Searching for Long-Lived Dark Photons with the Heavy Photon Search Experiment

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Introduction

SLAC

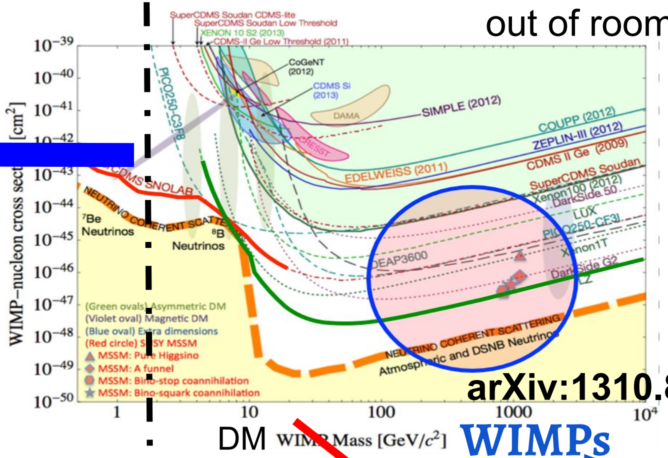
- A heavy photon (or dark photon, or A’) is a **hypothetical vector boson** that couples to electric charge. Motivated by many sub-GeV dark matter models
- The Heavy Photon Search (HPS) is a **fixed target experiment** at Jefferson Lab dedicated to searching for this hypothetical vector boson, an A’
- HPS uses two distinct methods to search for A’s - a **resonance search** and a **displaced vertex search** (focus on vertex search)

Lighter dark matter requires a **new, light force carrier!**

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

“Lee-Weinberg Bound”

WIMPs are running out of room!



arXiv:1310.8327

Light Dark Matter DM **WIMPs**

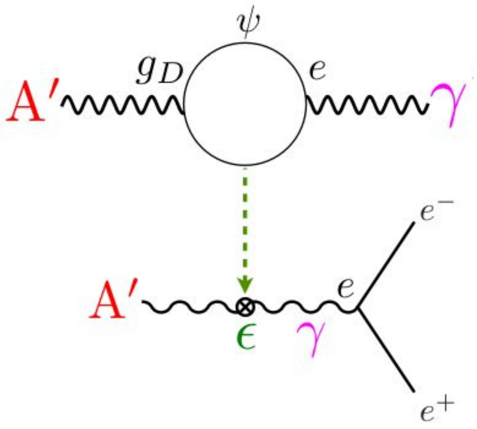
Heavy Photon Primer

B. Holdom Phys. Lett., B166:196–198, 1986

Suppose nature contains an **additional Abelian gauge symmetry** U′(1) (analogous to EM)

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

This gives rise to a **kinetic mixing term** where the SM photon mixes with a new gauge boson (an A′)

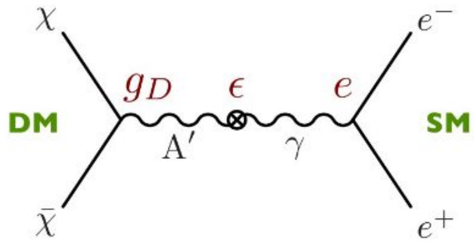


Two Parameter Model: Mass of A′ and ε

Induces a weak effective coupling of εe to SM fermions

$$\epsilon \sim \frac{e g_D}{16\pi^2} log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$

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



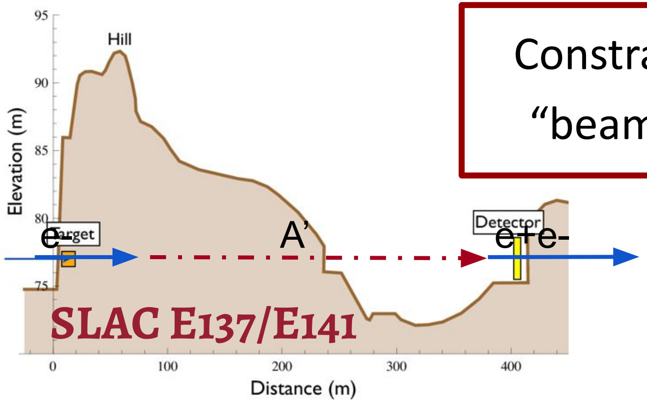
$$\alpha \equiv \frac{e^2}{4\pi}$$

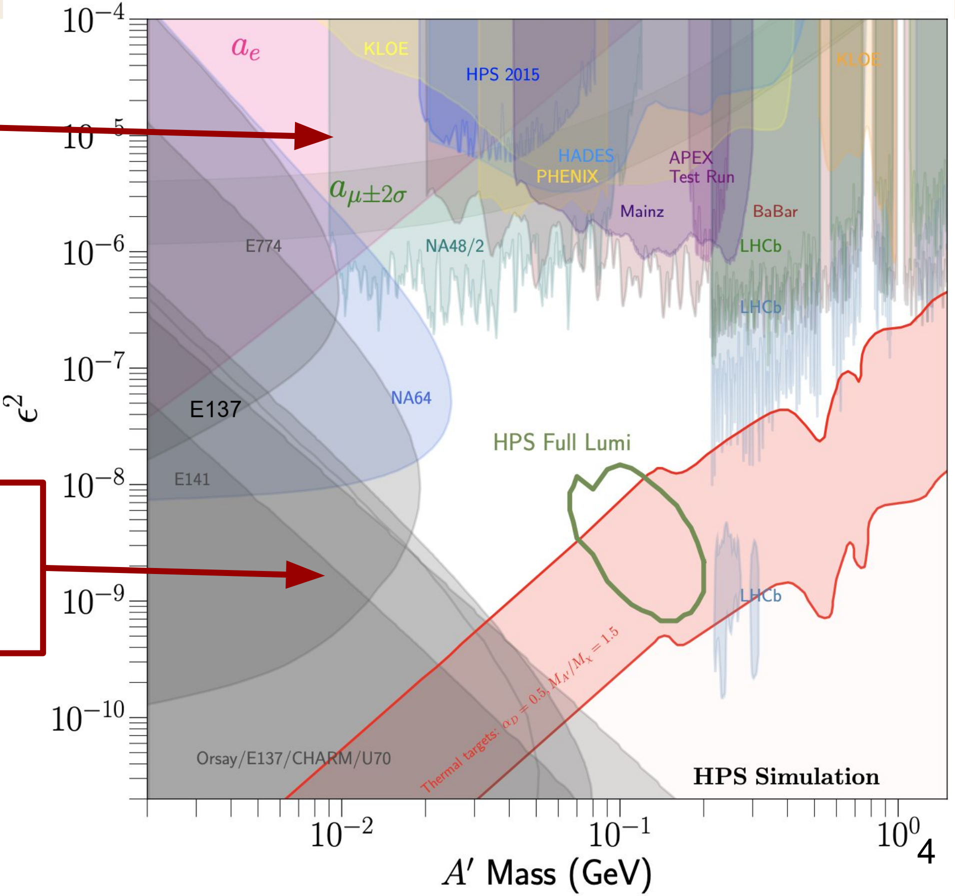
Existing Heavy Photon Constraints

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"





