The Heavy Photon Search Experiment

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Introduction

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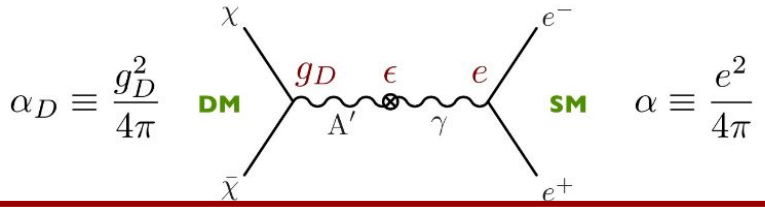
- A heavy photon (or dark photon, or A′) is a **hypothetical vector boson** that couples indirectly to electromagnetic particles
- The Heavy Photon Search (HPS) is a **fixed target experiment** at Jefferson Lab in Hall B that is dedicated to searching for this hypothetical vector boson, an A′
- HPS uses two distinct methods to search for A′s - a **resonance search** and a **displaced vertex search**
- Presented in this talk:
  - Introduction to heavy photon physics and motivations, and experimental overview
  - 2016 Engineering Run - first public results for both resonance and the displaced vertex searches
  - 2019 Physics Run - upgrades, commissioning, data taking, and status

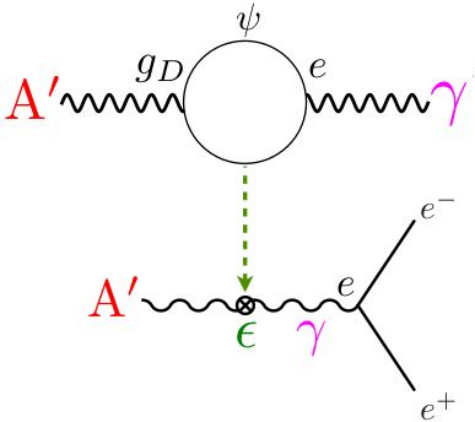
Heavy Photon Primer

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



This gives rise to a **kinetic mixing term** (the SM photon mixes with an A′). Induces a weak effective coupling of εe to SM fermions.

A′s are motivated by models of **"light dark matter"** (MeV-GeV scale) which require a **new, comparably light force carrier.**



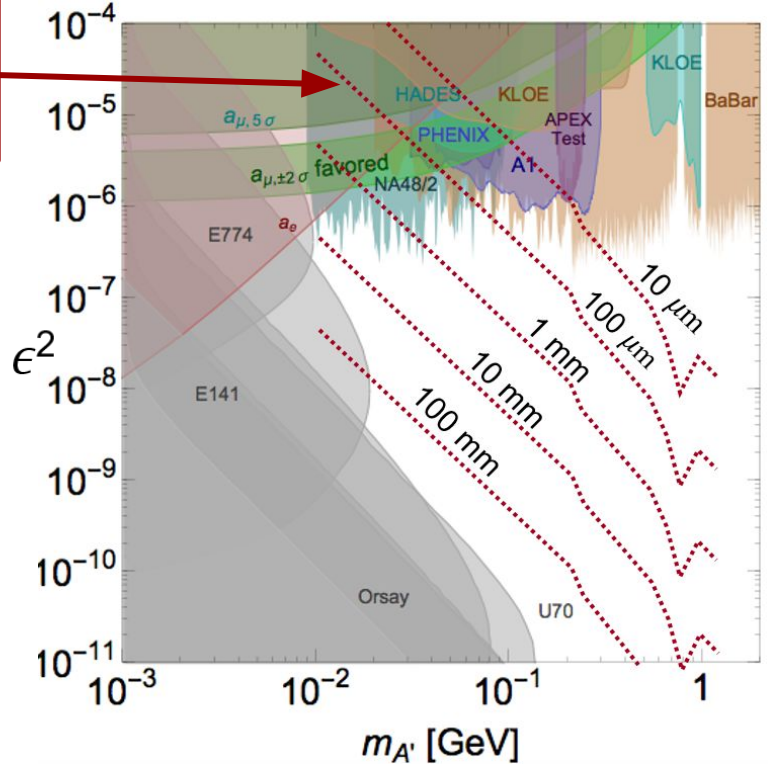
2 Parameter Model: Mass of A′ and ε

A′s circumvent the **"Lee-Weinberg Bound"** which requires dark matter mass > 2 GeV for interactions through weak SM bosons

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

Existing Heavy Photon Constraints

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



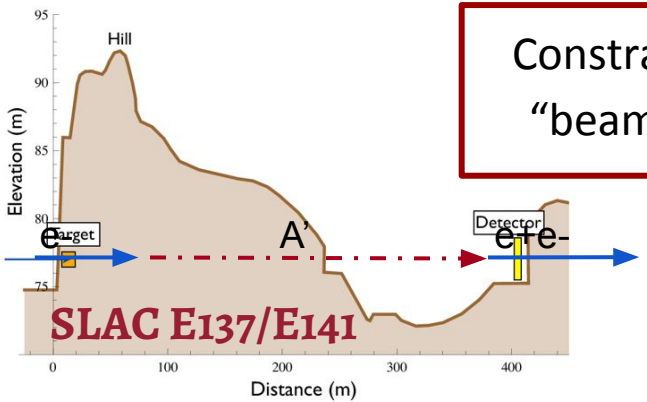
Existing Heavy Photon Constraints

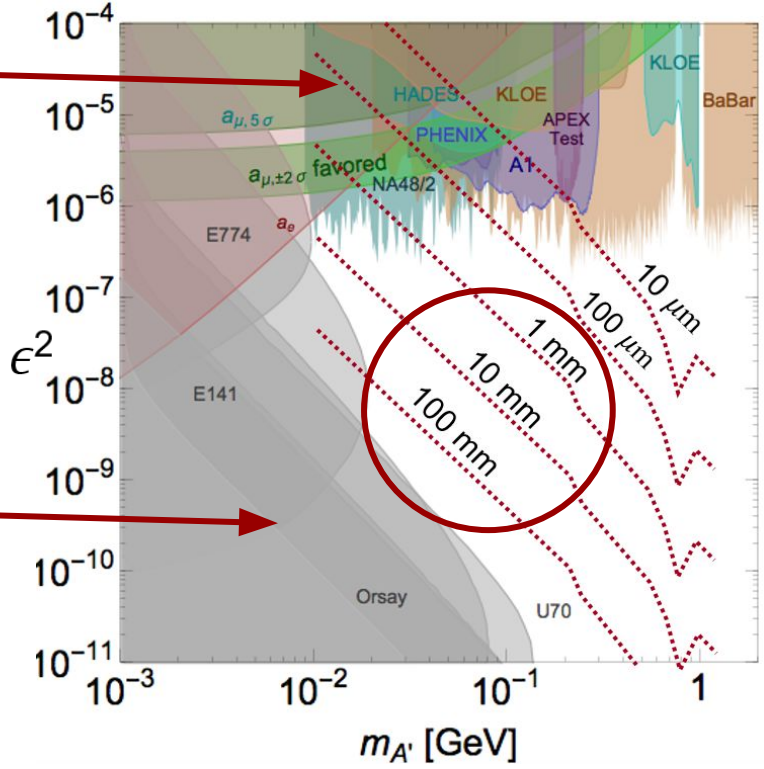
Large coupling searches are generally **"bump hunts"** for $m(l^+l^-)$ resonances

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

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

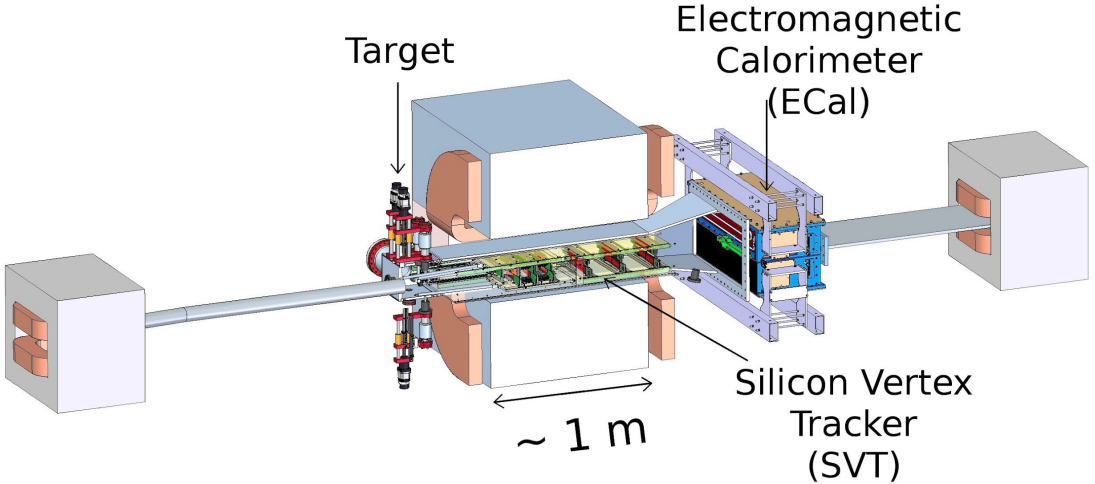
Constraints from "beam dumps"

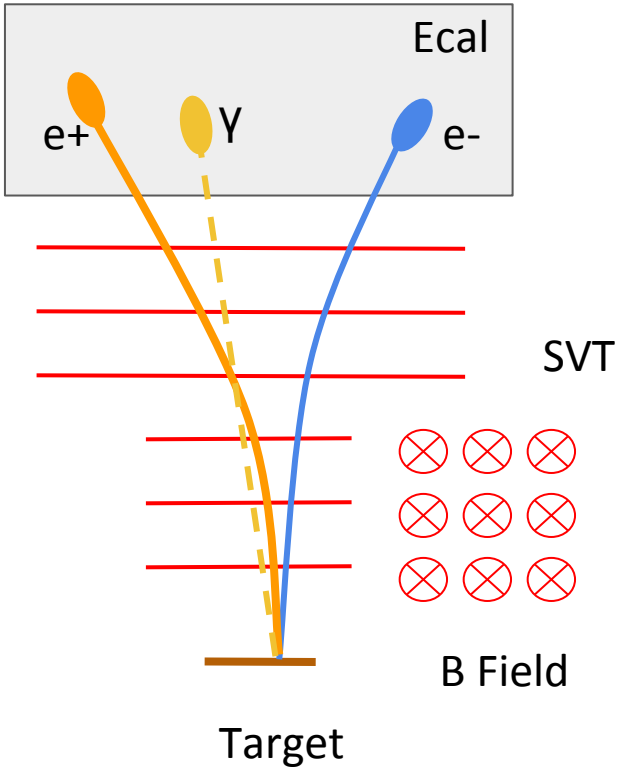




HPS Apparatus

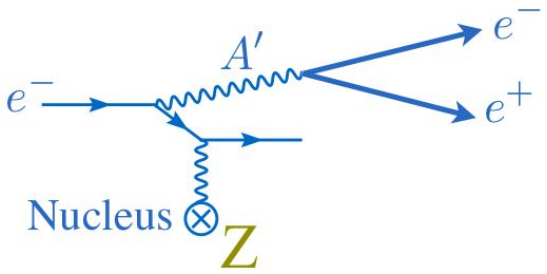
- Silicon Vertex Tracker (SVT) measures trajectories of e+e- and **reconstructs mass and vertex position**
- Electromagnetic Calorimeter (Ecal) provides **e+e- trigger with precision timing**
- Dipole magnet spreads e+e- pairs and provides curvature for momentum measurement and PID

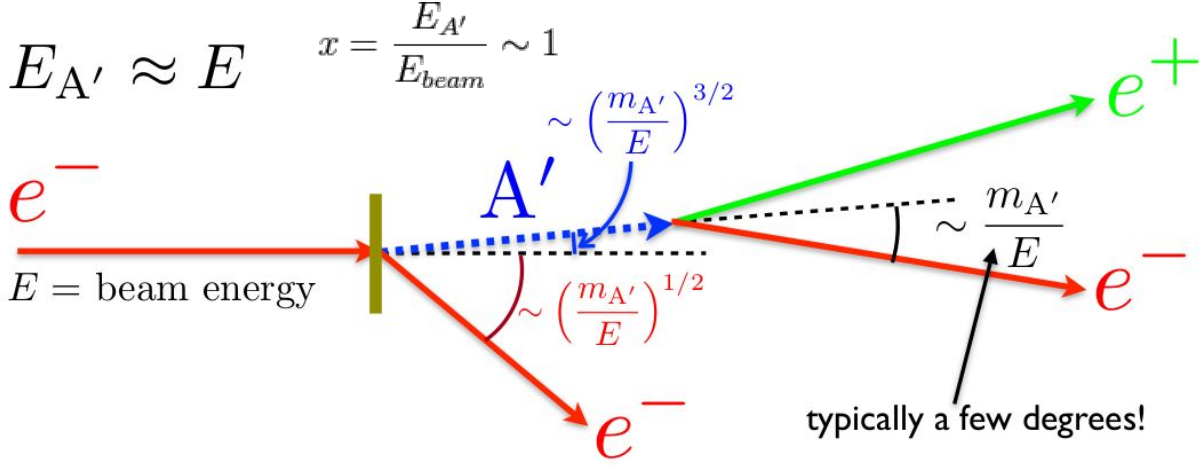




Heavy Photon Kinematics and Design Considerations

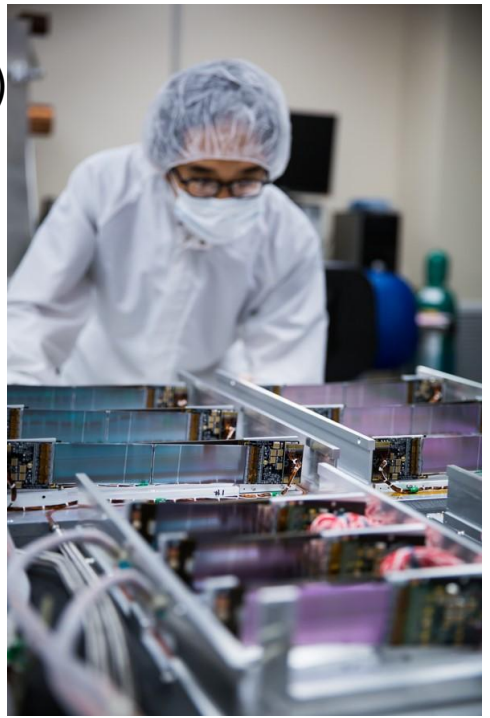
- A's can be produced in a process **analogous to Bremsstrahlung** (dark Bremsstrahlung)
- A's take most of beam energy - decay products are forward with small opening angle
- Detector **acceptance must be very forward** (very close to beam plane)



