MG16 5-10 JULY 2021

SIXTEENTH MARCEL GROSSMANN MEETING

ON RECENT DEVELOPMENTS IN THEORETICAL AND EXPERIMENTAL GENERAL RELATIVITY, ASTROPHYSICS AND RELATIVISTIC FIELD THEORIES

Dark (Heavy) Photon Search

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for the HPS Collaboration

Outline:

- What is a dark photon
- Dark Photon search at accelerators
- The HPS experiment
- Outlook & conclusions

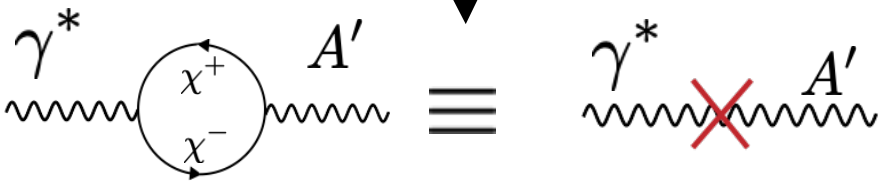
Dark Photons

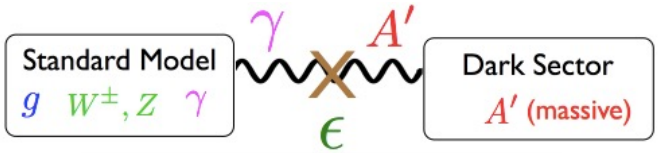
Holdom, Phys. Lett. B166, 1986

- Consider an additional *U(1)* hidden symmetry beyond the standard model.
- There will be kinetic mixing between the photon and the new gauge boson.
- General hypothesis to incorporate new physics in the SM: the A' acts as a "portal" between the SM and the new sector

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

Kinetic Mixing term.



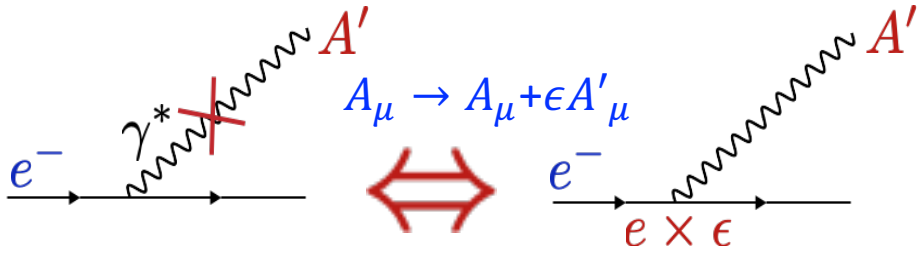


$$\epsilon \sim \frac{e g_D}{16\pi^2} log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$

GUT , string models $\epsilon \sim 10^{-12} - 10^{-2}$

Mixing

- Photon mixing with A' is equivalent to ordinary charged matter acquiring a *milli-charge* **εe** under the A'

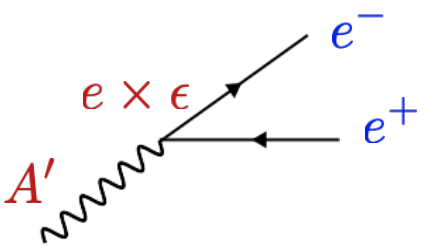


Dark Bremsstrahlung

New interaction term:

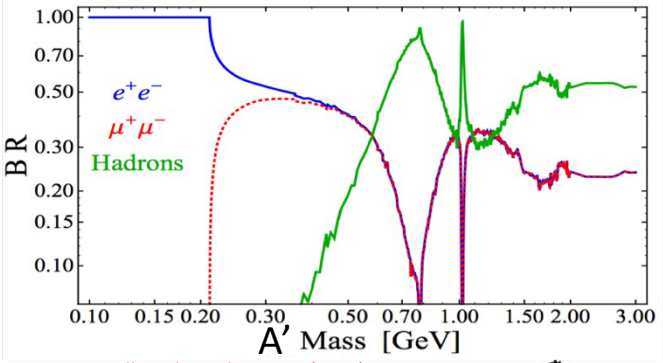
$$\mathcal{L}_{dark,\gamma} = -e\epsilon A'_\mu J^\mu_{em}.$$

- The parameters of the theory are ϵ and $m_{A'}$



A' will produce pairs :
e^+e^-,
$\mu^+\mu^-$,
$\pi^+\pi^-$, ...

A' Branching ratio

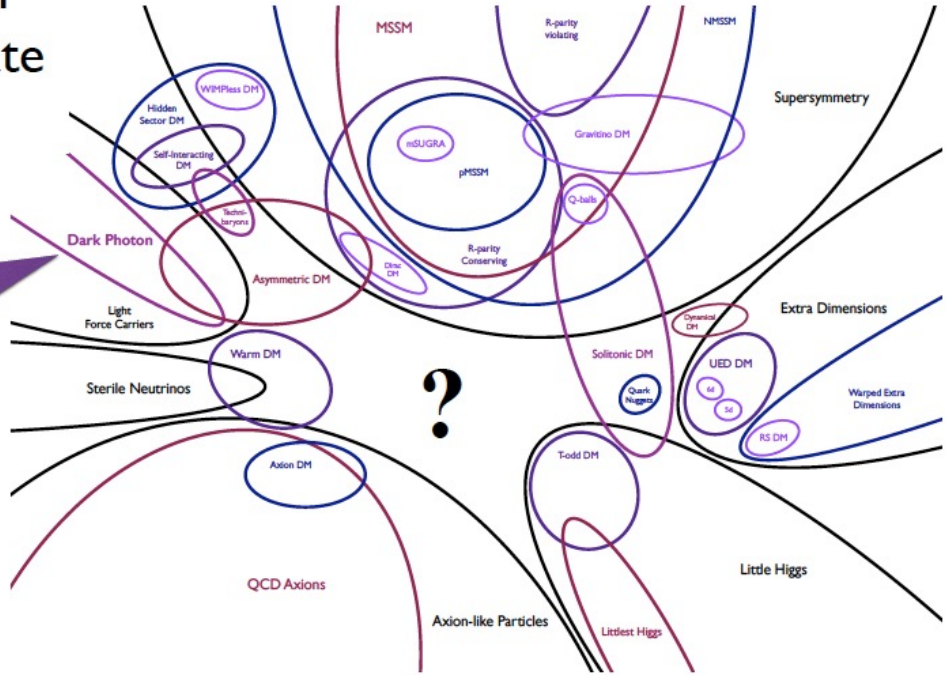


Falkowski et al. JHEP05 (2010) 077 1002.2952

Putting Dark Photon Search into Perspective

Venn Diagram
"DM Candidate
Landscape"

We are here

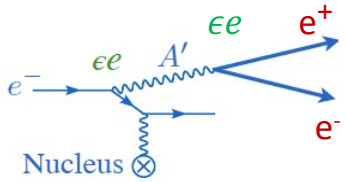


T. Tait from arXiv:1401.6085v1 [hep-ex]

Searching for Heavy Photons at Accelerators

If you can produce a photon you can produce a dark photon! (Paying for a small ϵ)

e fixed target

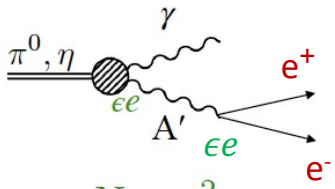


$N \propto \epsilon^2$

- dark bremsstrahlung
- $e+e- \rightarrow A'\gamma$

APEX @ Jlab
A1 @ Mainz
HPS @ Jlab
NA64 @ CERN
DarkLight @ Jlab

p fixed target



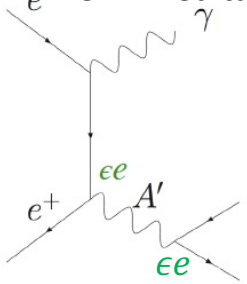
$N \propto \epsilon^2$

- meson decays
- dark bremsstrahlung

NA/48 @ Cern
MiniBoone @ Fermilab
SeaQuest @ Fermilab
SBN @ Fermilab
SHIP @ Cern

e^+e^- colliders

e^- e^+ - fixed target

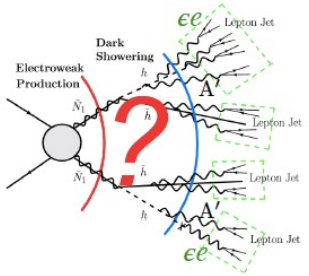


$N \propto \epsilon^2$

- $e+e- \rightarrow A'\gamma$
- meson decays

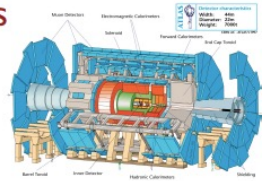
PADME @ LNF
BABAR @ SLAC
KLOE @ LNF
BELLE II @ KEK

