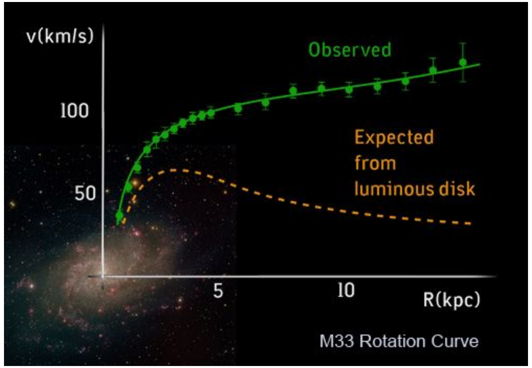
First Results from the Heavy Photon Search

Omar Moreno
on behalf of the HPS Collaboration

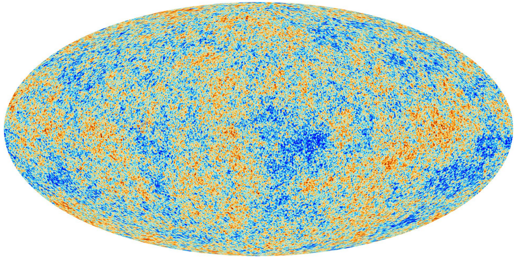
JLab Physics Seminar
Newport News, VA
May 3, 2017

The evidence for Dark Matter

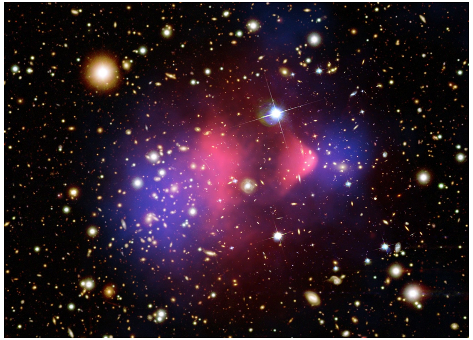
Galactic Rotation Curves



Structure of Cosmic Microwave Background

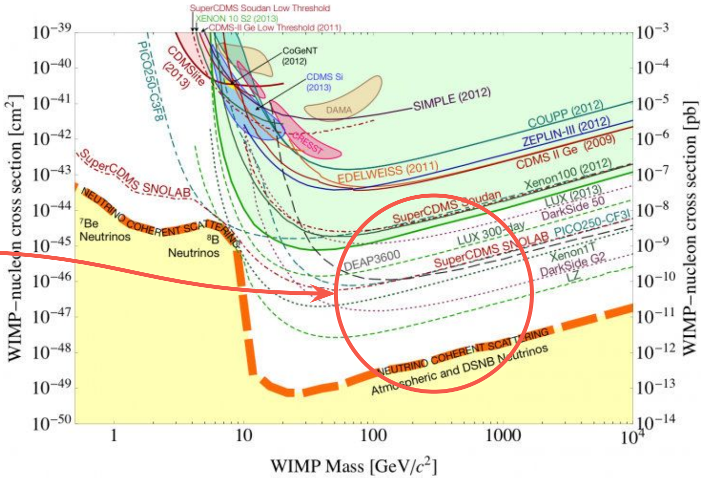


Gravitational Lensing



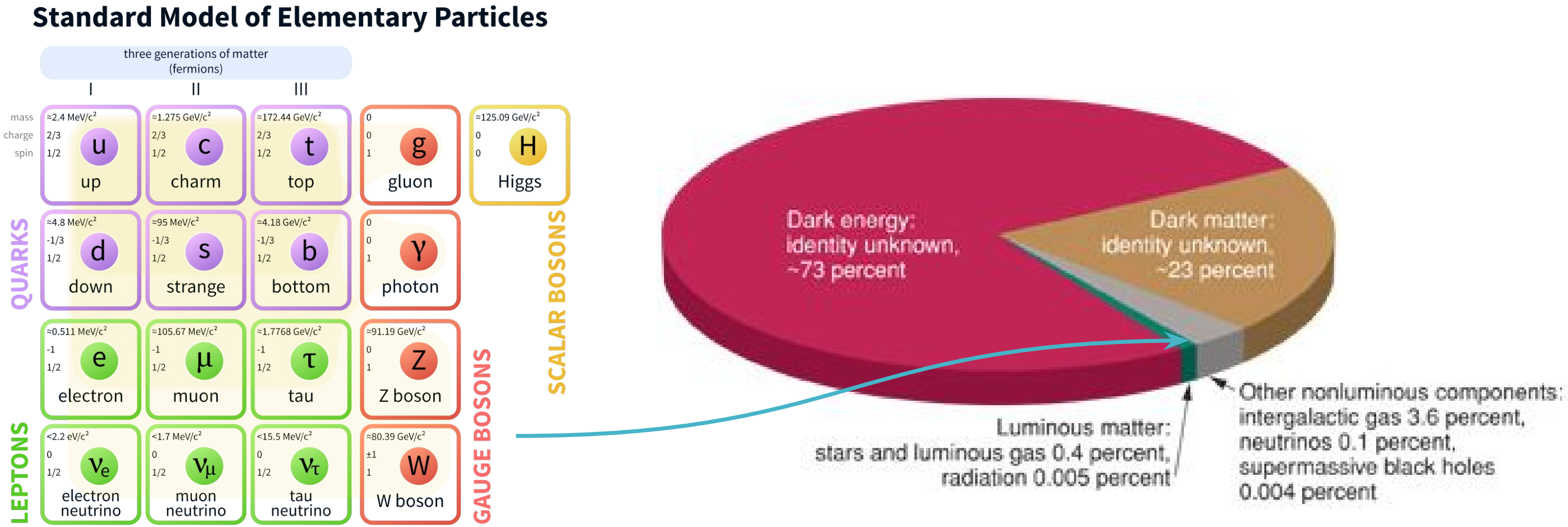
There is strong evidence for the existence of Dark Matter, but remains undetected.

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 **SuperCDMS**, **LZ** or **LHC** in the coming years.



Light Dark Matter

Light Dark Matter (i.e. DM MeV-GeV range) is the next most reasonable candidate but **requires a new force** to achieve the correct thermal relic (WIMP's limited by Lee-Weinberg Bount to 2 GeV).



Given how complex the Standard Model is, why should we expect Dark Matter to be any simpler? **What would a dark force look like?**

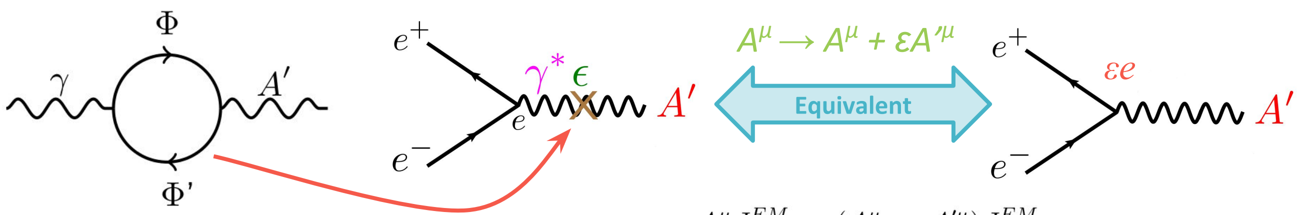
Heavy Photon Primer

If nature contains an additional Abelian gauge symmetry, *U'(1)*

Holdom, Phys. Lett. B166, 1986

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

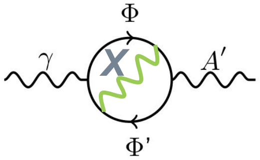
This gives rise to a **kinetic mixing** term where the photon mixes with a new gauge boson (“dark/heavy photon” or *A'*) through the interactions of massive fields → **induces a weak coupling to electric charge**



$$A^{\mu} J^{EM}_{\mu} \rightarrow (A^{\mu} + \epsilon A'^{\mu}) J^{EM}_{\mu}$$

Coupling strength can have a wide range.
If *U'(1)* is embedded in a Grand Unified Theory (e.g. *SU(5)*) then the kinetic mixing can be generated through the interaction of split multiplets

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



$$\rightarrow \quad \epsilon \sim 10^{-6} - 10^{-3}$$

Heavy Photon Parameter Space

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U'(1) can be broken → $m_{A'} > 0$

Possible origin for mass: related to m_Z by small parameter

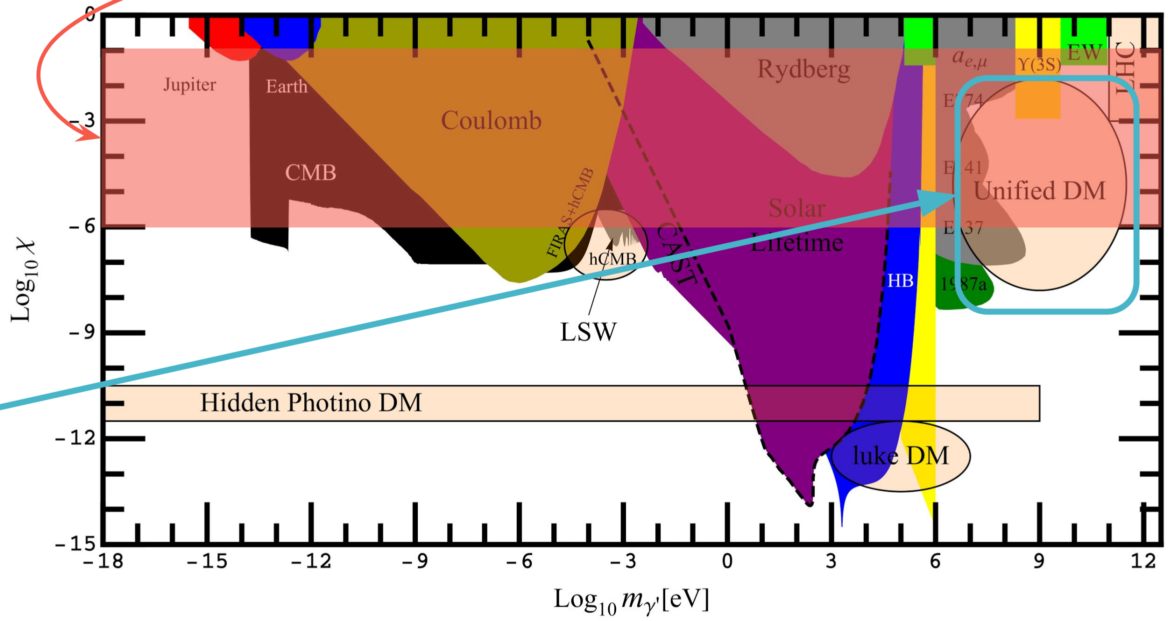
e.g. SUSY+kinetic mixing

scalar coupling to SM Higgs:

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

Mass range also motivated astrophysical anomalies

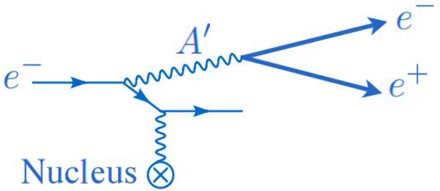
$\epsilon \sim 10^{-6} - 10^{-1}$



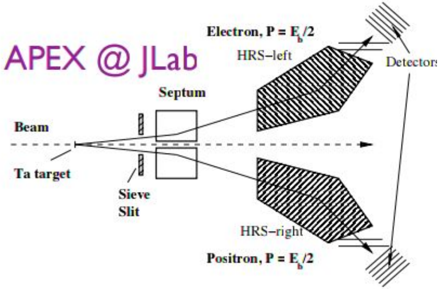
Searching for a Heavy Photon

If there are photons, there will also be heavy photons - M. Graham

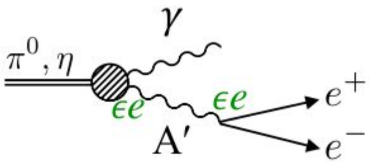
e- Fixed Target



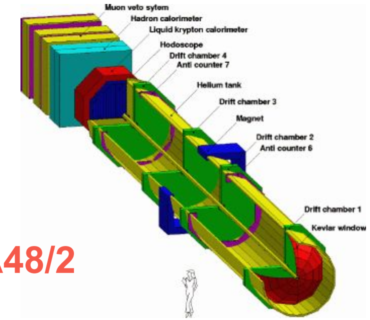
$$\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2}$$



p Fixed Target

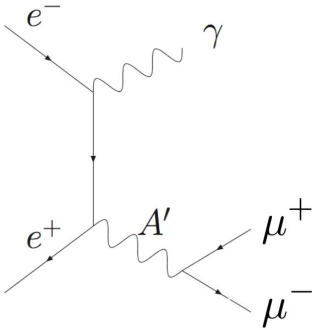


$$\sigma \sim \varepsilon^2$$



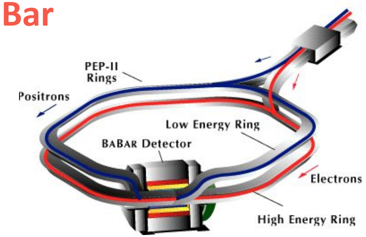
NA48/2

Colliders



$$\sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2}$$

BaBar



Existing Constraints

Most constraints come from "bump hunt" searches looking for a resonance in the e^+e^- invariant mass spectrum.

