Dark Matter at Accelerators - HPS and LDMX

August 31, 2022

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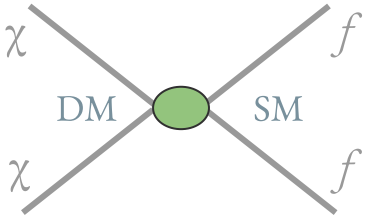
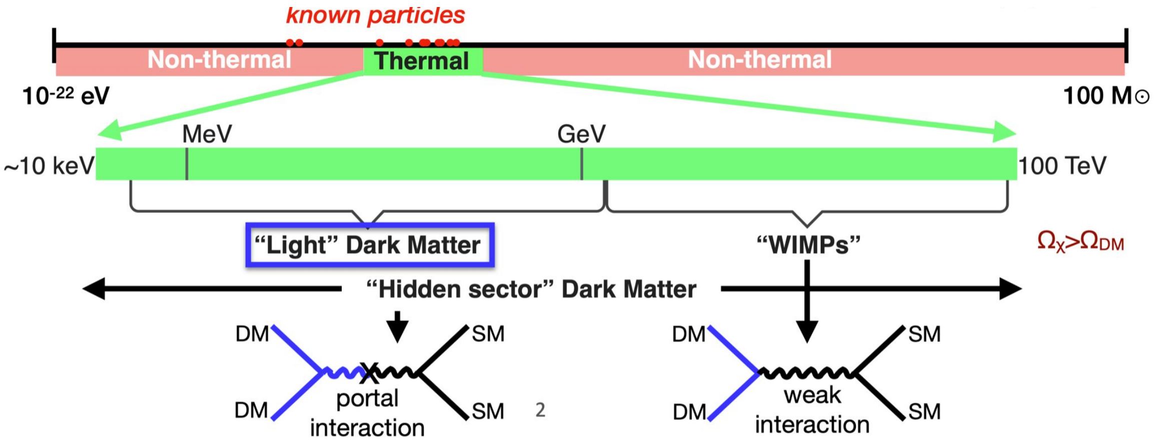
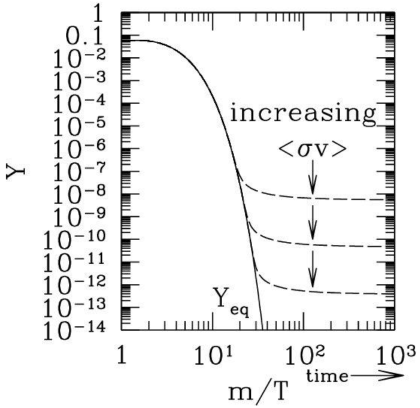
Dark Matter - A Thermal Relic



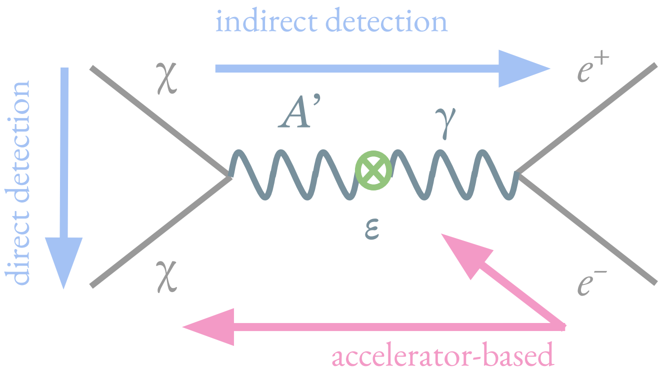
- **A thermal relic** - simple and predictive model of dark matter (DM)
- WIMPs are popular, but accessible parameter space is running out of room
- Increasing interest in expanding the thermal DM search to **“Light” DM** in the MeV-GeV mass range

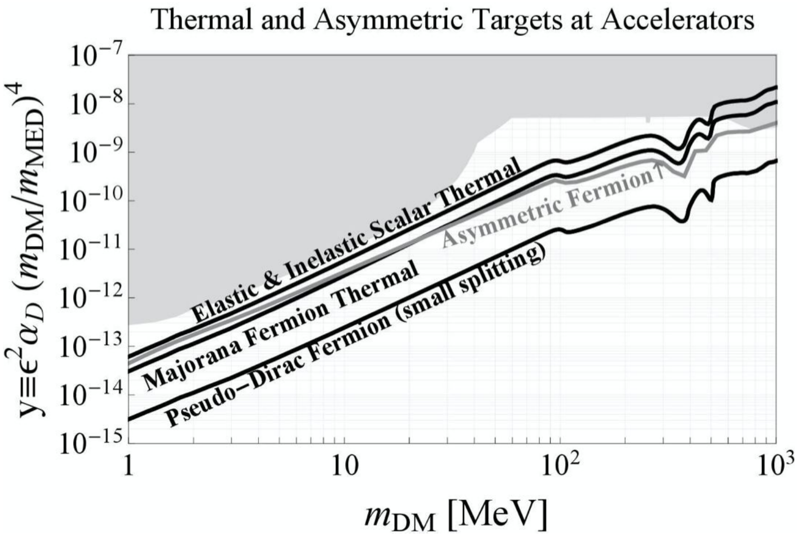




Light Dark Matter

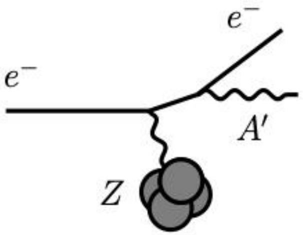
- Simplest prediction includes a **dark photon** (heavy photon or A') that mixes with the SM photon
- **Thermal targets** make attainable predictions with accelerators

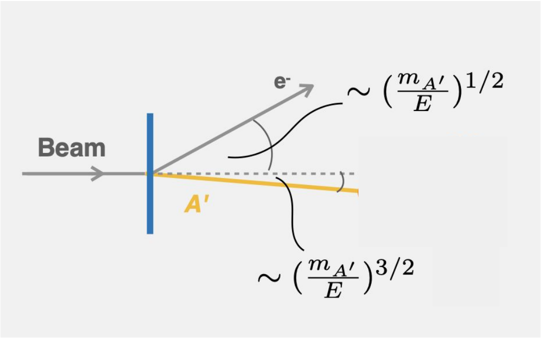




Dark Photon Production

- 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

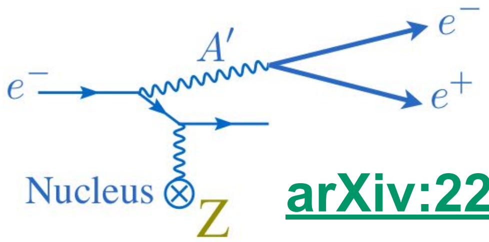




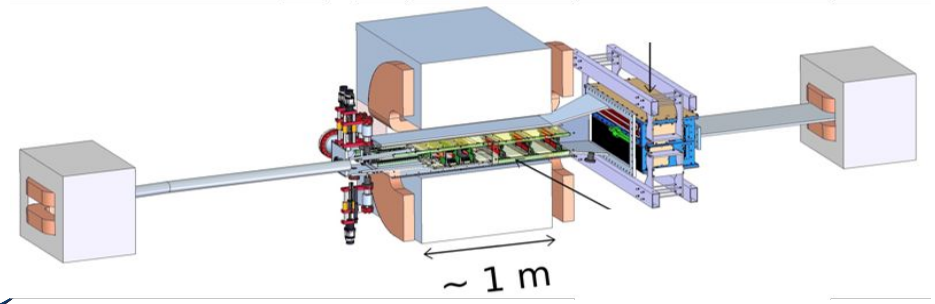
Dark Photon Decays - Complementary Searches

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

Heavy Photon Search
(HPS) at Jefferson Lab

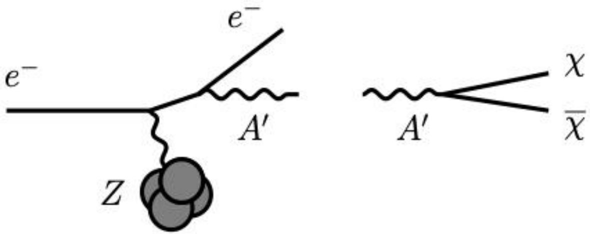


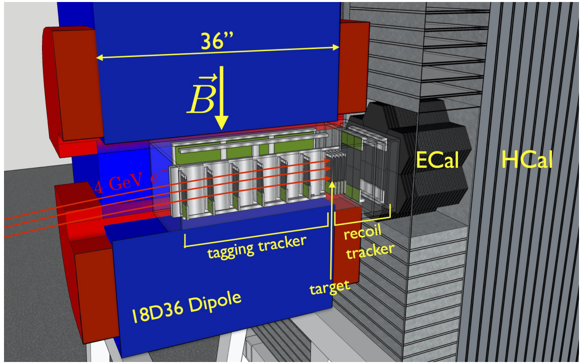
arXiv:2203.08324



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

Light Dark Matter eXperiment
(LDMX) at SLAC

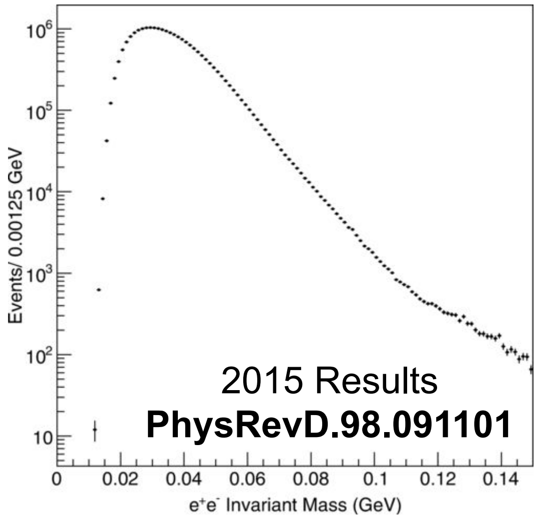


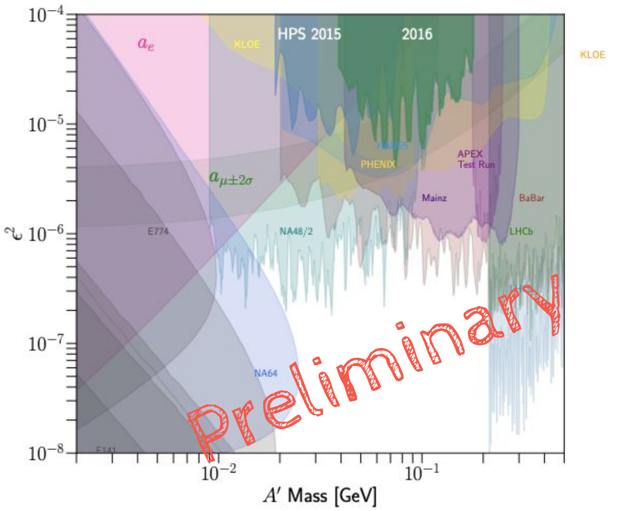


HPS Data and Results

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

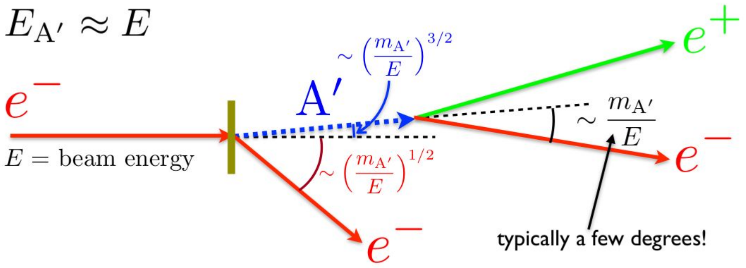
Data Run	Beam Energy (GeV)	Beam Current (nA)
2015 Engineering Run	1.05	50
2016 Engineering Run	2.3	200
2019 Physics Run (Upgraded)	4.55	~150
2021 Physics Run (Upgraded)	3.7	~120

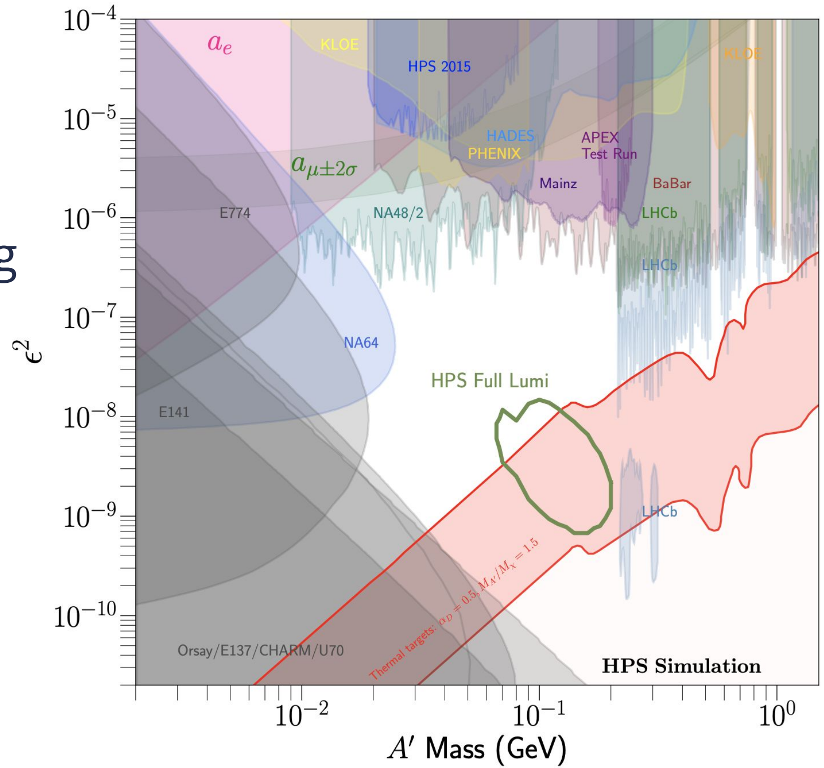




Dark Photon Visible Parameter Space

- The center is a **highly motivated**, yet **unprobed** region of parameter space
  - Small production cross-section
  - Short, but finite lifetime $c\tau \propto \frac{1}{\epsilon^2 m_{A'}}$
- 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

