

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

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# Introduction

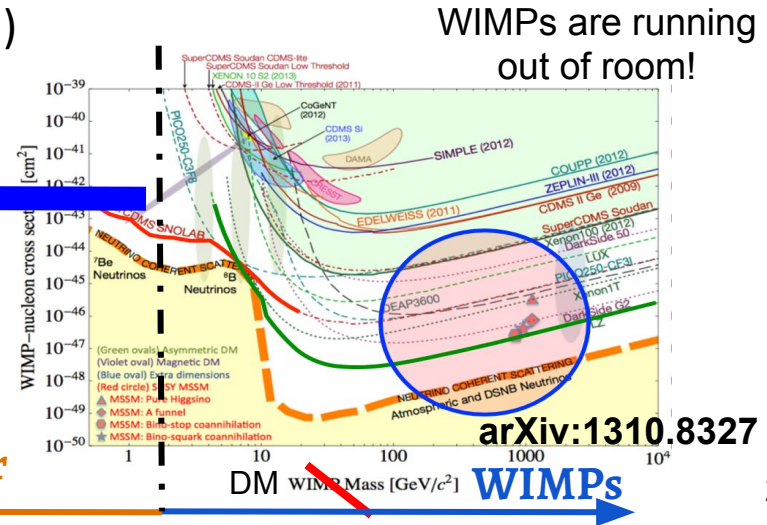
- A heavy photon (or dark photon, or  $A'$ ) is a **hypothetical vector boson** that couples to electric charge. Motivated by many sub-GeV dark matter models
- The Heavy Photon Search (HPS) is a **fixed target experiment** at Jefferson Lab dedicated to searching for this hypothetical vector boson, an  $A'$
- 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!**

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Rightarrow m_\chi \geq 2\text{GeV}$$

**“Lee-Weinberg Bound”**

Light Dark Matter



# Heavy Photon Primer

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

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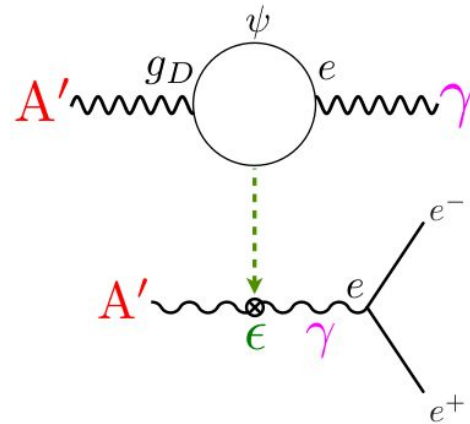
Suppose nature contains an **additional Abelian gauge symmetry**  $U'(1)$  (analogous to EM)

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

Induces a weak effective coupling of  $\epsilon e$  to SM fermions

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

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



Two Parameter Model:  
Mass of  $A'$  and  $\epsilon$

$$\alpha_D \equiv \frac{g_D^2}{4\pi} \quad \text{DM} \quad \text{SM} \quad \alpha \equiv \frac{e^2}{4\pi}$$

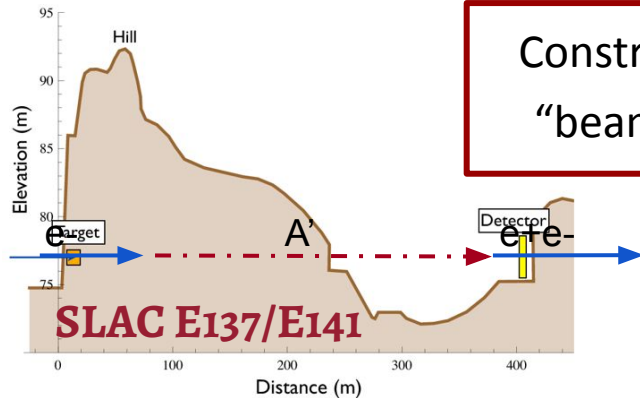
The diagram shows two dark matter particles (chi and chi-bar) annihilating into a heavy photon (A') via a vertex with coupling g\_D. The A' then decays into an electron-positron pair (e- e+) via a kinetic mixing vertex (epsilon).

# Existing Heavy Photon Constraints

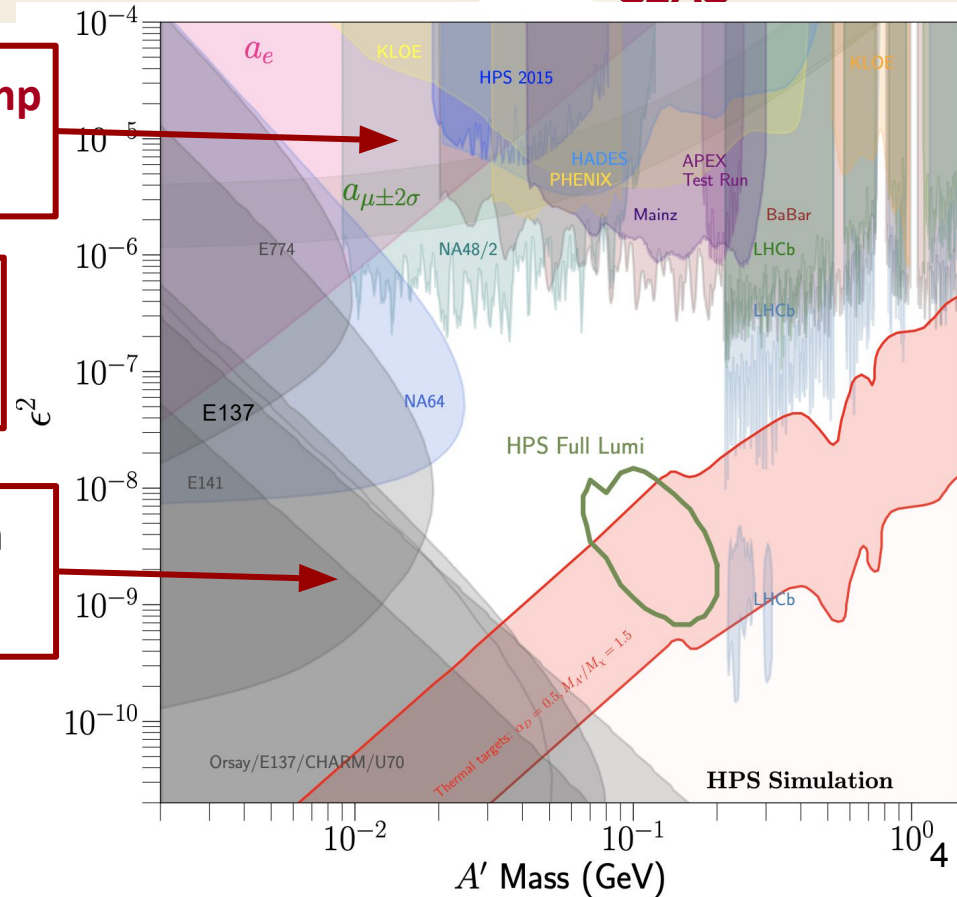
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Large coupling searches are generally “**bump hunts**” for  $m(l^+l^-)$  resonances

