The Heavy Photon Search at JLab

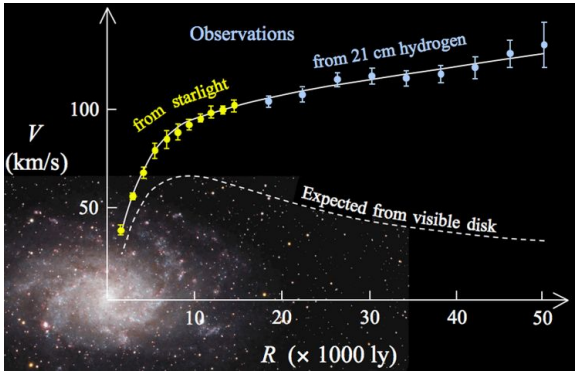
March 15, 2023

Matt Solt, University of Virginia

LDMX

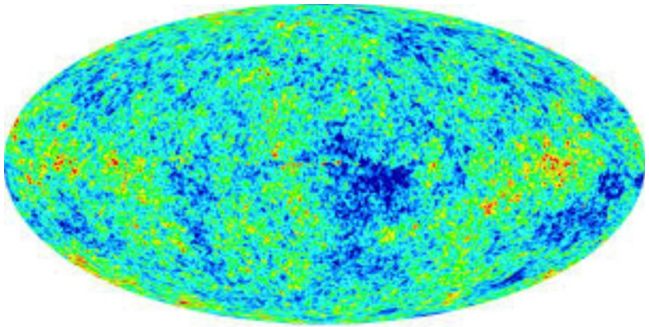
The Existence of Dark Matter

- 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

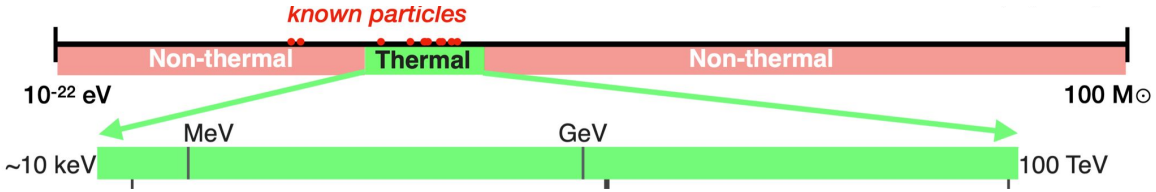
Gravitational Lensing



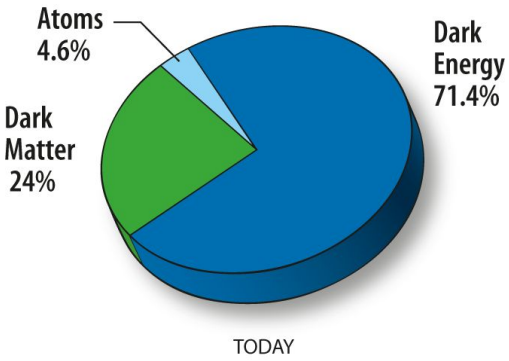
Cosmic Microwave Background

A Thermal Relic

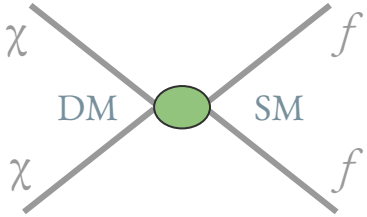
- Astrophysical evidence of DM does not constrain the mass scale very well
- **A thermal relic** - simple and predictive model of dark matter (DM)
- Thermal DM constrains DM mass to ~mass scale of SM particles and relates the annihilation cross-section to the observed relic abundance (~85%)



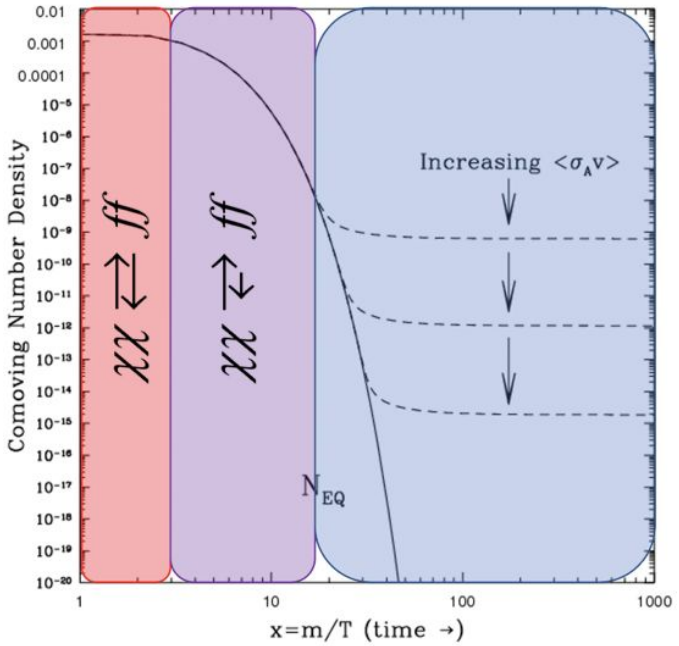
The range of (non-)thermal DM mass spans a range of ~(90) 7 orders of magnitude!



A Thermal Relic



arXiv:9506380

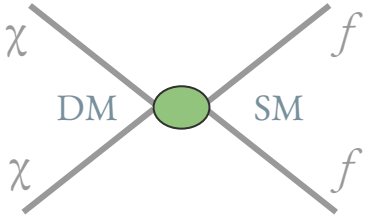


- What is a thermal origin of DM?
  - **1.** Assume DM was in thermal equilibrium with SM particles
  - **2.** The universe expands and cools such that DM pairs are no longer produced
  - **3.** The universe expands and cools such that DM annihilations cease
- The present DM density Ω_χ is related to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

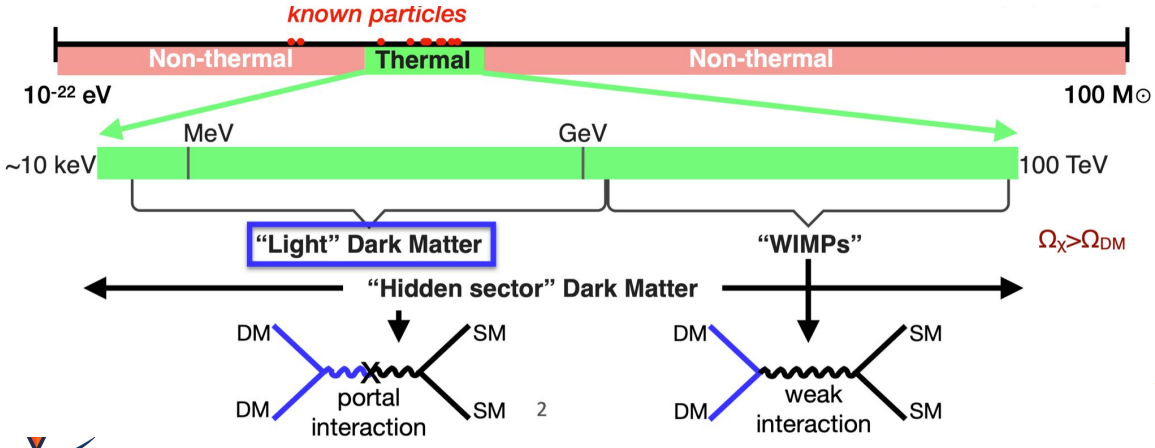
$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \rightarrow \langle \sigma v \rangle = 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

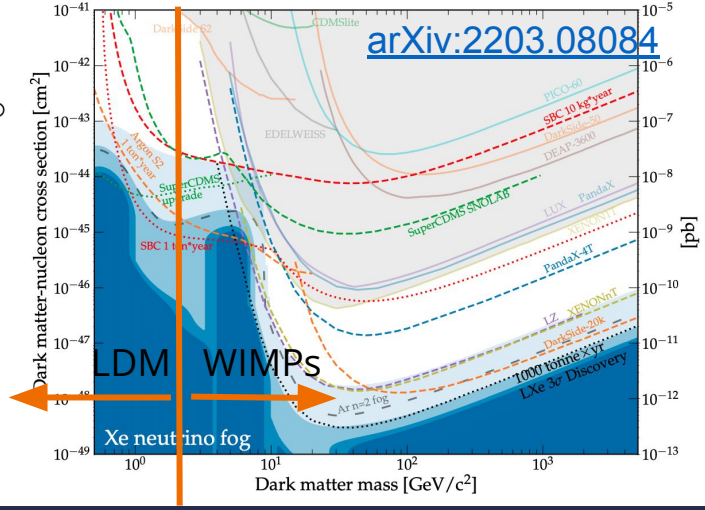
Any proposed mechanism must yield ≤ 85% DM!

A Thermal Relic - WIMPs and LDM



- WIMPs are popular, but accessible parameter space is running out of room
- Increasing interest in expanding the thermal DM search to “Light” DM (LDM) in the MeV-GeV mass range
- LDM requires non-SM “portal” interaction due to the Lee-Weinberg Bound

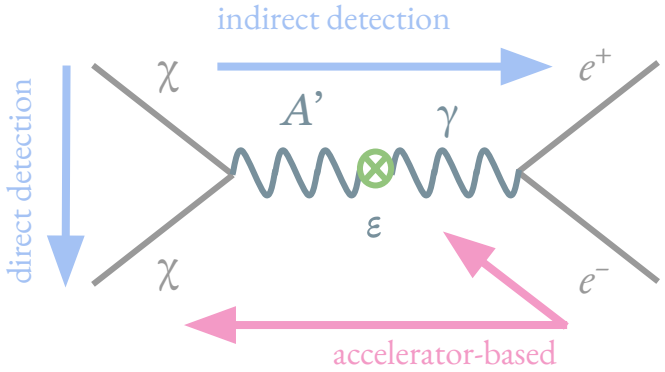




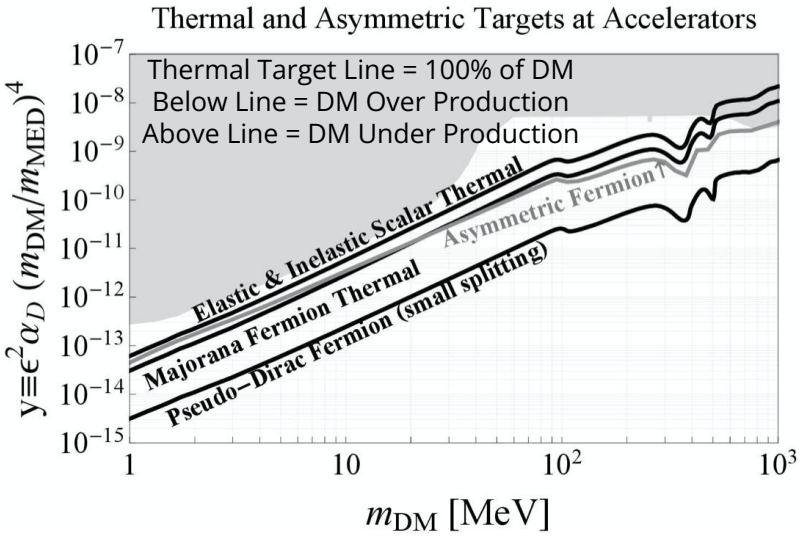
Matt Solt

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



A Brief History of Heavy (Dark) Photons

- An additional U(1) symmetry proposed by B. Holdom 1985

  Phys. Lett., B166:196–198

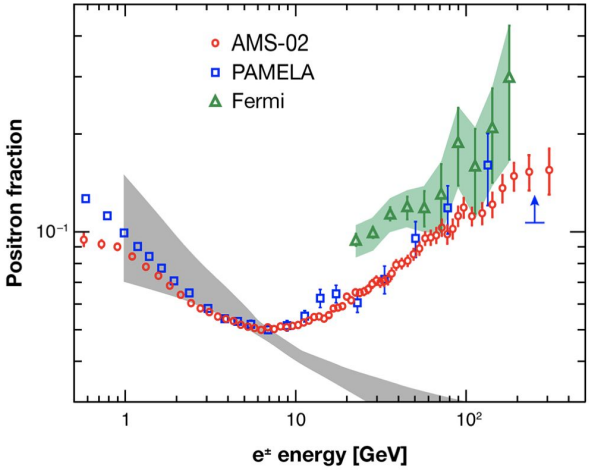
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \epsilon_Y F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

Kinetic mixing term → A′ mixes with SM photon → **Effective coupling to electric charge**

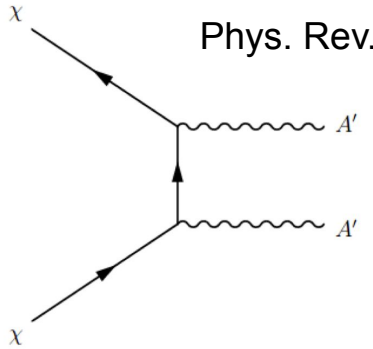
A Brief History of Heavy (Dark) Photons

- An additional U(1) symmetry proposed by B. Holdom 1985
- PAMELA measures **positron fraction excess** in 2009. This is explained by N. Arkani-Hamed et. al. as DM annihilation through an A′

Nature, 458:607–609



Phys. Rev., D79:015014

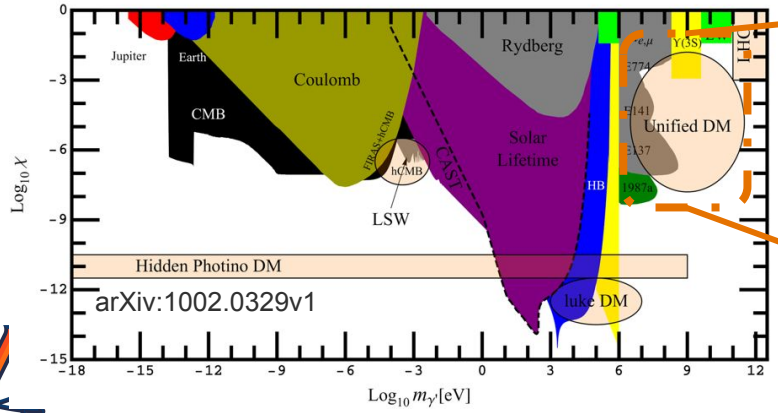


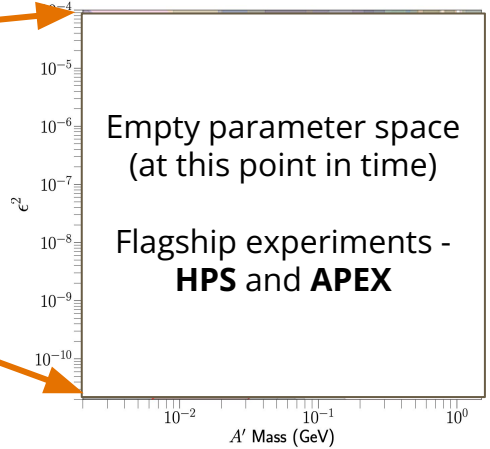
DM explanation of positron excess has since been disfavored by AMS (most likely explanation is a pulsar origin)

A Brief History of Heavy (Dark) Photons

- An additional U(1) symmetry proposed by B. Holdom 1985
- PAMELA measures **positron fraction excess** in 2009. This is explained by N. Arkani-Hamed et. al. as DM annihilation through an A’
- Bjorken, Essig, Schuster, Toro (B.E.S.T.) proposed several **fixed target** techniques to probe the A’ parameter space motivated by DM

Phys. Rev., D80:075018

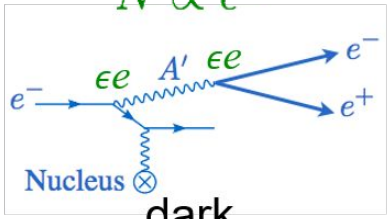




Types of Experiments Searching for Dark Photons

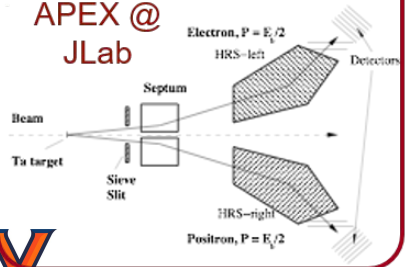
e^- fixed target

$N \propto \epsilon^2$



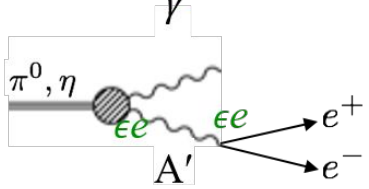
dark bremsstrahlung

APEX @ JLab

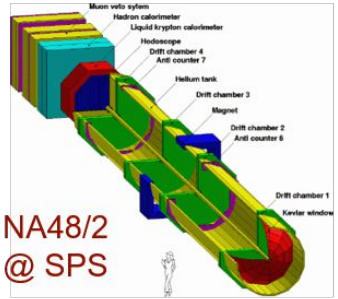


p fixed target

$N \propto \epsilon^2$

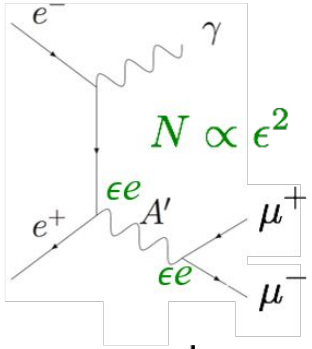


meson decays

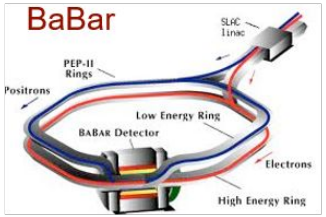


NA48/2 @ SPS

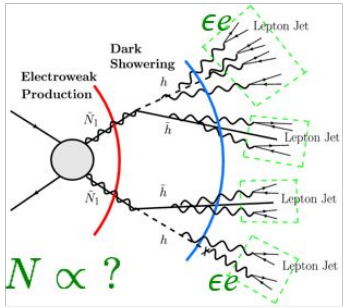
e^+e^- colliders



+ meson decays

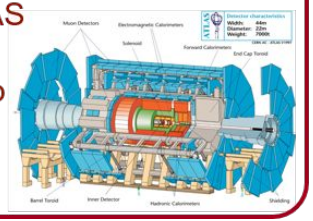


pp collider



"lepton jets"
+ meson decays

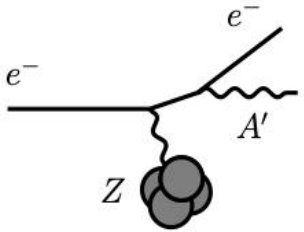
ATLAS
CMS
LHCb

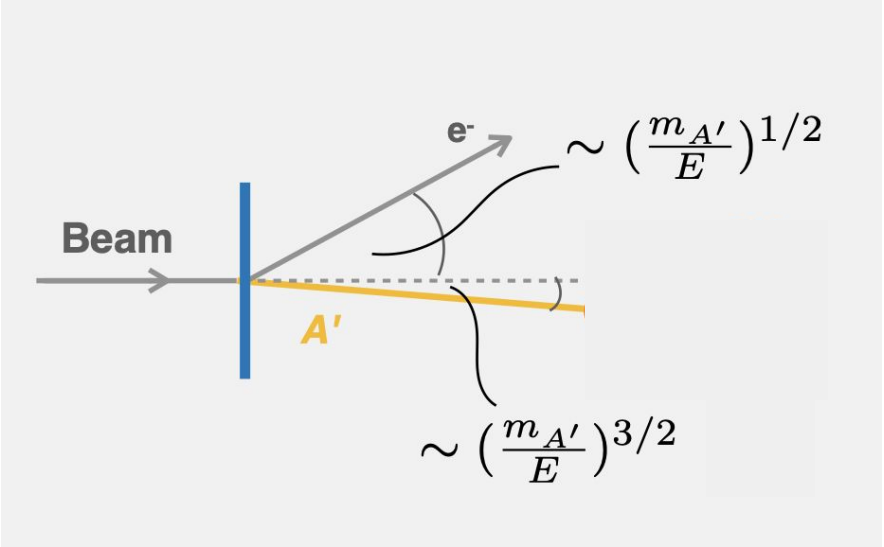


Anytime you can produce a photon, you can produce a dark photon

Dark Photon Production with a Fixed Target

- 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

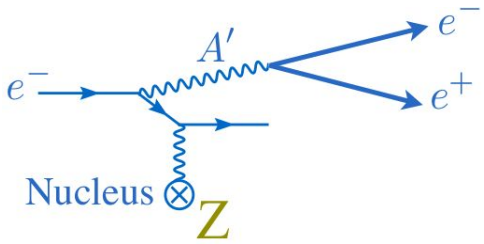


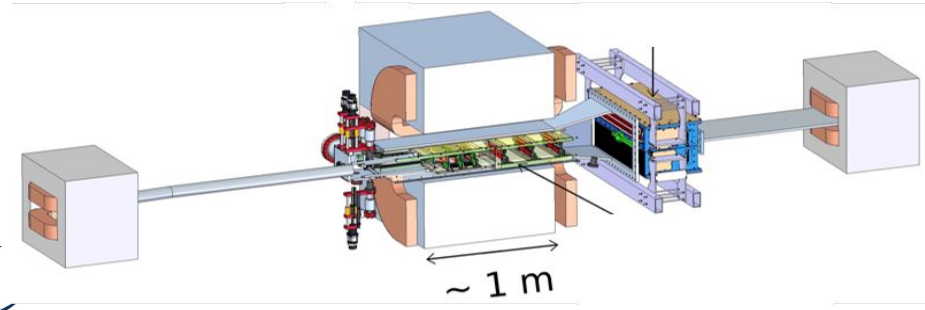


Dark Photon Decays - Complimentary Searches

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

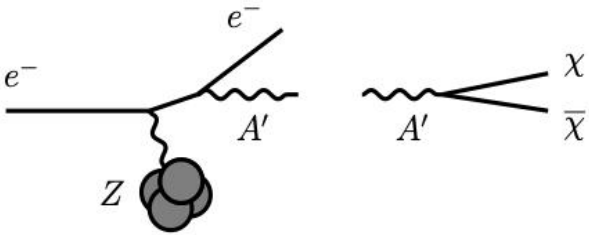
Heavy Photon Search (HPS) at Jefferson Lab

