The Heavy Photon Search Experiment

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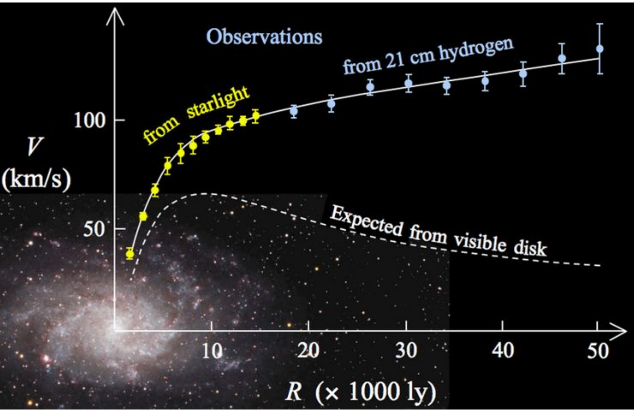
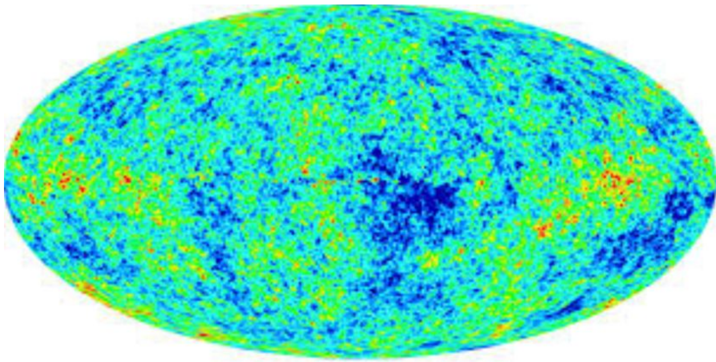
Introduction

- A heavy photon (or dark photon, or A') is a **hypothetical vector boson** that couples indirectly to electromagnetic particles
- 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**
- Motivation for A's and light dark matter, the experimental setup, initial results, and the future of HPS are presented

The Existence of Dark Matter

- There is clear evidence for the **existence of dark matter** (DM)
  - Galactic rotation curves, gravitational lensing, and CMB
- The fundamental nature of DM is a **central puzzle in particle physics**
- What are some ideas for what DM could be?

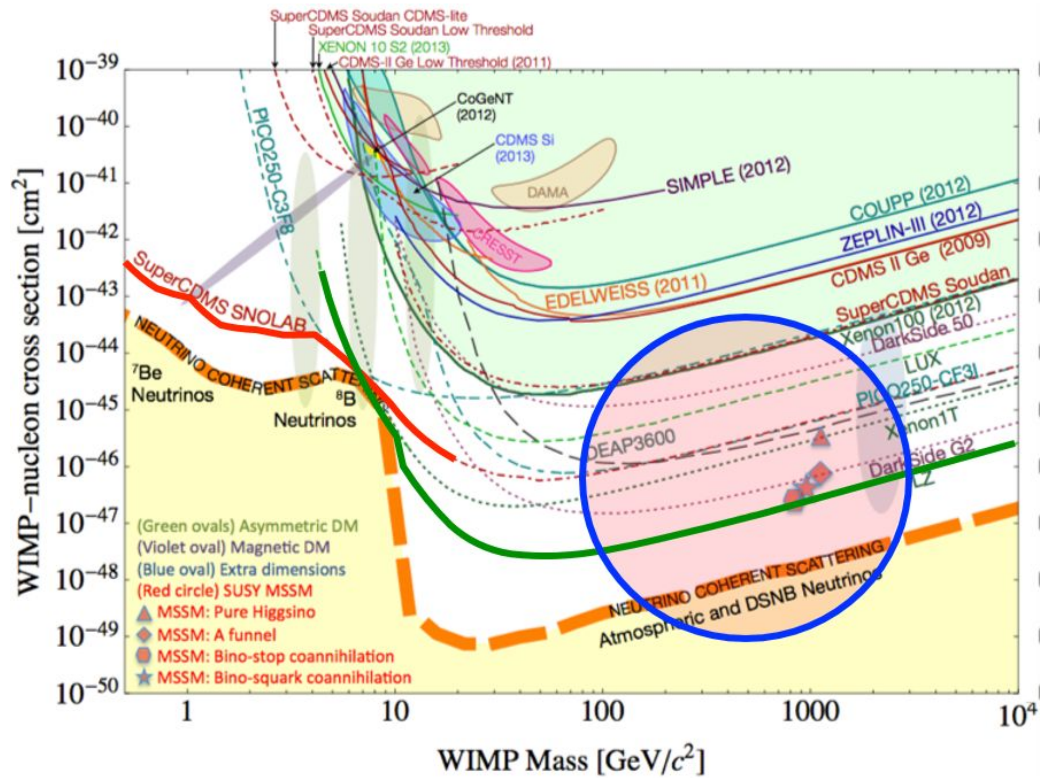




Weakly Interacting Massive Particles

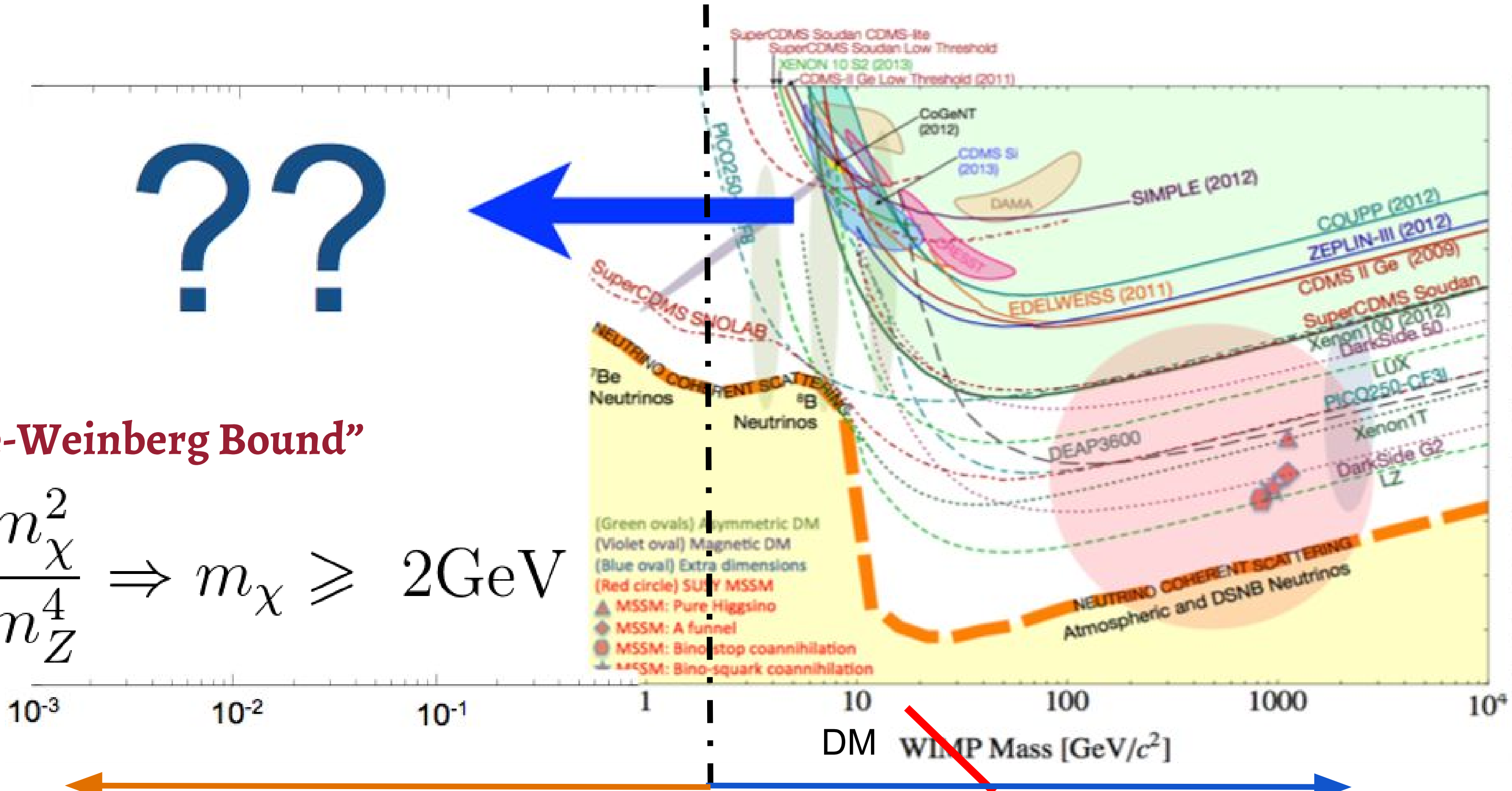
- Assume **DM is thermal** (i.e. was in equilibrium with SM matter in the early universe)
- **WIMPs are most popular model** for thermal DM, but have yielded null results so far
- WIMPs will either be found or most of the accessible parameter space will be ruled out within the next few years
- **Are there other places to look?**

arXiv:1310.8327



Light Dark Matter

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



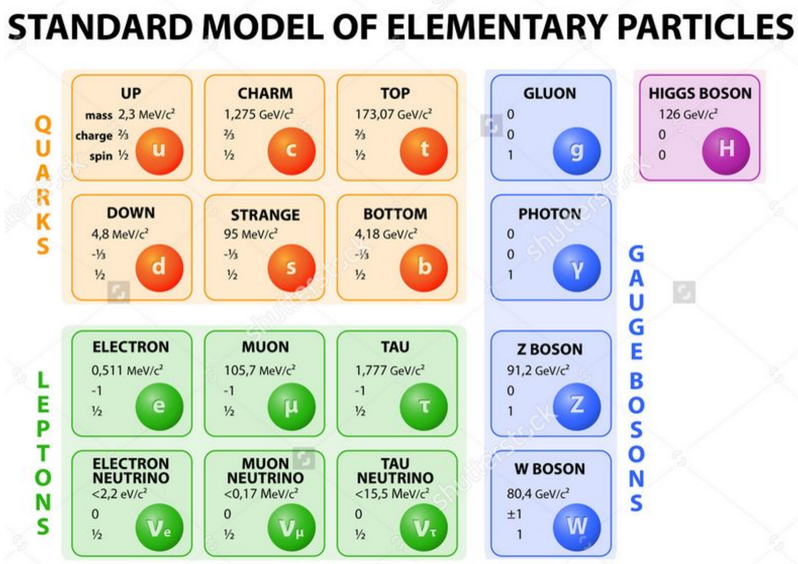
"Lee-Weinberg Bound"

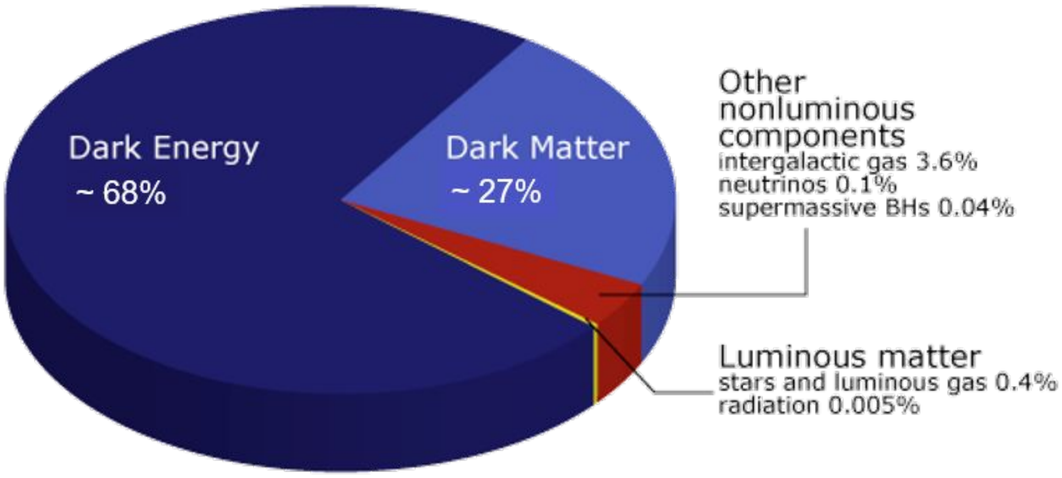
$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Rightarrow m_\chi \geqslant \; 2\text{GeV}$$

Light Dark Matter **WIMPs**

The Standard Model

- The SM is the best description of nature at the fundamental level, but is **only 4% of the universe**
- SM is also complicated with several forces and many types of particles. **Why should DM be any different/simpler?**





Heavy Photon Primer

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

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

Heavy Photon Primer

- 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') through interactions of massive fields (i.e. a "vector portal")

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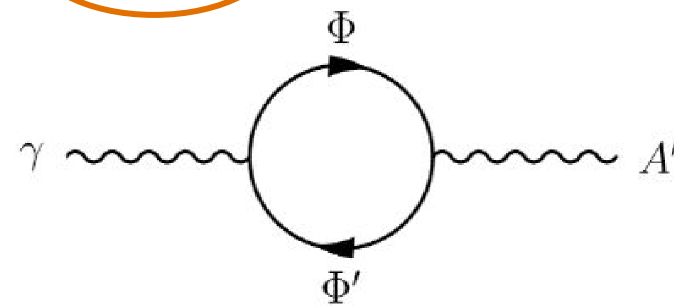

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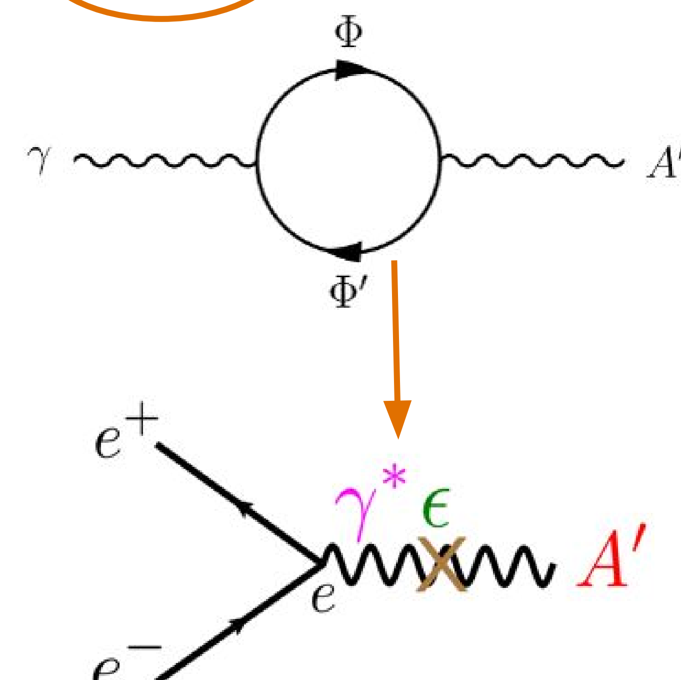
- This gives rise to a **kinetic mixing term** where the SM photon mixes with a new gauge boson (an A') through interactions of massive fields (i.e. a "vector portal")
- Induces a weak effective coupling of εe to SM fermions

$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} \ln\left(\frac{m_\Phi}{m_{\Phi'}}\right) \sim 10^{-3} - 10^{-1}$$

- GUT theories motivate log(ε) ~ -5 to -3

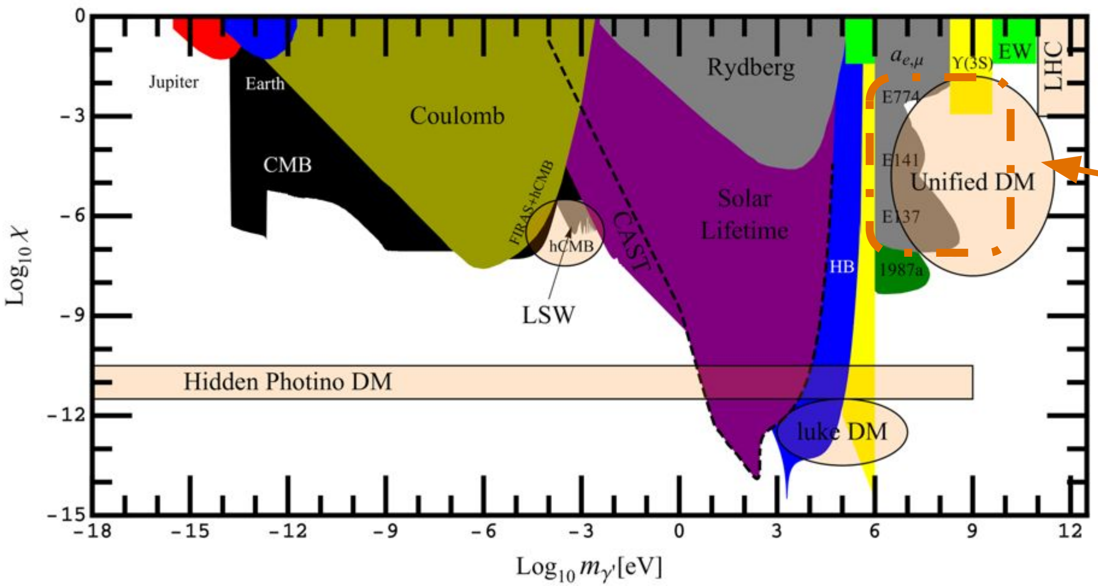
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \epsilon_Y F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$