pp collider

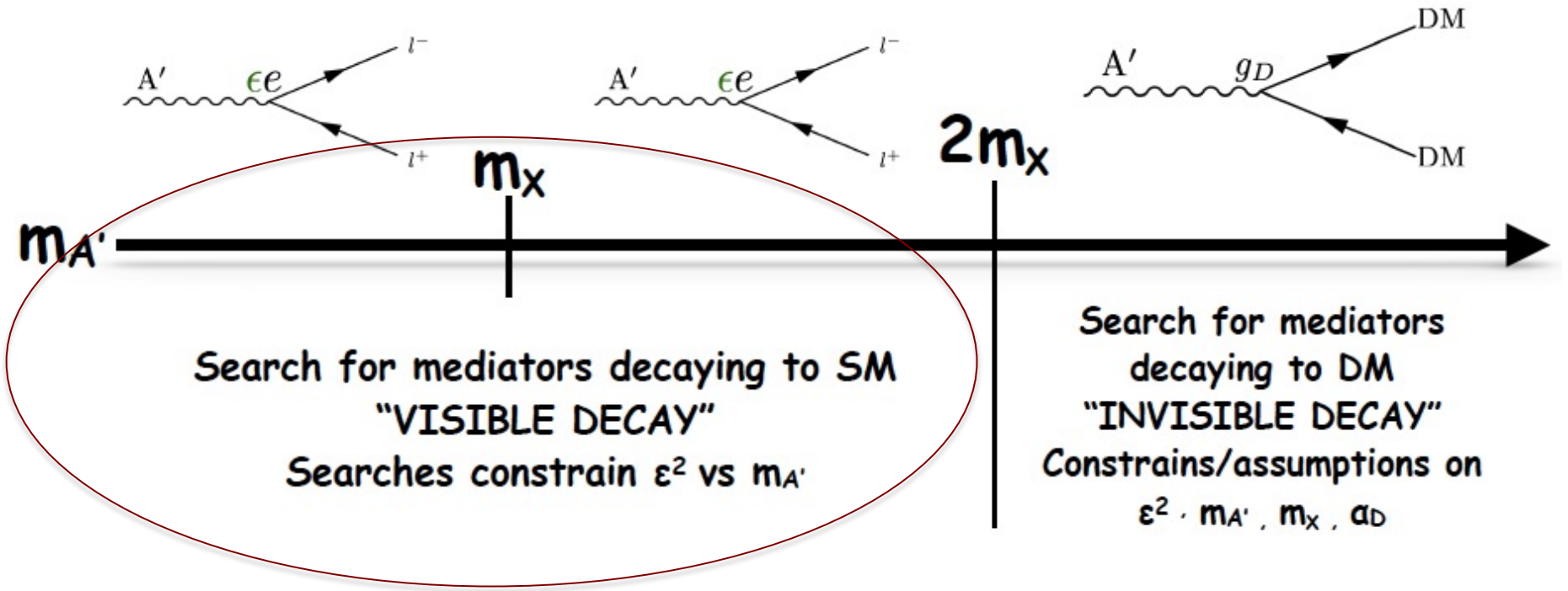


- "lepton jets" $N \propto ?$
- meson decays $N \propto \epsilon^2$

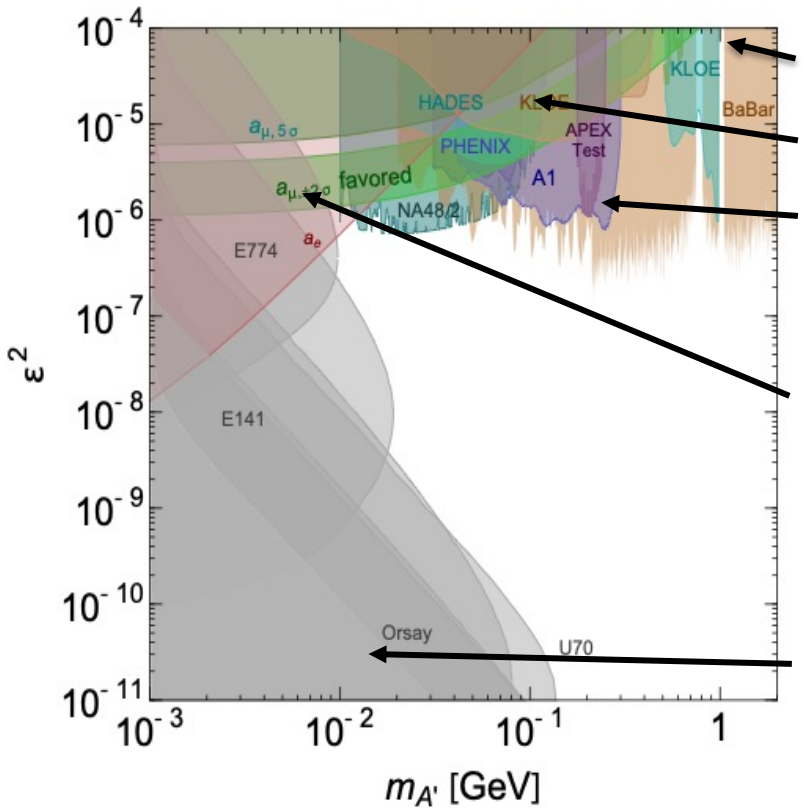
ATLAS
CMS
LHCb



Mass Hierarchy and Hunting Strategies



A’ Visible decay - Exclusion Plot in 2015



Generally “bump hunts” searches

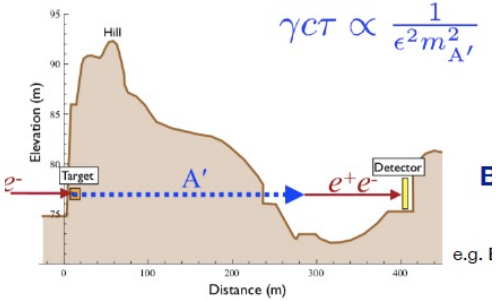
Searching for a needle in a haystack

e.g. searching a resonance in the invariant mass spectrum of lepton pairs over a huge background of QED events

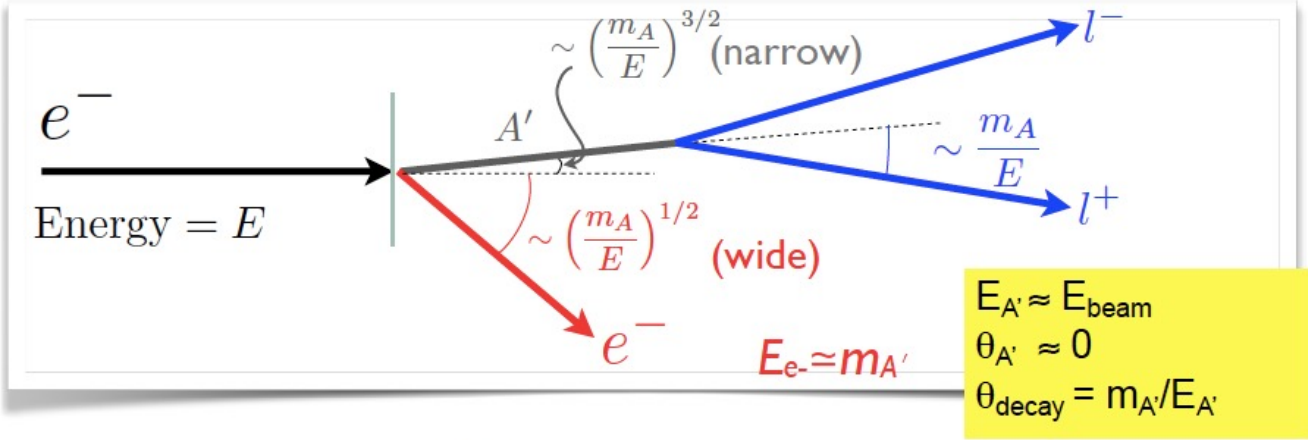
$e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-/\mu^+\mu^-$

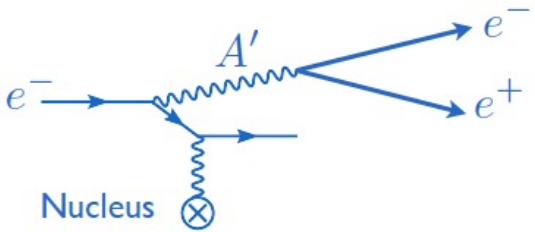
A’ becomes long lived at small coupling

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



HPS experiment detecting A' decays

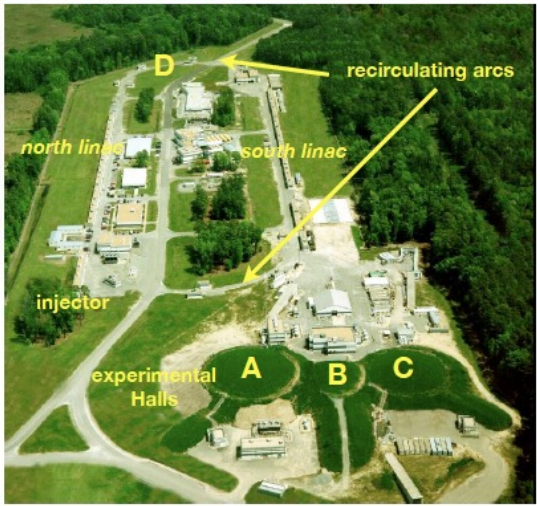




Need:

- Small angle detection of e+ e-
- Very high luminosity
- Good invariant mass resolution

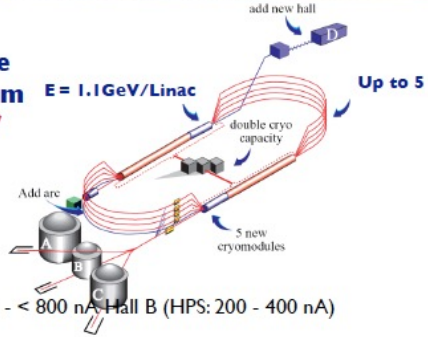
HPS experiment at JLAB



JLab completed the energy upgrade from 6 to E_{max} =12 GeV

E = 1.1GeV/Linac

Up to 5



HIGH

Intensity

I_{beam} < 100 μA Hall A, C - < 800 nA Hall B (HPS: 200 - 400 nA)

Frequency

~ DC beam, 2 ns bunch separation (1 bunch ~ 10000 e^-)

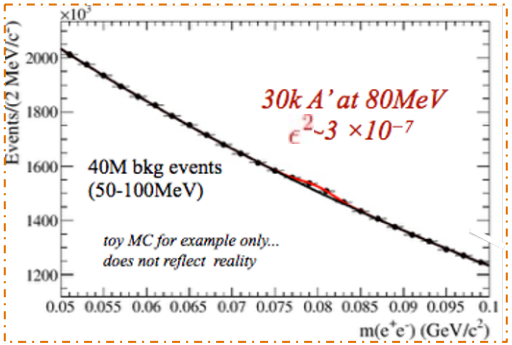
Spread out beam background over time for manageable occupancies

