First Results from the Heavy Photon Search Experiment

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On behalf of the Heavy Photon Search Experiment

Thirteenth Conference on the Intersections of Particle and Nuclear Physics

May 29 - June 3, 2018

Palm Springs, California

Light Dark Matter

There is strong evidence for the existence of Dark Matter (DM), but it's nature continues to elude us.

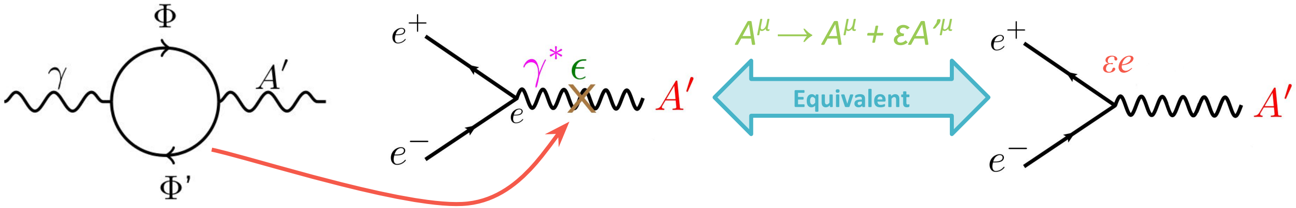
- Weakly Interacting Massive Particle (WIMP) Dark Matter are a motivated candidate but searches for them in the most favorable areas have yielded nothing … will be ruled out or found by next gen experiments (e.g. **SuperCDMS**, **LUX/LZ**) in the coming years.
- **Light Dark Matter** (i.e. DM MeV-GeV range) is a reasonable candidate but **requires a new force** to achieve the correct thermal relic (WIMP's limited by Lee-Weinberg Bound to 2 GeV).

Consider the case where DM interacts via a vector mediator (dark/heavy photon, *A'*)

Holdom, Phys. Lett. B166, 1986

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

kinetic mixing between SM photon and the dark photon → induces weak coupling to electric charge



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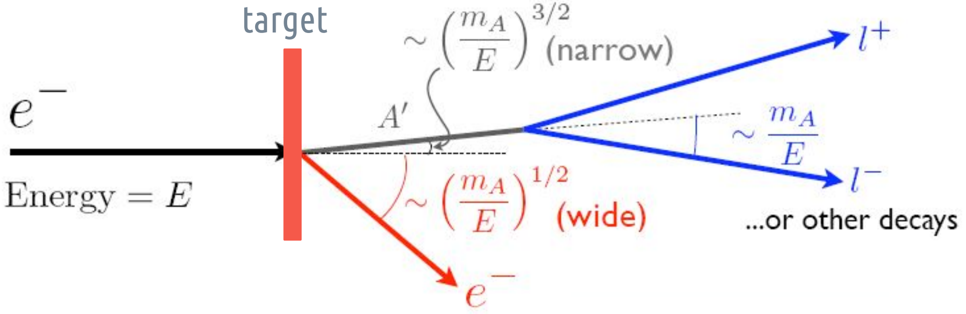
Fixed Target Kinematics

Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets subsequently decaying to l^+l^-



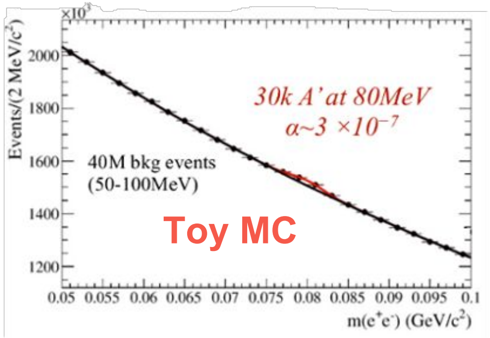
Kinematics are very different from bremsstrahlung

- Production is sharply peaked at x ≈ 1 ⟶ A' takes most of the beam energy
- *A'* decay products opening angle, $m_{A'}/E_{beam}$

The HPS experiment was designed to make use of such a production mechanism to search for a heavy photon using two methods:

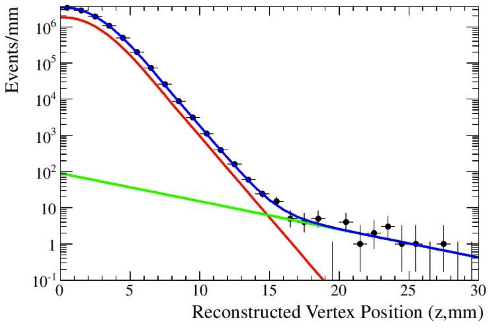
Resonance Search (Bump Hunt)

Look for a excess above the large QED background ⟶ Large signal required so limited to large coupling.



