Dark Matter at Accelerators - HPS and LDMX

November 20, 2021

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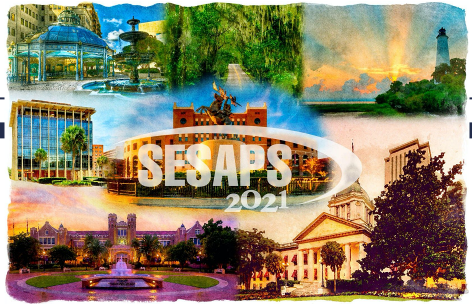
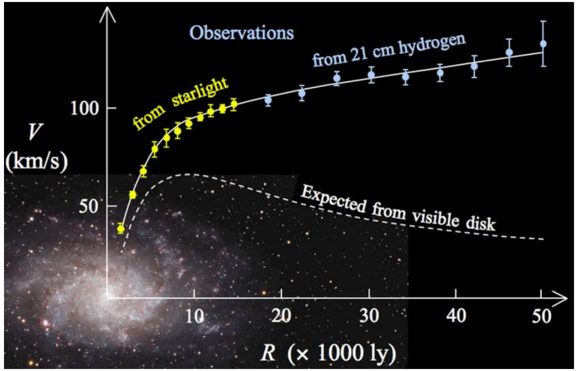


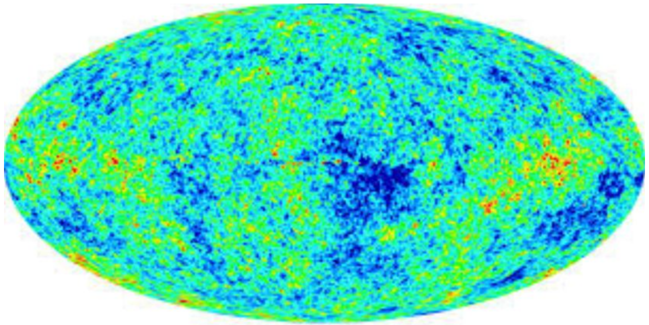
The Existence of Dark Matter

- 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

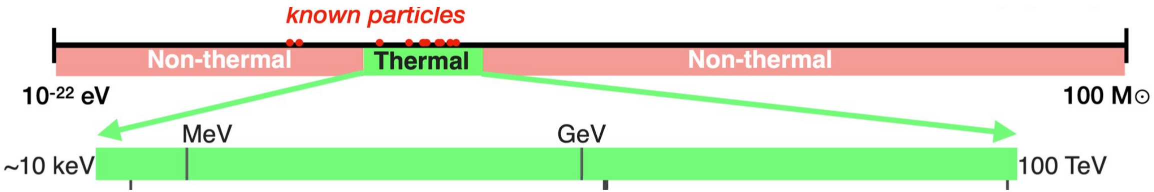
Gravitational Lensing



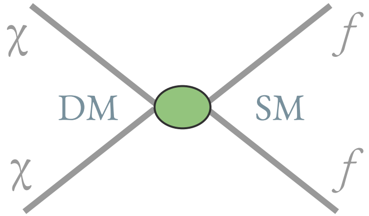
Cosmic Microwave Background

A Thermal Relic

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

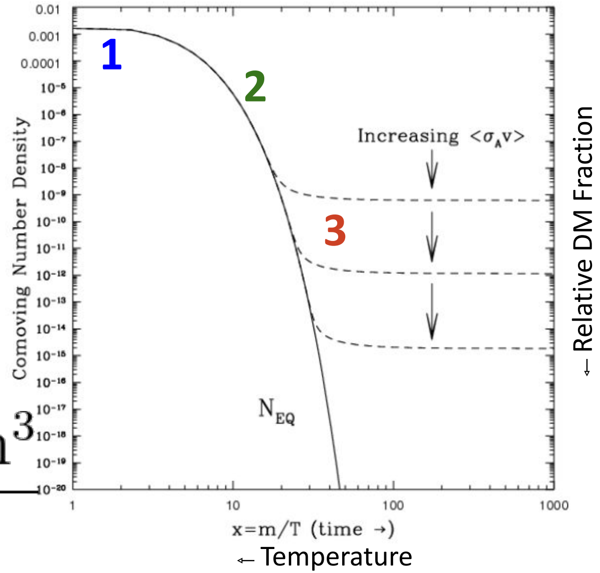


A Thermal Relic



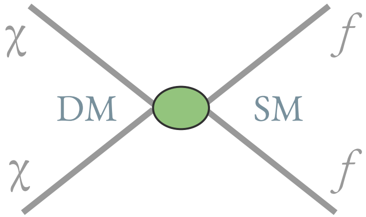
- What is the origin of DM? Any proposed mechanism must yield 85% DM!
  - **1.** Assume DM was in thermal equilibrium with SM particles
  - **2.** The universe expands and cools such that DM pairs are no longer produced
  - **3.** The universe expands and cools such that DM annihilations cease.
- The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

arXiv:hep-ph/9506380v1

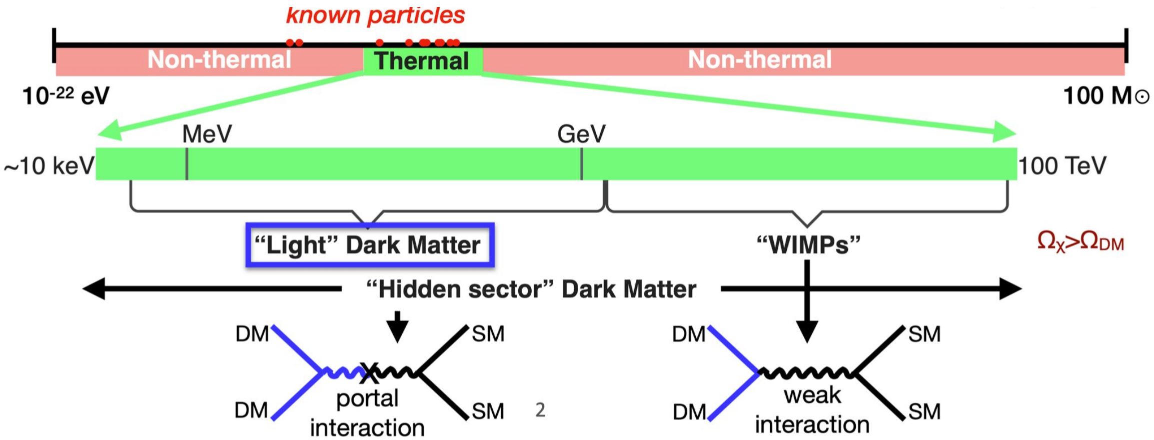


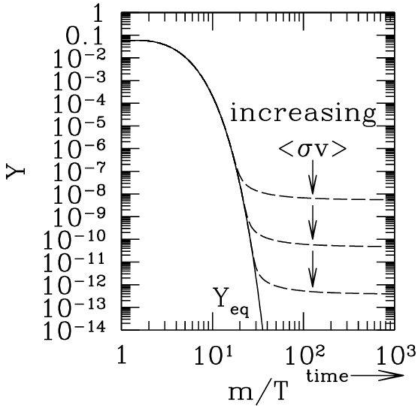
$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle} \longrightarrow \langle\sigma v\rangle = 3\times 10^{-26}\,\frac{\mathrm{cm}^3}{\mathrm{s}}$$

A Thermal Relic



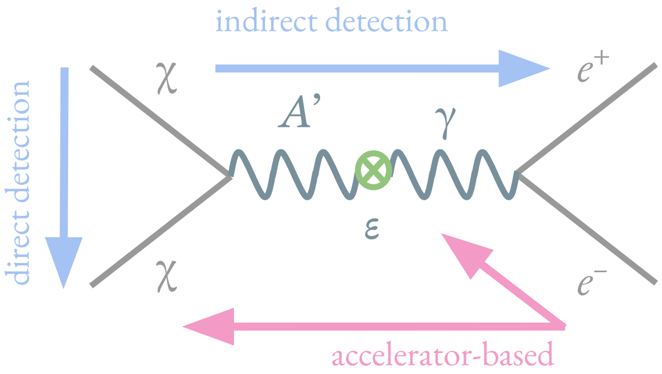
- A thermal relic - simple and predictive model of dark matter (DM)
- WIMPs are popular, but accessible parameter space is running out of room
- Increasing interest in expanding the thermal DM search to “Light” DM in the MeV-GeV mass range

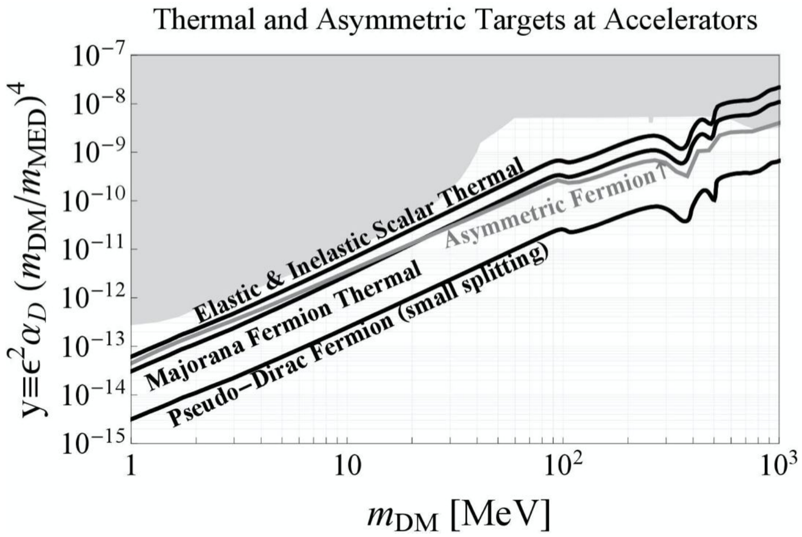




Light Dark Matter

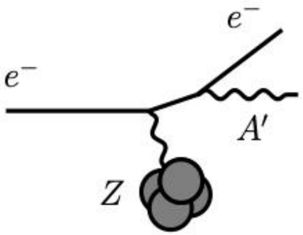
- Simplest prediction includes a dark photon (heavy photon or A’) that mixes with the SM photon
- Thermal prediction targets make attainable predictions with accelerators

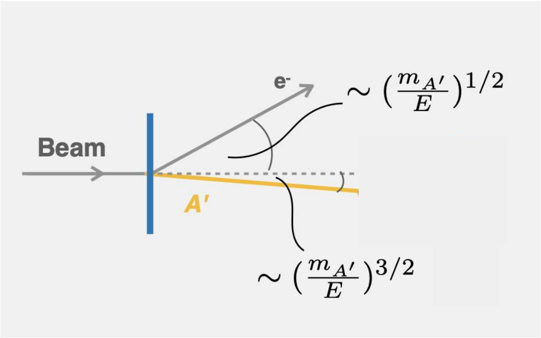




Dark Photon Production

- Kinetic Mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$ - anytime you can produce a photon, you can produce a dark photon. ε is the kinetic mixing parameter
- Fixed Target Signal Characteristics:
    - Dark bremsstrahlung A' production
    - A's take most of the beam energy, soft recoil electron
    - A's are very forward with small opening for decay products

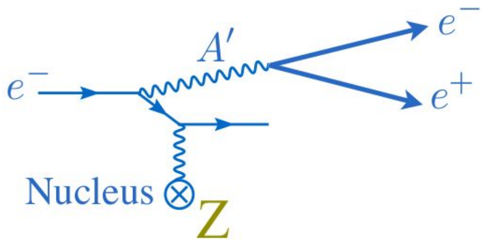


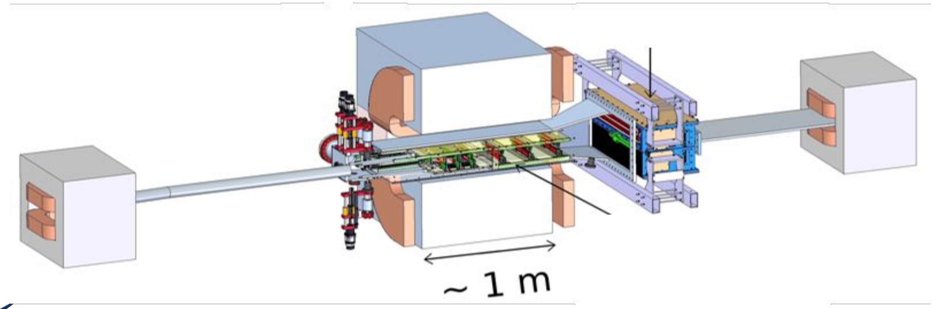


Dark Photon Decays - Complimentary Searches

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

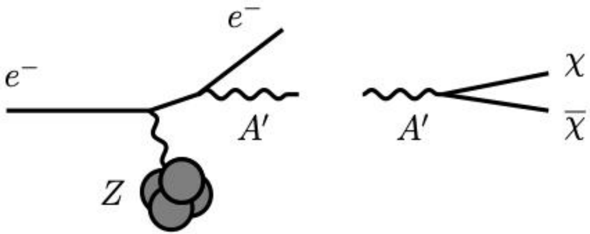
Heavy Photon Search (HPS) at Jefferson Lab

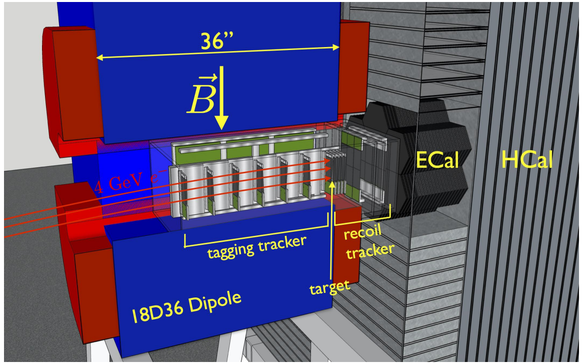




$$2m_{DM} < m_{A'}$$

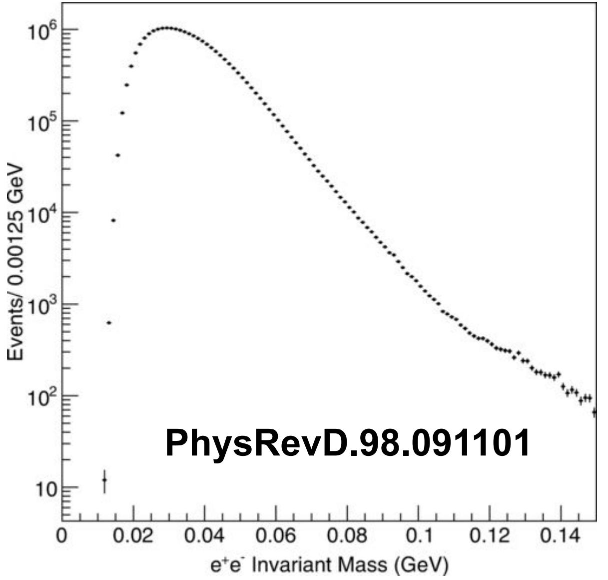
Light Dark Matter eXperiment (LDMX) at SLAC





HPS Data and Results

- Results from 2015 resonance search are published
- Resonance search and **displaced vertex search** for 2016 are expected to publish soon.



