Jefferson Lab
Thomas Jefferson National Accelerator Facility

University of New Hampshire

HEAVY PHOTON SEARCH

The Heavy Photon Search experiment at Jefferson Lab

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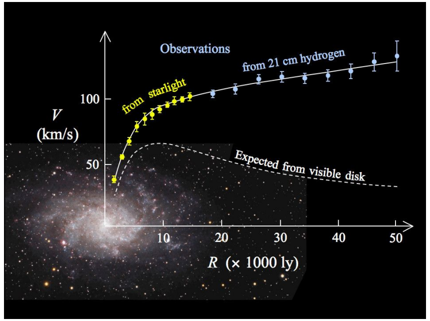
Evidence for dark matter

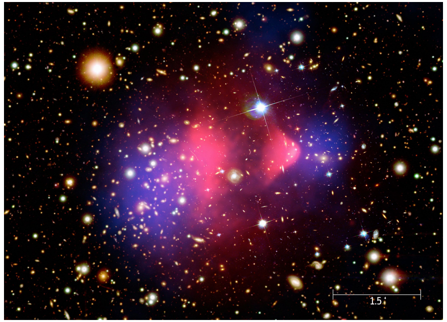
About 18 K published papers (according to inspire-hep) with a title containing a word "dark matter", however it's nature still remains elusive.



We don't know basic properties of DM:

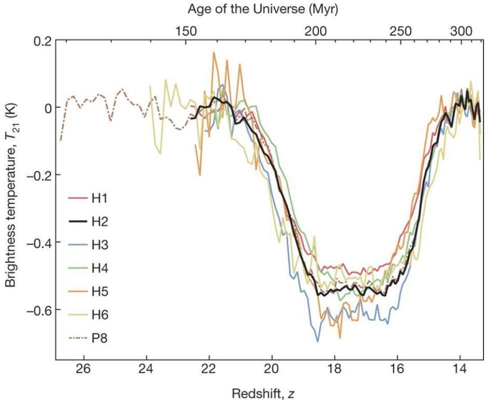
- it's mass, spin
- Does it interact with SM particles. if yes how?
- Is it stable, if not the lifetime
- Is there single flavor of DM particle, or there are multiple favors
- And so on...

All the evidence is based on cosmological observations.



There is vast variety of DM models, which are based on several portals.

The HPS experiment searches for a so called Heavy Photon (aka dark photon, U boson), which is one of well motivated portals for DM and SM interactions.

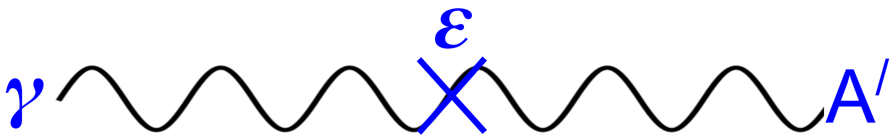


The dark photon A’

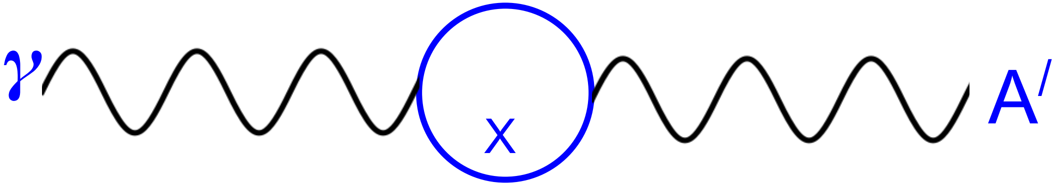
What if Nature contains an additional broken U(1) (Abelian) force mediated by a massive vector boson, A$^{/}$? Bob Holdom, Phys.Lett.,B166, 2, (1986)

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

Kinetic mixing



Induces week coupling to electric charge

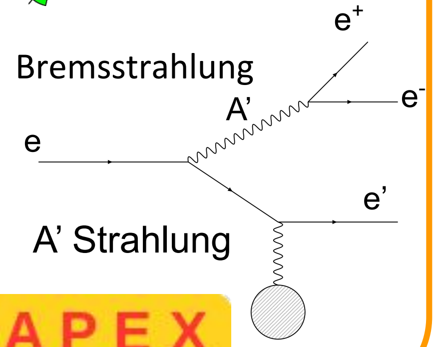


Generated by heavy particles X interacting with γ and A$^{/}$

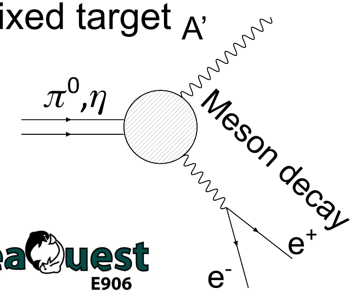
Where can A's be produced

Where there are photons, there can be dark photons!

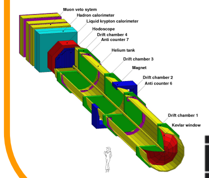
Electron on fixed target

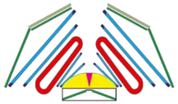


Protons/kaons on fixed target

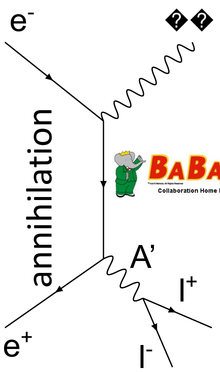


SeaQuest E906

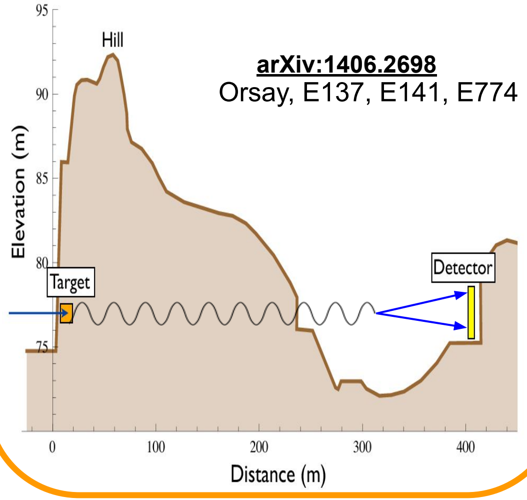




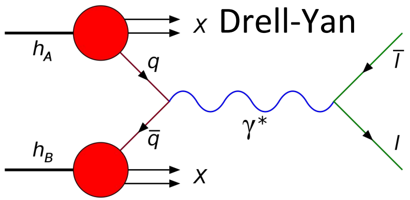
e^-e^+ colliders

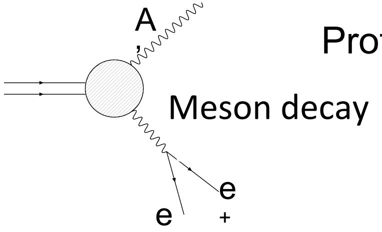


Beam dump experiments



Proton-Proton collisions

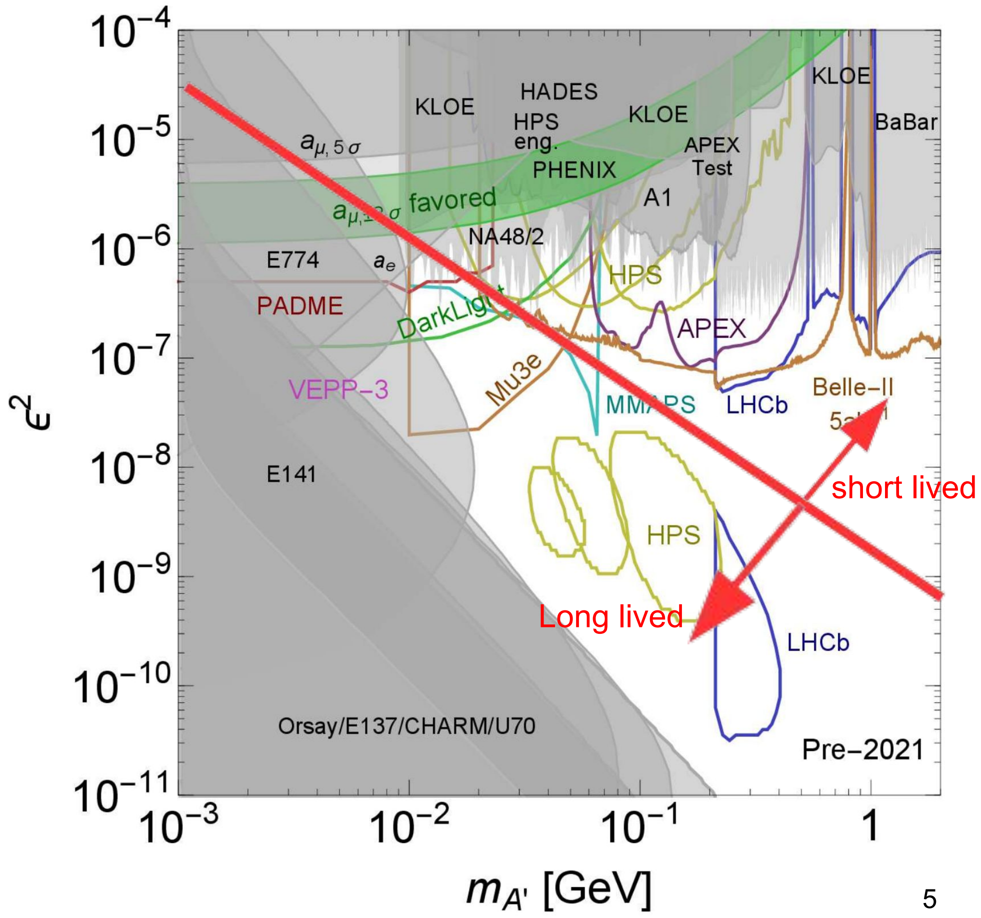




Constrains

$$l_0 \equiv \gamma c \tau \propto \frac{1}{\epsilon^2 m_{A'^2}}$$

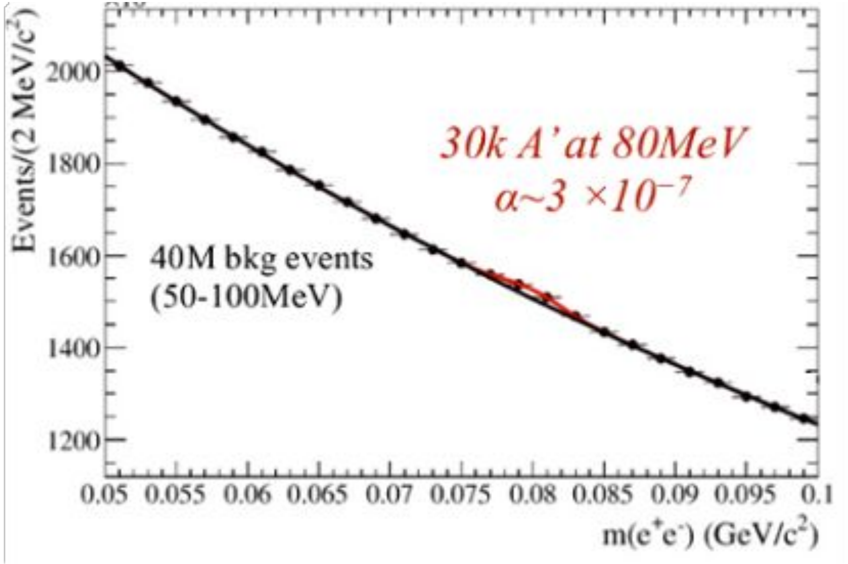
Different strategies are used for different mass and ε regions.

