Samahang Pisika ng Pilipinas
Physics Society of the Philippines

Exploring Light Dark Matter at Accelerators

July 19, 2023

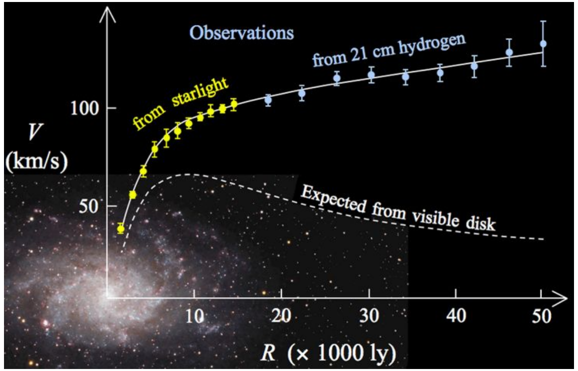
Matt Solt, University of Virginia

Heavy Photon Search

LDMX

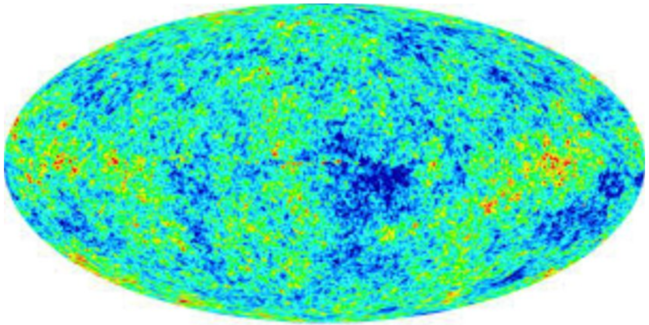
The Existence of Dark Matter

- 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

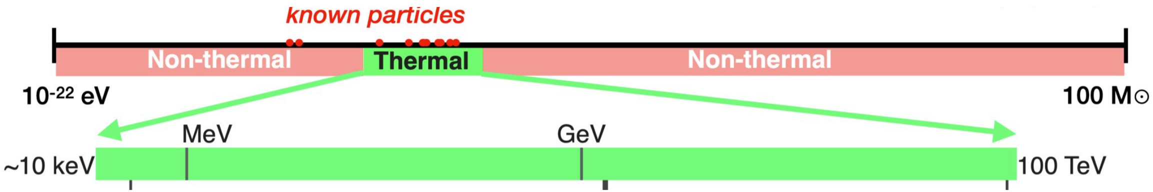
Gravitational Lensing



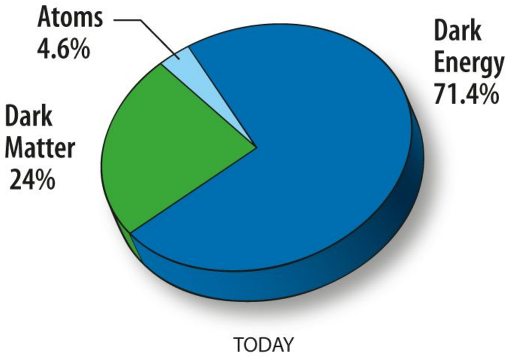
Cosmic Microwave Background

A Thermal Relic

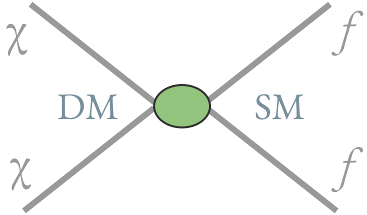
- 85% of the mass in the universe is dark matter, but astrophysical evidence of DM does not constrain the mass scale very well
- **A thermal relic** - simple and predictive model of dark matter (DM)
- Thermal DM constrains DM mass to ~mass scale of SM particles



The range of DM mass spans a range of ~90 orders of magnitude!
Thermal DM reduces this to ~7 orders of magnitude

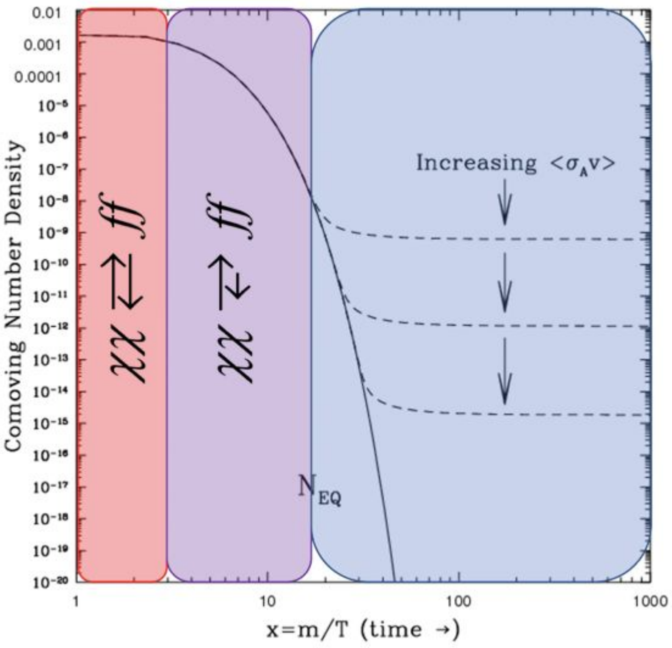


A Thermal Relic



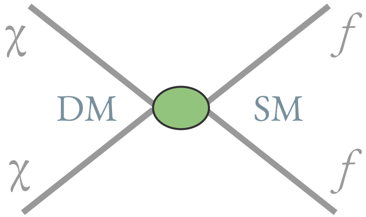
arXiv:9506380

- 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 $\langle\sigma v\rangle$



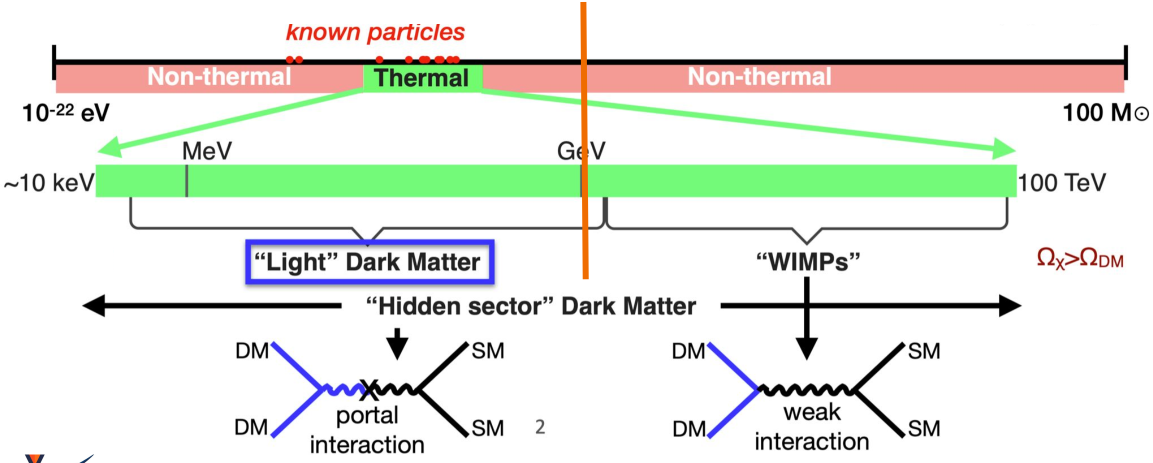
$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle} \longrightarrow \langle\sigma v\rangle = 3 \times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

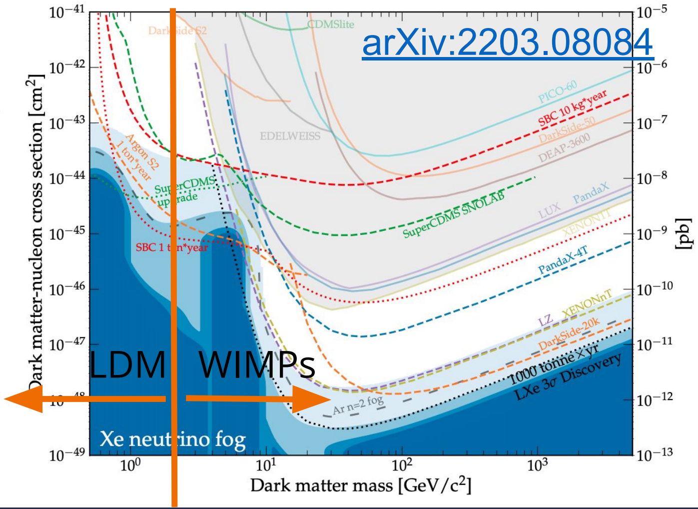
Any proposed mechanism must yield ≤ 85% DM!



A Thermal Relic - WIMPs and LDM

- WIMPs are well-motivated, but accessible parameter space is shrinking
- 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

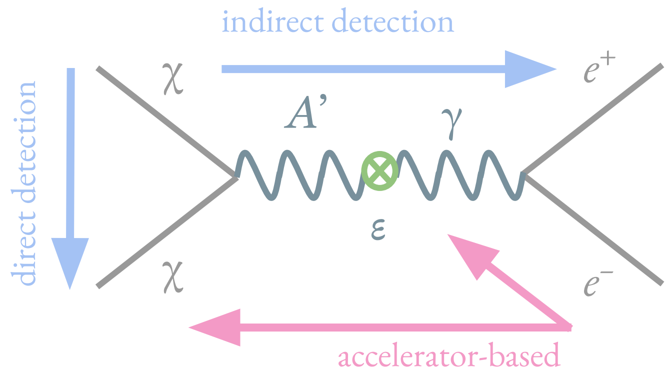




2

Matt Solt

Heavy (Dark) Photon Primer

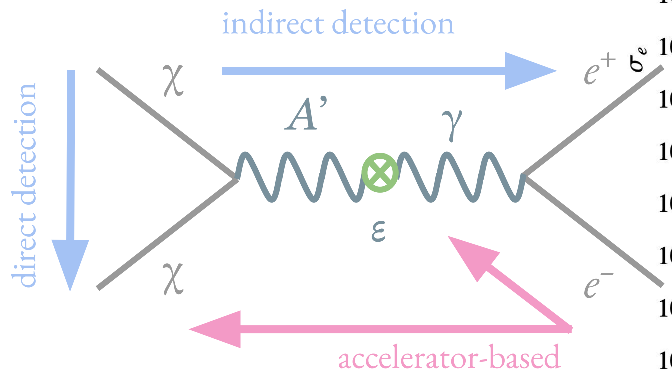


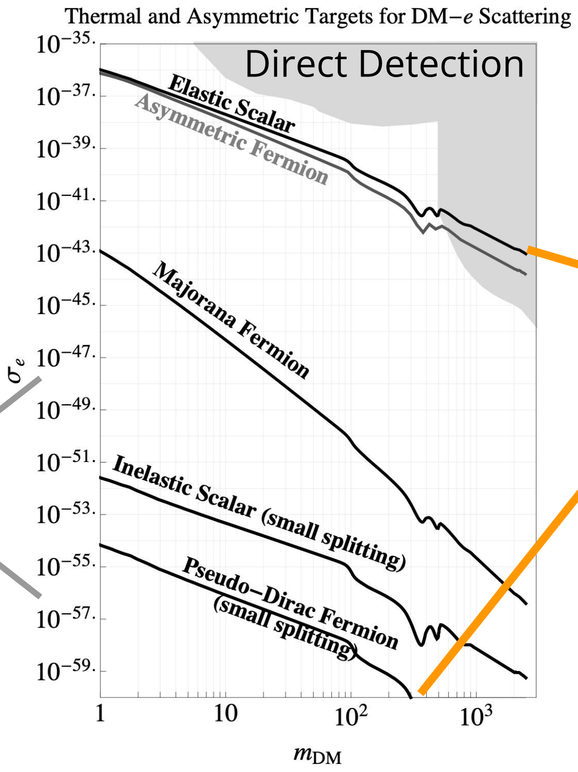
Phys. Lett., B166:196–198

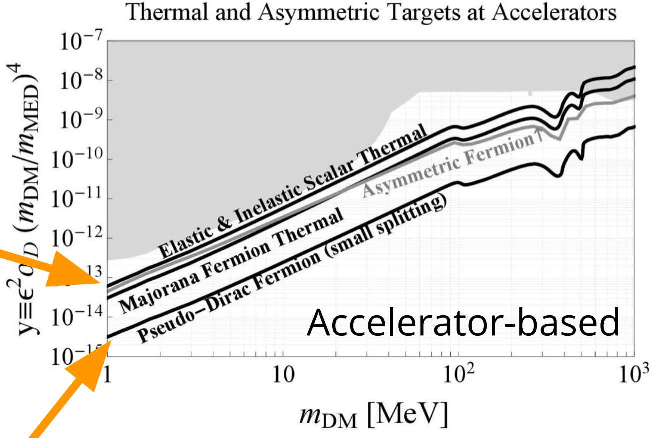
- An additional U'(1) symmetry proposed by B. Holdom 1985 - includes a massive dark photon (heavy photon or A')
- Kinetic mixing (ε) allows for A' mixing with SM photon: **Effective coupling to electric charge**
  - Allows for **thermal contact** of DM-SM in the early universe
  - Allows for us to exploit DM-SM interactions using **experiments today**
  - Thermal light dark matter models with dark photons are **very predictive**

Advantage of DM Production at Accelerators

Thermal DM makes **clear prediction targets** that are **attainable** by a variety of current experiments





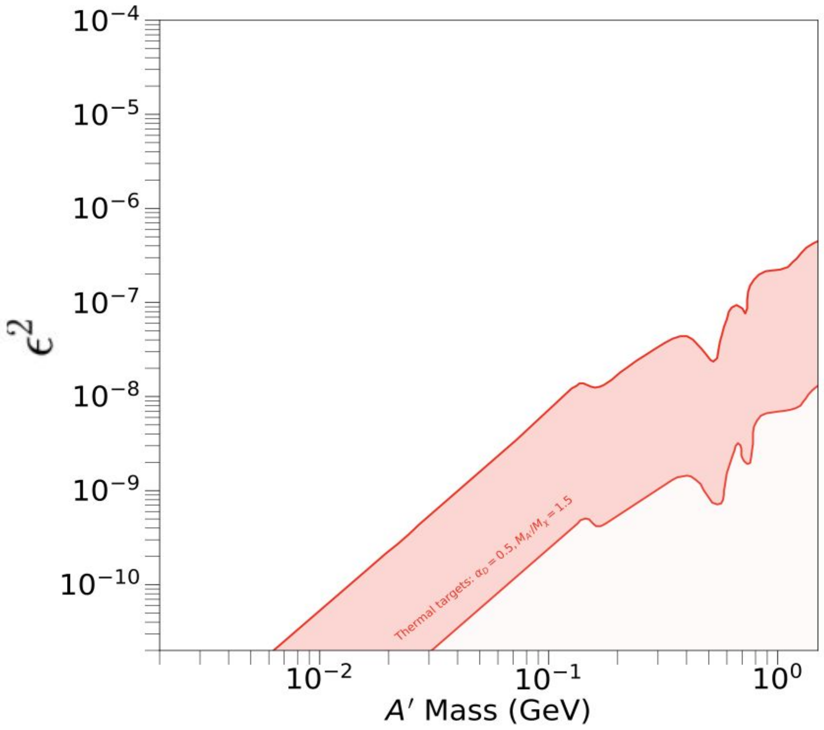


Accelerator-based experiments are fairly **model-independent**. Thermal targets can be probed with current and next generation experiments (e.g. **HPS**, **LDMX**, etc.)