Heavy Photon Parameter Space

- Possible origin for mass related to mass of Z by small parameter

(SUSY + kinetic mixing → scalar coupling to SM Higgs)



arXiv:1002.0329v1

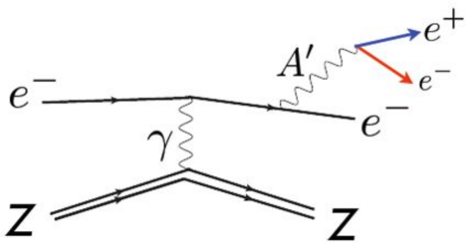
$$m_{A'} \sim \sqrt{\epsilon}\, m_Z \approx \mathrm{MeV} \ - \ \mathrm{GeV}$$

- This is the SM-like mass range. Must consider **both visible and invisible decays**

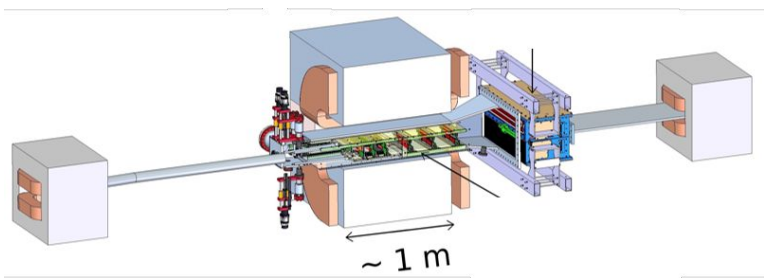
Heavy Photon Signatures

A' favors decay to SM fermions (visible)

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



Heavy Photon Search



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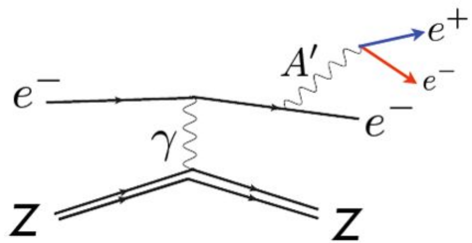

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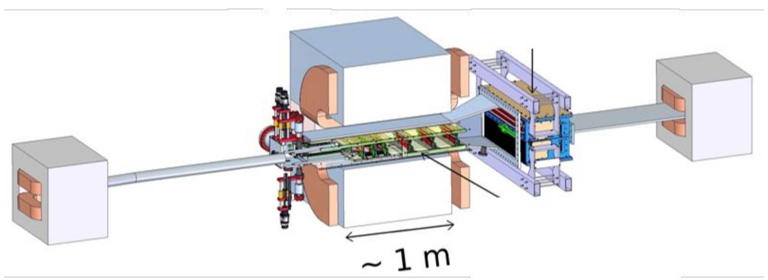
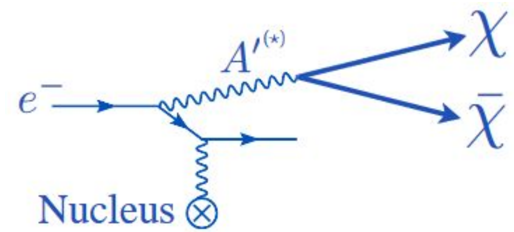
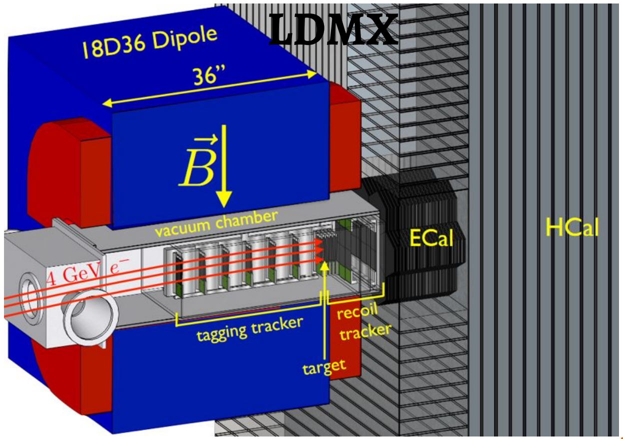


A' favors decay to DM (invisible)

$$2m_{DM} < m_{A'} \text{ with } g_D \gg \epsilon e$$

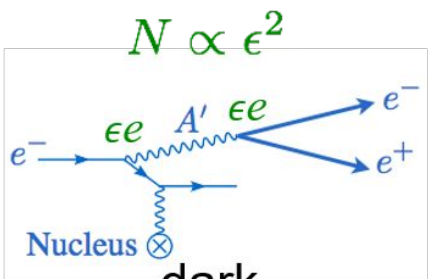


*Omar Moreno next talk



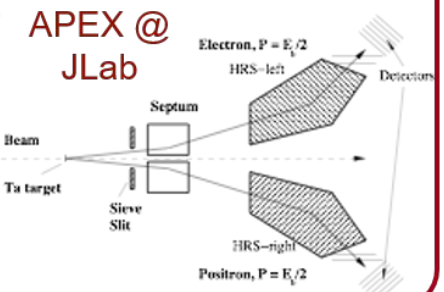
Experiments Searching for Heavy Photons

e^- fixed target

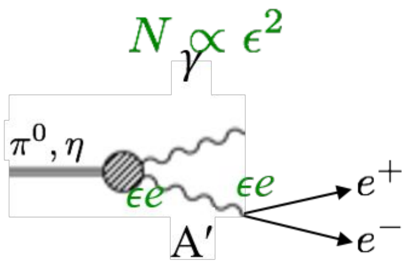


dark bremsstrahlung

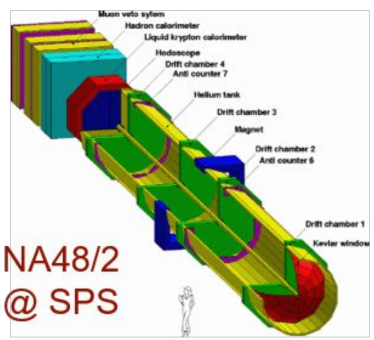
APEX @ JLab



p fixed target

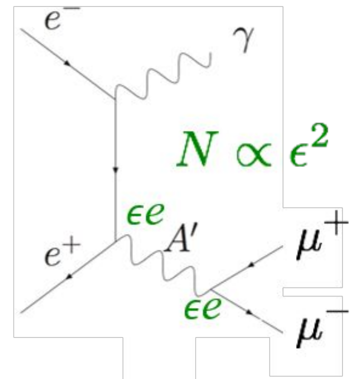


meson decays



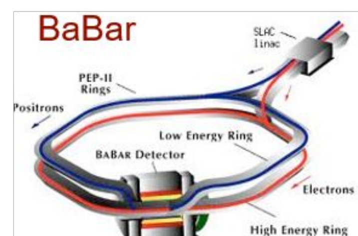
NA48/2 @ SPS

e^+e^- colliders

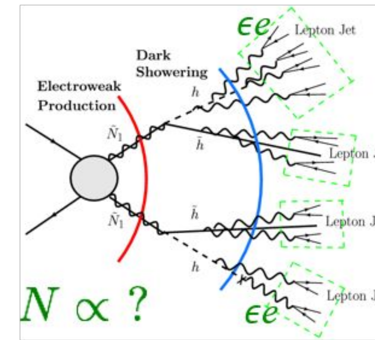


+ meson decays

BaBar

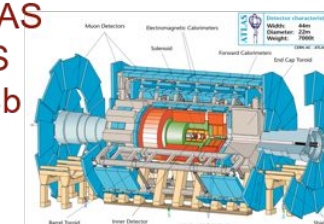


pp collider



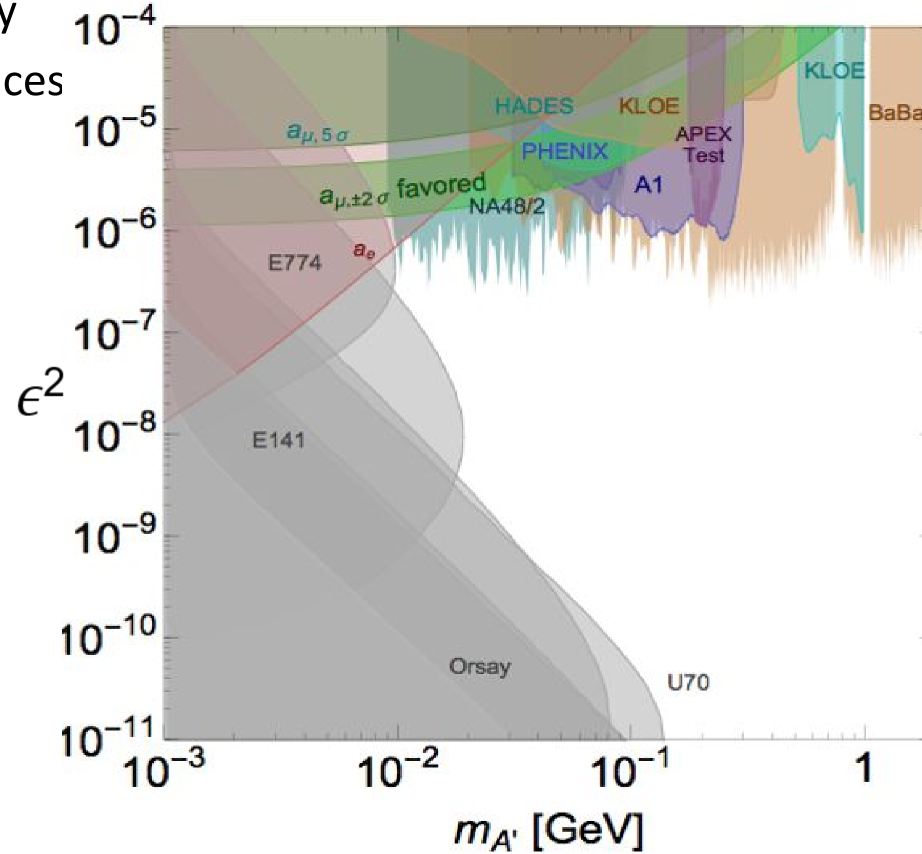
"lepton jets"
+ meson decays

ATLAS
CMS
LHCb



Existing Heavy Photon Constraints

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

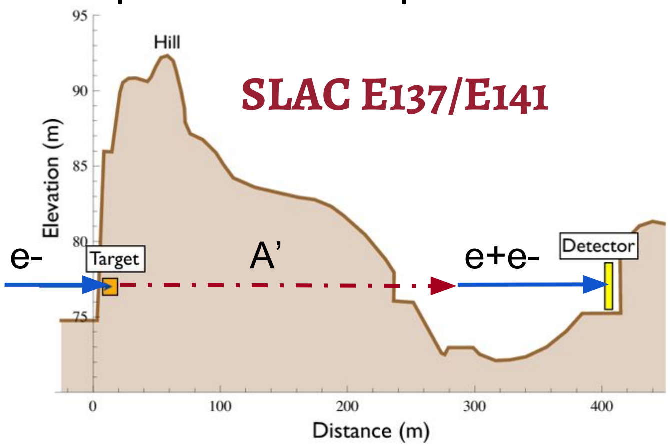


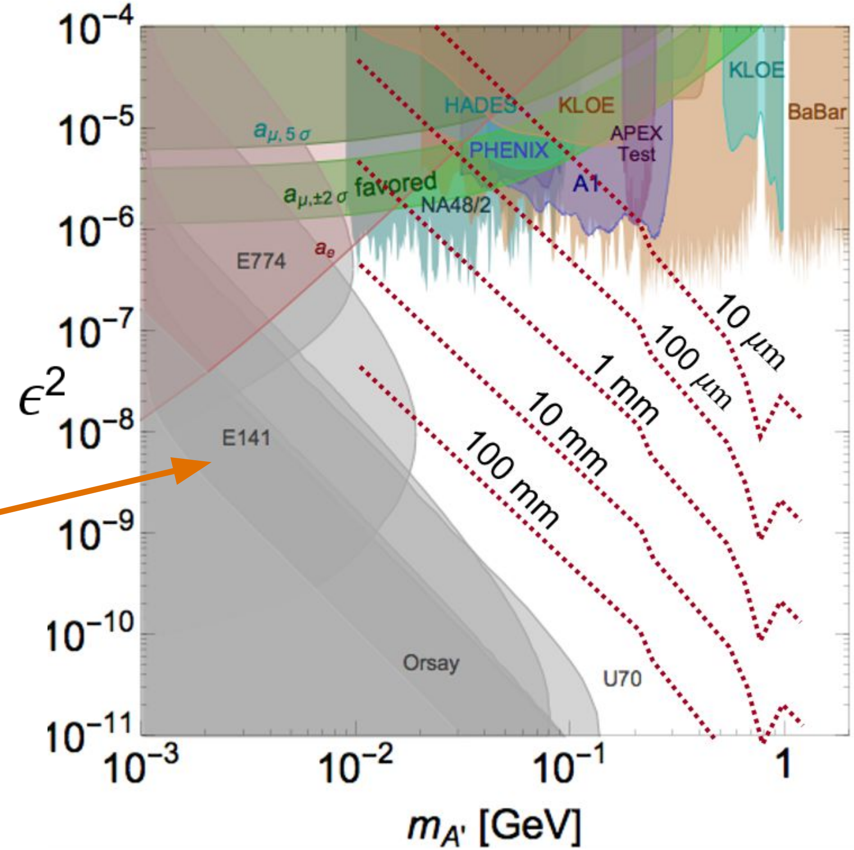
Existing Heavy Photon Constraints

- Large coupling searches are generally **"bump hunts"** for $m(l^+l^-)$ resonances
- A's with small coupling are **long-lived**

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

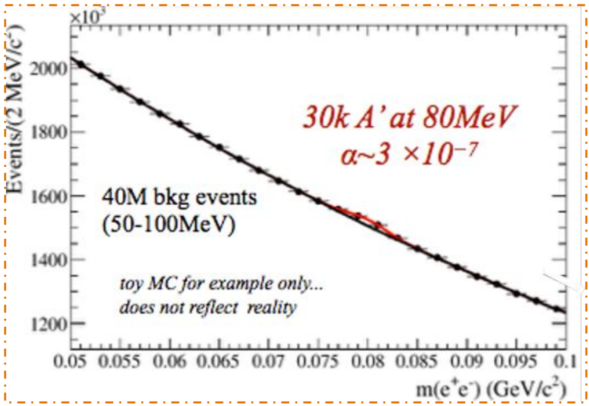
- Constraints from "beam dump" experiments are possible