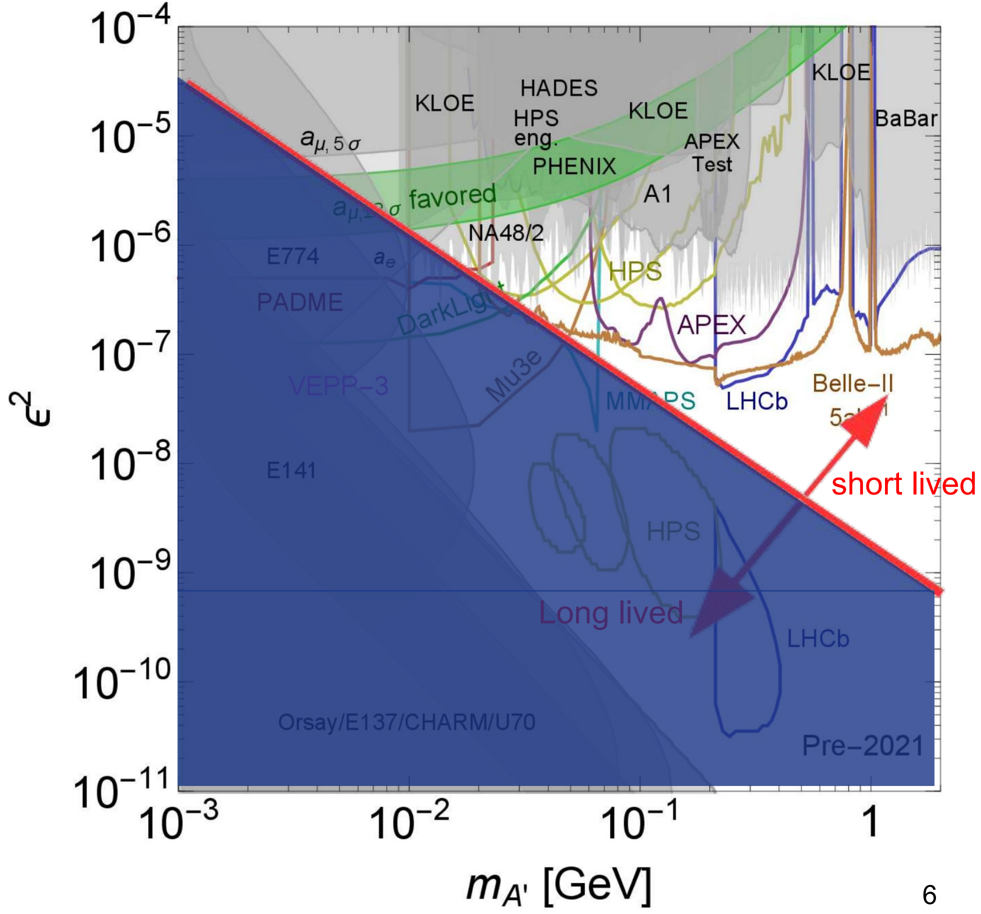


Constrains

$$l_0 \equiv \gamma c \tau \propto \frac{1}{\epsilon^2 m_{A'^2}}$$

Resonance search: a bump over a large background is expected for short lived particles.