Quality

Tight beam spot in y helps tracking & vertexing

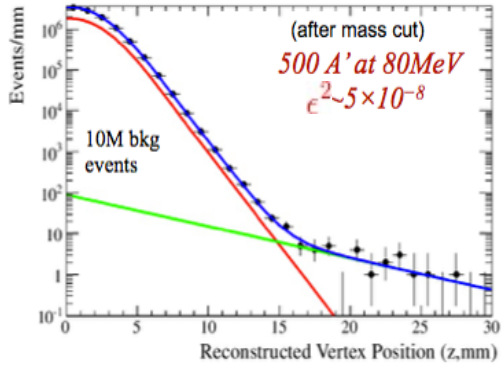
Very low halo = low background

HPS experiment at JLAB



BUMP-HUNT

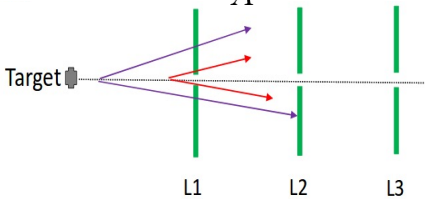
"Large" signal,
huge QED background

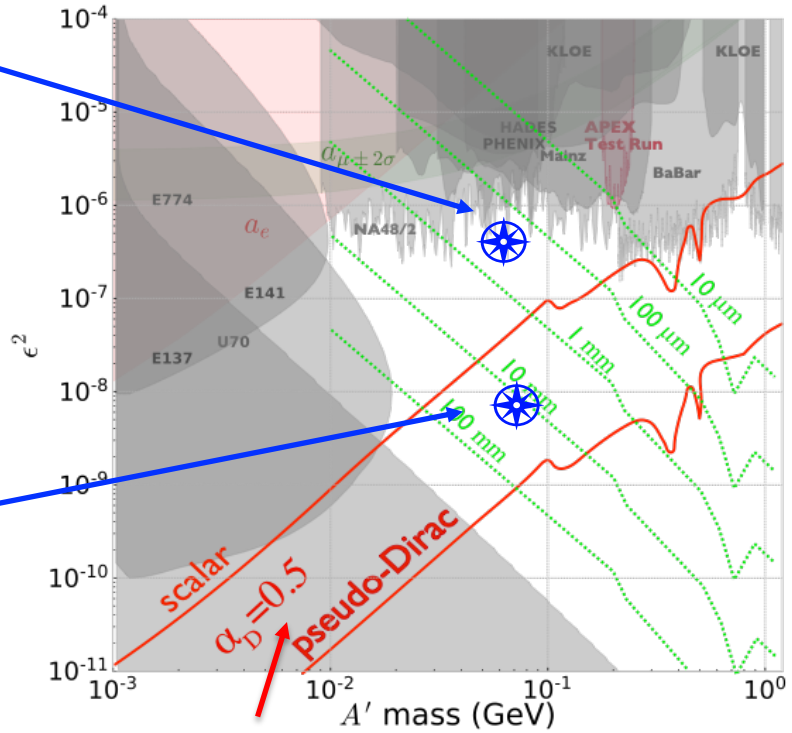


Detached Vertex

Small signal,
very little background

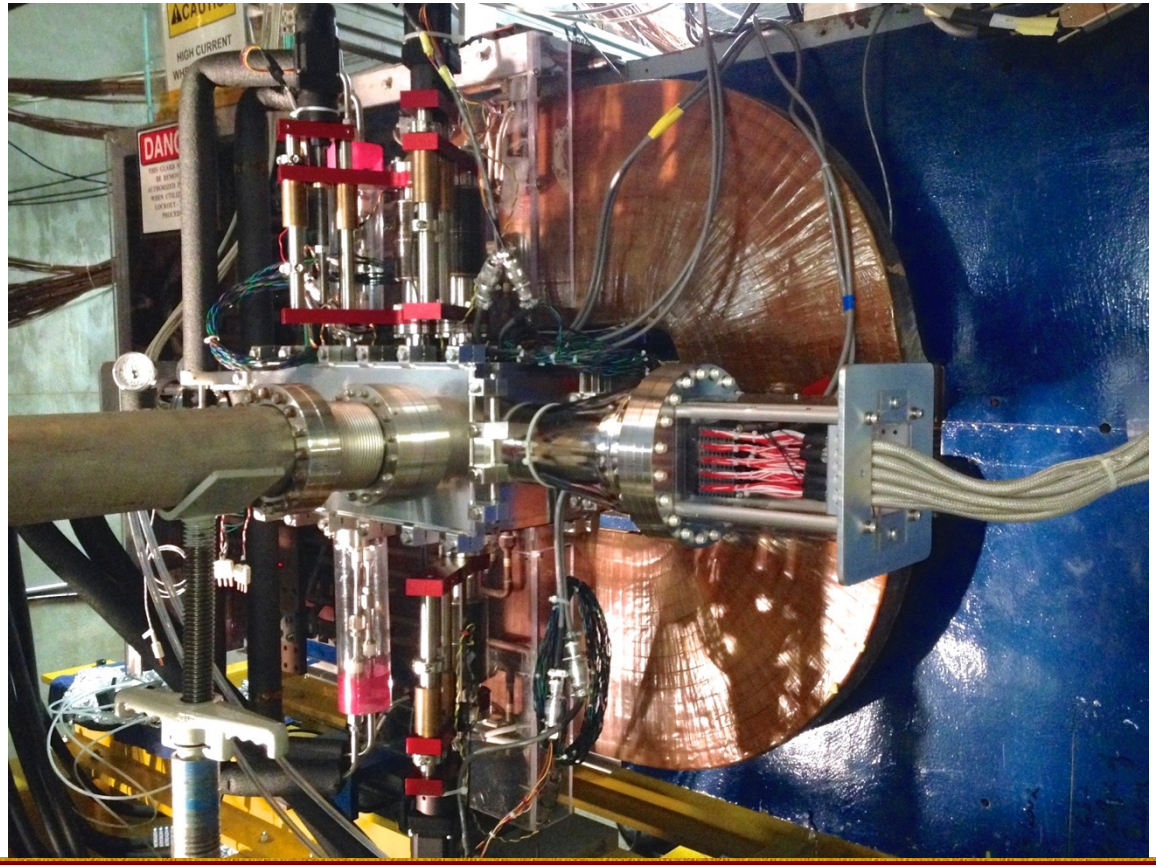
$$\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$$





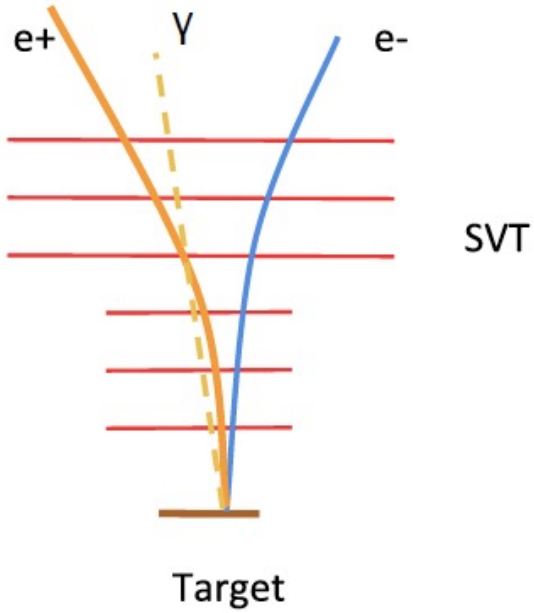
Region motivated by thermal relic targets

HPS experiment at JLAB



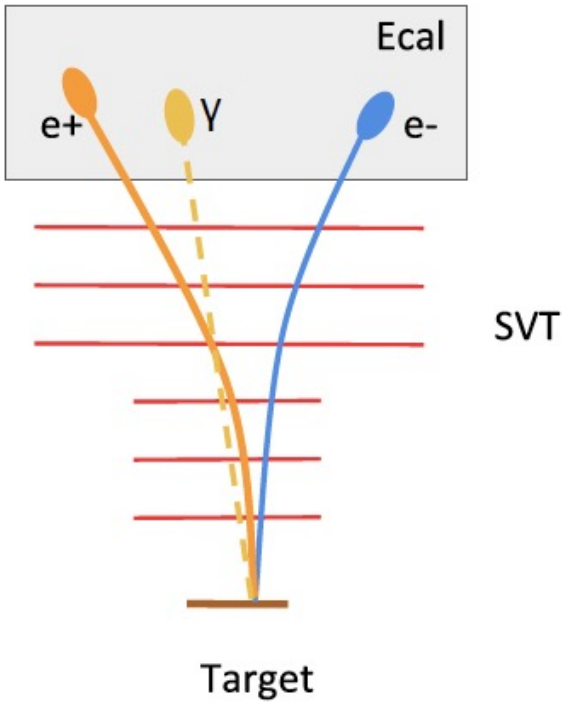
HPS detector

- Silicon Vertex Tracker (SVT) measures trajectories of e+e- and **reconstructs mass and vertex position**