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

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


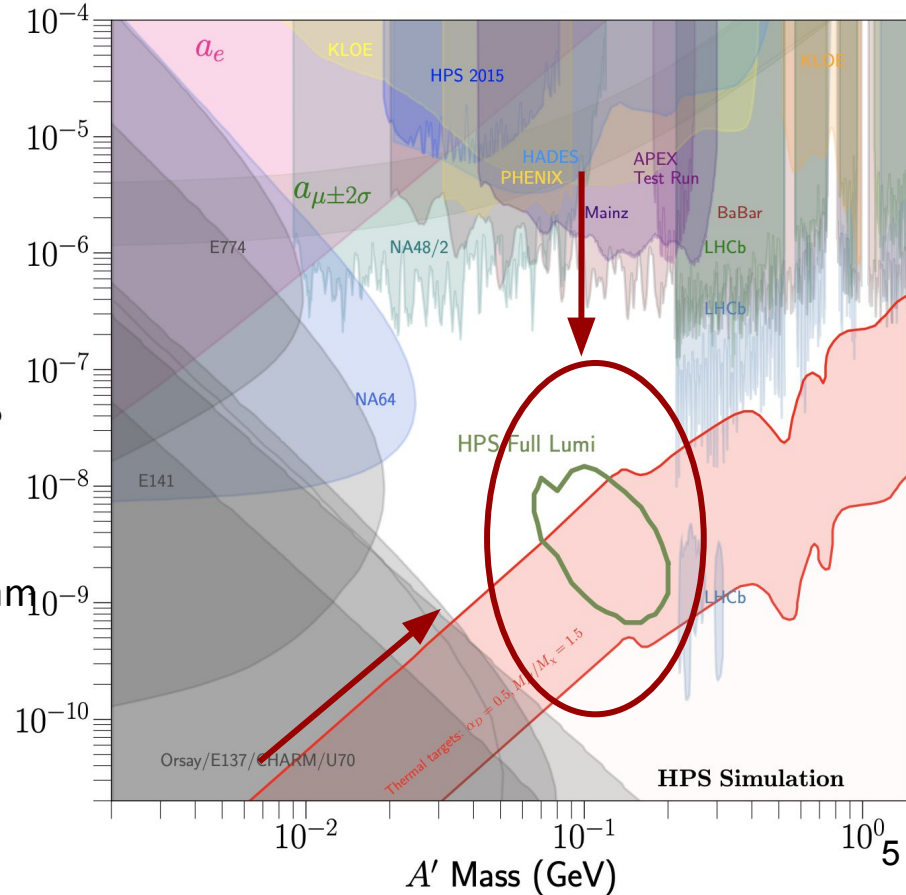
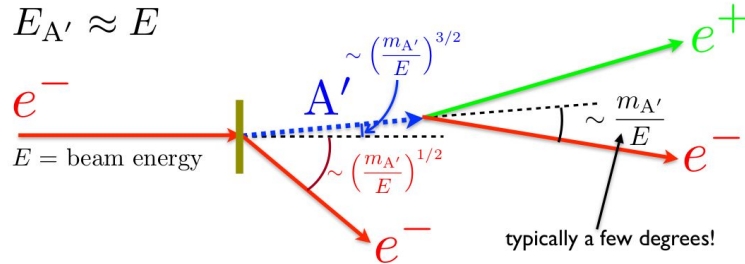
Constraints from “beam dumps”



# Probing New Heavy Photon Territory

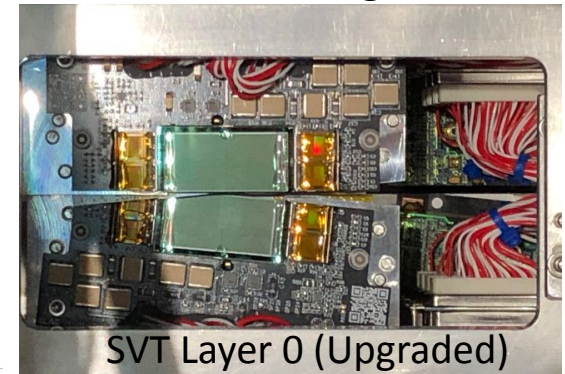
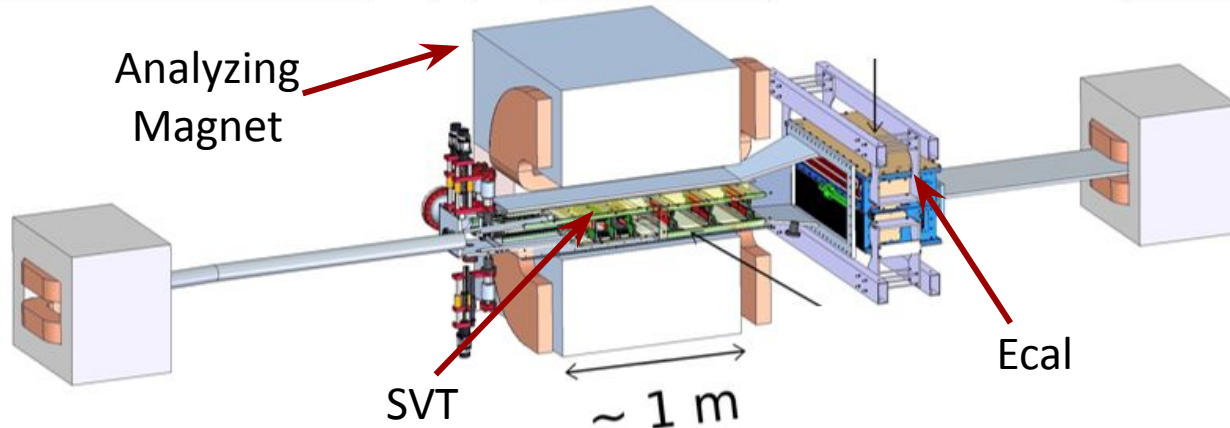
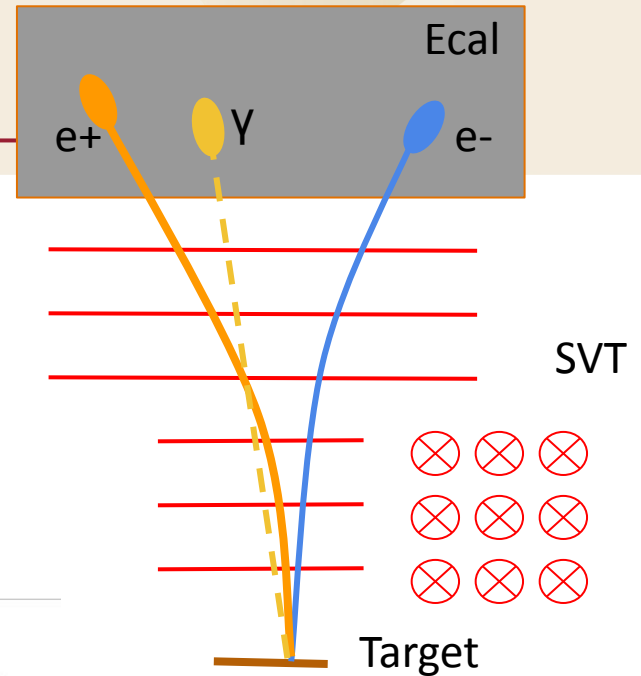
- The center is a highly motivated, yet unprobed region of parameter space
  - Small production cross-section
  - Short, but finite lifetime
- HPS - a fixed target precision vertexing experiment attempting to probe this
  - Large prompt QED backgrounds
  - $A'$  kinematics require sensitive detector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