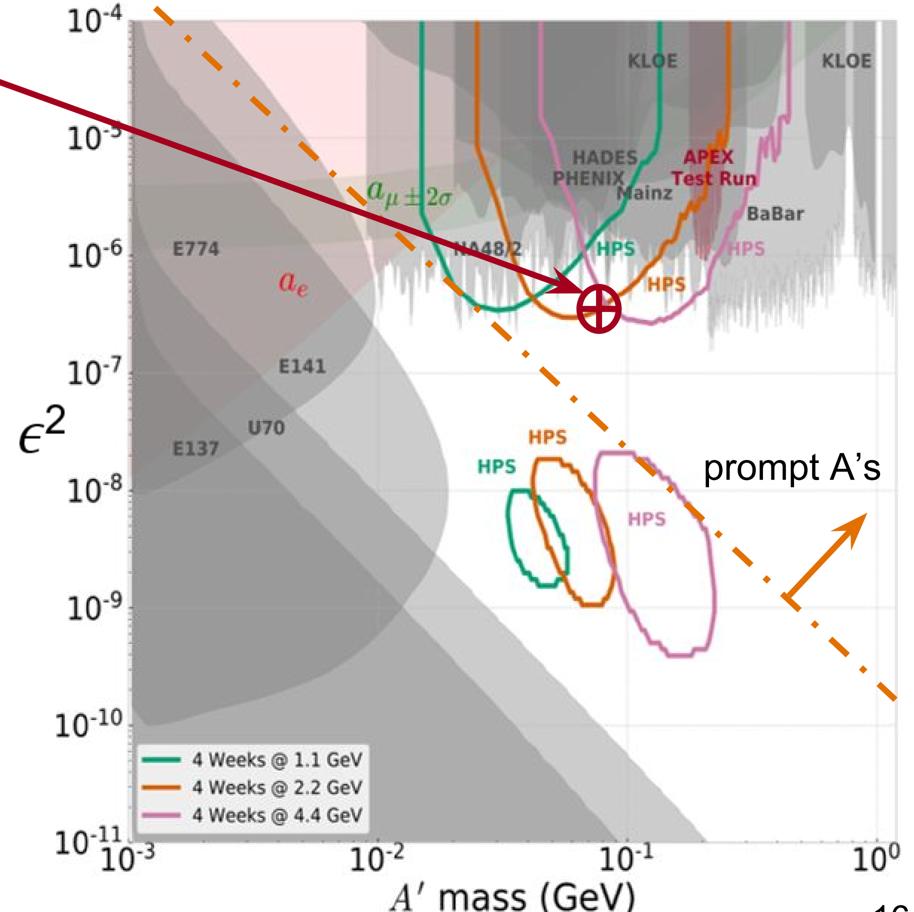




Heavy Photon Signatures in HPS

“Large” signal, huge QED background (**bump hunt**)





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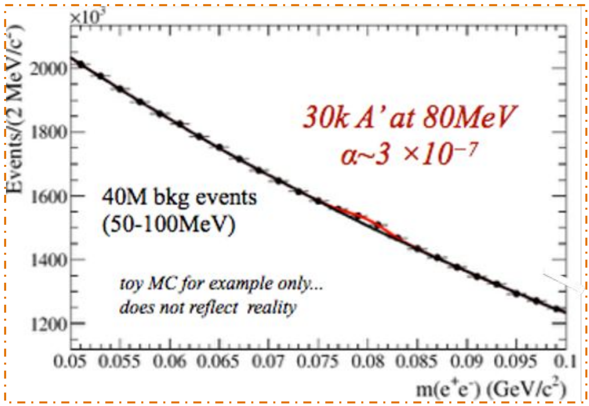
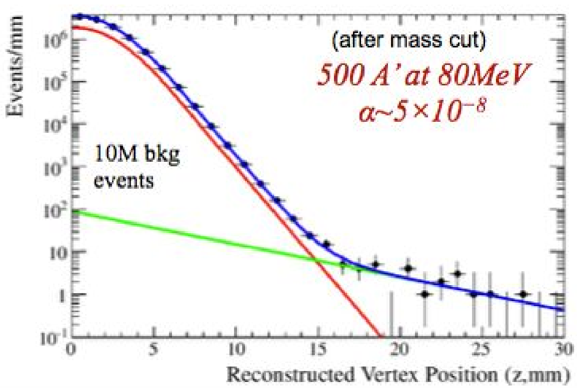
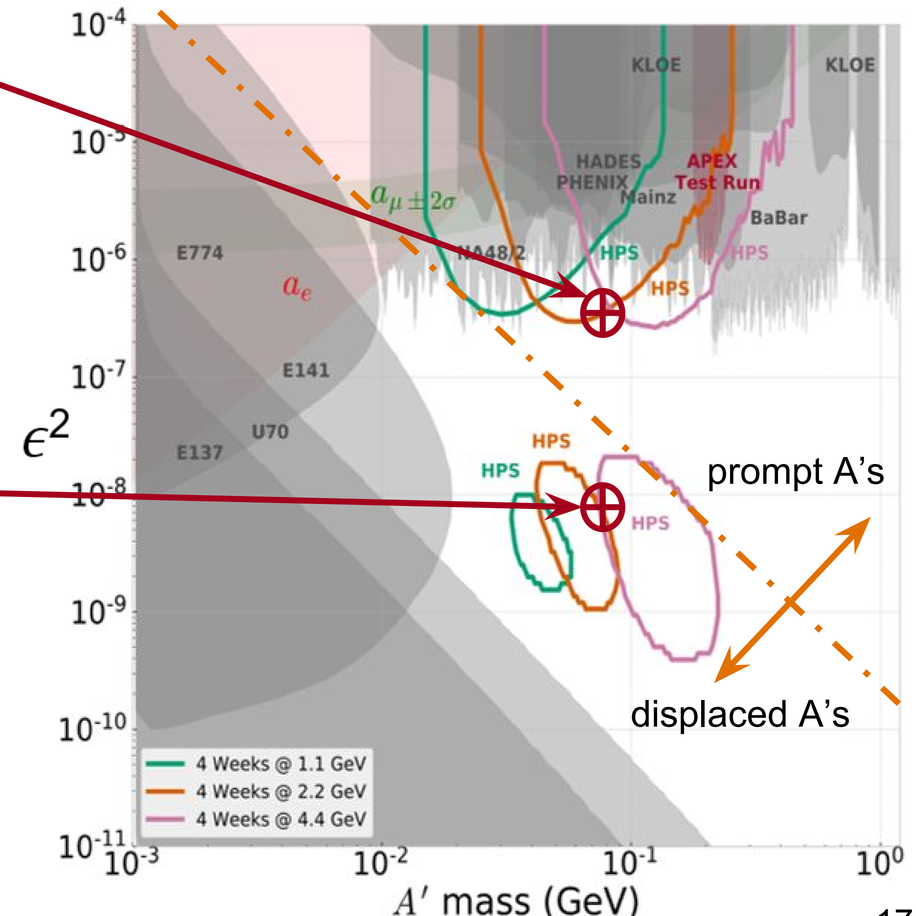


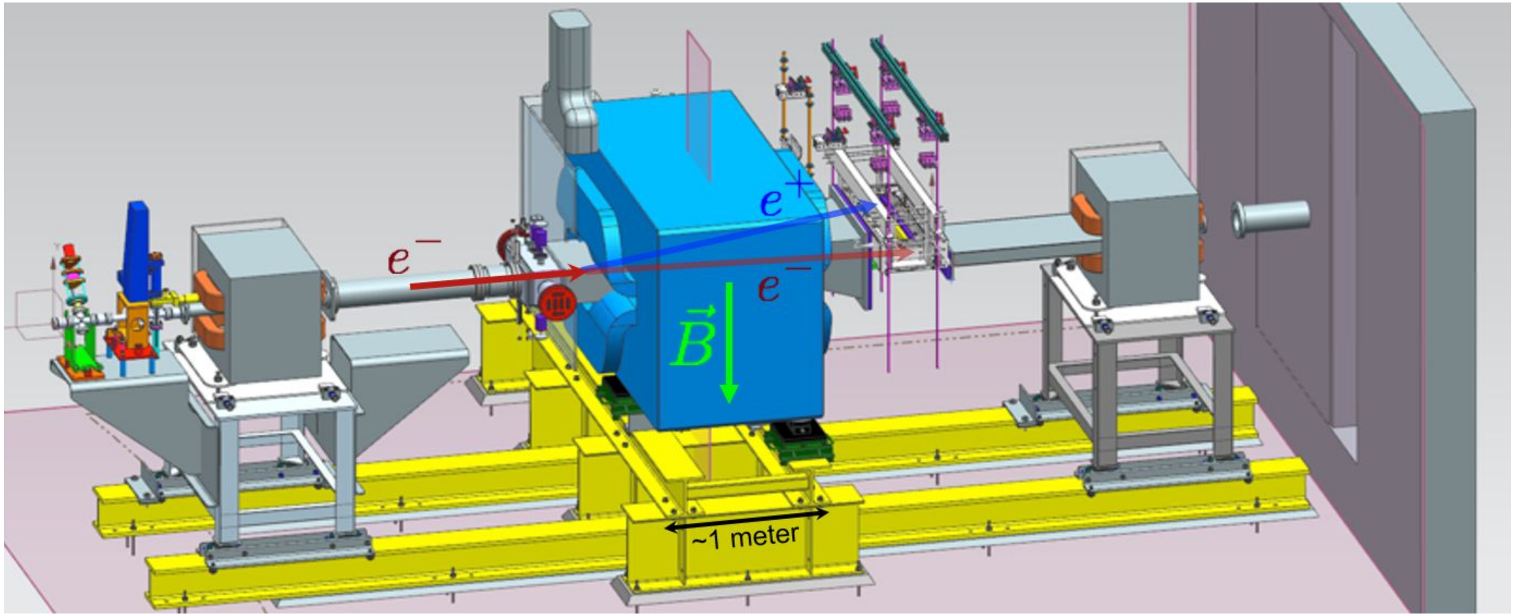
Small signal, no background (**vertex search**)





The Heavy Photon Search Experiment

- HPS is a **fixed-target search** for **visibly decaying dark photons** using the CEBAF electron beam (1-11 GeV) in Hall B at Jefferson Lab
- A's can be produced in a process **analogous to Bremsstrahlung** in a thin W foil
- Large dipole magnet spreads e+e- pairs and provides momentum measurement

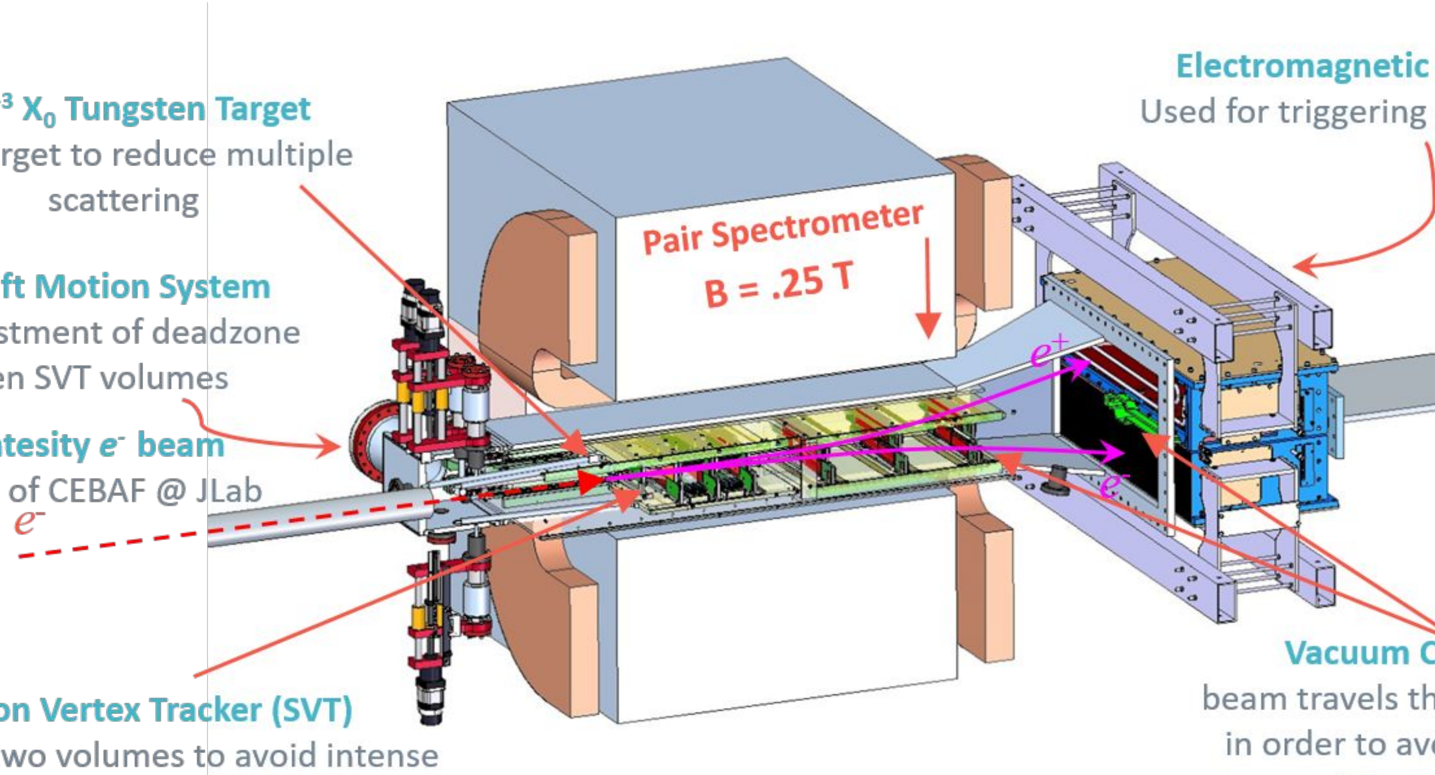


HPS Detector

~10^{-3} X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

High intesity e^- beam
Courtesy of CEBAF @ JLab



Electromagnetic Calorimeter
Used for triggering and particle ID

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

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

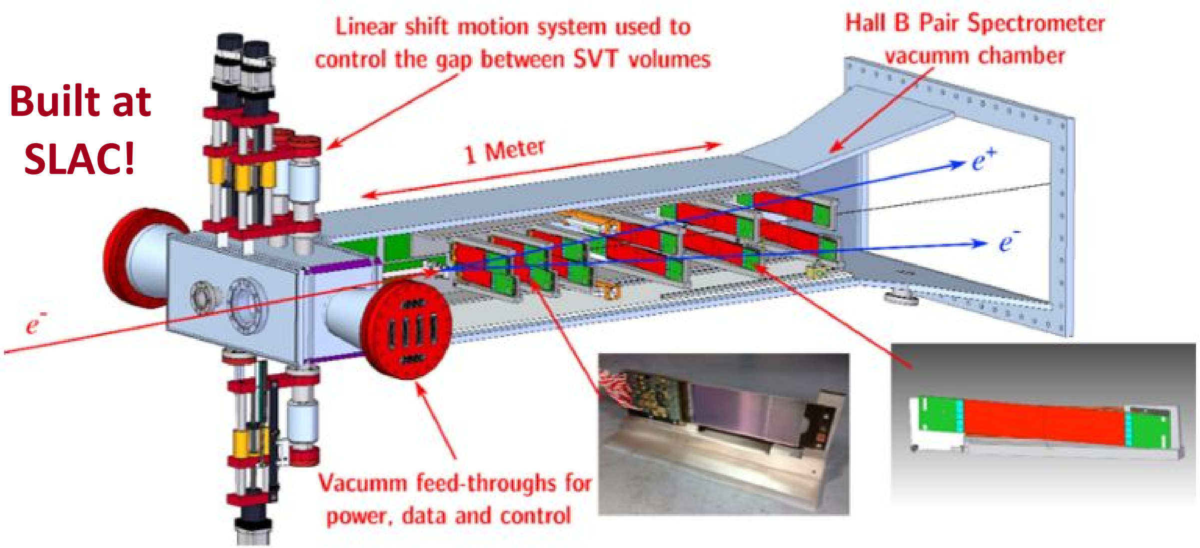
SVT + ECal DAQ capable of 50 kHz

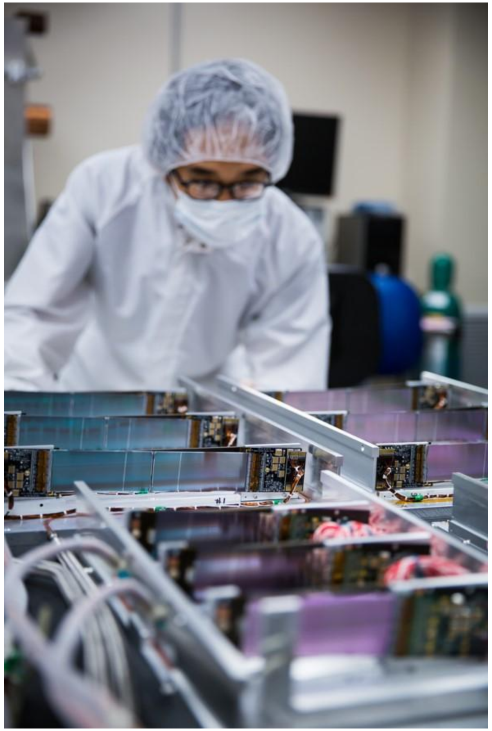
Installed within the Hall B alcove at Jefferson Lab downstream of the CLAS12 detector

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
- 50 kHz max trigger rate
- L1-L3 vertically retractable from beam
- L4-L6 are double wide for acceptance purposes

Built at SLAC!





