The Heavy Photon Search experiment at Jefferson Lab

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on behalf of HPS collaboration

ICHEP2016

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Outline

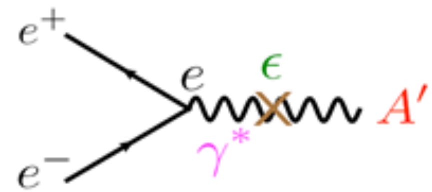
- Motivation
  - What is heavy/dark photon
  - How to detect dark photon
- Setup
  - Silicon Vertex Tracker
  - Electromagnetic Calorimeter
- Performance
  - 2015 Run
  - 2016 Run

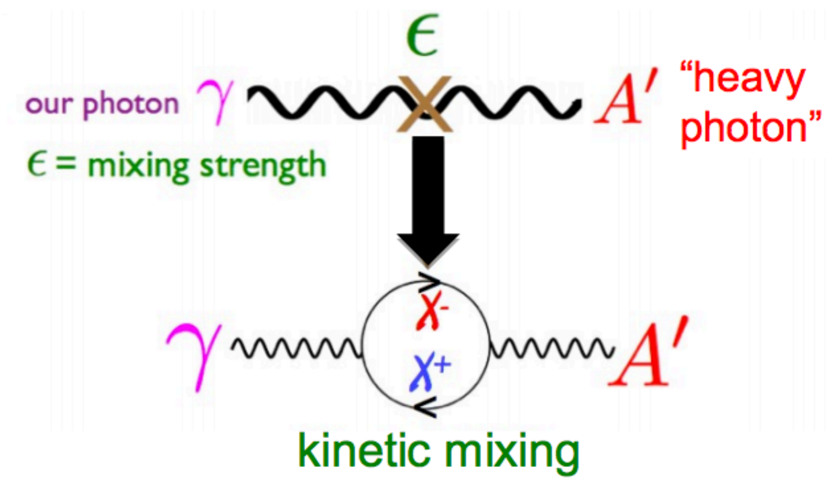
What is a Dark Photon?

- Nature may have an additional *U(1)* symmetry. (*Holdom, Phys. Lett B166, 1986*)

- This gives rise to a **kinetic mixing** term where the photon mixes with a new gauge boson ("dark/heavy photon" or *A'*) through the interactions of massive fields → induces a weak coupling to electric charge

- 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^-





Where to look for a Dark Photon?

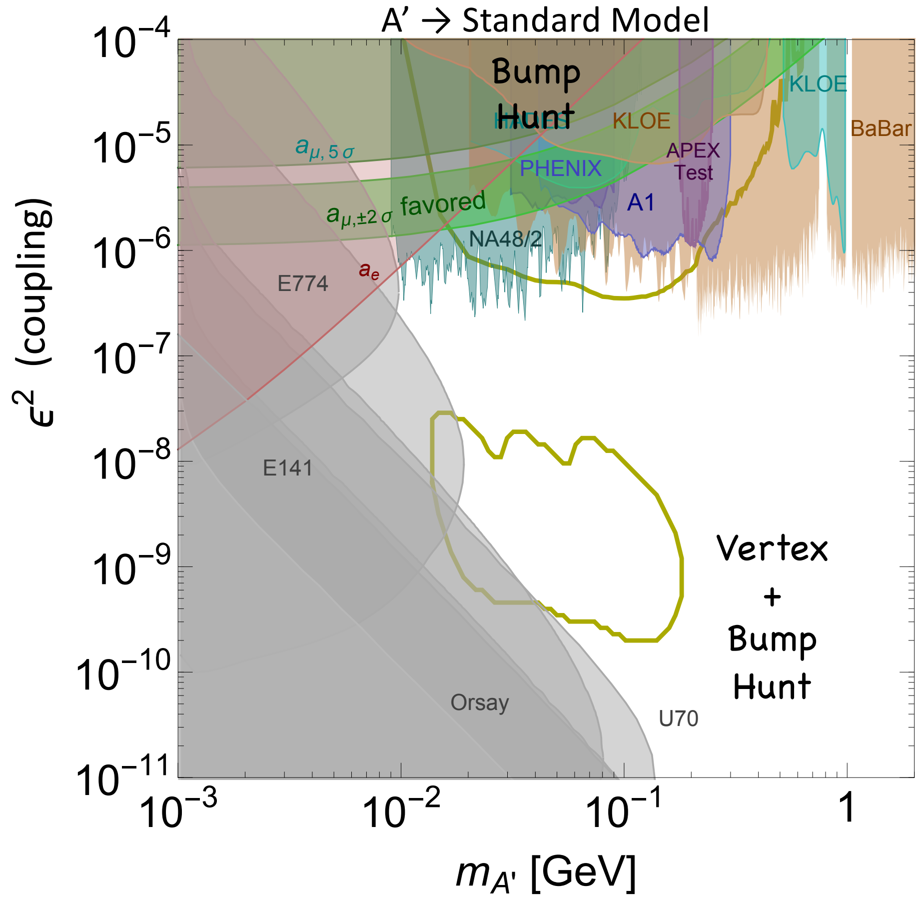
- Heavy photons could explain experimental anomalies in particle physics and astrophysics

- A' is characterized by its mass $m_{A'}$, coupling to charge εe.

- Mass range is limited on the left by detector acceptance, on the right by production cross-section

- Resonance search reach is limited on the bottom by statistics

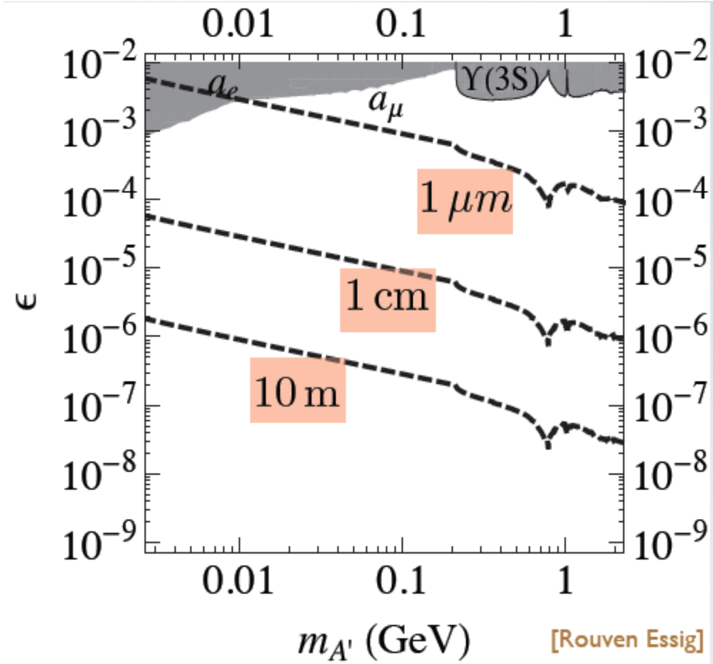
- Vertexing reach is limited on the upper right by the resolvable decay length (tails of the trident vertex distribution)



HPS in a search for Heavy Photons

- **HPS is a new, special purpose experiment**, dedicated to searching for an A' decaying to e^+e^- in the unique territory with $\varepsilon << 10^{-3}$ which is accessible with a vertex detector.
- **Small couplings means very few events** what requires lots of luminosity.
- **Lots of luminosity means lots of background, low Signal/Background.**
- **But small couplings also make the A' long-lived**. (A powerful secondary vertex signature)
- **It's all in the tails!** The A' decay length signal is in the tails of the prompt trident signal. Understanding and controlling the tails of the trident vertex distribution are crucial!

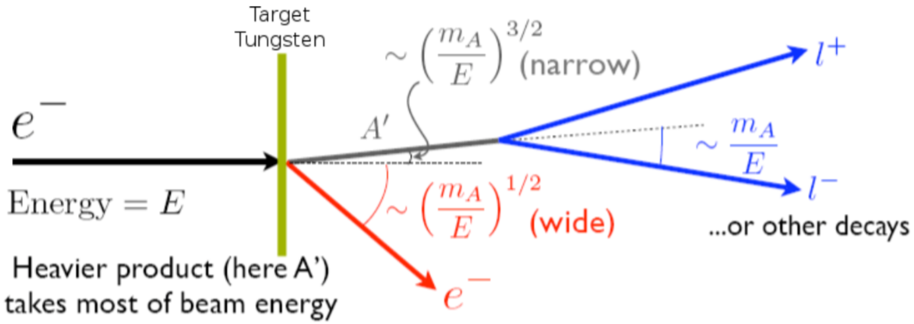
Decay Length $c\tau$



HPS – Fixed Target Experiment

- Even though A' particles are produced by a process analogous to ordinary photon bremsstrahlung, the rate and kinematics differ in several key ways:

  - The A' productions cross section is suppressed relative to photon bremsstrahlung by a factor of $m^2_e \varepsilon^2 / m^2_{A'}$



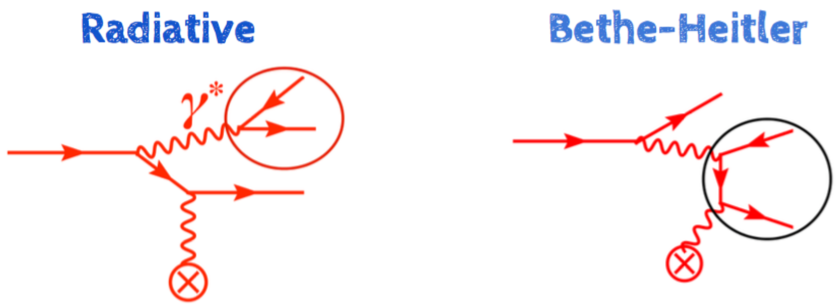
$E_{A'} \approx E_{beam}$
$\theta_{A'} \approx 0$
$\theta_{decay} = m_{A'}/E_{A'}$

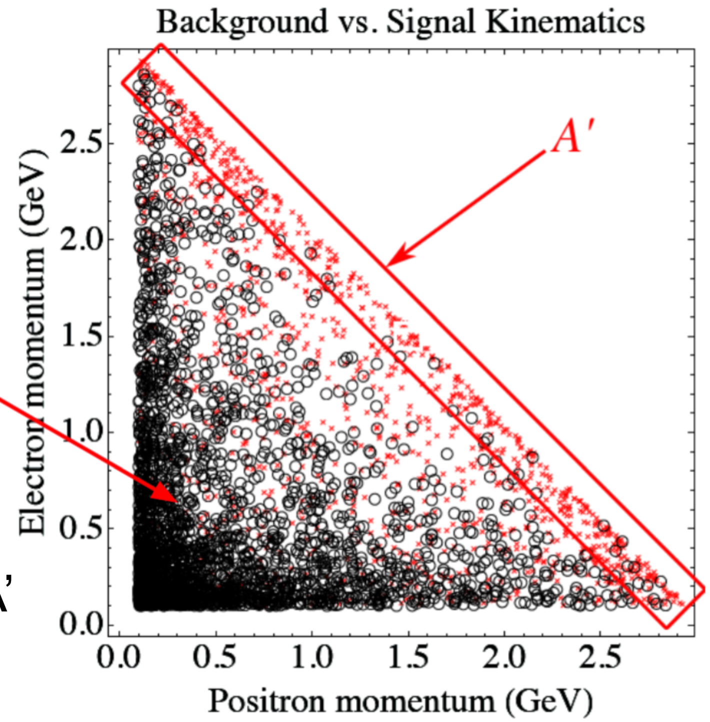
  - The A' is produced very forward → opening angle of its decay products is $\sim m_{A'}/E_{beam}$.

