LDMX: The Light Dark Matter eXperiment

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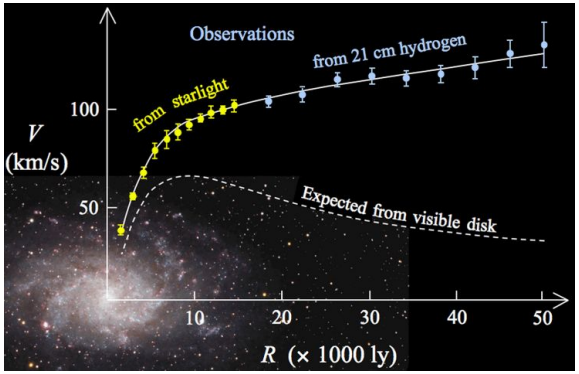
NuFACT 2022

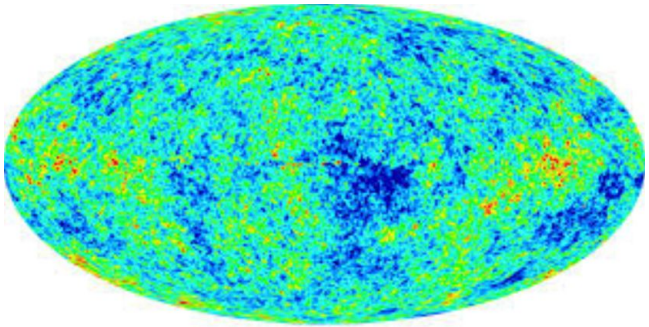
The Existence of Dark Matter

- There is clear evidence for the **existence of dark matter** (DM)
- The fundamental nature/origin of DM is a **central puzzle in particle physics**
- SM can't account for DM. What are some ideas for what DM could be?



Galactic Rotation Curves

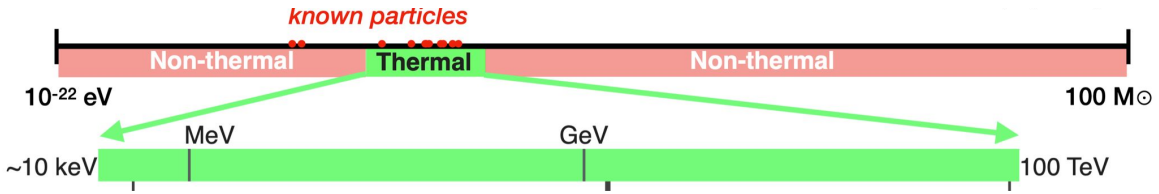
Gravitational Lensing



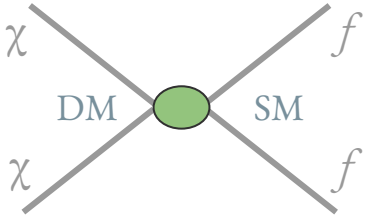
Cosmic Microwave Background

A Thermal Relic

- A thermal relic - simple and predictive model of dark matter (DM)



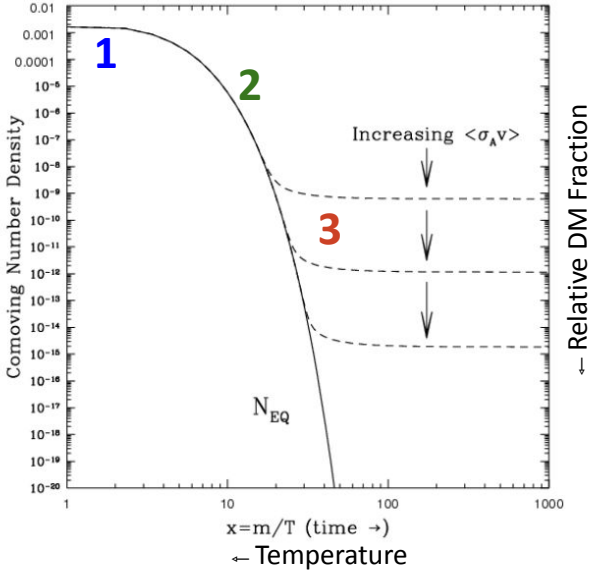
A Thermal Relic



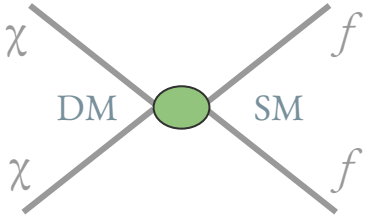
- What is the origin of DM? Any proposed mechanism must yield 85% DM!
  - **1.** Assume DM was in thermal equilibrium with SM particles
  - **2.** The universe expands and cools such that DM pairs are no longer produced
  - **3.** The universe expands and cools such that DM annihilations cease.
- The present DM density Ω_χ is related to the DM annihilation cross-section $\langle \sigma v \rangle$

$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \rightarrow \langle \sigma v \rangle = 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

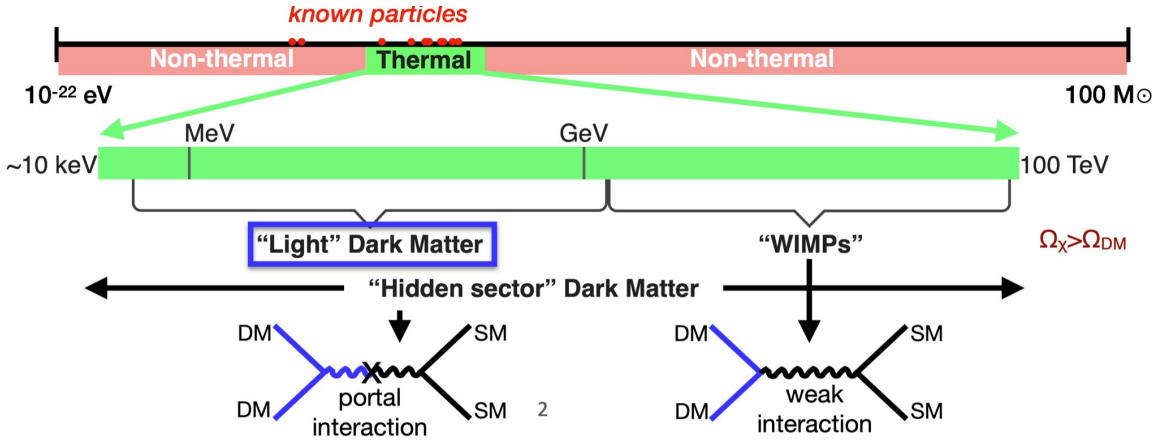
arXiv:hep-ph/9506380v1

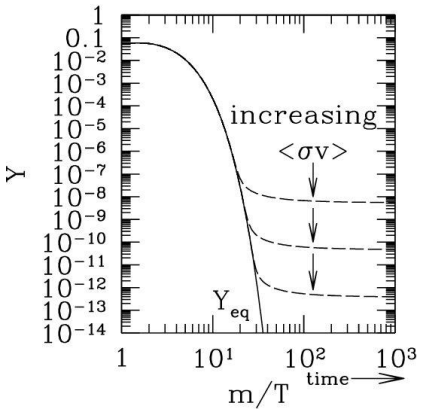


A Thermal Relic



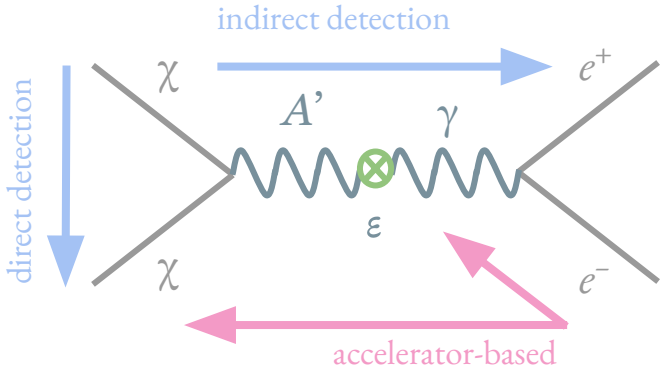
- A thermal relic - simple and predictive model of dark matter (DM)
- WIMPs are popular, but accessible parameter space is running out of room
- Increasing interest in expanding the thermal DM search to “Light” DM in the MeV-GeV mass range



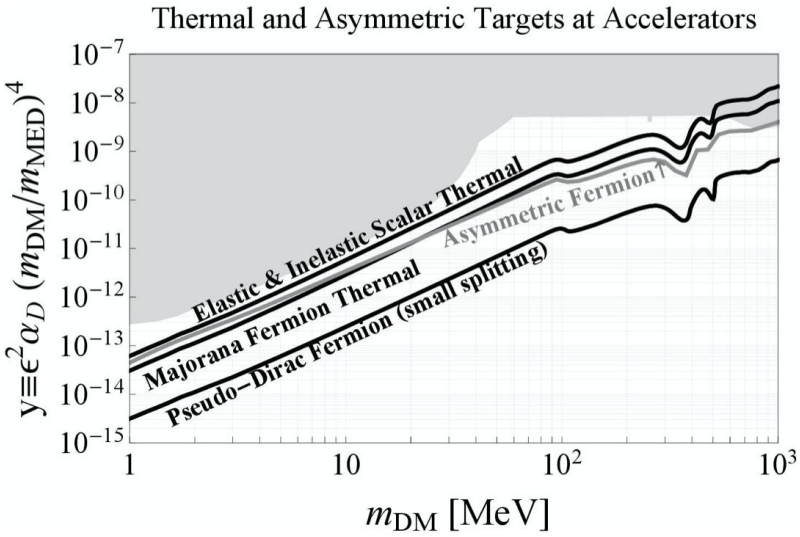


Light Dark Matter

- Simplest prediction includes a dark photon (heavy photon or A') that undergoes kinetic mixing with the SM photon
- Thermal prediction targets make attainable predictions with accelerators

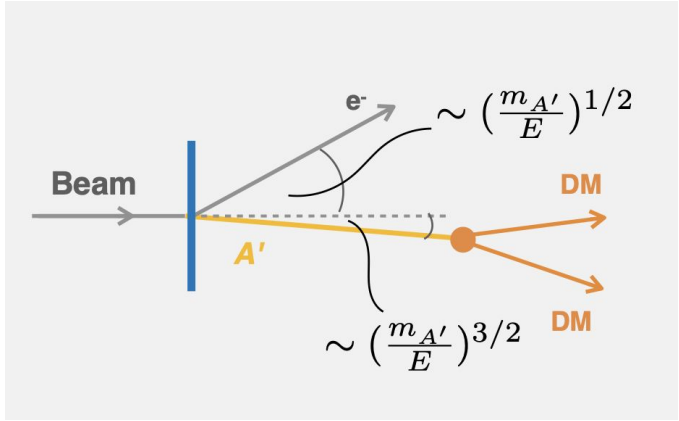


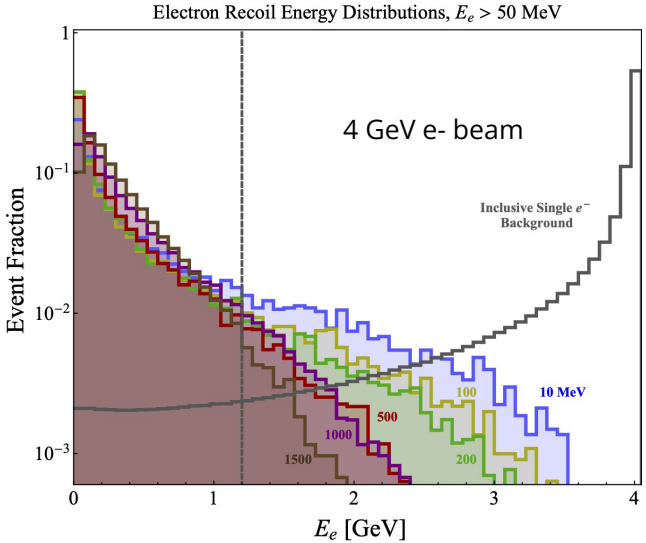
Kinetic Mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