Jefferson Laboratory and CEBAF

- JLab (Newport News, VA) has the Continuous Electron Beam Accelerator Facility (CEBAF) that can simultaneously deliver intense 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**

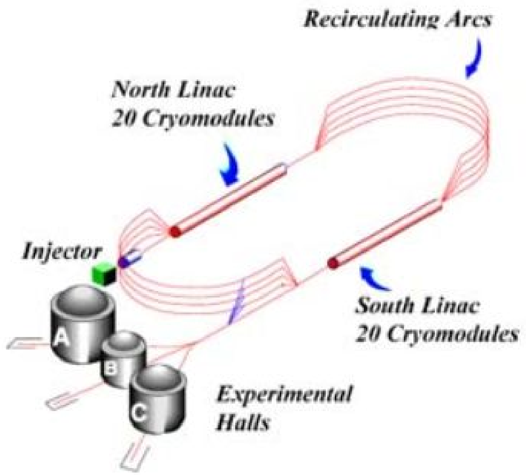
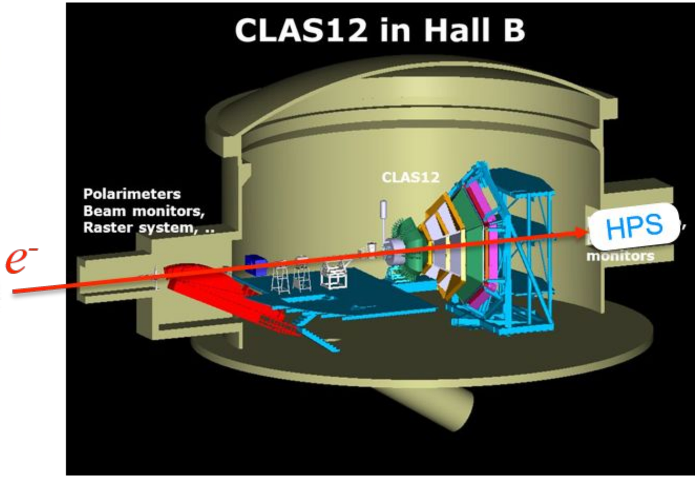
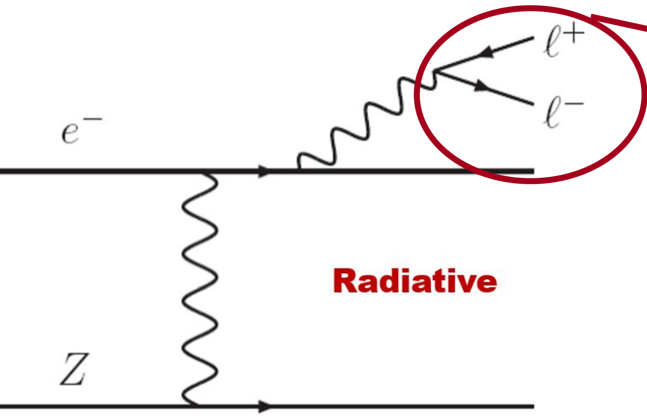


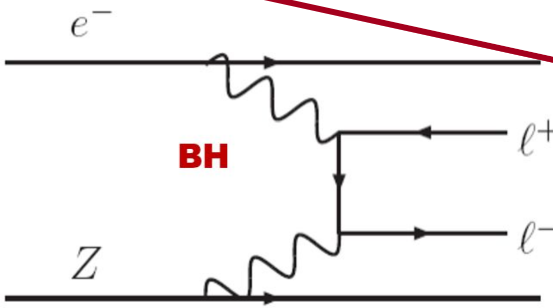
Figure 1: Layout of CEBAF.

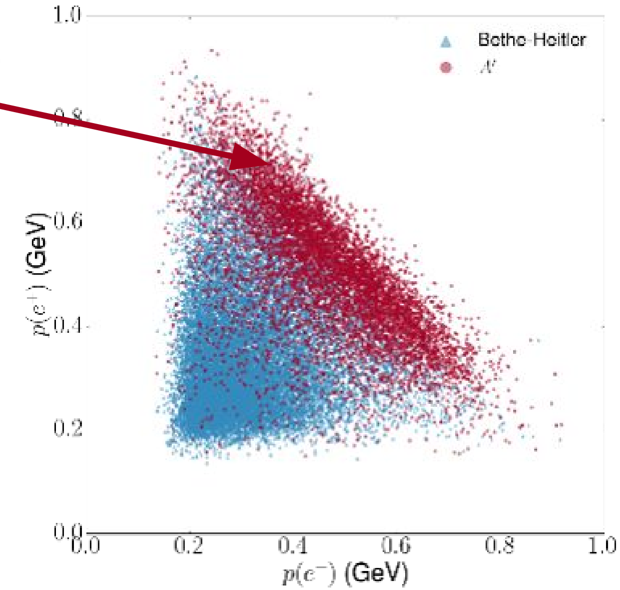


Trident Backgrounds

- **Radiative tridents** have identical kinematics for e+e- pair (irreducible)







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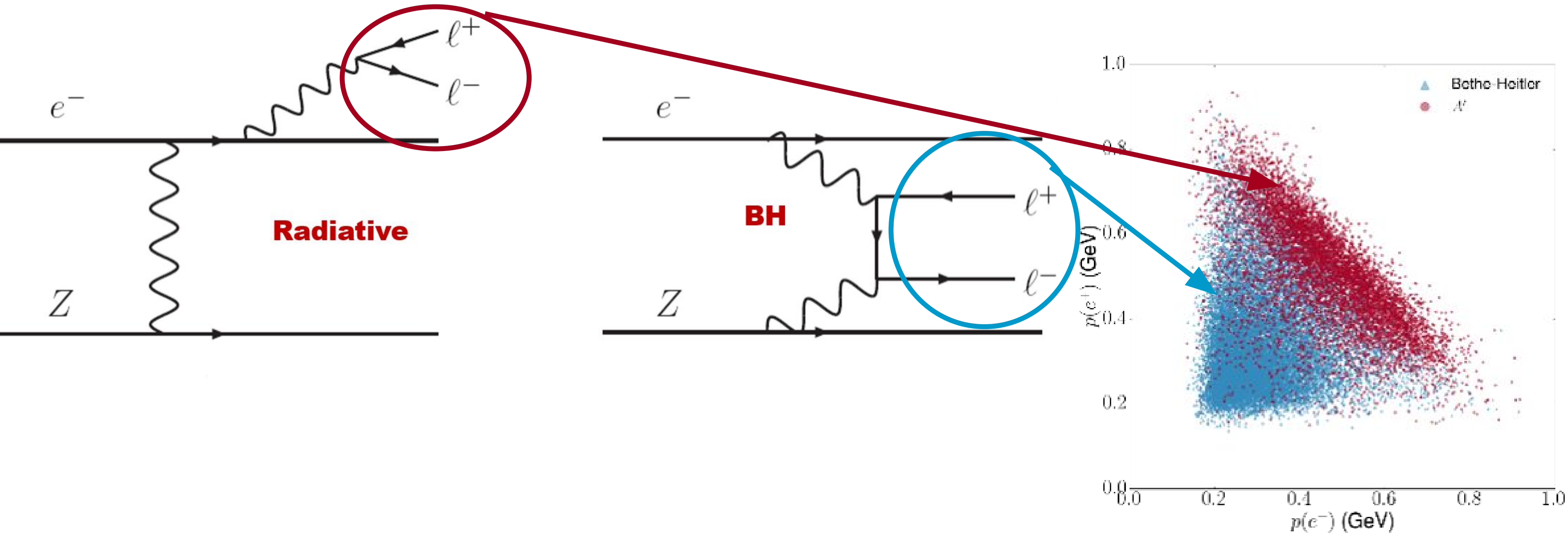
- **Radiative tridents** have identical kinematics for e+e- pair (irreducible)
- **Bethe-Heitler tridents** are kinematically distinct, but still dominant in signal region



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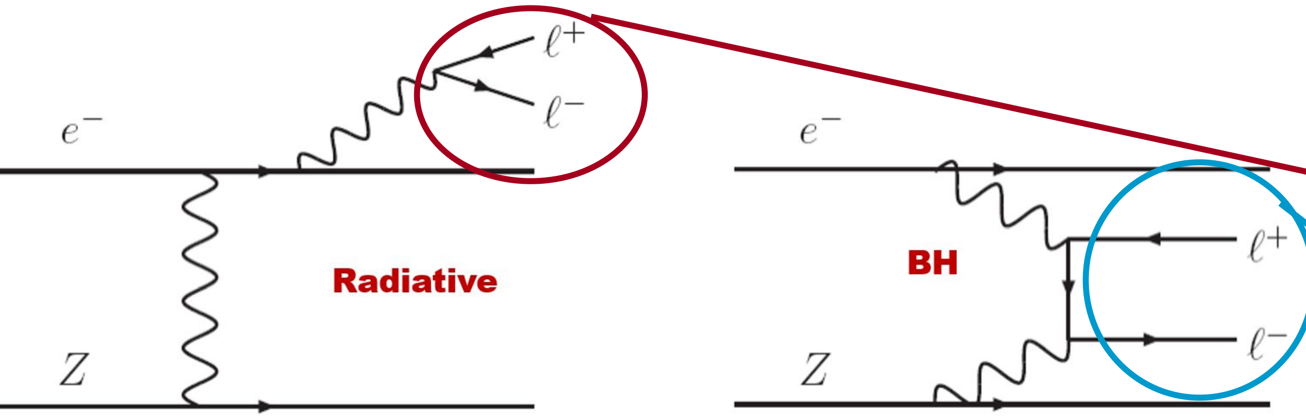
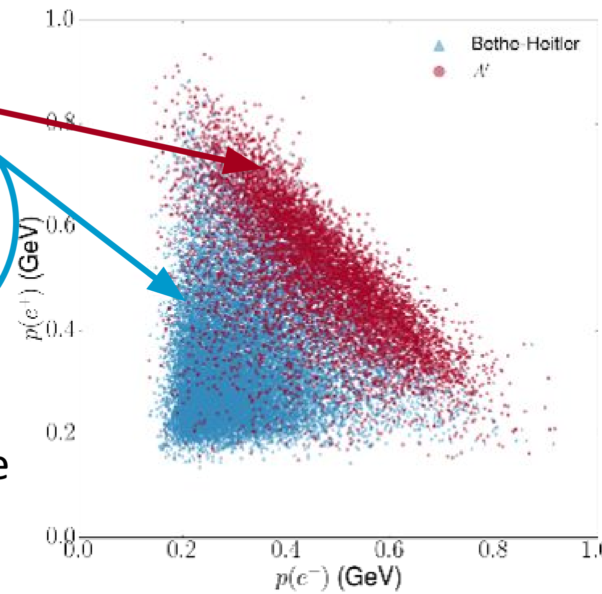


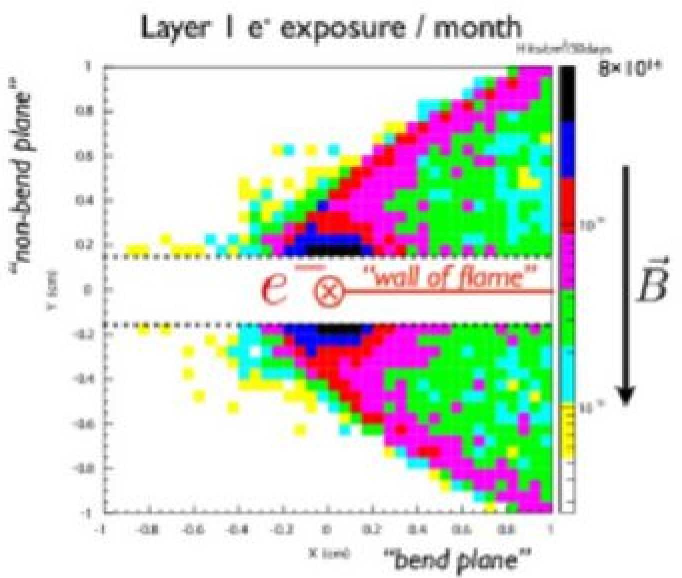


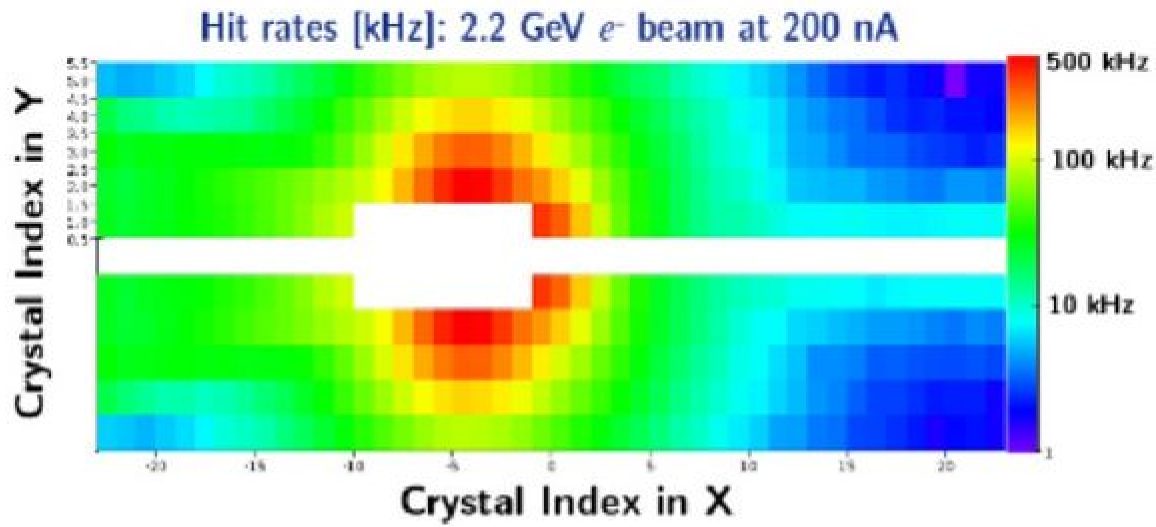
- Radiative tridents provide reference for expected signal rate

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

Beam Backgrounds

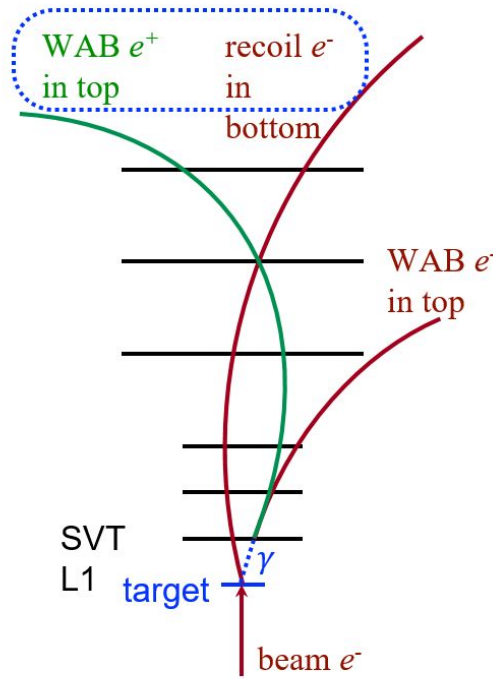
- Background is dominated by **electrons scattering in the target**
- Detector (vertical) acceptance down to +/- 15 mrad (which means L1 of SVT is **0.5 mm from beam axis!**)
- This provides challenges for occupancies, data rates, and radiation tolerances





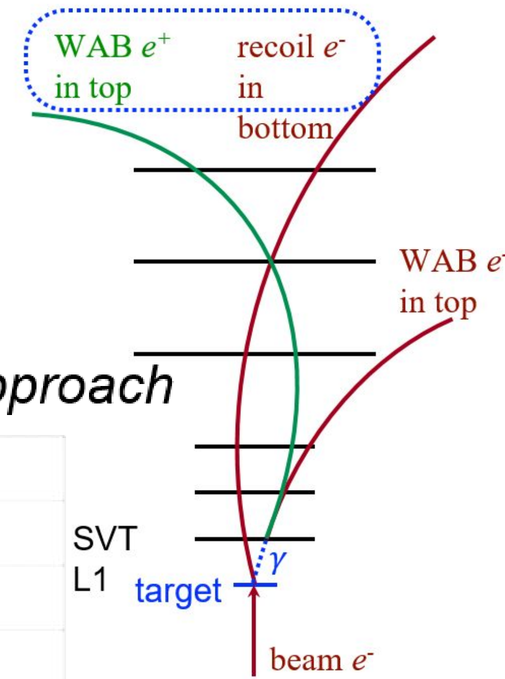
Wide Angle Bremsstrahlung

- Converted photons in tracker or target are common, but pairs are in the same hemisphere. Recoils are generally soft
- Recoil electron and a conversion positron in opposite hemispheres can trigger: **rate comparable to tridents**