Dark Photon Visible Parameter Space

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

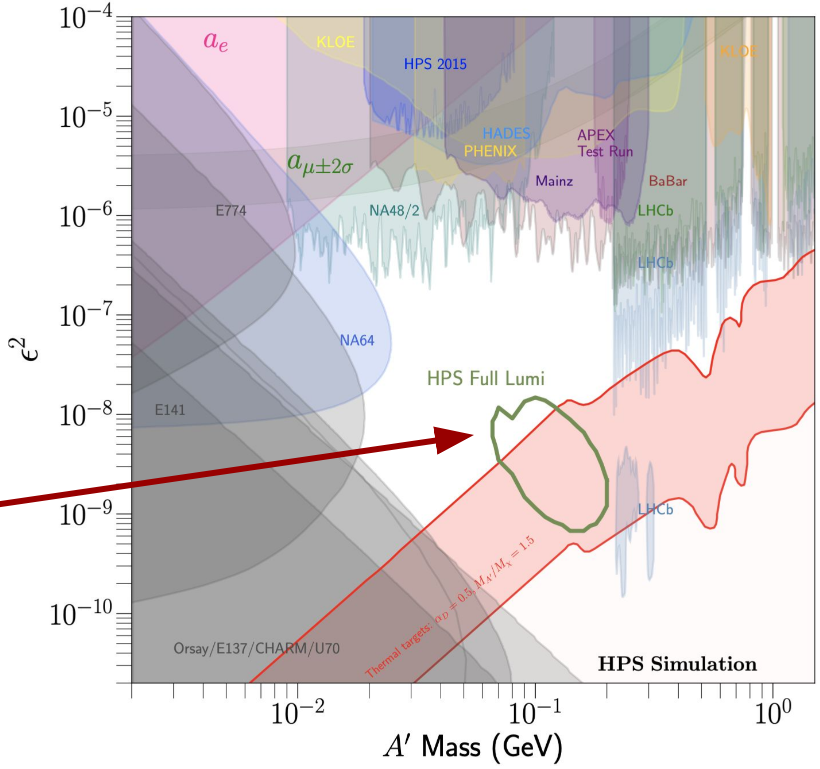
- Theoretically motivated parameter space for A's that decay to SM particles - two parameter model (ε and mass)
- Highly motivated "thermal targets" contained in the red band



Dark Photon Visible Parameter Space

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

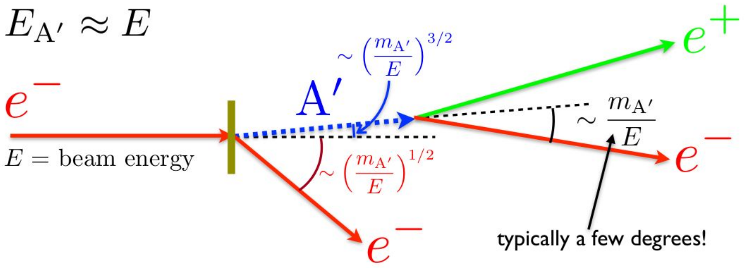
- Theoretically motivated parameter space for A's that decay to SM particles - two parameter model (ε and mass)
- Highly motivated "thermal targets" contained in the red band
- Highly motivated, yet unprobed region of parameter space
  - Small production cross-section
  - Short, but finite lifetime ("long-lived")

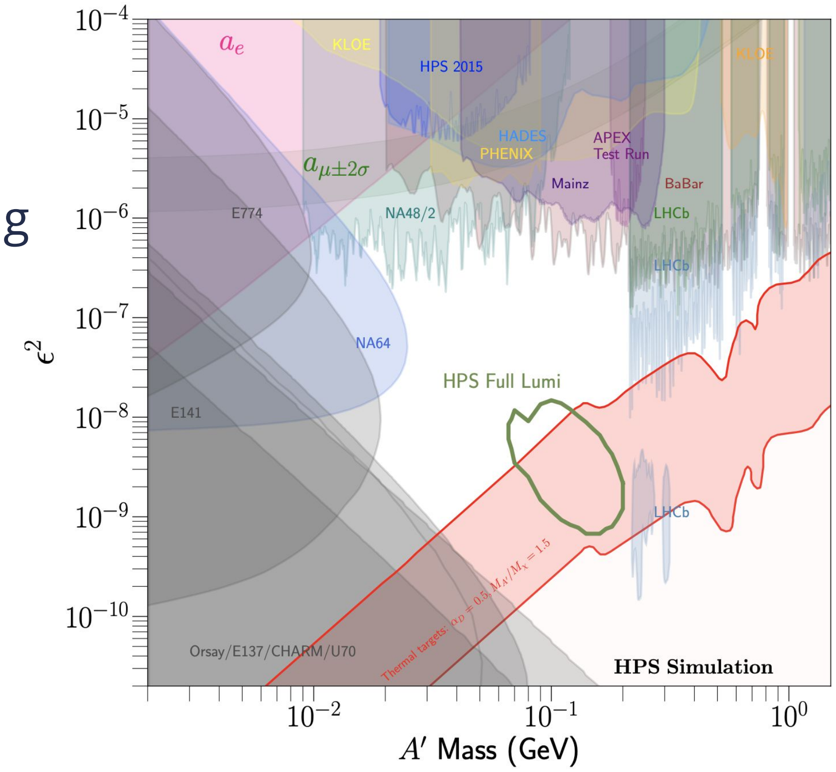


Dark Photon Visible Parameter Space

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

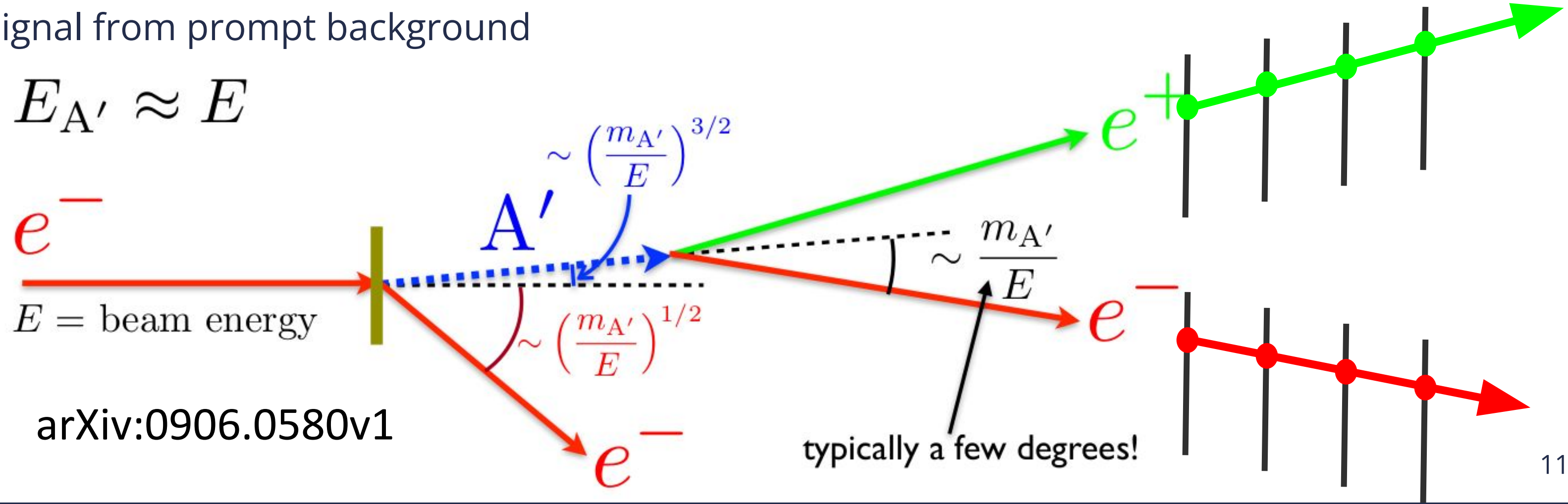
- Probing this region requires a new type of search for dark photons - a **displaced vertex search**
- HPS - a fixed target precision vertexing experiment. Challenges:
  - Large prompt QED backgrounds
  - A' kinematics require sensitive detector components to be 0.5 mm from the beam





HPS Concept

- 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**
  - HPS can vertex A’s with mm-scale precision - separates long-lived signal from prompt background



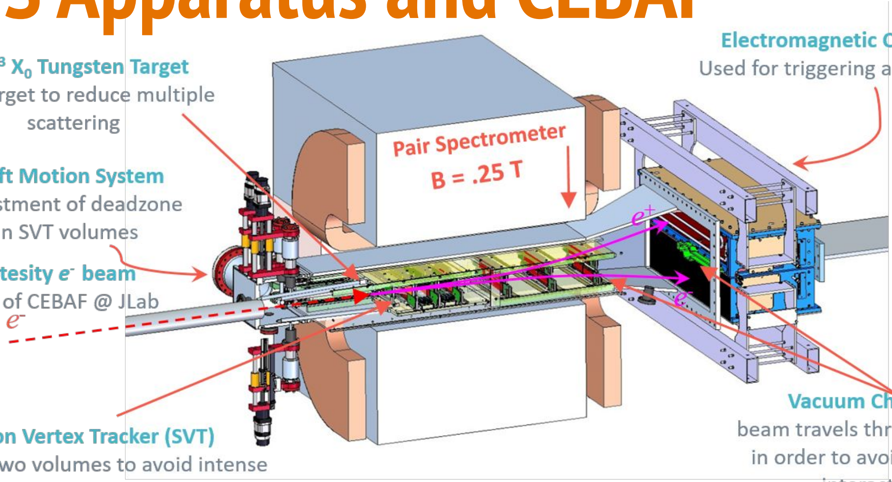
arXiv:0906.0580v1

HPS Apparatus and CEBAF

$\sim 10^{-3}$ 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



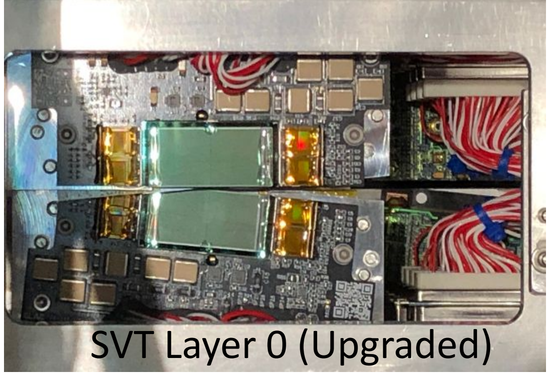
Electromagnetic Calorimeter
Used for triggering and particle ID

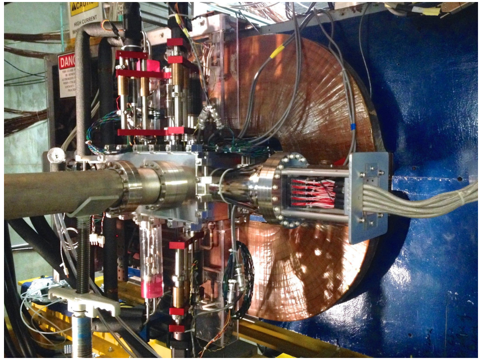
Vacuum Chambers
beam travels through vacuum in order to avoid beam-gas interactions

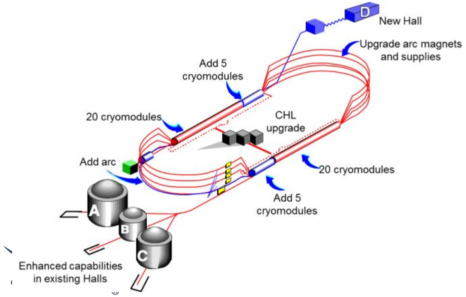
Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Measures momentum and vertex precisely.

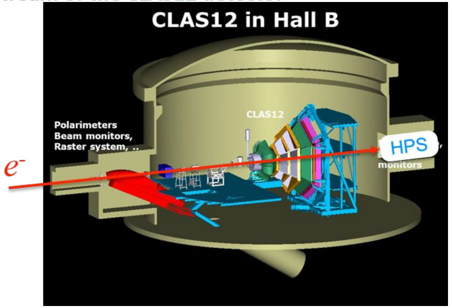
SVT + ECal DAQ capable of 50 kHz

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





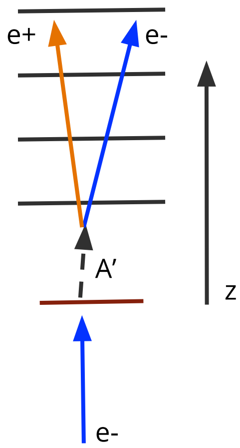


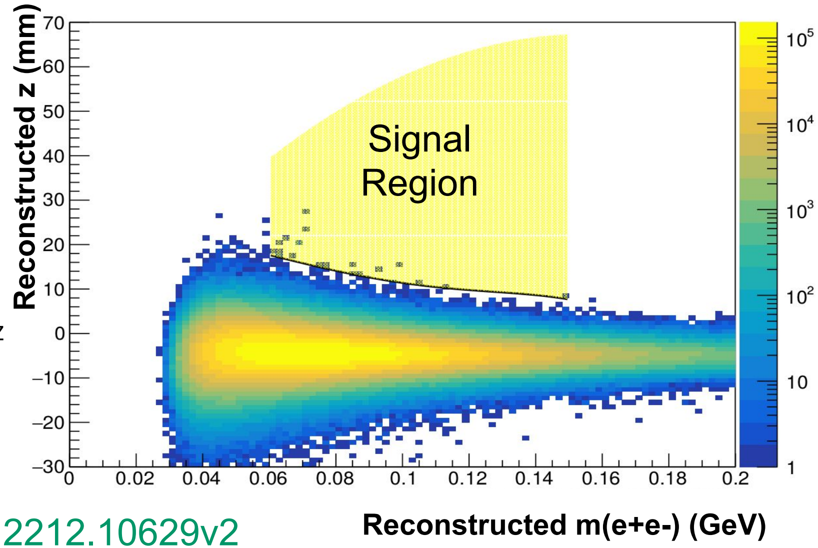


HPS is run at Jefferson Lab (Newport News, VA) using the CEBAF facility which provides a continuous, high current e- beam with small beam spot and beam tails ($\sim 10^{-6}$)