$$E_{A'} \approx E$$



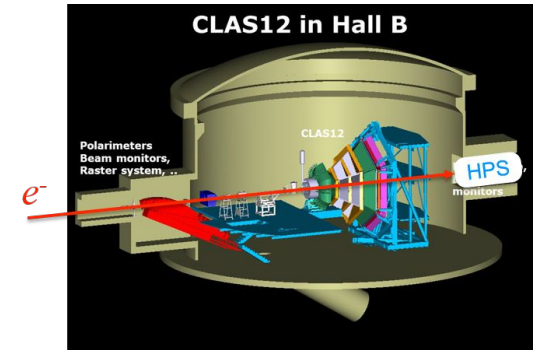
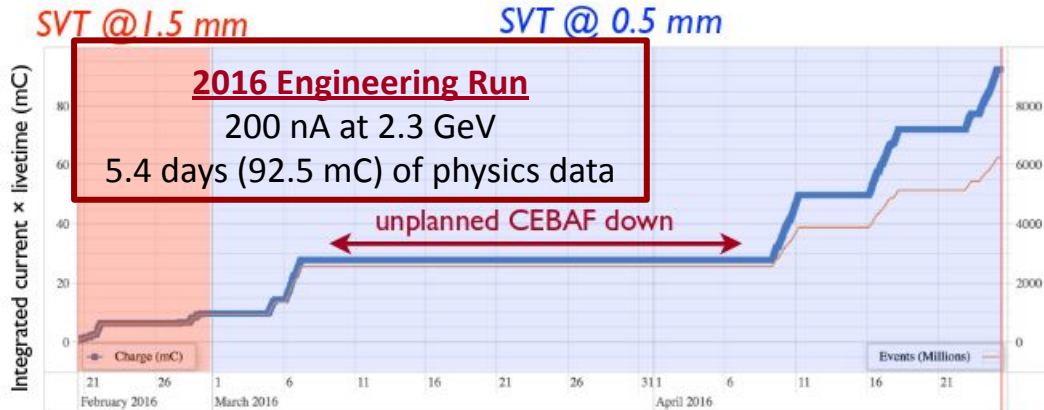
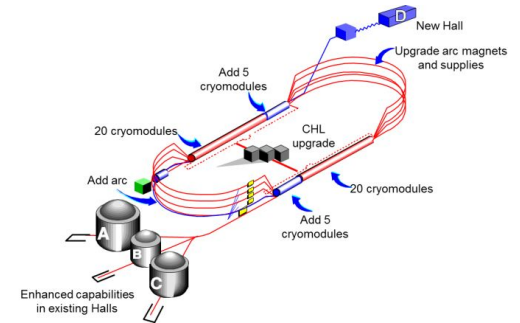
# HPS Apparatus

- 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



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



# Trident Backgrounds

- **Radiative tridents**

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

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

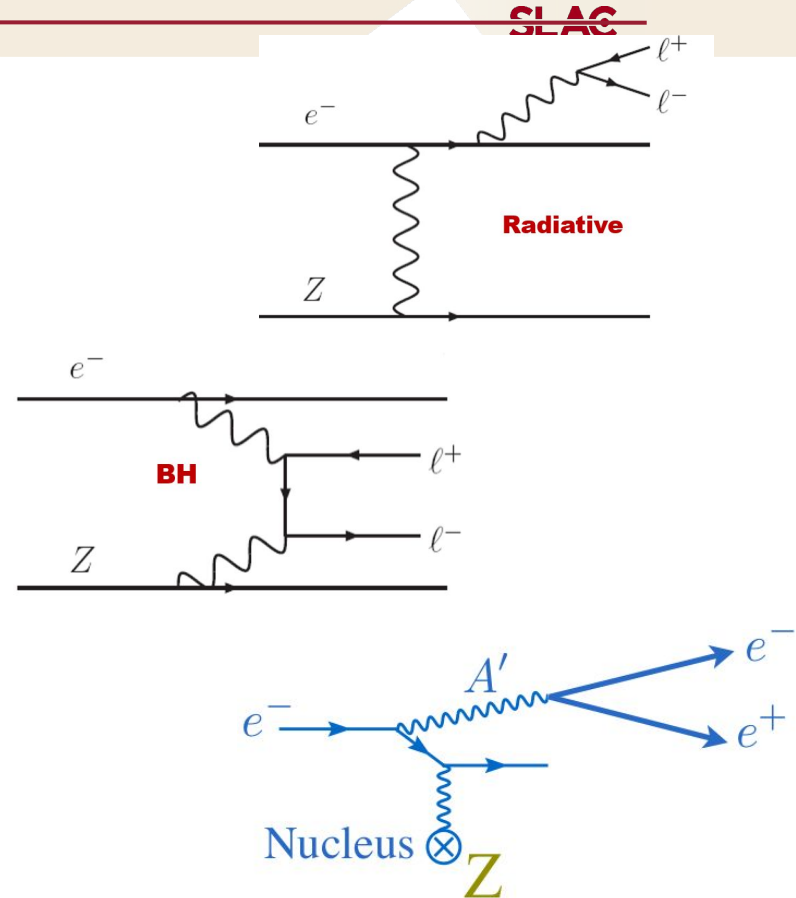
- **Bethe-Heitler (BH) tridents**

- 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

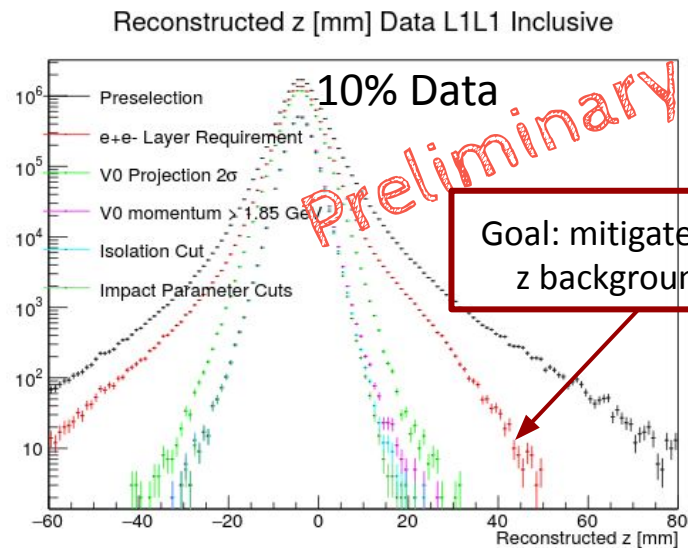
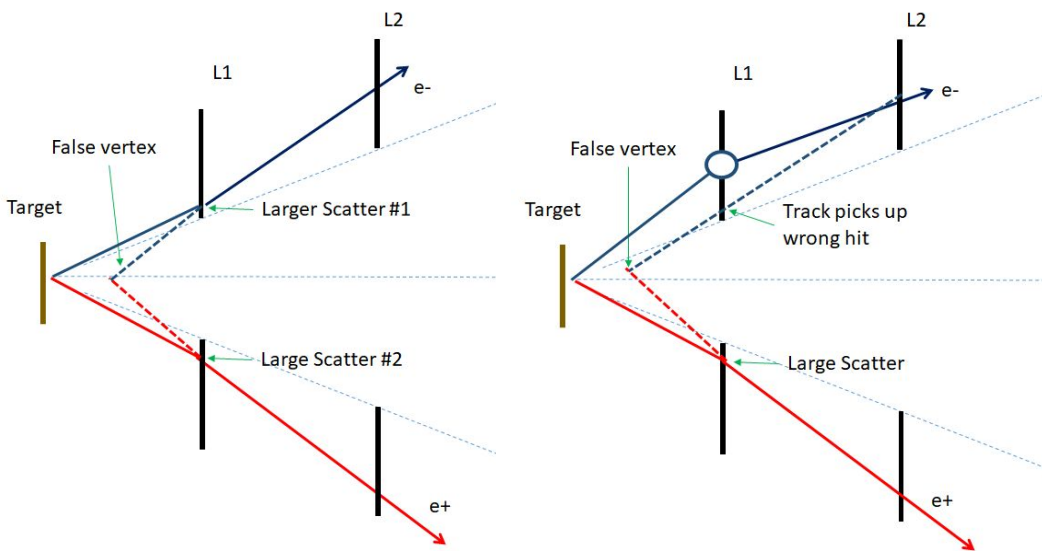
- Distinguishing the prompt QED tridents from displaced signal is the challenge of the analysis