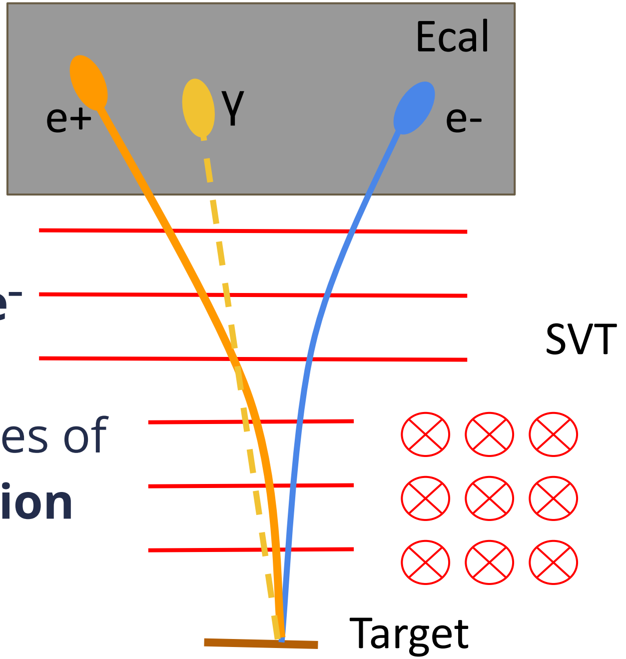


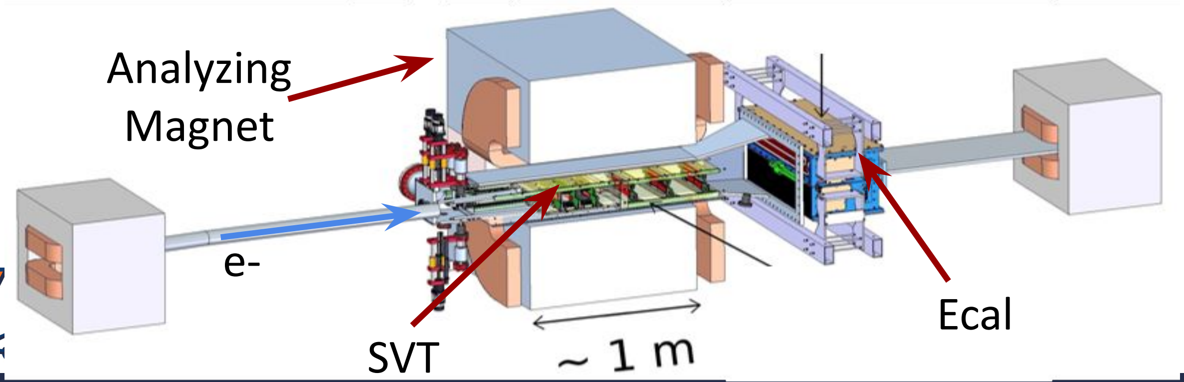


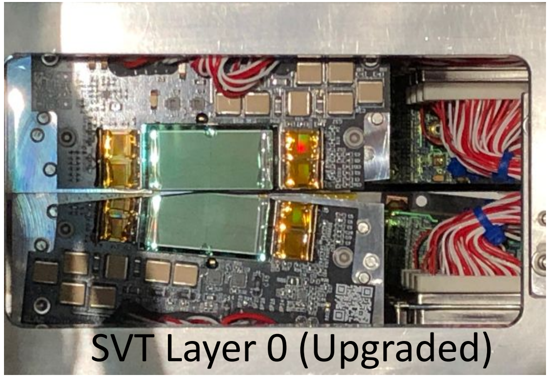
$$2m_e < m_{A'} < 2m_{DM}$$

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

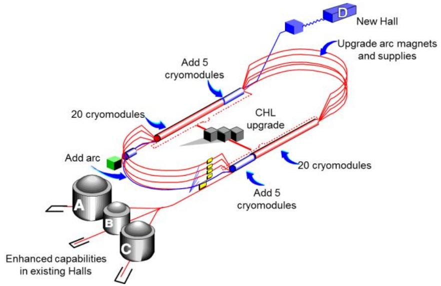


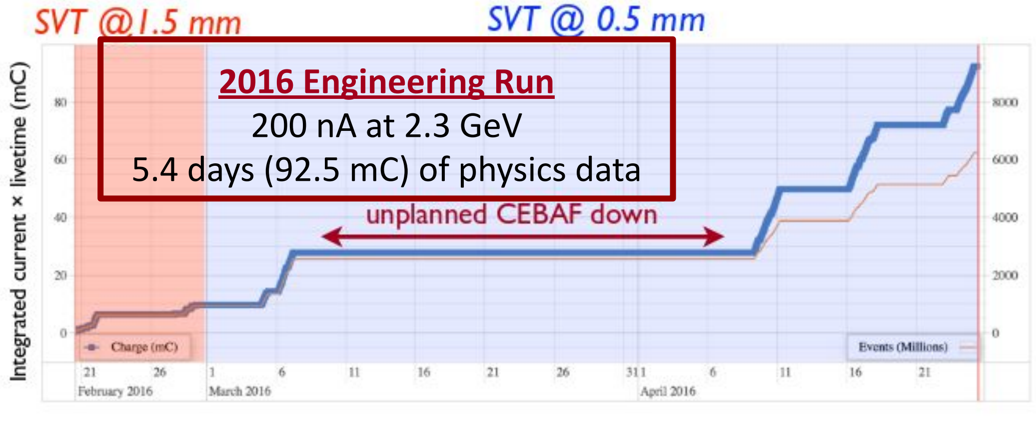


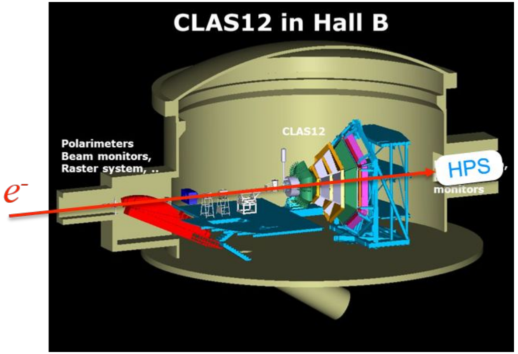


Jefferson Lab and CEBAF

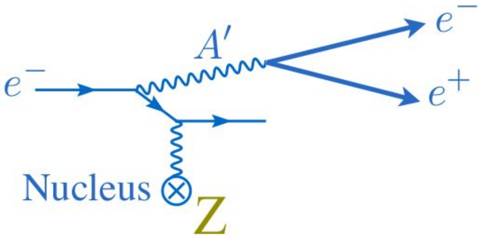
- JLab (Newport News, VA) has the Continuous Electron Beam Accelerator Facility (CEBAF) that can simultaneously deliver intense **continuous** electron beams of different energies to 4 halls
- 2.2 GeV per pass up to 12 GeV and 2 ns bunch pulse
- **Provides small beam spot with small tails** (~10^{-6})



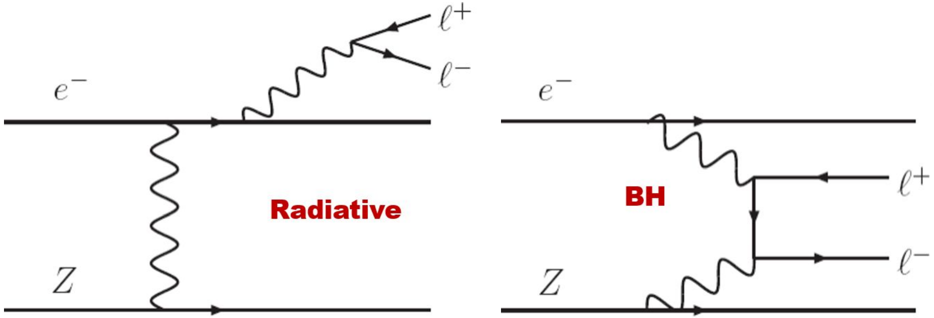


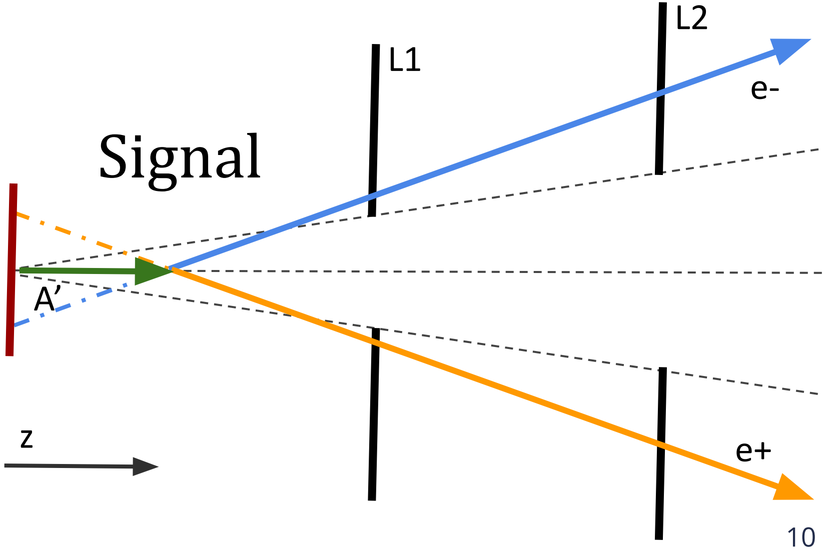


Prompt Trident Backgrounds



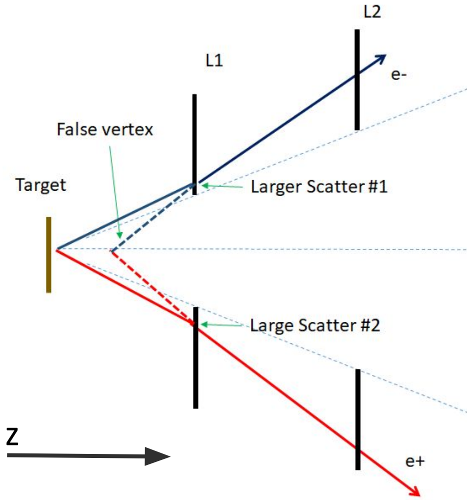
- **Radiative tridents** and **Bethe-Heitler (BH) tridents** are prompt
- Distinguishing the prompt QED tridents from displaced signal is the challenge of the analysis - ~1 signal for ~10^6 prompt background