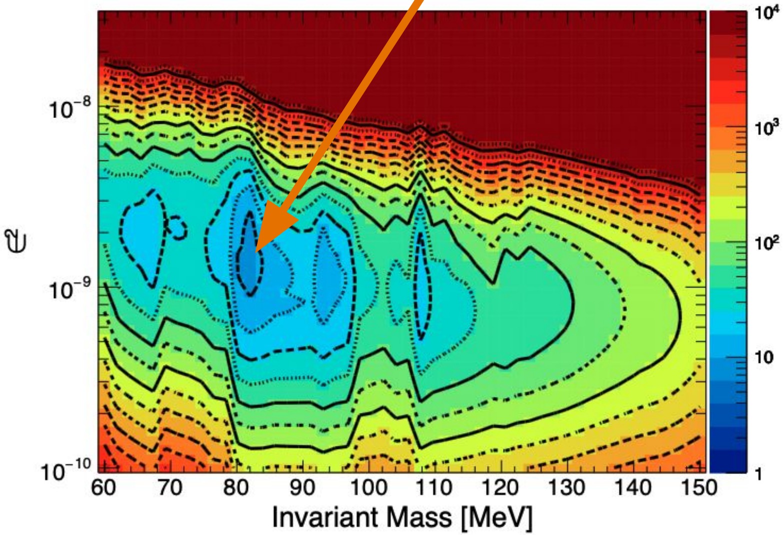
2016 Displaced Vertex Search Results

Optimal sensitivity is a factor of ~8 from exclusion at 90% confidence





arXiv:2212.10629v2



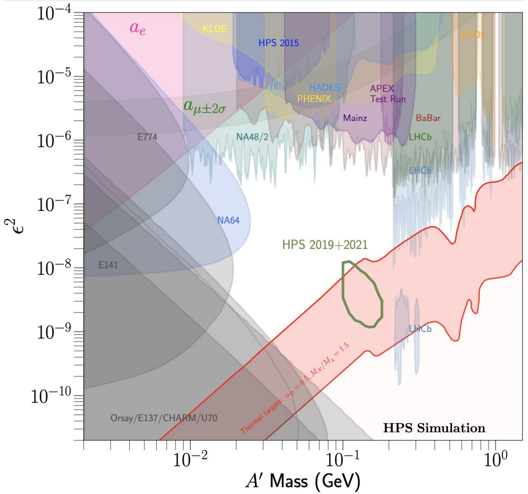
Challenge: Distinguishing the prompt QED tridents from displaced signal (~1 signal for ~10^6 prompt background)
Success: Nearly zero-background search was achieved

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

HPS Current Data and Status

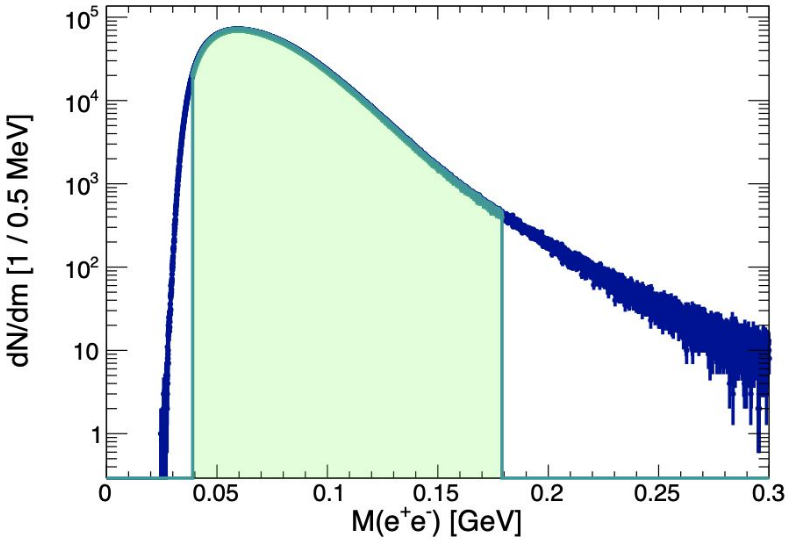
- Analysis from 2015/2016 motivated **several simple upgrades**: additional tracking layer and upgraded trigger
- HPS is approved for 180 days of running: analysis from 2019 & 2021 runs are expected to yield exclusions, and **potential discovery**, of A's
- Other models of interest with long-lived particles: SIMPs, ALPs, etc.

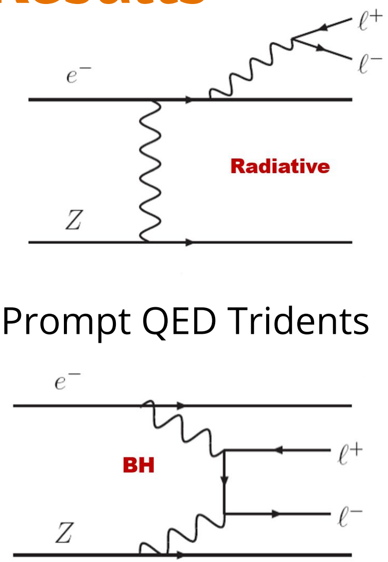
Data Run	Beam Energy (GeV)	Beam Current (nA)	Beam Time
2015 Engineering Run	1.05	50	1.7 Days
2016 Engineering Run	2.3	200	5.4 Days
2019 Physics Run (Upgraded)	4.55	~150	~4 Weeks
2021 Physics Run (Upgraded)	3.7	~120	~4 Weeks

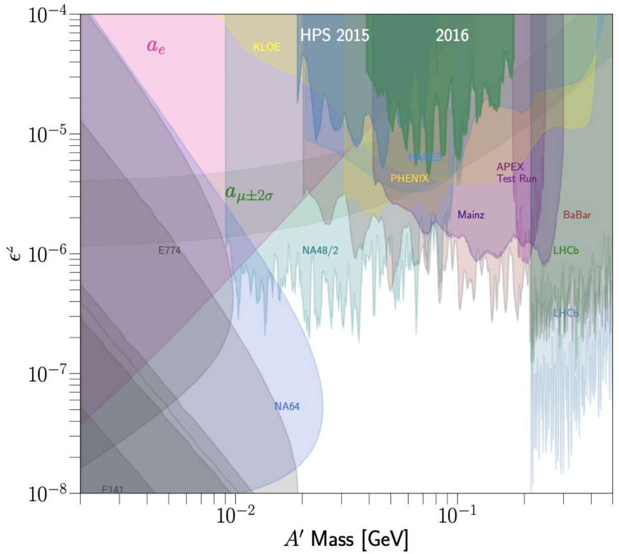


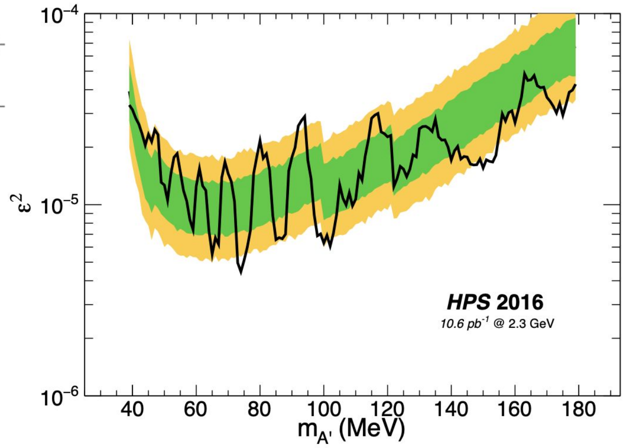
2016 Resonance Search Results

arXiv:2212.10629v2







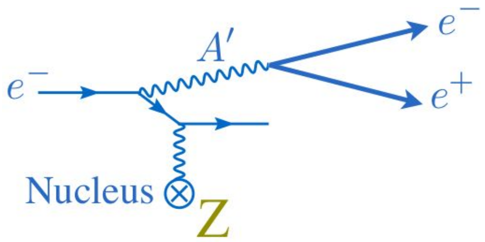


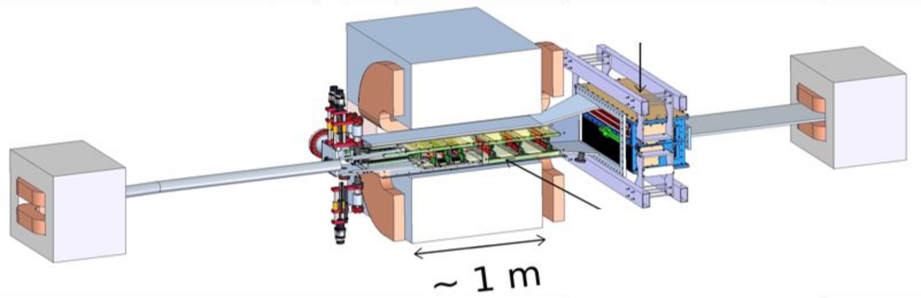
- **No observed excess** over prompt QED tridents
- Exclusions consistent with several other experiments

Dark Photon Decays - Complementary Searches

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

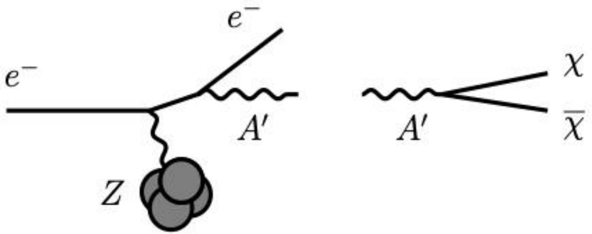
Heavy Photon Search (HPS) at Jefferson Lab

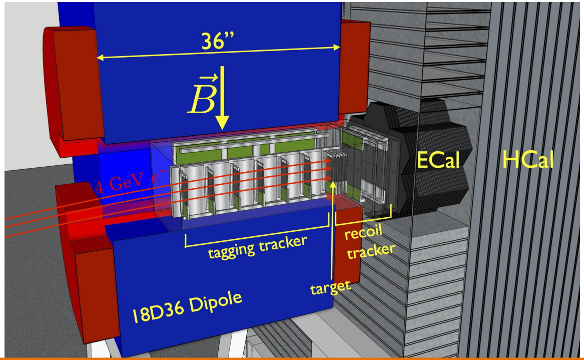




$$2m_{DM} < m_{A'}$$

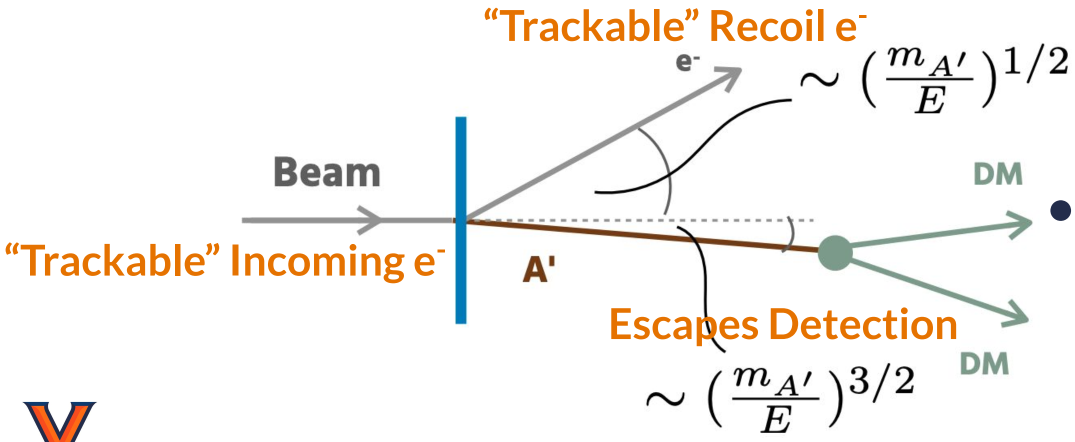
Proposed Light Dark Matter eXperiment (LDMX) at SLAC

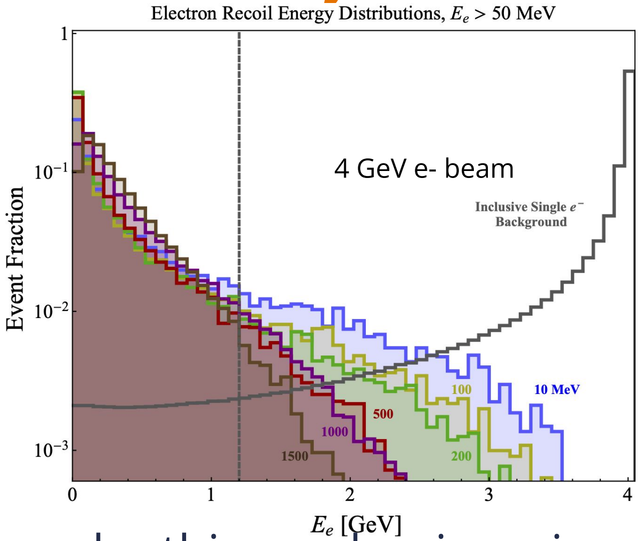




Dark Photon with a Fixed Target - Invisible Decay

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

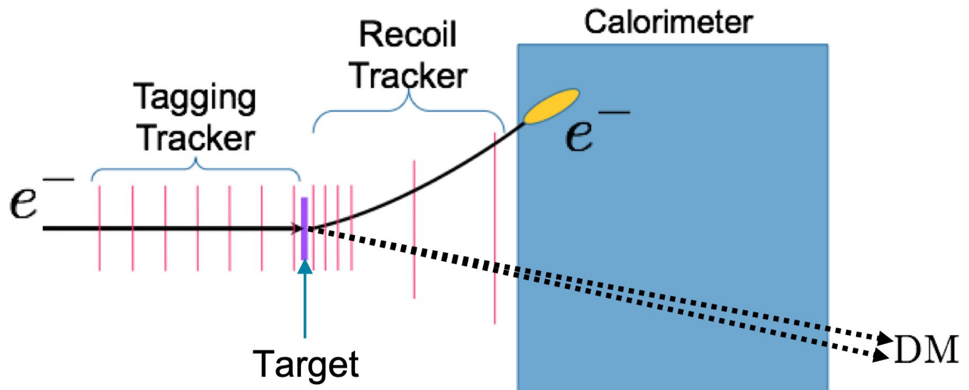


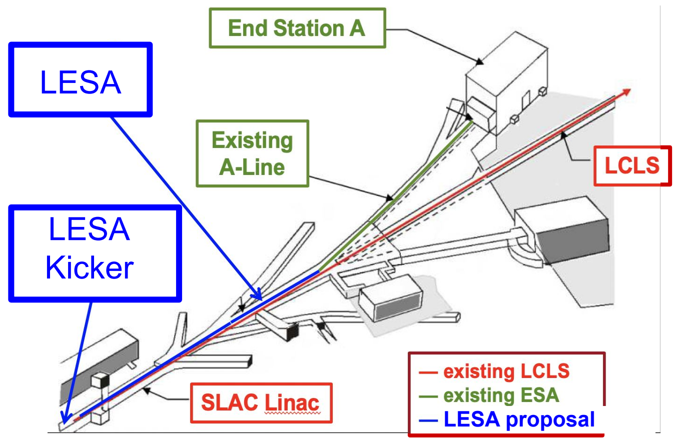


- Can probe this mechanism via a missing momentum search. We need...
  - High momentum resolution
  - High veto efficiency of Standard Model backgrounds