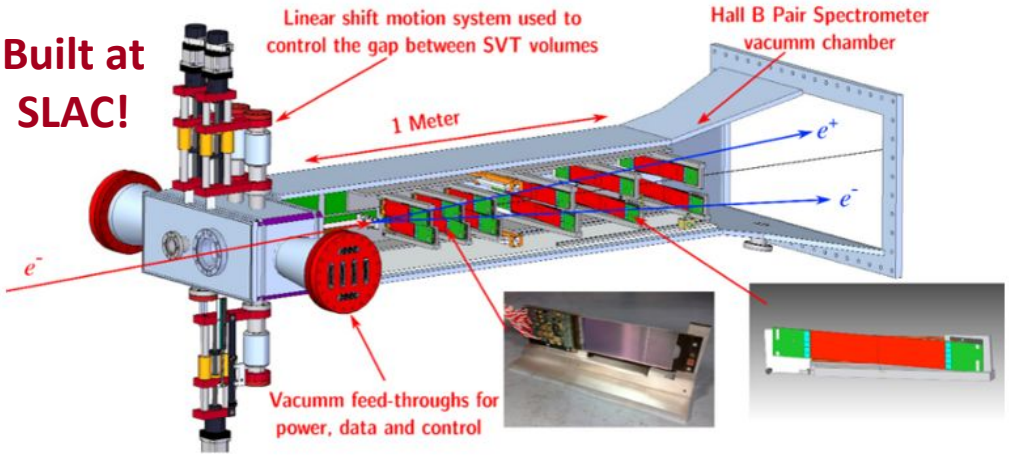


Silicon Vertex Tracker

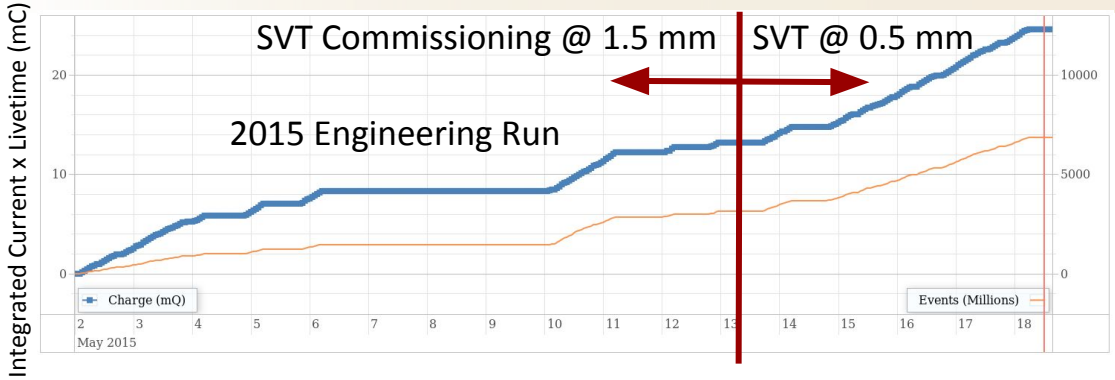
- Detector (vertical) acceptance down to +/- 15 mrad (which means L1 of SVT is **0.5 mm from beam axis!**). Split into two halves: top/bottom
- 6 layers of silicon microstrips (~0.7% radiation length per layer)
- Each layer has 2 sensors - axial/stereo strips for 3D hit position
- L1-L3 vertically retractable from beam
- L4-L6 are double wide for acceptance purposes



Built at SLAC!



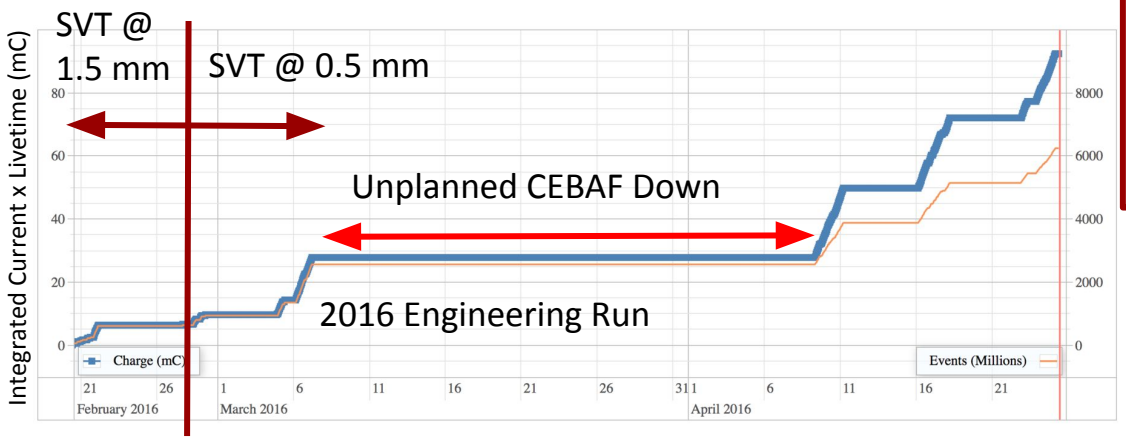
2015 & 2016 Engineering Runs



2015 Engineering Run

50 nA at 1.06 GeV

1.7 days (10 mC) of physics data



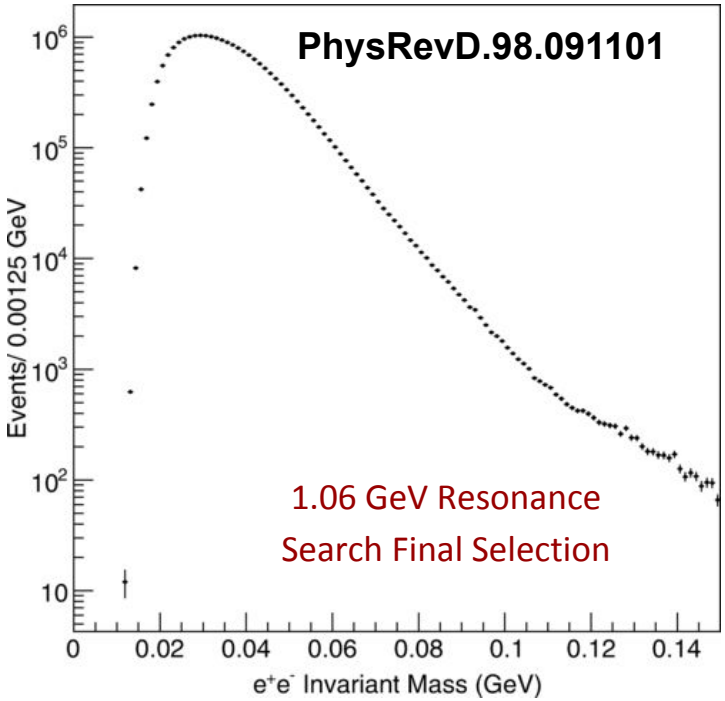
2016 Engineering Run

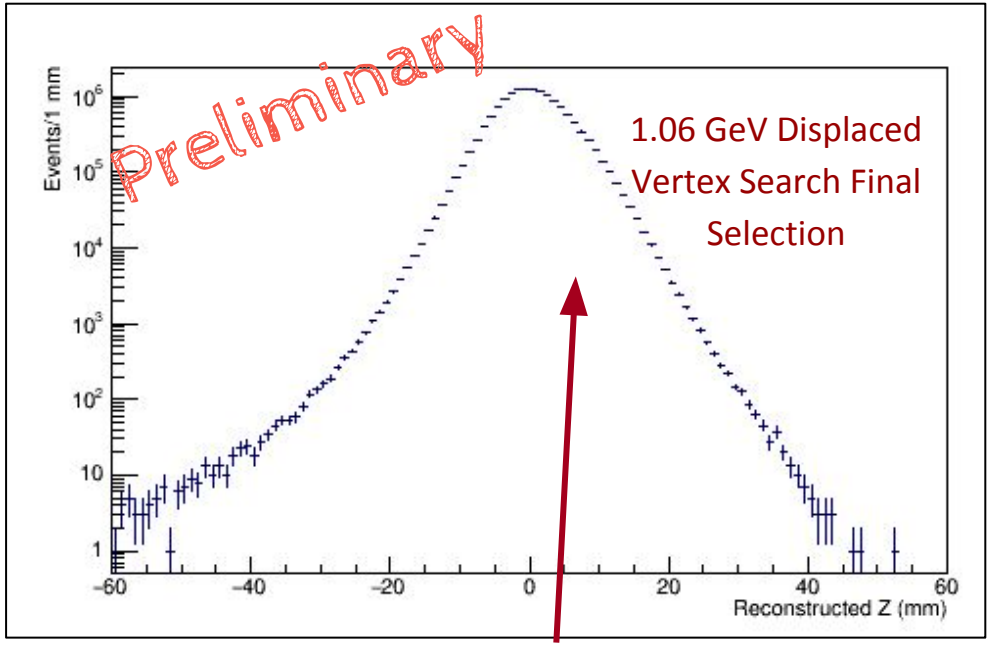
200 nA at 2.3 GeV

5.4 days (92.5 mC) of physics data

180 days of data taking approved by JLab PAC!

e+e- Backgrounds





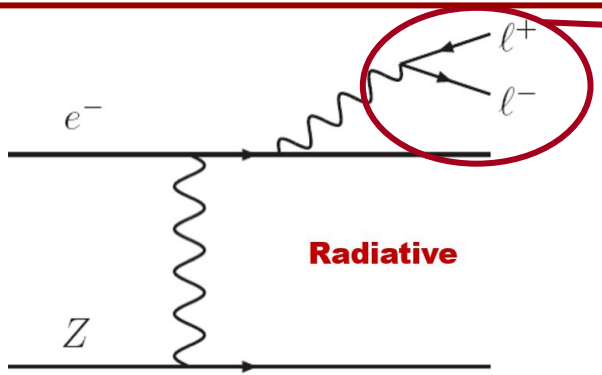
Large number of prompt e+e- pairs observed

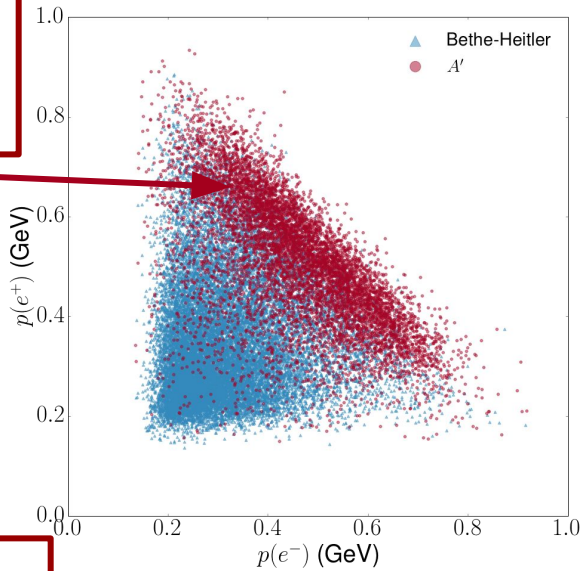
What are these e+e- backgrounds?

Vertex resolution + tails are dominated by multiple coulomb scattering in tracker

Trident Backgrounds

Radiative tridents have identical kinematics to A′s; constitute an irreducible prompt background





Radiative tridents provide reference for expected signal rate

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

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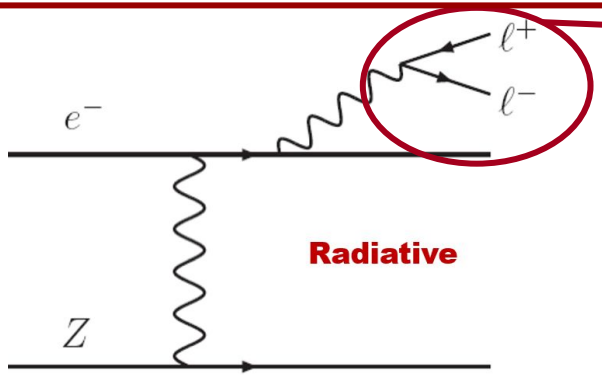
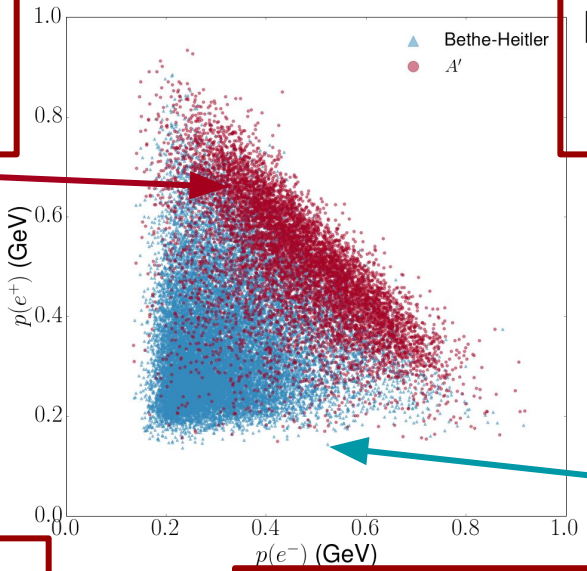
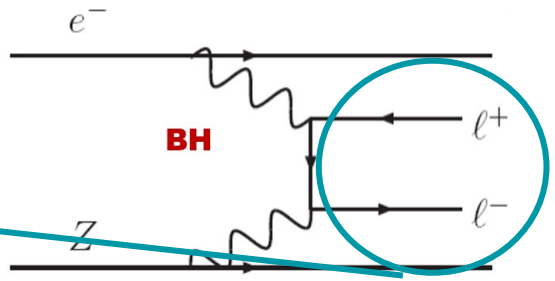