Probing New Heavy Photon Territory

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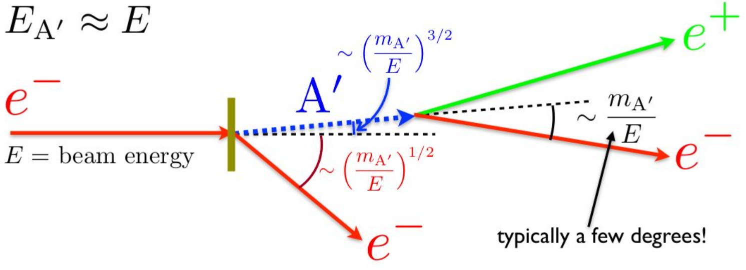
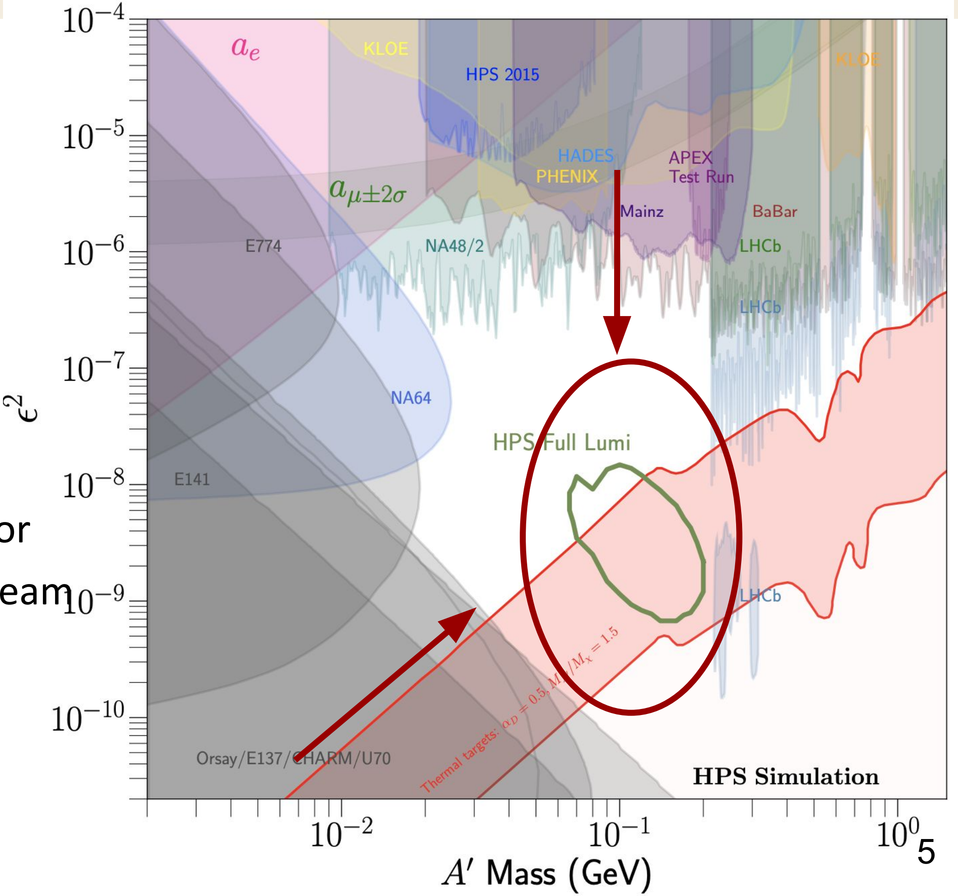
- The center is a highly motivated, yet unprobed region of parameter space
  - Small production cross-section
  - Short, but finite livetime
- HPS - a fixed target precision vertexing experiment attempting to probe this
  - Large prompt QED backgrounds
  - A’ kinematics require sensitive detector components to be 0.5 mm from the beam

