University of New Hampshire

Status update for the Heavy Photon Search experiment

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University of New Hampshire

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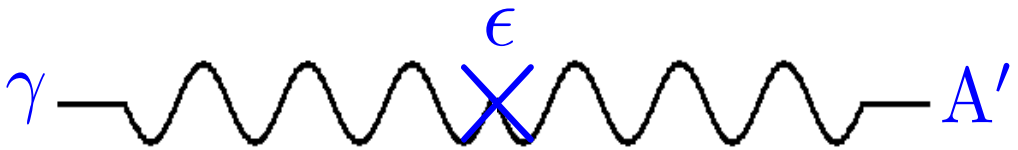
Introduction

What if Nature contains an additional broken U(1) (Abelian) force mediated by a massive vector boson, A'?

Bob Holdom, Phys.Lett.,B166, 2, (1986)

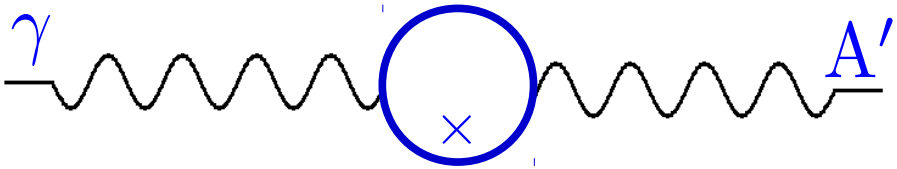
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m_{A'^2} A'^{\mu} A'_{\mu}$$

Kinetic Mixing



ϵ is the mixing strength

generated by heavy particles
$\times$ interacting with γ and A'

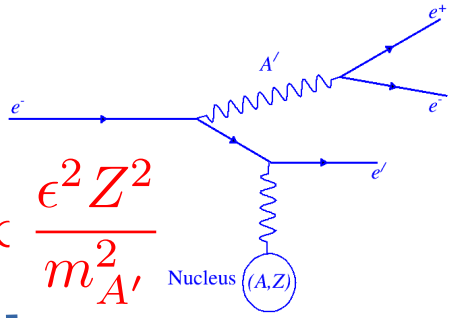


Many Dark Matter searches are based on this hypothesis

Producing A' in fixed target experiments

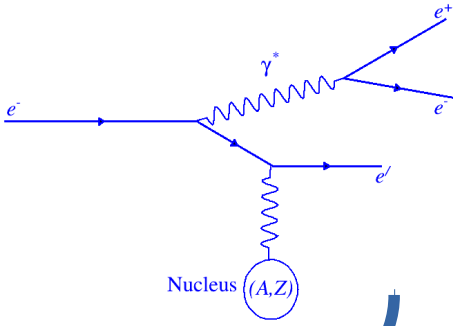
Since A' "can" couple to electric charge, then it is possible to expect it to be produced in a Bremsstrahlung process

A' production

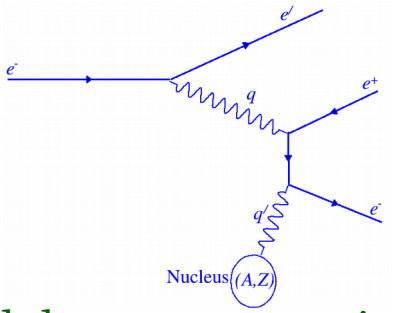


$$\sigma \propto \frac{\epsilon^2 Z^2}{m_{A'}^2}$$

Production of Timelike photon (radiative Tridents)



Bethe Heitler



Much larger cross section,
But very different kinematics

Indistinguishable kinematics

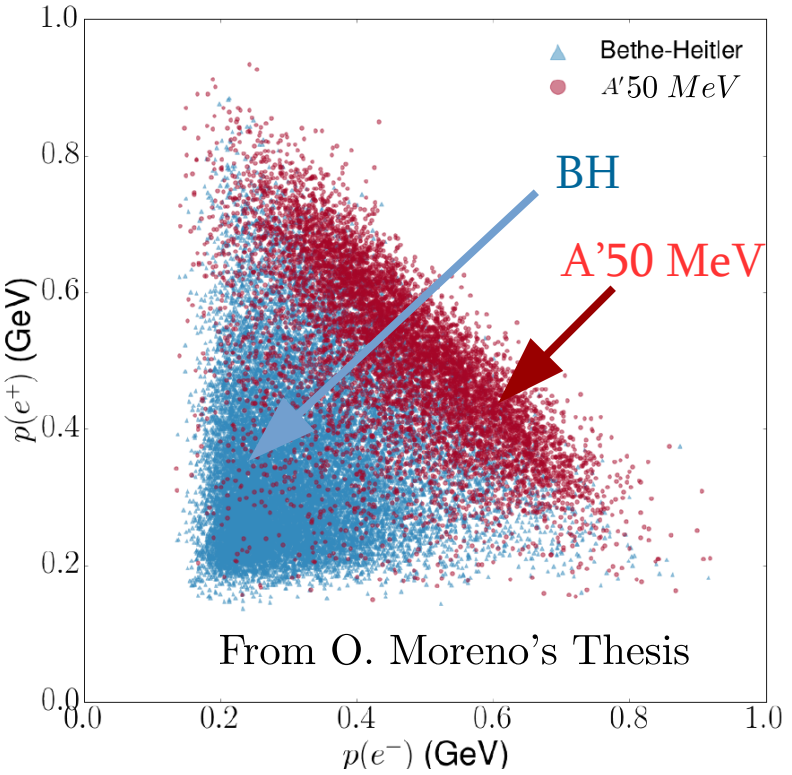
Angle: Forward

$$\theta_{A' \max} \sim \max\left(\frac{\sqrt{m_{A'} m_e}}{E_0}, \frac{m_{A'}^{3/2}}{E_0^{3/2}}\right)$$

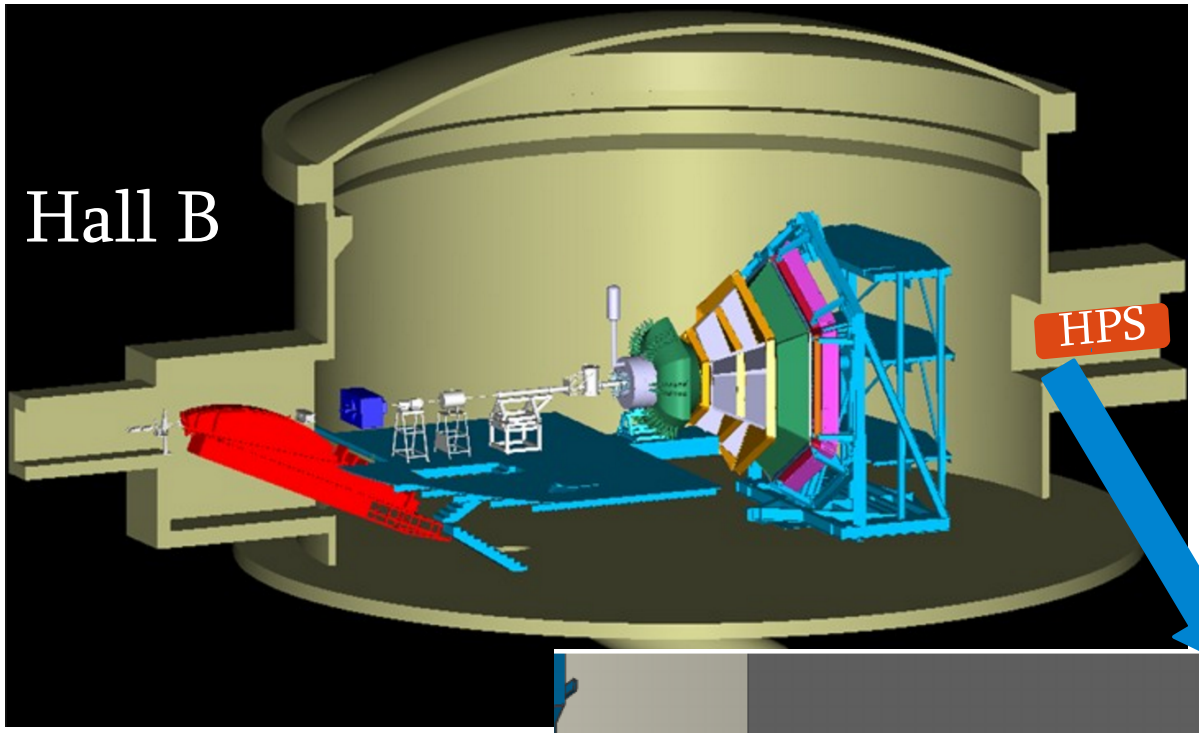
Energy: A'takes almost all the beam energy

$$\frac{E_{A'}}{E_{beam}} \sim 1 - max\left(\frac{m_e}{m_{A'}}, \frac{m_{A'}}{E_0}\right)$$

$$\frac{\sigma(eA \to e' A' (\to e^- e^+))}{\sigma(eA \to e' \gamma^* (\to e^- e^+))} = \left(\frac{3\pi\epsilon^2}{2N_f \alpha}\right) \frac{m_{A'}}{\delta m}$$