Data Run	Beam Energy (GeV)	Beam Current (nA)
2015 Engineering Run	1.05	50
2016 Engineering Run	2.3	200
2019 Physics Run (Upgraded)	4.55	~150
2021 Physics Run (Upgraded)	3.7	~120

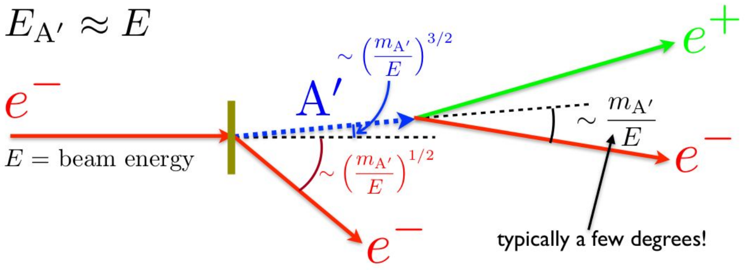
Dark Photon Visible Parameter Space

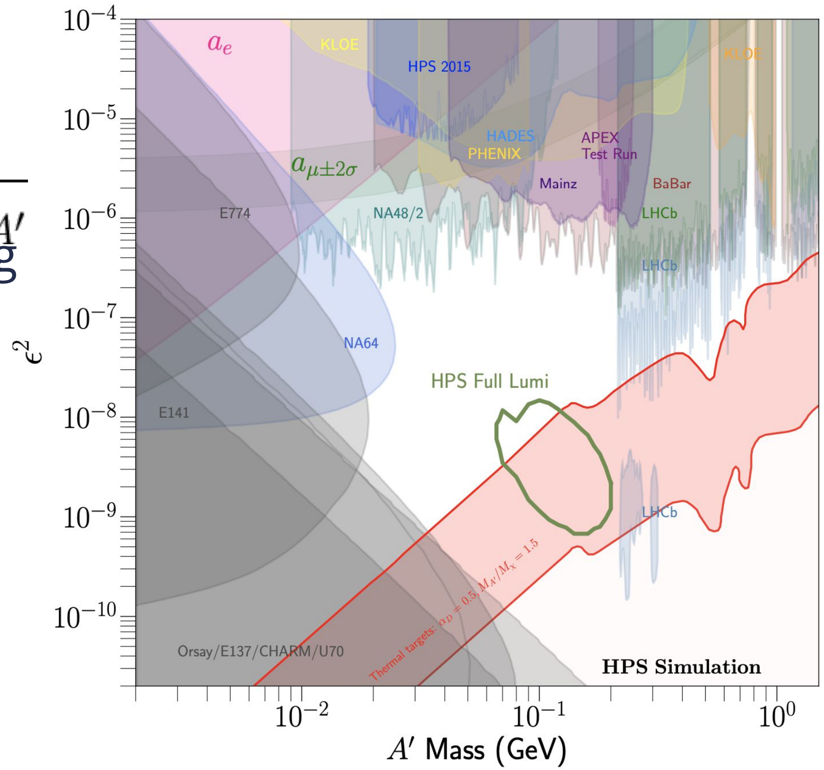
$$2m_e < m_{A'} < 2m_{DM}$$

- The center is a highly motivated, yet unprobed region of parameter space
  - Small production cross-section
  - Short, but finite livetime

$$c\tau \propto \frac{1}{\epsilon^2 m_{A'}}$$

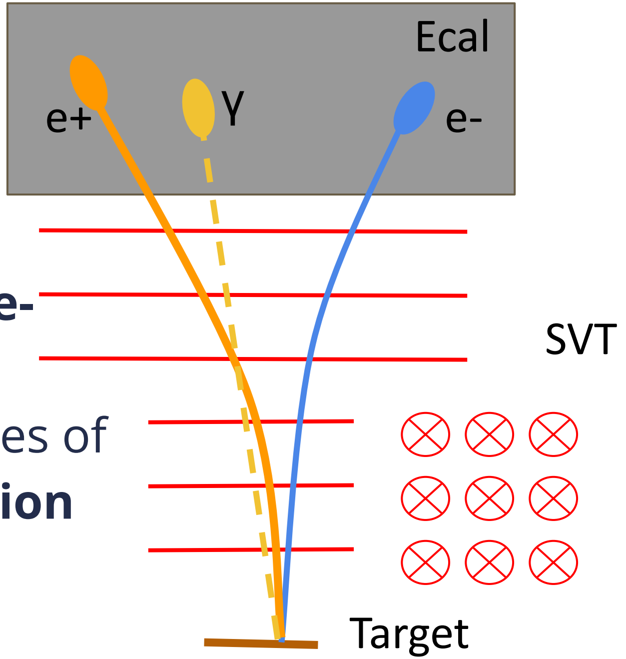
- HPS - a fixed target precision vertexing experiment attempting to probe this
  - Large prompt QED backgrounds
  - A' kinematics require sensitive detector components to be 0.5 mm from the beam

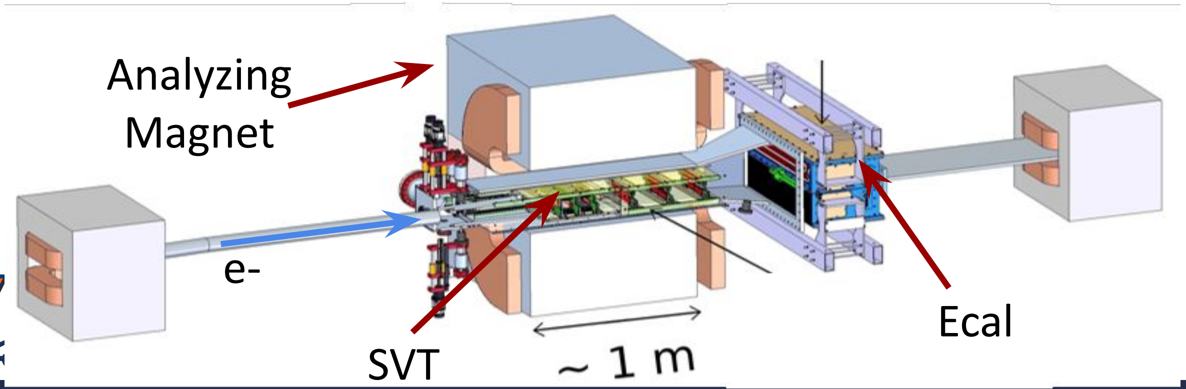


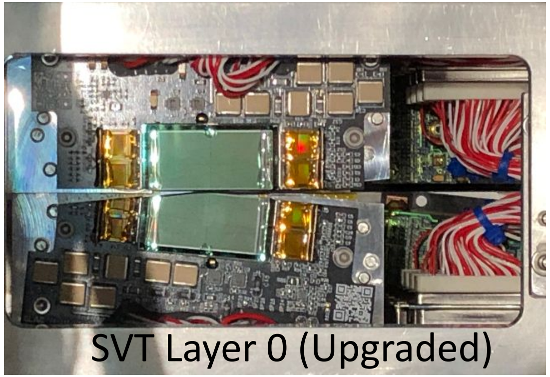


HPS Apparatus

- Electromagnetic Calorimeter (Ecal) provides **e+e- trigger with precision timing**
- Silicon Vertex Tracker (SVT) measures trajectories of e+e- and **reconstructs mass and vertex position**
- Dipole magnet spreads e+e- pairs and provides curvature for momentum measurement

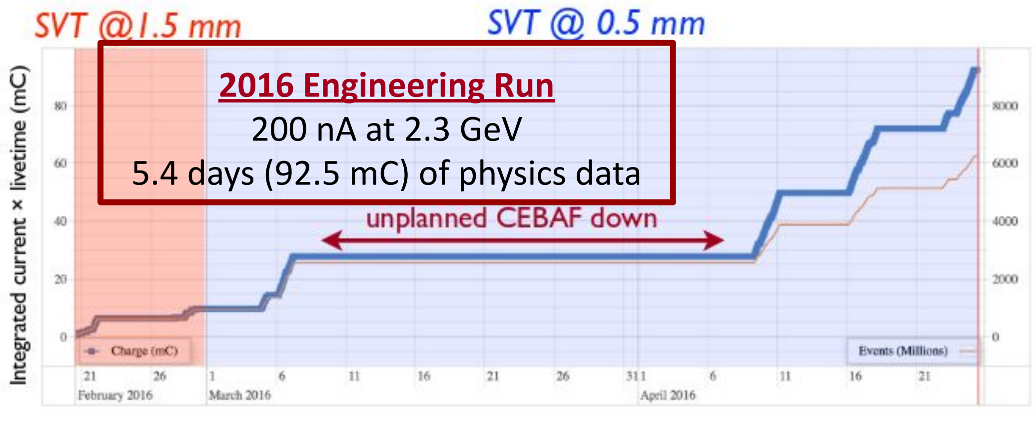


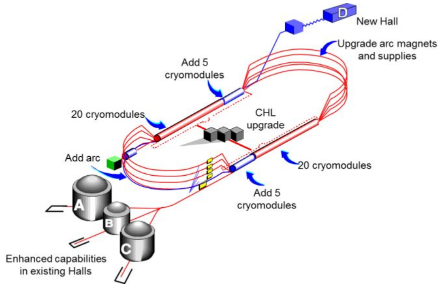


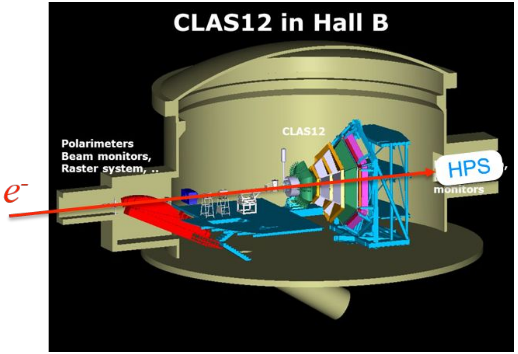

SVT Layer 0 (Upgraded)

Jefferson Lab and CEBAF

- JLab (Newport News, VA) has the Continuous Electron Beam Accelerator Facility (CEBAF) that can simultaneously deliver intense **continuous** electron beams of different energies to 4 halls
- 2.2 GeV per pass up to 12 GeV and 2 ns bunch pulse
- **Provides small beam spot with small tails** (~10^{-6})

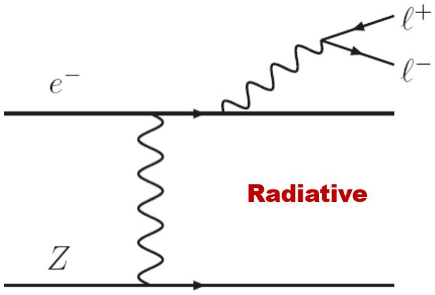


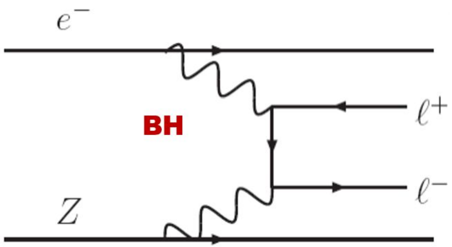


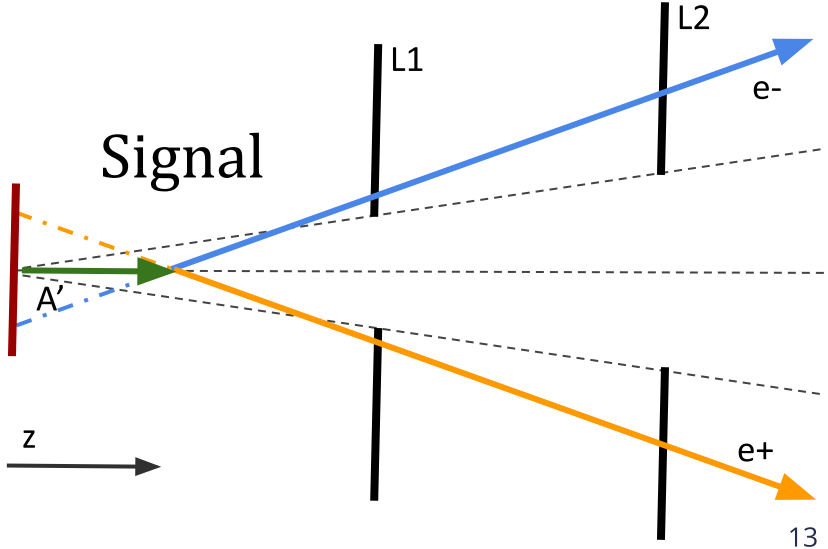


Prompt Trident Backgrounds

- **Radiative tridents** and **Bethe-Heitler (BH) tridents** are prompt
- Distinguishing the prompt QED tridents from displaced signal is the challenge of the analysis - ~1 signal for ~1e6 prompt background

