Searching for Heavy Photons in Hall B

Holly Szumila-Vance
Heavy Photon Search Collaboration
Old Dominion University, Department of Physics

GSPDA lunch seminar at Jefferson Lab
24 May 2017

OLD DOMINION
UNIVERSITY

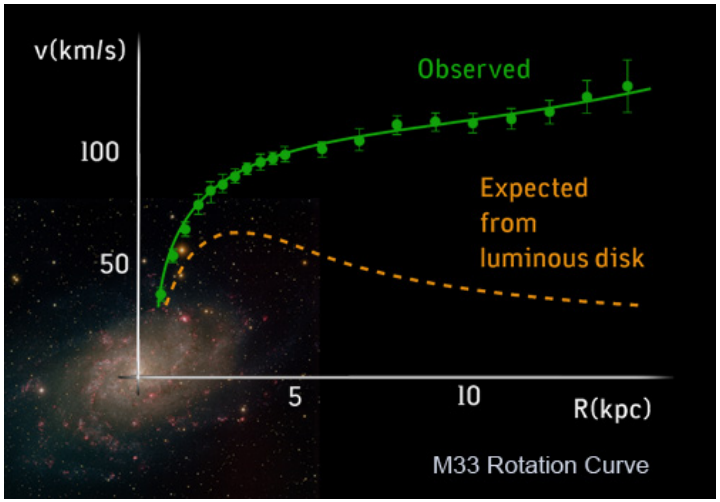
Overview

- Motivation
- Heavy Photon Search experiment
- Experiment performance
- Preliminary results
- What’s next

Nature is described well by Standard Model, but we are missing something…

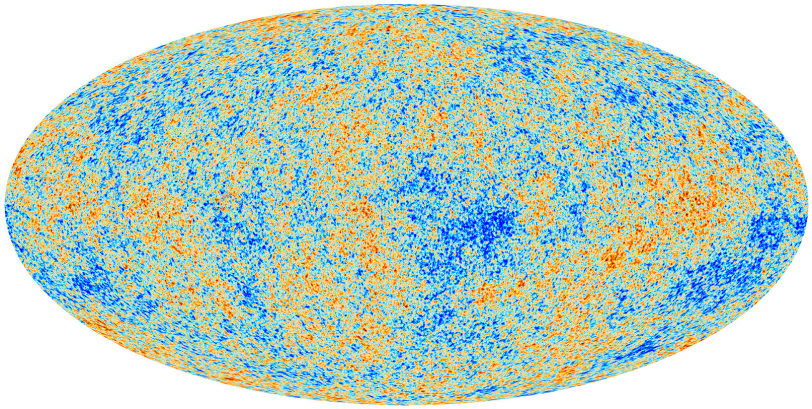
Strong evidence for dark matter!