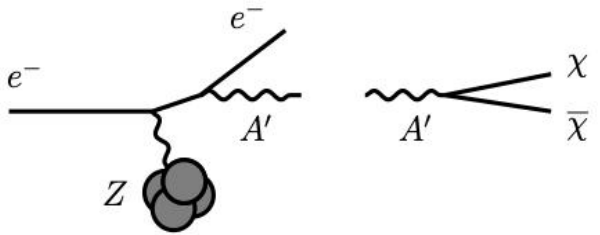


Dark Photon with a Fixed Target

- Fixed Target Signal Characteristics:
  - Dark bremsstrahlung A′ production, invisible decay
  - **A's take most of the beam energy; only visible final state particle is a soft recoil electron**



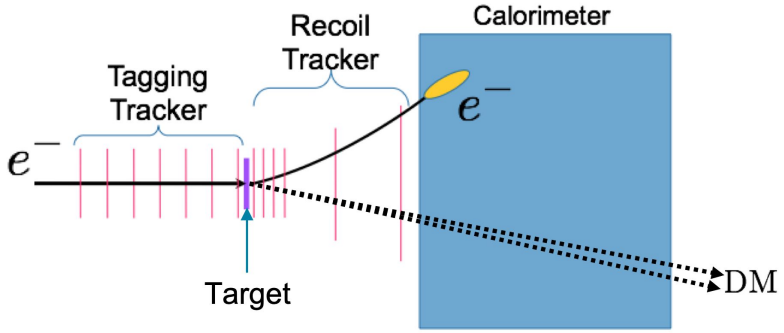


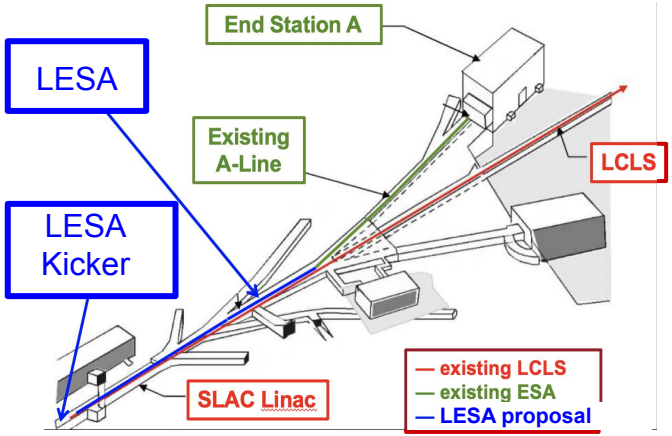


- Can probe this mechanism through a missing momentum search. We need…
  - High momentum resolution
  - High veto efficiency of SM backgrounds

LDMX Concept

- Missing momentum and energy approach
  - DM production identified by missing energy/momentum in detector
  - Equipped for particle ID e/gamma
  - Recoil pT used as discriminator/identifier

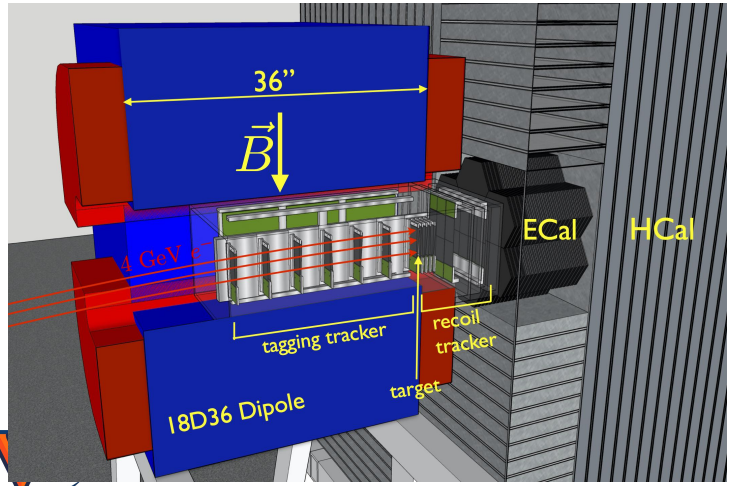


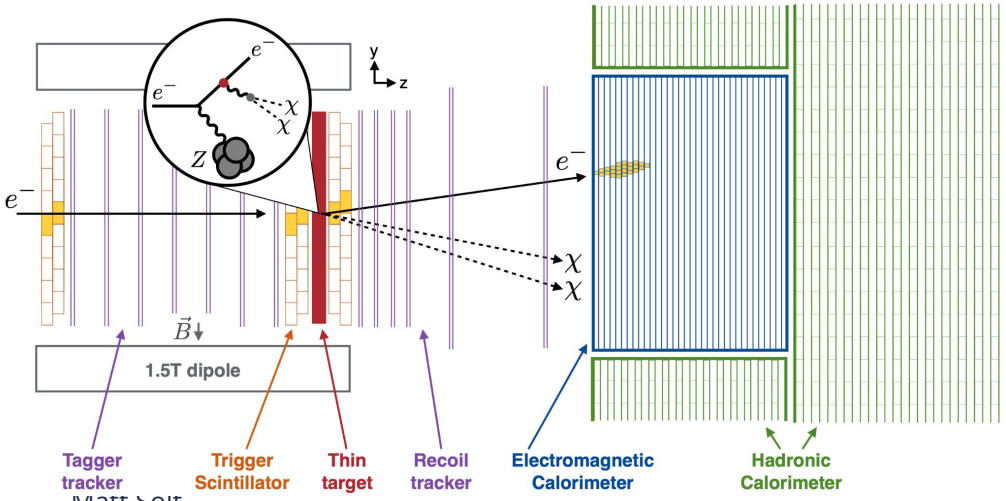


- 4 and 8 GeV e- beam provide by SLAC
  - Parasitically use the LCLS II beam with a dedicated transfer line (LESA)
  - Individual tagging and reconstruction of up to 1e16 electrons
  - Low current, high repetition rate 37 MHz, μ = 1

LDMX Design

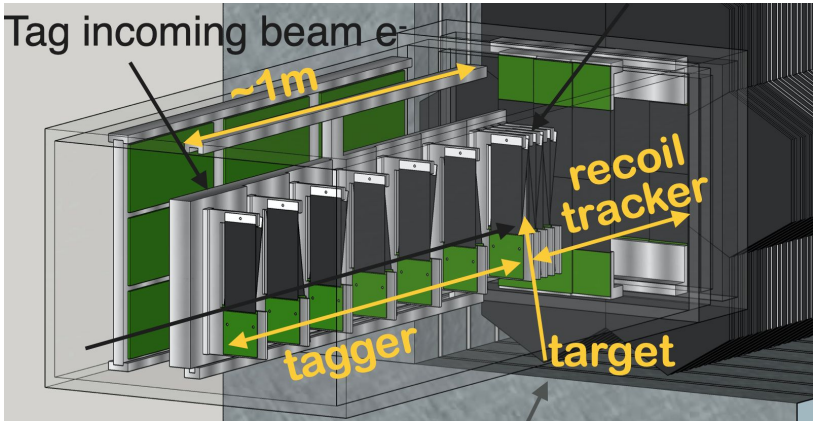
- Need hermetic detector designed for high rates and high radiation doses
  - **Tagging/recoil tracker**: fast with high momentum resolution and large acceptance
  - **Electromagnetic calorimeter**: fast, good energy resolution, and high granularity
  - **Hadronic calorimeter**: high veto efficiency of neutral hadrons

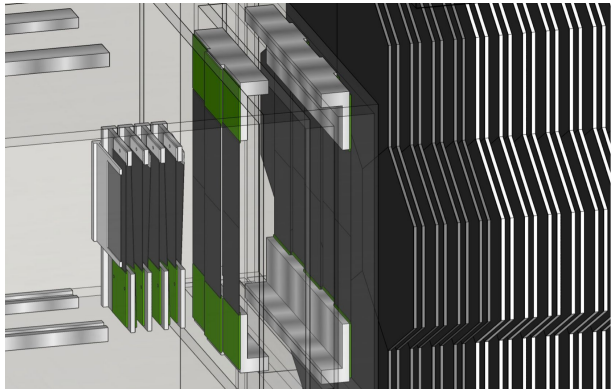




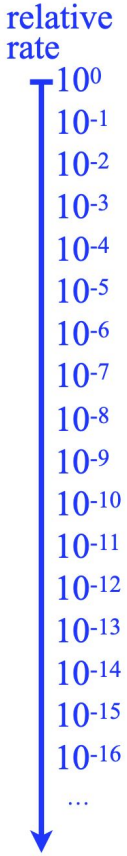
Tracker and Trigger Scintillator

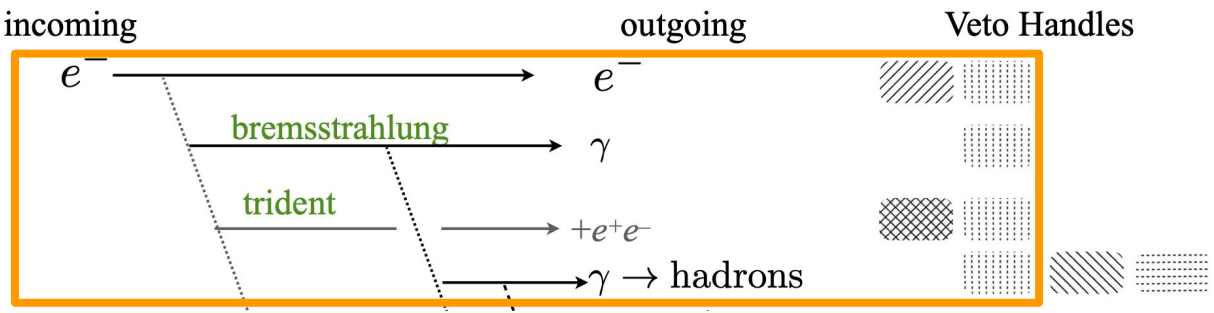
- Tagging tracker
  - Measures incoming beam electron
- Recoil tracker (based on Heavy Photon Search design)
  - Measures recoil electron and vetoes extra particles
- Trigger Scintillator
  - Arrays of scintillator bars provide fast count of incoming electrons
  - Used an input to the missing energy trigger

