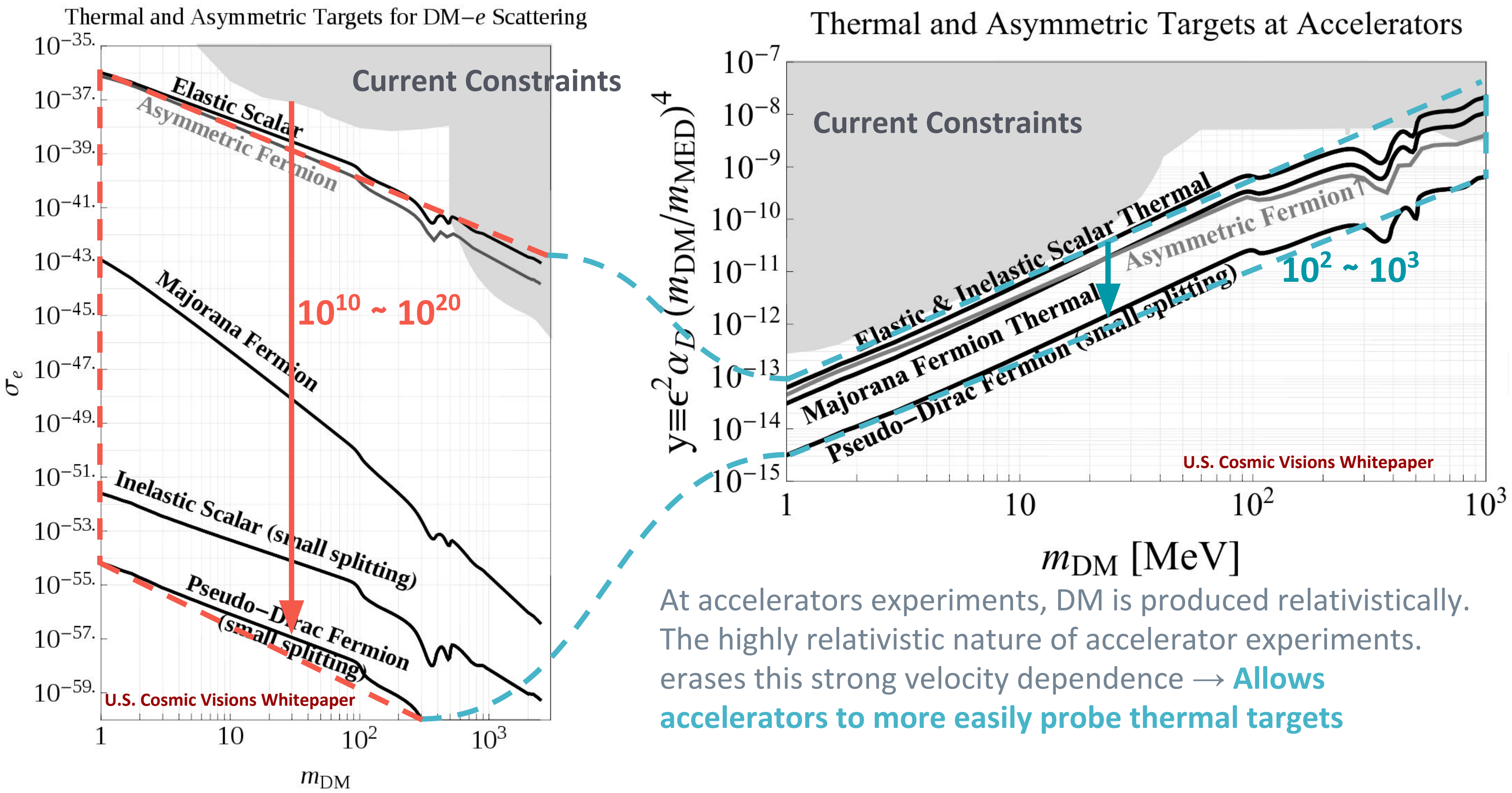
Thermal DM Targets in MeV to GeV Range



As an example, let’s focus on the case where DM interacts via a vector mediator (aka dark photon, heavy photon, A’)

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

Thermal DM Targets in MeV to GeV Range



U.S. Cosmic Visions Whitepaper

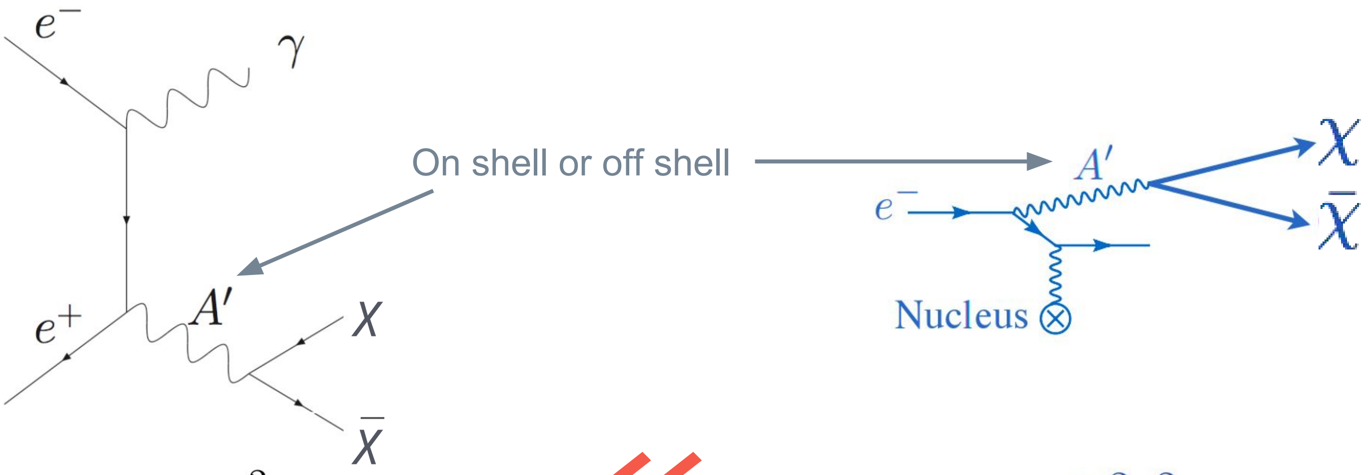
U.S. Cosmic Visions Whitepaper

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 thermal targets**

Accelerator Based Searches

Maximize dark mediator (A') production → Greater LDM yields

Colliders **Fixed Target**



On shell or off shell

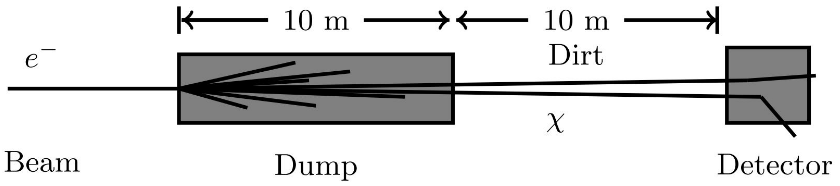
$$\sigma \propto \frac{\epsilon^2}{E_{\mathrm{cm}}^2} \ll \sigma \propto \frac{Z^2\epsilon^2}{m_{\mathrm{A'}}^2}$$

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

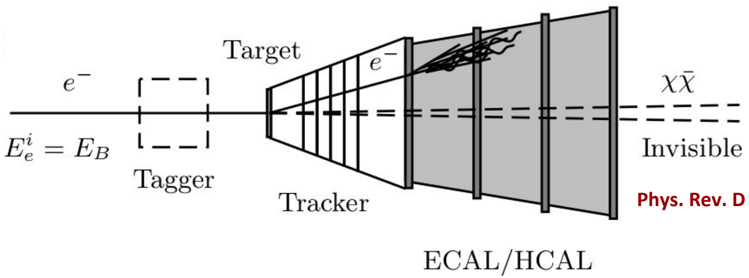
Fixed Target: Beam Dump vs Missing Momentum

arXiv:1607.01390

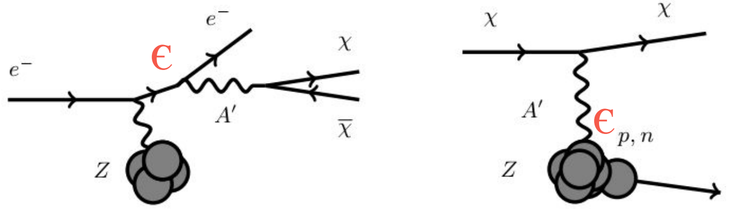
Beam Dump

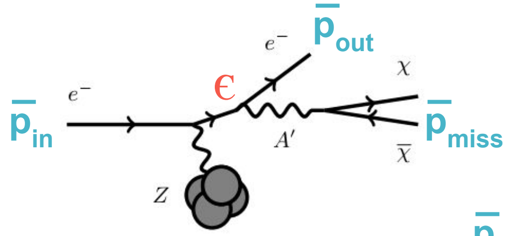


Missing Momentum



Phys. Rev. D 91, 094026





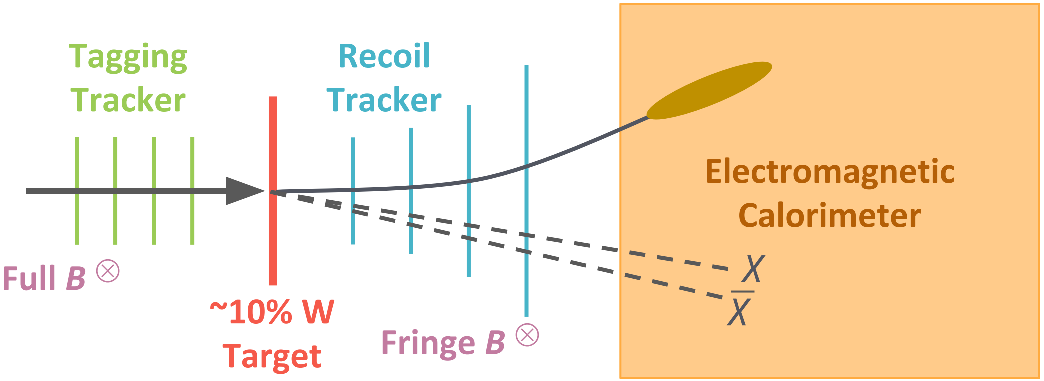
$$\bar{p}_{in} = \bar{p}_{out} + \bar{p}_{miss}$$

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

Missing momentum approach results in the highest signal yields!