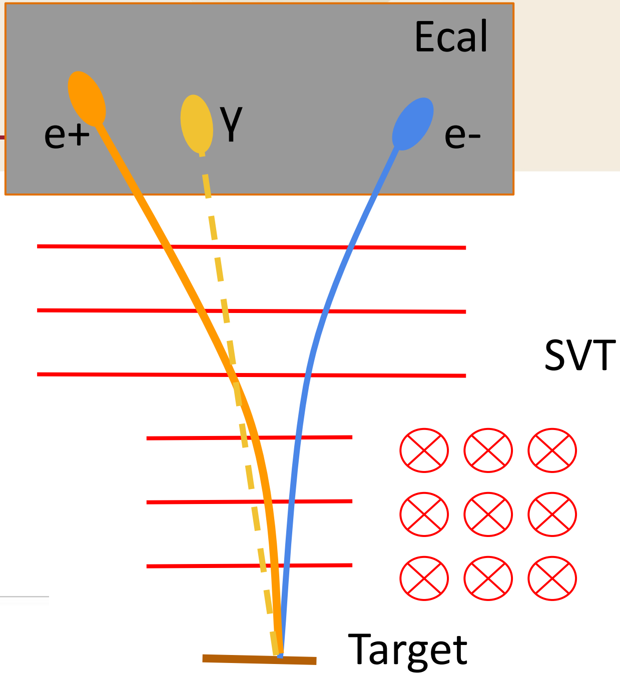
$E_{A'} \approx E$

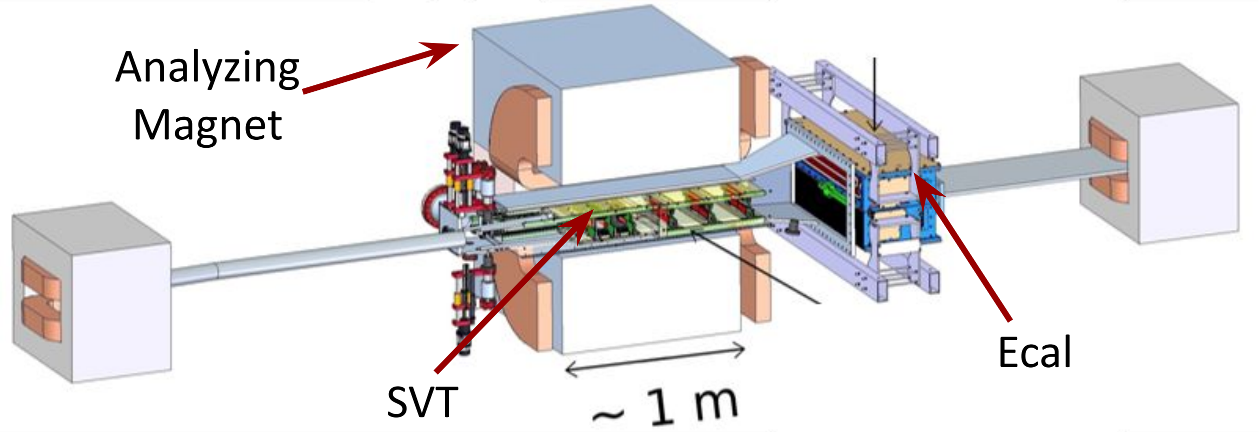


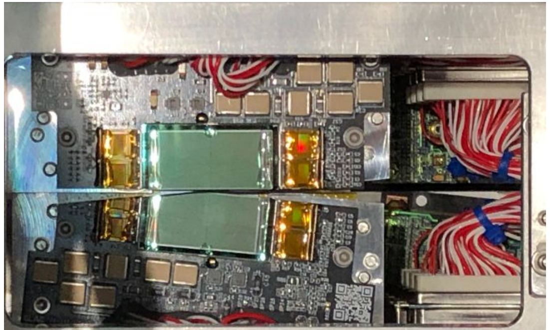


HPS Apparatus

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

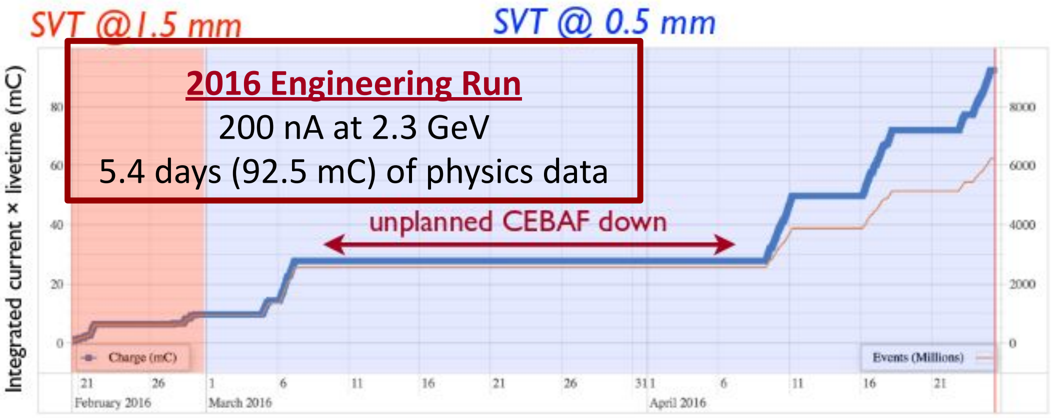


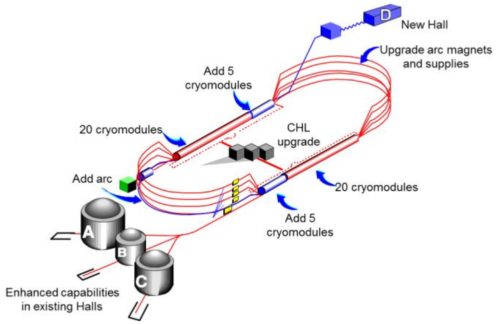


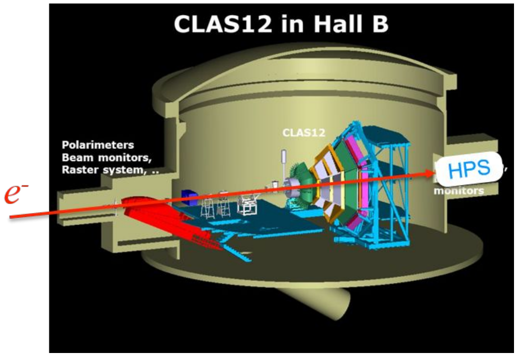

SVT Layer 0 (Upgraded)

Jefferson Laboratory 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 experiment halls
- 2.2 GeV per pass up to 12 GeV and 2 ns bunch pulse
- **Provides small beam spot with small tails** (~10^{-6})







Trident Backgrounds

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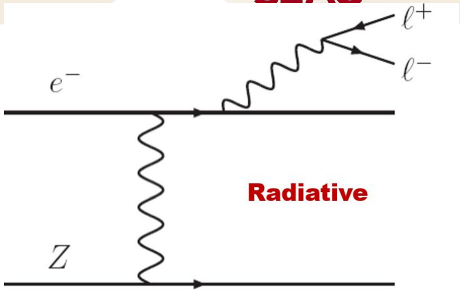
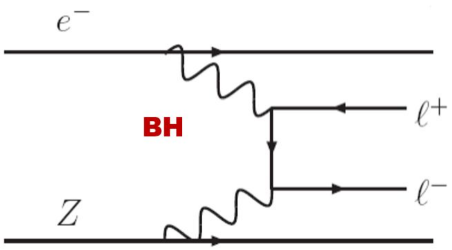
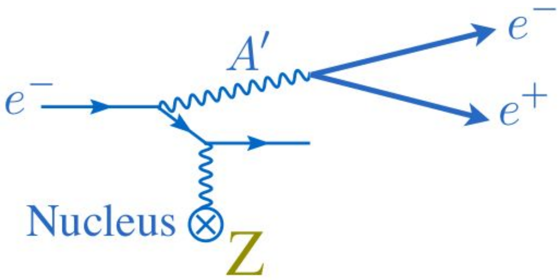
- **Radiative tridents**
  - Identical kinematics to A's; constitute an irreducible prompt background
  - Provide reference for expected signal rate

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

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

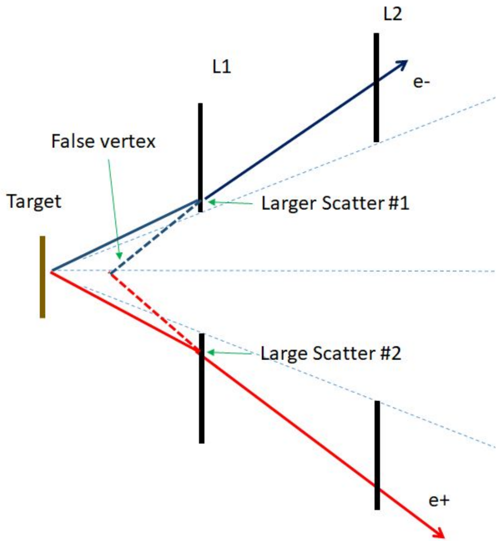


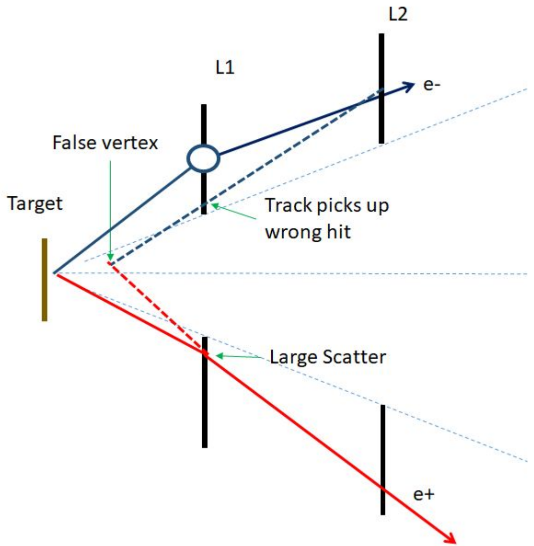


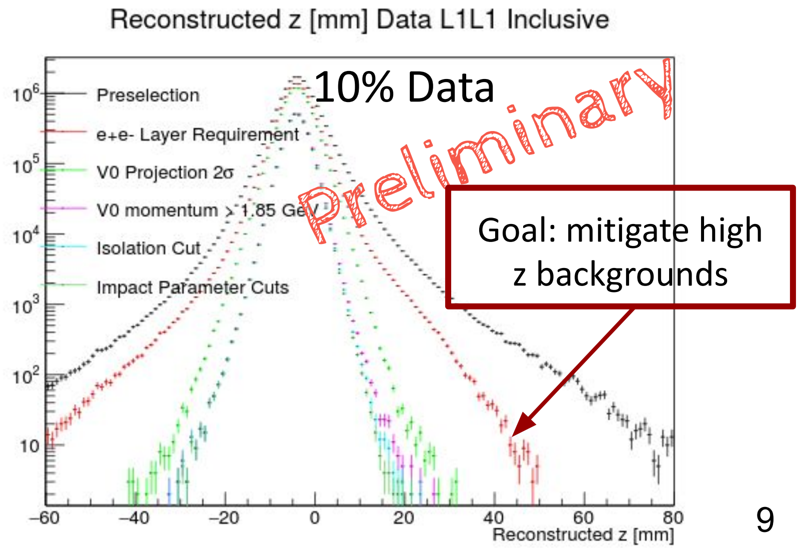


Displaced Vertex Search Event Selection

- Displaced vertex search is blinded with the selection tuned on 10% of the 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