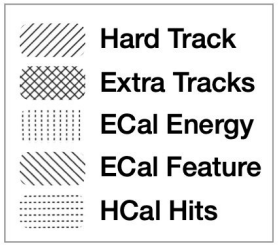




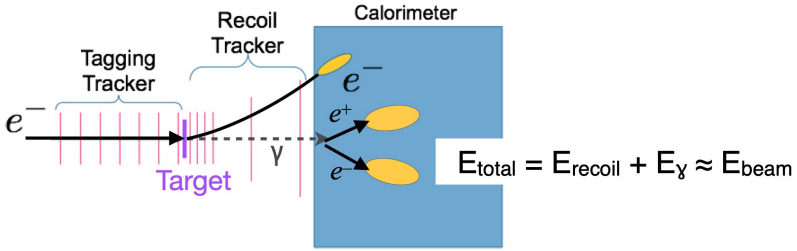
Backgrounds



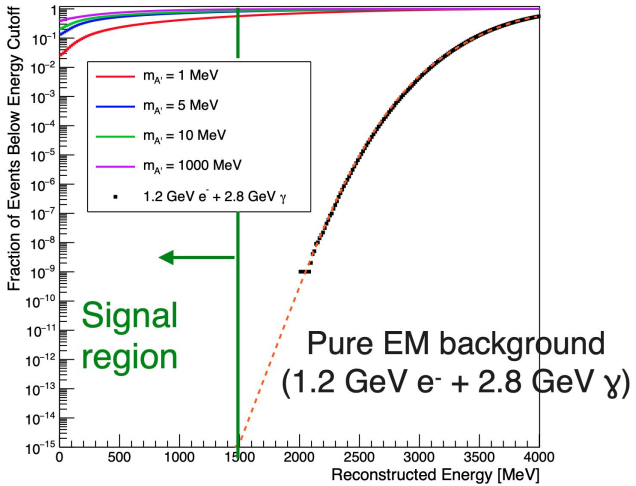


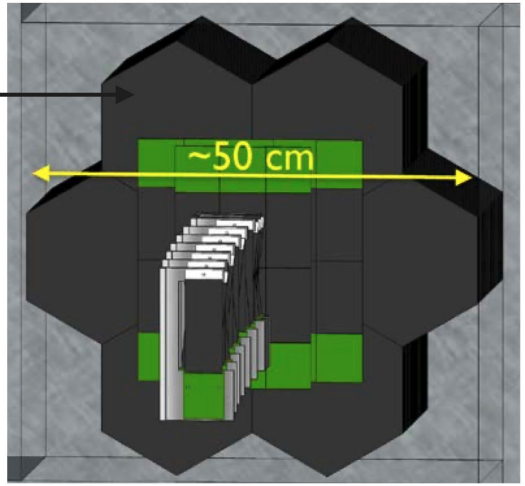


Electromagnetic Calorimeter



- 40 X0 Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - Provides fast missing energy trigger
  - Dense, radiation hard, full shower containment, and high granularity





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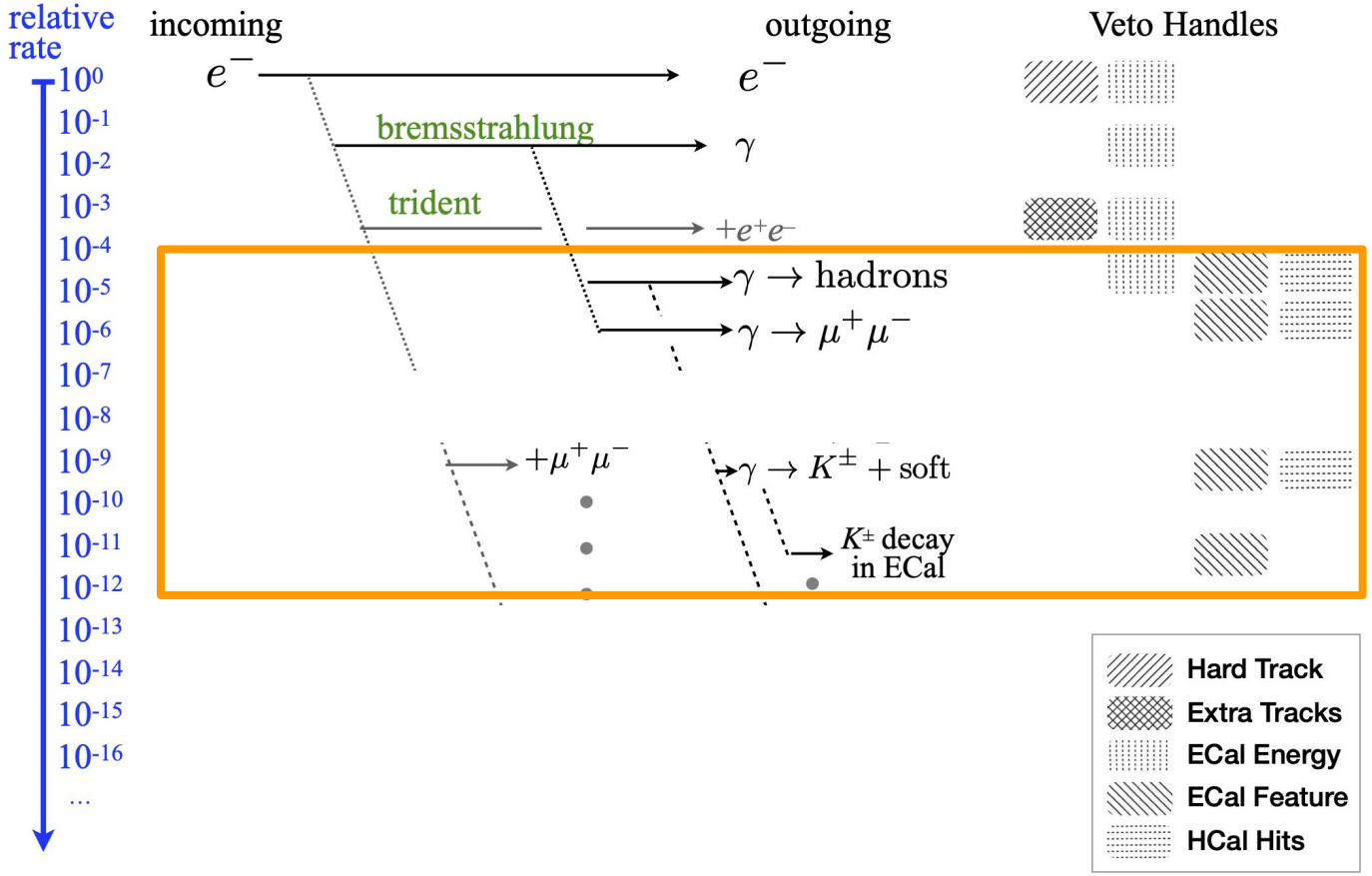
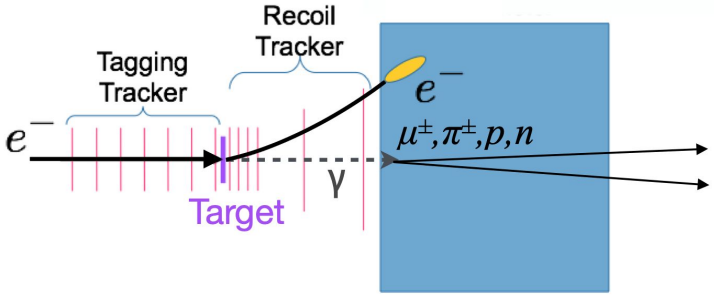
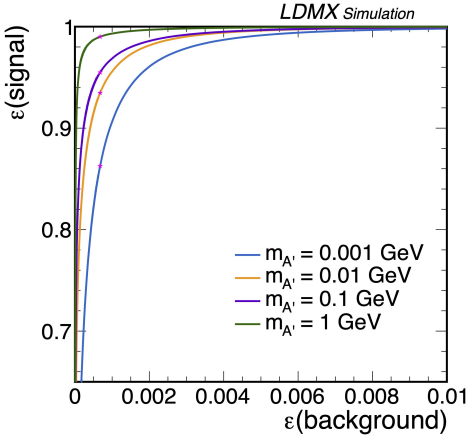


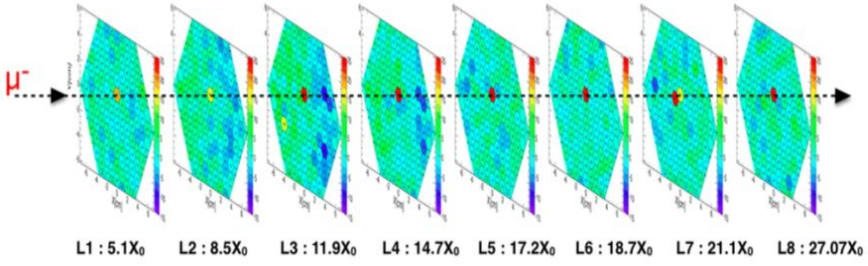
Ecal Veto

- More difficult to veto: Rare photon reactions that deposit low energy in the Ecal
  - Exploit longitudinal/transverse shower shapes and train a boosted decision tree (BDT)
  - High granularity Ecal enables MIP tracking





A.Martelli on behalf of CMS, arXiv:1708.08234



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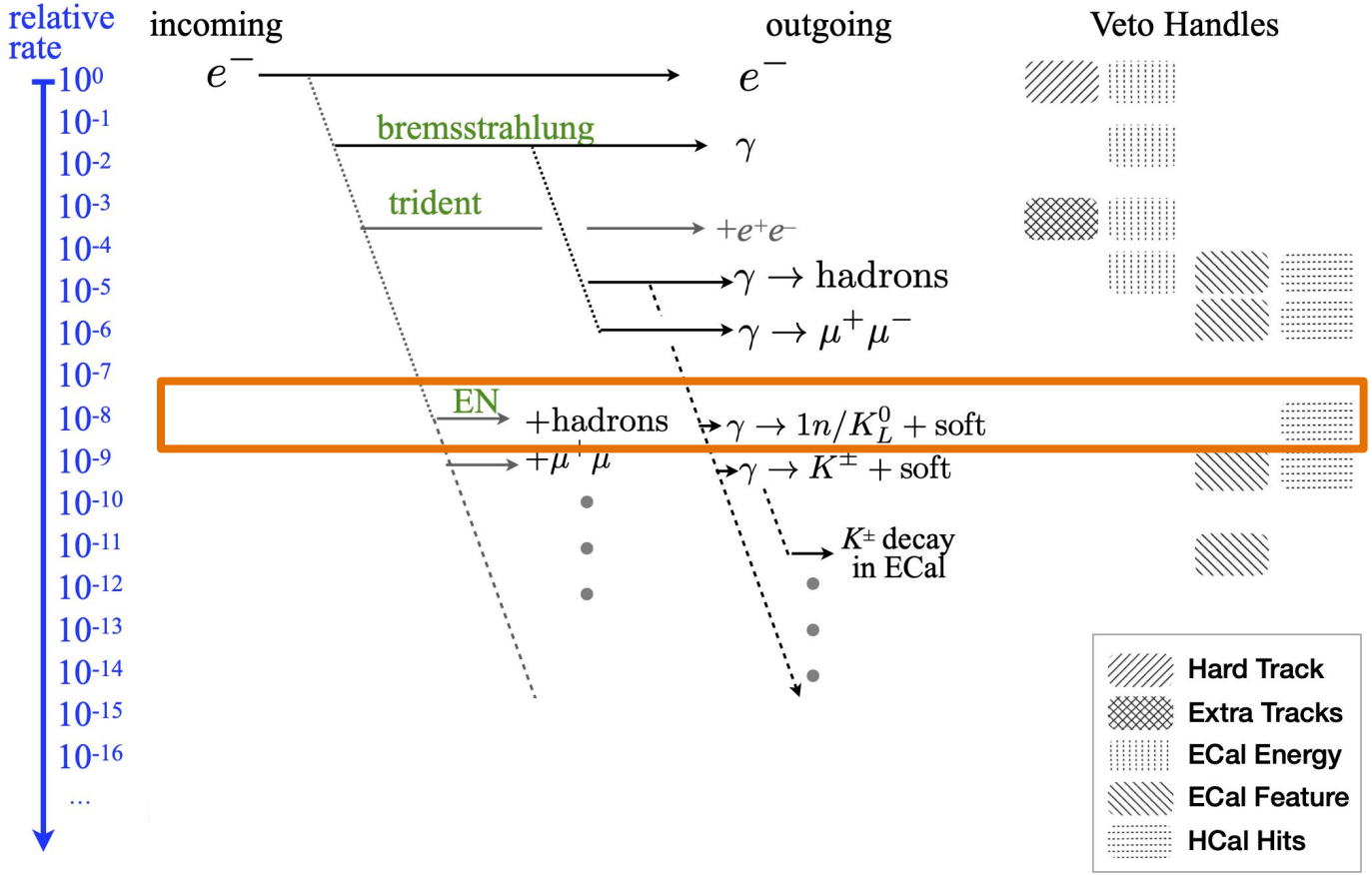
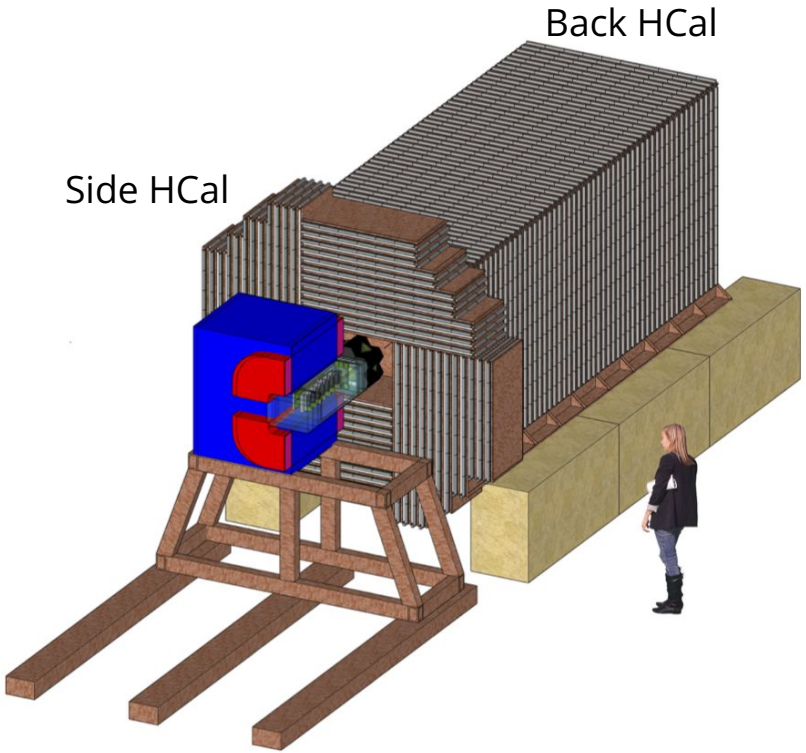