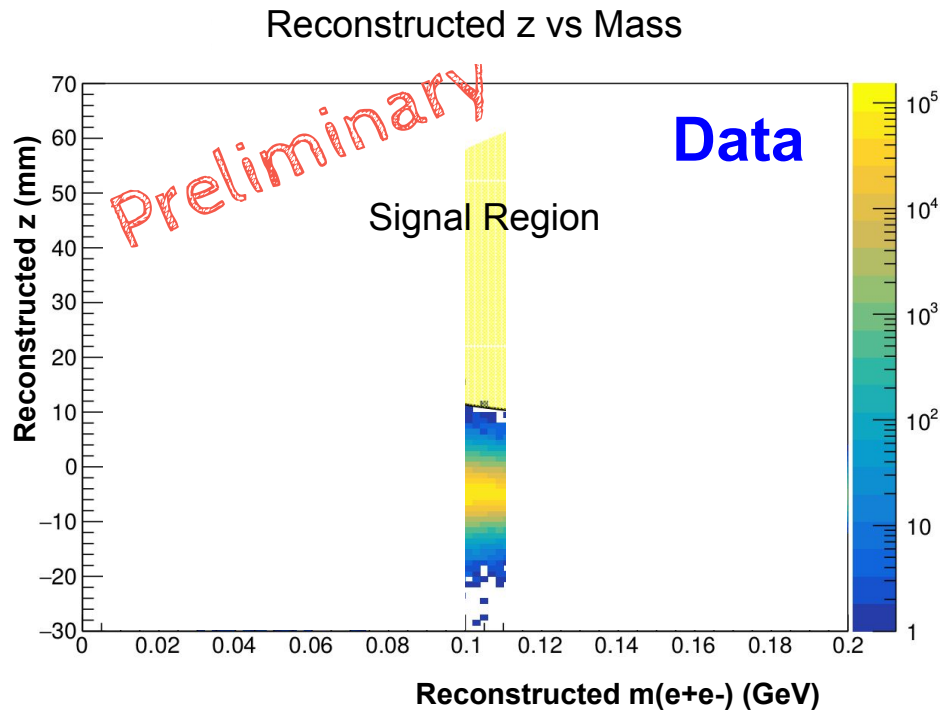
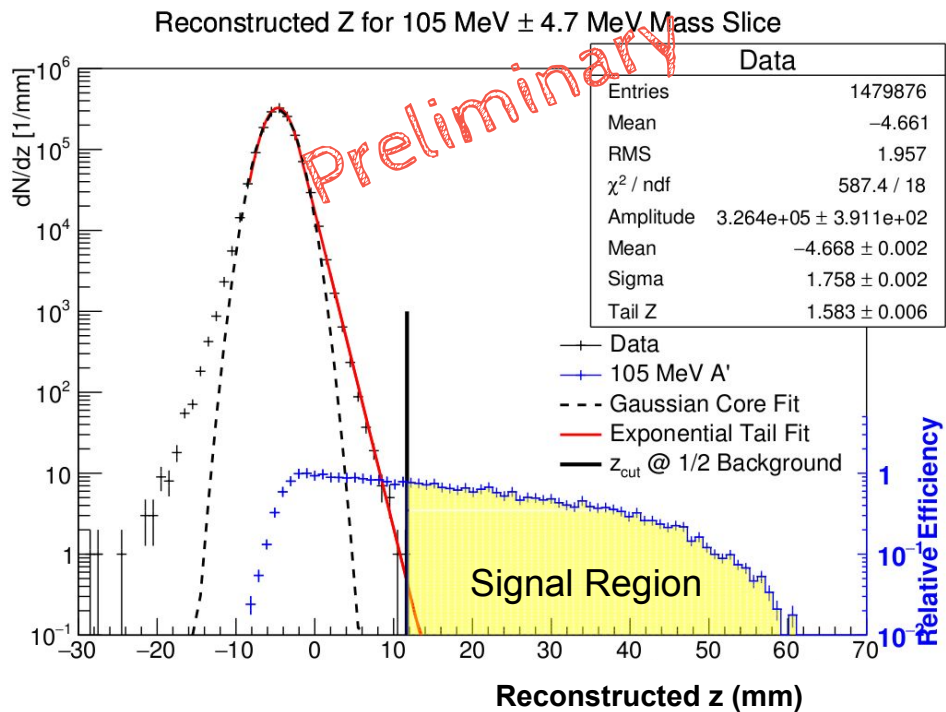


# Displaced Vertex Search Event Selection

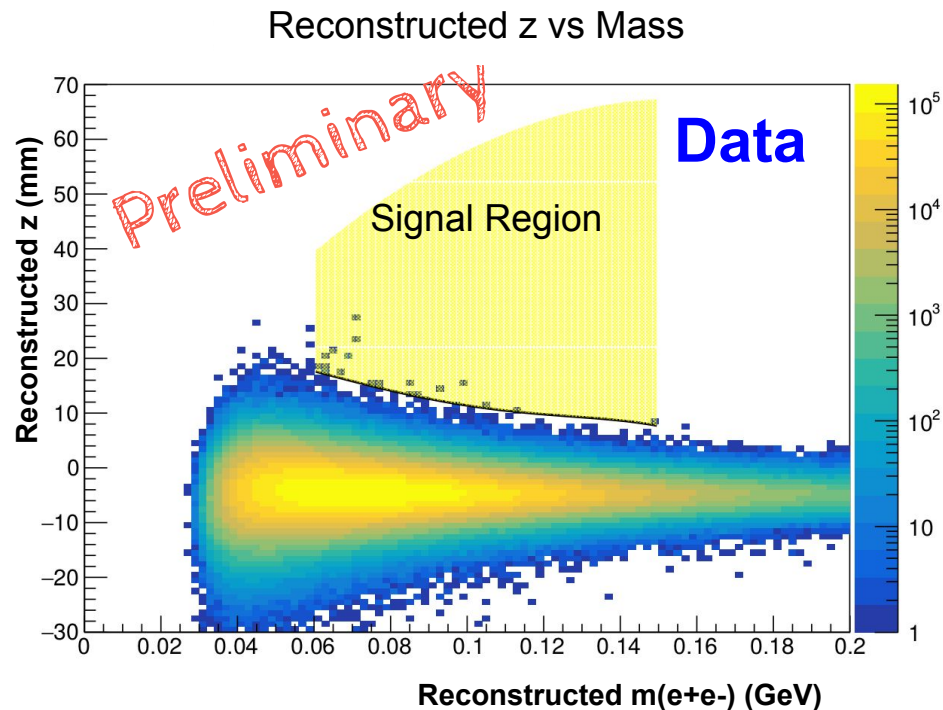
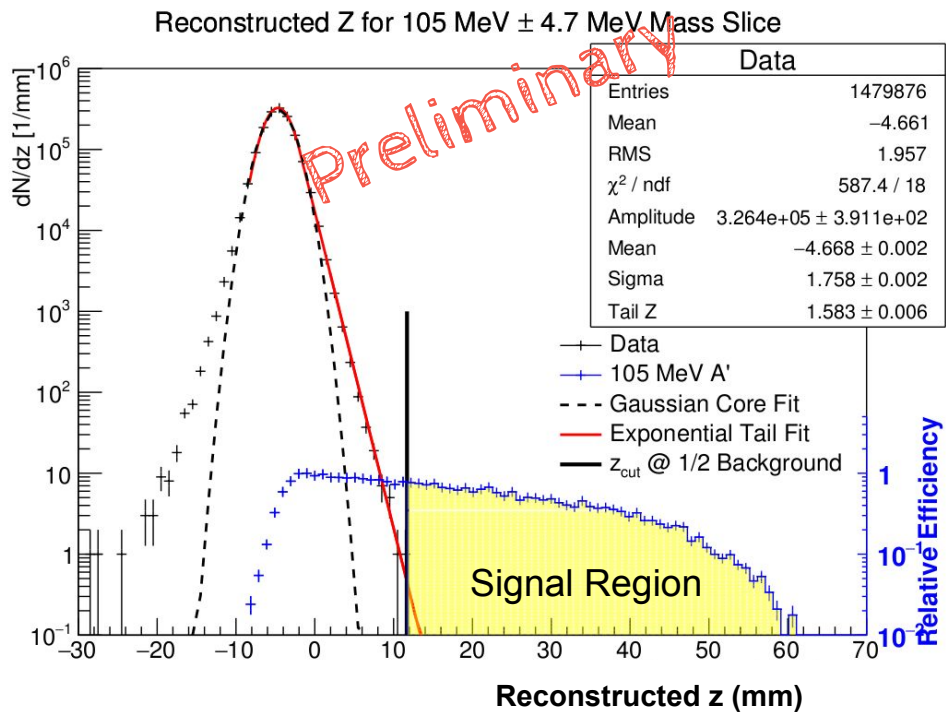
- Displaced vertex search is blinded with the selection tuned on 10% of the data
- Two main backgrounds from prompt trident processes: large Coulomb scatters in layer 1 of the tracker and mis-tracking
  - Require strict selections on track quality and vertex quality & require layer 1 hits