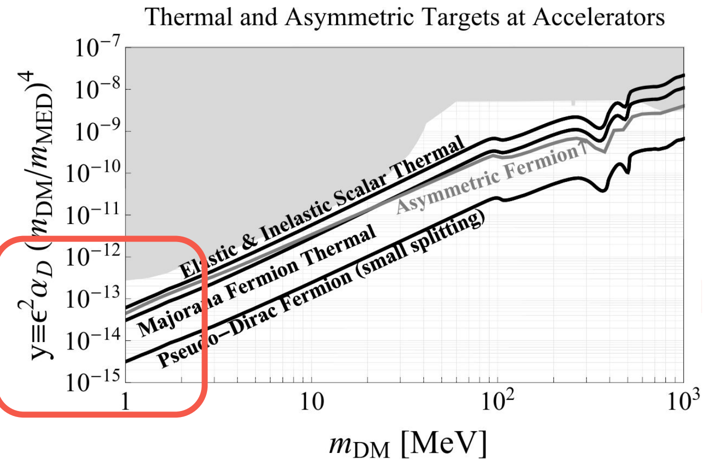
The Light Dark Matter eXperiment

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



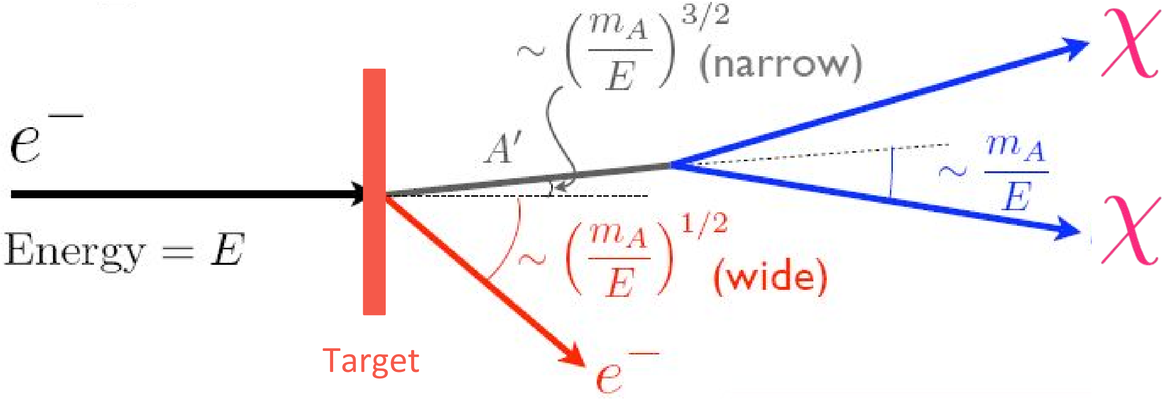
$$\sigma \propto \epsilon^2 \rightarrow N_{\text{signal}} \simeq N_{e\text{-}} \times y|_{1\ \text{MeV}}$$

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



Dark Bremsstrahlung Kinematics

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

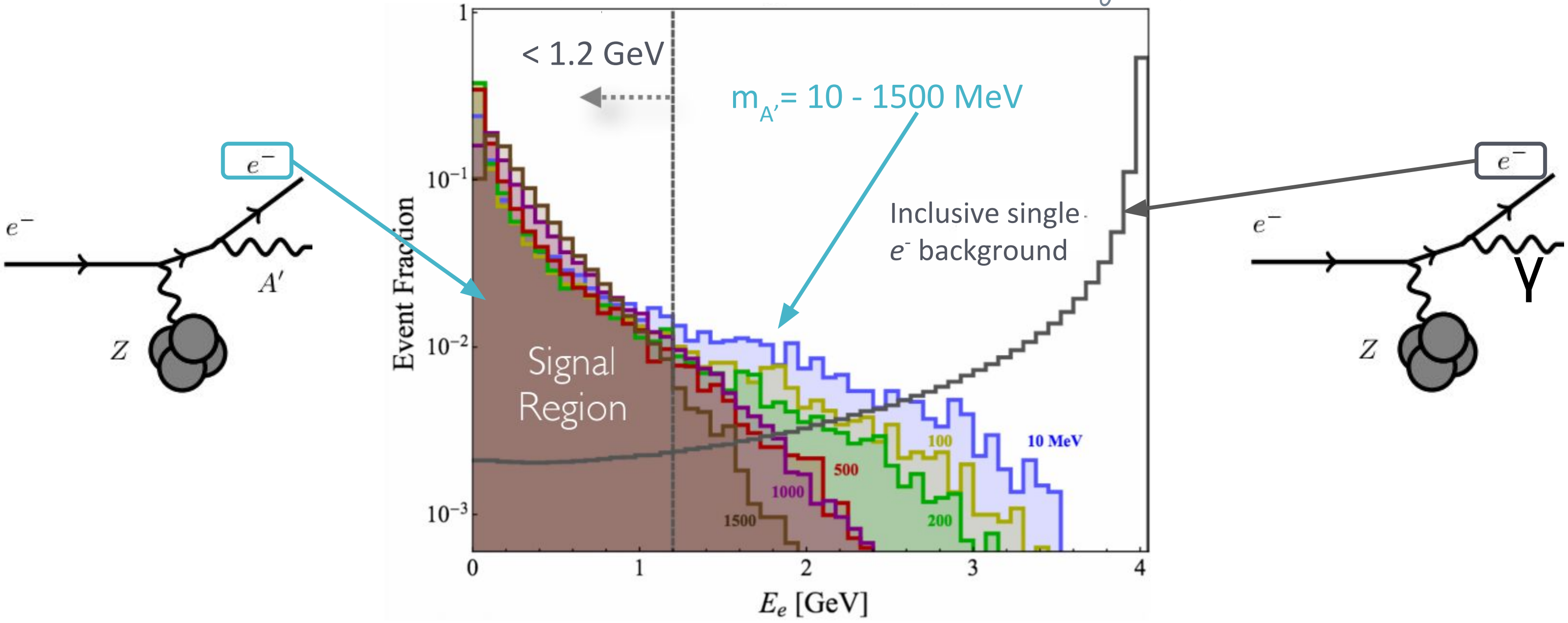


but with different rates and kinematics

- ✔ 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

Dark Bremsstrahlung Kinematics

Recoil energy distribution, 4 GeV e^- on 10%X_0 target



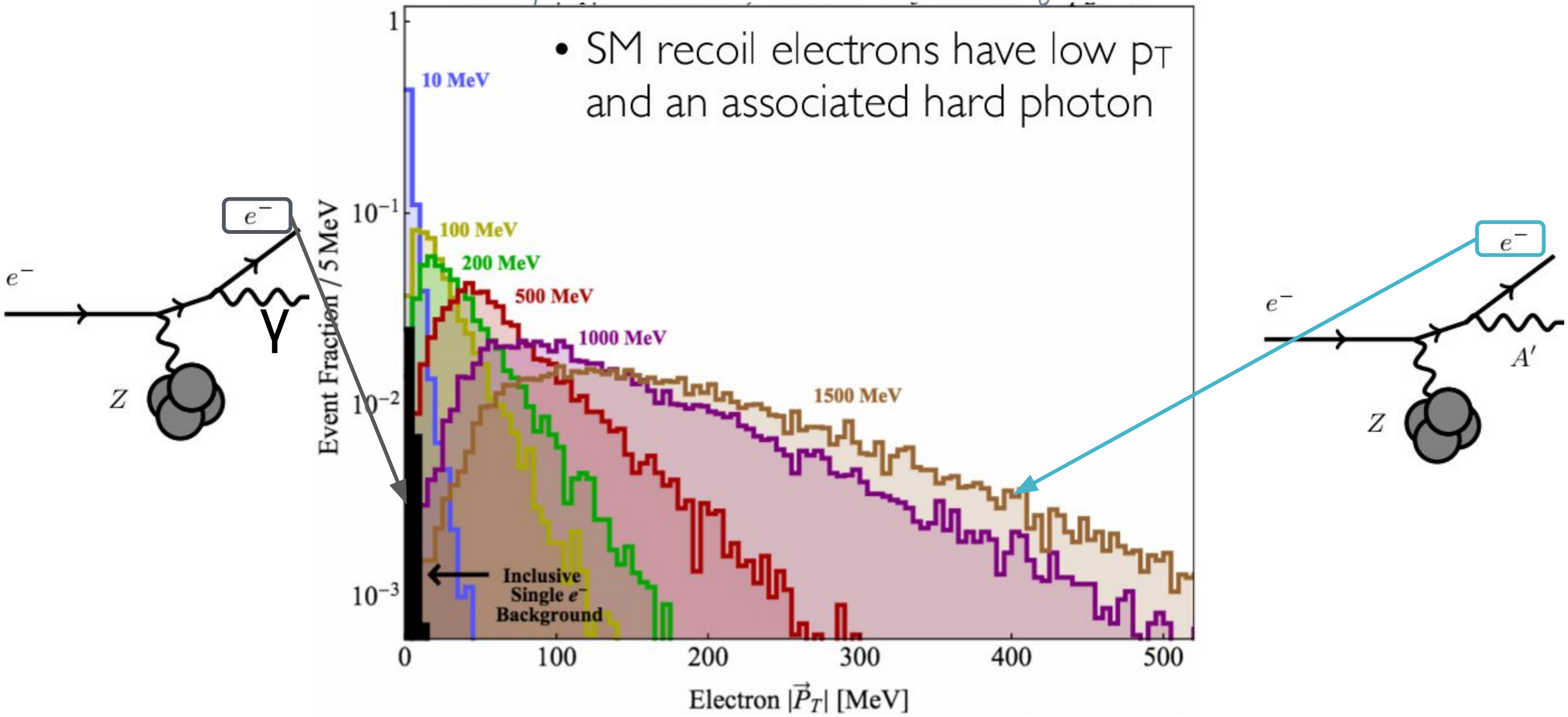
Recoil kinematics allow efficient signal definition providing ~30× background rejection