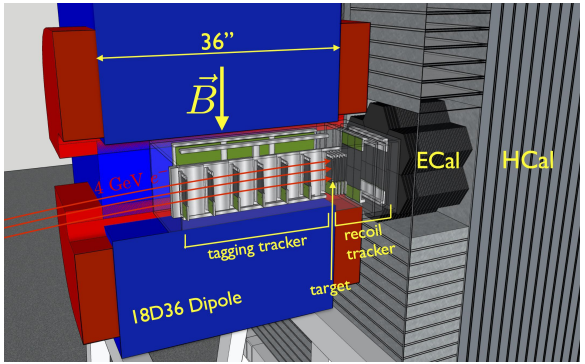




$$2m_{DM} < m_{A'}$$

Light Dark Matter eXperiment (LDMX) at SLAC





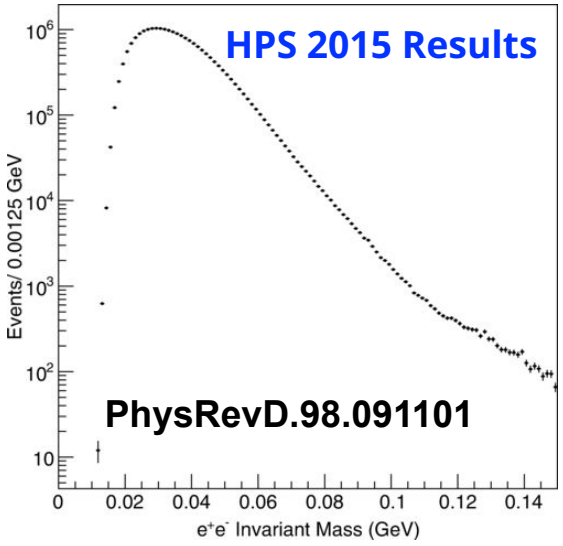
HPS Current Data and Status

- Results from 2015 resonance search are published
- Resonance search and **displaced vertex search** for 2016 are expected to publish soon. This is the focus of this seminar.

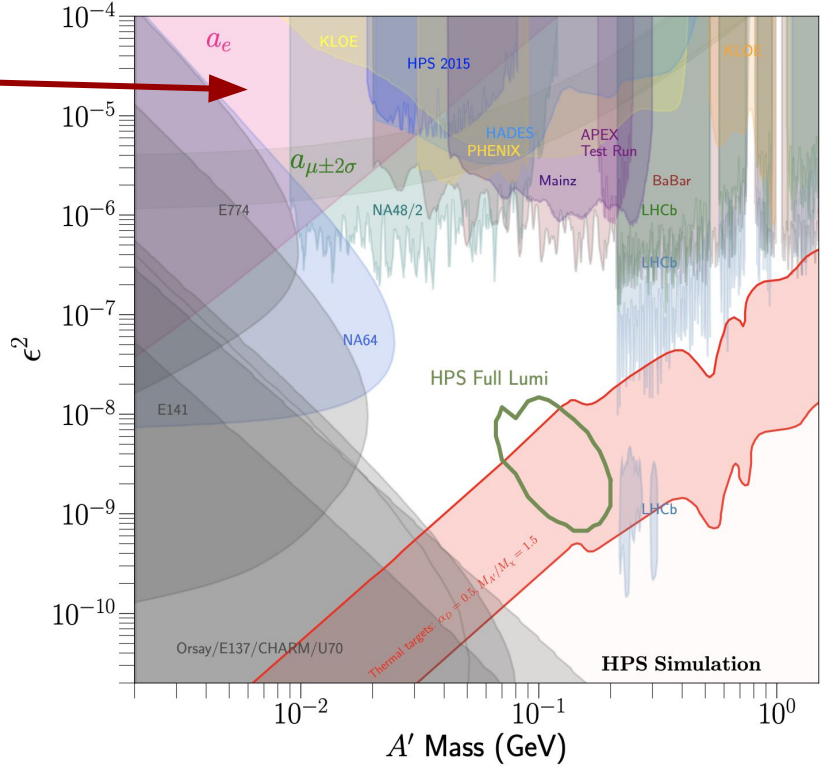
Data Run	Beam Energy (GeV)	Beam Current (nA)	Beam Time
2015 Engineering Run	1.05	50	1.7 Days
2016 Engineering Run	2.3	200	5.4 Days
2019 Physics Run (Upgraded)	4.55	~150	~4 Weeks
2021 Physics Run (Upgraded)	3.7	~120	~4 Weeks

Existing Dark Photon Constraints for Visible Decays

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



Prompt QED Tridents

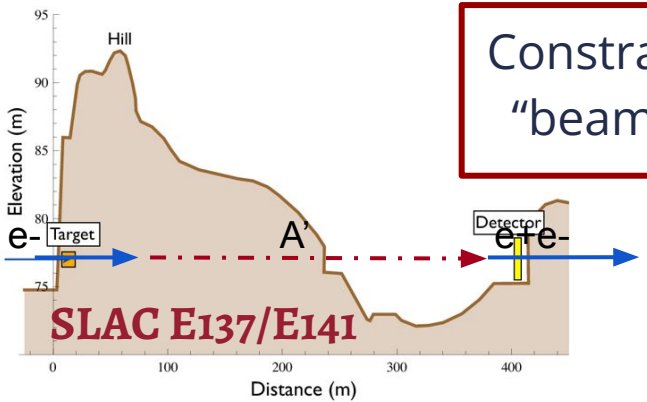


Existing Dark Photon Constraints for Visible Decays

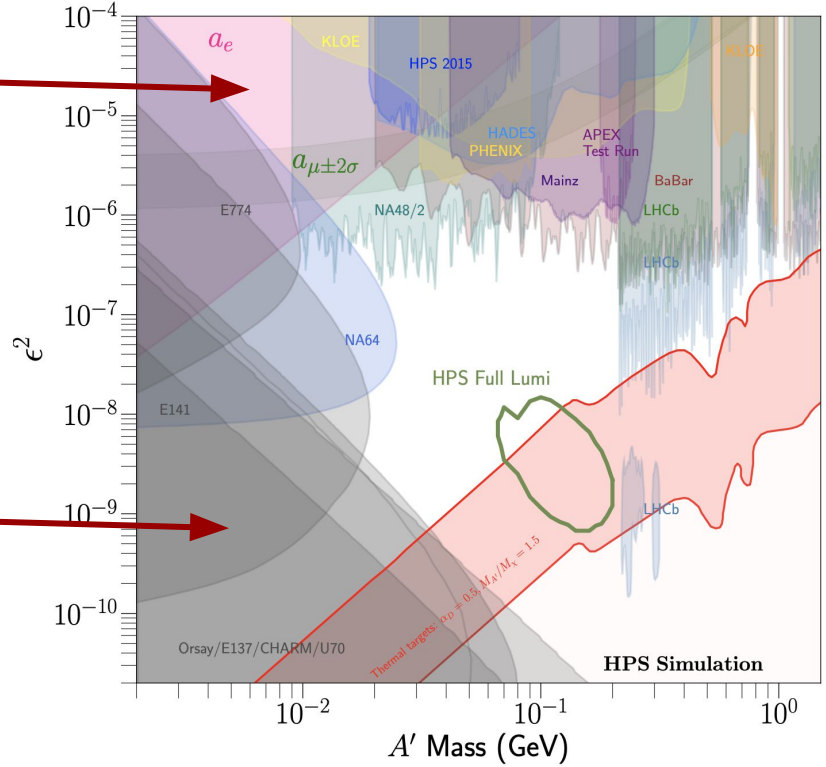
Large coupling searches are generally **"bump hunts"** for $m(l^+l^-)$ resonances

A's with small coupling are **long-lived**

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



Constraints from "beam dumps"

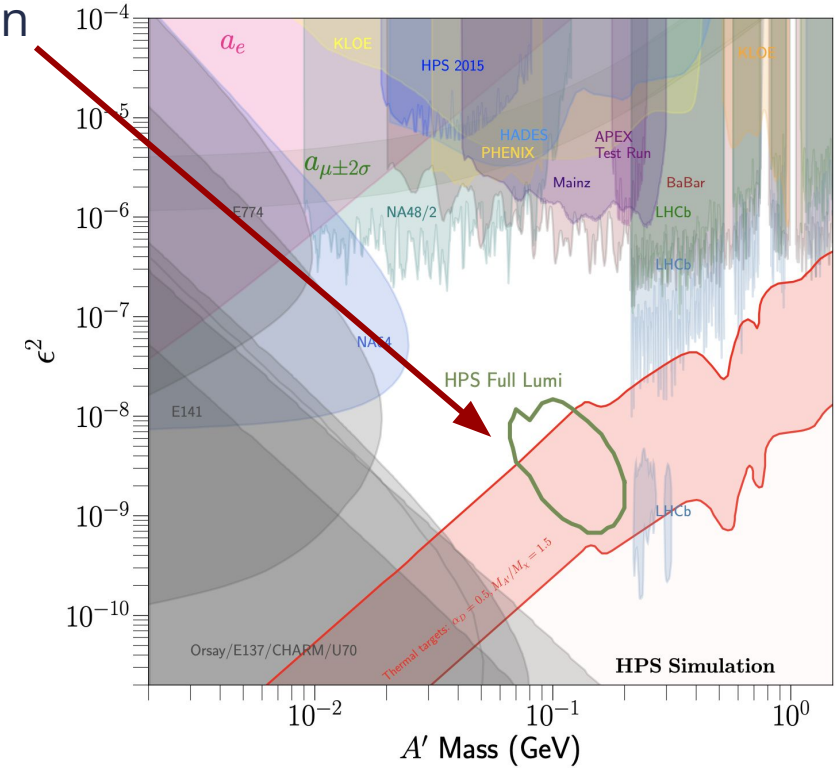


Dark Photon Visible Parameter Space

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

- Highly motivated, yet unprobed region of parameter space
  - Small production cross-section
  - Short, but finite lifetime

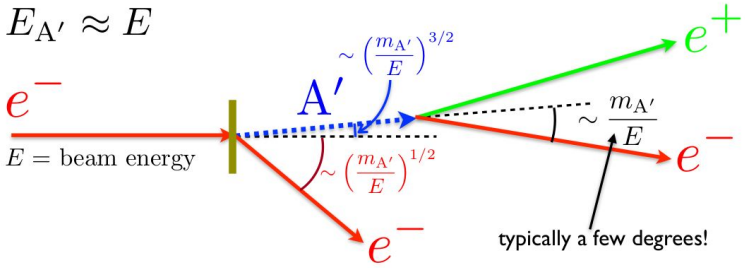
$$c\tau \propto \frac{1}{\epsilon^2 m_{A'}}$$

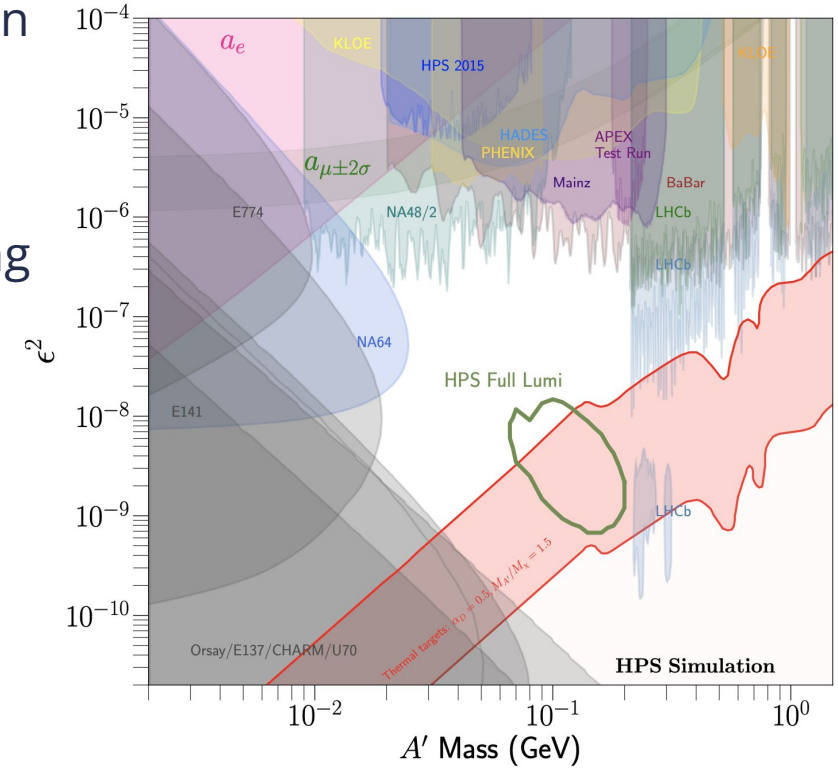


Dark Photon Visible Parameter Space

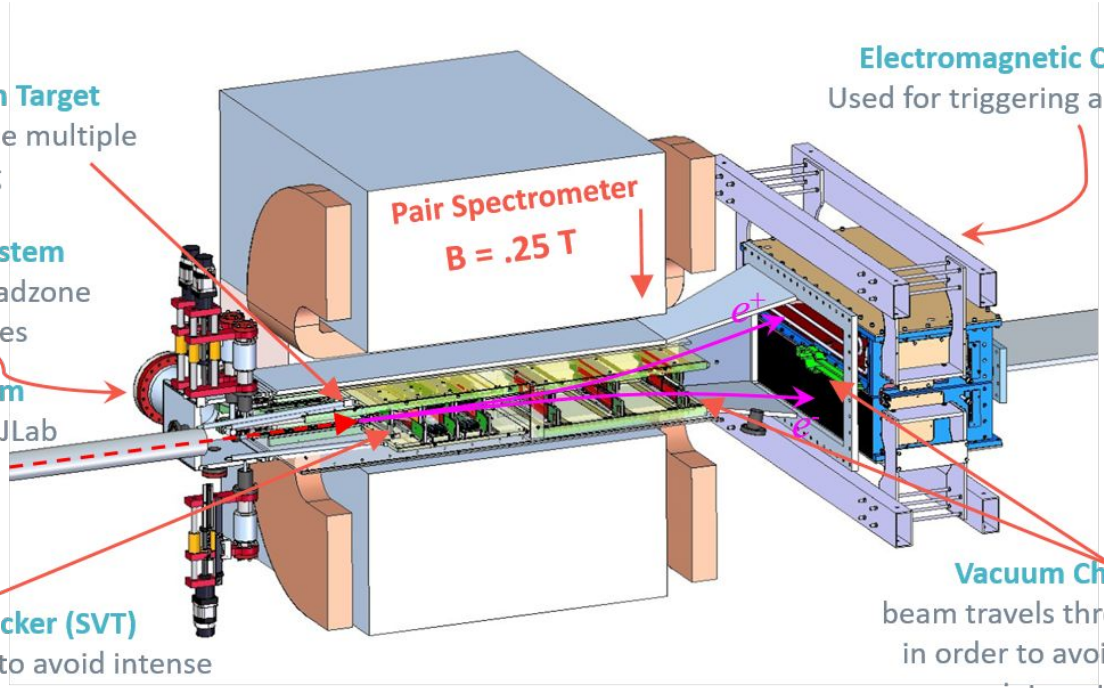
$$2m_e < m_{A'} < 2m_{DM}$$

- Highly motivated, yet unprobed region of parameter space
  - Small production cross-section
  - Short, but finite lifetime
- HPS - a fixed target precision vertexing experiment. Challenges:
  - Large prompt QED backgrounds
  - A′ kinematics require sensitive detector components to be 0.5 mm from the beam





HPS Apparatus



~10^{-3} X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

High intesity e^- beam
Courtesy of CEBAF @ JLab

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Measures momentum and vertex precisely.