As coupling decreases, A' becomes long lived $\longrightarrow$ constraints can be placed using beam dump experiments

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

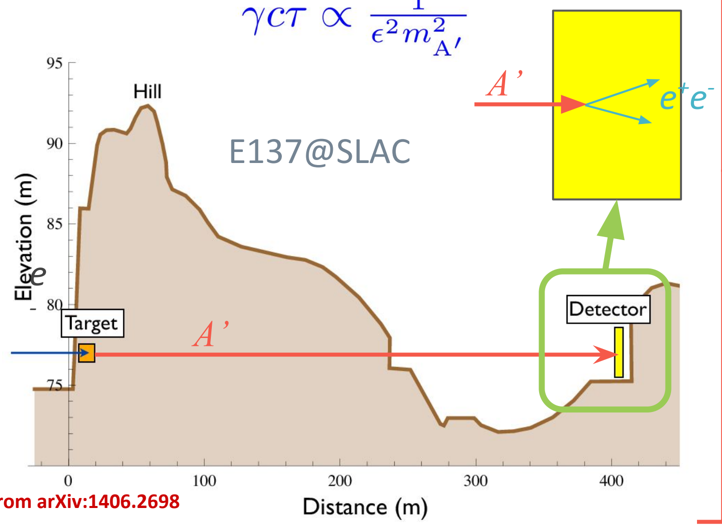
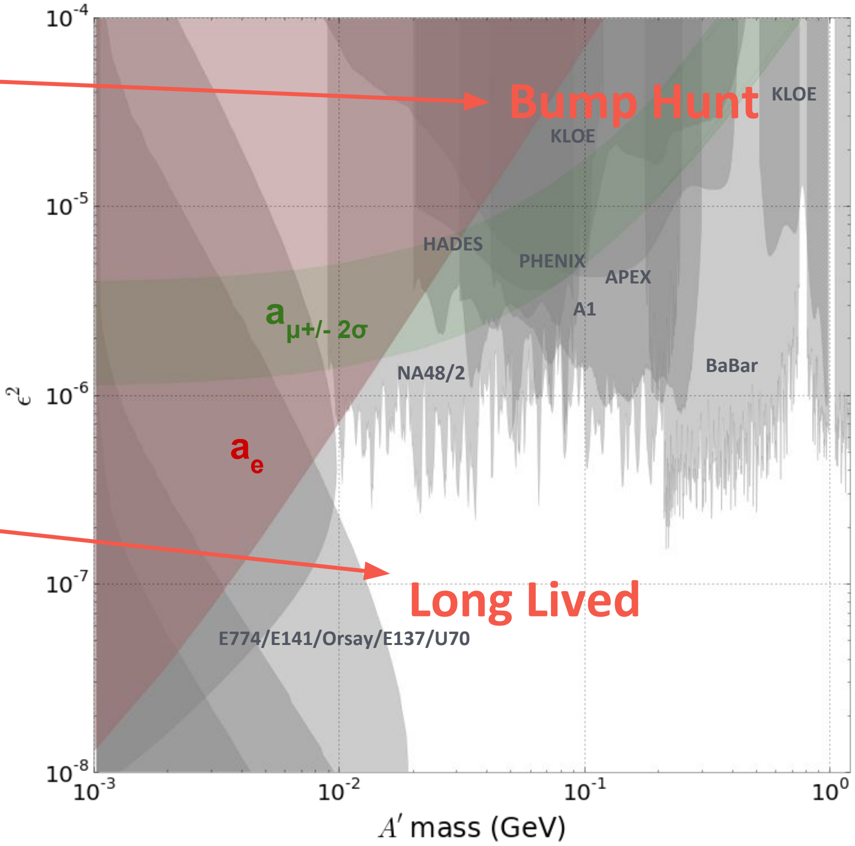
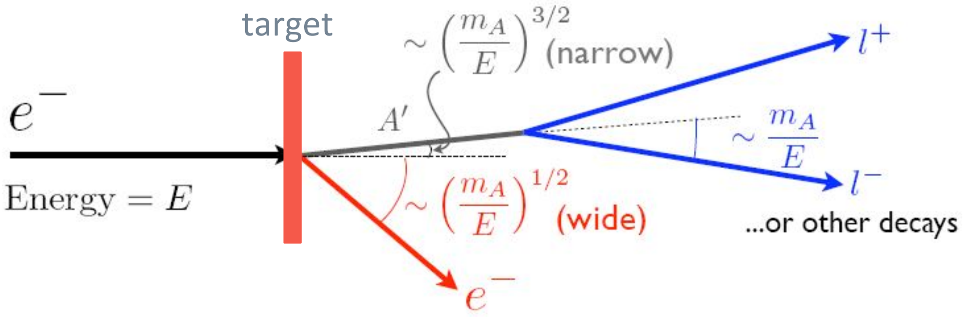


Image from arXiv:1406.2698



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^-



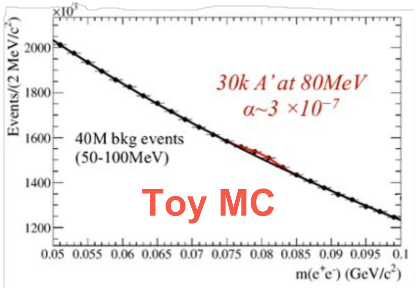
Kinematics are very different from bremsstrahlung

- ✔ 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:

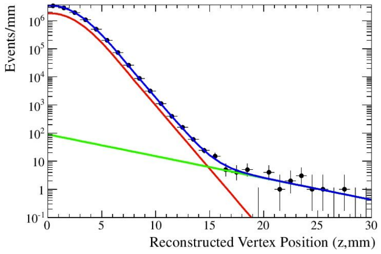
Resonance Search (Bump Hunt)

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



Displaced Vertex + Bump Hunt

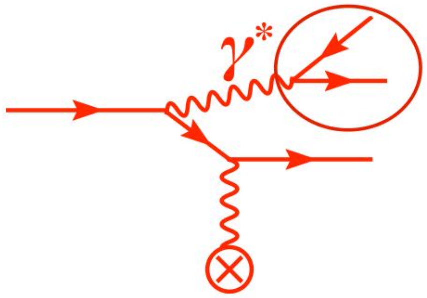
Long lived *A'* will have a displaced vertex ⟶ Will help cut down prompt backgrounds but limited to small coupling



Physics Backgrounds

Two physics backgrounds collectively known as **tridents**

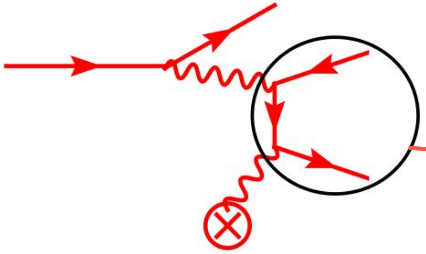
Radiative



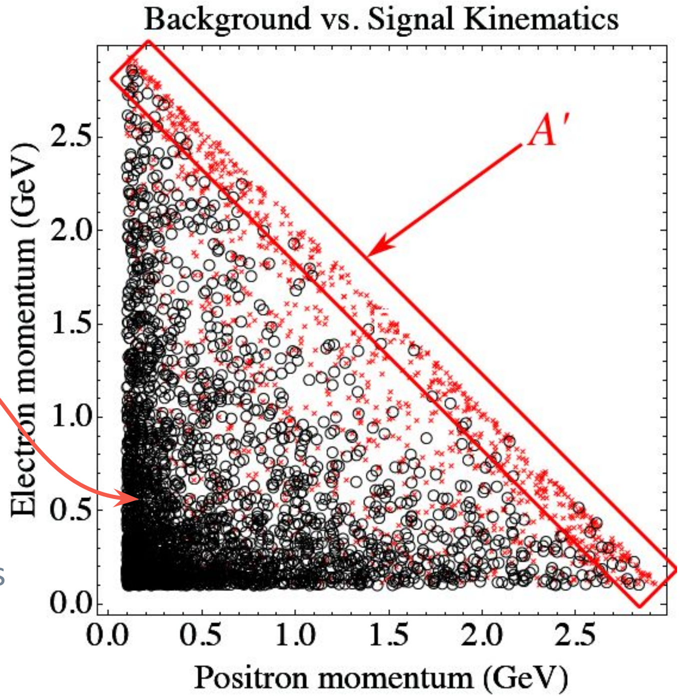
Irreducible.
Kinematically identical to A′ for $m(e^+e^-) = m_{A'}$ and can be used to understand expected A′ rates.

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

Bethe-Heitler



Dominant but is also kinematically distinct to the A′ → One of the electrons is produced forward the other one is soft



HPS Design Considerations

The A' decay products opening angle is small

- ✓ Need to be detected in the very forward region

Maximizing the acceptance to low mass A' decays requires placement of the detector close to the beam plane

- ✓ Need small beam size with minimal halo

Bump Hunt: Requires good mass resolution to fight high backgrounds

Displaced Vertex: Distinguishing A' decay vertices as Non-prompt requires good vertex resolution

- ✔ Both require a tracking system and magnet that are placed as close to the target as possible
- ✔ Minimize tracker material to reduce multiple scattering and improve resolutions

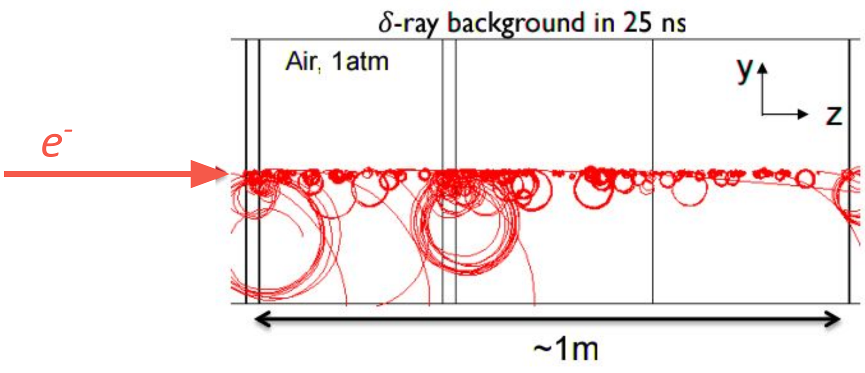
Small coupling $\longrightarrow$ small cross-section

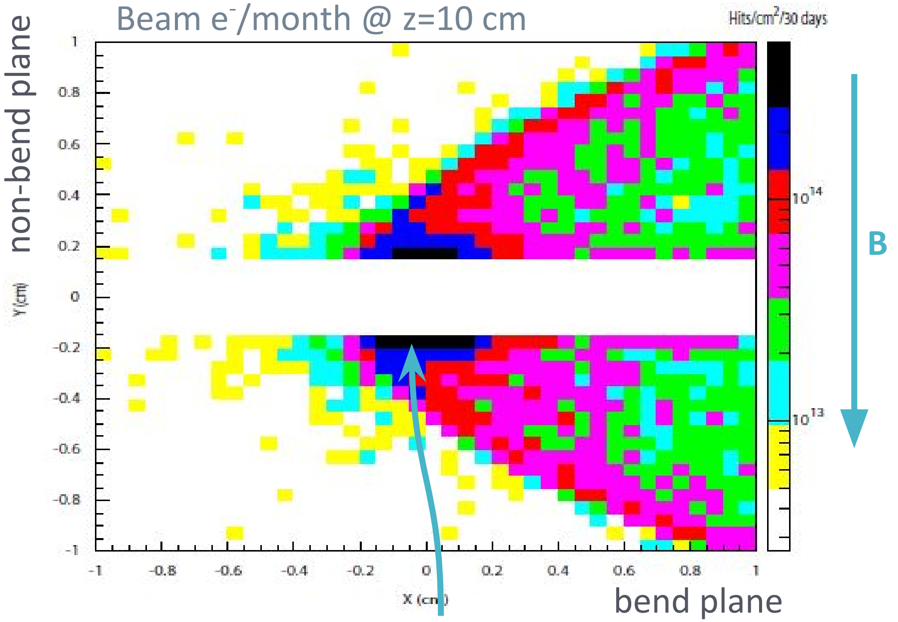
- ✔ Requires high intensity beam
- ✔ High occupancy will require fast readout and trigger system

Beam Backgrounds

Beam backgrounds dominate occupancy. Mitigating backgrounds requires

- ✔ High currents, thin targets to minimize scattering
- ✔ Operation in vacuum to eliminate secondaries
- ✔ DC beam to spread out background in time
- ✔ Fast Ecal to trigger on e^+e^- pairs at high rate in short window





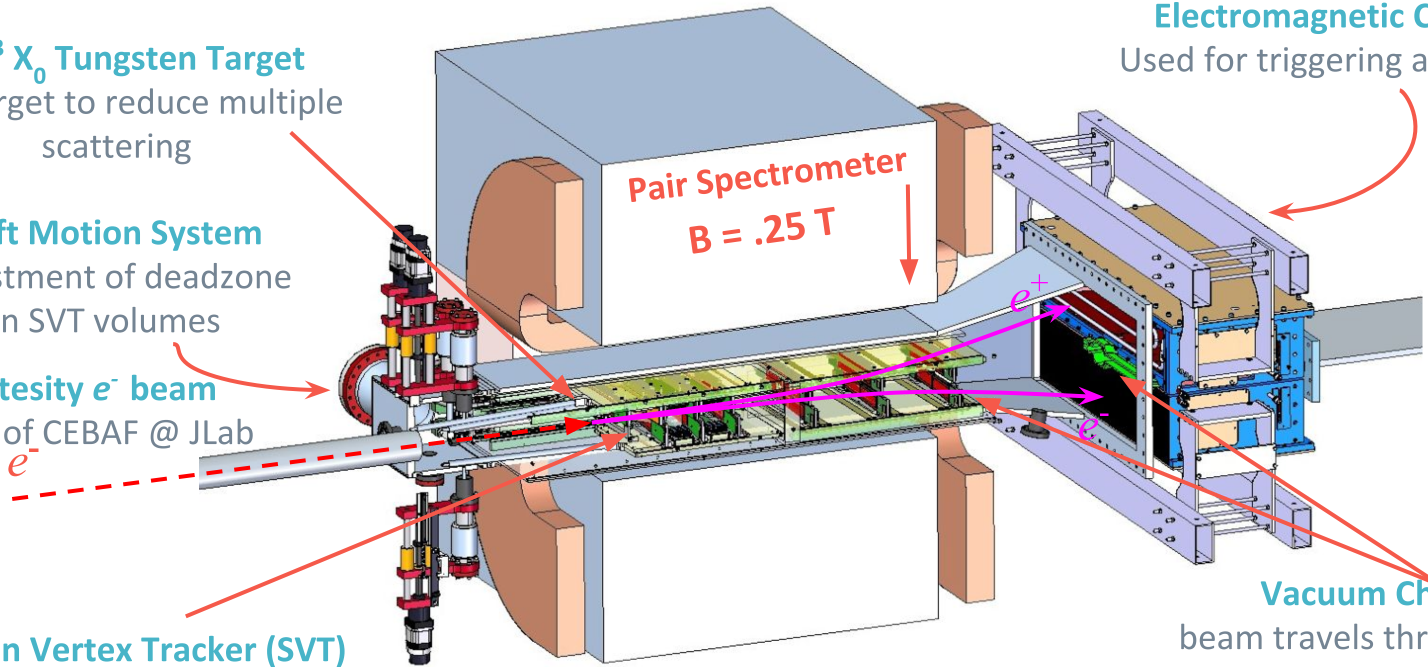
4 MHz/mm² @ 15 mm in SVT Layer 1

The HPS Apparatus

~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

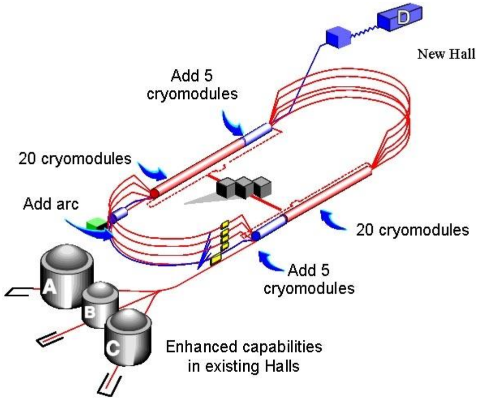
SVT + ECal DAQ capable of 50 kHz

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

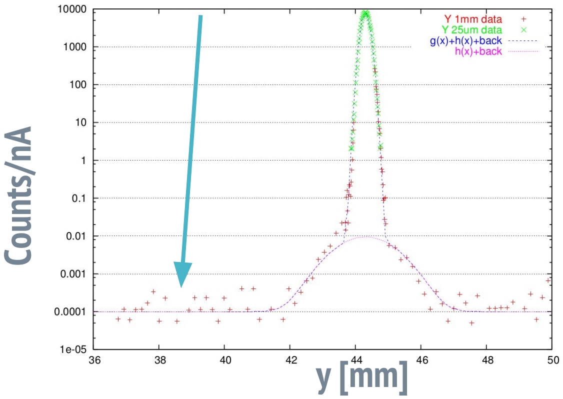
Continuous Electron Beam Accelerator Facility