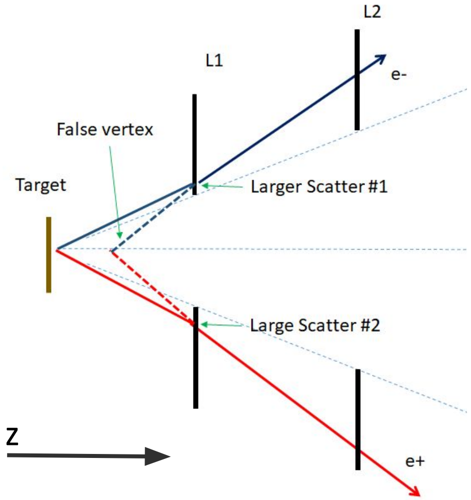


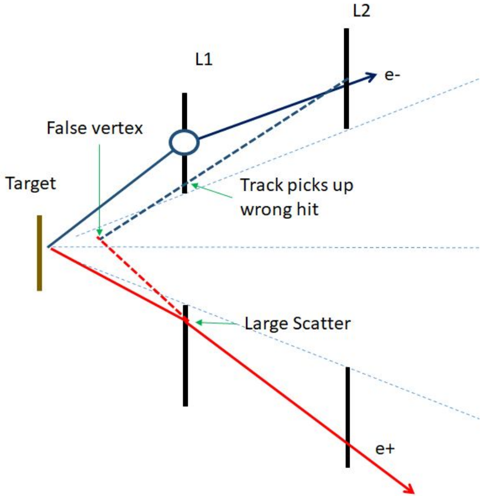


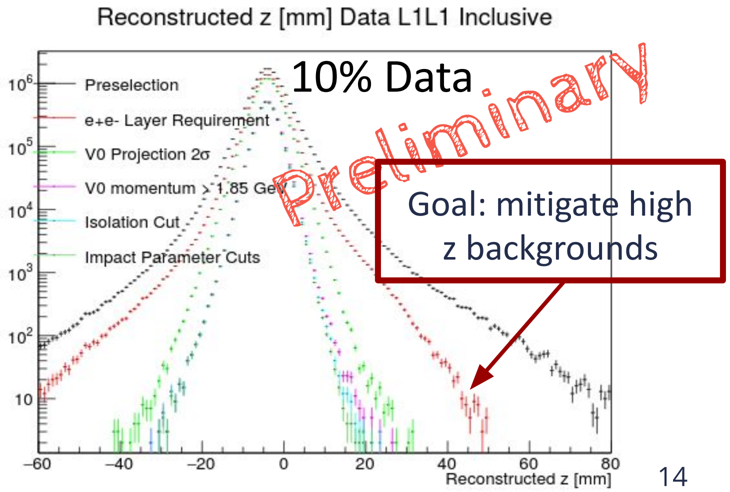


Displaced Vertex Search Event Selection

- Displaced vertex search is blinded with the selection tuned on 10% data
- Two main backgrounds from prompt trident processes: large Coulomb scatters in layer 1 of the tracker and mis-tracking
  - Require strict selections on track quality and vertex quality & require layer 1 hits

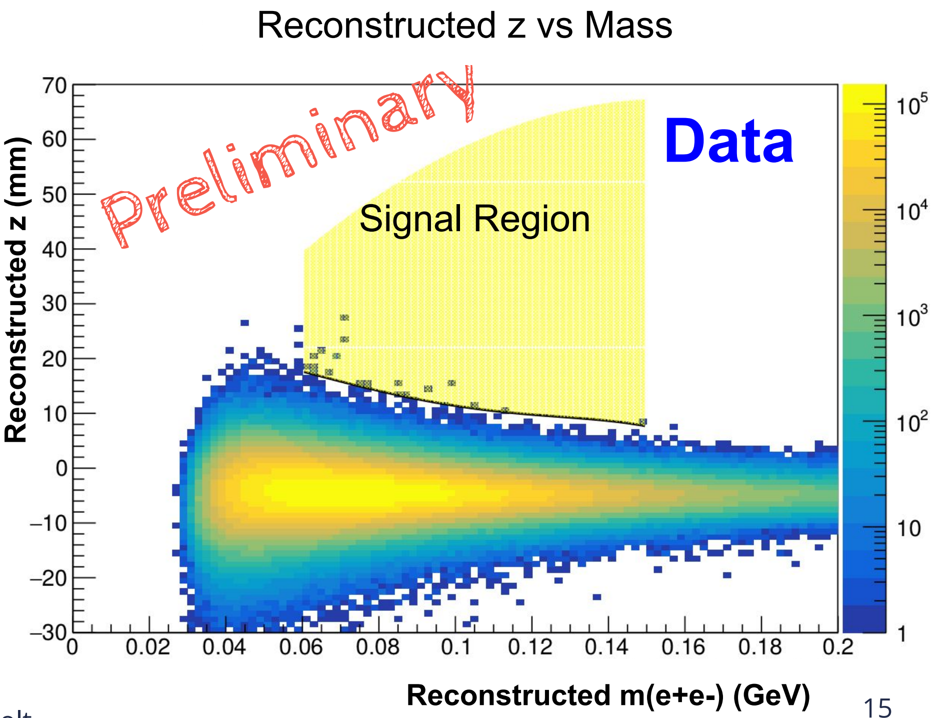






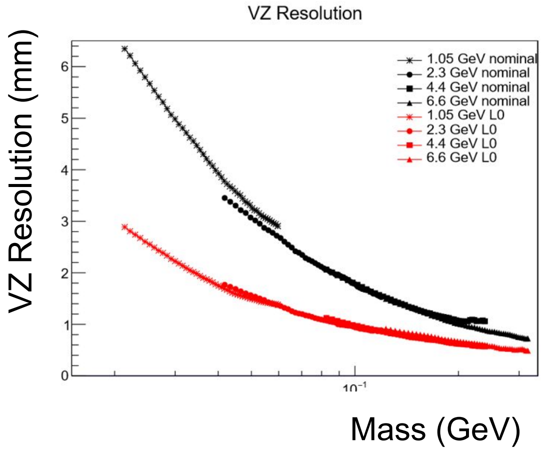
Displaced Vertex Search Backgrounds

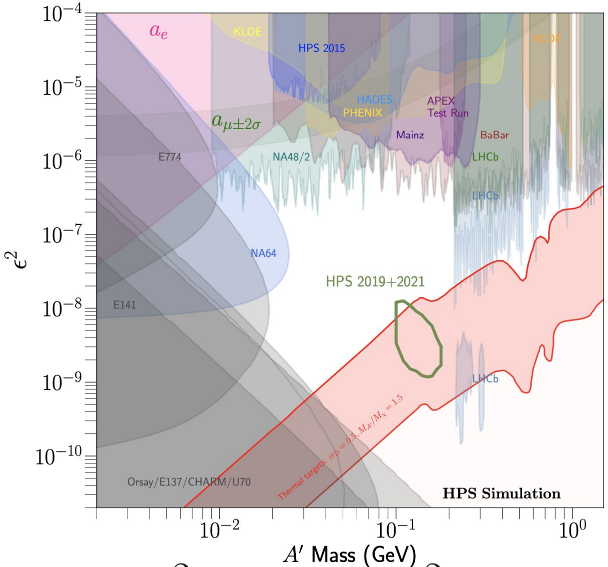
- How much signal do we expect?
  - ~0.5 events at maximum sensitivity, not enough for A' exclusion
- Did we achieve the expected level of background necessary for a search?
  - **YES! A major accomplishment** (for mass greater than 70 MeV)
- What about mass less than 70 MeV?
  - This is currently under investigation, most likely a background



The Future of HPS

- Analysis from 2015/2016 motivated several simple upgrades
  - **Add a tracking layer** (Layer 0) between target and current first layer
  - Dramatically improves vertex resolution, hence the vertex reach
- Probing other models with displaced vertices such as Strongly Interacting Massive Particles (SIMPs)
- HPS is approved for 180 days of running
  - Analysis from runs in 2019 and 2021 are expected to yield exclusions, and potential discovery, of A's

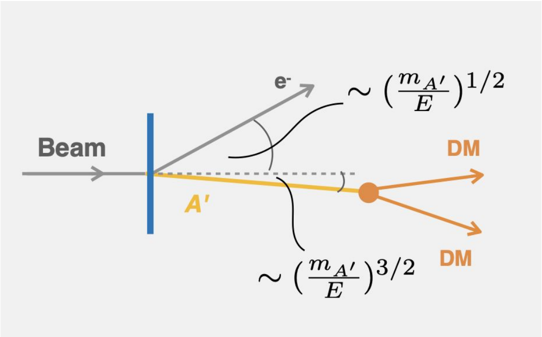


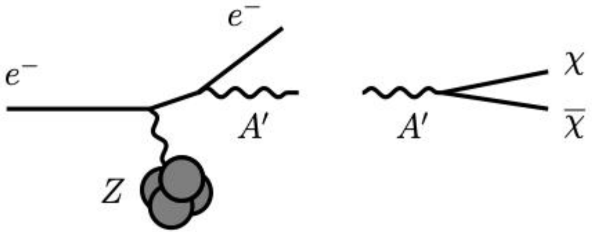


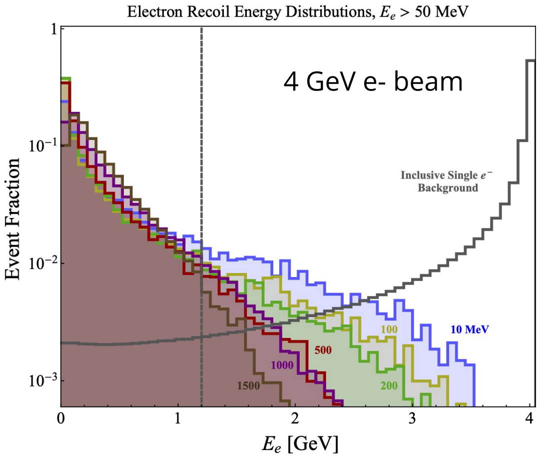
$$2m_e < m_{A'} < 2m_{DM}$$

LDMX

- Fixed Target Signal Characteristics:
  - Dark bremsstrahlung A’ production
  - A’s take most of the beam energy
  - Only visible final state particle is a soft recoil electron



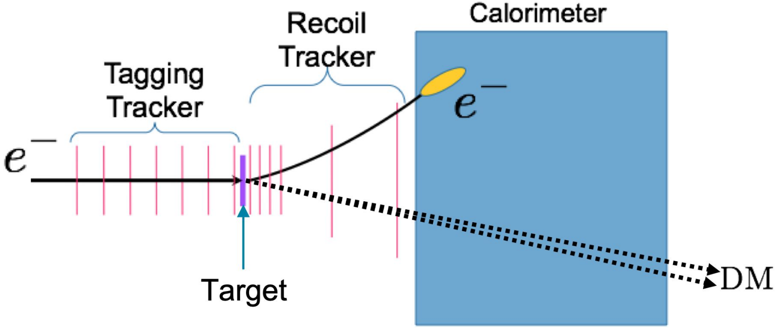


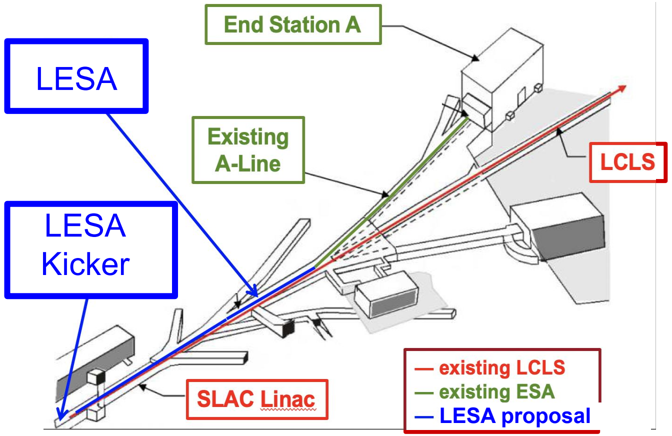


- Can probe this mechanism through a missing momentum search. We need…
  - High momentum resolution
  - High veto efficiency of Standard Model backgrounds

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

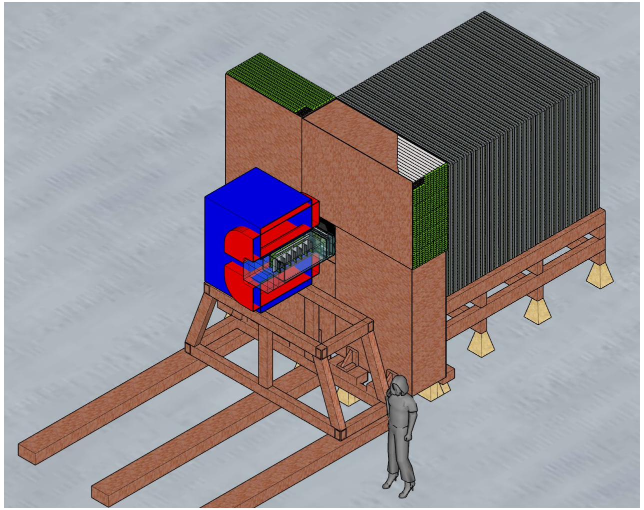


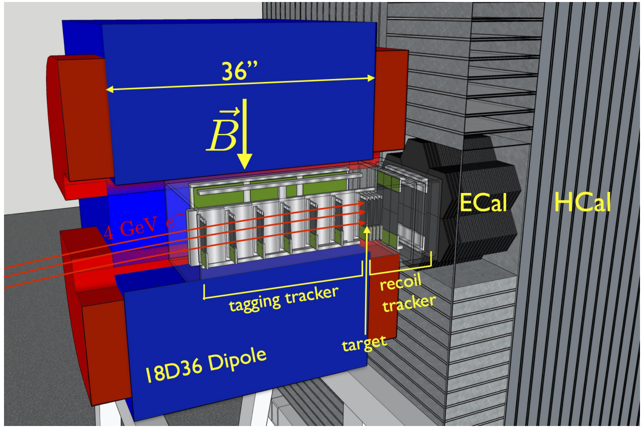


- 4 and 8 GeV e- beam provide by SLAC
  - Parasitically use the LCLS II beam with a dedicated transfer line (LESA)
  - Individual tagging and reconstruction of up to 1e16 electrons
  - Low current, high repetition rate 37 MHz, μ = 1

