The Heavy Photon Search at JLab

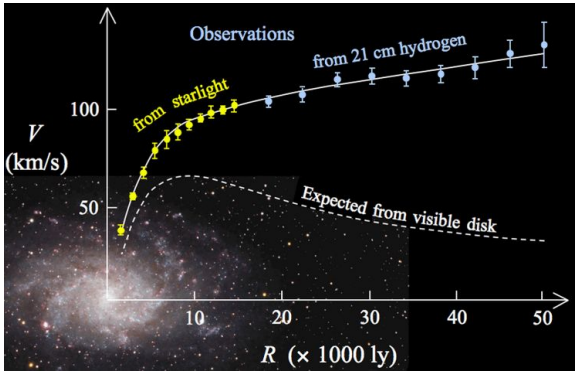
April 19, 2023

Matt Solt, University of Virginia

University of Minnesota HEP Seminar

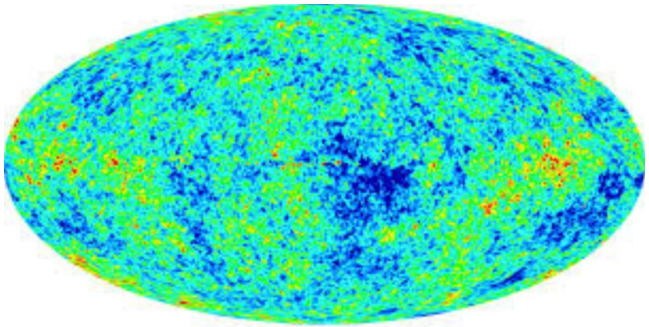
The Existence of Dark Matter

- 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

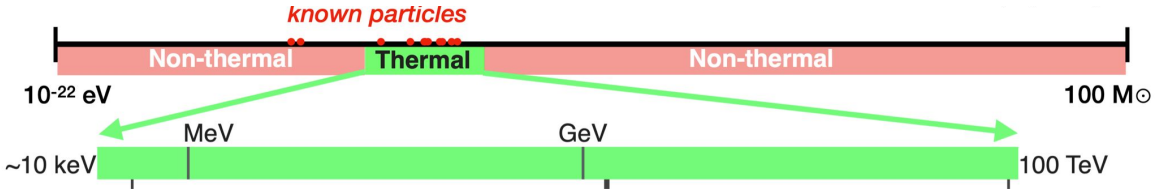
Gravitational Lensing



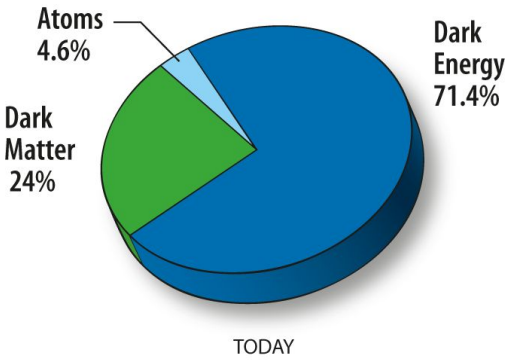
Cosmic Microwave Background

A Thermal Relic

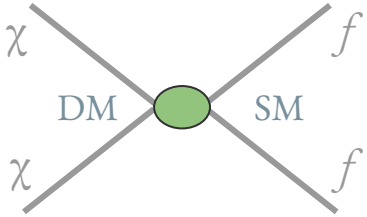
- Astrophysical evidence of DM does not constrain the mass scale very well
- **A thermal relic** - simple and predictive model of dark matter (DM)
- Thermal DM constrains DM mass to ~mass scale of SM particles and relates the annihilation cross-section to the observed relic abundance (~85%)



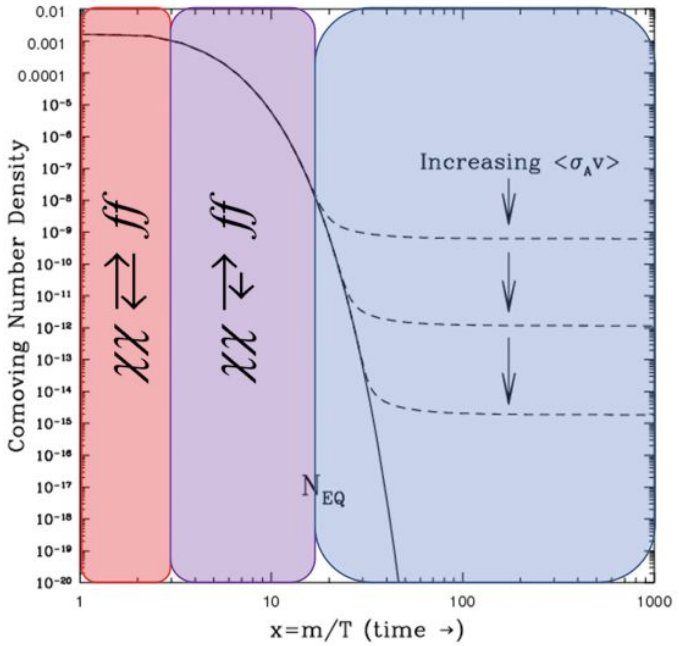
The range of (non-)thermal DM mass spans a range of ~(90) 7 orders of magnitude!



A Thermal Relic



arXiv:9506380

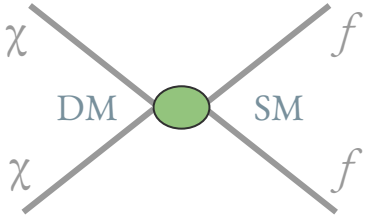


- What is a thermal origin of DM?
  - **1.** Assume DM was in thermal equilibrium with SM particles
  - **2.** The universe expands and cools such that DM pairs are no longer produced
  - **3.** The universe expands and cools such that DM annihilations cease
- The present DM density Ω_χ is related to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

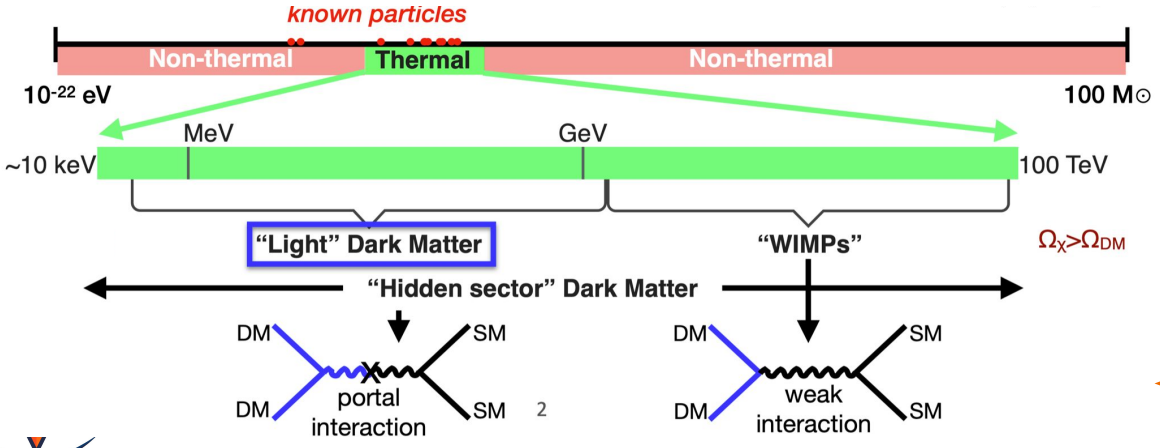
$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \rightarrow \langle \sigma v \rangle = 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

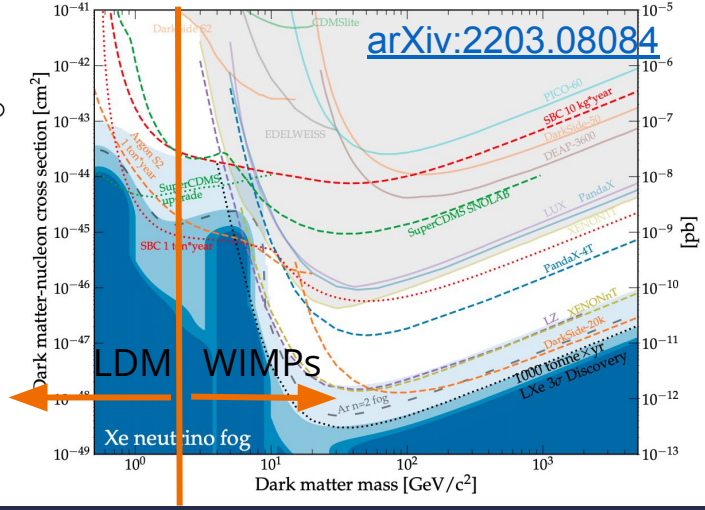
Any proposed mechanism must yield ≤ 85% DM!

A Thermal Relic - WIMPs and LDM



- WIMPs are 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





Matt Solt

Heavy Photon Primer

Phys. Lett., B166:196–198

- An additional U’(1) symmetry proposed by B. Holdom 1985
- The model includes an additional massive gauge boson - a heavy photon (dark photon or A’)

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

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

Heavy Photon Primer

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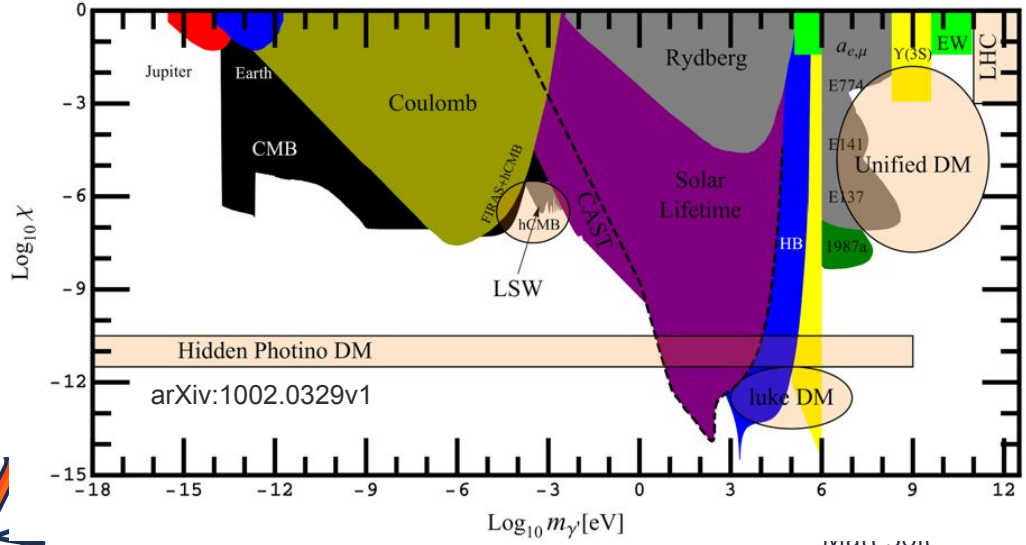

Two Parameter Model:

Mass of A′ and ε

*Updated exclusions in backup

Heavy Photon Primer

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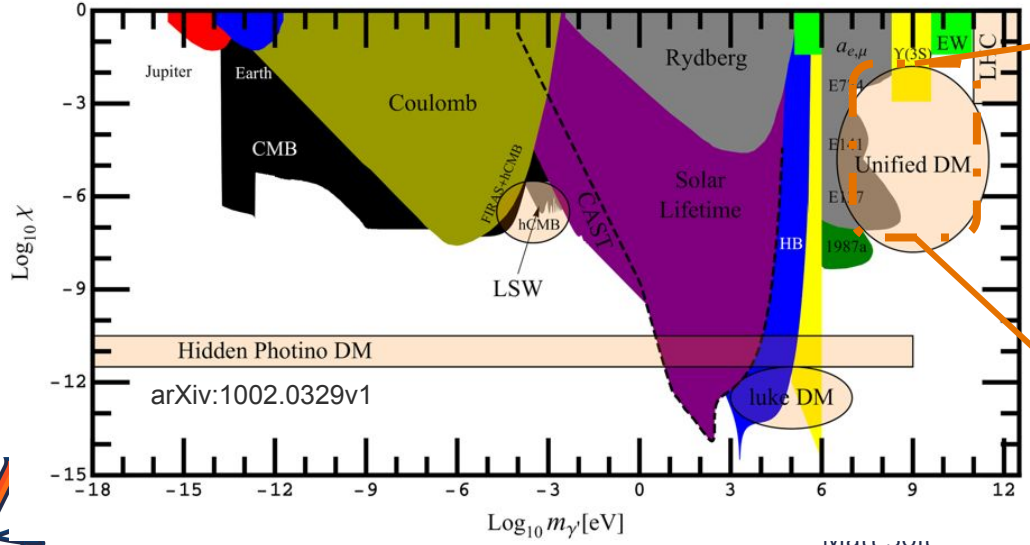
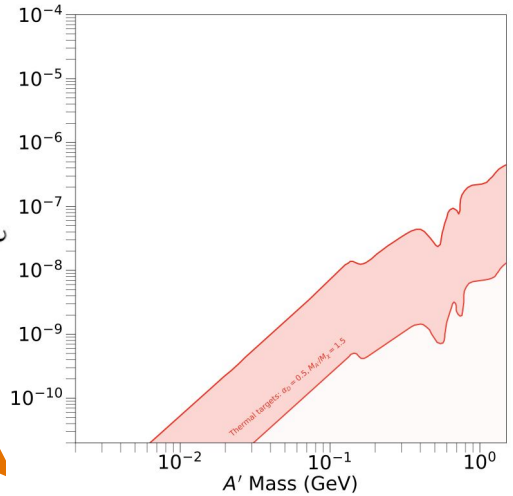
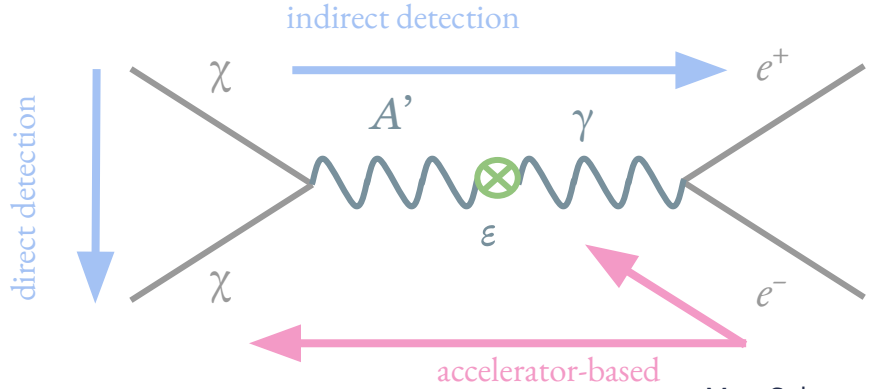