# Displaced Vertex Search Signal Region

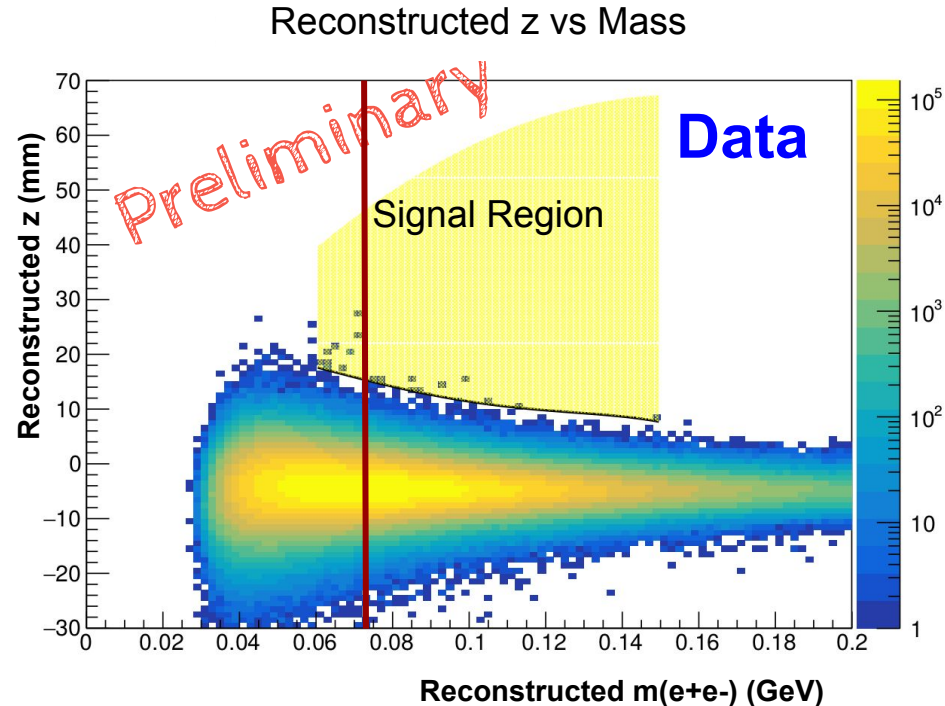


# Displaced Vertex Search Signal Region



# Displaced Vertex Search Backgrounds

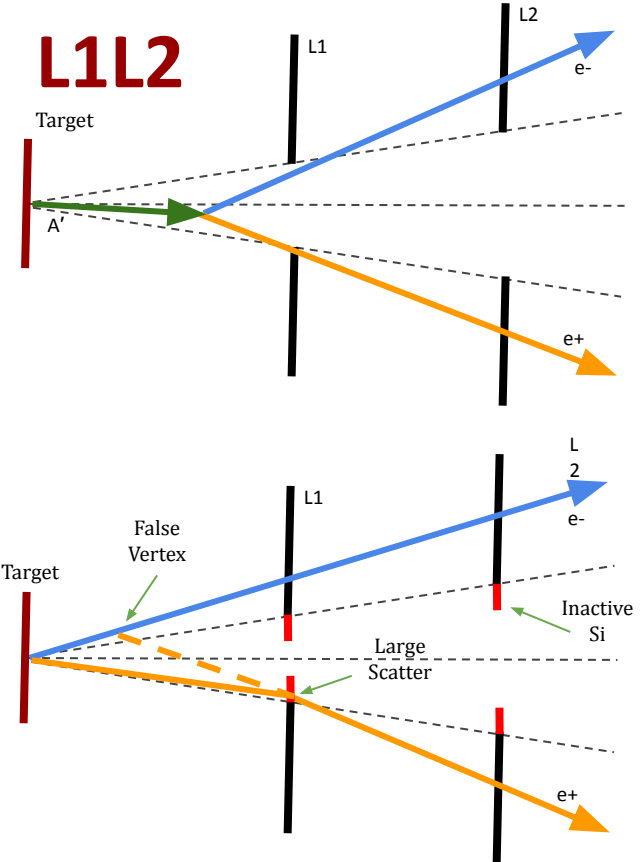
- Did we achieve the expected level of background necessary for a search?
  - **YES! A major accomplishment** (for mass greater than 70 MeV)
- What about mass less than 70 MeV?
  - **This excess is not observed in MC**
  - Most likely due to mis-tracking that is not currently properly modeled in MC
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



# A's with Longer Livetimes

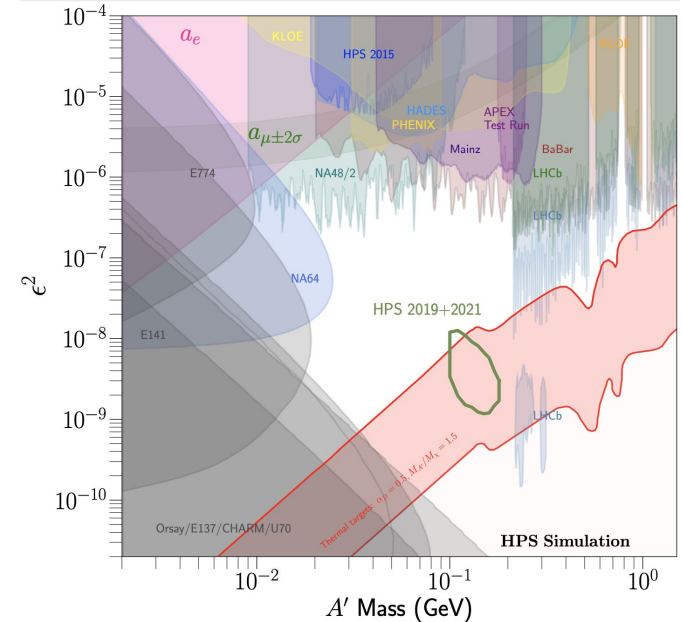
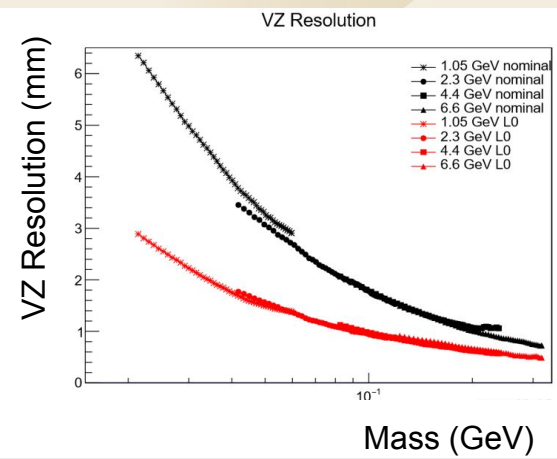
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- A's with longer livetimes will have  $e^+e^-$  daughters that may miss layer 1 of the tracker
- Divide analysis into L1L1 (both particles hit L1) and L1L2 (one particles misses L1) categories
- Additional backgrounds for L1L2
  - Hit inefficiencies
  - 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!