Bethe-Heitler (BH) tridents have softer e+e- pairs, but still dominates the signal region



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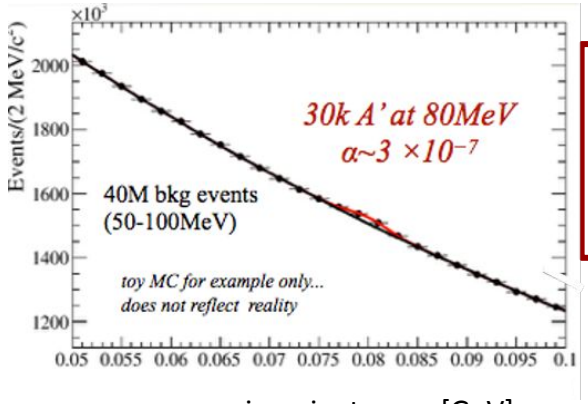
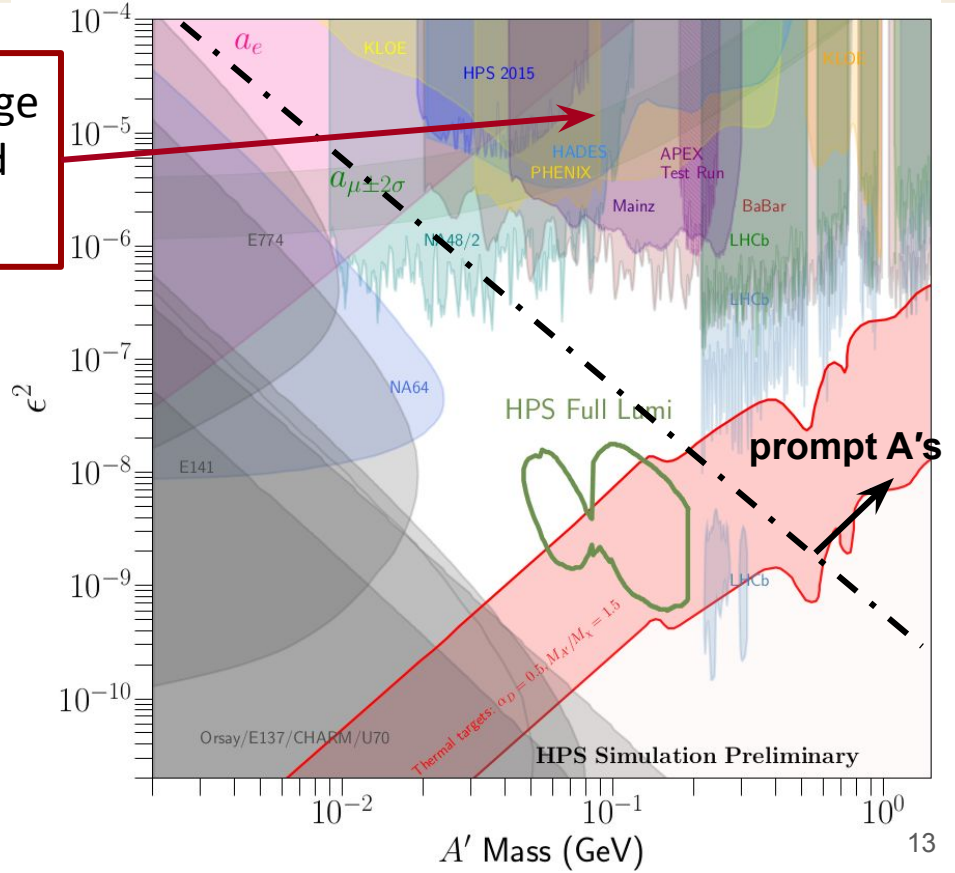
Converted photons in tracker or target. Simple cuts eliminate about 80% of these e+e- pairs with minimal signal loss

Heavy Photon Signatures in HPS



"Large" signal, huge QED background (**bump hunt**)

e+e- backgrounds are mostly prompt QED tridents



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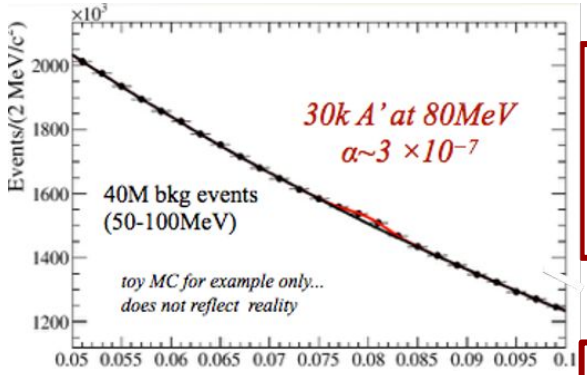
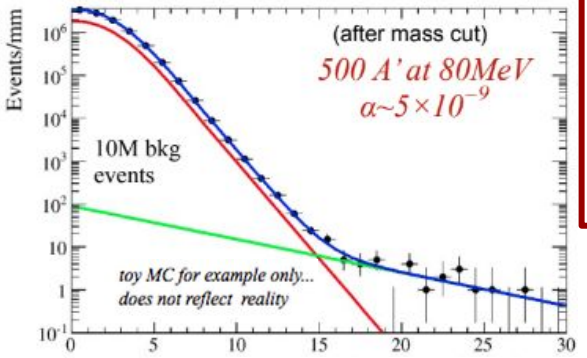
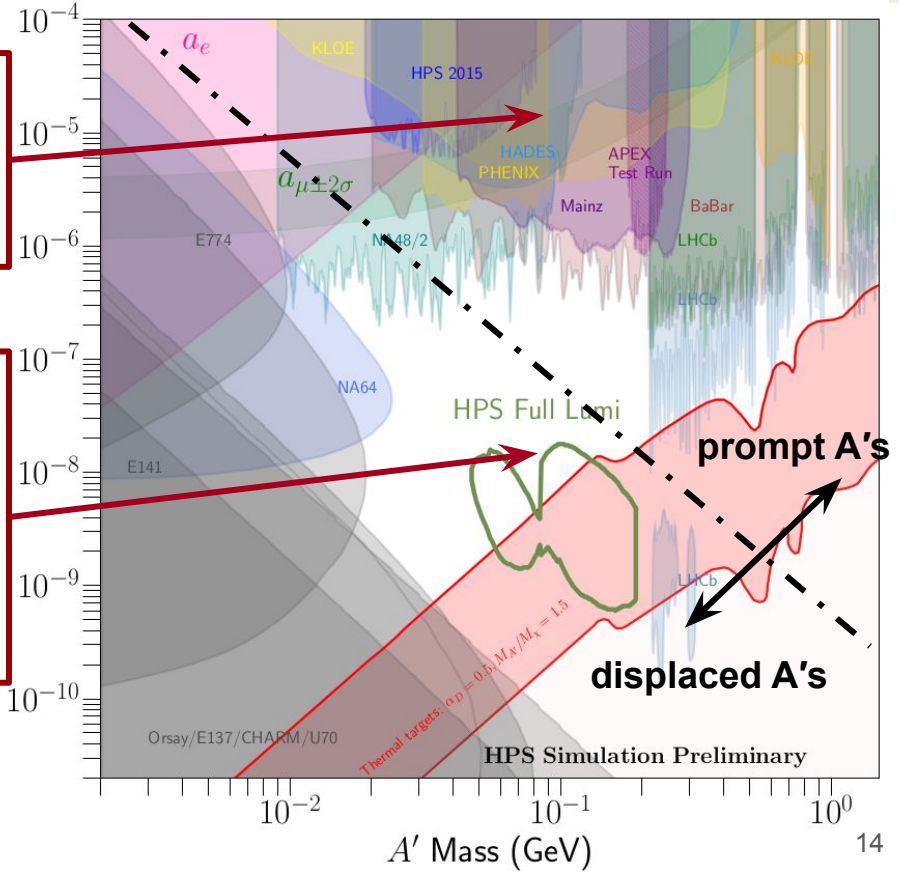




"Large" signal, huge QED background (**bump hunt**)

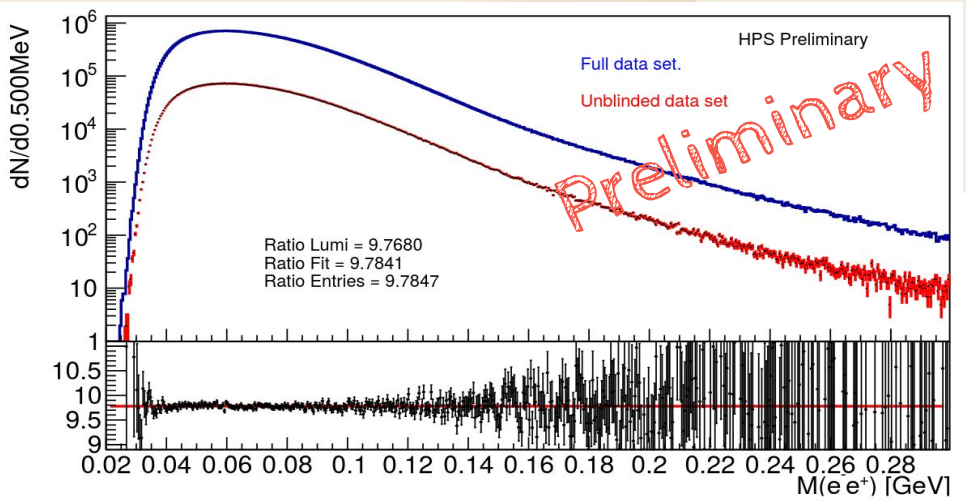
Small signal, very little background (**vertex search**). Must suppress background by ~10^9

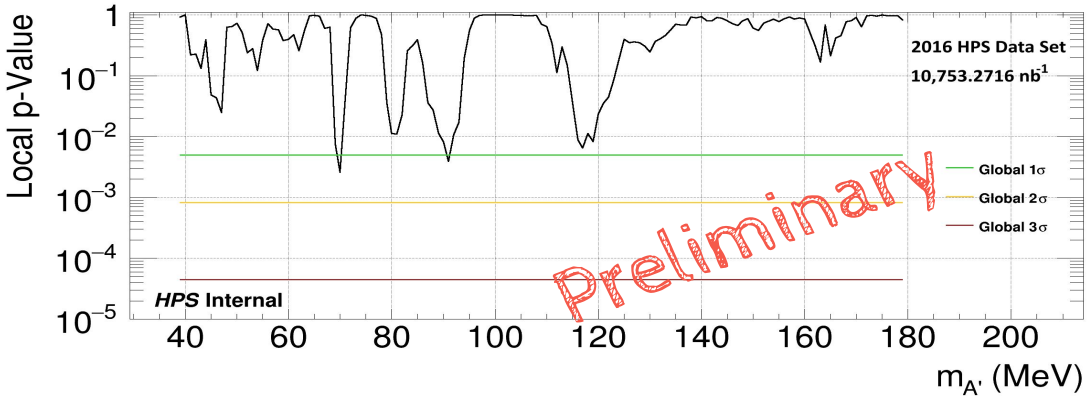
$$c\tau \propto \frac{1}{\epsilon^2 m_{A'}}$$