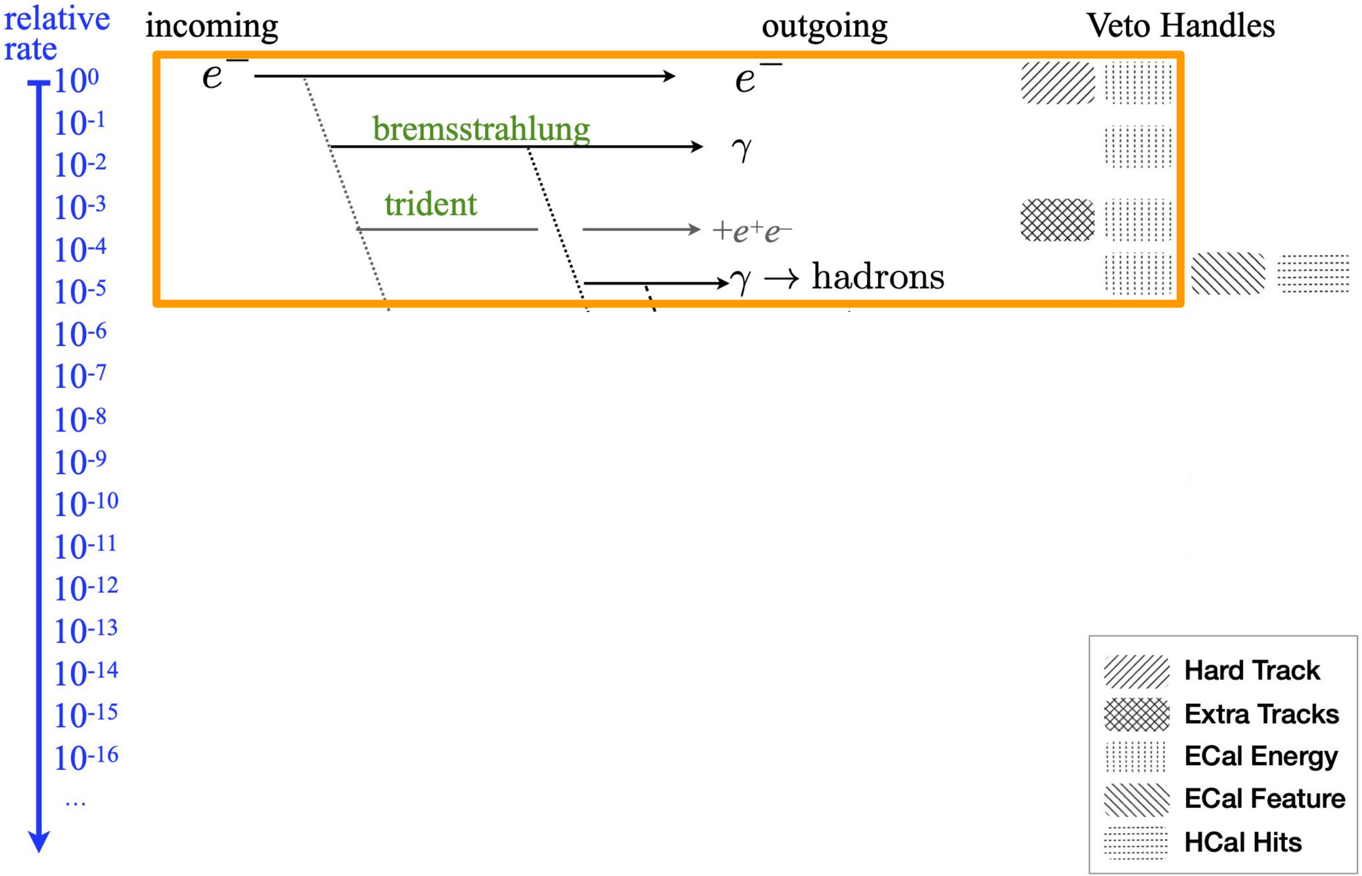
LDMX Design

- Detector designed for high rates and high radiation doses
  - **Tagging/recoil tracker**: fast with high momentum resolution and large acceptance (based on HPS tracker design)
  - **Electromagnetic calorimeter**: fast, good energy resolution, and high granularity
  - **Hadronic calorimeter**: high veto efficiency of neutral hadrons

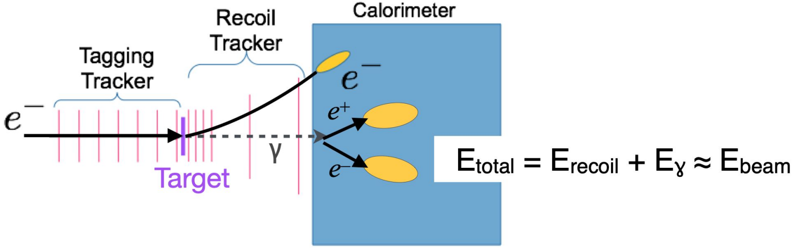




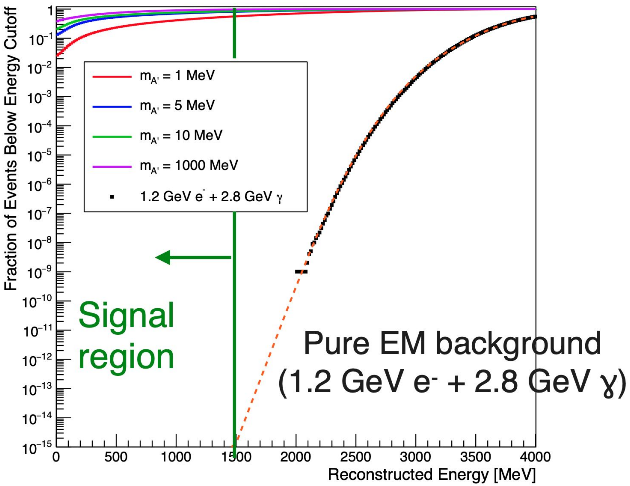
Backgrounds

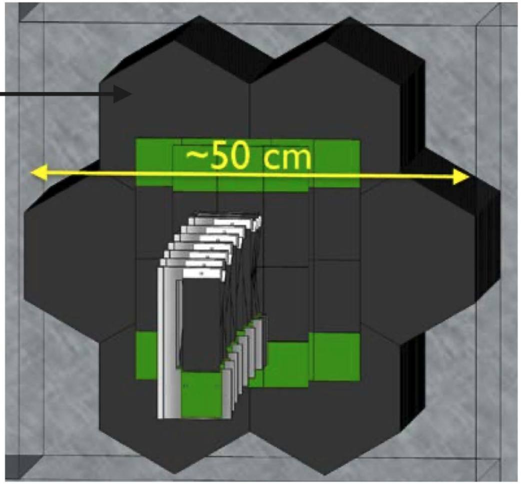


Electromagnetic Calorimeter

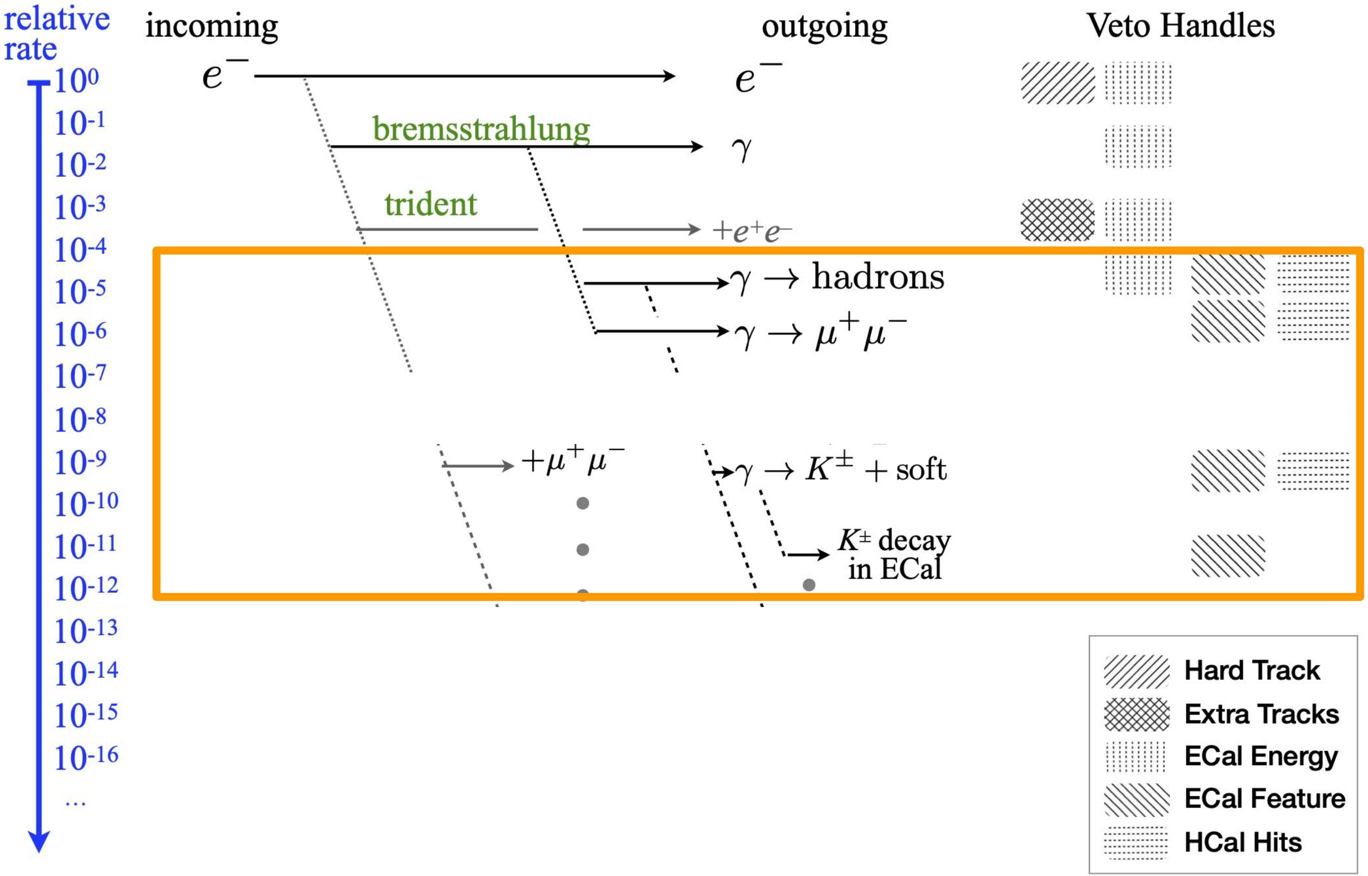


- 40 X0 Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - Provides fast missing energy trigger
  - Dense, radiation hard, full shower containment, and high granularity