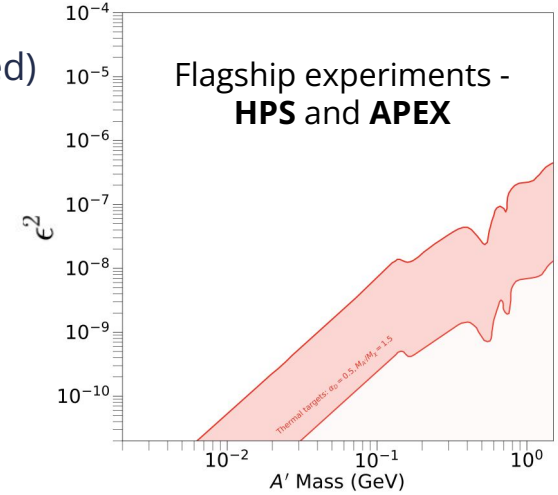


Heavy Photon Primer

- 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

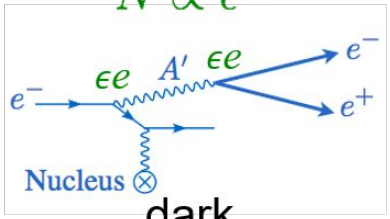




Types of Experiments Searching for Dark Photons

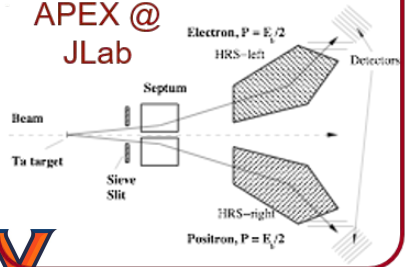
e^- fixed target

$N \propto \epsilon^2$



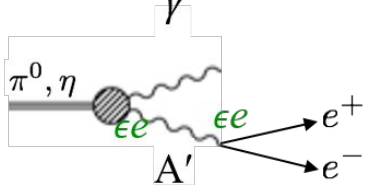
dark bremsstrahlung

APEX @ JLab

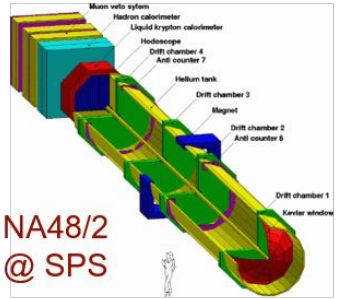


p fixed target

$N \propto \epsilon^2$

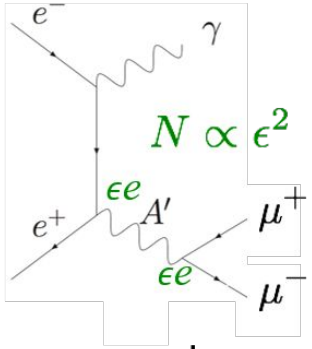


meson decays

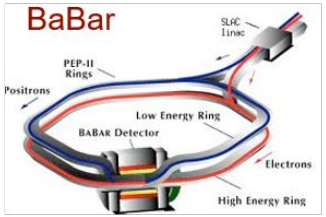


NA48/2 @ SPS

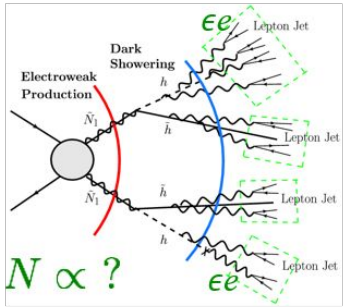
e^+e^- colliders



+ meson decays

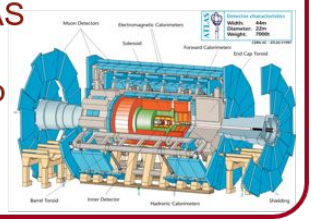


pp collider



"lepton jets"
+ meson decays

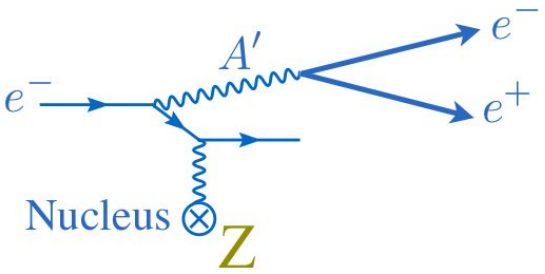
ATLAS
CMS
LHCb

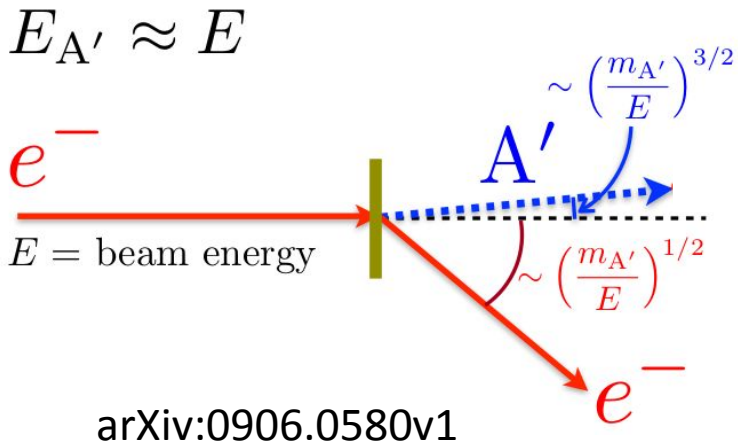


Anytime you can produce a photon, you can produce a dark photon

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



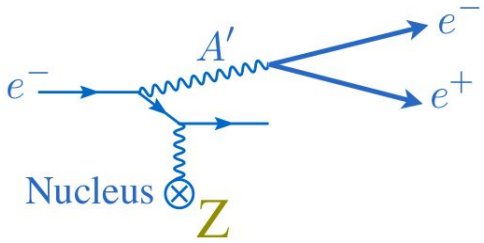


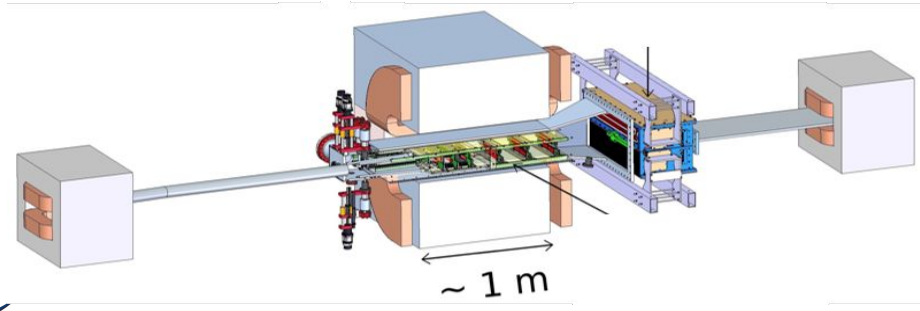
arXiv:0906.0580v1

Dark Photon Decays - Complimentary Searches

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

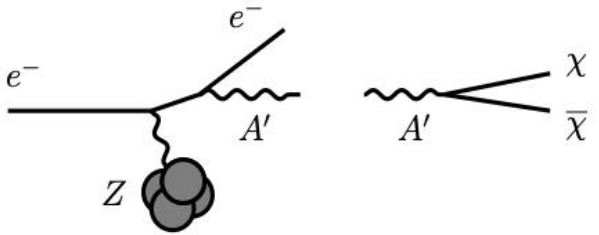
Heavy Photon Search (HPS) at Jefferson Lab

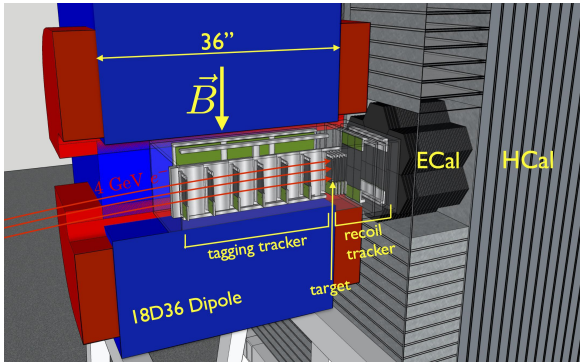




$$2m_{DM} < m_{A'}$$

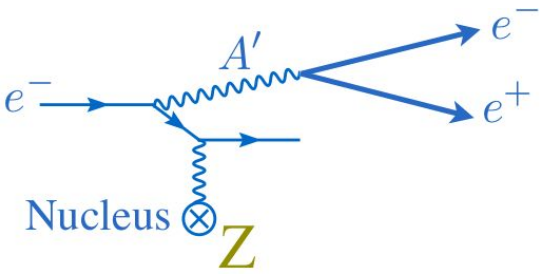
Proposed Light Dark Matter eXperiment (LDMX) at SLAC

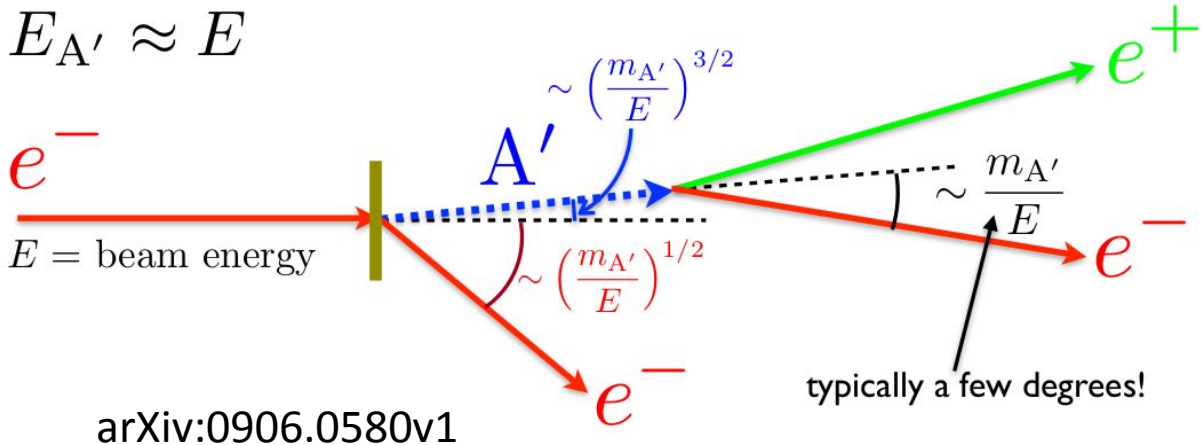




Dark Photon Production with a Fixed Target

- 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**

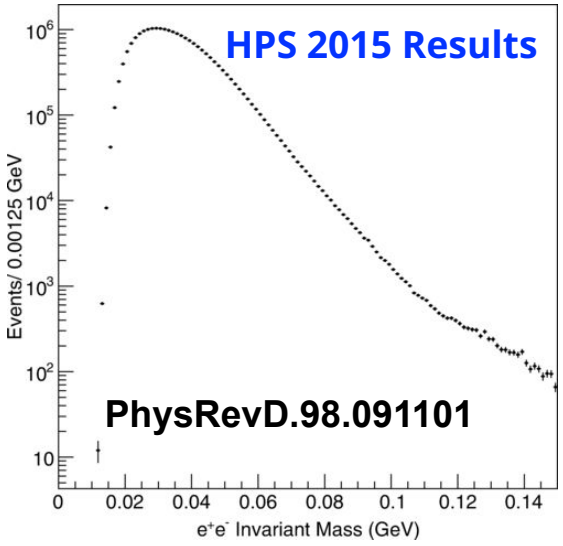




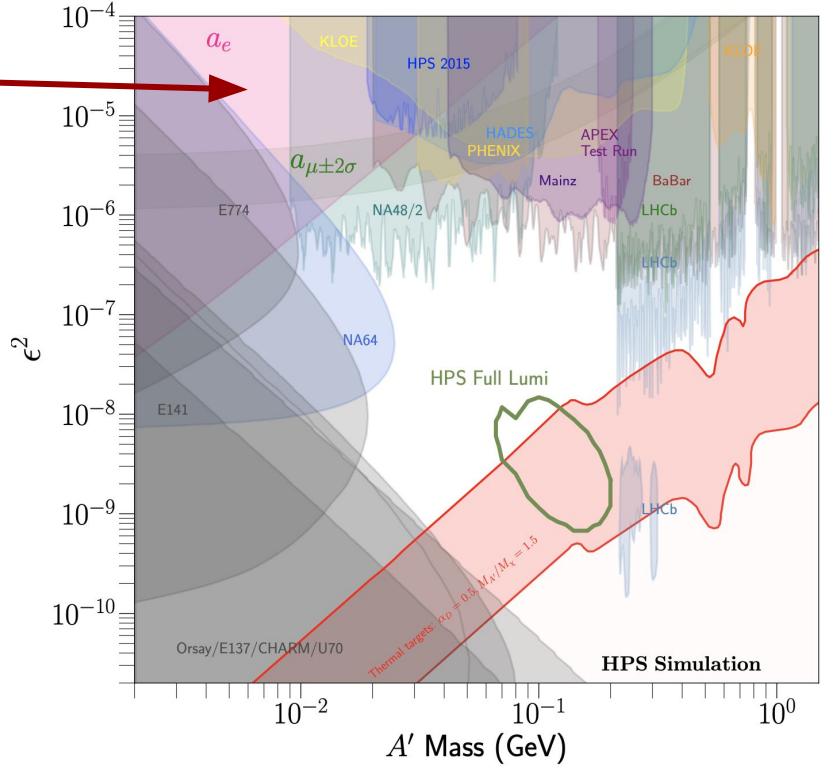
arXiv:0906.0580v1

Existing Dark Photon Constraints for Visible Decays

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



Prompt QED Tridents

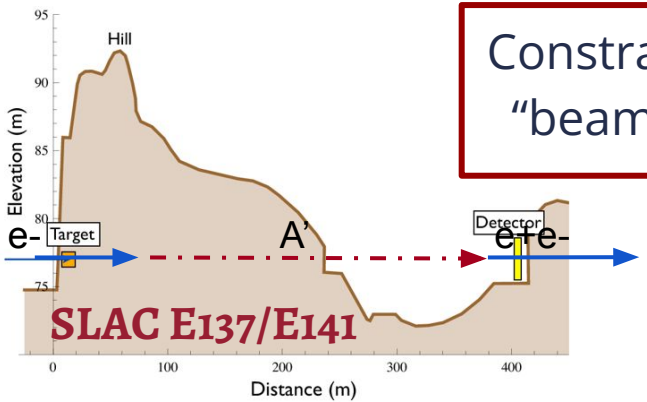


Existing Dark Photon Constraints for Visible Decays

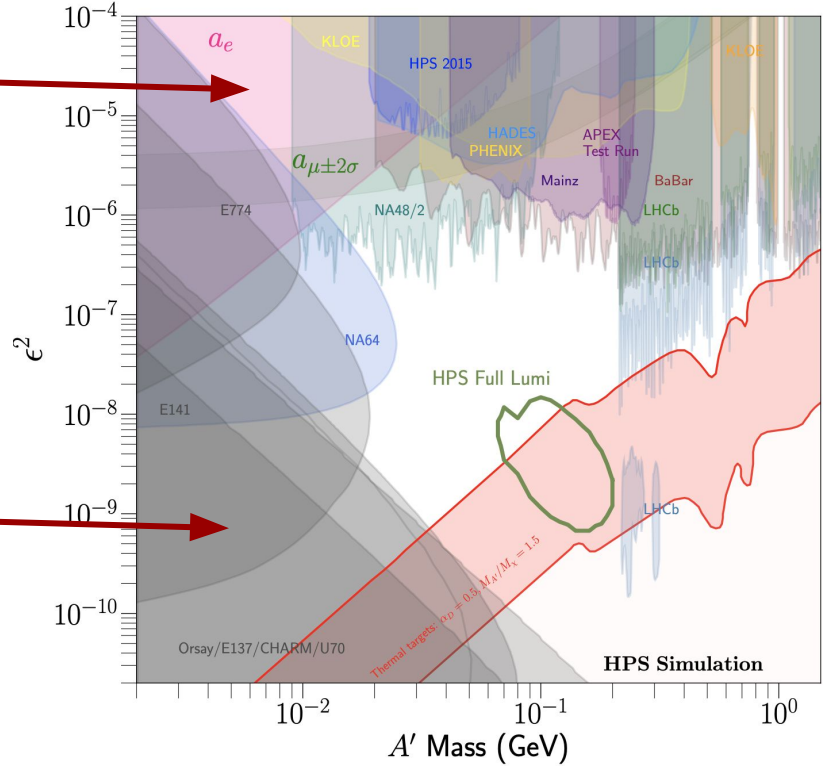
Large coupling searches are generally **"bump hunts"** for $m(l^+l^-)$ resonances