  - The A' will take most of the incident beam energy.

  - Long lived A' will have a displaced vertex → Will help cut down prompt backgrounds.

HPS Backgrounds



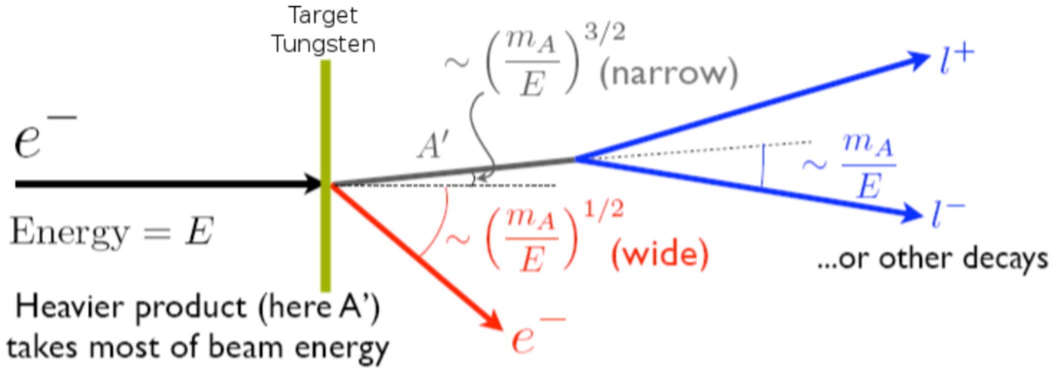


- **Two physics backgrounds collectively known as "tridents":**
  - **Radiative** - Irreducible. Kinematically identical to A' production and decay into e^+e^-
  - **Bethe-Heitler** - Dominant but is also kinematically distinct to the A'. Even after kinematic cuts, Bethe-Heitler dominates.

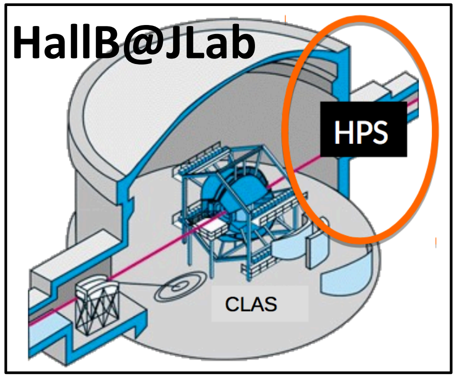
- **Beam Backgrounds**
  - Coulomb scattering in the target
  - Secondary particle production: bremsstrahlung and delta-rays
  - Pair conversion of bremsstrahlung photon

HPS Design Choices

- **Vertexing A' decays requires detectors close to the target**.
- **Invariant mass is an essential signature** Good momentum/mass resolution is required (resonance search).
- **Vertexing** and resonance search need tracking and a magnet. (Displaced Vertex)
- **Trigger with a high rate, radiation hard EM Calorimeter.** Placed downstream of the magnet, it can ID e^+ and e^-.
- Large forward acceptance/moderate currents requires placing **sensors as close as possible to the beam.**
- High occupancy will require **fast readout and trigger system.**



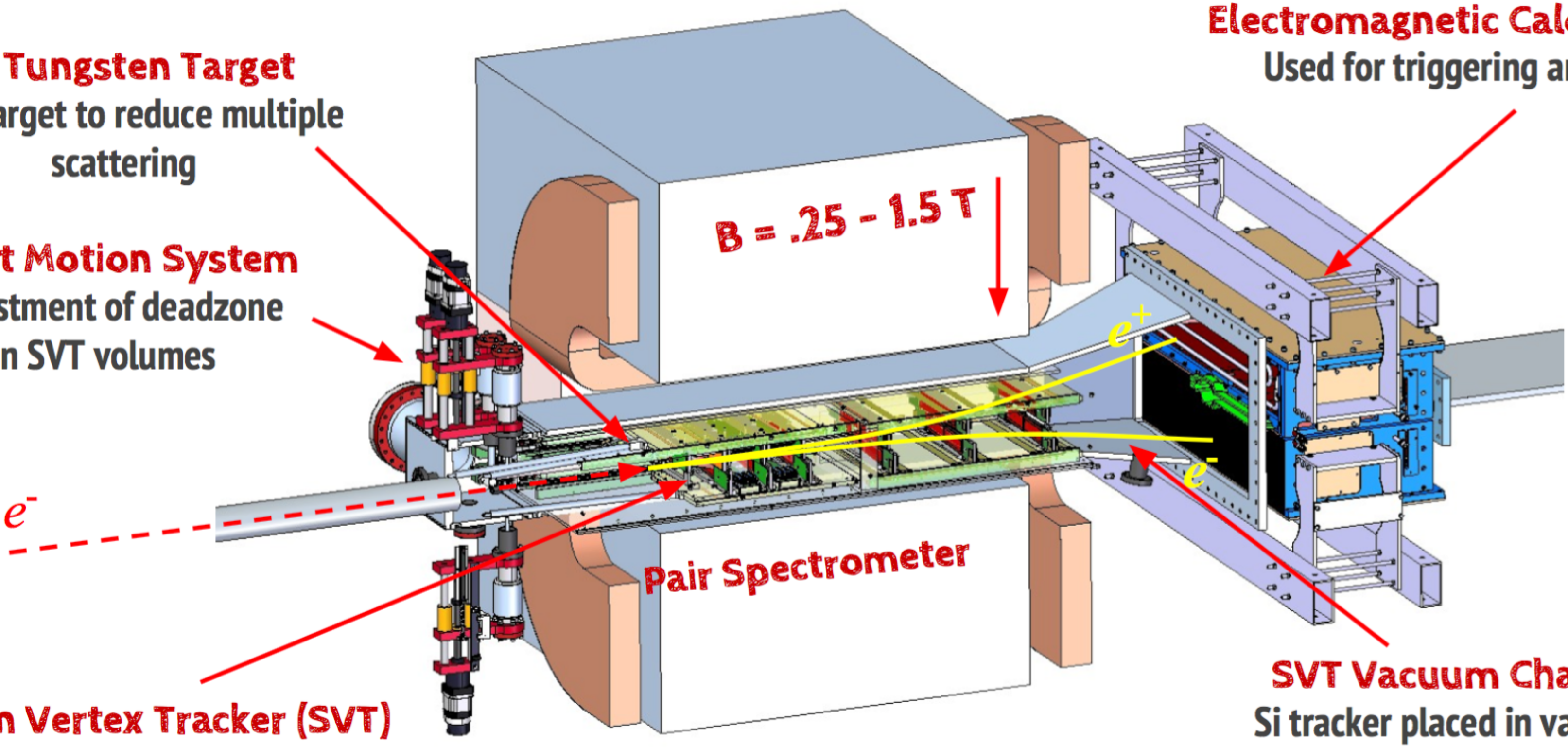
HPS Setup



$\sim 10^{-3}$ X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

Electromagnetic Calorimeter
Used for triggering and particle ID



Silicon Vertex Tracker (SVT)
Used for precise momentum and vertex determination

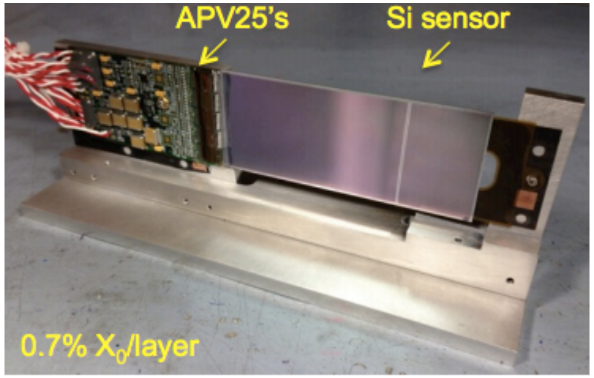
SVT Vacuum Chamber
Si tracker placed in vacuum in order to avoid backgrounds due to beam-gas interactions

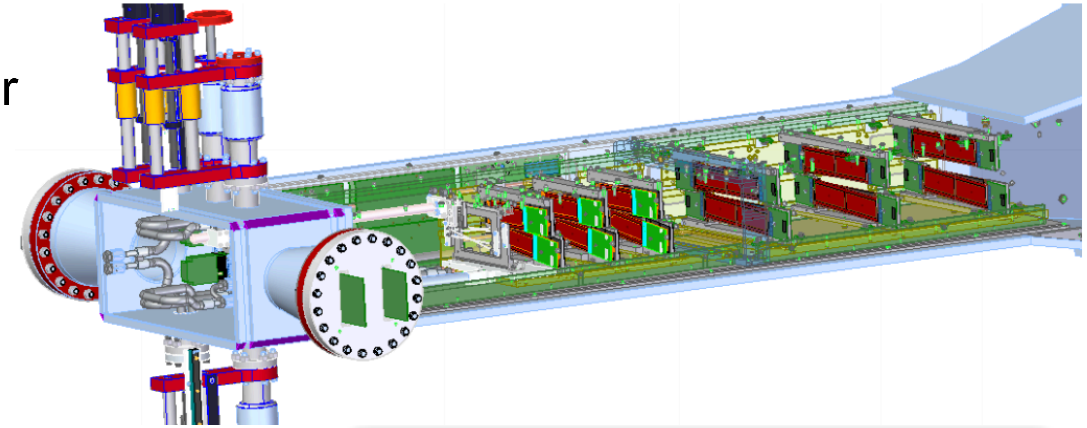
SVT + ECal DAQ capable of 50 kHz

Silicon Vertex Tracker (SVT)