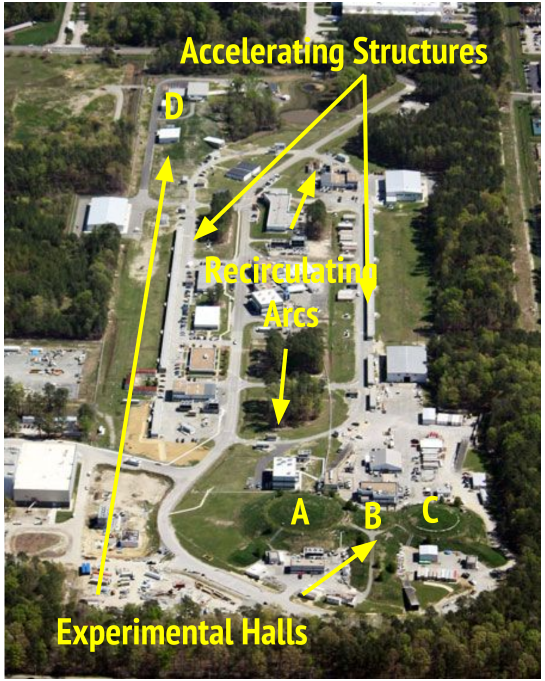
Simultaneous delivery of **intense** electron beams of different energies to four experimental halls.

- ✓ **Hall A, C:** I_{beam} < 100 μA, **Hall D:** I_{beam} < 5 μA, **Hall B:** I_{beam} < 500 nA
- ✓ With energy upgrade, $E_{beam} = n$ x 2.2 GeV, n <= 5 up to a maximum of 11 GeV (12 GeV for Hall D)
- ✓ Beam delivery is nearly continuous → 2 ns bunch structure
- ✓ Capable of providing small beam spot with small tails which will help improve vertexing



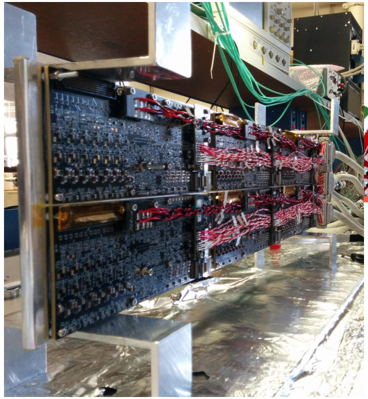
Beam halo/tails 10^{-7}

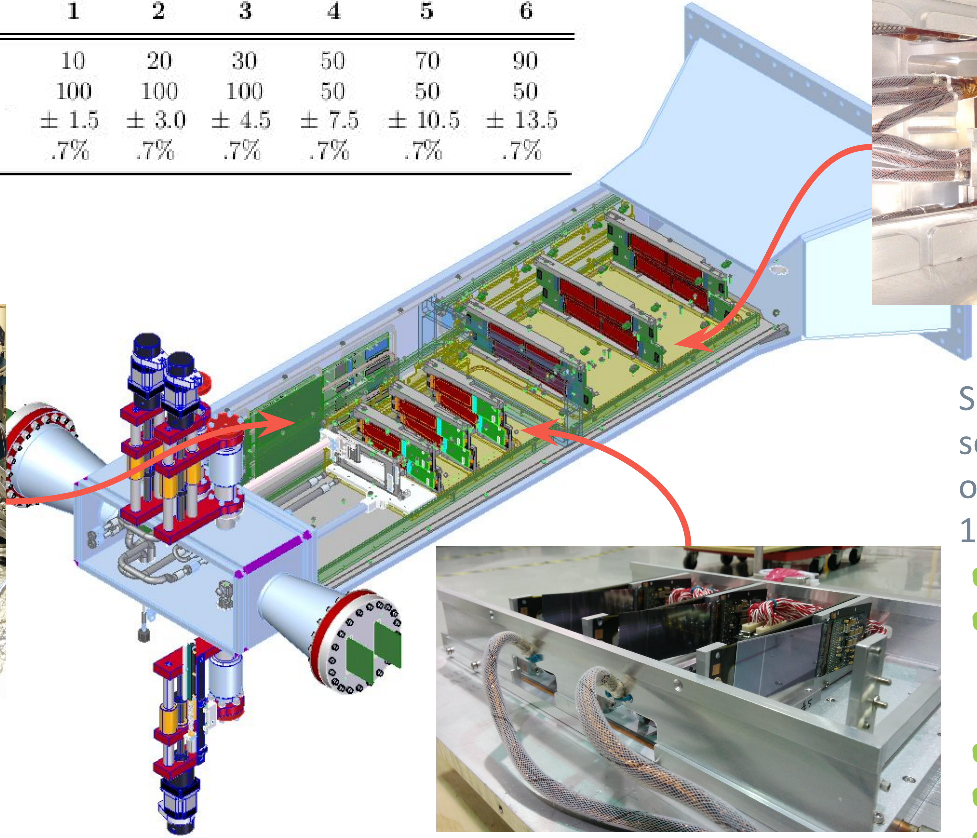


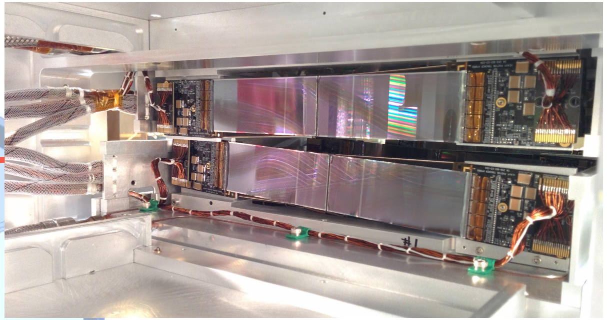


Silicon Vertex Tracker

Layer	1	2	3	4	5	6
z position from target (cm)	10	20	30	50	70	90
Stereo angle (mrad)	100	100	100	50	50	50
Nominal dead zone in y (mm)	$\pm$ 1.5	$\pm$ 3.0	$\pm$ 4.5	$\pm$ 7.5	$\pm$ 10.5	$\pm$ 13.5
Material budget	.7%	.7%	.7%	.7%	.7%	.7%

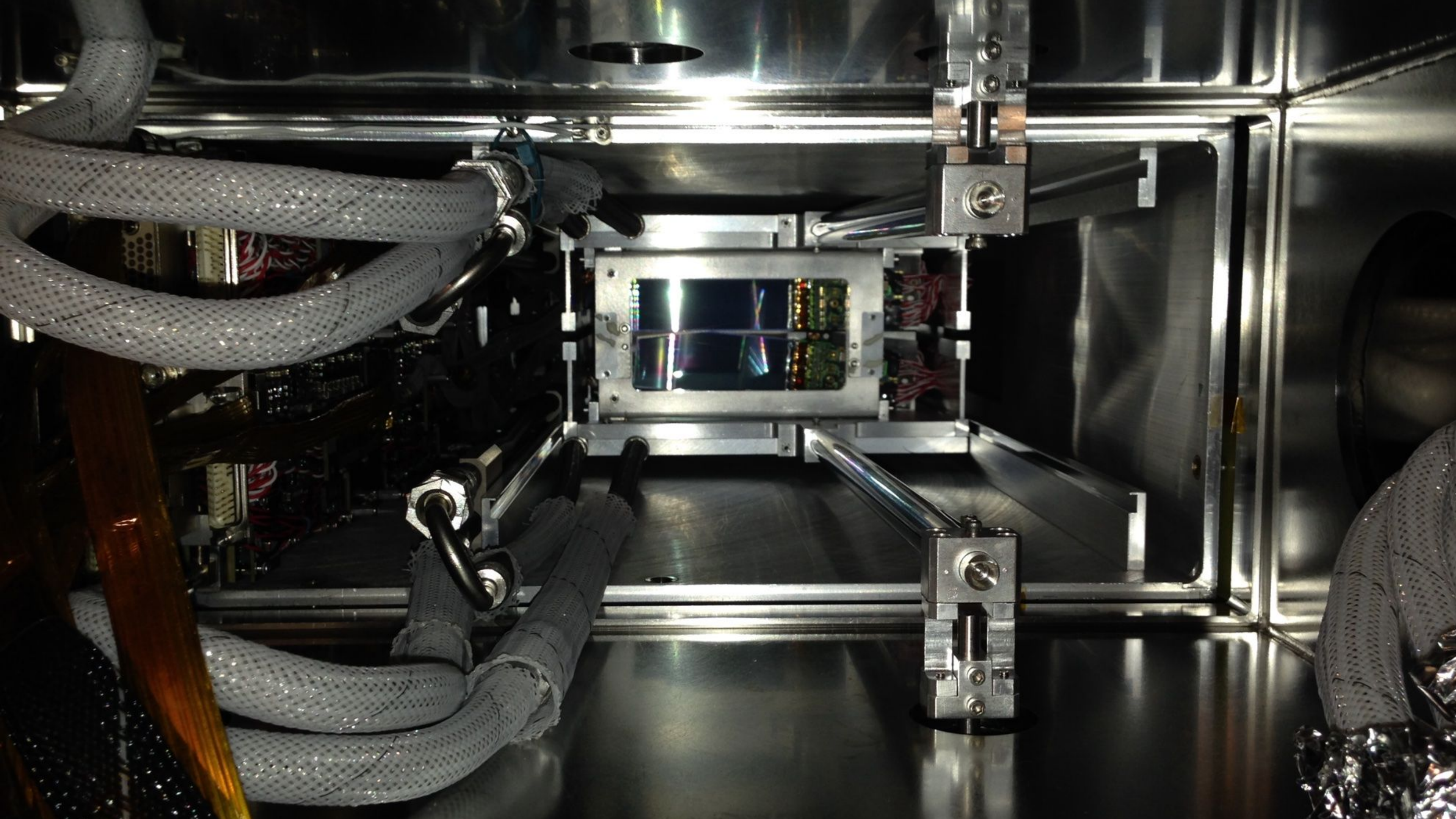






Six layers of pairs of Si microstrip sensors → One axial and the other at small angle stereo (50 & 100)

- ✔ Layer 1-3: single sensor
- ✔ Layer 4-6: double width coverage to better match Ecal acceptance
- ✔ 36 sensors
- ✔ 180 APV25 chips
- ✔ 23,004 channels