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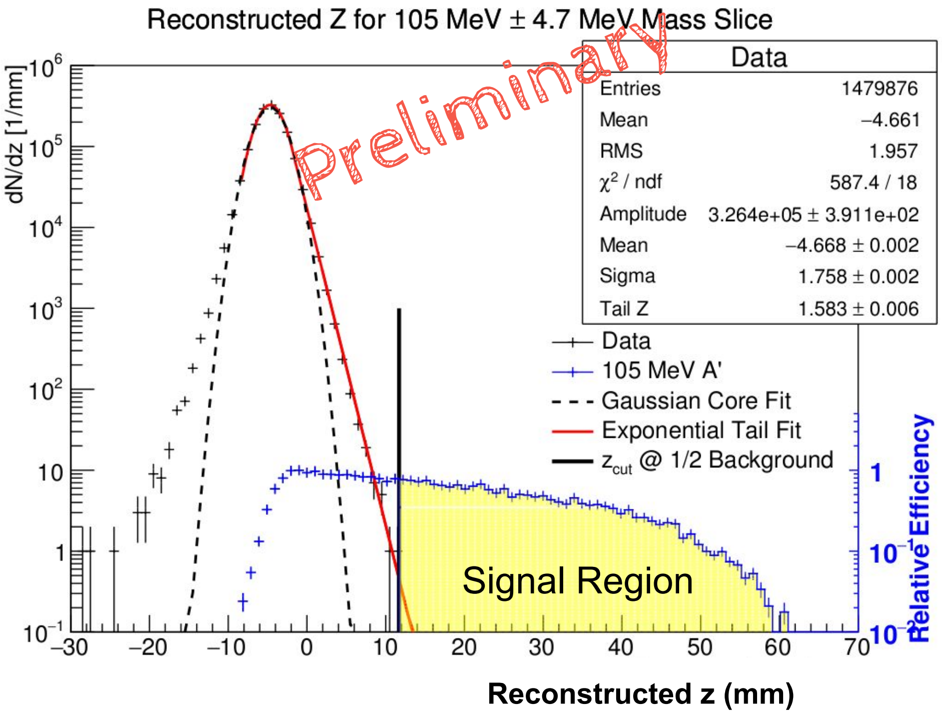
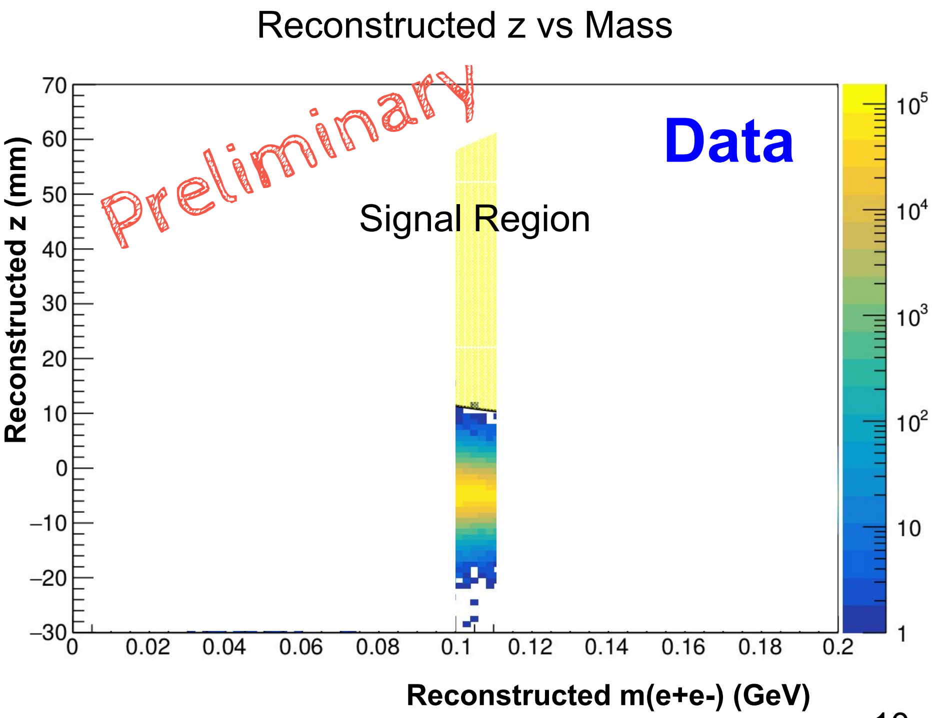
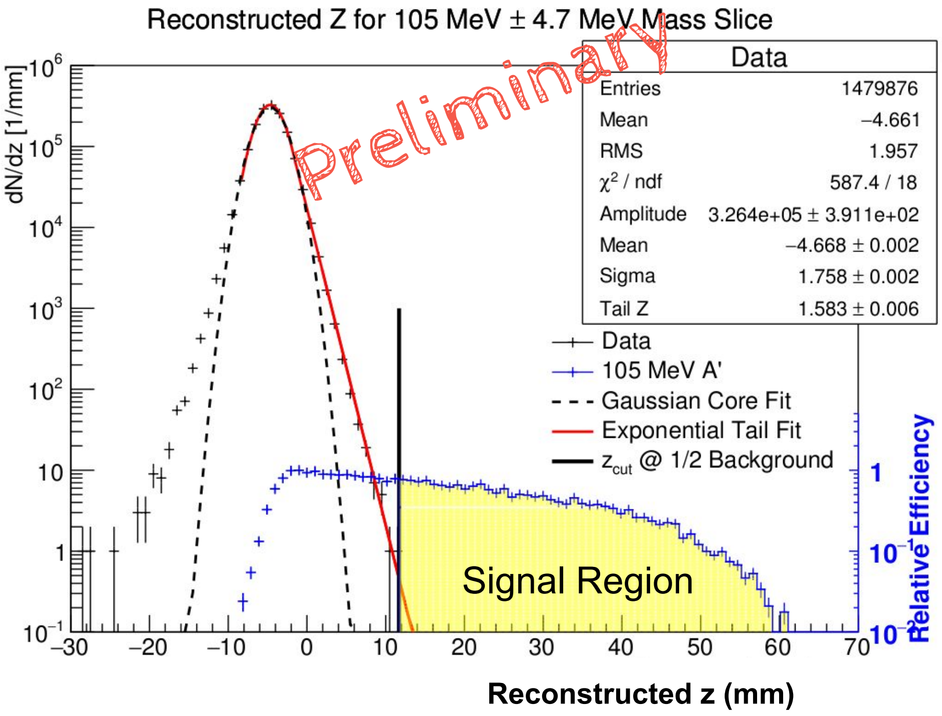
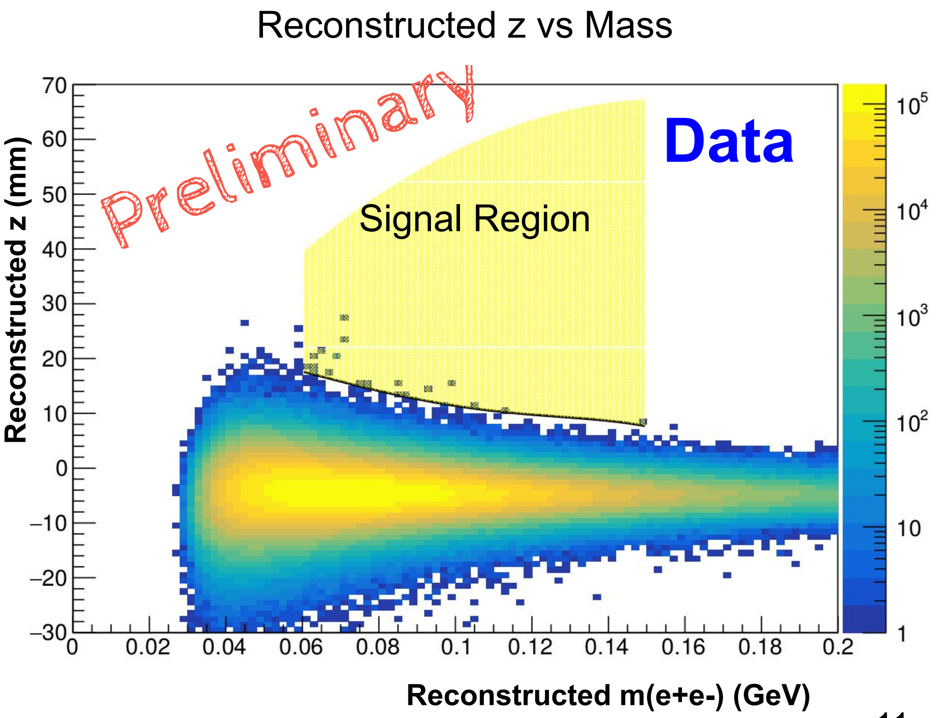