- ✔ **Tagging tracker**: Track with |p| = E_{beam} on expected trajectory
- ✔ **Recoil tracker**: Single track, with |p| < 0.3 E_{beam}, that points back to tag in target
- ✔ **Calorimeters**: Shower consistent with recoil track and no other activity

Dark Bremsstrahlung Kinematics

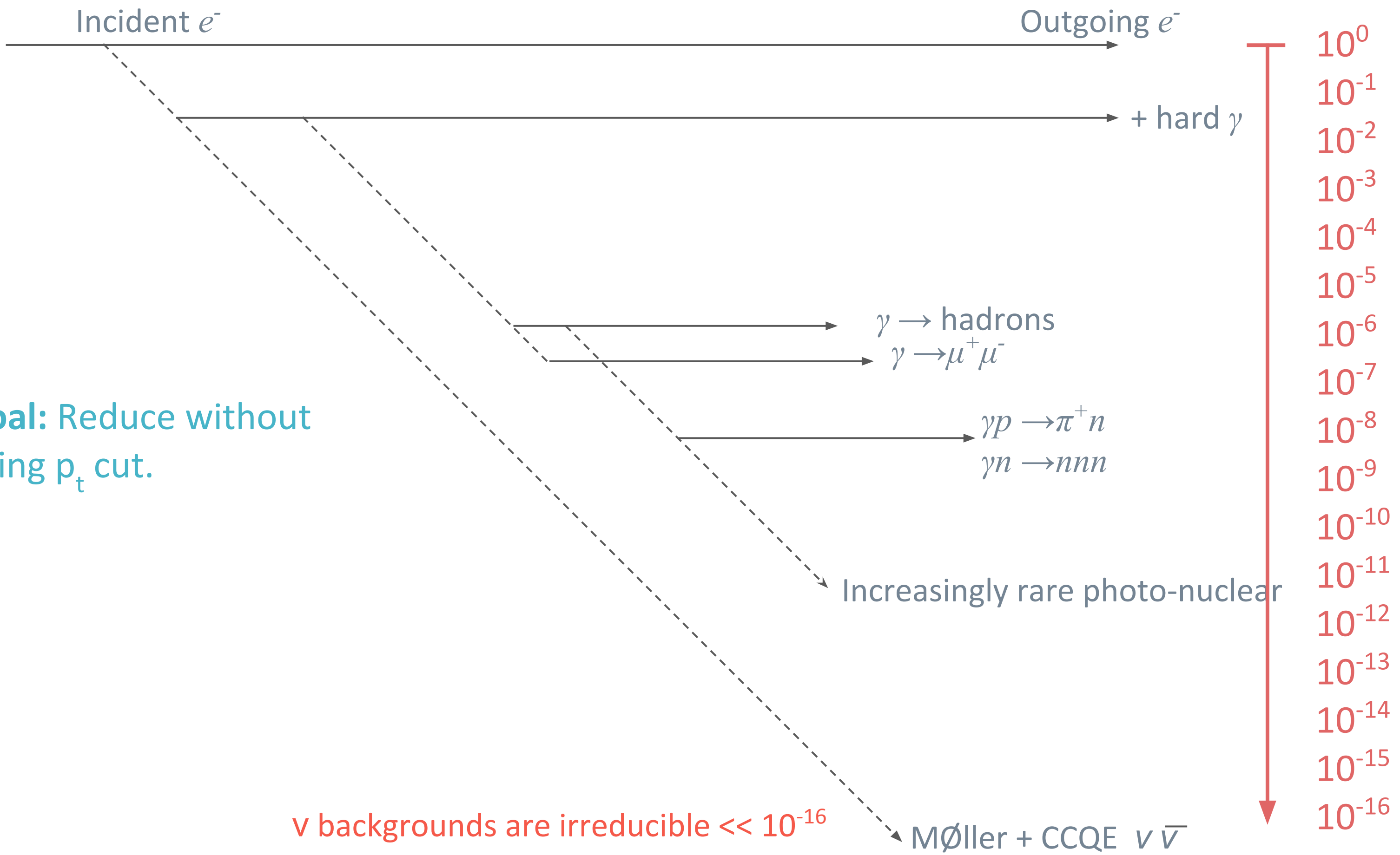
Recoil p_T distribution, 4 GeV e^- on 10%X_0 target

- SM recoil electrons have low p_T and an associated hard photon



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

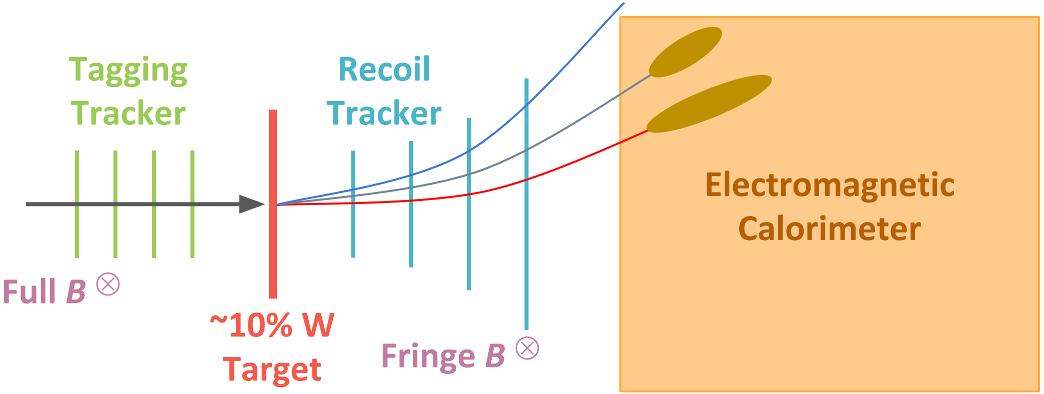
Missing Momentum Backgrounds



Goal: Reduce without using p_t cut.

ν backgrounds are irreducible << 10^{-16}

LDMX Design Considerations



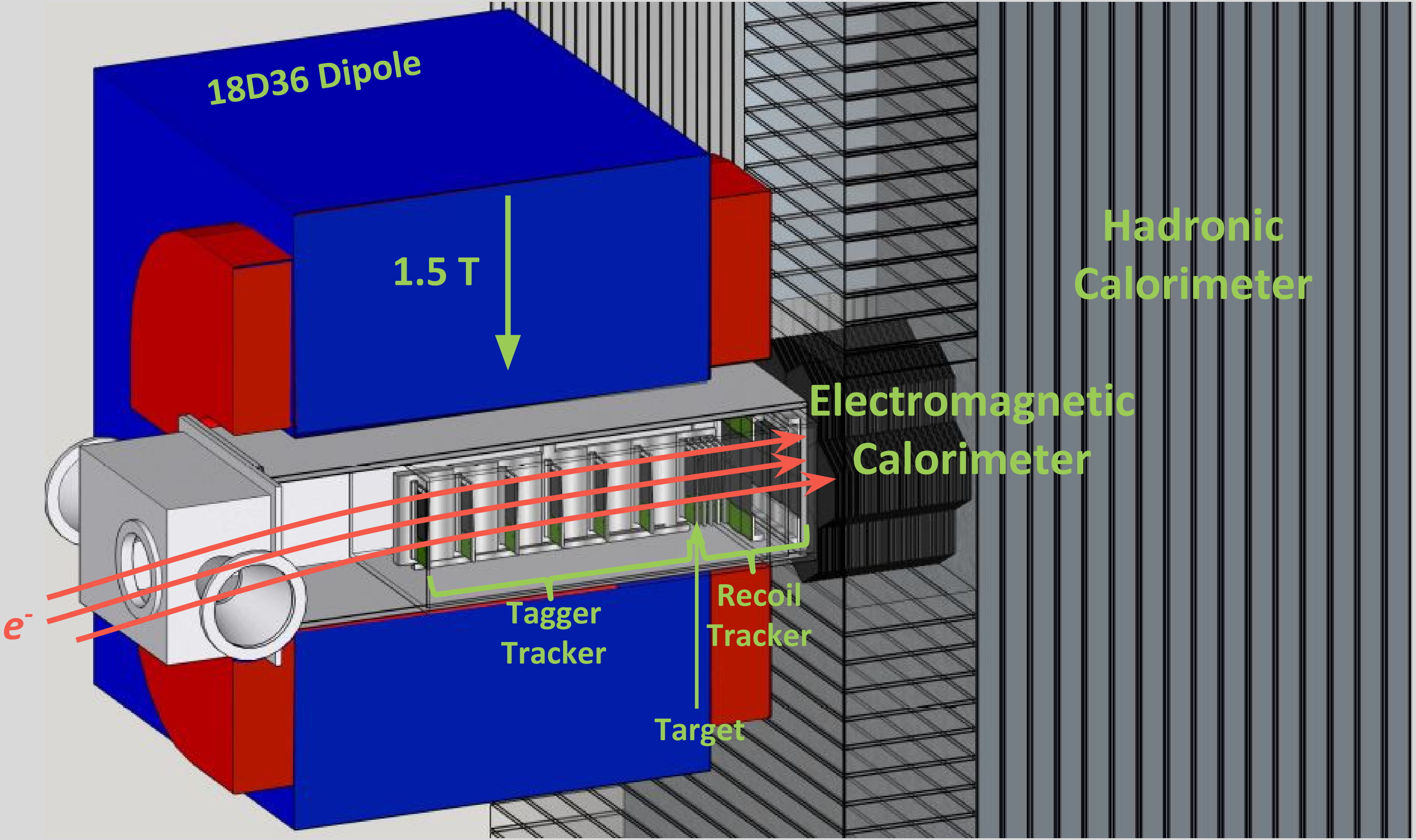
Beam that allows individual tagging and reconstruction of 10^{16} incident e^-

