The Heavy Photon Search Experiment

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On behalf of the Heavy Photon Search Experiment

U.S. Cosmic Visions: New Ideas in Dark Matter
University of Maryland
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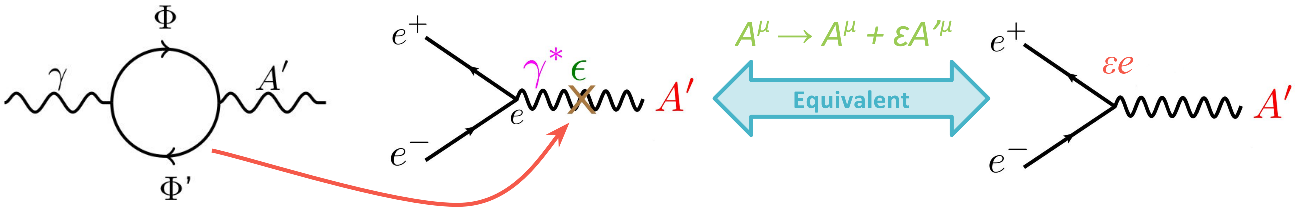
What is a Heavy Photon?

Consider a theory in which nature contains an additional Abelian gauge symmetry, *U'(1)*

Holdom, Phys. Lett. B166, 1986

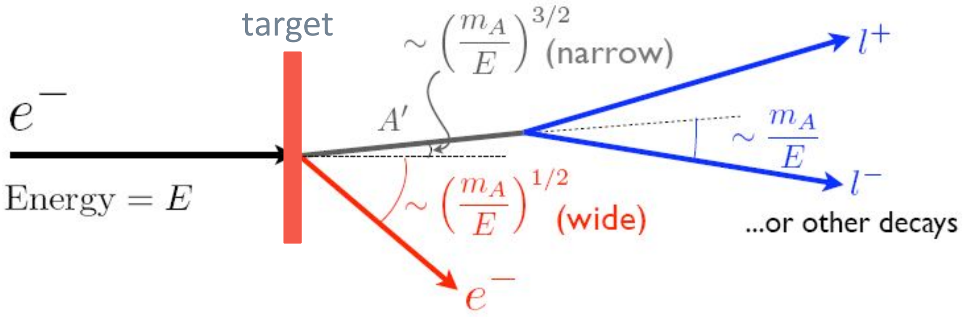
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

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**



Searching for a Heavy Photon

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^-



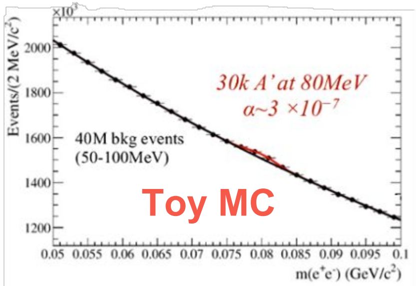
Kinematics are very different from bremsstrahlung

- ✔ 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 small coupling.



Displaced Vertex + Bump Hunt

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

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

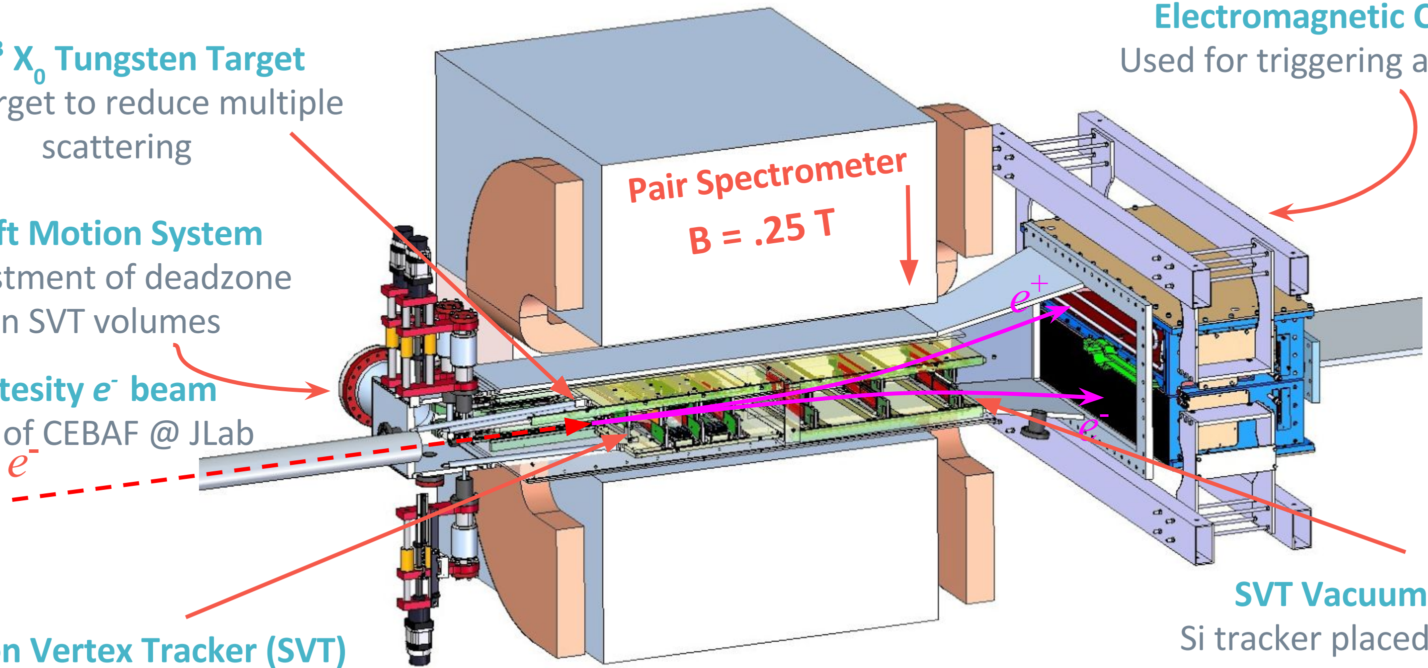
Displaced Vertex: Distinguishing A' decay vertices as Non-prompt requires good vertex resolution

- ✔ Both require a tracking system and magnet that are placed as close to the target as possible
- ✔ Mass and vertex resolution will be dominated by multiple scattering so tracker material needs to be minimized

Small coupling $\longrightarrow$ small cross-section

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

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

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Used for precise momentum and vertex determination

Electromagnetic Calorimeter
Used for triggering and particle ID

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

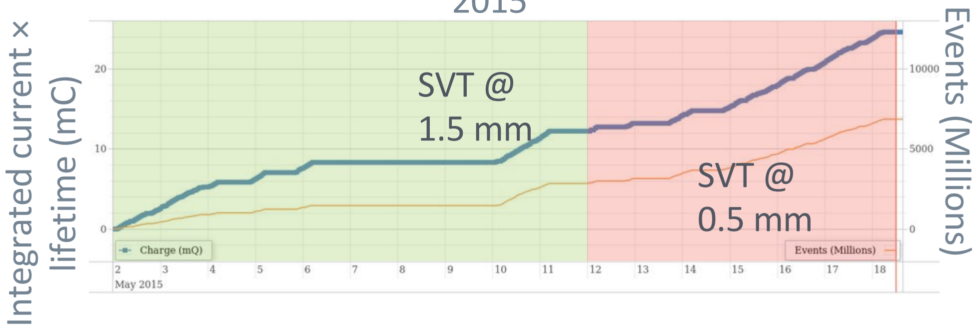
HPS has successfully completed two engineering runs at JLab

- ✔ First took place in the Spring of 2015 using a 50 nA, 1.056 GeV electron beam
- ✔ Second took place in the Spring of 2016 using a 200 nA, 2.3 GeV electron beam

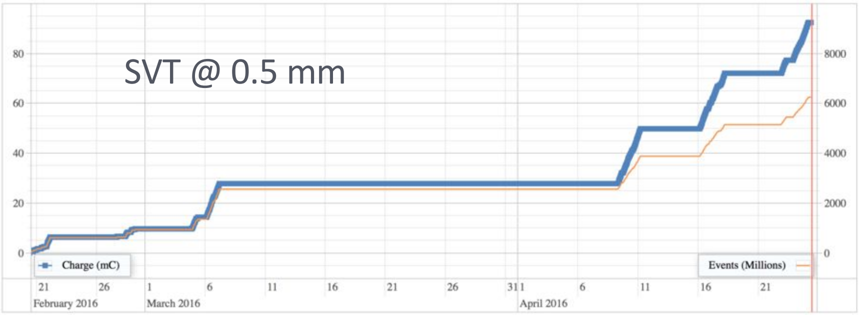
Goal: Understand the performance of the detector and take physics data.

- ✔ 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 at 0.5 mm
- ✔ 2016: 92.5 mC with the SVT at 0.5 mm

2015



2016



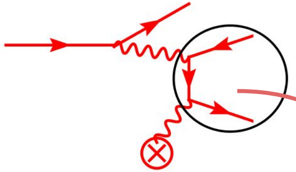
The results shown in this talk used the unblinded portion (500 uC or ~74 nb^{-1}) data taken at 0.5 mm.

Backgrounds

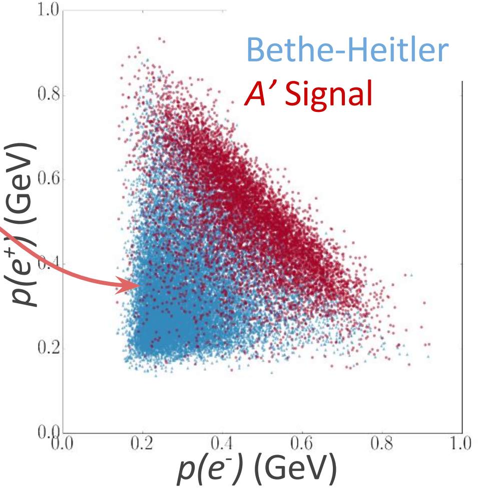
The search for an *A′* involves looking for a narrow resonance in the e^+e^- invariant mass spectrum on top of a large, continuous background composed of several components