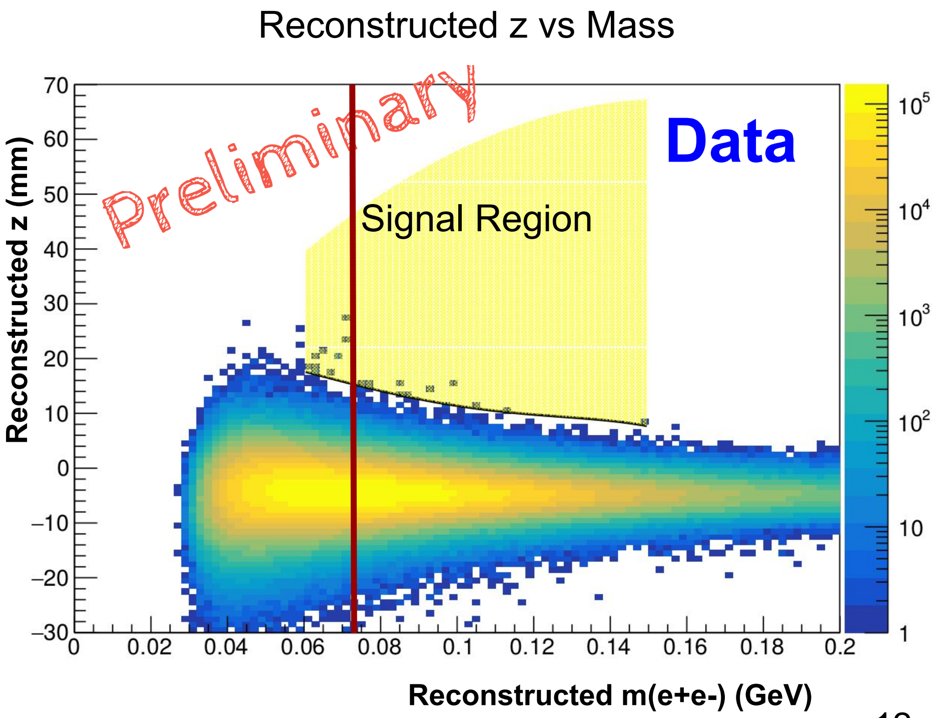
Displaced Vertex Search Signal Region





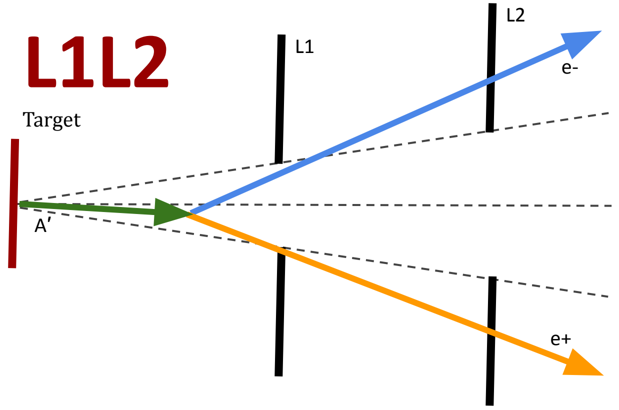
Displaced Vertex Search Backgrounds

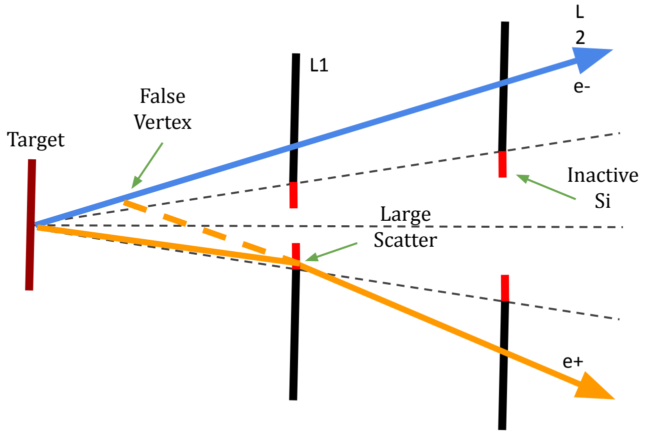
- Did we achieve the expected level of background necessary for a search?
  - **YES! A major accomplishment** (for mass greater than 70 MeV)
- What about mass less than 70 MeV?
  - **This excess is not observed in MC**
  - Most likely due to mis-tracking that is not currently properly modeled in MC
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



A's with Longer Livetimes

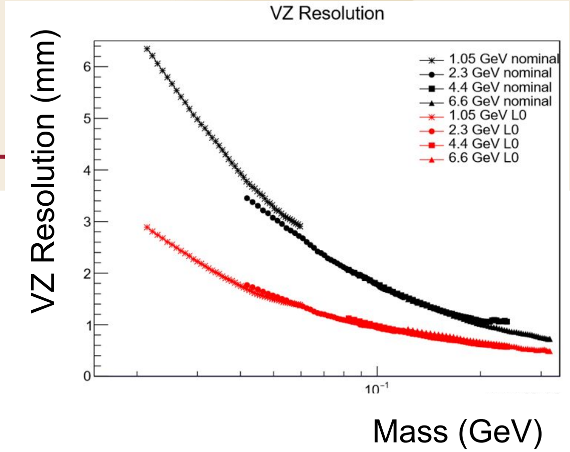
- A's with longer livetimes will have e+e- daughters that may miss layer 1 of the tracker
- Divide analysis into L1L1 (both particles hit L1) and L1L2 (one particles misses L1) categories
- Additional backgrounds for L1L2
  - Hit inefficiencies
  - Large Coulomb scatters in inactive Si
  - Brem conversion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

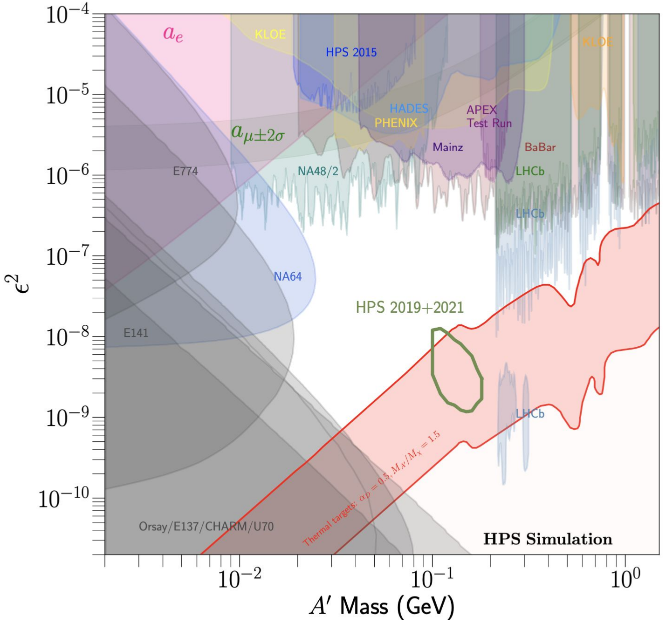




The Future of HPS

- 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 (future) 2021 are expected to yield exclusions, and potential discovery, of A's





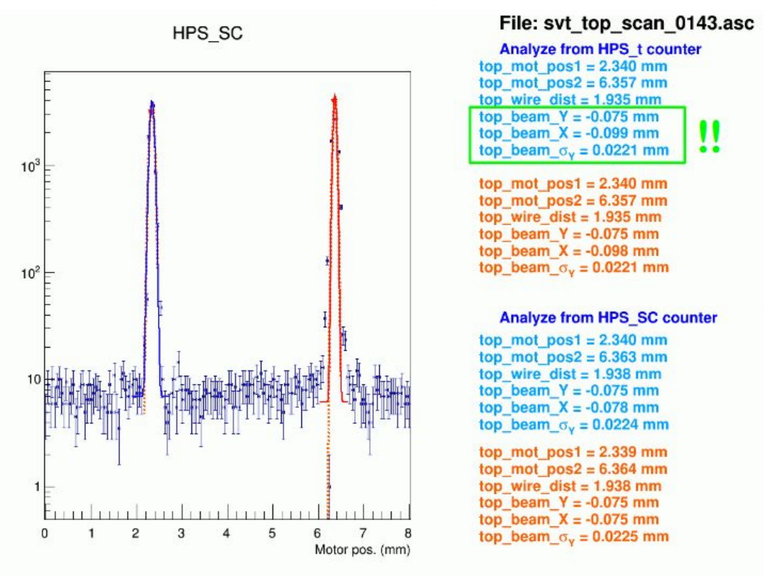
Conclusion

- Heavy photons are well-motivated as the force carrier which mediates LDM-LDM and LDM-SM interactions
- **HPS has successfully completed** both the displaced vertex and resonance searches for the 2016 Engineering Run at 2.3 GeV. Publication is expected soon
  - **Displaced vertex search technique works for HPS!**
  - Informs future exclusion potential for higher luminosity runs with detector upgrades
- Existing data from the 2019 run and future data from the 2021 run with minor detector upgrades are expected to yield real exclusions for the A’ model
  - See Alic Spellman’s talk on July 13 at 3:00 pm for more detail