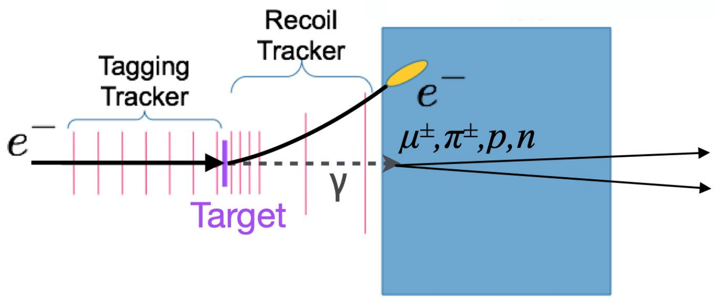


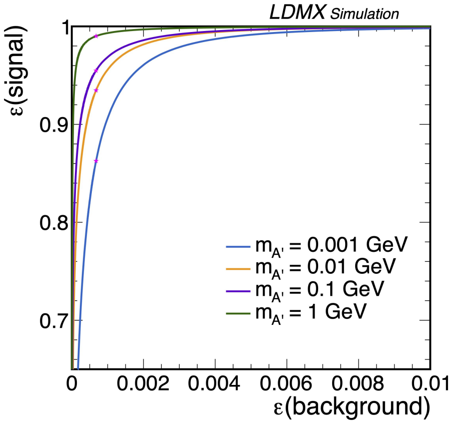
Backgrounds



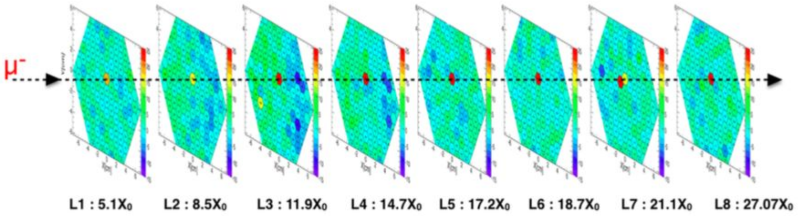
Ecal Veto

- 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

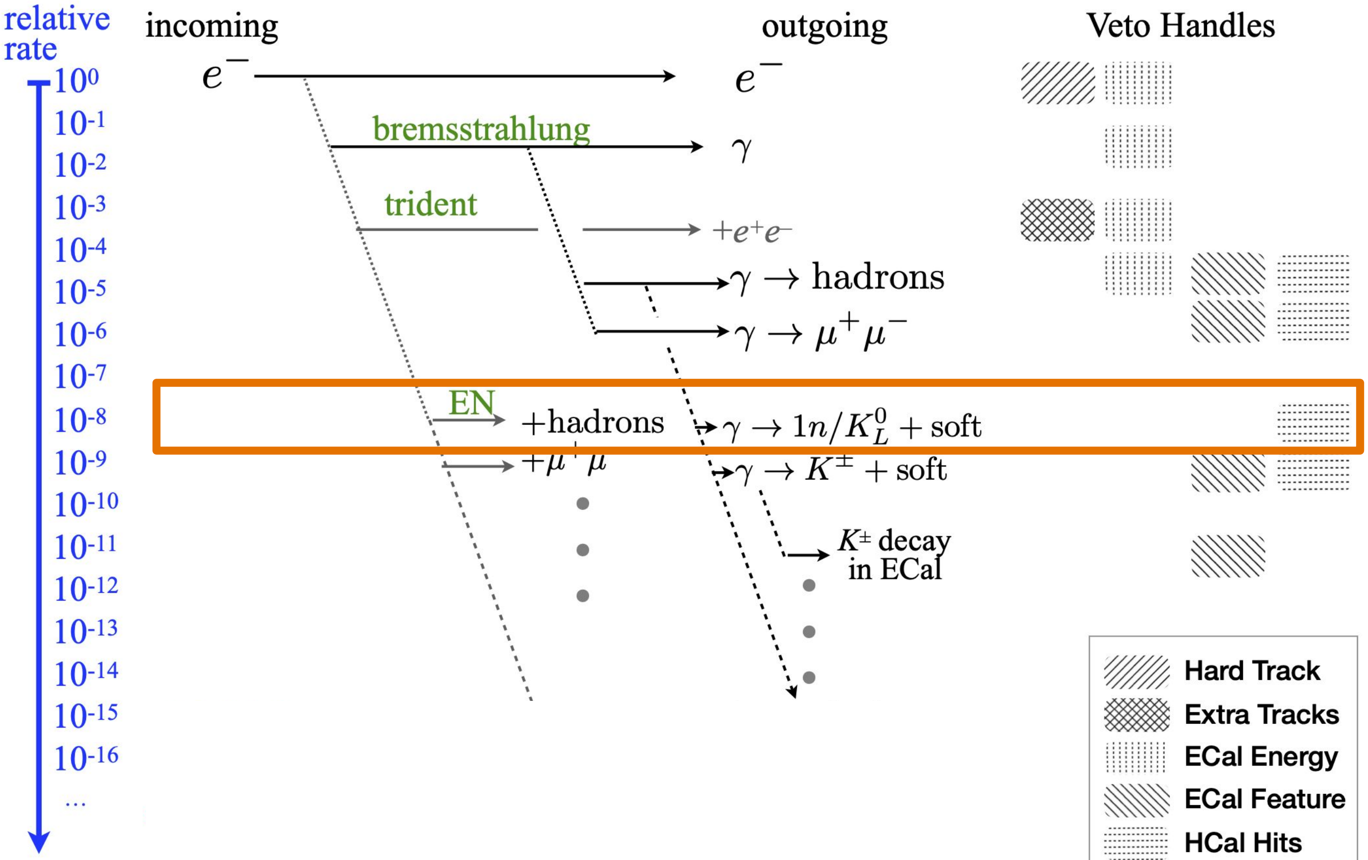




A.Martelli on behalf of CMS, arXiv:1708.08234

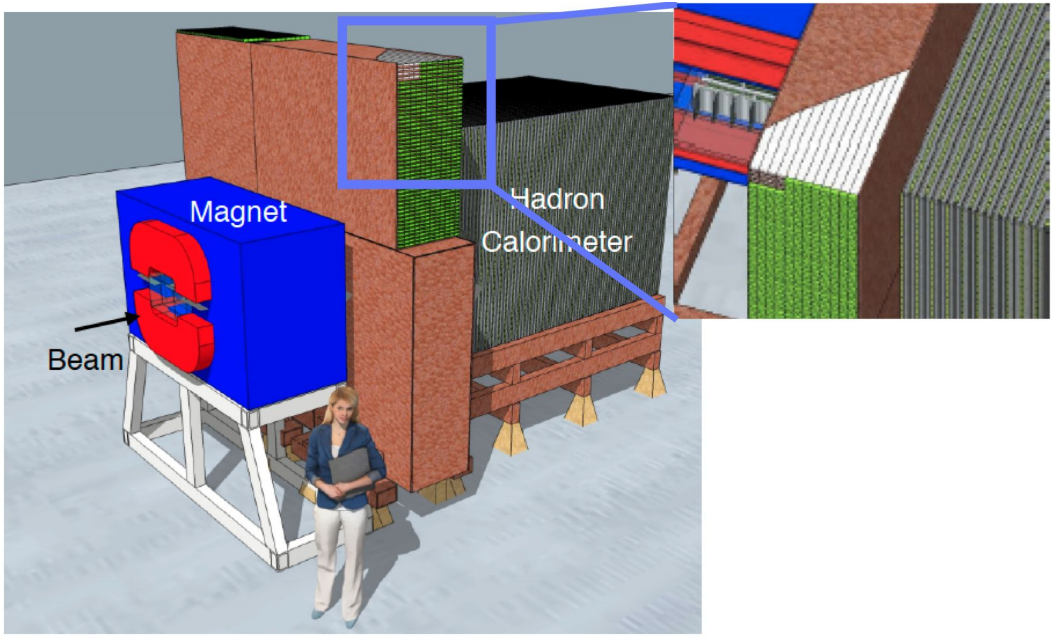


Backgrounds



Hadronic Calorimeter

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



Backgrounds

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

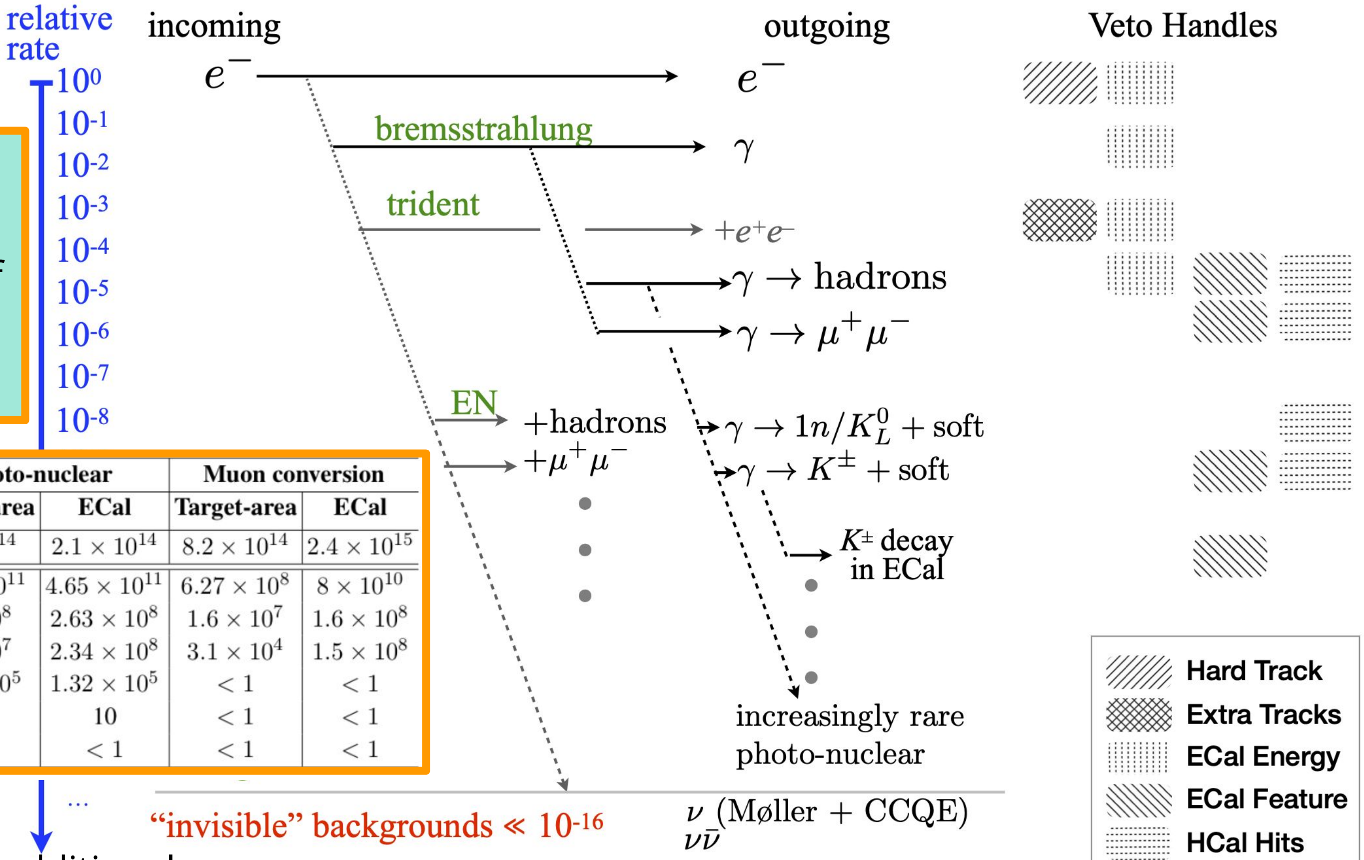


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ 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

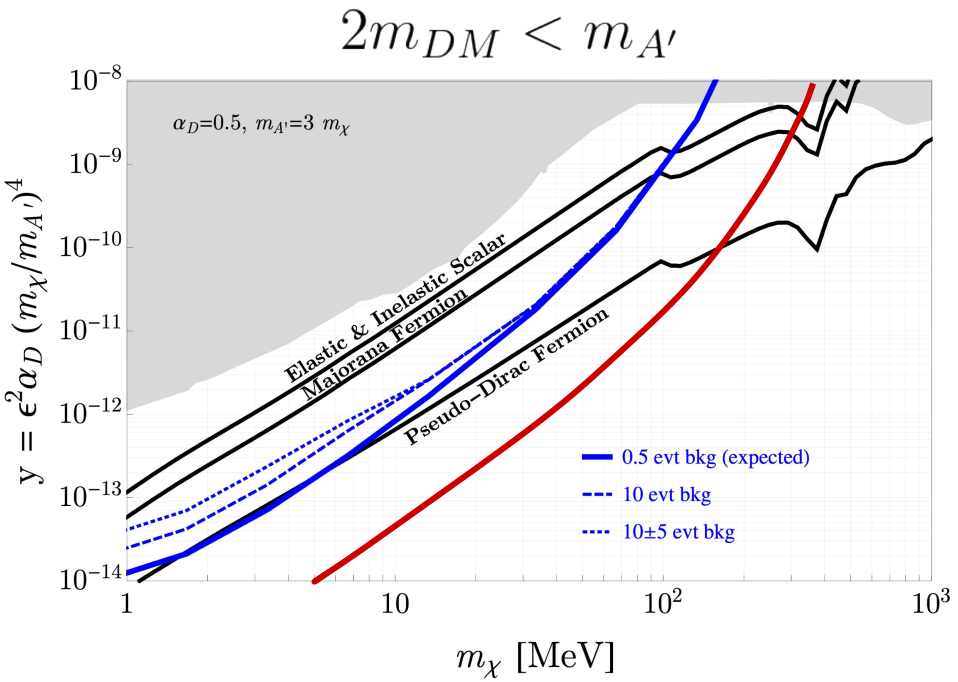
Recoil e- pT is an additional discriminator on backgrounds

arXiv:1912.05535

LDMX Sensitivity

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

arXiv:1808.05219

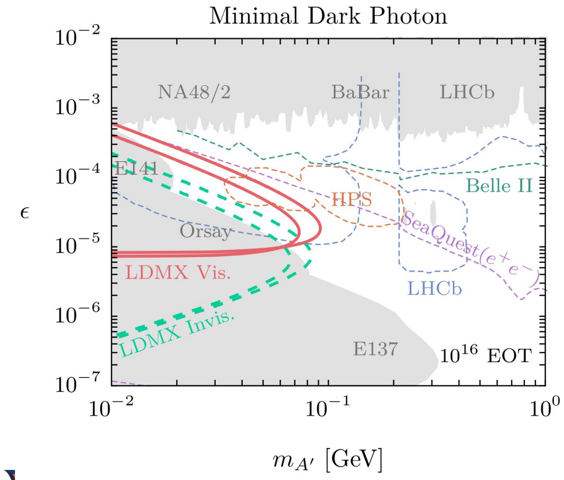


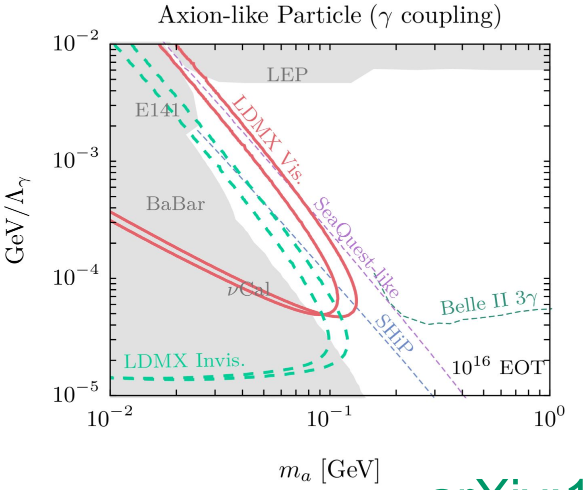
2020	2023	2025	2027
Detector Development	Construction	Phase I data taking	Phase II construction & operation