Physics Backgrounds

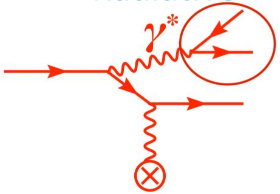
Bethe-Heitler



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



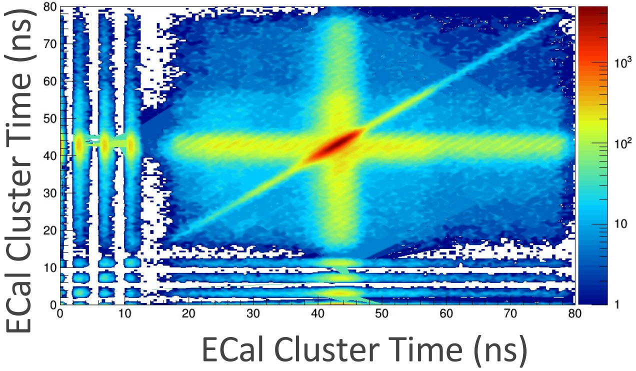
Radiative



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

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

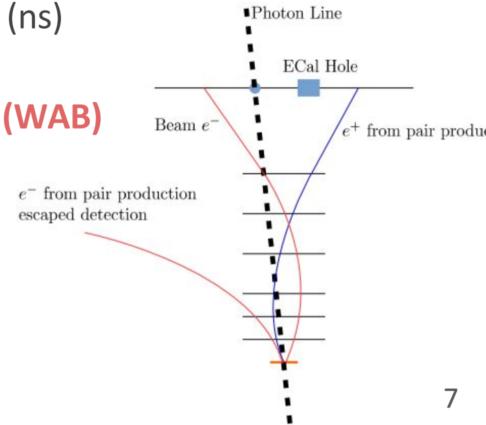
Accidentals



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



Suppressing Wide Angle Bremsstrahlung

Missing Layer 1 Hit

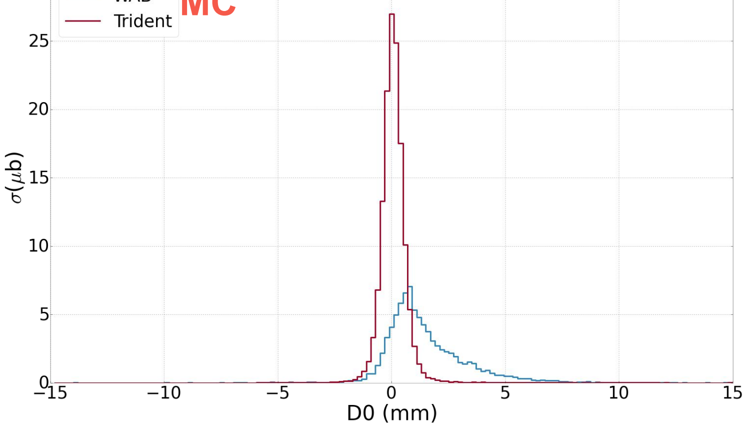
A majority of conversions will occur in layer 1 of the Silicon Vertex Tracker → positron will be missing a layer 1 hit

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?

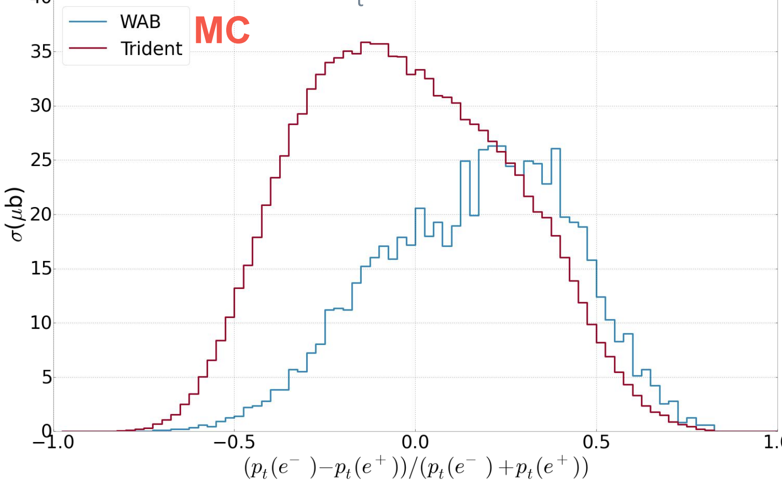
Positron Track Distance of Closest Approach

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.

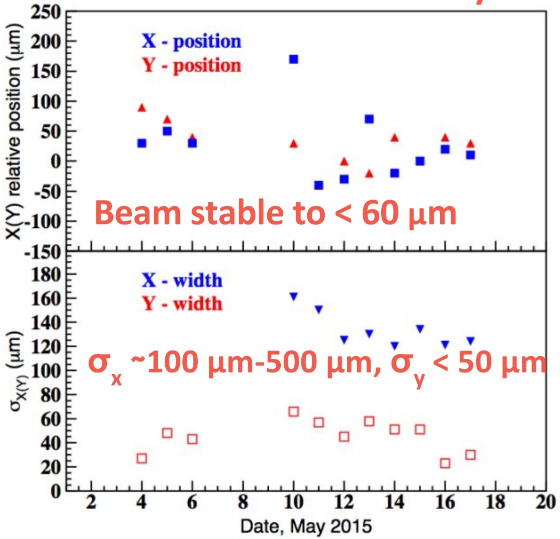


2015 Engineering Run Performance

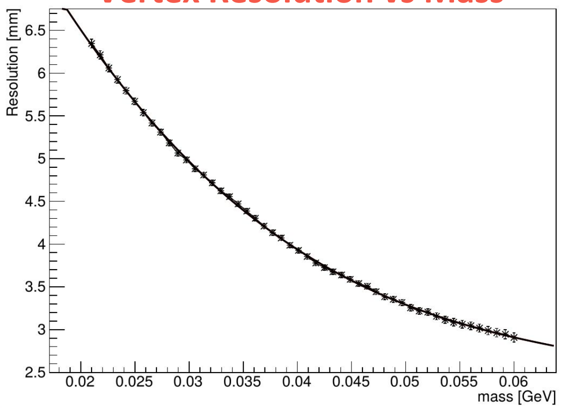
The 2015 engineering run has demonstrated that HPS is ready to do a meaningful search for heavy photons

- ✔ 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'*

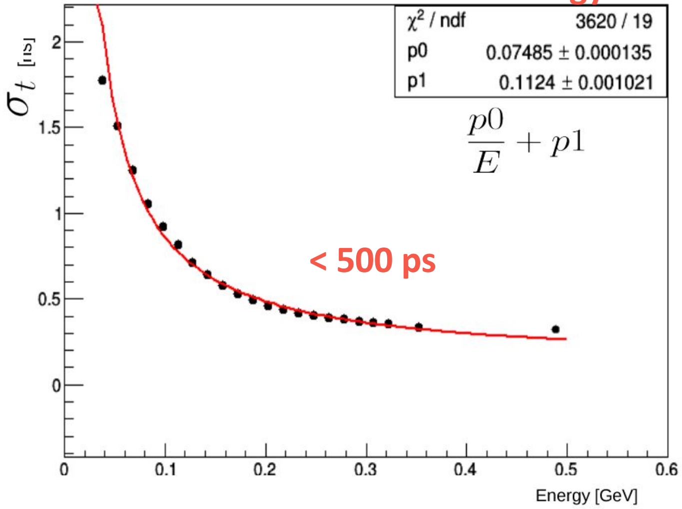
Beam Position Stability



Vertex Resolution vs Mass

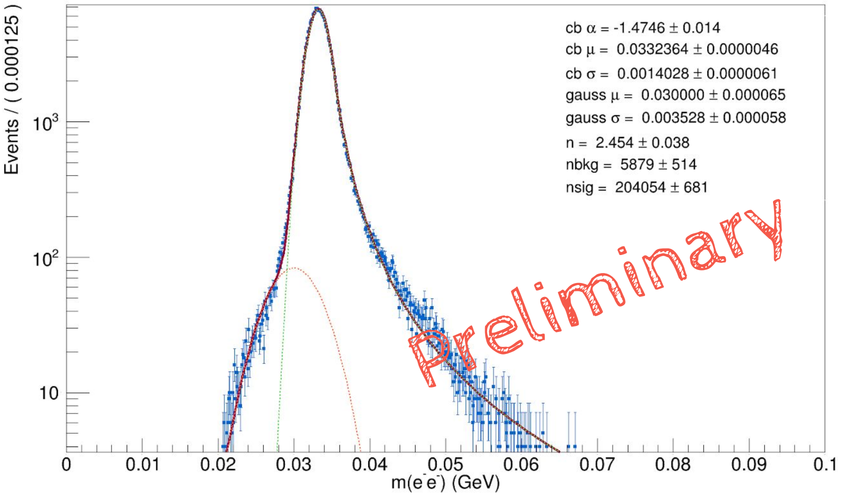


Ecal time resolution vs Energy

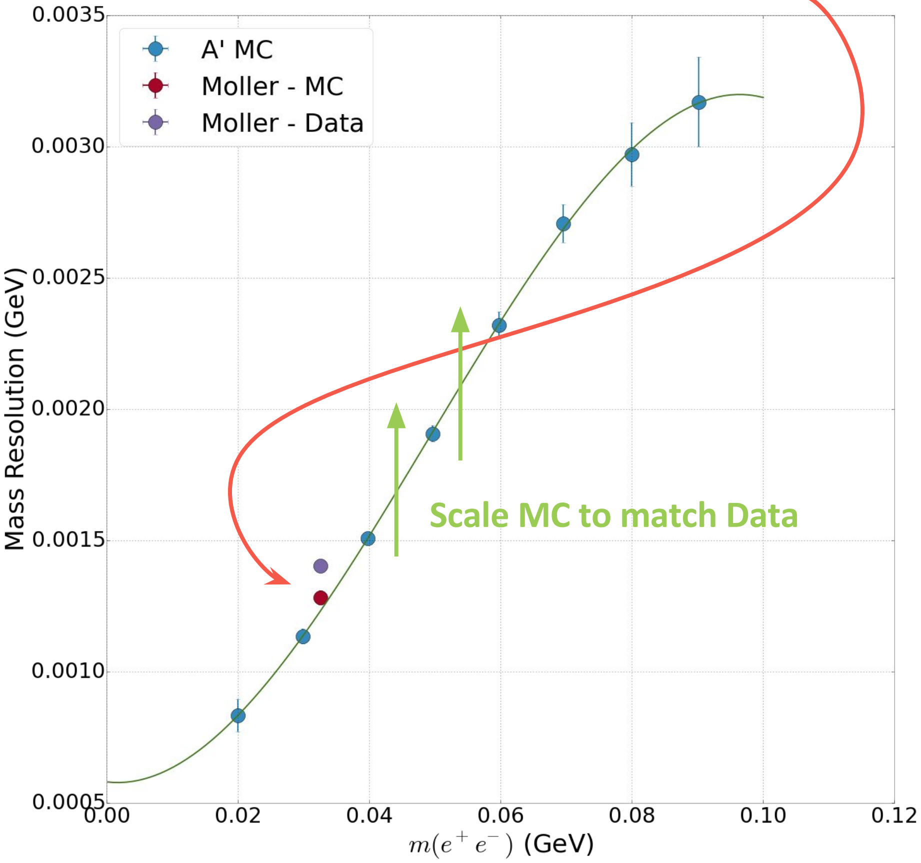


e+e- Mass Resolution

- ✔ 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.