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

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



Constraints from "beam dumps"

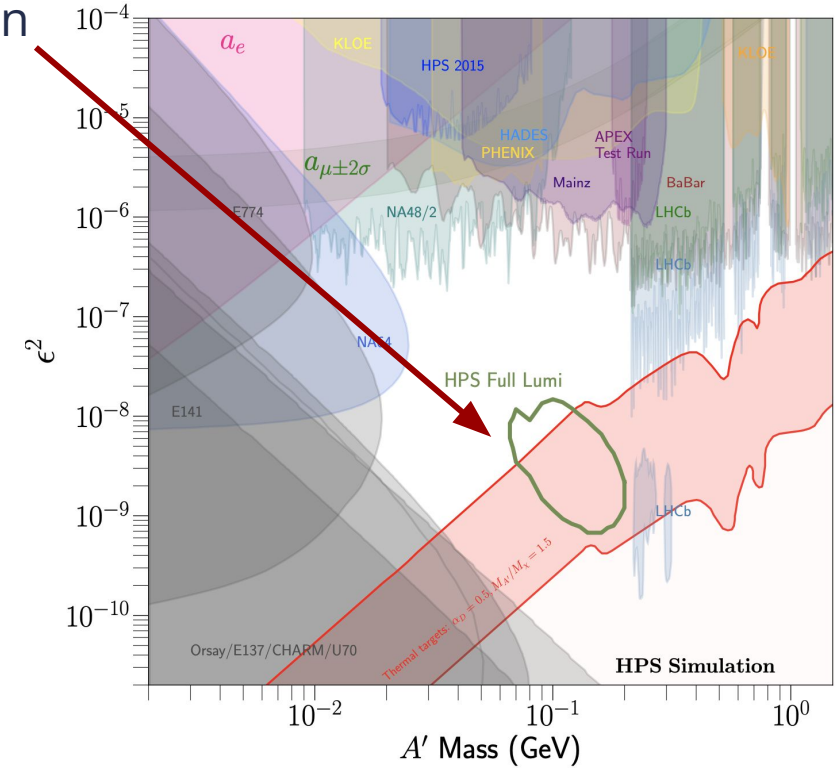


Dark Photon Visible Parameter Space

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

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

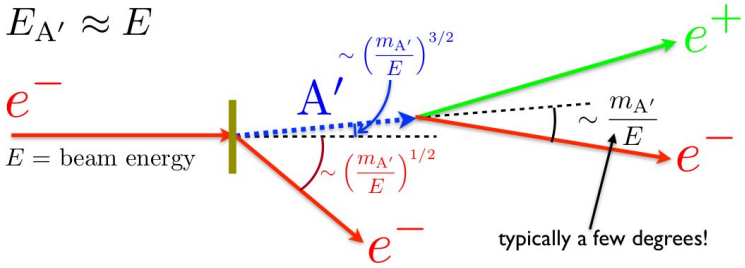
$$c\tau \propto \frac{1}{\epsilon^2 m_{A'}}$$

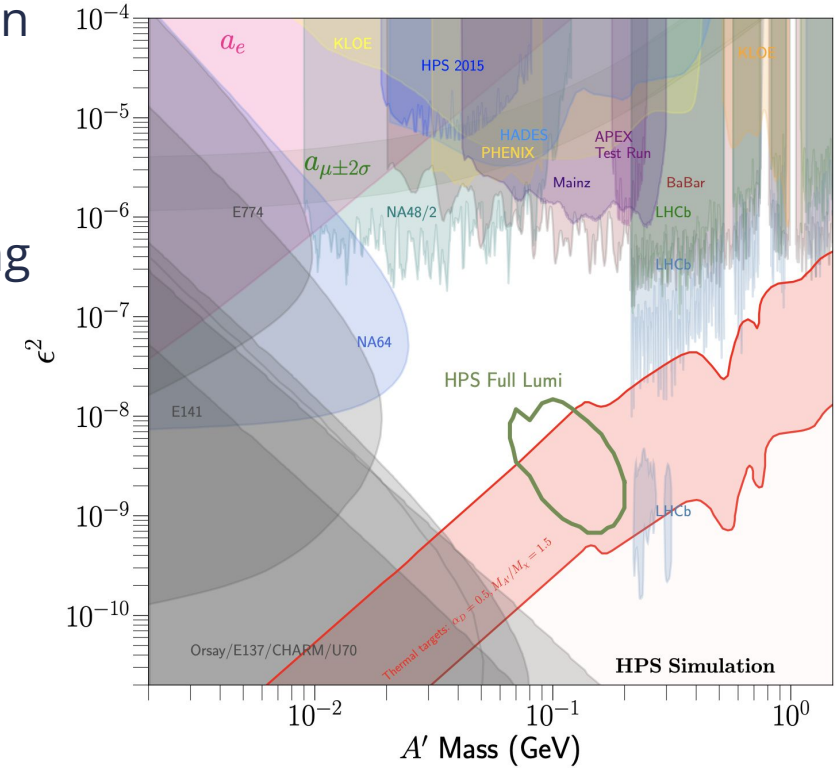


Dark Photon Visible Parameter Space

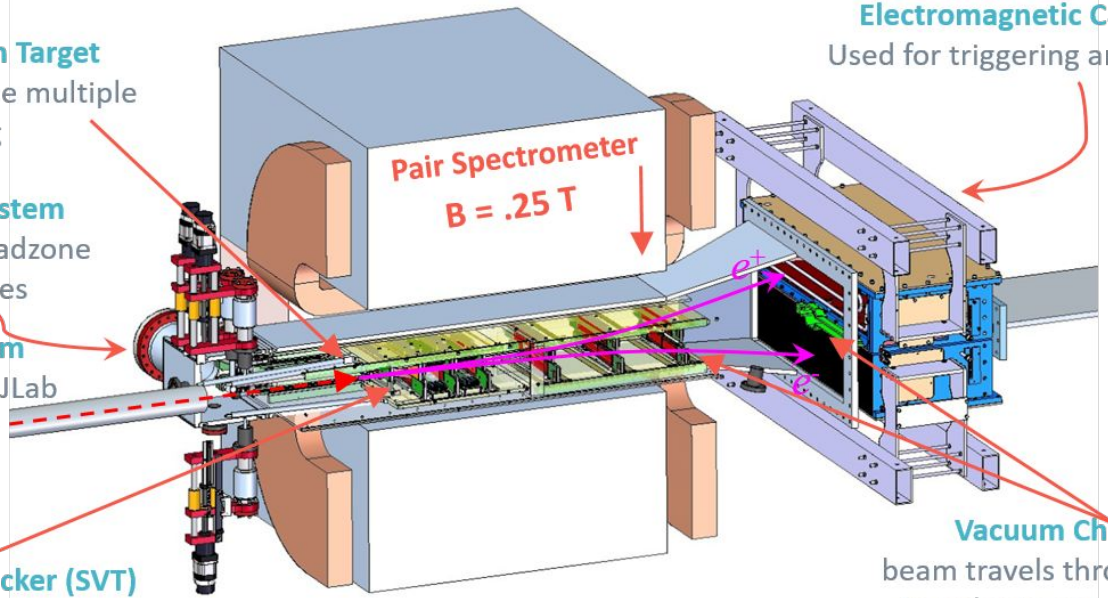
$$2m_e < m_{A'} < 2m_{DM}$$

- 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

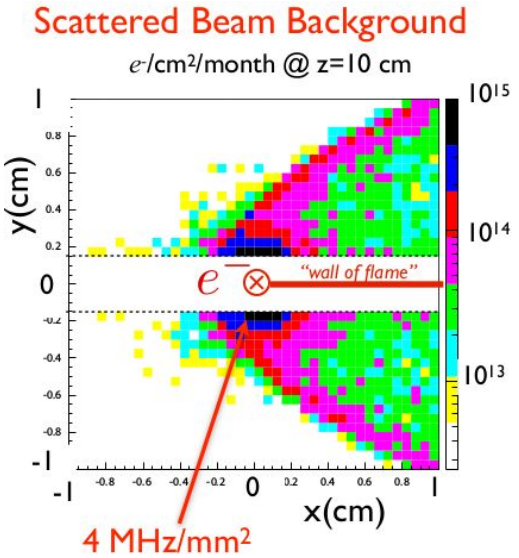
Vacuum Chambers
beam travels through vacuum in order to avoid beam-gas interactions

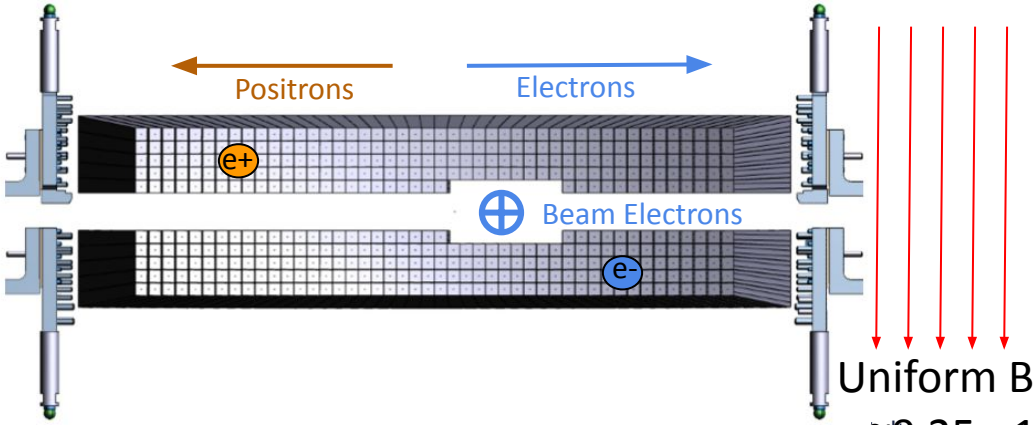
SVT + ECal DAQ capable of 50 kHz

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

Electromagnetic Calorimeter (Ecal)

- Ecal made out of 442 lead tungstate (PbWO4) 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





Uniform B Field
≈ 0.25 - 1.0 T

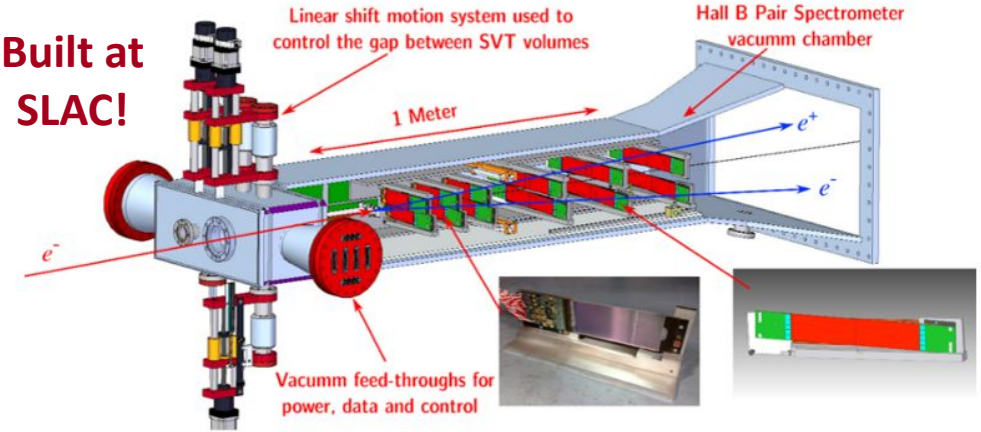
Trigger selects on opposite top/bottom clusters:

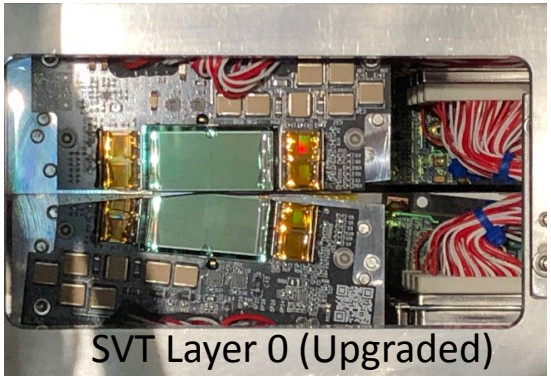
- Cluster Time Difference
- Cluster Energy
- Cluster Energy Sum
- Cluster Energy Difference
- Cluster Coplanarity

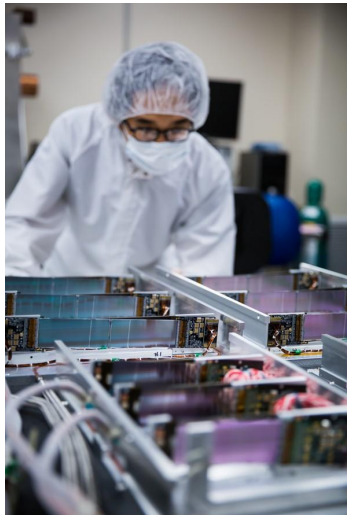
HPS Silicon Vertex Tracker

- 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!