Design:

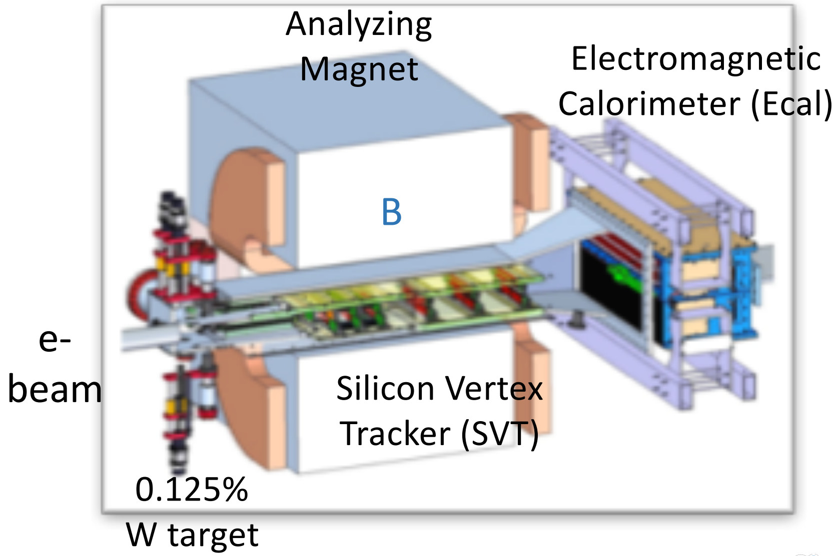
- **Six layers of pairs of Si microstrip sensors** → One axial and the other at small angle stereo (50 or 100 mrad)
- **Layers 4-6 are double width** in order to match calorimeter acceptance
- **Thin layers** in order to reduce multiple scattering (0.7%X_0 /layer)
- Total of 36 sensors and 23004 channels



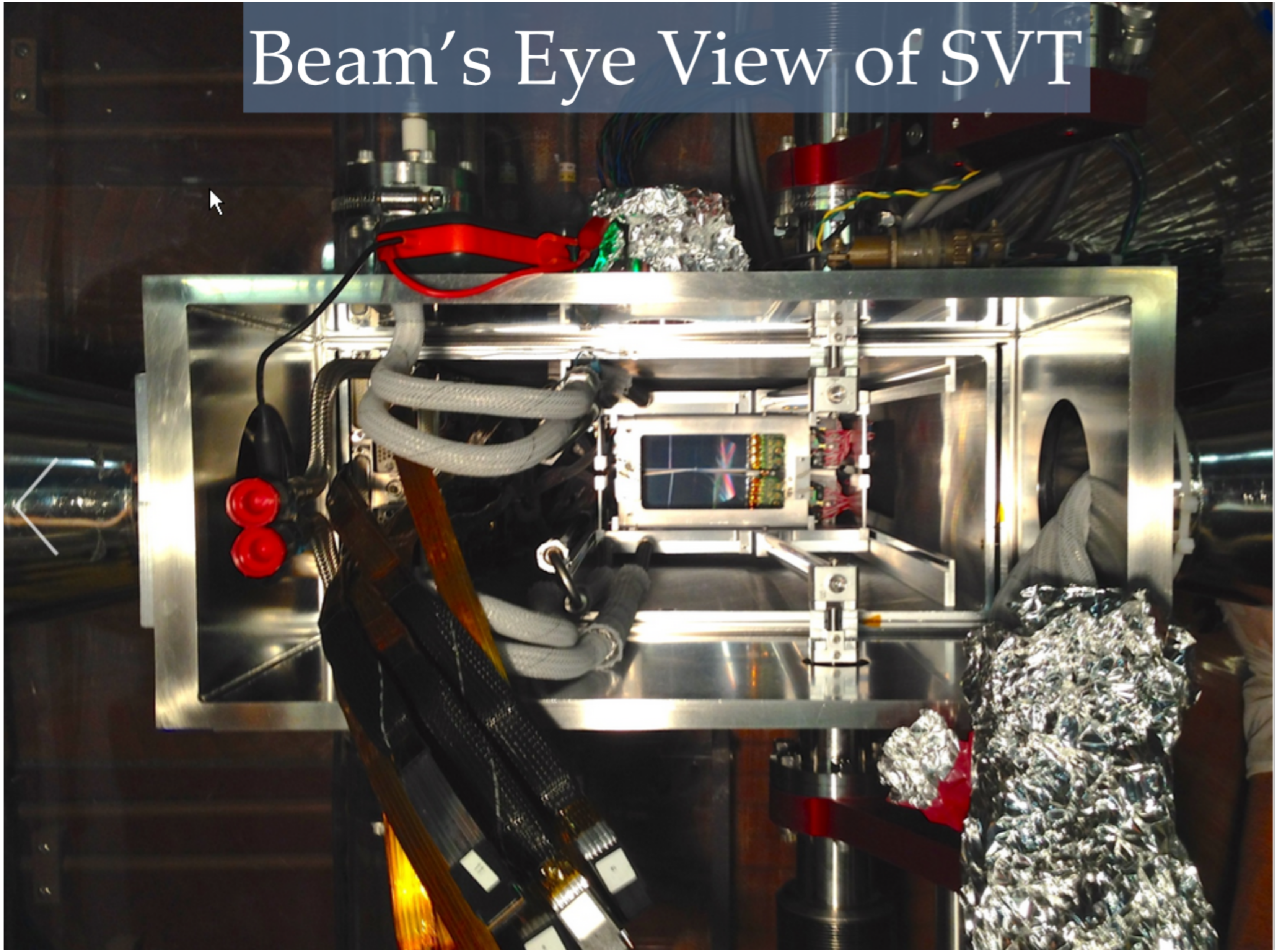


Readout

- Makes use of **APV25 readout chip**
- 40 MHz six sample readout helps achieve a **2 ns t_0 resolution** and fight pileup
- Low noise → S/N > 25
- **High radiation tolerance**

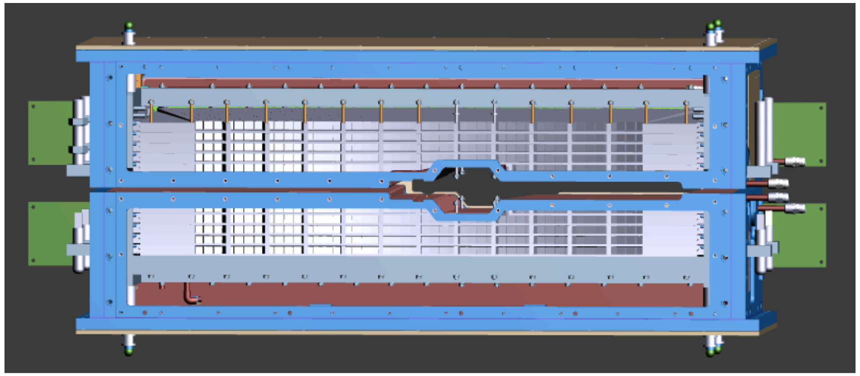


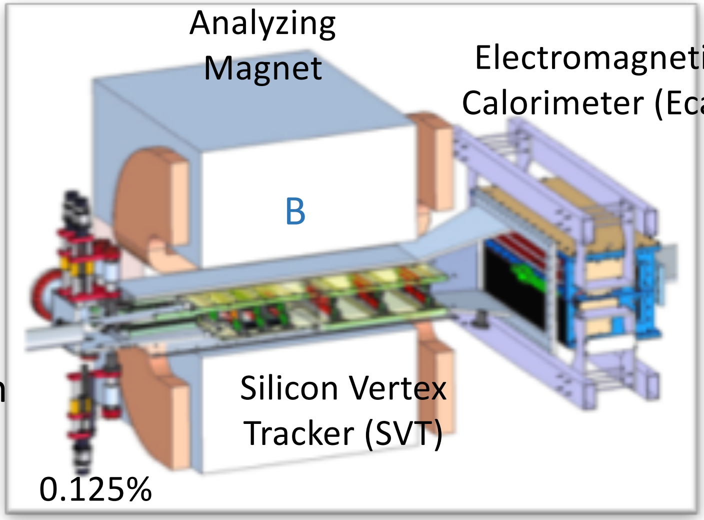
Silicon Vertex Tracker (SVT)