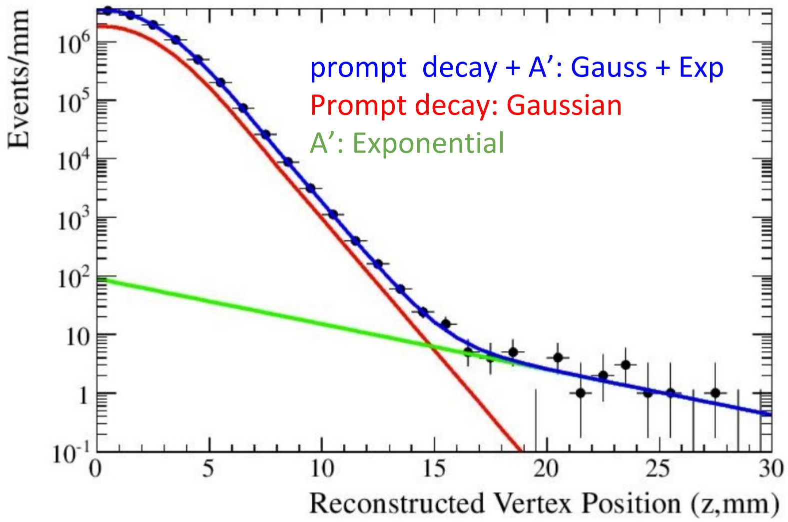


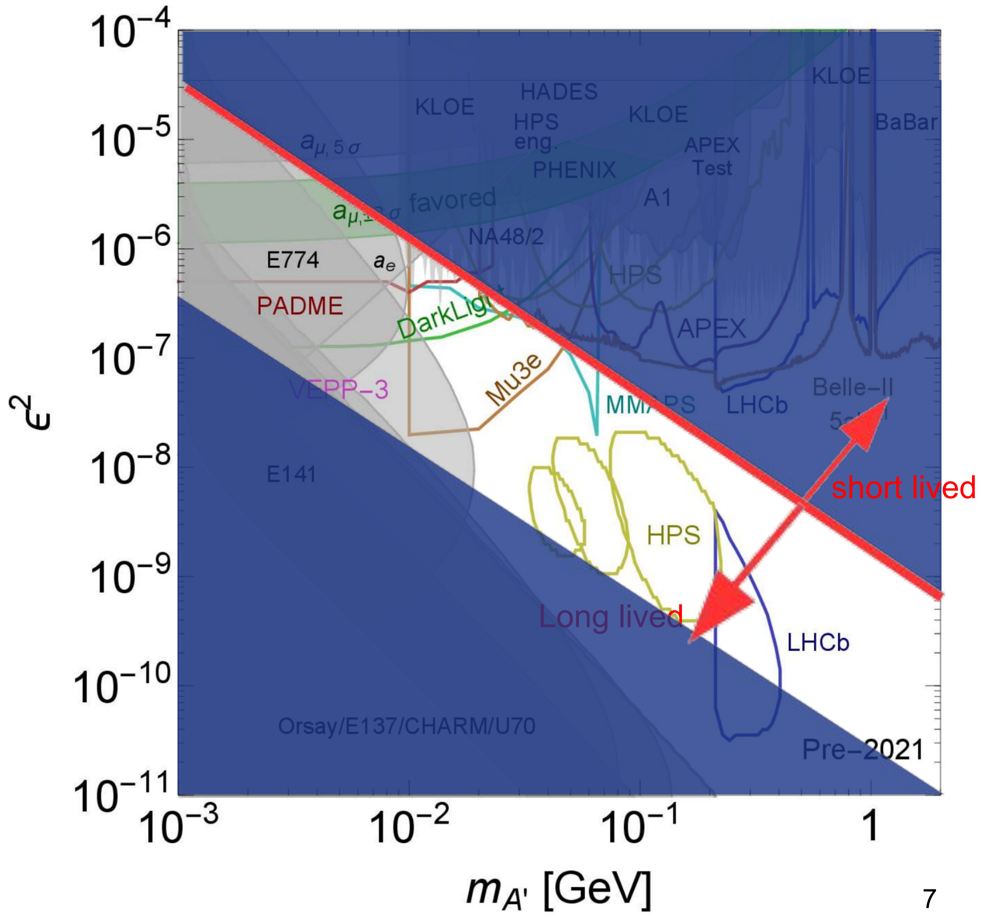


Constrains

$$l_0 \equiv \gamma c \tau \propto \frac{1}{\epsilon^2 m_{A'^2}}$$

Search for displaced vertex is used for long lived particles

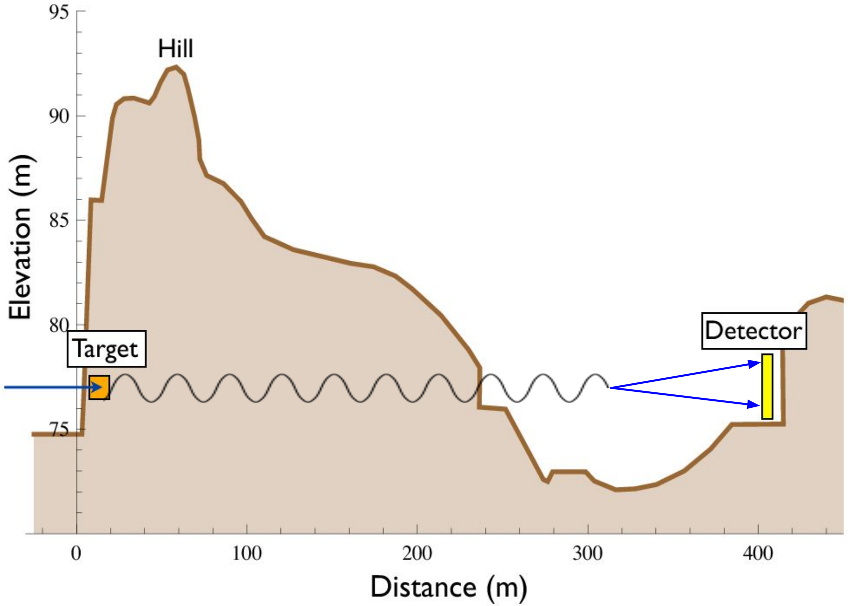


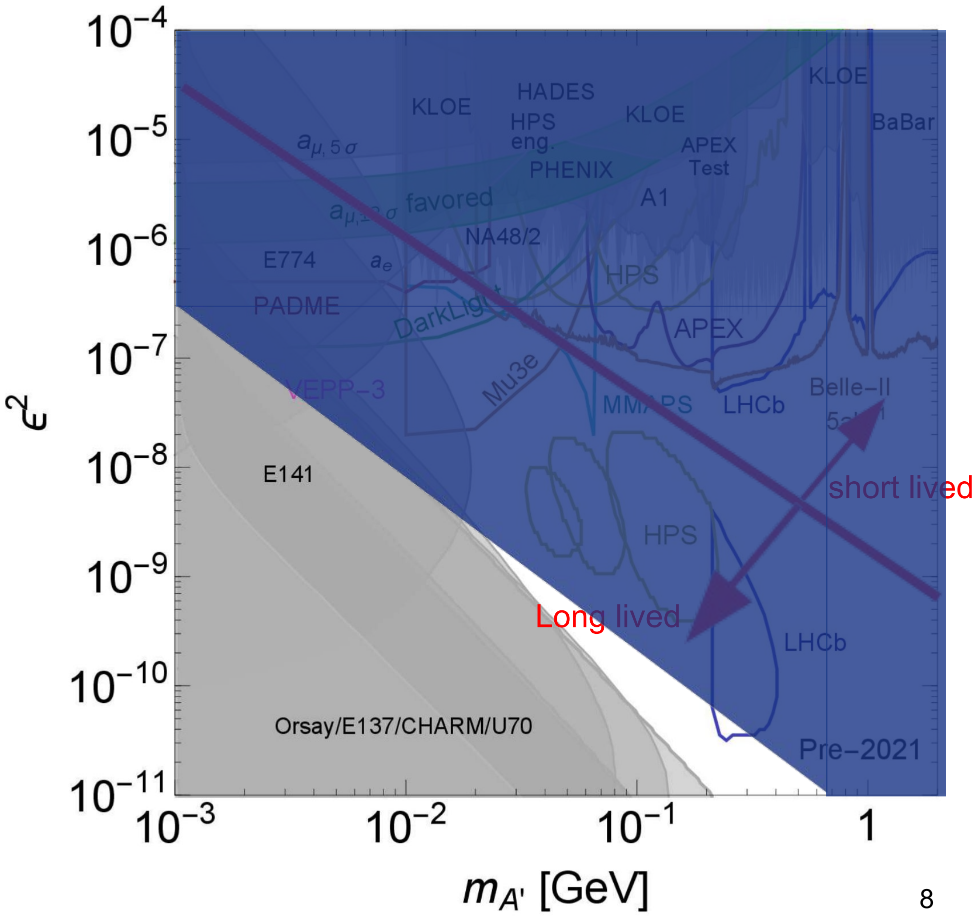


Constrains

$$l_0 \equiv \gamma c \tau \propto \frac{1}{\epsilon^2 m_{A'^2}}$$

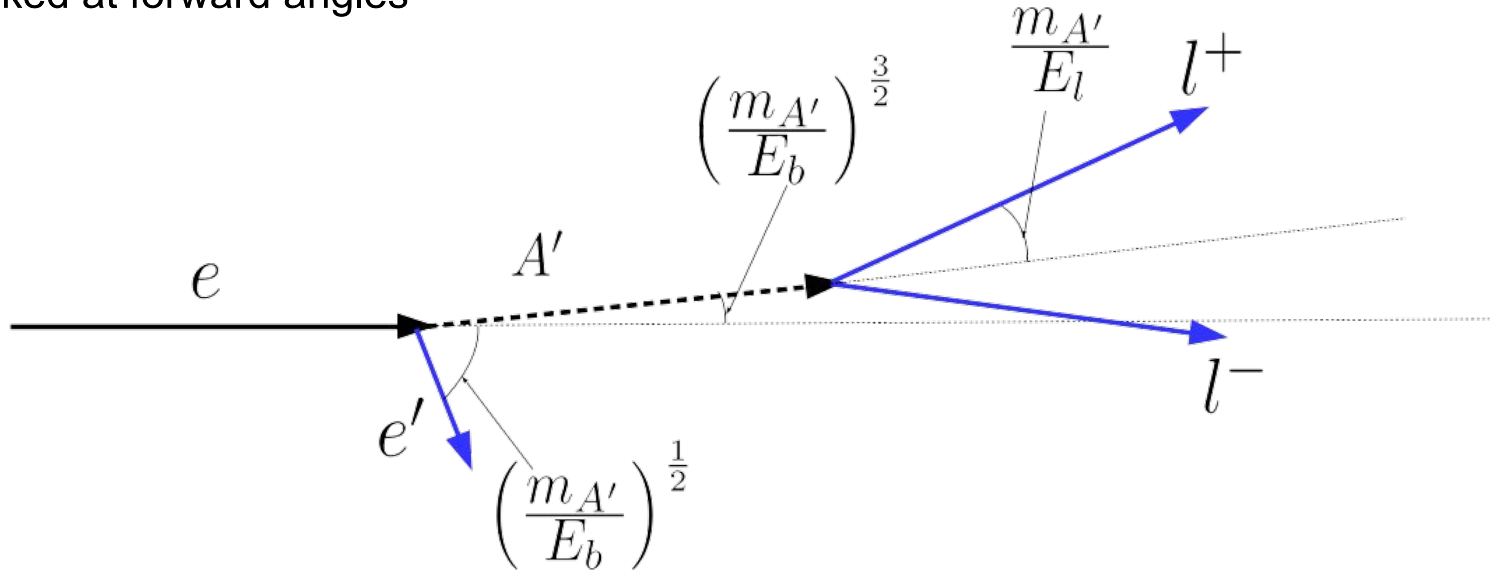
Beam dump experiments search for very long lived particles.





Electro-produced heavy photon kinematics on fixed targets

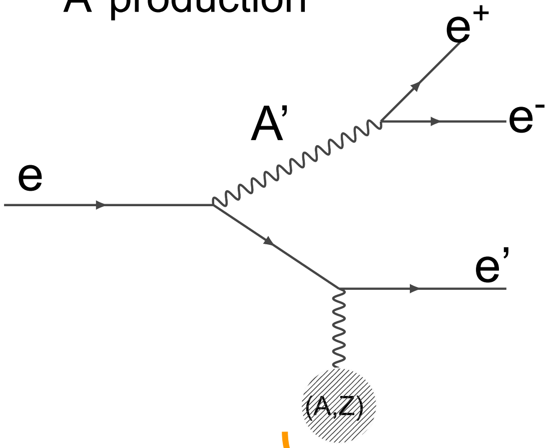
- Unlike Bremsstrahlung, A' takes almost all the beam energy
- Peaked at forward angles



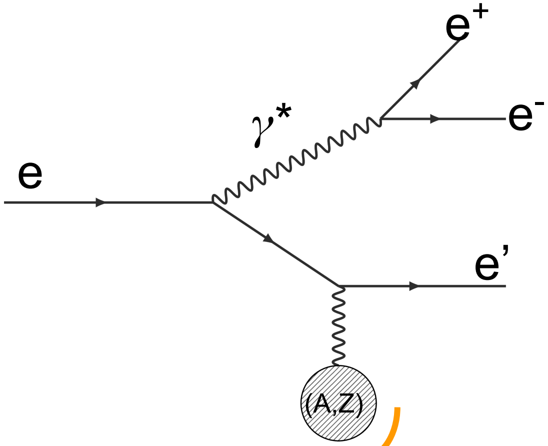
- Fixed target experiments are therefore designed to be sensitive to small angles
- Maximize acceptance for high E_{sum}

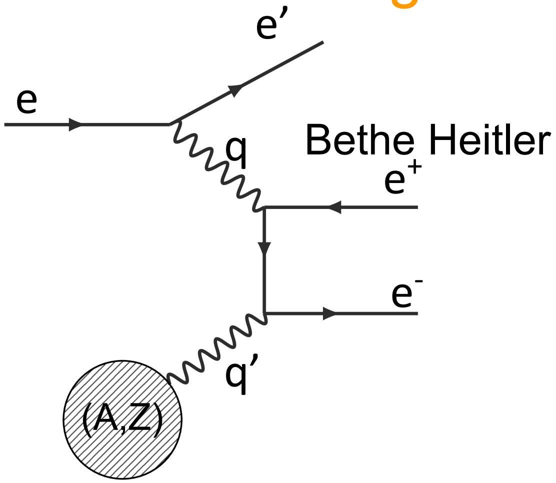
Background processes in A’ production w/ e- beam off fixed target

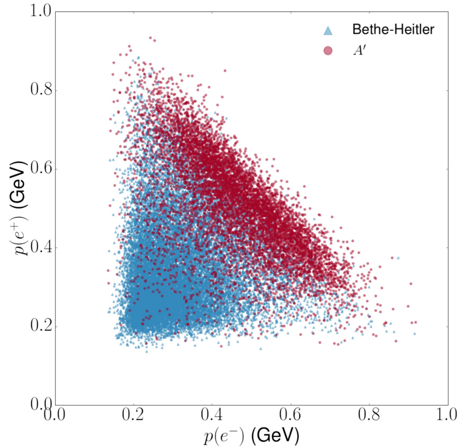
A’ production



Production of a time like photon (radiative tridents)





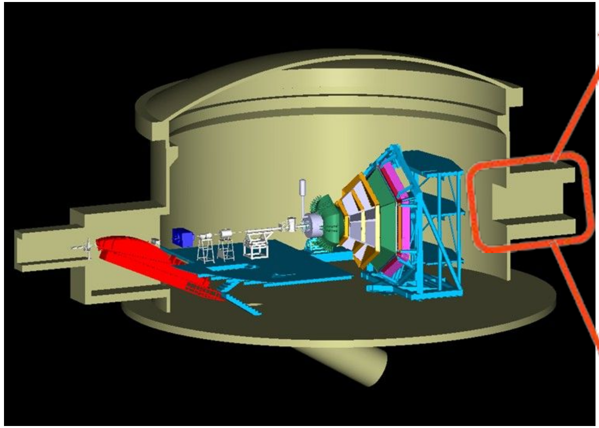


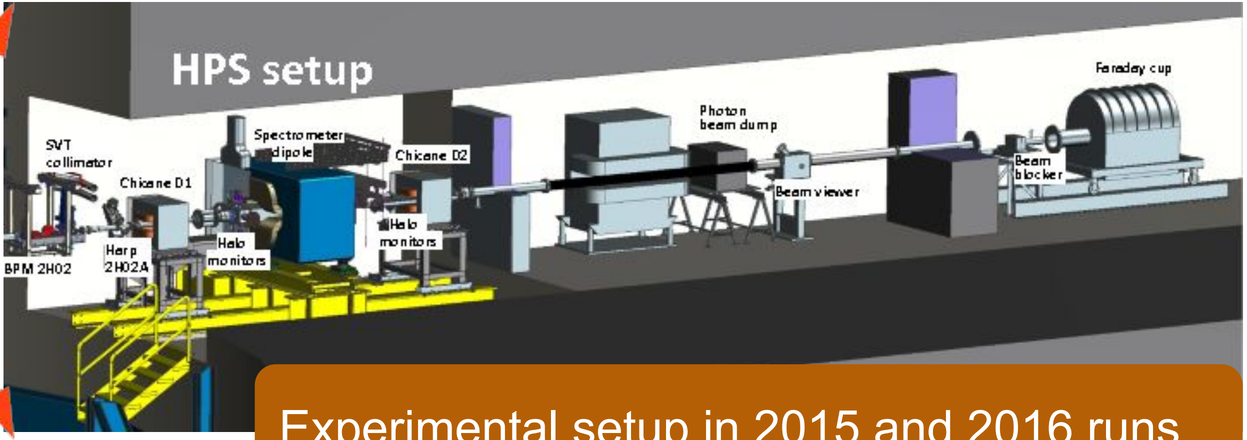
Same kinematics for fixed M(e⁻e⁺)