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## HPS Collaboration

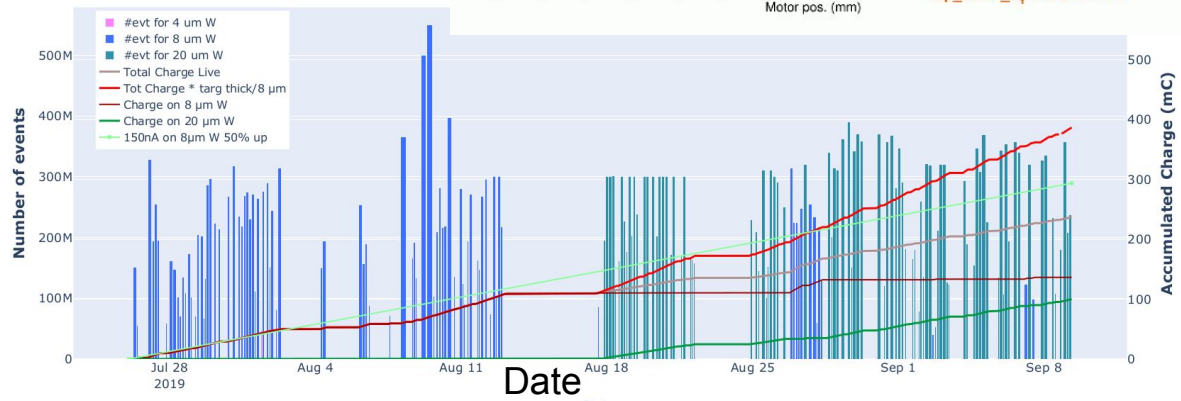
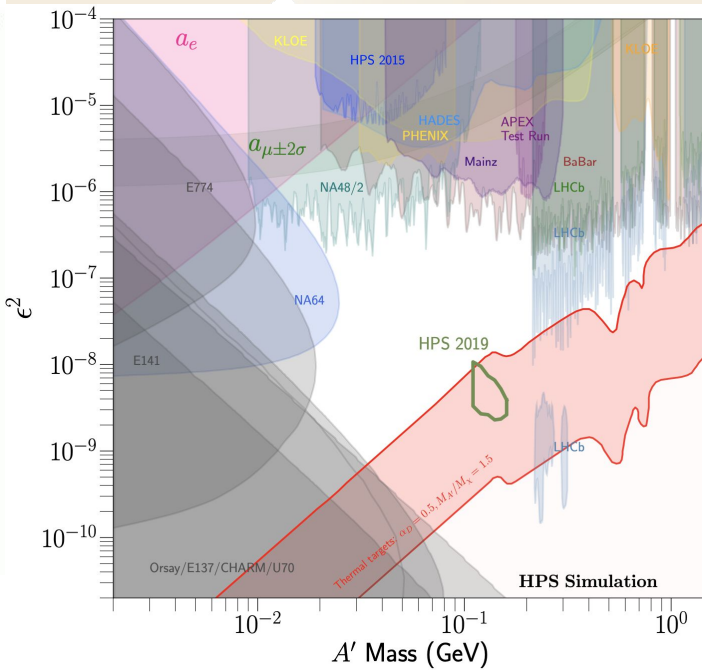
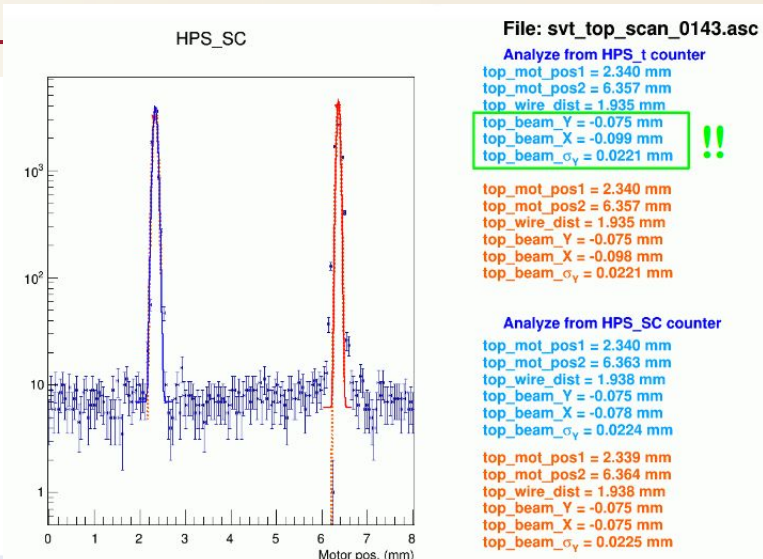
May 3 - 5, 2017

Jefferson Lab • Newport News, VA



# HPS Projected Reach With Upgrades

**4.55 GeV beam:**  
Achieved excellent  
beam at the target.

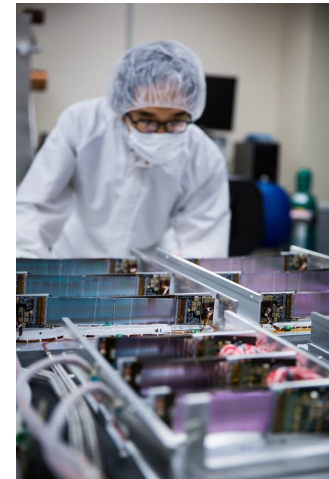
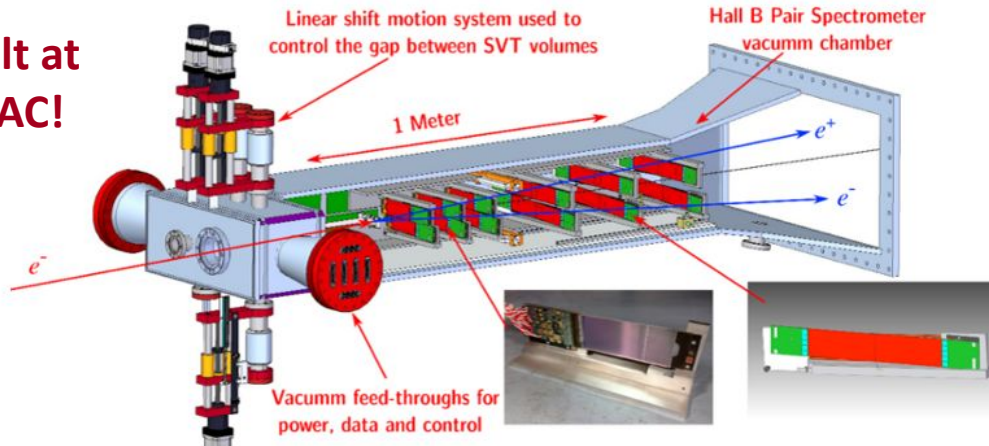