- ✔ 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 CEBAF @ JLab (up to 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

- ✔ Requirements for 10^{16} experiment close to limits of available technologies ➡ Two-stage approach to LDMX: **4×10^{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

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
  - ✔ Used to measure recoil e^- with p_{e-} ~ 50 - 1200 MeV

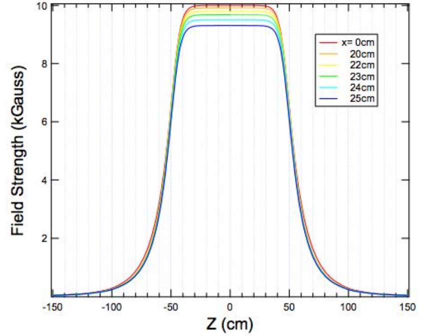
Single 18D36 dipole magnet → Two field regions

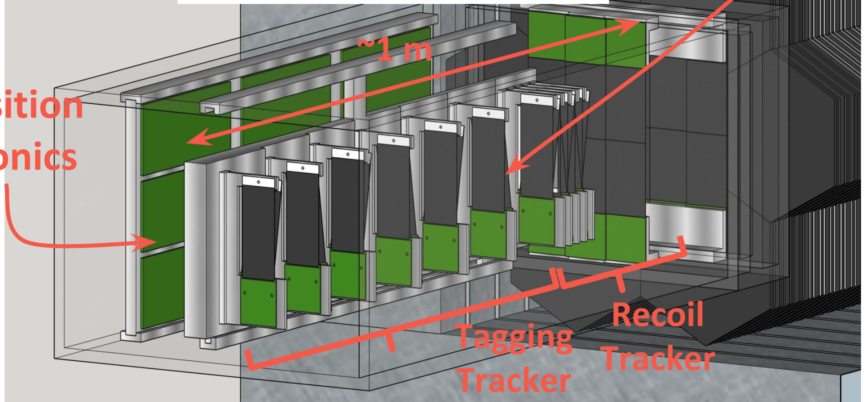
- ✔ Tagging tracker in central 1.5T field
- ✔ Recoil Tracker in fringe field

Tungsten target (0.1-0.3 X_0) between trackers

- ✔ Thickness balances signal rate against pT from MS

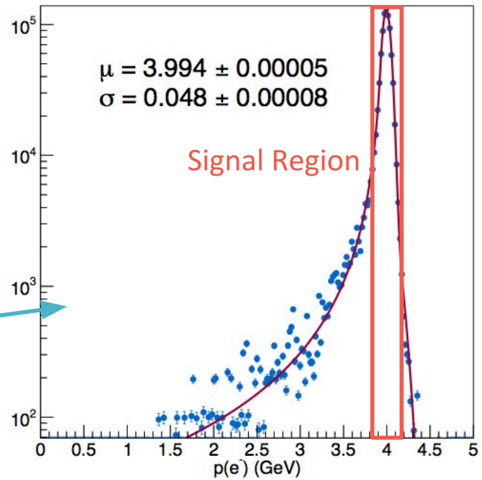
Scintillator downstream of the target vetoes Ecal trigger on empty buckets



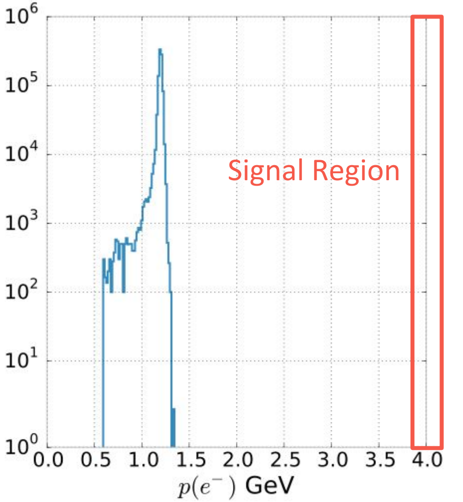


Tagging Tracker Performance

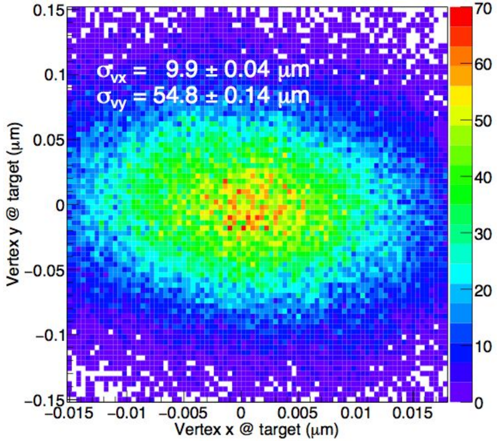
4.0 GeV e^- on 10% X0



1.2 GeV e^- worse case scenario



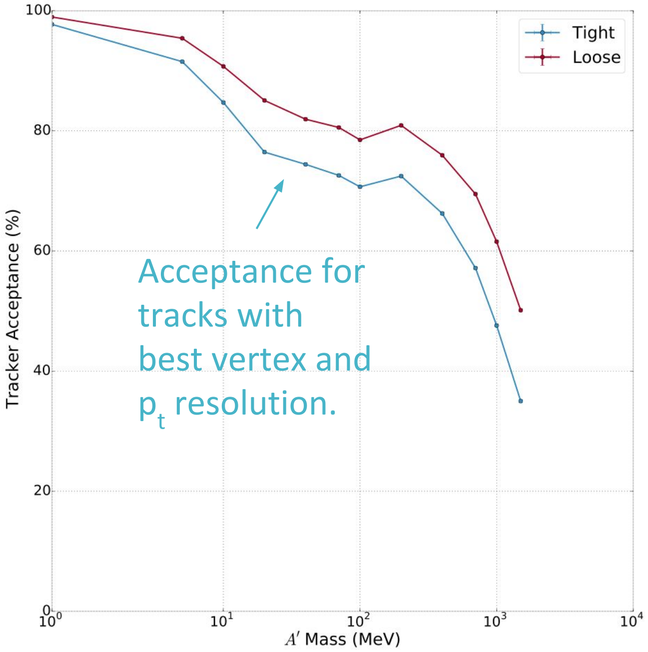
Momentum resolution of ~1% allows **rejection of off-energy components in beam**



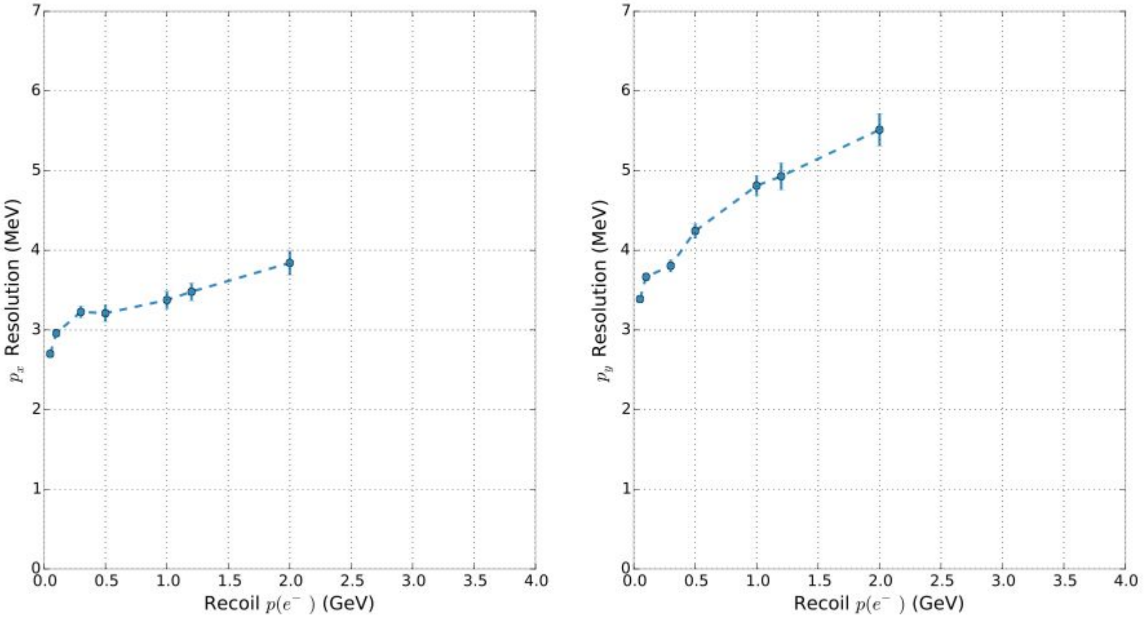
Momentum Resolution at target is small compared to 4 MeV smearing from multiple scattering in 10% X0 target ⟶ **Good p_T resolution**

Recoil Tracker Performance

Good acceptance over a wide range of A′ masses



Acceptance for tracks with best vertex and p_t resolution.