LDMX Concept

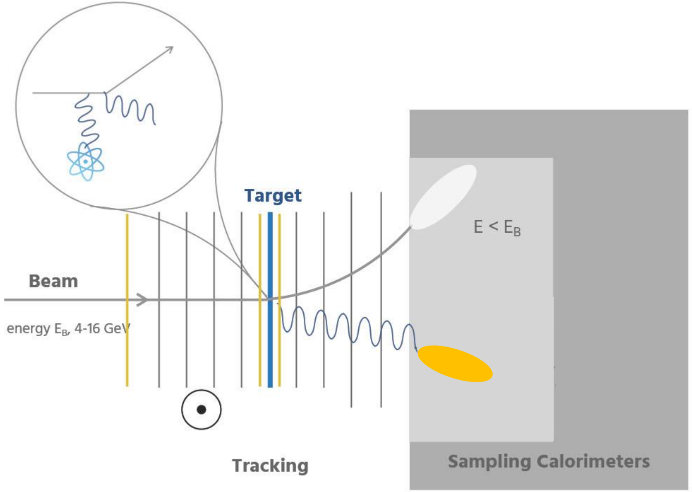
- Missing momentum and energy approach
  - DM production identified by missing energy/momentum in detector
  - Individual tagging and reconstruction of up to 10^{16} electrons - need low current, high repetition rate 37 MHz of O(1) electrons. Planned to run at SLAC End Station A
  - Backgrounds rejected by sampling calorimeters - Ecal and Hcal





Missing Momentum Backgrounds

Goal: Achieve 0 background for 10^{16} electrons on target (EoT)



Large rate of bremmstrahlung. These are mitigated by Missing Energy Trigger in the Ecal

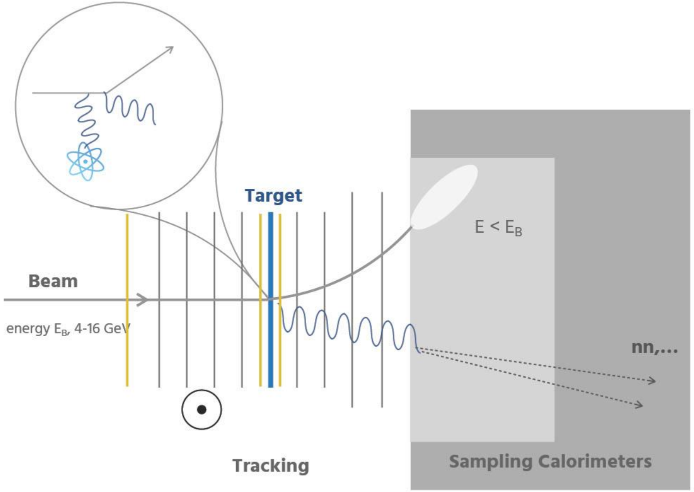
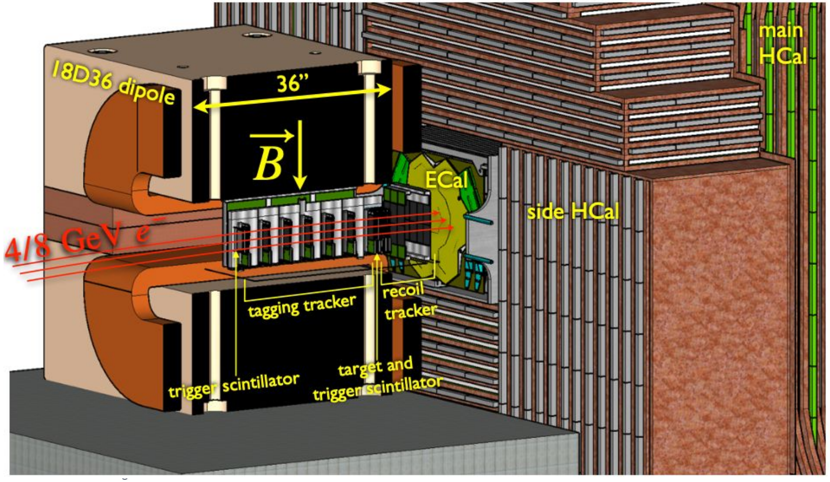
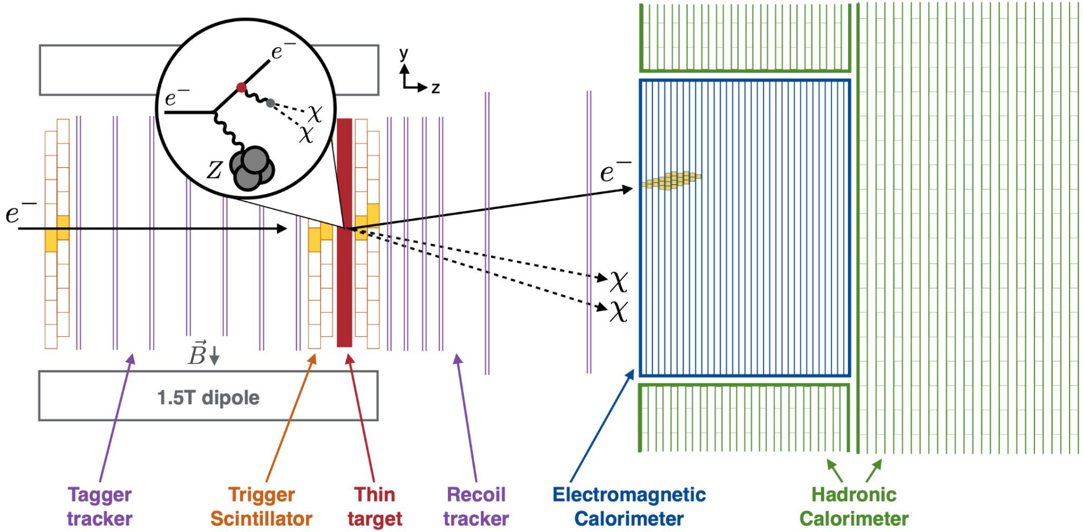


Photo-nuclear process (PN) are more rare but more challenging. These are mitigated by a high granularity Ecal and a deep Hcal

LDMX Design

- Need hermetic, radiation tolerant detector designed for high beam rates
  - **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
  - **Trigger Scintillator**: scintillator bars provide fast count of incoming electrons





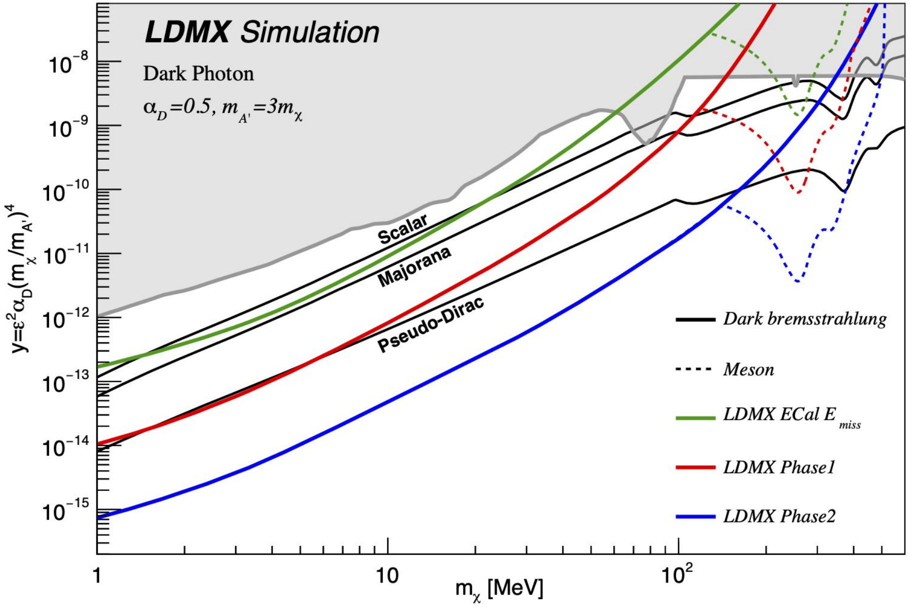
LDMX Sensitivity

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

arXiv:1912.05535

arXiv:1808.05219

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



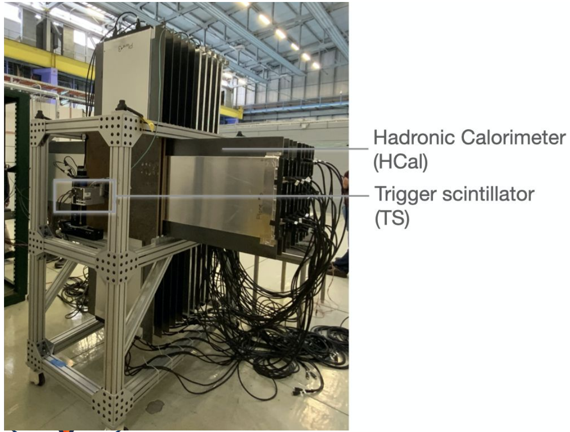
Phase 1: 4 GeV, 10^{14} electrons on target

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

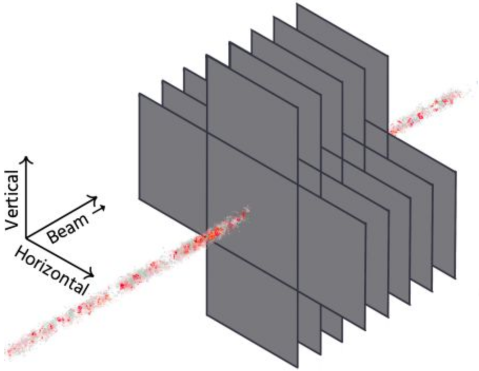
LDMX is based on existing technology from other experiments (HPS, CMS, and Mu2e)
We are “shovel ready” to build LDMX

CERN Test Beam

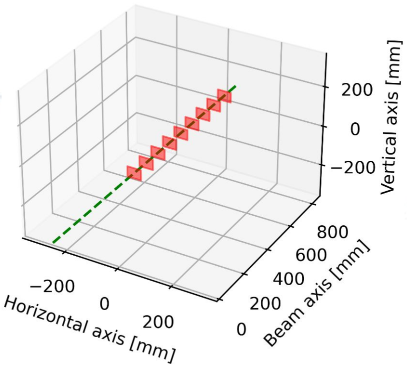
- Recent successful test beam at CERN PS in April 2022 with Hcal and trigger scintillator (TS) prototypes
- Demonstrated successful operations, readout & electronics, and basic physics capabilities of two subsystems



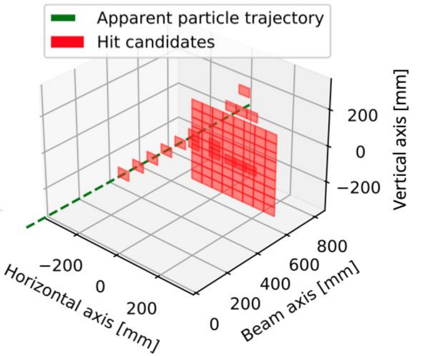
Beam & HCal orientation



Muon Candidate



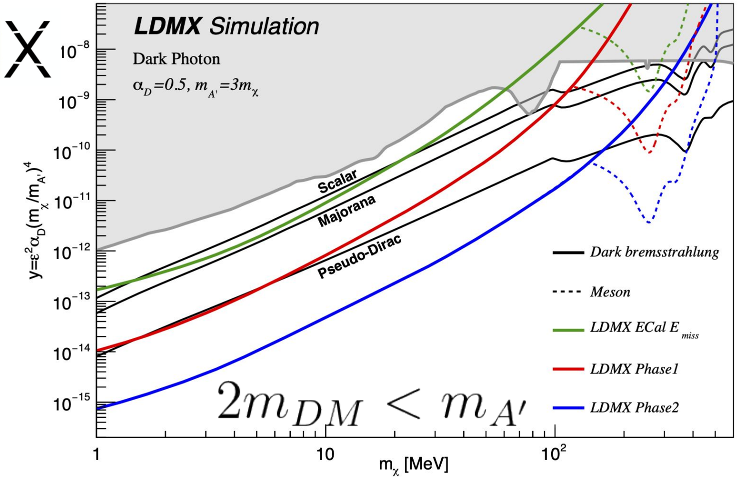
Pion Candidate

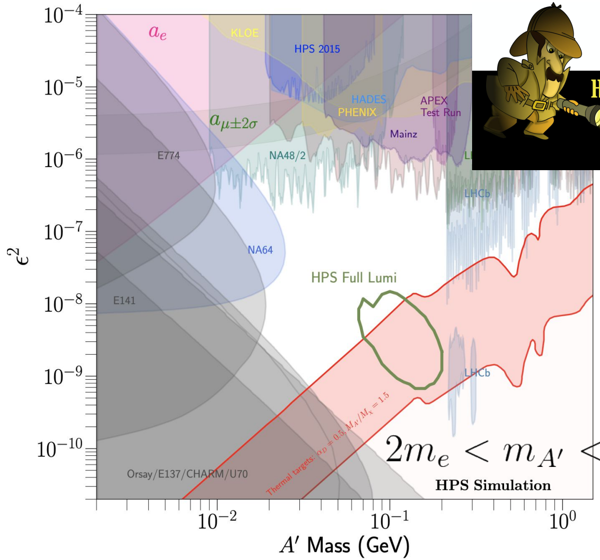


Preliminary results, data analysis is ongoing

Conclusion

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

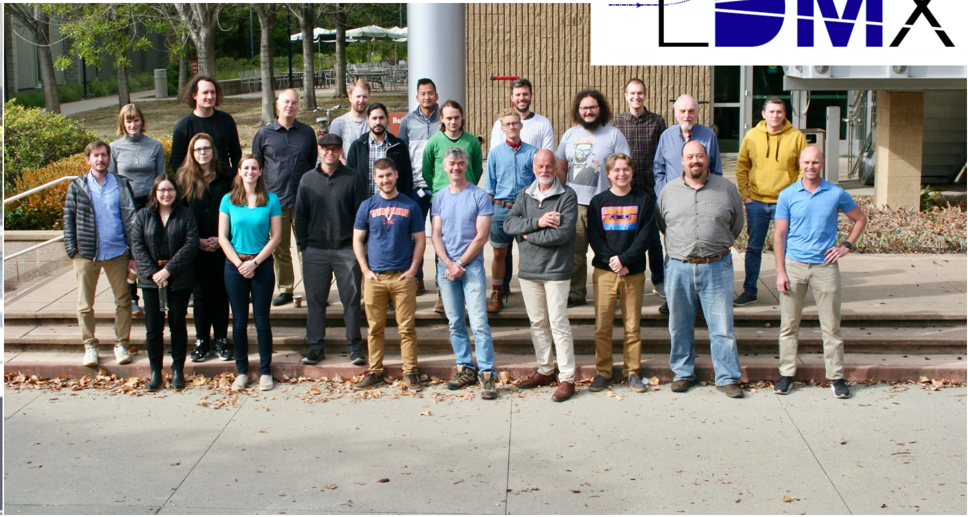




Thank You!