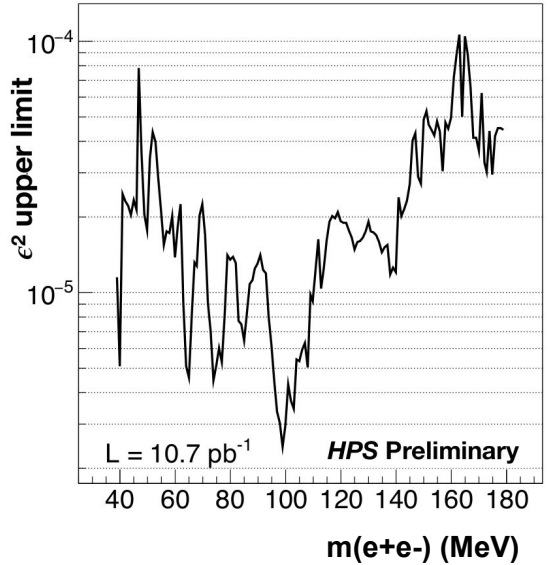


Resonance Search Results

- 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 other experiments

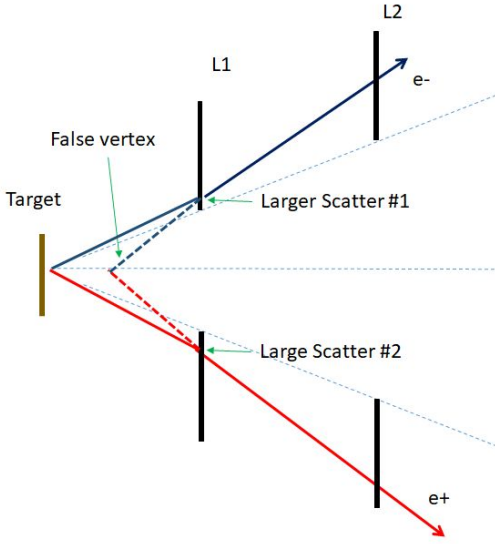


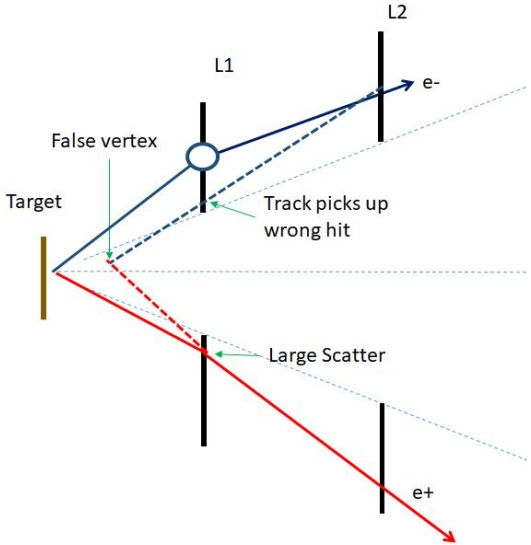


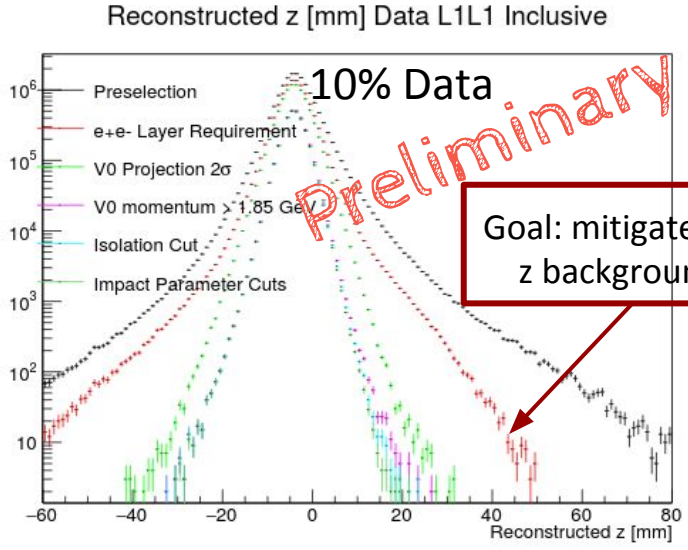


Displaced Vertex Search Event Selection

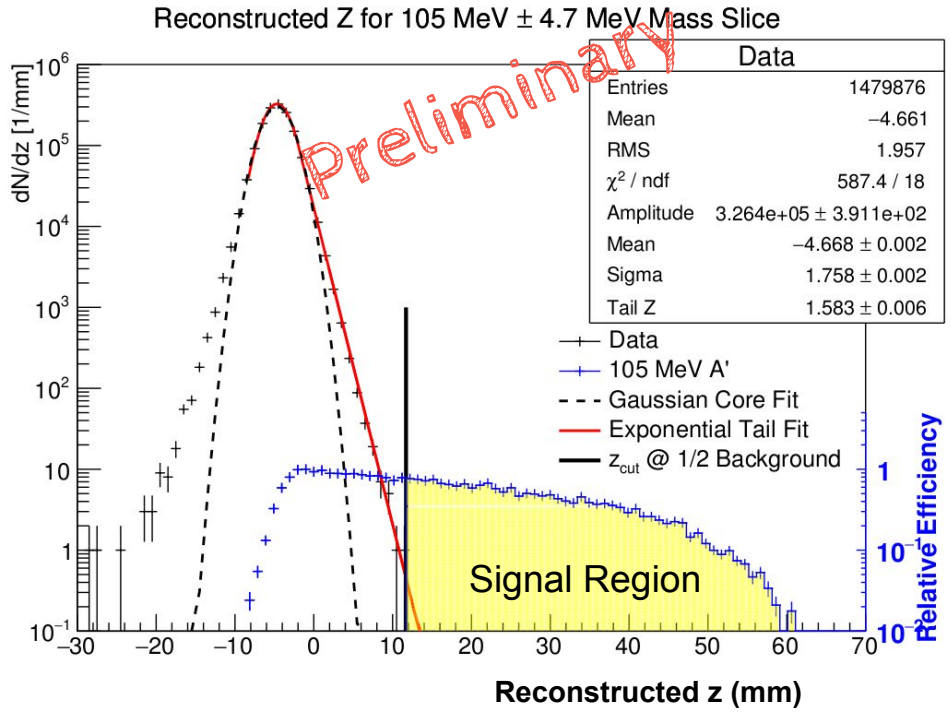
- In addition to bump hunt analysis, the displaced vertex analysis requires extra cleanup to reduce backgrounds at large z.
  - Two main backgrounds - large scatters in layer 1 of the tracker and mis-tracking
  - Require stricter selections on track quality and vertex quality & require layer 1 hits
  - Displaced vertex search is also blinded with the selection tuned on 10% of the data







Displaced Vertex Search Signal Region



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

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

Gaussian Core

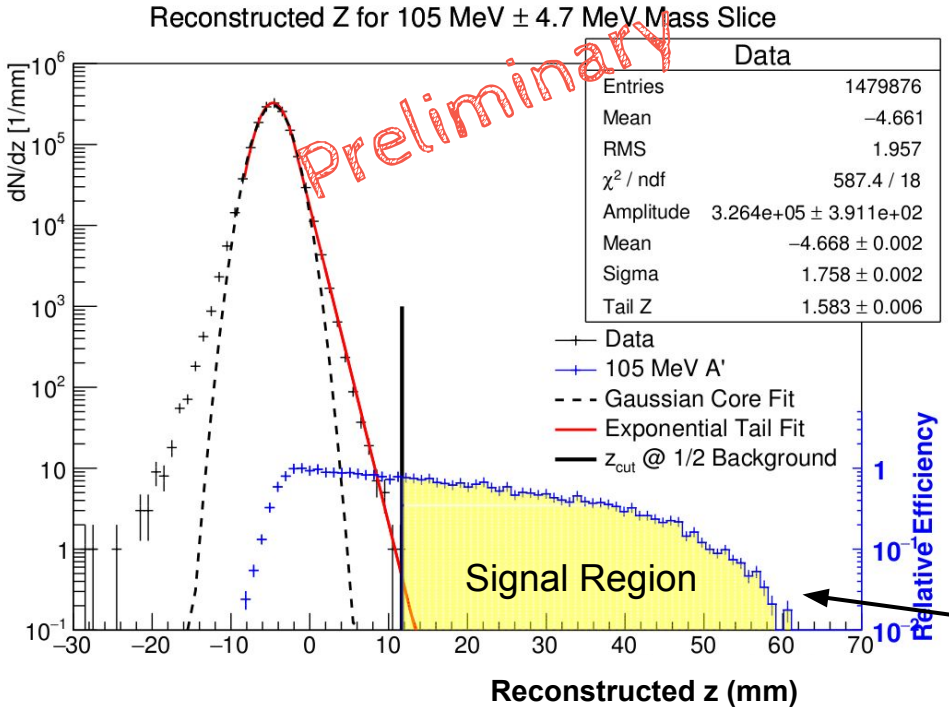
+

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

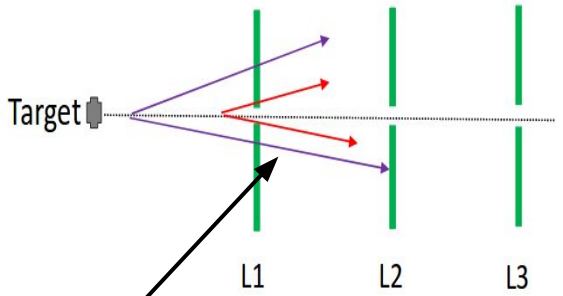
Exponential Tail

- 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

Displaced Vertex Search Signal Region

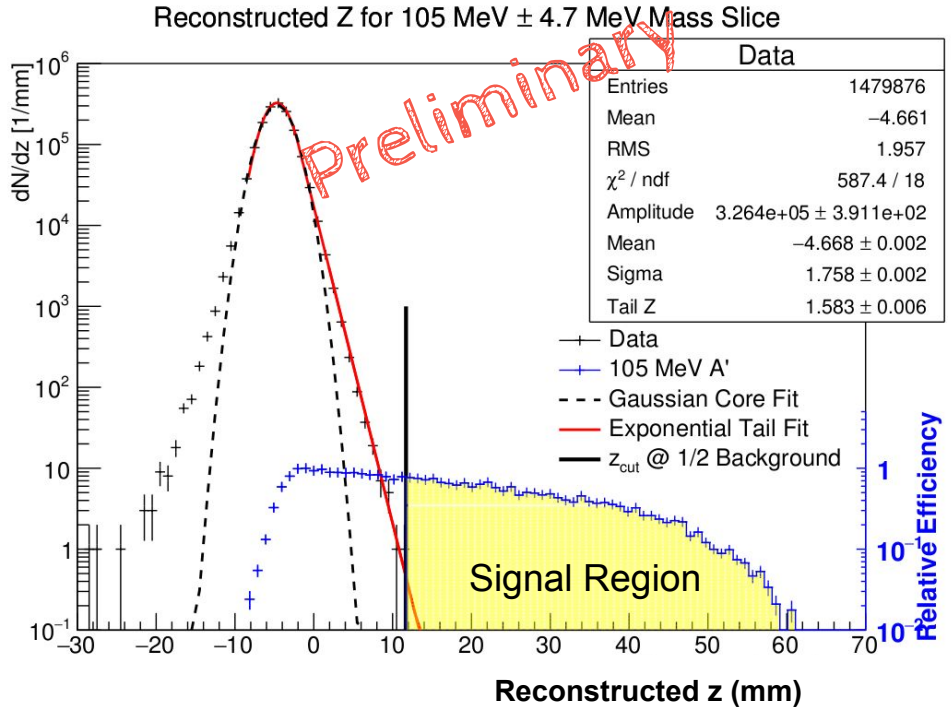


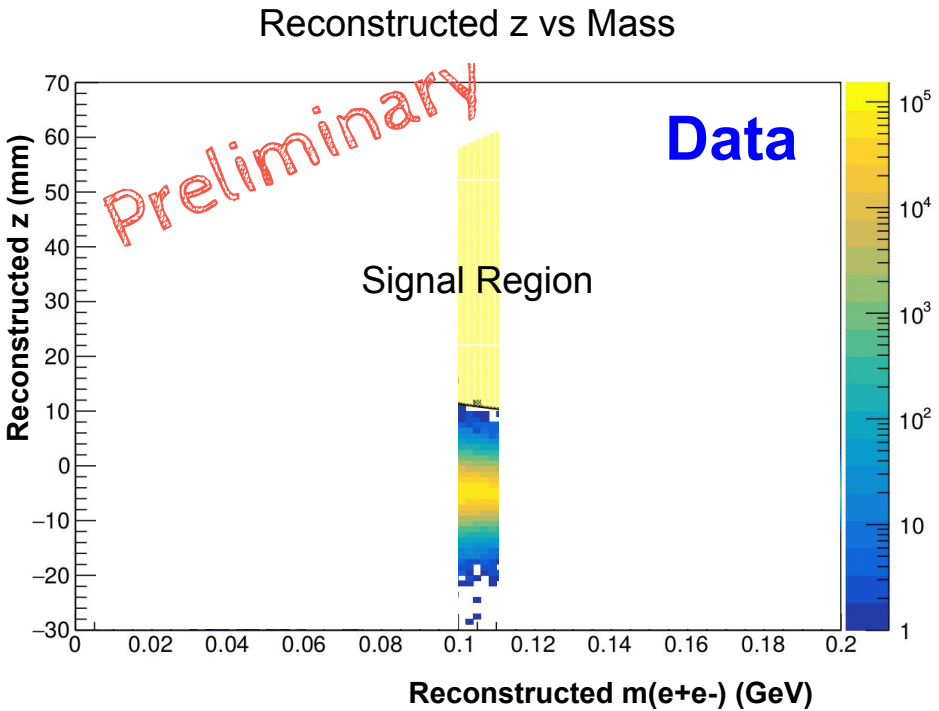
We require layer 1 hits.
Relaxing this restriction is discussed later.



Signal falls off rapidly due to **geometrical acceptance**

Displaced Vertex Search Signal Region





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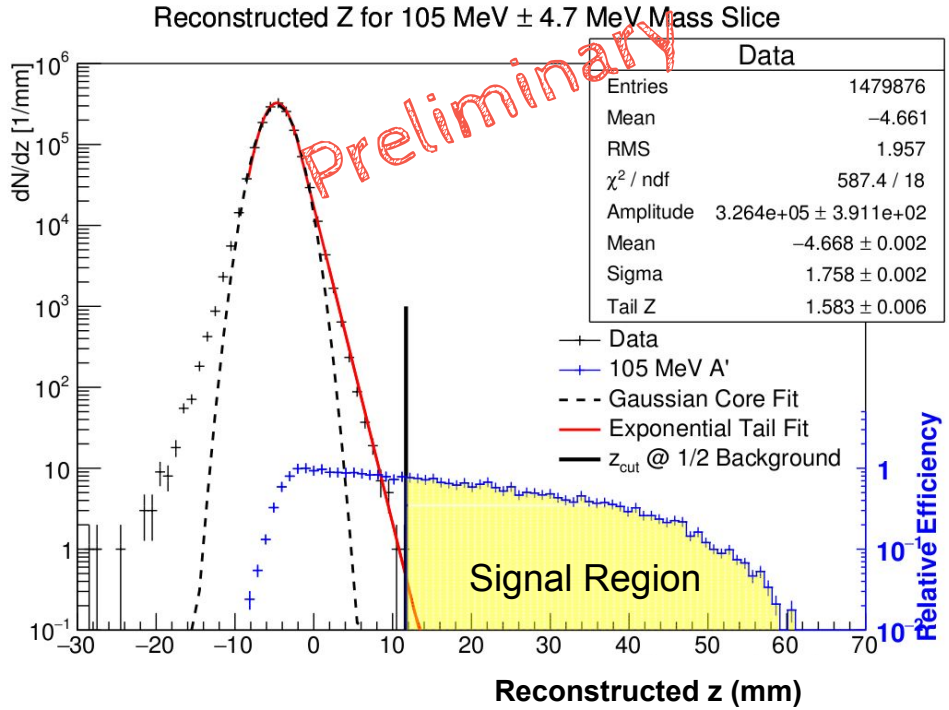