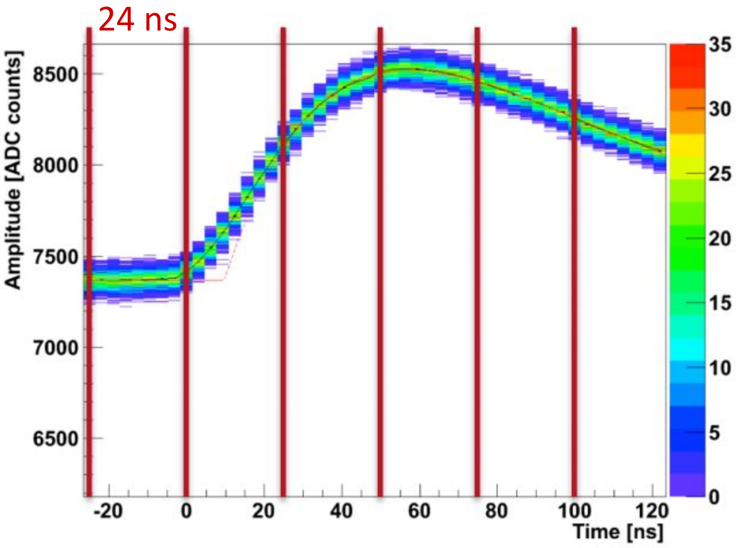


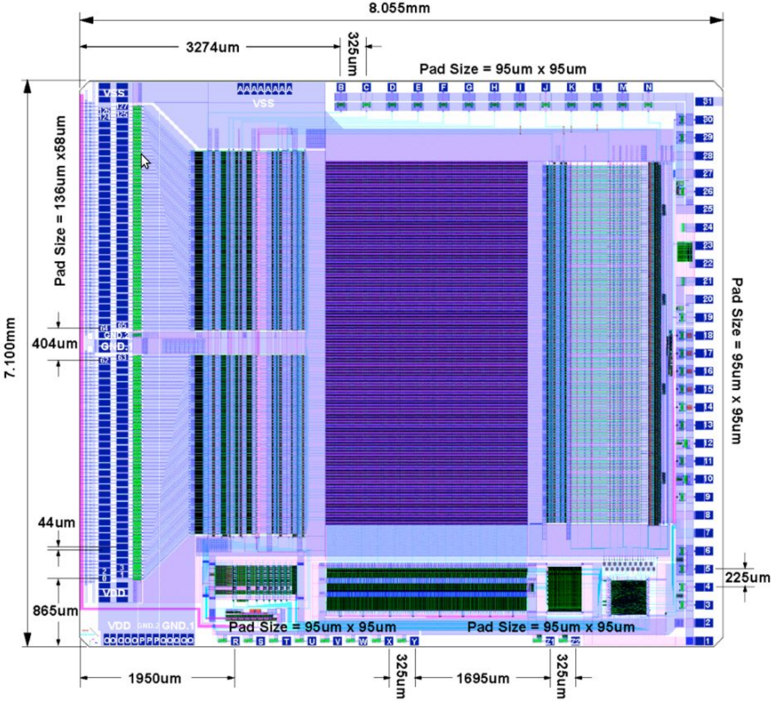
Readout Electronics: APV25

Originally developed for CMS

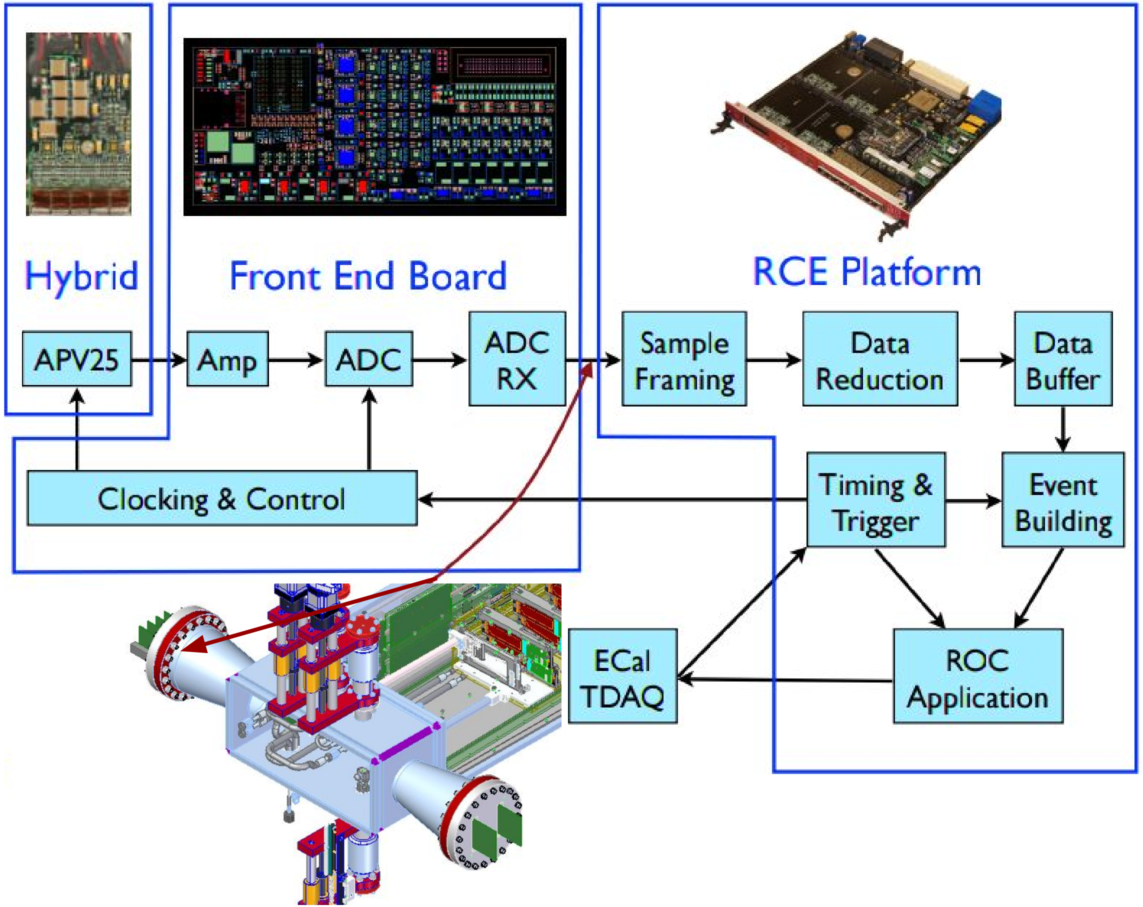
- ✔ Radiation tolerant
- ✔ Low noise (S/N>25)
- ✔ 40 MHz "Multi-peak" 6 sample readout allows for shaper output reconstruction
- ✔ 2 ns resolution

# Readout Channels	128
Input Pitch	44μ
Shaping Time	50 ns nom. (adjustable)
Output Format	multiplexed analog
Noise Performance	$270 + 36 \times C(pF)\ e^-$
Power Consumption	345 mW

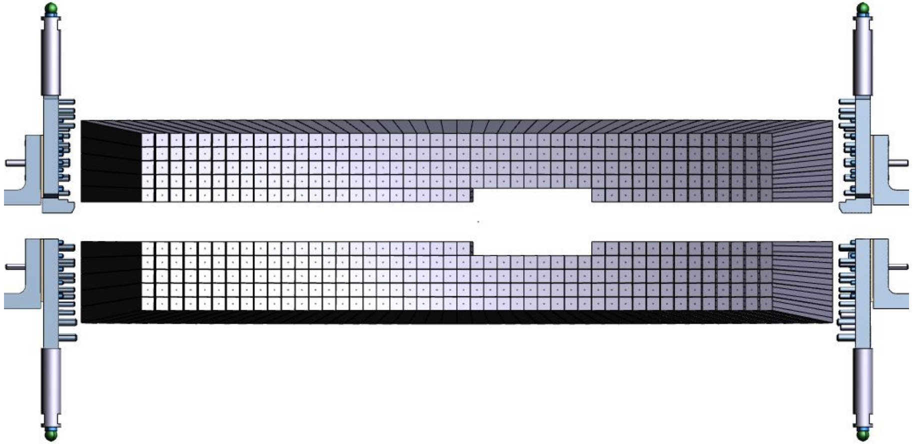


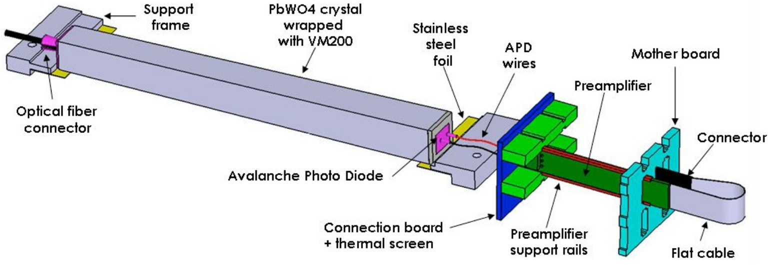


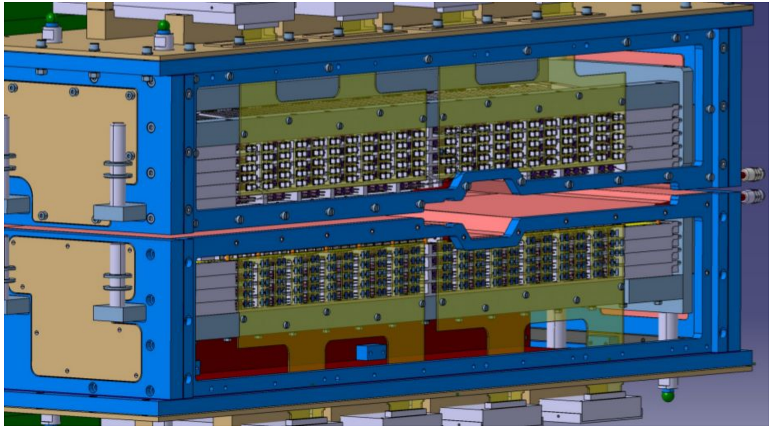
SVT DAQ


Hybrid
Front End Board
RCE Platform
APV25
Amp
ADC
ADC RX
Sample Framing
Data Reduction
Data Buffer
Clocking & Control
Timing & Trigger
Event Building
ECal TDAQ
ROC Application

ECal





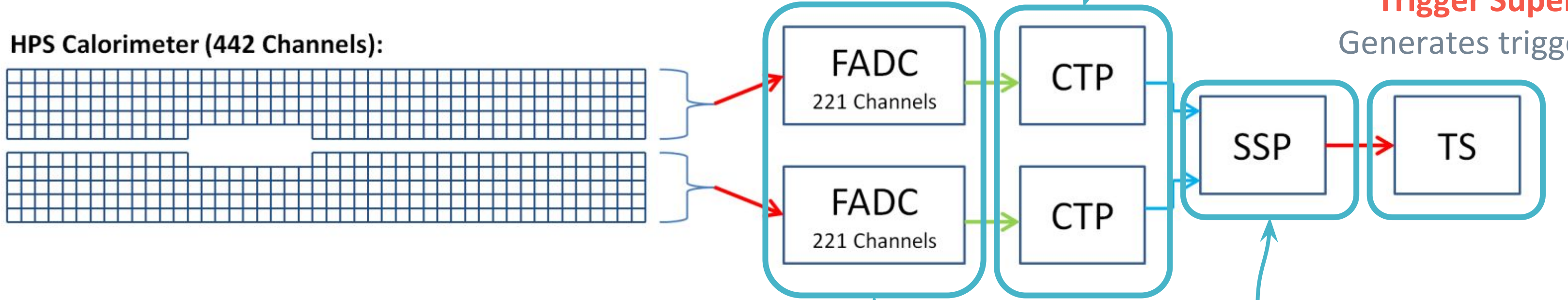


- ✓ 442 $PbWO_4$ crystals coupled to avalanche photodiode readout
- ✓ FADC readout at 250 MHz ⟶ allows for a narrow trigger window (8ns)
- ✓ Trigger and DAQ capable of a rate > 100 kHz

Trigger

Crate Trigger Processor
Contains cluster finding algorithm. Searches for clusters in every 3x3 array of crystals. If sum exceeds threshold and is isolated, amplitude, position, time and hit are reported to SSP.

Trigger Supervisor
Generates trigger signal



Flash ADC
Samples Ecal crystal APD's @ 250 MHz. If signal crosses threshold, integrated amplitude and crossing time is sent to CTP

Sub-System Processor
Searches for pairs that within an 8 ns window and applies a topological selection

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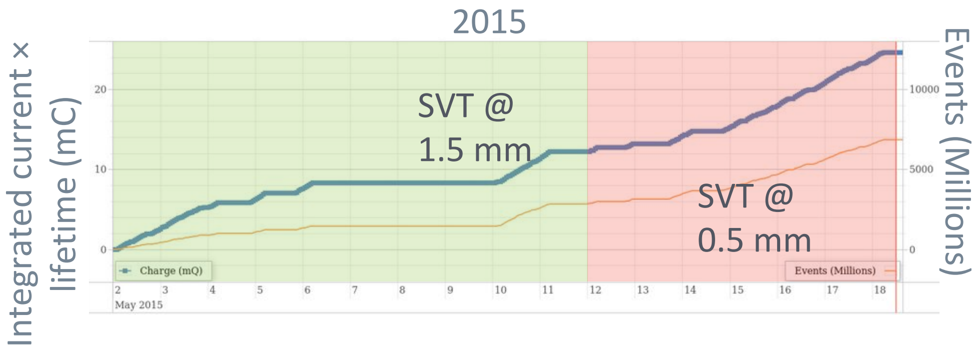
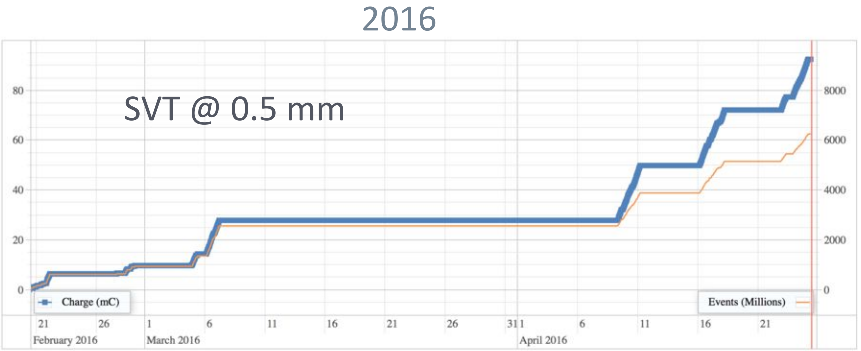
HPS Engineering Runs

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: active 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

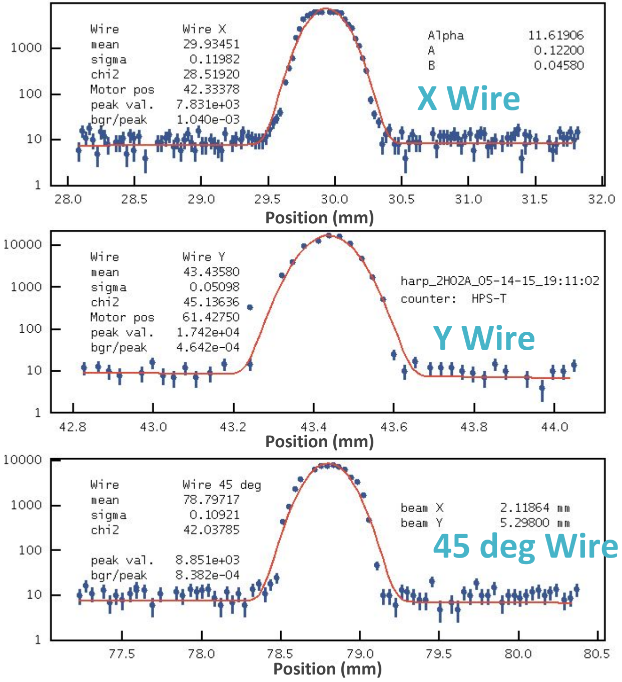




The results shown in this talk used the full 2015 Engineering run dataset.

Beam Quality

Beam profiles from Harp scan.

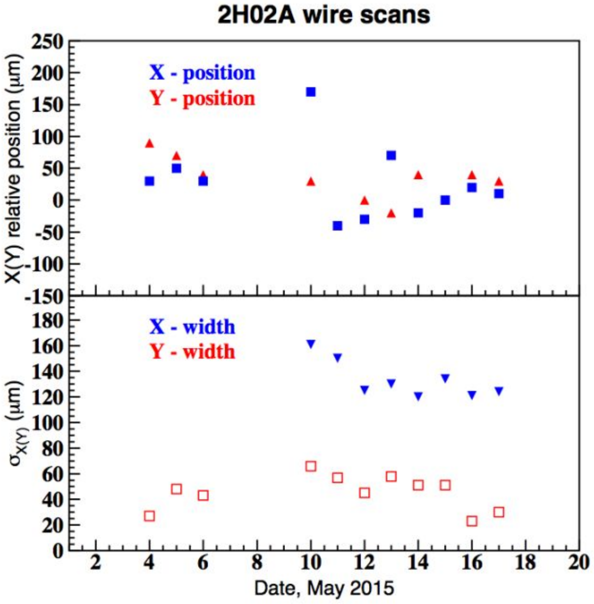


Successful running of the HPS apparatus requires a high quality beam with very low halo.

- ✔ σ_x ~100 μm to 500 μm: Spreads the target heat load to avoid damage.
- ✔ σ_y < 50 μm: Required to keep occupancies down and for vertexing

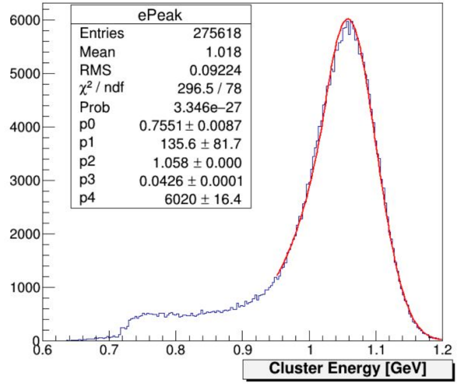
Beam profile and position was measured using a harp 234 cm upstream of the target.