Electromagnetic Calorimeter
Used for triggering and particle ID

Vacuum Chambers
beam travels through vacuum in order to avoid beam-gas interactions

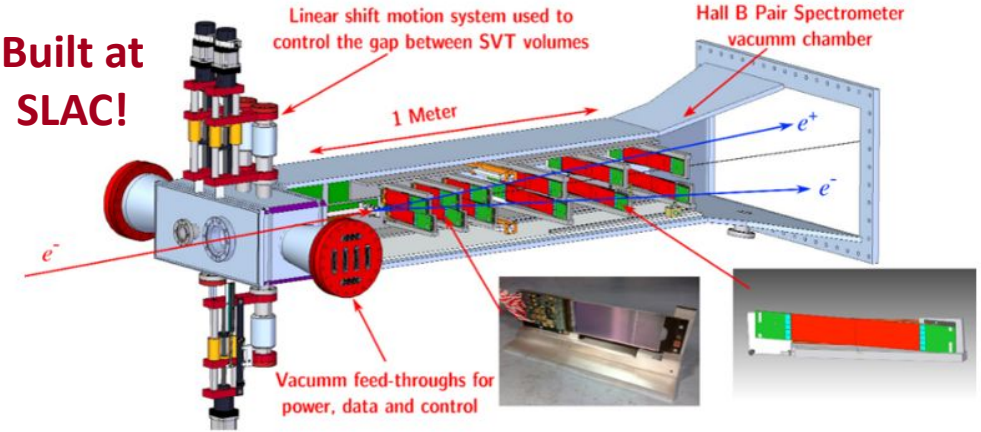
SVT + ECal DAQ capable of 50 kHz

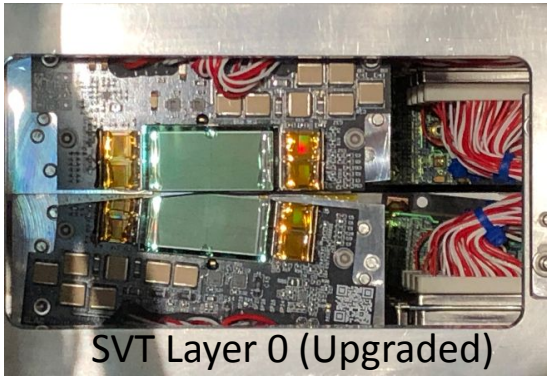
Installed within the Hall B alcove at Jefferson Lab downstream of the CLAS12 detector

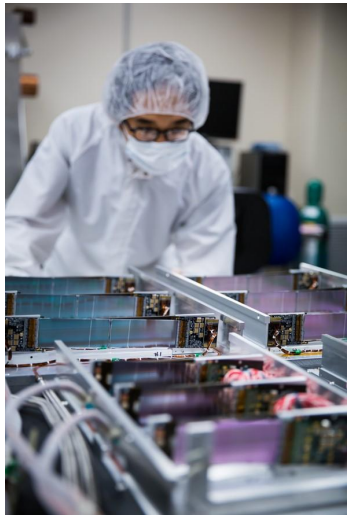
HPS Silicon Vertex Tracker

- 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!

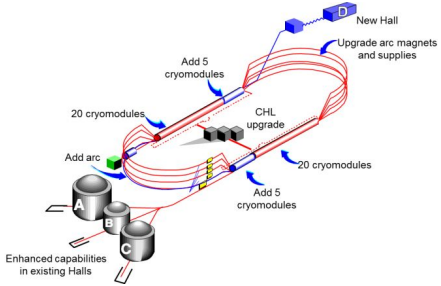


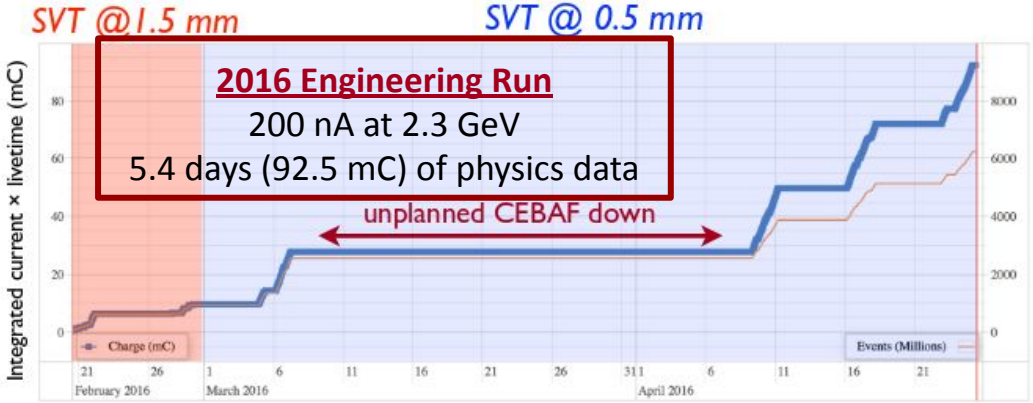

SVT Layer 0 (Upgraded)

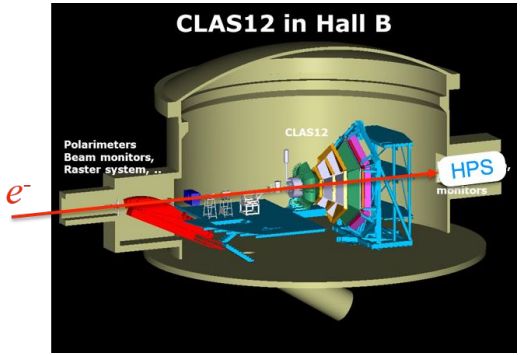


Jefferson Lab and CEBAF

- 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})

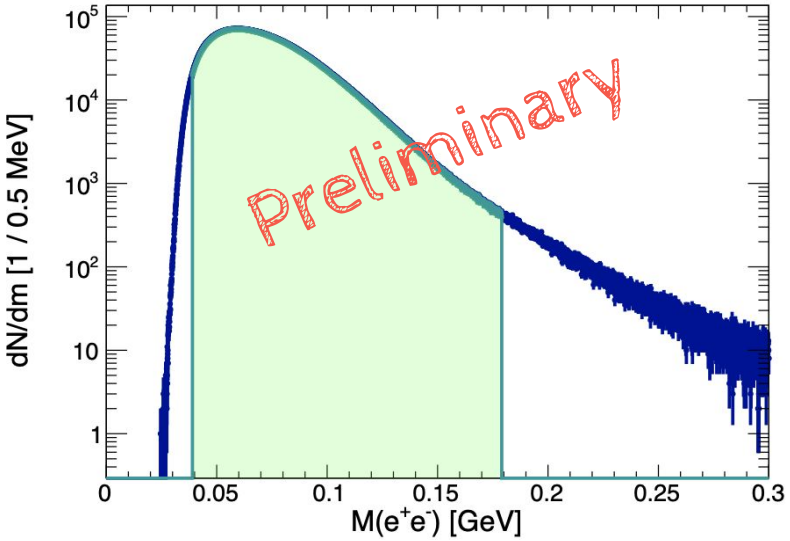




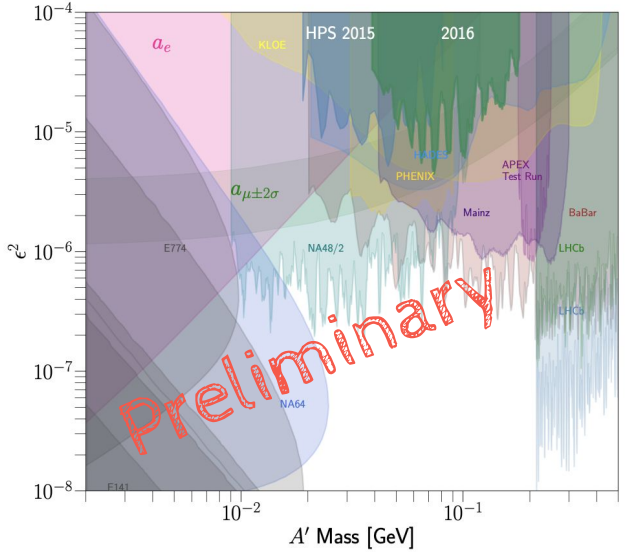


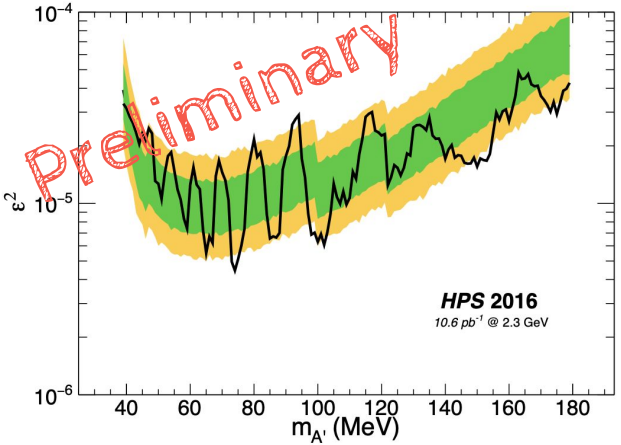
2016 Resonance Search Results

arXiv:2212.10629v2



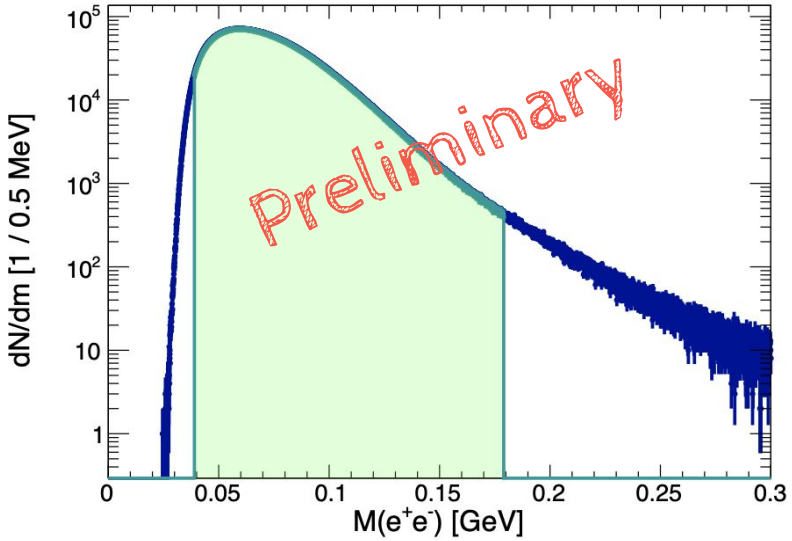
What are these e+e- backgrounds?

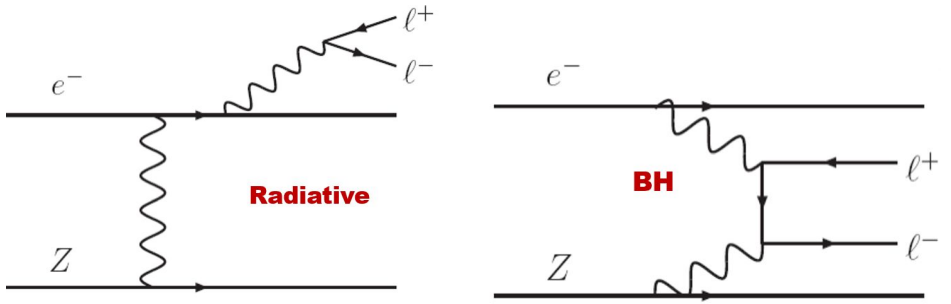




Prompt Trident Backgrounds

arXiv:2212.10629v2

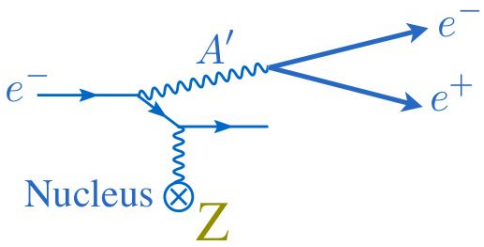


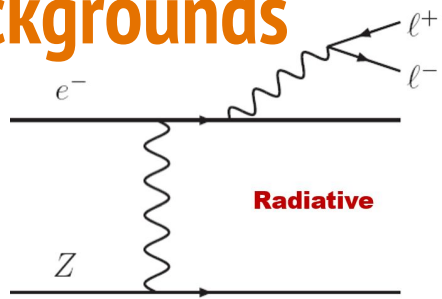


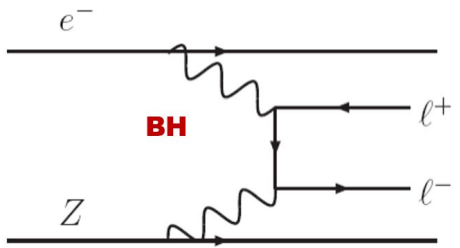
Challenge: Distinguishing the prompt QED tridents from displaced signal
~1 signal for ~10^6 prompt background

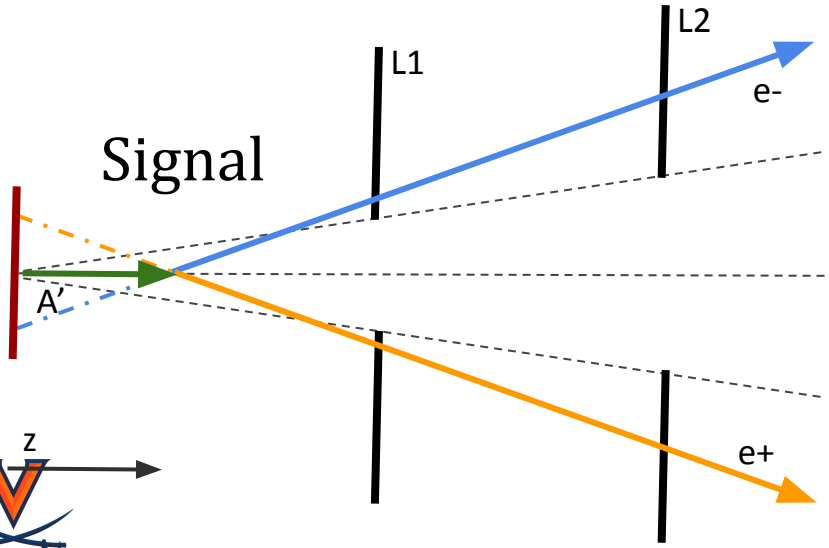
What are these e+e- backgrounds?
Prompt QED tridents - Radiative and Bethe-Heitler (BH)

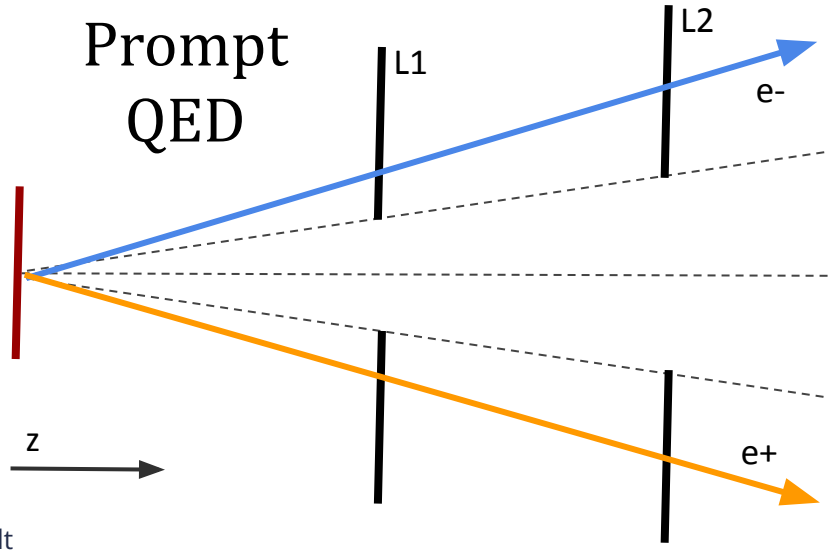
Signal vs Prompt Trident Backgrounds





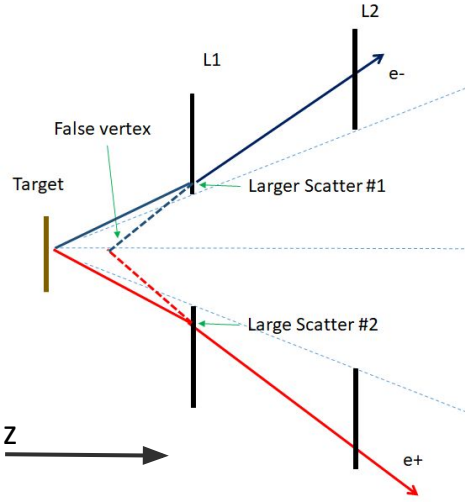


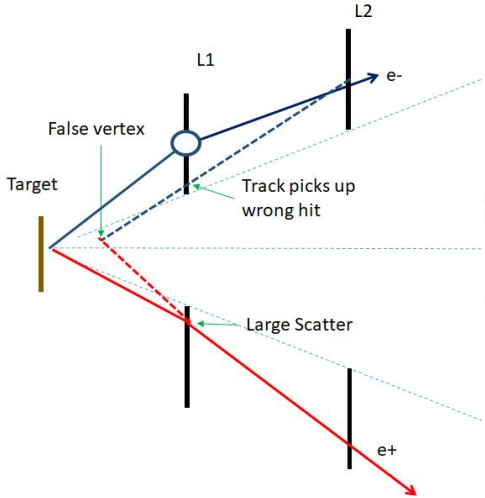


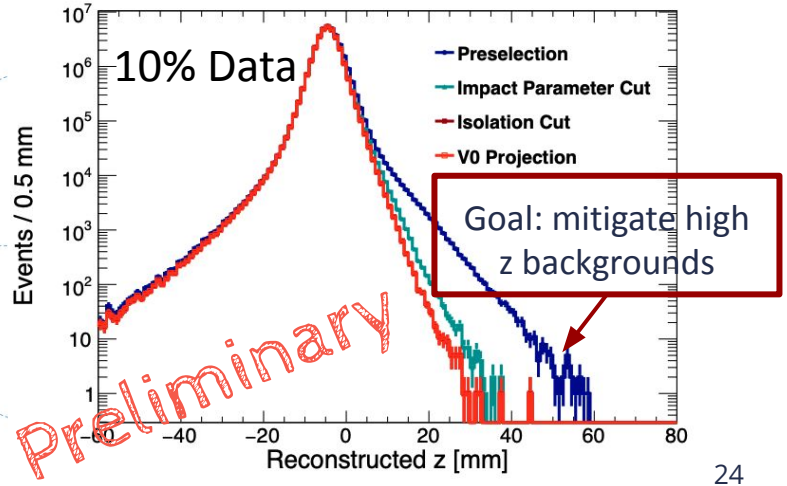


Displaced Vertex Search Event Selection

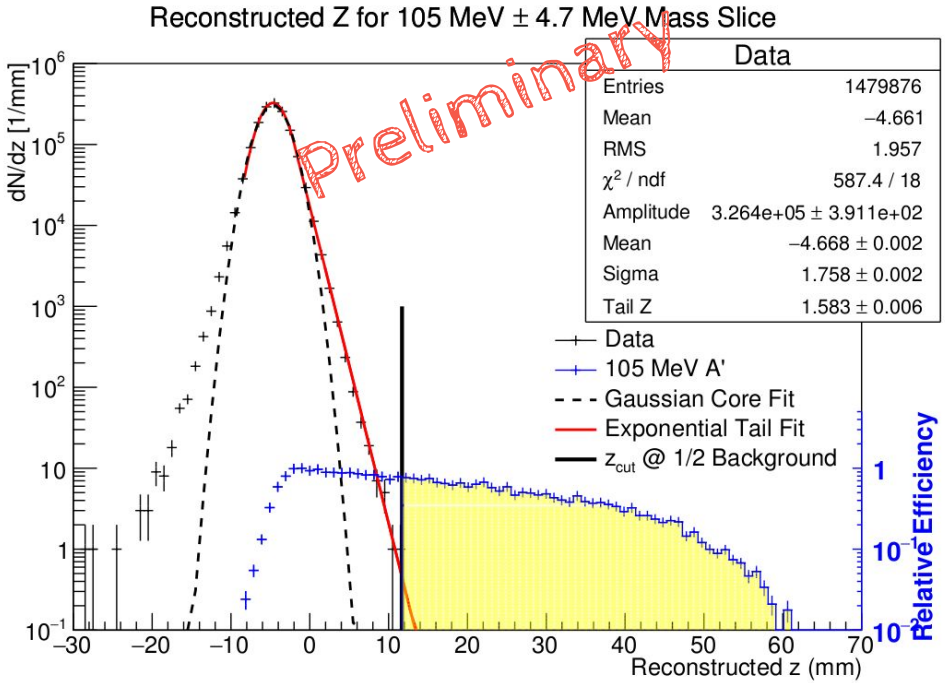
- Displaced vertex search is blinded with the selection tuned on 10% data
- Two main backgrounds from prompt trident processes: large Coulomb scatters in layer 1 of the tracker and mis-tracking
  - Require strict selections on track quality and vertex quality & require layer 1 hits