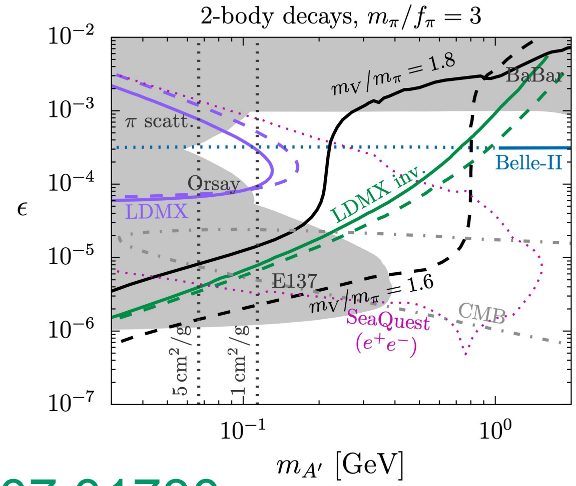
Proposed LDMX baseline schedule

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





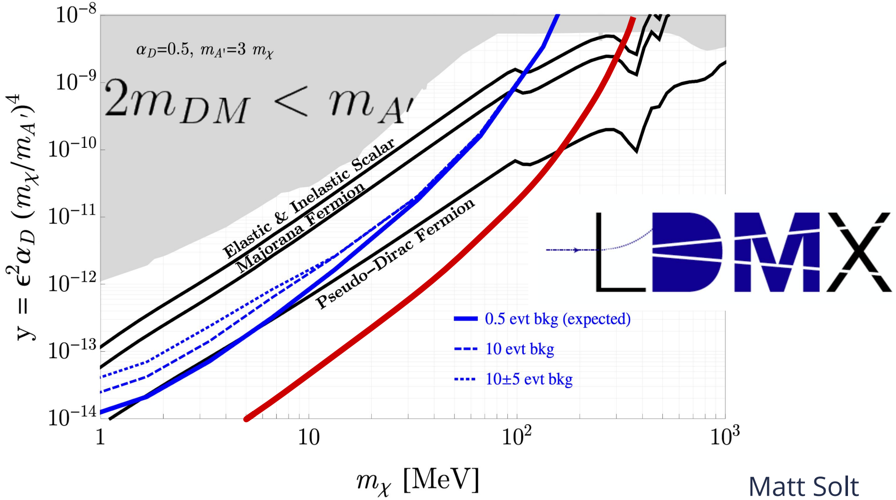


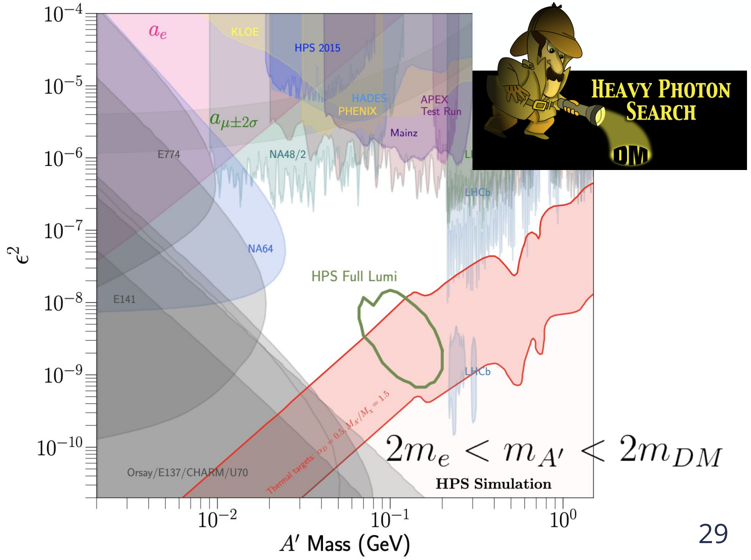
Projections are for 8 GeV and 16 GeV beams

[arXiv:1807.01730]

Conclusion

- Thermal relic models offer plausible and predictive models of dark matter
- HPS is expected to set limits in a highly motivated and untouched region of parameter space
- LDMX can conclusively probe such models in the sub-GeV mass range through a missing momentum search





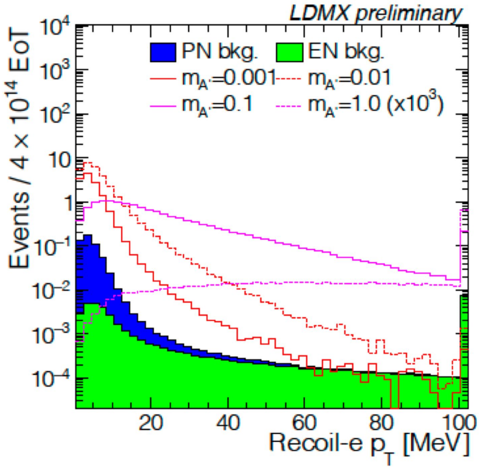
Thank You!

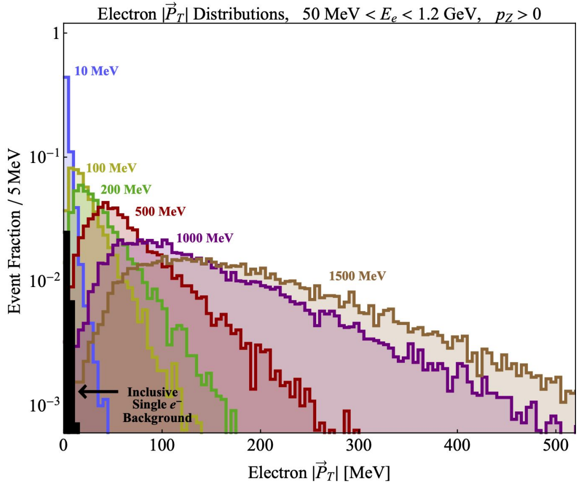
LDMX

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

Signal Kinematics

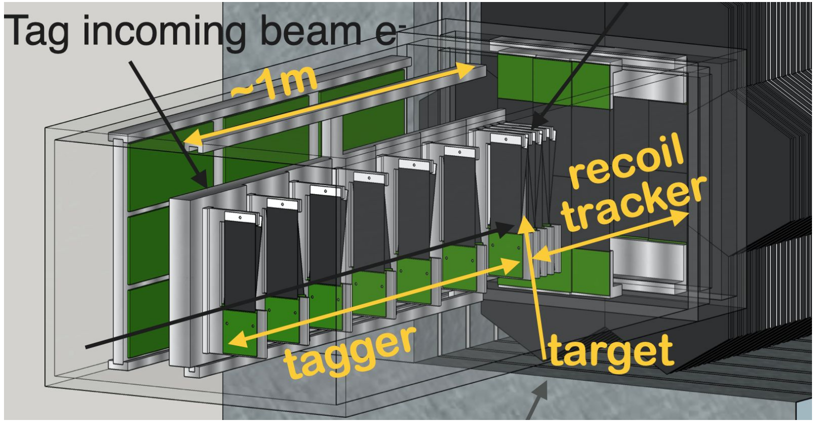
- Transverse momentum of recoil election is the last veto handle
- Currently not used in veto efficiency estimates, but as a backup discriminator
- Transverse momentum can also be used to estimate/constrain DM mass scale

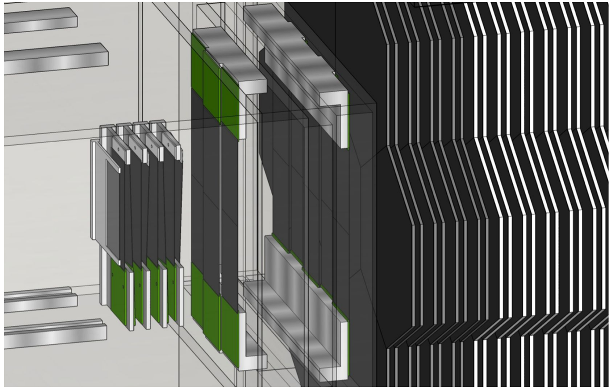




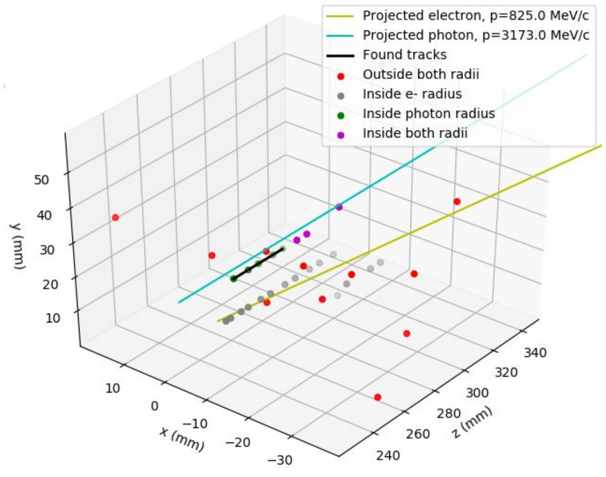
Tracker and Trigger Scintillator

- Tagging tracker
  - Measures incoming beam electron
- Recoil tracker (based on HPS 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