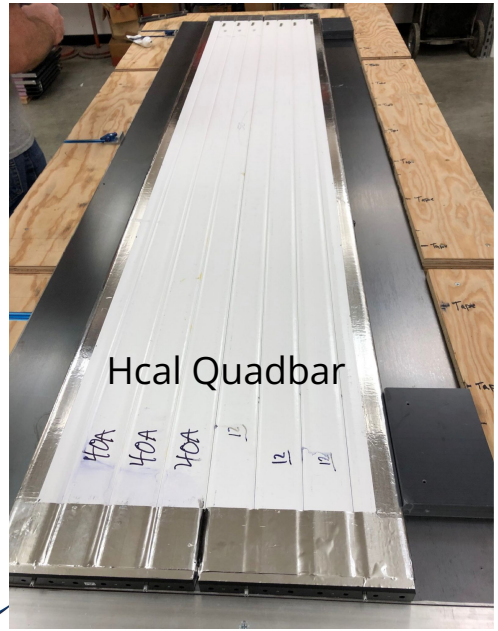
Hadronic Calorimeter

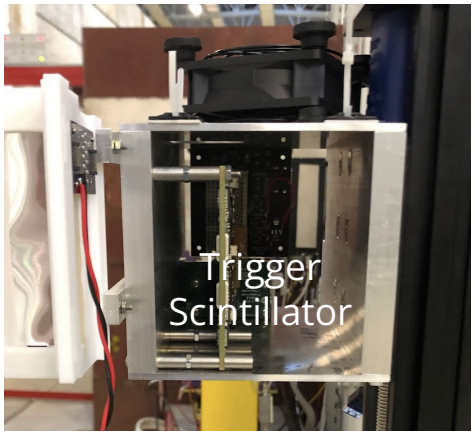
- Sampling calorimeter with segmented plastic/steel
  - Readout by wavelength shifting fibers and SiPMs (based on the Mu2e Cosmic Ray Veto design) - **Craig Group on Tuesday WG4**
  - Highly efficient veto for PN processes that produce neutral hadrons. Desire 1e-6 rejection
  - Side HCal rejects wide angle bremsstrahlung and $\gamma \rightarrow \mu^+\mu^-$



CERN Test Beam

Recent successful test beam with HCal prototype at CERN PS in April, 2022





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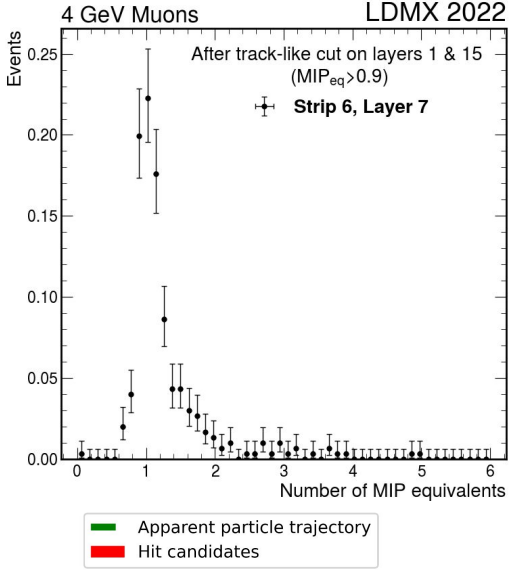
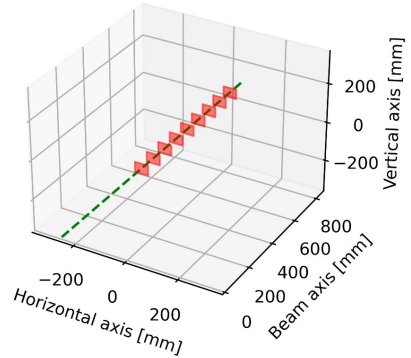


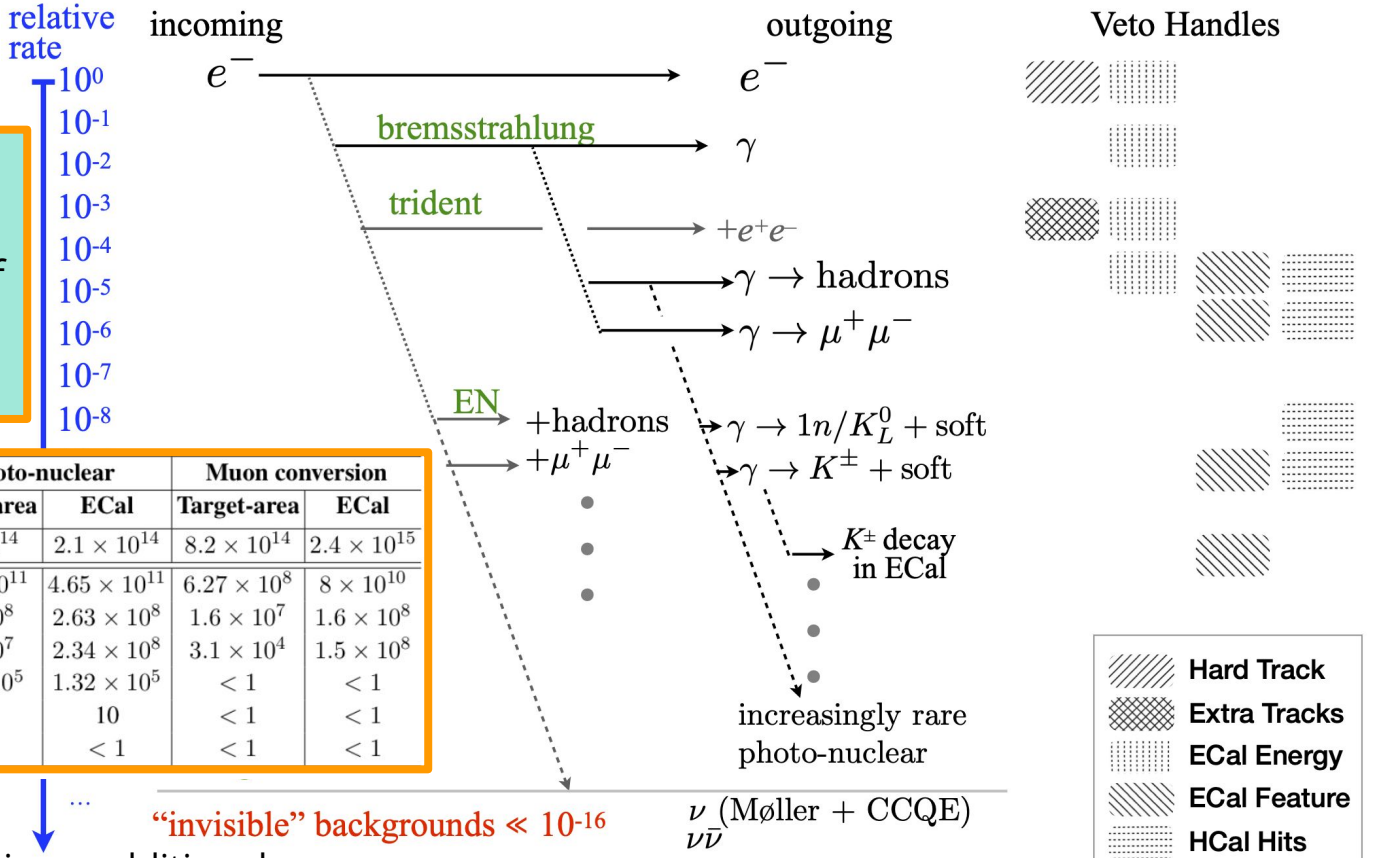


Data analysis is ongoing

Backgrounds

All systems combined: < 1 background event with signal efficiency of ~30-50% for O(1e14) EoT!

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1



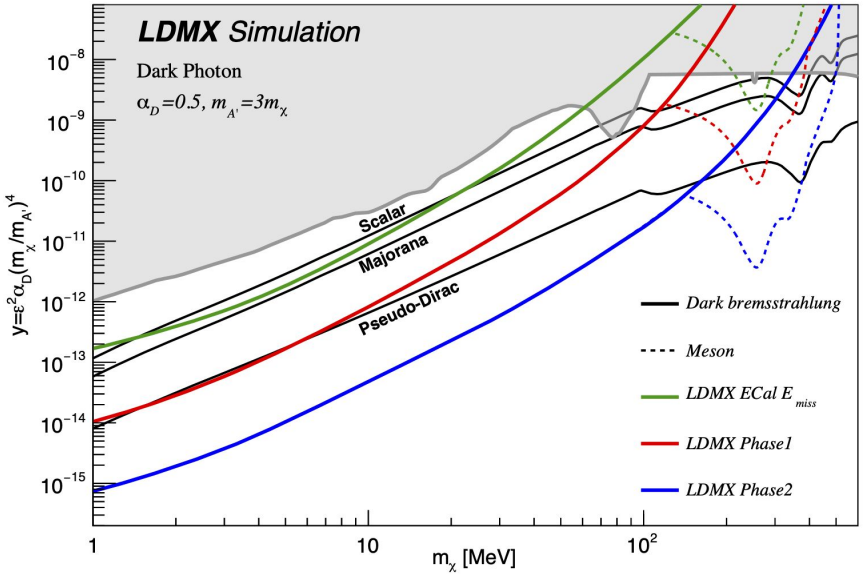
Recoil e- pT is an additional discriminator on backgrounds

arXiv:1912.05535

LDMX Sensitivity

$$2m_{DM} < m_{A'}$$

Phase 1: 4 GeV,
10^{14} electrons
Phase 2: 8 GeV,
10^{16} electrons



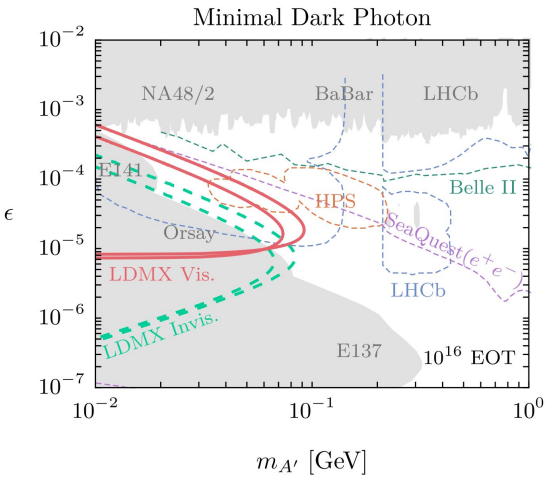
arXiv:1808.05219

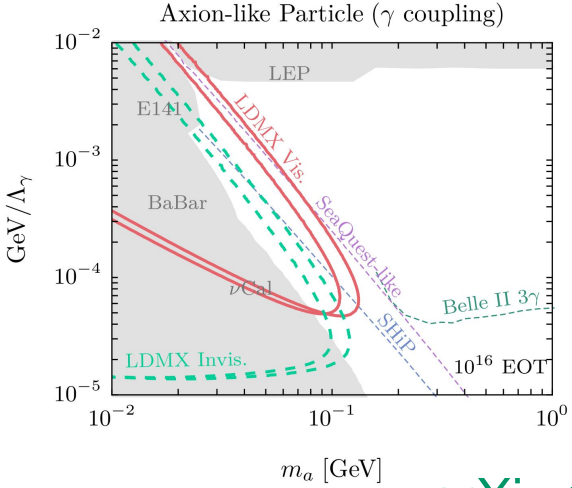
2020	2023	2025	2027
Detector Development	Construction	Phase I data taking	Phase II construction & operation