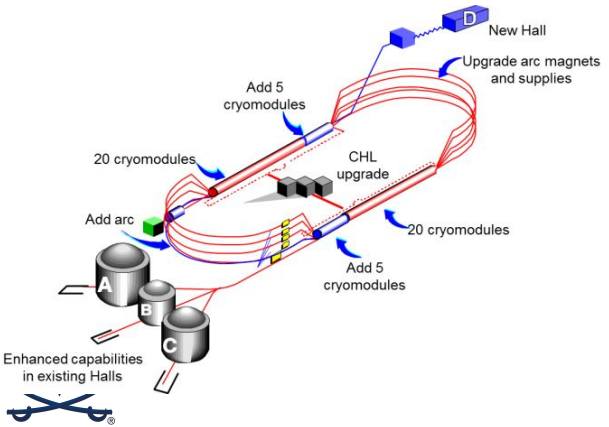


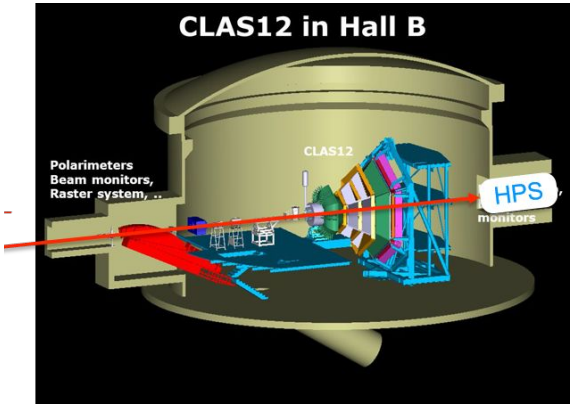

SVT Layer 0 (Upgraded)

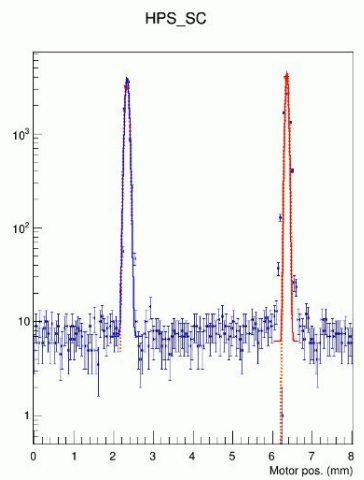


Jefferson Lab and CEBAF

- 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 & small tails** (~10^{-6})







File: svt_top_scan_0143.asc

Analyze from HPS_t counter

top_mot_pos1 = 2.340 mm
top_mot_pos2 = 6.357 mm
top_wire_dist = 1.935 mm
top_beam_Y = -0.075 mm
top_beam_X = -0.099 mm
top_beam_σ_y = 0.0221 mm

!!

top_mot_pos1 = 2.340 mm
top_mot_pos2 = 6.357 mm
top_wire_dist = 1.935 mm
top_beam_Y = -0.075 mm
top_beam_X = -0.098 mm
top_beam_σ_y = 0.0221 mm

Analyze from HPS_SC counter

top_mot_pos1 = 2.340 mm
top_mot_pos2 = 6.363 mm
top_wire_dist = 1.938 mm
top_beam_Y = -0.075 mm
top_beam_X = -0.078 mm
top_beam_σ_y = 0.0224 mm

top_mot_pos1 = 2.339 mm
top_mot_pos2 = 6.364 mm
top_wire_dist = 1.938 mm
top_beam_Y = -0.075 mm
top_beam_X = -0.075 mm
top_beam_σ_y = 0.0225 mm

Matt Solt

HPS Current Data and Status

- Results from 2015 resonance search are published
- Resonance search and **displaced vertex search** for 2016 are submitted for publication. 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

HPS Current Data and Status

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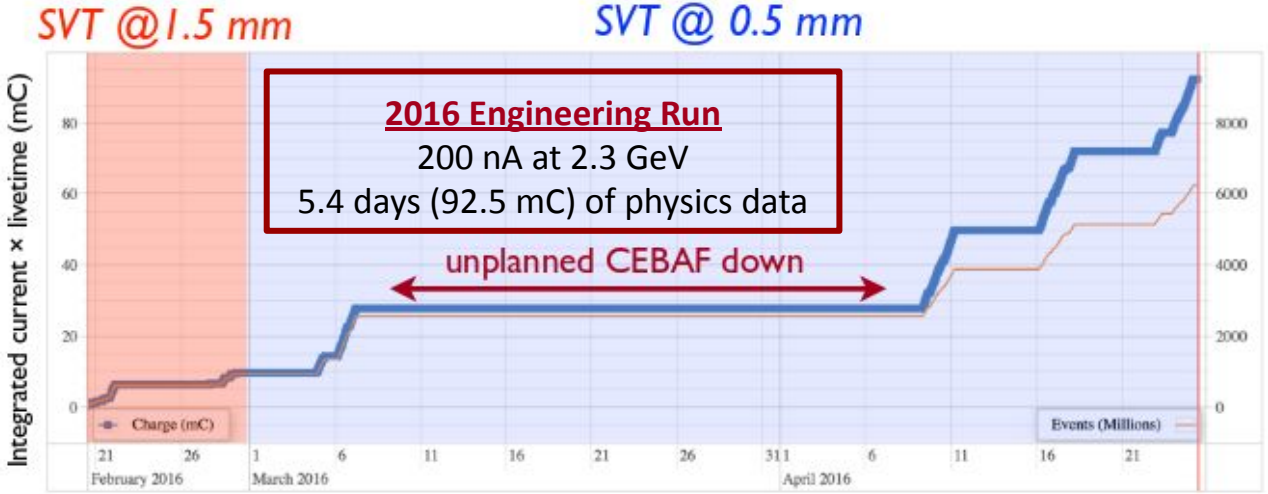
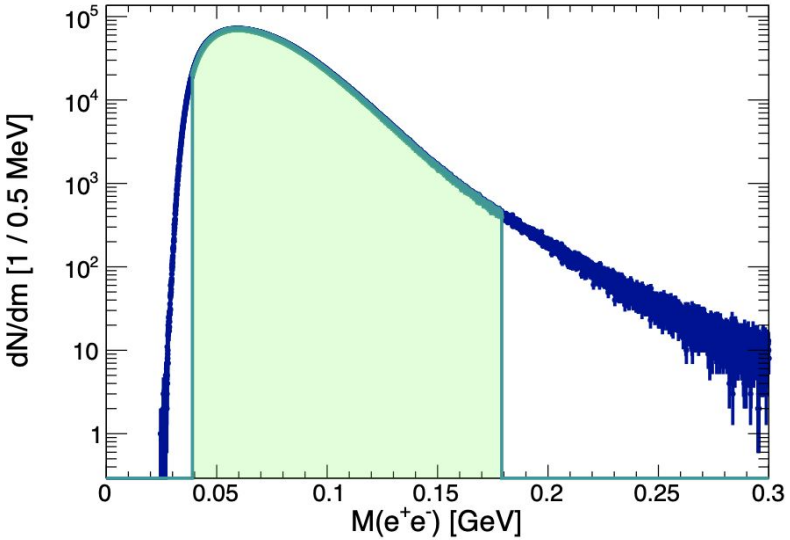
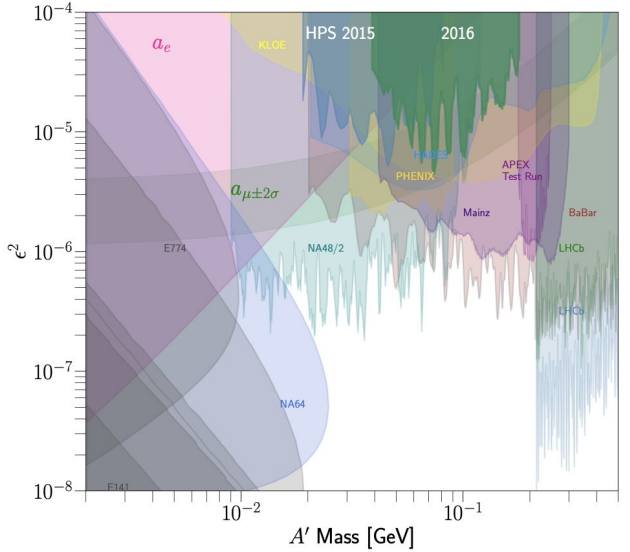
- Resonance search and **displaced vertex search** for 2016 are submitted for publication. This is the focus of this seminar

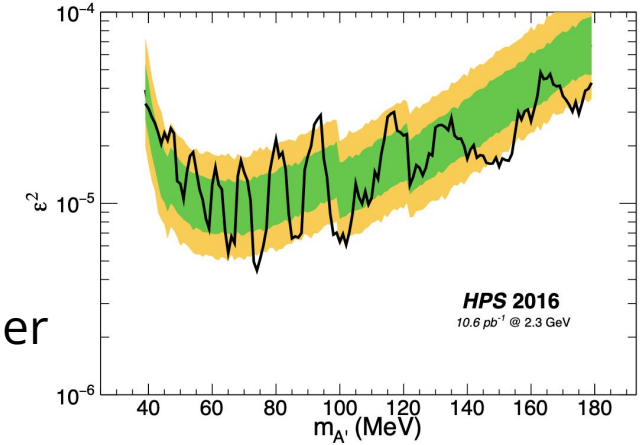


2016 Resonance Search Results

arXiv:2212.10629v2



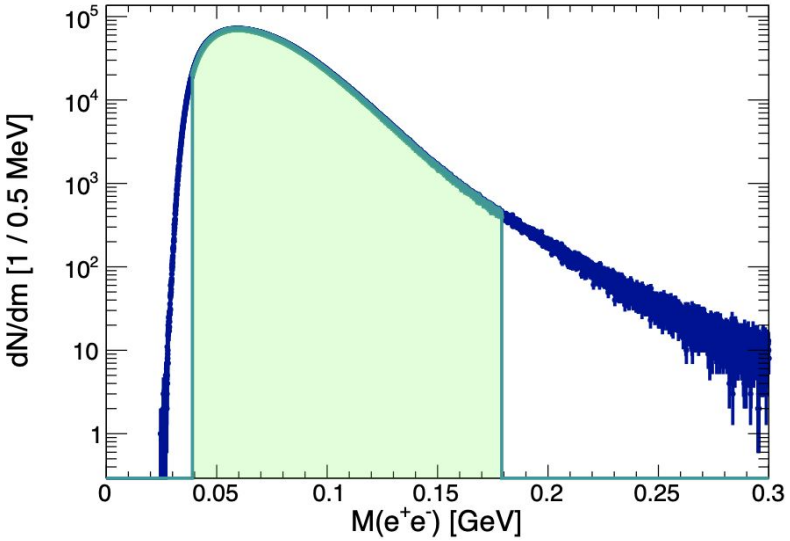


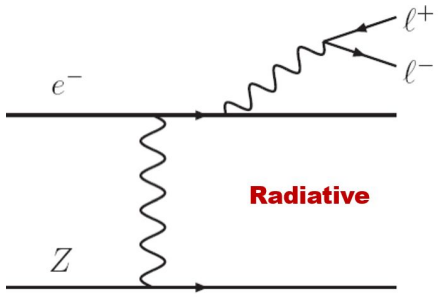


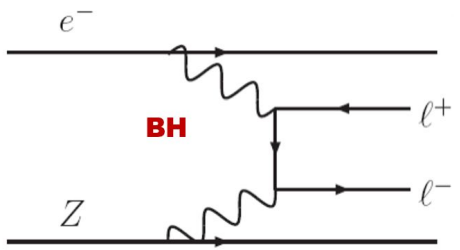
- No observed excess
- Exclusions consistent with several other experiments

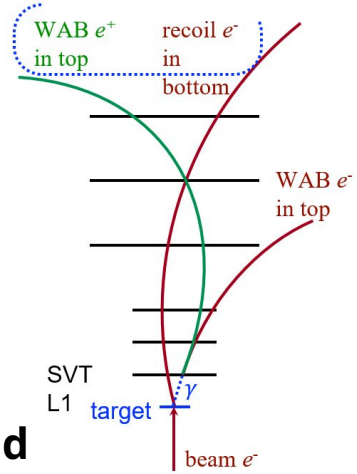
Prompt Trident Backgrounds

arXiv:2212.10629v2







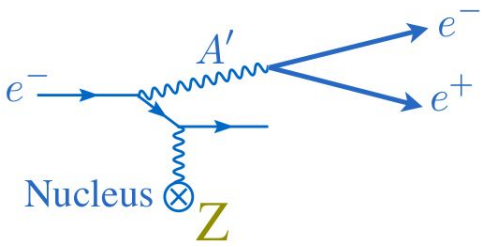


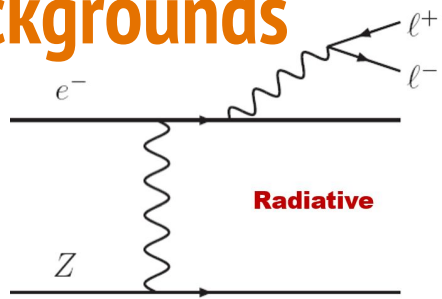
Challenge: Distinguishing the prompt QED tridents from displaced signal ~1 signal for ~10^6 prompt background

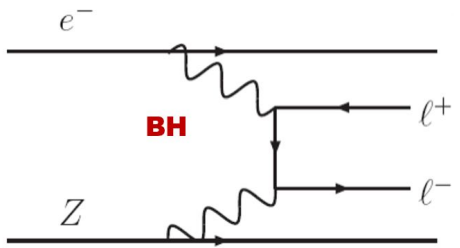
What are these e+e- backgrounds?