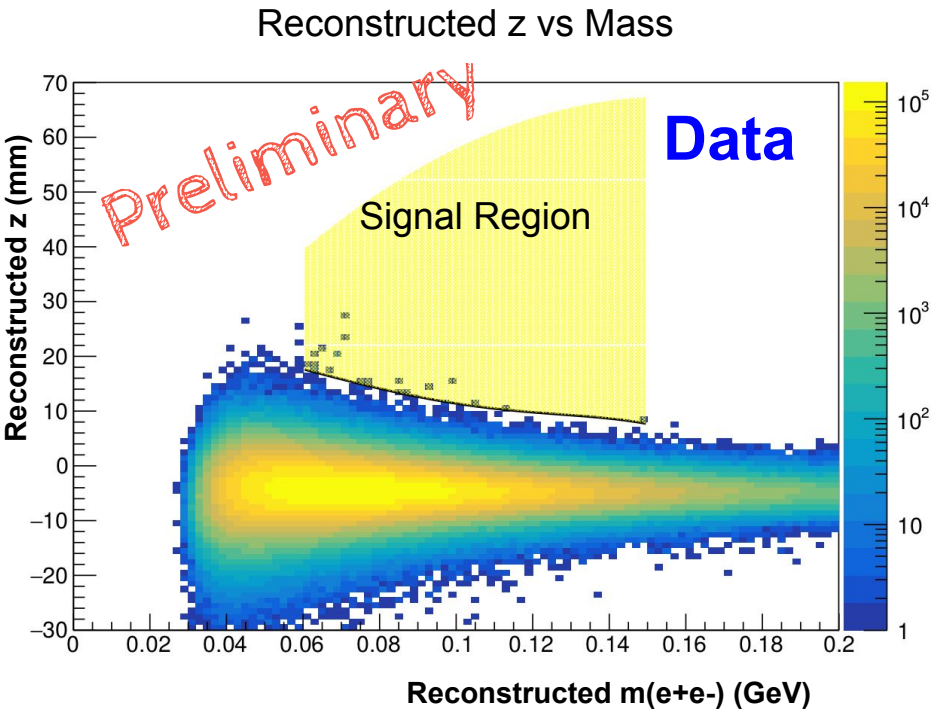

Displaced Vertex Search Final Results

arXiv:physics/0203002v2

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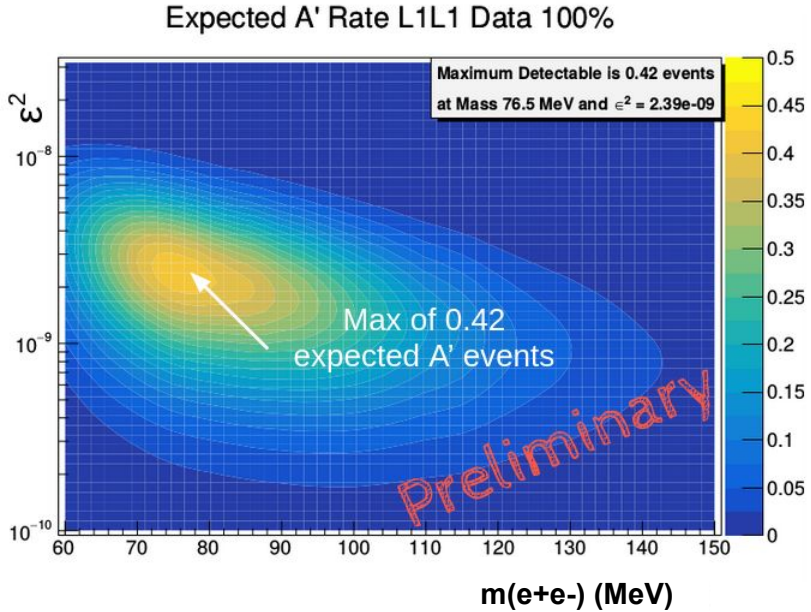
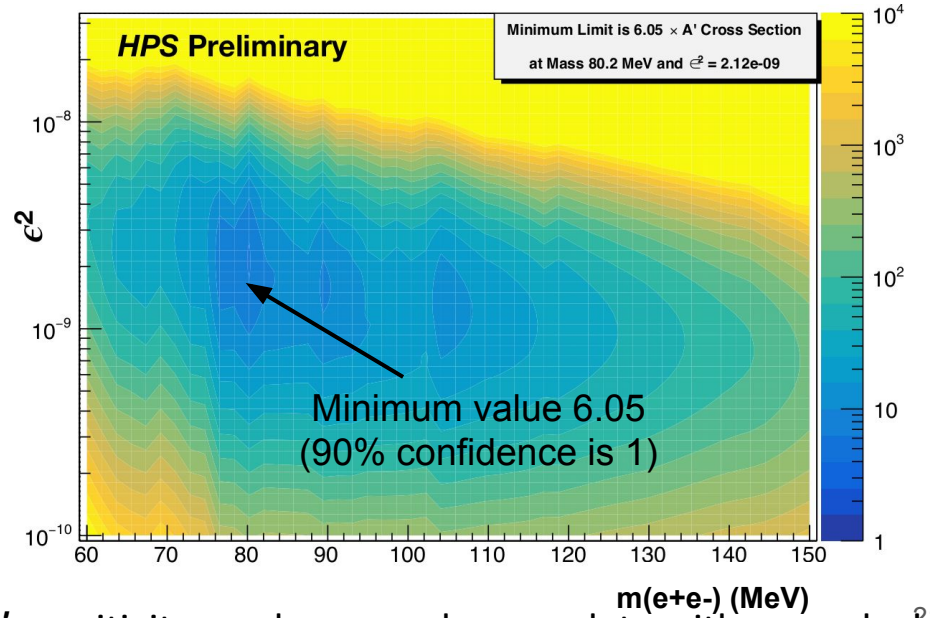
Plot the expected number of A′ events integrated past zcut.

$$N_{A'} = \int_{z_{cut}}^{z_{max}} \mathrm{sig}(m, \epsilon, z)\, \mathrm{accept}(m, z)\, \mathrm{eff}_{cut}(m, z)\, dz$$

Optimum Interval Method (OIM) was developed for DM direct detection and is used to set a limit.





Proof of principle, though not enough luminosity for A′ sensitivity, we have much more data with upgrades!

Discussion of Excess Displaced Vertices at Low Mass

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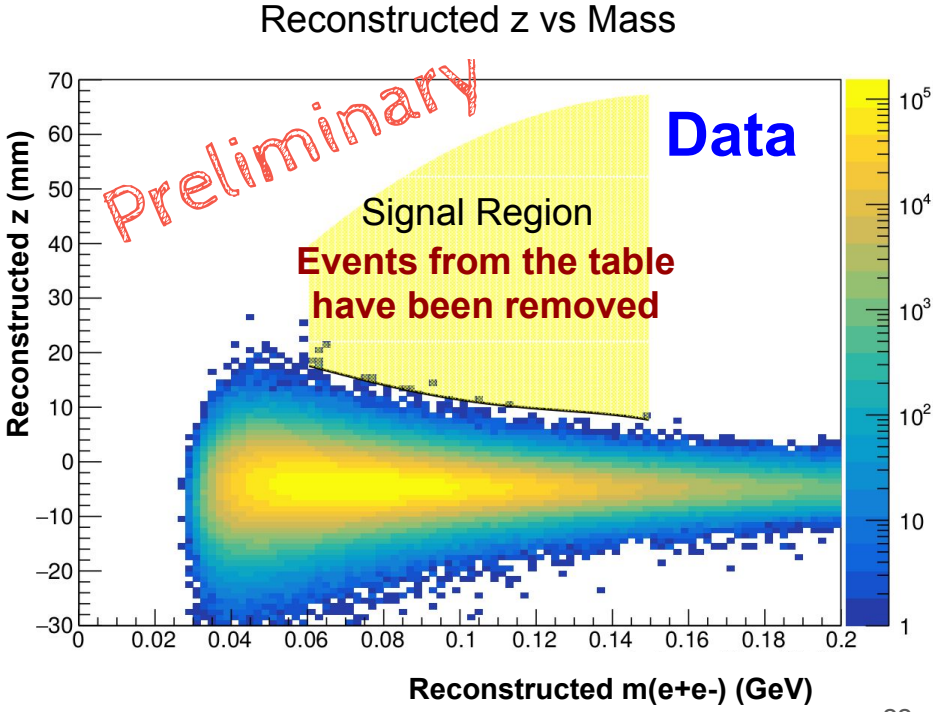
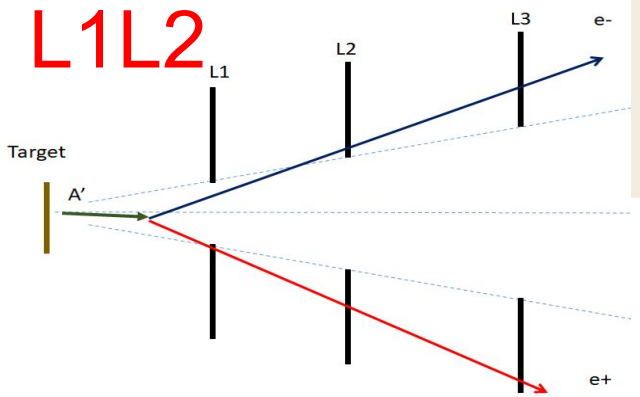
- These events are under investigation
- Possible backgrounds - Beam-gas interaction (< 0.1 events) and Mis-tracking + hit inefficiency (likely)
- Possible signal (unlikely, see below)

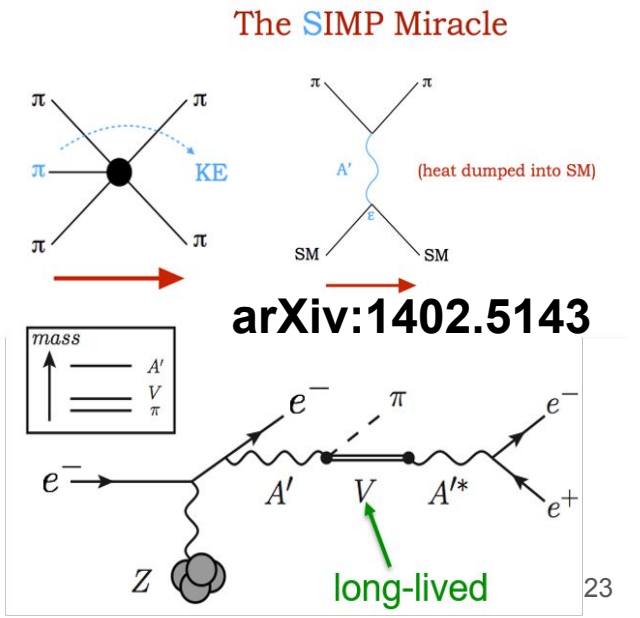
Δz_{cut}	VZ (mm)	Mass (MeV)	χ^2_{unc}	VY (n_σ)
0.44	17.67	63.17	8.55	0.18
0.50	17.12	66.21	7.90	1.41
3.80	20.03	68.19	4.63	0.55
4.51	20.72	68.24	0.13	3.61
7.75	23.33	71.48	1.52	2.95
11.74	27.27	71.71	0.12	2.49
2.22	15.62	84.02	8.65	1.04
3.54	15.05	98.57	4.55	0.06



Future of the 2016 Vertexing Analysis

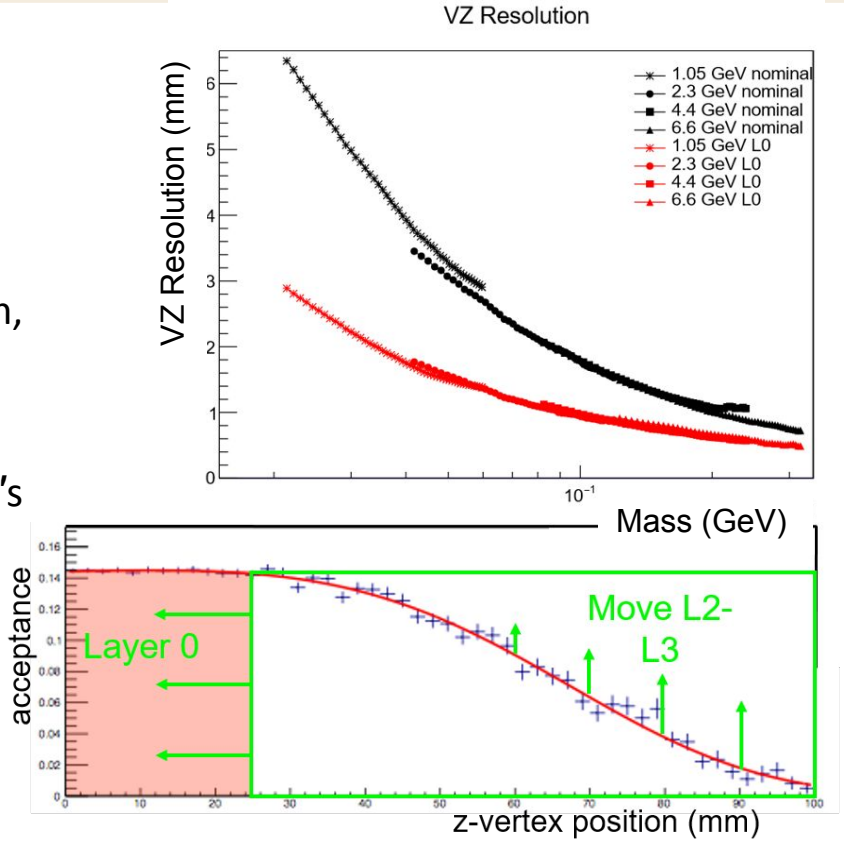
- So far we required layer 1 hits, but A′s can live long enough such that the e+ and/or e- daughter can miss layer 1
  - This introduces **more complicated backgrounds** - hit inefficiencies, scattering in the inactive sensor, conversions, etc. A quantitative study of these backgrounds is ongoing.
- **Possibly sensitive to Strongly Interacting Massive Particles** (SIMPs) in 2016 data
  - HPS can probe long-lived dark vectors (V) in a similar method to searching for A′s
  - Mechanism contains missing energy due to dark pions - search in lower e+e- momentum sum region than A′s