Reach projection contour scaled to  
the 2019 Physics Run luminosity

# Silicon Vertex Tracker

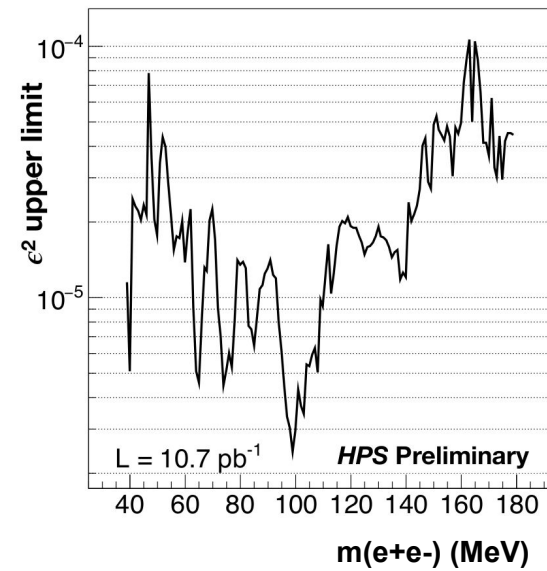
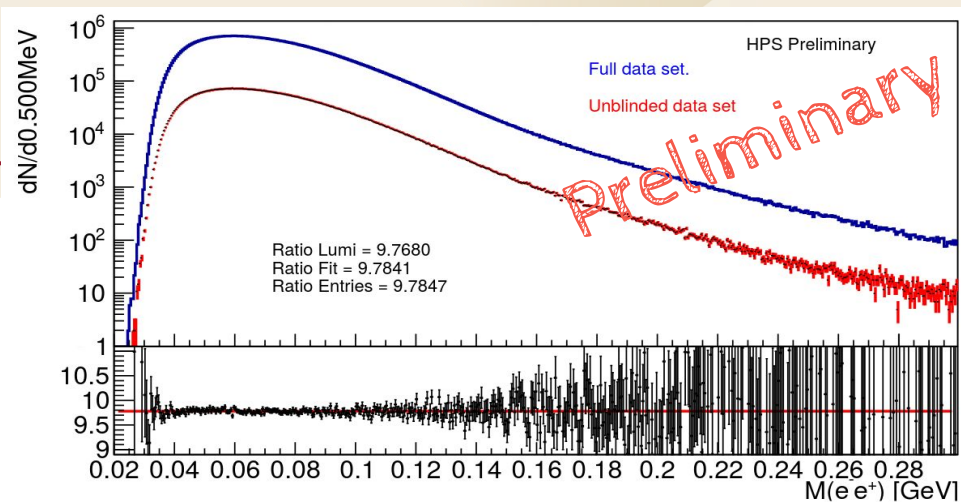
- SVT measures trajectories of  $e^+e^-$  and **reconstructs mass and vertex position**
- 6 layers of silicon microstrips ( $\sim 0.7\%$  radiation length per layer)
- Each layer has axial/stereo strips (100 mrad) for 3D hit position
- SVT is split to avoid “sheet of flame”; Also, very large scattered beam backgrounds!
- Silicon is very close to beam for good forward coverage ( $\frac{1}{2}$  mm from the beam!)
- L4-L6 are double wide for acceptance purposes

Built at  
SLAC!



# Resonance Search Results

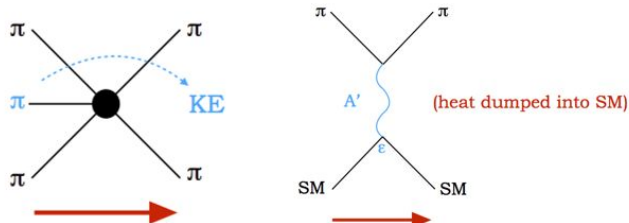
- Preliminary results for the resonance search for the 2016 Engineering Run
  - Blinded analysis - event selection tuned on 10% of the full data set
  - No significant excess found
  - Preliminary limits are consistent with several earlier experiments



# Other Possible Signatures at HPS

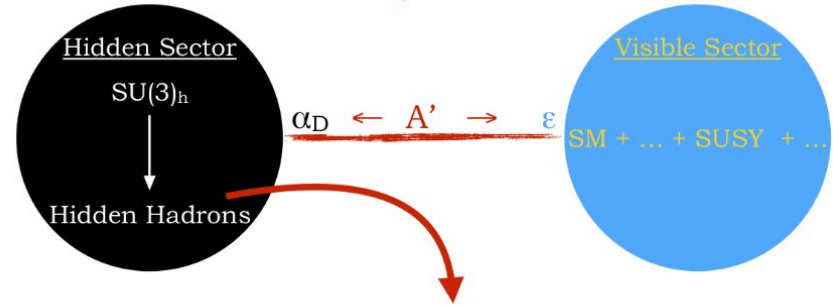
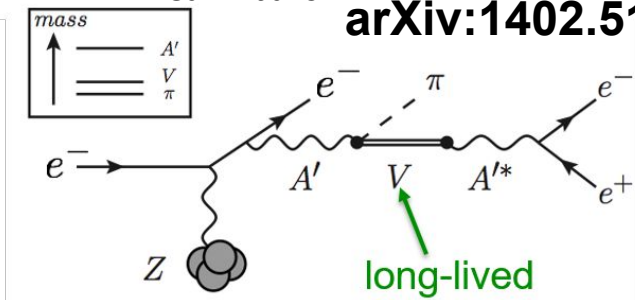
Can we probe other models? Strongly Interacting Massive Particles (SIMPs) are one such example, motivated by SIMP miracle

## The SIMP Miracle



“Cannibalism”

arXiv:1402.5143

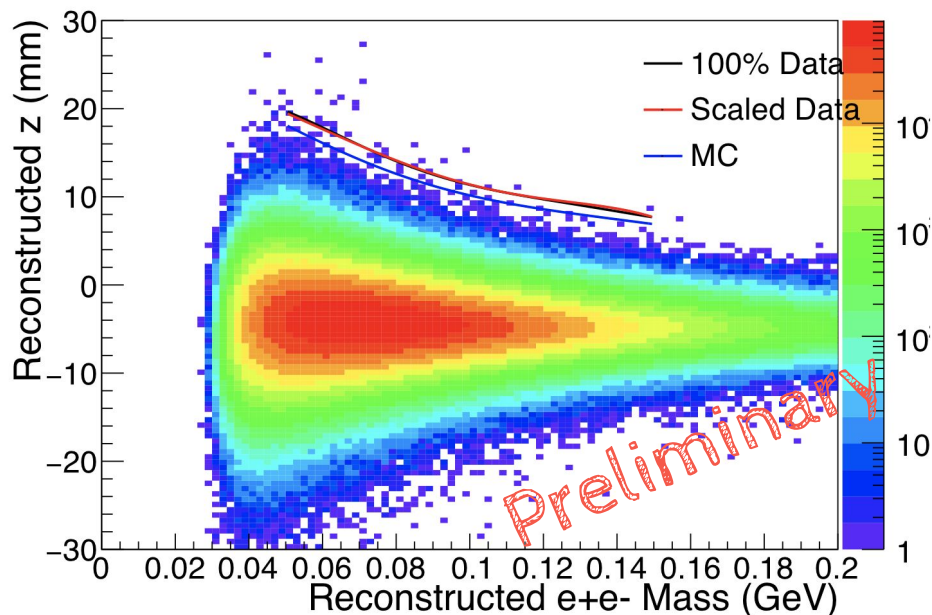


pions “ $\pi$ ”  $\equiv \pi^0, \eta^0, K^0, \bar{K}^0, \pi^\pm, K^\pm$   
 vector mesons “ $V$ ”  $\equiv \rho^0, \omega, \phi, K^{*0}, \bar{K}^{*0}, \rho^\pm, K^{*\pm}$