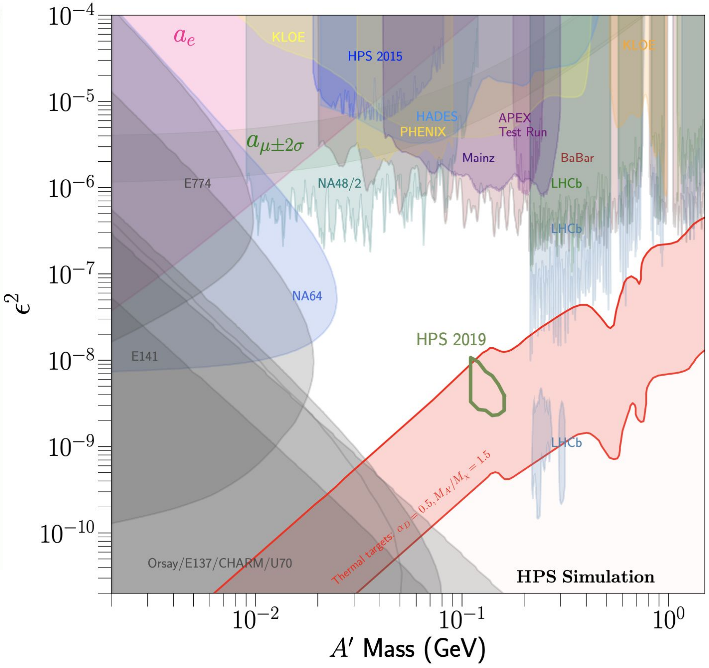
Thank You!

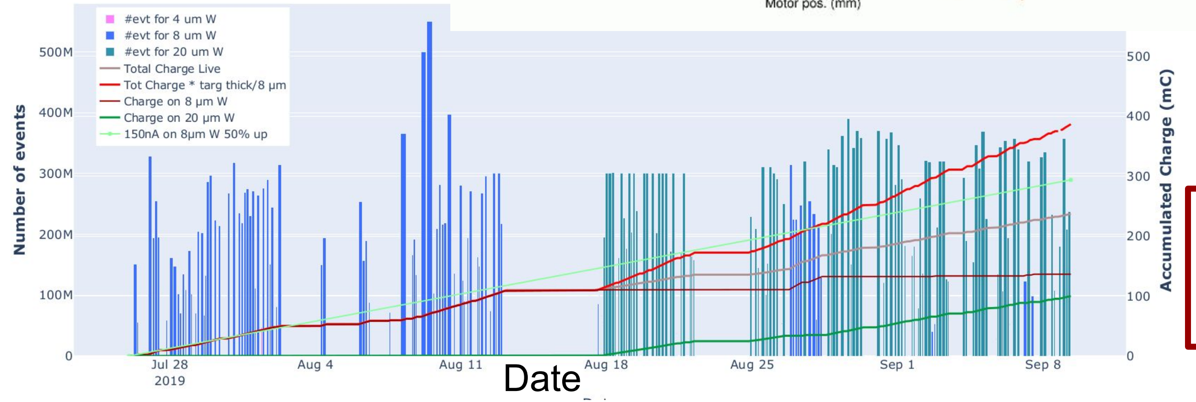

HPS Collaboration
May 3 - 5, 2017
Jefferson Lab • Newport News, VA

HPS Projected Reach With Upgrades



4.55 GeV beam: Achieved excellent beam at the target.



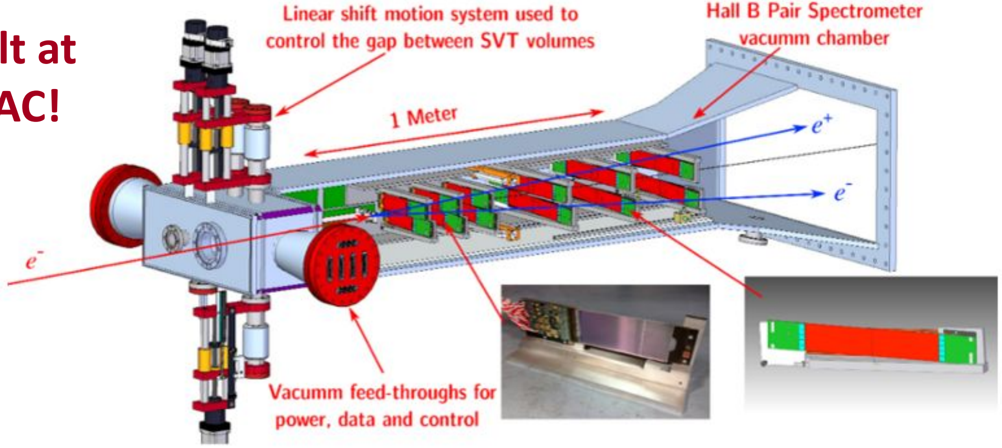


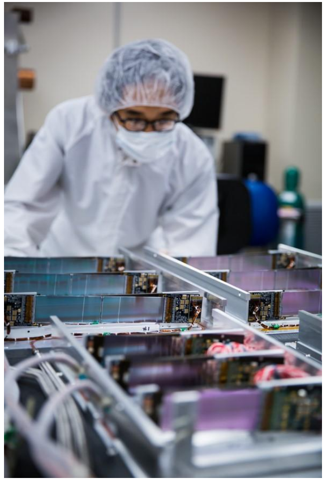
Reach projection contour scaled to the 2019 Physics Run luminosity

Silicon Vertex Tracker

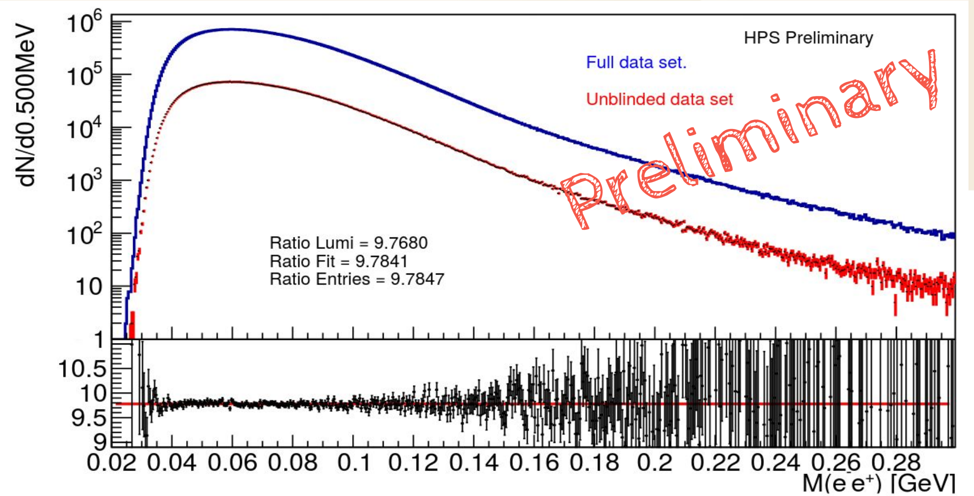
- SVT measures trajectories of e+e- and **reconstructs mass and vertex position**
- 6 layers of silicon microstrips (~0.7% radiation length per layer)
- Each layer has axial/stereo strips (100 mrad) for 3D hit position
- SVT is split to avoid “sheet of flame”; Also, very large scattered beam backgrounds!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

Built at SLAC!