Displaced Vertex + Bump Hunt

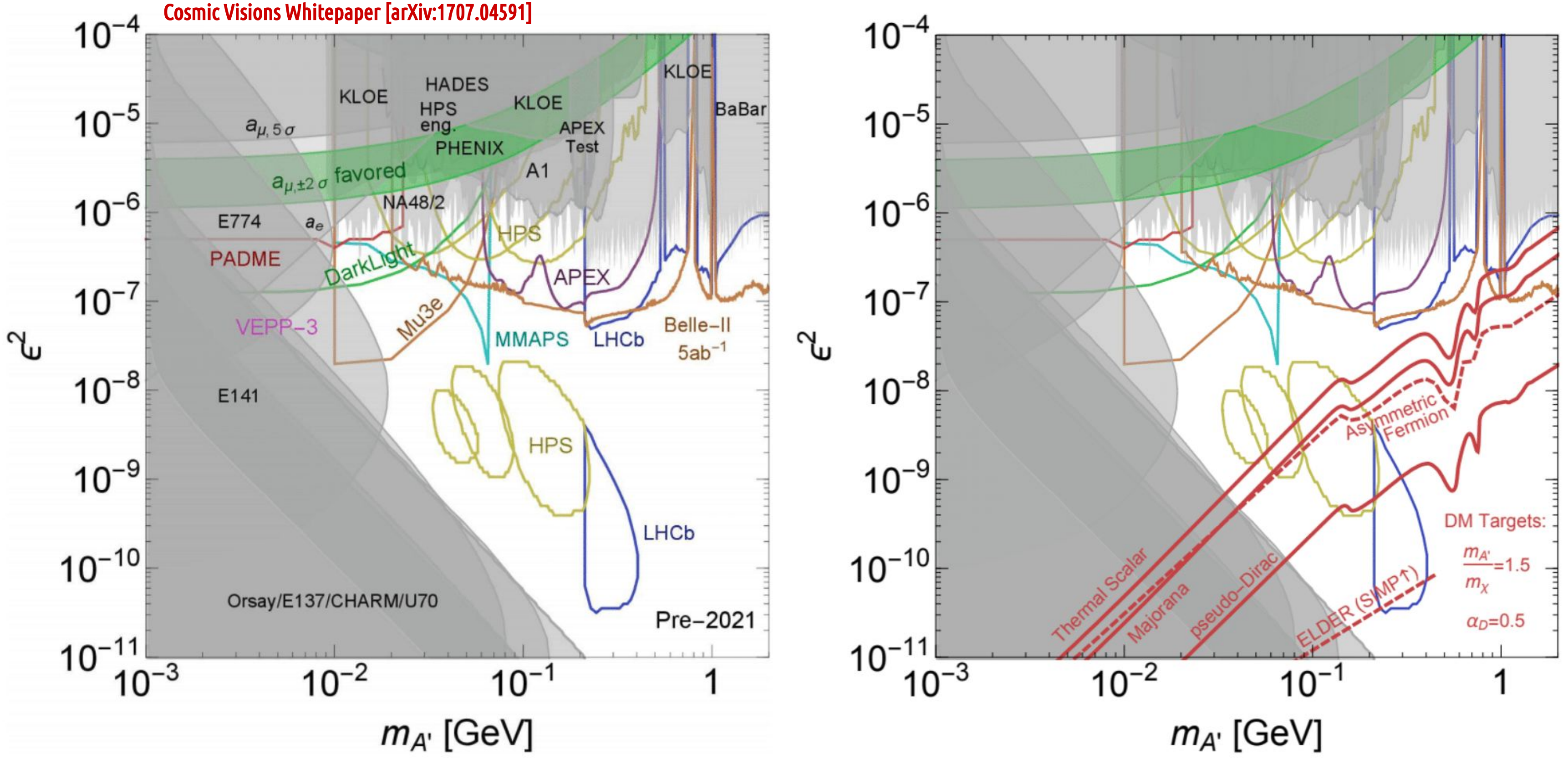
Long lived *A'* will have a displaced vertex ⟶ Will help cut down prompt backgrounds but limited to small coupling



HPS Reach

HPS will have sensitivity to territory motivated by thermal dark matter!

Cosmic Visions Whitepaper [arXiv:1707.04591]



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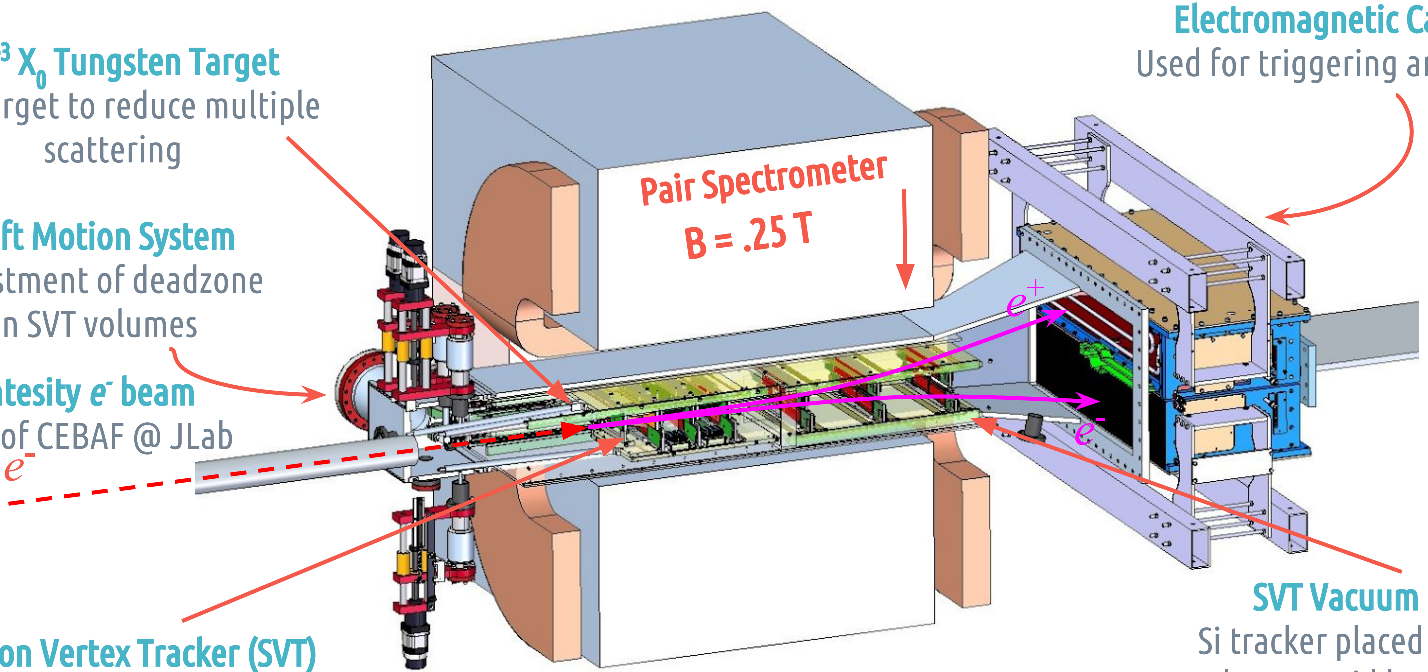
The HPS Apparatus

$\sim 10^{-3} X_0$ 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. Used for precise momentum and vertex determination

SVT Vacuum Chamber
Si tracker placed in vacuum in order to avoid backgrounds due to beam-gas interactions