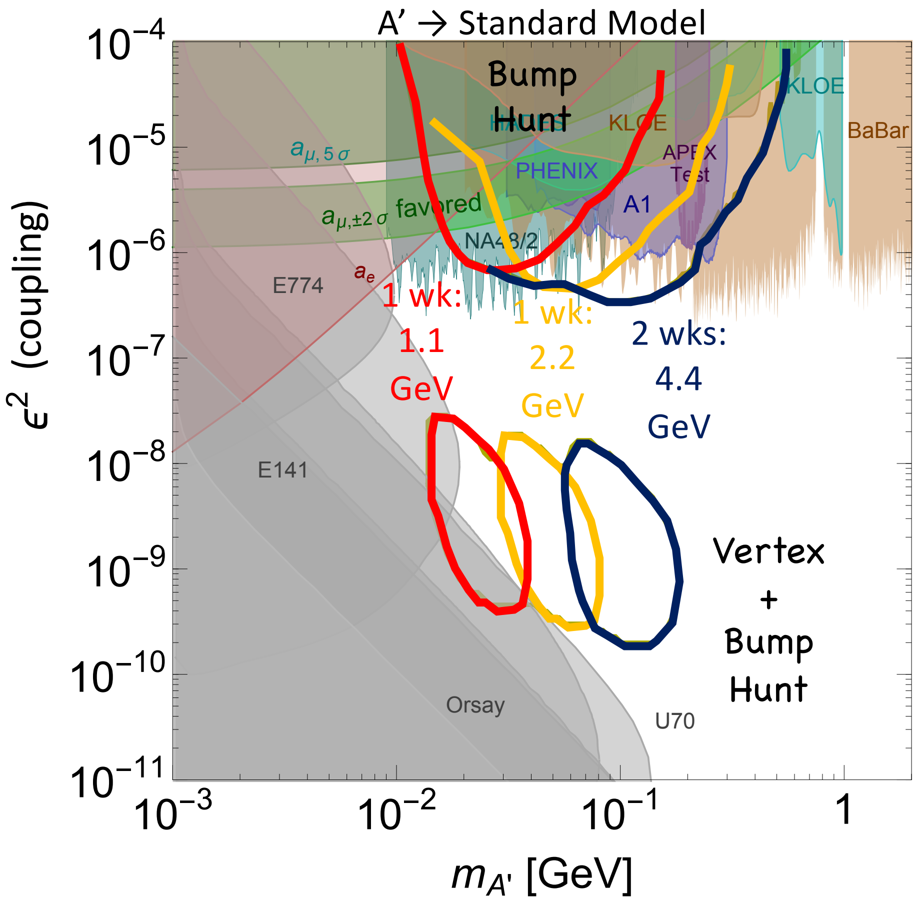
Electromagnetic Calorimeter

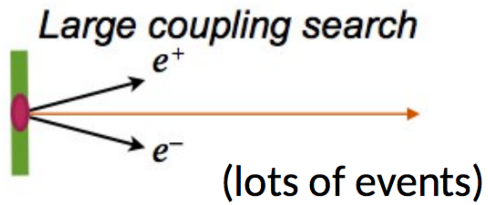
- Build of 442 **$PbW0_4$** crystals readout with **APDs** and preamplifiers
- FADC readout at 250 MHz → allows for a **narrow trigger window (8ns).**
- **FPGA based trigger selection** (Two clusters along with some constraints on their energy and geometry) reduces background trigger rate from 3 MHz to 27 kHz.
- **Trigger and DAQ capable of a rate > 50 kH**
- **Resolution: 4%/√E**





HPS Proposed Program

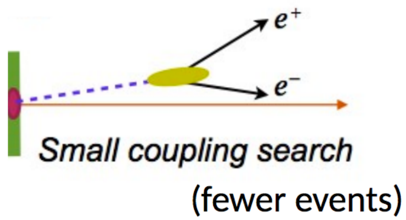




Runs status to date:

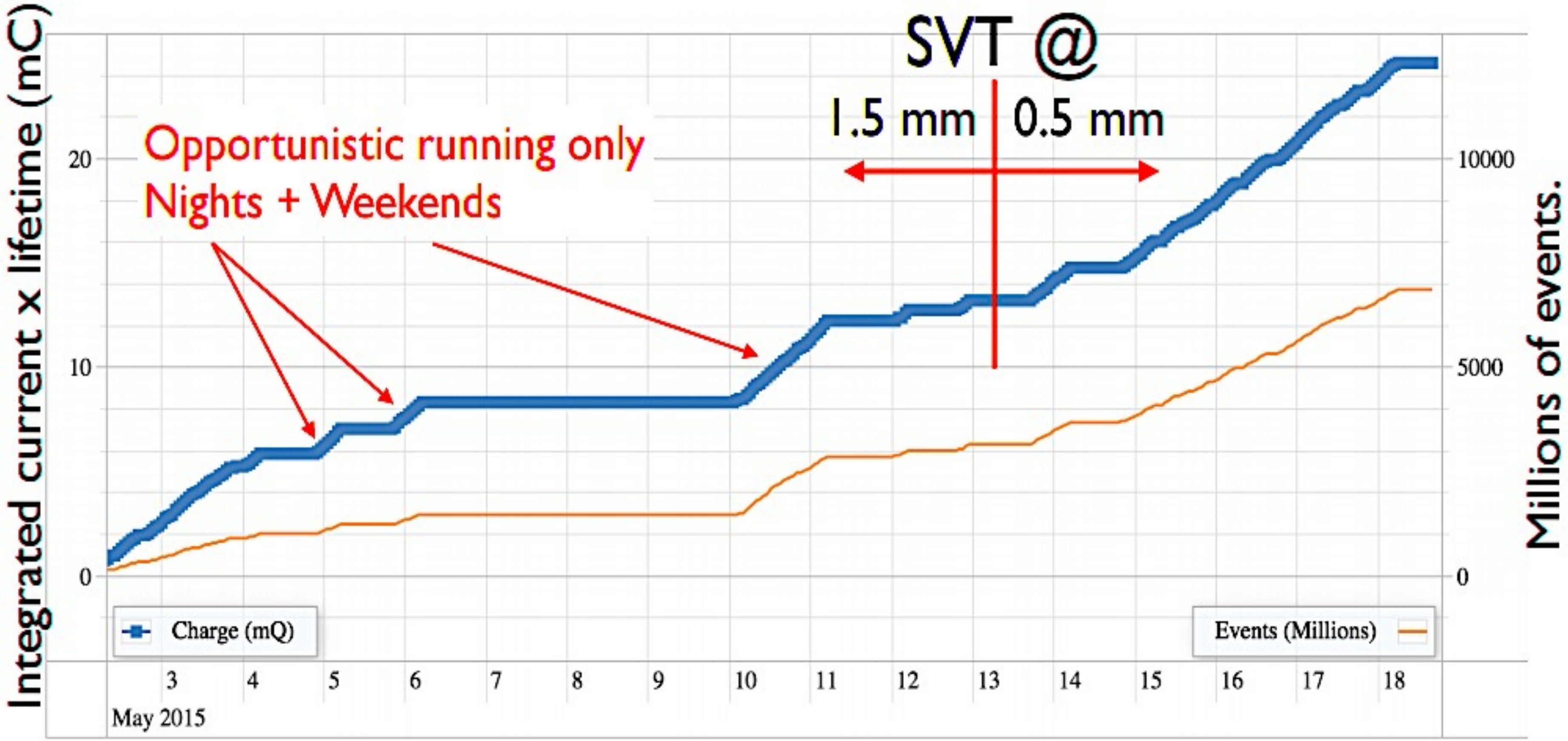
Spring 2015: Engineering Run
1.05 GeV, 50 nA
Achieved ~ 1.6 of 7 proposed days (SVT at 0.5 mm)
~ 1 of 7 proposed days (SVT at 1.5 mm)

Spring 2016: Physics Run
2.3 GeV, 200 nA
Achieved ~5 of 7 proposed days (SVT at 0.5 mm)