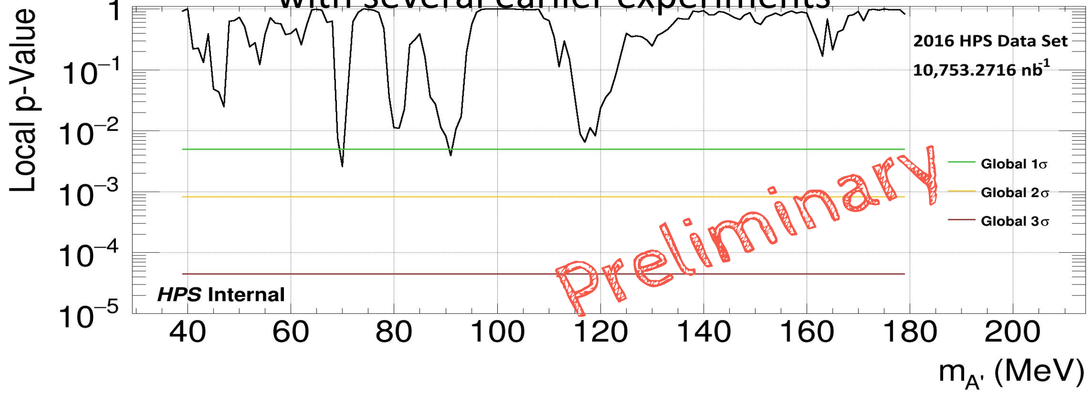


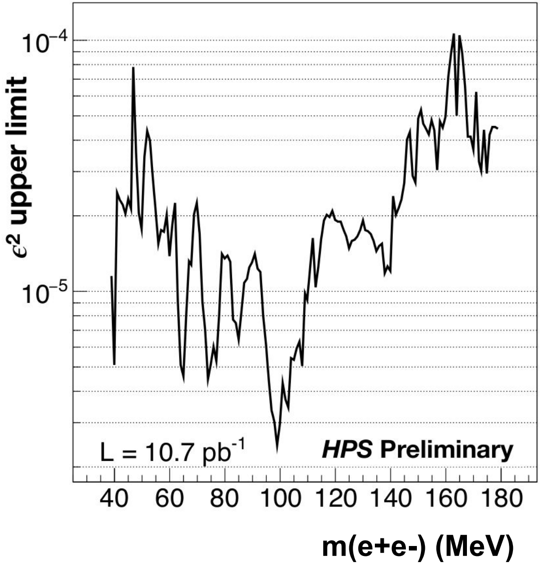


Resonance Search Results



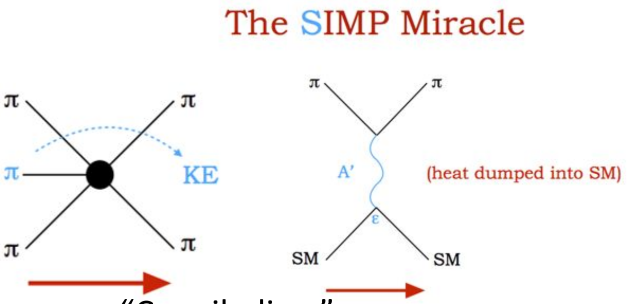
- Preliminary results for the resonance search for the 2016 Engineering Run
  - Blinded analysis - event selection tuned on 10% of the full data set
  - No significant excess found
  - Preliminary limits are consistent with several earlier experiments





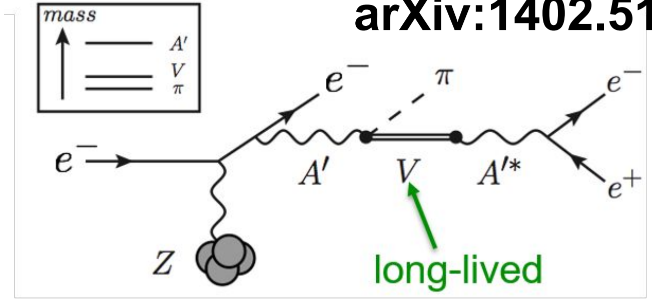
Other Possible Signatures at HPS

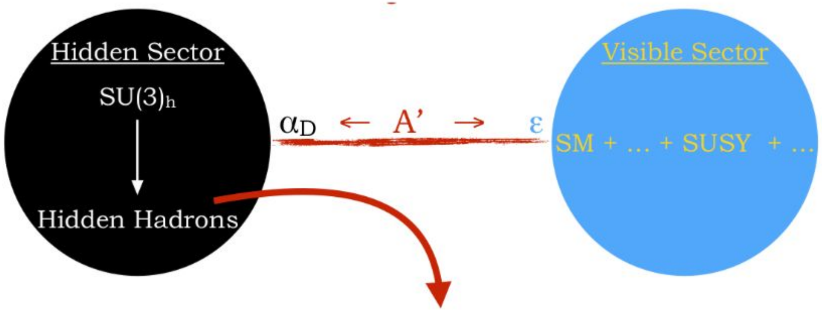
Can we probe other models? Strongly Interacting Massive Particles (SIMPs) are one such example, motivated by SIMP miracle



"Cannibalism"

arXiv:1402.5143



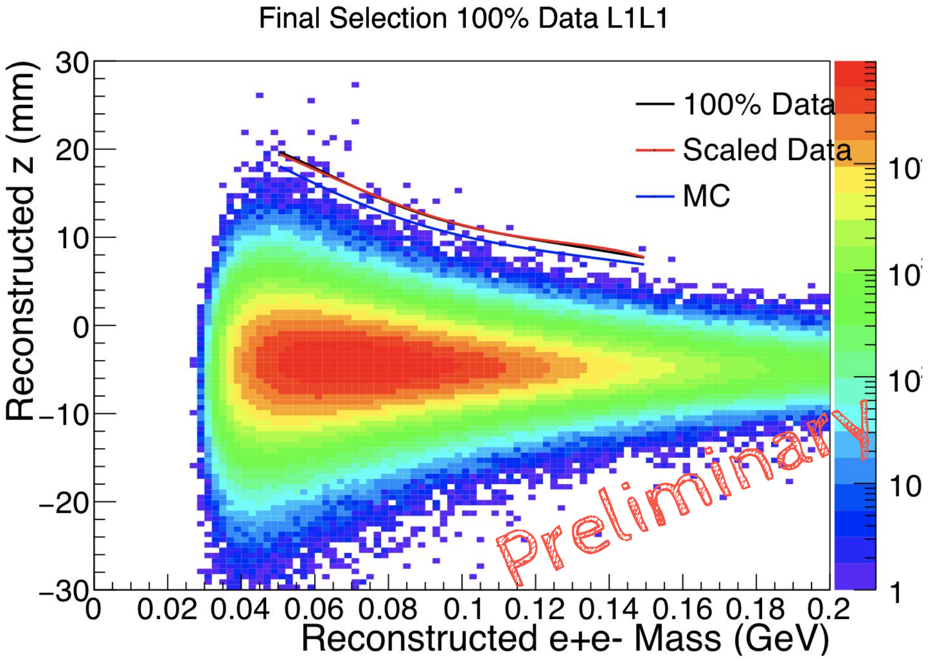


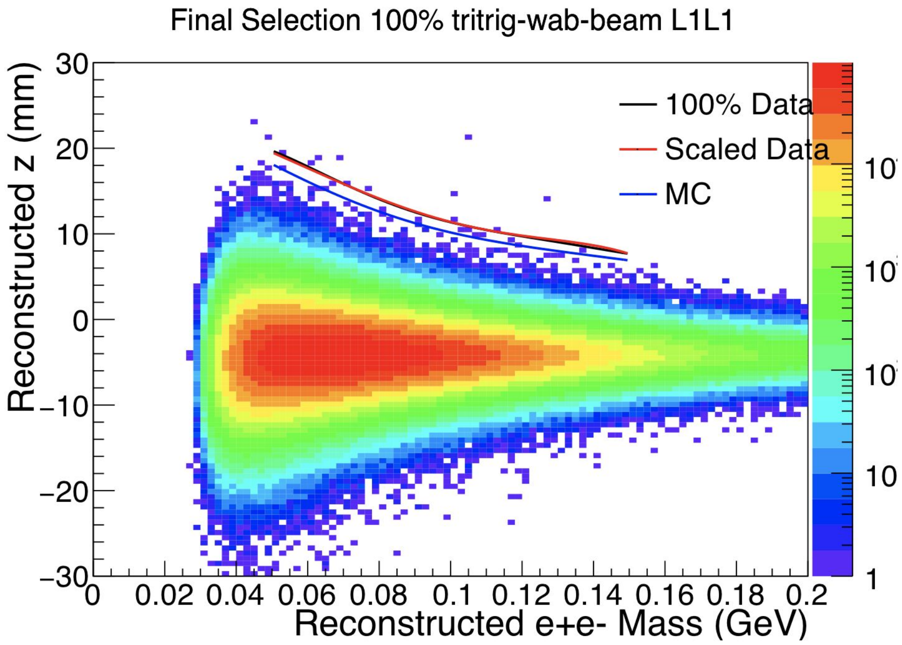
$$\text{pions “}\pi\text{”} \equiv \pi^0\ ,\ \eta^0\ ,\ K^0\ ,\ \overline{K^0}\ ,\ \pi^\pm\ ,\ K^\pm$$

$$\text{vector mesons “}V\text{”} \equiv \rho^0\ ,\ \omega\ ,\ \phi\ ,\ K^{*0}\ ,\ \overline{K^{*0}}\ ,\ \rho^\pm\ ,\ K^{*\pm}$$