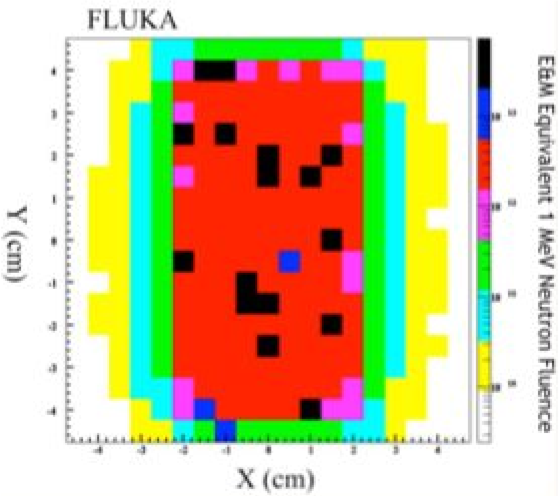


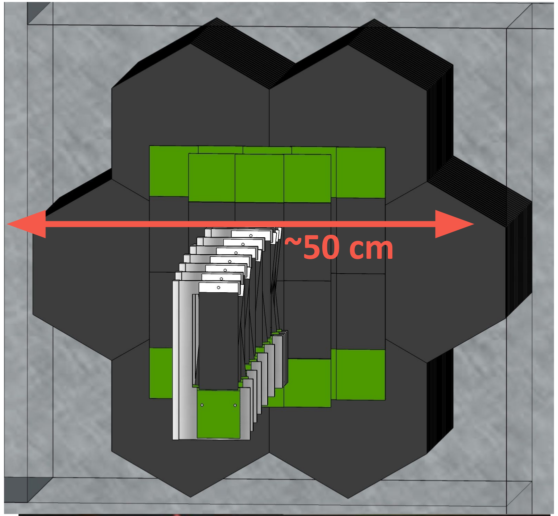
Delivers best possible resolution for p_T

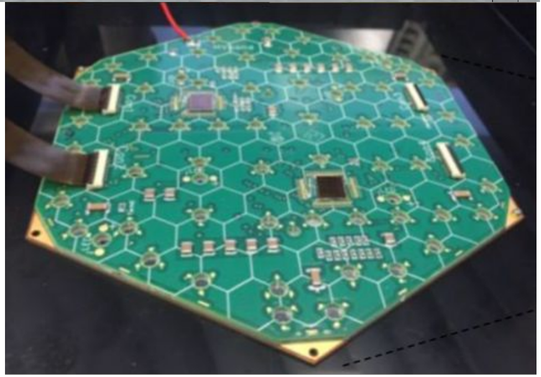
Electromagnetic Calorimeter

Si-W calorimeter developed for CMS upgrade
- ✔ Fast, dense, granular for high occupancies
- ✔ 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)





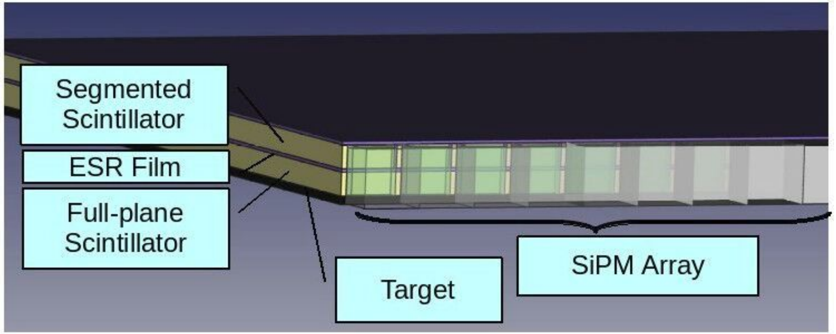


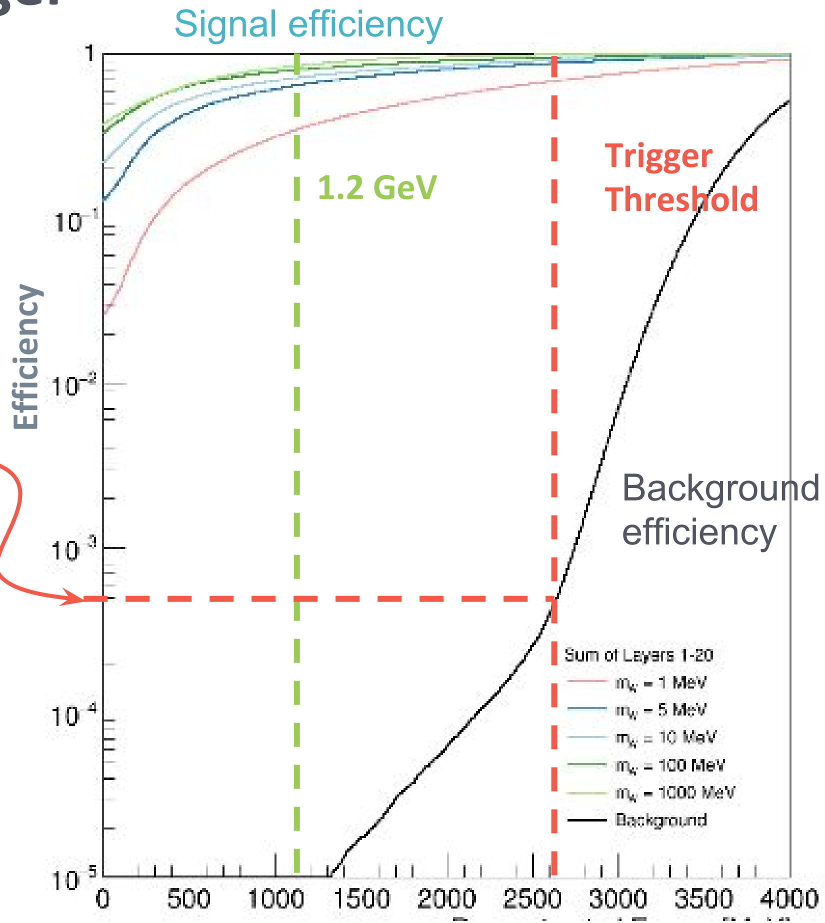
Trigger

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
- ✔ Veto on empty target scintillator

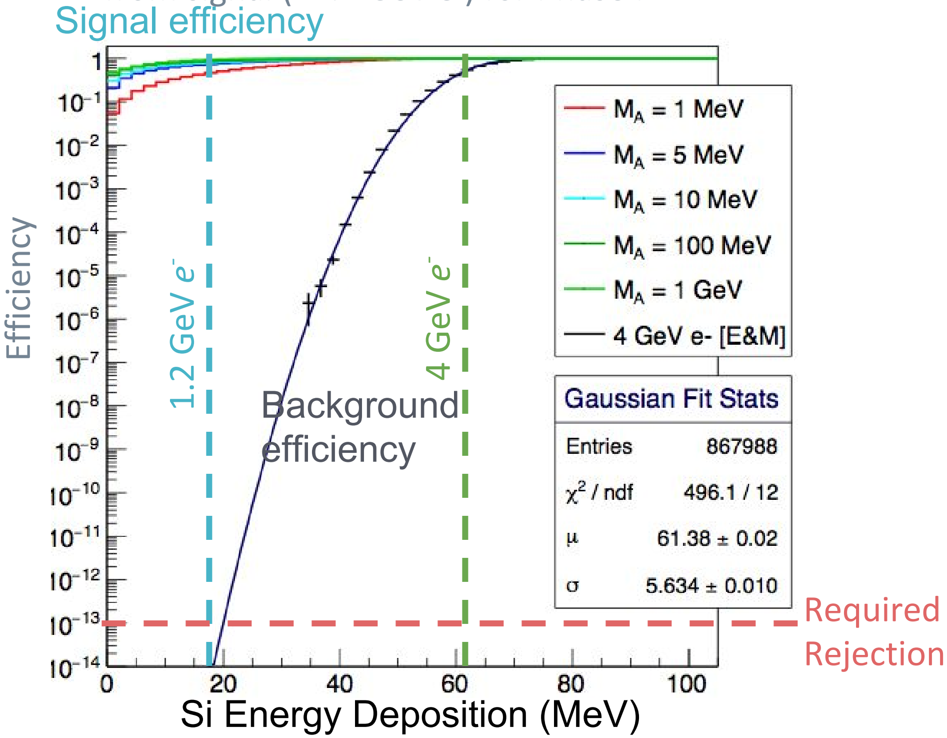
3 x 10^{-4} background rejection!