SVT + ECal DAQ capable of 50 kHz

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

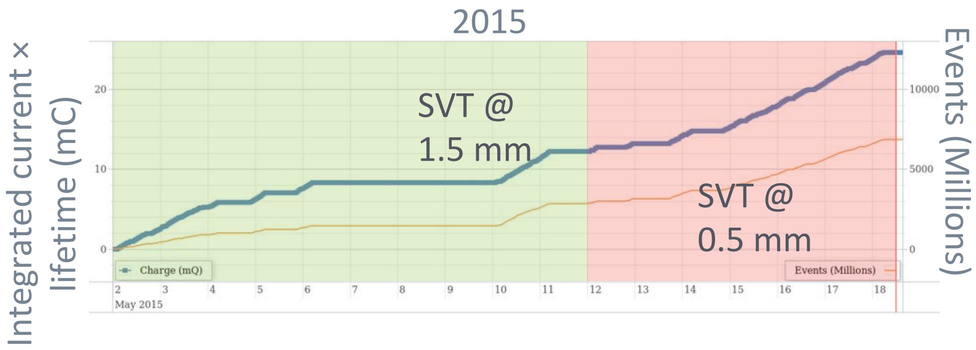
HPS Engineering Runs

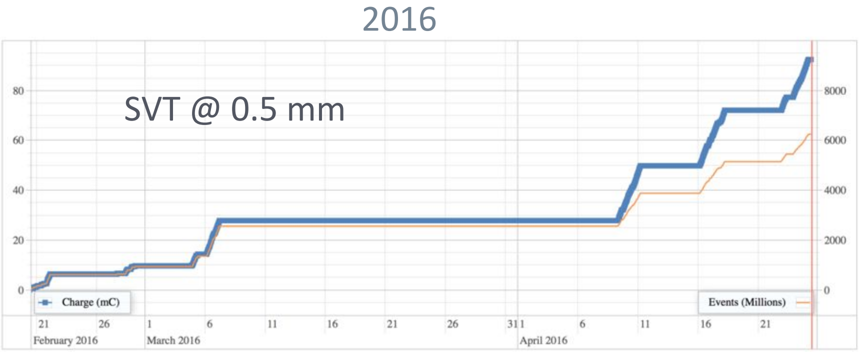
Two successful JLab engineering runs

- ✔ **Spring 2015:** 50 nA, 1.056 GeV electron beam (night and weekend running)
- ✔ **Spring 2016:** 200 nA, 2.3 GeV electron beam (weekend running)

Goal: Understand the performance of the detector and take physics data.

- ✔ For the 2015 run, data was taken with the Silicon Vertex Tracker (SVT) in two configurations: inactive edge at 1.5 mm and 0.5 mm from the beam plane
- ✔ 2015: 10 mC with the SVT at 1.5 mm and 10 mC (**1.7 PAC days**) at 0.5 mm
- ✔ 2016: 92.5 mC (**5.4 PAC days**) with the SVT at 0.5 mm





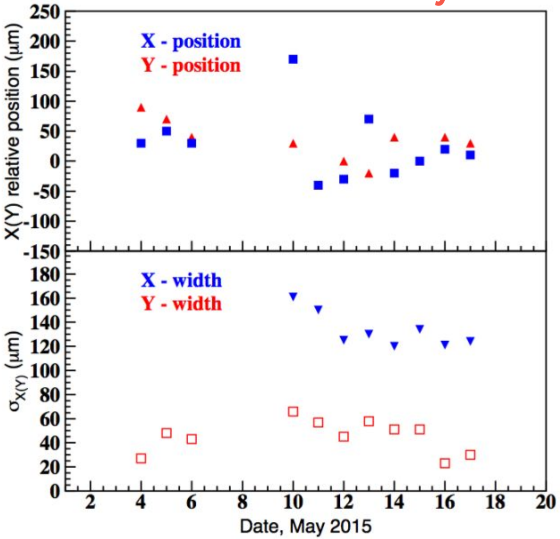
The results shown in this talk used the full 0.5 mm 2015 Engineering run dataset.

2015 Engineering Run Performance

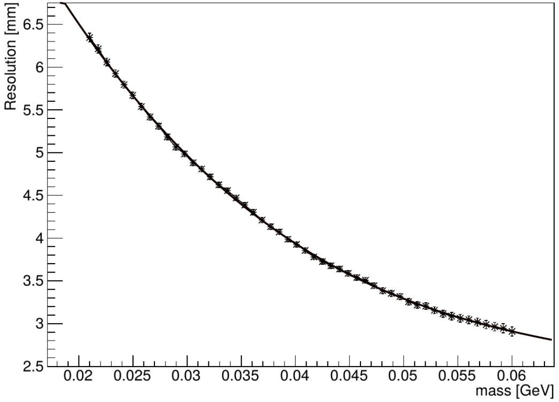
The 2015 engineering run has demonstrated that HPS is ready to do a meaningful search for heavy photons

- ✔ Hall B beamline was capable of delivering a small beam spot , low beam halo with high stability → allowed placing tracker 0.5 mm from the beam
- ✔ Excellent Ecal time and energy resolution allows for the efficient selection of true e+e- pairs
- ✔ Vertex resolution was as expected and sufficient to conduct a search for a displaced *A'*

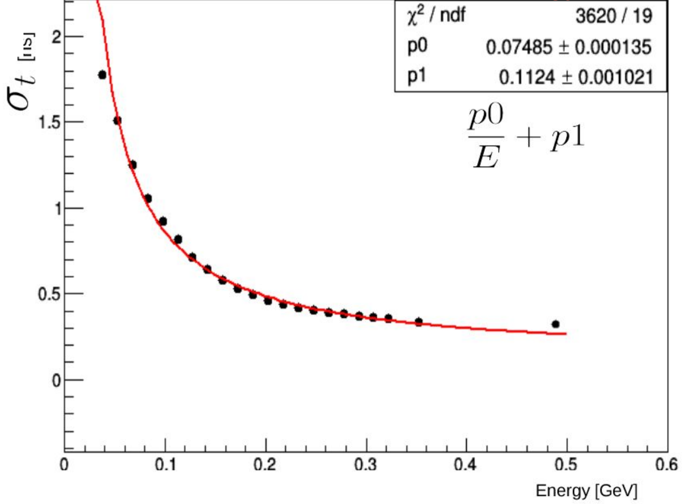
Beam Position Stability



Vertex Resolution vs Mass



Ecal time resolution vs Energy

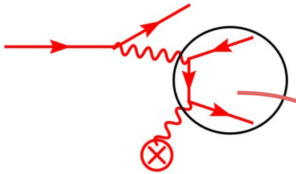


Backgrounds

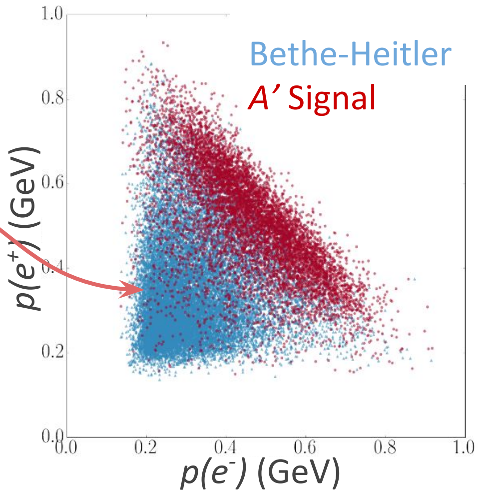
The search for an A' involves looking for a narrow resonance in the e^+e^- invariant mass spectrum on top of a large, continuous background composed of several components

Physics Backgrounds

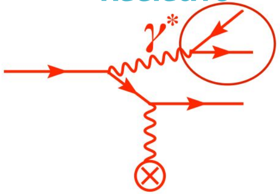
Bethe-Heitler



Dominant, but most lies below the A' signal region.