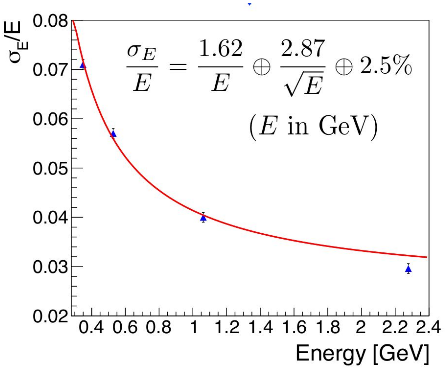
Fast Shut-Down was implemented in order to stop the beam in ~ 5 ms if halo counter rates increased above threshold.

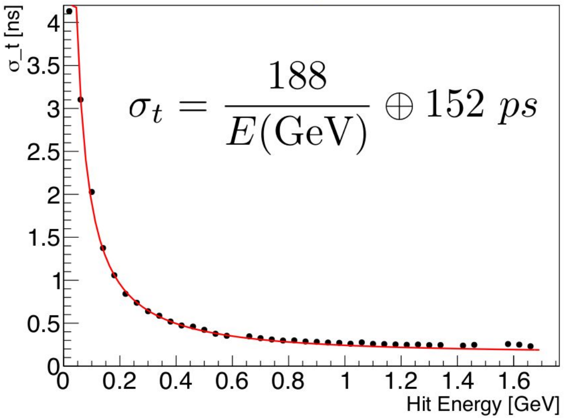


ECal Performance

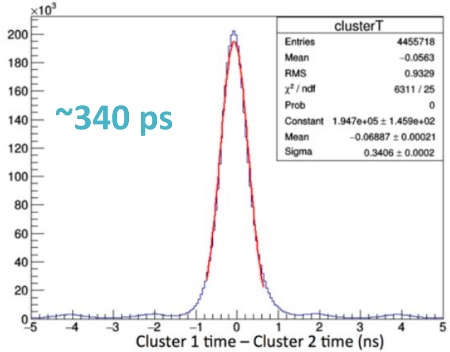
Use Coulomb scattered beam electrons to measure the energy resolution of the calorimeter ⟶ **~4%**

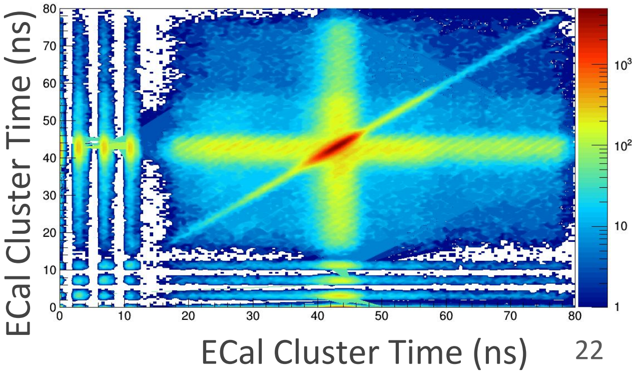




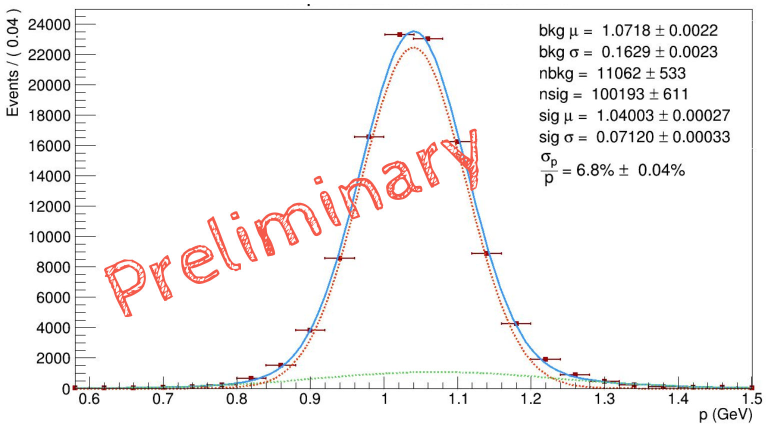


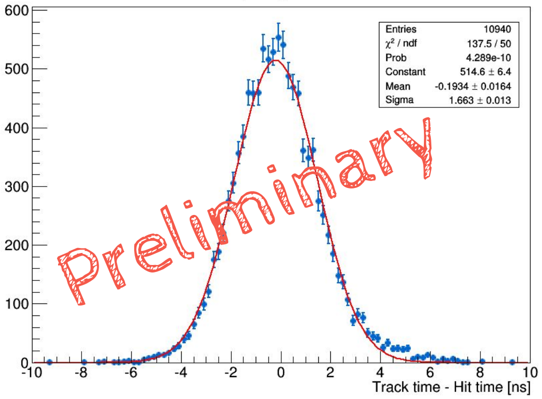
Good time resolution allows for ps Cluster coincident time resolution ⟶ used to identify e^+e^- pairs with high accuracy



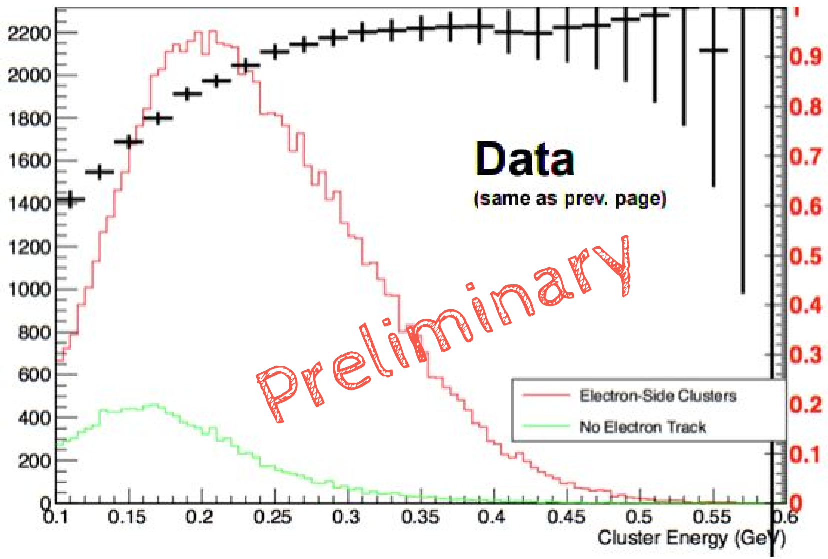


SVT Performance



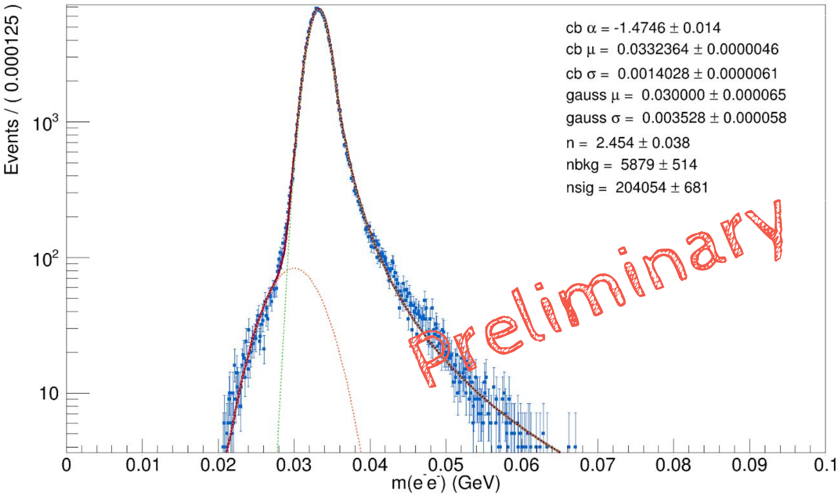


- ✔ SVT momentum scale is within 1% of expected (1.056 GeV) showing that SVT is well aligned
- ✔ Momentum resolution 6.8%
- ✔ t0 resolution ᔕ2ns
- ✔ Tracking efficiency ~95%

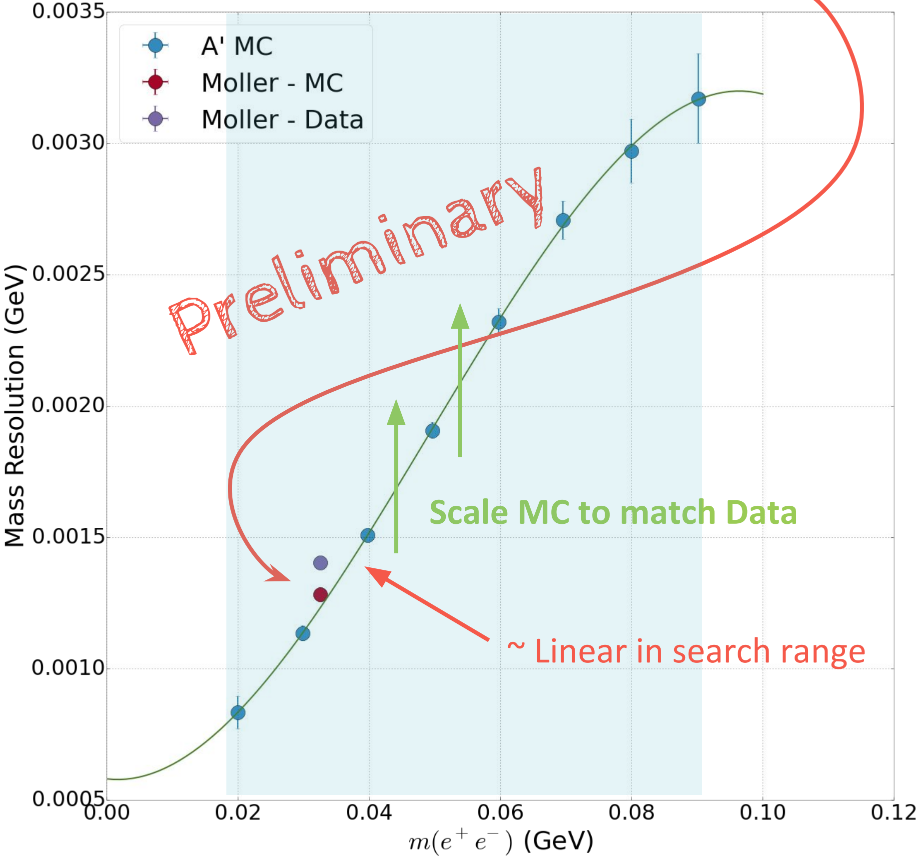


e^+e^- Mass Resolution

- ✔ 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.



Data Møller invariant mass is within 10% of Monte Carlo



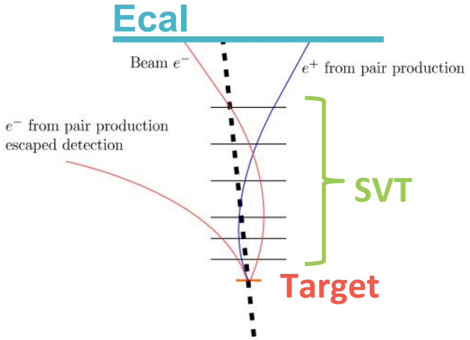
Comparing Data and Monte Carlo

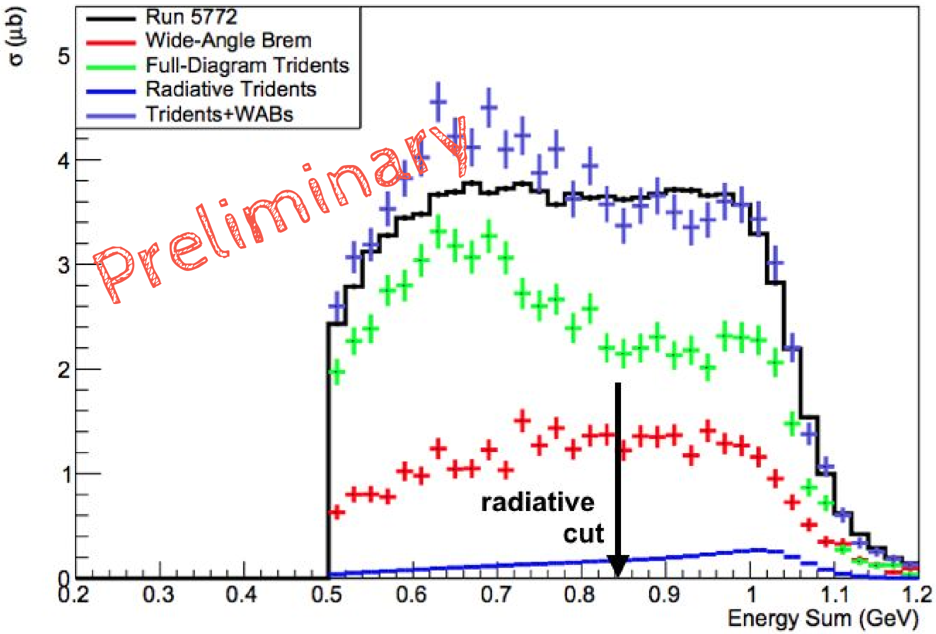
O. Moreno (SLAC National Accelerator Laboratory) JLab Physics Seminar, May 3, 2017

Good agreement between Data and MC is needed to calculate the amount of radiative tridents in our sample

Comparing Data and Monte Carlo revealed a new source of background → Wide Angle Brem

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





Once WAB's were included, rates agree at high energy sum → disagreement at low mass may be due to detector inefficiencies

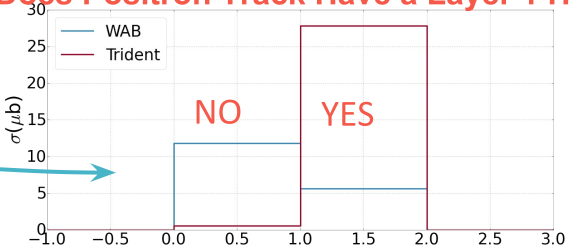
Suppressing Wide Angle Bremsstrahlung

Missing Layer 1 Hit

A majority of conversions will occur in layer 1 of the Silicon Vertex Tracker → positron will be missing a layer 1 hit

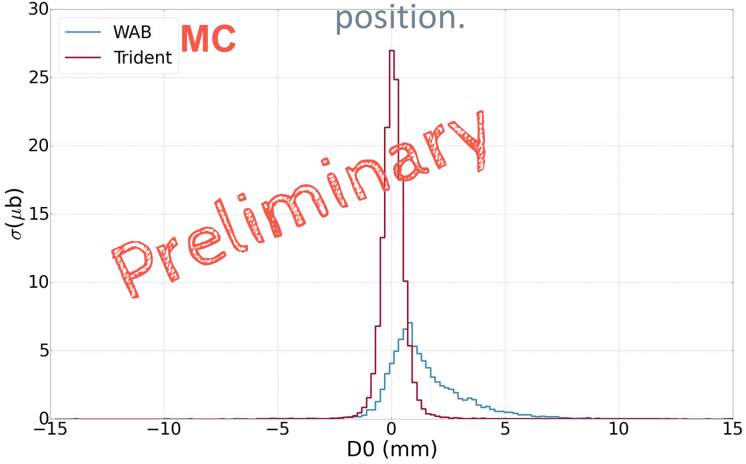
Layer 1 requirement removes 68% of WABS from final event sample! After all cuts, > 80% of WABs are rejected.