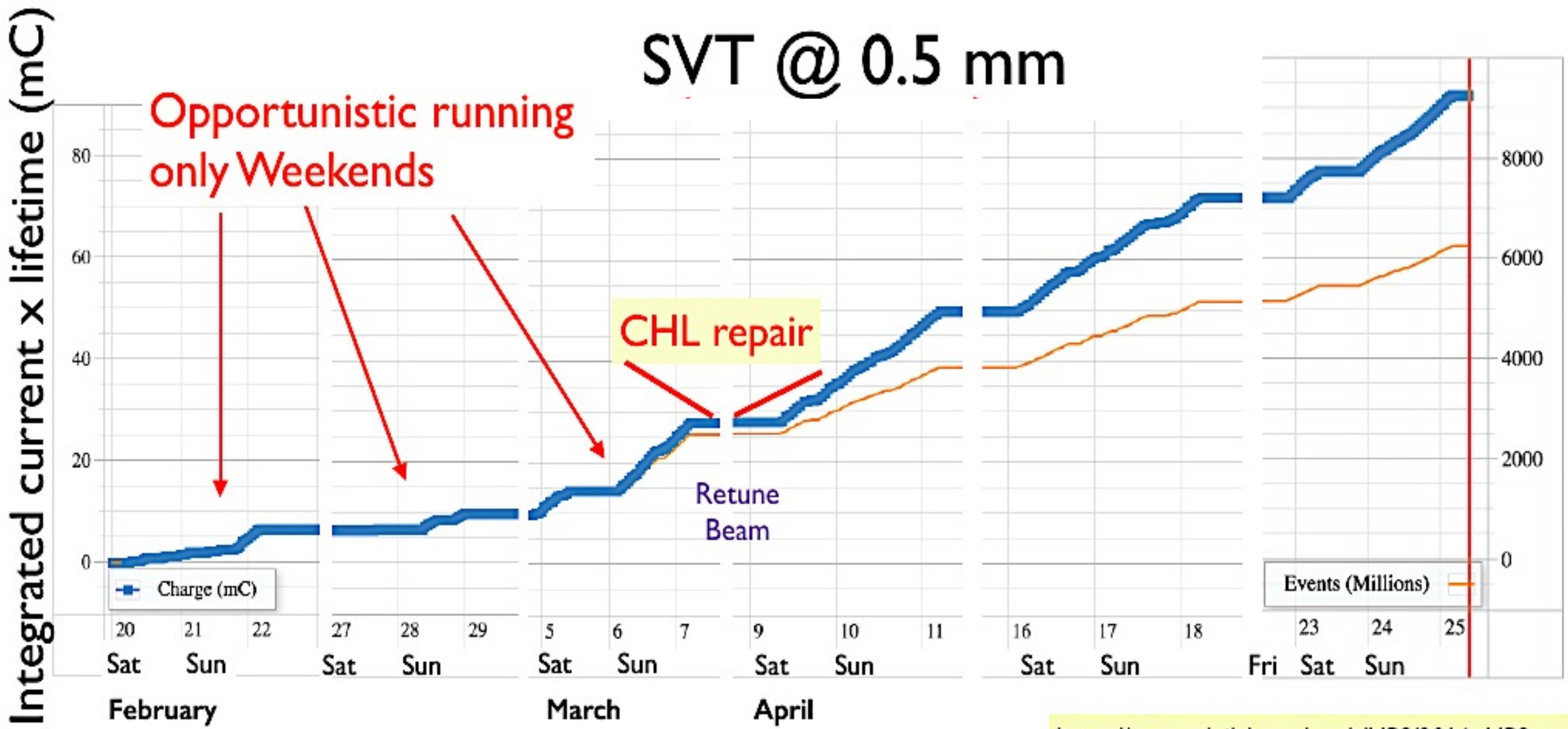
HPS 2015 Run

Goal: 30 mC
Achieved: 10 mC with SVT at +/-1.5 mm, 10 mC with SVT at +/-0.5 mm



HPS 2016 Run

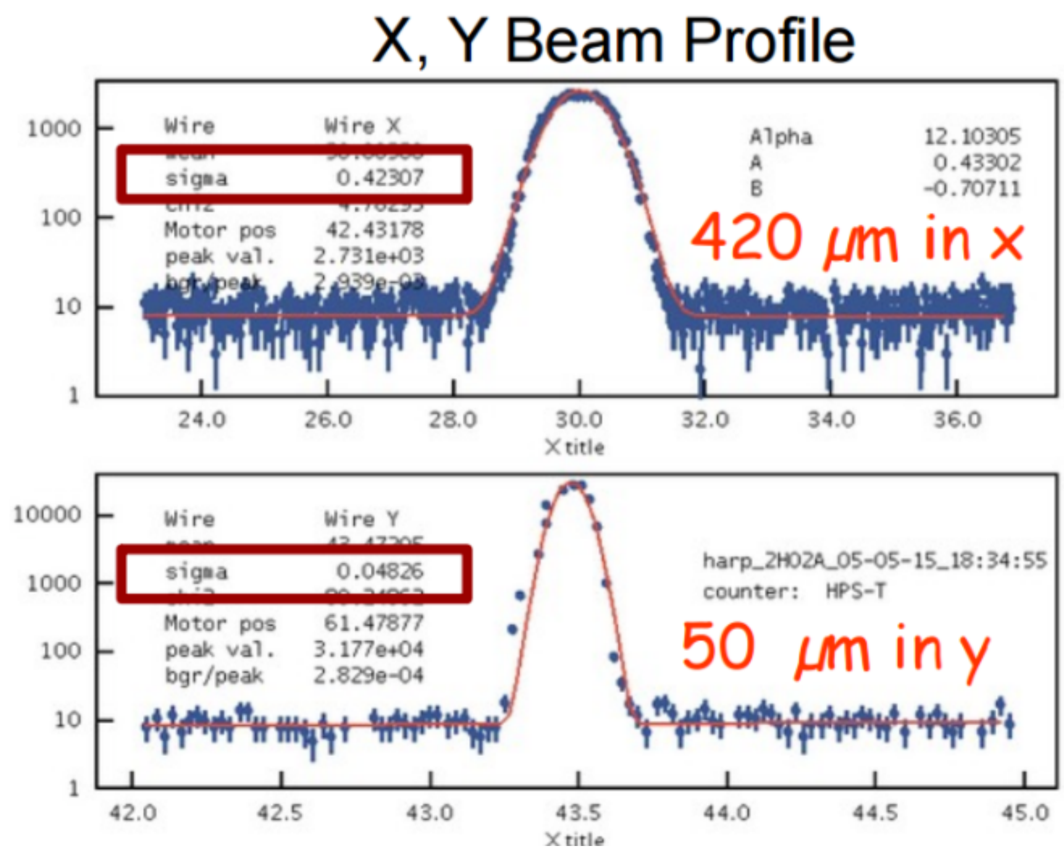
Goal: 120 mC
Achieved: 92.5 mC on target, 6.3 x 10^9 events (77% of proposed running)



https://userweb.jlab.org/~vpk/HPS/2016_HPS_statistics

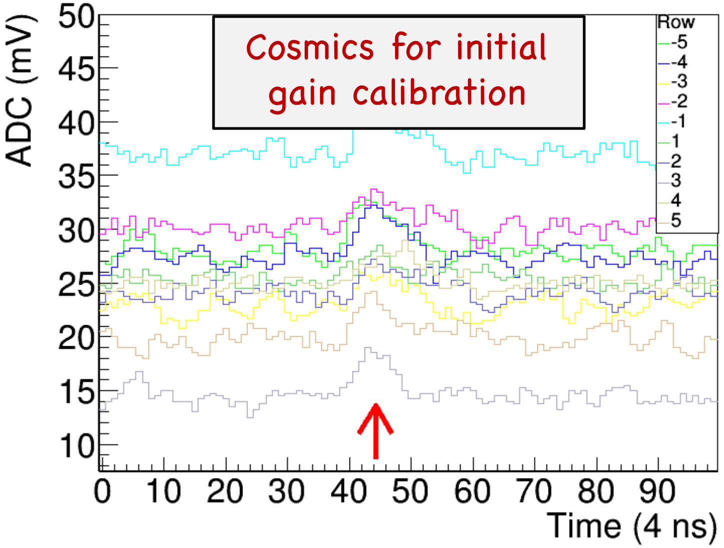
Beam quality

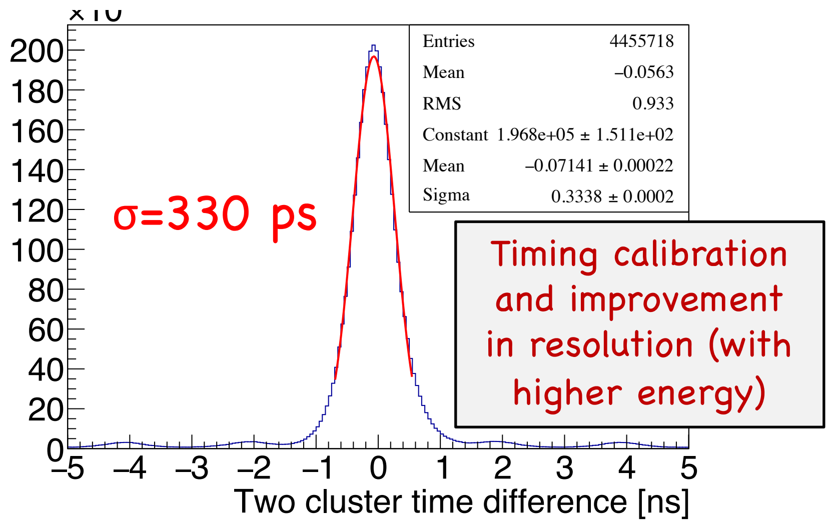
- HPS requires a very high quality beam, with very low halo.
- σ_X ~ 300 to 500 μm - To spread heat load.
- σ_Y ~ 15 - 50 μm -To help vertexting & tracking.
- The beam also needs to be very stable over time. A Fast Shut-Down stops the beam in <10 ms, if halo counters register above threshold counts.

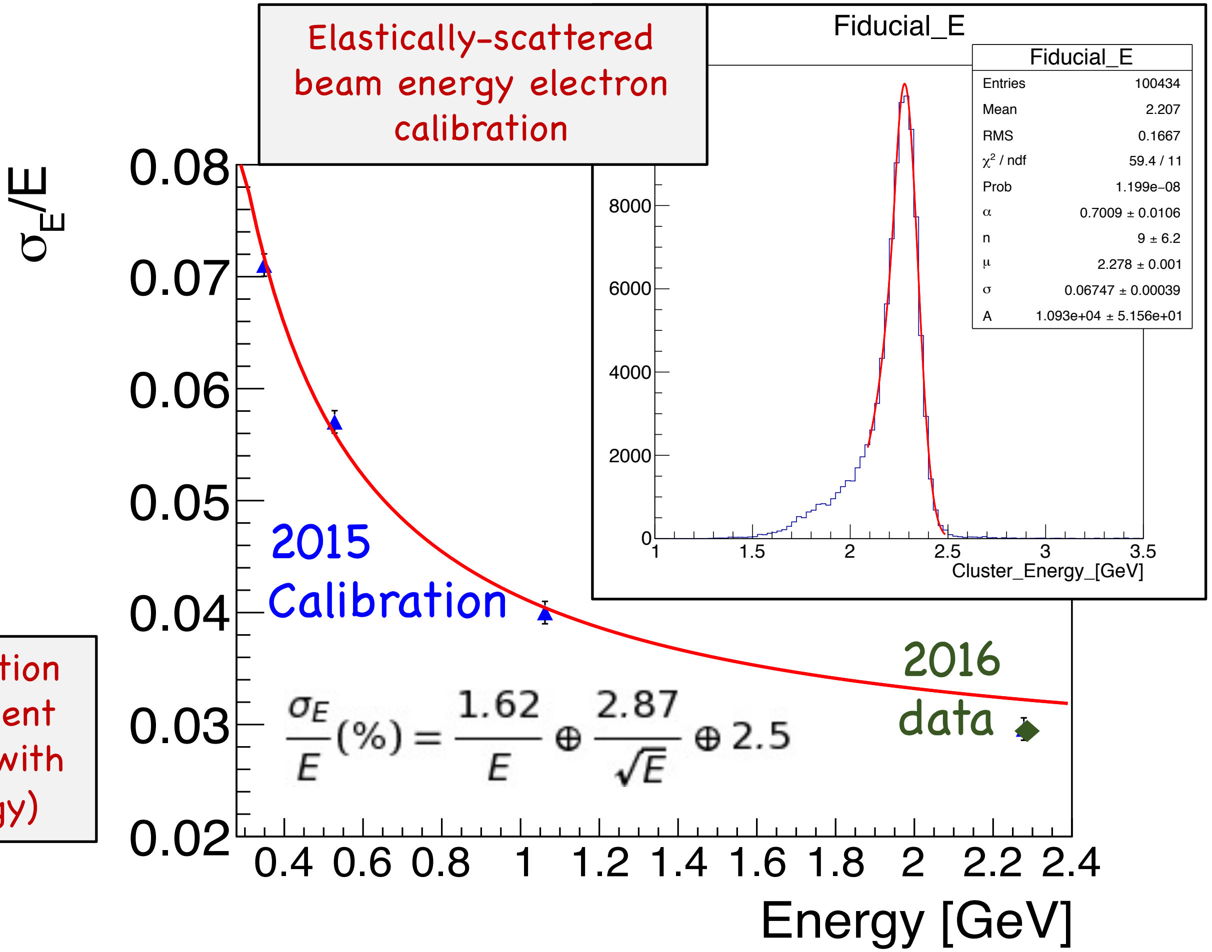


ECAL Performance

- **Time resolution ~330 ps**
- **Energy resolution**
  - **~4% @ 1.1 GeV**
  - **~3% @ 2.3 GeV**