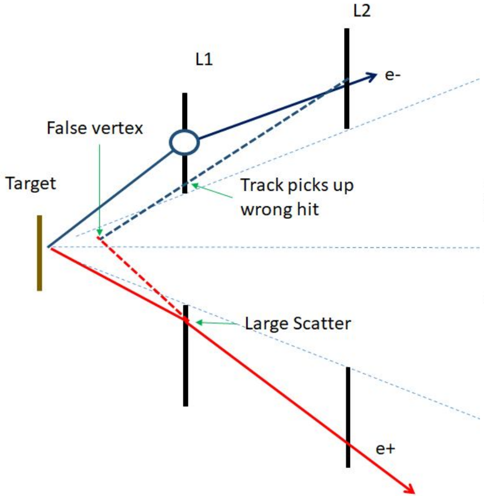


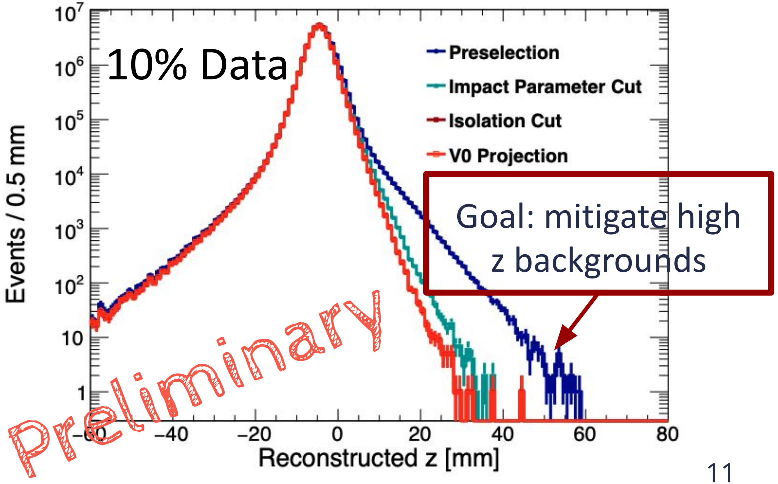


Displaced Vertex Search Event Selection

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

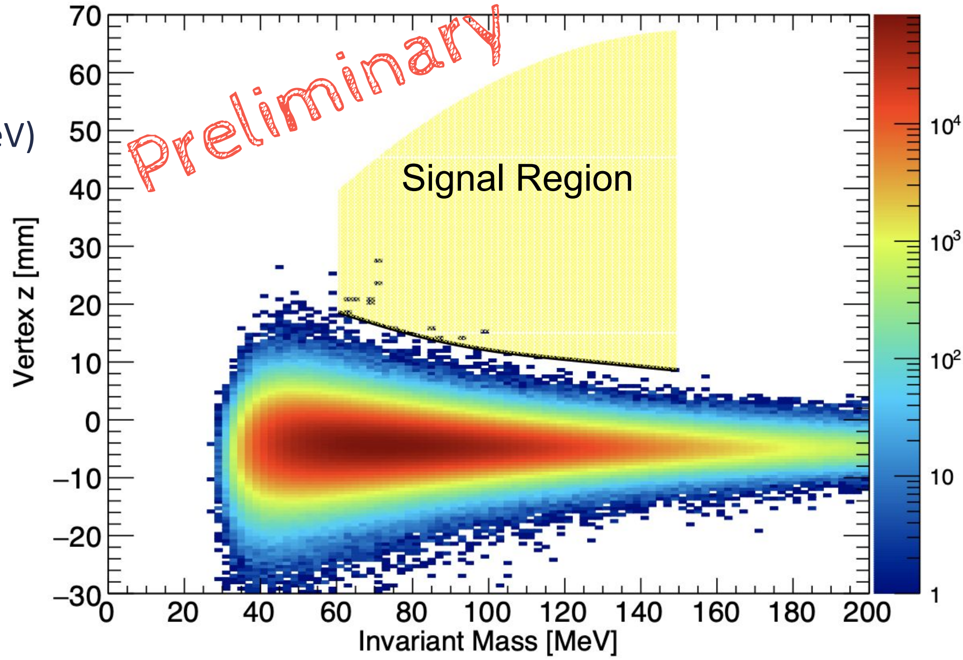






Displaced Vertex Search - Unblinded

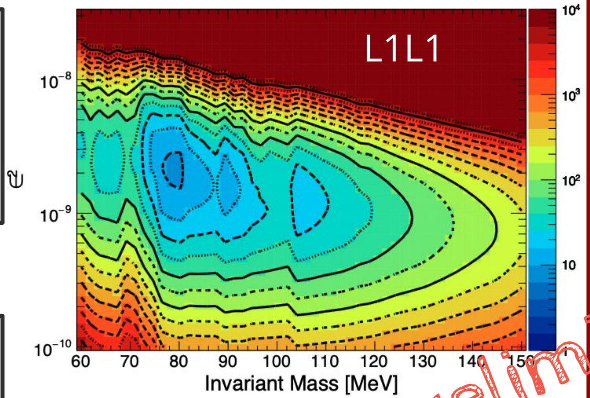
- Did we achieve the expected level of background necessary for a search?
  - **YES! A major accomplishment** (for mass > 70 MeV)
  - For mass < 70 MeV, this is currently under investigation, most likely a background
- How much signal do we expect?
  - ~0.5 events at maximum sensitivity, not enough for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

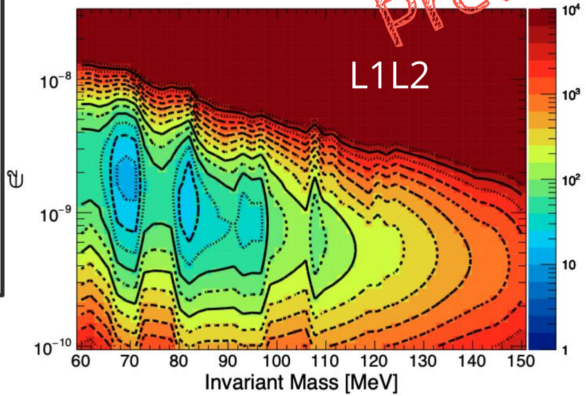


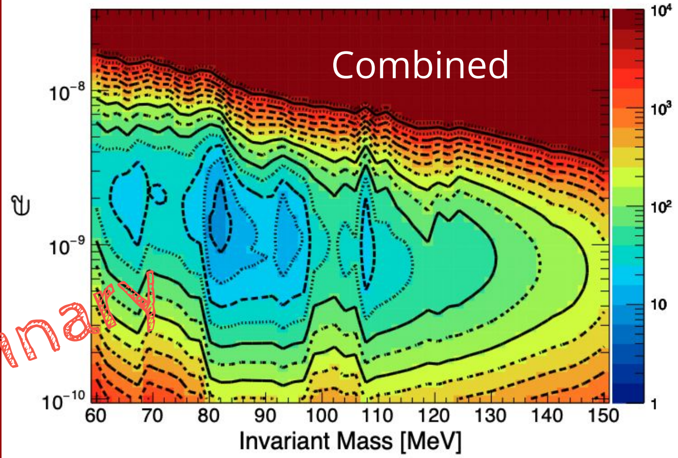
Displaced Vertex Search Final Results

Set limit using the Optimum Interval Method (OIM) ("L1L1")

Repeat analysis procedure for the case in which one of the A' daughters misses L1 of the SVT ("L1L2") . Combine results.



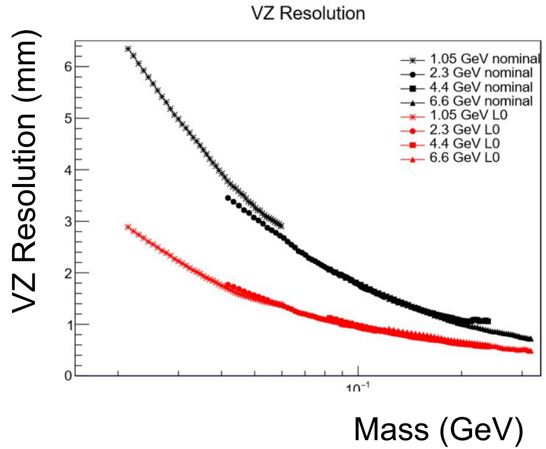


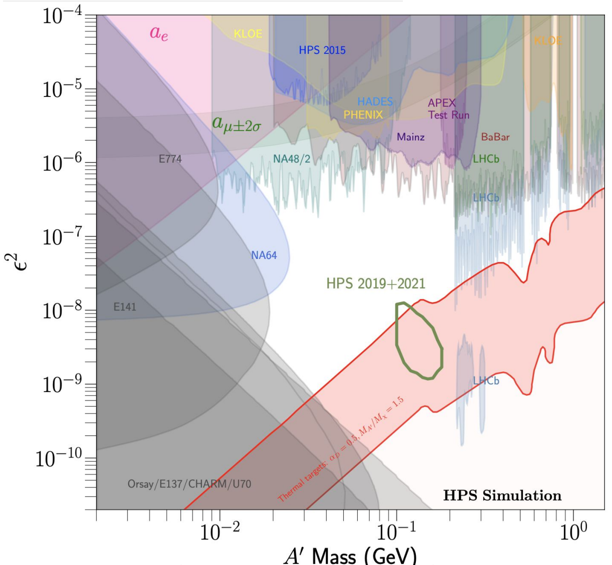


No exclusion to minimal dark photon model for this dataset, however **current datasets with upgrades…**

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
- HPS is approved for 180 days of running
  - Analysis from runs in 2019 and 2021 (~4 weeks each) are expected to yield exclusions, and potential discovery, of A's
- Probing other models with displaced vertices such as Strongly Interacting Massive Particles (SIMPs)





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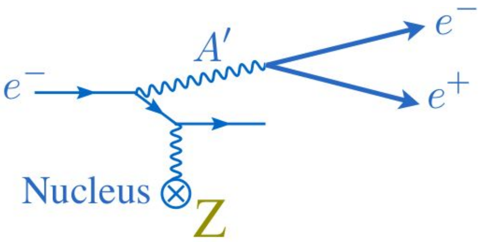
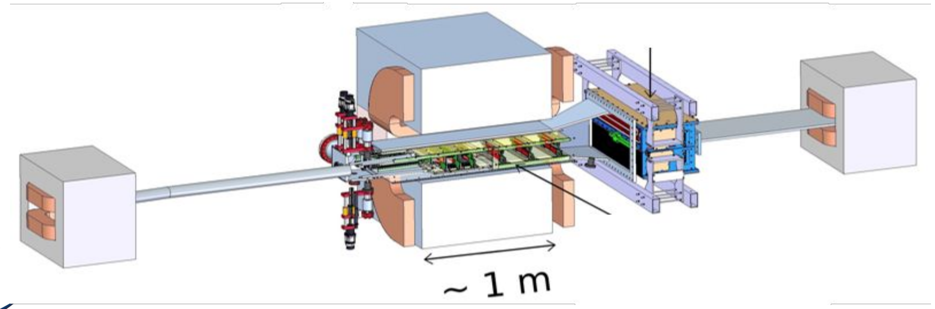
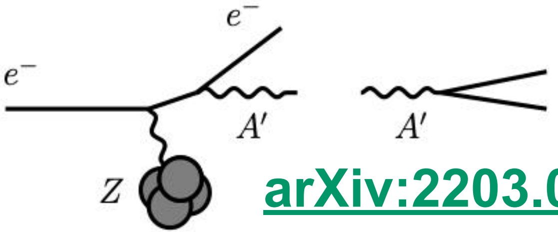


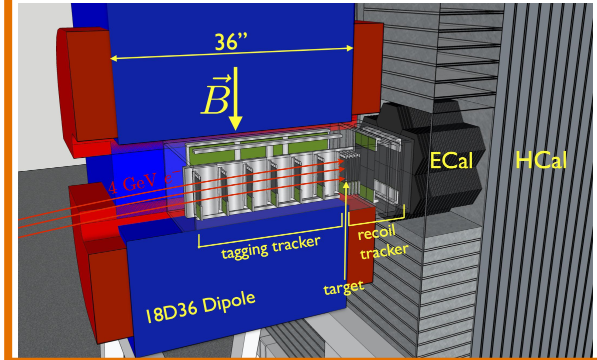


$$2m_{DM} < m_{A'}$$

Light Dark Matter eXperiment (LDMX) at SLAC

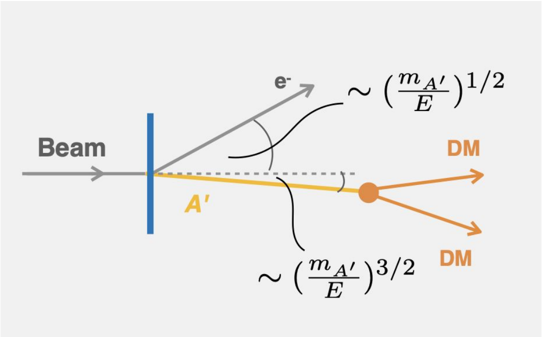


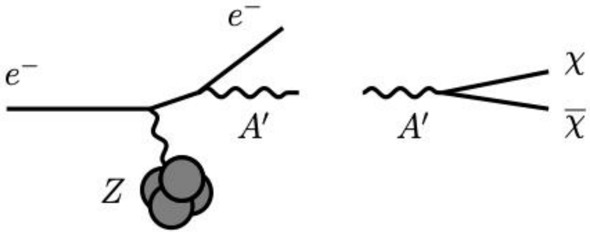
arXiv:2203.08192

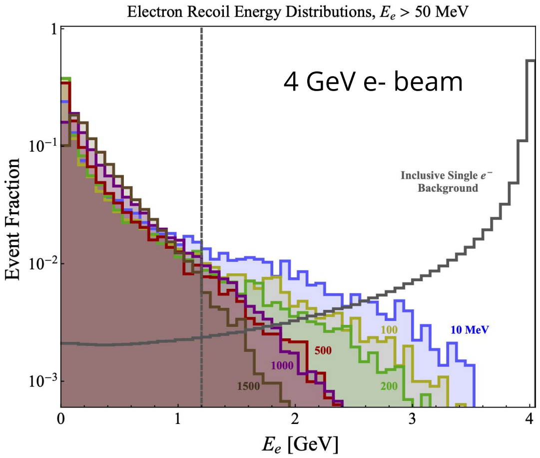


LDMX

- 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**



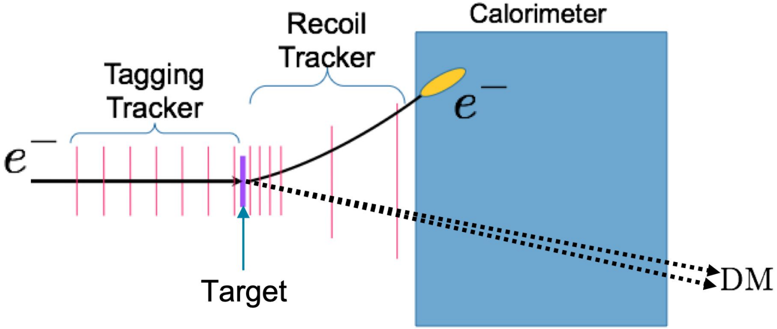


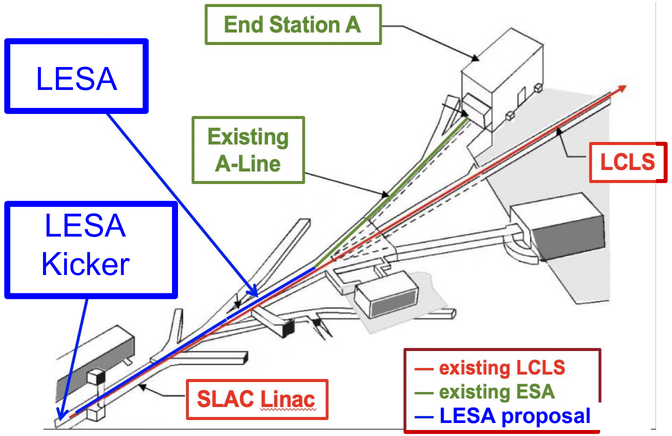


- Can probe this mechanism through a missing momentum search. We need...
  - High momentum resolution
  - High veto efficiency of Standard Model backgrounds