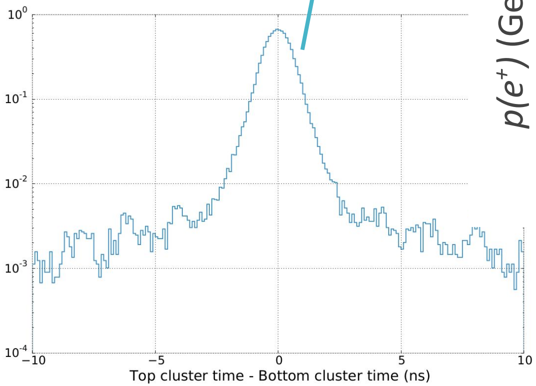


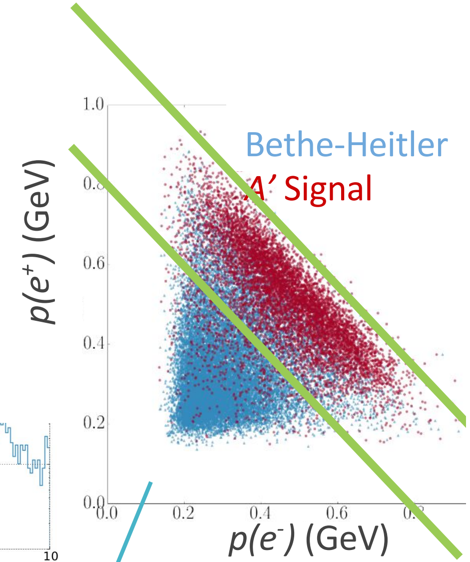
Data Møller invariant mass is within 10% of Monte Carlo

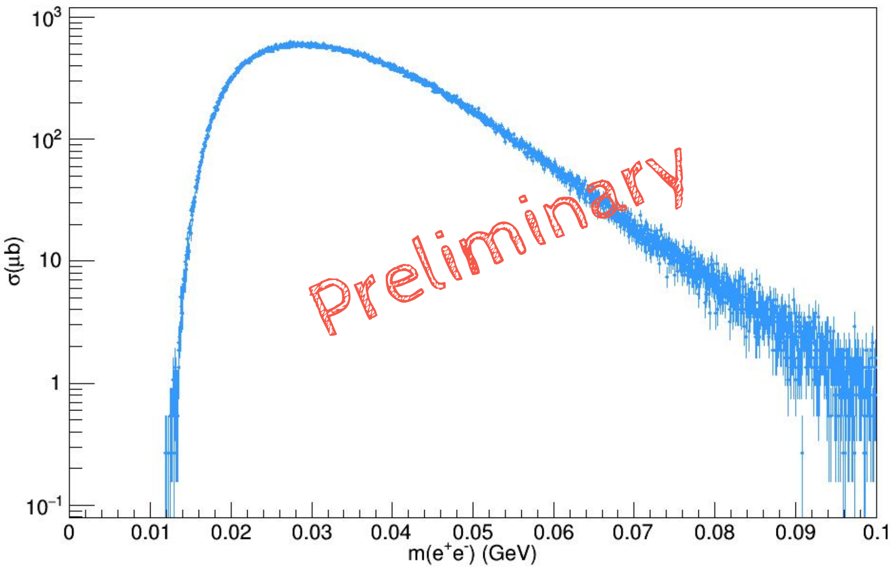


Bump Hunt Event Selection

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



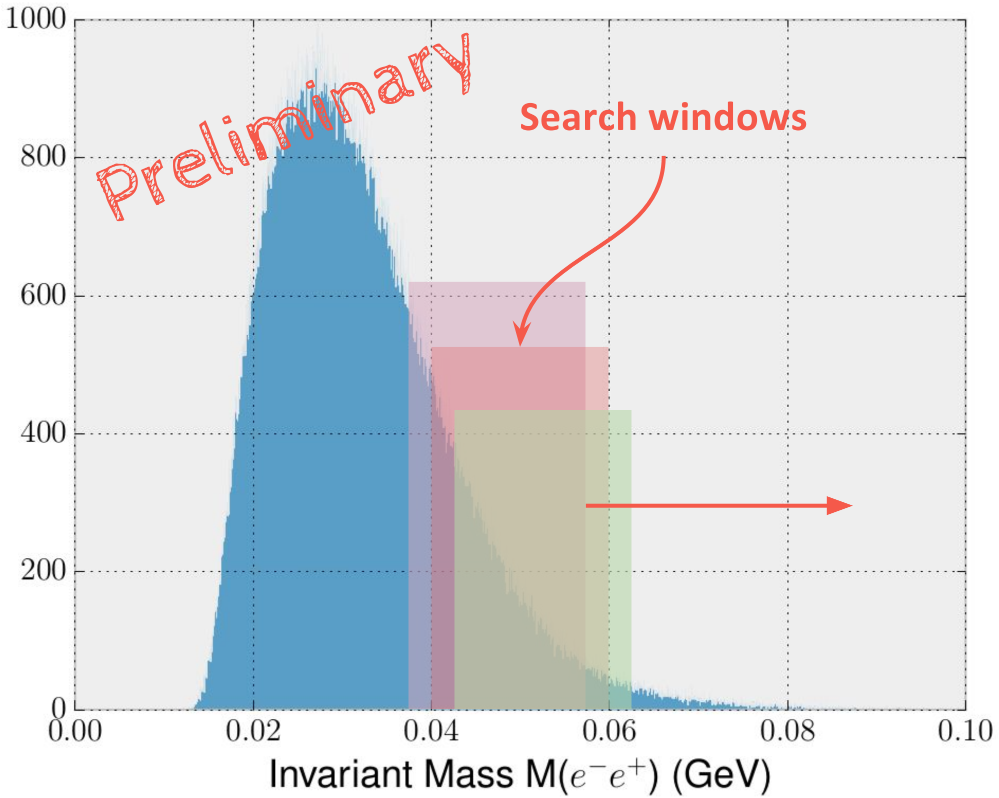




Requiring the sum of the e+e- pair momentum to be greater than 0.8 GeV greatly reduces the number of Bethe-Heitler background in our final sample.

Resonance Search Overview

- ✔ Search for a resonance in the mass range between 17 MeV and 90 MeV by scanning the e^+e^- invariant mass spectrum
  - ✔ Pseudo-experiments are used to set the optimal search window size
- ✔ 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

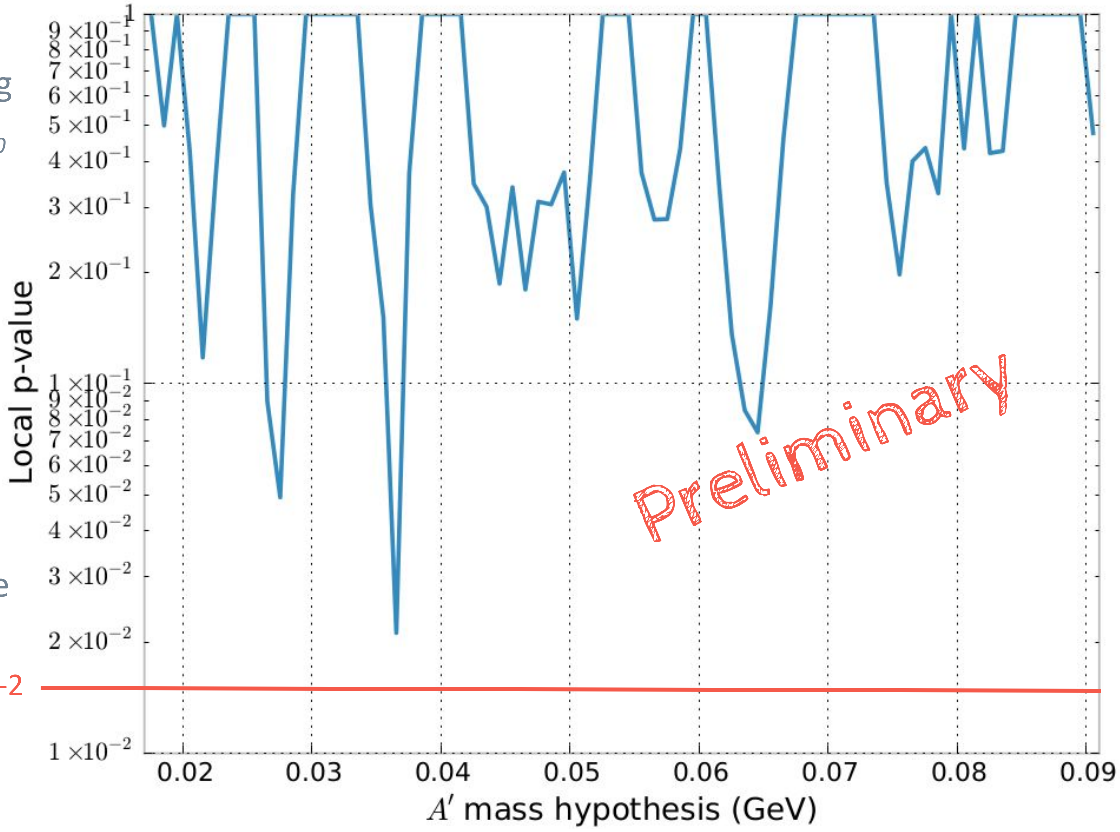
No significant bump was found!

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

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

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

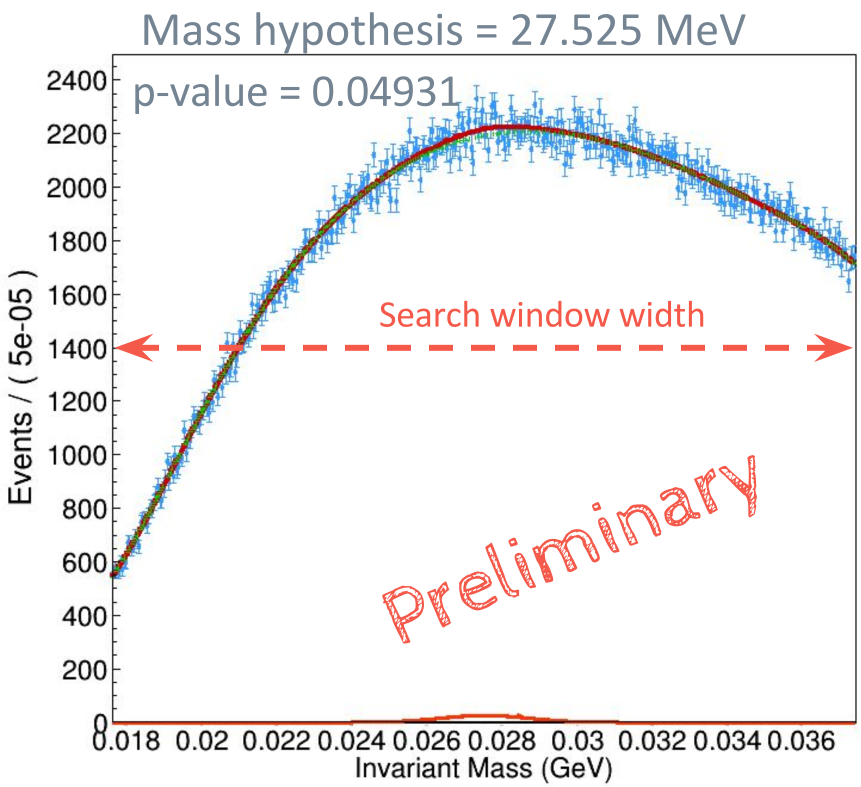
Use toy MC to determine the look-elsewhere correction