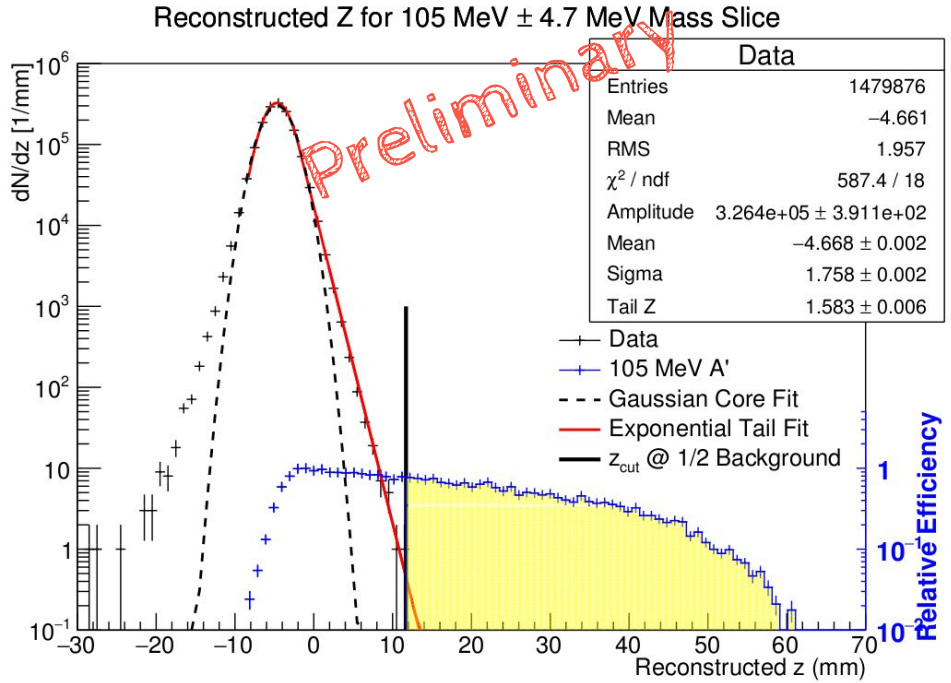


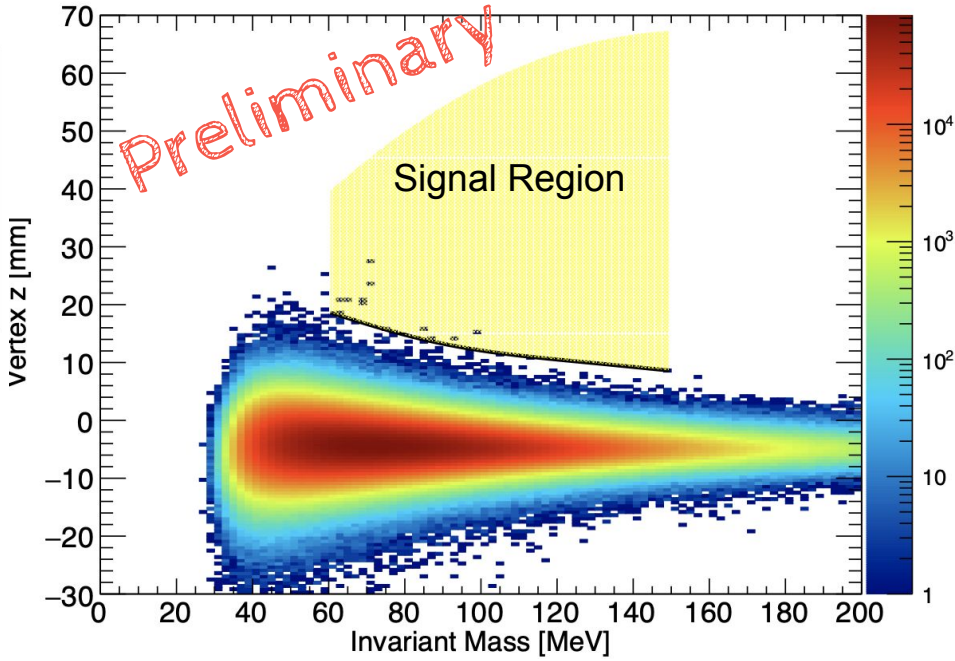
Displaced Vertex Search



- Define signal region (yellow): downstream of where the background model predicts 0.5 events (“z cut”)
- Goal: Can we achieve < 0.5 background events (per mass slice) in a blinded analysis?

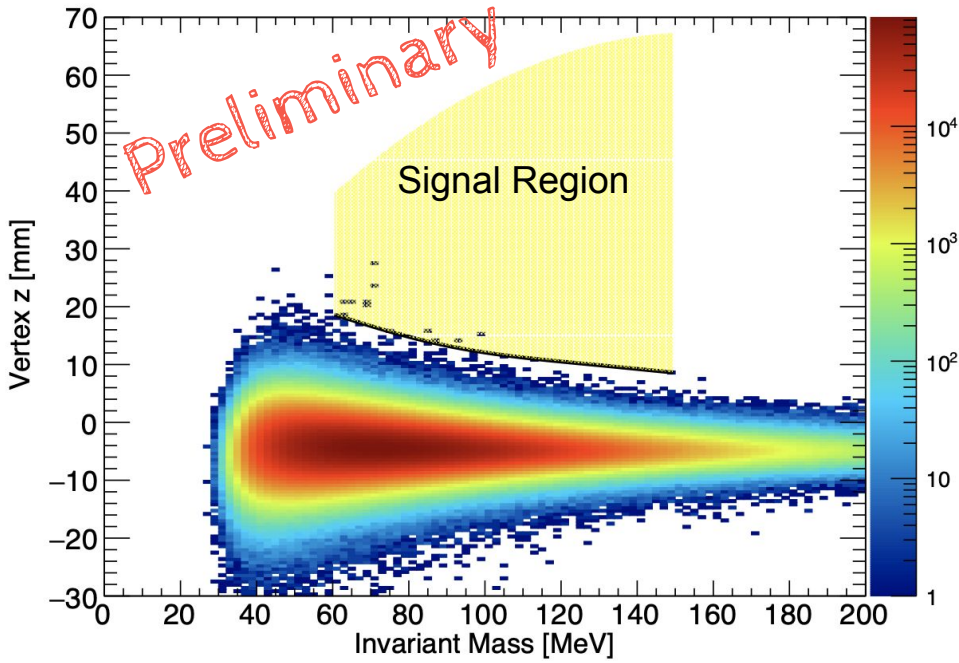
Displaced Vertex Search Unblinded





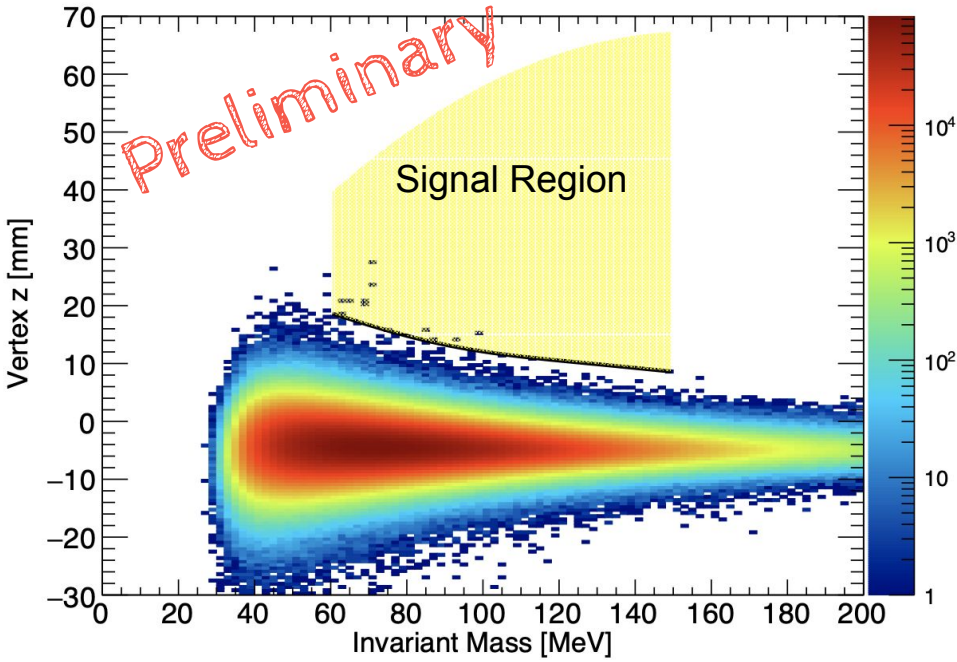
Displaced Vertex Search Unblinded

- How much signal do we expect?
  - ~0.5 events at maximum sensitivity, not enough for A’ exclusion at 90%



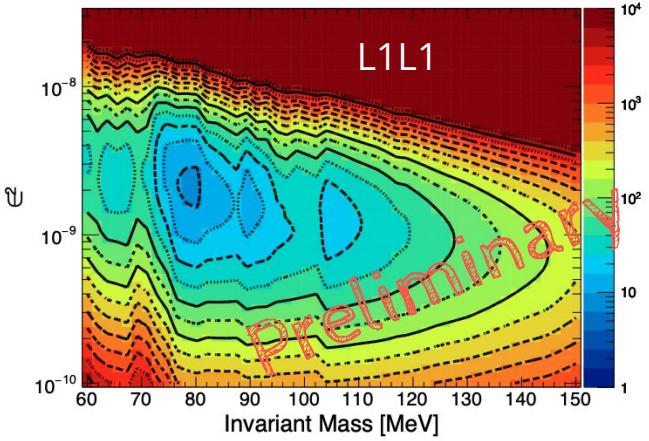
Displaced Vertex Search Backgrounds

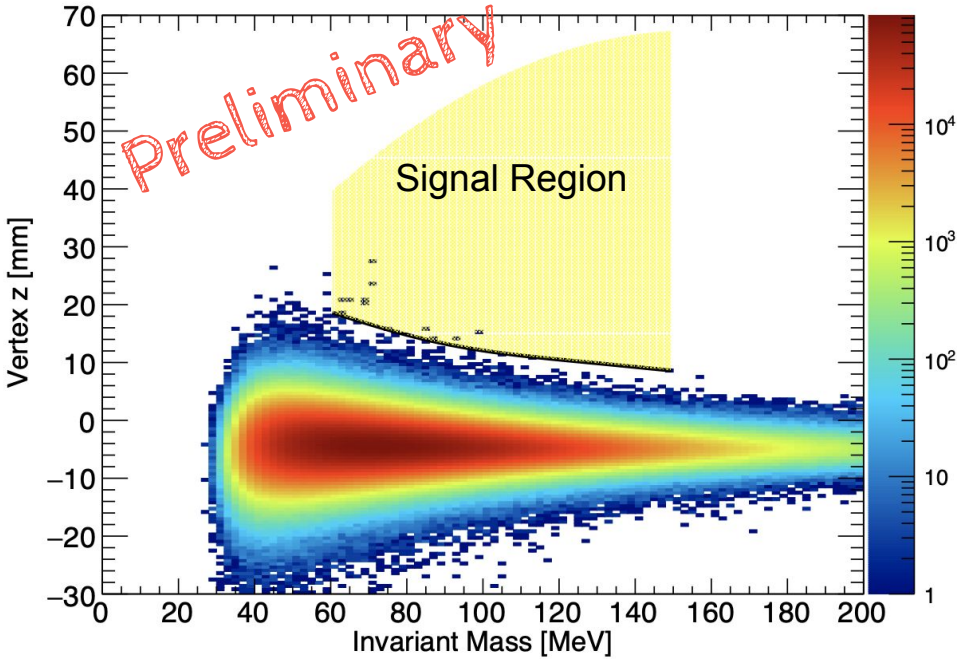
- How much signal do we expect?
  - ~0.5 events at maximum sensitivity, not enough for A’ exclusion at 90%
- Did we achieve the expected level of background necessary for a search?
  - **YES! A major accomplishment** (for mass greater than 70 MeV)
- What about mass less than 70 MeV?
  - This is currently under investigation, most likely a background



Displaced Vertex Search Unblinded

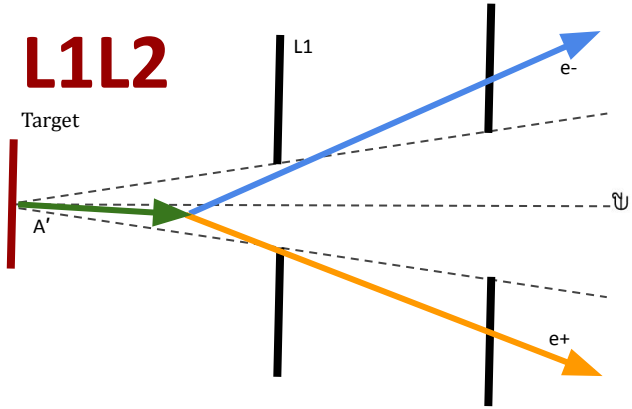
- Limits set via Optimum Interval Method
  - Not enough for A′ exclusion at 90%
  - Tightest existing constraints in this region of parameter space

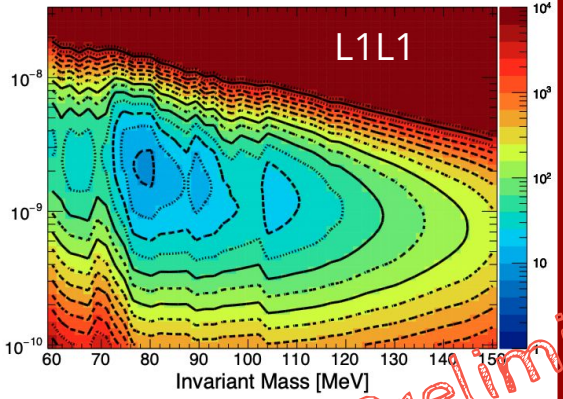


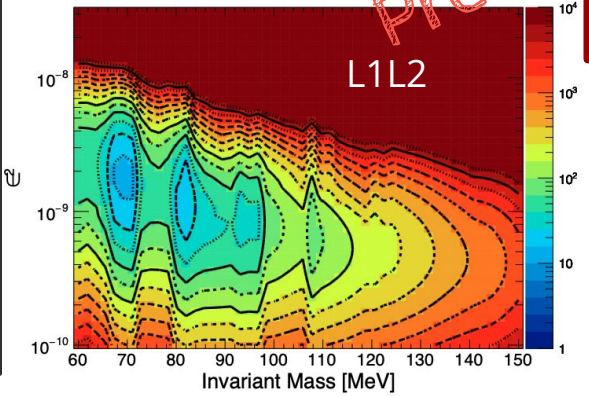


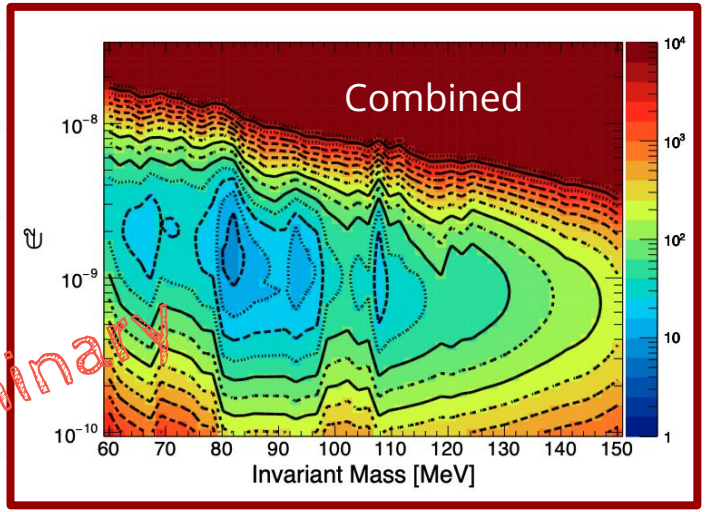
Displaced Vertex Search Final Results

arXiv:2212.10629v2







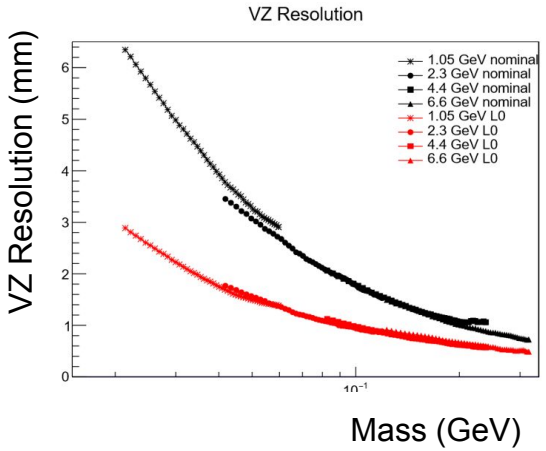


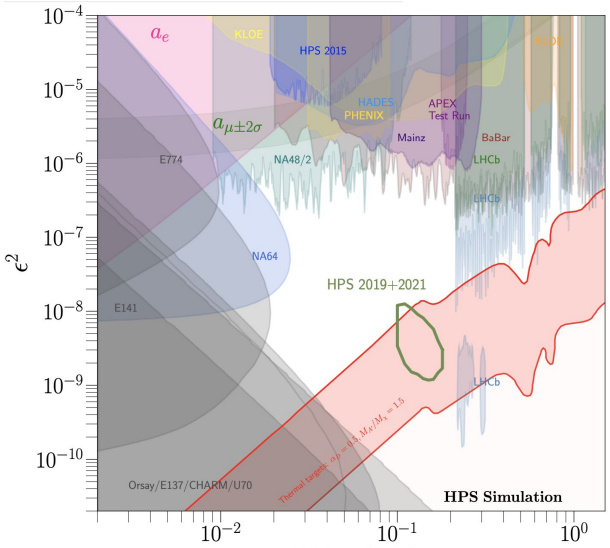
Repeat analysis procedure for the case in which one of the A' daughters misses L1 of the SVT ("L1L2") . Combine results.