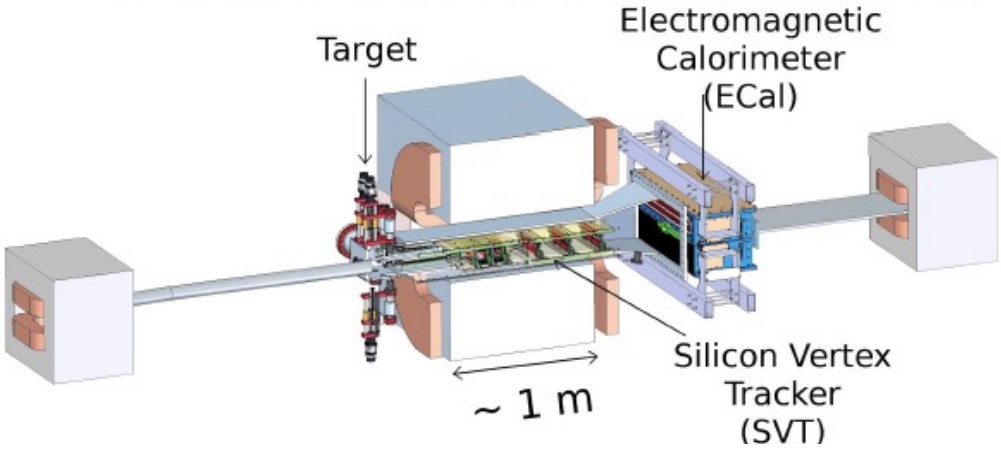
HPS detector

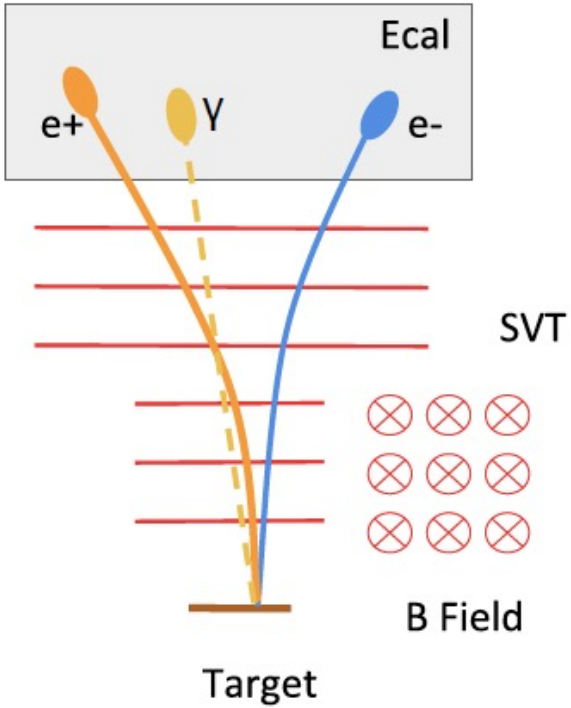
- Silicon Vertex Tracker (SVT) measures trajectories of e+e- and **reconstructs mass and vertex position**
- Electromagnetic Calorimeter (Ecal) provides **e+e- pair trigger with precision timing**



HPS detector

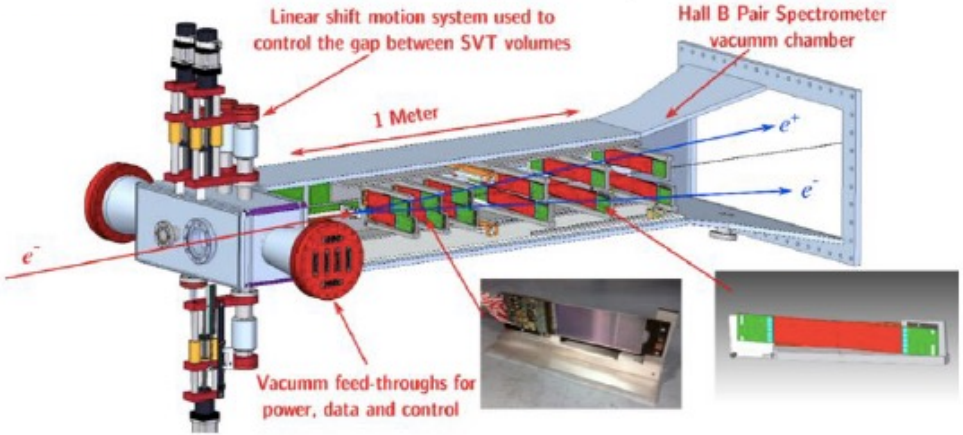
- Silicon Vertex Tracker (SVT) measures trajectories of e+e- and **reconstructs mass and vertex position**
- Electromagnetic Calorimeter (Ecal) provides **e+e- pair trigger with precision timing**
- Dipole magnet spreads e+e- pairs and provides curvature for momentum measurement and PID

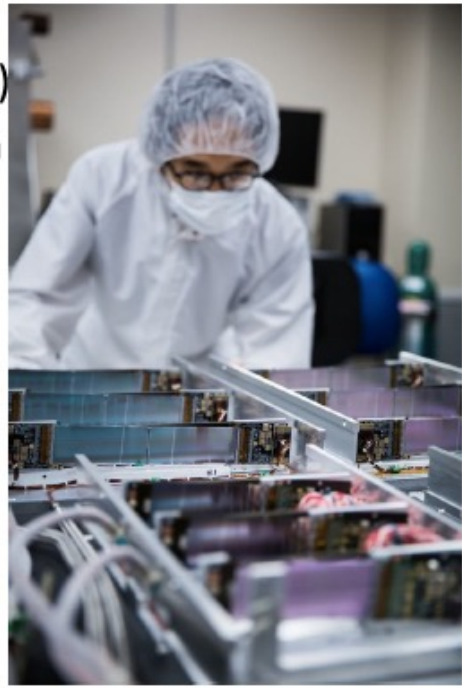




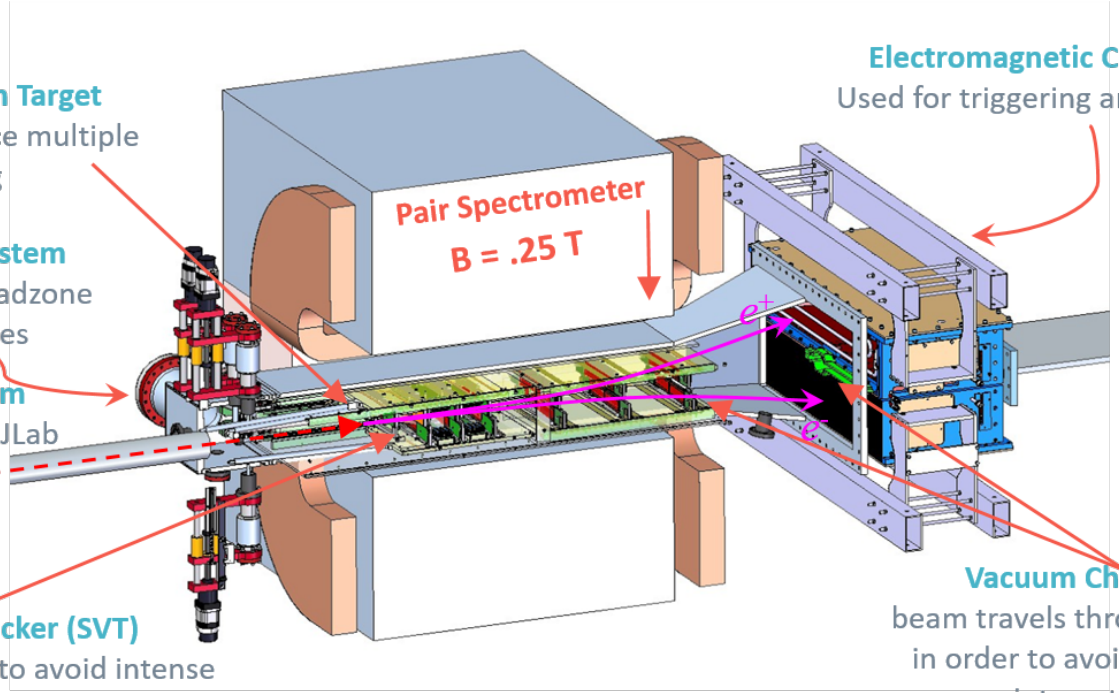
HPS Silicon Vertex Tracker

- Detector (vertical) acceptance down to +/- 15 mrad (which means L1 of SVT is **0.5 mm from beam axis!**). Split into two top/bottom halves
- 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





HPS Silicon Vertex Tracker



~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

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

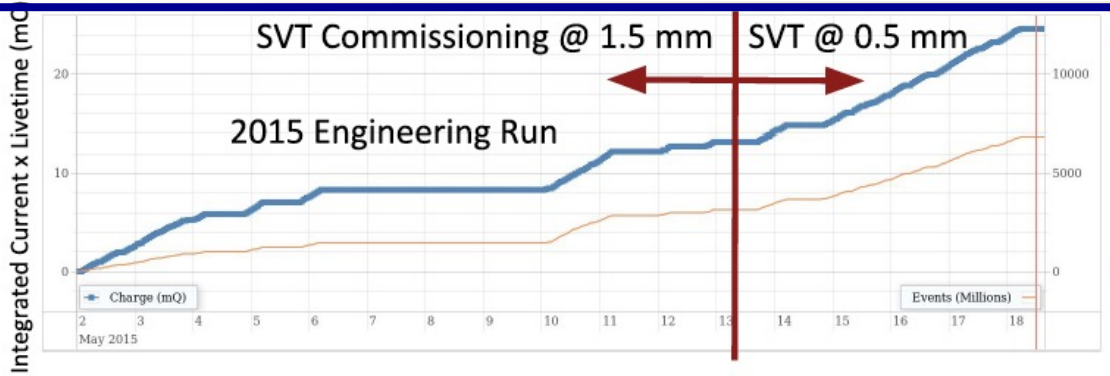
Electromagnetic Calorimeter
Used for triggering and particle ID