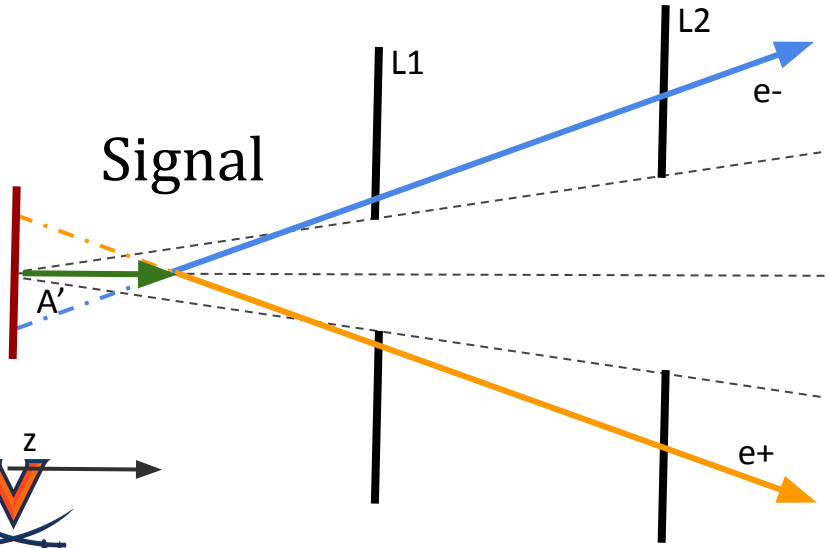
Prompt QED tridents - Radiative and Bethe-Heitler (BH) & Wide Angle Brems (WABs)

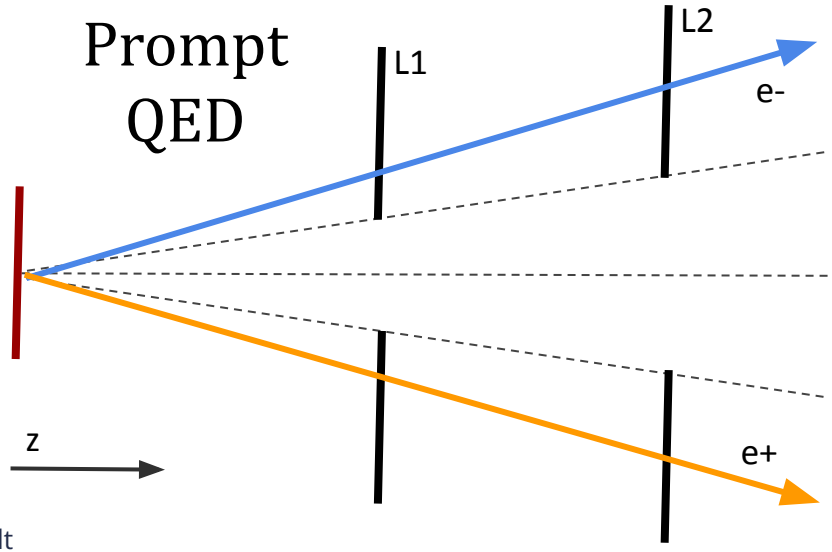
Signal vs Prompt Trident Backgrounds





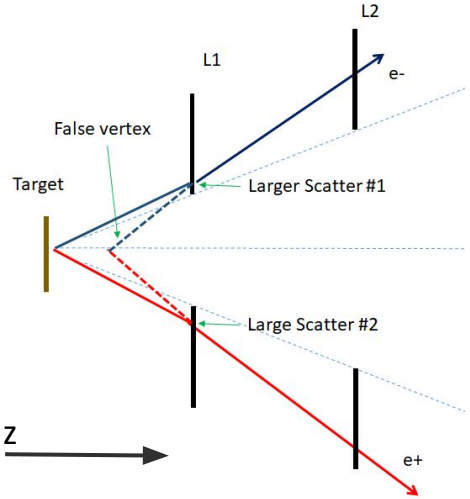


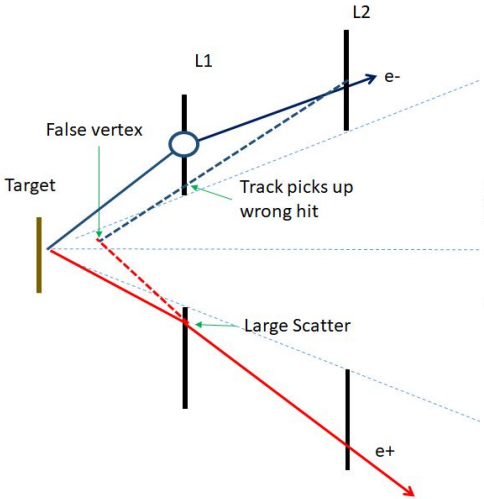


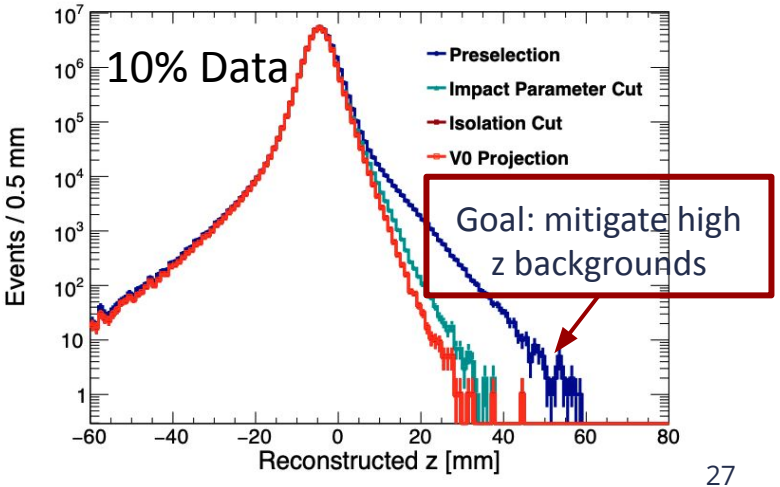


Displaced Vertex Search Event Selection

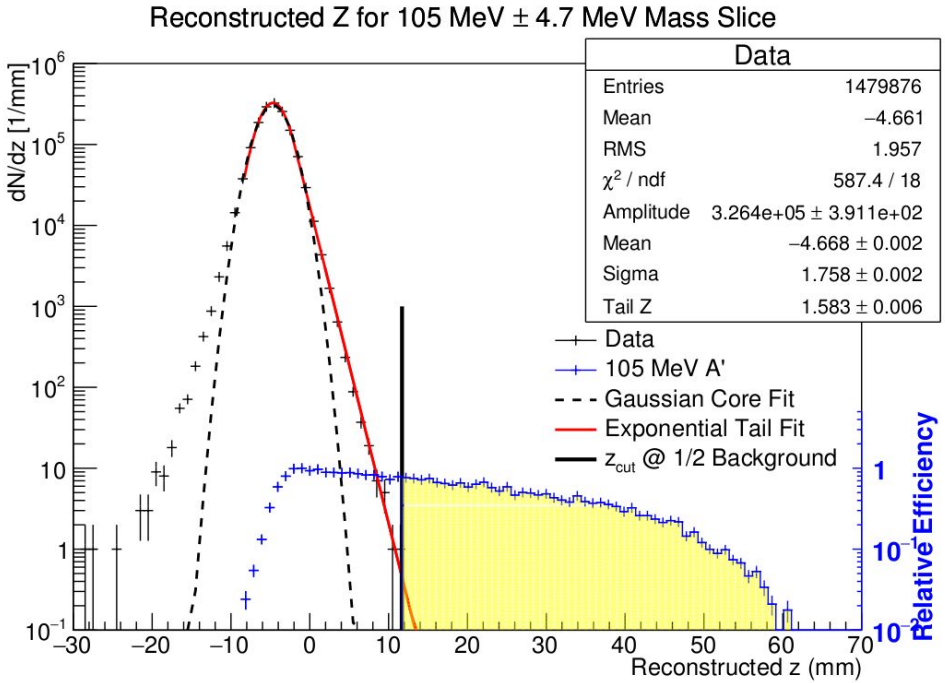
- Displaced vertex search is blinded with the selection tuned on 10% data
- Two main backgrounds from prompt trident processes: large Coulomb scatters in layer 1 of the tracker and mis-tracking
  - Require strict selections on track quality and vertex quality & require layer 1 hits





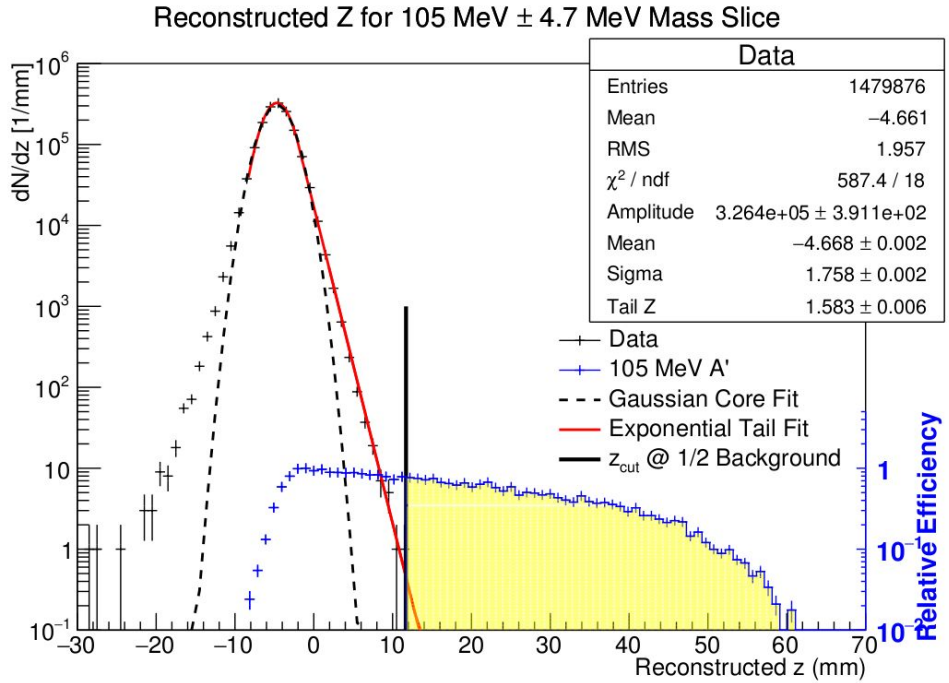


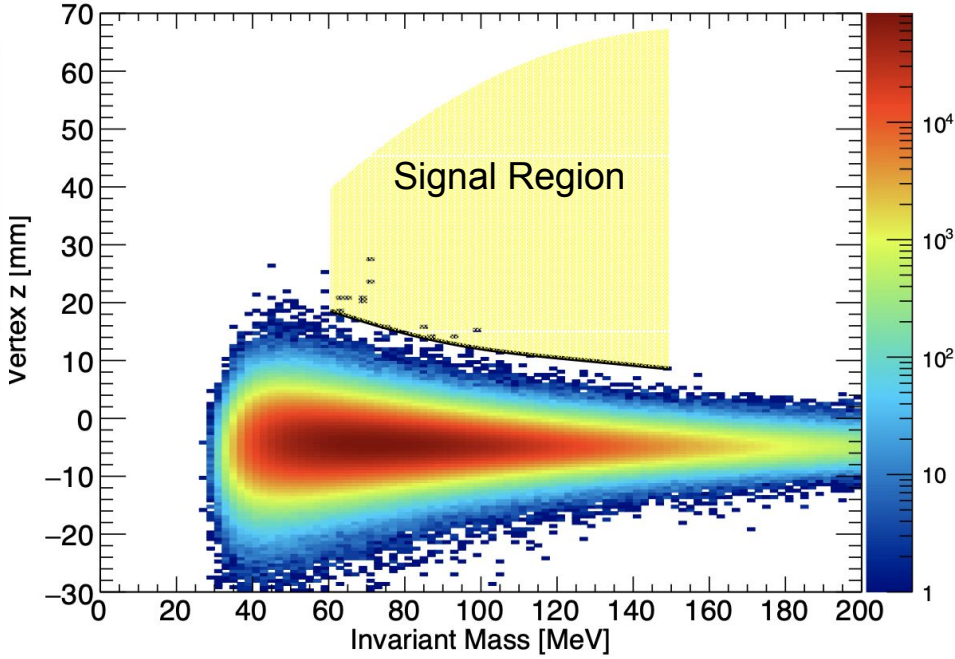
Displaced Vertex Search



- 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?

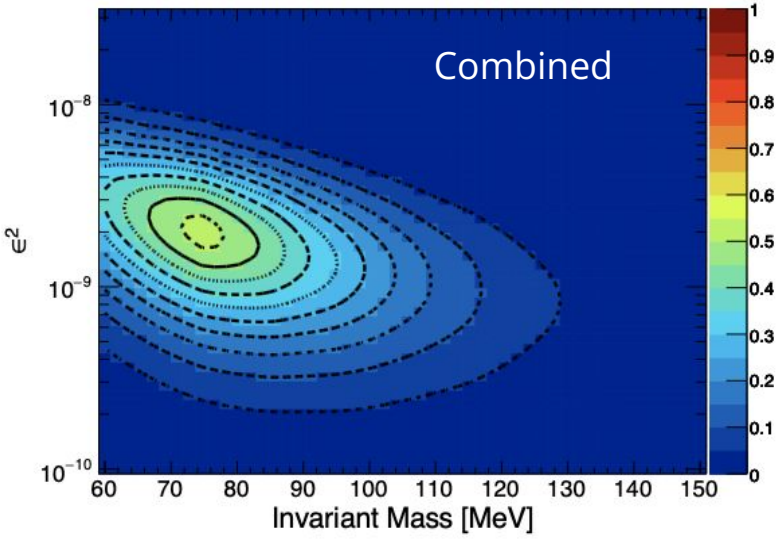
Displaced Vertex Search Unblinded

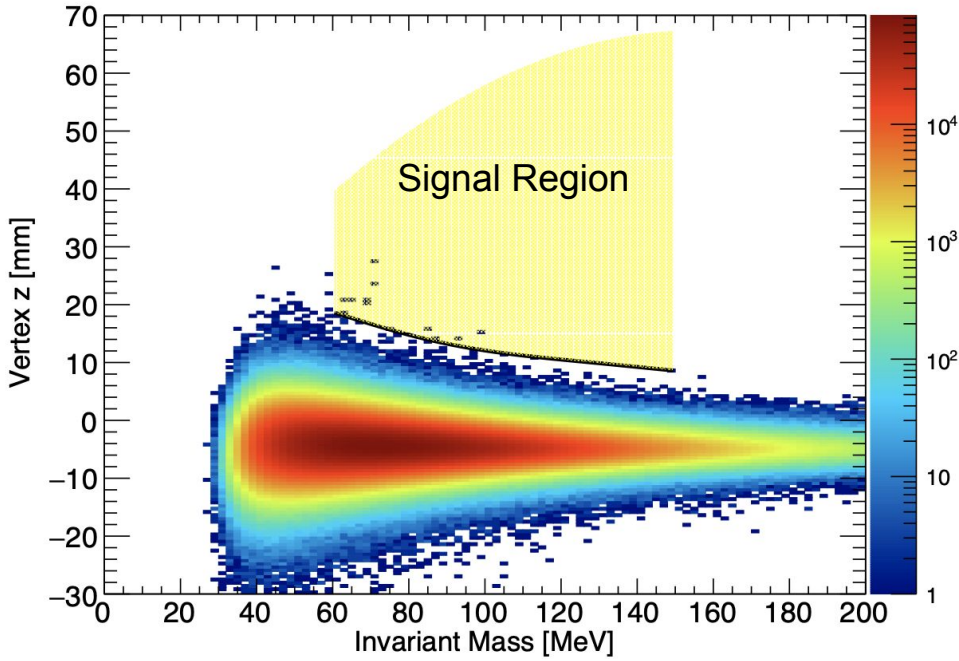




Displaced Vertex Search Unblinded

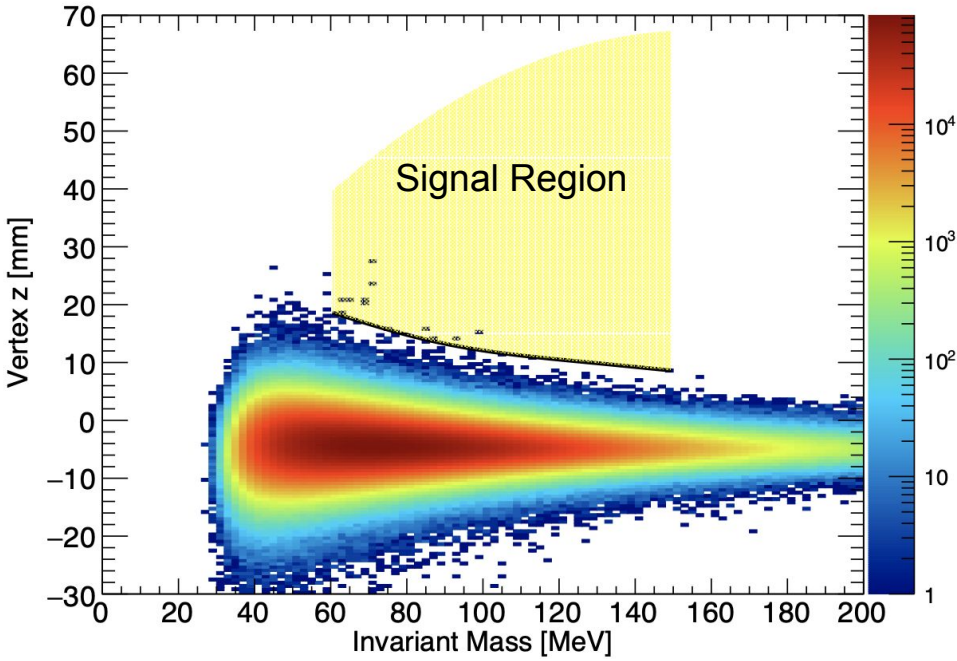
- How much signal do we expect?
  - ~0.5 events at maximum sensitivity, not enough for A’ exclusion at 90%