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

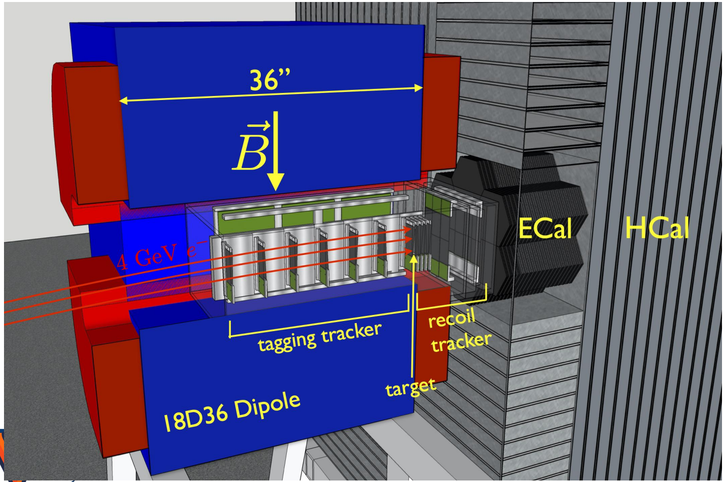


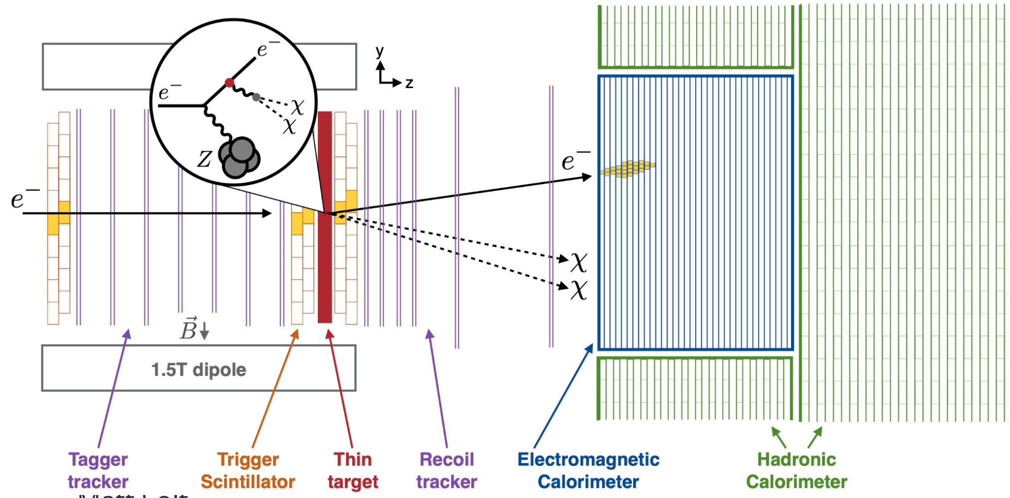


- 4 and 8 GeV e- beam provide by SLAC
  - Parasitically use the LCLS II beam with a dedicated transfer line (LESA)
  - Individual tagging and reconstruction of up to 10^{16} electrons
  - Low current, high repetition rate 37 MHz, μ = 1

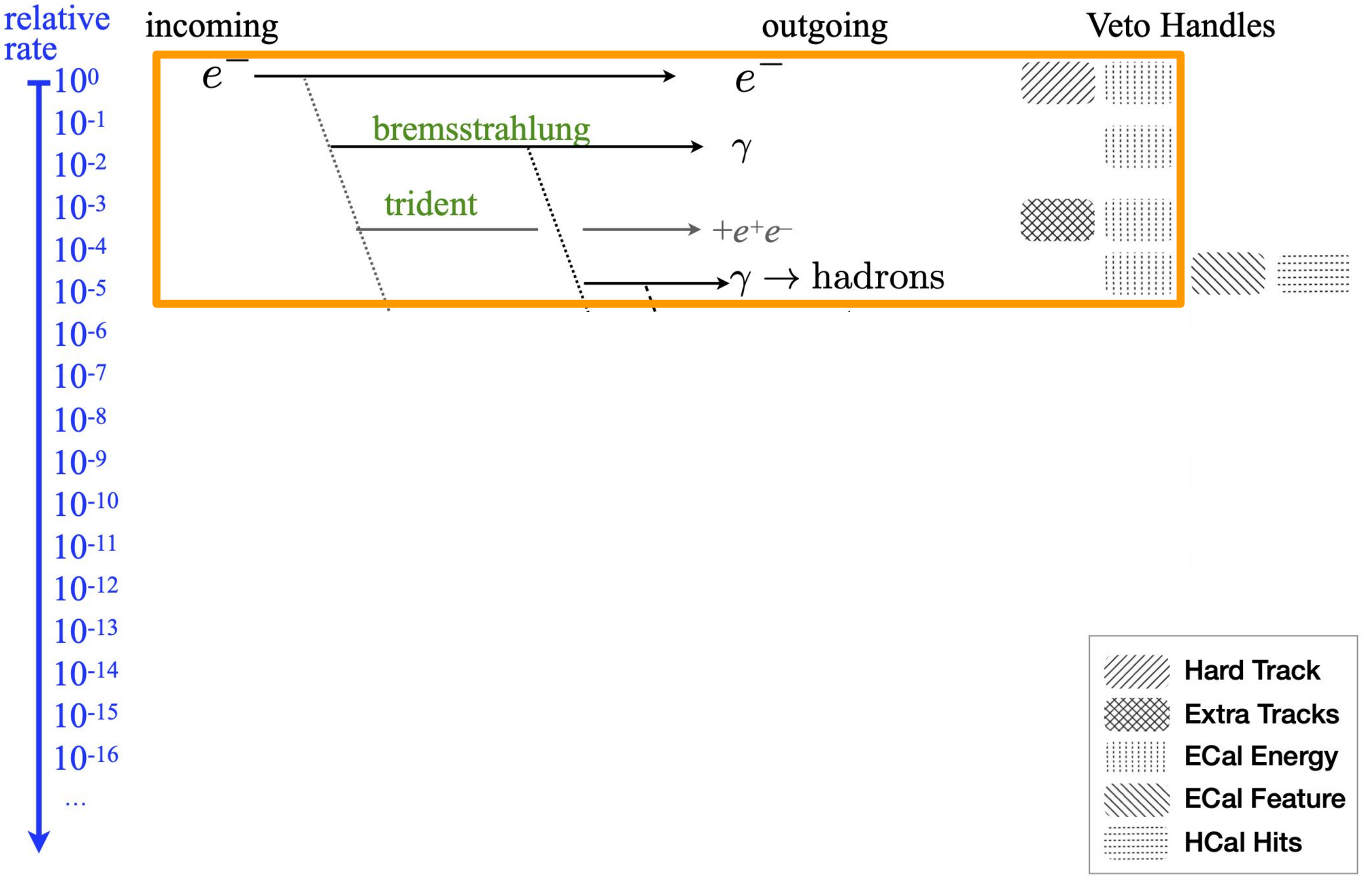
LDMX Design

- 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

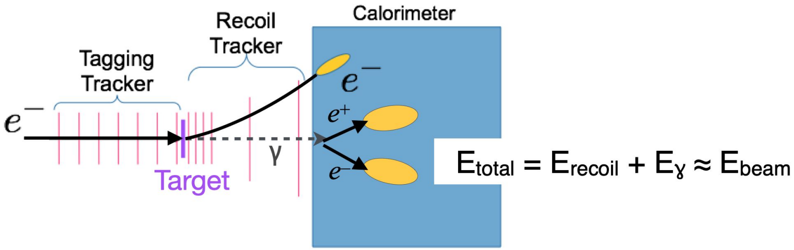




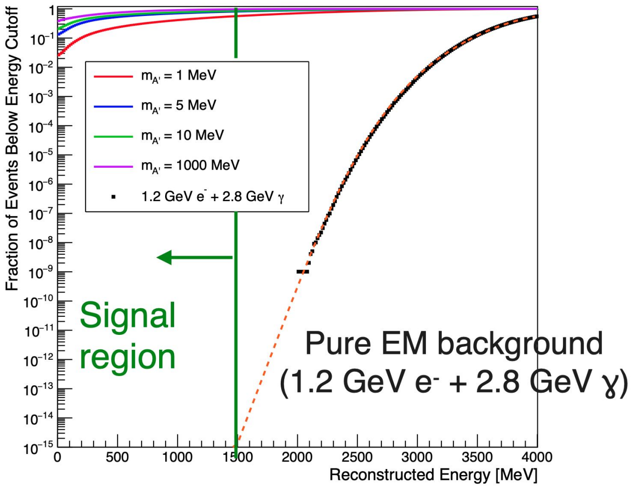
Backgrounds

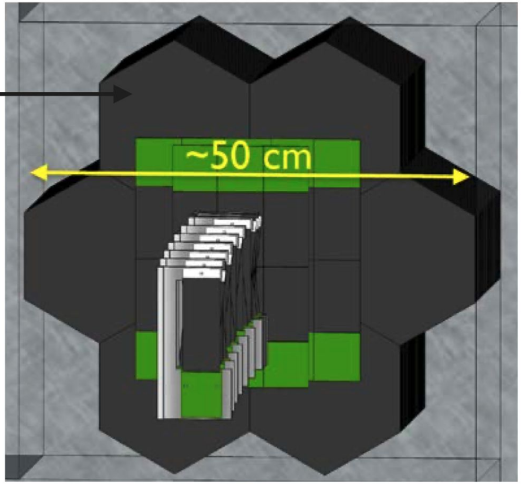


Electromagnetic Calorimeter



- 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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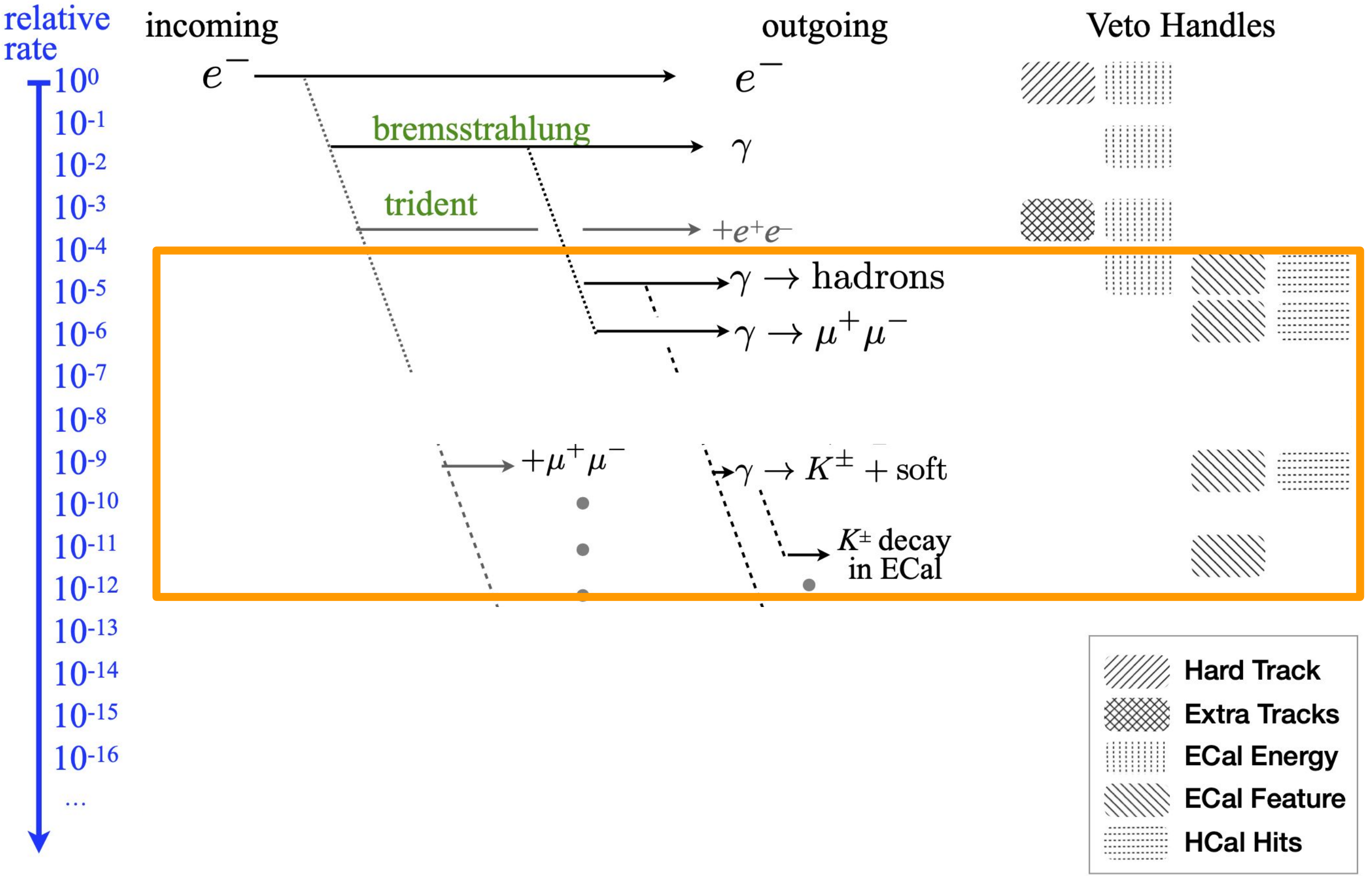
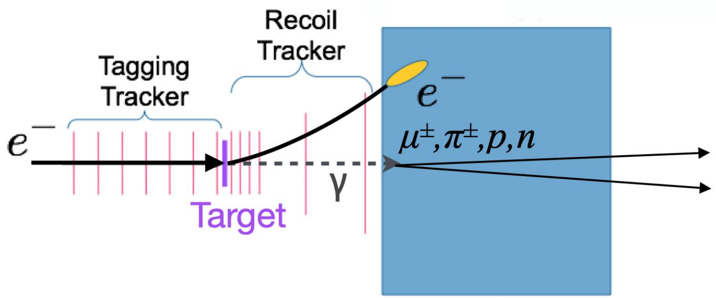
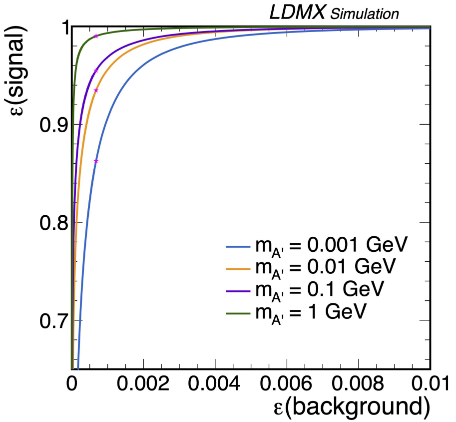