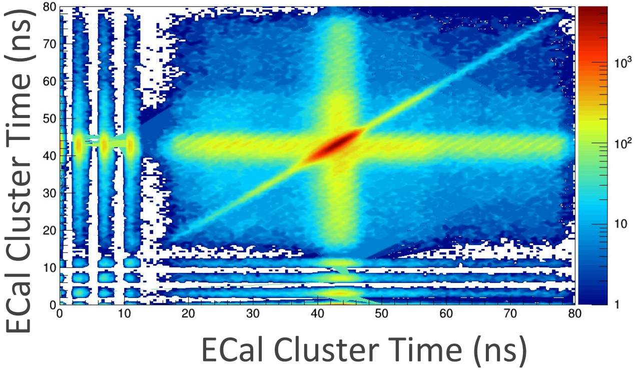
Radiative



Irreducible. Kinematically identical to A' but can be used to understand expected A' rates.

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

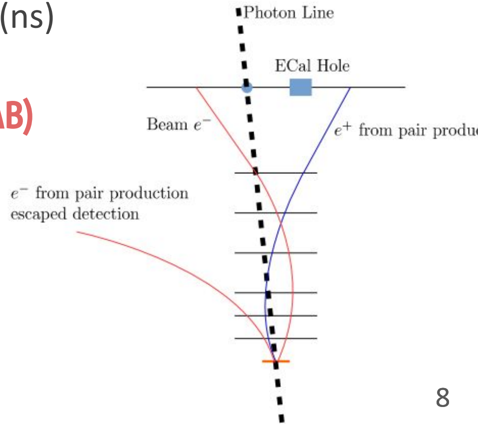
Accidentals



True e+e- pairs will have time-coincident clusters in the calorimeter. Can be suppressed using time cuts and cuts used to remove scattered beam electrons.

Wide Angle Bremsstrahlung (WAB)

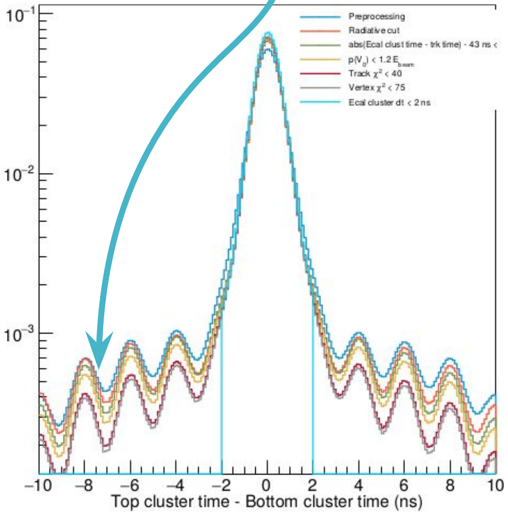
Conversions of photons produced in the target and first few layers of the SVT can mimic a trident e+e- pair

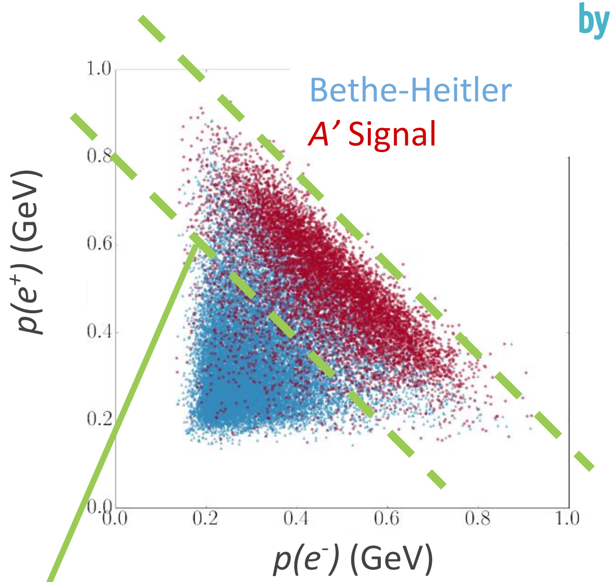


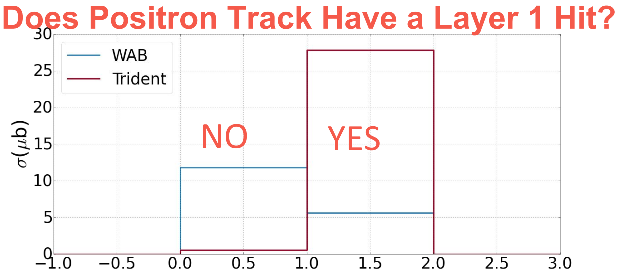
Bump Hunt Event Selection

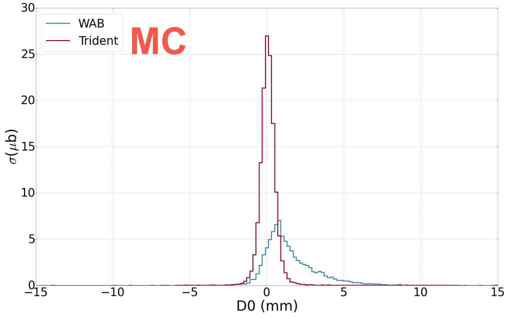
Apply kinematic and goodness of track and vertex fit cuts to clean up accidentals. **Reduces contamination from accidentals to < 1%.**

Requiring a **layer 1 hit removes 68% of WABS** from final event sample. Additional cuts on the distance of closest approach and p_t asymmetry **rejects WAB's by > 80% of WABs.**









Requiring the sum of the e^+e^- pair momentum to be $0.8E_{beam} < p(e^+e^-) < 1.2E_{beam}$ GeV and greatly reduces the number of Bethe-Heitler background in our final sample.