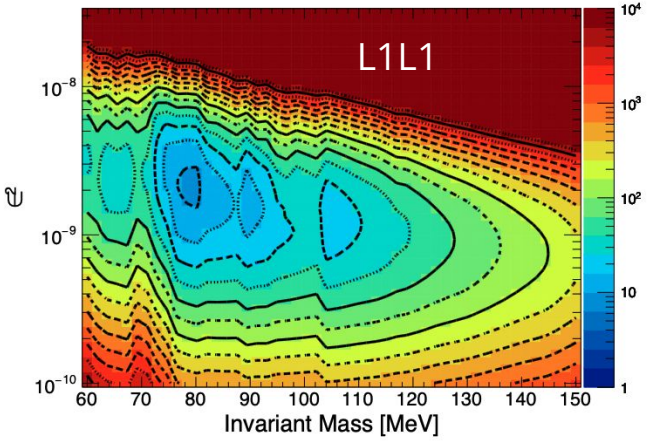
Displaced Vertex Search Backgrounds

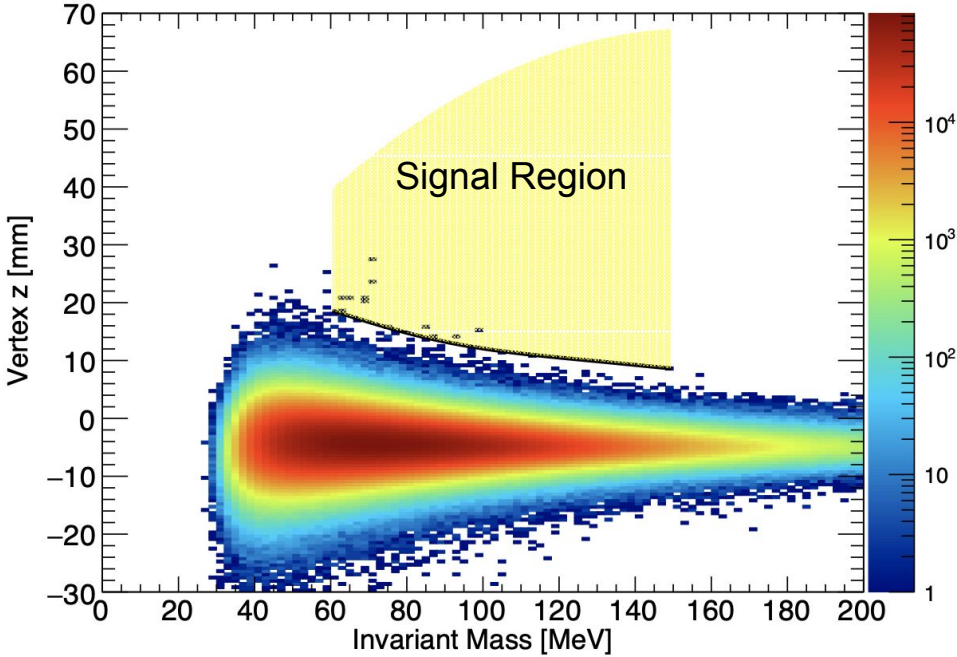
- How much signal do we expect?
  - ~0.5 events at maximum sensitivity, not enough for A’ exclusion at 90%
- Did we achieve the expected level of background necessary for a search?
  - **YES! A major accomplishment** (for mass greater than 70 MeV)
- What about mass less than 70 MeV?
  - This is currently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



Displaced Vertex Search Unblinded

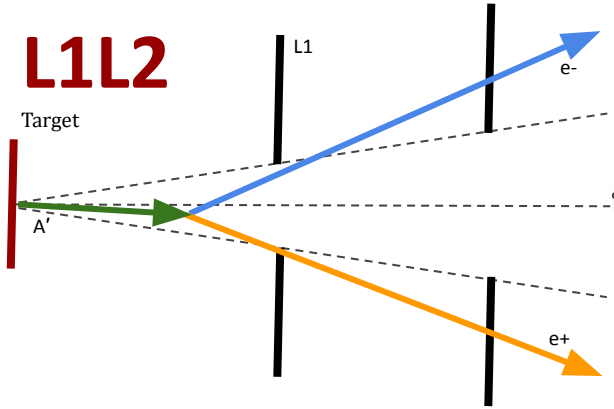
- Limits set via Optimum Interval Method
  - Not enough for A′ exclusion at 90%
  - Tightest existing constraints in this region of parameter space

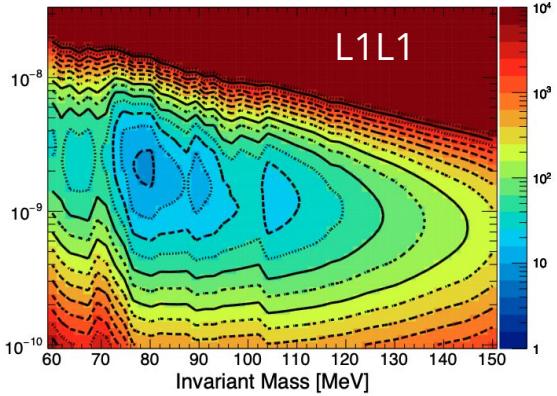


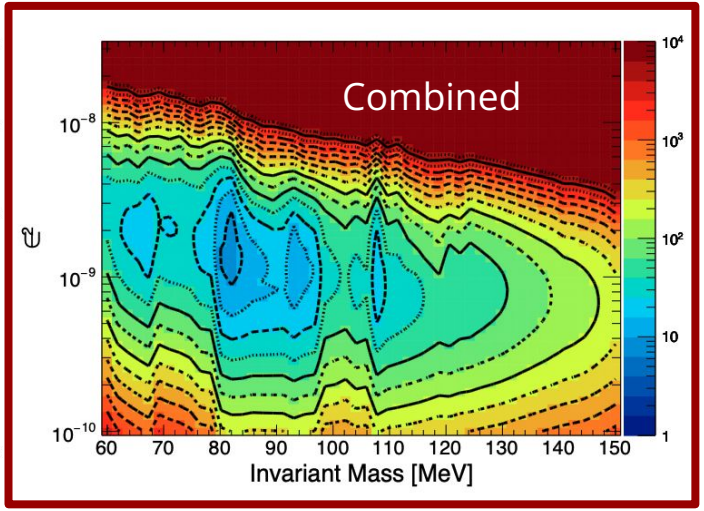


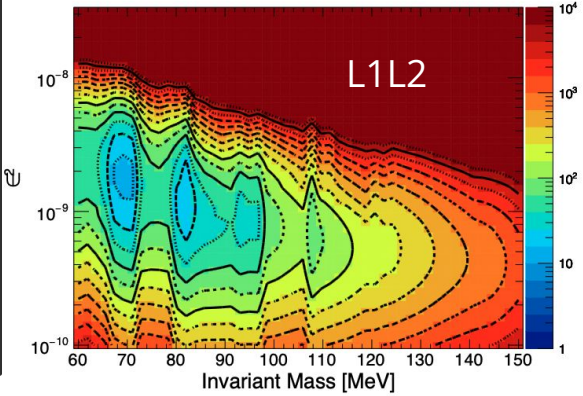
Displaced Vertex Search Final Results

arXiv:2212.10629v2







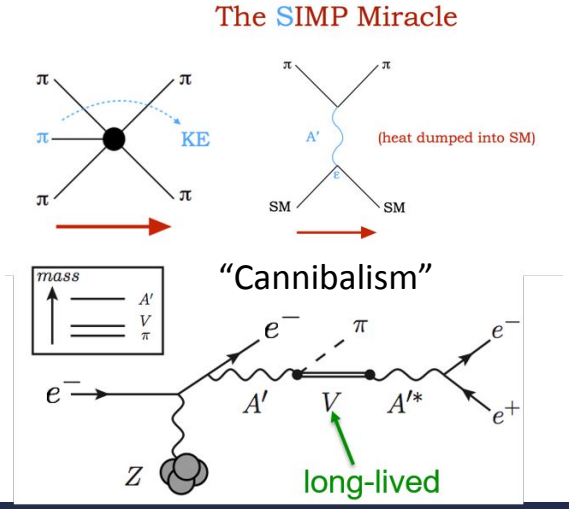


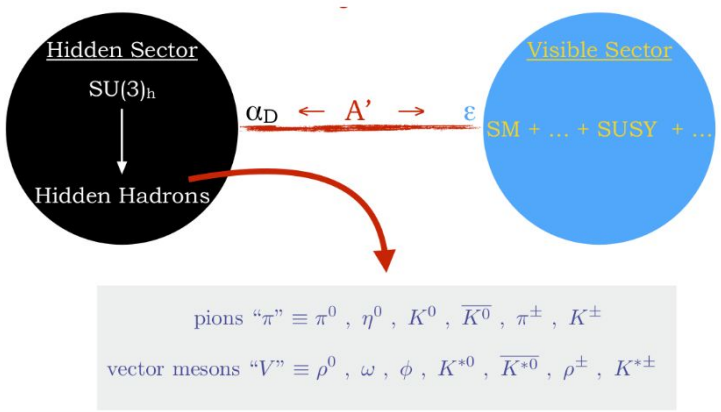
Repeat analysis procedure for the case in which one of the A' daughters misses L1 of the SVT ("L1L2") . Combine results.

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

Other Models of Interest

- Displaced vertices via electro-production on ~cm-scale is unexplored parameter space for many more interesting models
  - Strongly Interacting Massive Particles (SIMPs) (A. Spellman, UC Santa Cruz)
  - Inelastic Dark Matter (T. Eichlersmith, University of Minnesota)





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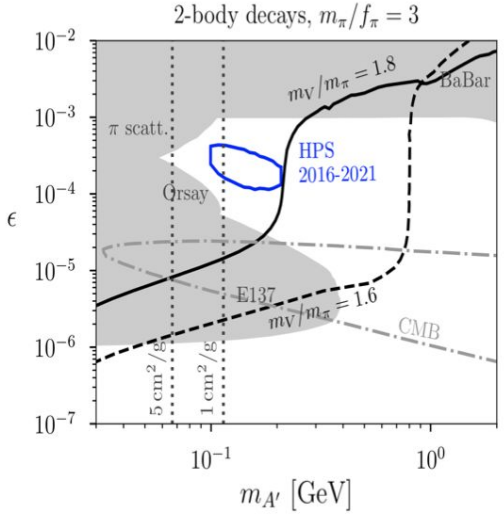
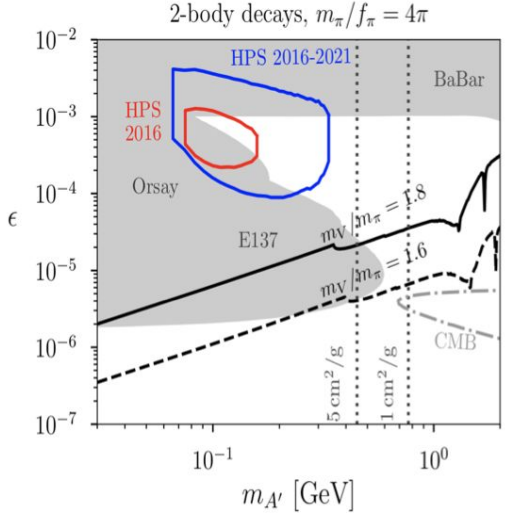
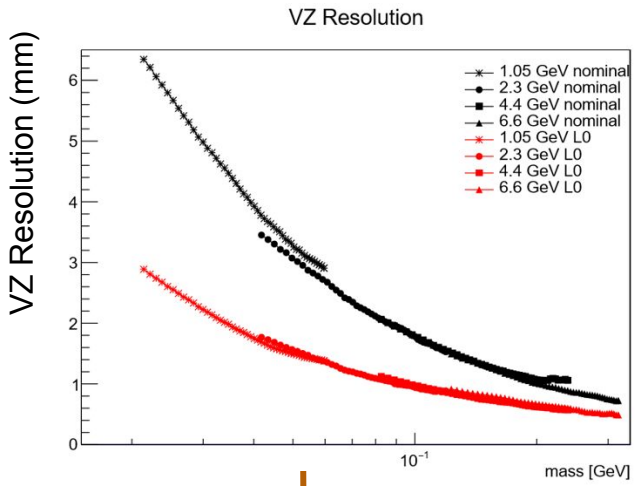