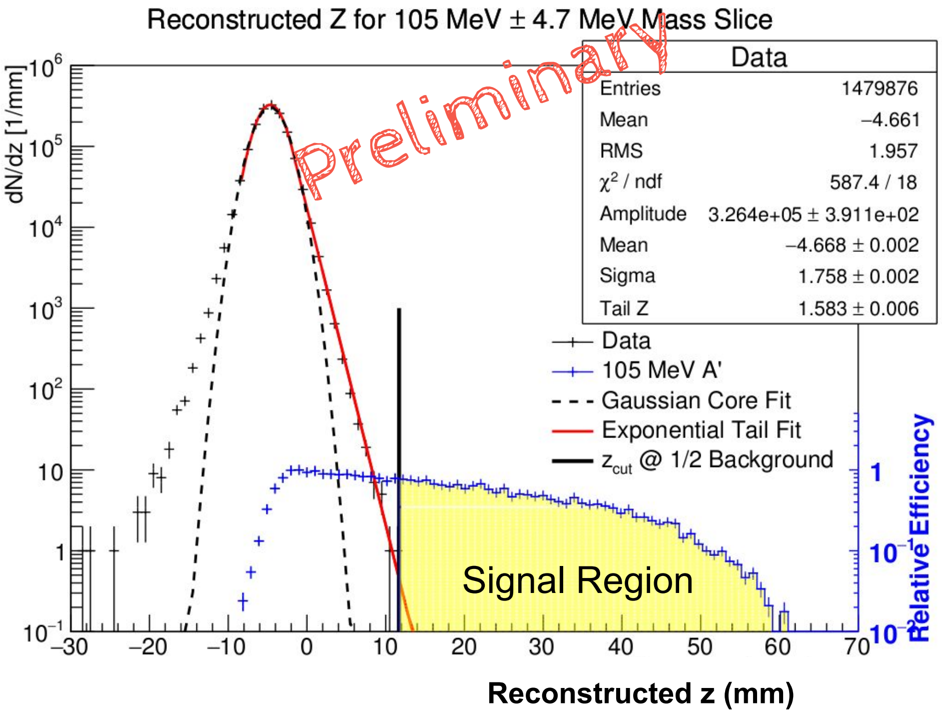
Proposes an additional SU(3) symmetry in a hidden sector. Allows for self-interacting DM and more complex structure

L1L1 Data/MC Comparison





Displaced Vertex Search Signal Region



- Start with a single mass slice and fit the background spectrum

$$F\left(\frac{z - z_{mean}}{\sigma_z} < b\right) = A e^{-\frac{(z - z_{mean})^2}{2\sigma_z^2}}$$

$$F\left(\frac{z - z_{mean}}{\sigma_z} >= b\right) = e^{-\frac{b^2}{2} - b\frac{z - z_{mean}}{\sigma_z}}$$

Gaussian Core + Exponential Tail

- Select the *z* position ("zcut") where the background model predicts 0.5 background events and cut away everything upstream
- This defines signal region. Events remaining are candidates for a signal

Heavy Photon Kinematics and Design Considerations

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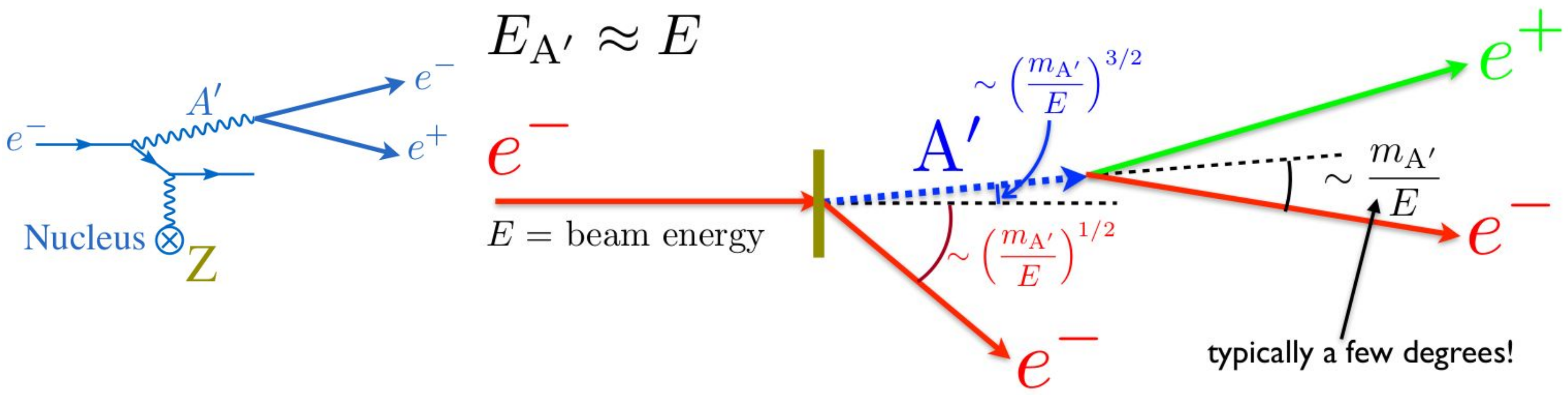
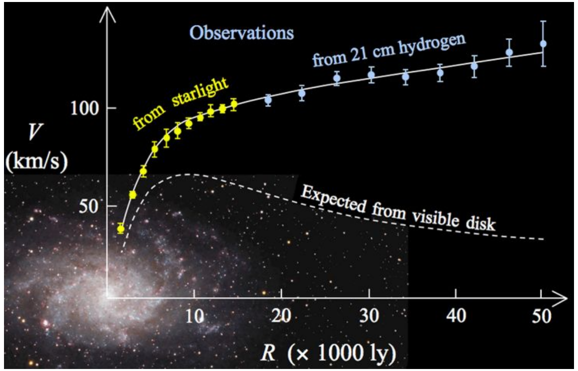
- A's can be produced in a process **analogous to Bremsstrahlung**
- A's take most of beam energy - decay products are forward with small opening angle
- Detector **acceptance must be very forward** (very close to beam plane)
- Small couplings -> small cross-section (rates). Need high intensity beam



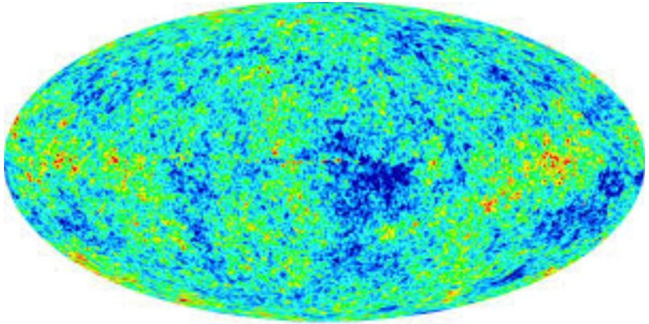
The Existence of Dark Matter

- There is clear evidence for the **existence of dark matter** (DM)
- The fundamental nature and 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

DM makes up ~85% of the total mass in the universe. **Weakly interacting massive particles (WIMPs) is most popular model** due to the so-called "WIMP Miracle"