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Bump Hunt Event Selection

HEAVY PHOTON SEARCH

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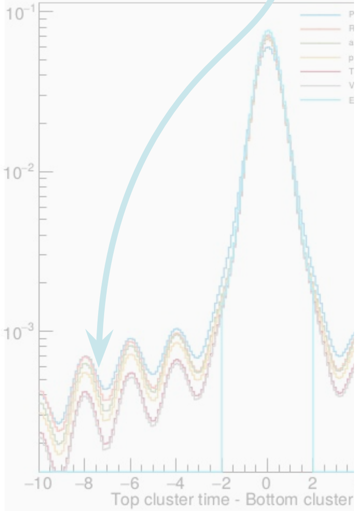
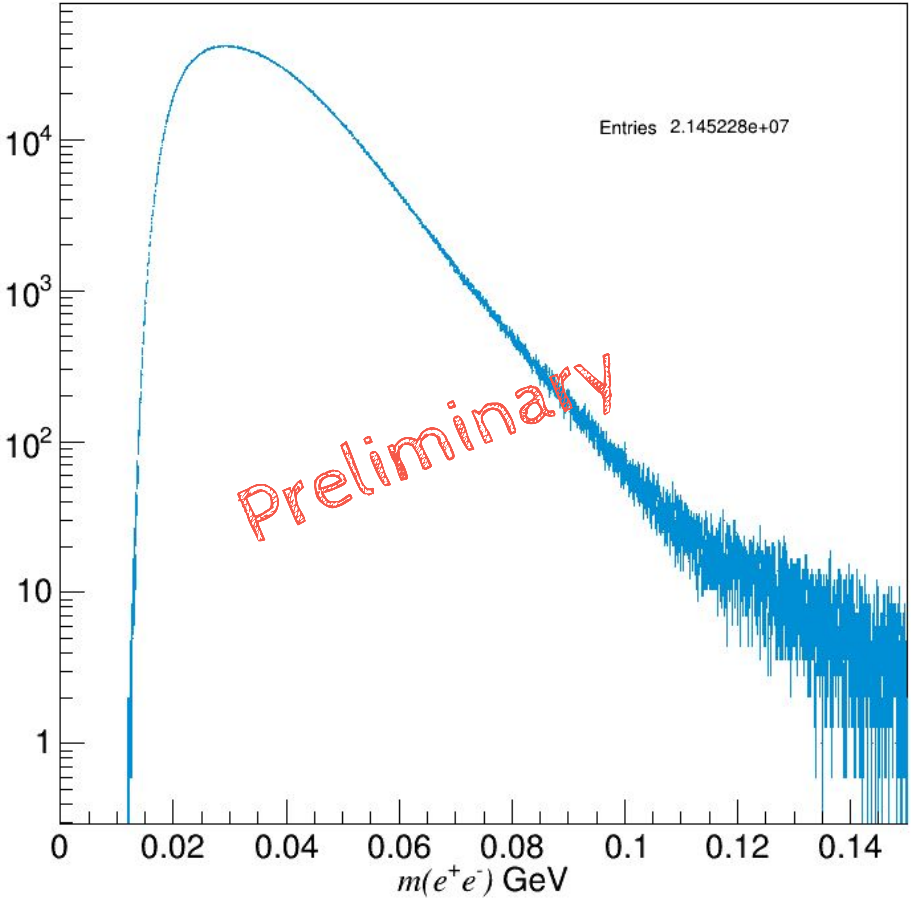
Apply kinematic and g
accidentals. **Reduces c**



Requiring the sum of t
$0.8E_{beam} < p(e^+e^-) < 1.2$
Bethe-Heitler backgro



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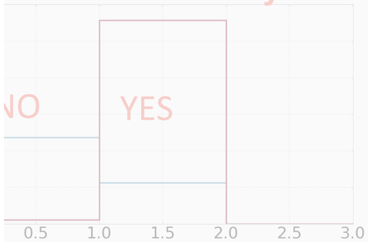
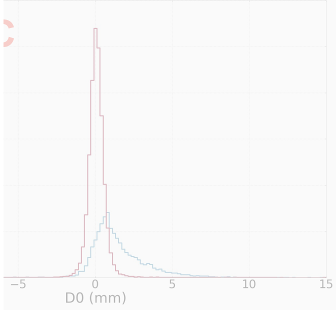
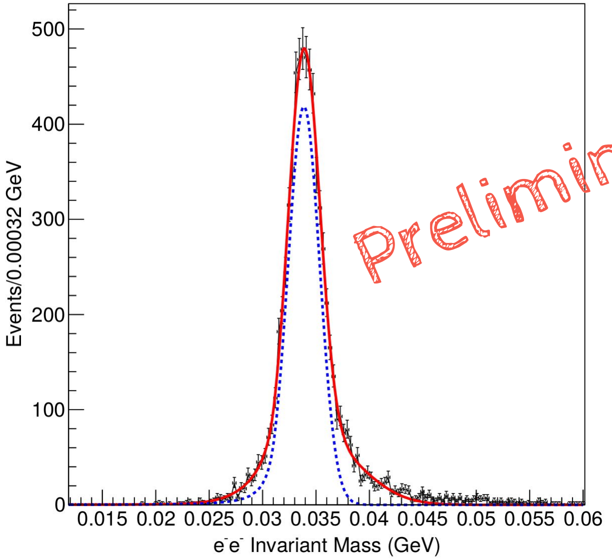
n Track Have a Layer 1 Hit?