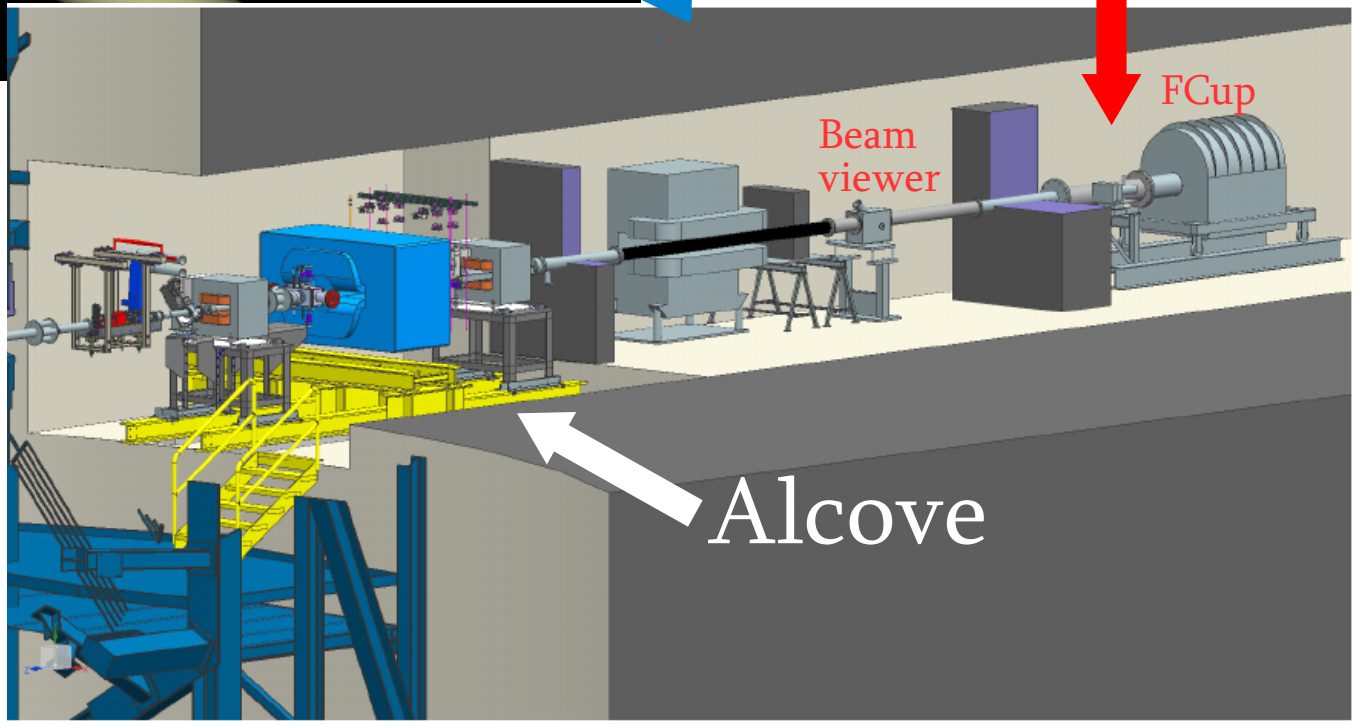


HPS setup in the Jlab Hall B



HPS is located in the downstream alcove

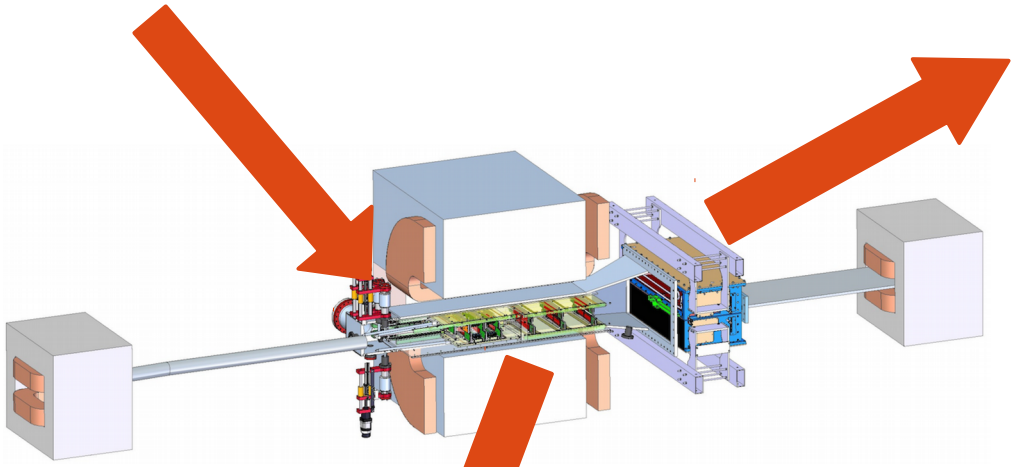
Downstream tunnel

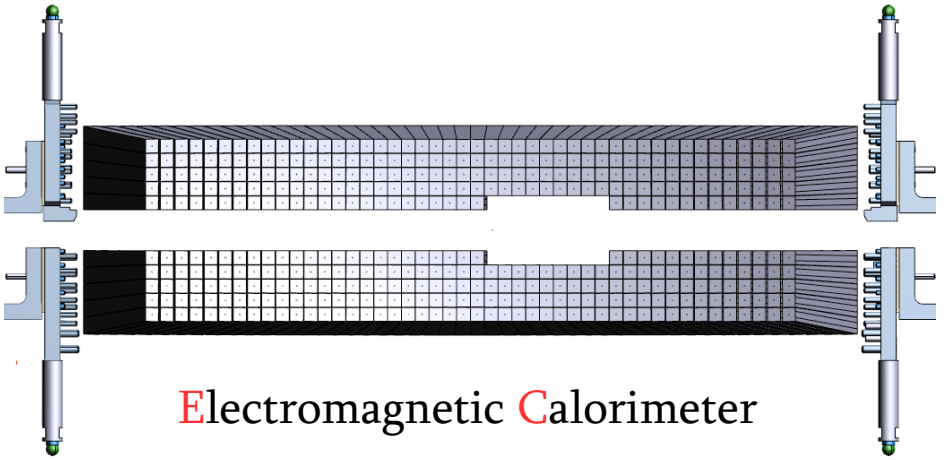


HPS experimental setup

Chicane system with 3 dipole magnets

4 μm tungsten target





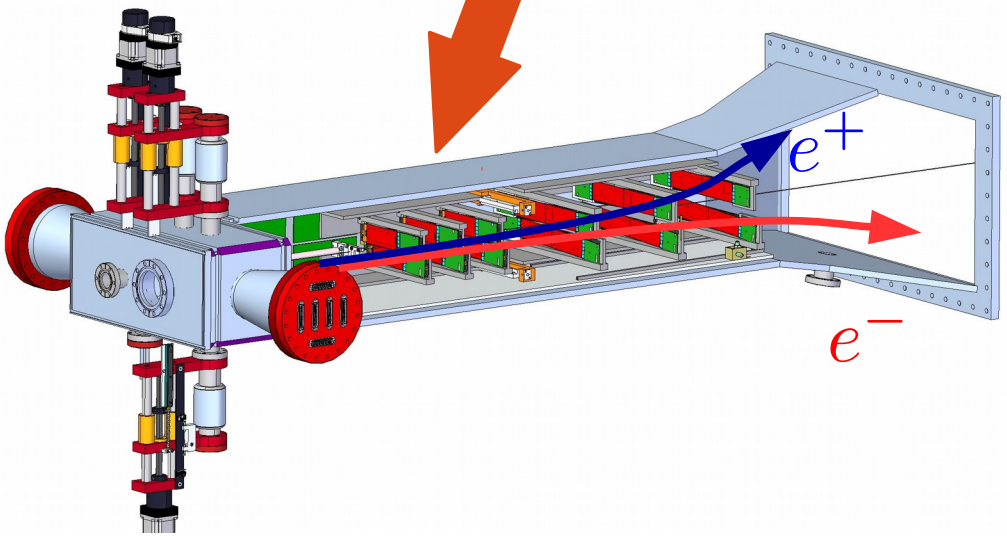
Electromagnetic Calorimeter

442 $PbW0_4$ Crystals

Initiates the trigger (Main, and 3 diagnostic)

Measures particle's energy

Resolution $\frac{4\%}{\sqrt{E}}$ at 1 GeV



Silicon Vertex Tracker

6 layers of silicon microstrip (axial+stereo)

1^{st} layer of silicon is at 0.5 mm from the beam

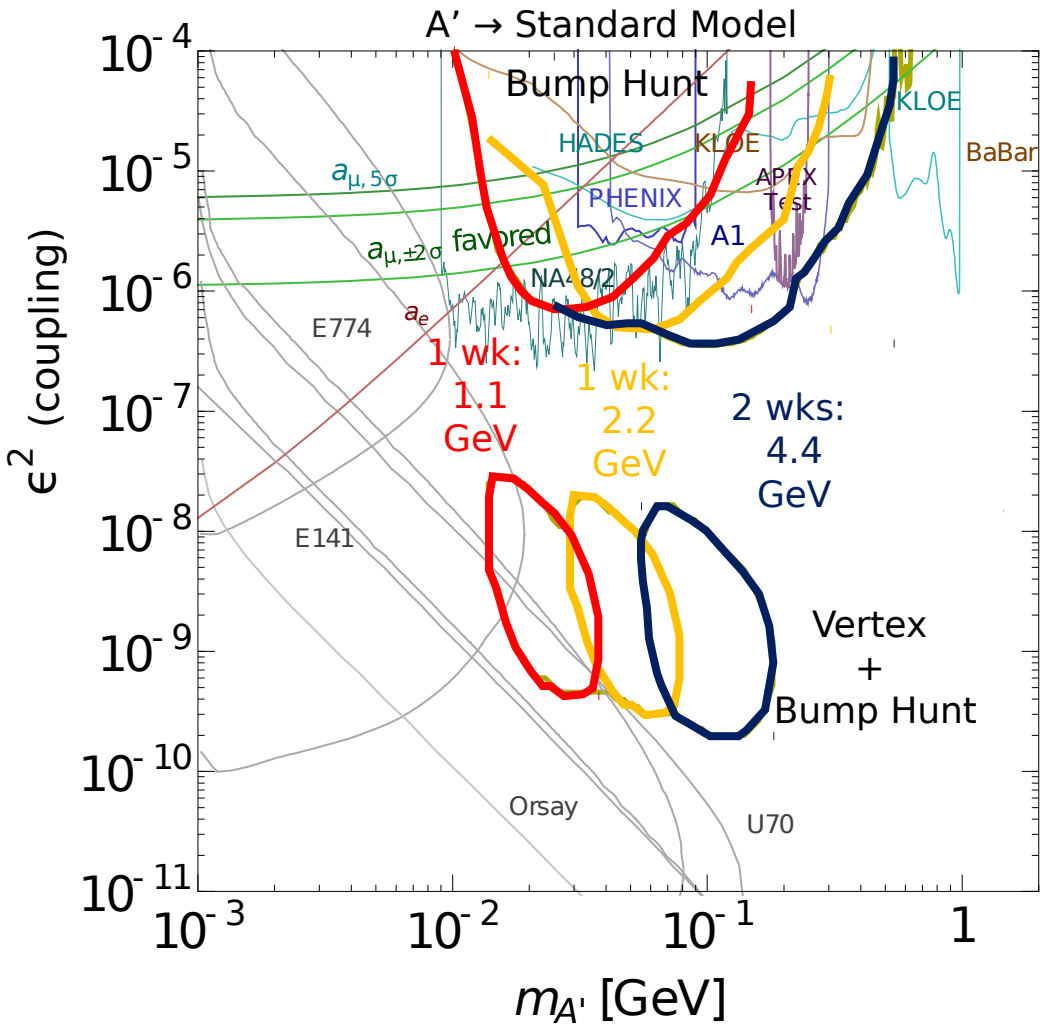
Measures charged particle's momentum

Vertical hit resolution $\approx 6\ \mu m$
Horizontal hit resolution $\approx 60\ \mu m$ (1st 3)
and $\approx 120\ \mu m$ (3 other layers)

HPS Estimated reach

180 approved days

Opportunistic runs:
Run only after work hours (2015)
And only on weekends (2016)



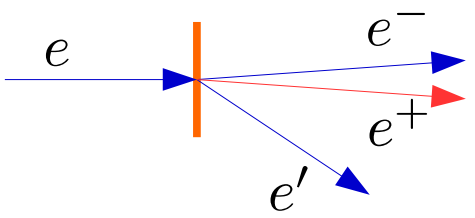
2015 Spring:

Beam current: 50 nA
Beam energy: 1.05 GeV
24% of proposed amount of production data

2016 Spring:

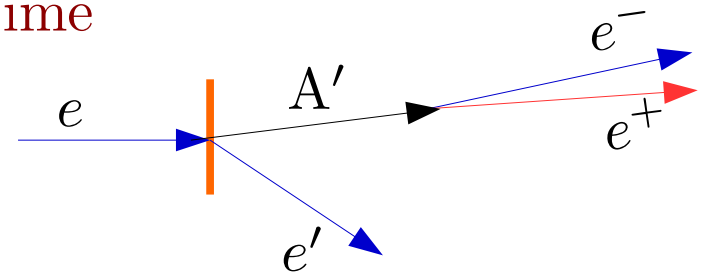
Beam current: 200 nA
Beam energy: 2.3 GeV
77% of proposed amount of production data