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

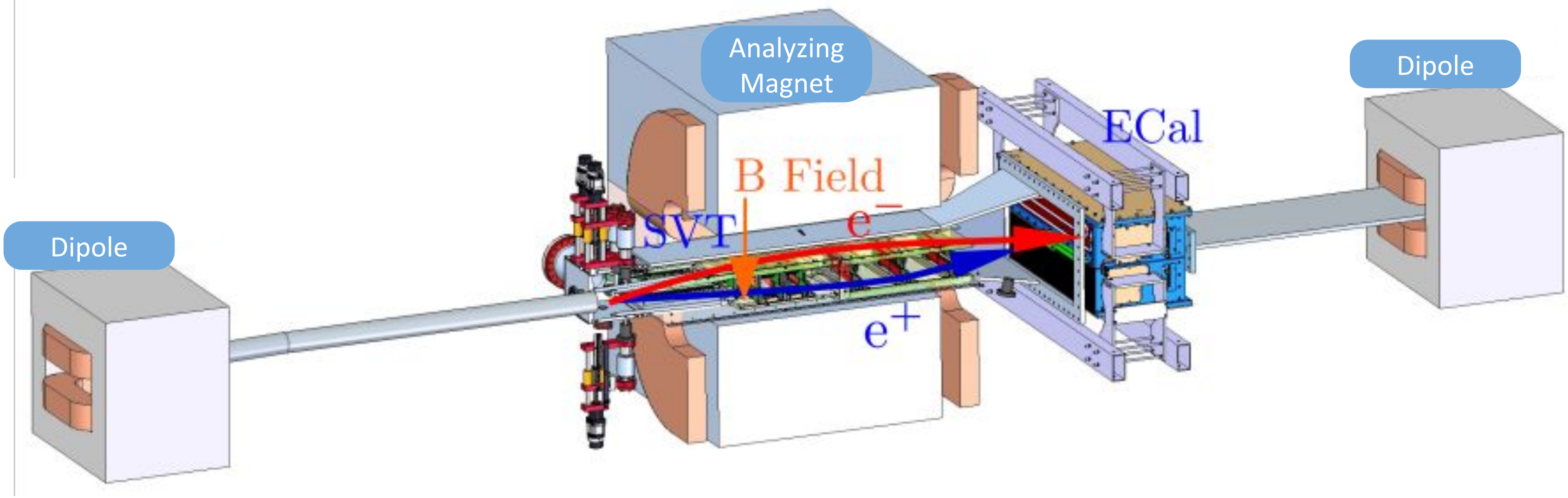
Known QED process => ε can be calculated by above ratio

It is critical to have a good mass resolution

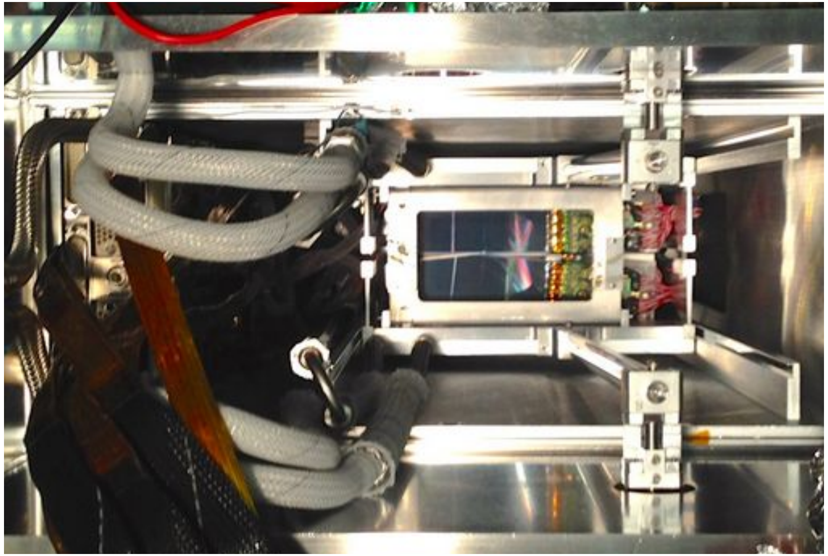




Experimental setup in 2015 and 2016 runs



Main beam requirements

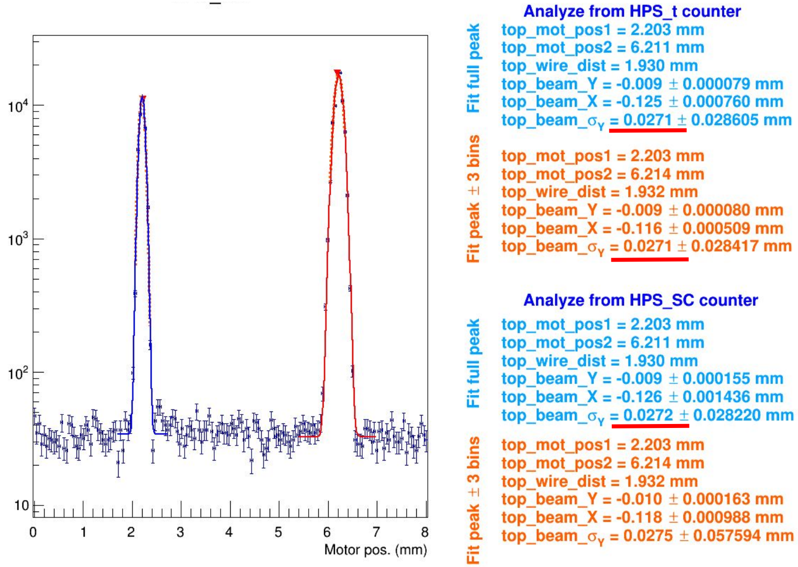


Only <u>500 μ</u> between the beam and the edge of the silicon

The beam stability (within 100μ) is very important!

Needed A Narrow beam ($\sigma_Y < 50\,\mu$) for a good mass resolution

Halo < 10^{-3}

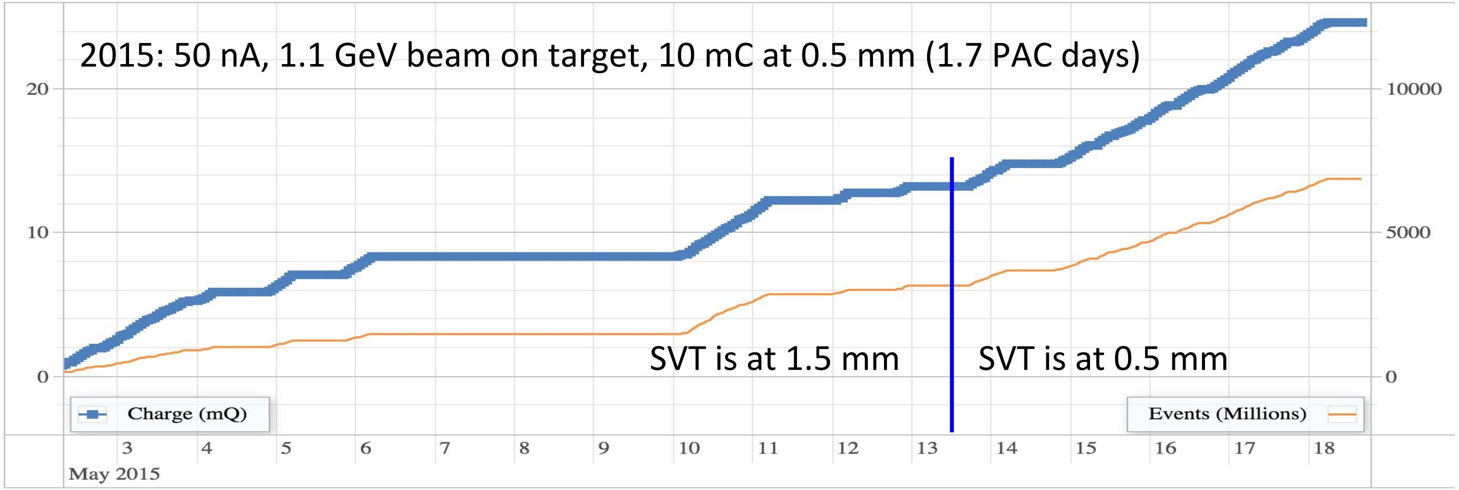


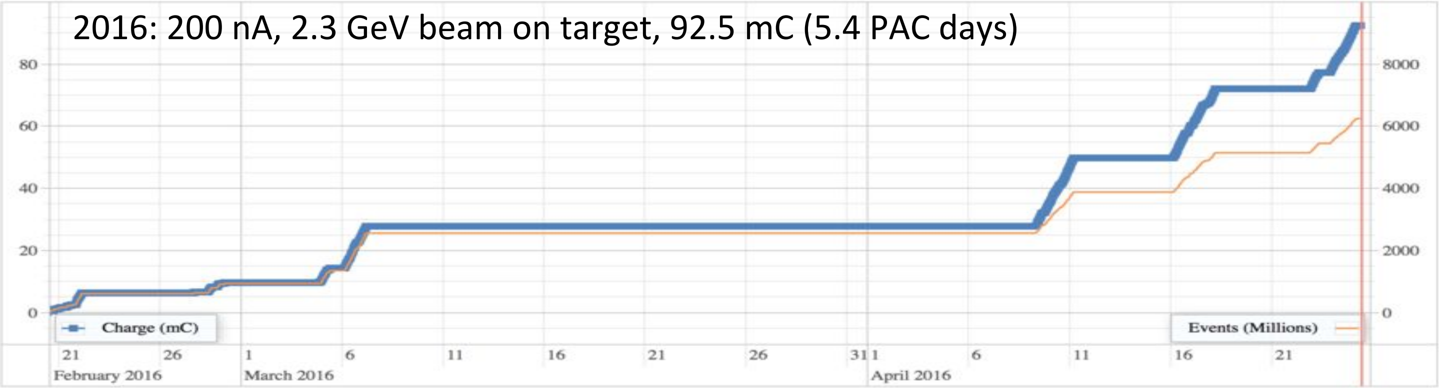
Thanks to CEBAF crew, Most of the time $\sigma_Y < 30\,\mu$

Achieved beam stability better than 50 μ

JLab **F**ast **S**hut **D**own (FSD) system will catch any significant beam excursions within <u>5 ms</u>.