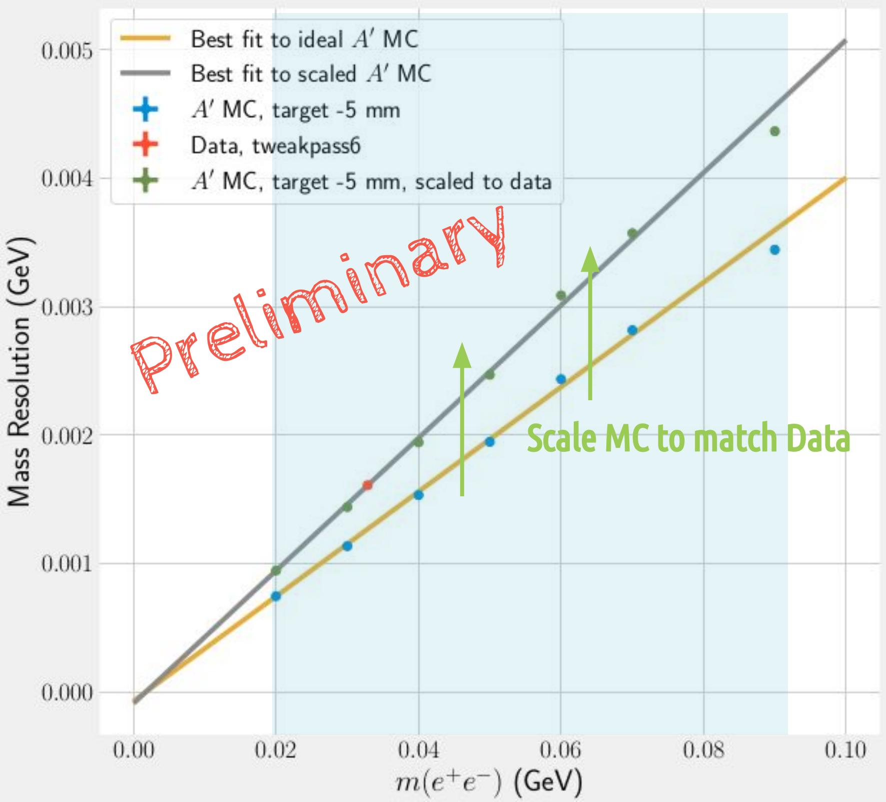


e^+e^- Mass Resolution

- ✔ Determined the resolution as a function of mass using A' and Møller Monte Carlo
- ✔ From data, use the Møller invariant mass distribution to measure the mass resolution
- ✔ Scale the MC mass resolution parameterization to match the data observation.

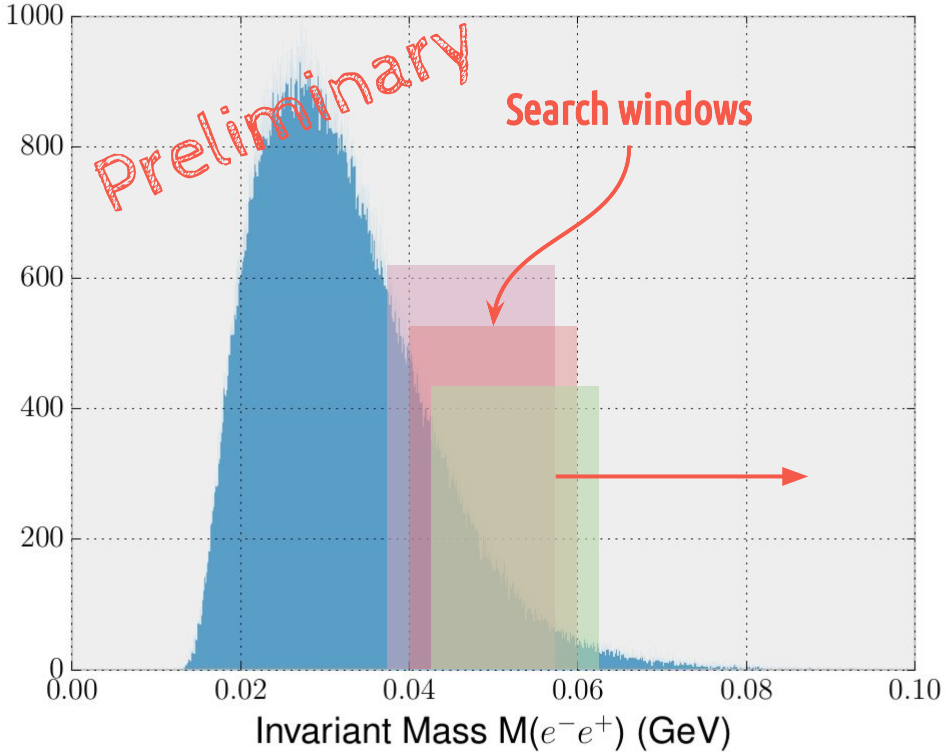


Discrepancy between data and MØller Monte Carlo is due to mismatch of momentum resolutions



Resonance Search Overview

- ✔ Search for a resonance within a window in the mass range between 18 MeV and 95 MeV by scanning the ***e^+e^-*** invariant mass spectrum in 1 MeV step sizes.
  - ✔ Pseudo-experiments were used to set the optimal search window size ⟶ $11\sigma_{mass}$ at the edges and $17\sigma_{mass}$ in the center
- ✔ Maximize the Poisson likelihood within the range using a composite model with the signal described as a **Gaussian** and a **7th order Chebyshev polynomial to model the background**
- ✔ Use Likelihood ratio to quantify significance of any excess i.e. "bump"
- ✔ Determine the 2σ signal upper limit at each mass hypothesis by inverting the likelihood ratio
- ✔ Translate the signal upper limit into the coupling-mass phase space