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

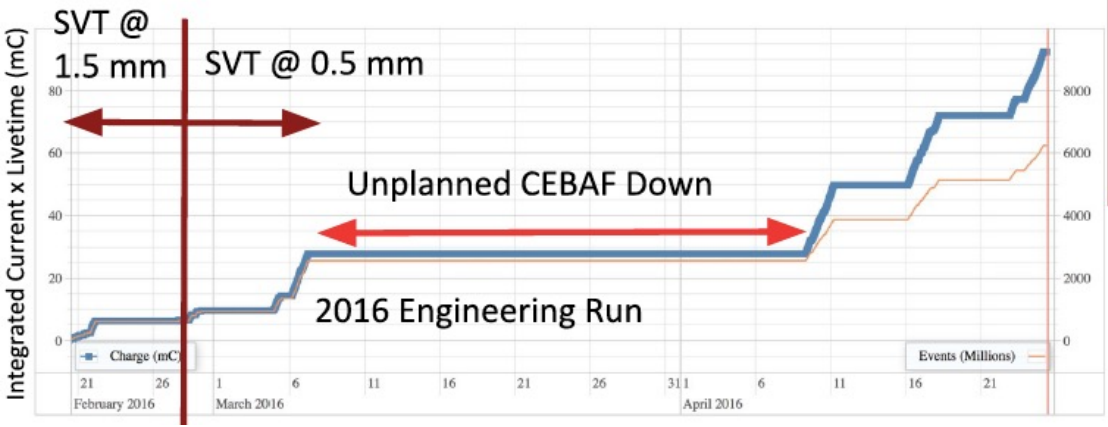
SVT + ECal DAQ capable of 50 kHz

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

HPS DATA TAKING



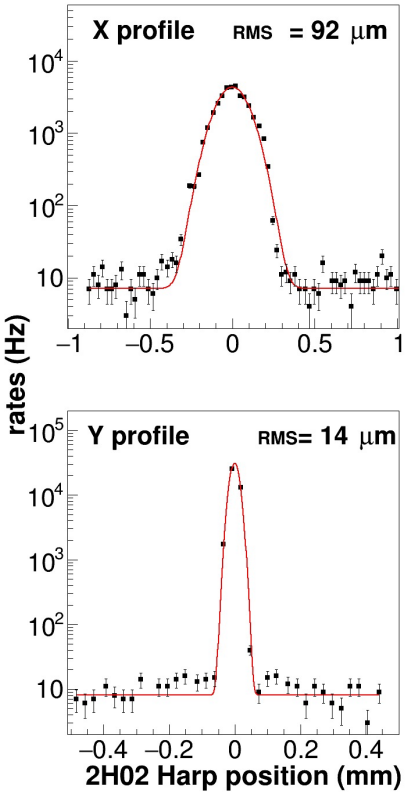
2015 Engineering Run
50 nA at 1.06 GeV
1.7 days (10 mC) of physics data



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!

Beam Quality

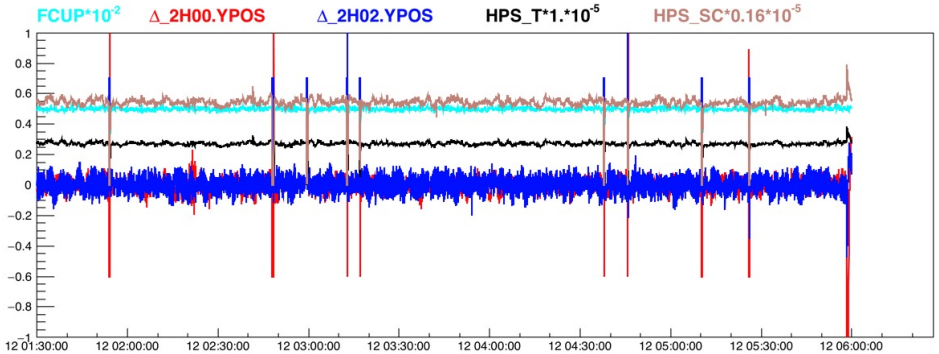


2016 Beam profile

- HPS requires a very high quality beam, with very low halo.
  - σ_X ~ 30 -100 μm - To spread heat load.
  - σ_Y ~ 15 - 50 μm - To help vertexting & tracking.

- The beam also needs to be very stable over time.

A Fast Shut-Down stops the beam in <10 ms, if halo counters register above threshold counts.

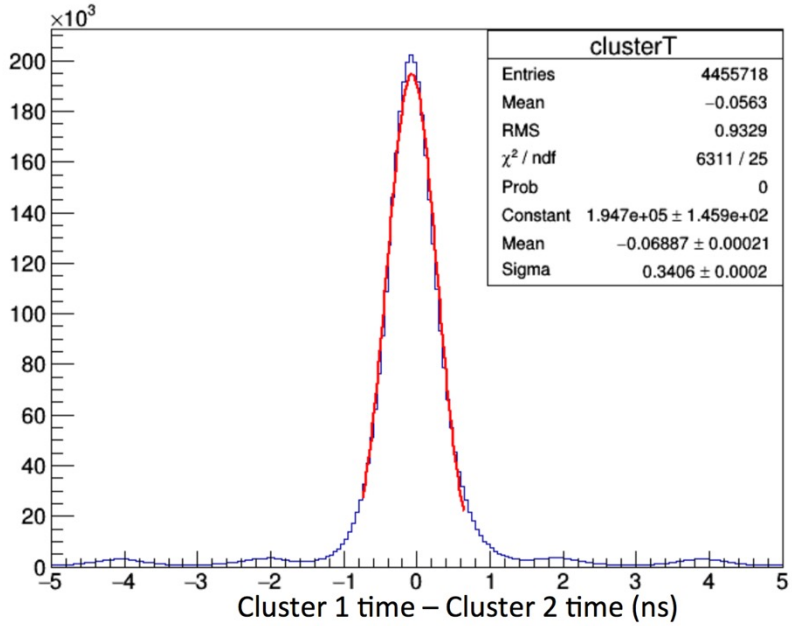


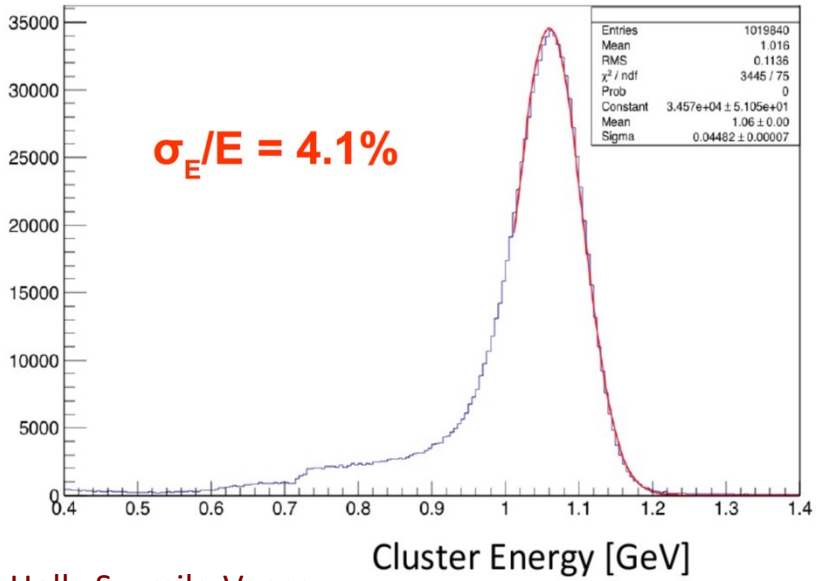
E- CAL performances

Full energy electrons used for calibration

Timing resolution ~ 340 ps

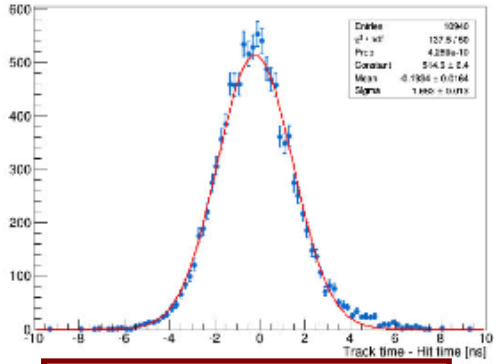
Energy resolution ~ 4%





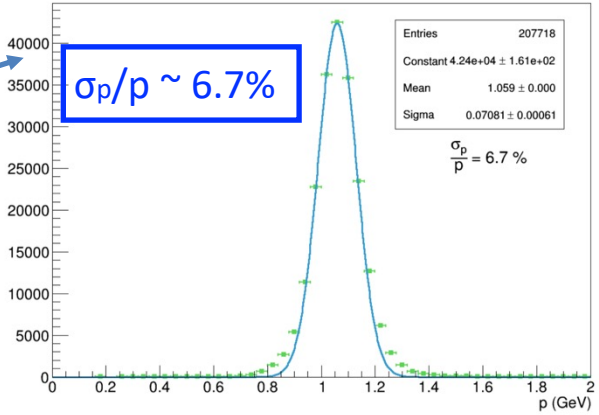
By Holly Szumila-Vance

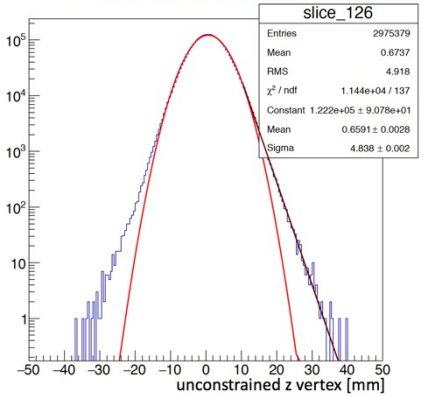
Tracker performances

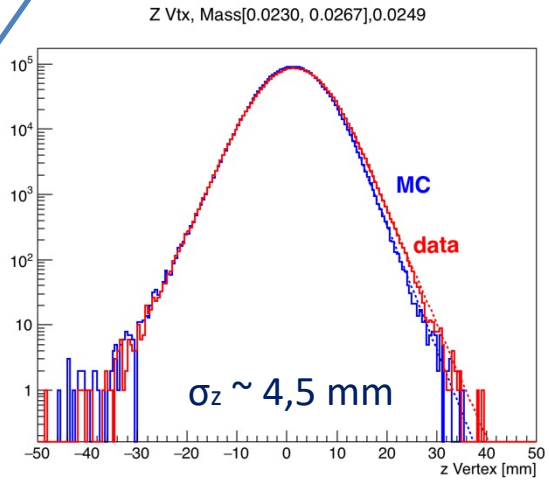


2.2 ns hit time resolution

Tracker has good timing and momentum resolution.