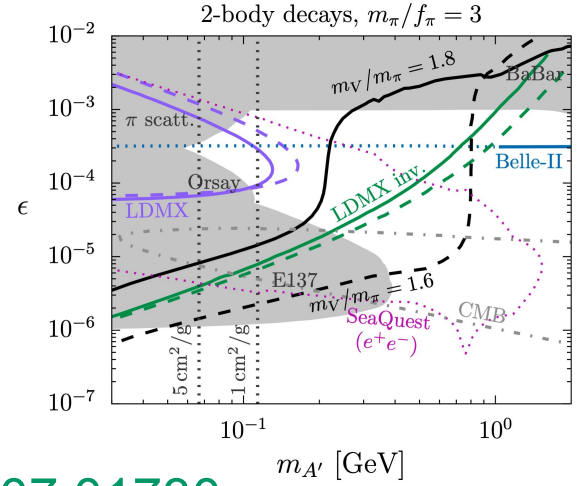
Proposed LDMX baseline schedule

LDMX Visible Signatures

- Broad physics potential for LDMX beyond missing momentum search
  - Displaced visible decays - minimal dark photon, ALPs, SIMPs, etc.
  - Electronuclear measurements for neutrino physics **(Wes Ketchum on Tuesday WG2)**







Projections are for 8 GeV and 16 GeV beams

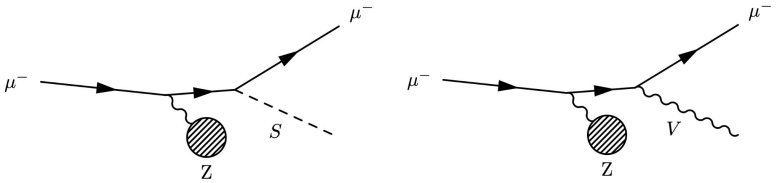
arXiv:1807.01730

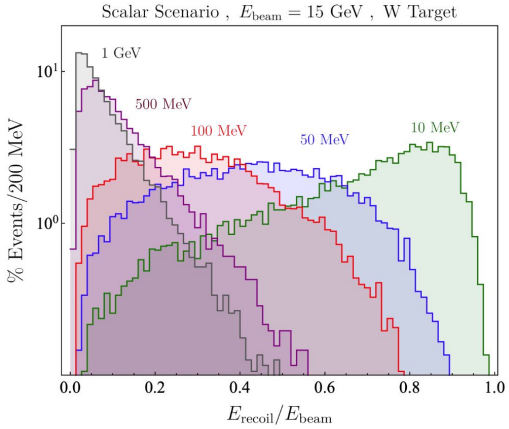
Muon Missing Momentum Experiments

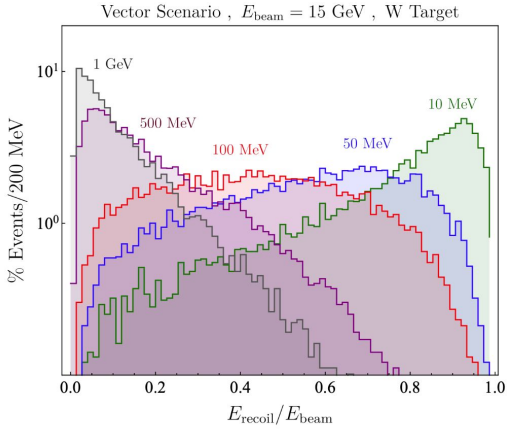
- Proposed Muon Missing Momentum Experiment (M^3) at Fermilab using an LDMX-like apparatus arXiv:1804.03144v1
- Advantage over electron beams like LDMX - Bremsstrahlung backgrounds are suppressed: $(m_e/m_\mu)^2 \approx 2 \times 10^{-5}$
- Advantage over high energy muon beams (e.g. proposed NA64μ experiment at CERN/SPS) - compact design with high momentum resolution arXiv:1412.1400v2

Muon Missing Momentum Experiment (M^3)

- Missing momentum search for muon-philic invisibly decaying particles- scalars (S) and vectors (V)
- Proposed M^3 at Fermilab in two phases
  - Phase I - 1e10 MOT 15 GeV: **Motivated by Muon g-2 parameter space**
  - Phase II - 1e13 MOT 15 GeV: **Motivated by models of thermal dark matter**







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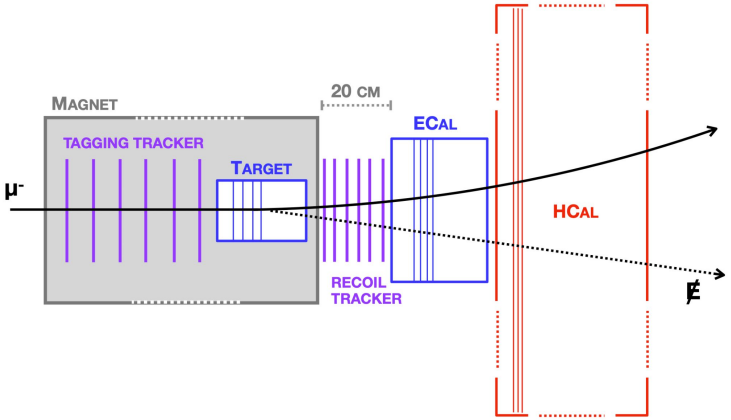
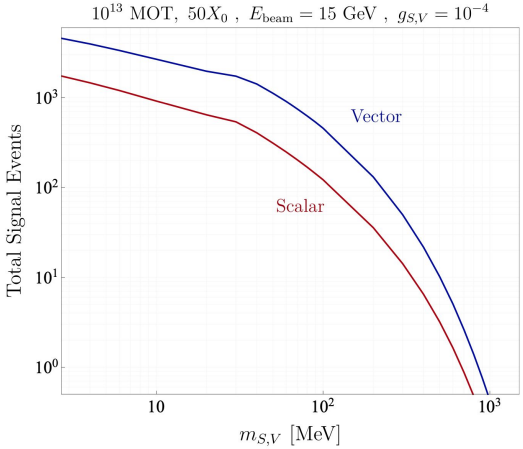
Proposed Detector M³

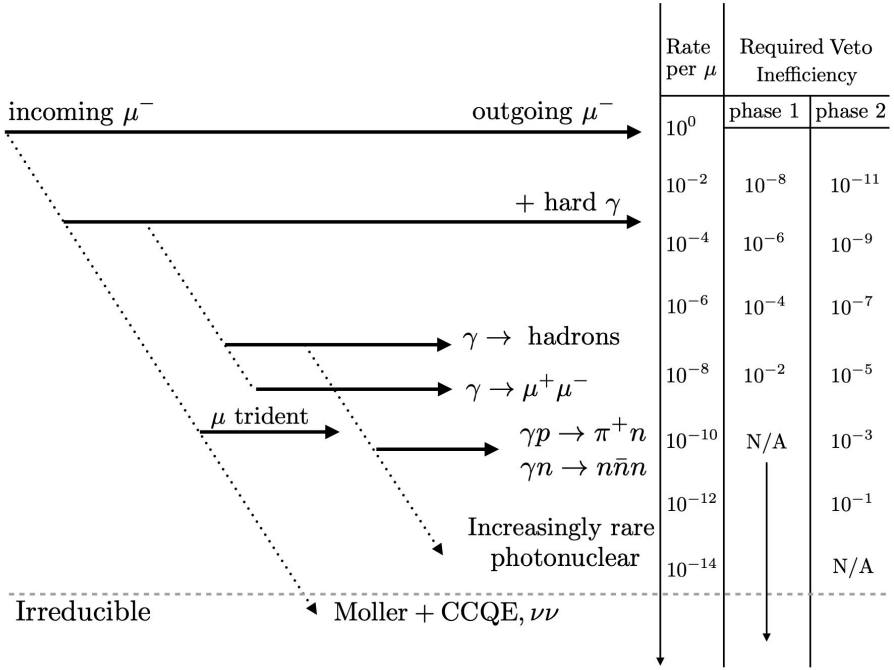
- LDMX-like detector: tagging/recoil tracker, Ecal, and Hcal
- Main difference - thick active target 50 X0
  - Proposed to be ~25 cm deep Si-W sampling calorimeter (LDMX Ecal material)
  - LYSO is also a viable possibility
  - Detects muon energy loss from SM processes within the target





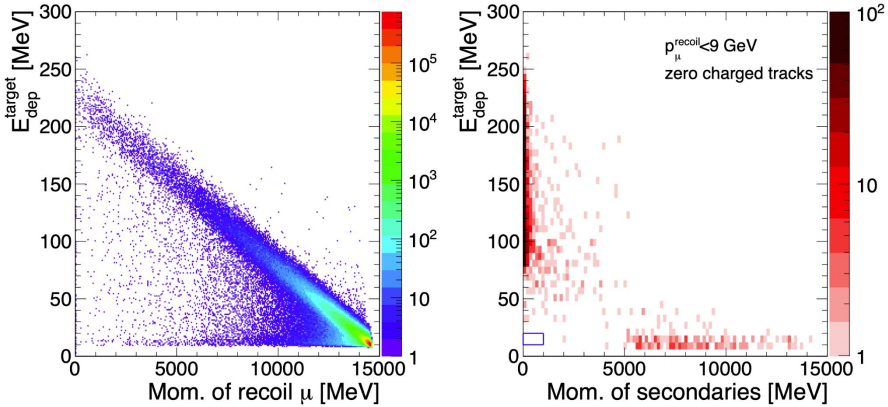
M³ Backgrounds (I)

- Reducible backgrounds
  - Single bremsstrahlung backgrounds
  - Photo-nuclear hadronic events
  - Muon pair production
  - Suppressed from electron beam experiments
- Irreducible backgrounds
  - Neutrino pair production
  - Moller + CCQE
  - Expected to be <<1e-13



M³ Backgrounds (II)