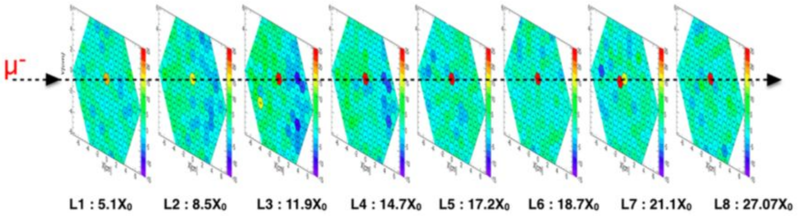
Ecal Veto

- More difficult to veto: Rare photon reactions (PN) 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**

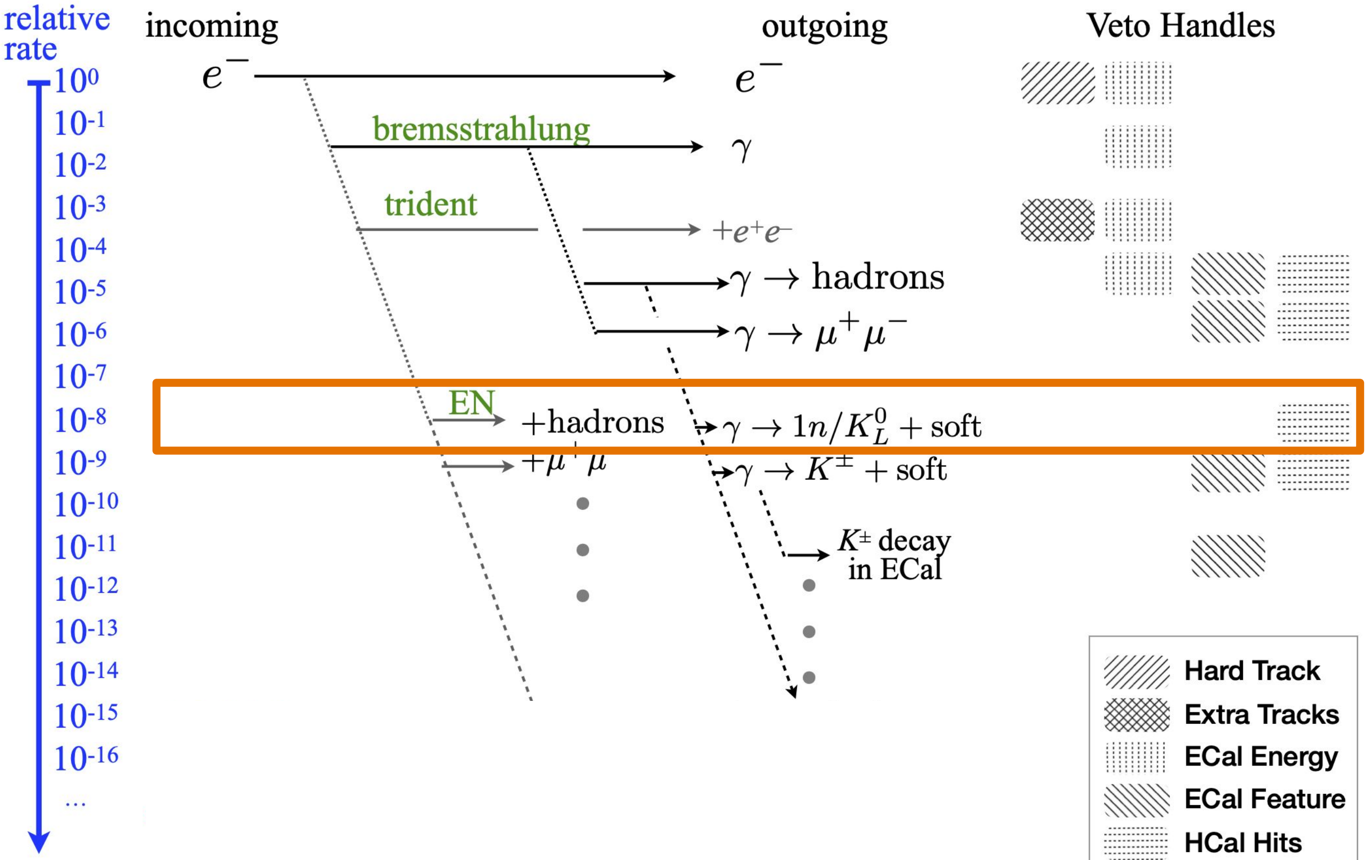




A.Martelli on behalf of CMS, arXiv:1708.08234

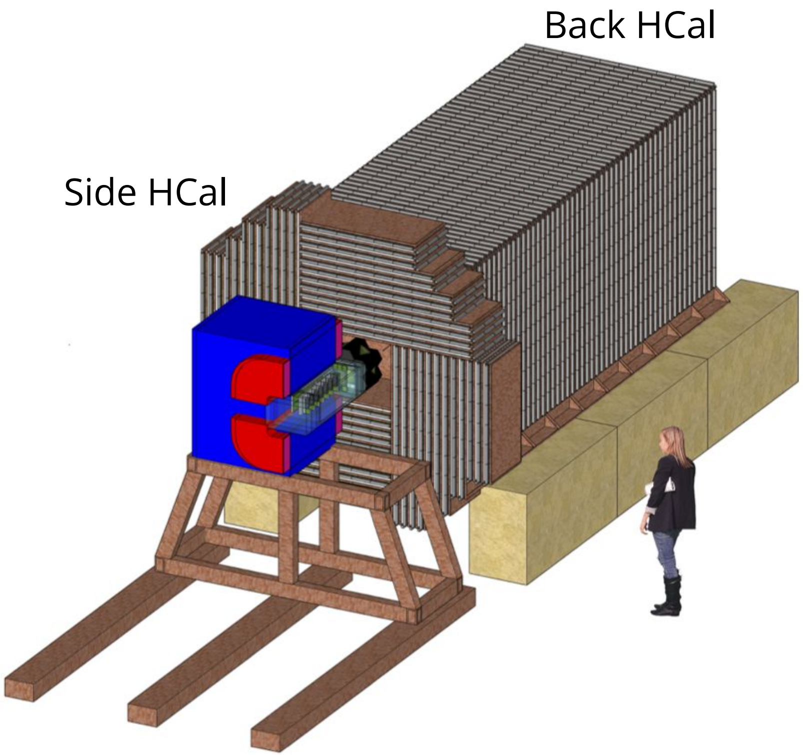


Backgrounds



Hadronic Calorimeter

- Sampling calorimeter with segmented plastic/steel
  - 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 ~10^6 rejection
  - Side HCal rejects wide angle bremsstrahlung and $\gamma \rightarrow \mu^+ \mu^-$



Backgrounds

All systems combined:
< 1 background event
with signal efficiency of
~30-50% for O(10^{14})
EoT!

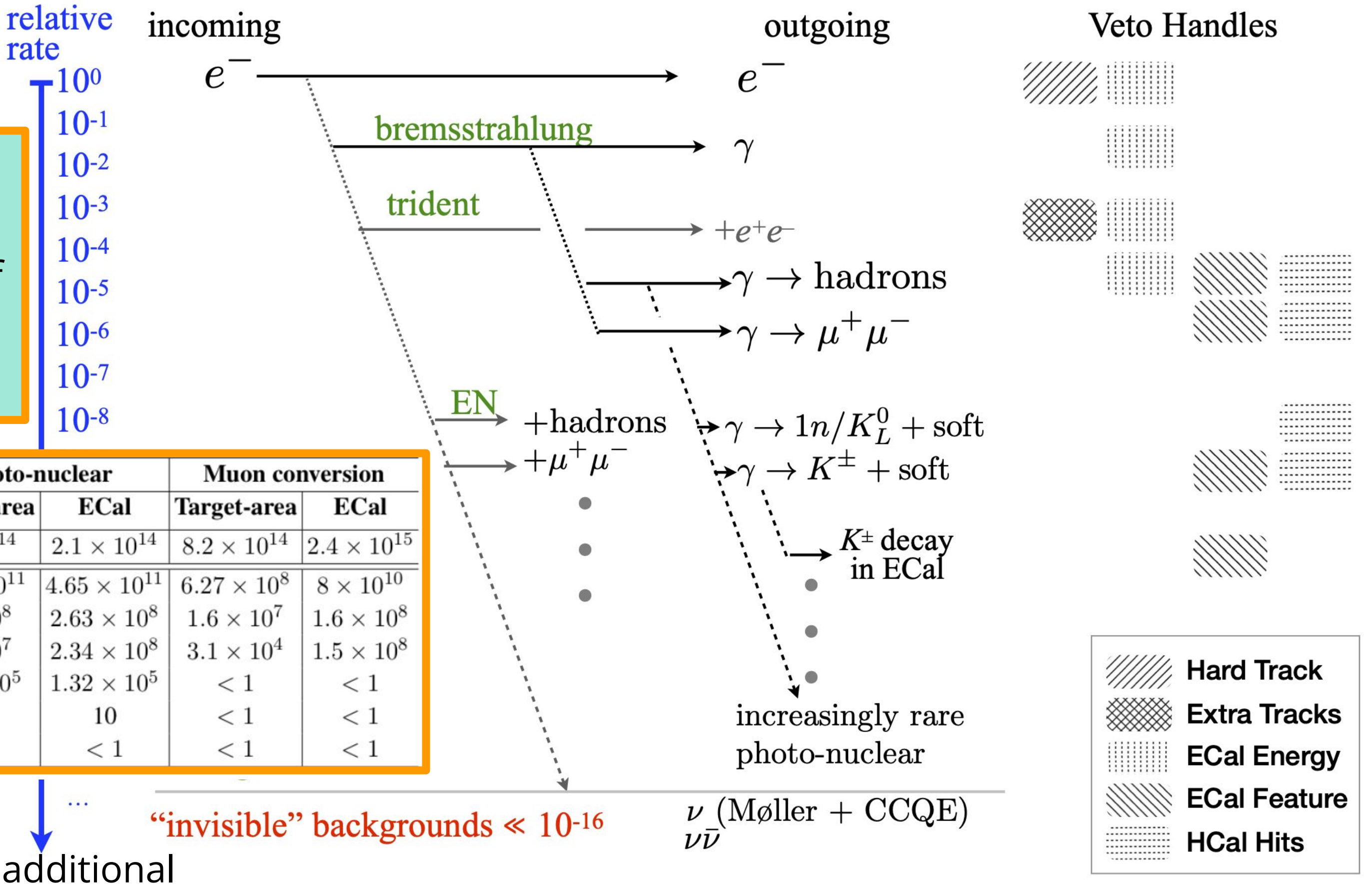


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p <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

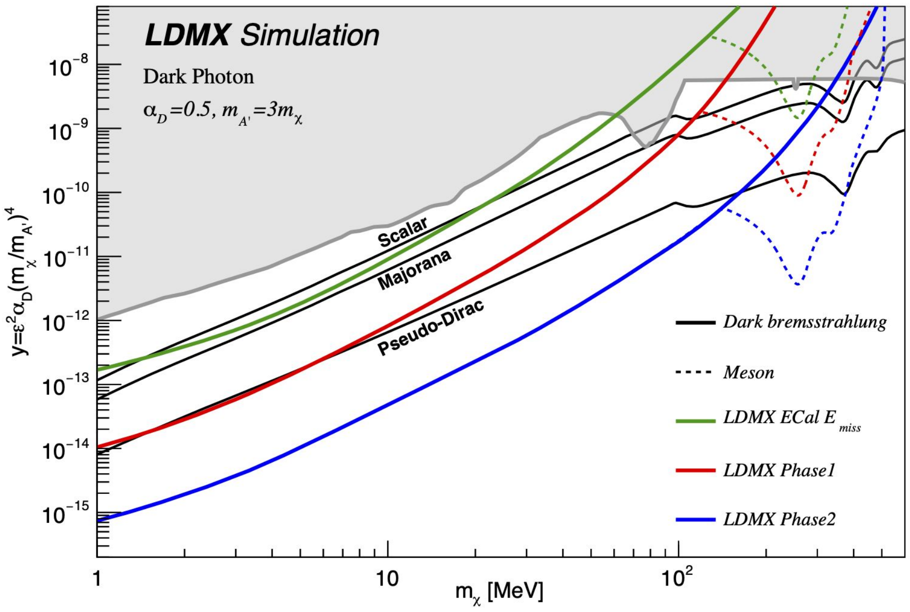
$$2m_{DM} < m_{A'}$$

LDMX Sensitivity

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

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

[arXiv:1808.05219]