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

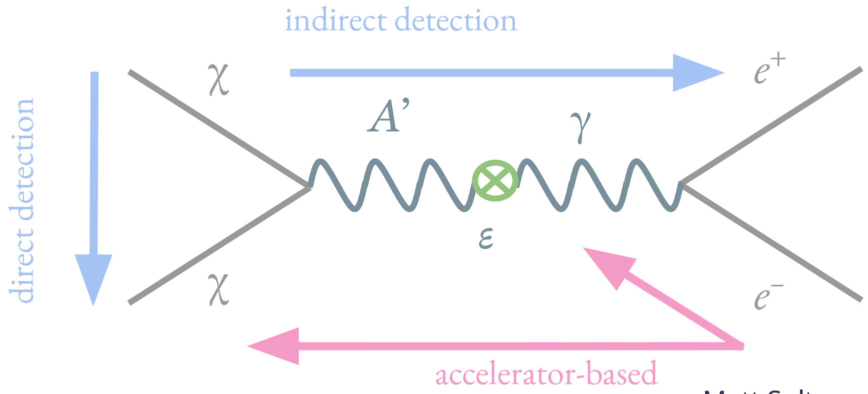
Heavy Photon Search

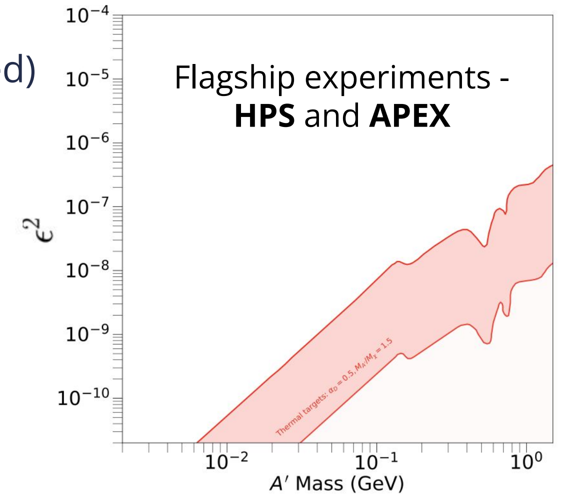


Heavy Photon Primer

- Bjorken, Essig, Schuster, Toro (B.E.S.T.) proposed several **fixed target** techniques to probe the A' parameter space motivated by DM
- Highly motivated MeV-GeV parameter space DM
  - Highly predictive and attainable **"thermal targets"**
  - PAMELA positron fraction excess in 2009 (DM annihilation explanation has since been disfavoured)

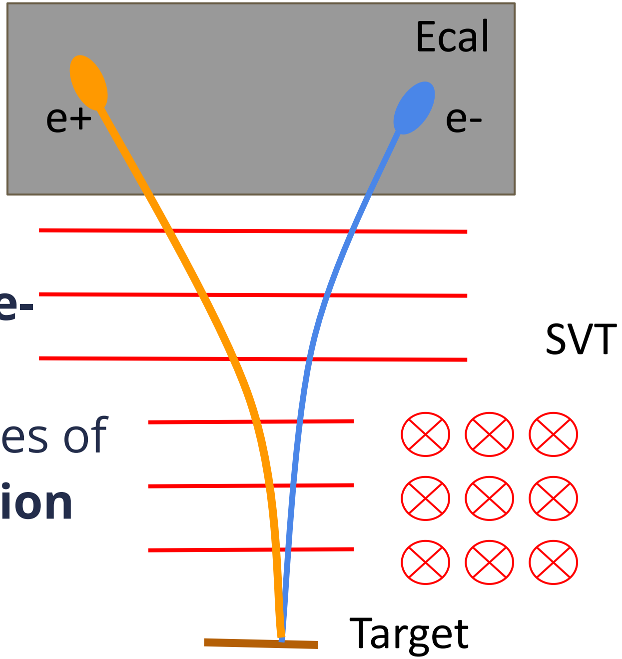
Phys. Rev., D80:075018

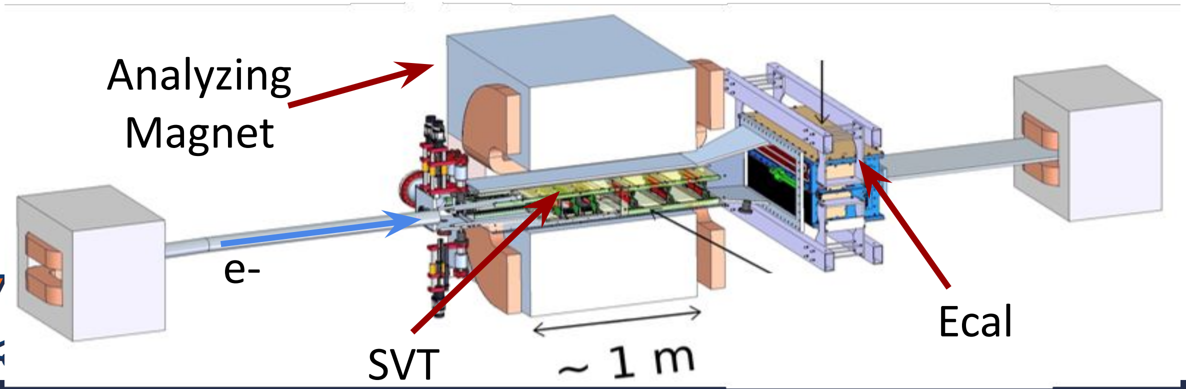


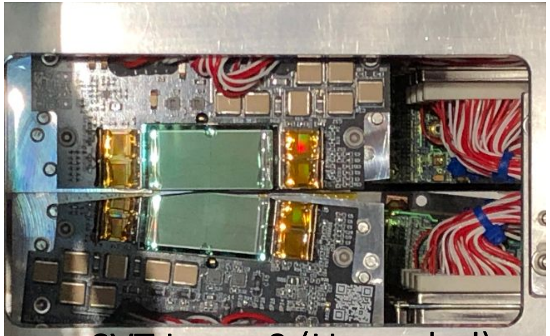


HPS Apparatus

- 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

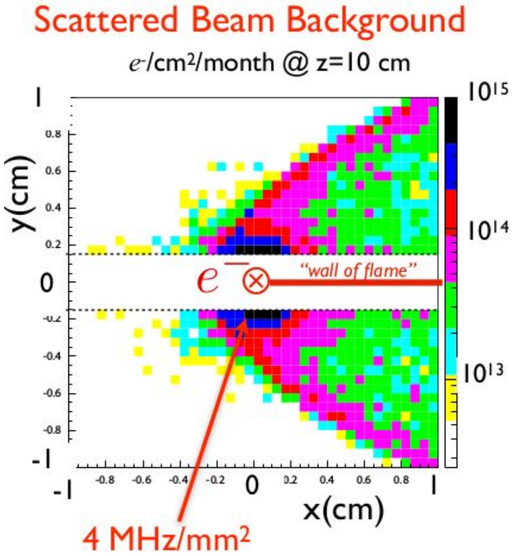


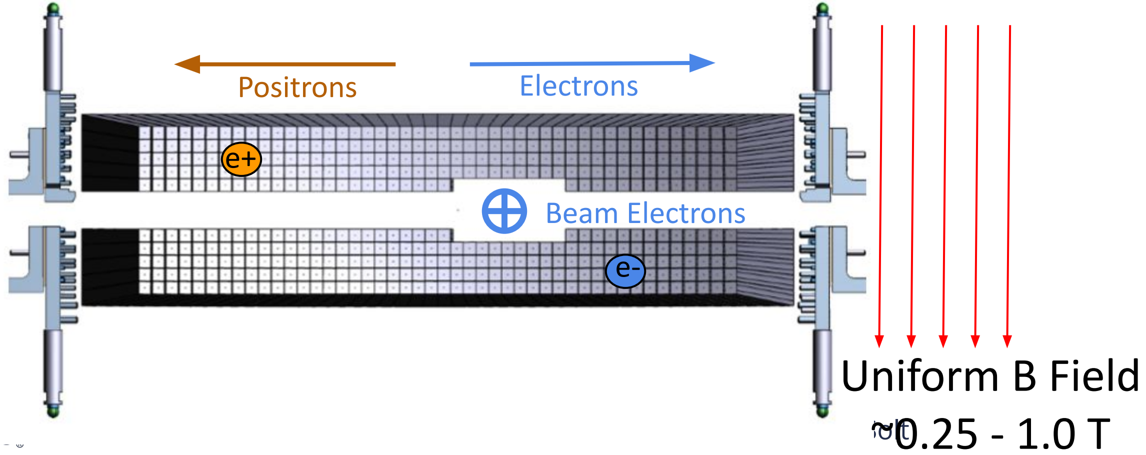



SVT Layer 0 (Upgraded)

Electromagnetic Calorimeter (Ecal)

- Ecal made out of 442 lead tungstate ($PbWO_4$) crystals and built by JLab/Orsay/INFN
- Split in top/bottom halves to avoid “wall of flame”
- Background is dominated by **electrons scattering in the target.** Trigger eliminates 10’s MHz of these





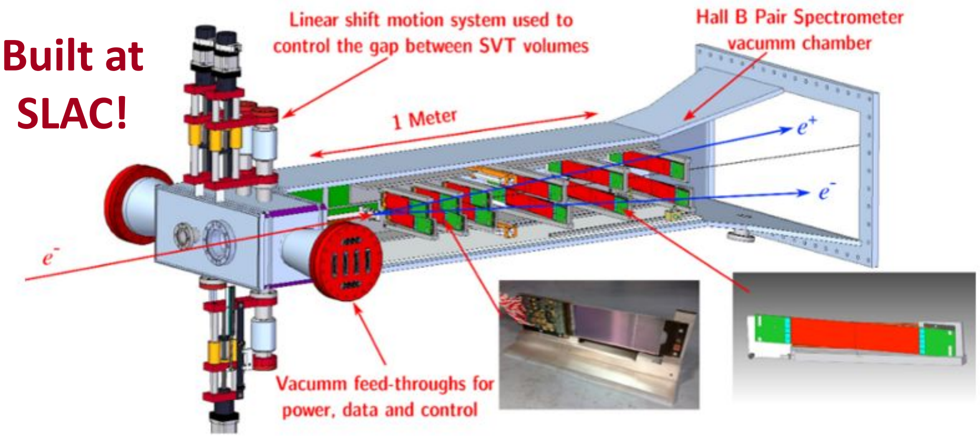
Trigger selects on opposite top/bottom clusters:

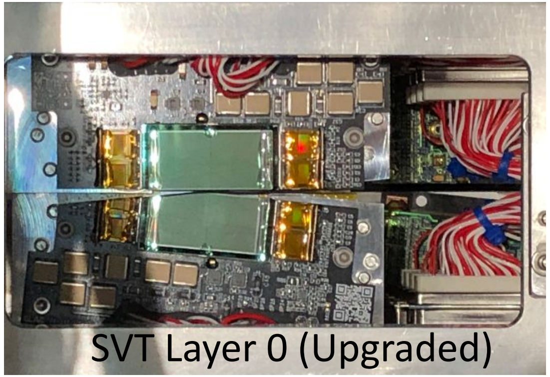
- Cluster Time Difference
- Cluster Energy
- Cluster Energy Sum
- Cluster Energy Difference
- Cluster Coplanarity

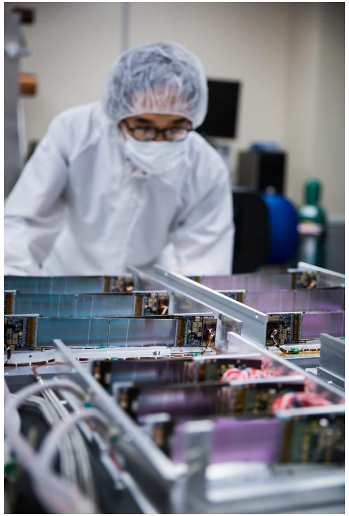
HPS Silicon Vertex Tracker

- 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 for 3D hit position (50 or 100 mrad)
- 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)

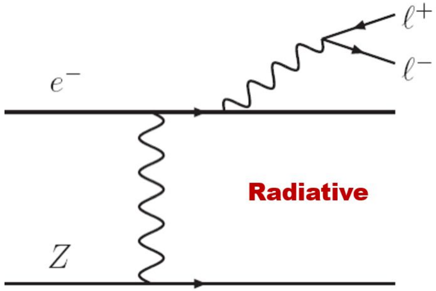


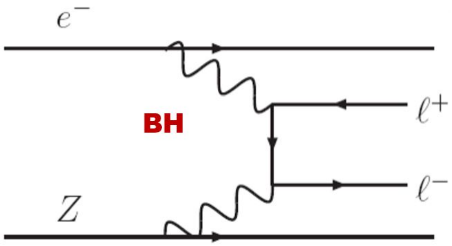
Trident Backgrounds

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

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

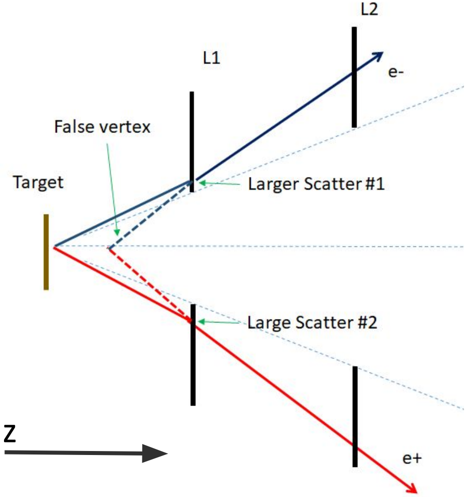
- **Bethe-Heitler (BH) tridents**
  - Softer e+e- pairs, but still dominates the signal region
- **Converted photons** in tracker or target
  - Simple cuts eliminate about 80% of these e+e- pairs with minimal signal loss
- Distinguishing the prompt QED tridents from displaced signal is the challenge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