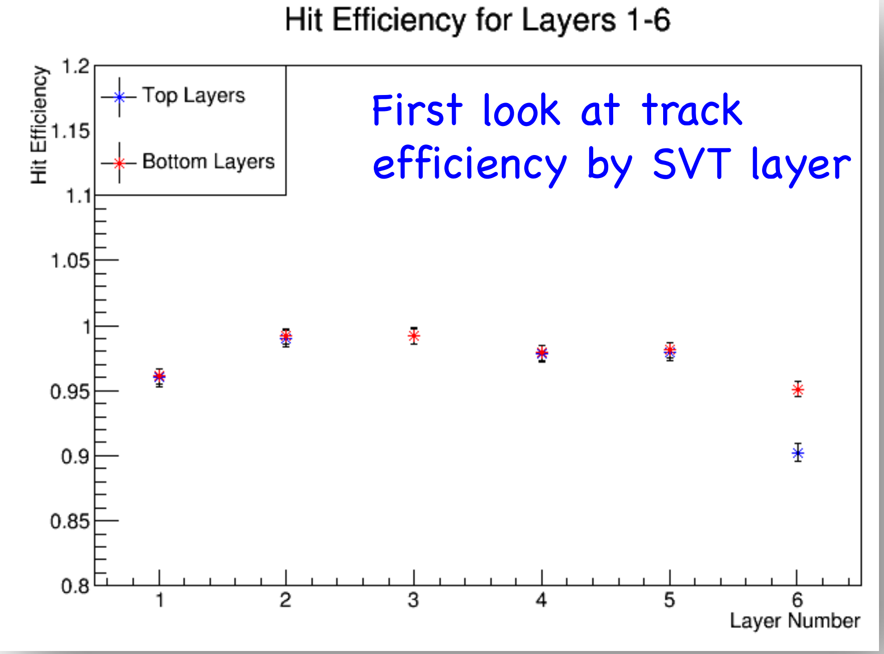


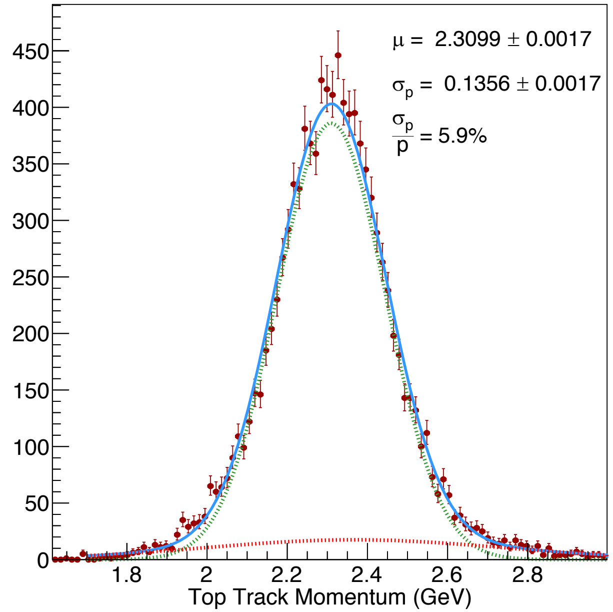


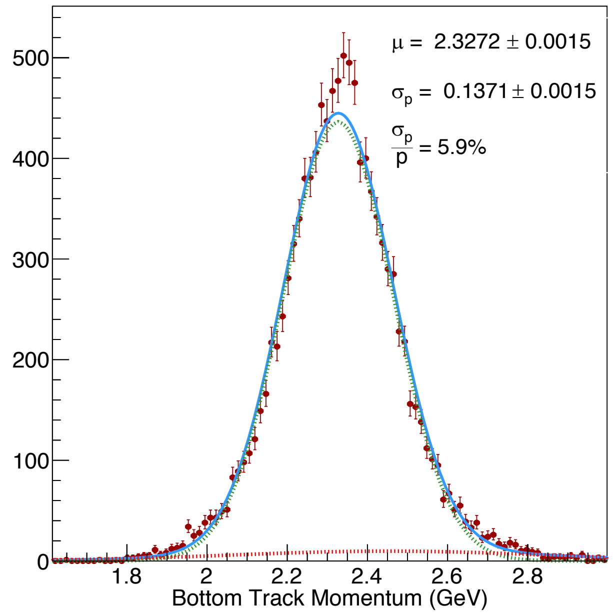


SVT Performance

- **Momentum resolution**
  - **~7% @ 1.1 GeV**
  - **~5.9% @ 2.3 GeV**
- **Hit efficiency >95%**
  (except of layer 6th)

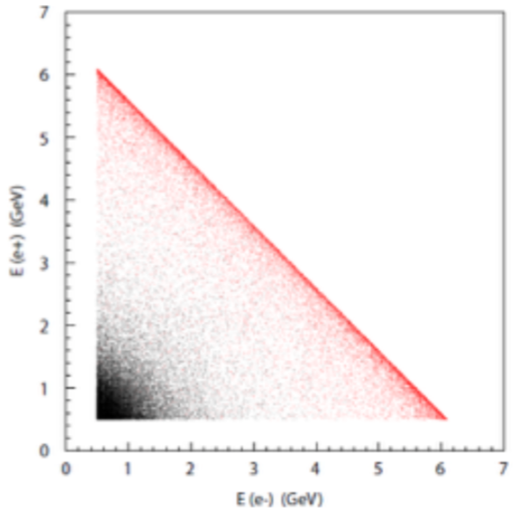




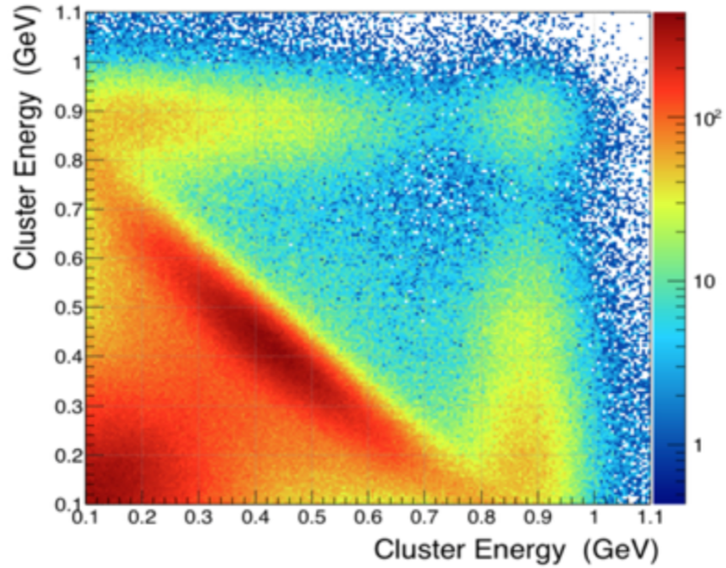


Invariant mass

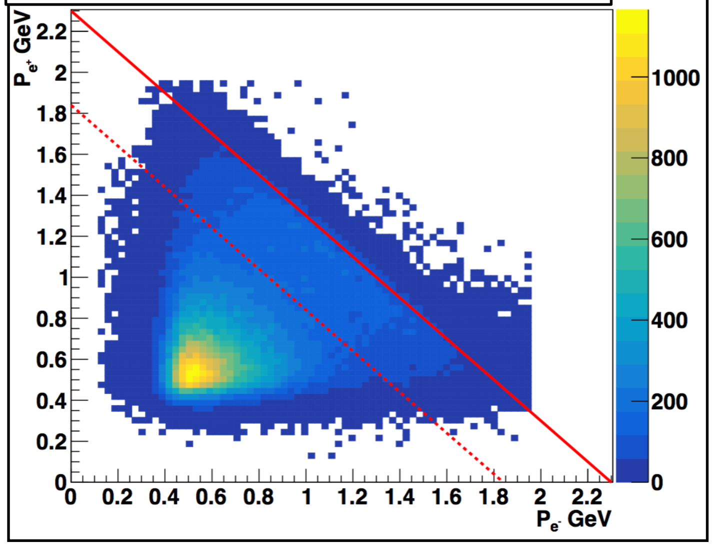
e^+ vs e^- Energy (Simulation)



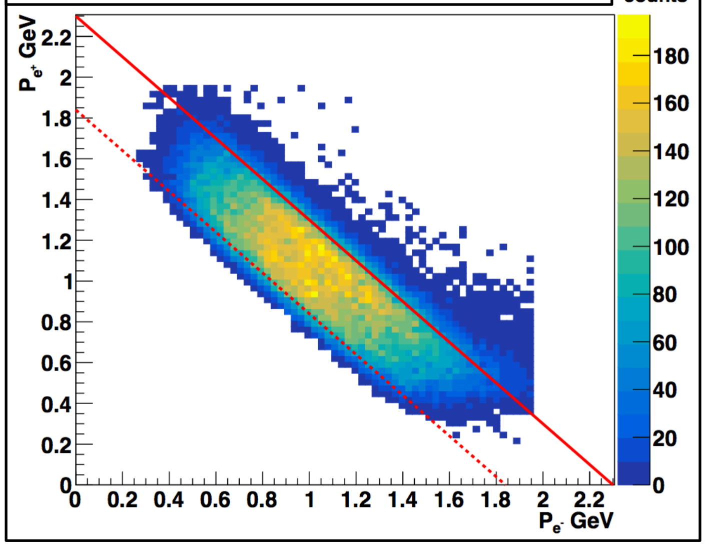
Cluster energy (Data)



e^+ vs e^- momentum (Data)