Opportunistic engineering runs

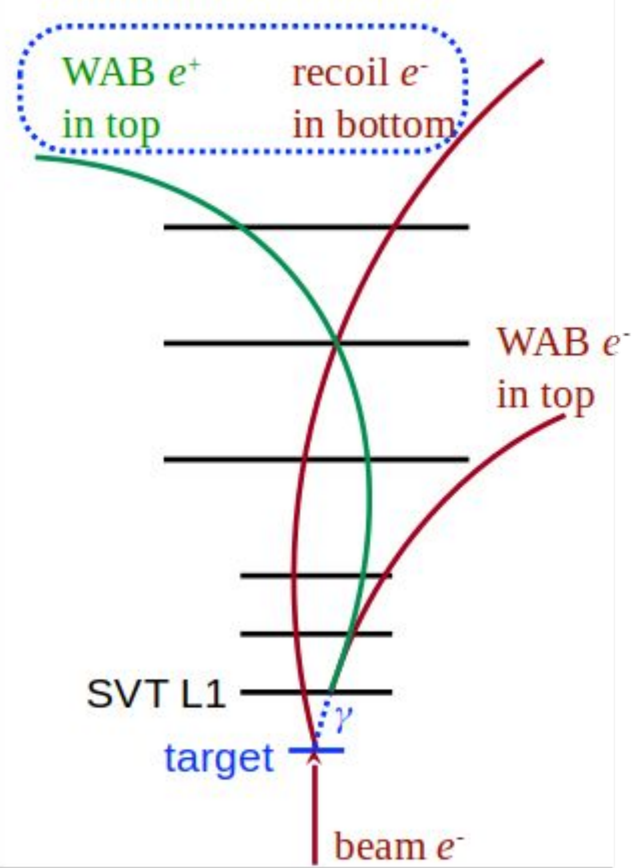




Wide Angle Bremsstrahlung and pair conversion

Obtained using MC

A good understanding of background is critical in this analysis! Reminder: $\boldsymbol{\varepsilon}^2 \sim \boldsymbol{\sigma}_{A'}/\boldsymbol{\sigma}_{RAD}$, and $\boldsymbol{\sigma}_{RAD} \sim f_{RAD}\boldsymbol{\sigma}_{Tot}$.

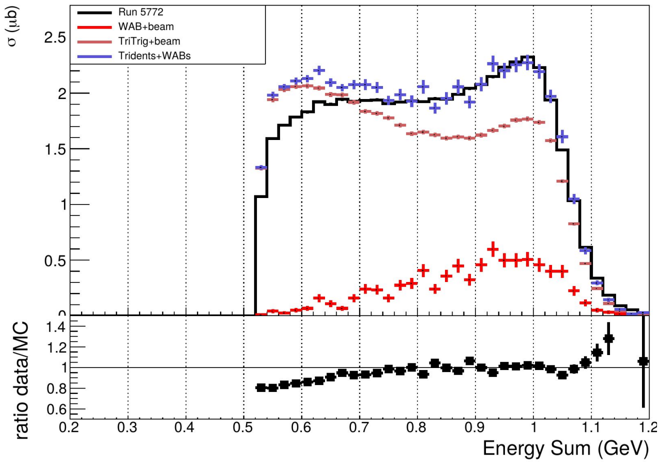


Radiative tridents and BH were taken into account and included in simulations, but data would not agree with the MC

During the analysis we realized that in the final state there is a significant contribution from the two step process: WAB → conversion in SVT layers

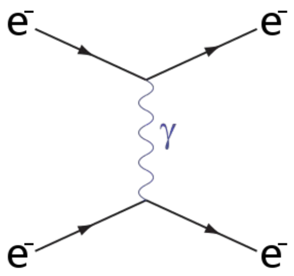
WABs aren't in any of the standard generators or MC systems (GEANT4, EGS).

Cuts: requiring a hit in L1 and DOCA cut removes 80% of these events, without significant loss of tridents



Mass resolution

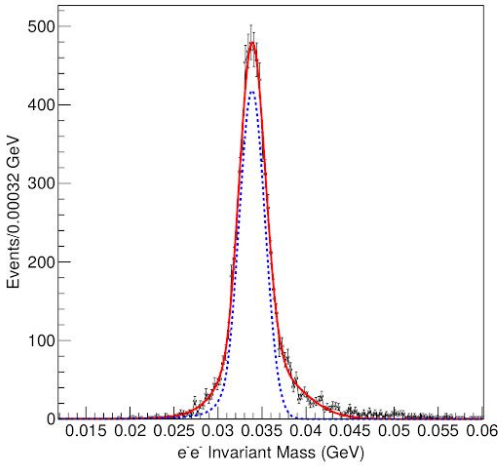
Good understanding of the mass resolution is a critical component in the "Bump Hunt" analysis

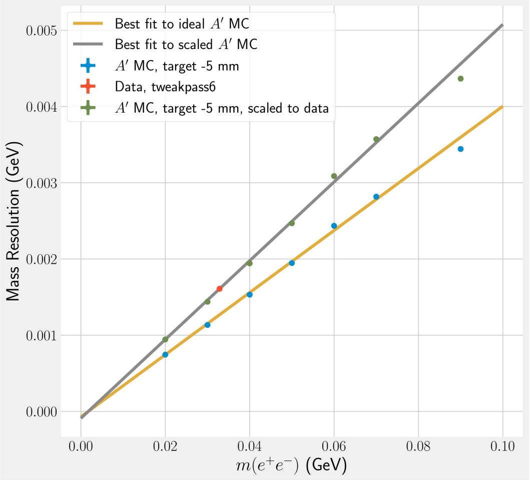


We know the mass resolution of the data at a single point, Moeller pair c.m. energy.

We have to rely on the Monte Carlo mass resolution for all other masses

$$M(ee) \equiv \sqrt{2 \cdot E_b \cdot m_e} = 32.7\ MeV$$



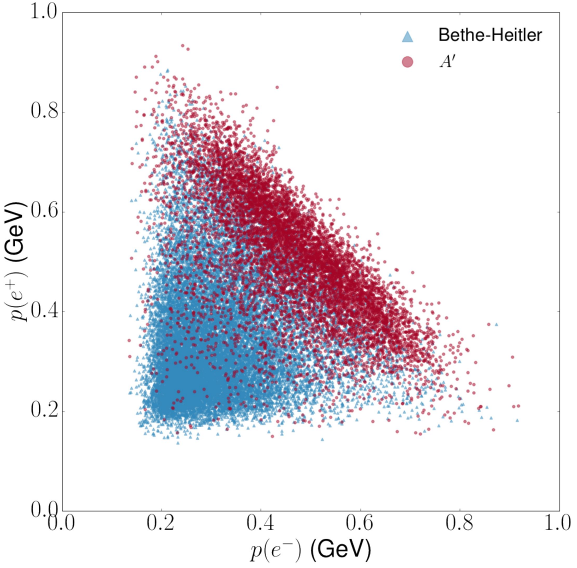


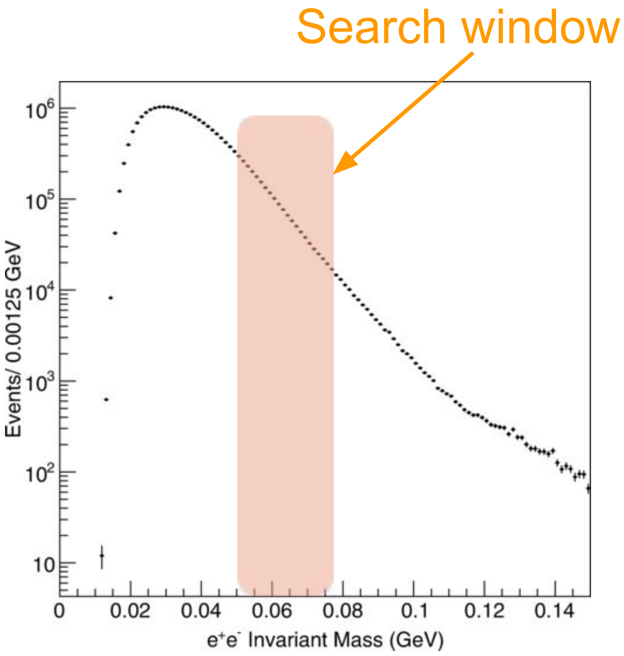
- The mass resolution difference between the Data and MC is due to momentum resolution difference between the data and MC.

- Linear fit of MC A' masses

- Scale MC to match the data Moeller resolution

Resonance search with 2015 data

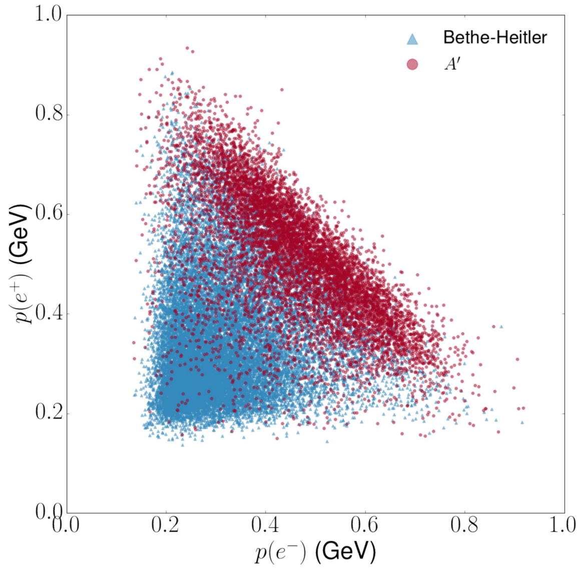


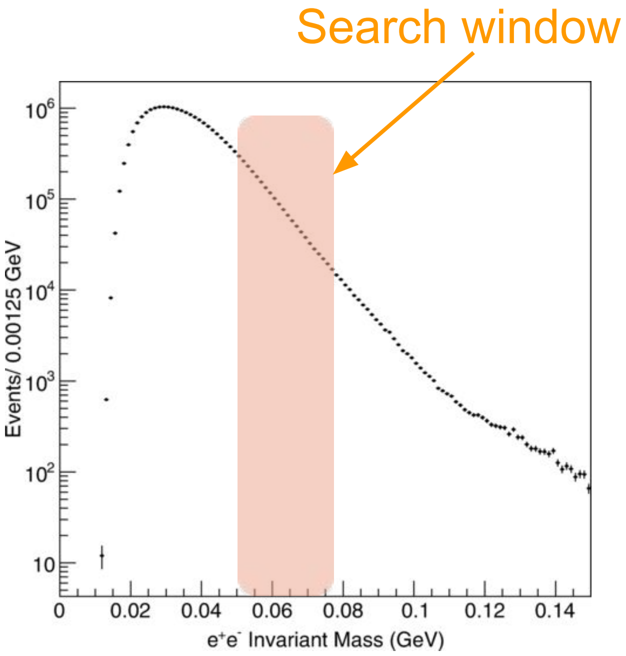


- -Range 19 MeV – 81 MeV
- -Scan w/ 0.5 MeV step
- -Search for the peak in the given mass range
- - Maximize Poisson Likelihood with Bgr only, and Bgr+signal hypothesis
- - Use log likelihood ratio to quantify any excess/bump

Use MC to correct significance for "look elsewhere" effect.
4000 pseudo data is generated, to provide mapping between the local p-value and the global p-value