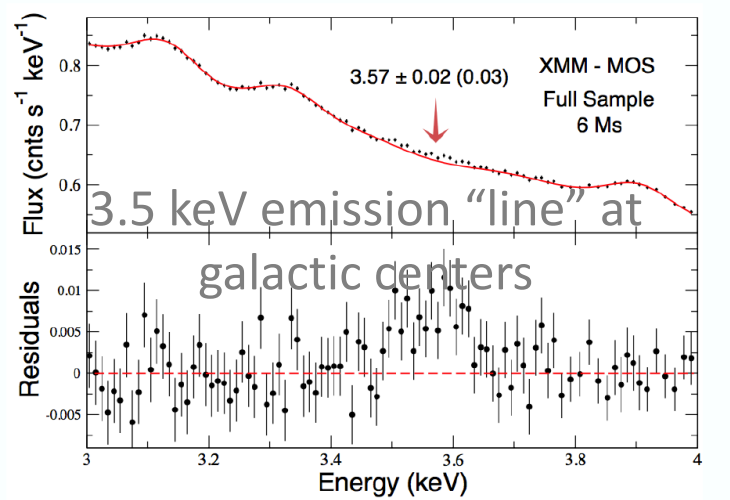
Galaxy rotational velocities



Gravitational Lensing

Cosmic Microwave Background structure

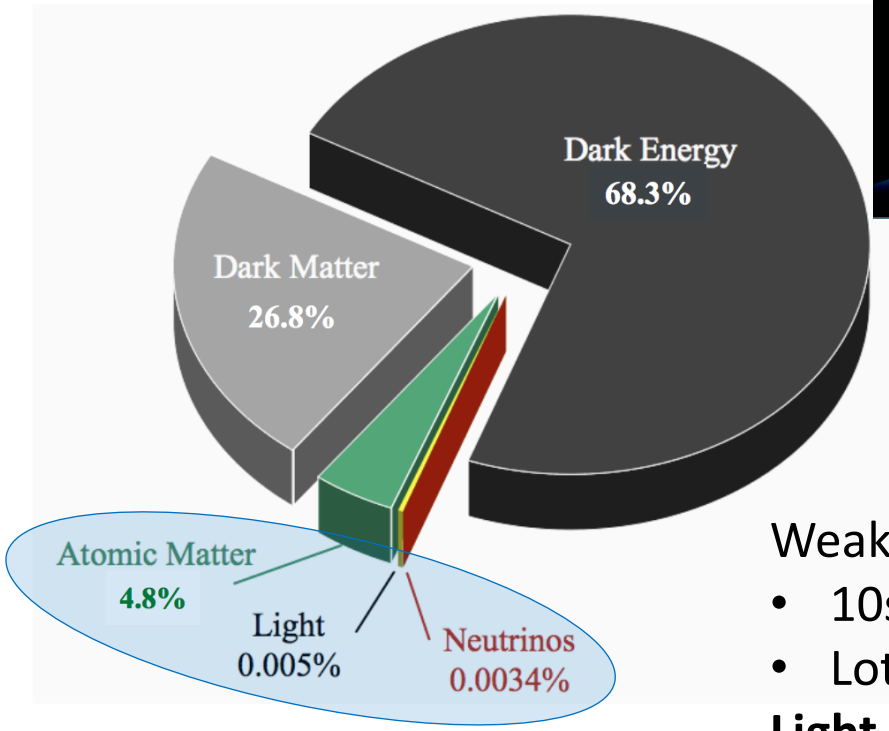




3.5 keV emission "line" at galactic centers

Bulbul et.al.

Exploring the Dark Sector



Dark Sector:

$U(1)_D$ x …

Dark Forces?

Neutral under SM forces

Standard Model:

$U(1)_Y$ x $SU(2)_W$ x $SU(3)_S$

EM Weak Strong

Dark Matter theories

Weakly Interacting Massive Particle (WIMP)s:

- 10s-100s GeV mass range
- Lots of searches, not detected so far

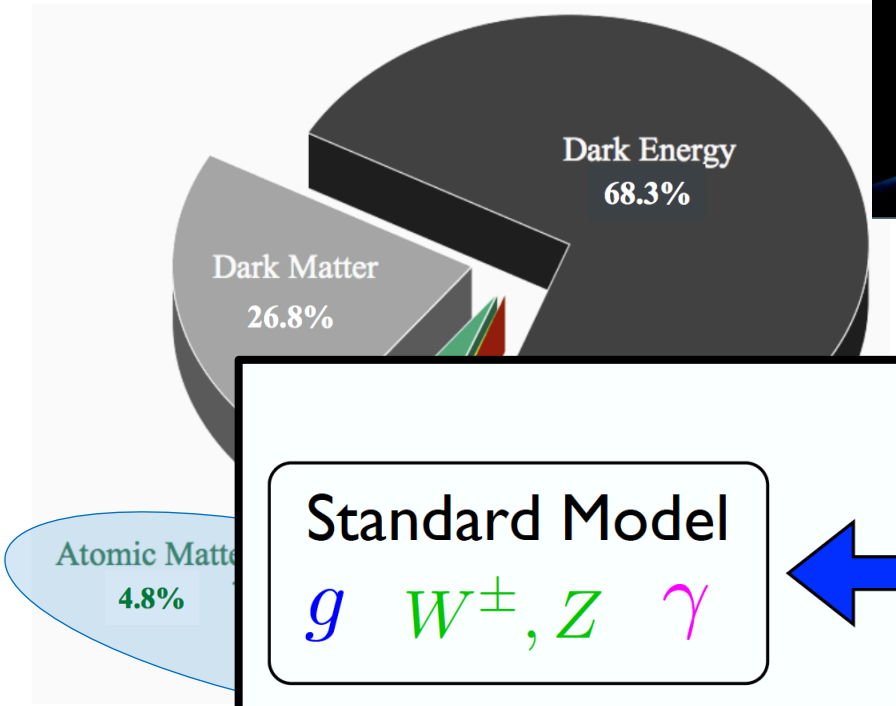
Light Dark Matter:

- MeV-GeV mass range
- Requires new force for correct relic abundance

Strongly Interacting Massive Particles (SIMPs):

- MeV-GeV mass range
- Strongly interacts with itself

Exploring the Dark Sector



Dark Sector:

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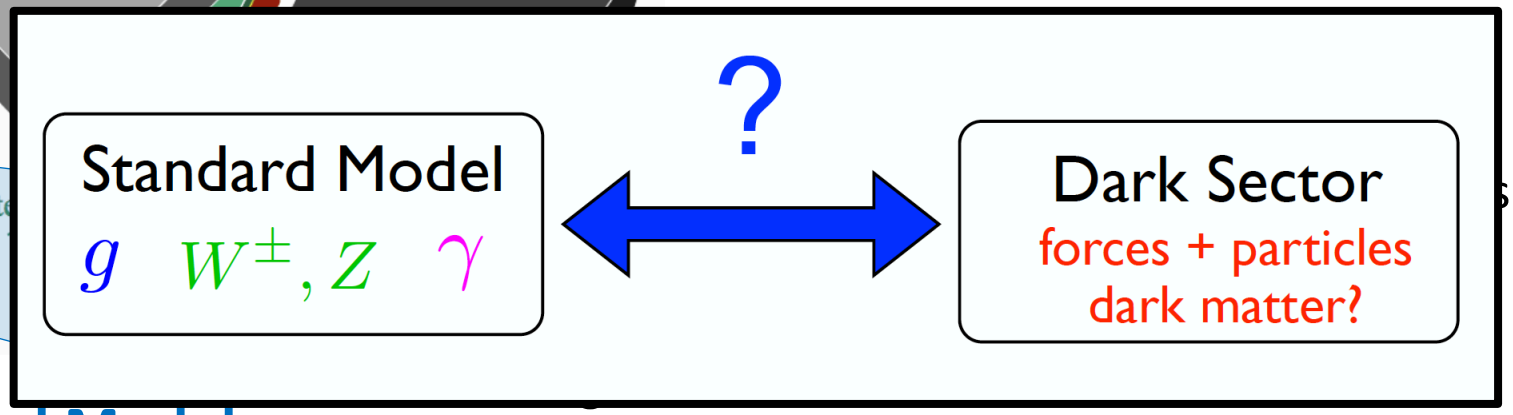
Dark Forces?

Neutral under SM forces



Standard Model:

$U(1)_Y$ x $SU(2)_W$ x $SU(3)_S$

EM Weak Strong

- MeV-GeV mass range
- Requires new force for correct relic abundance

Strongly Interacting Massive Particles (SIMPs):