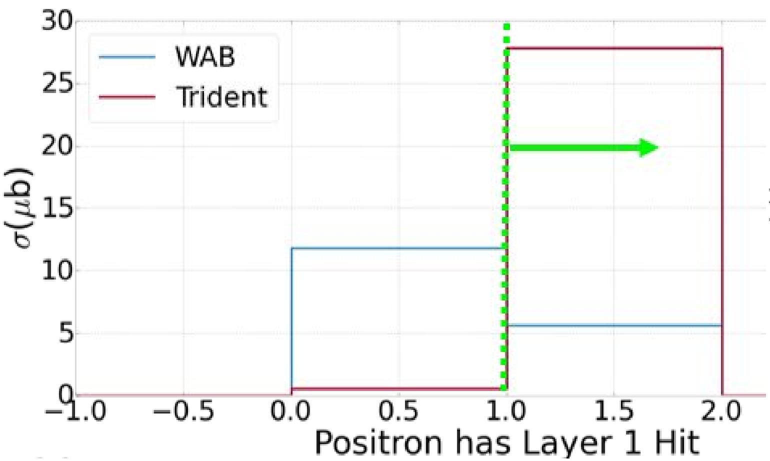


Wide Angle Bremsstrahlung

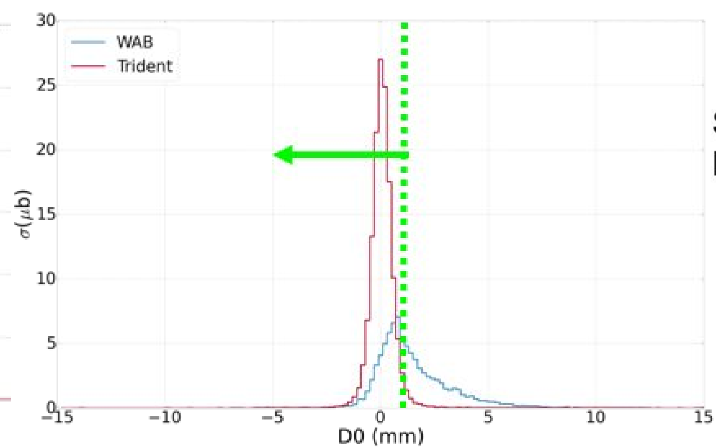
- Converted photons in tracker or target are common, but pairs are in the same hemisphere. Recoils are generally soft
- Recoil electron and a conversion positron in opposite hemispheres can trigger: **rate comparable to tridents**
- Simple cuts **eliminate about 80% with minimal signal loss**



e^+ has Layer 1 hit



e^+ distance of closest approach



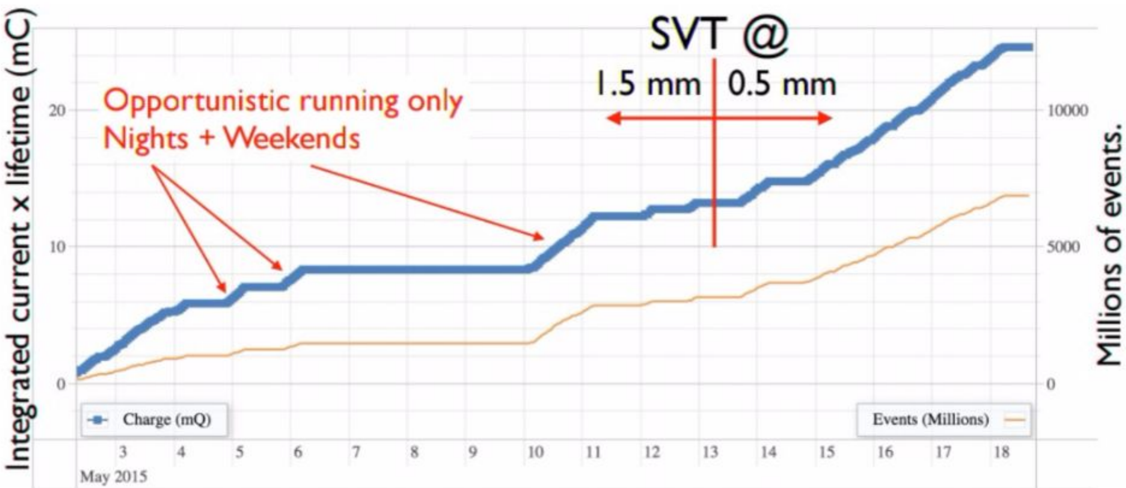
2015 & 2016 Engineering Runs

2015 Engineering Run

50 nA at 1.06 GeV

1.7 days (10 mC) of physics data

2015 & 2016 Engineering Runs



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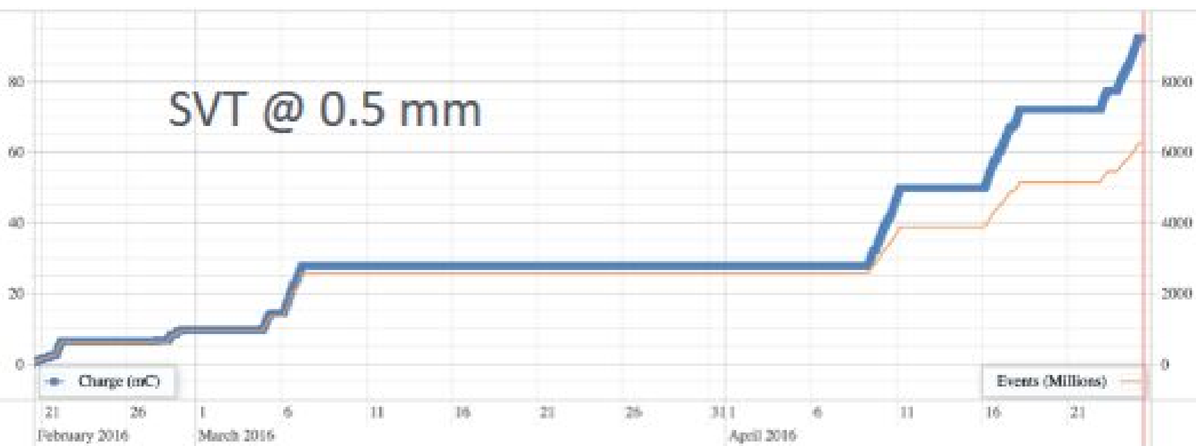


2016 Engineering Run
200 nA at 2.3 GeV
5.4 days (92.5 mC) of physics data

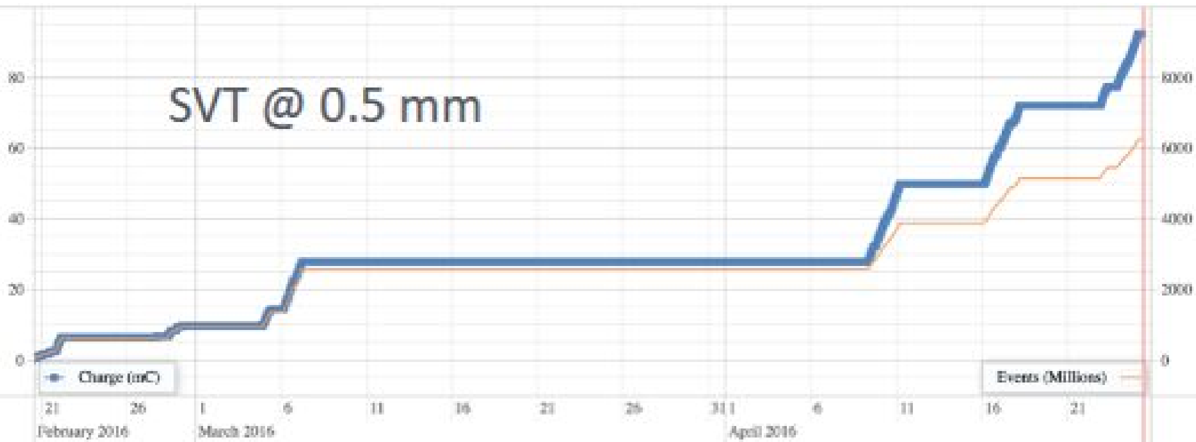
2015 & 2016 Engineering Runs

SLAC

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

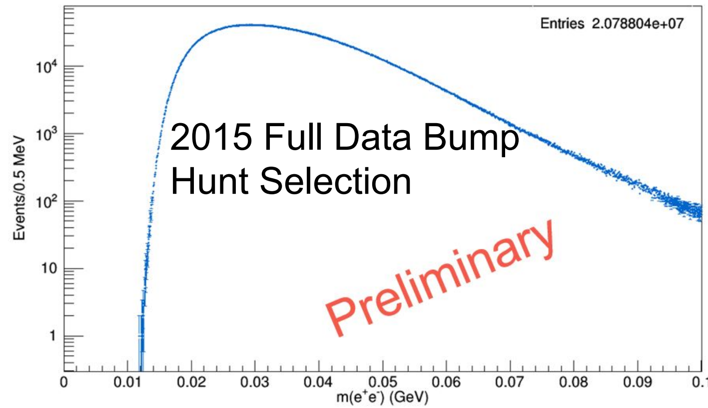
180 days of data taking approved by JLab PAC!

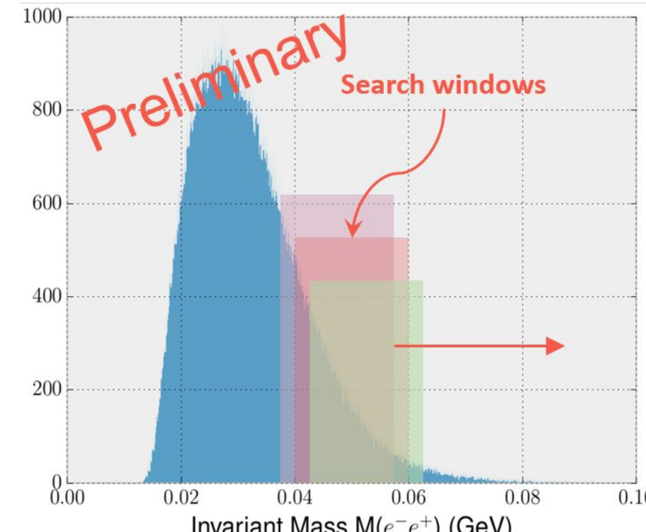
HPS Analysis Status

- **2015 Bump Hunt analysis is complete**
  - Presented at JLab seminar in May of 2017 (Omar Moreno)
- **2015 Vertexing analysis is currently in progress**
  - We might have interesting physics sensitivity (SIMPs), but not for the minimal A' model…
- Brief overview and status of these analyses will be presented in the next few slides
- 2016 Bump Hunt and Vertexing analysis are waiting (we are learning A LOT from the 2015 data)

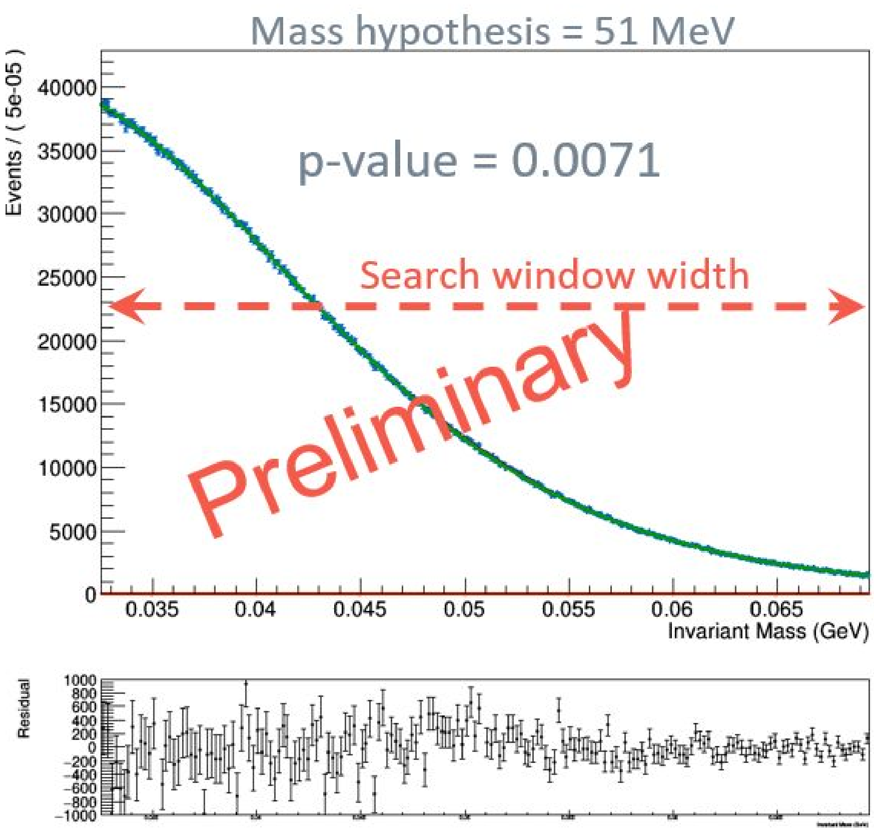
Resonance Search

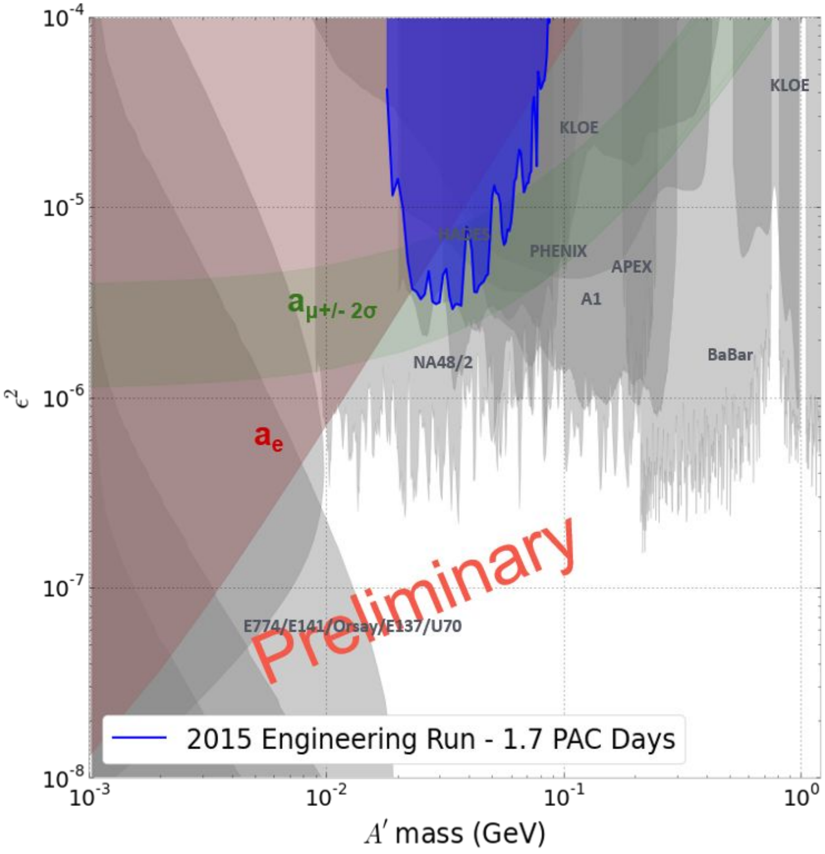
- Scan mass spectrum between 17-80 MeV using search windows
- Search for a bump by fitting a polynomial background plus a Gaussian signal
- Use a likelihood ratio to quantify the significance of any bump
- Bound upper limit with expected limit to avoid exaggerated exclusion from downward fluctuations (power constrained limit)
- Plot the 2σ exclusion in A’ parameter space





2015 Resonance Search Results

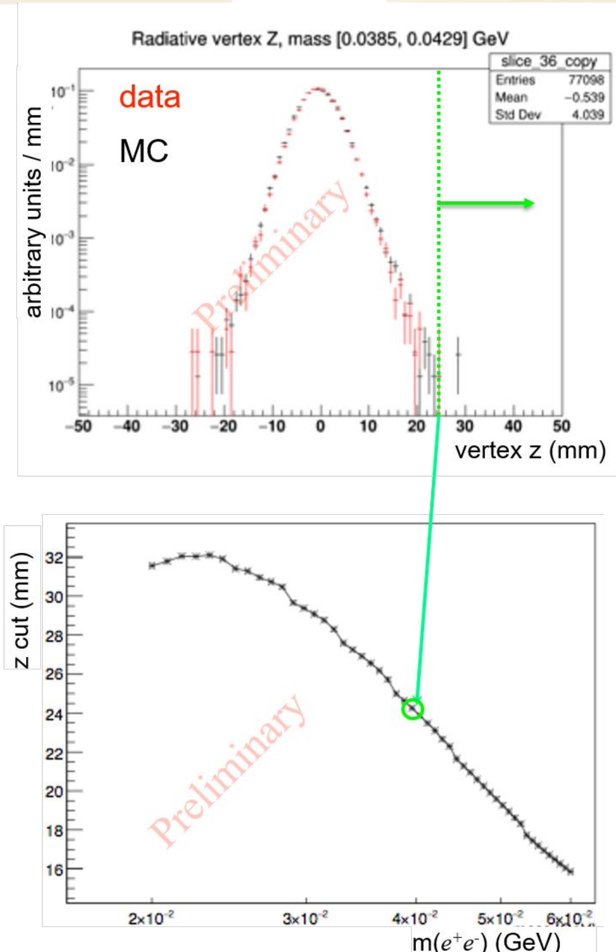




No Significant Bumps Found!