Resonance search with 2015 data





-Range 19 MeV – 81 MeV

-Scan w/ 0.5 MeV step

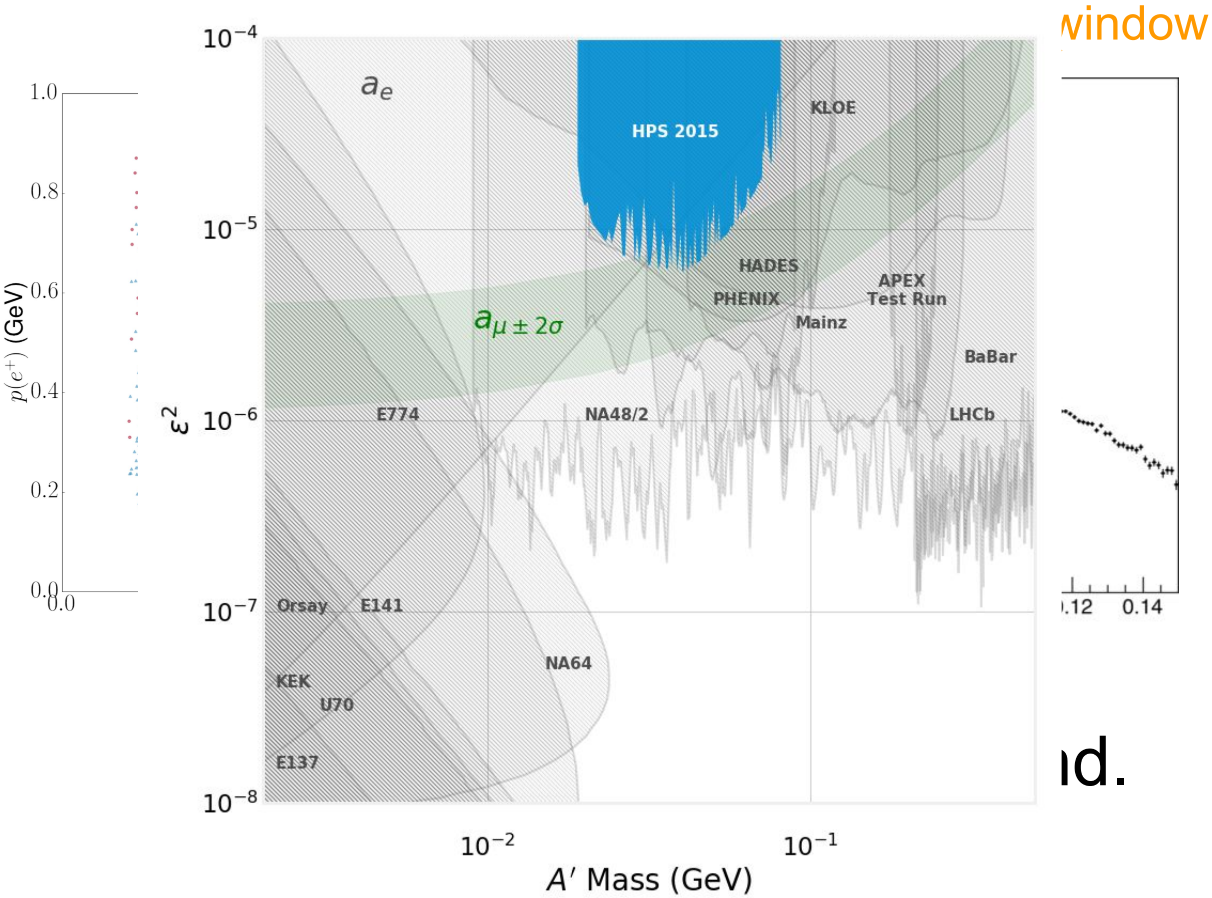
-Search for the peak in the given mass range

- Maximize Poisson Likelihood with Bgr only, and Bgr+signal hypothesis

- Use log likelihood ratio to quantify any excess/bump

No significant peak is found.
2σ limit is placed

Resonance search with 2015 data



-Range 19 MeV – 81 MeV

-Scan w/ 0.5 MeV step

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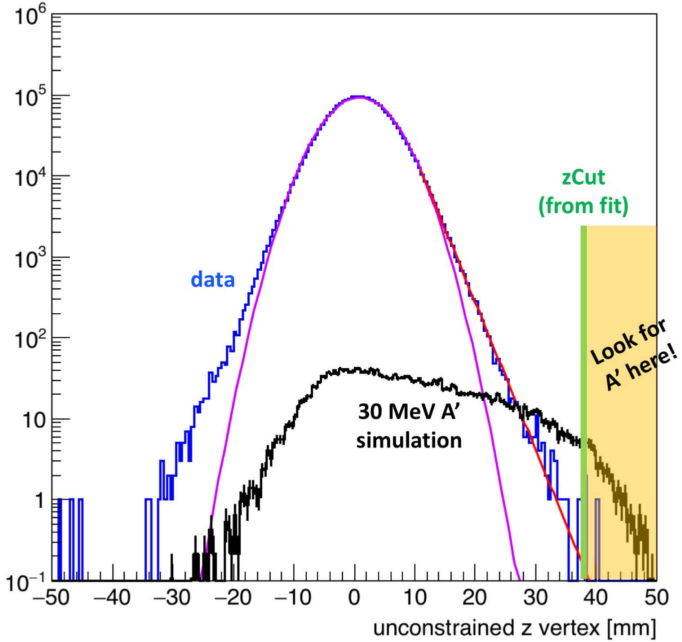
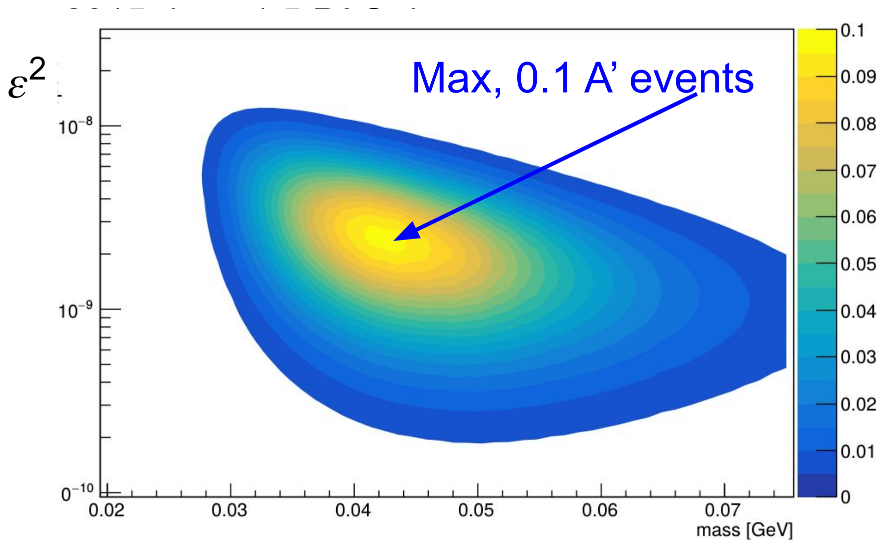
Vertexing analysis

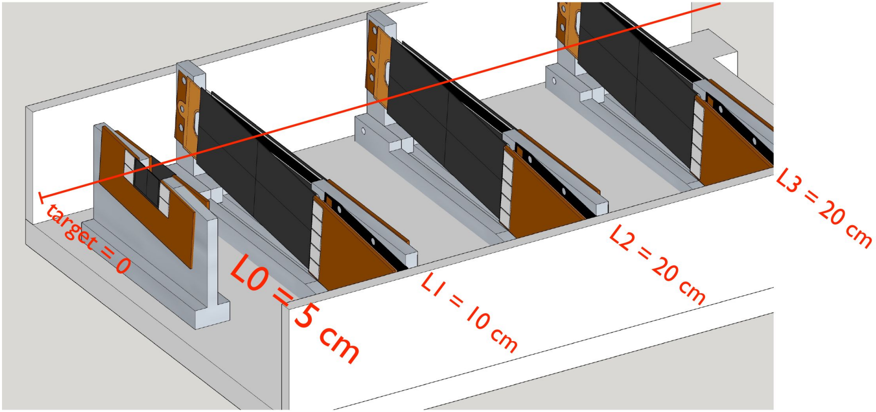




Analysis is in a quite advanced state, however with 1.5 days of data, we will not have any reach (2.5 expected A' events).

No reach for 2016 data, however we are investigating possibilities with SiMP scenario, we might have a reach with SiMPs.

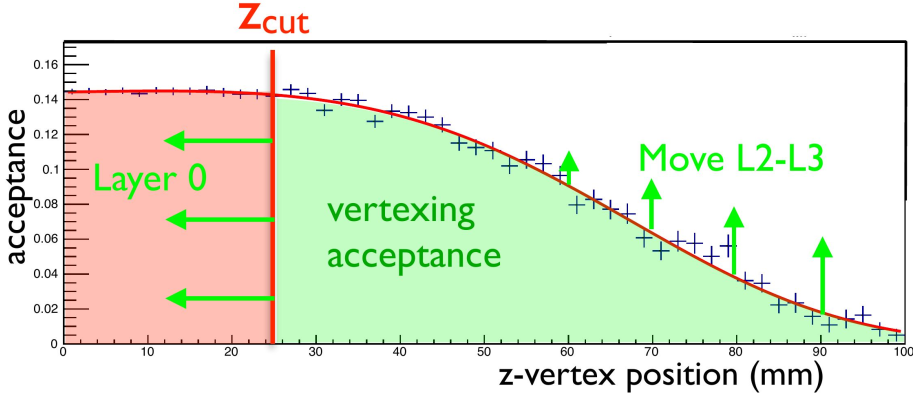
SVT upgrade

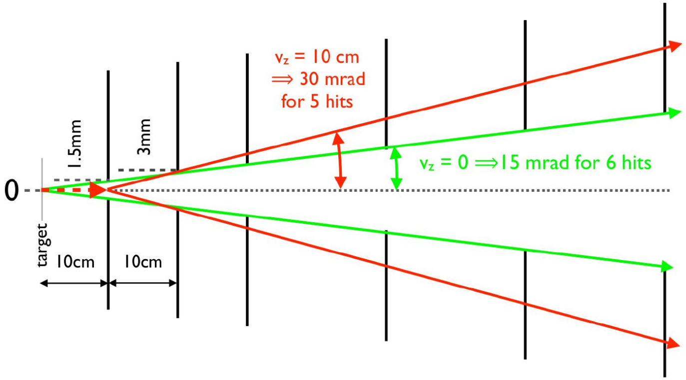


- Adding a new thin SVT layer at 5 cm downstream of the target, will significantly improve the vertexing resolution.