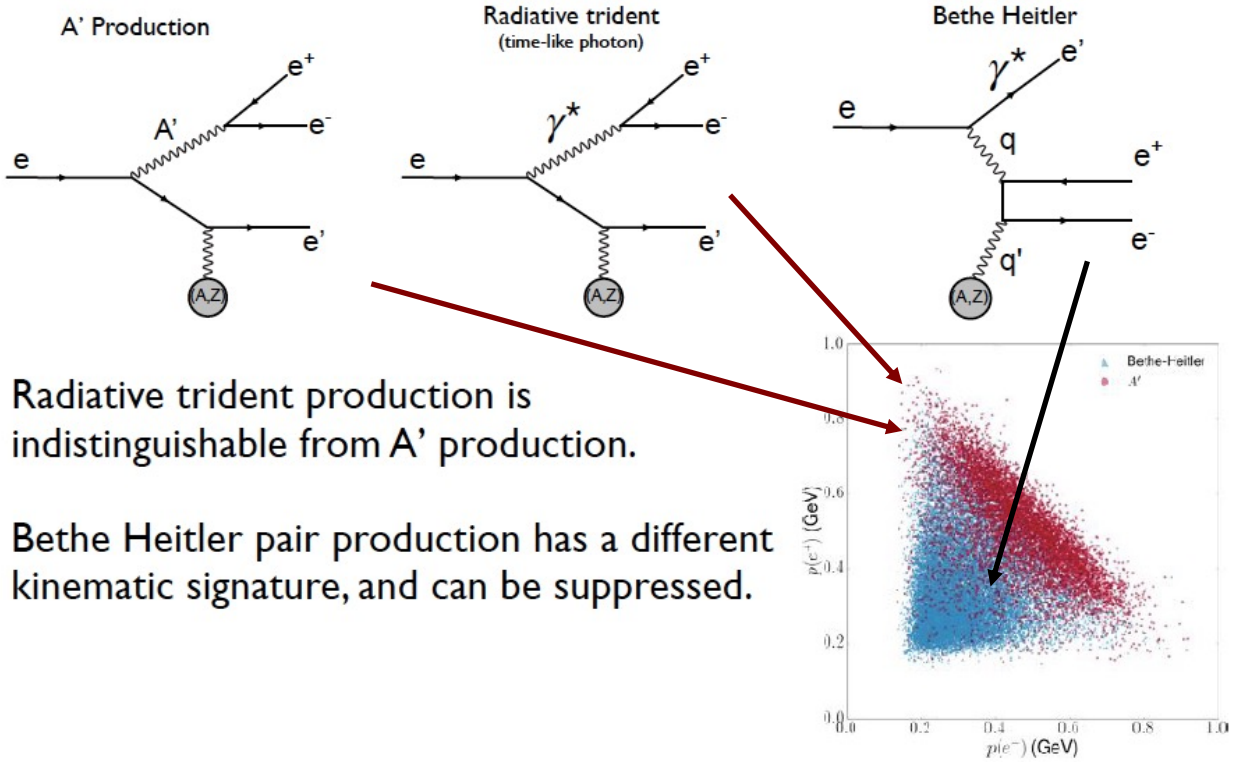




Very good vertex resolution for small angle tracks!

Track vertexes are well understood and agree with MC.

QED Backgrounds



Radiative trident production is indistinguishable from A' production.

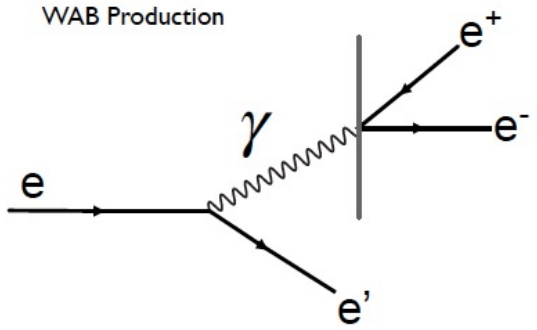
Bethe Heitler pair production has a different kinematic signature, and can be suppressed.

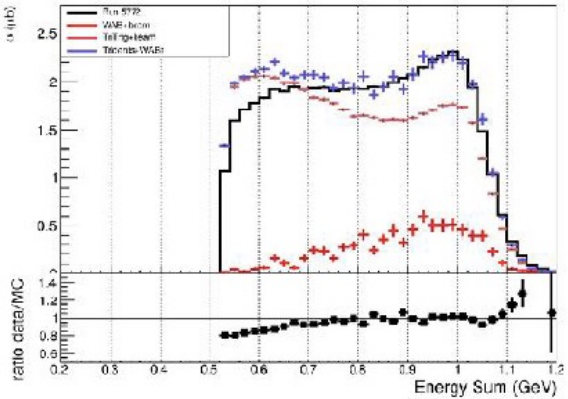
Background: WAB

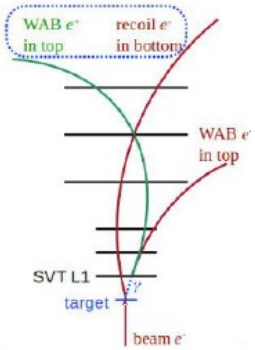
Wide Angle Bremsstrahlung (WAB) followed by a conversion of the photon was an unexpected background in the experiment.

This is not in the standard MC codes, because of approximations.

Once added, data and MC are in good agreement.





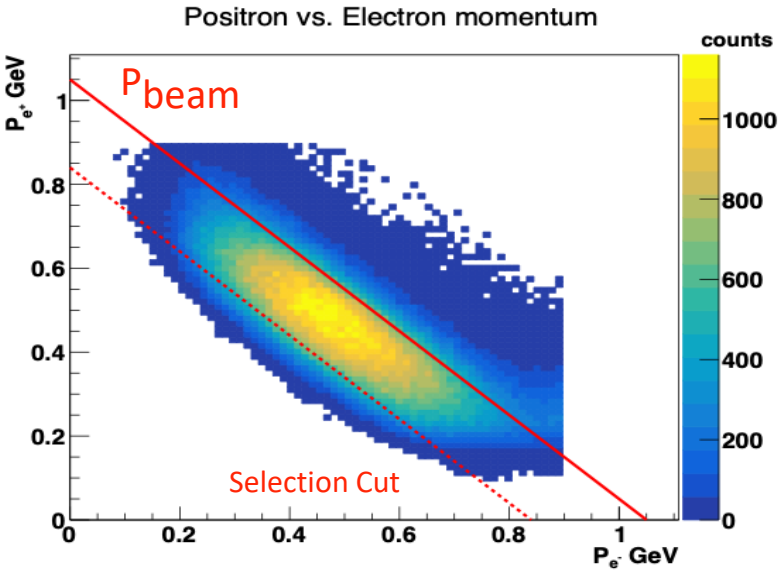


Selected track pairs

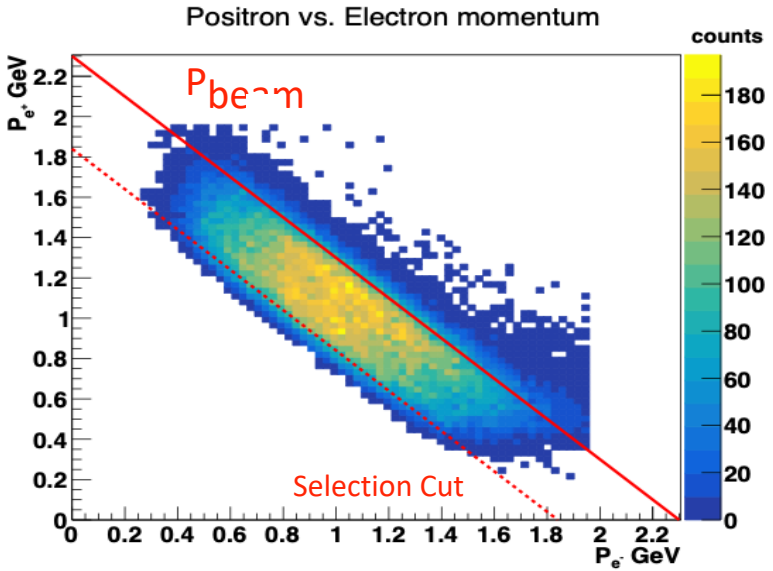
Selection cut: $0.8\ P_{beam} < P_{e+} + P_{e-} < 1.2 P_{beam}$