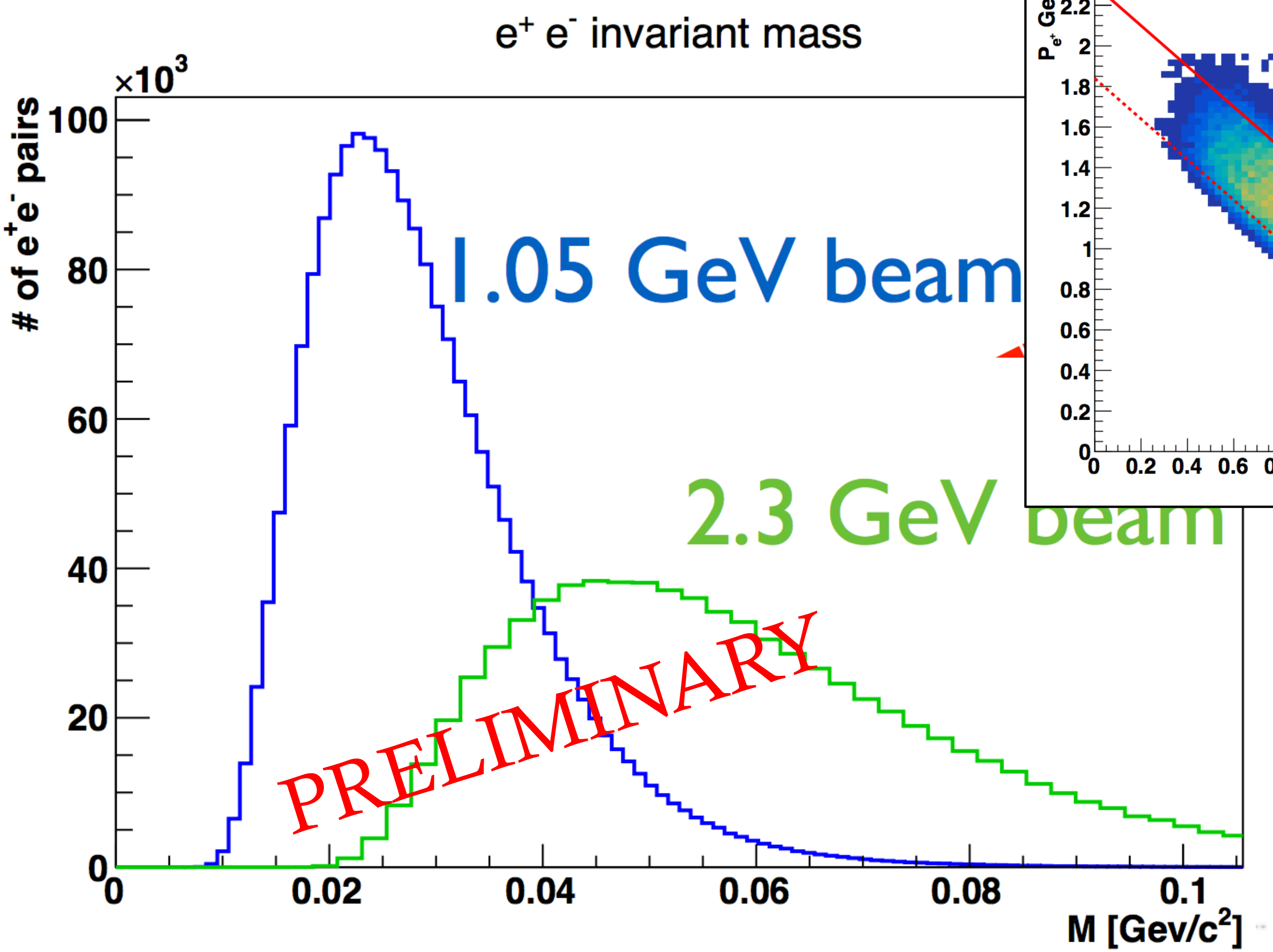


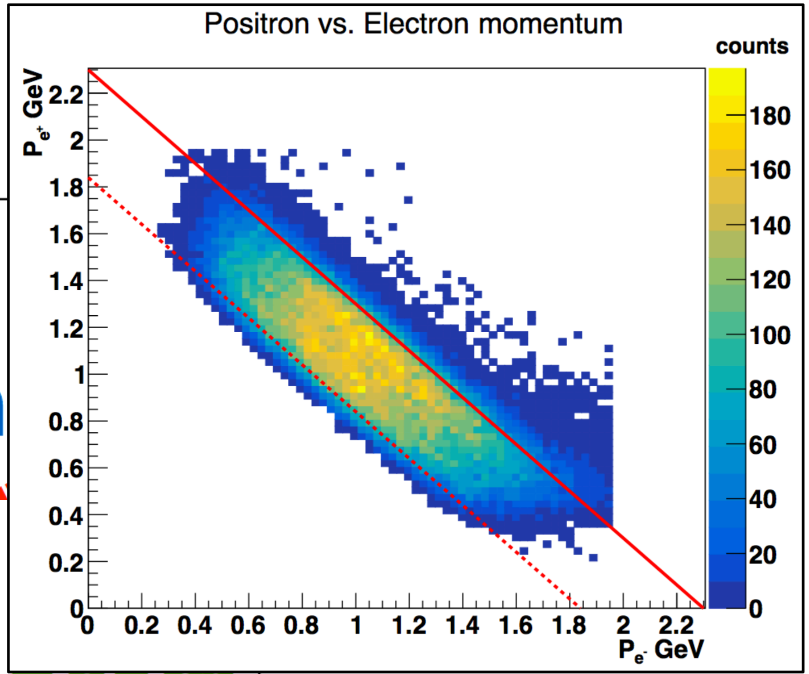
e^+ vs e^- momentum (Data)



Invariant mass

Radiative Cut





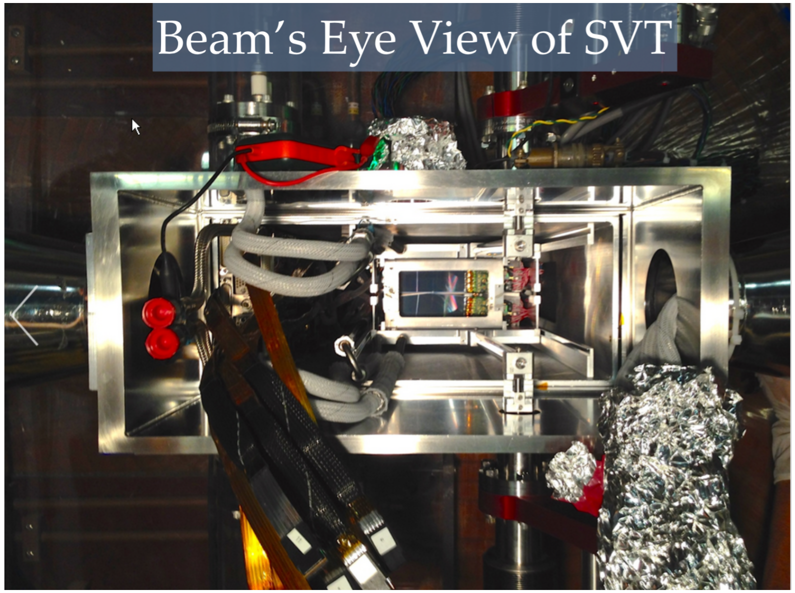
Summary

- The HPS experiment has successfully completed its first physics data taking with:
  - 1.05 GeV beam, during the 2015 “Engineering Run”
  - 2.3 GeV during 2016 “Engineering Run 2”

- Opportunistic running, with CLAS12 installation during the day, is a challenge, but possible.

- NIM papers underway

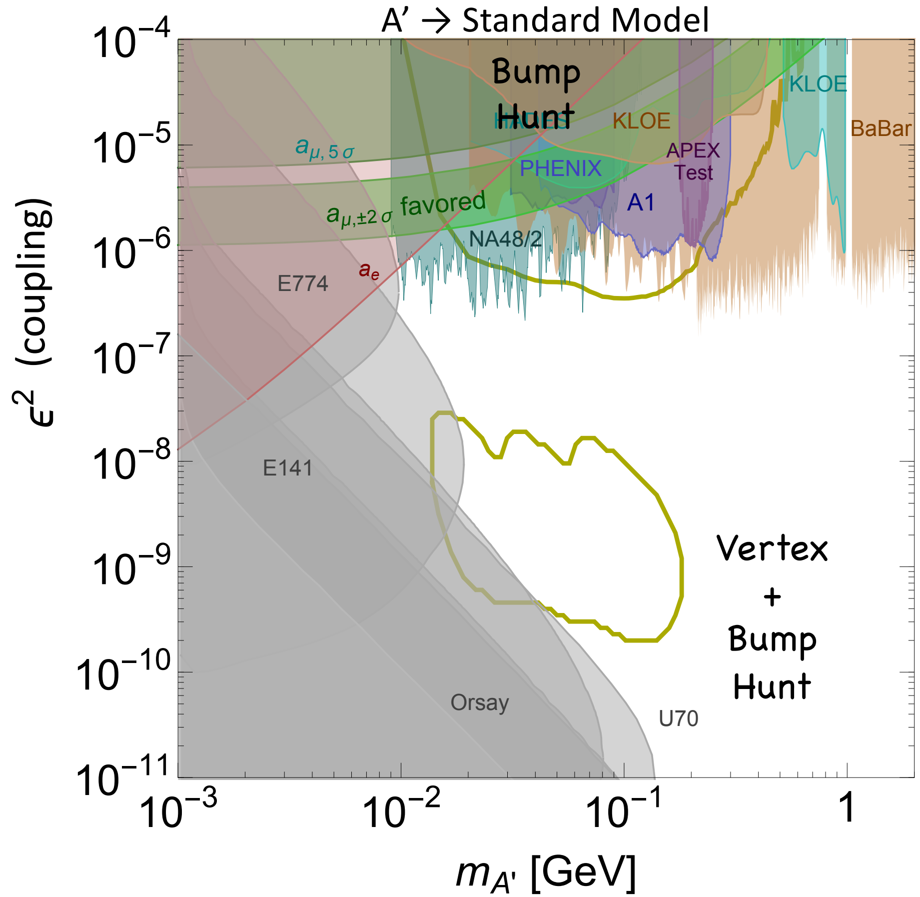
- Blind data analysis using 10% of the data
  - Bump hunt analysis nearly complete
  - Vertex cut analysis well advanced
  - In progress:
    - Fix cuts
    - Unblind data (100%)



Backup

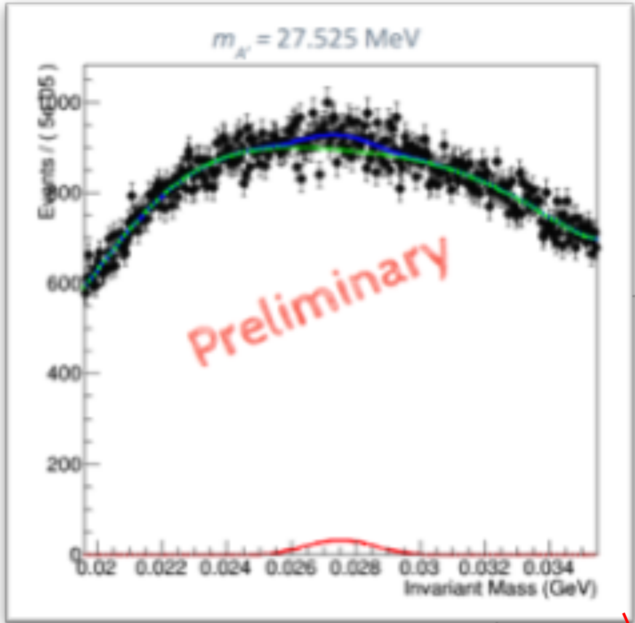
Where to look for a Dark Photon?