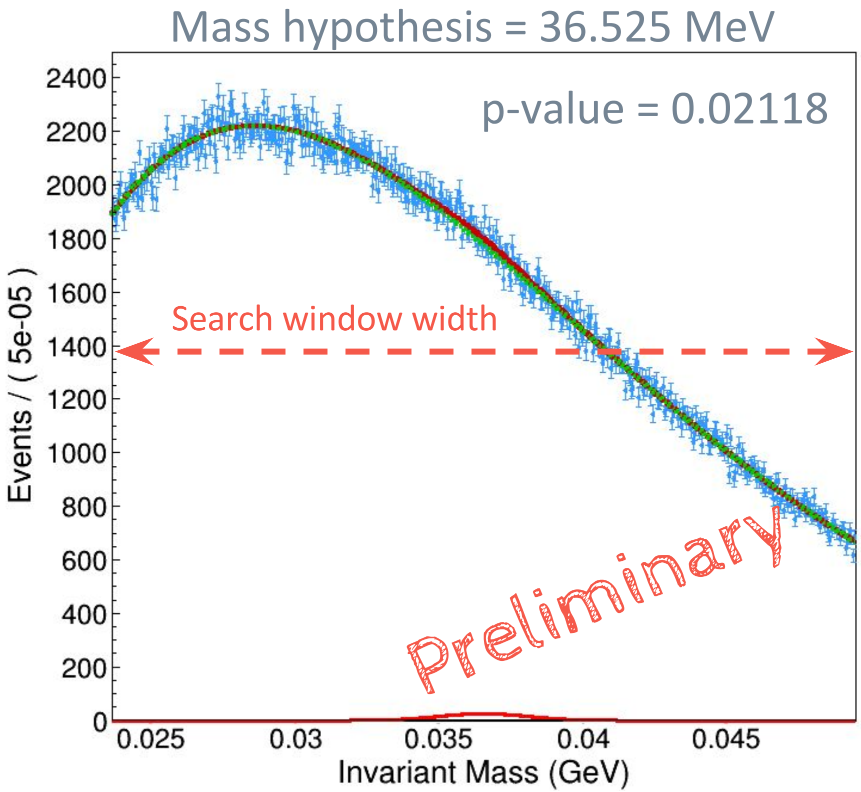


1σ global @ ~1.5×10^{-2}

Most Significant Bumps

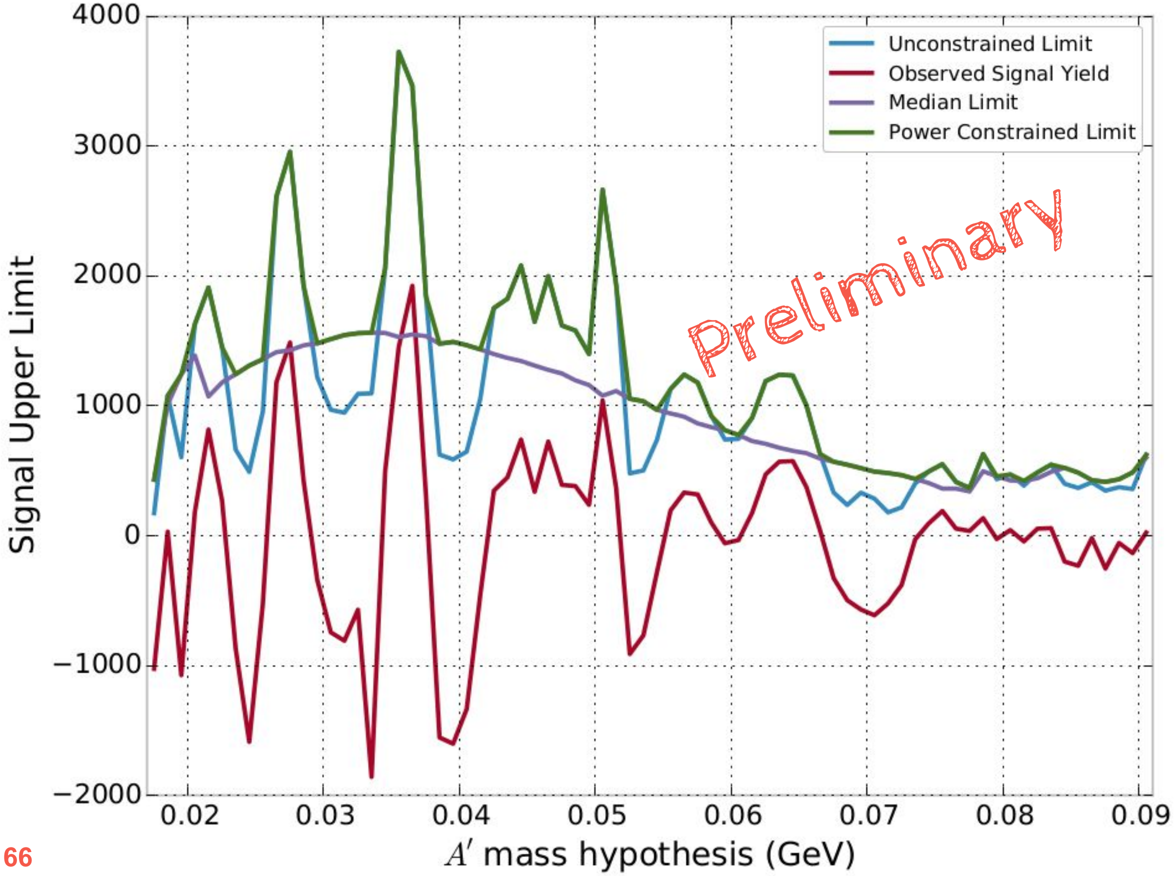
The two bumps with the smallest p-values





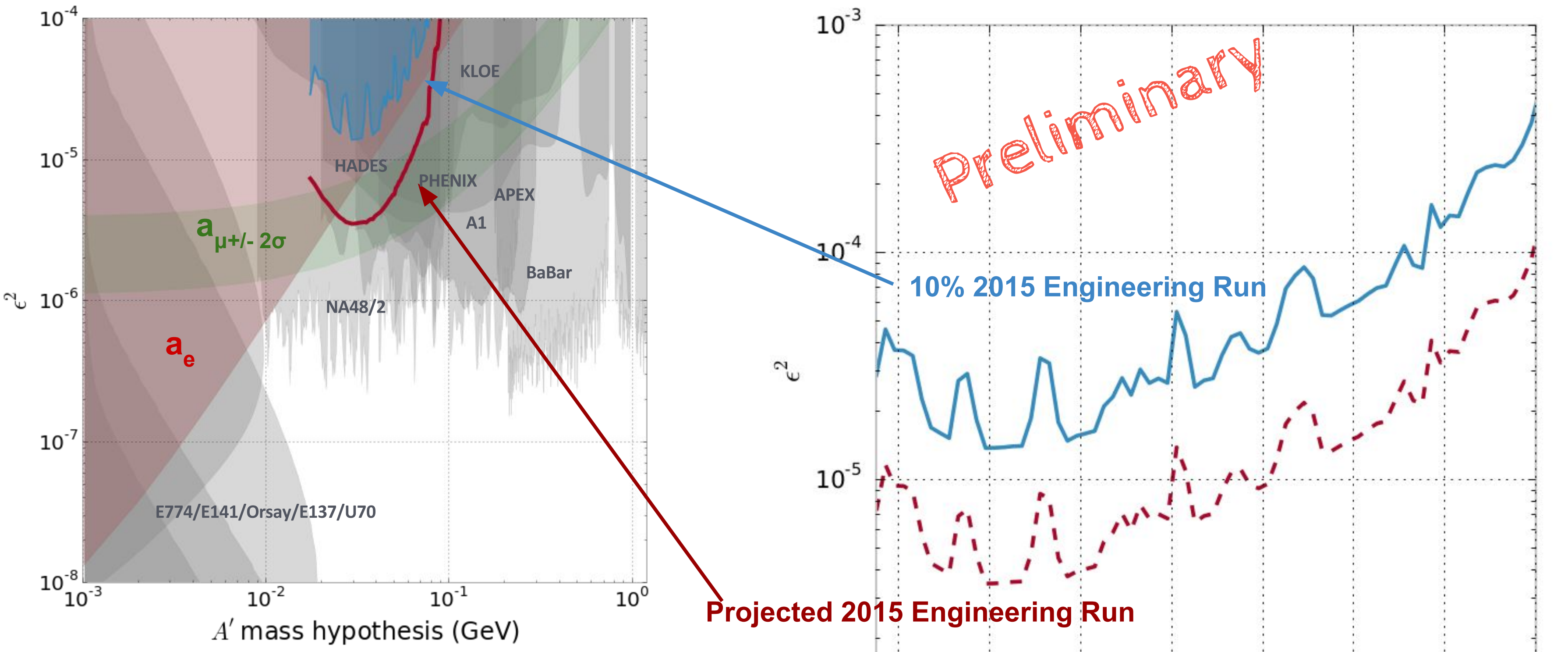
Power Constrained 2σ Limits

Use power constrained limits ⟶ Require that the experiment has enough sensitivity to a signal yield before excluding



Power Constrained Limits: arXiv:1105.3166

Upper Limit on Coupling Strength



No new territory is expected to be covered using the Engineering run data → **Review of full result is underway and will be released this Spring**

Status of Displaced Vertex Search

Vertex search using 2015 data is still ongoing

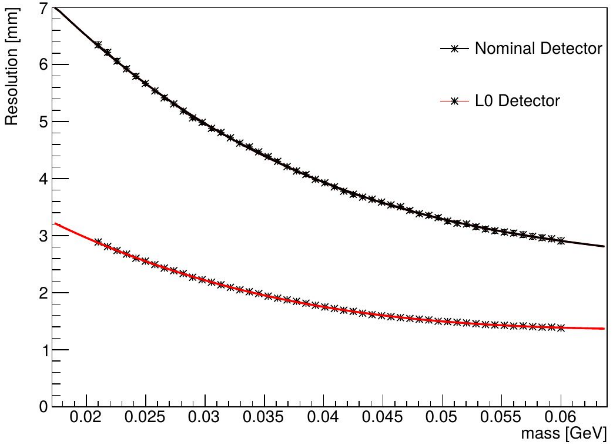
- ✔ One thesis has been completed, another one will be completed soon.