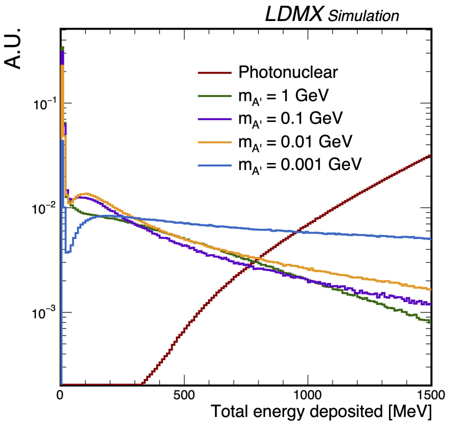


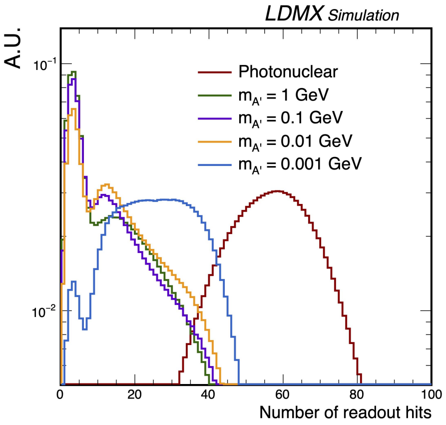


Ecal BDT

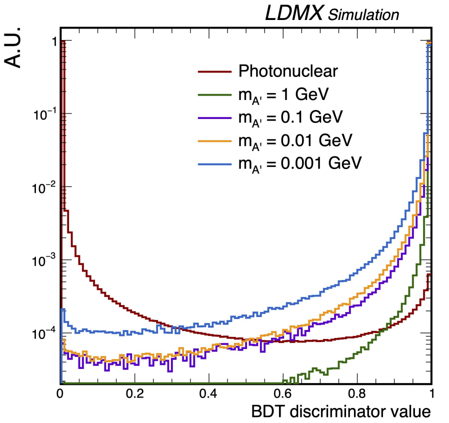


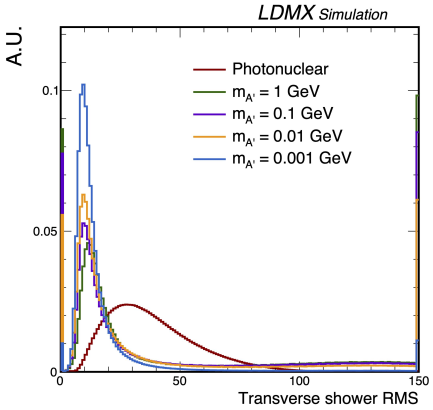
MIP Tracking





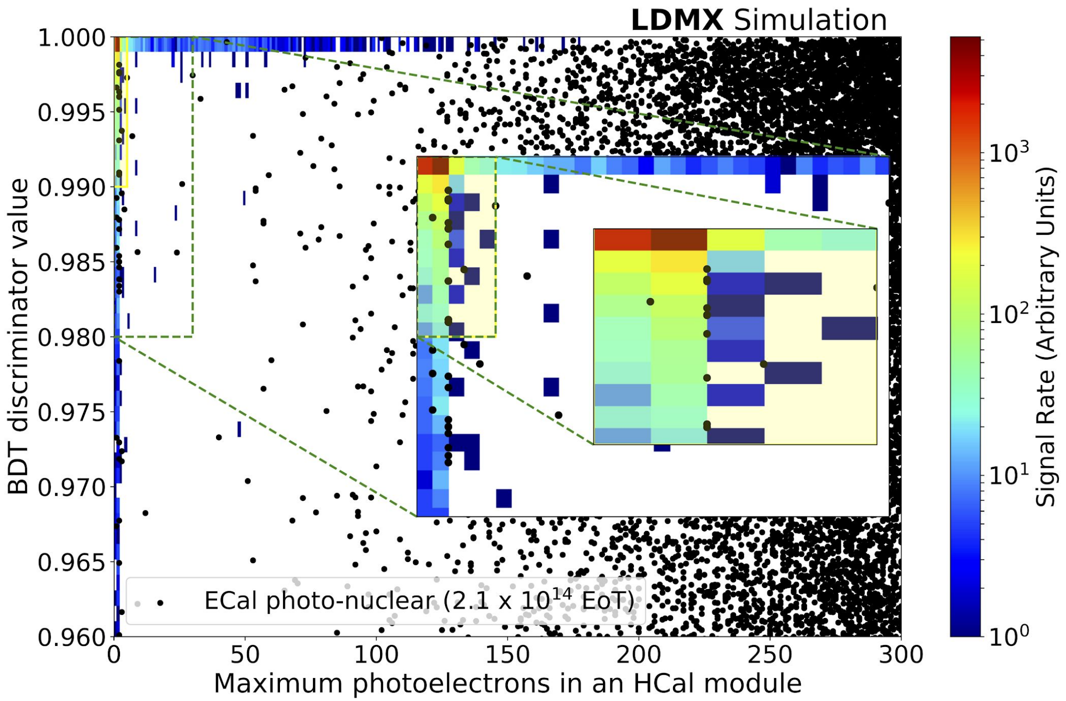
BDT Variables



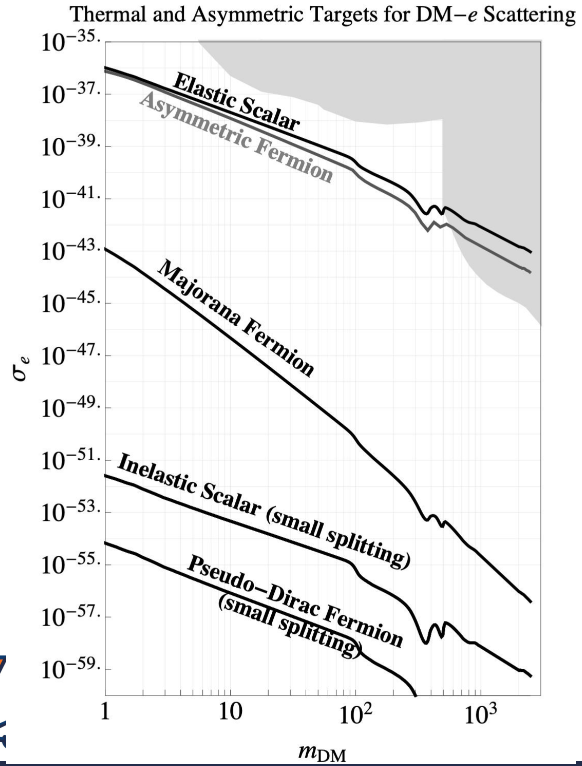


Ecal/Hcal Vetoes

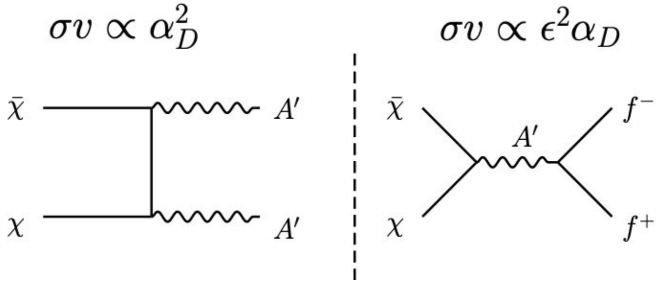
- Ecal BDT > 0.99
- Hcal max PEs is > 5

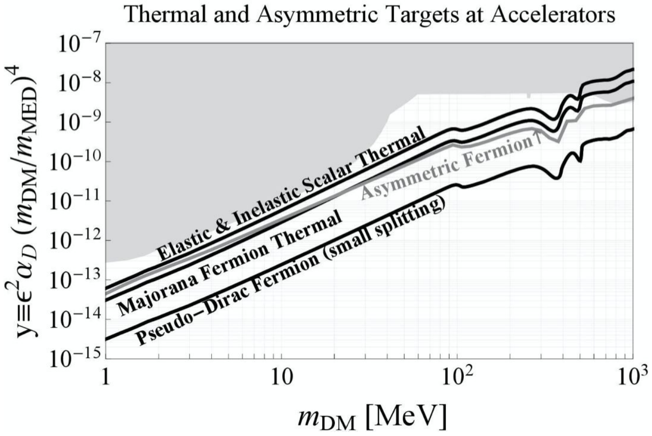


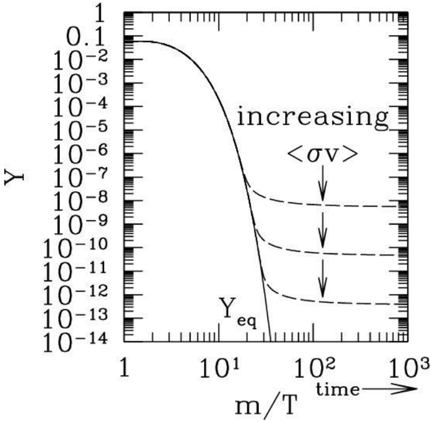
Advantage of DM Production at Accelerators



Non-relativistic vs semi-relativistic DM scattering



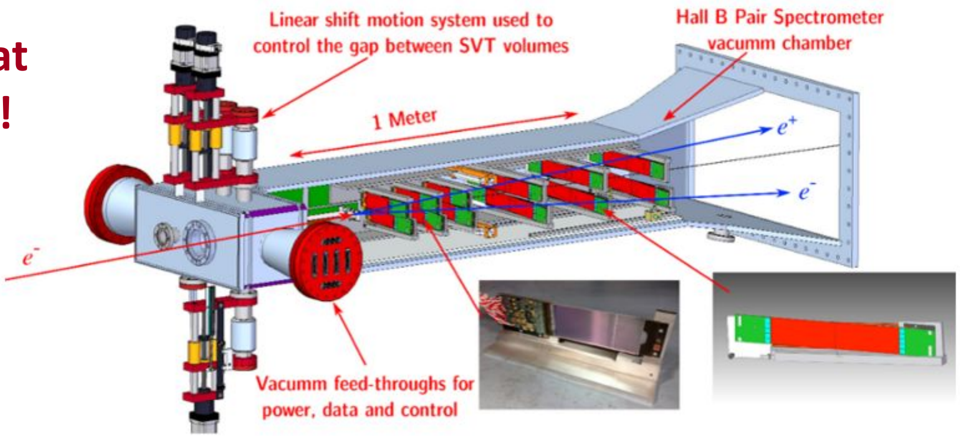


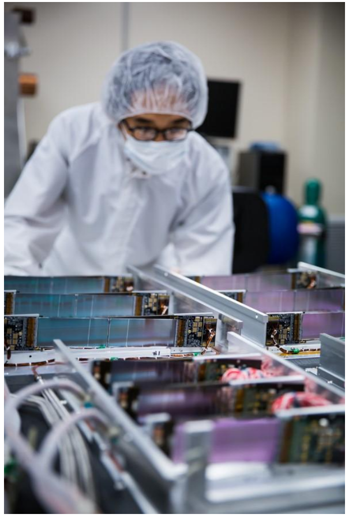


HPS Silicon Vertex Tracker

- SVT measures trajectories of e+e- and reconstructs mass and vertex position
- 6 layers of silicon microstrips (~0.7% radiation length per layer)
- Each layer has axial/stereo strips (100 mrad) for 3D hit position
- SVT is split to avoid “sheet of flame”; Very large scattered beam backgrounds!
- Silicon is close to beam for good forward coverage (½ mm from the beam!)
- L4-L6 are double wide for acceptance purposes

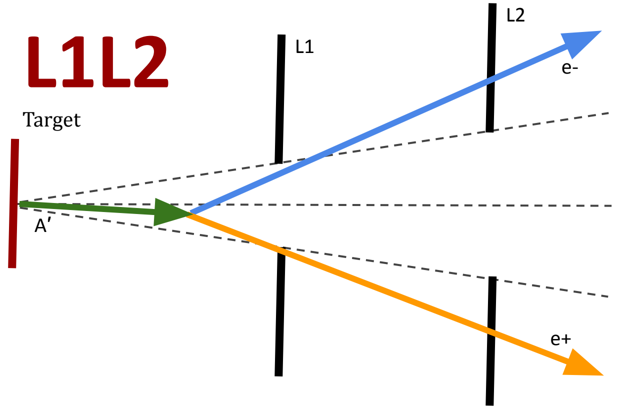
Built at SLAC!

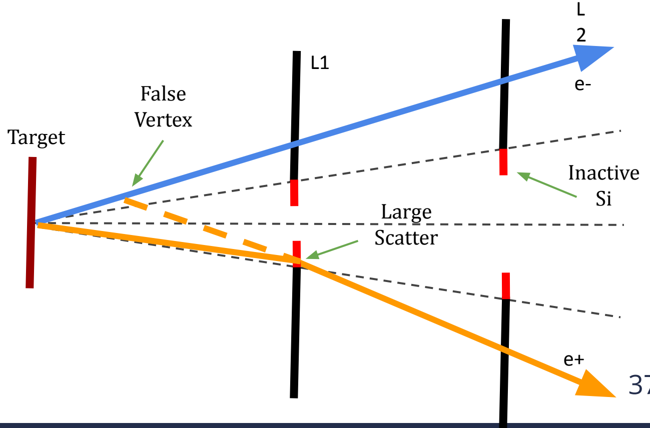




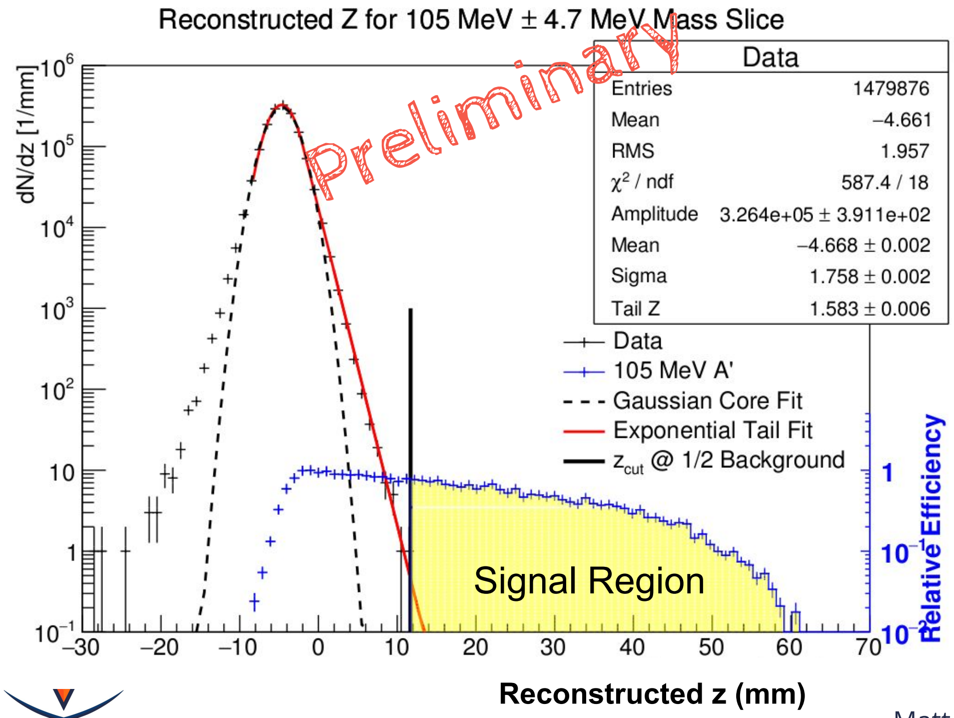
HPS A's with Longer Livetimes

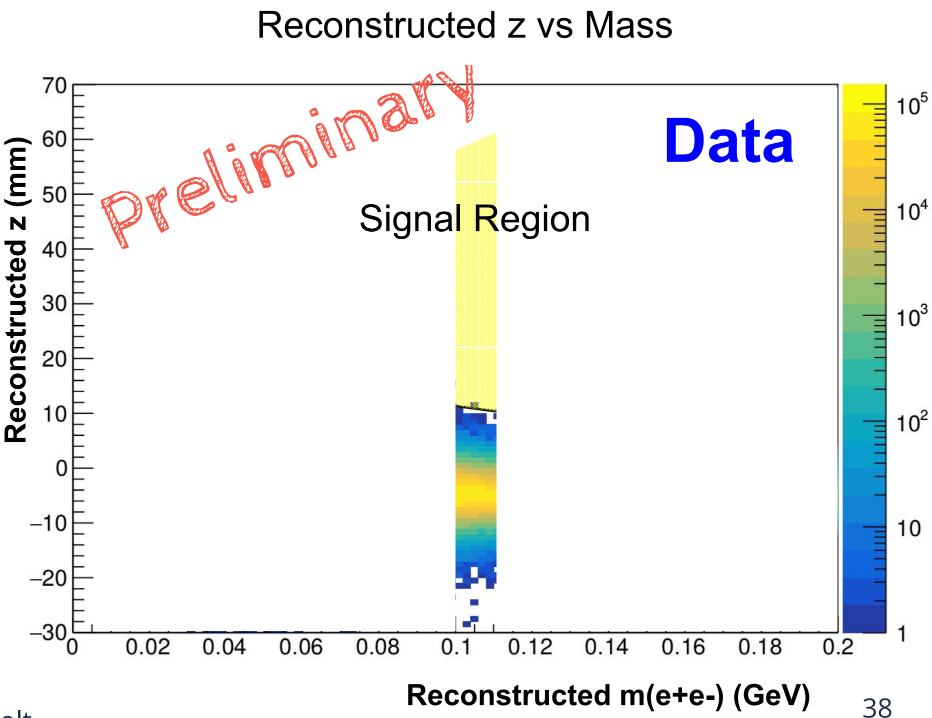
- A's with longer livetimes will have e+e- daughters that may miss layer 1 of the tracker
- Divide analysis into L1L1 (both particles hit L1) and L1L2 (one particles misses L1) categories
- Additional backgrounds for L1L2
  - Hit inefficiencies
  - Large Coulomb scatters in inactive Si
  - Brem conversion in tracker Si
- L1L1 category was shown previously. L1L2 was recently unblinded, but is not public yet
- L1L1 + L1L2 combined result will be the final result