Prompt decay, but large coupling



Find a peak over a large background

Small coupling, but longer decay time



No background, few events are enough

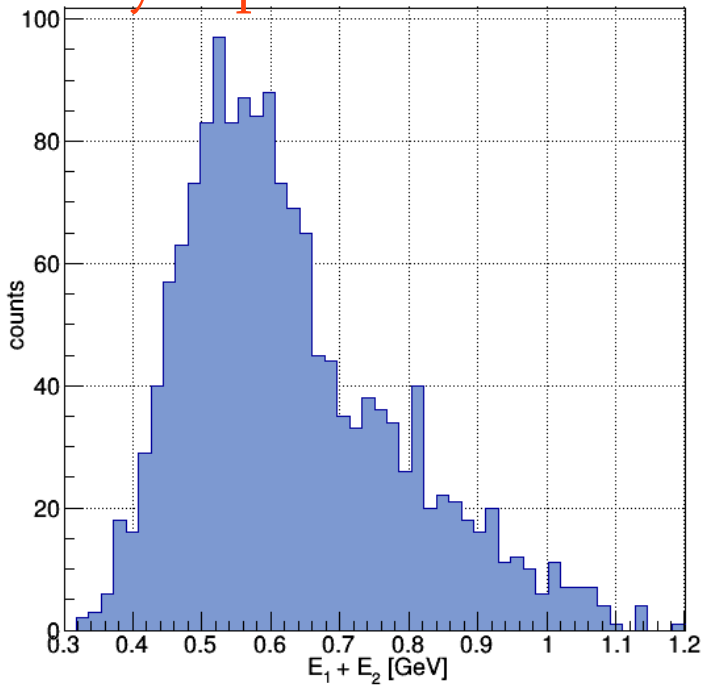
Differences between data and MC w/ 2 cluster events (no tracking)

Initial look into two cluster events

- Both are in Fiducial region
- Are inside the trigger window
- Coincident in time

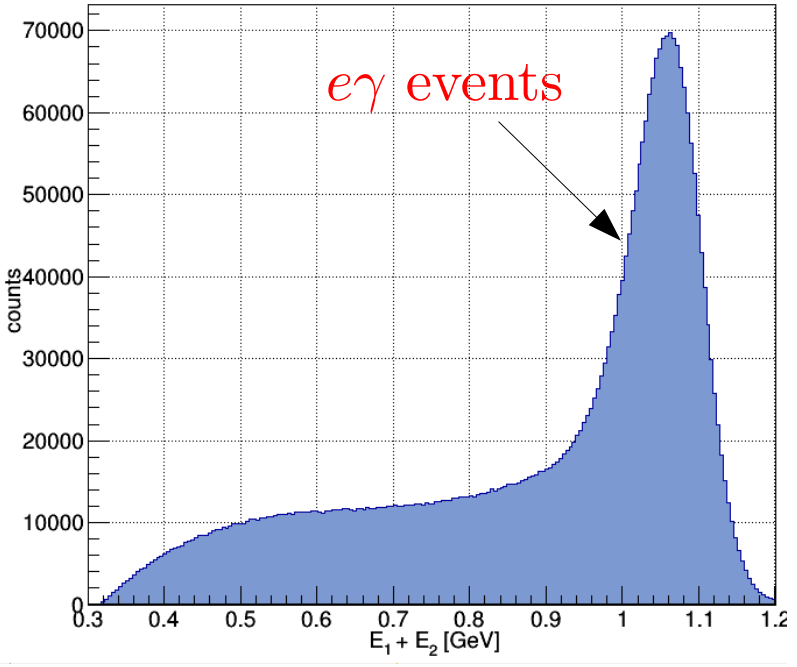
MC: Tridents mixed with the beam

Early Expectations from MC



Data

Data: 2 cluster energy sum



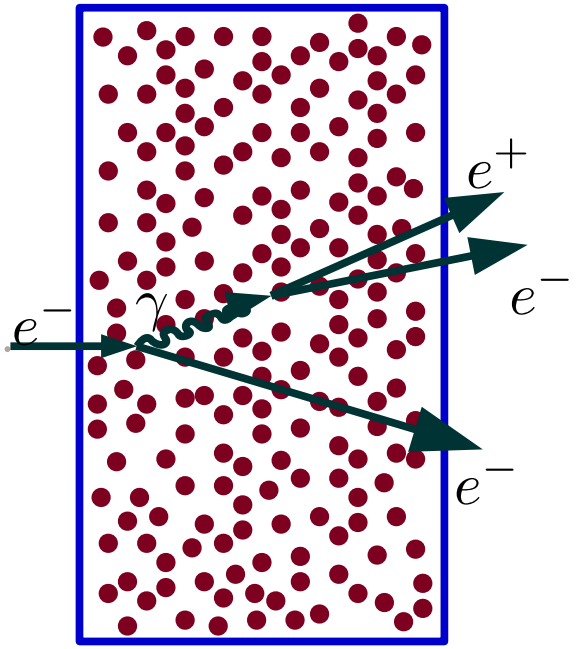
It appears to be significant contribution from the Wide Angle Bremsstrahlung (WAB) process

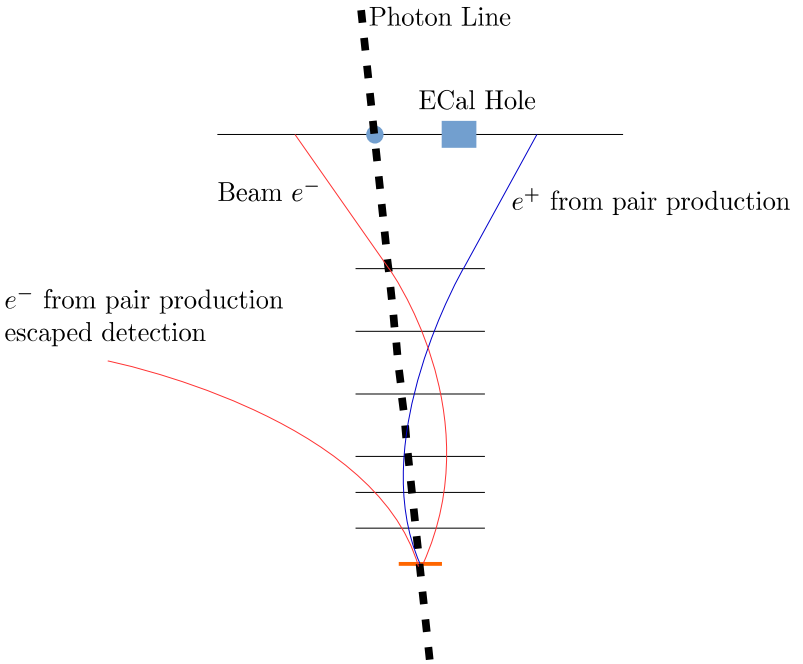
(It is a Bremsstrahlung, just scattering angles of photons are large)

In principle this should not affect much trident analysis, since with SVT one can easily exclude $e^-\gamma$ final states, but (next slide)...

Wide Angle Bremsstrahlung (WAB)

Two step process:
WAB then photon conversion





Photon conversions from the target, 1st and 2nd SVT layers can mimic trident signal

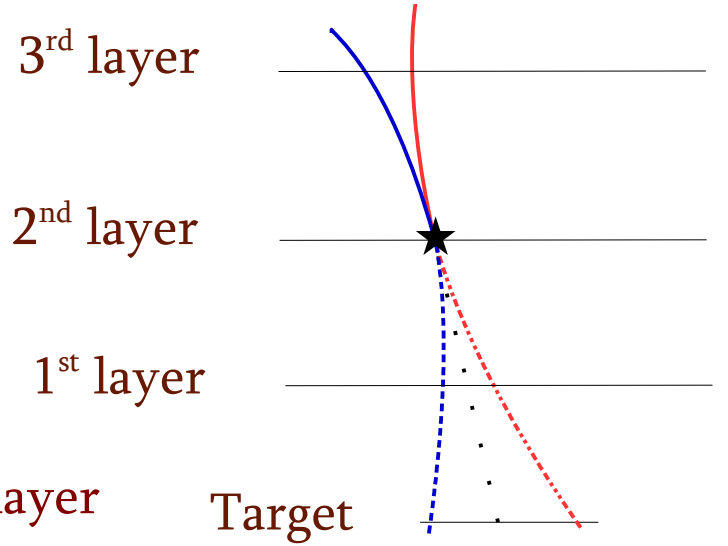
Both, WAB and photon conversion have large cross sections, so we have revised WAB contribution in the MC and data

The EGS5 program, that we are using for beam transport in the target, treats WABs incorrectly, resulting in the scattered electron escaping detection

Evidence of fake (WAB) tridents in the data

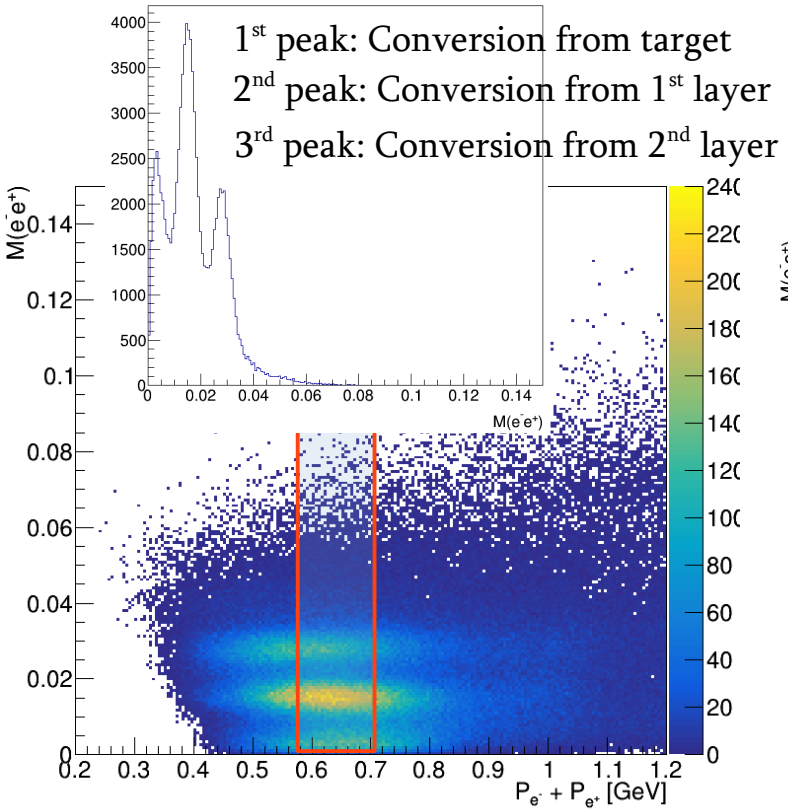
e^-e^+ pairs from WAB photon conversion have ~ 0 opening angle

- consequently ~ 0 invariant mass,
- and should be in the same detector half

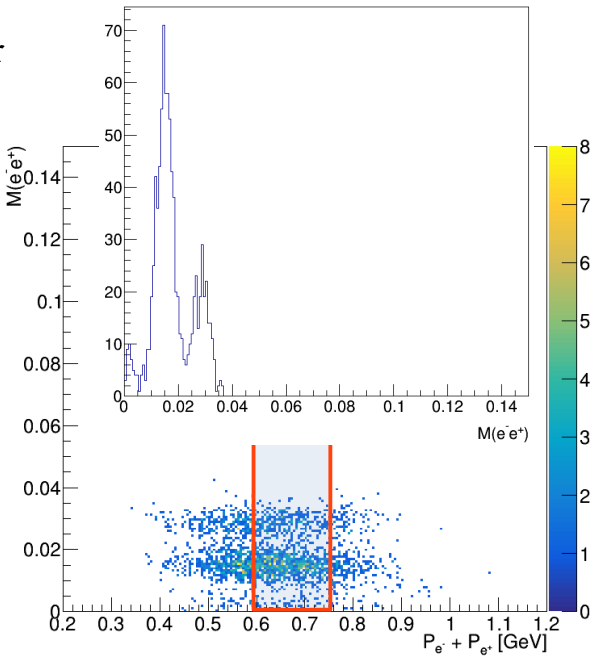


Peaks in the invariant mass spectrum correspond to the photon conversion in the target, 1st and 2nd SVT layer