Vertex Search

- First analysis requires e+e- hits in SVT L1 (L1L1)
  - This is only part of the acceptance, require L1L2 and L2L2 exclusive categories in the future for full acceptance
- Plot vertex z in mass slices. Use MC to fit background as gaussian and exponential tail in each slice
- Define “zcut” as 0.5 background events expected for z > zcut
- Any event with a z vertex great than zcut is a candidate for signal



Vertex Search

- Vertex search is in progress, but will not have sensitivity for minimal A' model with 2015 data at 1.05 GeV

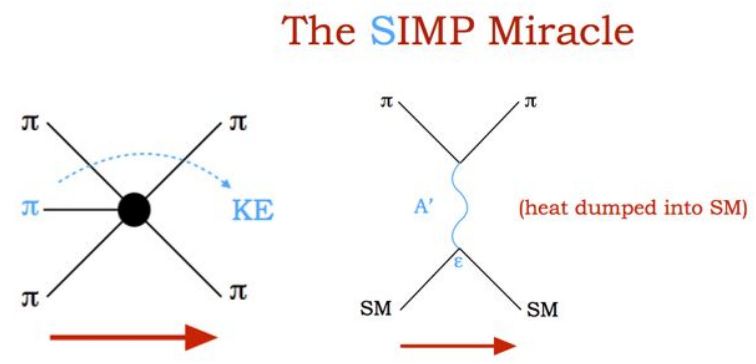
But…

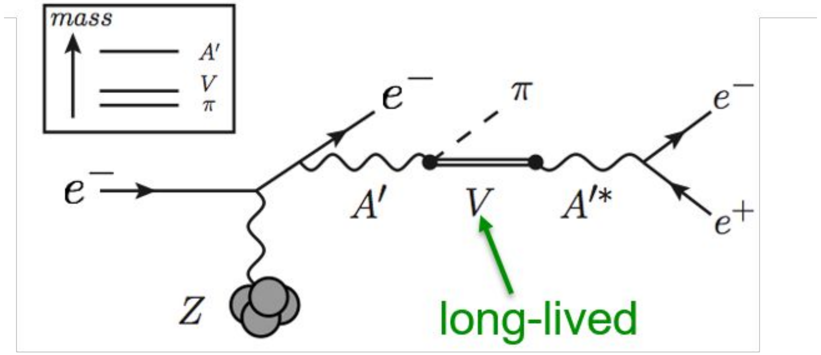
Vertex Search

- Vertex search is in progress, but will not have sensitivity for minimal A' model with 2015 data at 1.06 GeV

But…

1. **Possibly sensitive to Strongly Interacting Massive Particles** (SIMPs) in both 2015 and 2016 datasets
2. **Small upgrade projects** planned for next run (additional SVT layer and positron trigger)
3. **95% of data is still to come!**

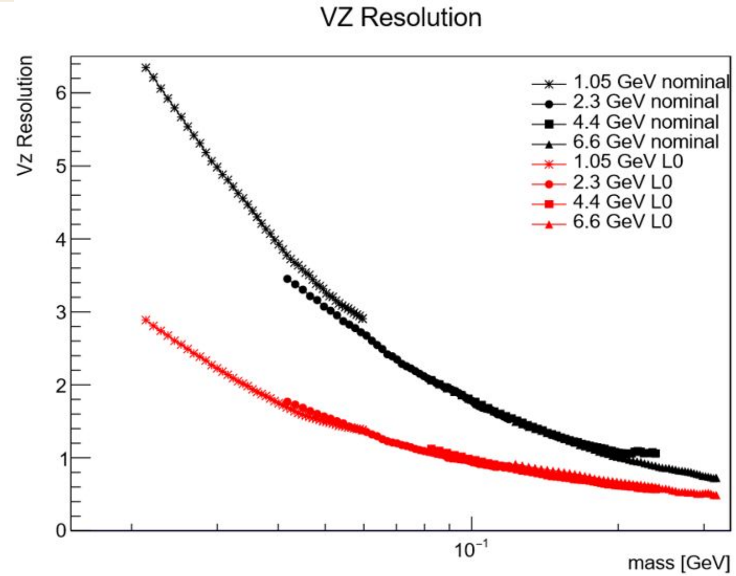




arXiv:1402.5143

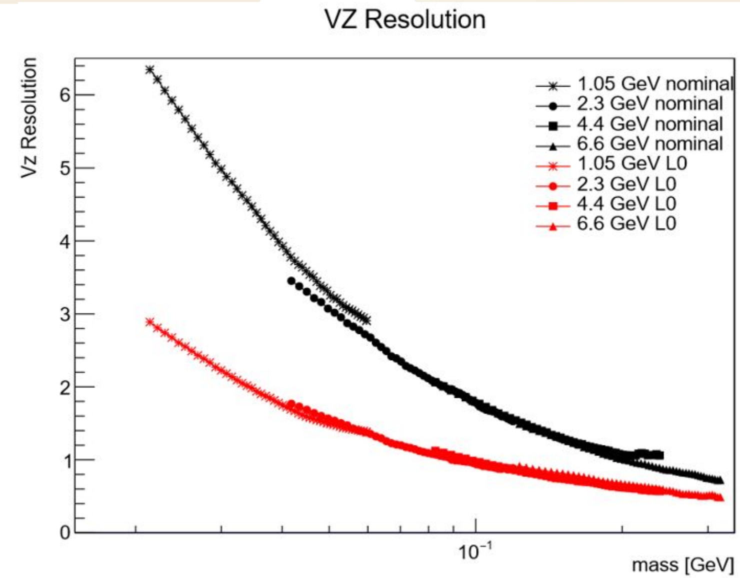
HPS Upgrades

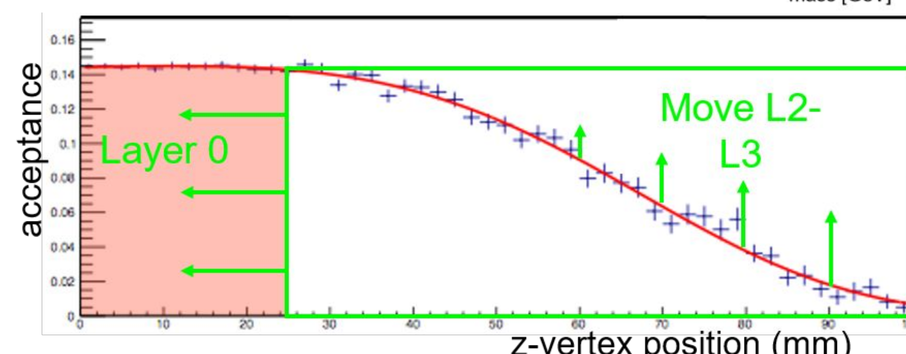
- **Add a tracking layer** (Layer 0) between target and current first layer
  - Dramatically improves vertex resolution, hence the vertex reach



HPS Upgrades

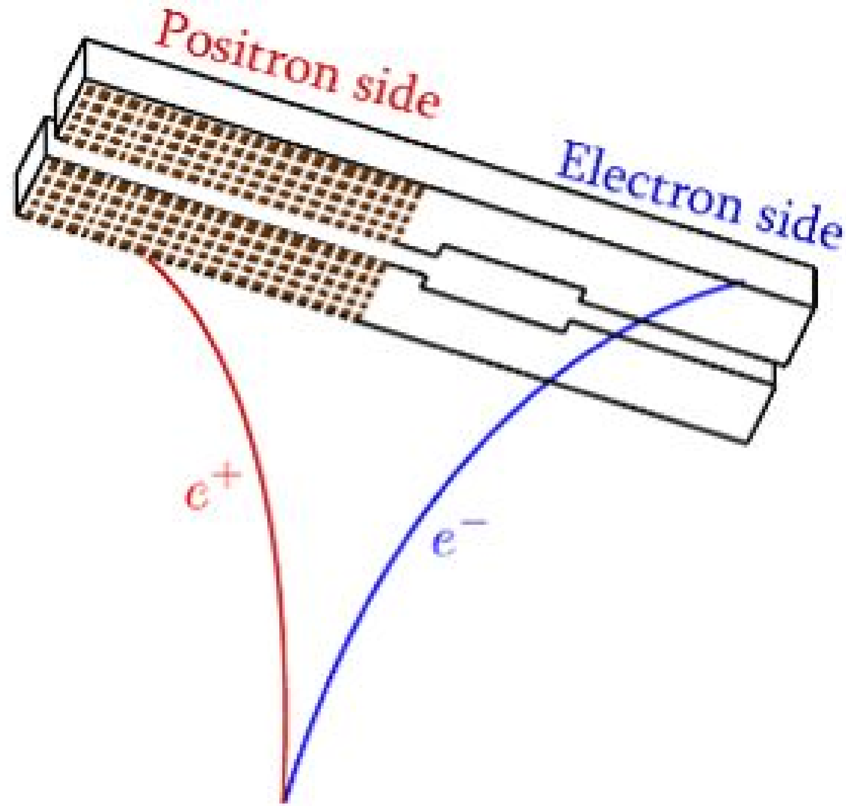
- **Add a tracking layer** (Layer 0) between target and current first layer
  - Dramatically improves vertex resolution, hence the vertex reach
- **Move L2-L3** slightly towards beam
  - Improves acceptance for longer-lived A's





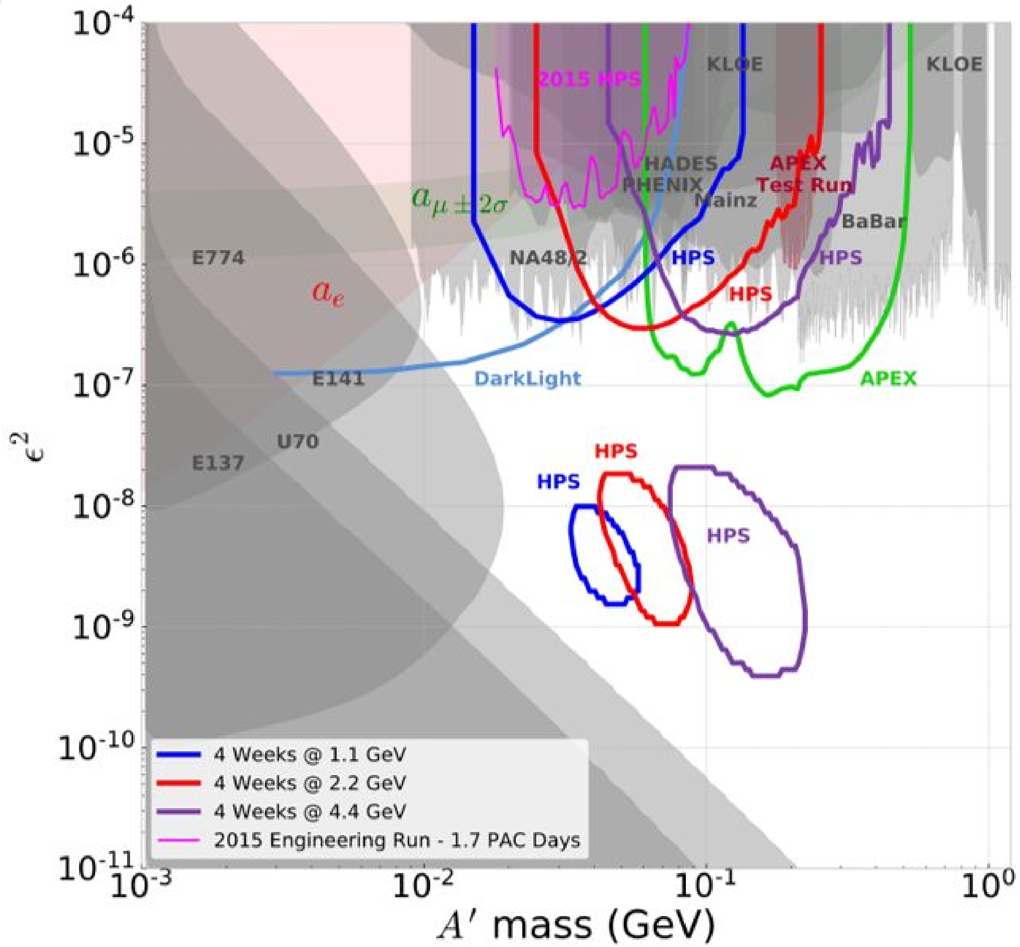
HPS Upgrades

- **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
- **Add positron hodoscope** inside vacuum chamber
  - Reduces acceptance losses in the "Ecal hole"
- Relatively simple. Currently awaiting formal approval



HPS Reach

- **Latest HPS reach estimates** including minor upgrades (L0 and positron trigger) for 4 weeks at 3 different beam energies
- Without upgrades, there is no vertexing reach at 4 weeks



Conclusion

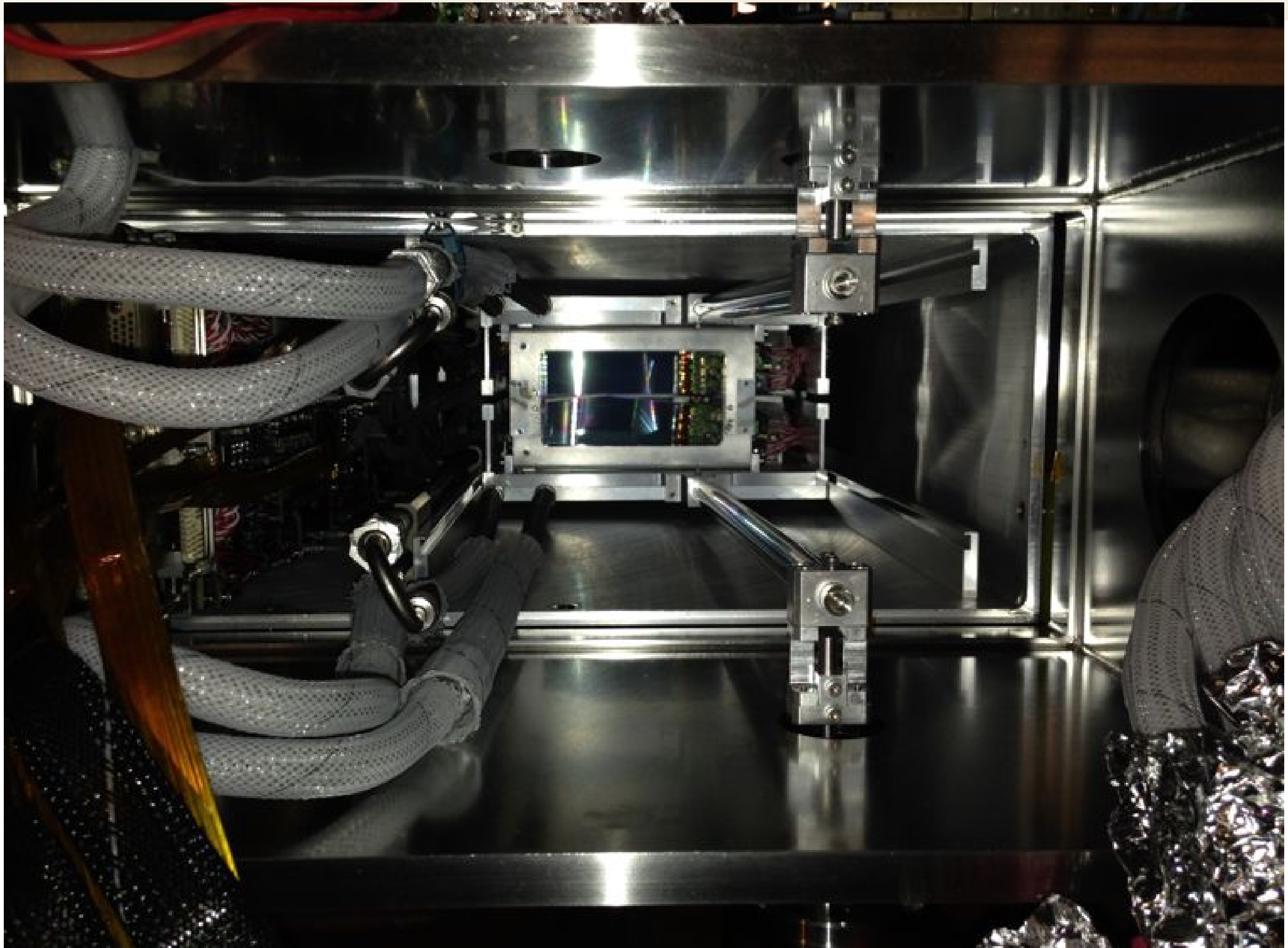
SLAC

- Heavy photons are still motivated as a proposed model for more “complex” dark matter and could be linked to light dark matter
- **HPS has successfully run** at two different beam energies (1.06 GeV in 2015 and 2.3 GeV in 2016)
- **First bump hunt results recently released!**
- Many more upcoming analyses to come out including vertexing, 2016 bump hunt, and possibly SIMPs
- HPS upgrades are small projects but provide dramatic improvements
- **HPS is getting ready for a lot of data taking in 2018 with potential upgrades!**

Questions?