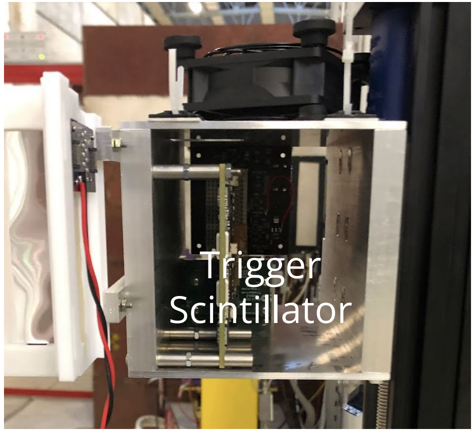


2020	2023	2025	2027
Detector Development	Construction	Phase I data taking	Phase II construction & operation

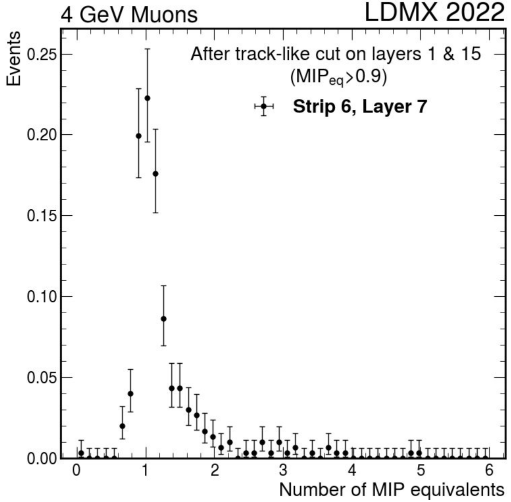
Proposed LDMX baseline schedule

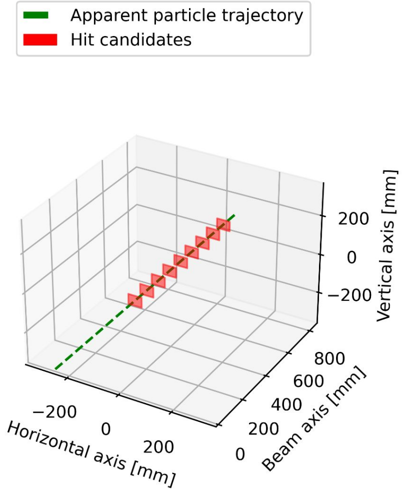
CERN Test Beam

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



Matt Solt

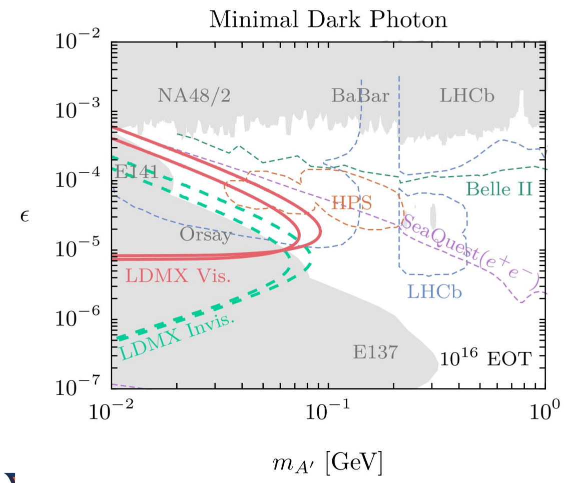


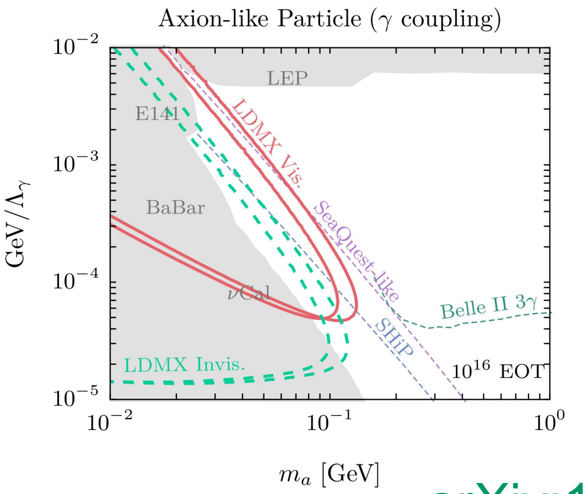


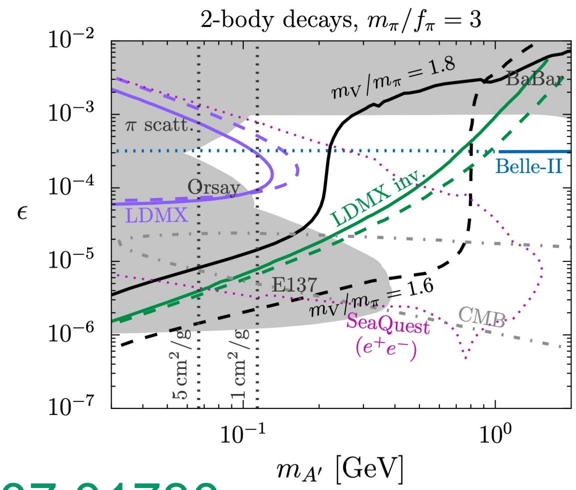
Data analysis is ongoing

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





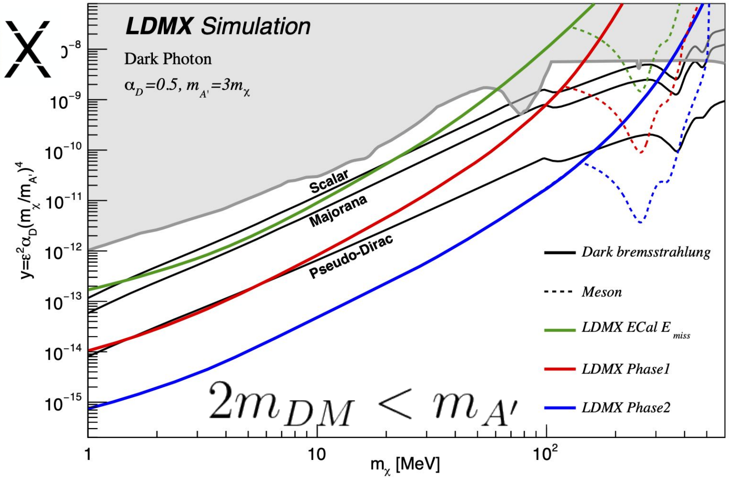


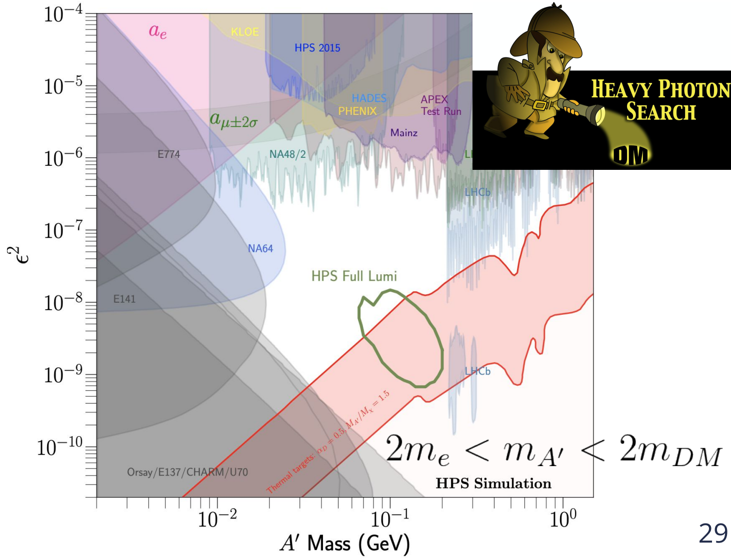
Projections are for 8 GeV and 16 GeV beams

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 many DM models in the sub-GeV mass range through a missing momentum search





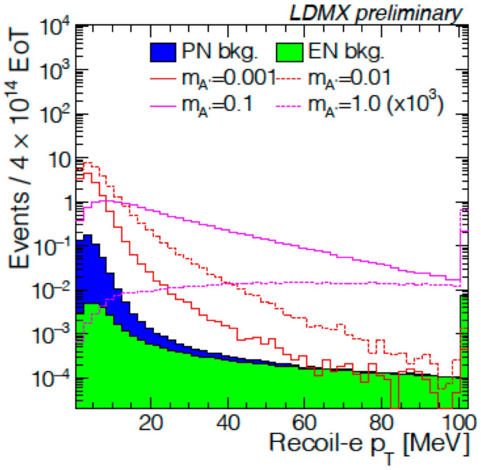
Thank You!

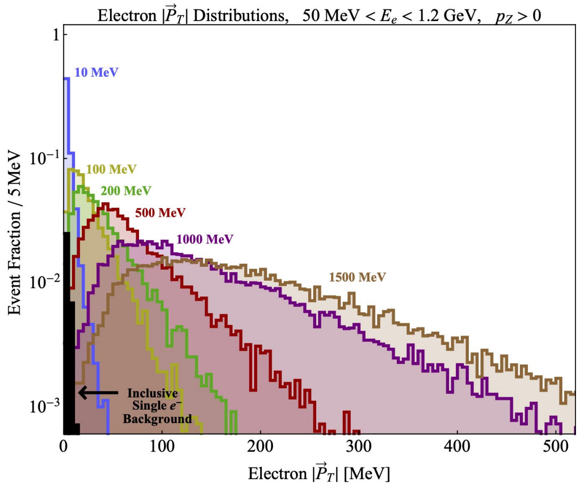
Caltech Fermilab Lunds Universitet University of Minnesota UCSB University of California Santa Barbara

LDMX Carnegie Mellon University SLAC National Accelerator Laboratory Stanford University Texas Tech University University of Virginia