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
- 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



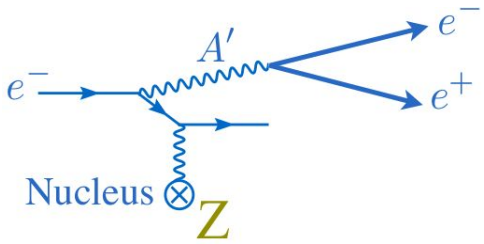


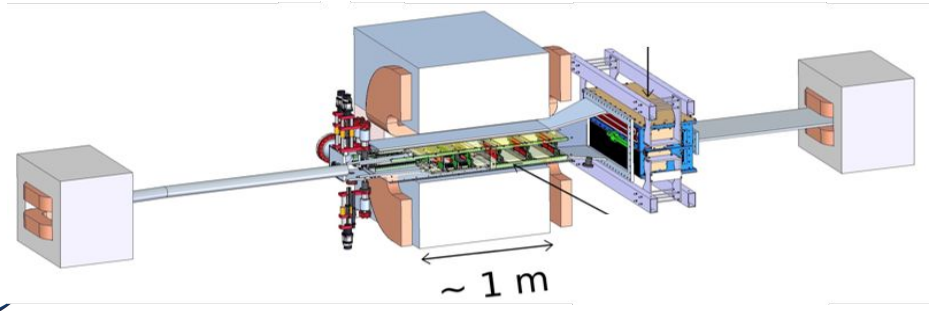
$$2m_e < m_{A'} < 2m_{DM}$$

Dark Photon Decays - Complimentary Searches

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

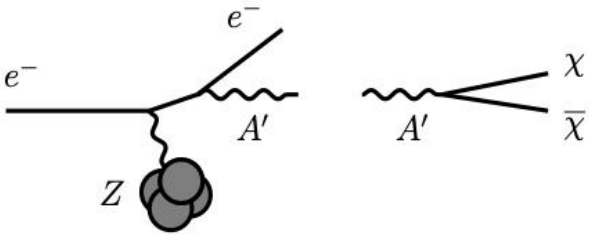
Heavy Photon Search (HPS) at Jefferson Lab

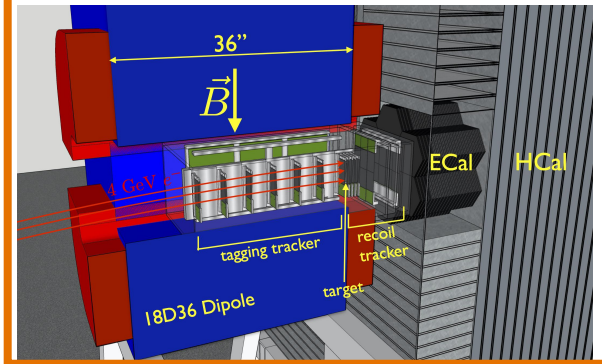




$$2m_{DM} < m_{A'}$$

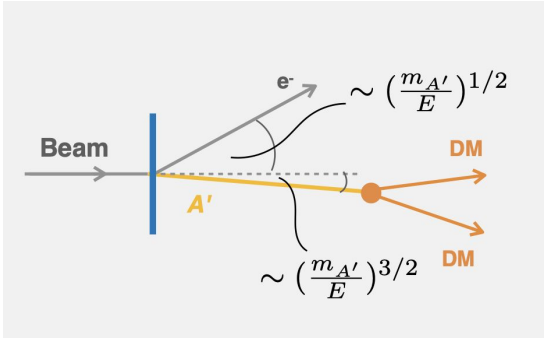
Light Dark Matter eXperiment (LDMX) at SLAC



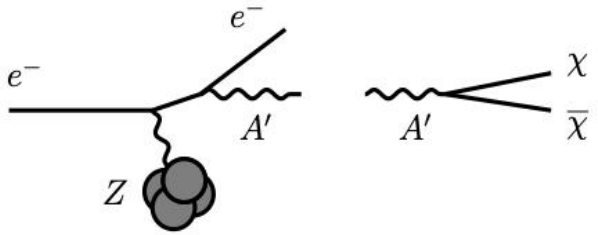


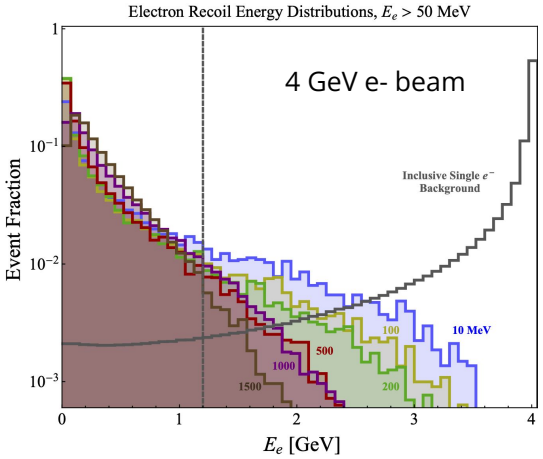
Matt Solt

LDMX



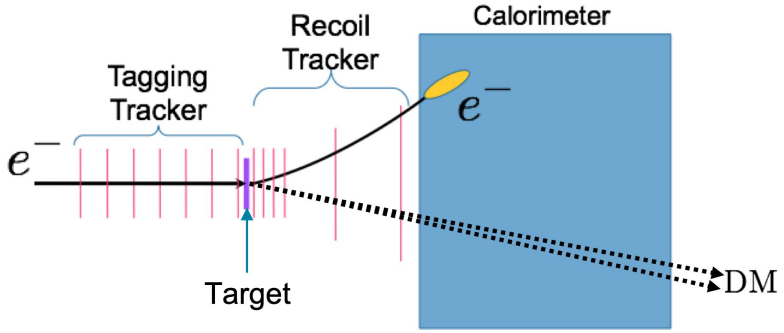
- Fixed Target Signal Characteristics:
  - Dark bremsstrahlung A’ production
  - A’s take most of the beam energy
  - Only visible final state particle is a soft recoil electron



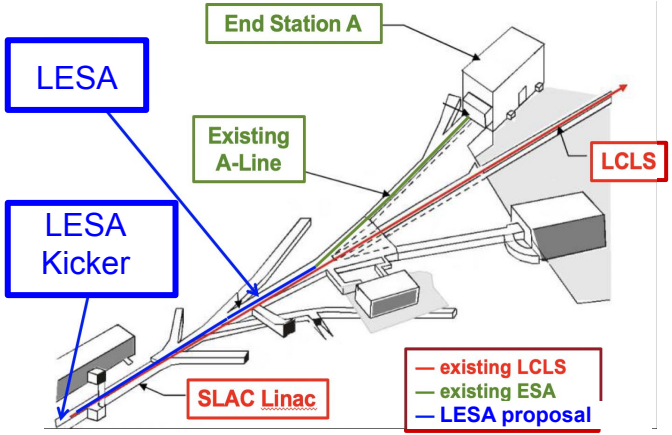


- Can probe this mechanism through a missing momentum search. We need…
  - High momentum resolution
  - High veto efficiency of Standard Model backgrounds

LDMX Concept



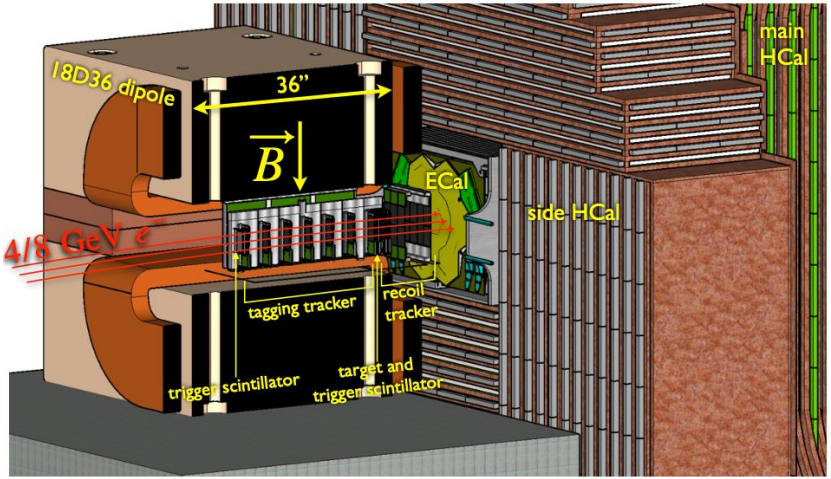
- Missing momentum and energy approach
  - DM production identified by missing energy/momentum in detector
  - Equipped for particle ID e/gamma
  - Recoil pT used as discriminator/identifier

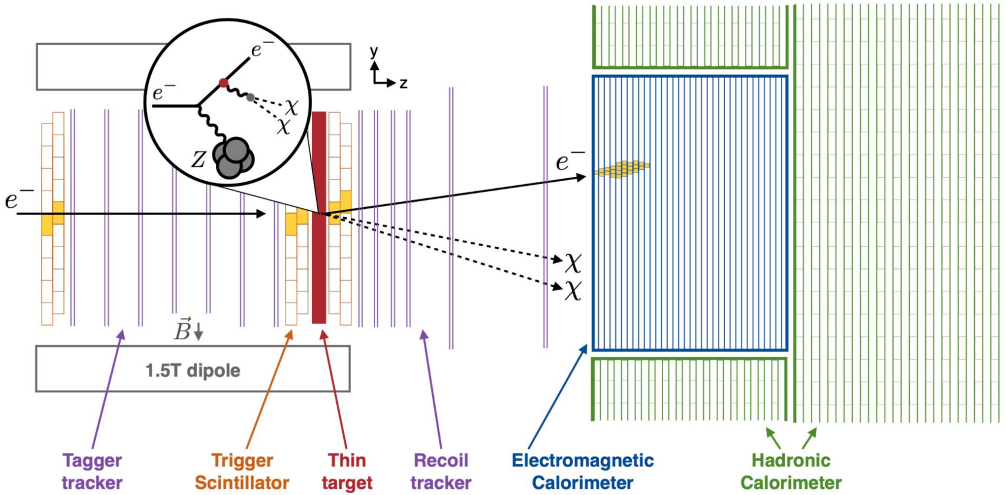


- 4 and 8 GeV e- beam provide by SLAC
  - Parasitically use the LCLS II beam with a dedicated transfer line (LESA)
  - Individual tagging and reconstruction of up to 1e16 electrons
  - Low current, high repetition rate 37 MHz, μ = 1

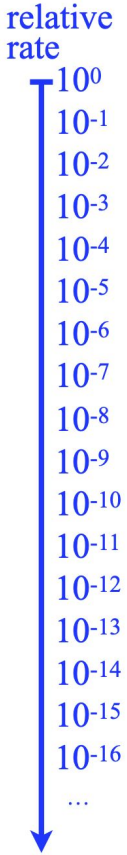
LDMX Design

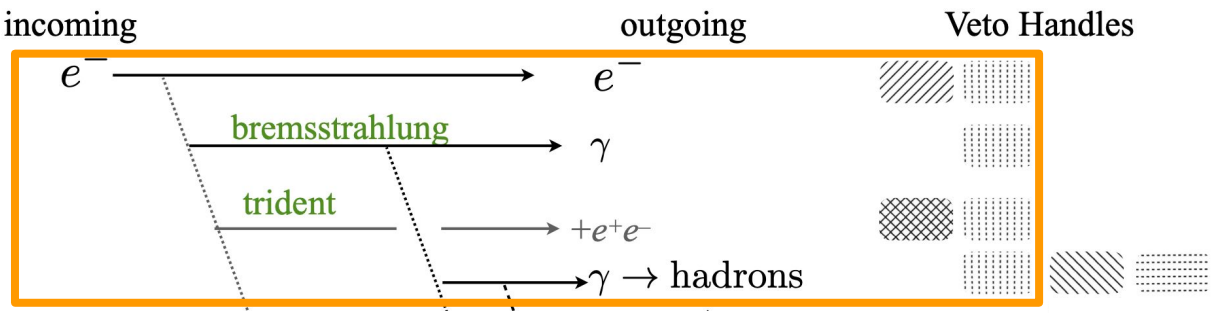
- Need hermetic detector designed for high rates and high radiation doses
  - **Tagging/recoil tracker**: fast with high momentum resolution and large acceptance (based on the HPS tracker design)
  - **Electromagnetic calorimeter**: fast, good energy resolution, and high granularity
  - **Hadronic calorimeter**: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

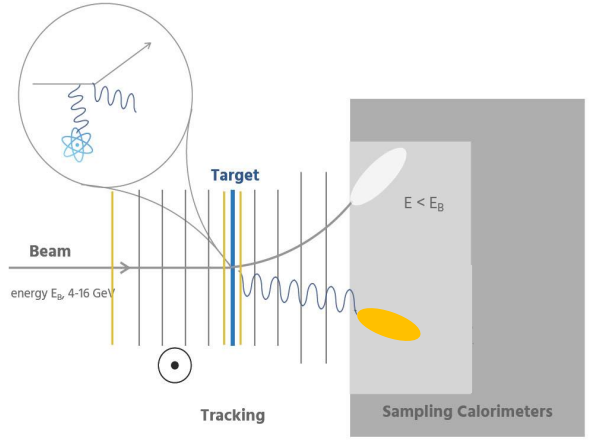


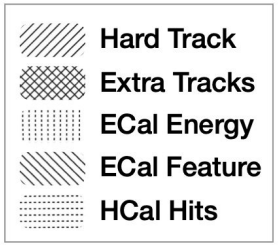


Backgrounds

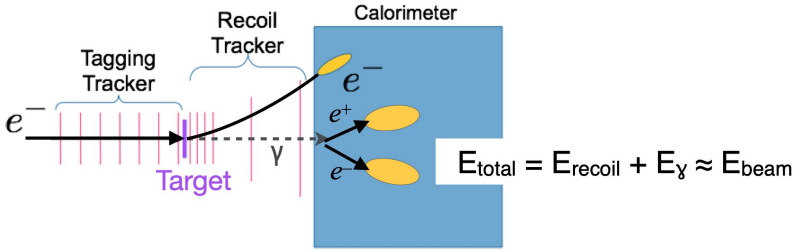




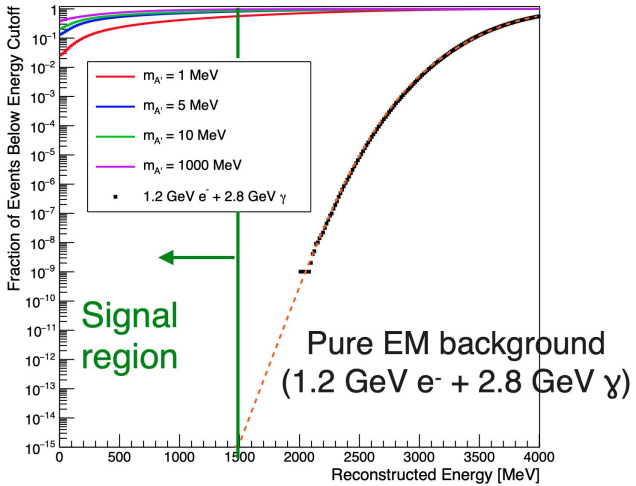


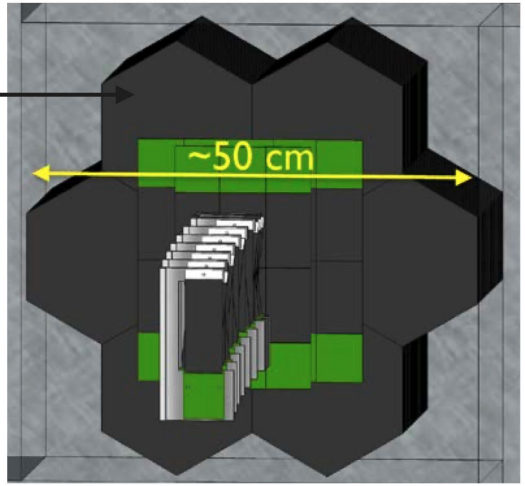


Electromagnetic Calorimeter

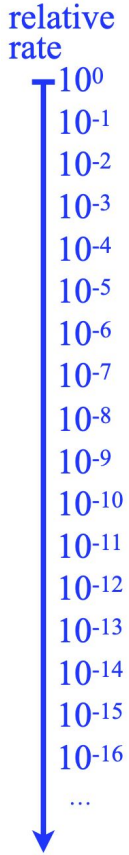


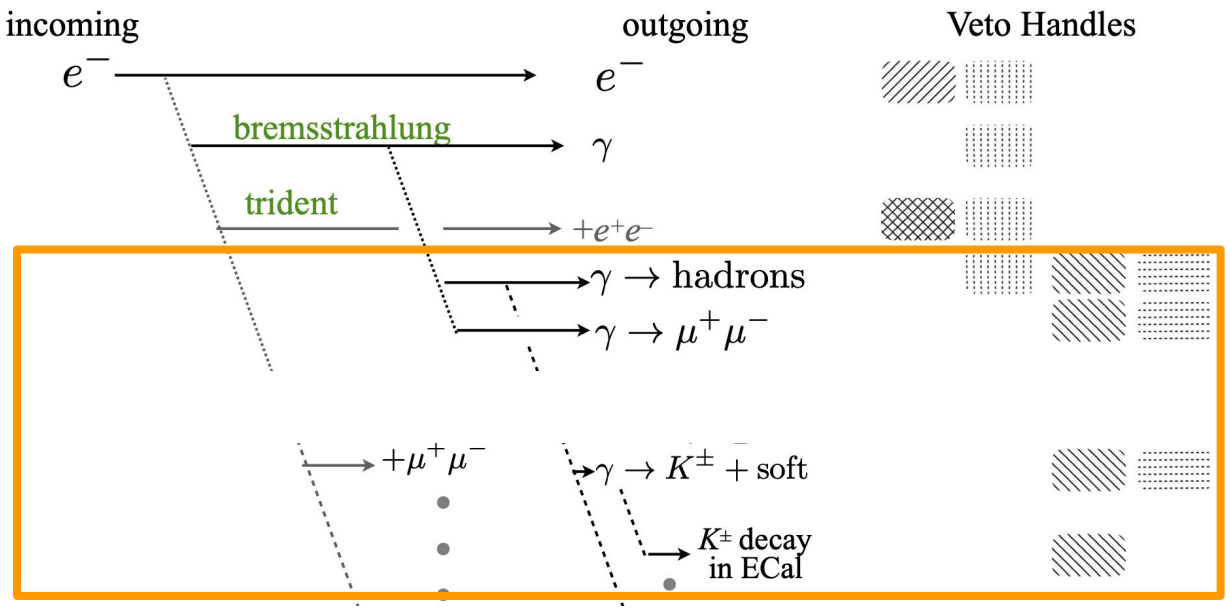
- 40 X0 Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - Provides fast missing energy trigger
  - Dense, radiation hard, full shower containment, and high granularity