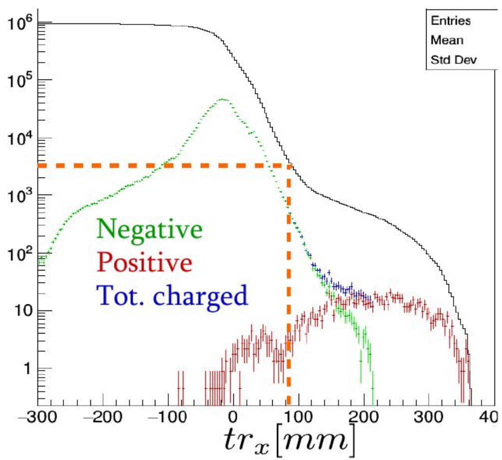
Reach is worse than we had projected → No vertex reach expected using 1.5 days of data

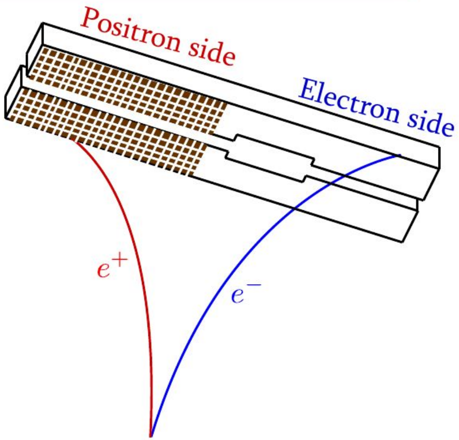
- ✔ Vertex decay efficiency assumed constant out to 10 cm
- ✔ MC used to make initial projections did not use the correct acceptance

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.







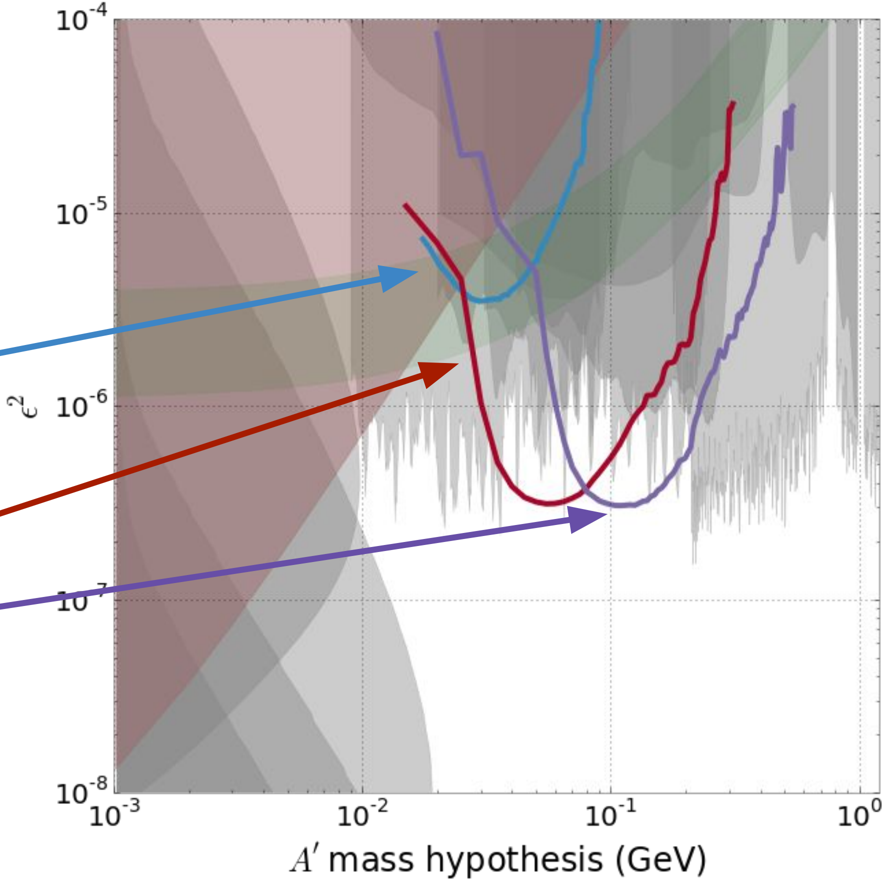
Bump Hunt Experimental Reach

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

First extended run is planned for the summer of 2018

2015 Engineering Run
1.5 days @ 1.05 GeV

2018-2020 Physics Run
12 Weeks @ 2.2 GeV
12 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

Several analyses are ongoing

- ✔ 2015 Bump hunt analysis is currently under review and will be unblinded
- ✔ 2016 Bump hunt analysis and 2015/16 Vertex analysis are ongoing

Upgrades are being proposed that will help HPS extend its reach

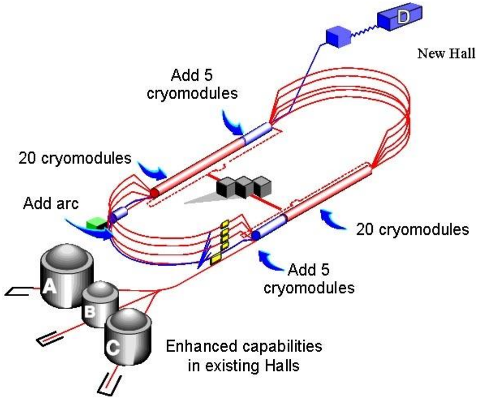
Back Up

O. Moreno (SLAC National Accelerator Laboratory) U.S. Cosmic Visions: New Ideas in Dark Matter, March 23-25 2017

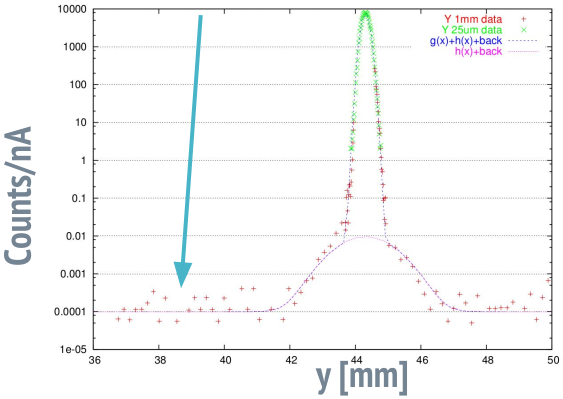
Continuous Electron Beam Accelerator Facility

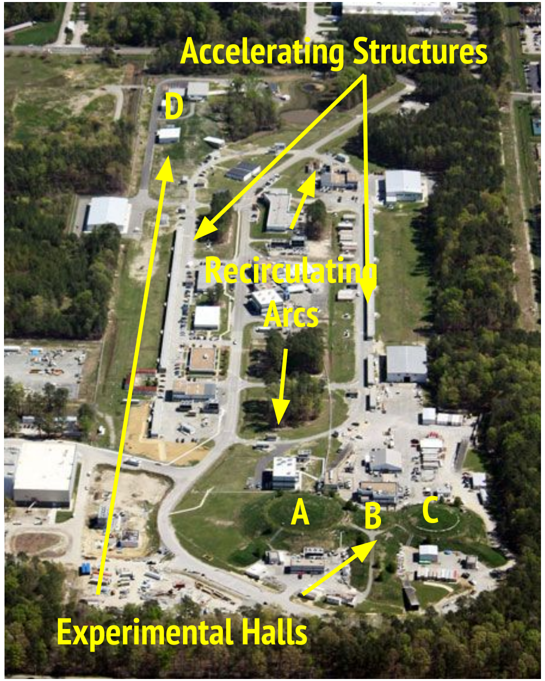
Simultaneous delivery of **intense** electron beams of different energies to four experimental halls.

- ✓ **Hall A, C:** I_{beam} < 100 μA, **Hall D:** I_{beam} < 90 μA, **Hall B:** I_{beam} < 500 nA
- ✓ With energy upgrade, $E_{beam} = n \times 2.2$ 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



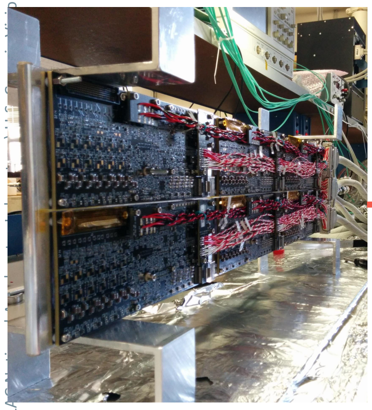
Beam halo/tails 10^{-7}

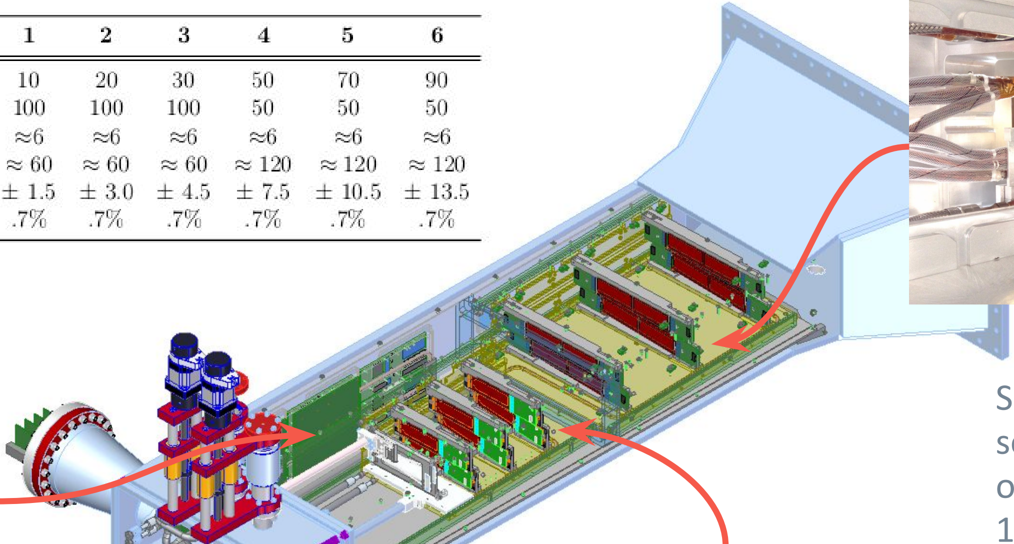


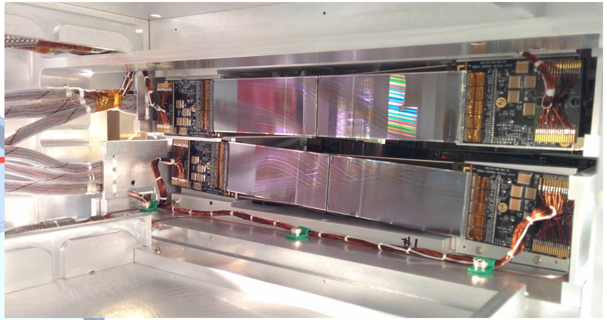


Silicon Vertex Tracker

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
Bend plane resolution (μm)	$\approx$6	$\approx$6	$\approx$6	$\approx$6	$\approx$6	$\approx$6
Non-bend plane resolution (μm)	$\approx$ 60	$\approx$ 60	$\approx$ 60	$\approx$ 120	$\approx$ 120	$\approx$ 120
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)