HPS Upgrades

- Analysis from 2015/2016 motivated simple upgrades
- **Add a tracking layer** (Layer 0) between target and current first layer
  - Dramatically improves vertex resolution, hence the vertex reach
- **Move L2-L3** slightly towards beam
  - Improves acceptance for longer-lived A's
  - Also replaced L1 with new thin sensor and moved closer to the beam



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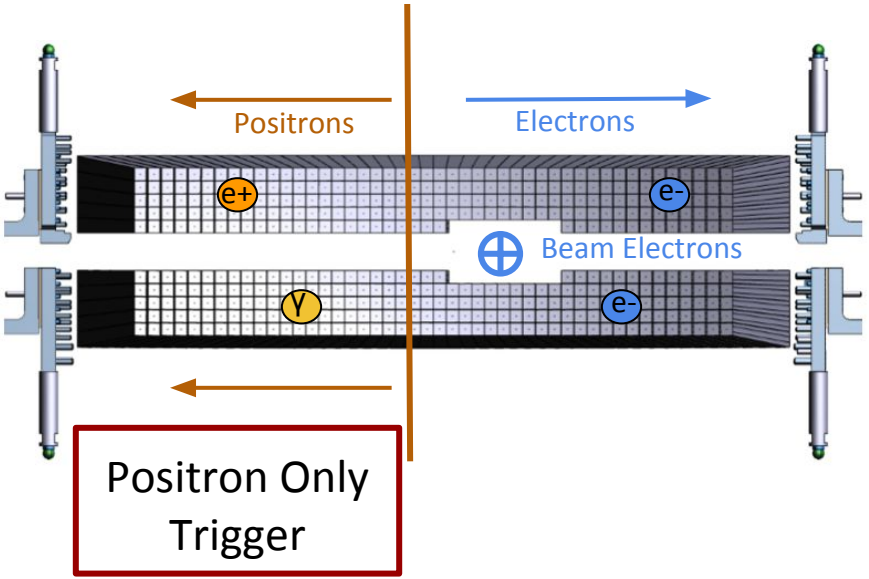
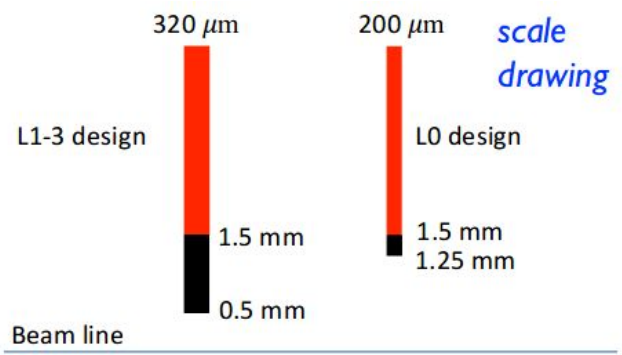
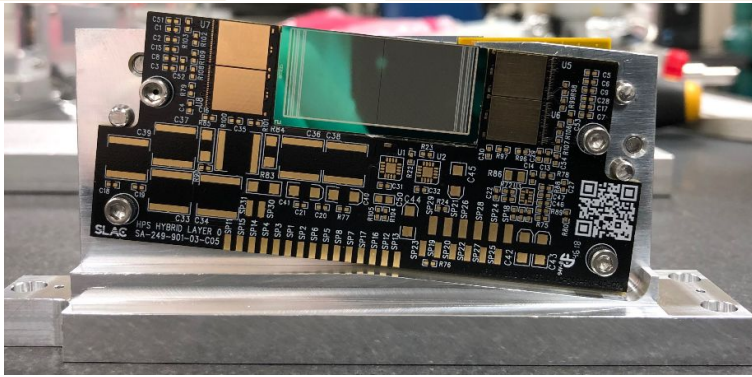
  - Also replaced L1 with new thin sensor and moved closer to the beam
- **Add hodoscope** inside vacuum chamber
  - Positron only trigger reduces acceptance losses in the "Ecal hole"

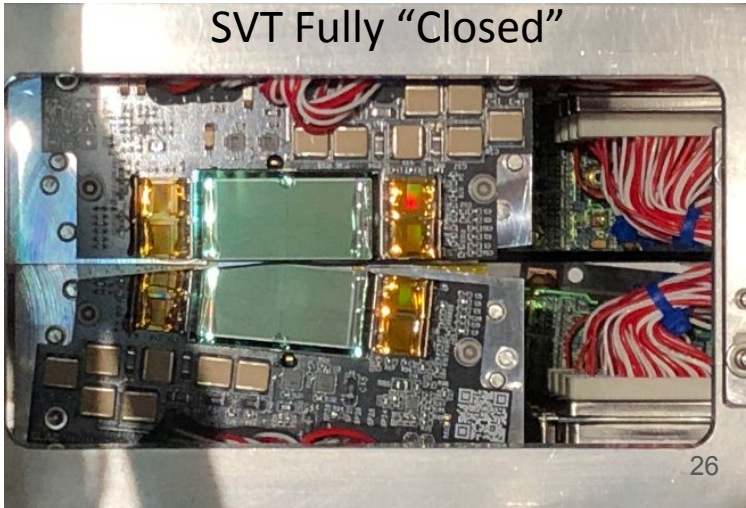


Installing HPS Upgrades

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

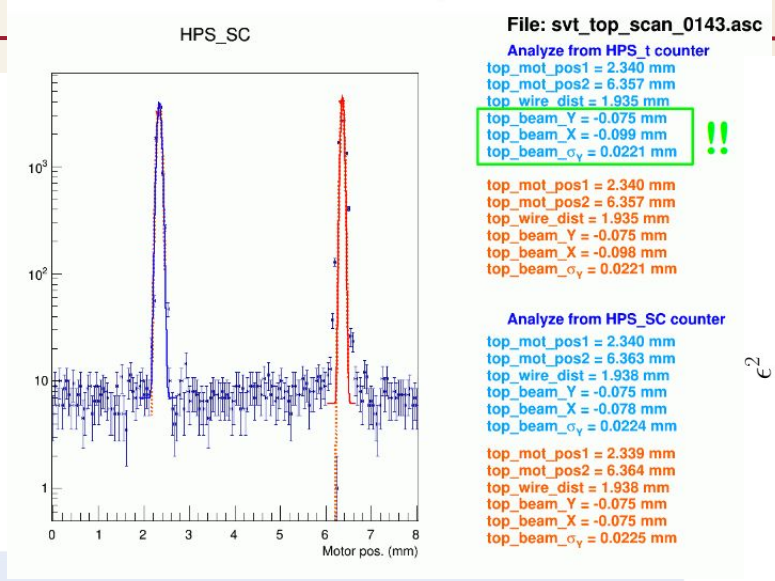


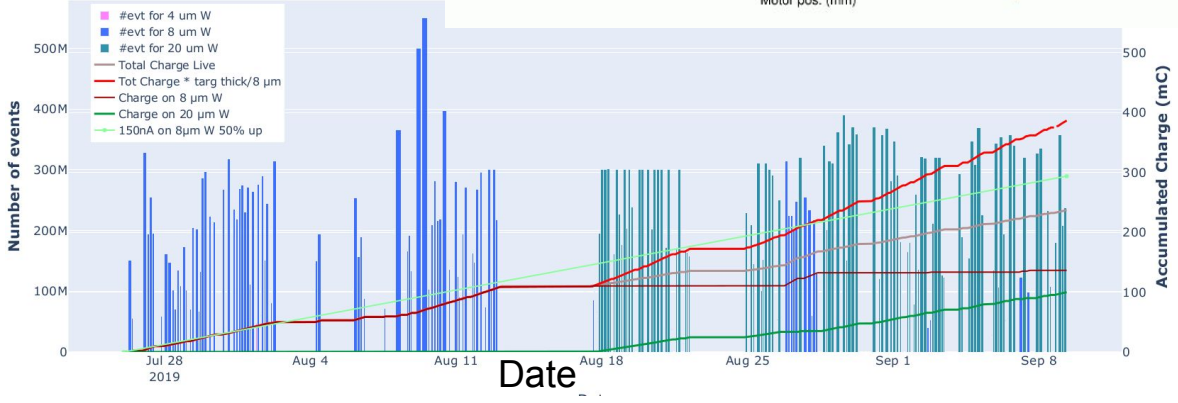


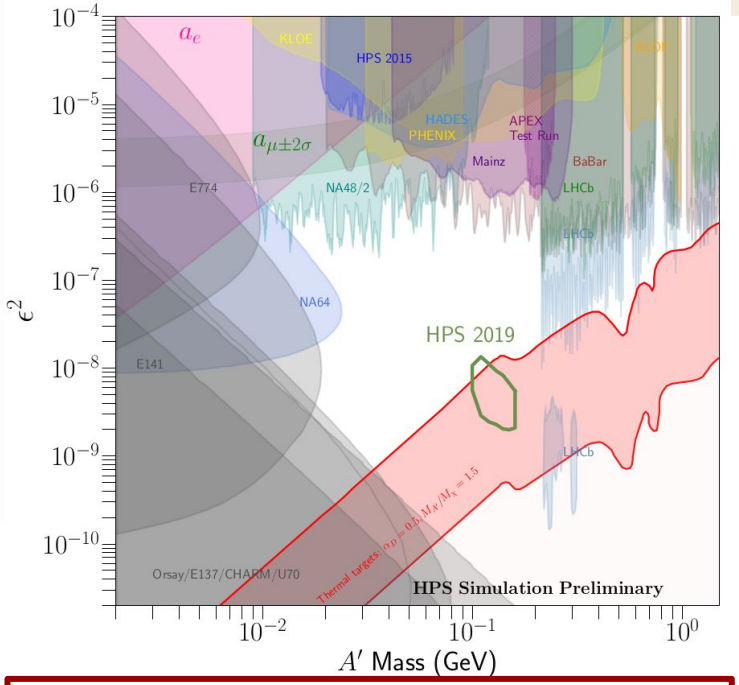


HPS Projected Reach With Upgrades

4.55 GeV beam: Achieved excellent beam at the target.





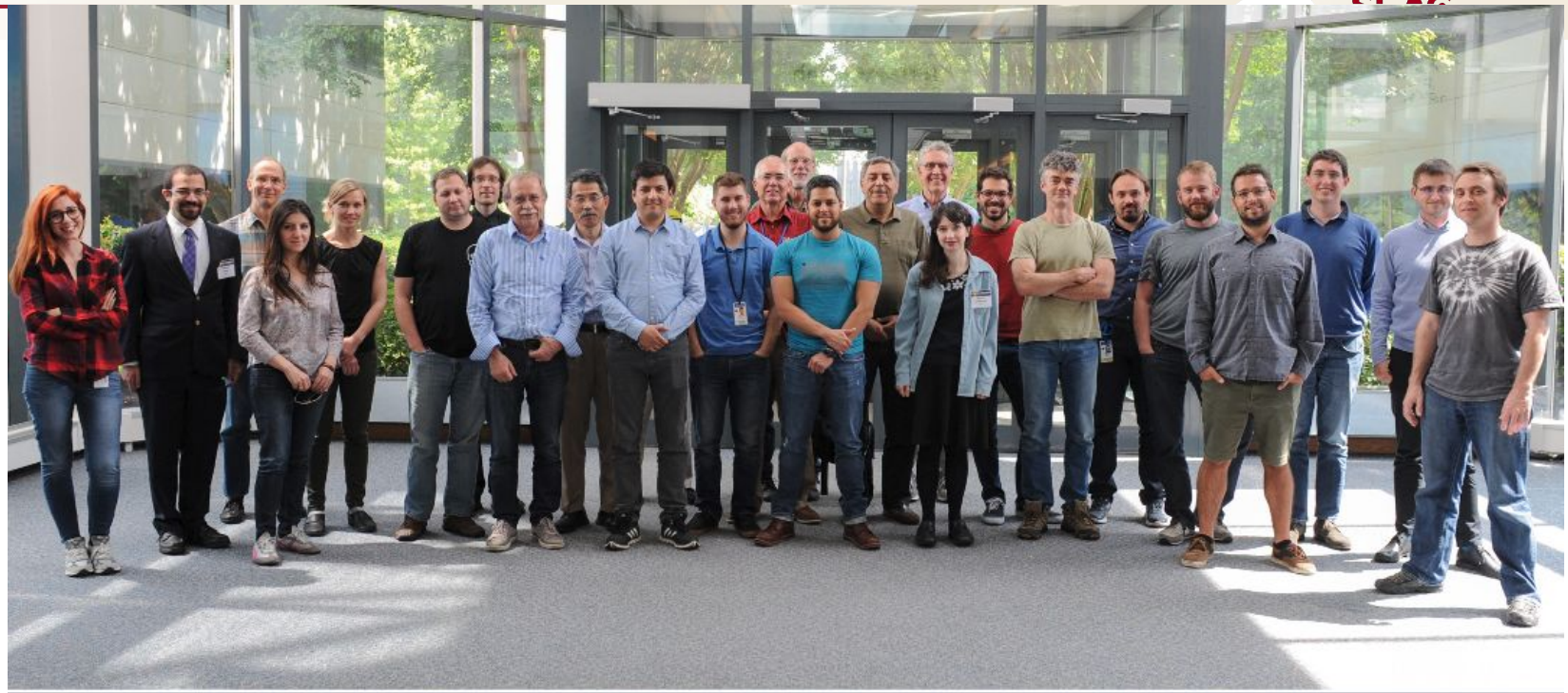


Reach projection contour scaled to the 2019 Physics Run luminosity

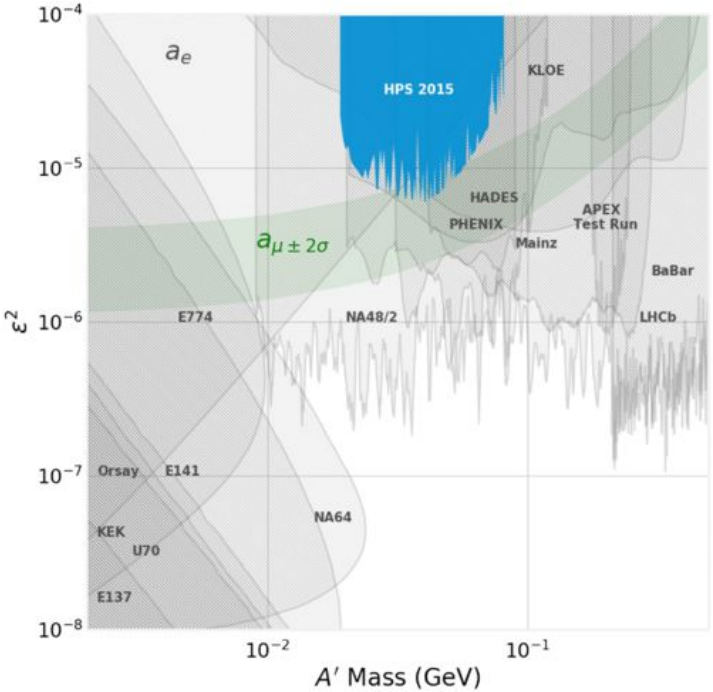
Conclusion

- Heavy photons are well-motivated as the particle that mediates light dark matter interactions with SM matter
- **HPS has successfully completed** two engineering runs at two different beam energies (1.06 GeV in 2015 and 2.3 GeV in 2016)
- **Resonance search** - results from 2015 are published and result from 2016 are now public. Both exclusions are consistent with several other experiments.
- **Displaced vertex search** - demonstrated proof of principle for the displaced vertex search. Analysis for A′s with longer livetimes and SIMPs are ongoing.
- **HPS successfully completed its first physics run** for 2 weeks at 4.55 GeV with tracker and trigger upgrades. This data has **real physics potential.**
- Possibility for more running in 2021 and beyond

Thanks! Questions?