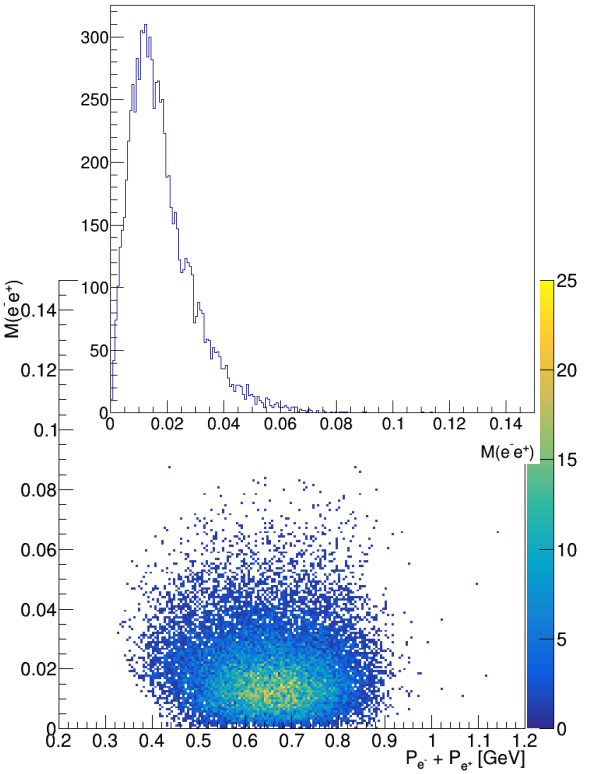
Data



WAB



TriTrig



WAB contribution in the P_{sum} spectrum

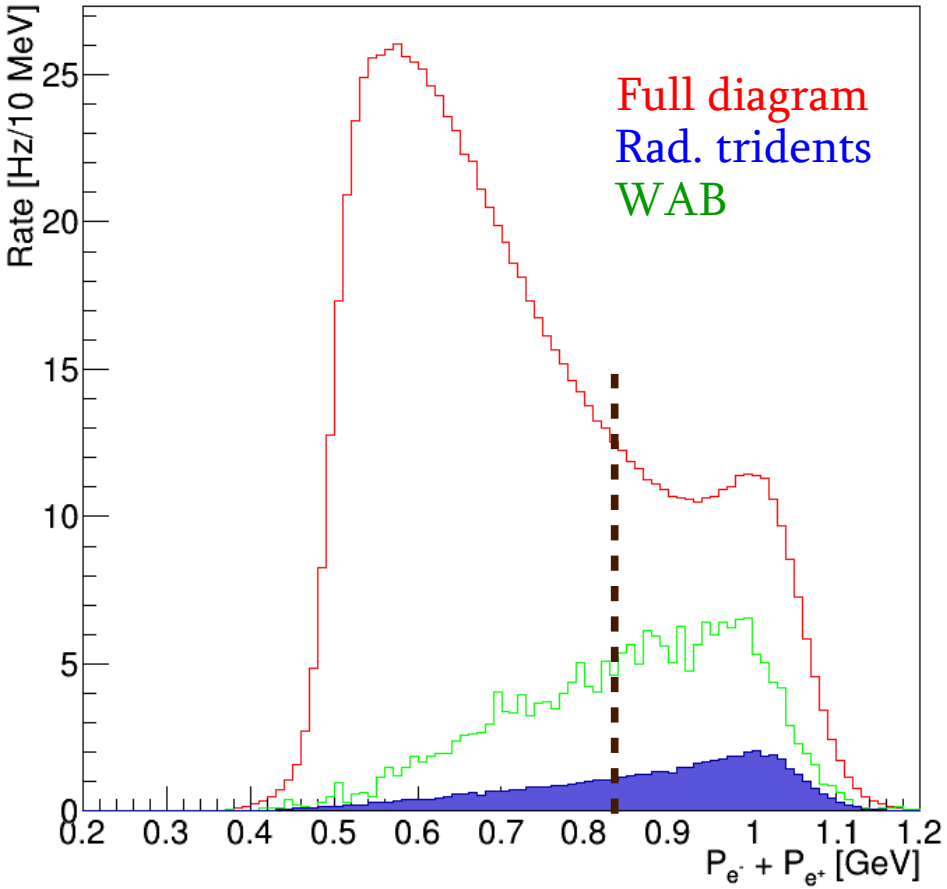
Note: The ratio $f_{rad} = \frac{N_{Rad}}{N_{Full}}$ is important for the calculation of ϵ

Rad. Tridents

$$\frac{\sigma(eA \to e' A'(\to e^- e^+))}{\sigma(eA \to e' \gamma^*(\to e^- e^+))} = \left(\frac{3\pi\epsilon^2}{2N_f\alpha}\right)\frac{m_{A'}}{\delta m}$$

To get the f_{Rad}, it is important to understand the P_{sum} distribution

Expectations from MC



Substantial contribution from WABs

Understanding the P_{sum} spectrum is currently under the investigation

P_{sum} distribution from data doesn't agree with MC

We are investigating several possibilities:

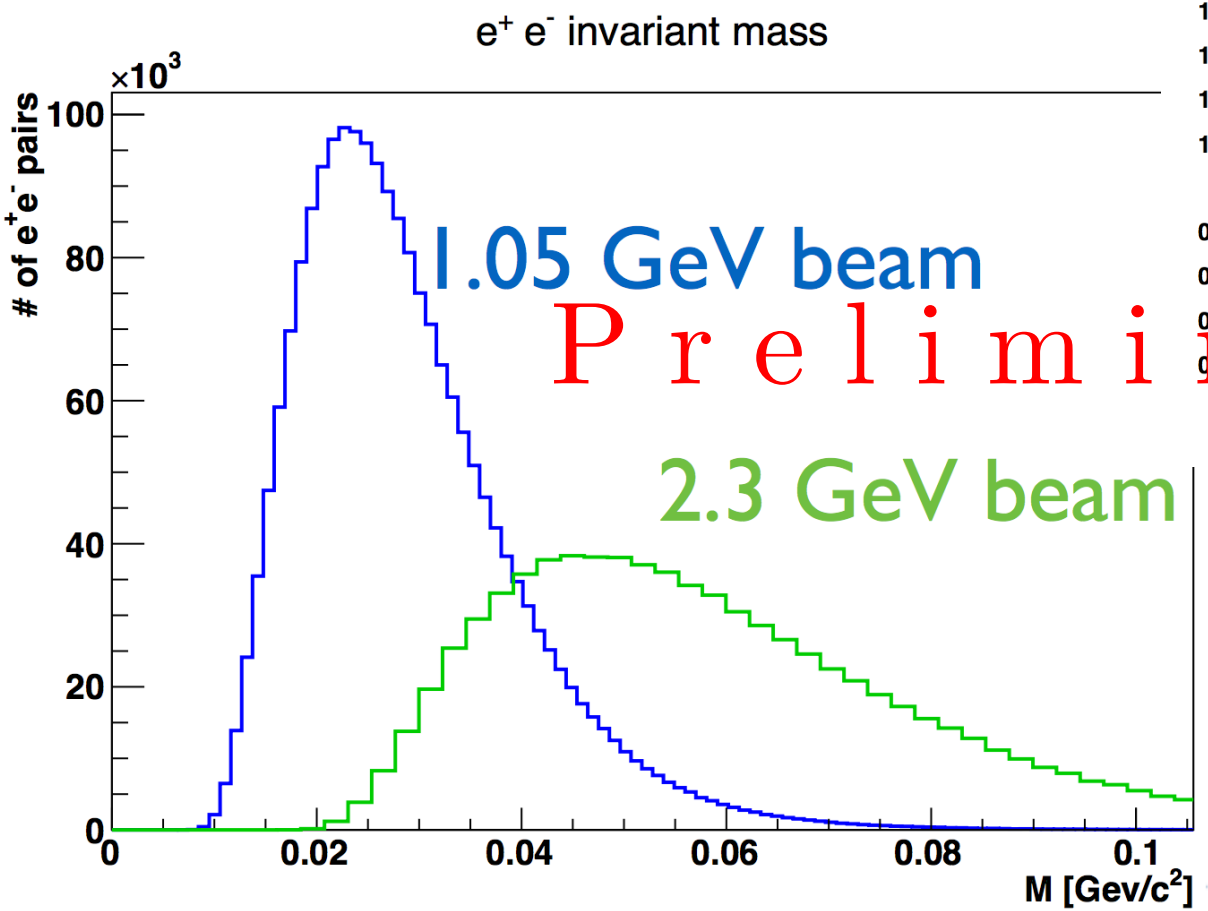
MC is wrong

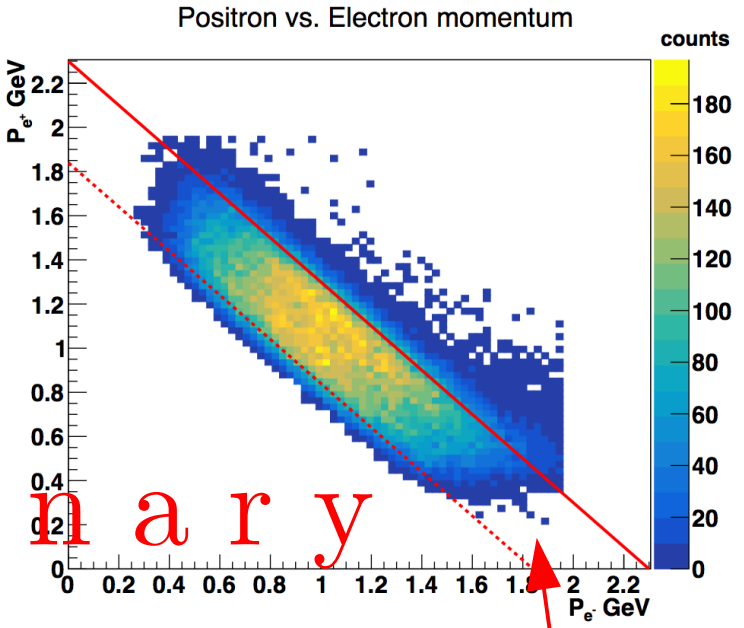
Tracking efficiencies

Final selection sample

- Blinded data: only 10% of data is allowed to be looked at
- As soon as analysis cuts are finalized, codes will be frozen, and the whole data set will be unblinded