Selects A' signal over Bethe-Heitler background

$E_{beam} = 1.05$ GeV

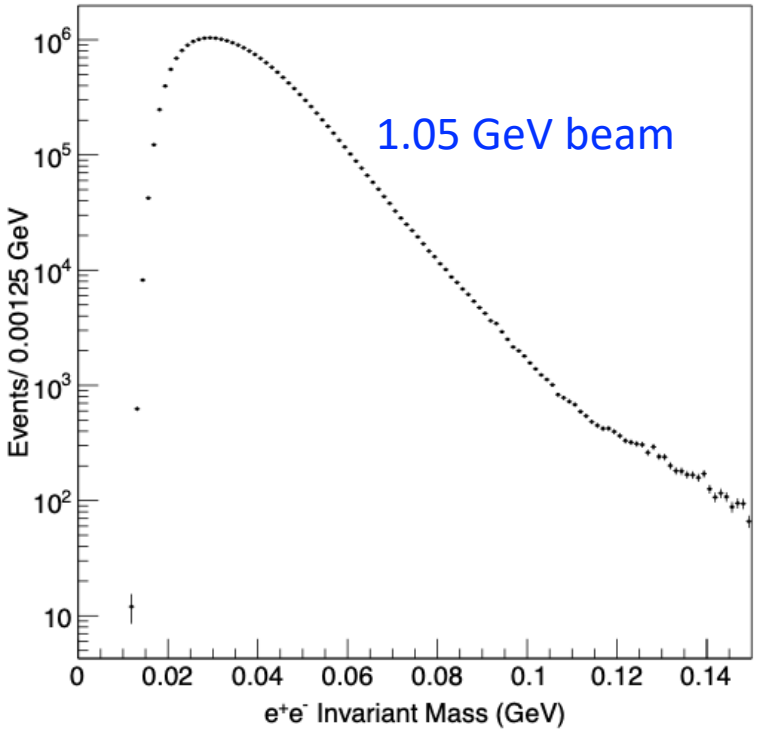


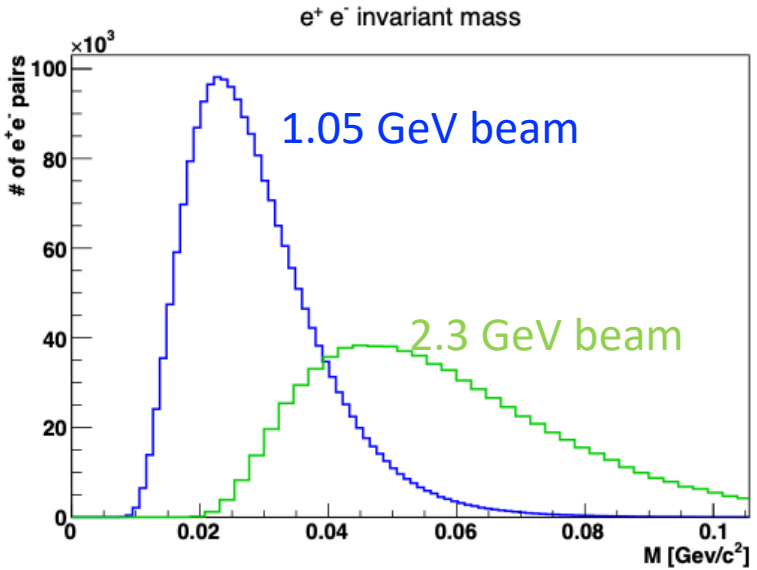
$E_{beam} = 2.3$ GeV



Bump Hunting - Pair Mass Distribution

e^+e^- pair invariant mass distribution for 2015 run





On a linear scale, tiny fraction of the data to illustrate relative mass coverage of different beam energies.

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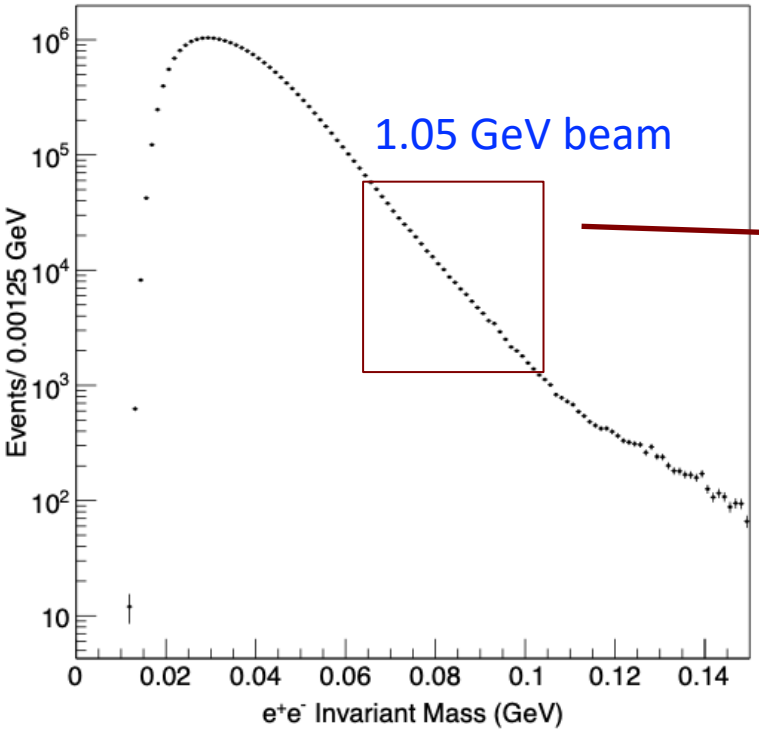
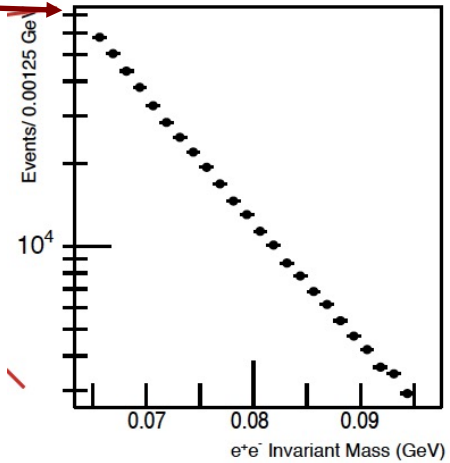
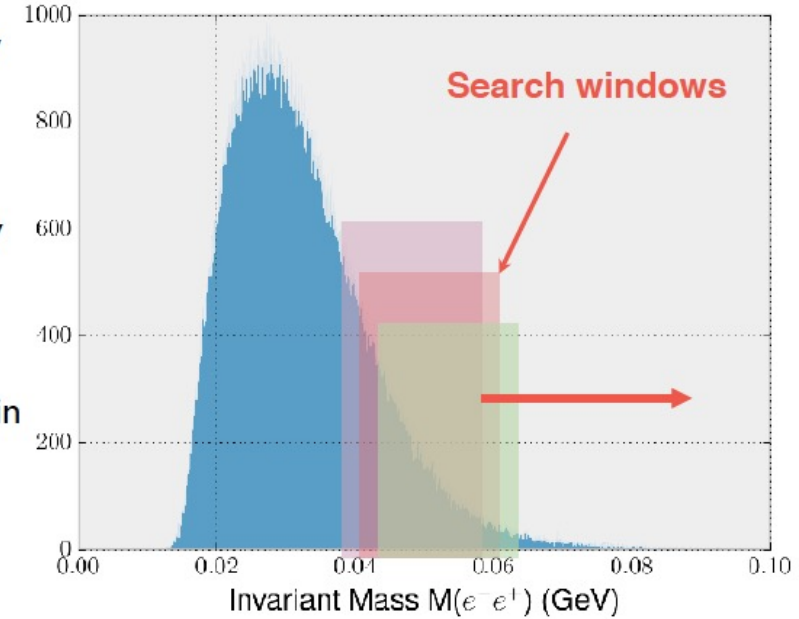


Zooming in shows that even for the limited run, the distribution is very smooth.



Bump Hunting – Resonance search

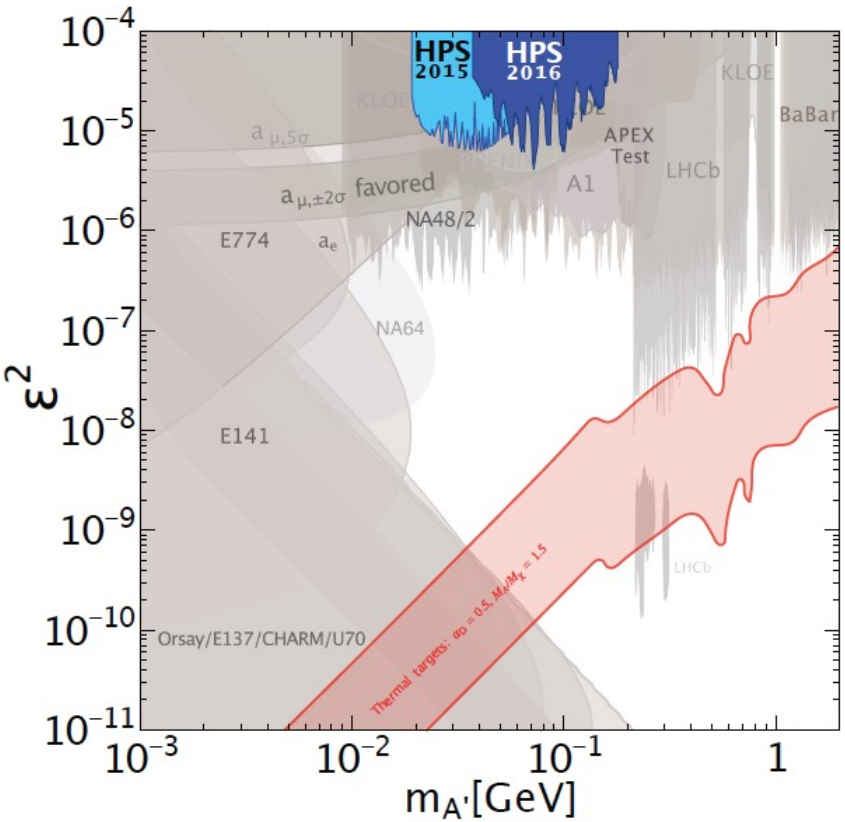
- Search for a resonance within a window in the mass range between 19 MeV and 81 MeV by scanning the e+e- invariant mass spectrum in 0.5 MeV step sizes.
- Maximize the Poisson likelihood within the range using a composite model with the signal described as a Gaussian and an exponential of a polynomial 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, taking into account the "look elsewhere effect".
- Translate the signal upper limit in to the coupling-mass phase space.