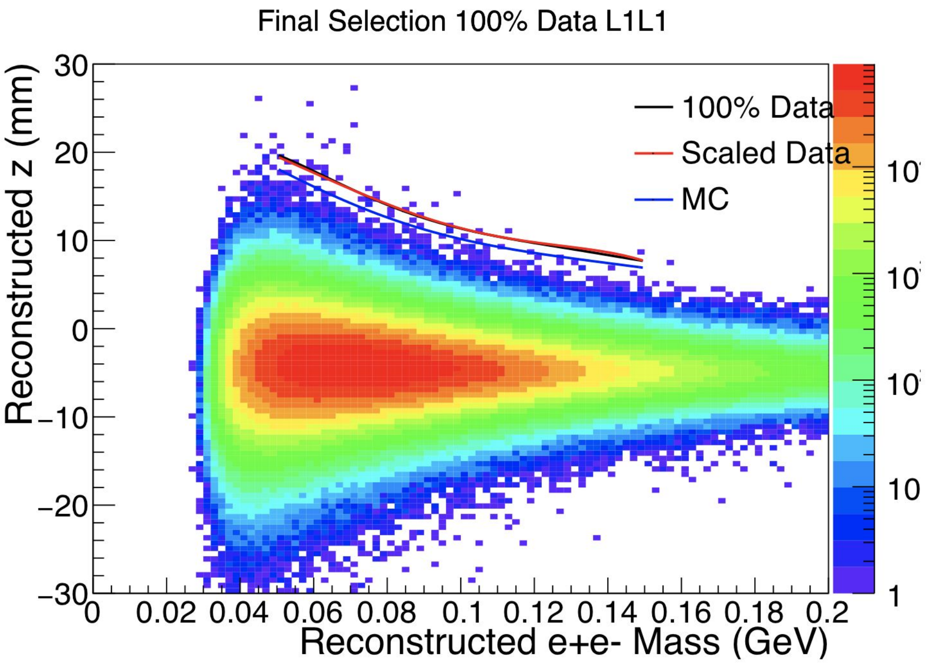


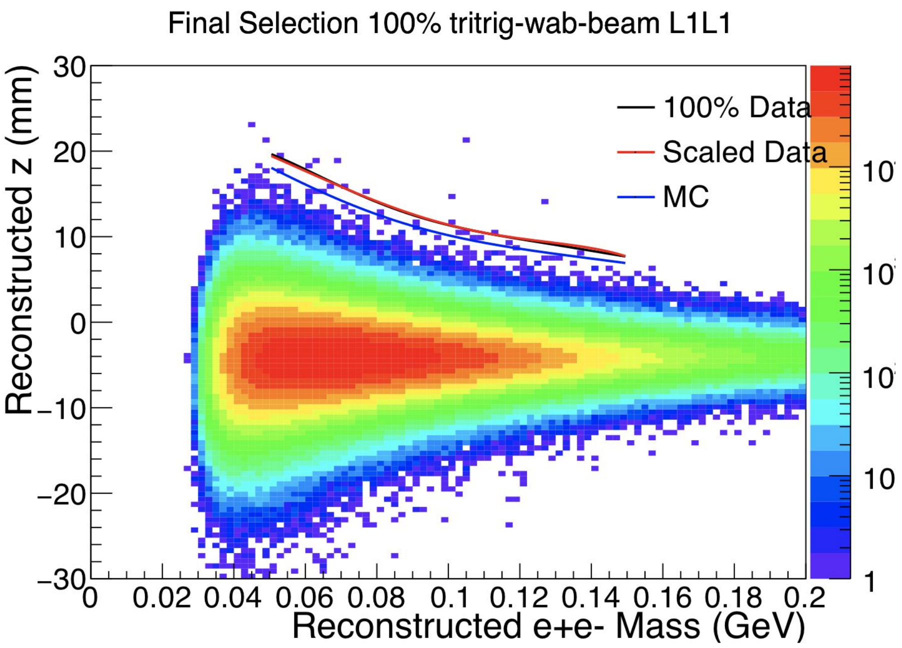
Displaced Vertex Search Signal Region





HPS L1L1 Data/MC Comparison



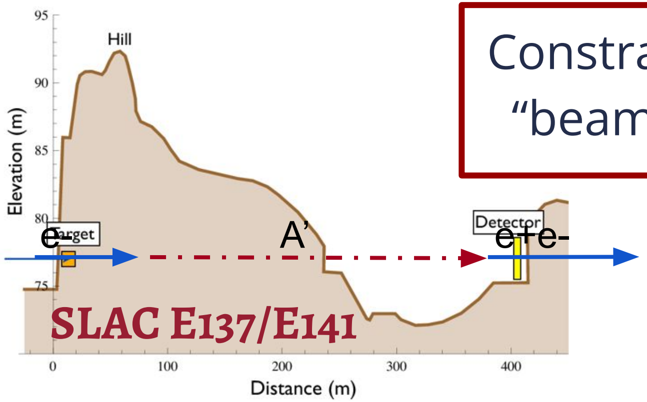


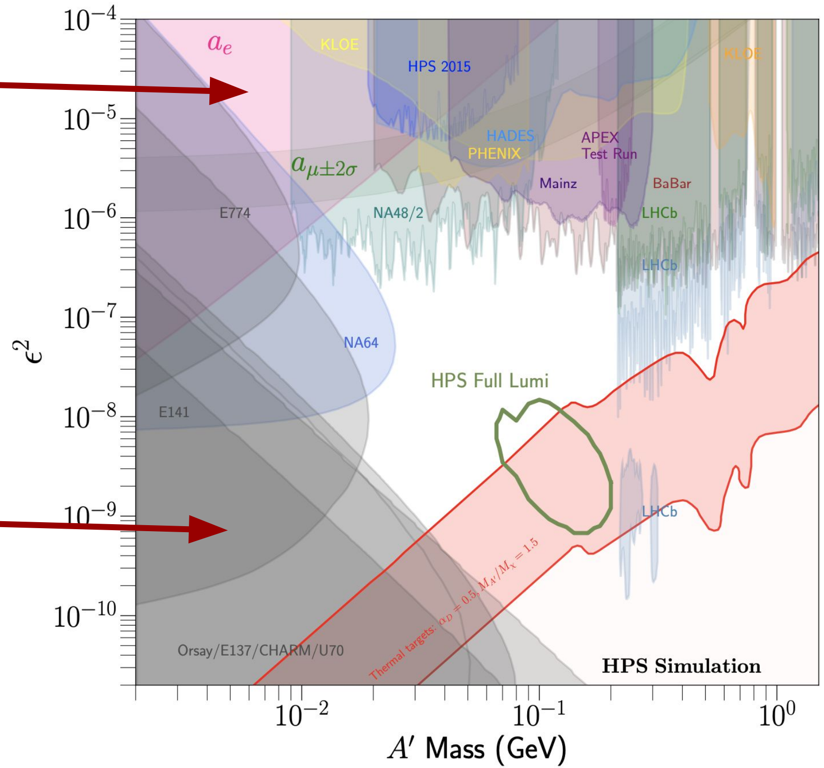
Existing Dark Photon Constraints for Visible Decays

Large coupling searches are generally **"bump hunts"** for $m(l^+l^-)$ resonances

A's with small coupling are **long-lived** $$c\tau \propto \frac{1}{\epsilon^2 m_{A'}}$$

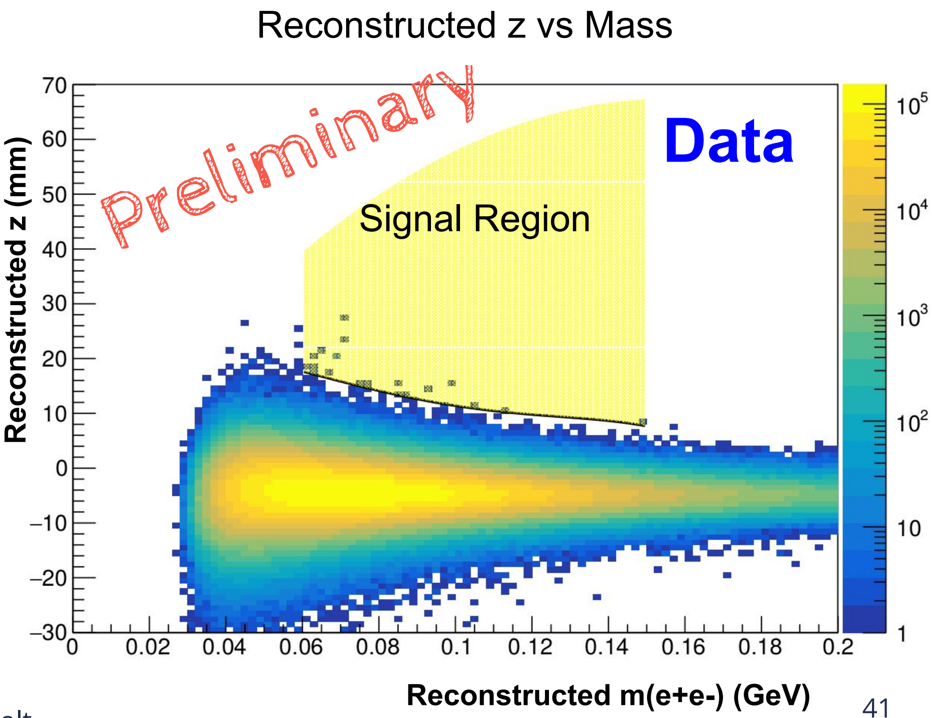
Constraints from "beam dumps"





Displaced Vertex Search Backgrounds

- Did we achieve the expected level of background necessary for a search?
  - **YES! A major accomplishment** (for mass greater than 70 MeV)
- What about mass less than 70 MeV?
  - **This excess is not observed in MC**
  - Most likely due to mis-tracking that is not currently properly modeled in MC
  - This is currently under investigation
- How much signal do we expect?
  - ~0.5 events at peak sensitivity, not enough for A' exclusion
  - Limit is currently under review

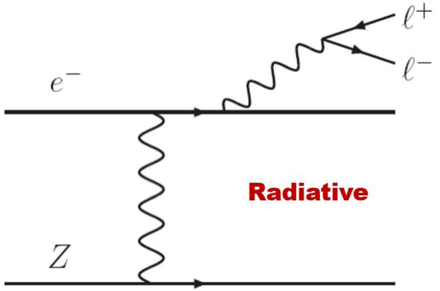


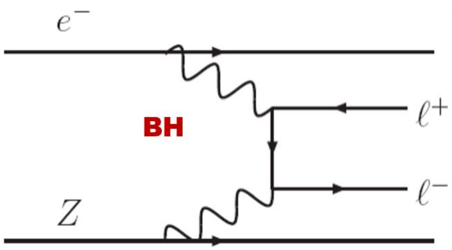
Trident Backgrounds

- **Radiative tridents**
  - Identical kinematics to A′s; constitute an irreducible prompt background
  - Provide reference for expected signal rate

$$\frac{d\sigma(e^-Z \to e^-Z(A' \to l^+l^-))}{d\sigma(e^-Z \to e^-Z(\gamma^* \to l^+l^-))} = \frac{3\pi\epsilon^2}{2N_{eff}\alpha}\frac{m_{A'}}{\delta m}$$

- **Bethe-Heitler (BH) tridents**
  - Softer e+e- pairs, but still dominates the signal region
- **Converted photons** in tracker or target
  - Simple cuts eliminate about 80% of these e+e- pairs with minimal signal loss
- Distinguishing the prompt QED tridents from displaced signal is the challenge of the analysis





Light Dark Matter

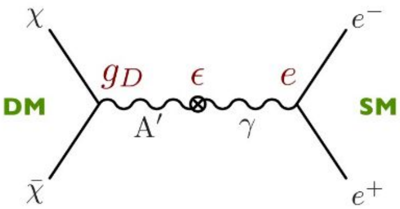
"Lee-Weinberg Bound"

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

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

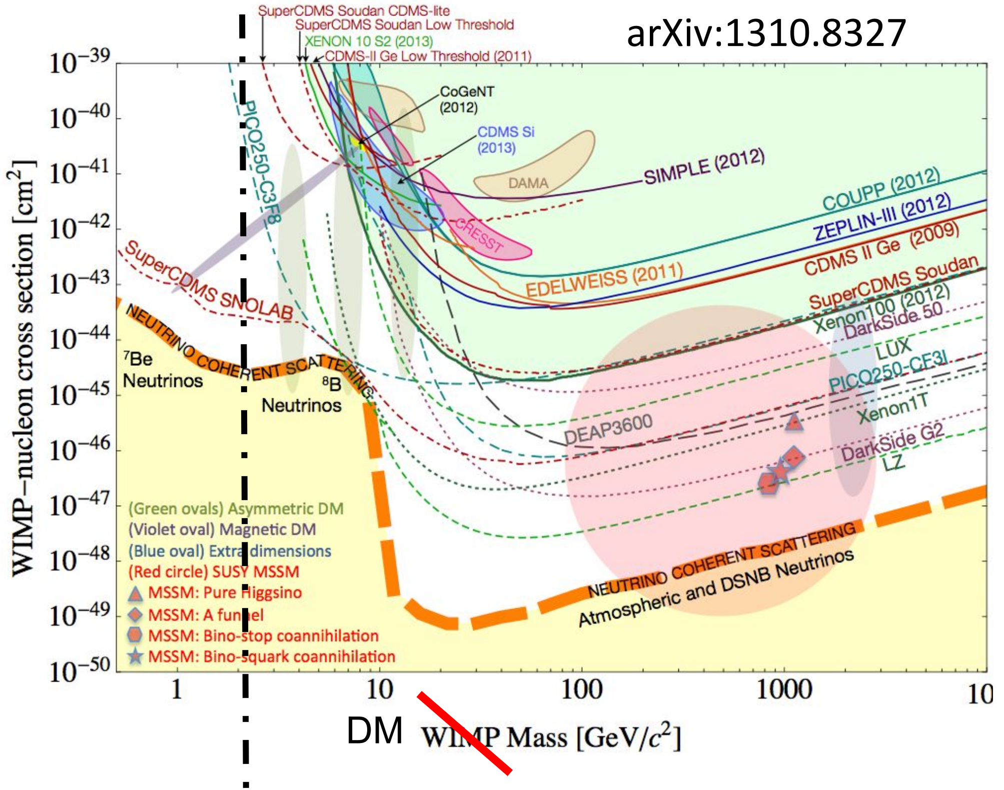
A simple/natural candidate: heavy/dark photon (A′)

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



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

arXiv:1310.8327



Light Dark Matter ← → WIMPs