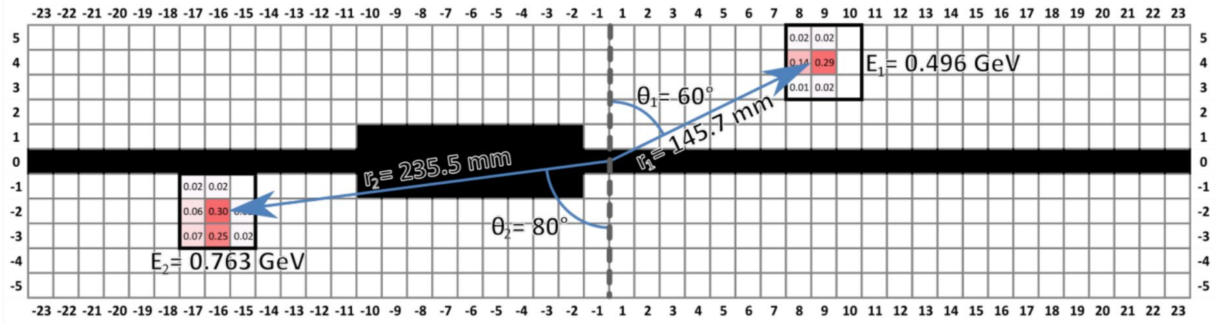
- Thin layer, will not add much background, about half of material (0.4% X_0)

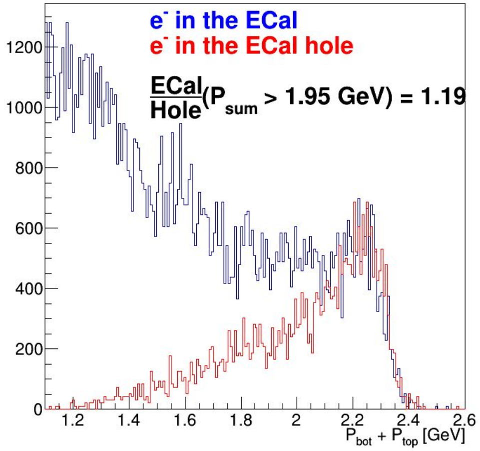
- Moving SVT Layers 2-3 closer to the beam will increase the acceptance for displaced vertices.

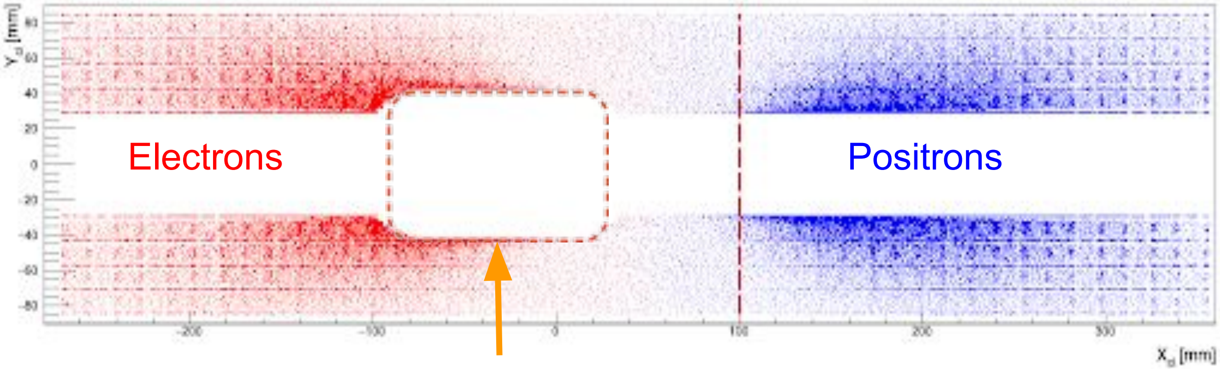


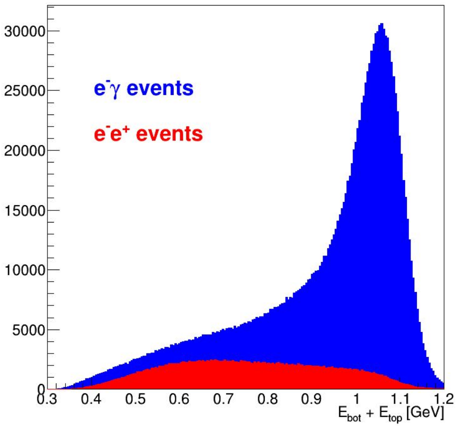


Hodoscope upgrade



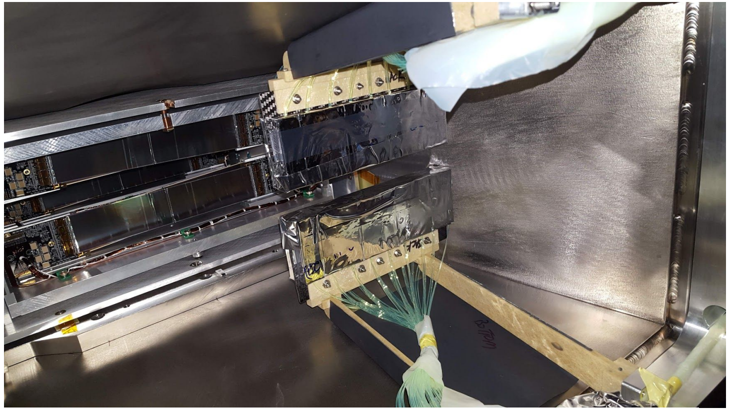






- Events w/ electron in the gap are lost
- The pair trigger accepts a lot of $e^-\gamma$ events.

Hodoscope upgrade

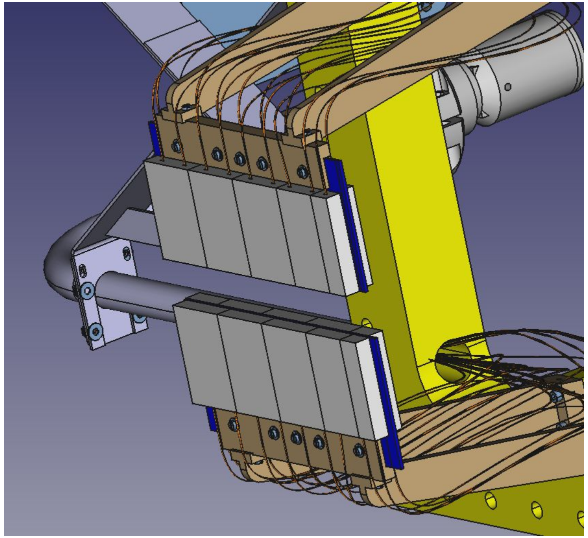


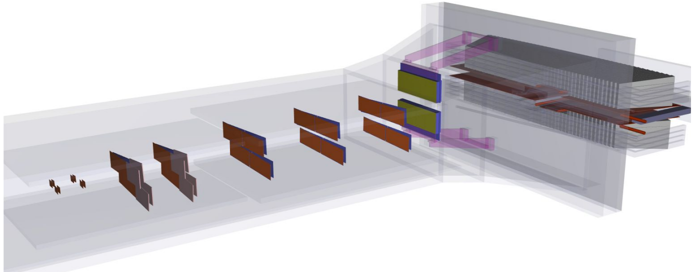
Installed between the tracker and the ECal

Two identical sectors: Top and bottom (similarly to ECal)

Two layers, Each layer consists of 5 scintillator tiles.

Light propagated to PMT through WLS fibers





New trigger requires a positional and time coincidence between the hodoscope, and a cluster in the positron side (No requirement for a presence of another cluster), and hence recover events where electron passed through the ECal hole.

Will highly suppress $e^- \gamma$ events

Status of 2019 summer run

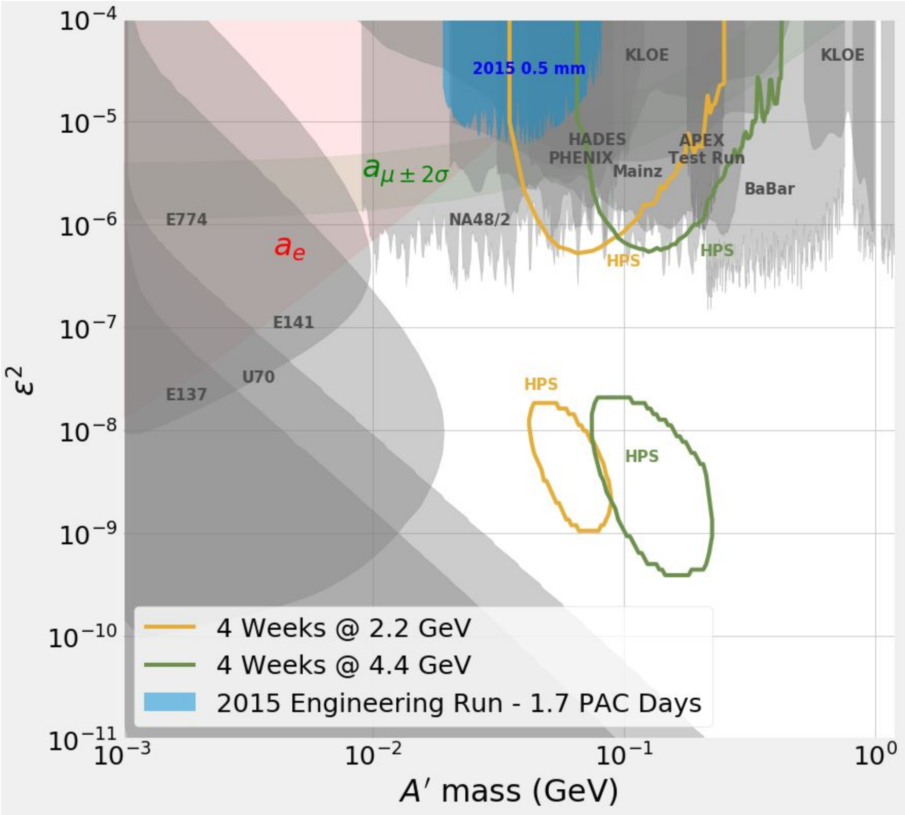
To compensate downtimes, and also reduce the damage of silicon from X rays , a new target frame is installed with 8 μ (the nominal one), 15 μ and 20 μ foils, and almost up to the end of the run we run with 20 μ target

Despite the hard start and issues during the run, HPS collected about half of the expected statistics