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

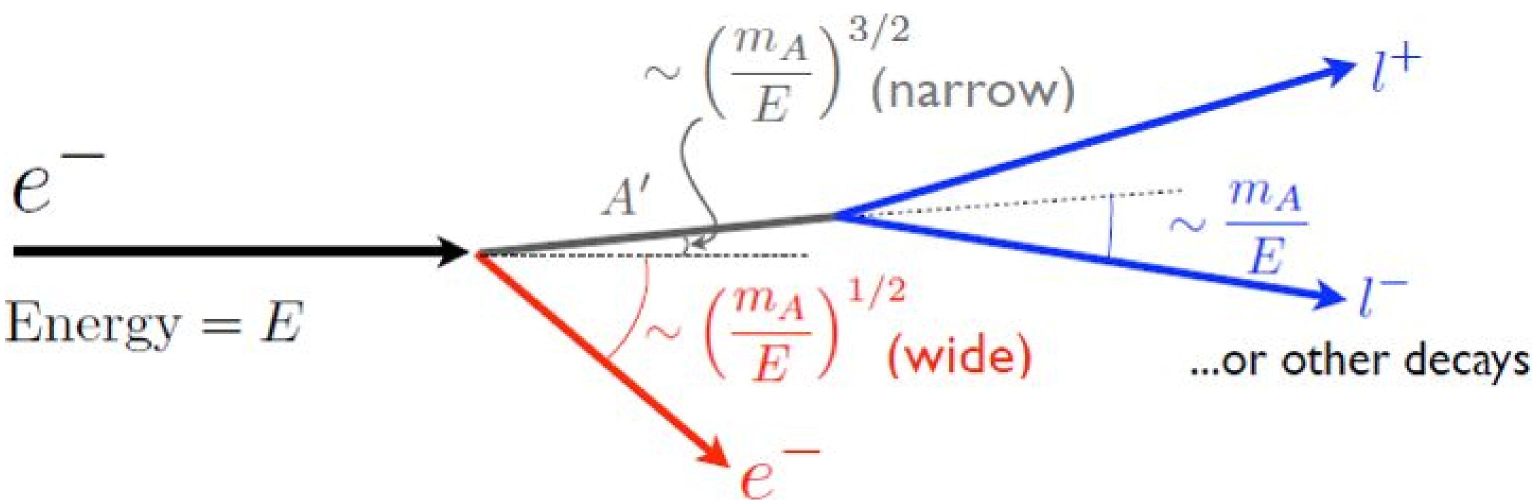
HPS SVT



HPS SVT

Heavy Photon Kinematics and Design Considerations

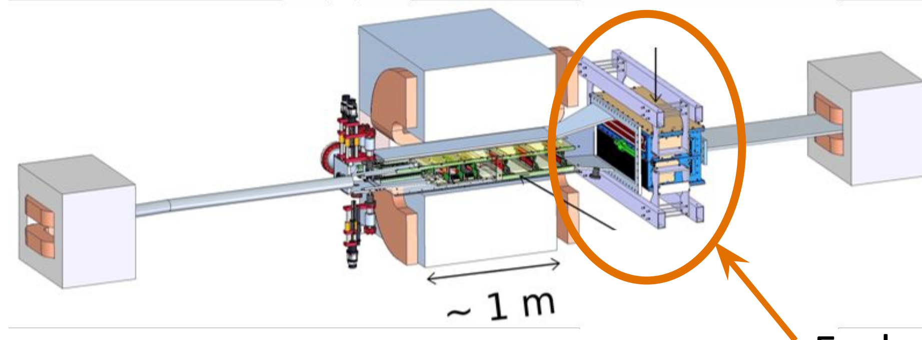
- A' decay products have very small opening angle (take most of beam energy)
- Detector **acceptance must be very forward** (very close to beam plane)
- **Bump Hunt**: need good mass resolution
- **Vertexing**: requires excellent vertex resolution, thin target, tracker under vacuum, and minimal tracker material
- Small couplings -> small cross-section (rates). Need high intensity beam



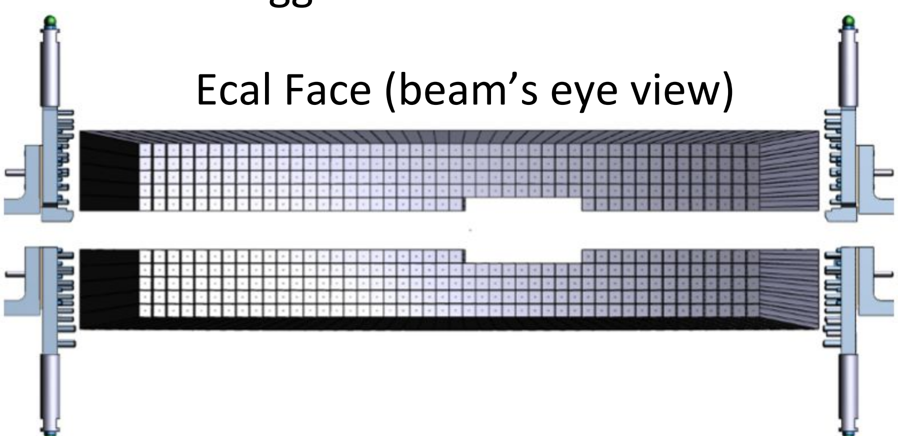
Electromagnetic Calorimeter

SLAC

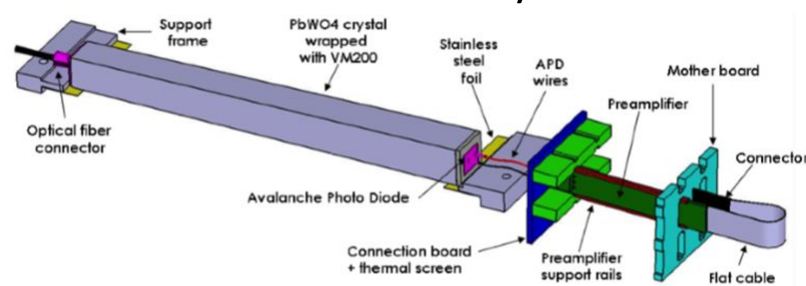
- Ecal made out of 442 lead tungstate ($PbWO_4$) and built by JLab/Orsay/INFN
- **Provides e+e- trigger with precision timing**
- >100 kHz max trigger rate with 8 ns trigger window



Ecal Face (beam's eye view)