Bump hunt: search for a peak over $M(e^-e^+)$ background

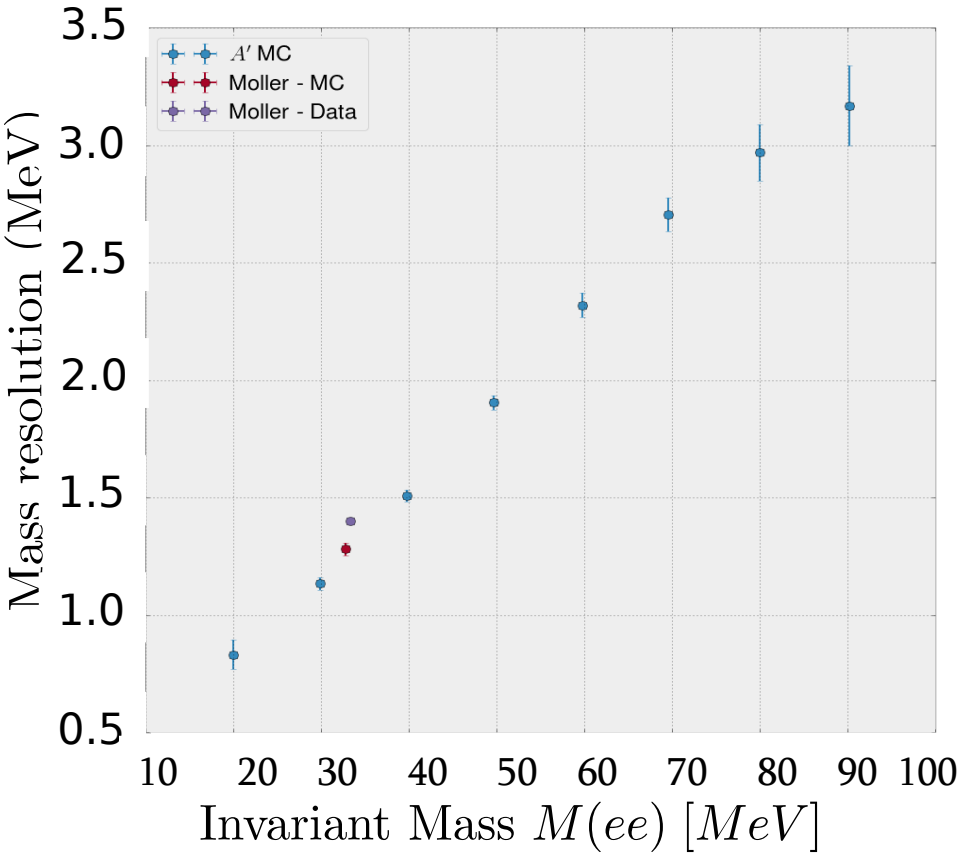


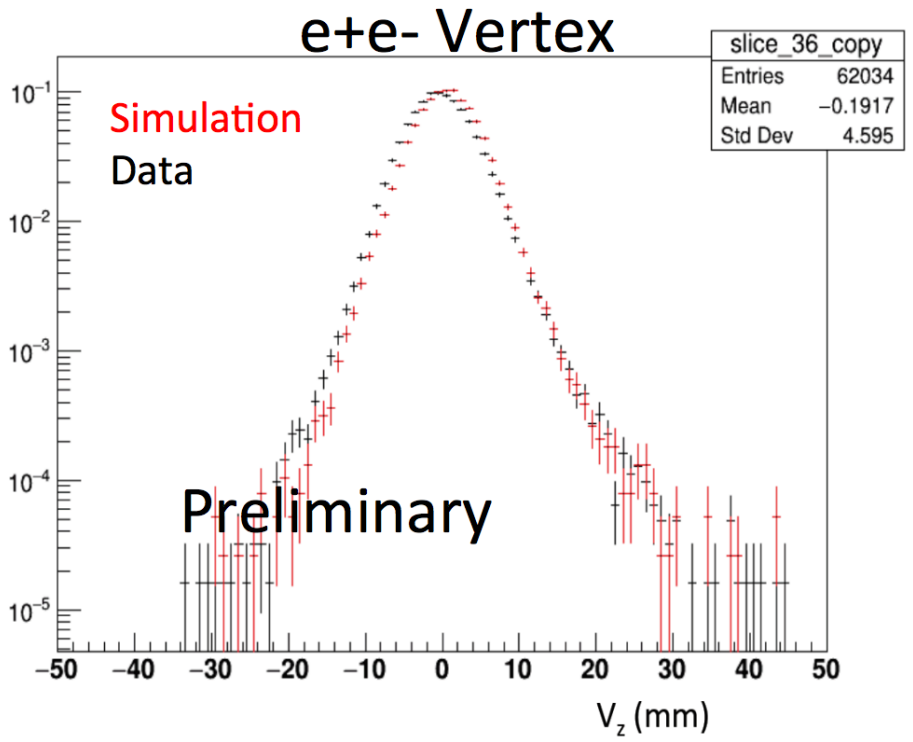


A' dominant region

Mass and vertexing resolutions

Critical parameters for bump hunt and vertexing analysis





Parameter	Proposal value	Measured value
Beam current	50 nA	50 nA
SVT occupancy	<1%	1.00%
Pair mass res. @ 34 MeV/c2	1.5 MeV	1.5 MeV
Pair vertex res. @ 40 MeV/c2	4.4 mm	4.6 mm

Bump hunt technique

Given the tiny decay width of the dark photon (if it exist), it should appear as a Gaussian peak with σ equal to the detector resolution on top of the $M(e^-e^+)$ distribution

Scan over $M(e^-e^+)$ spectrum for any significant peak

Maximizing likelihood function

$$\mathcal{L}(\mu,\theta) = \prod_{k=1}^{n_{\text{bins}}} \frac{(S_k+B_k)^{n_k}}{n_k!} e^{-(S_k+B_k)}$$

A'+bgr is modeled through this function

Signal yeld — Chebishev Polynomials

$$P(M(e^-e^+)) = \mu \cdot \phi(M(e^-e^+)) + B \cdot p(M(e^-e^+, \mathbf{t}))$$

Gaussian (mean $= M(A')$, $\sigma =$ det. resol) — Bgr

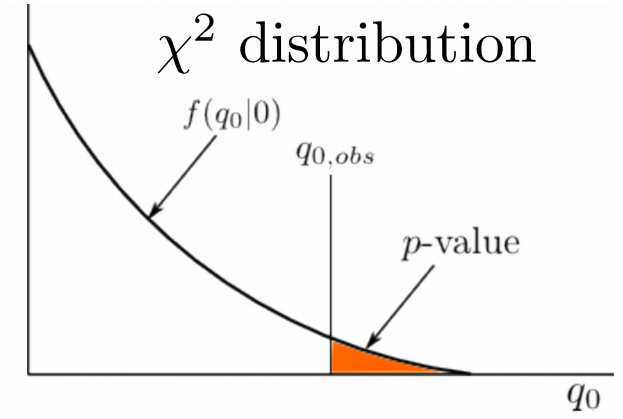
Discovery if p-value $< 3\times10^{-7}(5\sigma)$

Significance of the signal

Null Hypothesis ($\mu = 0$)

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

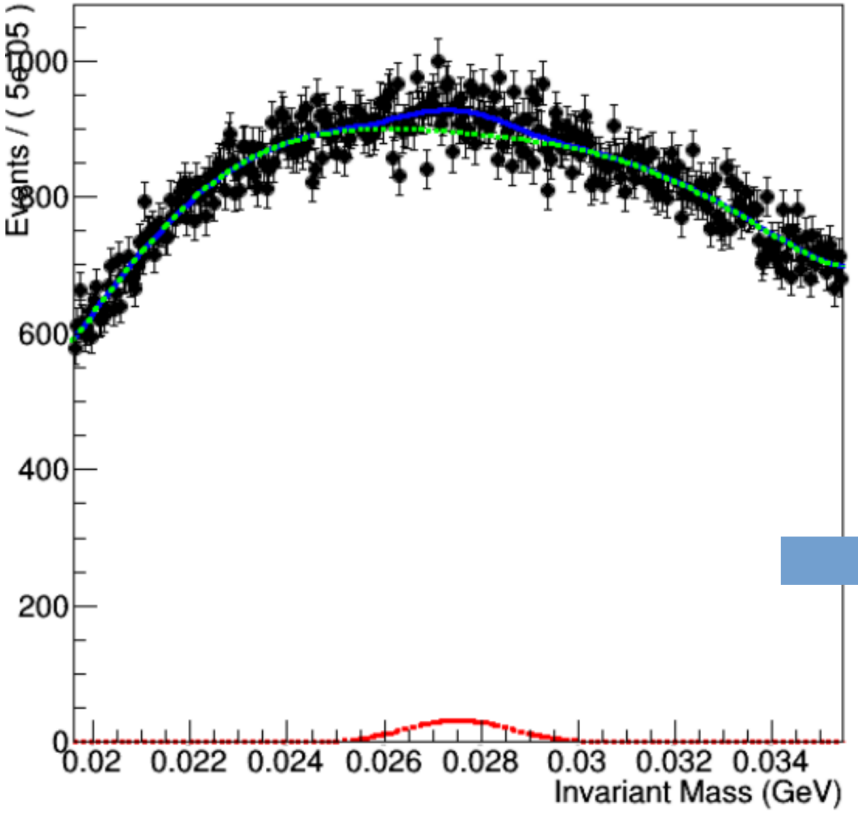
μ is a free parameter



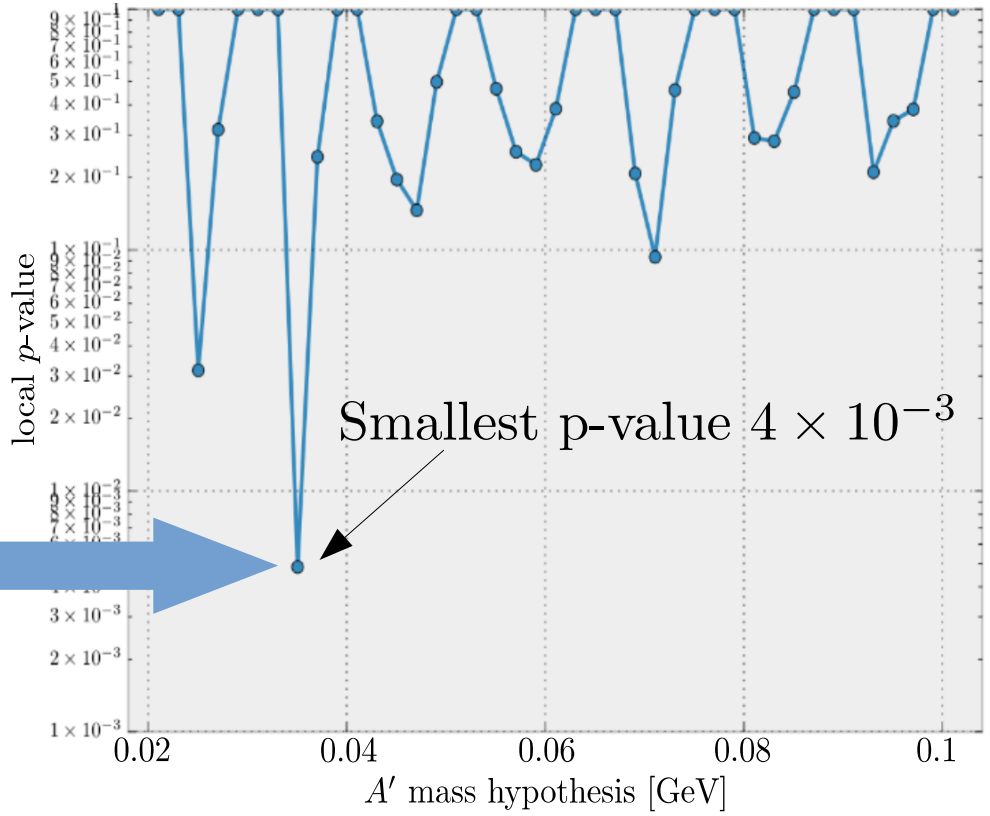
From O. Moreno's Thesis

Bump hunt results

Most significant peak



Distribution of p-values



No significant peak is found, so next step is to calculate exclusion limits on ϵ

Bump hunt selection is being optimized and the limit calculation is in progress

From O. Moreno's Thesis

Towards publication

Completed tasks

- Detector calibrations are done
- Analysis frameworks are close to be finalized to extract, or to provide upper limit for the signal
- Full data sample has been reconstructed, waiting for the green light to be unblinded