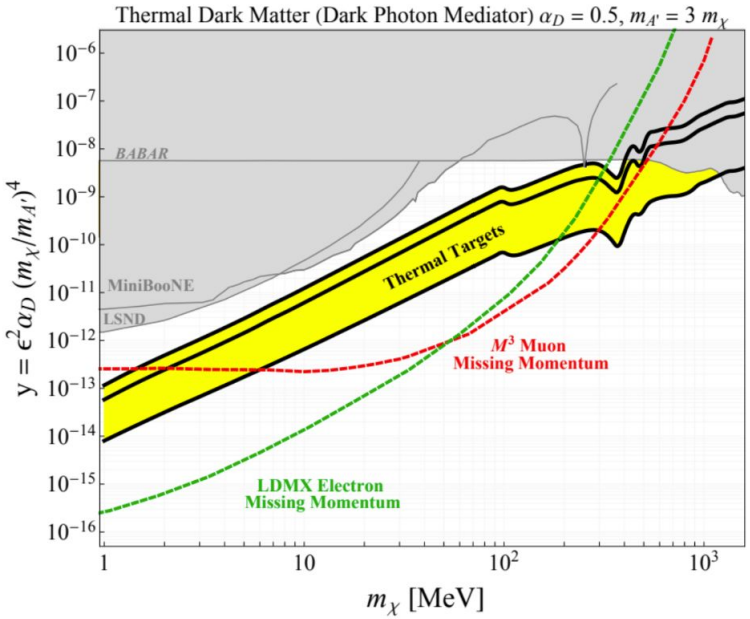
- Beam-related backgrounds
  - Muon energy spread
  - Pion contamination (additional hadron absorbers between Phase I and II)
  - Require recoil muon momentum < 9 GeV, 0 charged tracks, and 10 MeV < E_dep < 20 MeV. Simulations show 0 background for 1e7 MoT
  - There are several other useful handles from the active target



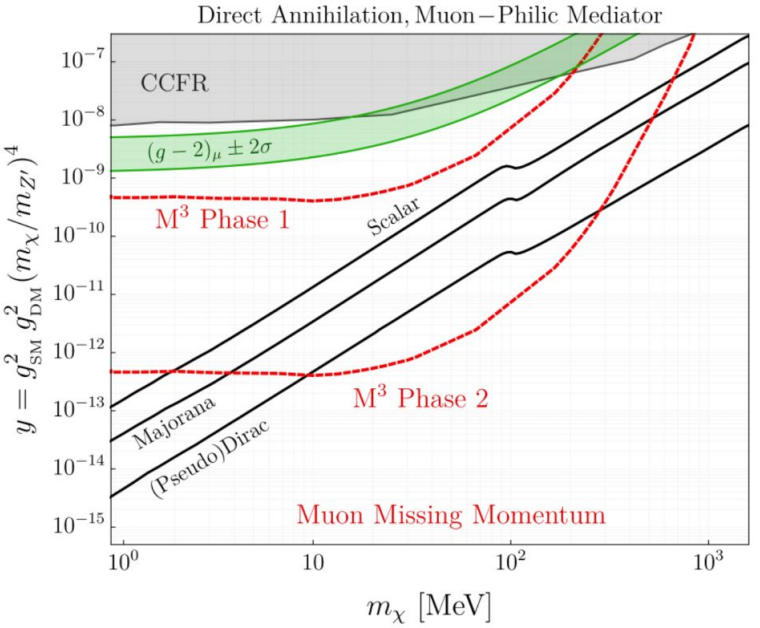
Zero background for 1e13 MoT can potentially be achieved

Matt Solt

M³ Projections



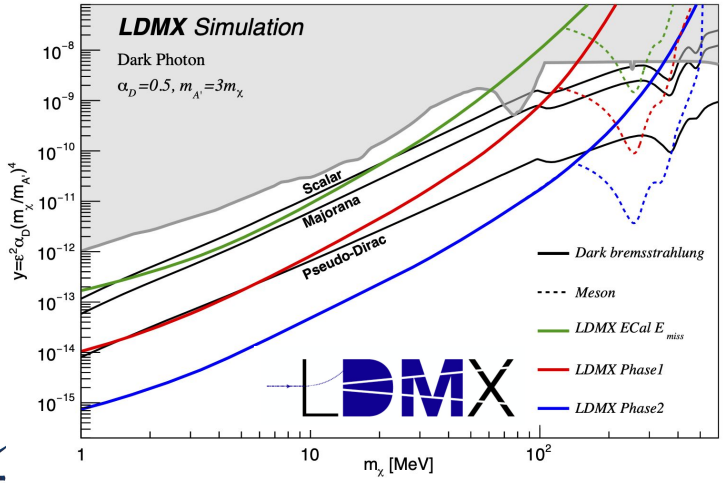
Complimentary DM parameter space with e- beams

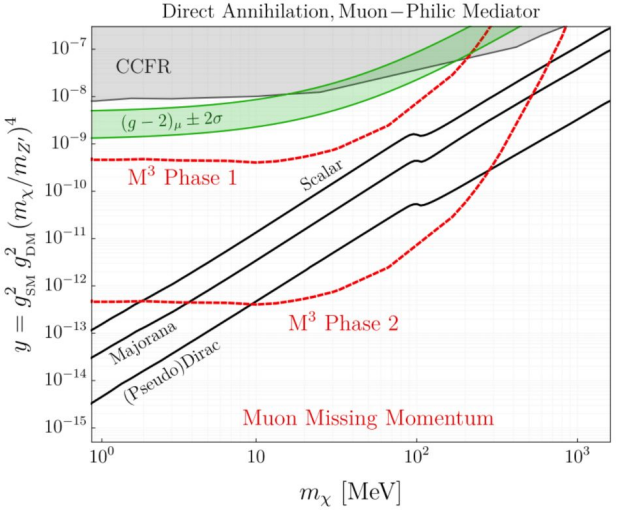


Phase I = 1e10 MOT: **g-2 anomaly**
Phase 2 = 1e13 MOT: **dark matter**

Conclusion

- Thermal relic models offer plausible and predictive models of dark matter
- LDMX can conclusively probe many such models in the sub-GeV mass range through a missing momentum search
- Proposed M³ at Fermilab can test muonic forces motivated by muon g-2 and thermal relic models





Thank You!

Caltech Fermilab LUNDS UNIVERSITET UNIVERSITY OF MINNESOTA UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA SLAC NATIONAL ACCELERATOR LABORATORY STANFORD UNIVERSITY TEXAS TECH UNIVERSITY UNIVERSITY of VIRGINIA

Prepared for submission to JHEP
FERMILAB-PUB-18-087-A, PUPT-2557

M^3: A New Muon Missing Momentum Experiment to Probe $(g-2)_\mu$ and Dark Matter at Fermilab

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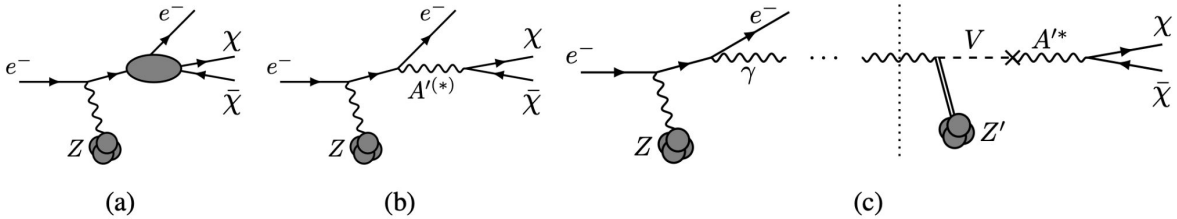
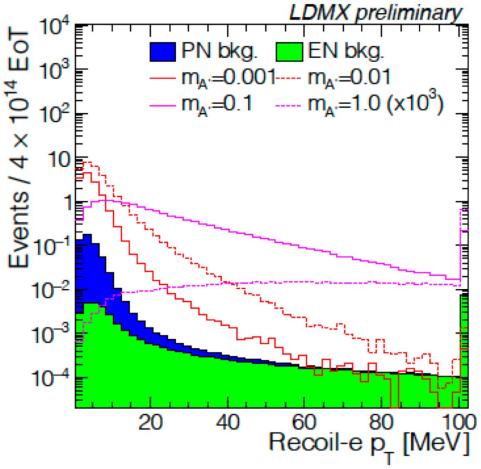
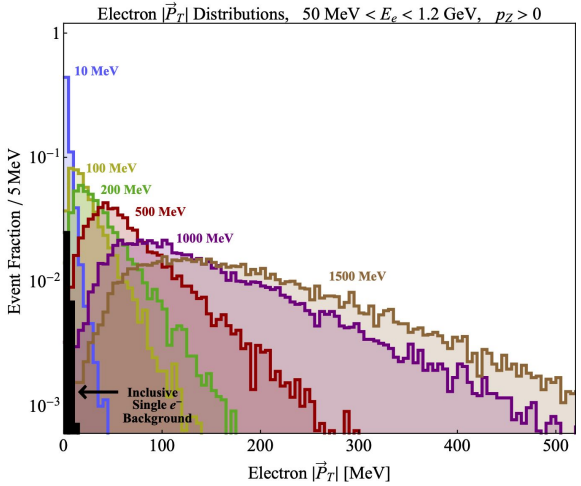
Signal Kinematics

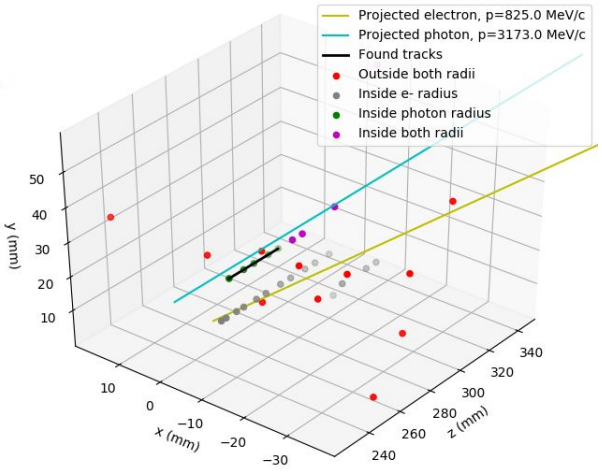
- Transverse momentum of recoil election is the last veto handle
- Currently not used in veto efficiency estimates, but as a backup discriminator
- Transverse momentum can also be used to estimate/constrain DM mass scale