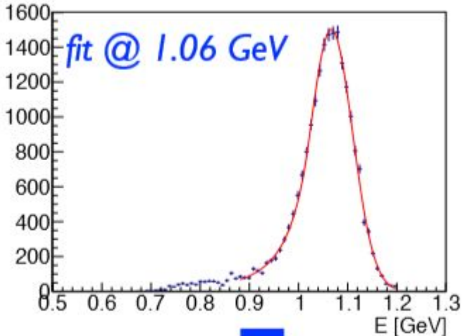


Ecal Crystal

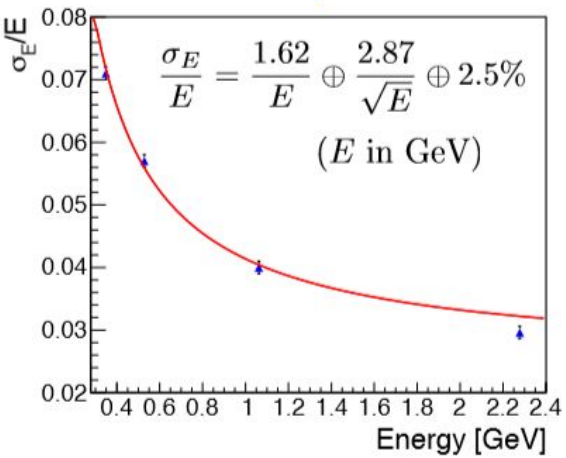


Ecal Performance

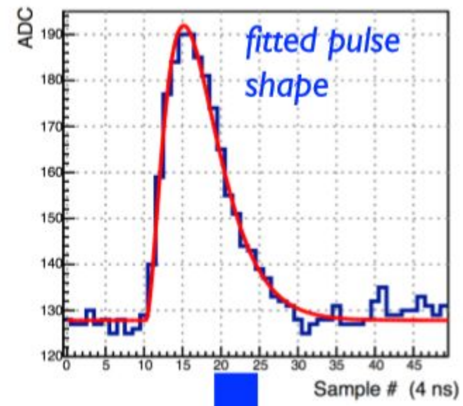
cluster energy resolution

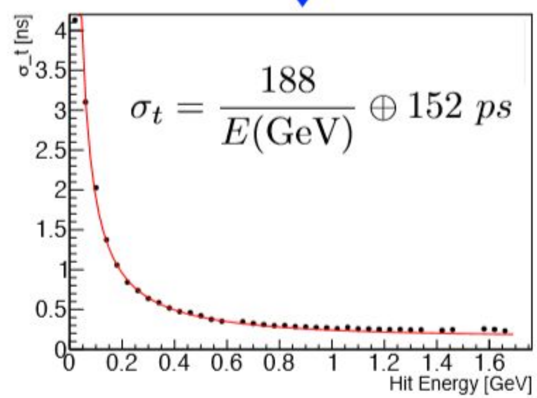


Slide courtesy of Tim Nelson

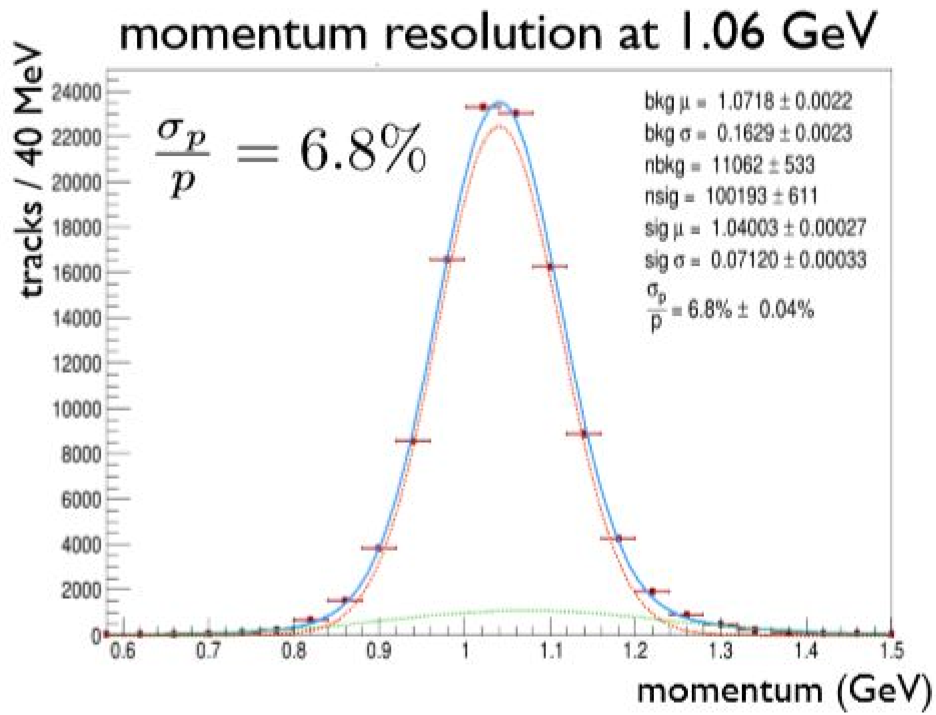


single-crystal time resolution





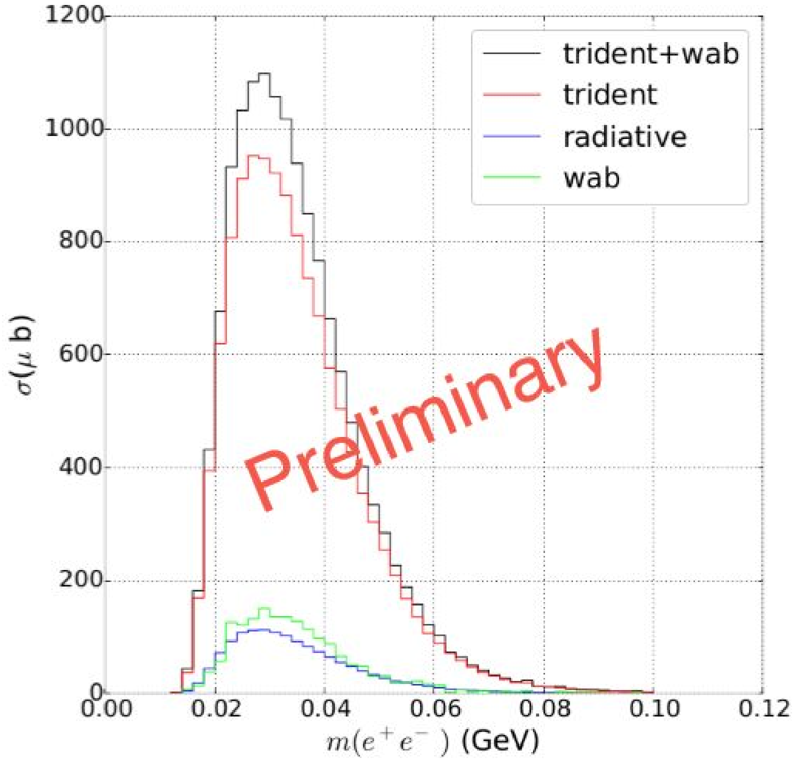
SVT Momentum Resolution

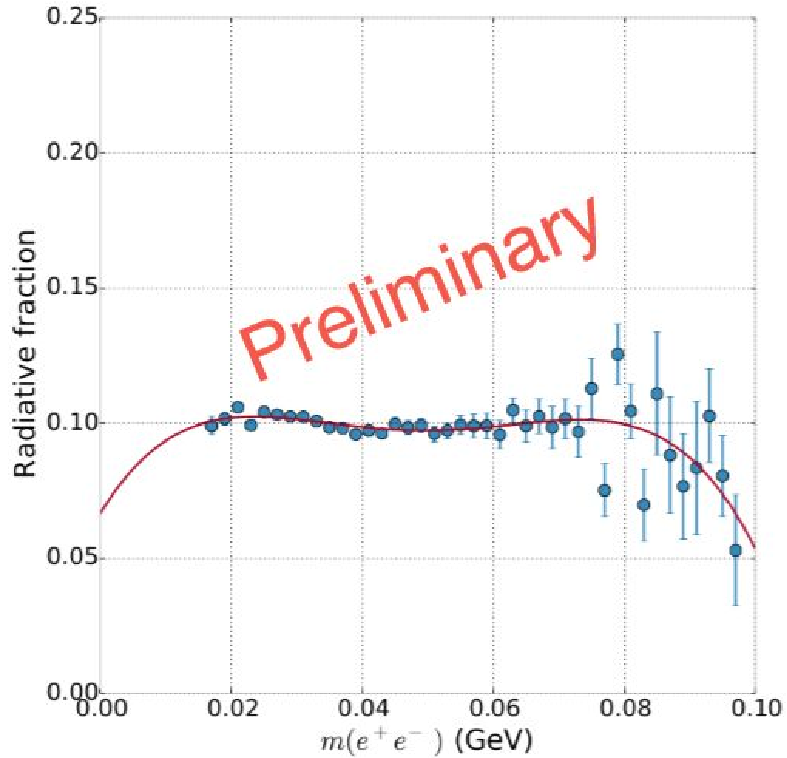


Radiative Fraction

~10% of total yield are radiative tridents

Slide courtesy of Tim Nelson



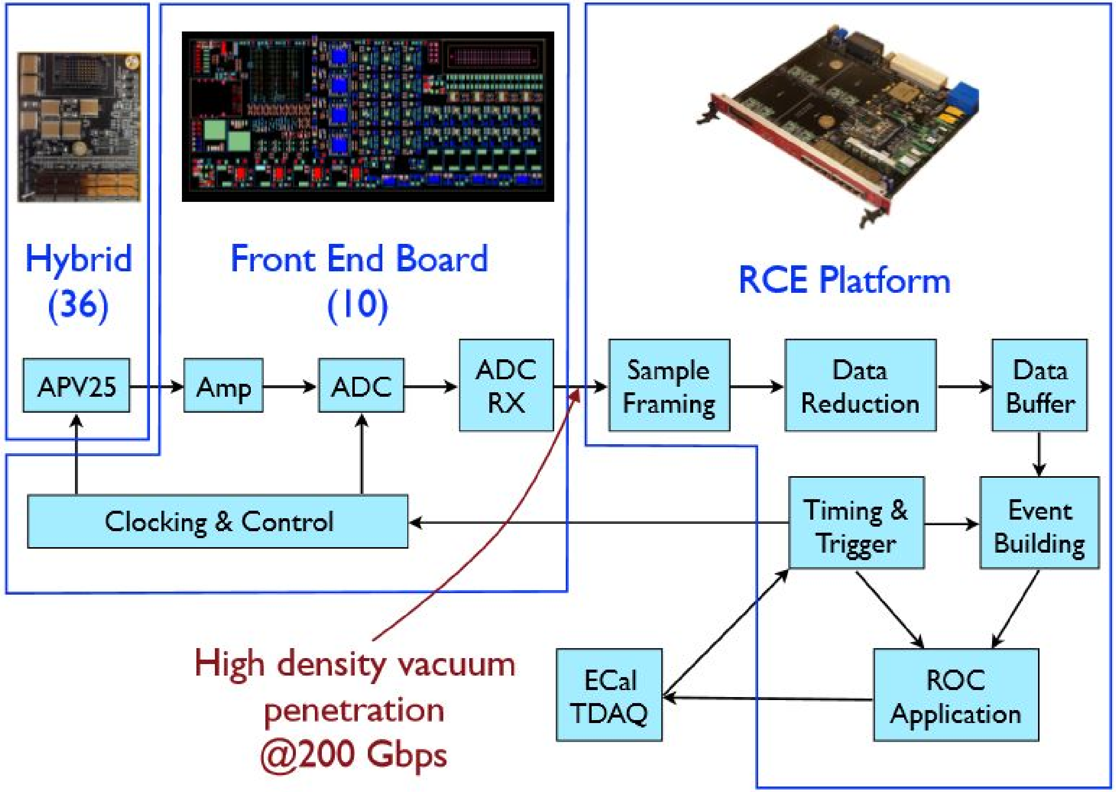


SVT DAQ

Based upon SLAC RCE platform (ATLAS upgrade, DUNE, LSST…)

Some unique challenges too…

- CMS APV25 multi-peak readout for 2 ns time resolution
- In-vacuum ADC, voltage generation and power distribution/control on very dense Front End Boards
- Vacuum penetration for digital signals via high-density PCB through flange w/ external optical conversion.
- Supports trigger rates up to 50 kHz, raw data rates in excess of 100 gbit/sec.

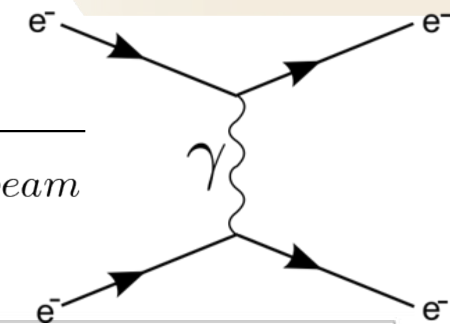


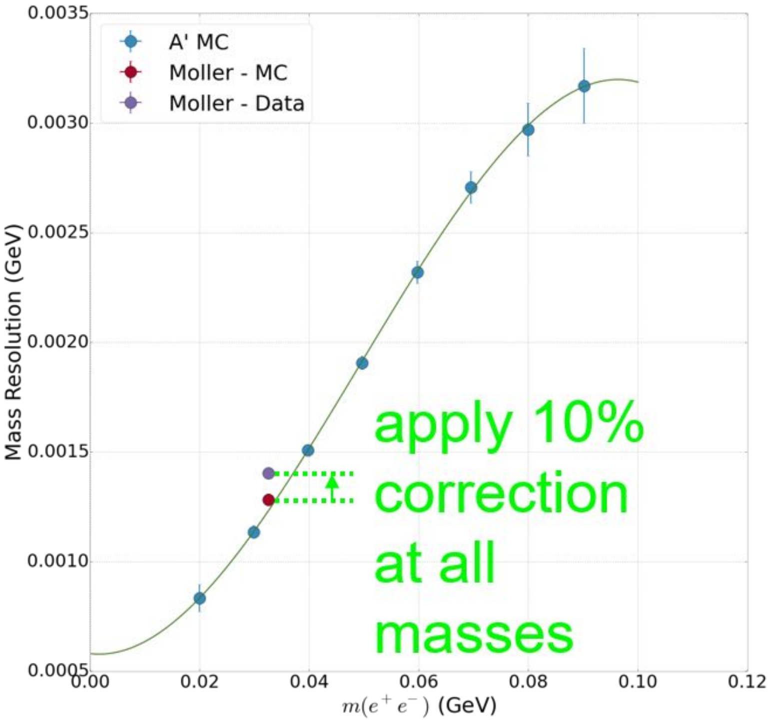
Slide courtesy of Tim Nelson

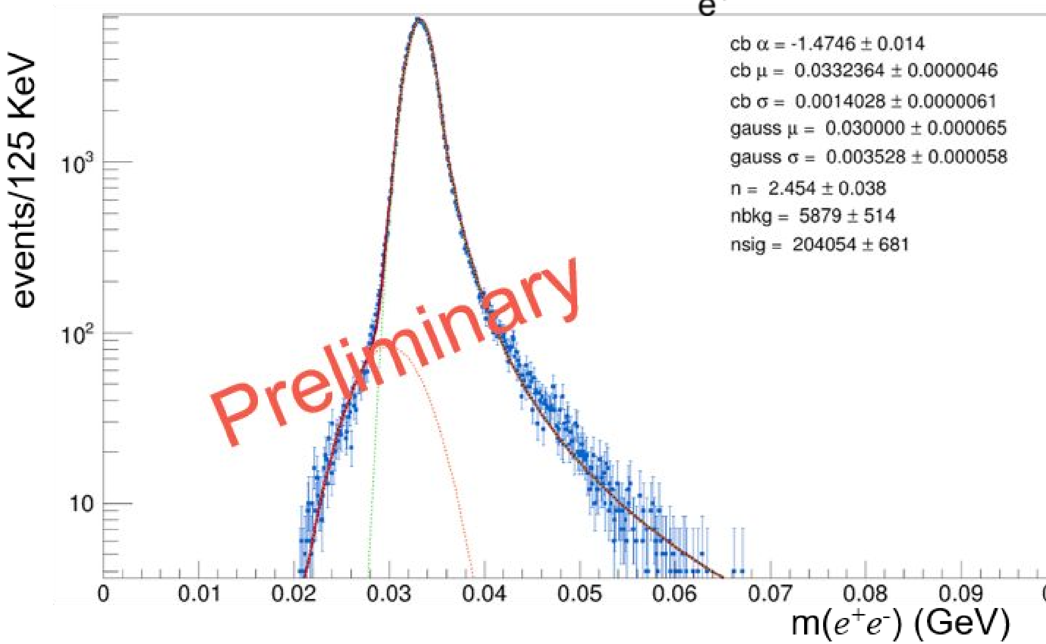
HPS Mass Resolution

- Mass resolution is linear (from A' MC), normalize to Moller pairs

$$E_{CM} = \sqrt{2m_e E_{beam}}$$







Vertex Search

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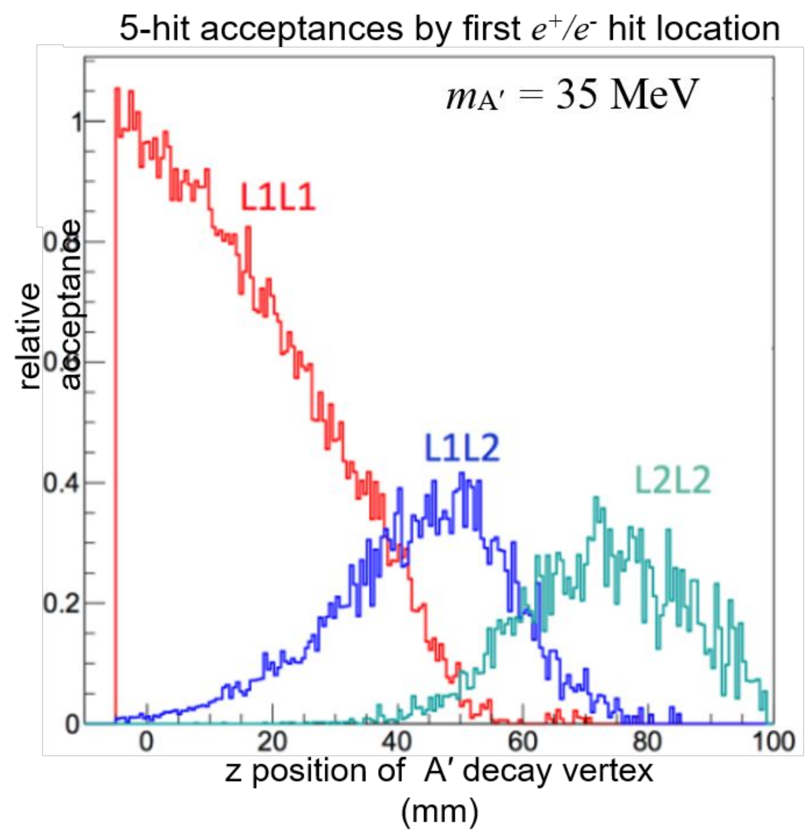


Thermally Produced Dark Matter

SLAC

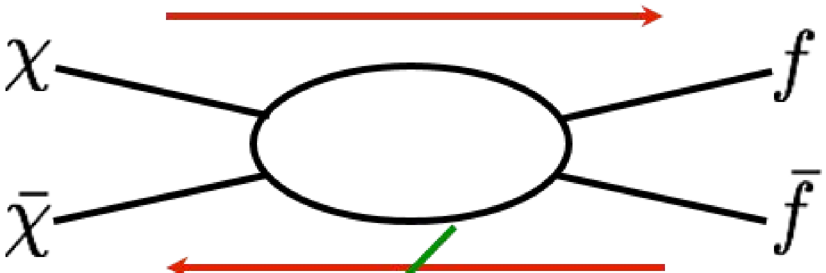
- Very general/simple mechanism for DM production in the early universe

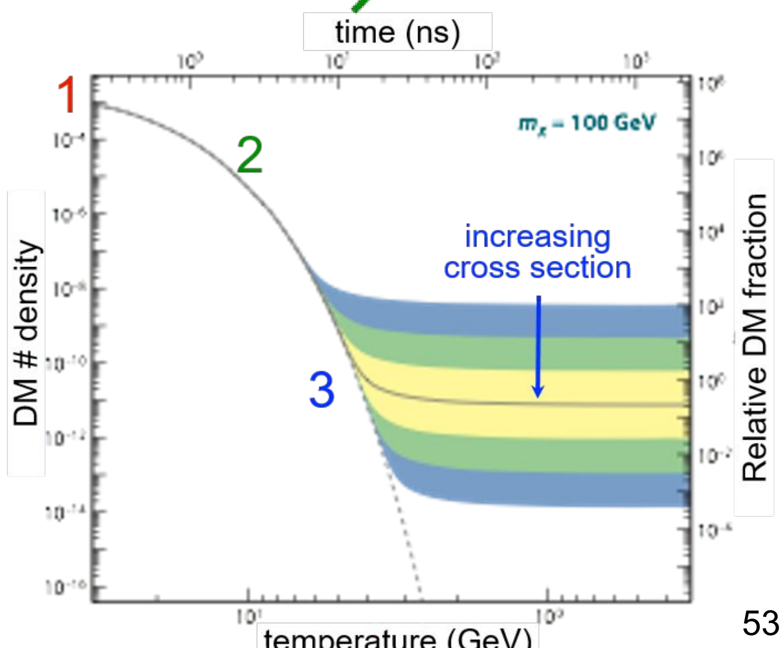
1. Assume DM is in thermal equilibrium with SM particles
2. Universe cools so SM cannot produce DM pairs
3. Universe expands so DM stops annihilating "freeze out"

$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle}$$

"WIMP Miracle"

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Rightarrow m_\chi \approx 100 \text{ GeV}$$

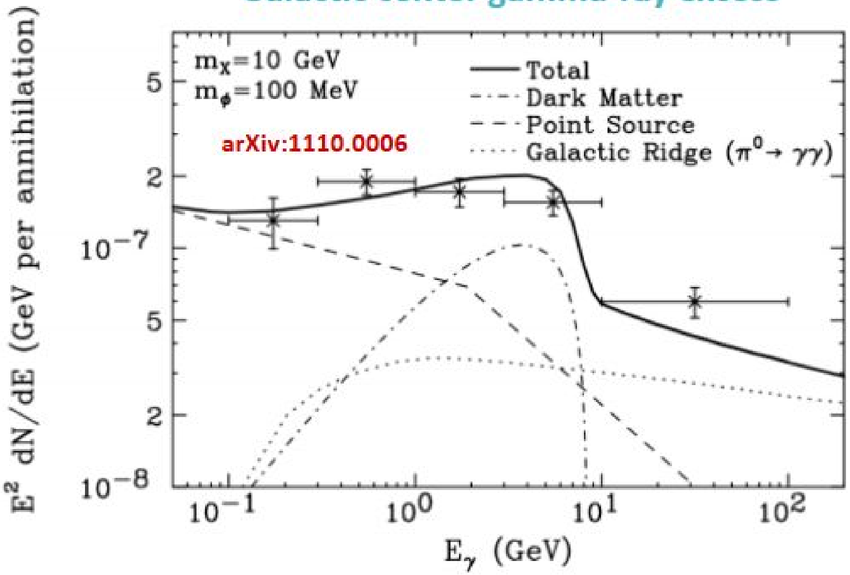




Other anomalies with DM/heavy photon interpretation

SLAC

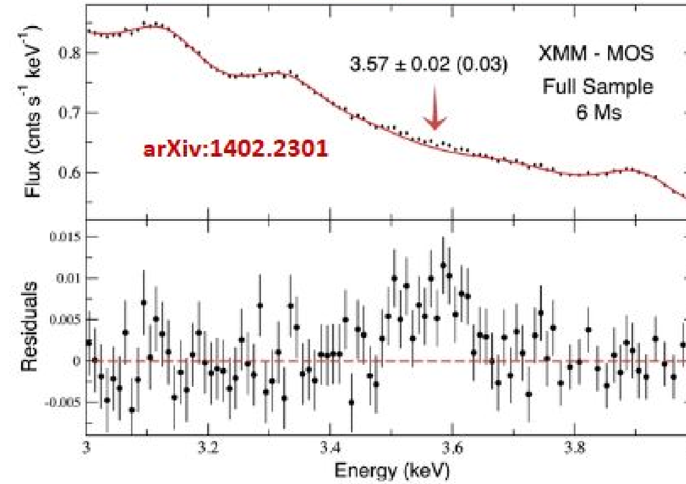
Galactic center gamma-ray excess



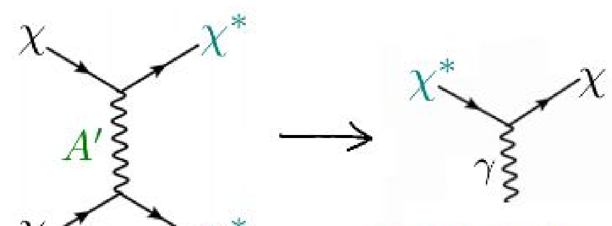
~10 GeV DM annihilating to 100 MeV A'?

arXiv:1206.2929

3.5 keV γ-ray line



eXciting Dark Matter?



arXiv:1402.6671

Slide courtesy of Omar Moreno