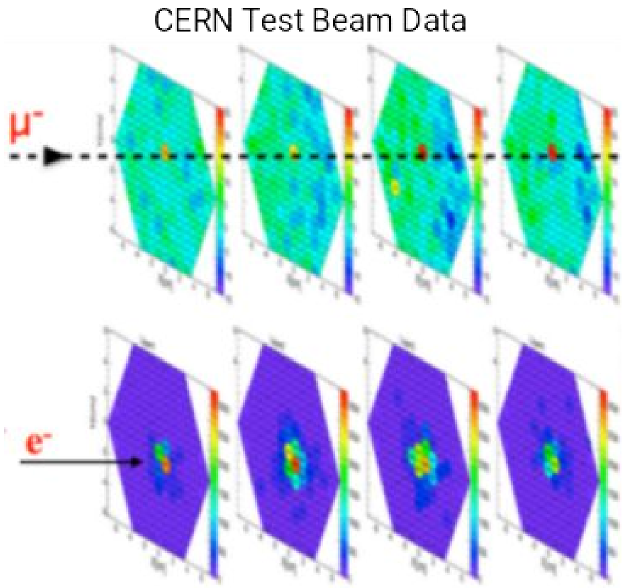


Ecal Performance

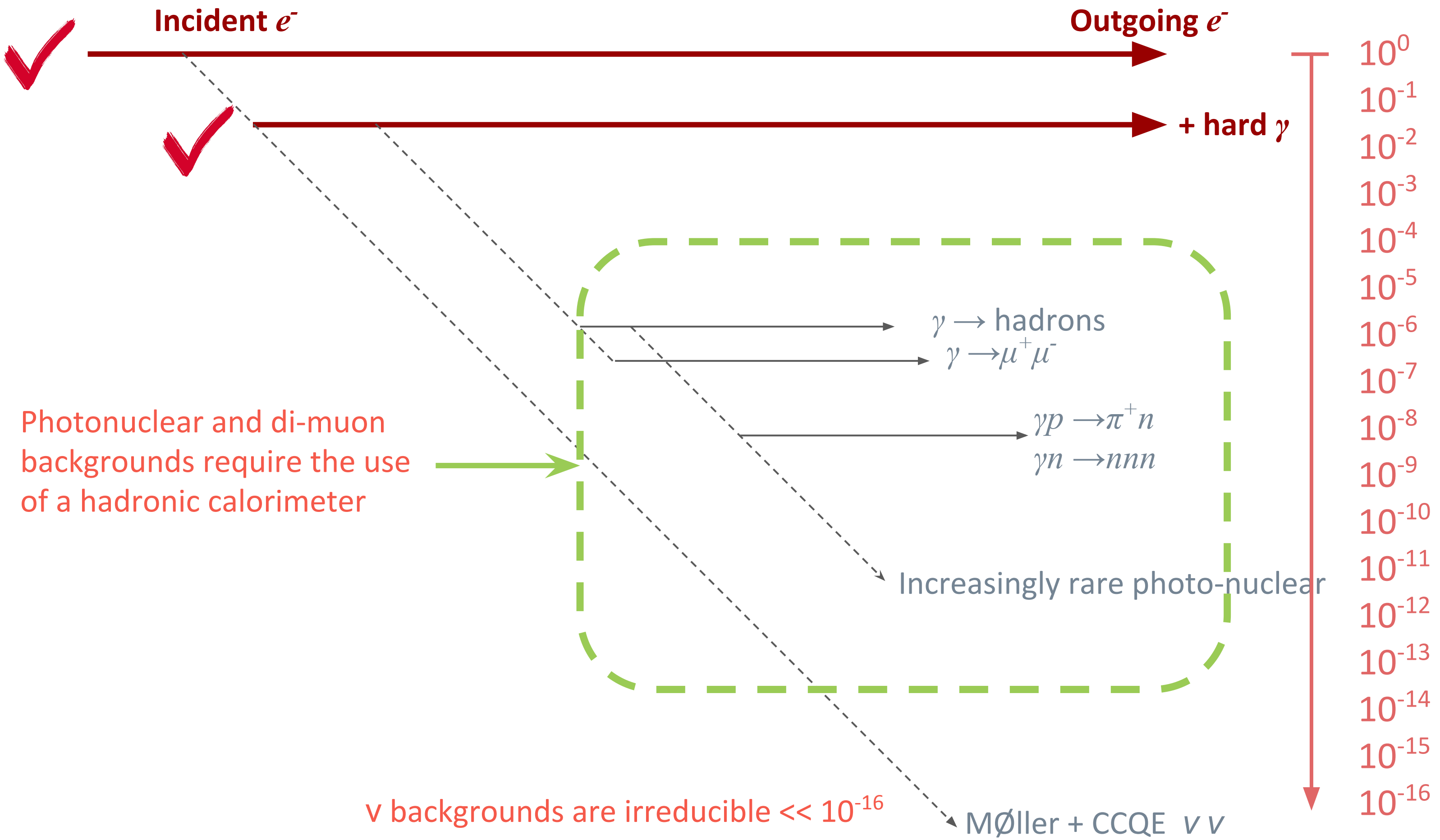
Ecal can distinguish EM showering backgrounds from signal (<1.2 GeV e^-) for Phase I



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



Missing Momentum Backgrounds



Photonuclear and di-muon backgrounds require the use of a hadronic calorimeter

ν backgrounds are irreducible << 10^{-16}

Hadronic Calorimeter

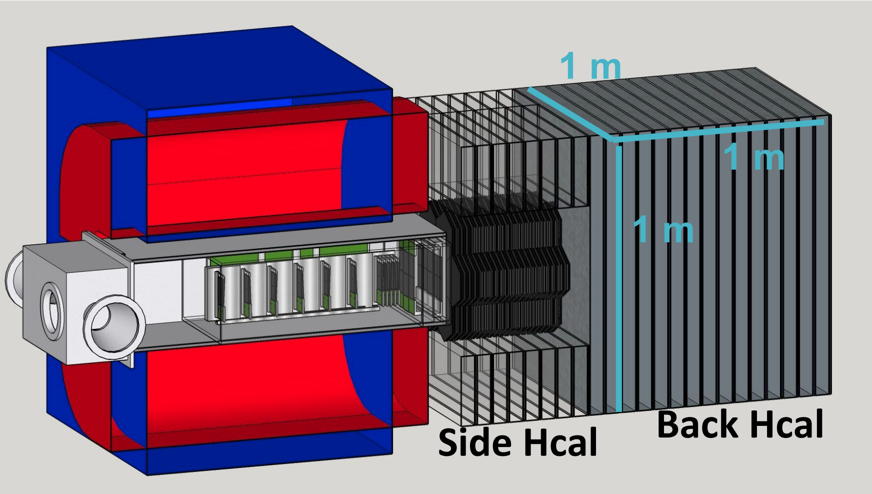
Makes use of CMS upgrade hardware

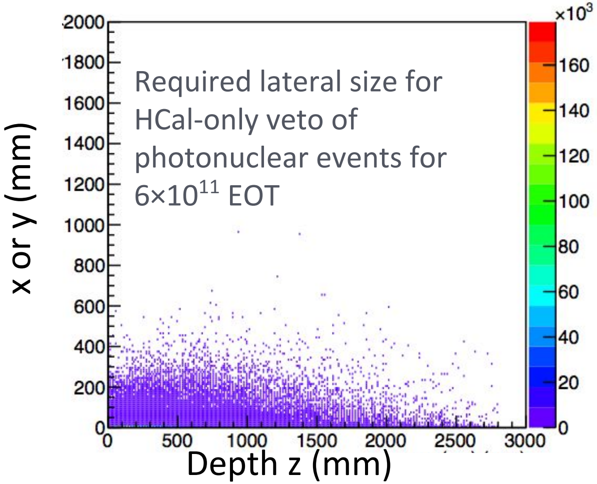
- ✔ Steel absorber/plastic scintillator
- ✔ SiPM readout via WLS fibers

Surround ECal as much as possible

- ✔ Many PN events have a high multiplicity of soft neutral hadrons
- ✔ Also catches wide-angle brems (≳ 25 deg.)

Initial studies indicate that Hcal will need to be larger than 1m^3.




Required lateral size for HCal-only veto of photonuclear events for 6×10^{11} EOT

Testing rejection for a larger Hcal in MC, which will be sculpted down by dropping hits once the photonuclear veto has been optimized.

Rejecting Photonuclear Backgrounds

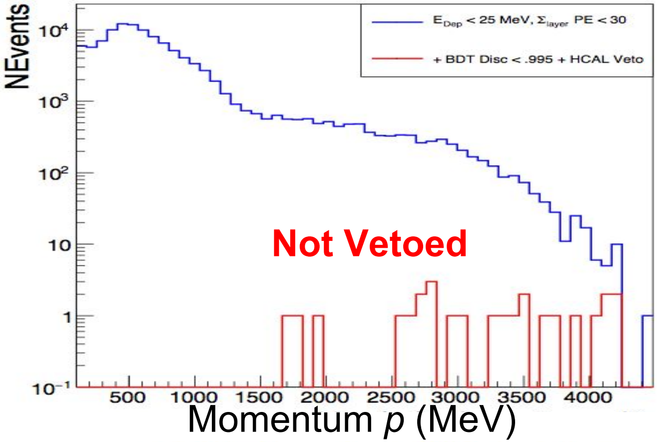
Photonuclear backgrounds can occur in the target, recoil tracker or Ecal

Have several handles that can be used to veto these backgrounds

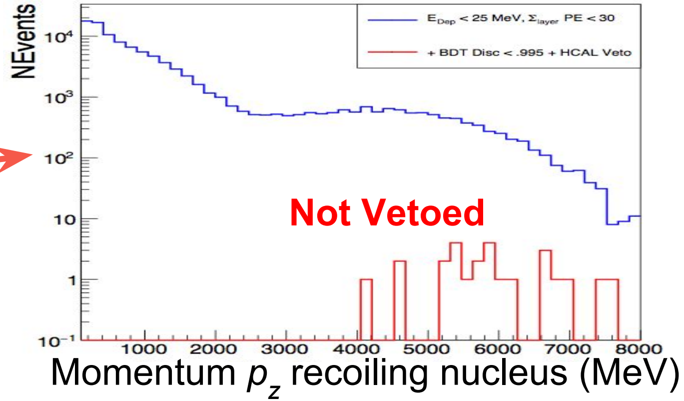
- ✔ Trigger pad → used to reject PN from the target
- ✔ Recoil tracker → used to reject PN from the target and recoil tracker
- ✔ Ecal
- ✔ Hcal

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^{13} e^- on target → These events tend to have a large momentum transfer