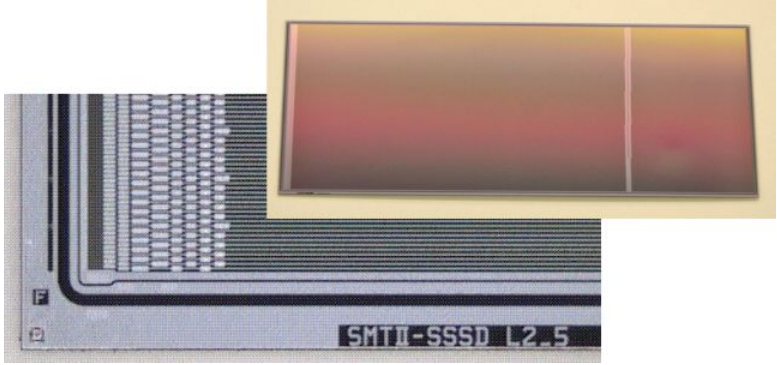
- ✔ Layer 1-3: single sensor
- ✔ Layer 4-6: double width coverage to better match Ecal acceptance
- ✔ 36 sensors
- ✔ 180 APV25 chips
- ✔ 23,004 channels

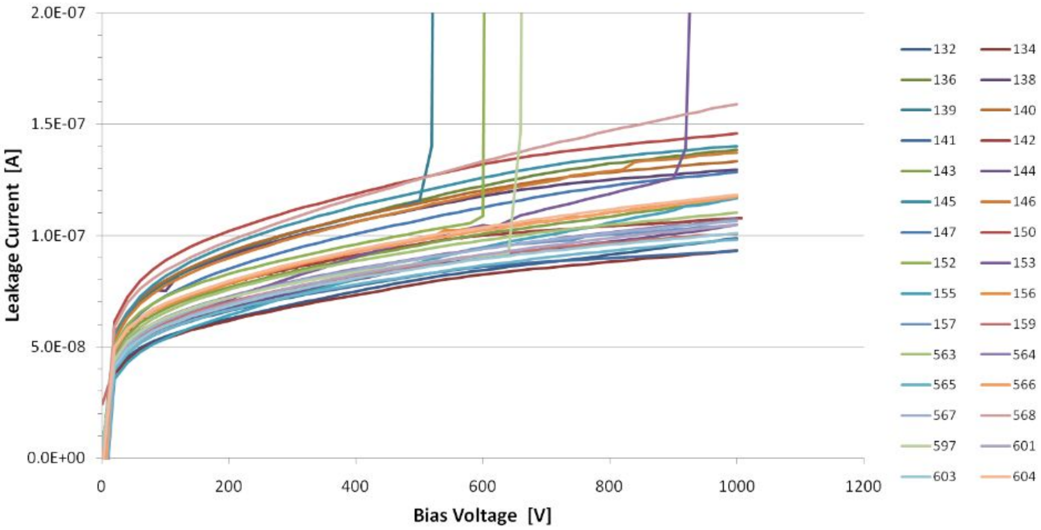
Silicon Microstrip Sensors

Developed for D0 RunIIb upgrade

- ✔ Radiation tolerant: expect fluence of 4.8×10^{15} e^- in 6 months of running
  - ✔ Breakdown voltage: ~1000 V
- ✔ < 1 $\%X_0$ per layer

Cut dimensions (L×W)	100 mm x 40.34 mm
Active area (L×W)	98.33 mm x 38.34 mm
Readout (Sense) pitch	60 (30) μm
# Readout (Sense) strips	639 (1277)
Breakdown voltage	> 1000 V
Depletion voltage	> 130 V
Bias Resistor Value	0.8 ± 0.3 MΩ
AC Coupling Capacitance	> 12 pF/cm
Total Interstrip Capacitance	< 1.2 pF/cm
Defective Channels	< 1 %