Fit Results

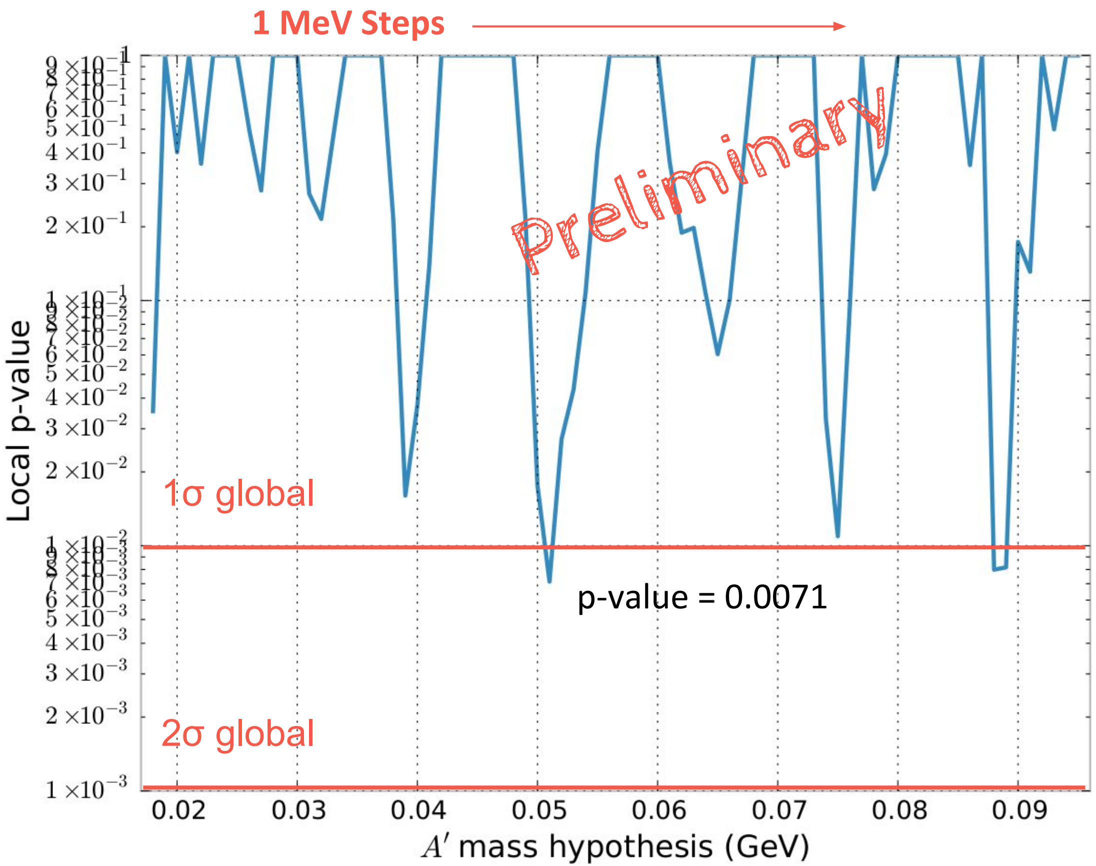
No significant bump was found!

Establishing whether the signal+background model is significantly different from the background-only model is typically done using the profile likelihood ratio and test statistic q_0

$$q_0 = \begin{cases} -2\ln\frac{\mathcal{L}(0,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \hat{\mu} > 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

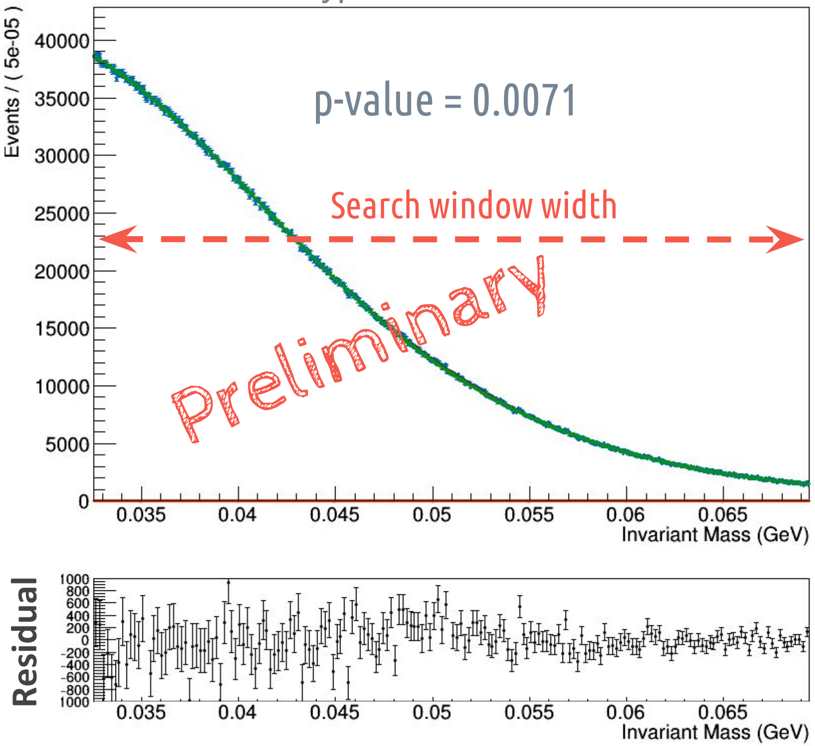
$$p = \int_{q_{0,obs}}^{\infty} f(q_0|0)\,dq_0$$