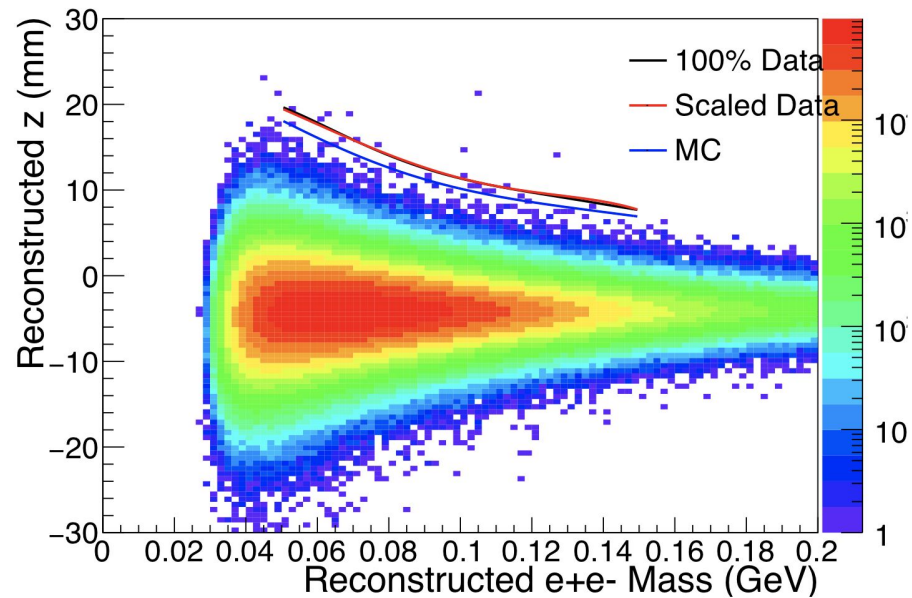
Proposes an additional SU(3) symmetry in a hidden sector. Allows for self-interacting DM and more complex structure

# L1L1 Data/MC Comparison

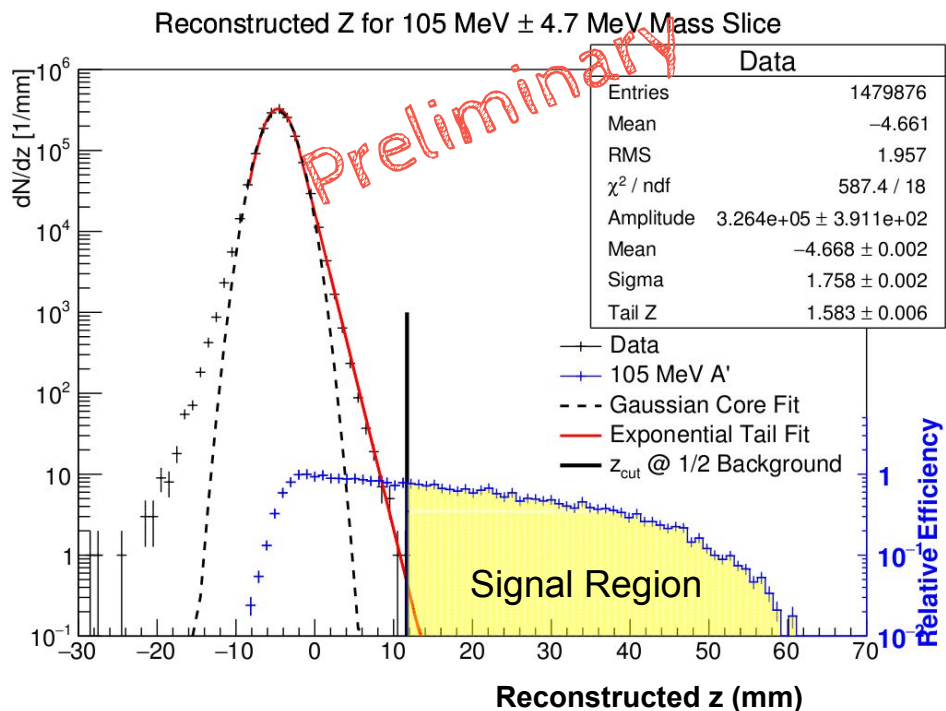
Final Selection 100% Data L1L1



Final Selection 100% tritrig-wab-beam L1L1



# Displaced Vertex Search Signal Region



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

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

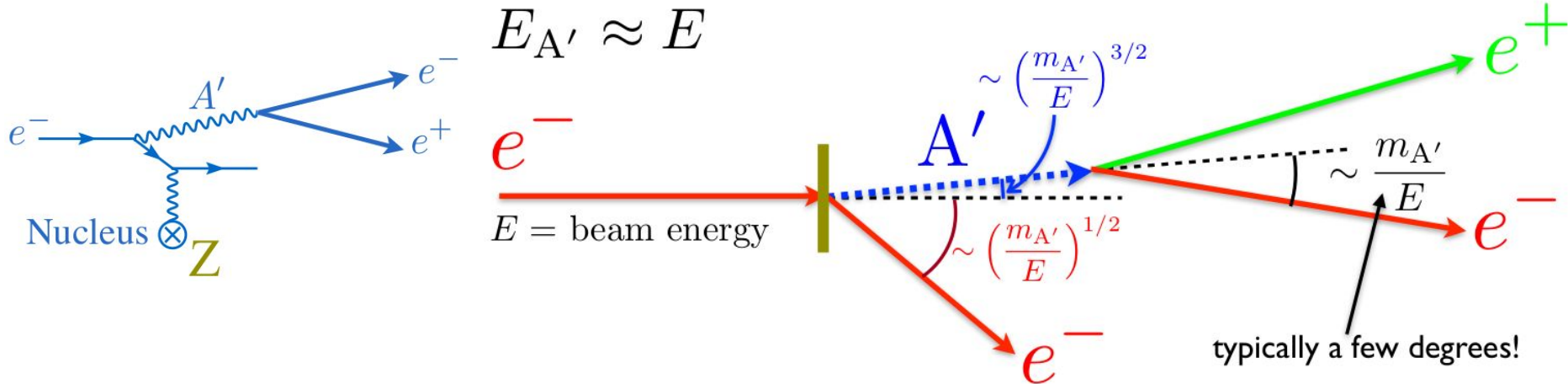
$$F\left(\frac{z - z_{\text{mean}}}{\sigma_z} \geq b\right) = e^{-\frac{b^2}{2} - b \frac{z - z_{\text{mean}}}{\sigma_z}} \quad \text{Exponential Tail}$$

- 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

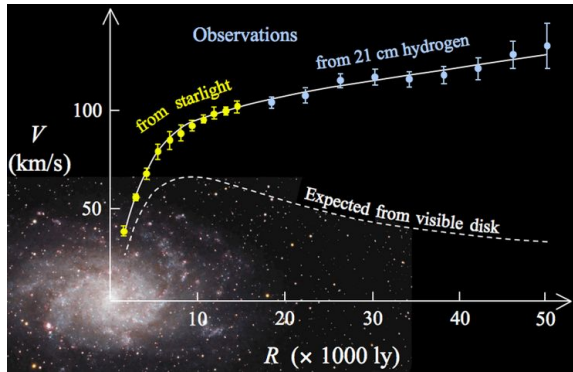
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- $A'$ 's can be produced in a process **analogous to Bremsstrahlung**
- $A'$ 's take most of beam energy - decay products are forward with small opening angle
- Detector **acceptance must be very forward** (very close to beam plane)
- Small couplings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



# The Existence of Dark Matter

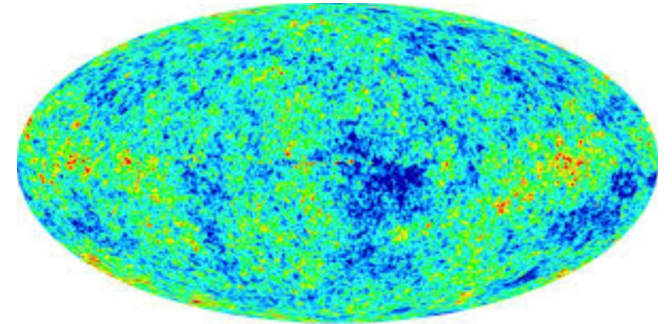
- There is clear evidence for the **existence of dark matter** (DM)
- The fundamental nature and origin of DM is a **central puzzle in particle physics**
- SM can't account for DM. What are some ideas for what DM could be?



Galactic Rotation Curves



Gravitational Lensing



Cosmic Microwave Background

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