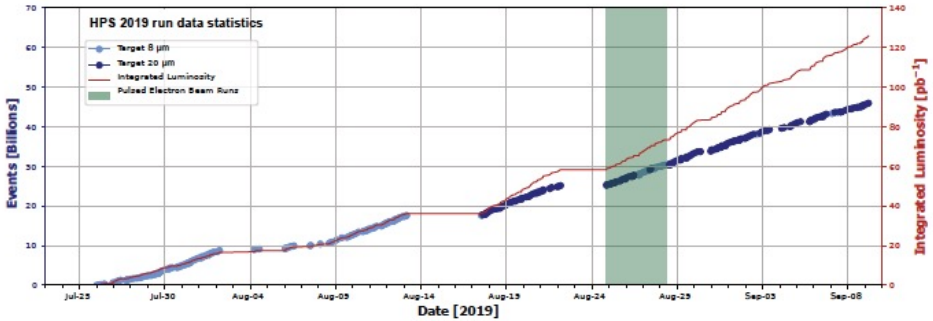
2σ upper limit on reach plot

2015 and 2016
Engineering runs did not have enough data to set a new limit.

This was only
1.7 days (10 mC @ 1.06 GeV)
5.4 days (92.5 mC @ 2.3 GeV)
of data, out of a total of 180 PAC days for the experiment.



2019 data – detached vertex search

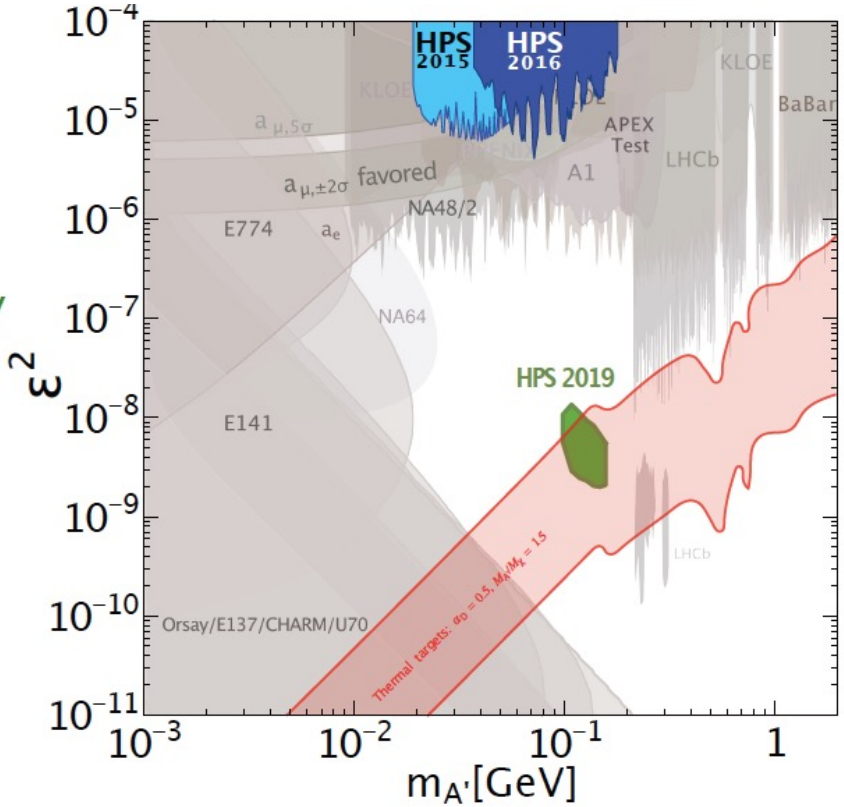


- First data run for HPS in 2019 with E_{beam} = 4.55 GeV
- About 26 days of beam on target, 255 mC of charge.
- Integrated luminosity ~ 128 pb^{-1}
- Upgraded detector to improve physics sensitivity:
  - Improve trigger by adding a hodoscope
  - Improve vertex resolution with added SVT layer
  - Improve acceptance by moving SVT layers

2019 data – projected reach

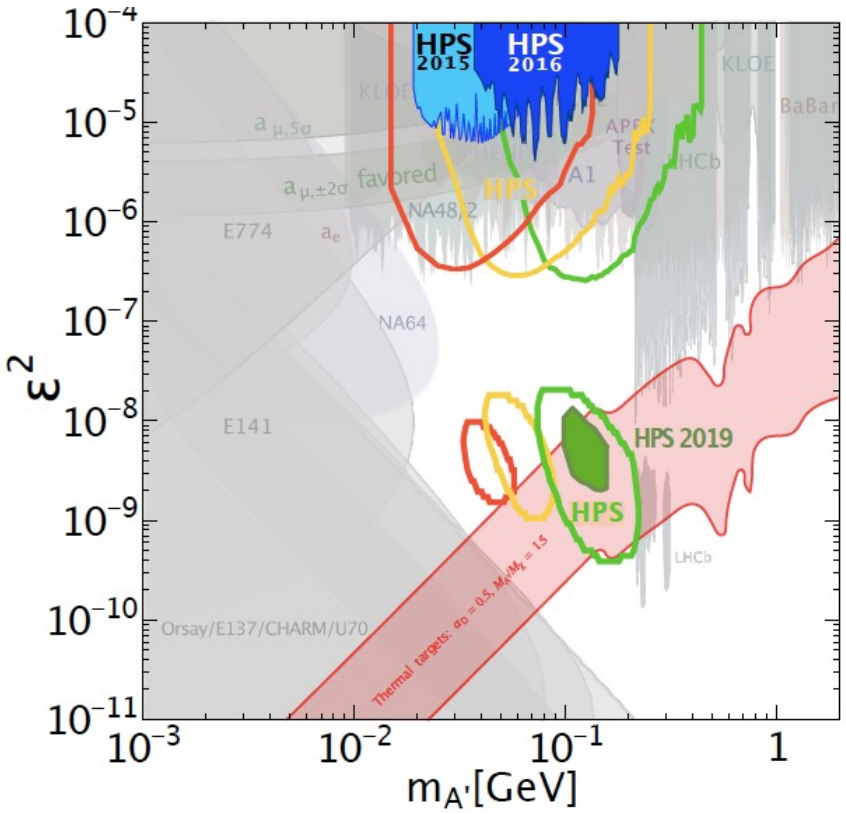
HPS Projected Reach with upgraded detector.

Summer 2019 Run
2 PAC Weeks @ 4.55 GeV



2019 + 2021 data – projected reach

HPS Projected Reach with upgraded detector.

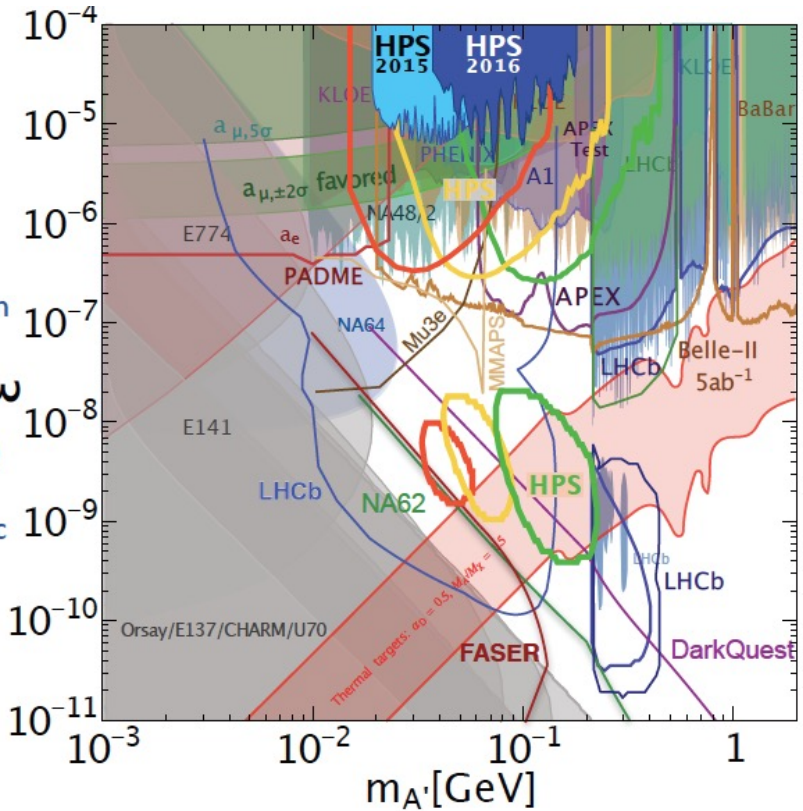


2019 + 2021 data – projected reach

All experiments with projected reach at 90% exclusion limits.

Warnings:

- Not all systematics are generally taken into account.
- Experiments often do not quite get what they hope for.
- Combining these curves is not (quite) as simple as this plot.
- Models with only leptonic or hadronic couplings evade many bounds.
- Above ~ 500 MeV in $M_{A'}$ this gets really hard!



Conclusions

- HPS has already taken several runs.
  - Engineering runs in 2015 and 2016 were successful
  - Showed the concept work and were used to have the rest of beam-time approved

- 2015 bump-hunt results at 1.06 GeV have been published
  PRD 98 (2018) n.9, 09101
- 2016 results on bump-hunt and vertex detection at 2.3 Gev will be published soon

- 2019 data at 4.55 GeV at analysis is in progress

- 2021 data taking at 3.7 GeV will start on August 23rd (vertex electronics upgrade)

- More data runs at 1.1 GeV and 2.3 GeV will improve the reach at lower A' masses.

Thank you !