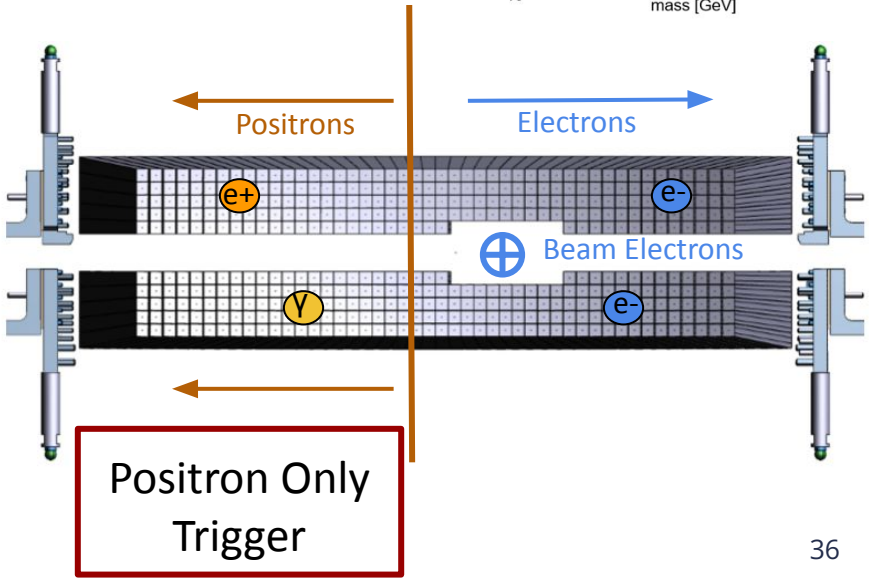


Additional model parameters de-couple the cross-section and lifetime

HPS Upgrades

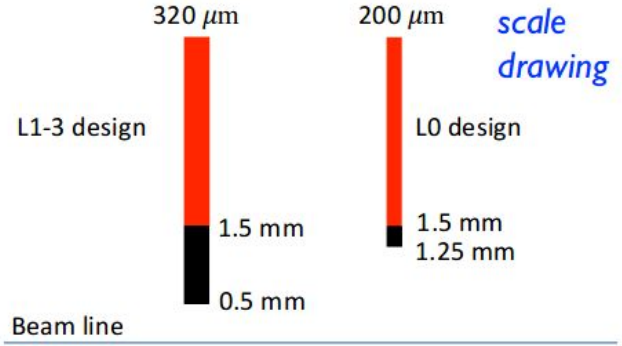
- Analysis from 2015/2016 motivated several simple upgrades
- **Add a tracking layer** (Layer 0) between target and current Layer 1
  - Dramatically improves vertex resolution, therefore the vertex reach
- **Add hodoscope** inside vacuum chamber, enables positron only trigger
  - Recovers electrons lost in the “electron hole” (factor of ~2 in signal acceptance)

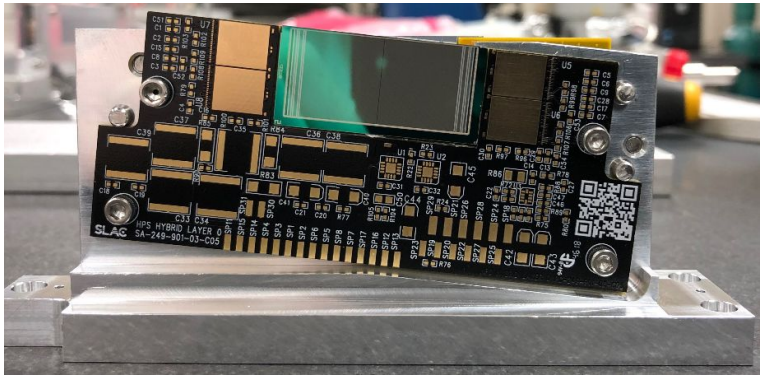


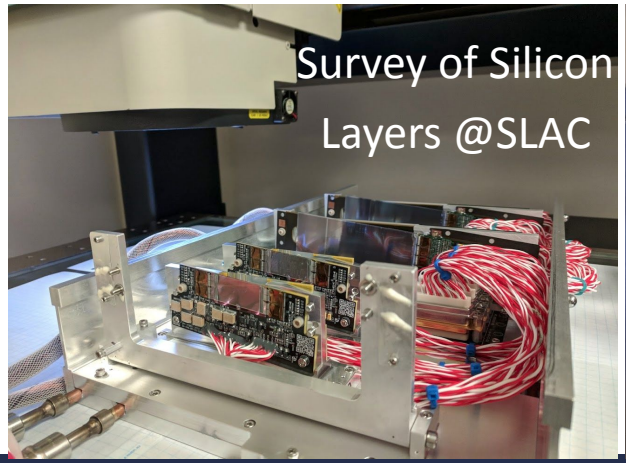


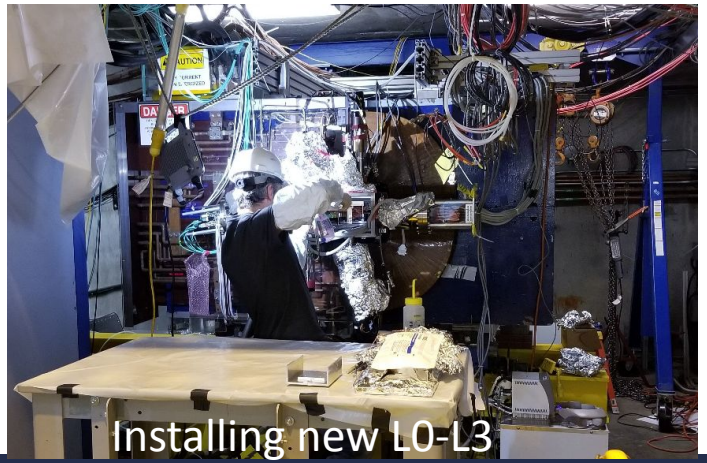
Installing HPS Upgrades - 2019 Run

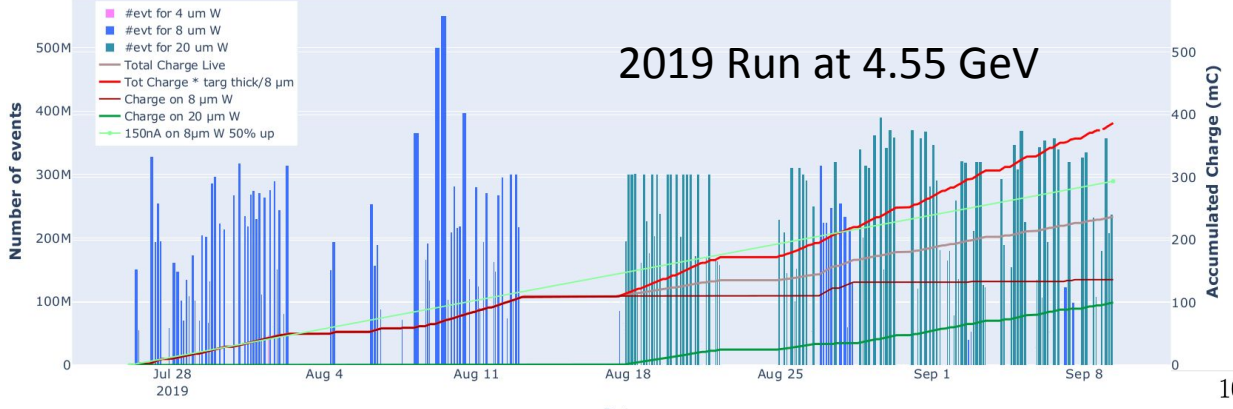
HPS upgrades successfully installed in May-June 2019 in time for June start

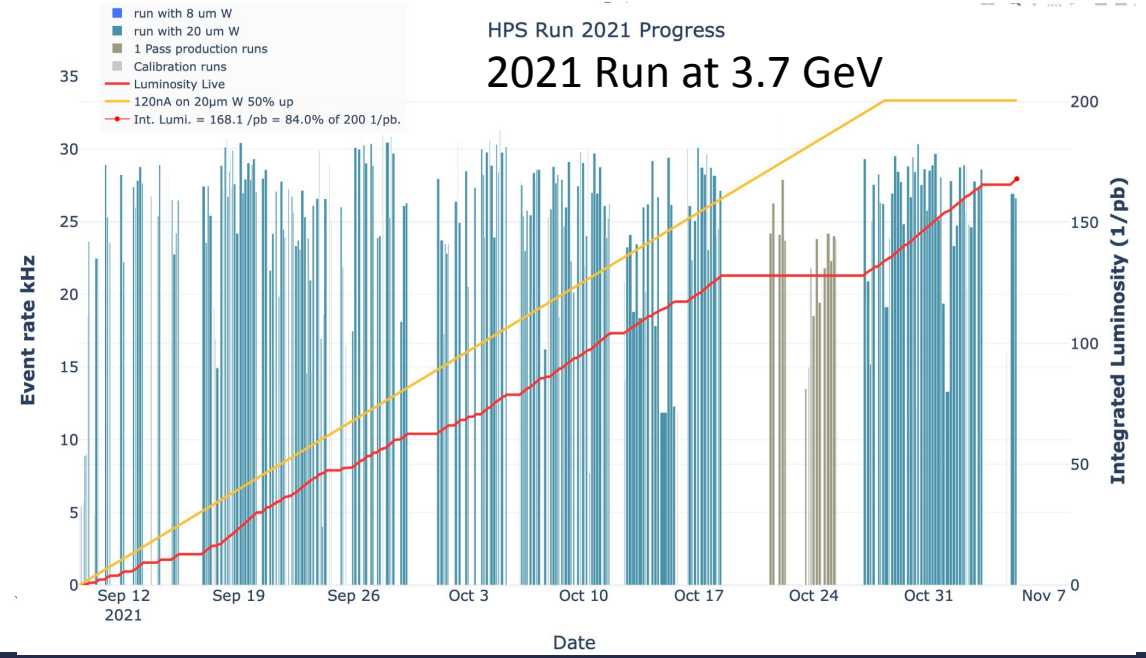


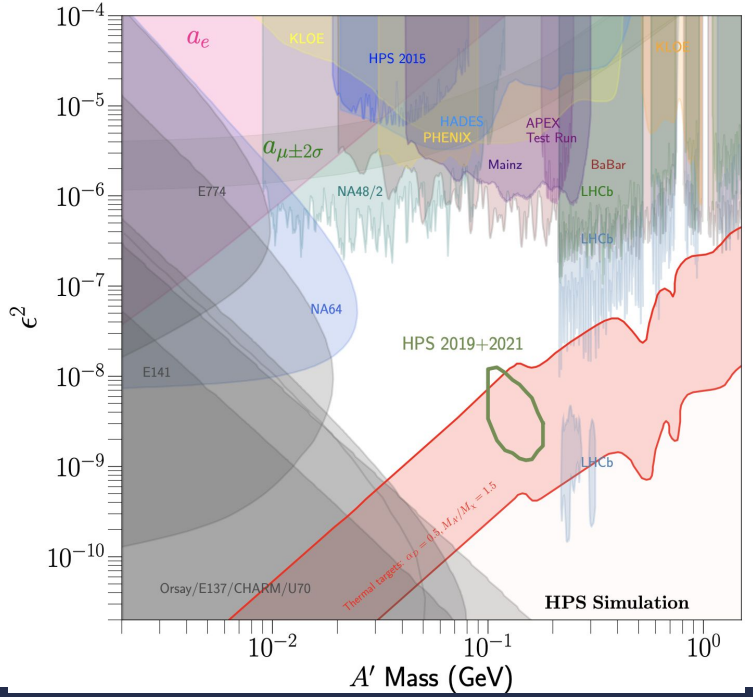







2019 Run at 4.55 GeV
#evt for 4 um W
#evt for 8 um W
#evt for 20 um W
Total Charge Live
Tot Charge * targ thick/8 μm
Charge on 8 μm W
Charge on 20 μm W
150nA on 8μm W 50% up
Number of events
Accumulated Charge (mC)
Jul 28
2019
Aug 4
Aug 11
Aug 18
Aug 25
Sep 1
Sep 8

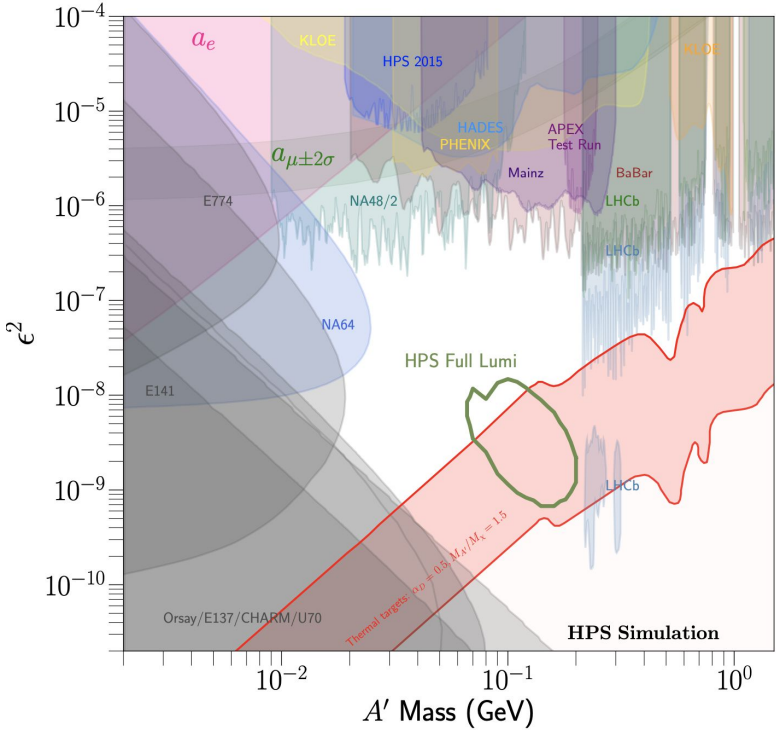

HPS Run 2021 Progress
2021 Run at 3.7 GeV
run with 8 um W
run with 20 um W
1 Pass production runs
Calibration runs
Luminosity Live
120nA on 20μm W 50% up
Int. Lumi. = 168.1 /pb = 84.0% of 200 1/pb.
Event rate kHz
Integrated Luminosity (1/pb)
Sep 12
2021
Sep 19
Sep 26
Oct 3
Oct 10
Oct 17
Oct 24
Oct 31
Nov 7
Date


a_e
KLOE
HPS 2015
HADES
PHENIX
APEX
Test Run
$a_{\mu\pm2\sigma}$
Mainz
BaBar
E774
NA48/2
LHCb
NA64
HPS 2019+2021
E141
Orsay/E137/CHARM/U70
HPS Simulation
ϵ^2
A' Mass (GeV)