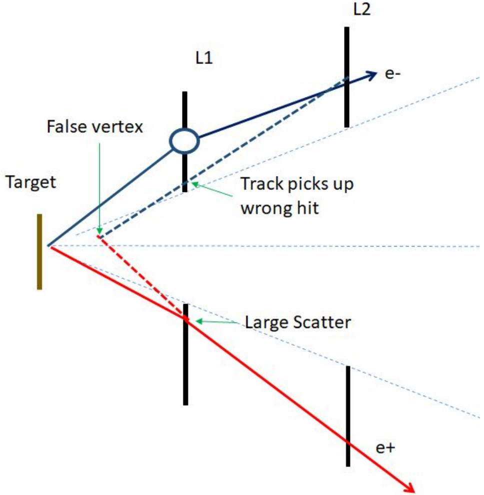


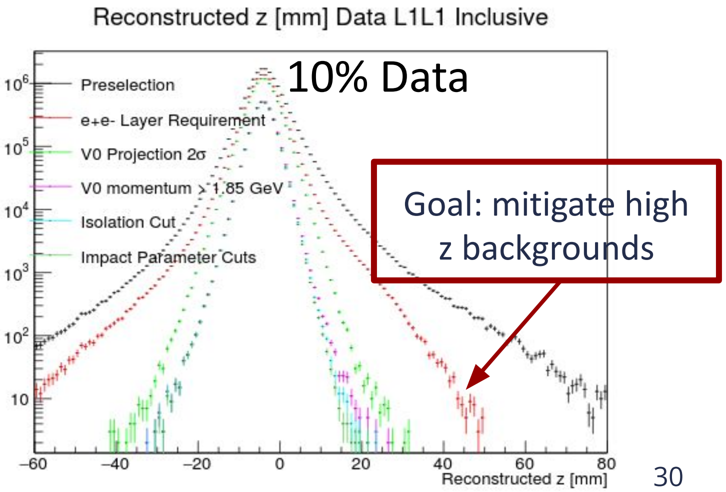


Displaced Vertex Search Event Selection

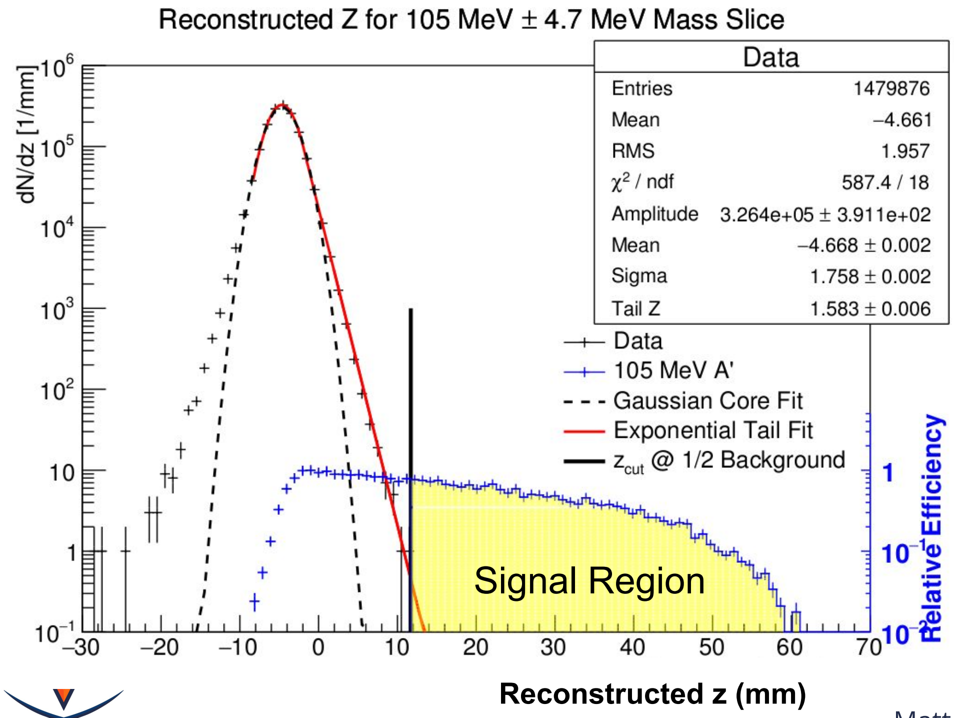
- Displaced vertex search is blinded with the selection tuned on 10% data
- Two main backgrounds from prompt trident processes: large Coulomb scatters in layer 1 of the tracker and mis-tracking
  - Require strict selections on track quality and vertex quality & require layer 1 hits

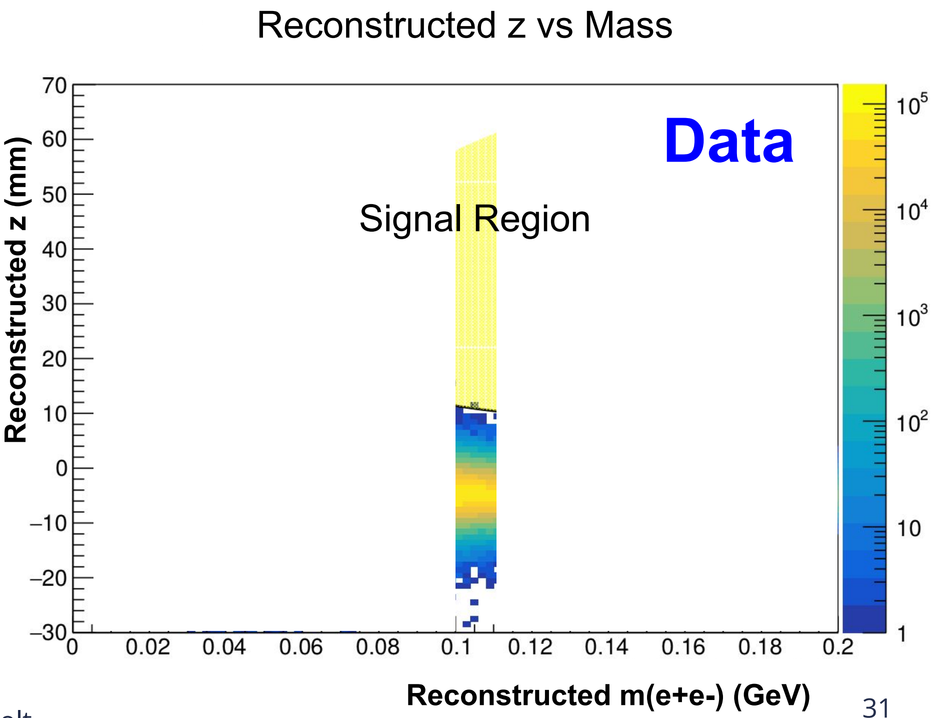




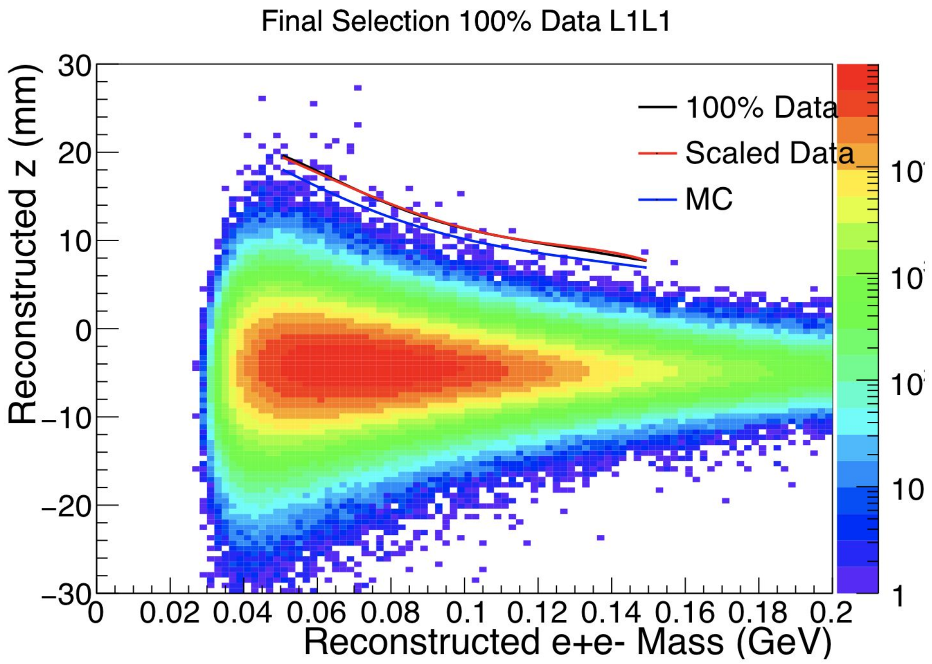


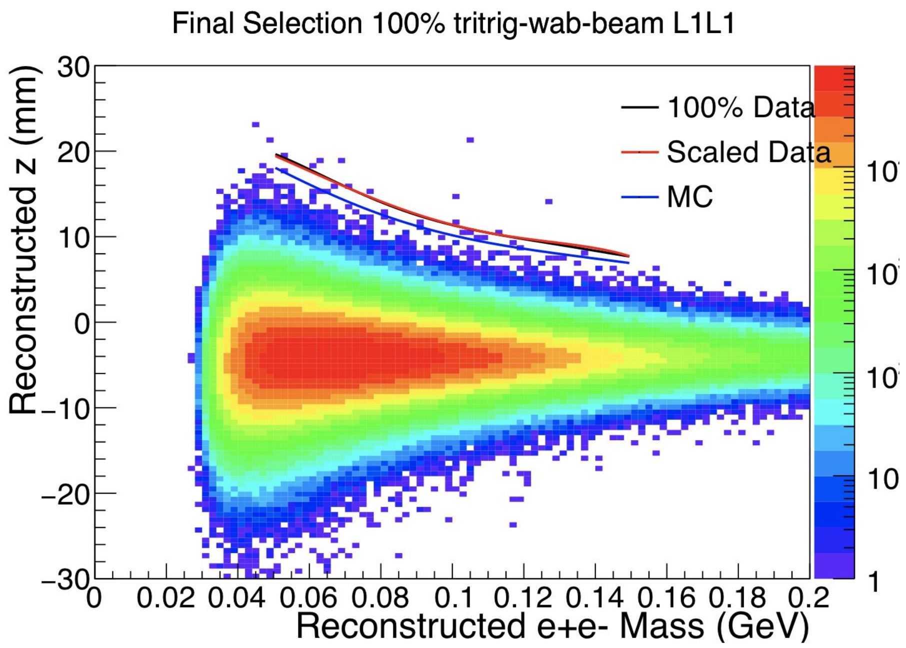
Displaced Vertex Search Signal Region





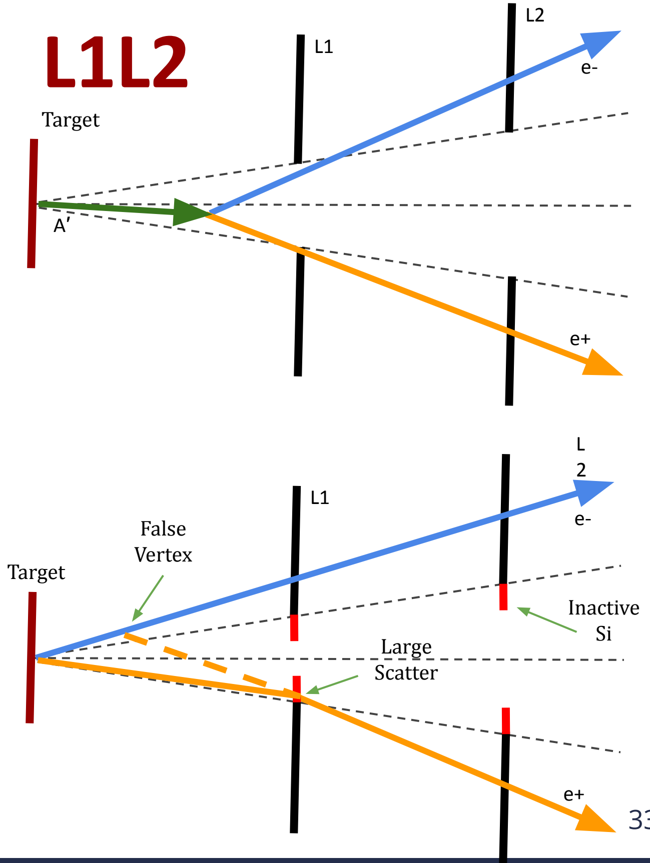
HPS L1L1 Data/MC Comparison





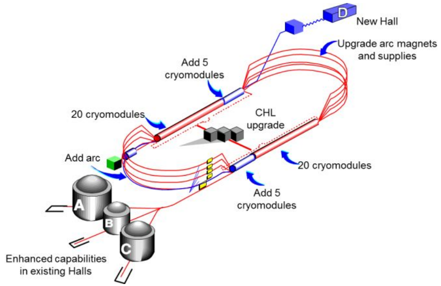
HPS A’s with Longer Livetimes

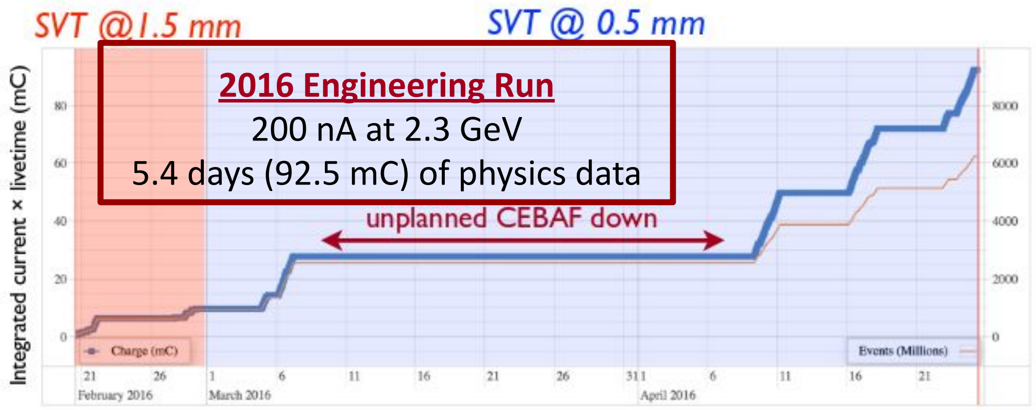
- A’s with longer livetimes will have e+e- daughters that may miss layer 1 of the tracker
- Divide analysis into L1L1 (both particles hit L1) and L1L2 (one particles misses L1) categories
- Additional backgrounds for L1L2
    - Hit inefficiencies
    - Large Coulomb scatters in inactive Si
    - Brem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

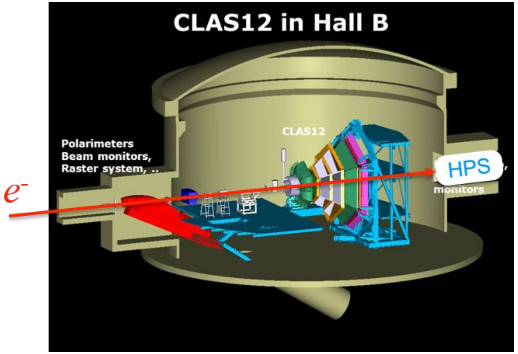


Jefferson Lab and CEBAF

- 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** ($\sim 10^{-6}$)