Highest Momentum Hadron in Backwards Direction



Geant4 Simulation : γ (E>= 2.5 GeV) + Z → hadrons

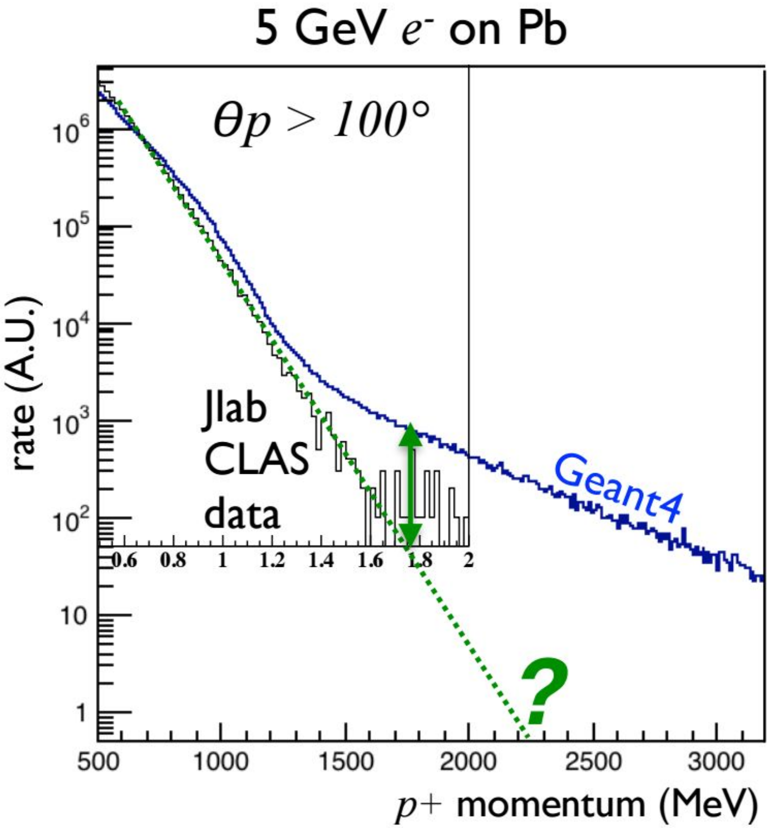


Photonuclear Events in Geant4

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

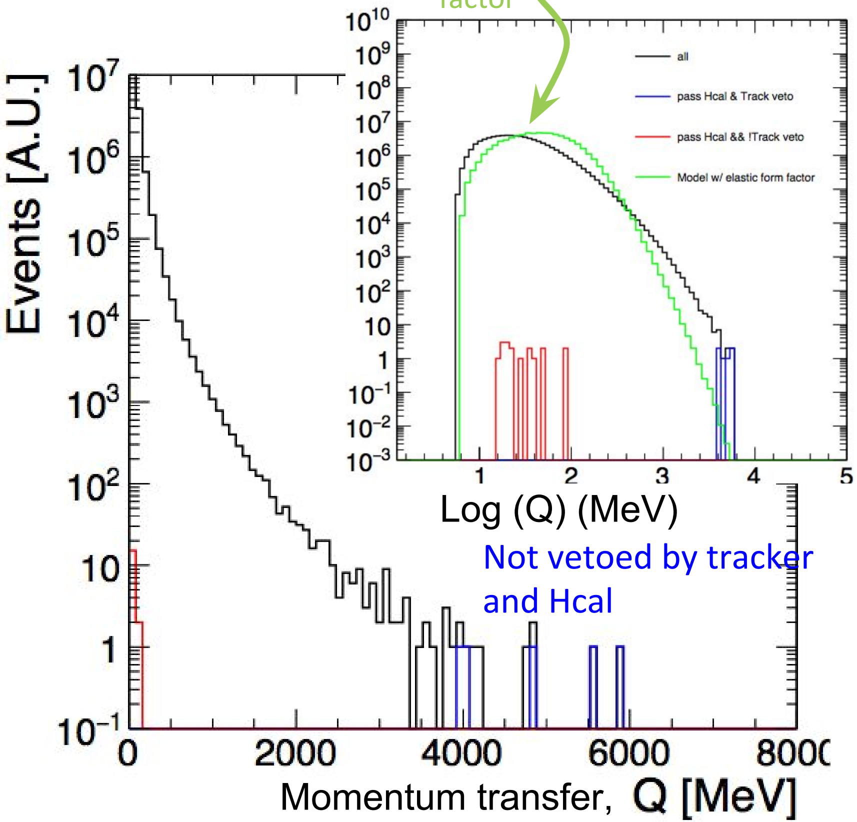
Di-muon backgrounds can occur in the target, recoil tracker or Ecal

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.

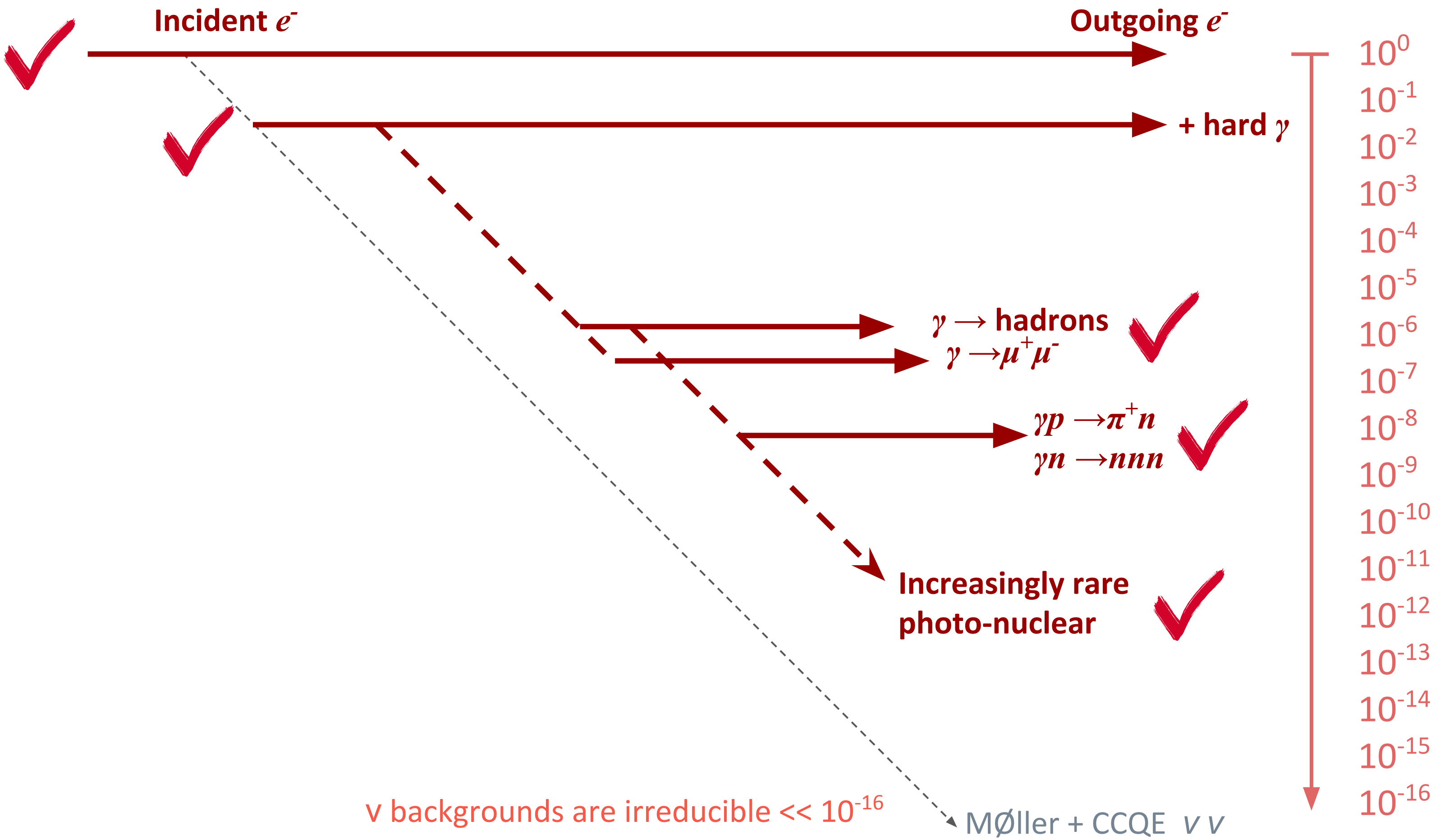
Geant4 also grossly overestimates rate of $\gamma \to \mu+\mu-$ events with extremely high q^2.



Model with elastic form factor

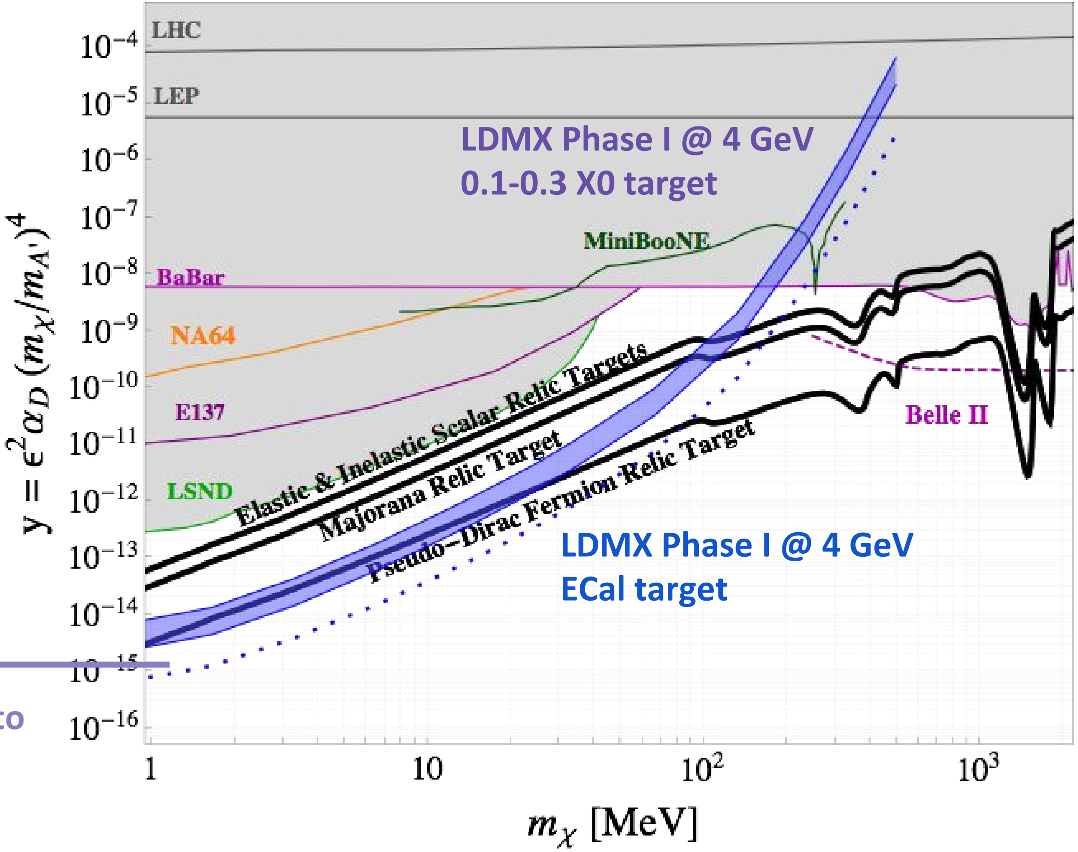
Not vetoed by tracker and Hcal

So What's Left?