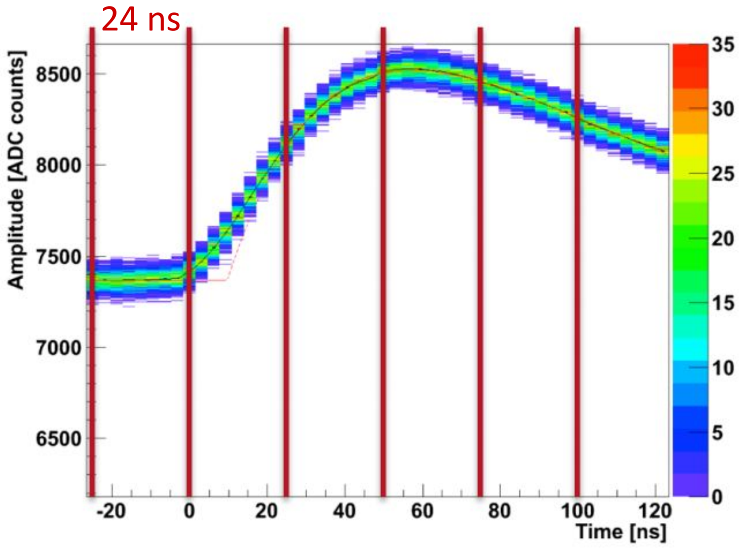


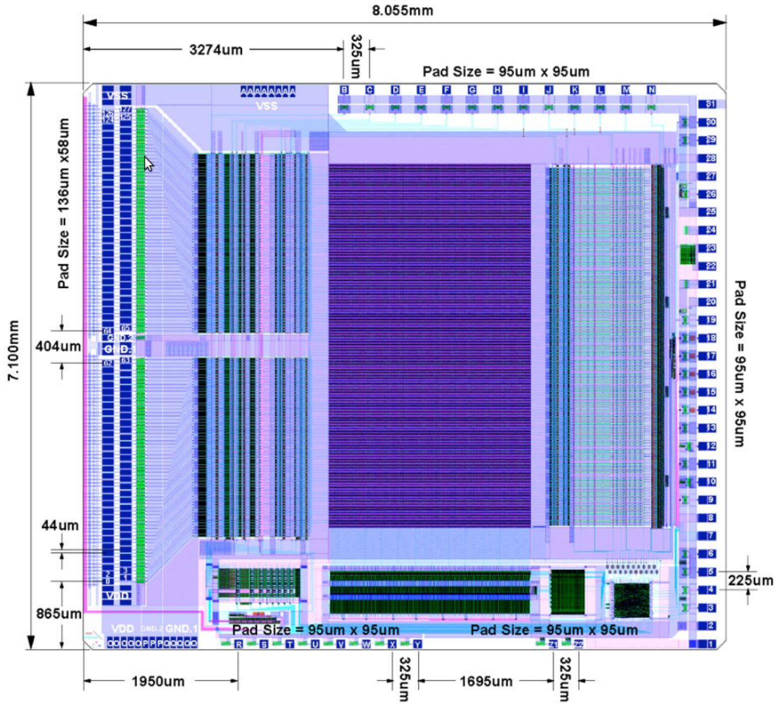
Readout Electronics: APV25

# 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

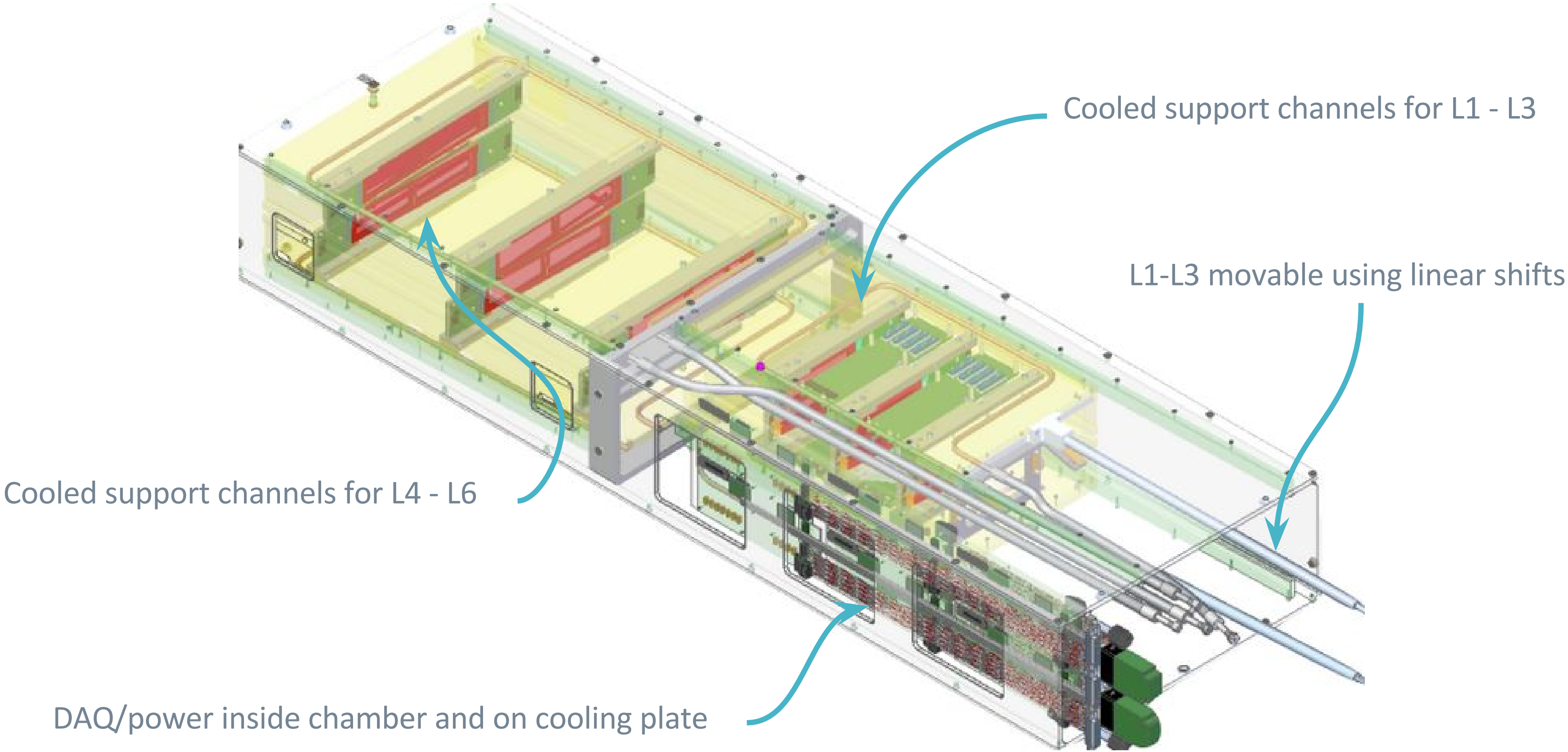
Originally developed for CMS

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

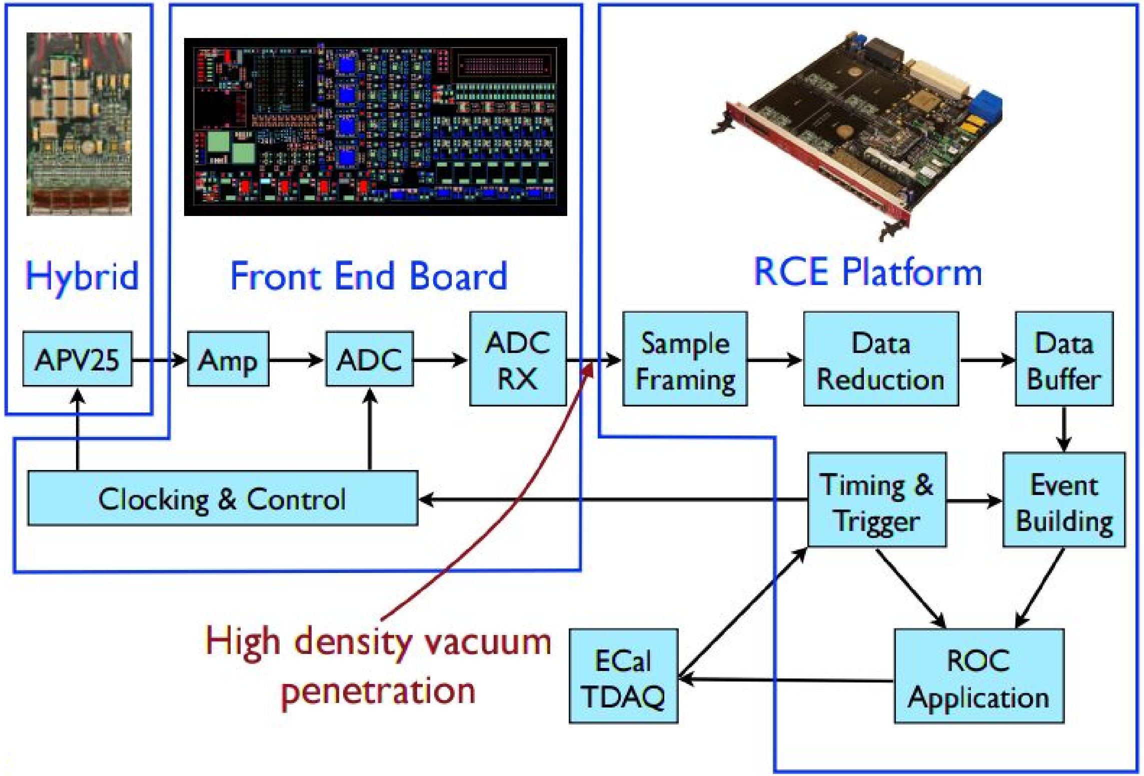




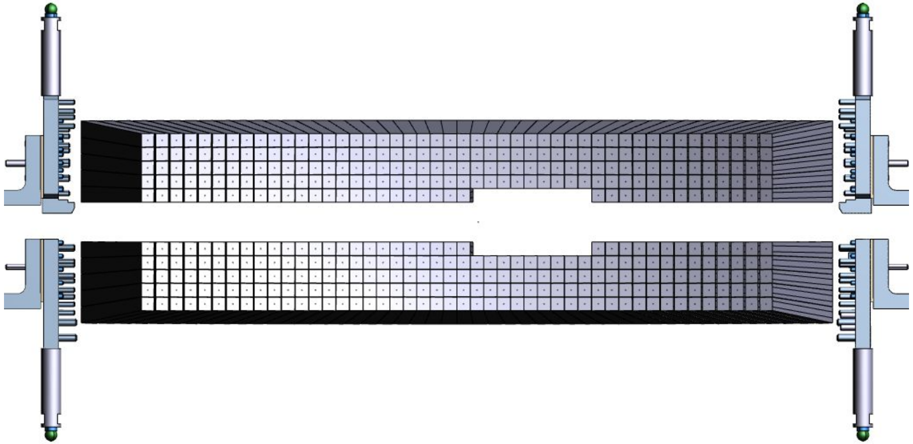
SVT Support, Cooling and Services

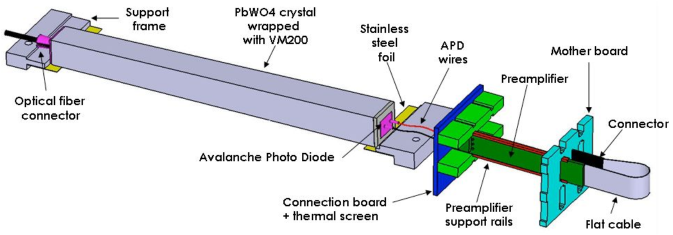


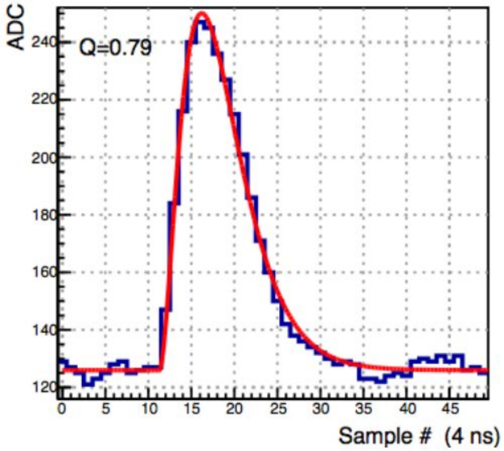
SVT DAQ


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
High density vacuum penetration

Electromagnetic Calorimeter







- Comprised of 442 PbW04 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 > 50 kHz

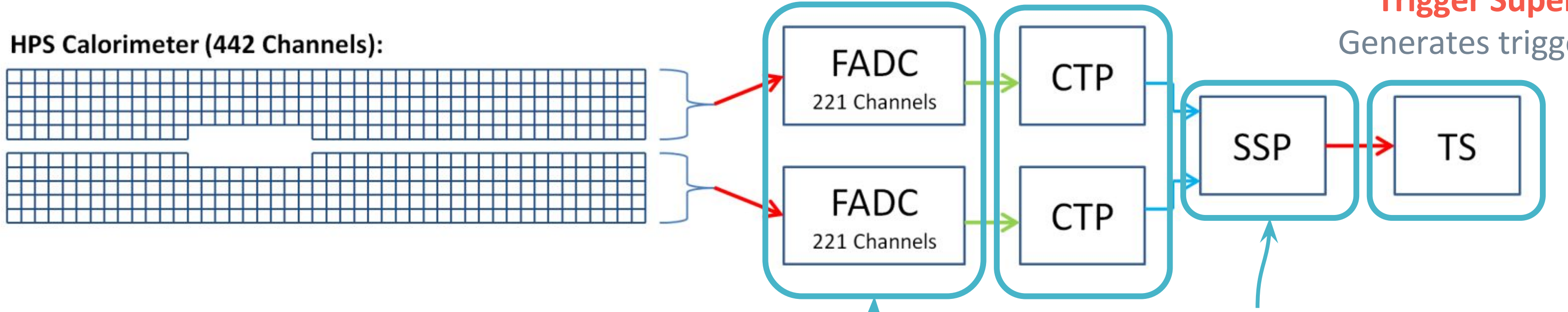
Trigger

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

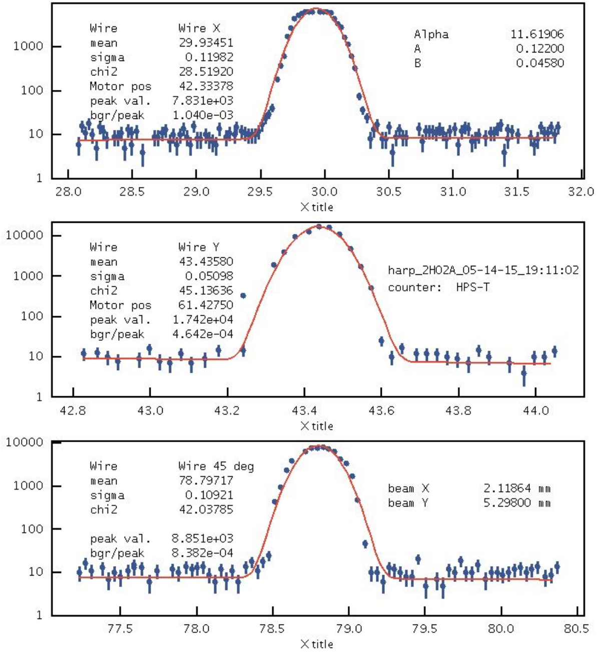
Samples Ecal crystal APD’s @ 250 MHz. If signal crosses threshold, integrated amplitude and crossing time is sent to CTP

Sub-System Processor

Searches for pairs that within an 8 ns window and applies a topological selection

Beam Quality

X, Y and 45 degree beam profiles from Harp scan.

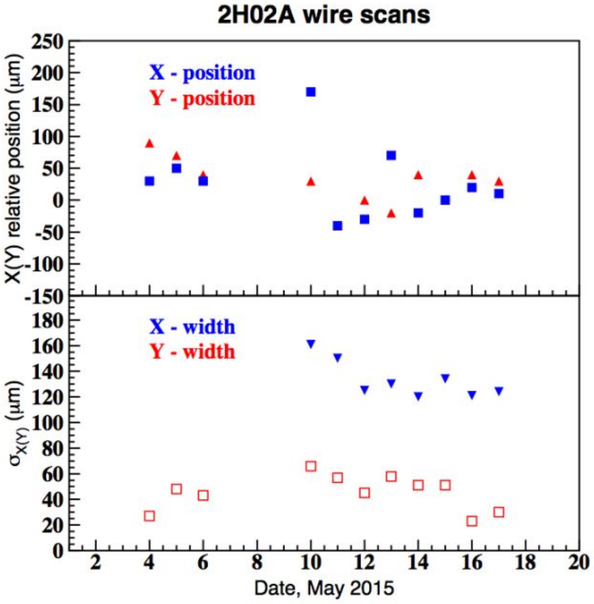


Successful running of the HPS apparatus requires a high quality beam with very low halo.