Does Positron Track Have a Layer 1 Hit?



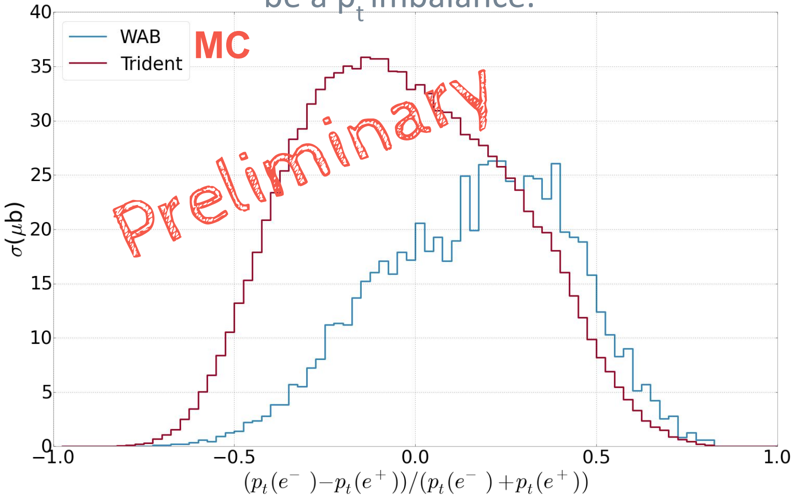
Positron Track Distance of Closest Approach

If a conversion occurs in the silicon, the positron track will extrapolate to the side of the nominal target position.



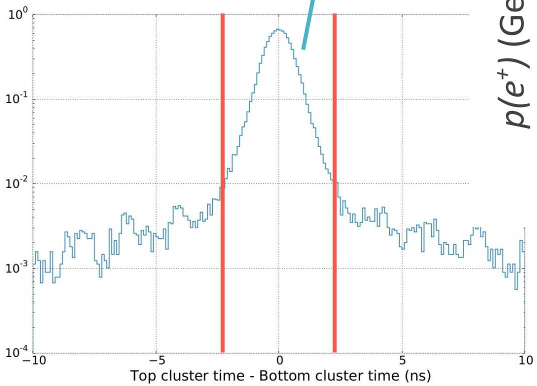
P_t Asymmetry

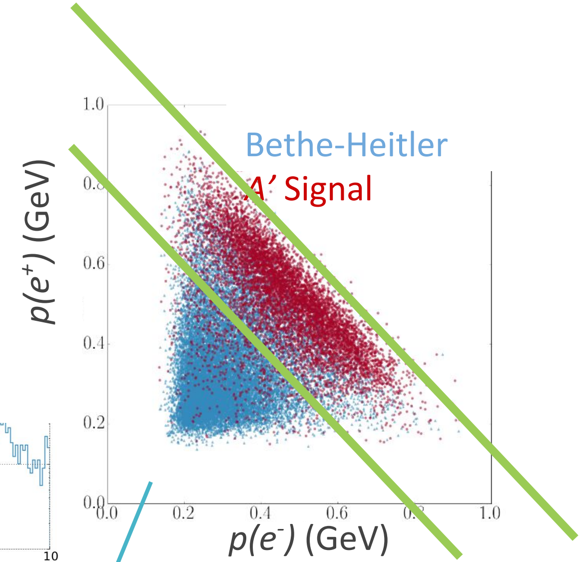
Because the conversion electron is missing there will be a p_t imbalance.



Bump Hunt Selection

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



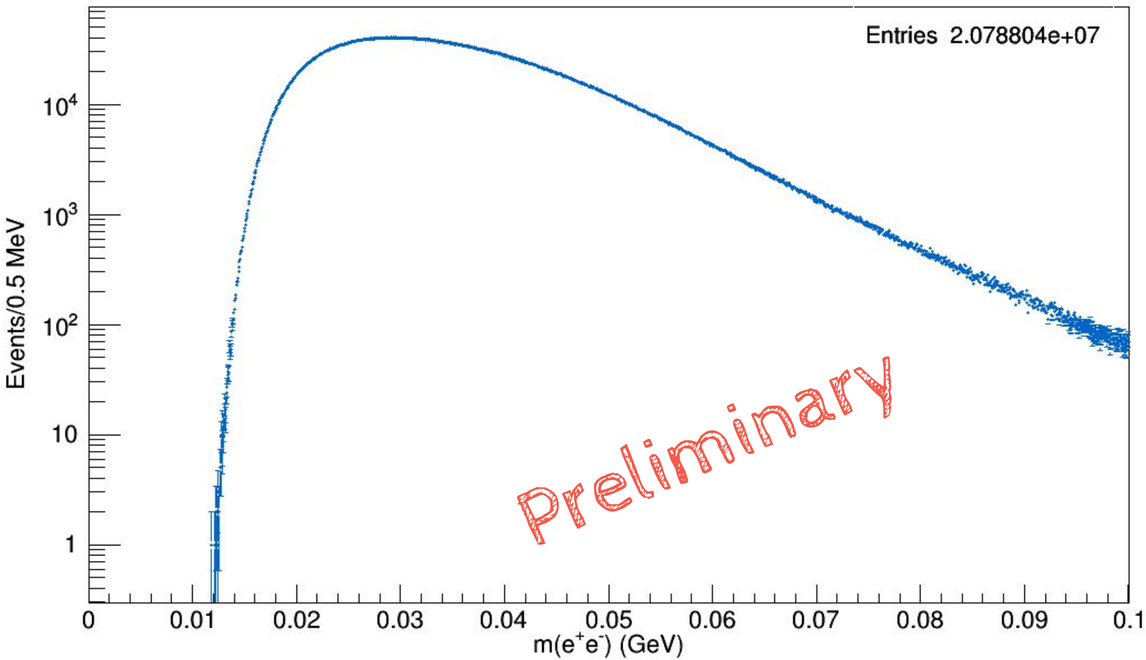


Requiring the sum of the e+e- pair momentum to be greater than 0.8 GeV greatly reduces the number of Bethe-Heitler background in our final sample.

Final invariant mass distribution

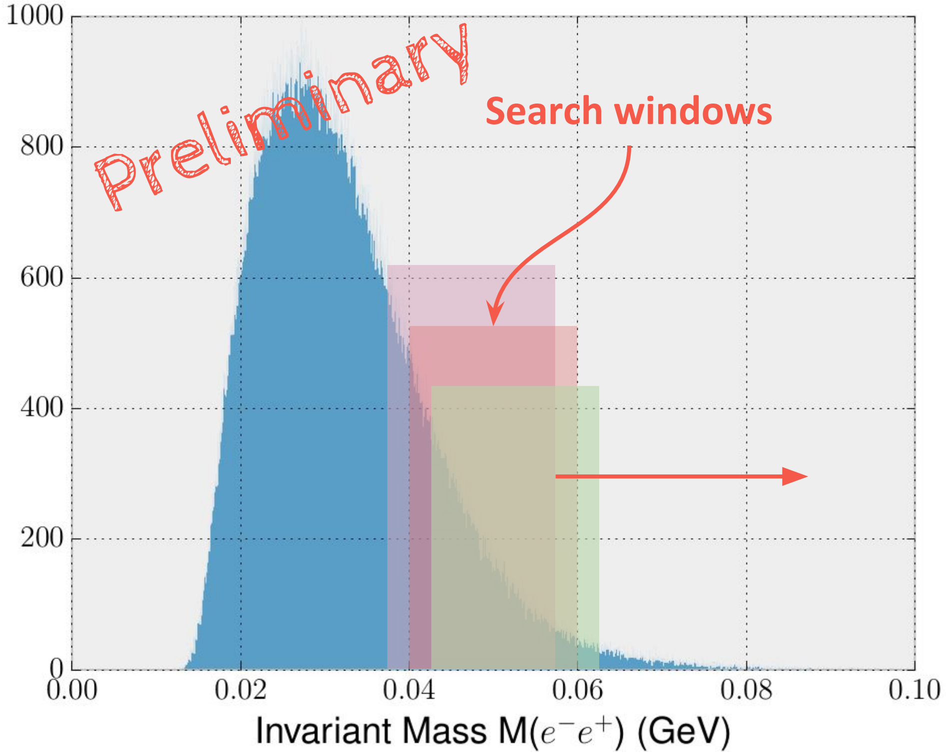
Final invariant spectrum contains 20.7 Million events taken at 0.5 mm

- ✔ Search uses 1.7 PAC days worth of data
- ✔ Histogram used in resonance search is composed on 2000, 0.5 MeV bins



Resonance Search Overview

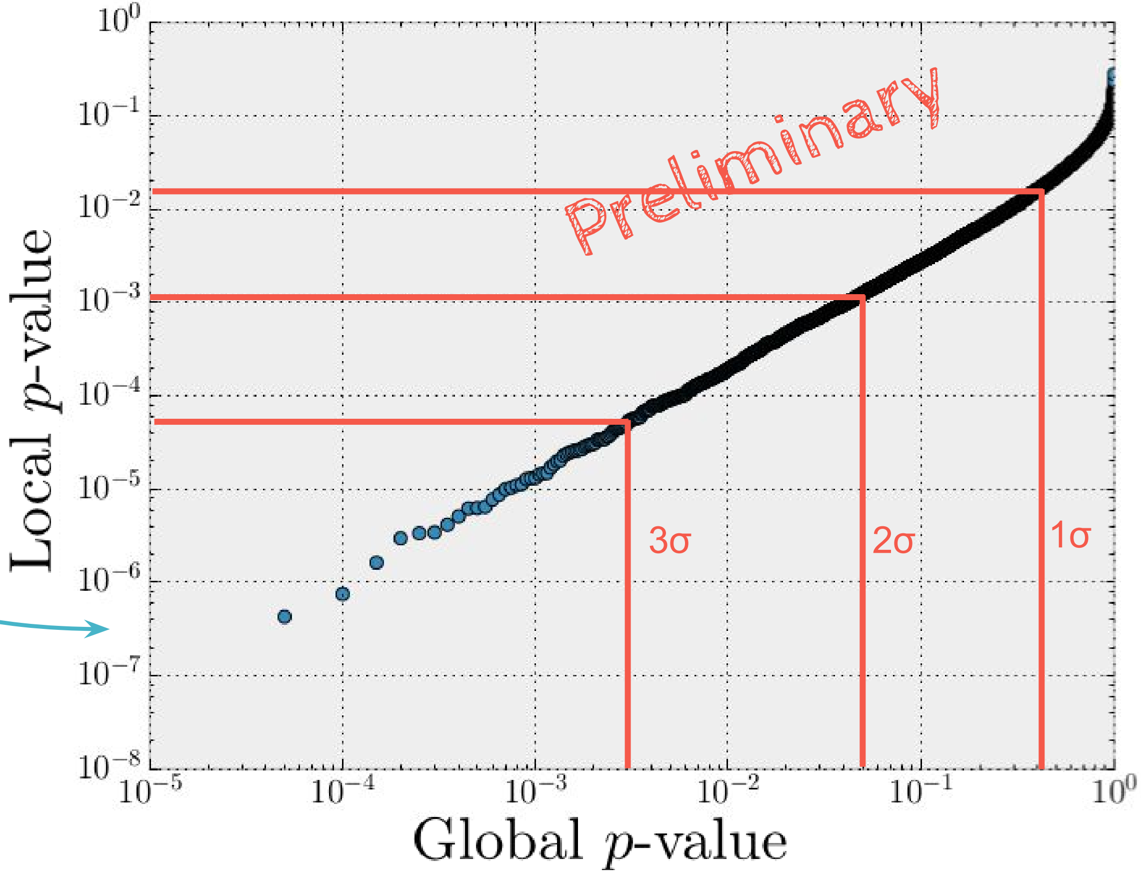
- ✔ Search for a resonance within a window in the mass range between 18 MeV and 95 MeV by scanning the e^+e^- invariant mass spectrum in 1 MeV step sizes.
  - ✔ Pseudo-experiments were used to set the optimal search window size → $11\sigma_{mass}$ at the edges and $17\sigma_{mass}$ in the center
- ✔ 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



Look Elsewhere Effect

We are doing multiple fits across our invariant mass spectrum so we are bound to find a bump at some point ⟶ The look-elsewhere effect (stats world ⟶ Bonferroni correction)

- ✔ Apply all previously described cuts to MC dataset
- ✔ Smooth the resulting MC invariant mass distribution to create a PDF
- ✔ Generate 10,000 toy distributions and perform a resonance search on each.
- ✔ Choose the smallest p-value from each scan, rank them and calculate the quantile