2015 Resonance Search Results (1.06 GeV)



PhysRevD.98.091101

- No significant bumps found, excluded parameter space consistent with other experiments' exclusions
- Expected signal rates derived from data and the radiative fraction

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

Systematic Description	Value
Radiative Fraction	
e^+e^- Composition	7%
Mass Resolution	
Fit to Møller mass spectrum	2.6%
Target position	1.5%
Fits	
Fit systematic <= 39 MeV	1.5%
Fit systematic > 39 MeV	1.4%

- Mass scale and mass resolution determined by Moller scattered e-e- pairs

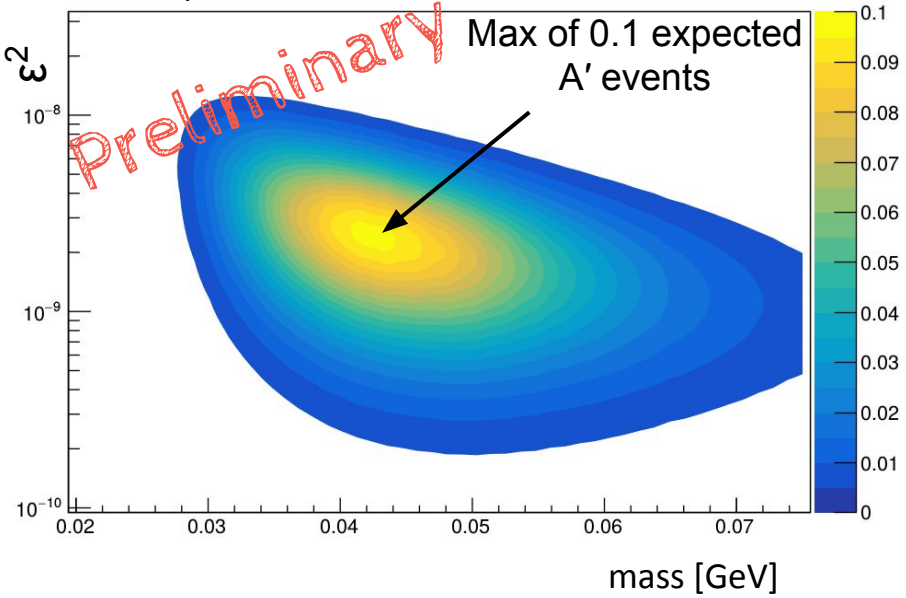
$$E_{CM} = \sqrt{2 m_e E_{beam}}$$ (32.9 MeV at 1.06 GeV beam)

- Resonance search is the foundation for the displaced vertex search

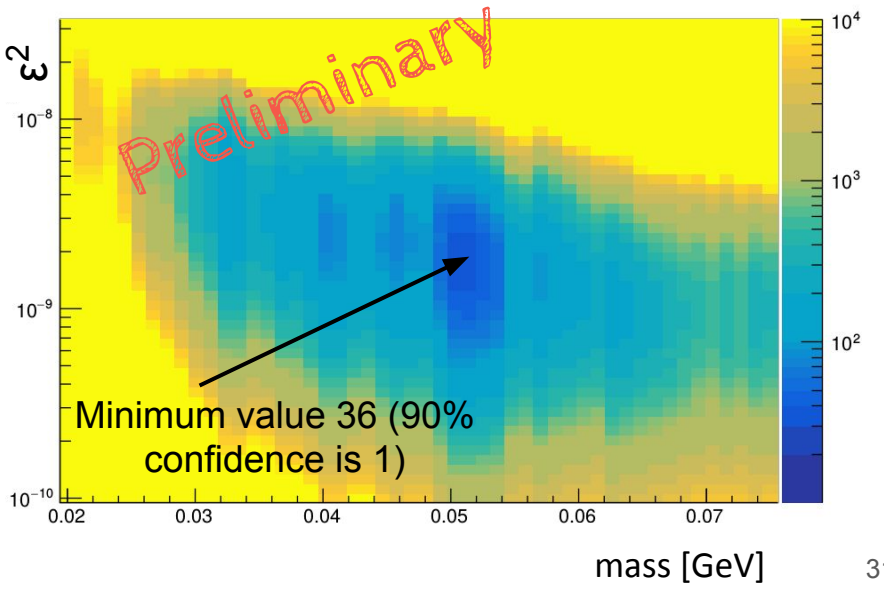
Displaced Vertex Analysis 2015 Results

SLAC

Expected A′ Events Detected Past ZCut



Optimum Interval Method Limit

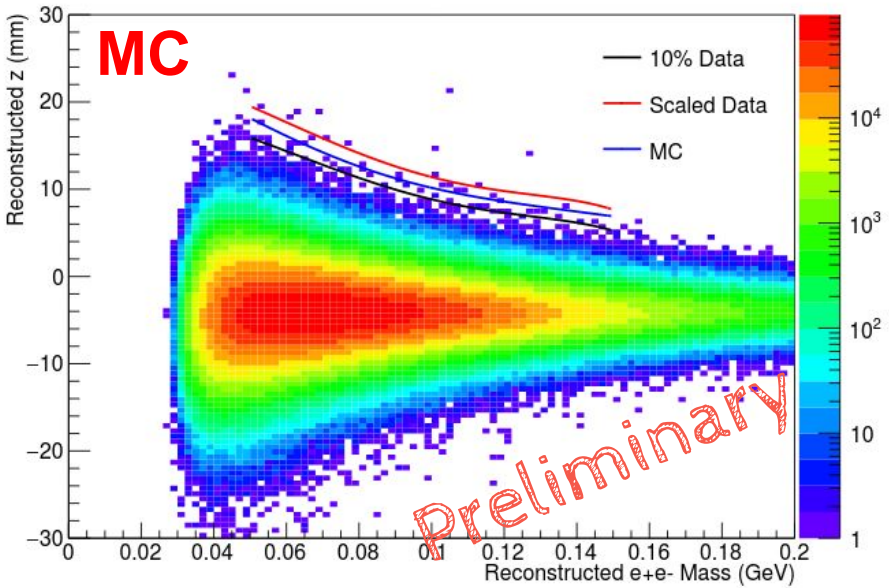


Discussion of Excess Displaced Vertices at Low Mass

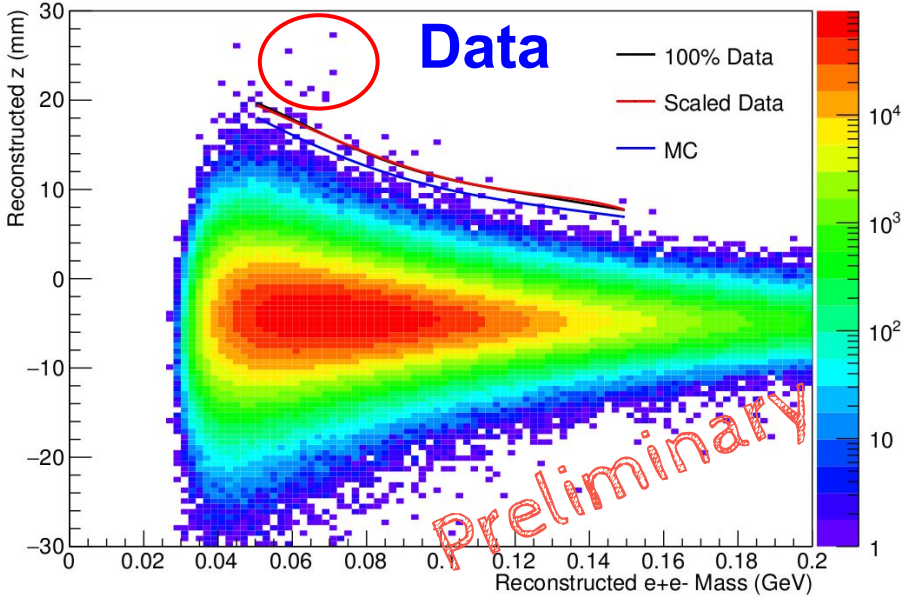
SLAC

- Equivalent background MC does not agree with the excess in data at low mass

Reconstructed z vs Mass

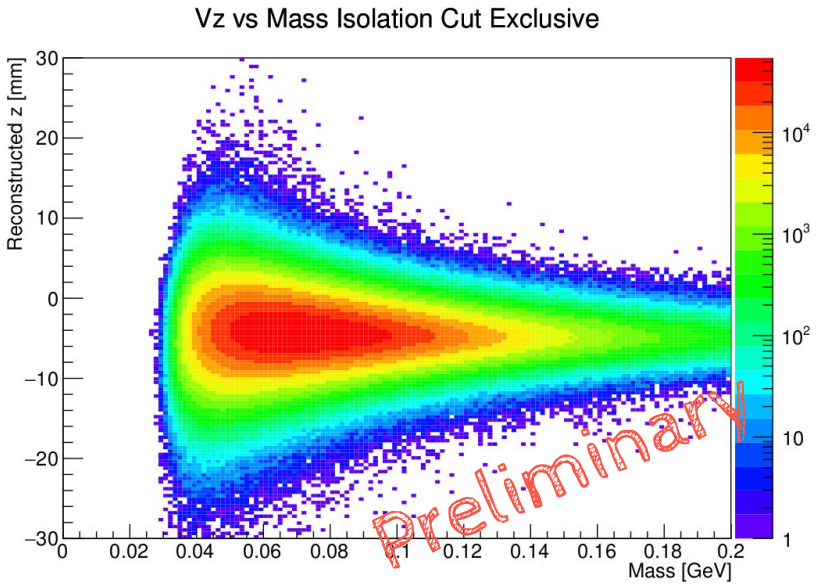


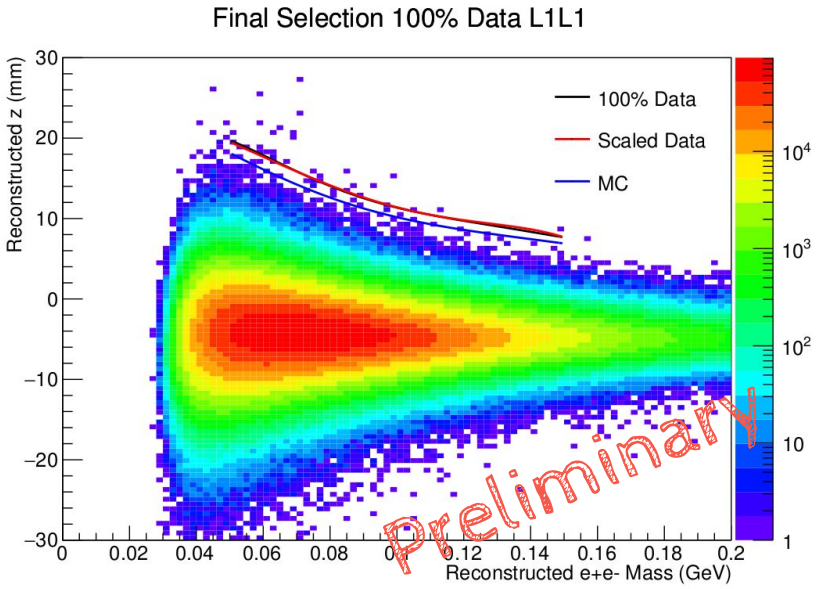
Reconstructed z vs Mass



Mistraking + Hit Inefficiencies

- Many of the high z events could be due to mistracks + hit efficiency effects
- The n-1 isolation cut plot (left) is a decent measure of mistracking.
  - One expects some fraction of these events to appear because of hit efficiency