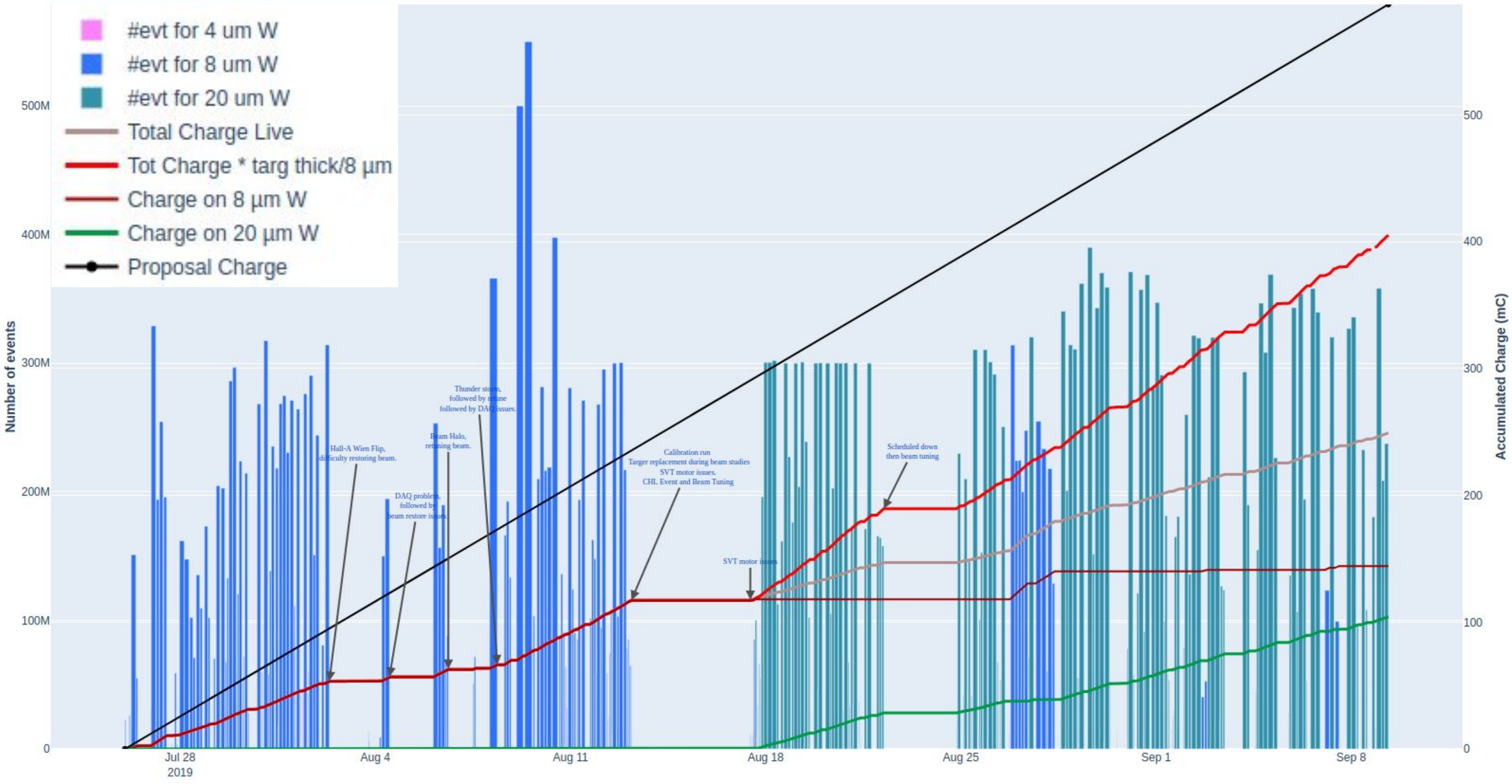
Data is now being calibrated.

Alignment of the detector is in progress

Estimating the new reach



Summer 2019: Physics run



Summary

- HPS experiment is searching for a new vector boson that is a well motivated and viable force particle between SM and DM

- The precision tracking detector allows to detect A’s through “resonance search” and “secondary vertex” strategies

- In 2015 and 2016 HPS successfully took opportunistic engineering runs, which allowed to understand the detector, develop analysis chains and led to important upgrades that improved the experiment reach.

- Physics data from 2015 run is already published

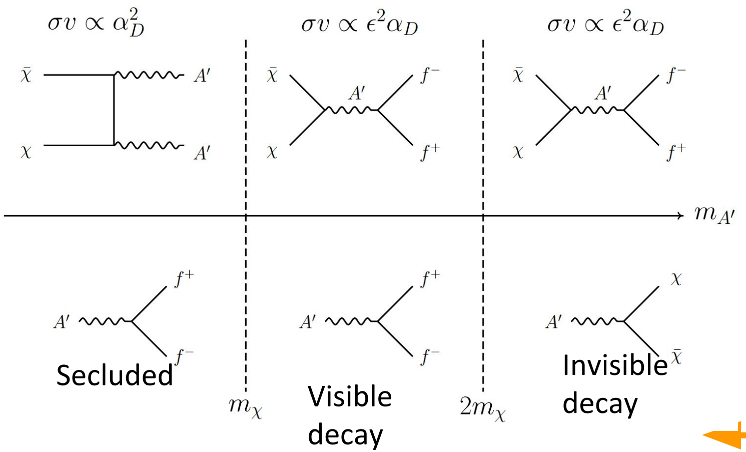
- In the summer of 2019 HPS took its first physics run, which has an opportunity to cover a new territory in the expected ε and mass range of A’

Backup

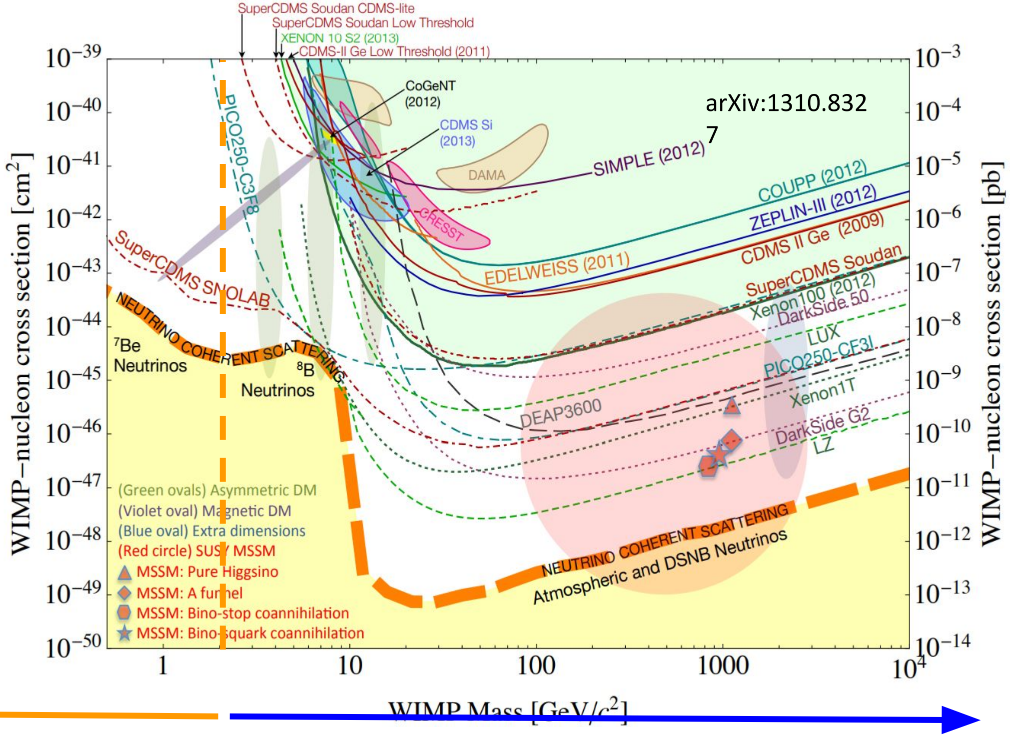
Light Dark Matter

Weakly Interacting Massive Particles (WIMPs) are well motivated DM candidates, however nothing is found yet.

Light Dark Matter: A new force carrier called "heavy photon" aka A', U boson.



HPS focuses on visible decay scenario



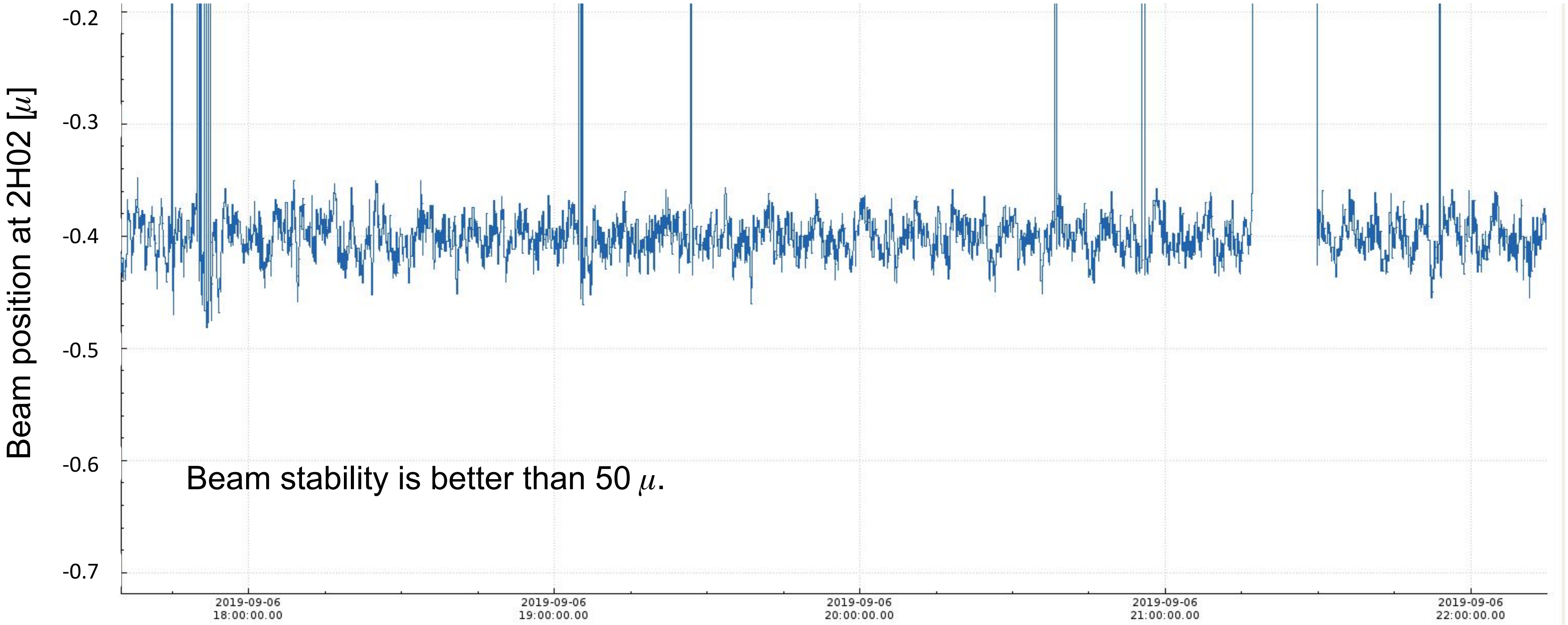
LDM

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

WIMPs

Lee-Weinberg Bound requires WIMP mass to be above 2 GeV

Beam stability



Summer 2019: Physics run

After about one week of commissioning, because of various reasons Accelerator had a downtime for about three weeks

We had some downtime too (different unexpected technical issues)

Official data taking started from July 25.

Thanks to JLab management for extending the run from Aug. 19 to Sept. 9