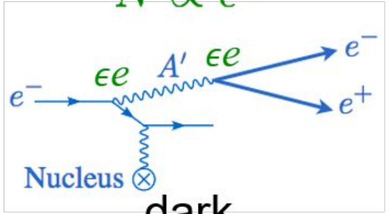




Types of Acclerator Experiments Searching for A’s

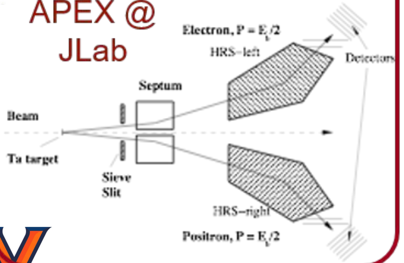
e^- fixed target

$N \propto \epsilon^2$



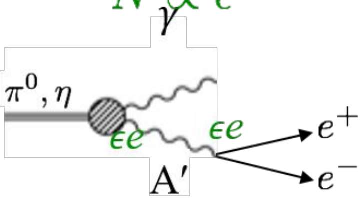
dark bremsstrahlung

APEX @ JLab

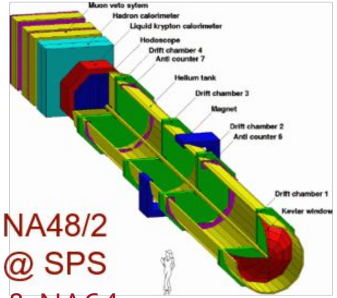


p fixed target

$N \propto \epsilon^2$



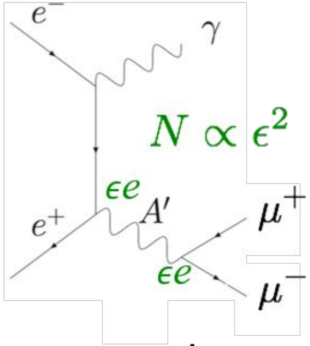
meson decays



NA48/2 @ SPS

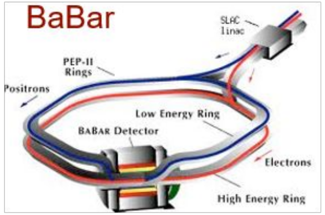
& NA64

e^+e^- colliders

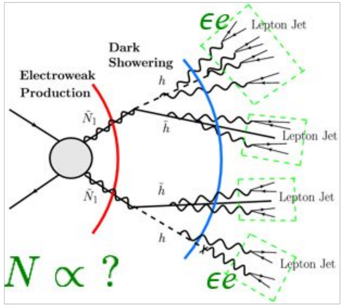


+ meson decays

BaBar



pp collider



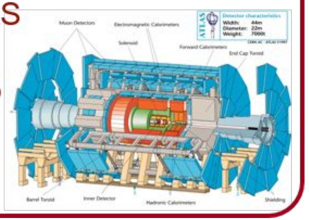
“lepton jets”

+ meson decays

ATLAS

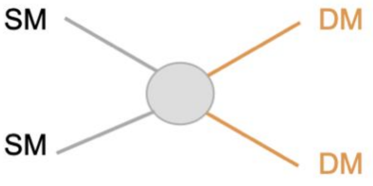
CMS

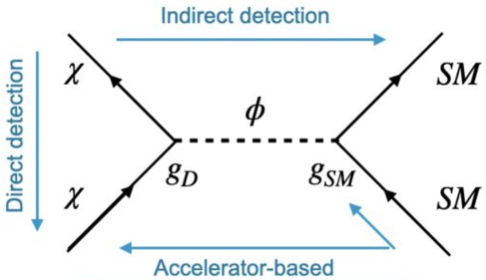
LHCb

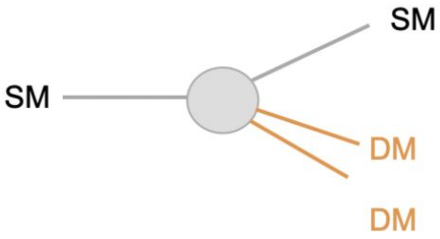


Anytime you can produce a photon, you can produce a dark photon

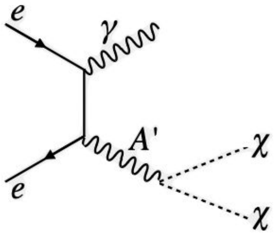
Advantage of Fixed Target Missing Momentum Search



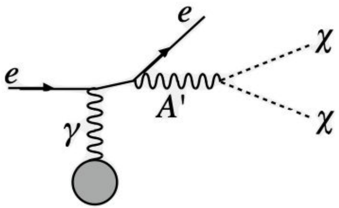




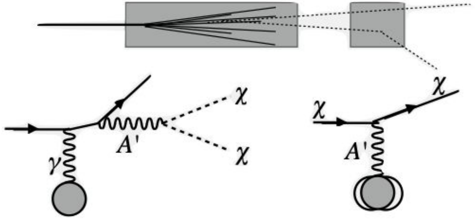
Collider



Missing Momentum



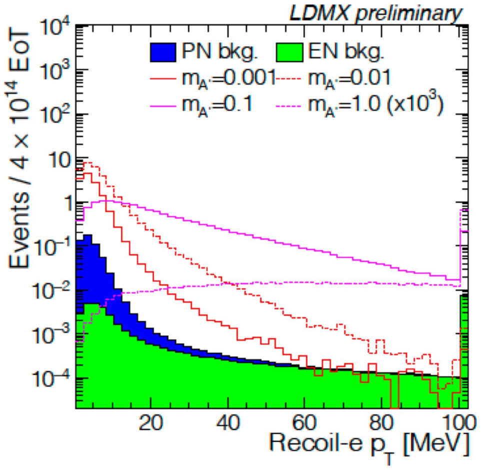
Beam dump

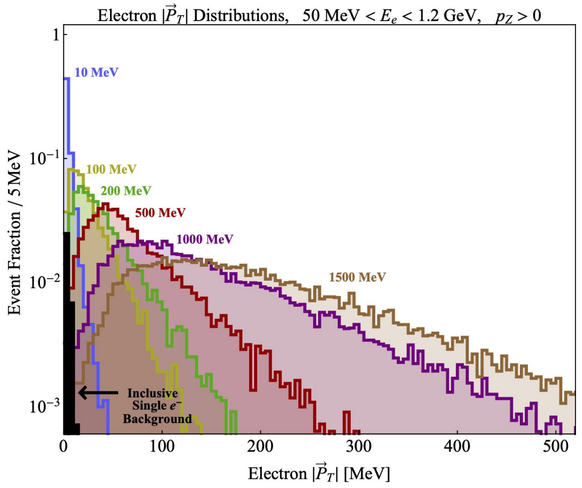


$\sigma_{coll} \propto \frac{\epsilon^2}{E_{com}^2}$ $<<$ $\sigma_{FT} \propto \frac{Z^2\epsilon^2}{m_{A'}^2}$ $N \propto \epsilon^2$ $>>$ $N \propto \epsilon^4$ Direct detection

Signal Kinematics

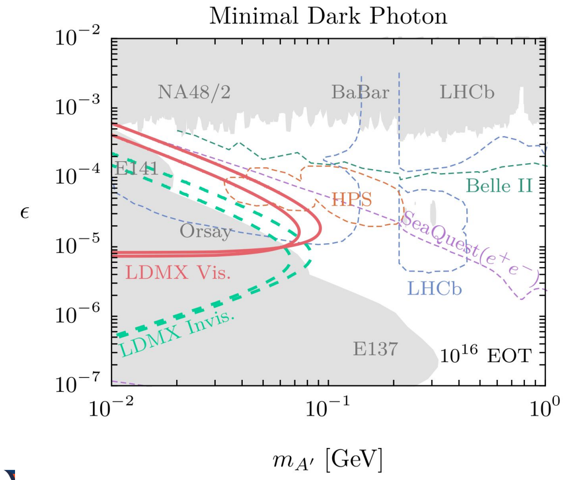
- Transverse momentum of recoil election is the last veto handle
- Currently not used in veto efficiency estimates, but as a backup discriminator
- Transverse momentum can also be used to estimate/constrain DM mass scale

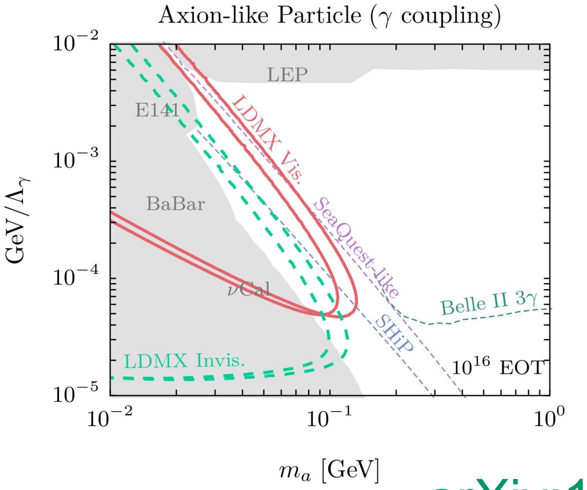


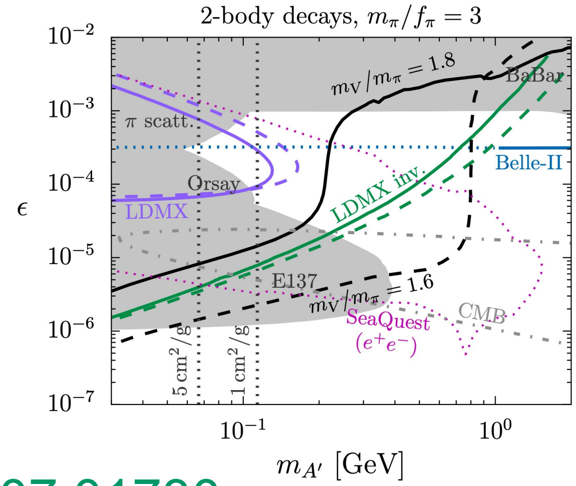


LDMX Visible Signatures

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





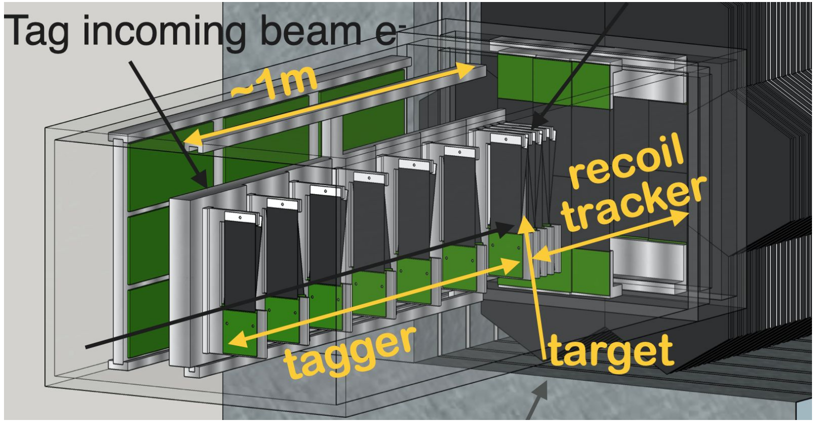


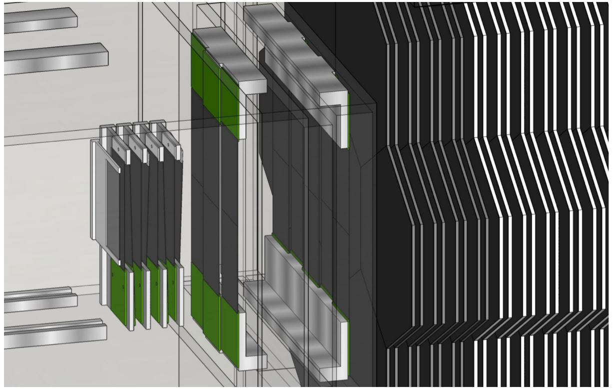
Projections are for 8 GeV and 16 GeV beams

[arXiv:1807.01730]

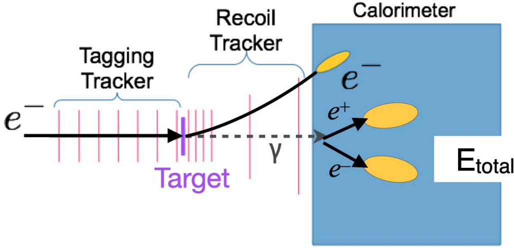
Tracker and Trigger Scintillator

- Tagging tracker
  - Measures incoming beam electron
- Recoil tracker (based on Heavy Photon Search design) arXiv:2212.10629v2
  - 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





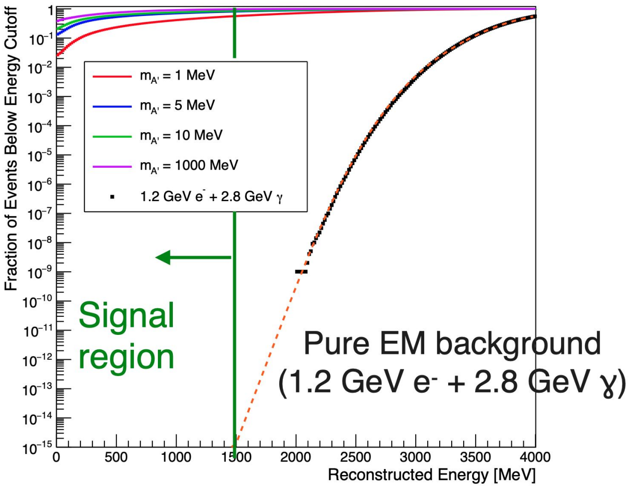
Electromagnetic Calorimeter

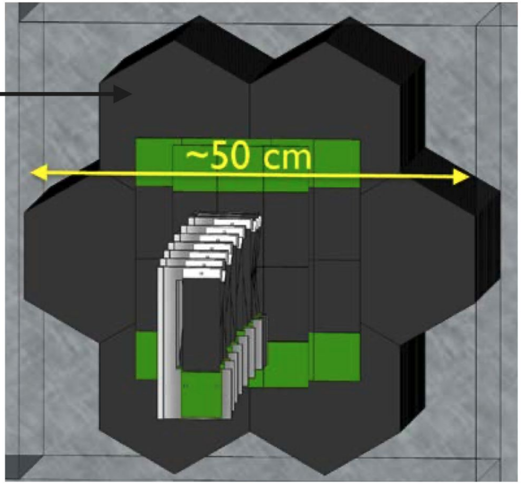


$E_{total} = E_{recoil} + E_\gamma \approx E_{beam}$

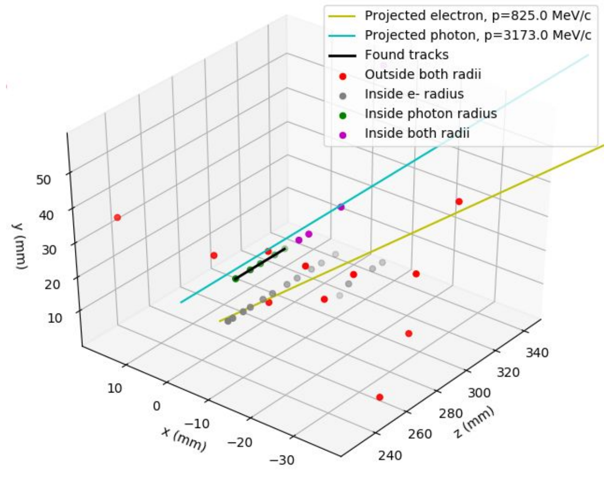
- 40 X_0 Si-W sampling calorimeter (based on CMS HGCal upgrade)
  - Provides fast missing energy trigger
  - Dense, radiation hard, full shower containment, and high granularity