Delaying factors

- A two step process eA→ eA γ(→ e-e+) (WAB) appears to contribute substantially to our (e+e-) pair sample. This process was not in the initial MC studies of our reach
  Work is in progress to account for it properly
- We have some disagreement between different MC generators and data. Actively working on resolving these discrepancies

Instrumentation papers

- ECal paper has been sent to NIM
- SVT and Beamline papers are in a quite advanced stage
- Work on Overall HPS detector is started

Summary

- HPS experiment allows heavy photon search through bump hunt and displaced vertex search
- HPS has completed successfully data taking in 2015 and 2016
- Analysis of the 10% of the data has demonstrated good ECal and SVT performance during these runs, and one paper has been submitted for publicattion to NIM, another three are expected soon
- We have completed 2 PhD dissertations and several more are in an advanced stage
- Ongoing studies to upgrade SVT w/ a 0^{th} layer => better mass and vertex resolution consequently higher reach
- 165 days of approved data taking still remain: extended physics runs in 2018 and later

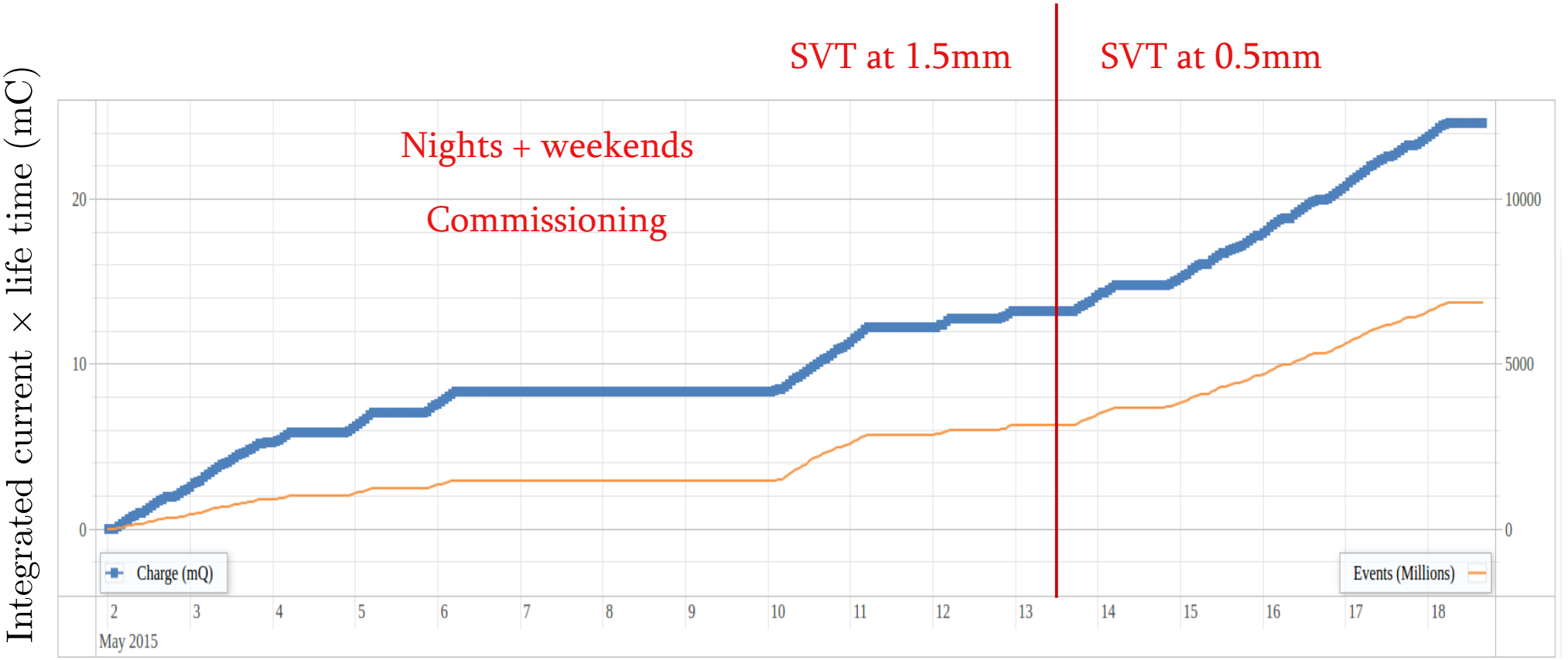
Backup

2015 run

1.05 GeV

Goal: 30 mC

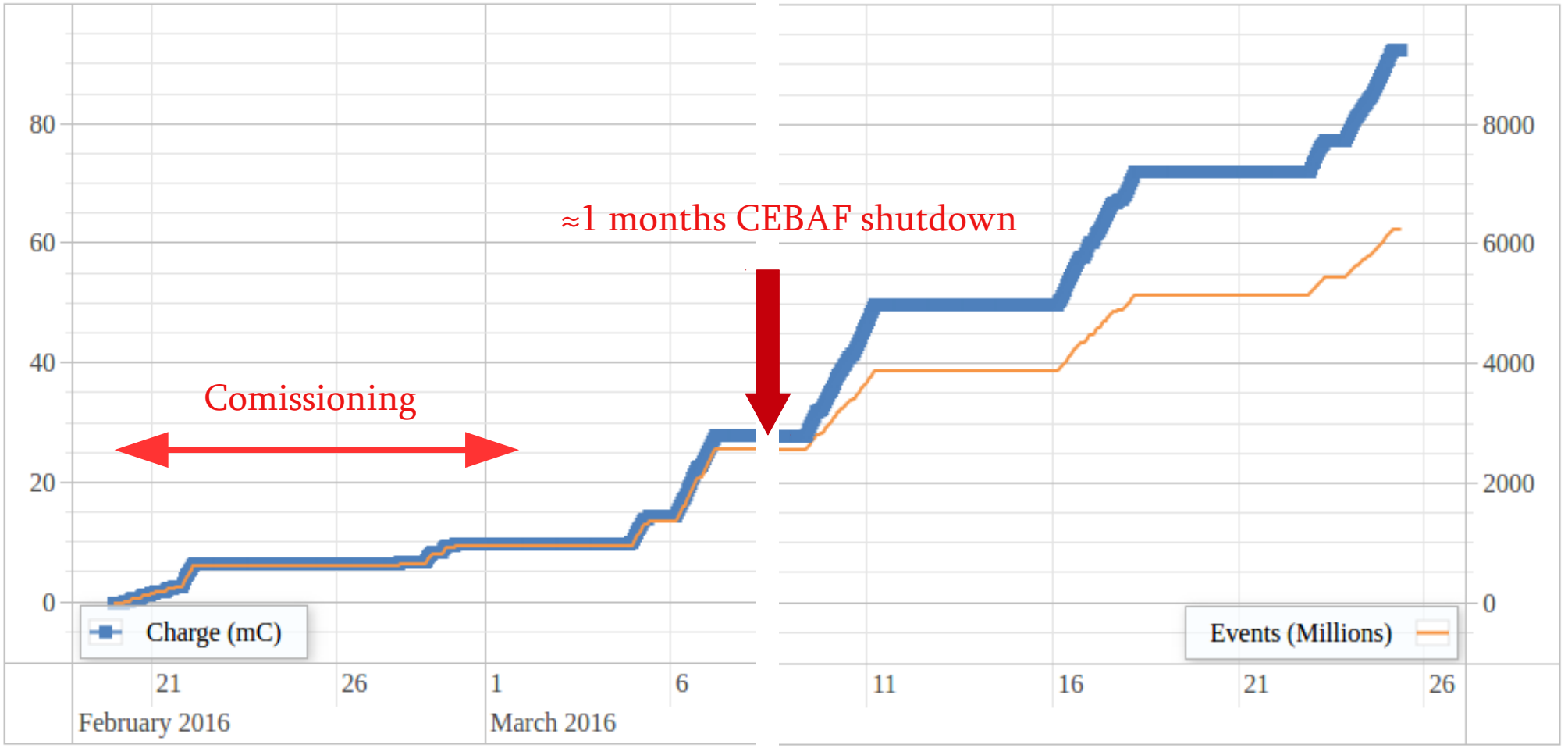
Achieved: 10 mC with SVT at 1.5 mm, 10 mC with SVT at 0.5 mm



2016 run

Goal: 120 mC 2.3 GeV Only weekends

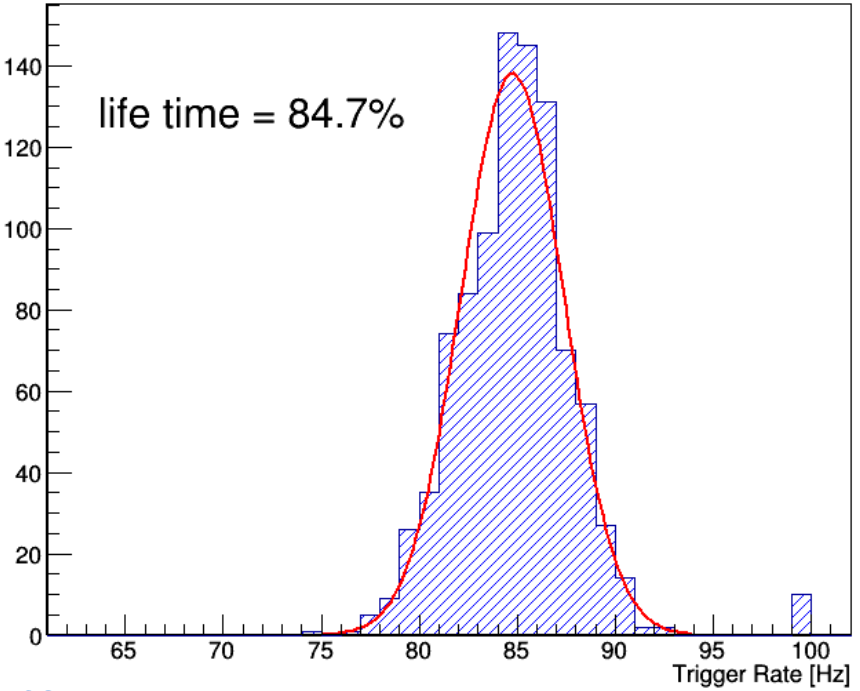
Achieved: 92.5 mC 6.3×10^9 triggers (77% of proposed running)