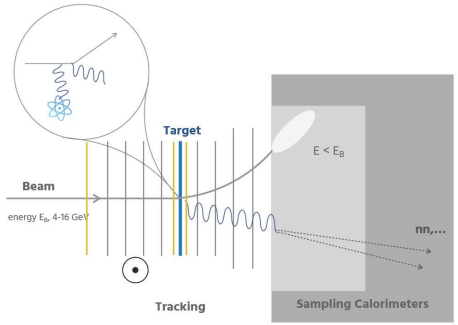


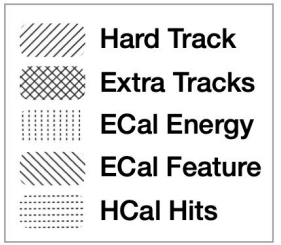


Backgrounds



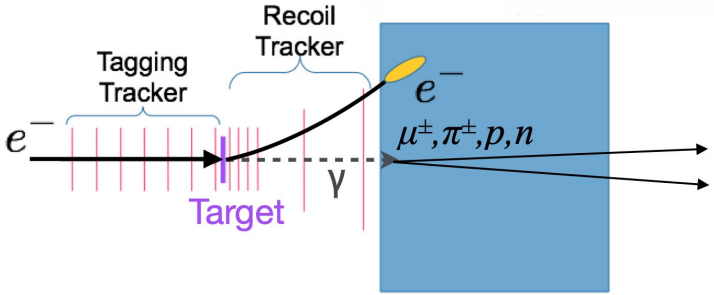


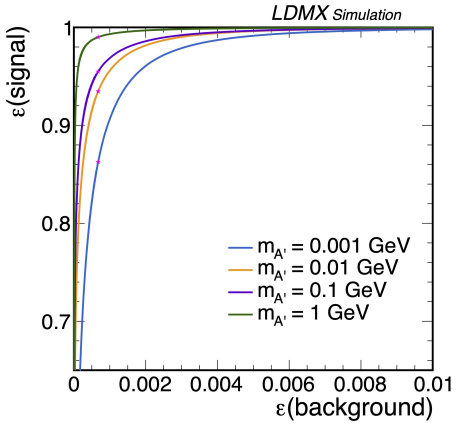




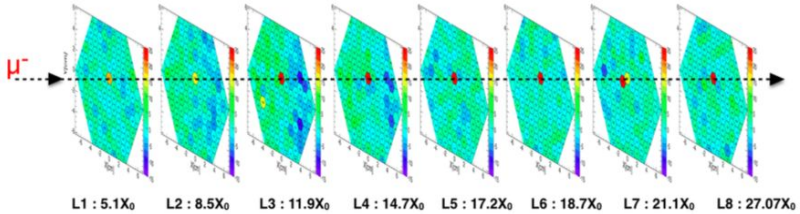
Ecal Veto

- 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

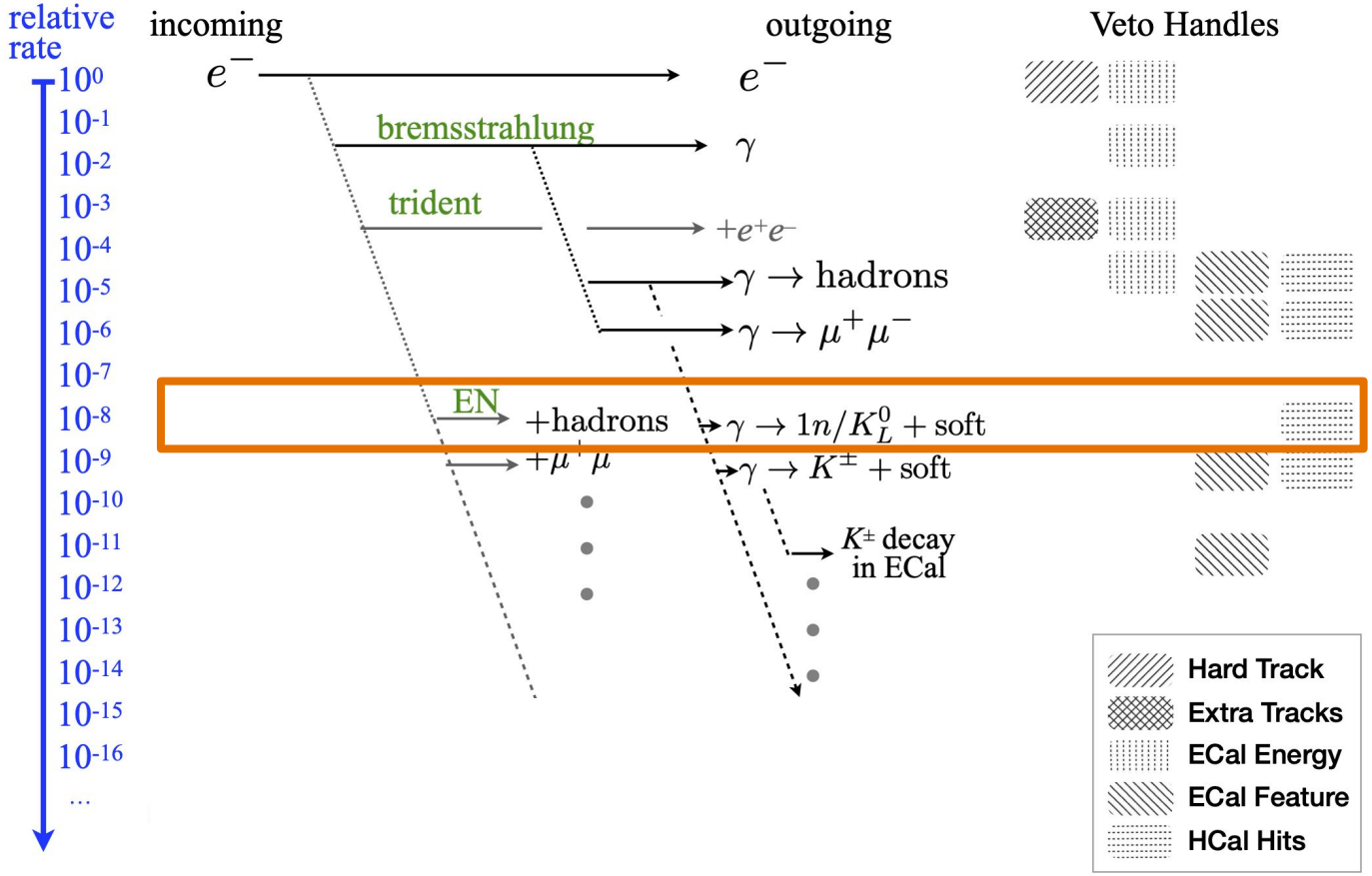




A.Martelli on behalf of CMS, arXiv:1708.08234

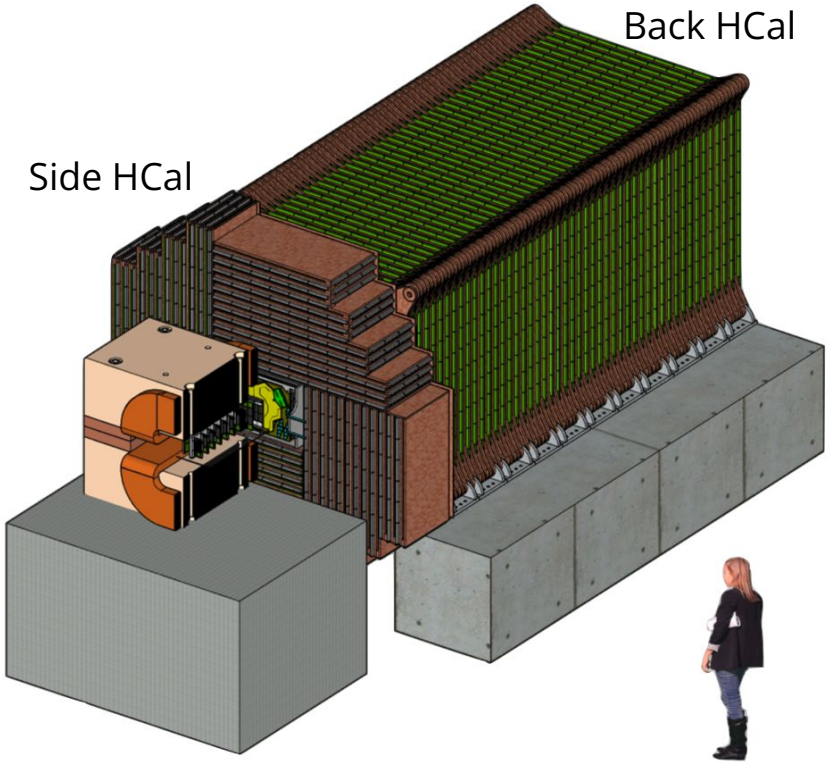


Backgrounds



Hadronic Calorimeter

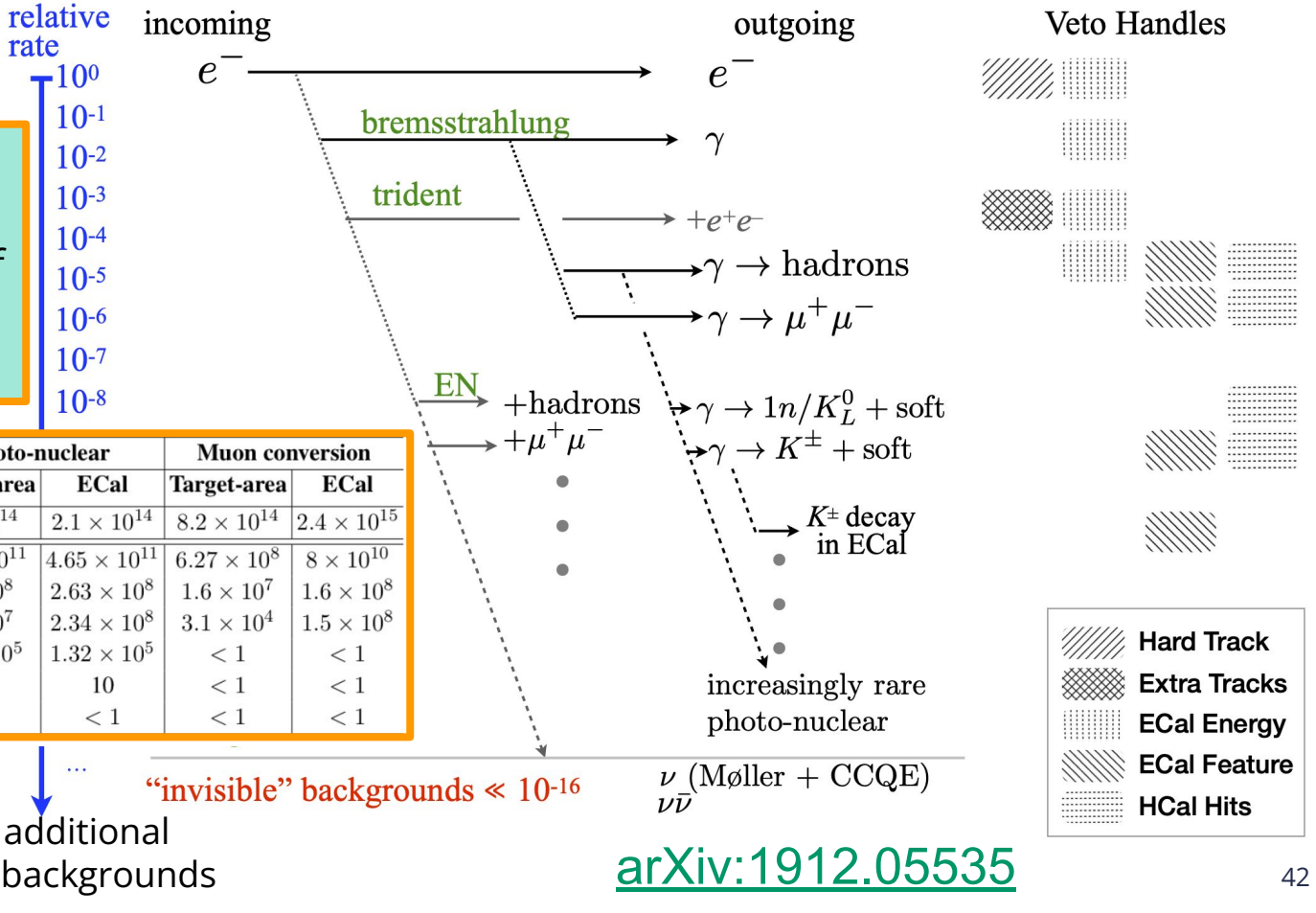
- Sampling calorimeter with segmented plastic/steel
  - Readout by wavelength shifting fibers and SiPMs (based on the Mu2e Cosmic Ray Veto design)
  - Highly efficient veto for PN processes that produce neutral hadrons. Desire 1e-6 rejection
  - Side HCal rejects wide angle bremsstrahlung and $\gamma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



Backgrounds

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

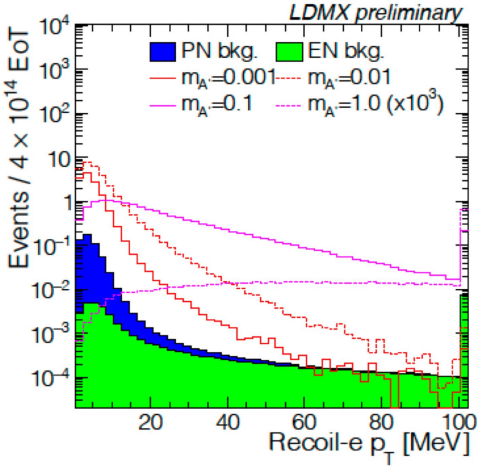


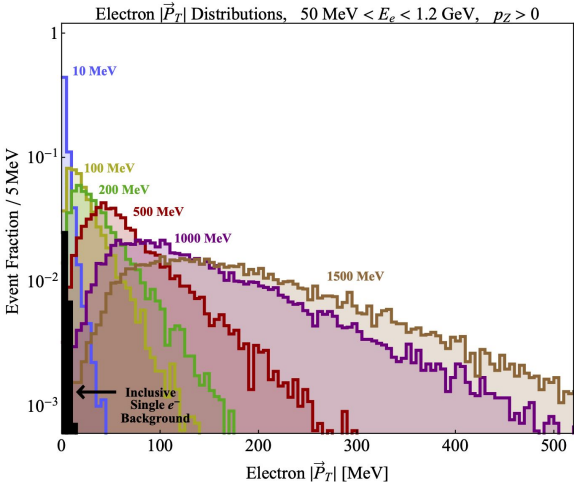
Recoil e- pT is an additional discriminator on backgrounds

arXiv:1912.05535

Signal Kinematics

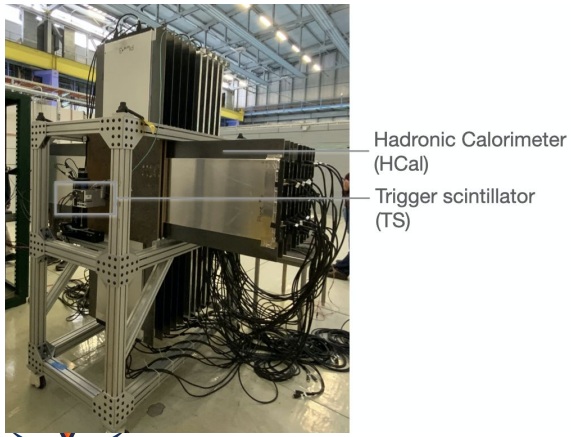
- Transverse momentum of recoil electron is the last veto handle
- Currently not used in veto efficiency estimates, but as a backup discriminator
- Transverse momentum can also be used to estimate/constrain DM mass scale

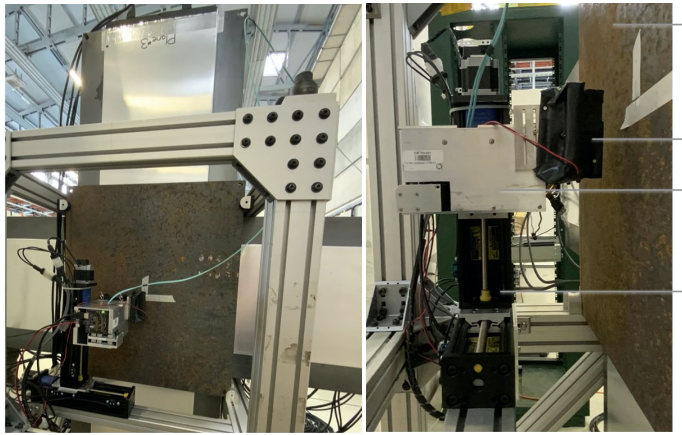




CERN Test Beam

- Recent successful test beam at CERN PS in April 2022 with Hcal and trigger scintillator (TS) prototypes
- Demonstrated successful operations, readout & electronics, and basic physics capabilities of two subsystems



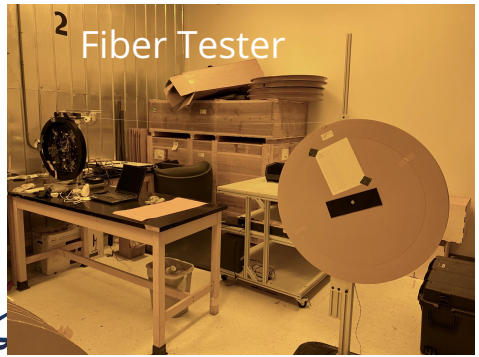


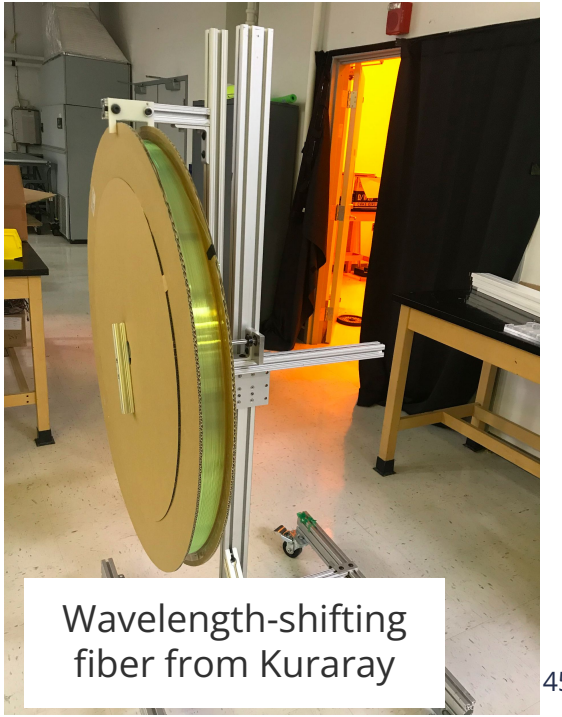
CERN Test Beam - Quad-bar Fabrication

Mu2e Cosmic Ray Veto (CRV) module factory at the
University of Virginia used for Hcal quad-bar fabrication