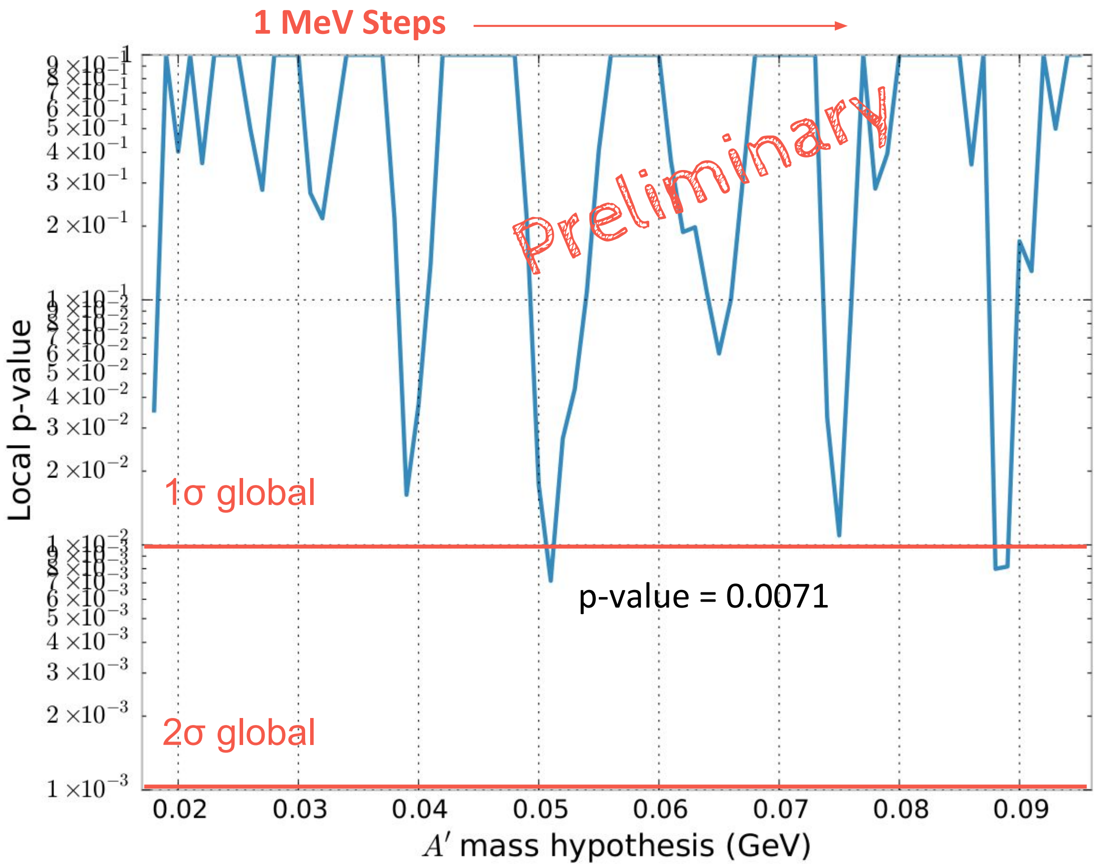
Fit Results

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

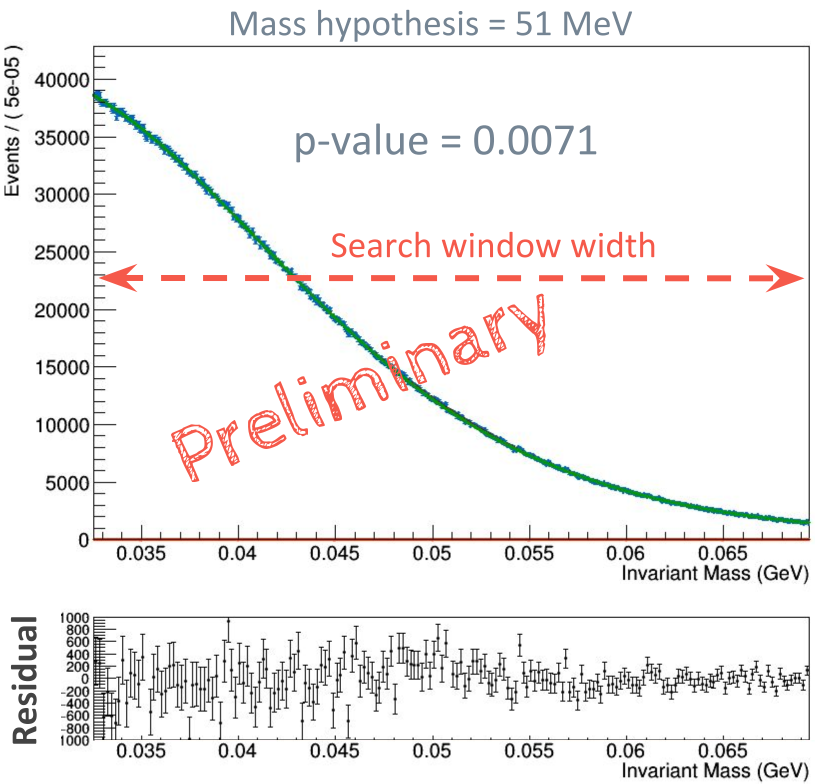
$$q_0 = \begin{cases} -2\ln \frac{\mathcal{L}(0,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \hat{\mu} > 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

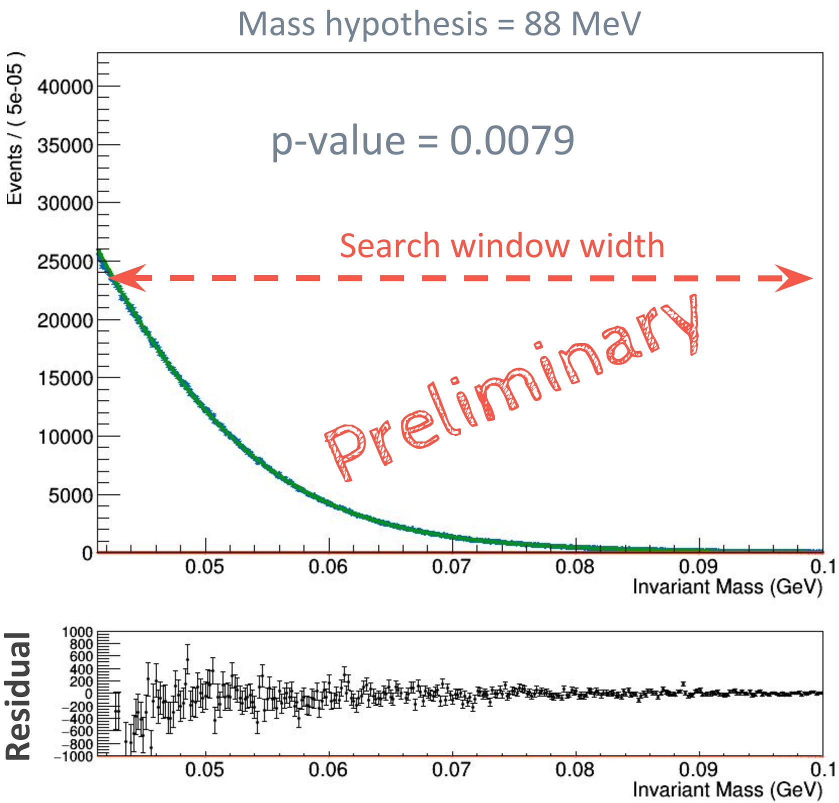
$$p = \int_{q_{0,obs}}^{\infty} f(q_0|0)\,dq_0$$

Use toy MC to determine the look-elsewhere correction



Most Significant Bumps

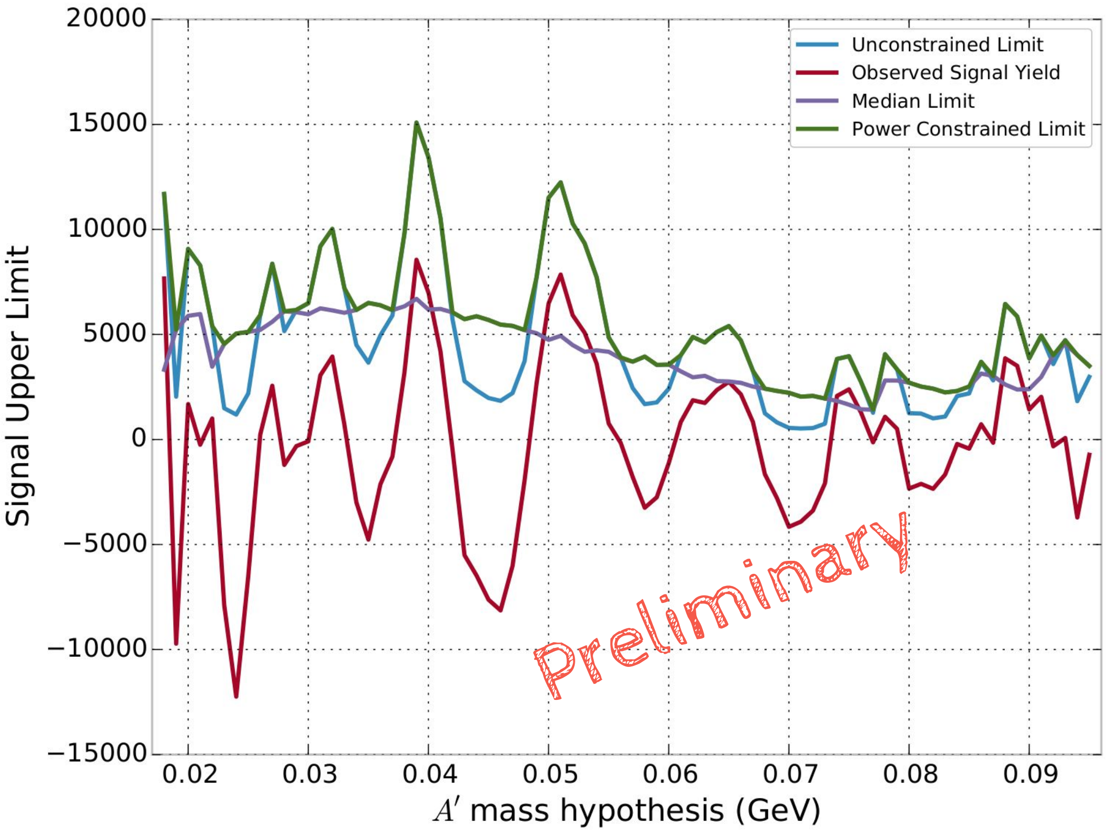




Power Constrained 2σ Limits

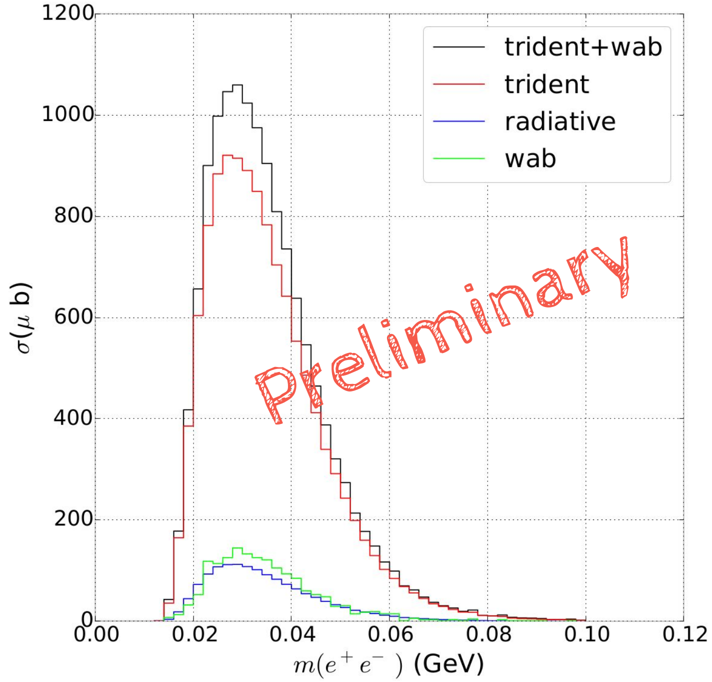
- ✓ Guards against setting a limit when no experimental sensitivity is expected
- ✓ Start by determining unconstrained upper limit, μ_{UL}
- ✓ Generate background only pseudo-data sets
- ✓ Fit each pseudo-data set with signal+background model using the same method described before and calculate upper limit → generate distribution of upper limits
- ✓ From the distribution of upper limits, calculate the median, μ_{median}

$$\mu_{pc} = \max(\mu_{\mathrm{UL}}, \mu_{\mathrm{median}})$$



Radiative Fraction

Translating the signal upper limit into the mass-coupling phase space requires knowledge of the fraction of radiative events in our event sample → use Monte Carlo to parametrize the radiative fraction as a function of mass.

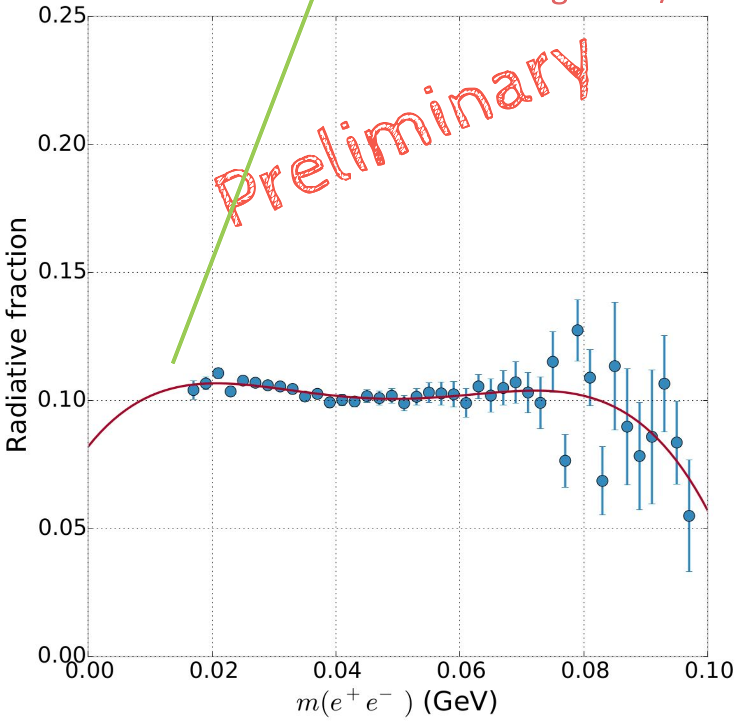


Power constrained upper limit

$$\epsilon^2 = \left(\frac{S_{max}/m_{A'}}{f \cdot \Delta B/\Delta m}\right) \times \left(\frac{2N_{eff}\alpha}{3\pi}\right)$$