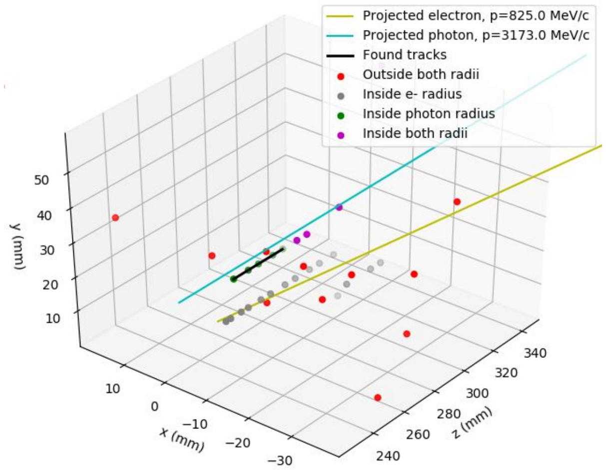
LDMX Signal Kinematics

- 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

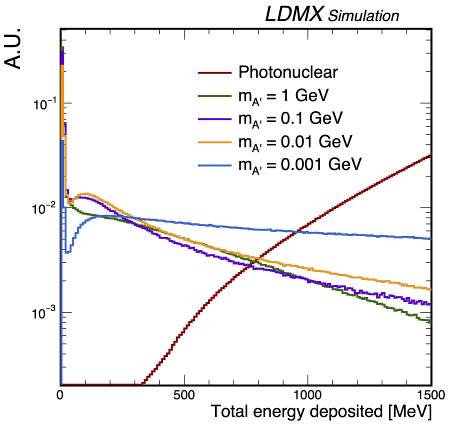


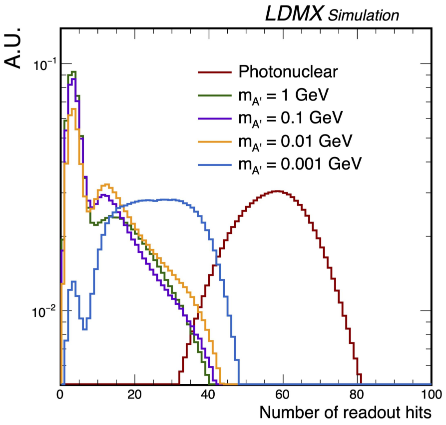


LDMX Ecal BDT

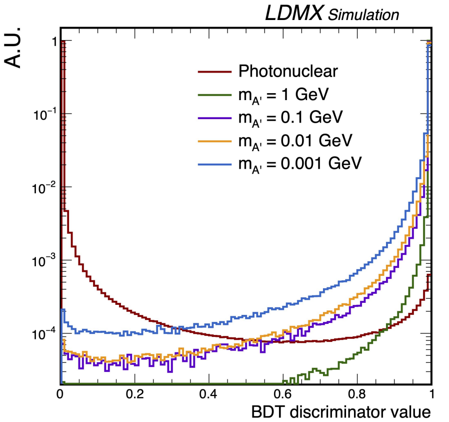


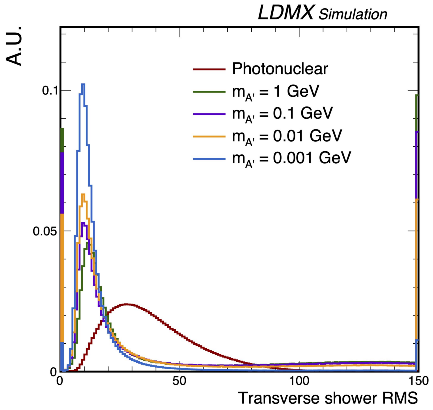
MIP Tracking





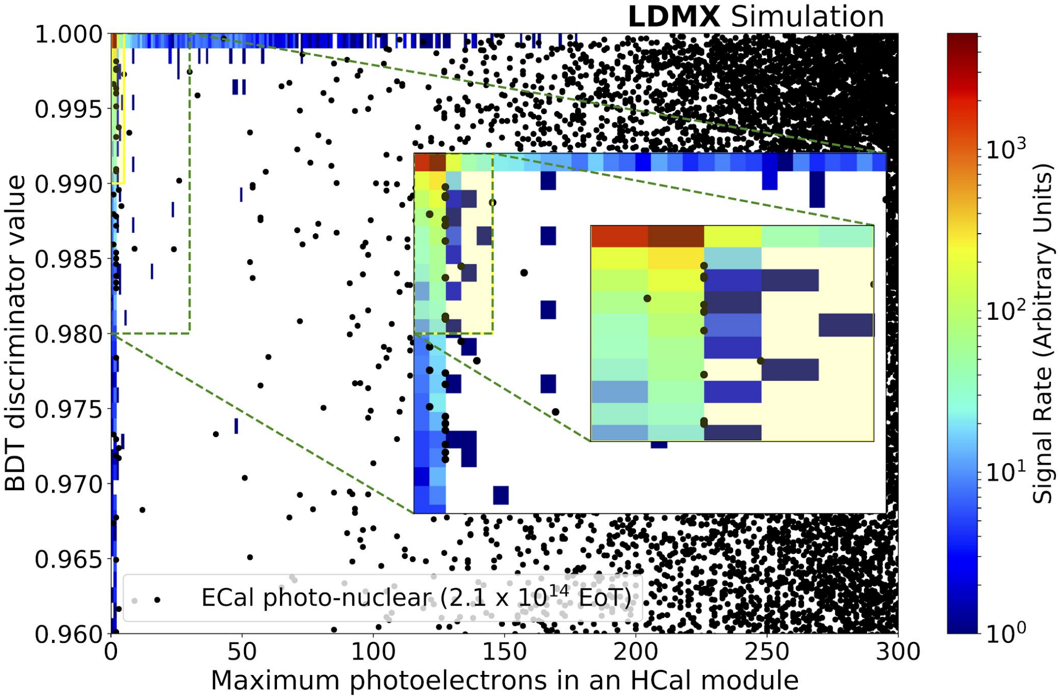
BDT Variables



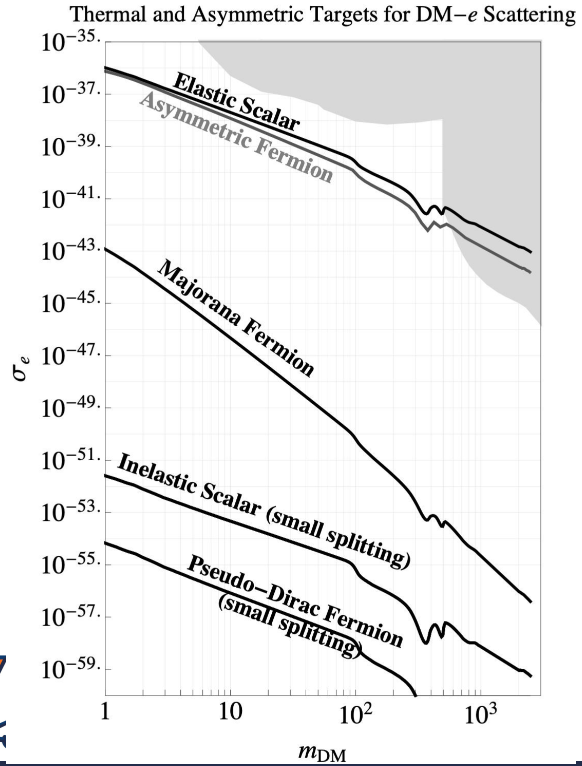


LDMX Ecal/Hcal Vetoes

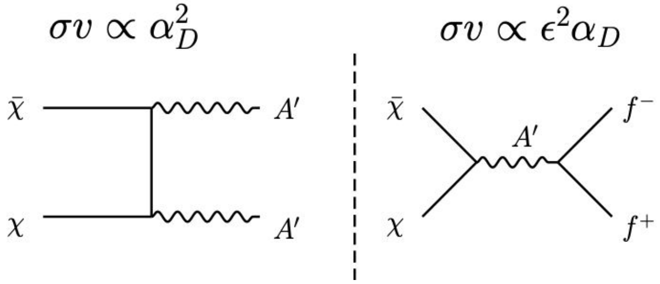
- Ecal BDT > 0.99
- Hcal max PEs is > 5

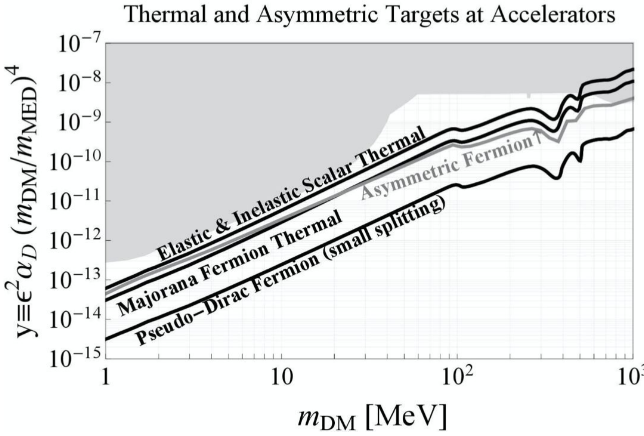


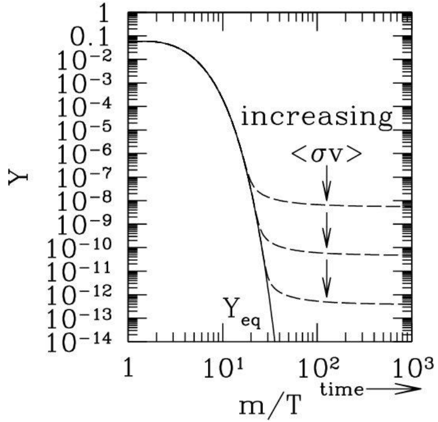
Advantage of DM Production at Accelerators



Non-relativistic vs semi-relativistic DM scattering

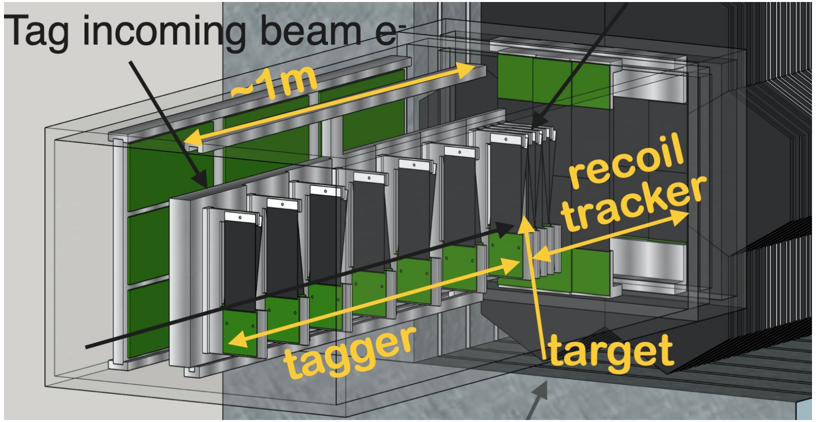


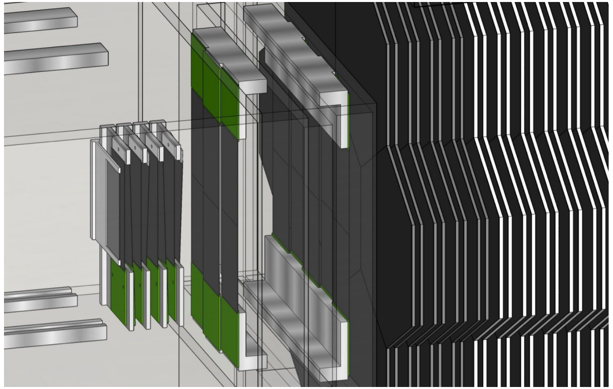




Tracker and Trigger Scintillator

- Trackers (based on HPS design)
  - Tagging tracker - measures incoming beam electron
  - Recoil tracker - 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

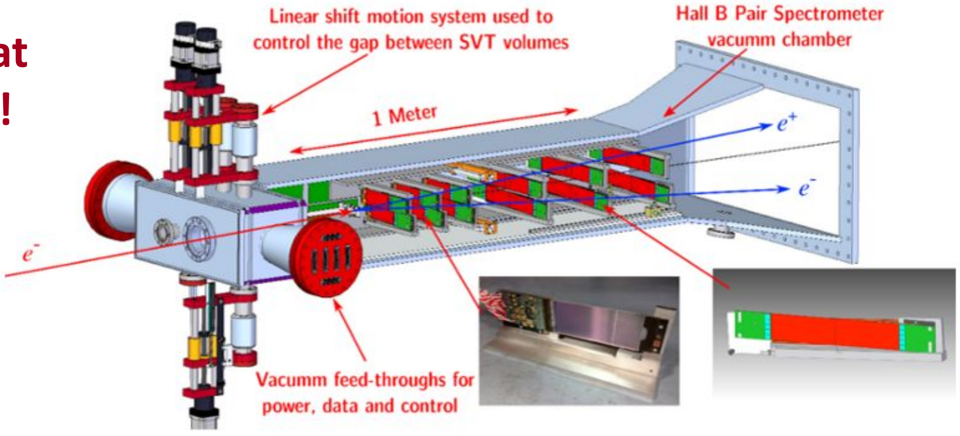


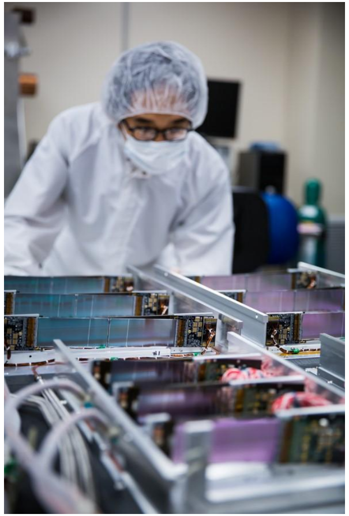


HPS Silicon Vertex Tracker

- SVT measures trajectories of e+e- and reconstructs mass and vertex position
- 6 (7) layers of silicon microstrips (~0.7% radiation length per layer)
- Each layer has axial/stereo strips (50/100 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

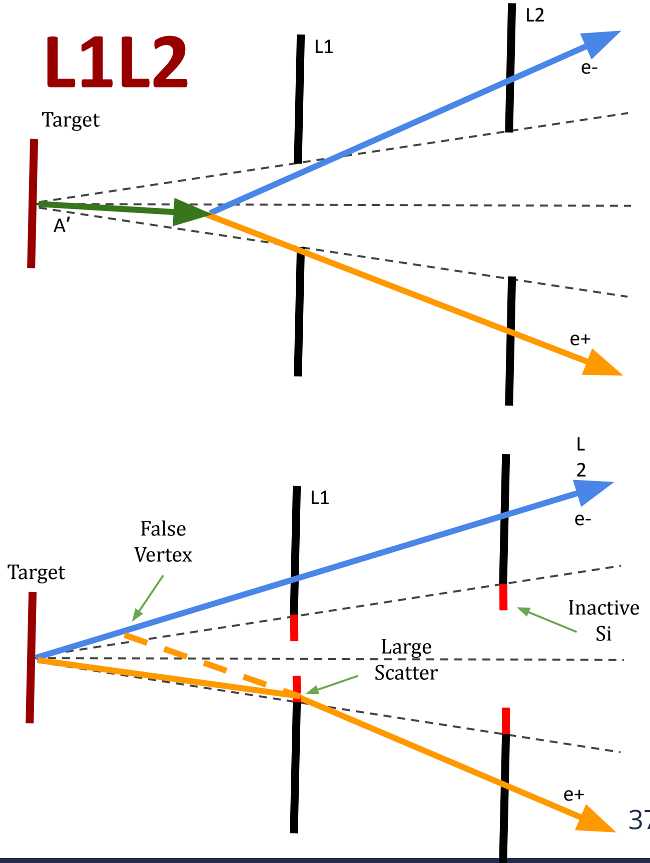
Built at SLAC!