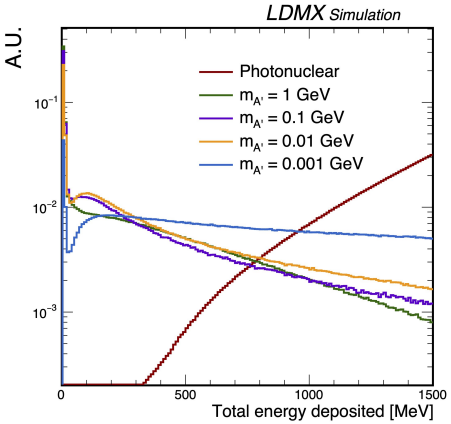


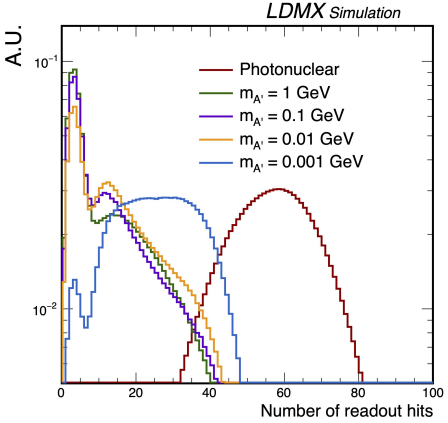


Ecal BDT

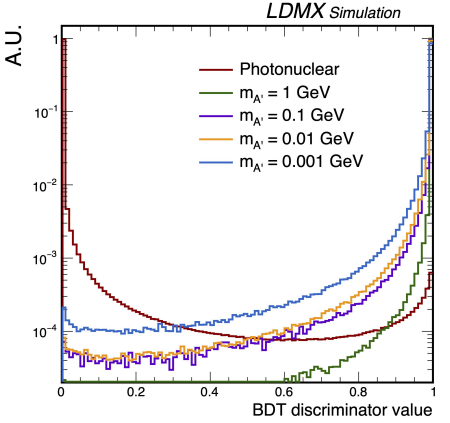


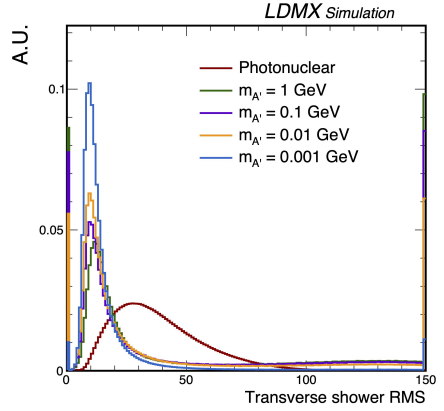
MIP Tracking





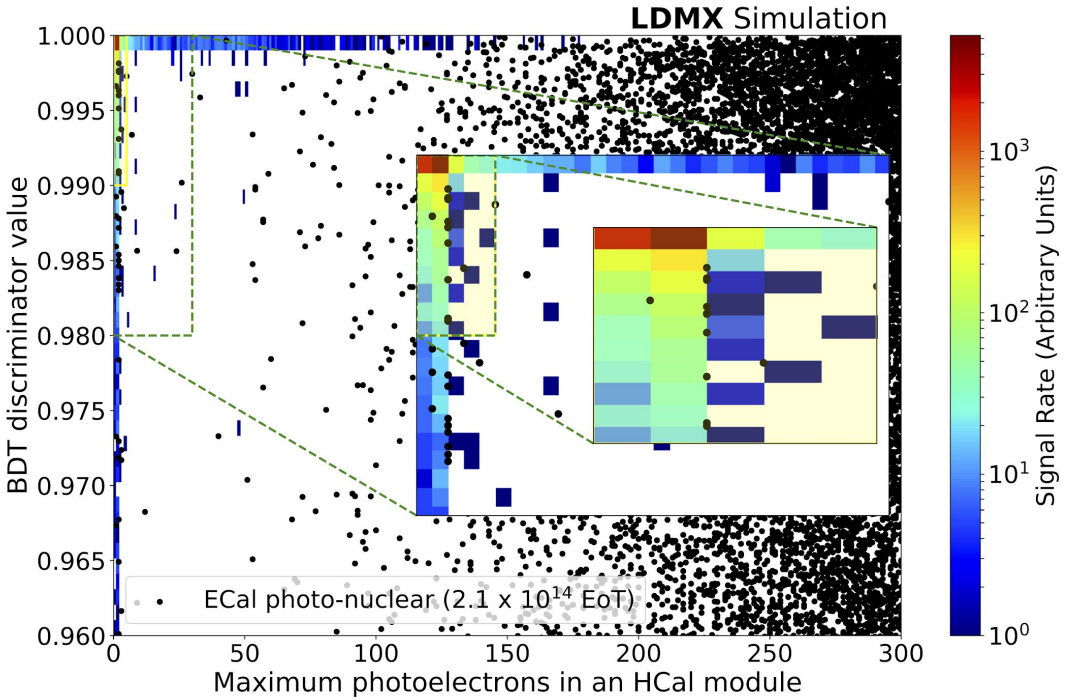
BDT Variables



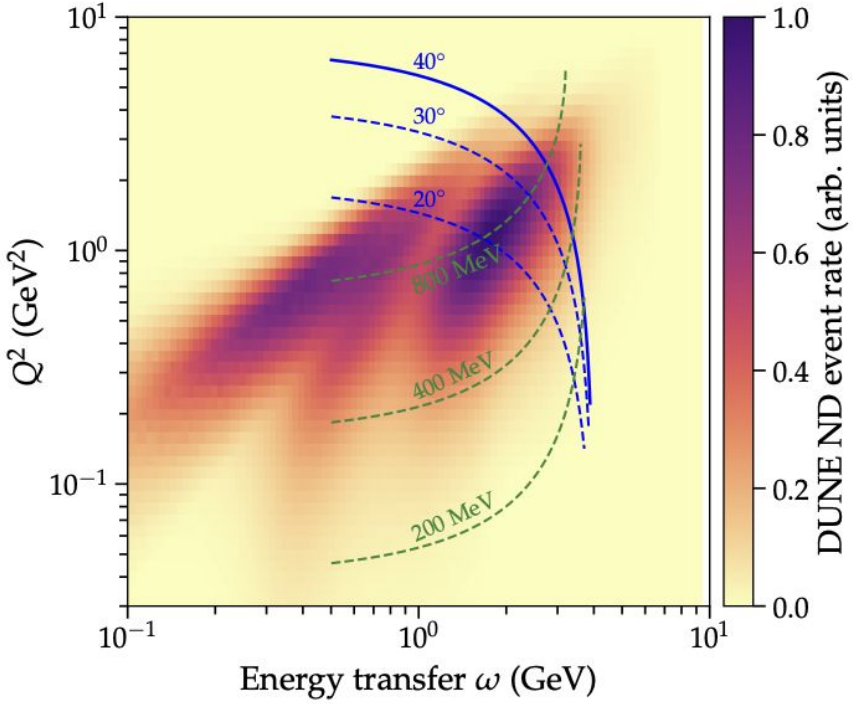


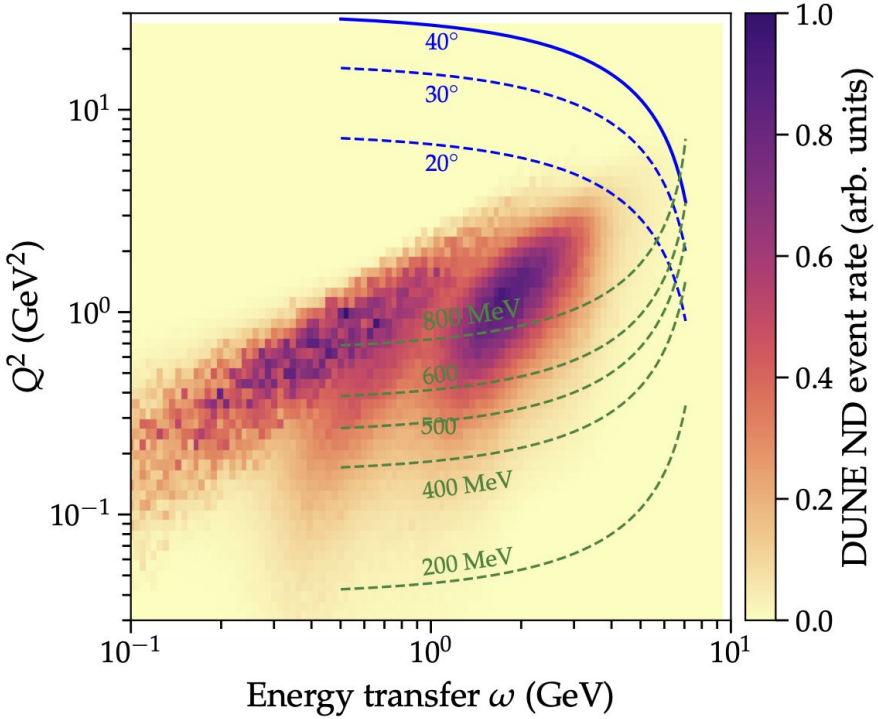
Ecal/Hcal Vetoes

- Ecal BDT > 0.99
- Hcal max PEs is > 5



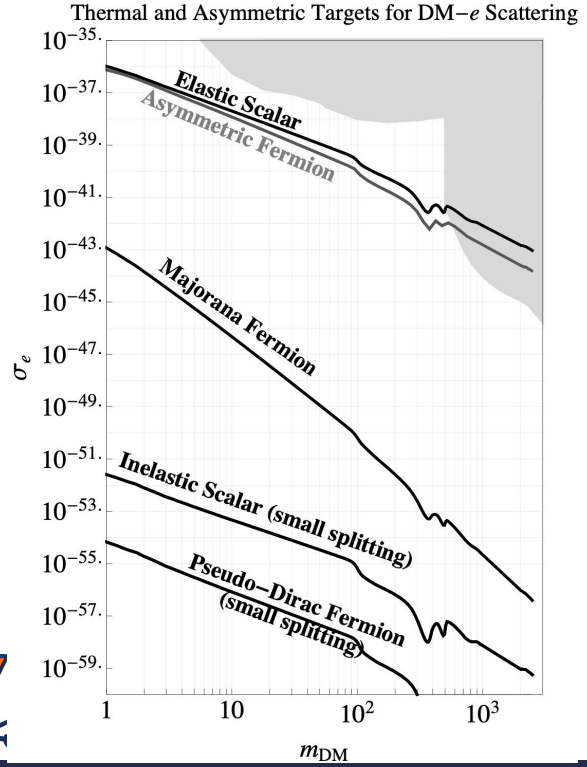
Electro-nuclear Scattering Measurements



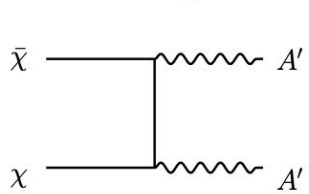


Advantage of DM Production at Accelerators

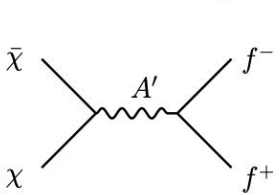
Non-relativistic vs semi-relativistic DM scattering