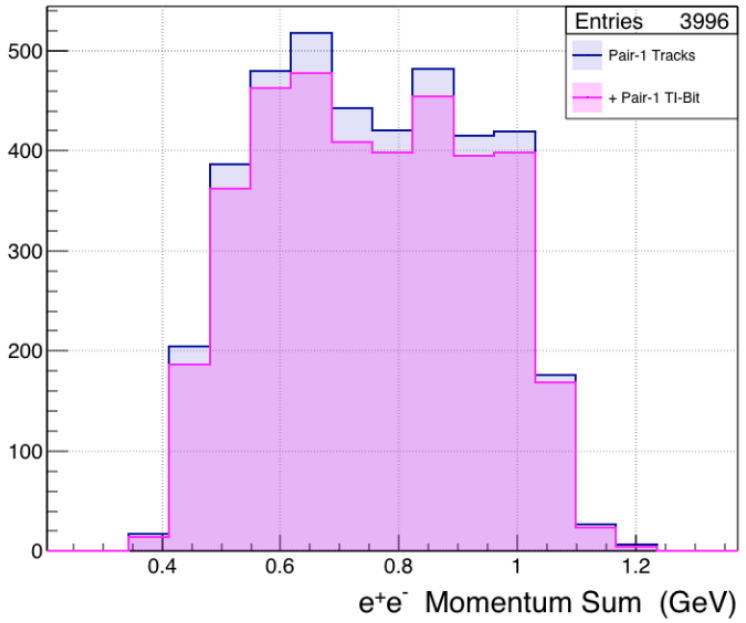
HPS efficiency

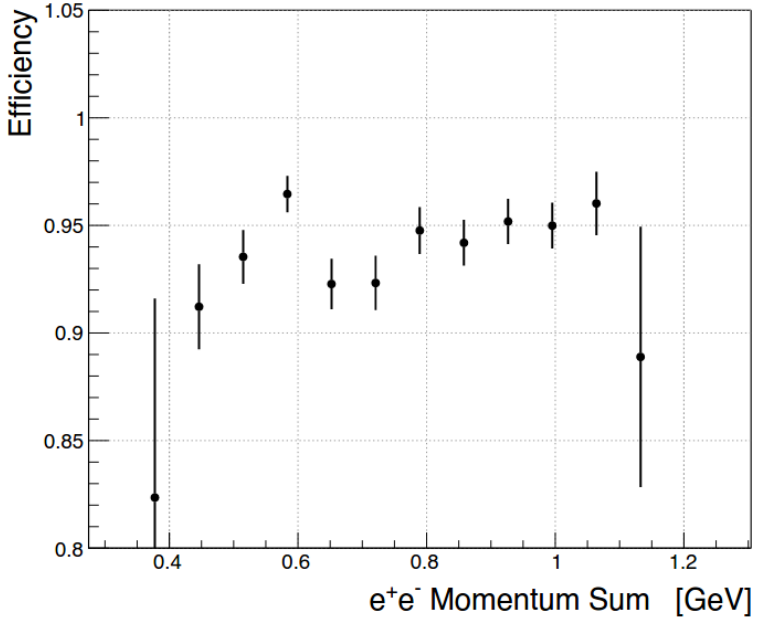
Online lifetime

Offline lifetime, from data



Trigger efficiency



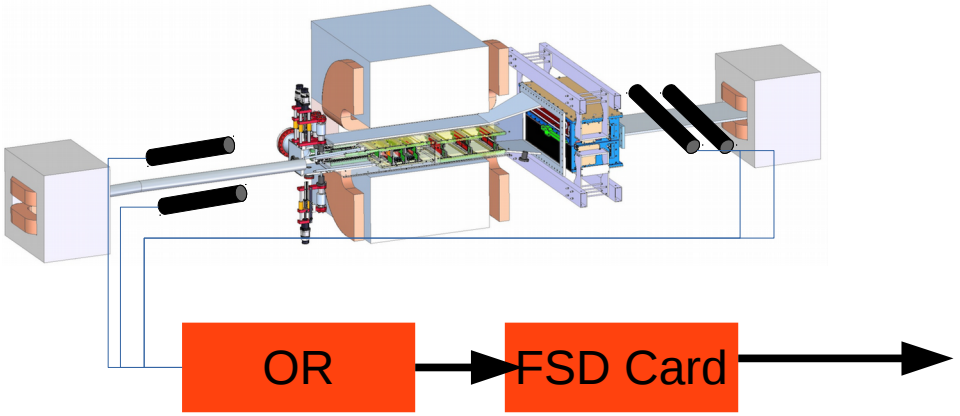


Beam motion studies

Small vertical beam motions ($\sim 0.5\ mm$) can damage silicon

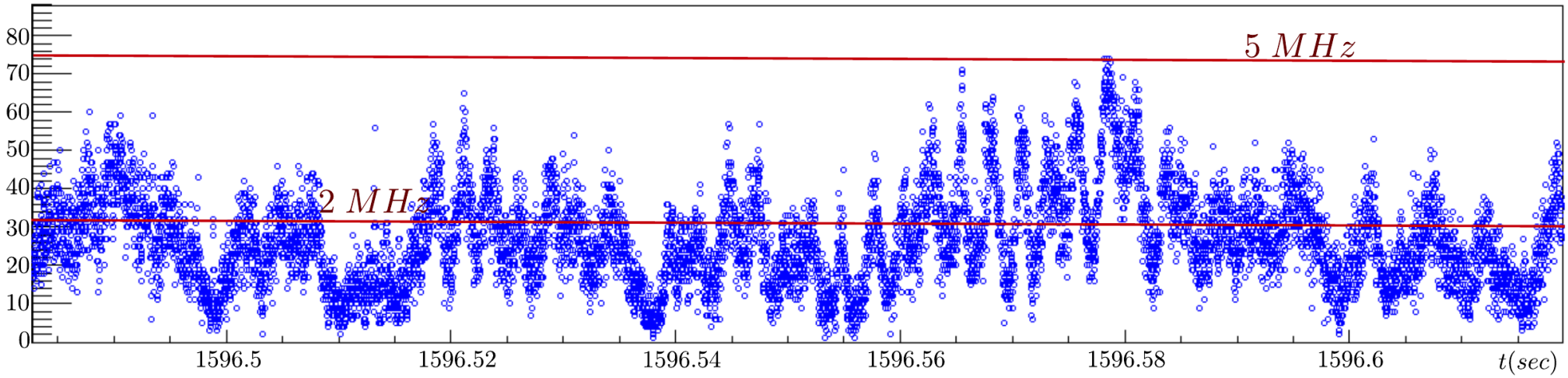
Signals from four halo counters summed up and as an input sent to Fast ShutDown card

Integration time: $1\ ms$



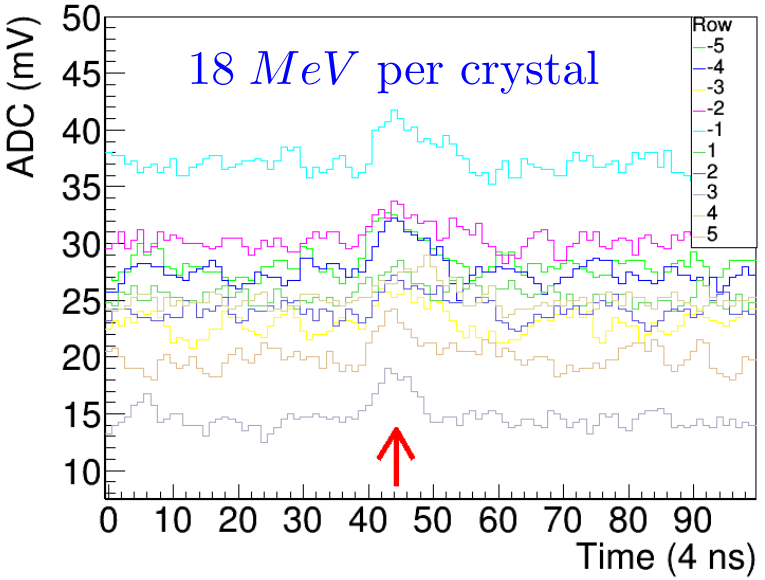
Placing harp wire close to the beam, with fast Struck scaler, we have measured fast beam motions