Use toy MC to determine the look-elsewhere correction

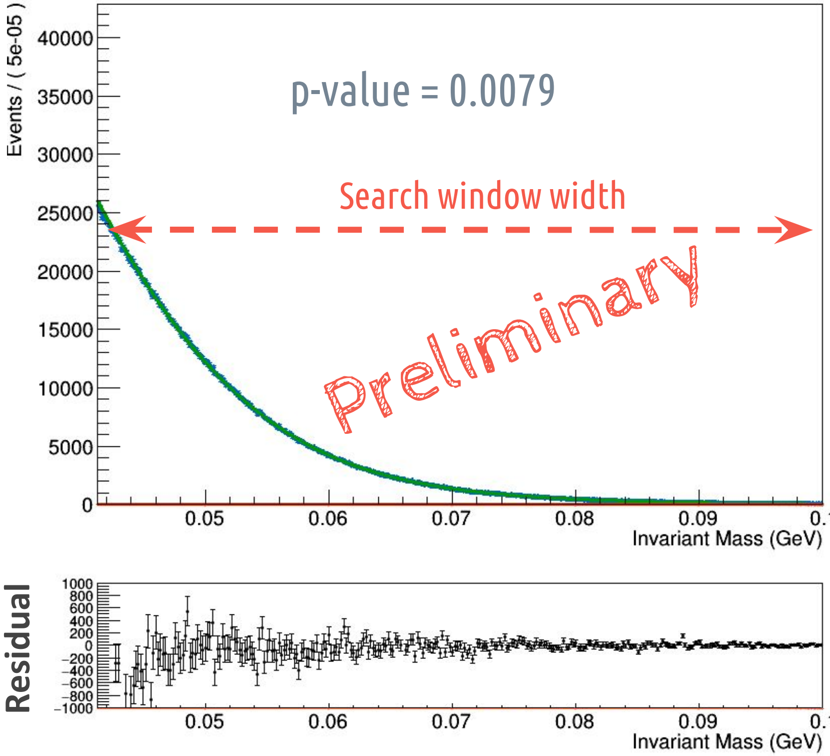


Most Significant Bumps

Mass hypothesis = 51 MeV



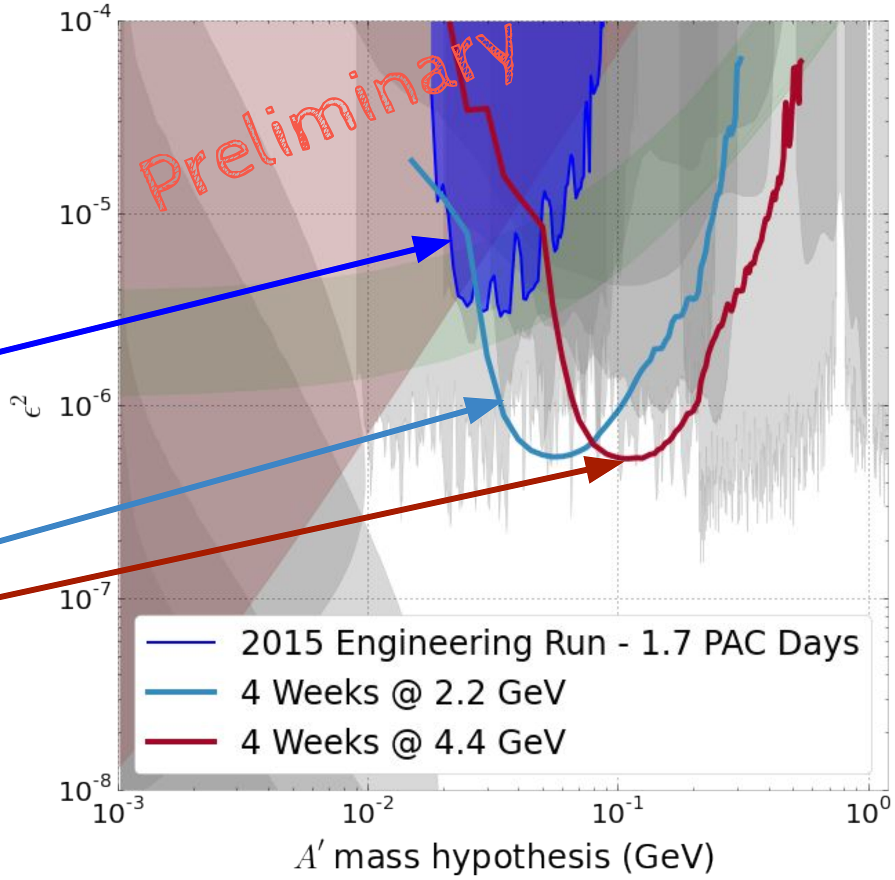
Mass hypothesis = 88 MeV



2σ Upper Limit on ε

2015 Engineering Run
1.7 PAC days @ 1.05 GeV

2018-2020 Physics Run
4 Weeks @ 2.2 GeV
4 Weeks @ 4.4 GeV



Summary and Outlook

The Heavy Photon Search has successfully completed engineering runs in 2015 and 2016
- Detector performance was found to be as expected
- An additional source of background (WAB's) was found and mitigated
- HPS is now fully approved for its full time

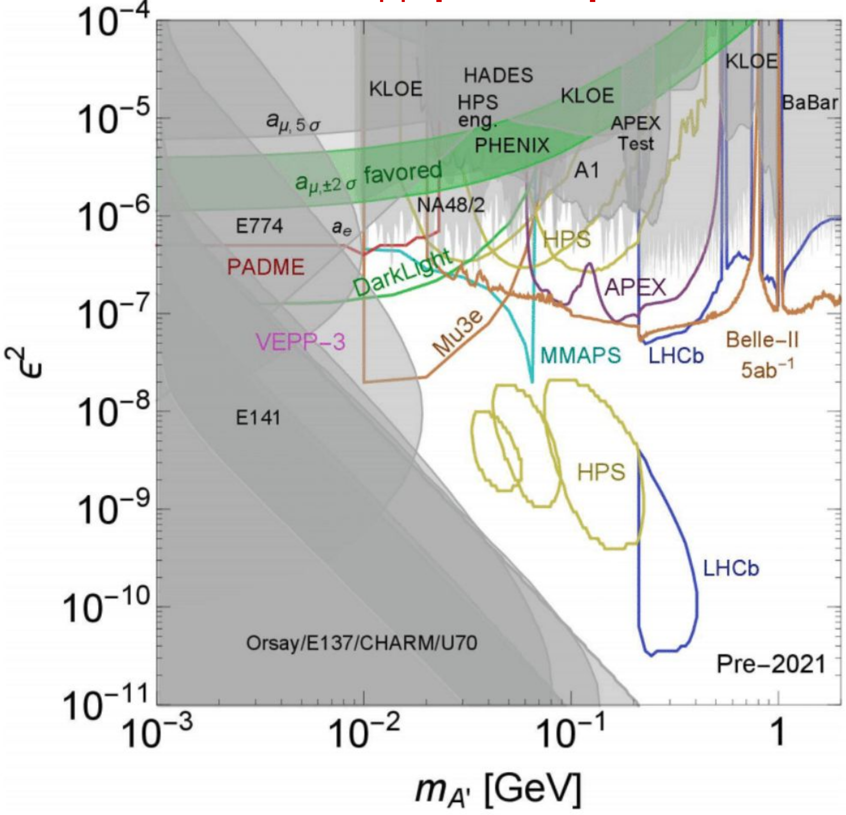
Publication of the 2015 bump hunt analysis is imminent!

Several analyses are ongoing
- 2016 Bump hunt analysis and 2015/16 Vertex analysis are ongoing

Upgrades to trigger and SVT are being built and will be installed Jan '19
- Will significantly extend the reach of HPS

Next run planned for summer of 2019 at 4.4 GeV

Cosmic Visions Whitepaper [arXiv:1707.04591]



Backup

HPS Upgrades

Vertex reach is worse than we had projected → No vertex reach expected using 1.7 days of data

- ✔ Vertex decay efficiency assumed constant out to 10 cm
- ✔ MC used to make initial projections did not use the correct acceptance

Modest upgrades will allow recovery of reach for future runs

- ✔ The layers of the SVT will be moved closer to the beam → Increase acceptance
- ✔ Add an additional thin layer to the SVT at 5 cm → Improves vertex resolution and vertex efficiency
- ✔ Implement a positron only trigger → Will allow recovery of some of the reach lost due to the ECal hole.