Inserting Fibers

Forming Quad-bars



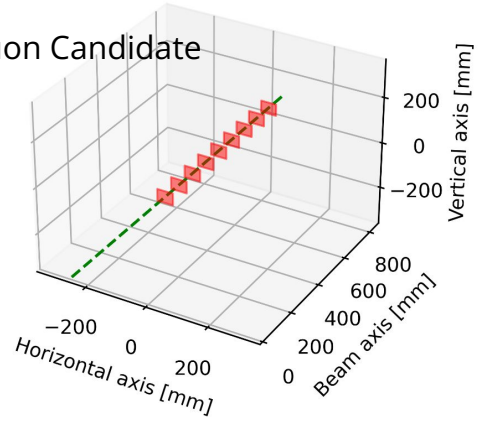


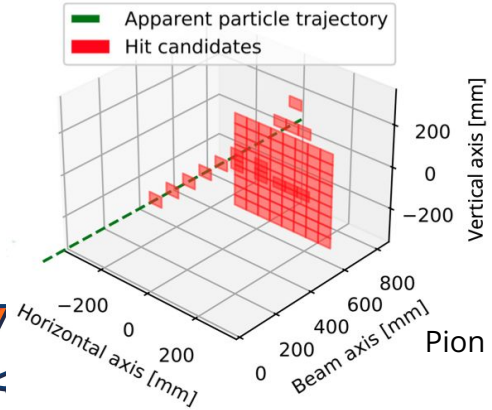
CERN Test Beam

CERN PS T9 Beamline

CERN Test Beam - Analysis

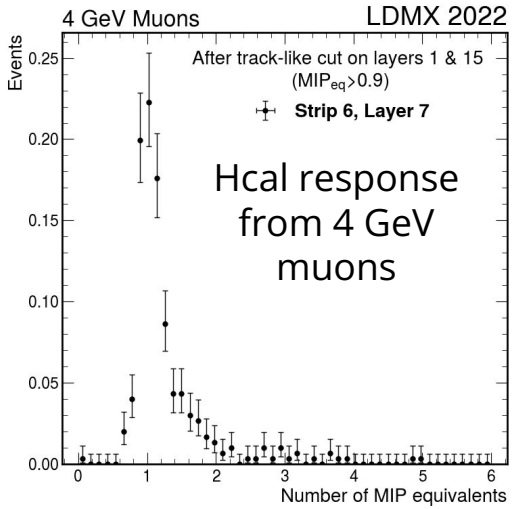
Muon Candidate

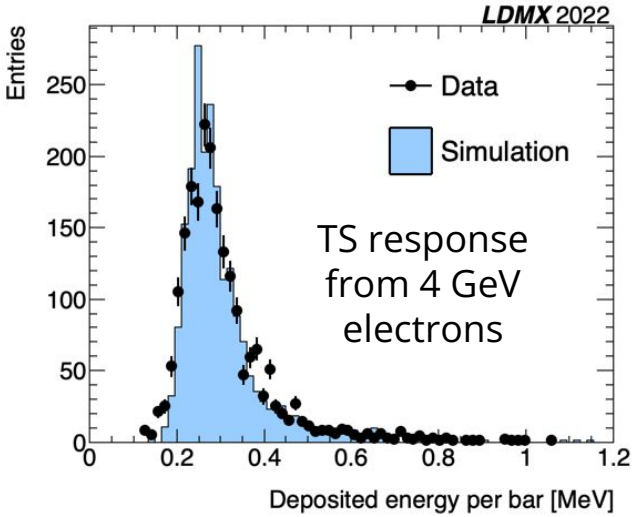




Pion Candidate

Preliminary results, data analysis is ongoing



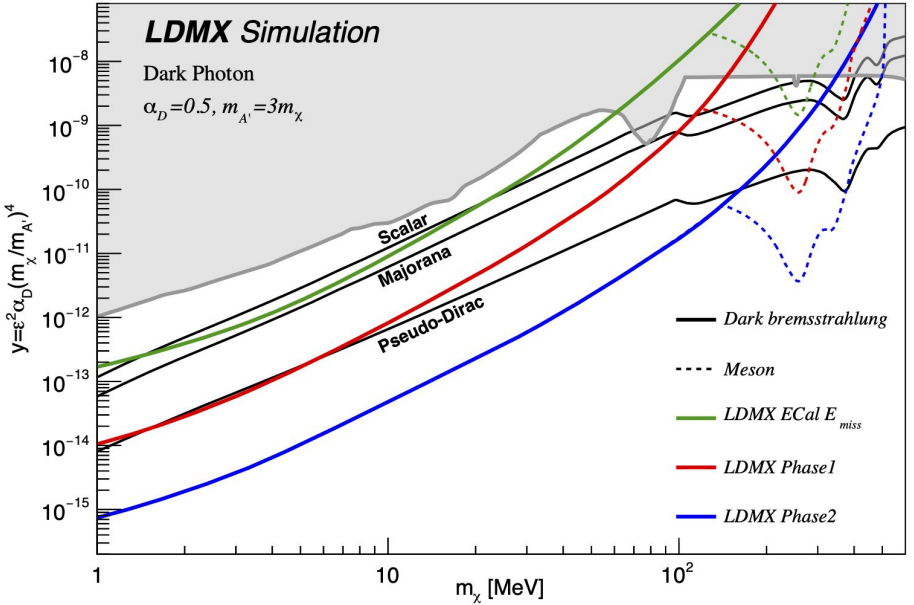


LDMX Sensitivity

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

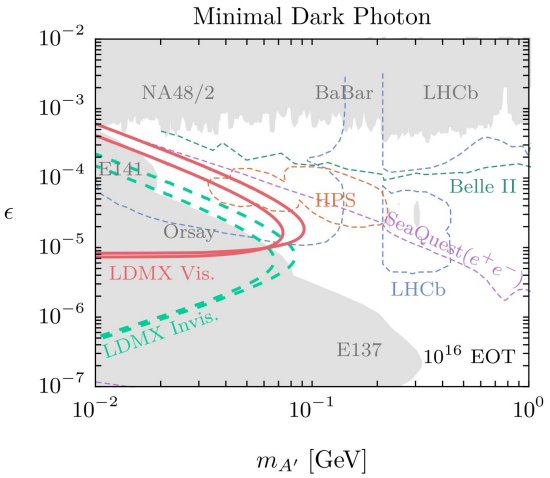
Phase 1: 4 GeV,
10^{14} electrons
Phase 2: 8 GeV,
10^{16} electrons

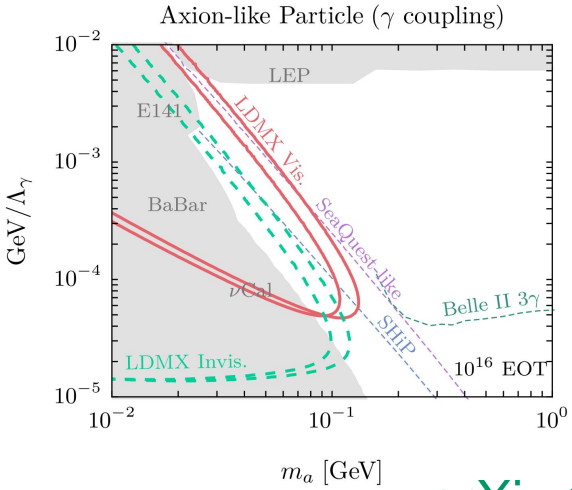
arXiv:1808.05219

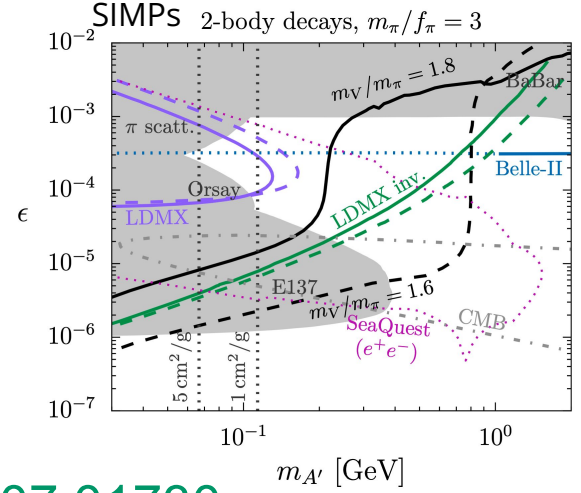


LDMX Visible Signatures

- Broad physics potential for LDMX beyond missing momentum search
  - Displaced visible decays - minimal dark photon, ALPs, SIMPs, etc.
  - Electronuclear measurements for neutrino physics





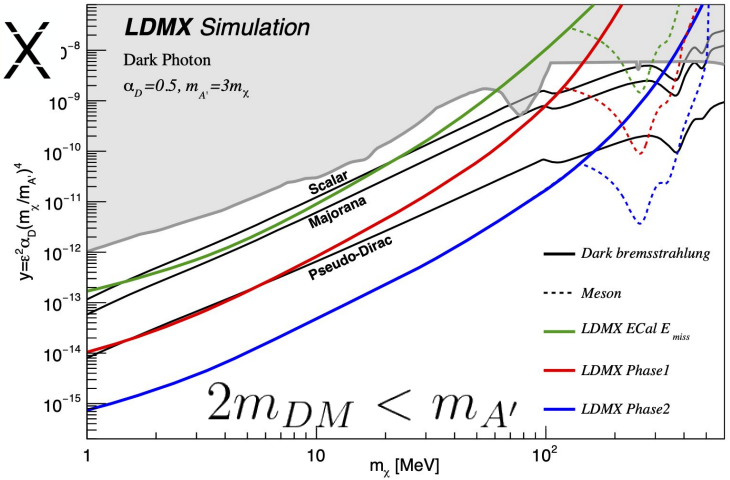


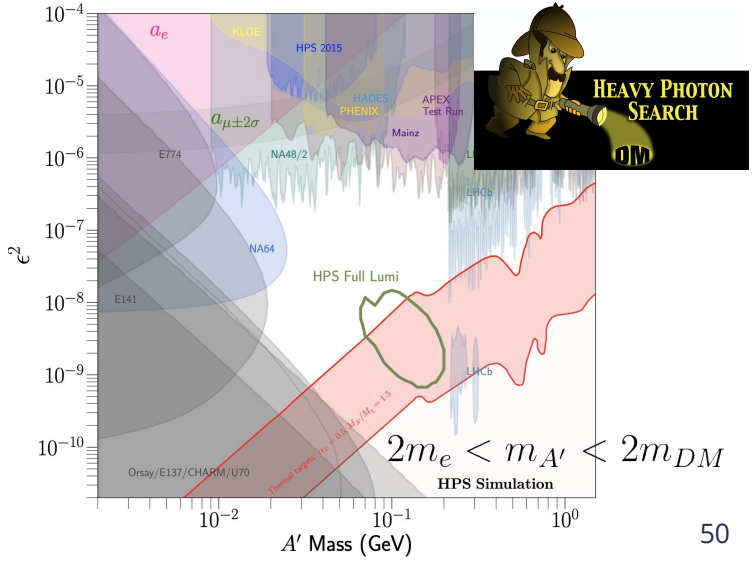
Projections are for 8 GeV and 16 GeV beams

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 via a displaced vertexing search
- LDMX can conclusively probe such models in the sub-GeV mass range through a missing momentum search





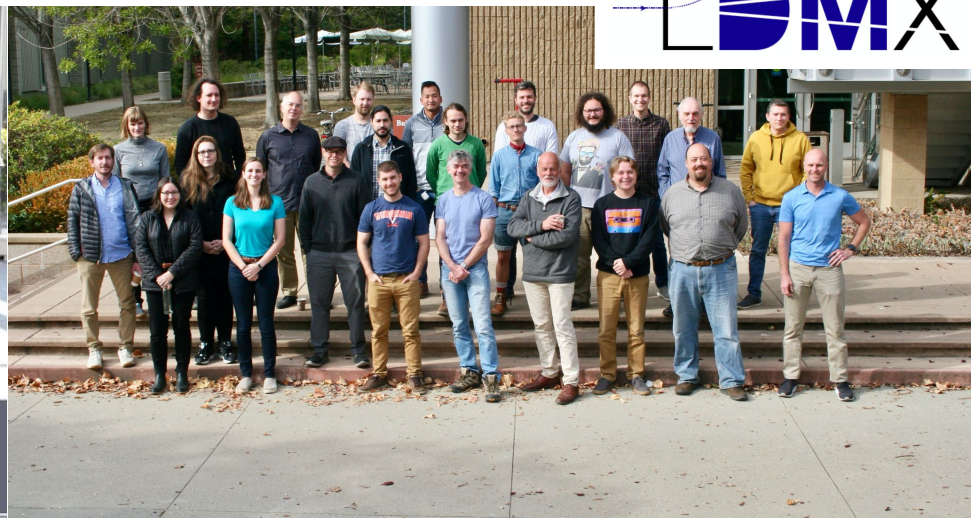
Thank You!

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

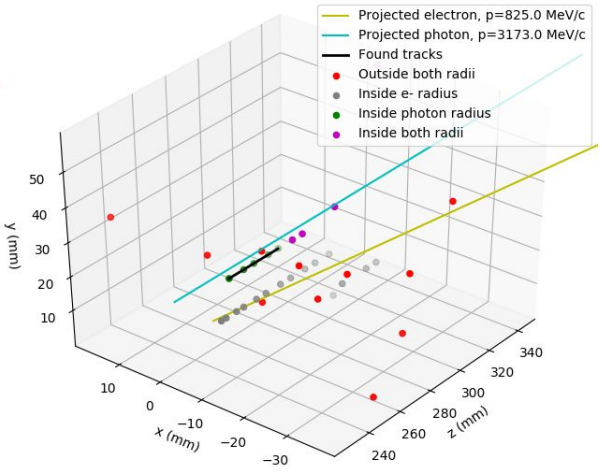
Carnegie Mellon University SLAC National Accelerator Laboratory Stanford University Texas Tech University University of Virginia

LDMX

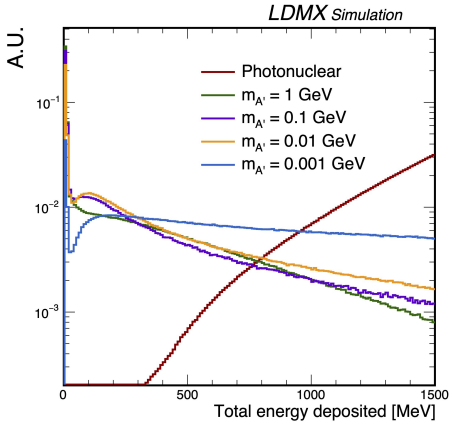
Heavy Photon Search

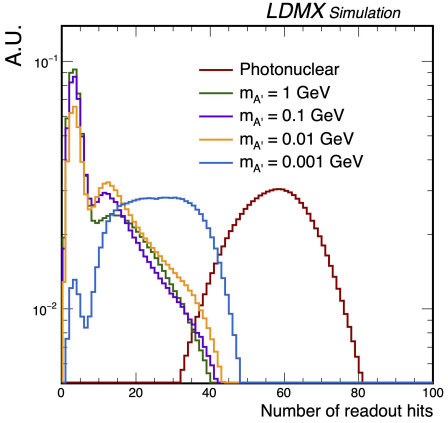


Ecal BDT

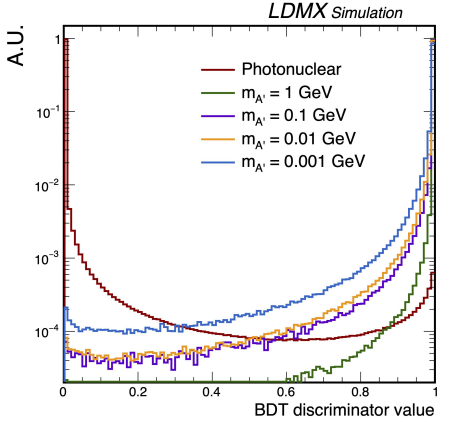


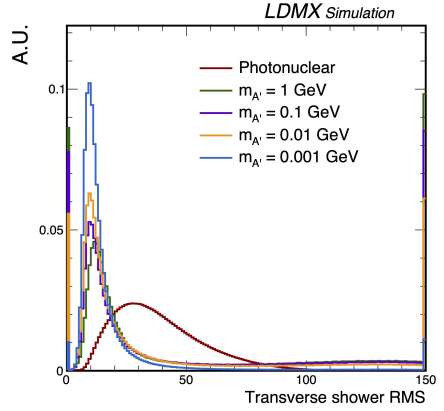
MIP Tracking





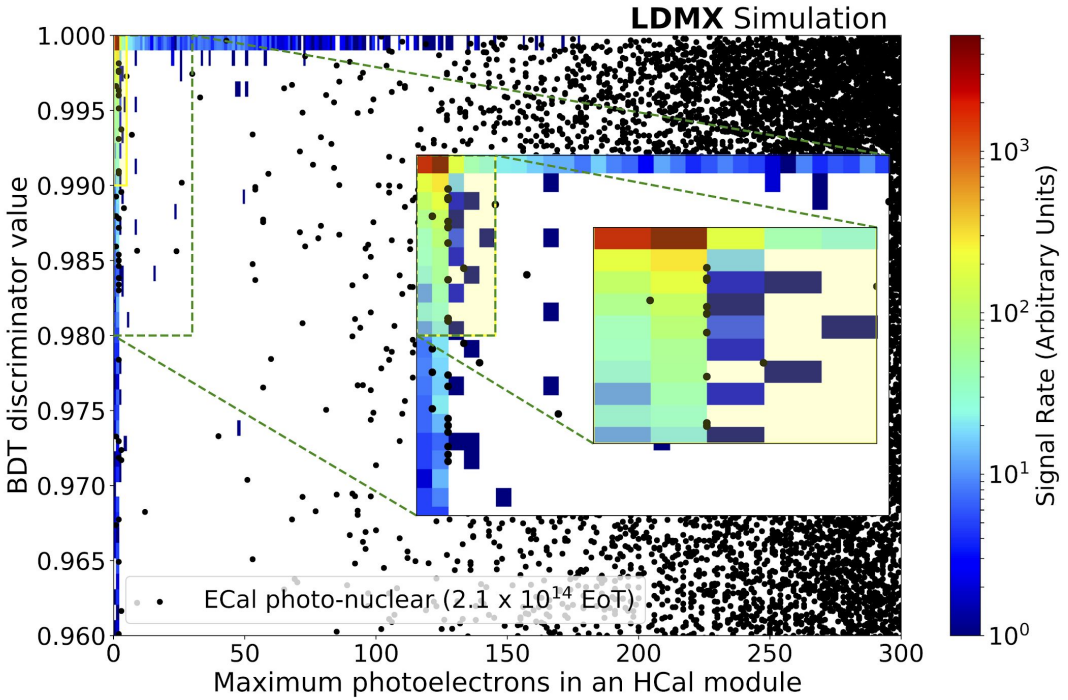
BDT Variables





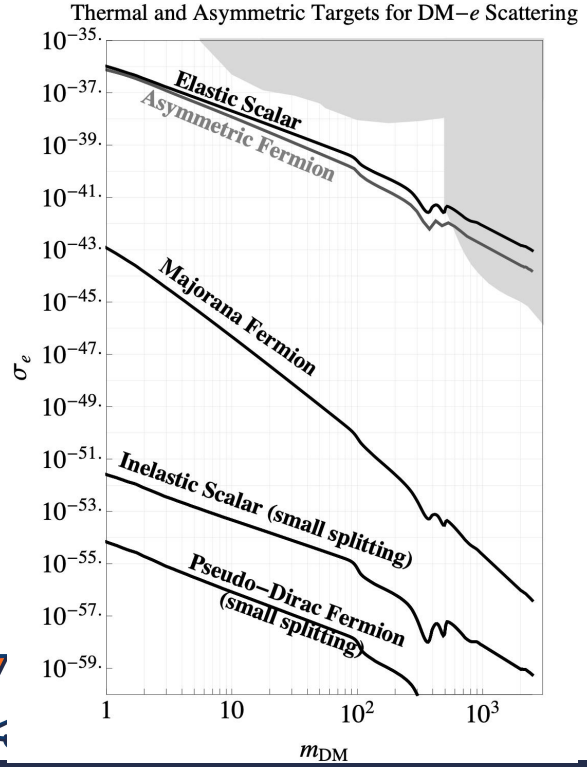
Ecal/Hcal Vetoes

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

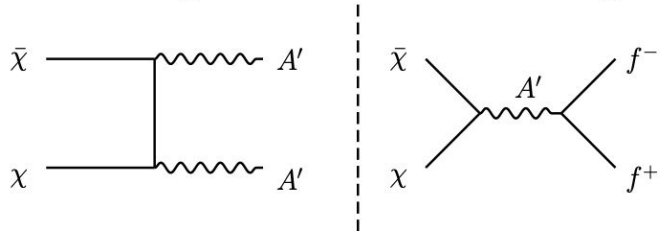


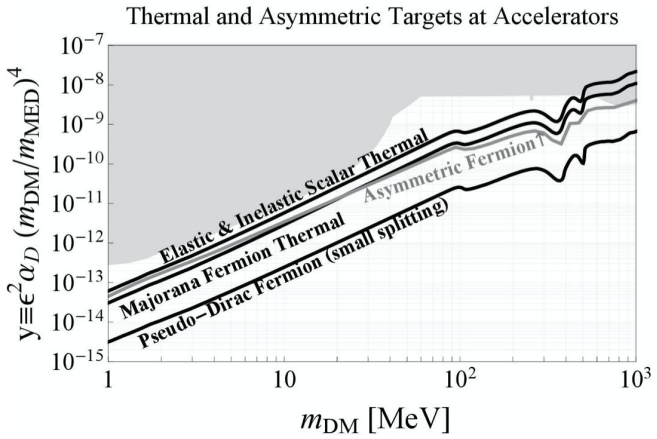
Advantage of DM Production at Accelerators

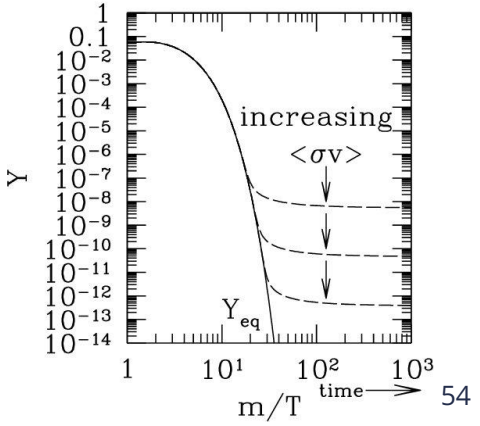
Non-relativistic vs semi-relativistic DM scattering