ν backgrounds are irreducible << 10^{-16}

LDMX Phase I Reach

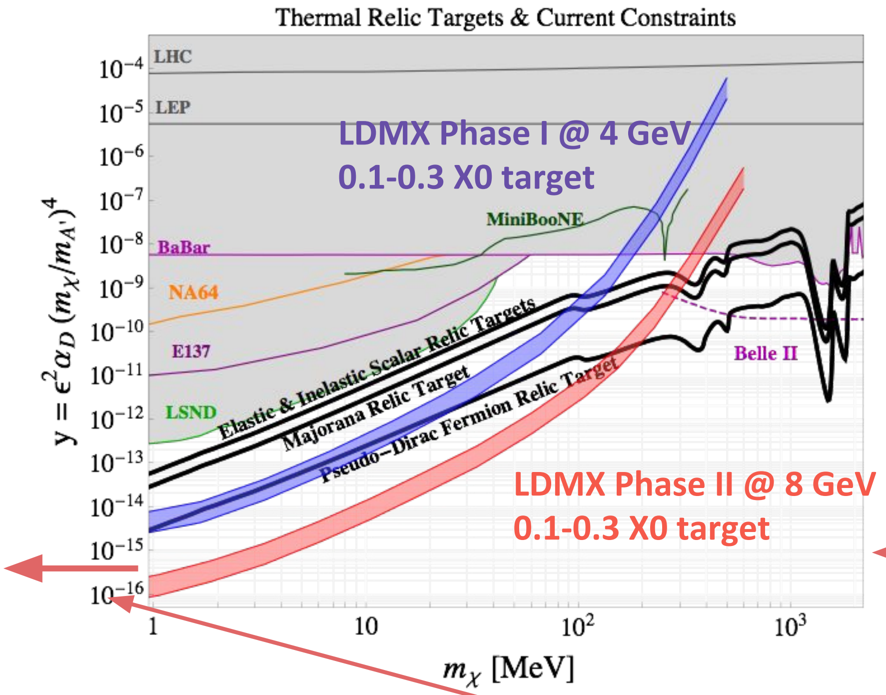


LDMX Phase I @ 4 GeV
0.1-0.3 X0 target

LDMX Phase I @ 4 GeV
ECal target

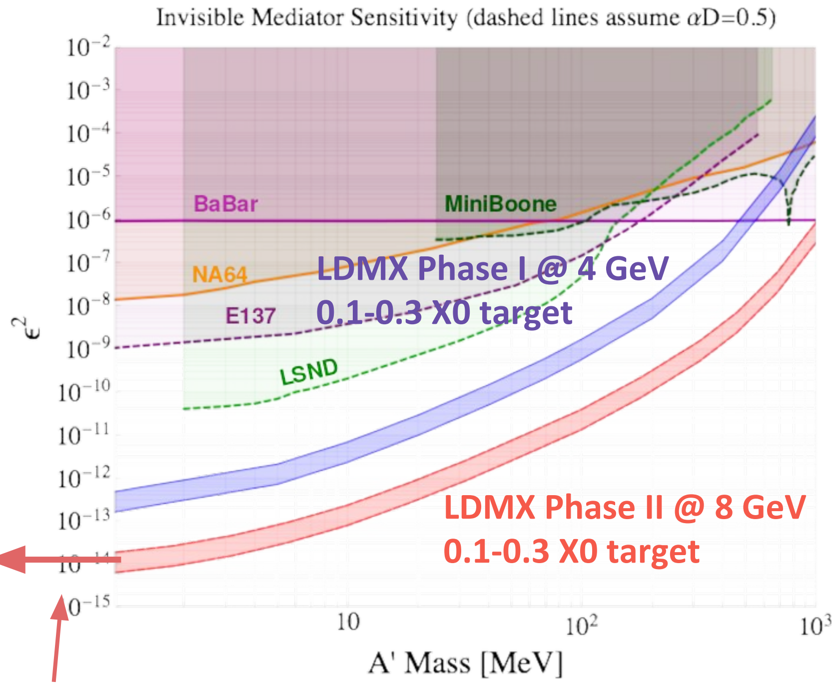
Sensitivity extends to lower masses

LDMX Phase II Reach



LDMX Phase I @ 4 GeV
0.1-0.3 X0 target

LDMX Phase II @ 8 GeV
0.1-0.3 X0 target



LDMX Phase I @ 4 GeV
0.1-0.3 X0 target

LDMX Phase II @ 8 GeV
0.1-0.3 X0 target

Sensitivity extends to lower masses

LDMX Physics Targets

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
☐ Dark Vectors decaying to neutrinos
☐ **Photonuclear and electronuclear measurements of interest for neutrino experiments --> drive to understand nuclear final state interactions (actively being explored as it is important)**
☐ Light pseudo-scalars
☐ Milli-charge particles --> investigating reach

LDMX Collaboration

SLAC NATIONAL ACCELERATOR LABORATORY	Norman Graf, Jeremy McCormick, Takashi Maruyama, Omar Moreno, Tim Nelson, Philip Schuster, Natalia Toro
UCSB	Owen Colegrove, Joe Incandela, Alex Patterson
UNIVERSITY OF MINNESOTA	Josh Hiltbrand, Jeremy Mans
Fermilab	Gordan Krnjaic, Nhan Tran, Andrew Whitbeck
Caltech	Bertrand Echenard, David Hitlin
UNIVERSITY OF CALIFORNIA SANTA CRUZ	Robert Johnson

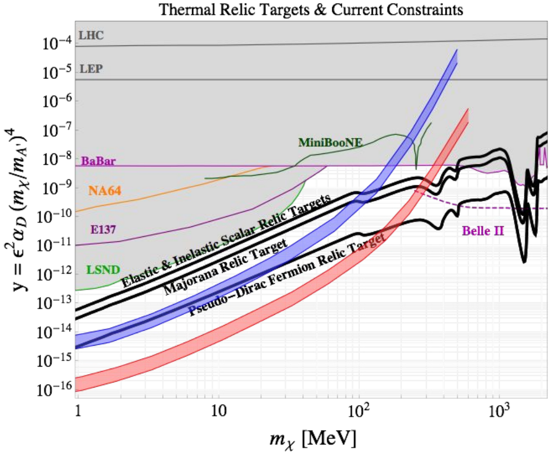
Always looking for new collaborators! If interested, email me at omoreno@slac.stanford.edu.

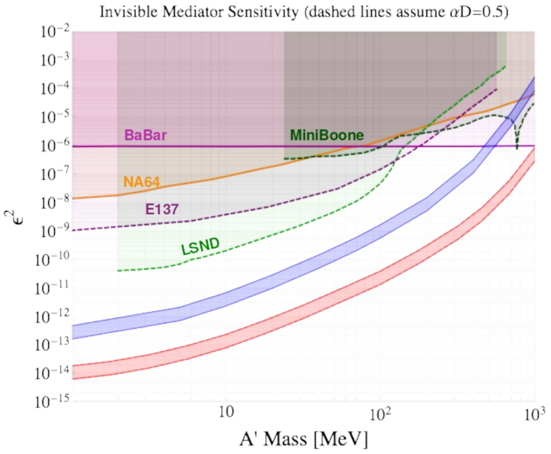
Summary and Outlook

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.


Thermal Relic Targets & Current Constraints

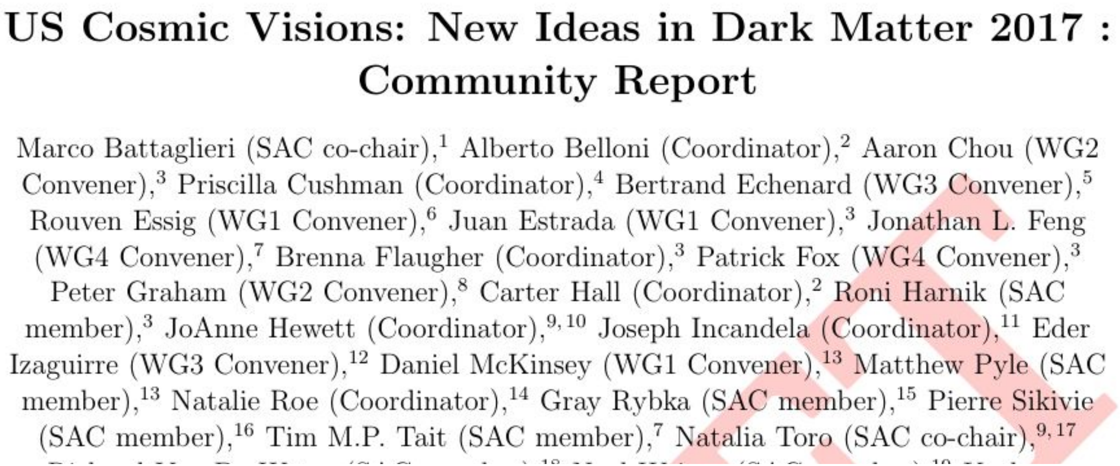

Invisible Mediator Sensitivity (dashed lines assume αD=0.5)

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]