- ✔ 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

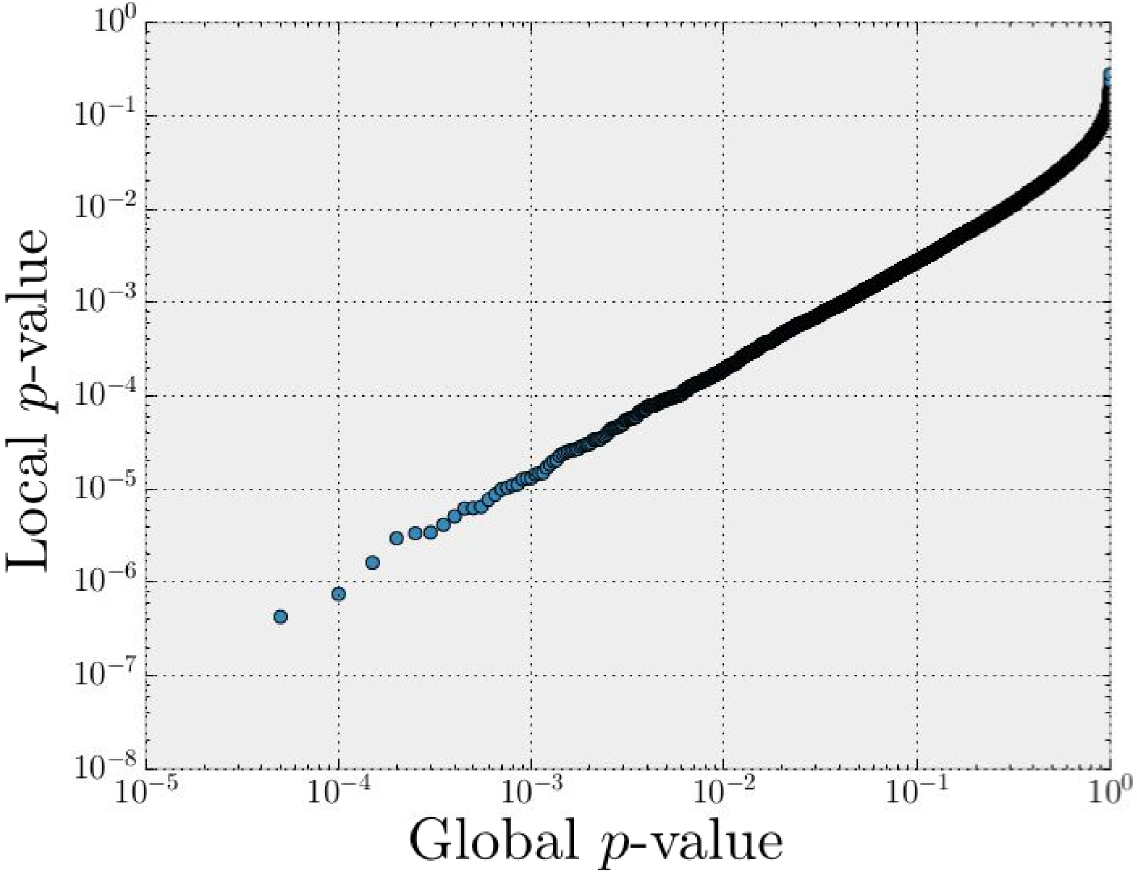
Beam profile and position was measured using a harp 234 cm upstream of the target.

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



Look Elsewhere

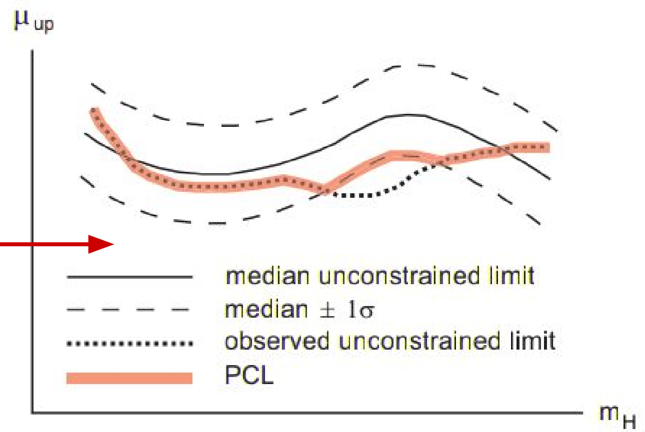
- ✓ Use MC to generate smooth invariant mass distribution ⟶ create pdf
- ✓ Generated 10,000 toys and perform a resonance search on each.
- ✓ Chose the smallest p-value from each scan, ranked them and calculate the quantile



50% Power Constrained Limits

- ✓ Unconstrained limits tend to lead to overcoverage i.e. values of μ that we have no power to tend to be included in the interval ⟶ spurious exclusions
- ✓ Use power constrained limit ⟶ require that the experiment has enough sensitivity to a value of μ before excluding i.e the power of test is above some threshold
- ✓ Start by determining unconstrained upper limit, μ_{up}
- ✓ Generate background only pseudo-data sets
- ✓ Fit each pseudo-data set with signal+background model using the same calculate upper limit ⟶ generate distribution of upper limits
- ✓ From the distribution of upper limits, calculate the mean, μ_{min}

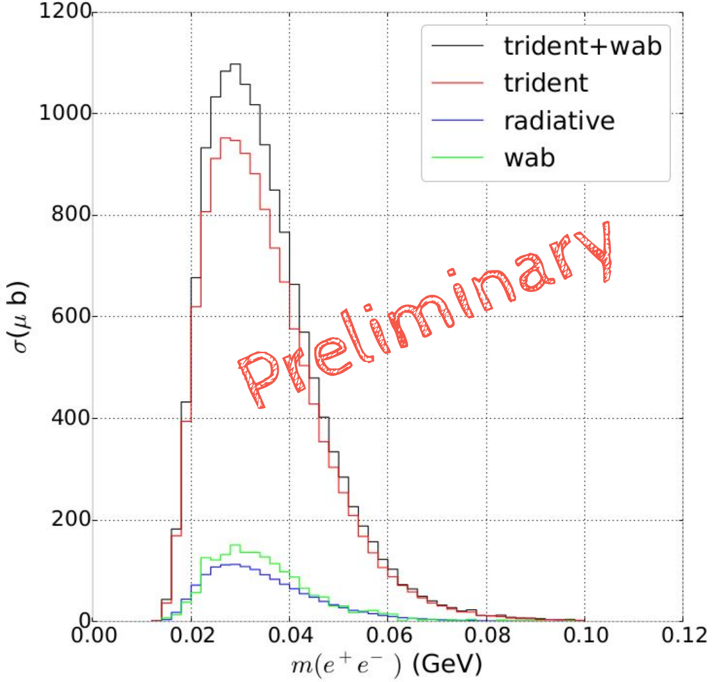
Similar to this, but this plot uses a power threshold set to 1 sigma. We use the median or 50%.

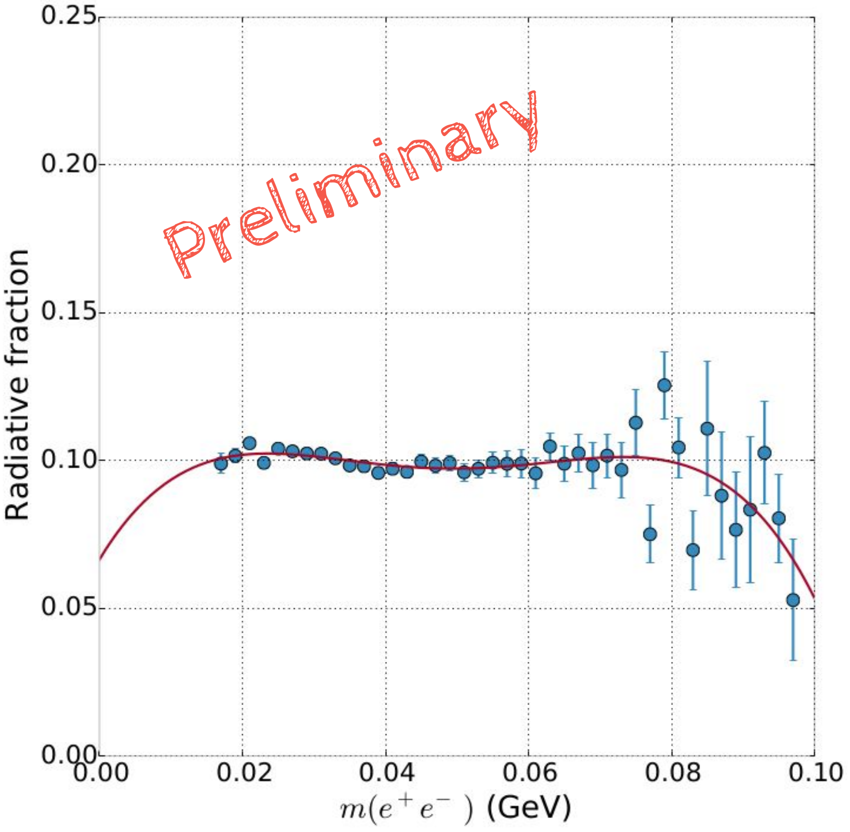


$$\mu_{pc} = \max(\mu_{\mathrm{UL}}, \mu_{\mathrm{median}})$$

Radiative Fraction

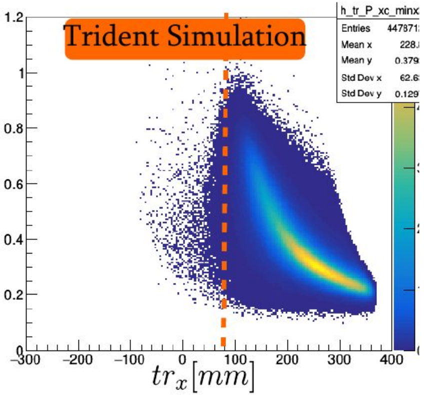
Translating the signal upper limit into the mass-coupling phase space requires knowledge of the fraction of radiative events in our event sample ⟶ use Monte Carlo to parametrize the radiative fraction as a function of mass.

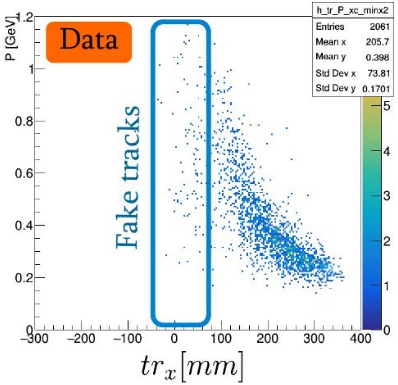


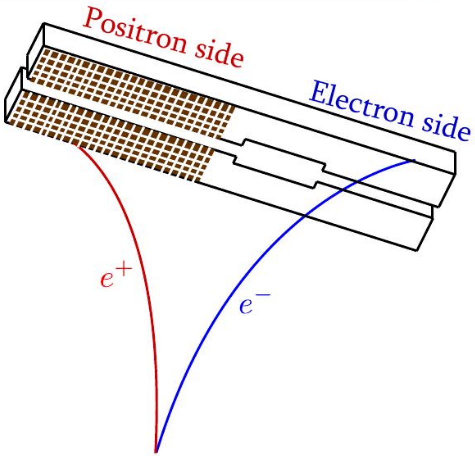


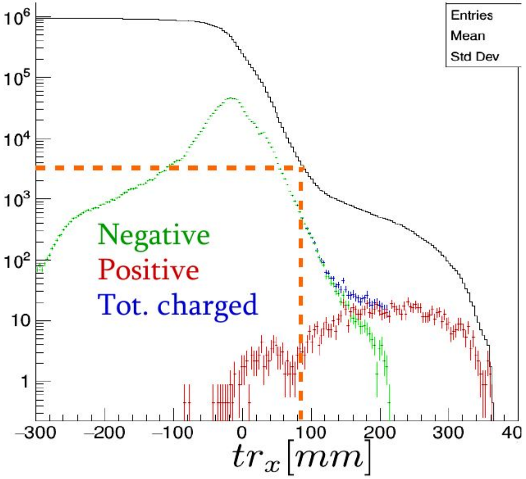
Design is not Final yet

Almost 100% of e⁺ have x > 90,









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

A’(50MeV) decay at 2.2 GeV