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

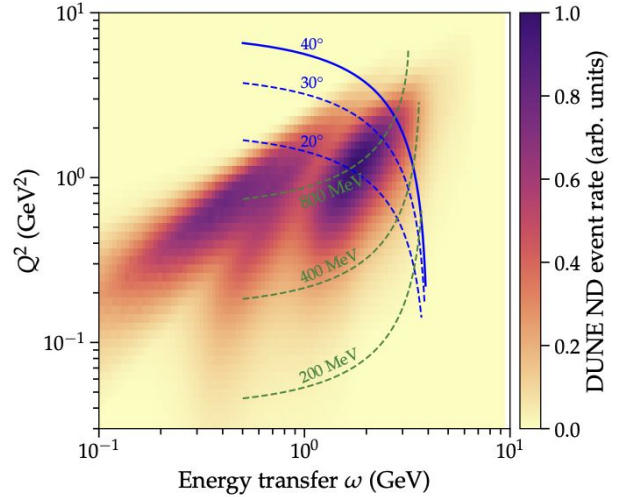




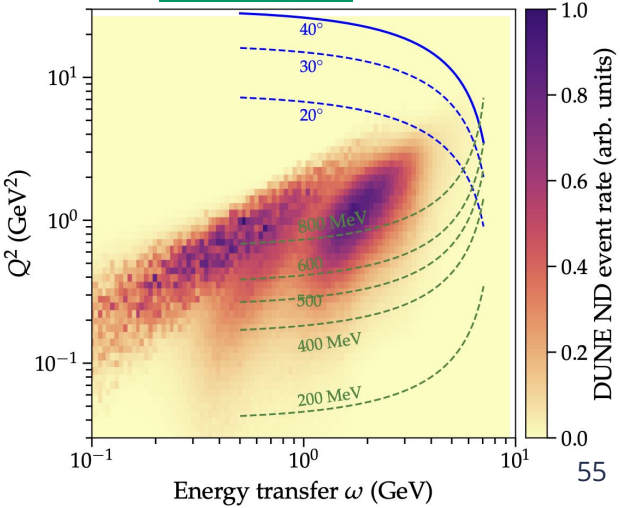


LDMX - A Broad Physics Program

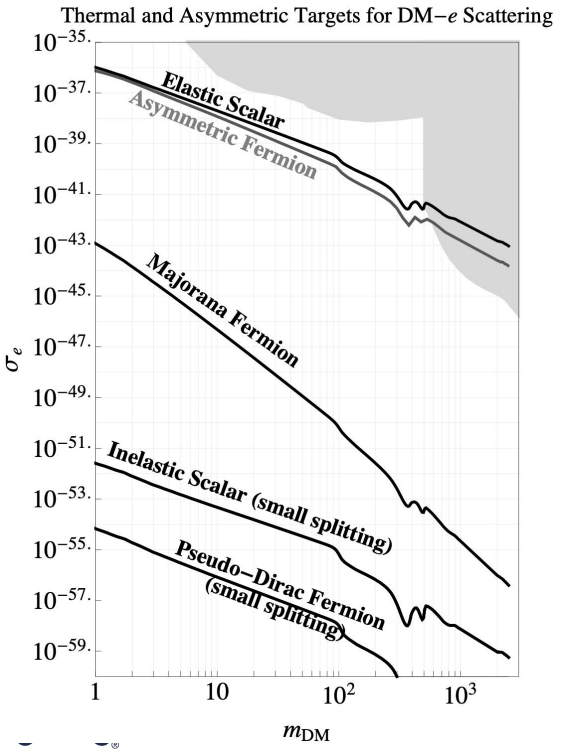
- LDMX offers a broader physics program beyond a missing momentum search for LDM
- Small angle acceptance (nearly hermetic) and fully reconstructing final and initial states allows for several unique measurements
  - Electro-nuclear scattering measurements of interest to neutrino experiments such as DUNE (right), can constrain neutrino production cross-sections
  - Searching for visibly decaying long-lived particles (next slide)



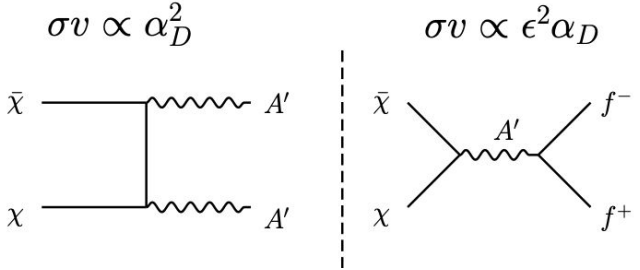
arXiv:1912.06140

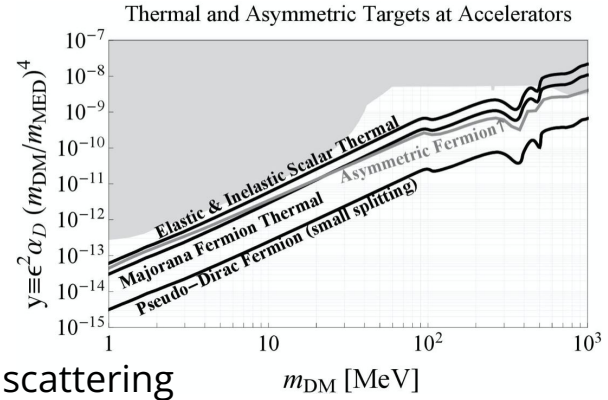


Advantage of DM Production at Accelerators



- LDM production at accelerators is fairly independent of specific DM model, a significant advantage over direction detection
- "Thermal targets" for sub-GeV dark matter models can be completely probed by near-future experiments

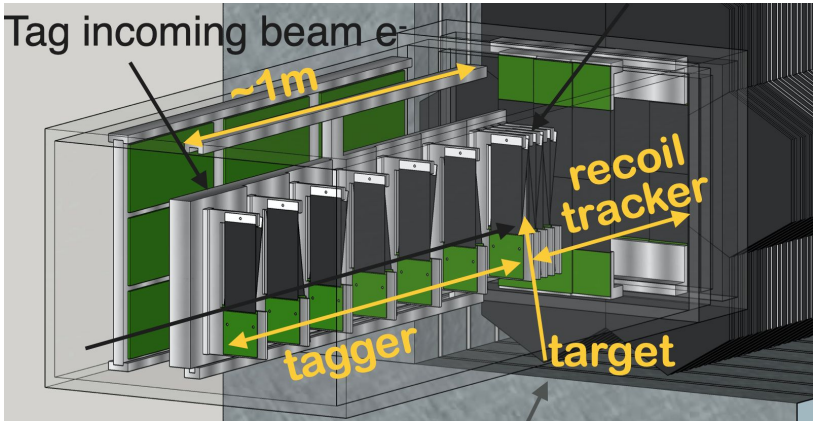


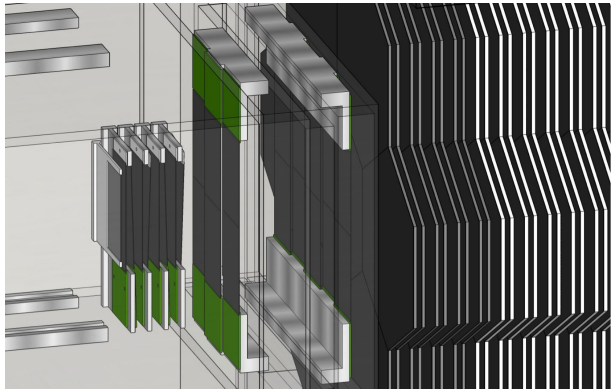


Non-relativistic vs semi-relativistic DM scattering

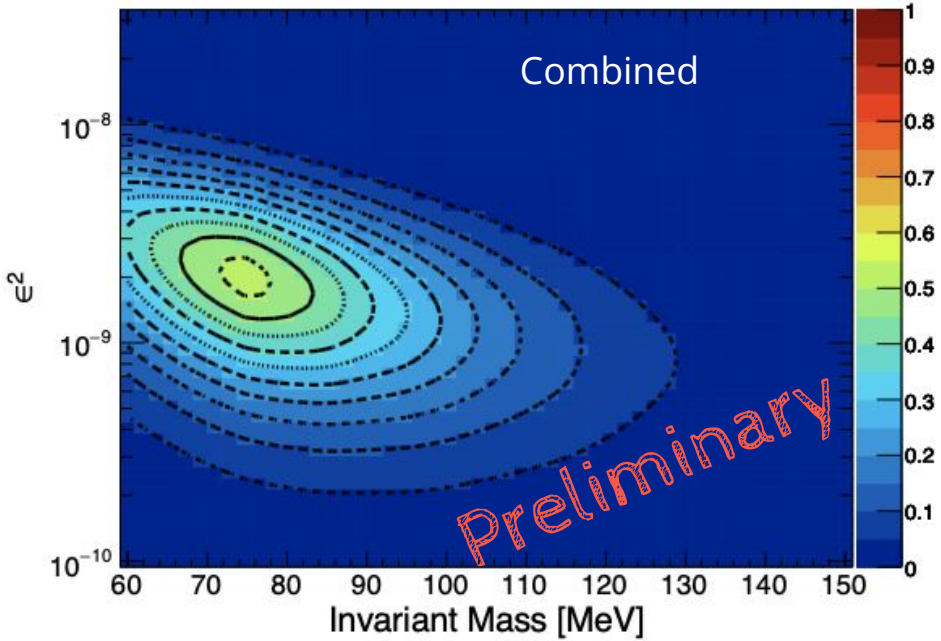
Tracker and Trigger Scintillator

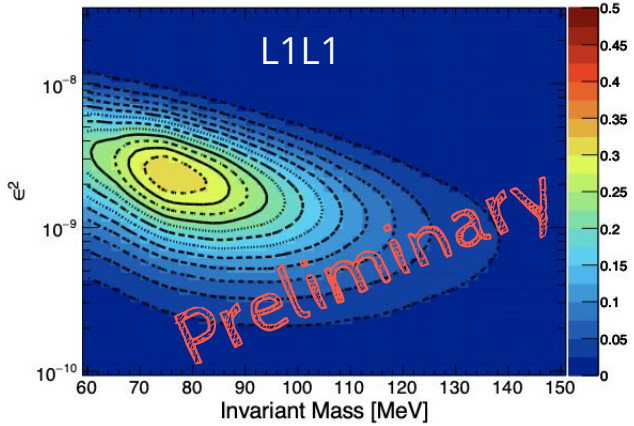
- Tagging tracker
  - Measures incoming beam electron
- Recoil tracker (based on Heavy Photon Search design)
  - Measures recoil electron and vetoes extra particles
- Trigger Scintillator
  - Arrays of scintillator bars provide fast count of incoming electrons
  - Used an input to the missing energy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

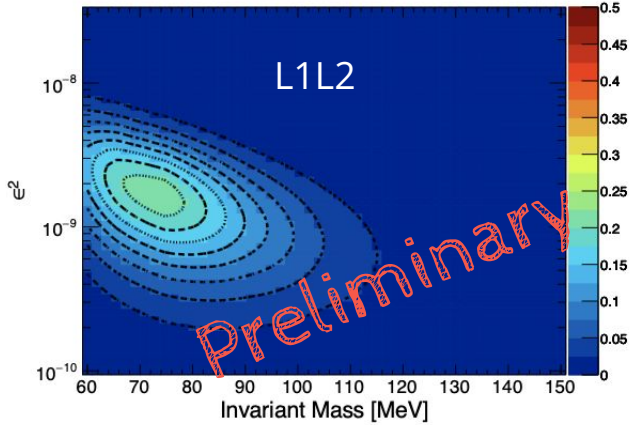




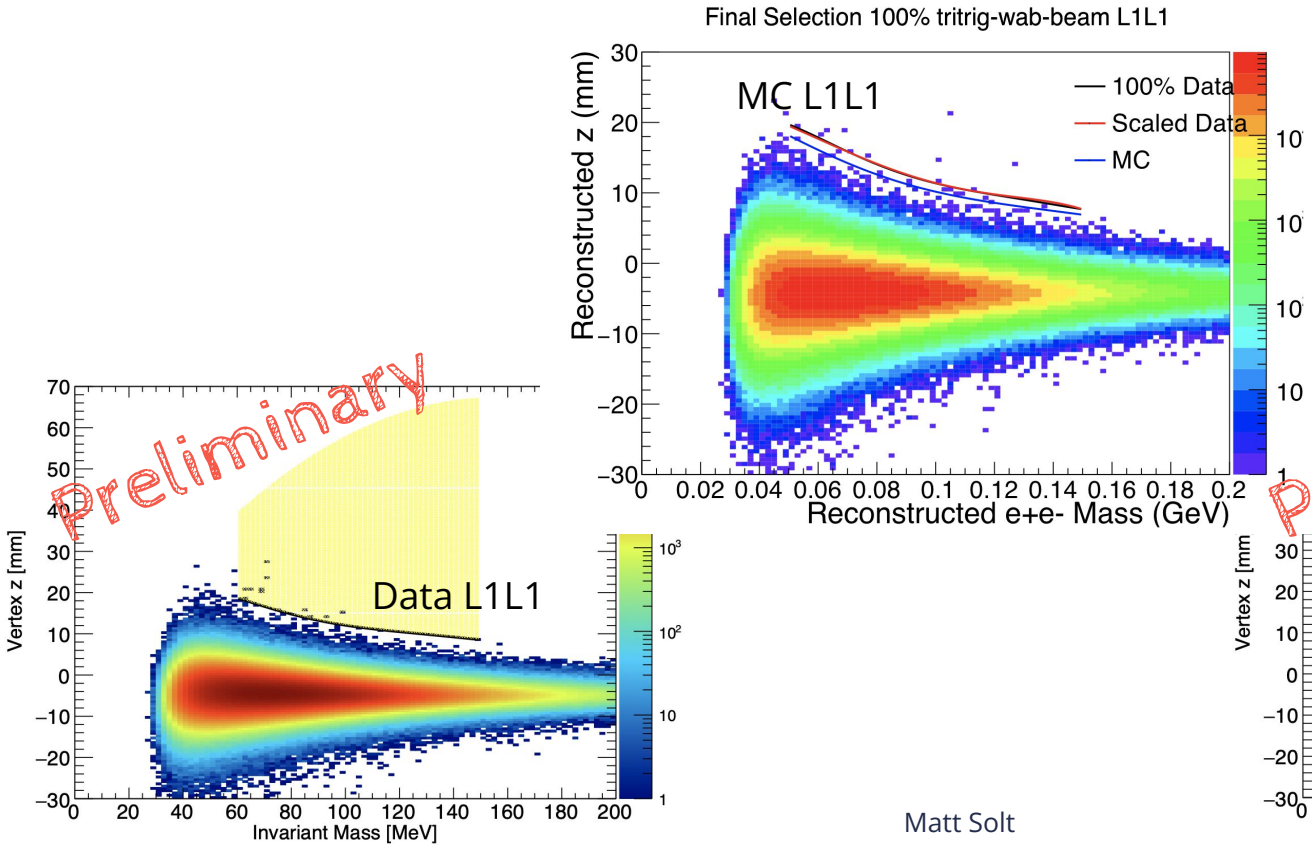
HPS Expected Signal Rate 2016

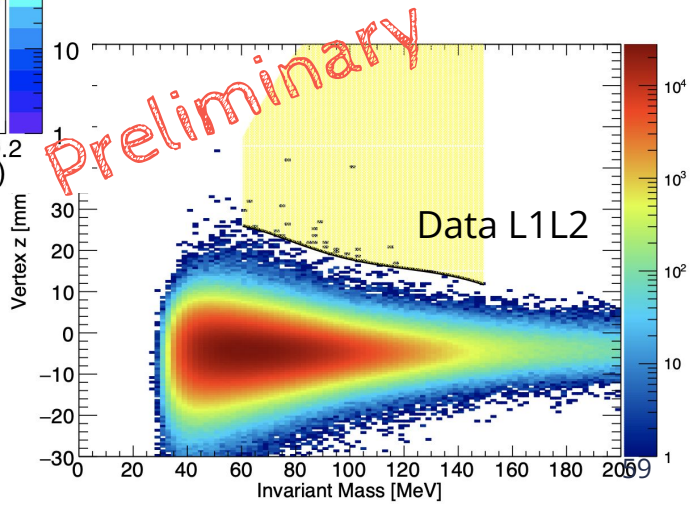






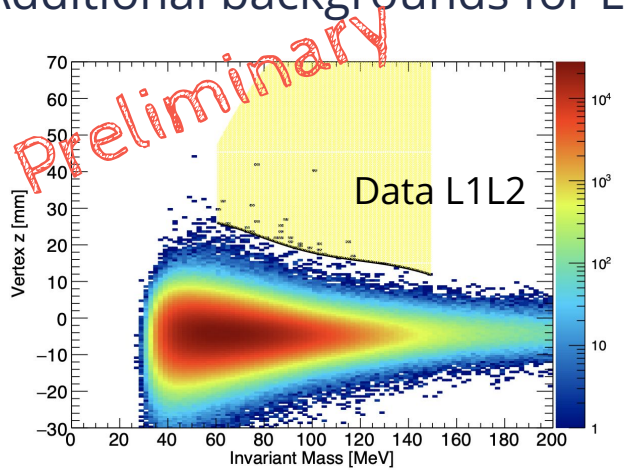
HPS Data/MC Comparison

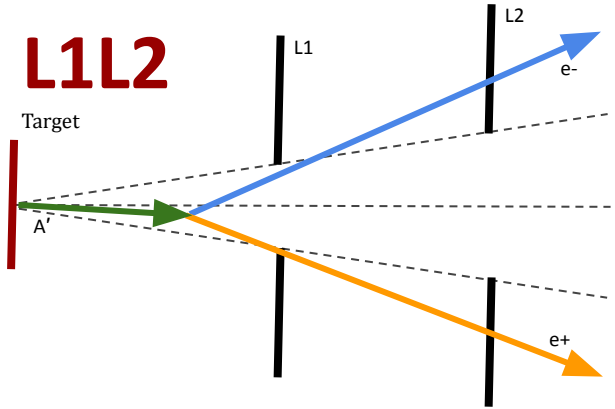


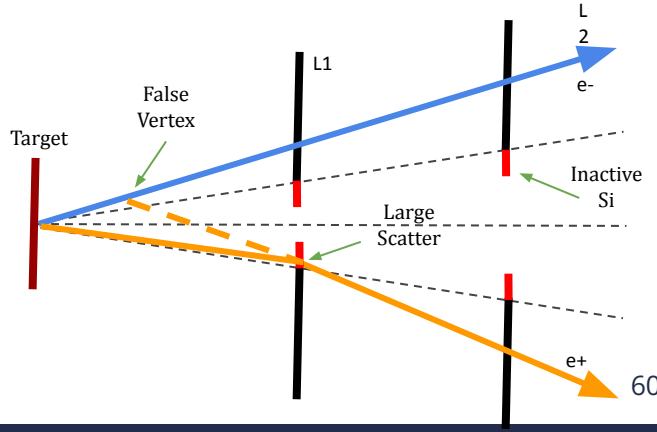


A's with Longer Lifetimes

- 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







Installing HPS Upgrades - 2019 Run

HPS upgrades successfully installed in May-June 2019 in time for June start