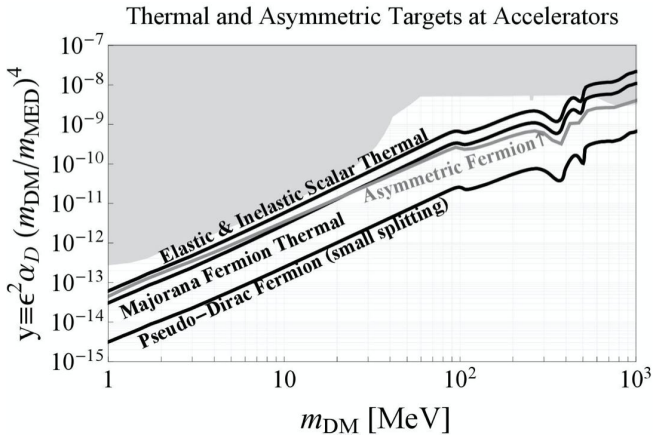


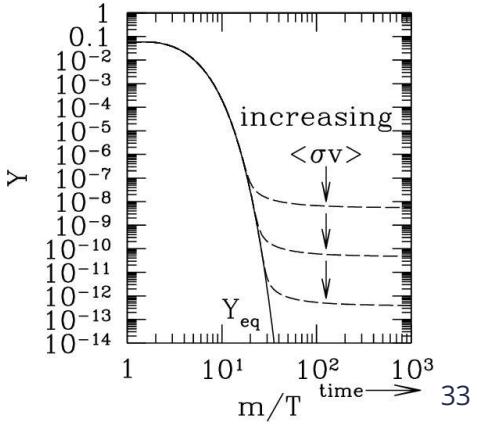
$\sigma v \propto \alpha_D^2$



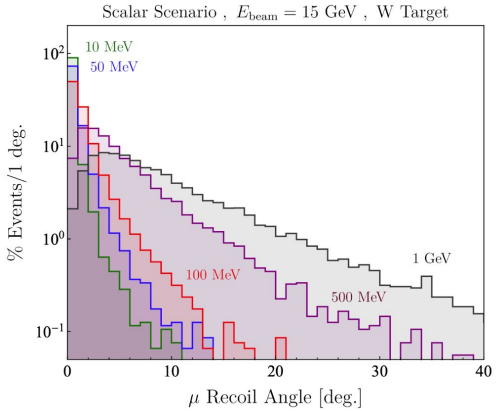
$\sigma v \propto \epsilon^2 \alpha_D$

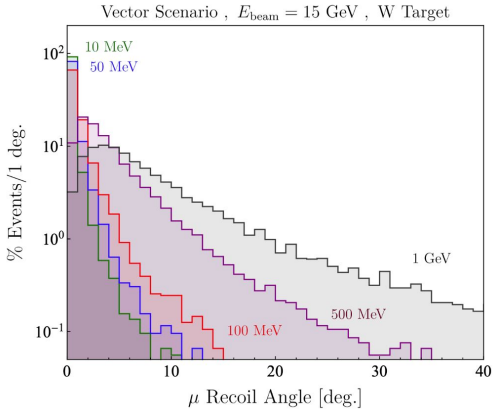


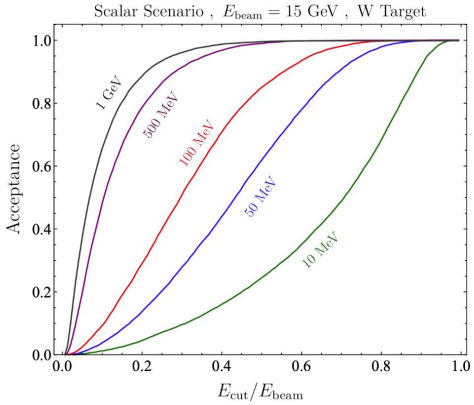


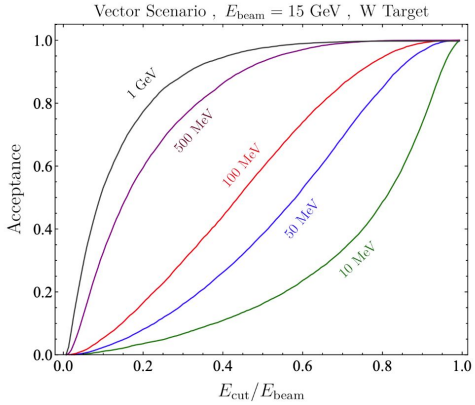


M³ Signal Acceptance

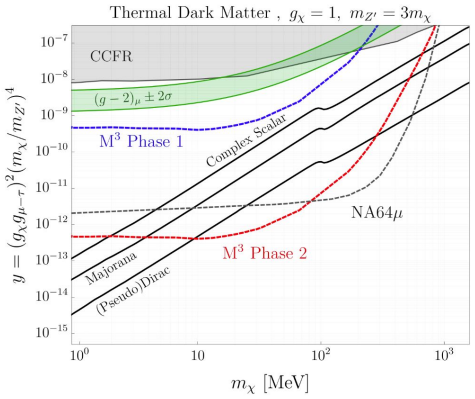


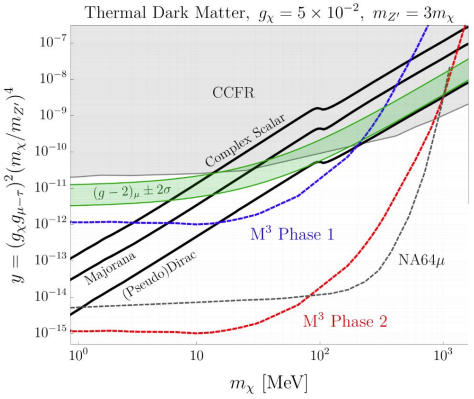


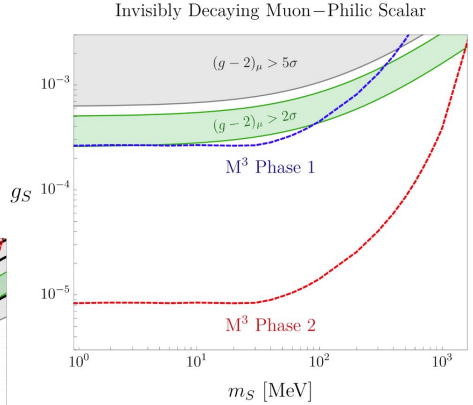


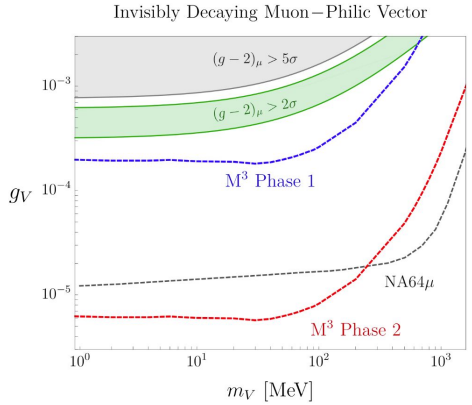


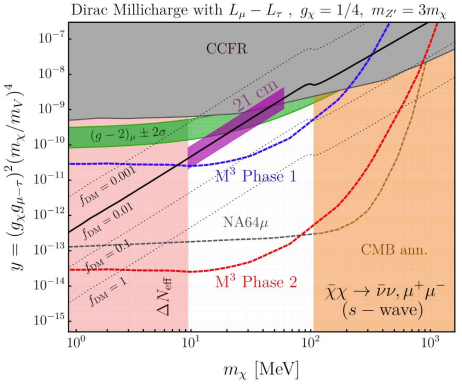
M³ Projections

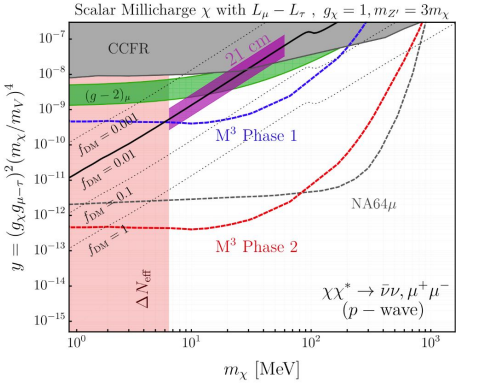








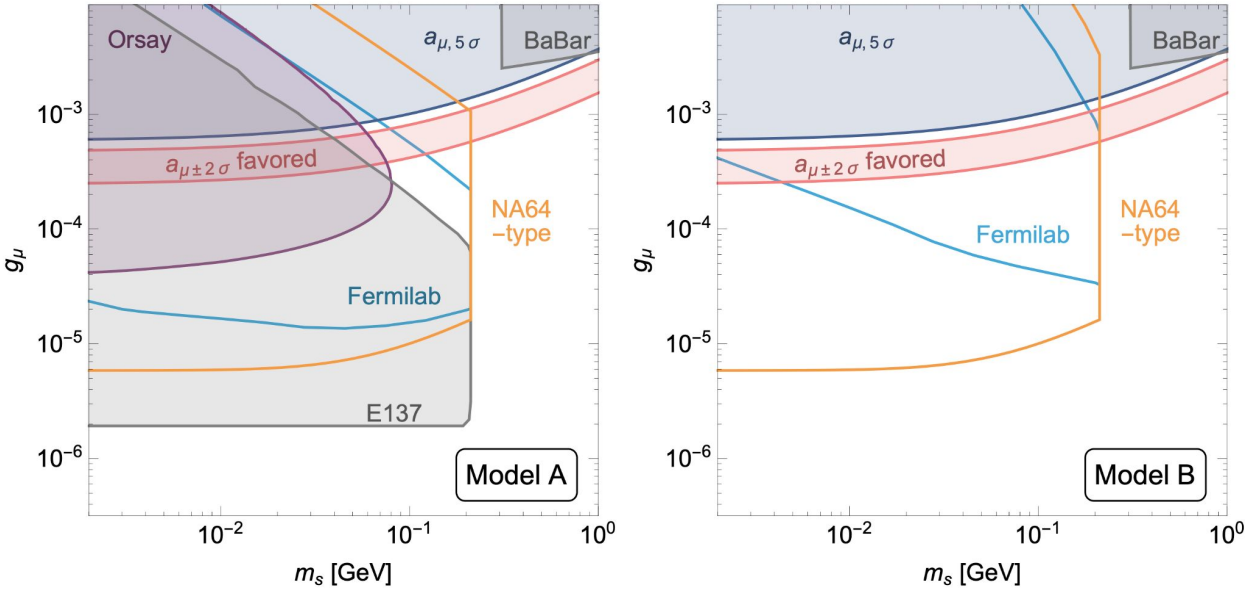




Phase I = 1e10 MOT

Phase 2 = 1e13 MOT

M³ Visible Decay Parameter Space



arXiv:1701.07437v3

Light Dark Matter

SLAC

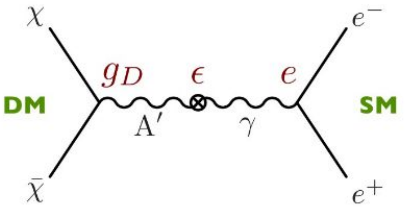
"Lee-Weinberg Bound"

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Rightarrow m_\chi \geqslant 2\ \mathrm{GeV}$$

Lighter dark matter requires a **new, comparably light force carrier.**

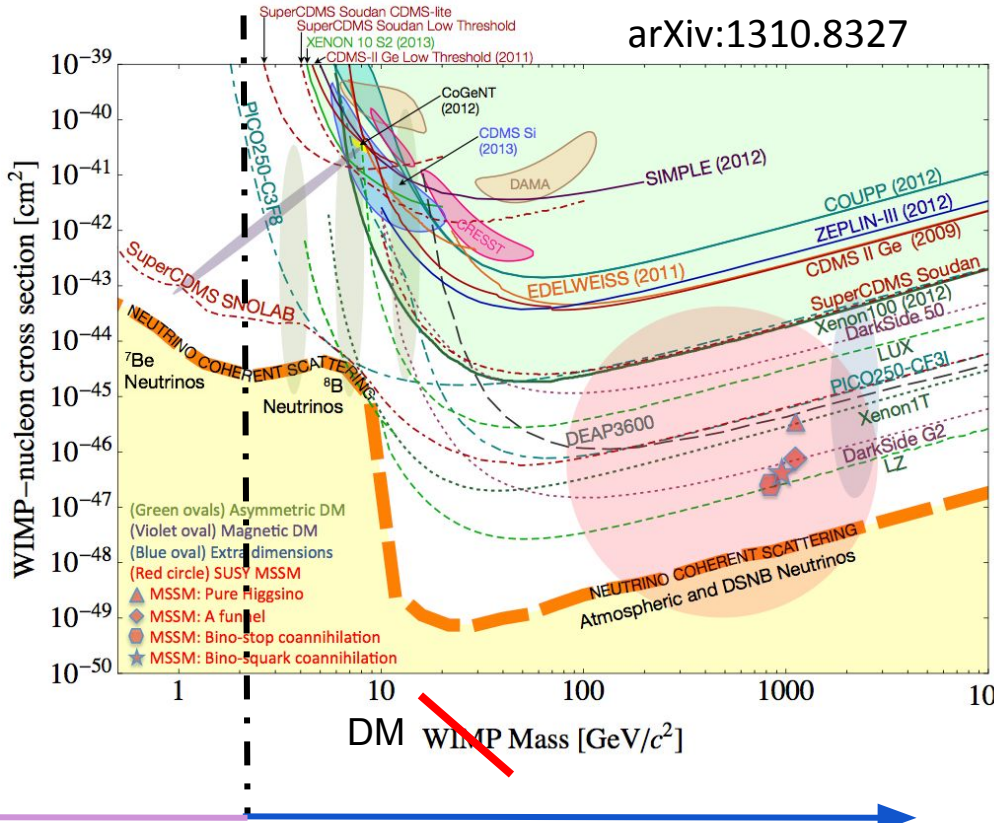
A simple/natural candidate: heavy/dark photon (A')

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$



$$\alpha \equiv \frac{e^2}{4\pi}$$

arXiv:1310.8327



Light Dark Matter

WIMPs