1

Background/MeV



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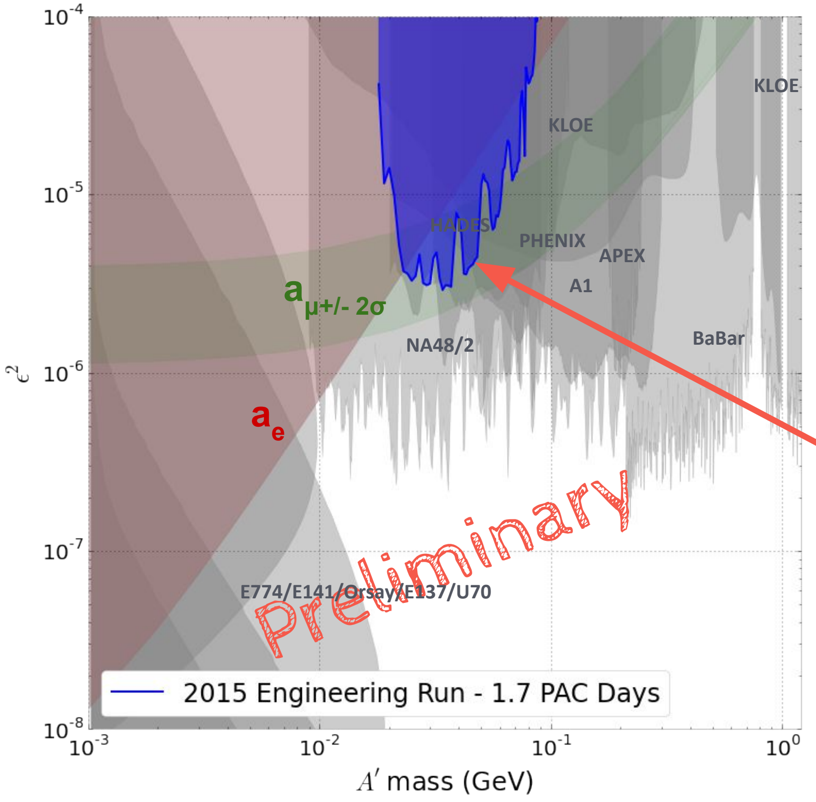
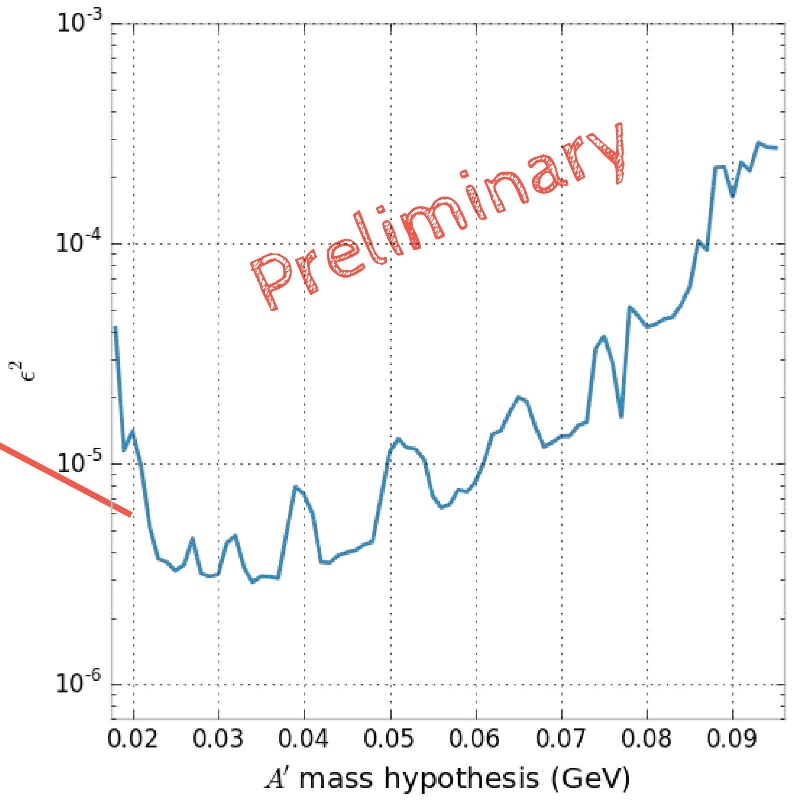
Upper Limit on Coupling Strength





Systematics

Study of systematics is still ongoing but will not dramatically impact final result.

Systematic	Value
Mass resolution	~10%
Luminosity	~1%
MC Background	~5%
Theory cross-section	~1.0%
Electron (Positron) Efficiency	>95%
Fitter Systematics	~1%

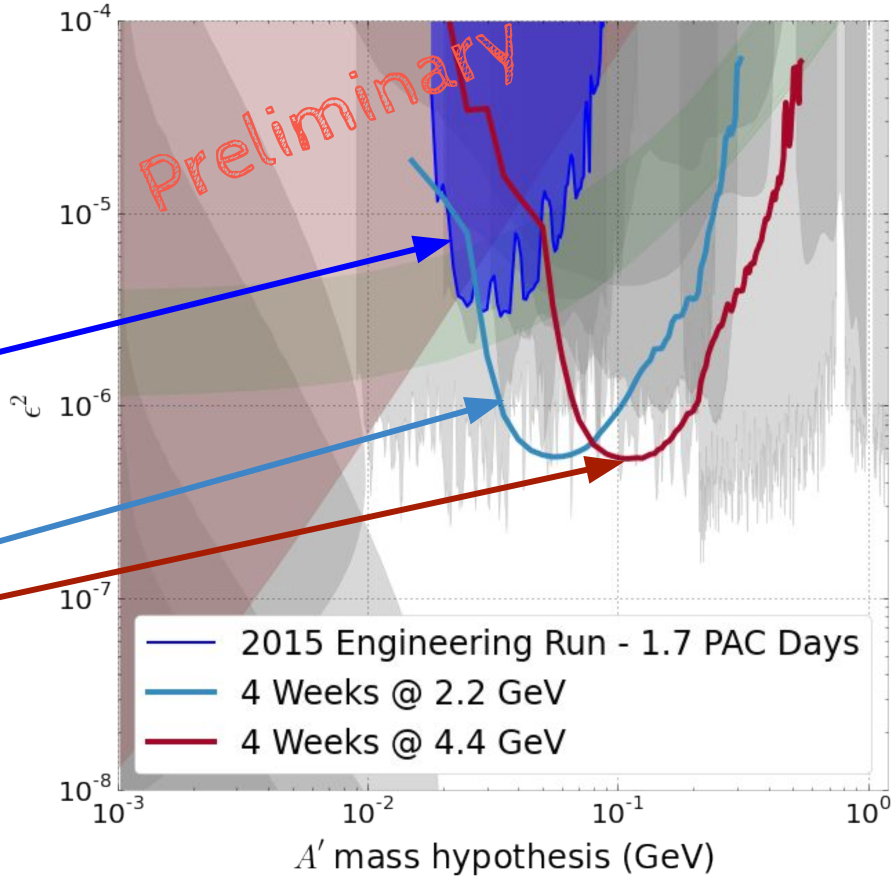
Bump Hunt Experimental Reach

HPS has been approved for its full time of running (180 PAC Days)!

First extended will take place in 2018

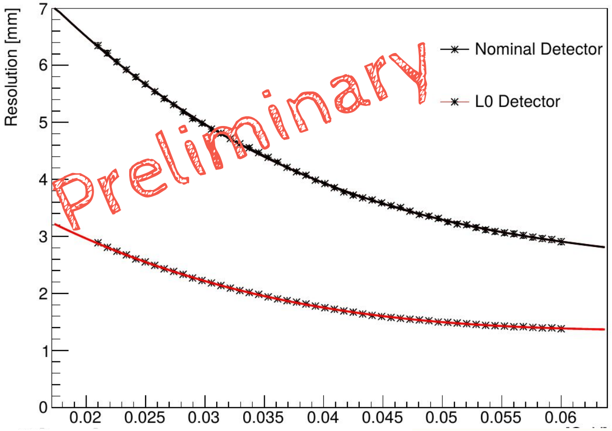
2015 Engineering Run
1.7 PAC days @ 1.05 GeV

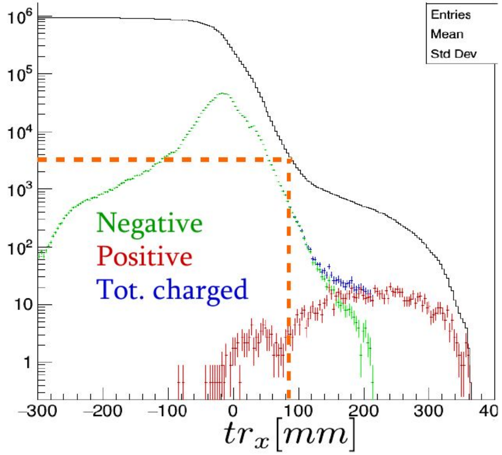
2018-2020 Physics Run
4 Weeks @ 2.2 GeV
4 Weeks @ 4.4 GeV

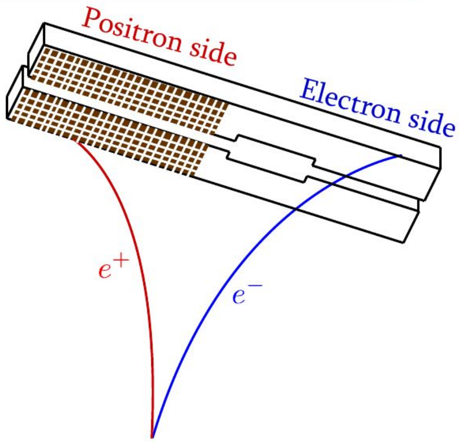


HPS Upgrades

- Vertex reach is worse than we had projected ⟶ No vertex reach expected using 1.5 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.







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 fully approved for its full time

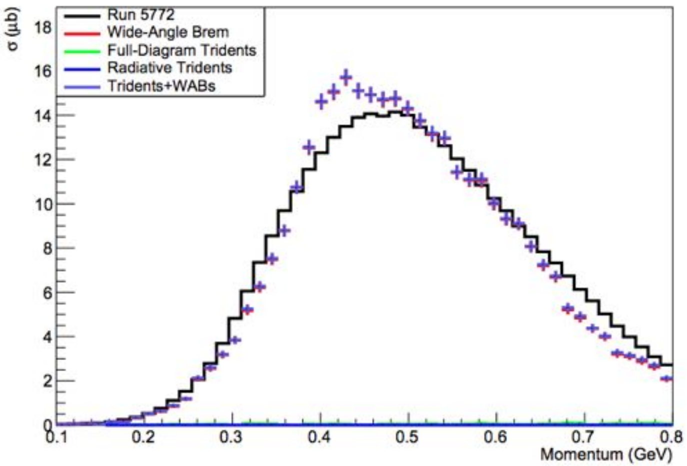
Several analyses are ongoing

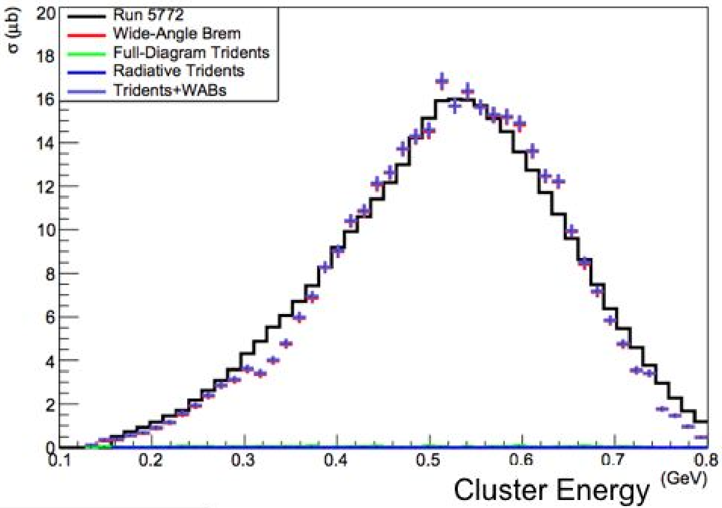
- ✔ 2015 Bump hunt analysis is now complete
- ✔ 2016 Bump hunt analysis and 2015/16 Vertex analysis are ongoing
  - ✔ One vertex analysis thesis using the 2015 data has been completed, another one will be completed soon.

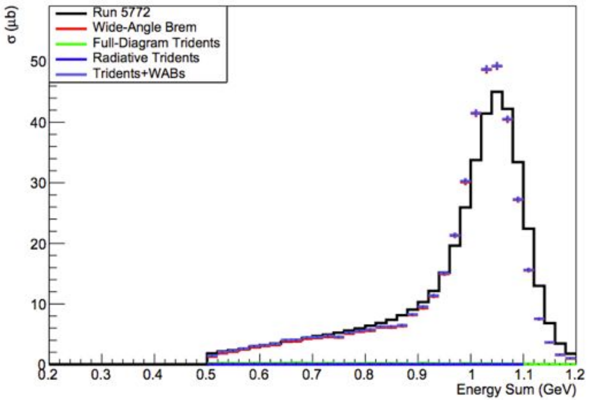
Upgrades are being proposed that will help HPS extend its reach

Backup

WAB MC vs Data

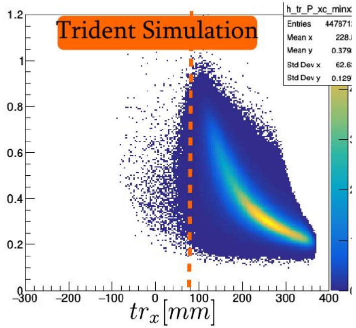


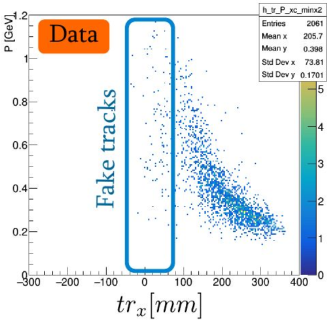




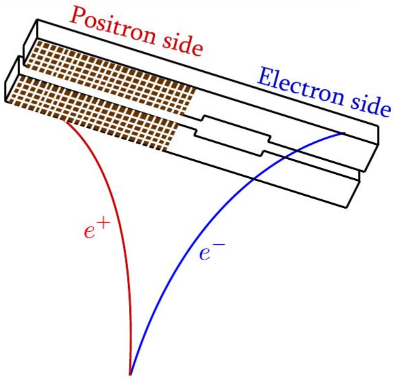
Positron Trigger

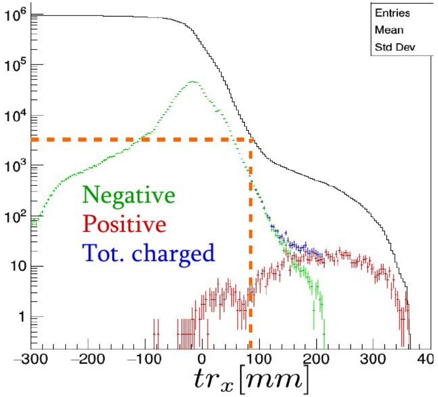
Almost 100% of e⁺ have x > 90,





Design is not Final yet





Total charged particle rate at x > 90 mm is less than 4KHz

In combination with Hodoscpe and Ecal, trigger rate will drop from 17 Khz to about 4 KHz

Vertex Efficiency

A'(50MeV) decay at 2.2 GeV