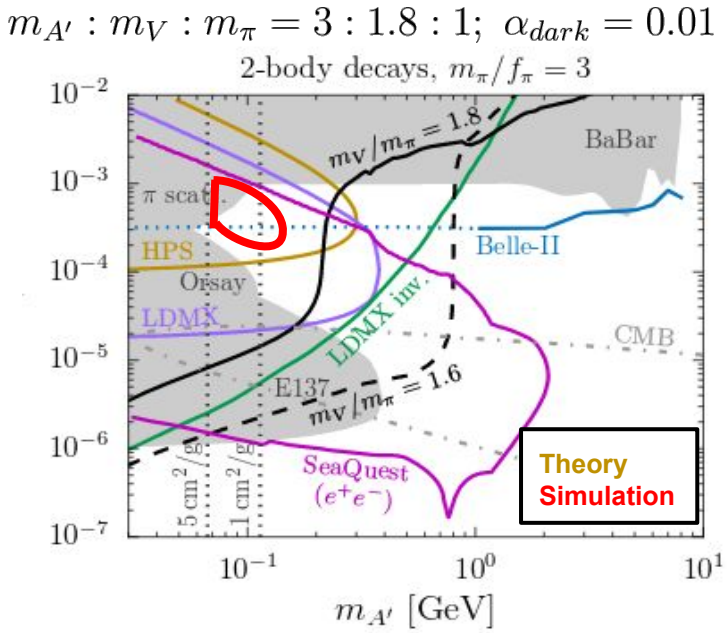


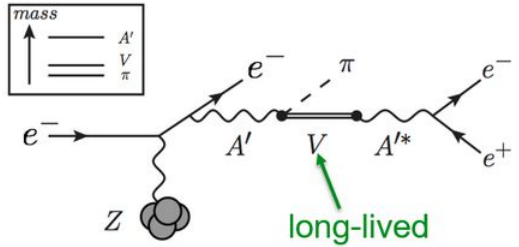


Preliminary SIMP Reach 2016 Engineering Run

SLAC

- **Possibly sensitive to Strongly Interacting Massive Particles** (SIMPs) in 2016 data
- Motivated by the "SIMP Miracle" (DM in ~1-10 GeV range)
- HPS can probe long-lived dark vectors (V) in a similar method to searching for A′s
- SIMP model decouples A′ cross-section and V livetimes. High rate of long-lived particles!
- Much of this analysis can be done in parallel with the minimal A′ search
- Stay with 1 slide





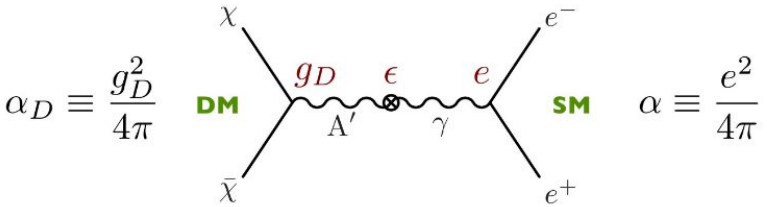
Light Dark Matter

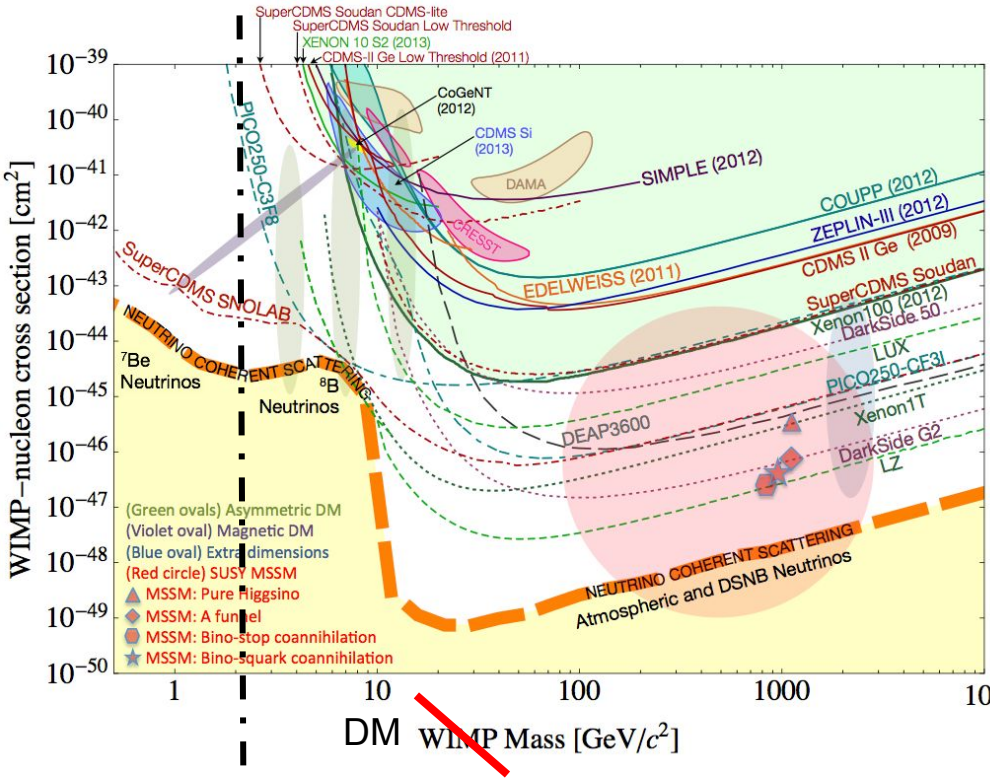
"Lee-Weinberg Bound"

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

Lighter dark matter requires a **new, comparably light force carrier.**

A simple/natural candidate: heavy/dark photon



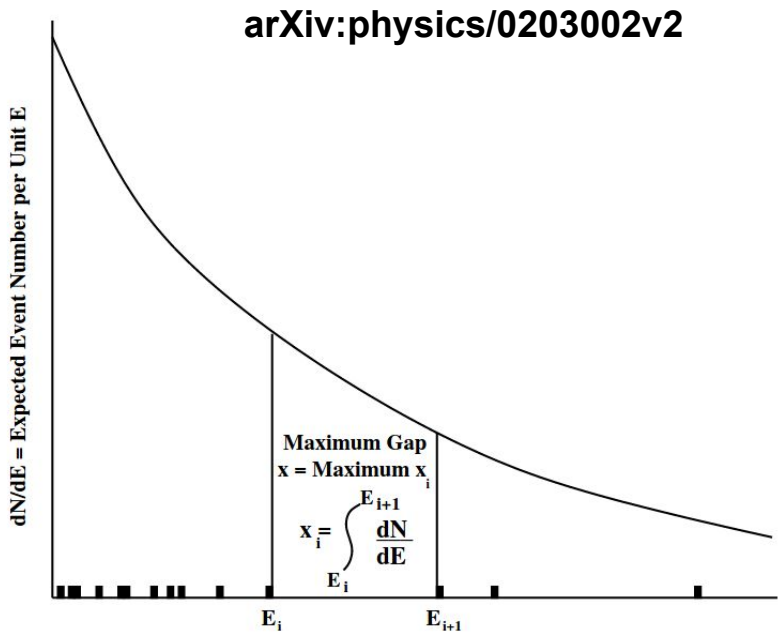


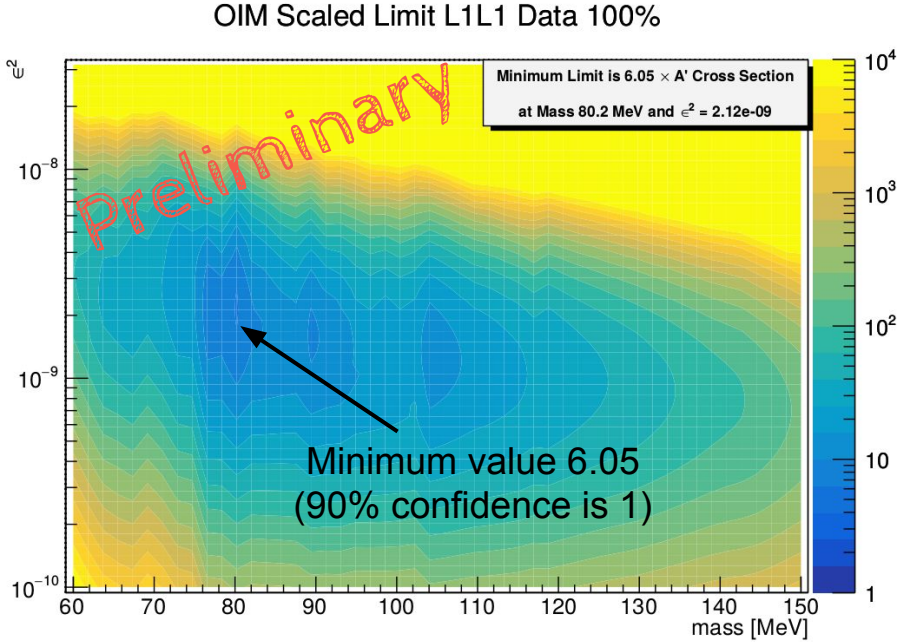
Light Dark Matter **WIMPs**

Displaced Vertex Search Final Results

SLAC

Optimum Interval Method (OIM) is ideally used for small signal where signal shapes are known, but background is not sufficiently known (e.g. direct DM detection)

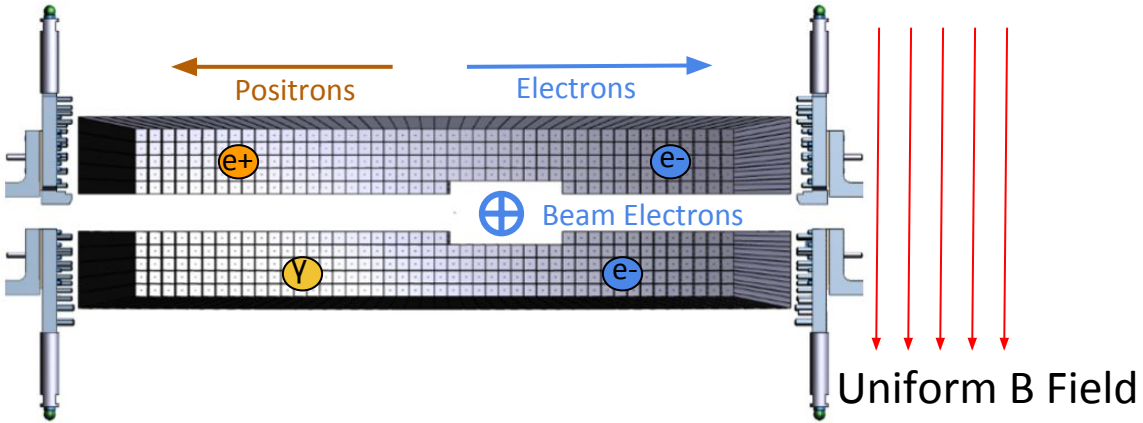




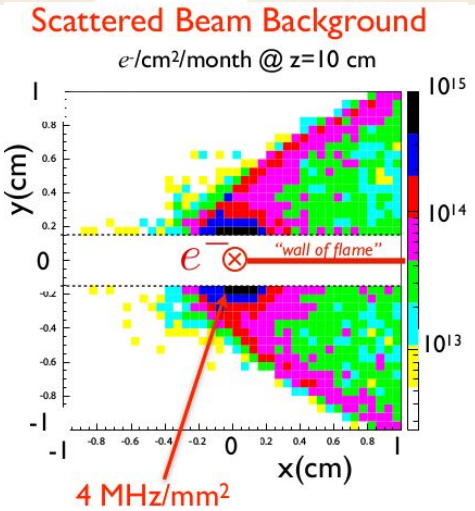
Proof of principle, though not enough luminosity for A′ sensitivity, we have much more data with upgrades!

Electromagnetic Calorimeter and Trigger

- Ecal made out of 442 lead tungstate (PbWO4) crystals and built by JLab/Orsay/INFN
- >100 kHz max trigger rate with 8 ns trigger window
- Background is dominated by **electrons scattering in the target.** Trigger eliminates 10's MHz of these
- Split in 2 halves: top/bottom to avoid "wall of flame"



Uniform B Field
~0.25 - 1.0 T

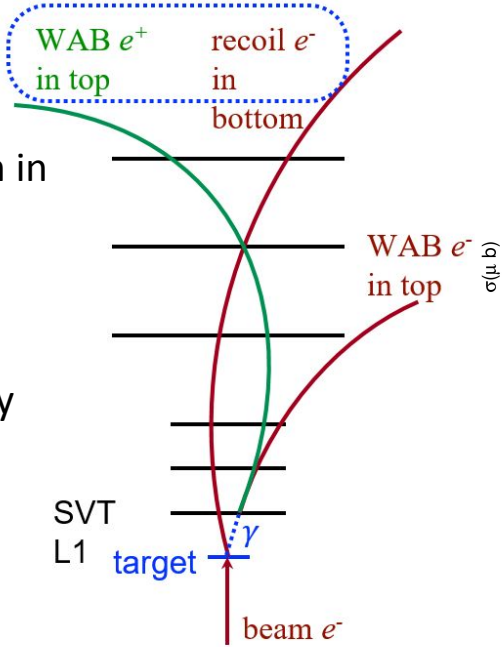


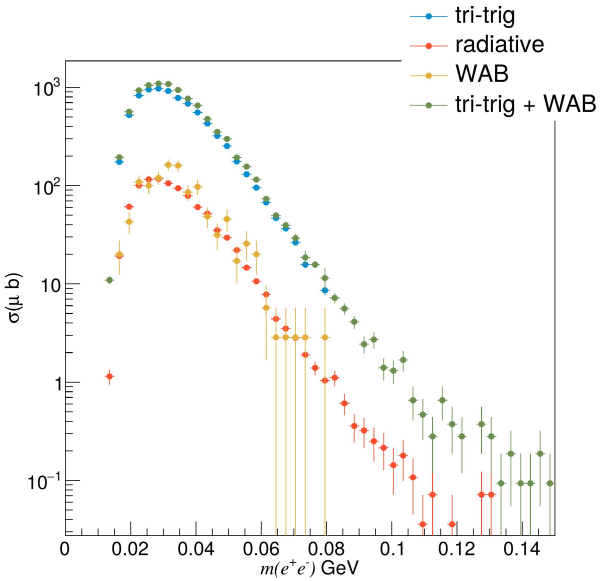
Trigger selects on opposite top/bottom clusters:

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

Converted Wide Angle Bremsstrahlung (WABs)

- Converted photons in tracker/target are common, but pairs in the same hemisphere
  - Recoils are generally soft, but can trigger with a conversion positron in opposite hemisphere: **rate comparable to tridents**
  - Daughter particles and recoil electron point back to the primary
- Simple cuts **eliminate about 80% with minimal signal loss**
  - Require a layer 1 positron hit





$$rad\ frac = \frac{rad\ e^+e^-pairs}{total\ e^+e^-pairs}$$