Conclusion

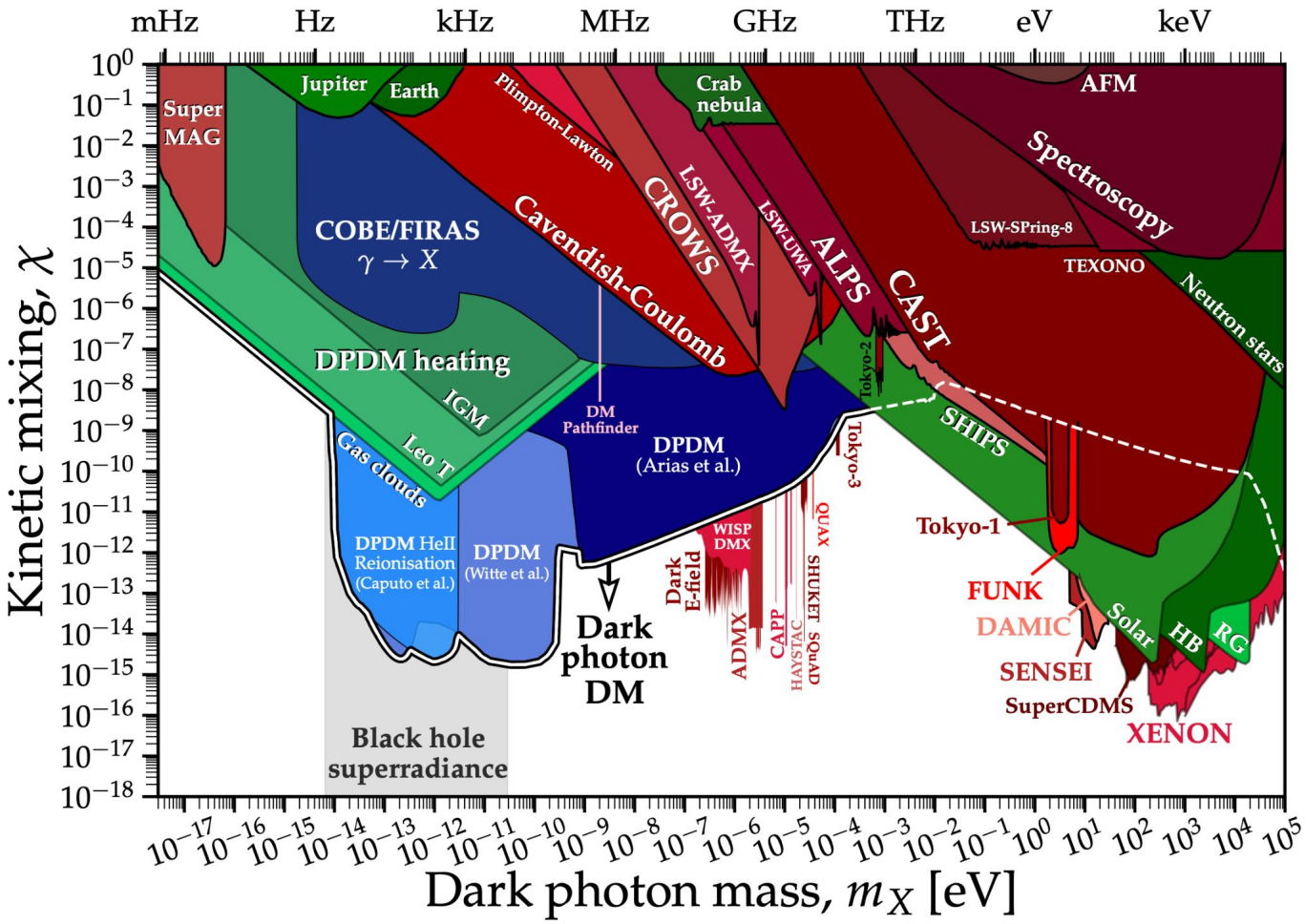
- Thermal relic models offer plausible and predictive models of dark matter
- HPS results from 2015 resonance search are published, and 2016 results have been submitted for publication
- Analysis from runs in 2019 and 2021 are expected to yield new exclusions, and potential discovery, of A's in a highly motivated region of parameter space
- HPS has completed ~60 days of running and is approved for 180 days

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



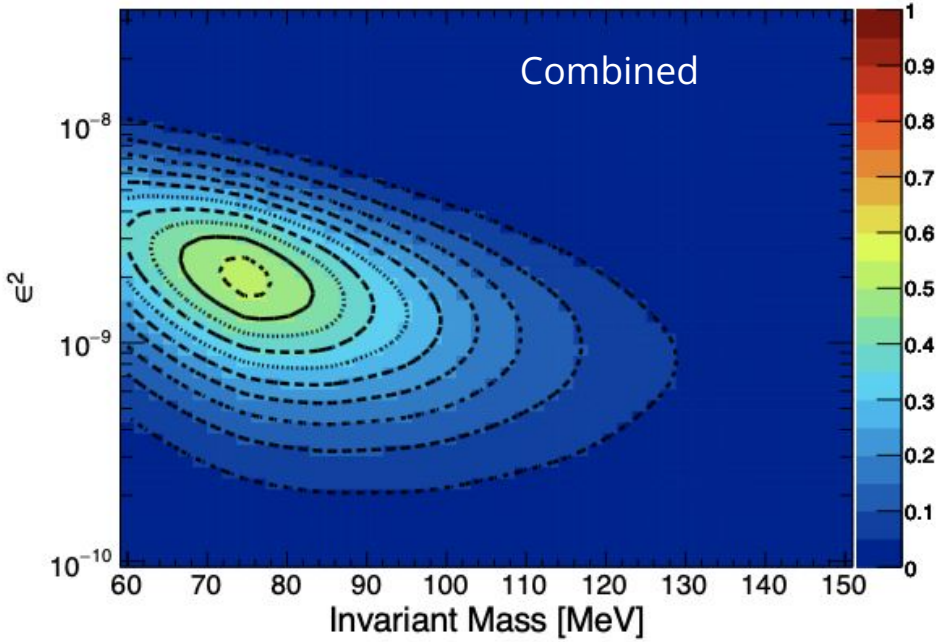
Thank You!

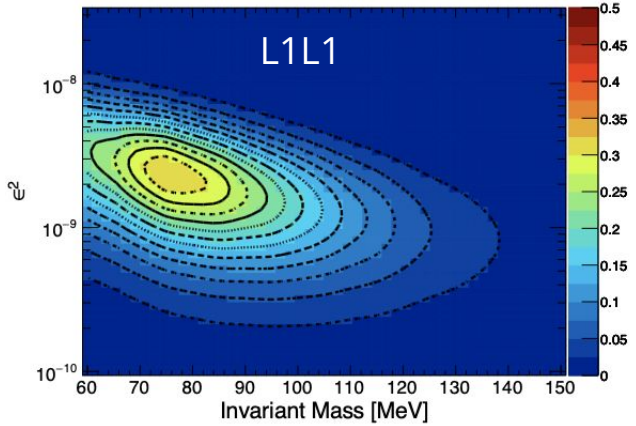

HEAVY PHOTON SEARCH
HPS Collaboration
May 3 - 5, 2017
Jefferson Lab • Newport News, VA

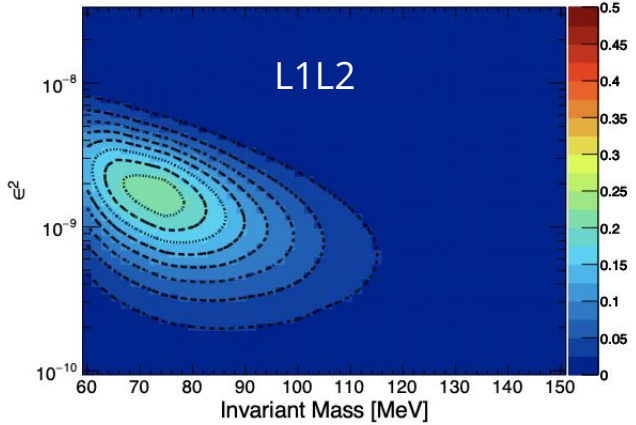


PhysRevD.104.095029

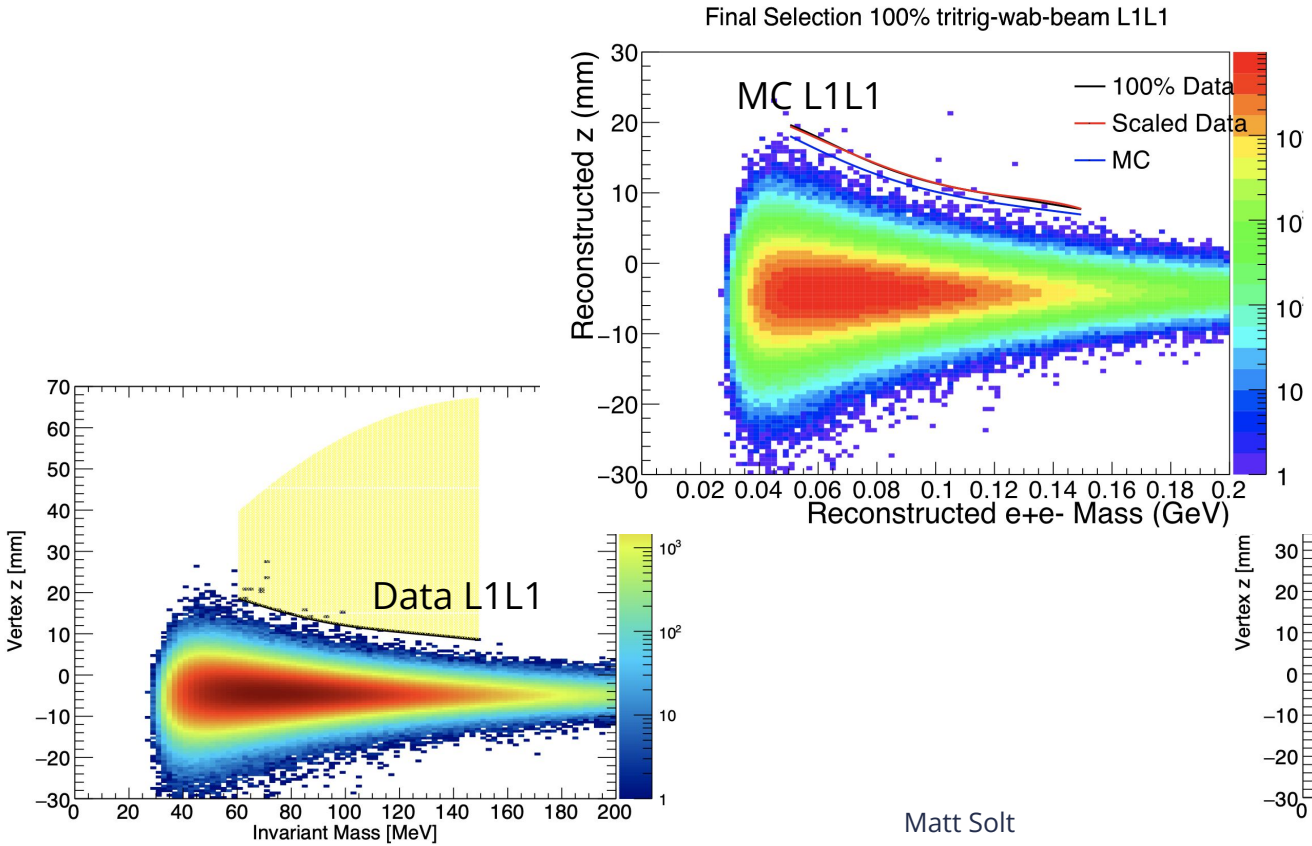
HPS Expected Signal Rate 2016

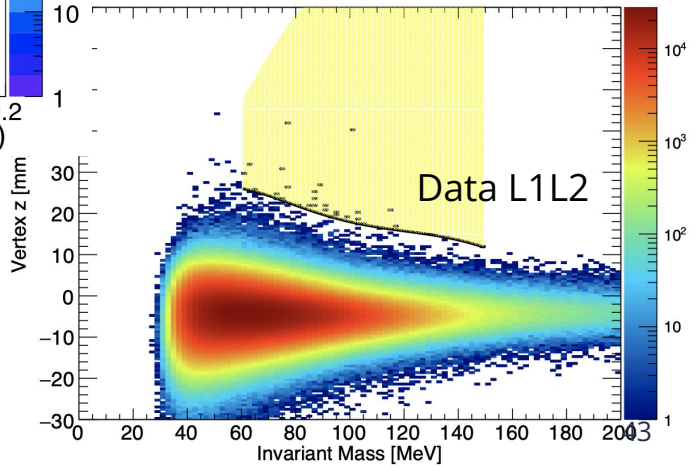






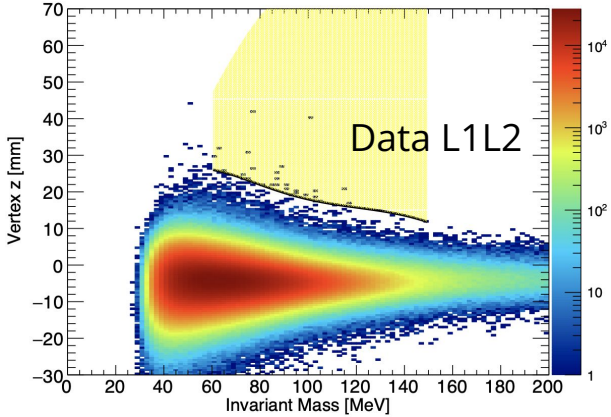
HPS Data/MC Comparison

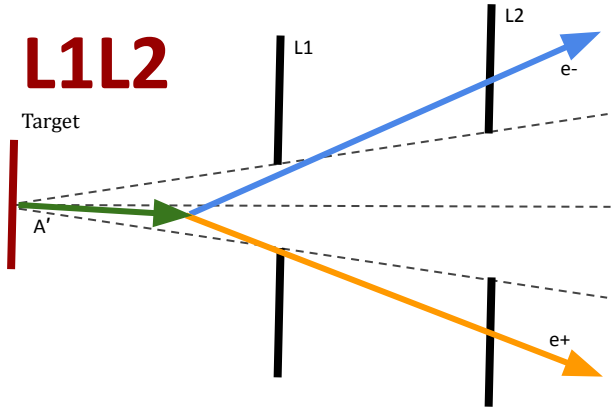


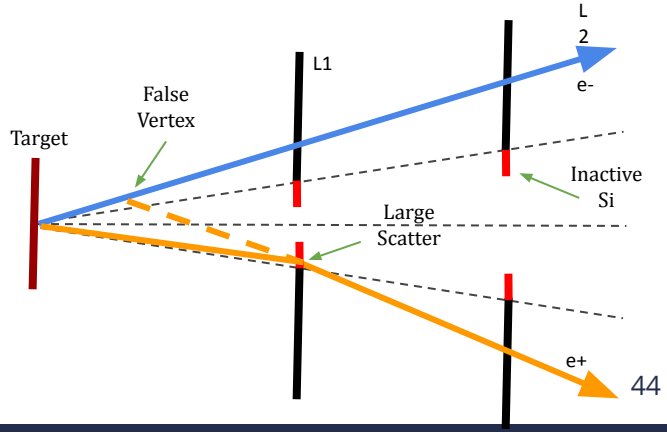


A's with Longer Lifetimes

- 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

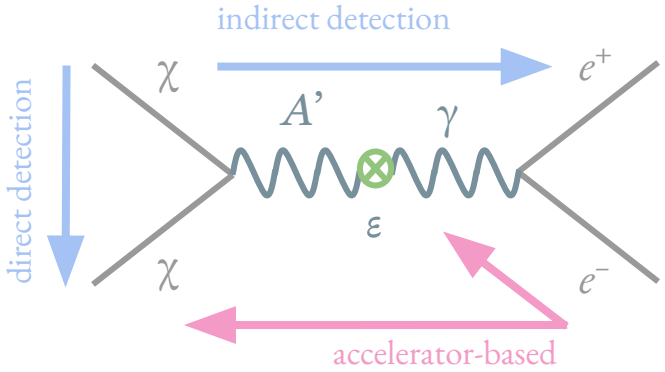






Light Dark Matter

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