We have estimated the fast motion amplitude: less than 20 μm

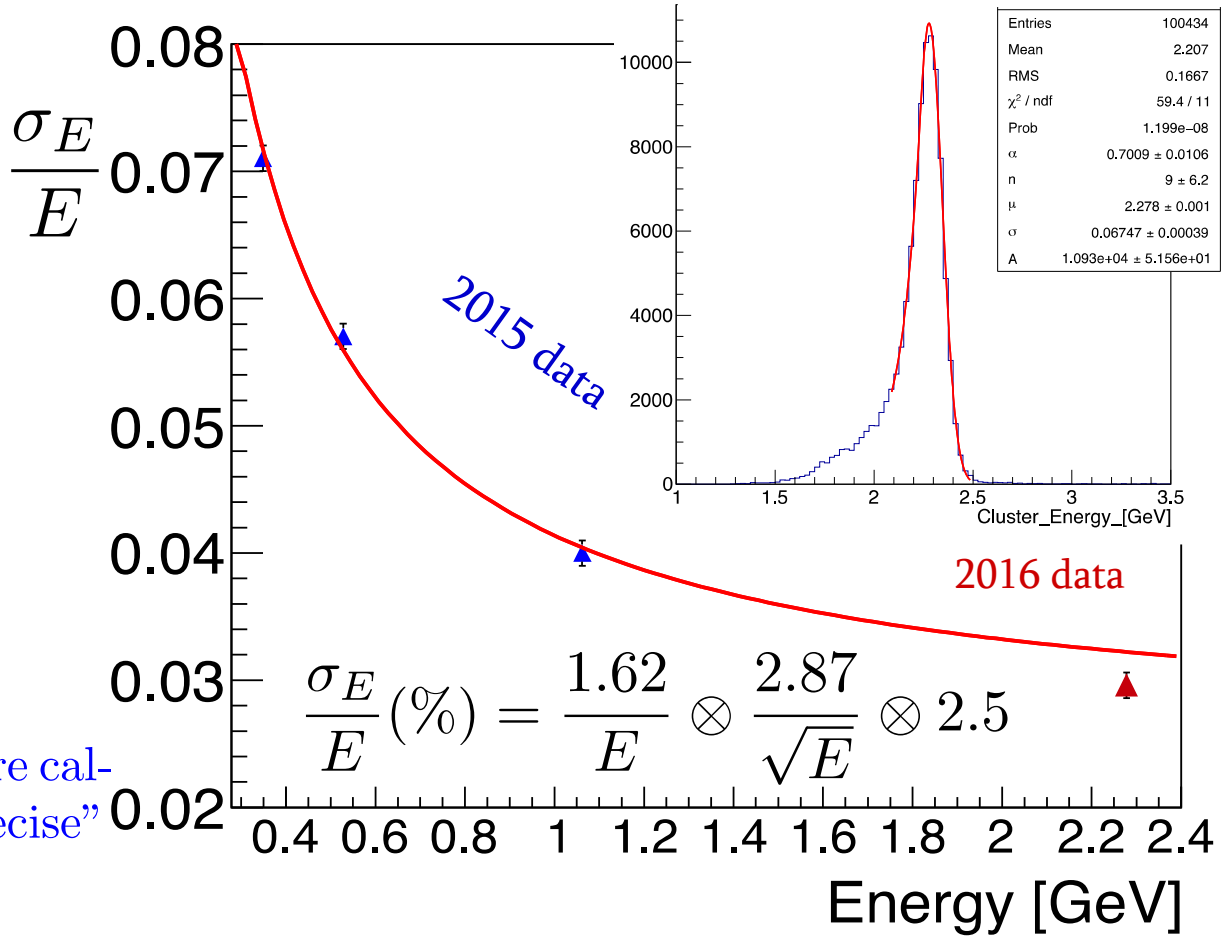


2016 Ecal performance

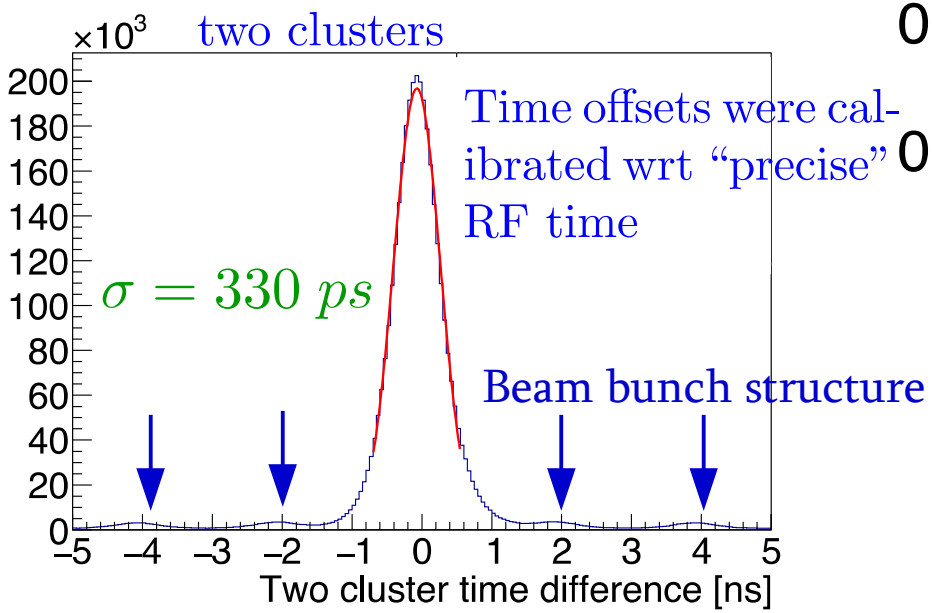
Cosmic gains for initial callibration



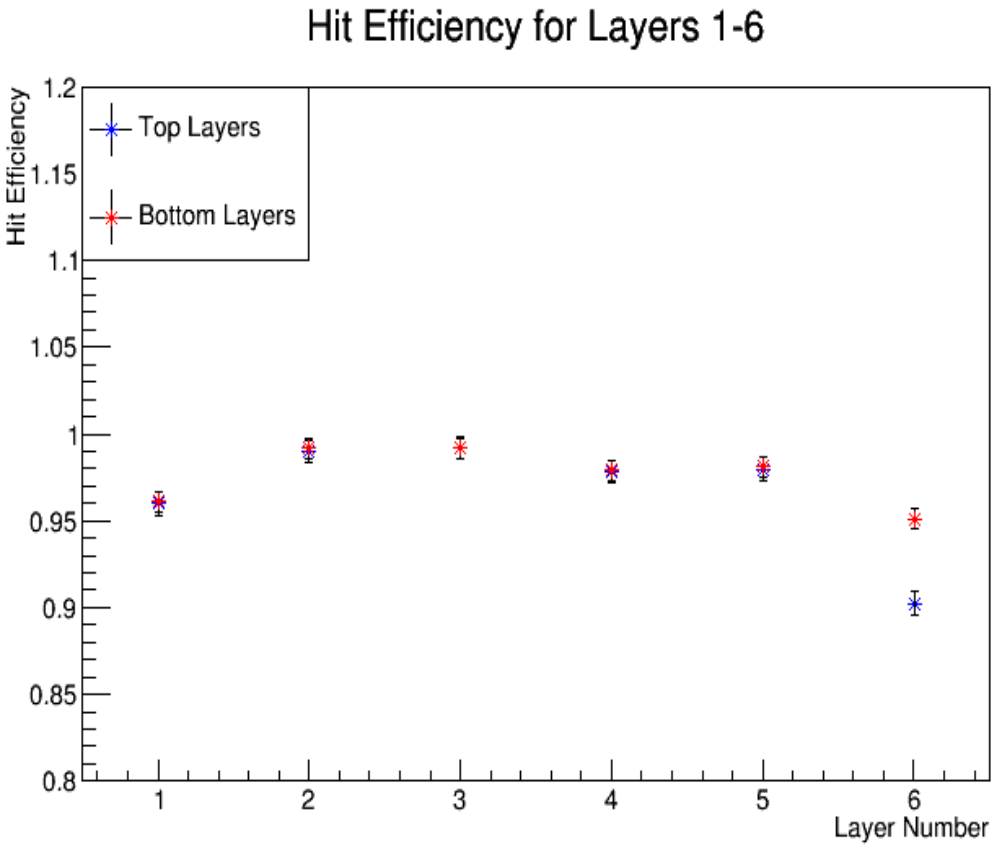
FEE peak in fiducial region

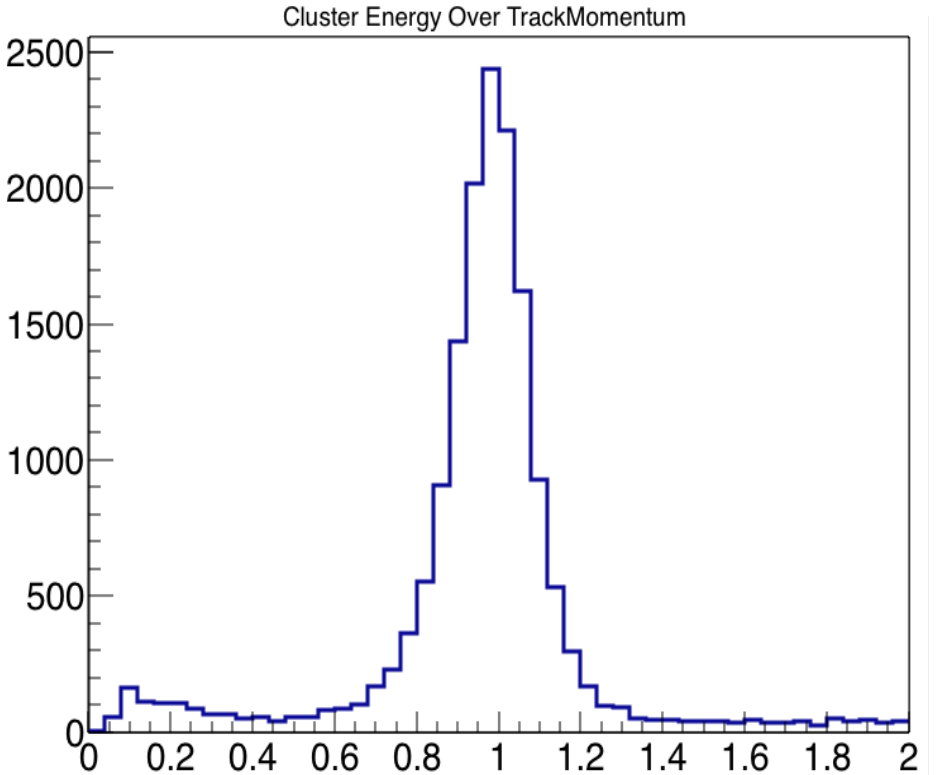


Time difference between two clusters



2016 SVT performance





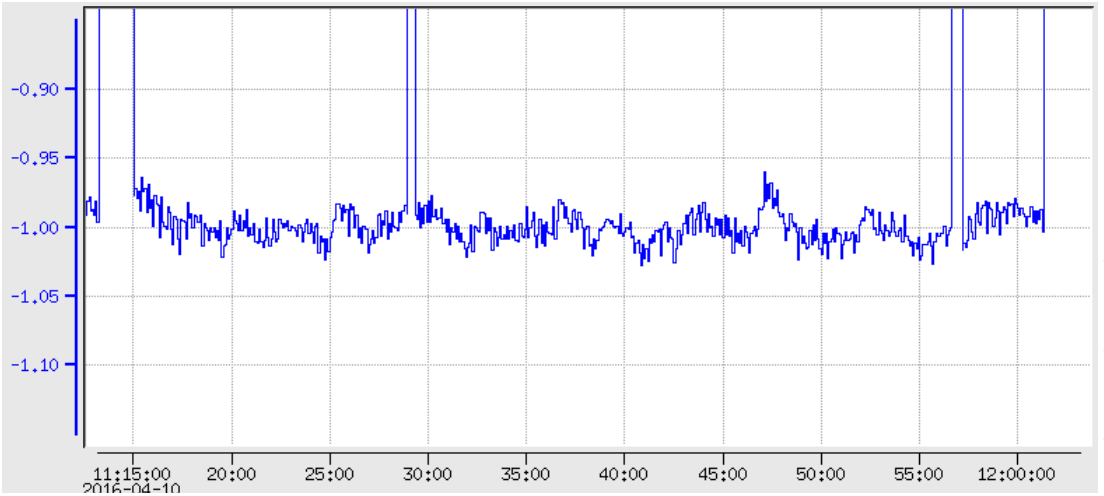
E/P for elastic events

Momentum resolution is $\sim 7\%$ at $1\ GeV$

Beam properties

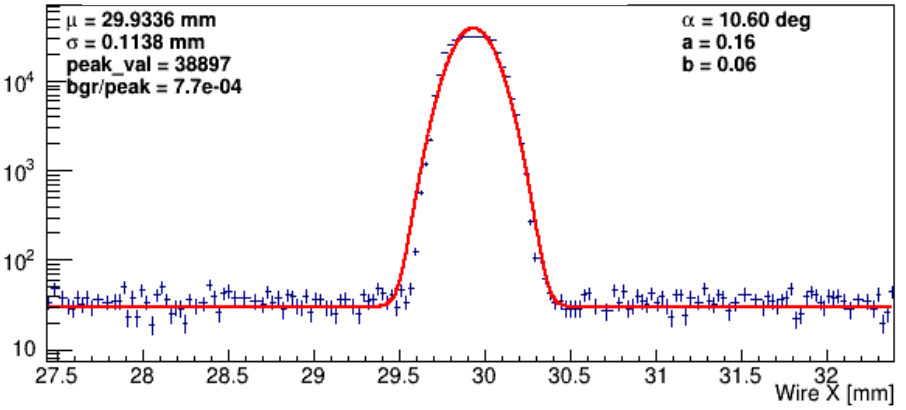
Before moving SVT to 0.5 mm beam properties were extensively studied

Good Beam position stability

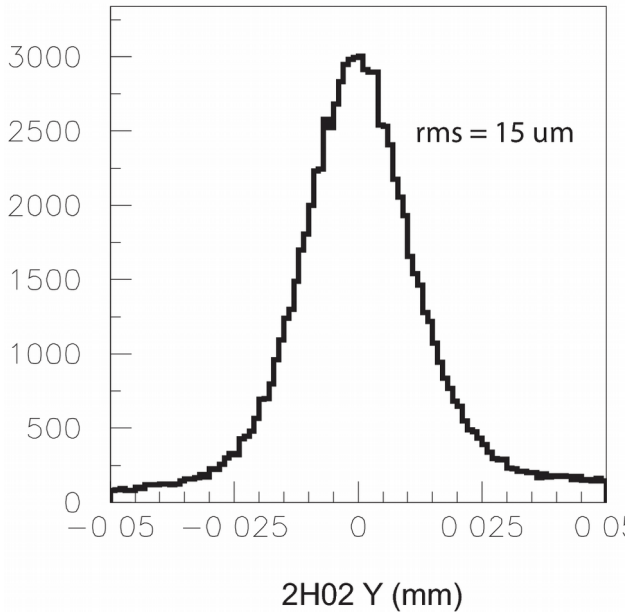


Narrow vertical beam size at the target: $\approx 50\ \mu m$

Horizontal profile



Vertical beam position distribution



Vertical profile