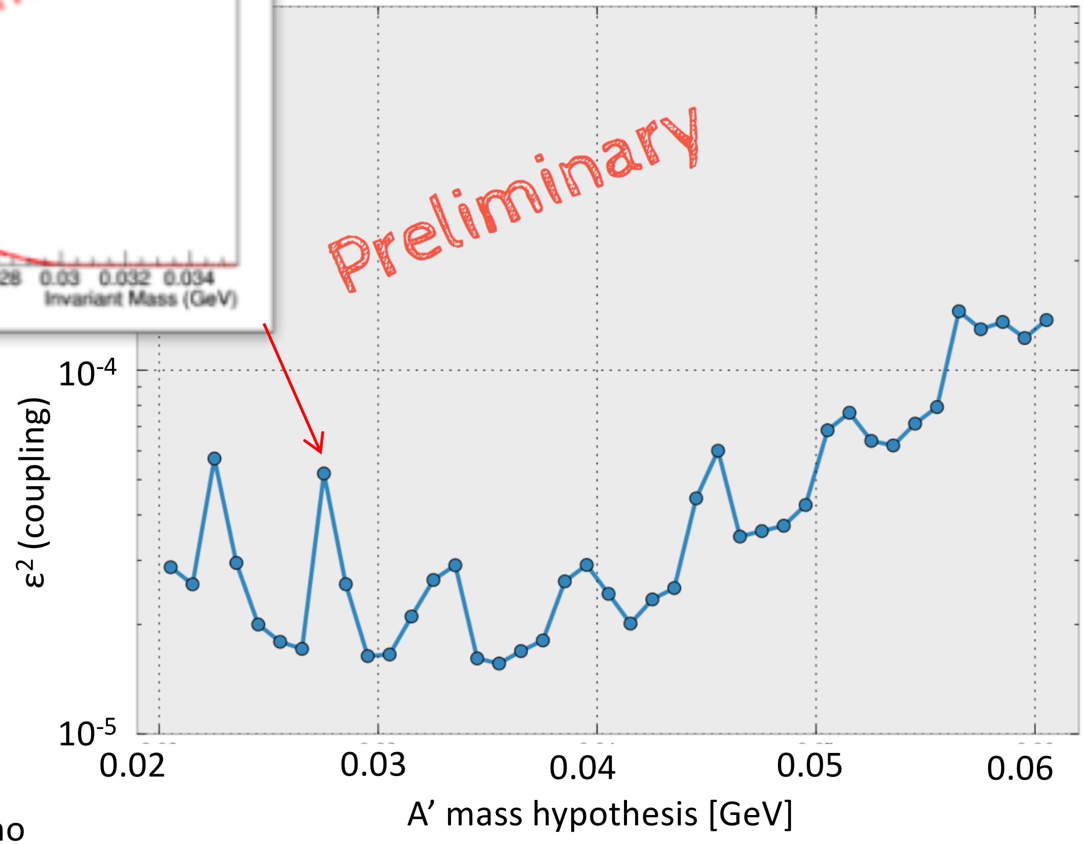
- Current limits:
  - Fixed target with e- beam
    APEX test run (JLab), Mainz (A1)
  - Fixed target with p beam
    Fermilab
  - Beam dump experiments
    E774, E141, u70, Orsay
  - Annihilation
    BABAR, BELLE, KLOE
  - Meson decay
    KLOE, BES-3, WASA-COSY, NA48/2 (CERN SPS), PHENIX)



2015 Run Bump Hunt

- 10% of 2015 data, SVT at 0.5 mm
- Conservative cuts
- Fits 7^{th} order polynomial background + A' peak



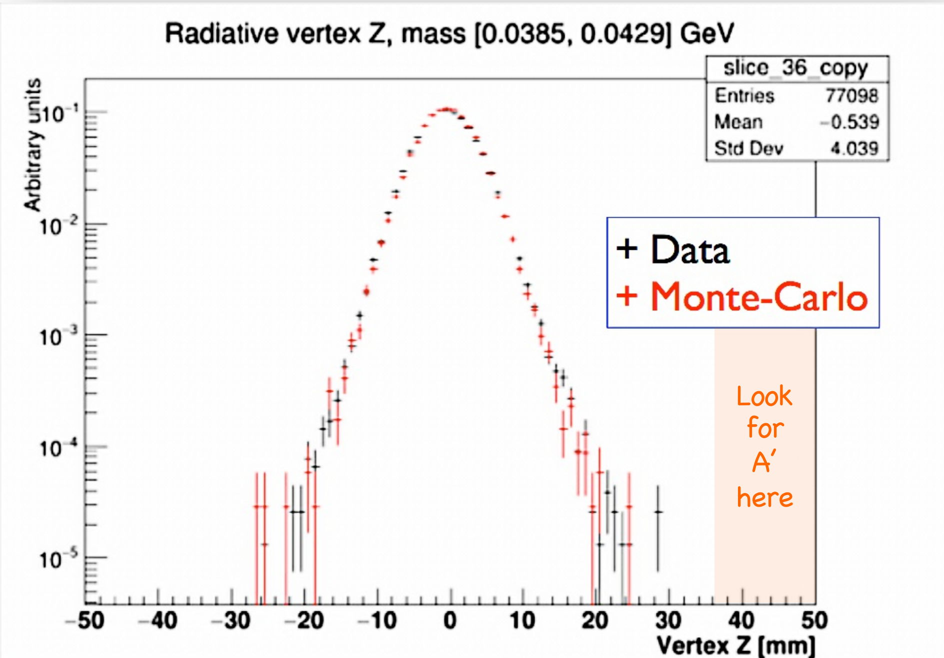


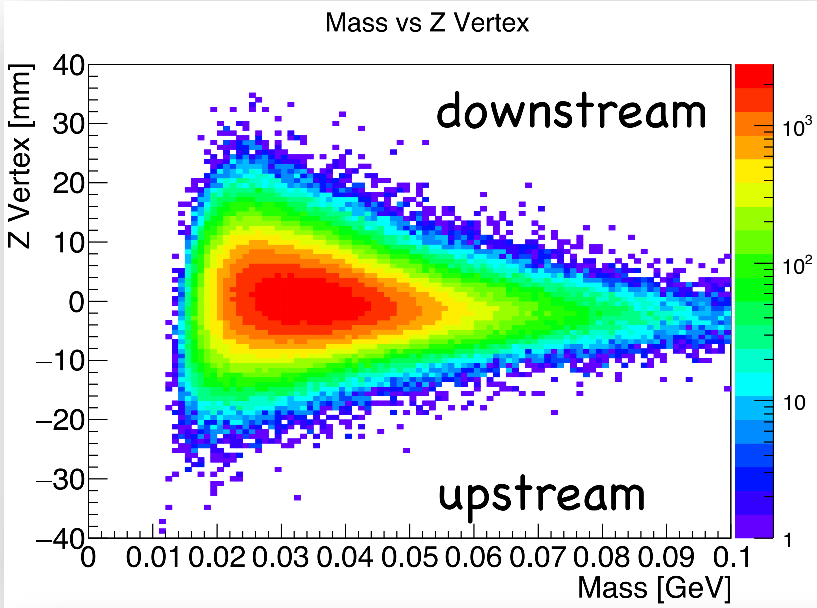
- Fix A' "peak" width, moving "peak" across spectrum to determine upper limits

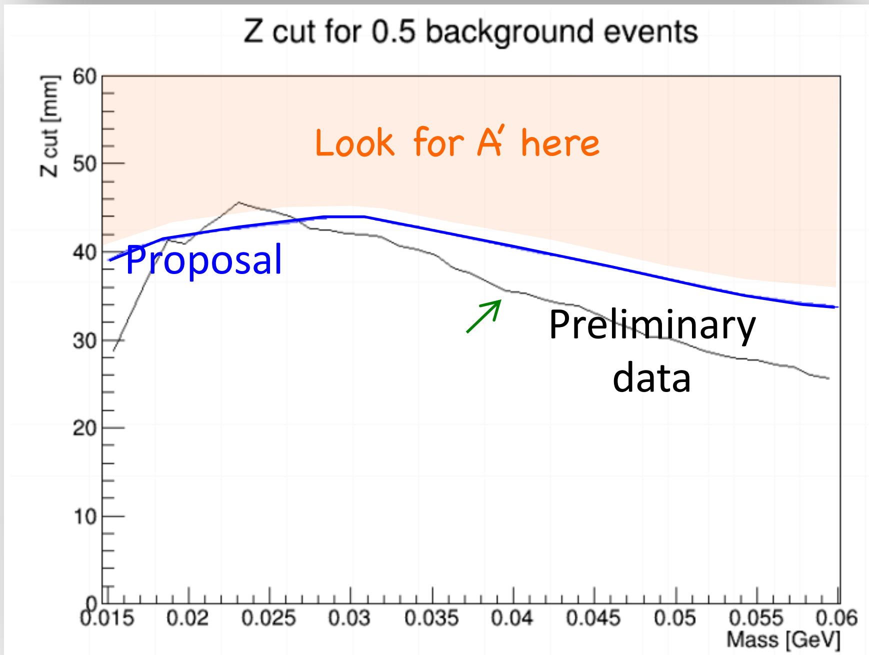
Plots from dissertation of Omar Moreno

2015 Run Vertex Search

- Search for long-lived A’ with separated vertex







Plot from Sho Uemura