10.17181/CERN.IV8M.1JY2

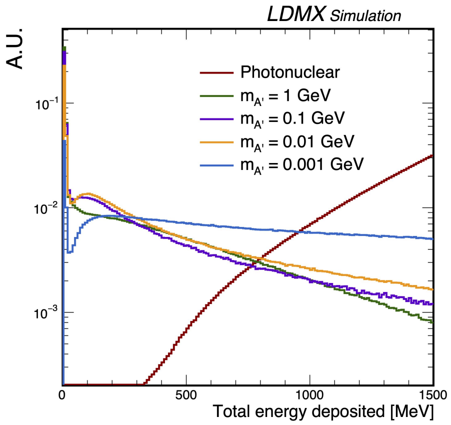


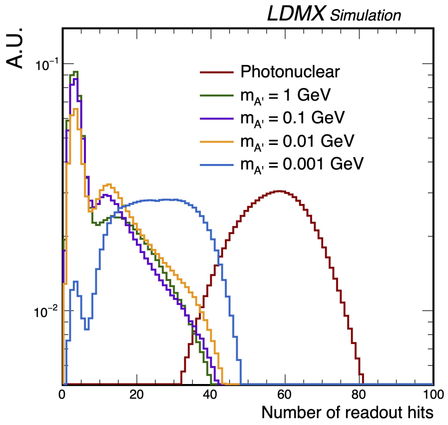


Ecal BDT

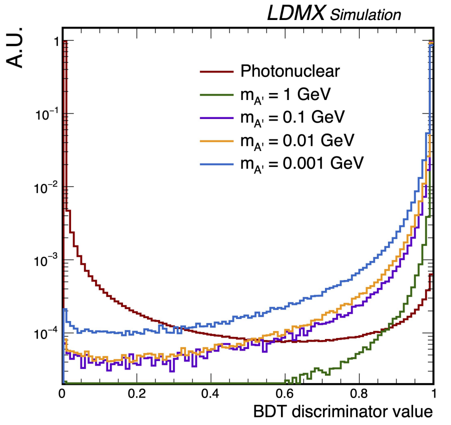


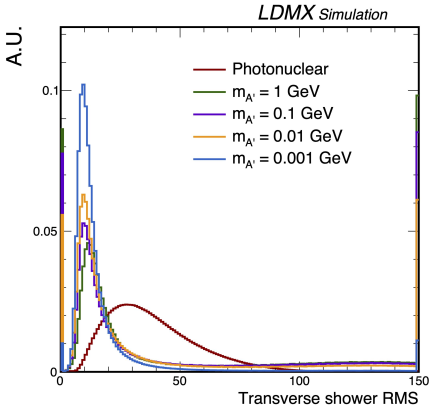
MIP Tracking





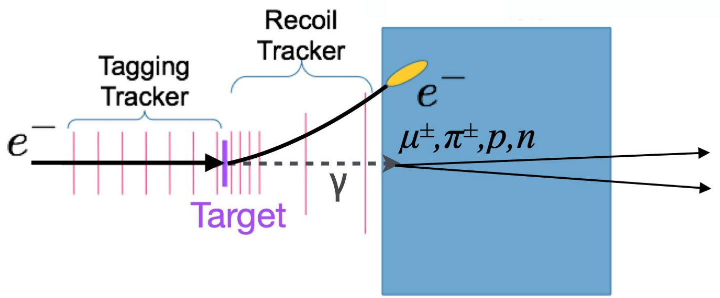
BDT Variables

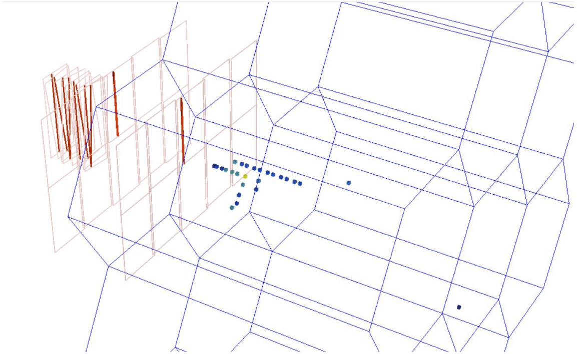


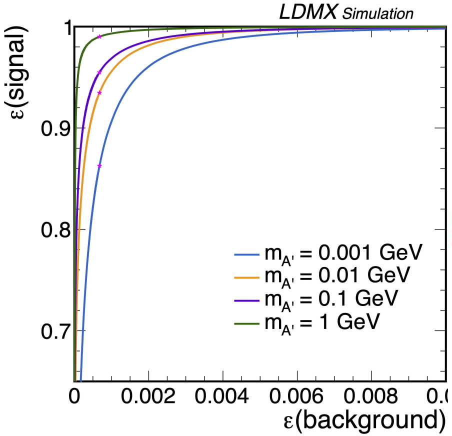


Ecal Veto

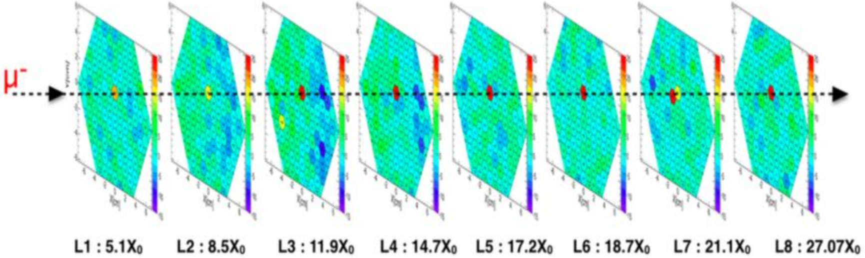
- More difficult to veto: Rare photon reactions that deposit low energy in the Ecal
  - Exploit longitudinal/transverse shower shapes and train a boosted decision tree (BDT)
  - High granularity Ecal enables MIP tracking





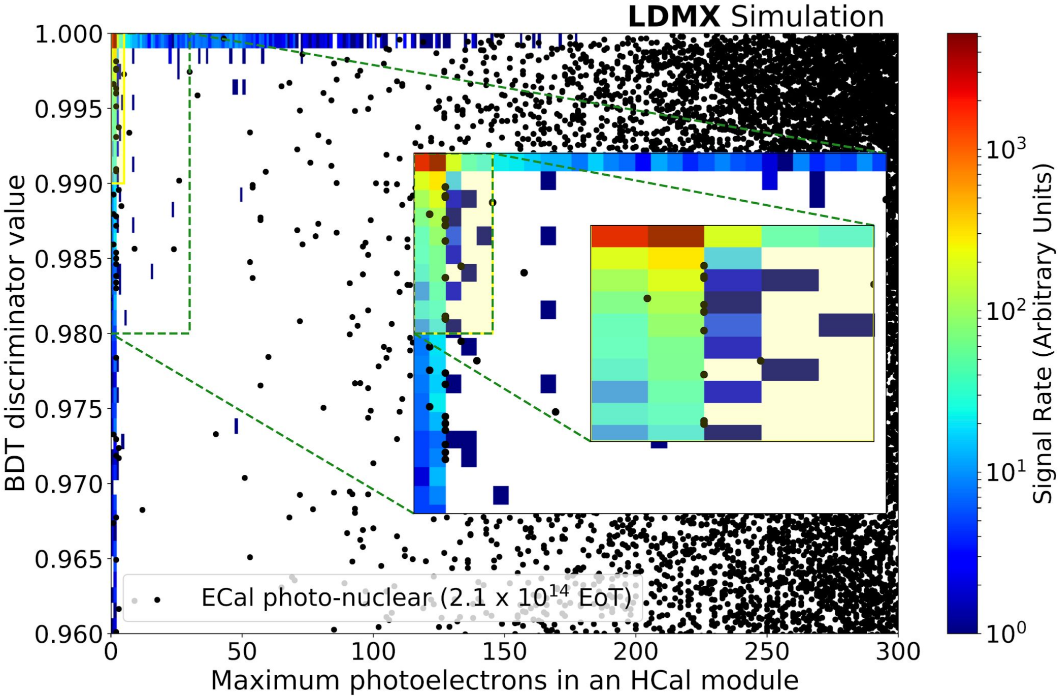


A.Martelli on behalf of CMS, arXiv:1708.08234



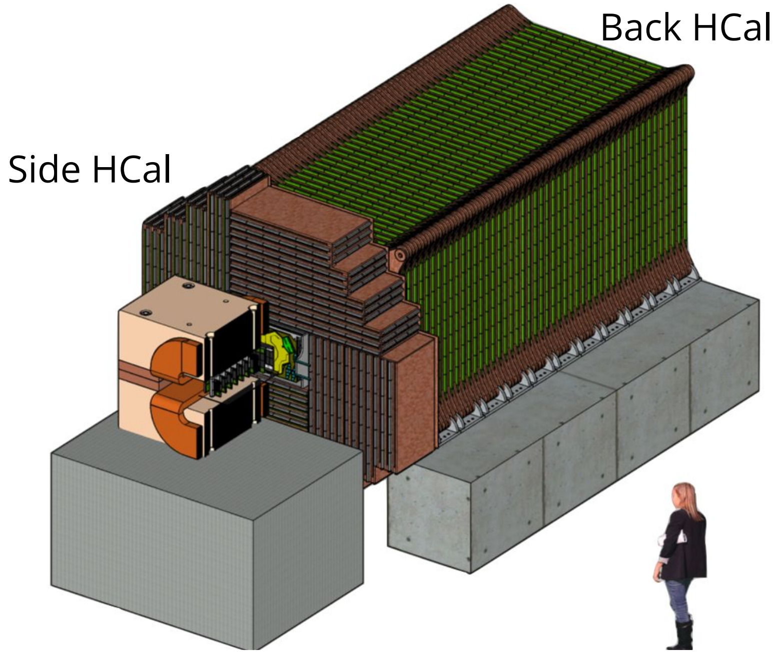
Ecal/Hcal Vetoes

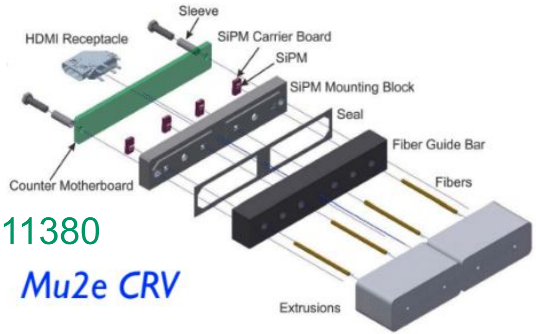
- Ecal BDT > 0.99
- Hcal max PEs is > 5

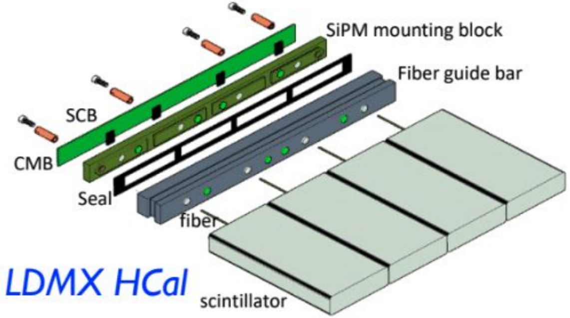


Hadronic Calorimeter

- 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 Photo-Nuclear (PN) processes that produce neutral hadrons. Desire 1e-6 rejection
  - Side HCal rejects wide angle brem and $\gamma \to \mu^+\mu^-$







arXiv:2210.11380

Backgrounds

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

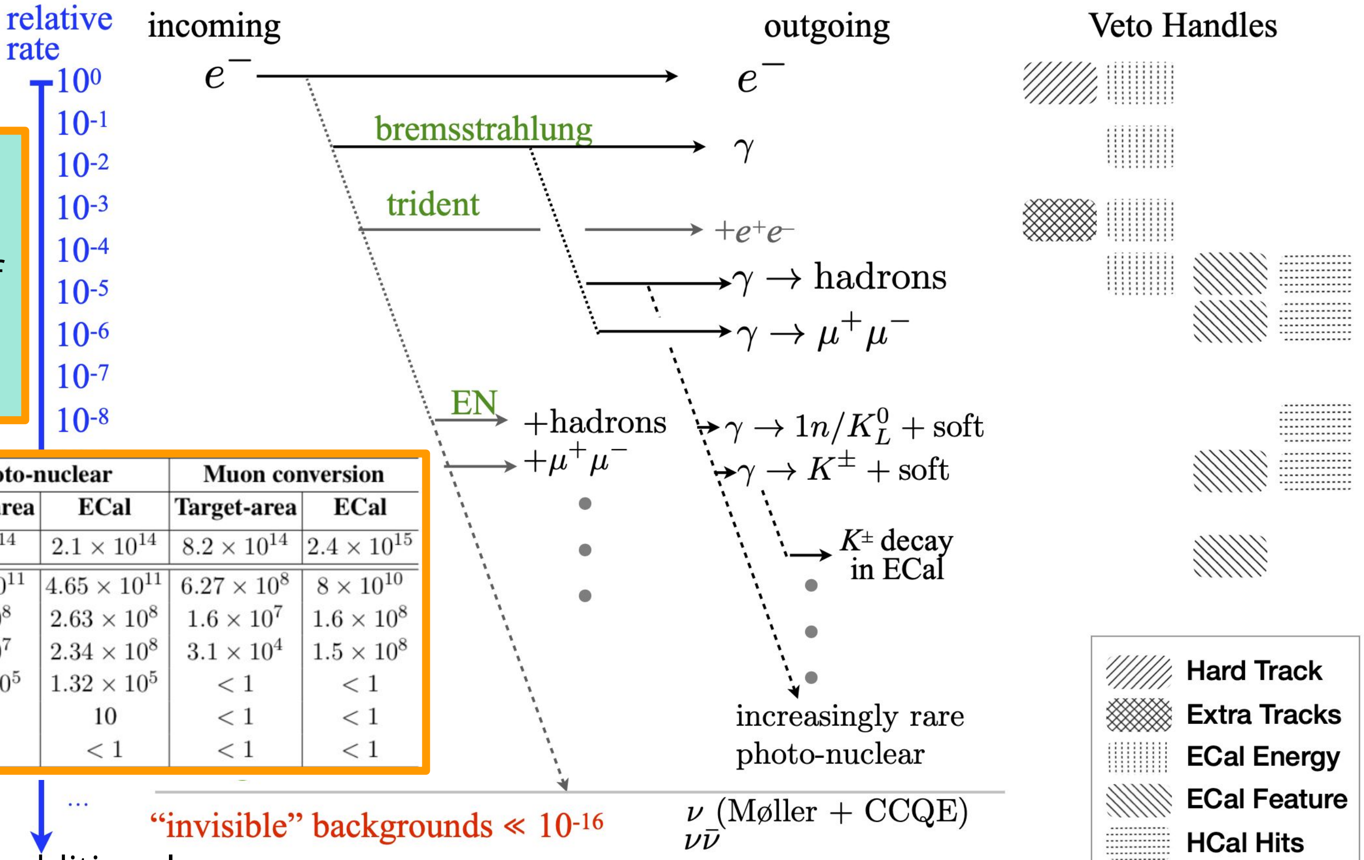


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p <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