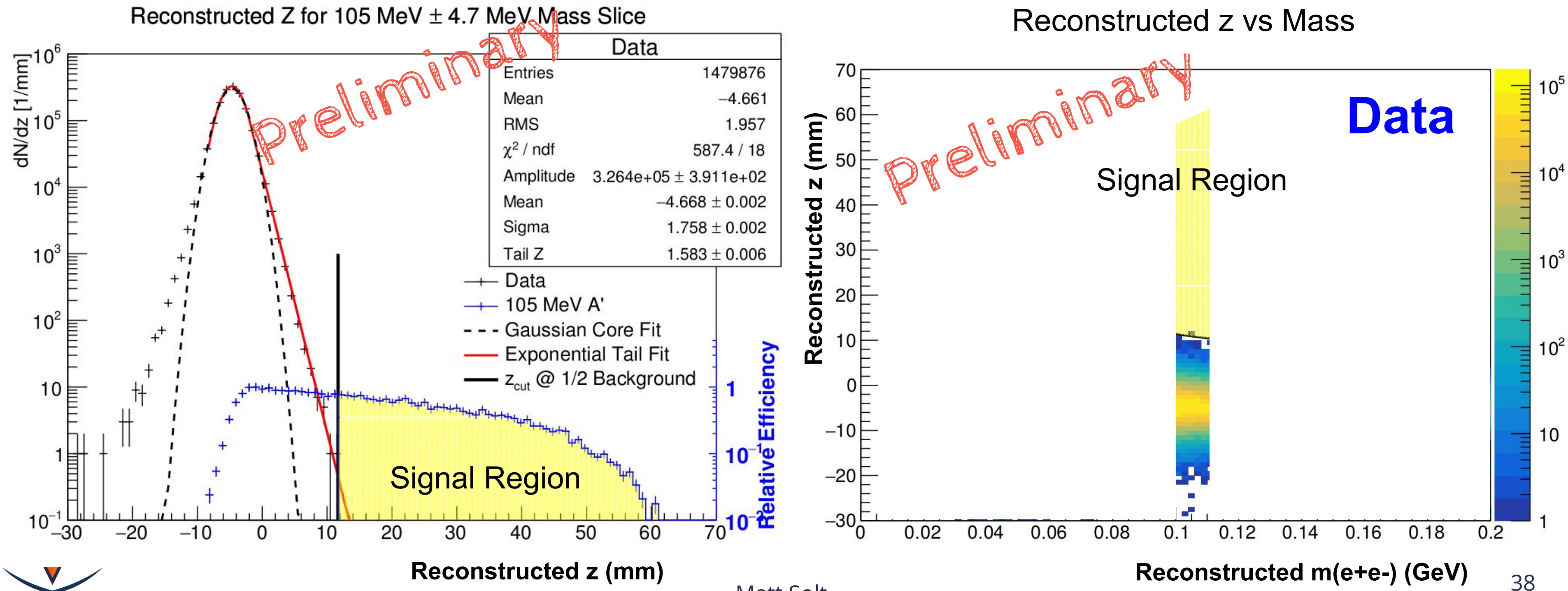


HPS A's with Longer Livetimes

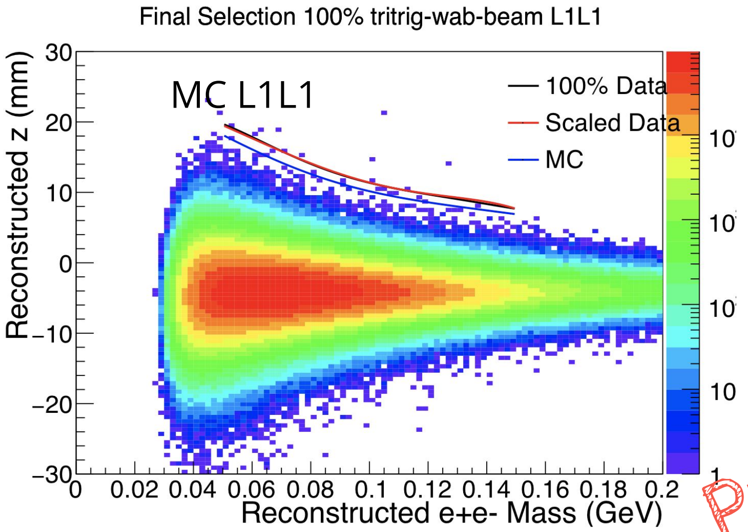
- A's with longer lifetimes will have e+e- daughters that may miss layer 1 of the tracker
- Divide analysis into L1L1 (both particles hit L1) and L1L2 (one particles misses L1) categories
- Additional backgrounds for L1L2
  - Hit inefficiencies
  - Large Coulomb scatters in inactive Si
  - Bremsstrahlung 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

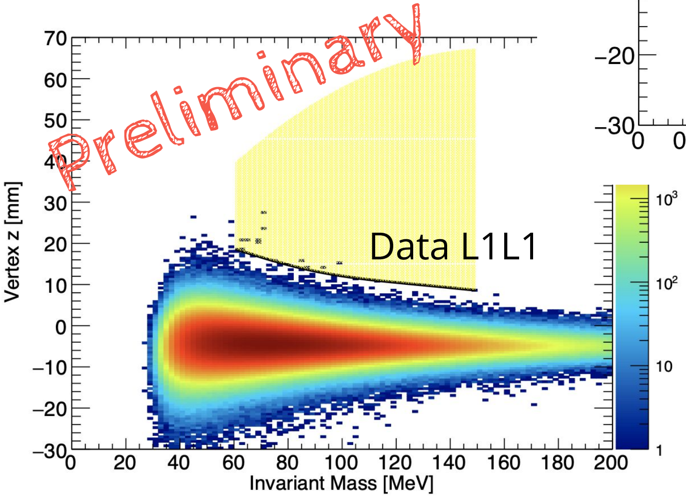


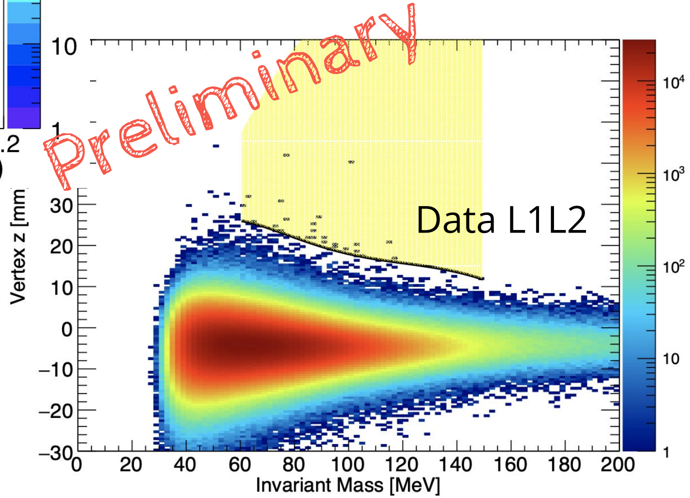
Displaced Vertex Search Signal Region



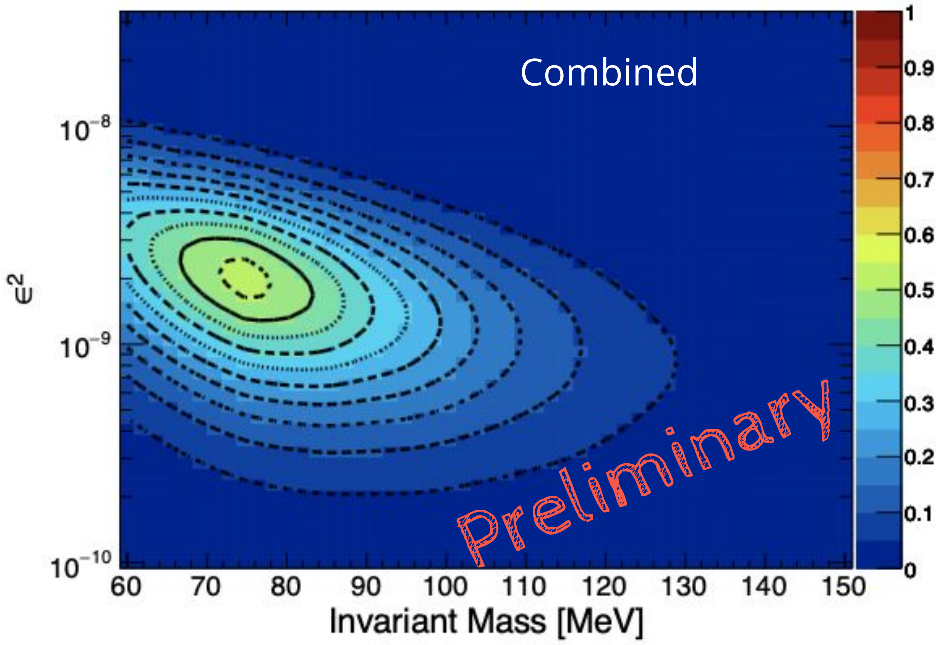
HPS Data/MC Comparison

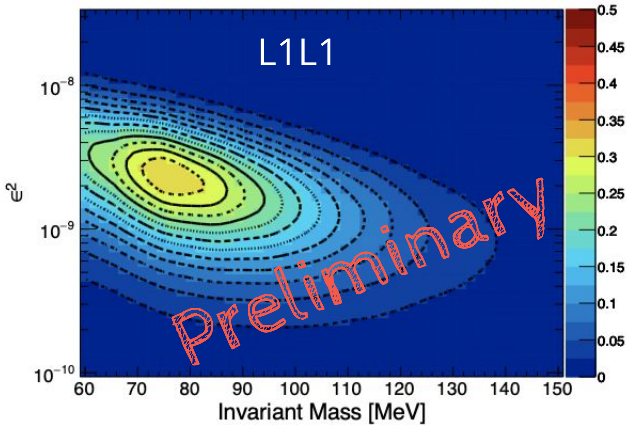


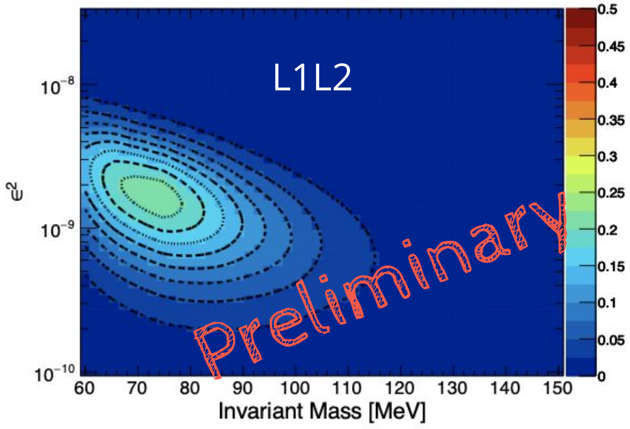




HPS Expected Signal Rate 2016





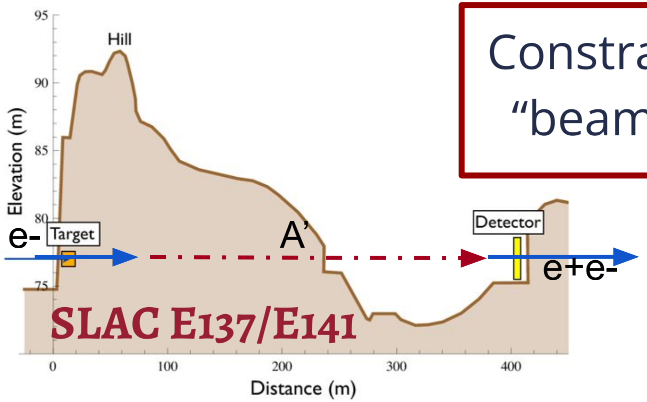


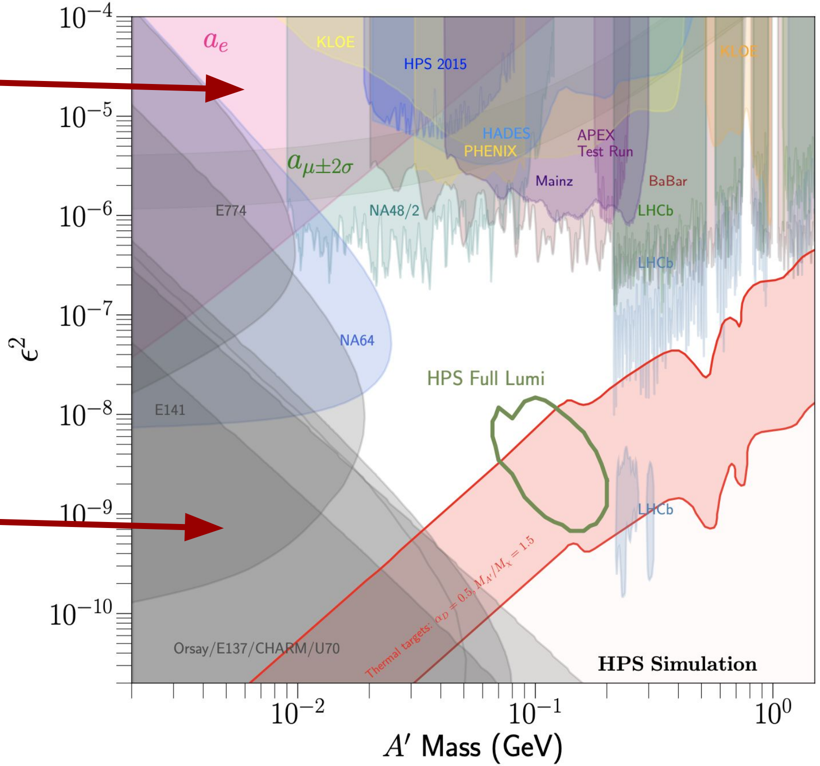
Existing Dark Photon Constraints for Visible Decays

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"





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

Matt Solt