- MeV-GeV mass range
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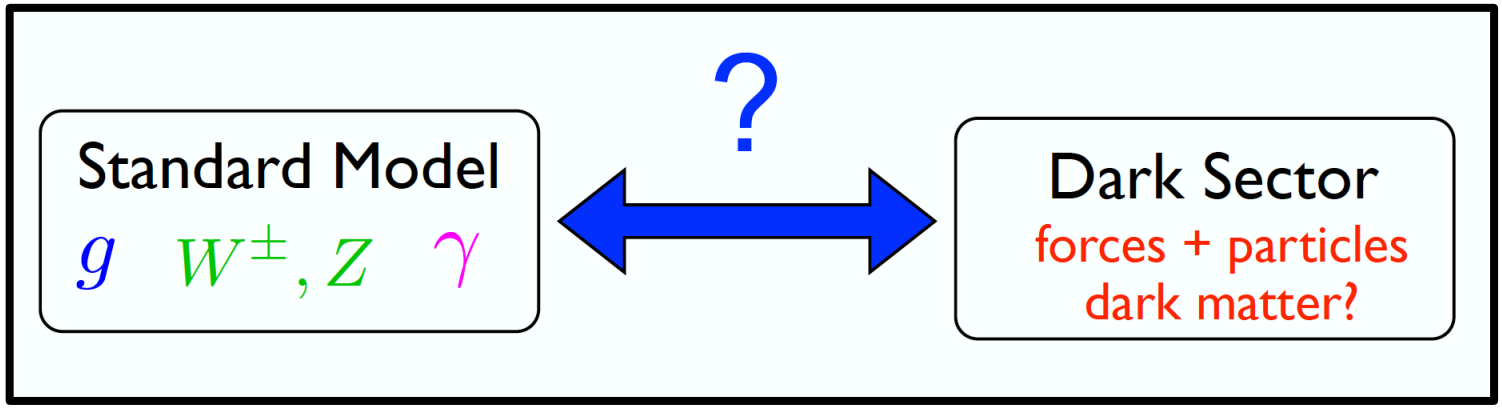
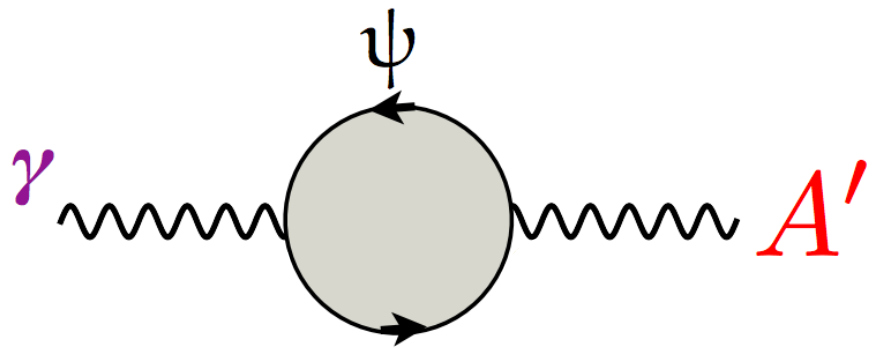

Standard Model
g $W^{\pm}, Z$ γ
?
Dark Sector
forces + particles
dark matter?

Extra Abelian U(1) gauge symmetry → new gauge boson!

Holdom, Phys Lett. B166, 1986

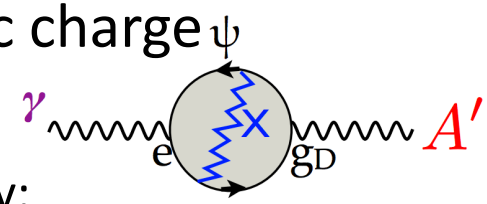
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \boxed{\frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^{\mu} A'_{\mu}$$

Heavy Photon
(aka: dark photon, A',
U-boson…)



Kinetic mixing induces a small coupling ϵe to electric charge

$$A_\mu \to A_\mu + \epsilon A'_\mu$$



Simplest case:

loop-level interaction

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

Grand Unified Theory:

two-loop interactions and higher

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

Mass of heavy photon is less constrained

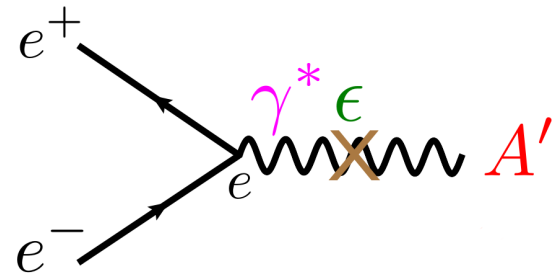
Methods of heavy photon production

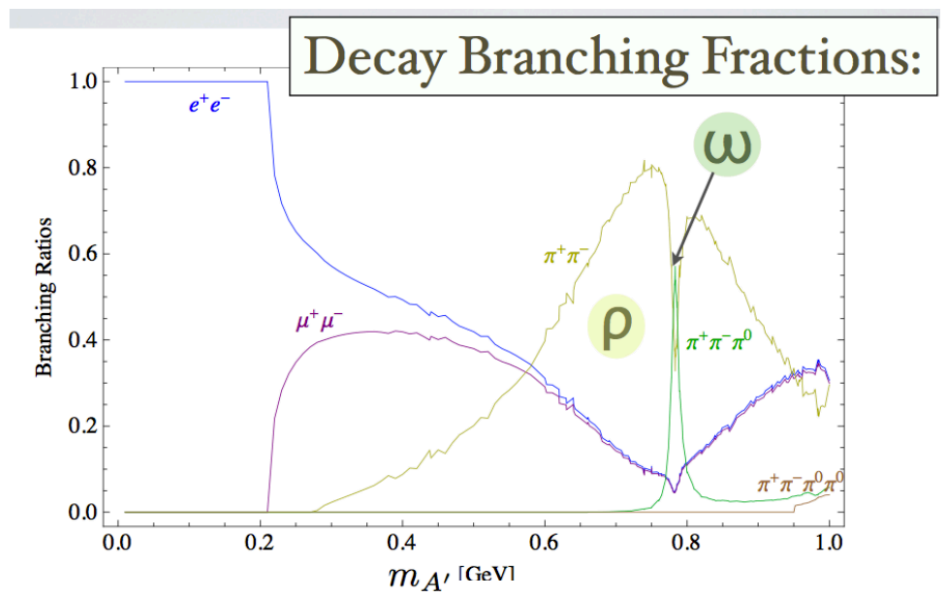
"Wherever there are photons (and sufficient phase space), there are dark photons."
–Philip Schuster

(Z here is atomic number of nucleus)

- Bremsstrahlung
  - $e^- Z \rightarrow e^- Z A'$
- e+e- annihilation
  - $e^- e^+ \rightarrow \gamma A'$
- pZ → X + meson
  - $\pi^0 \rightarrow \gamma A'$
  - $\eta \rightarrow \gamma A'$
  - $\phi \rightarrow \gamma A'$
- Drell-Yan
  - $q\bar{q} \rightarrow \gamma A'$

$A' \rightarrow e^+ e^-$
$\rightarrow \mu^+ \mu^-$
$\rightarrow \pi^+ \pi^-$



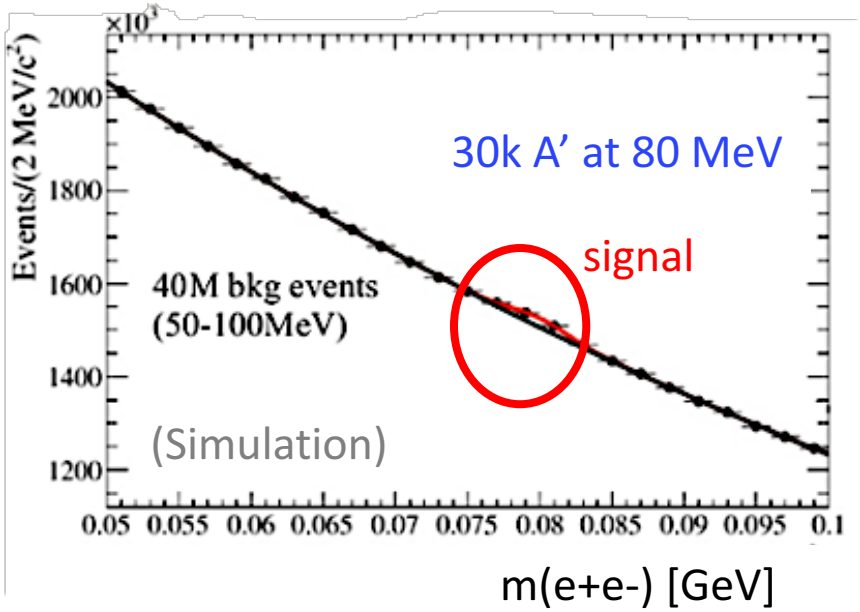


Methods of heavy photon detection

Visible decays:

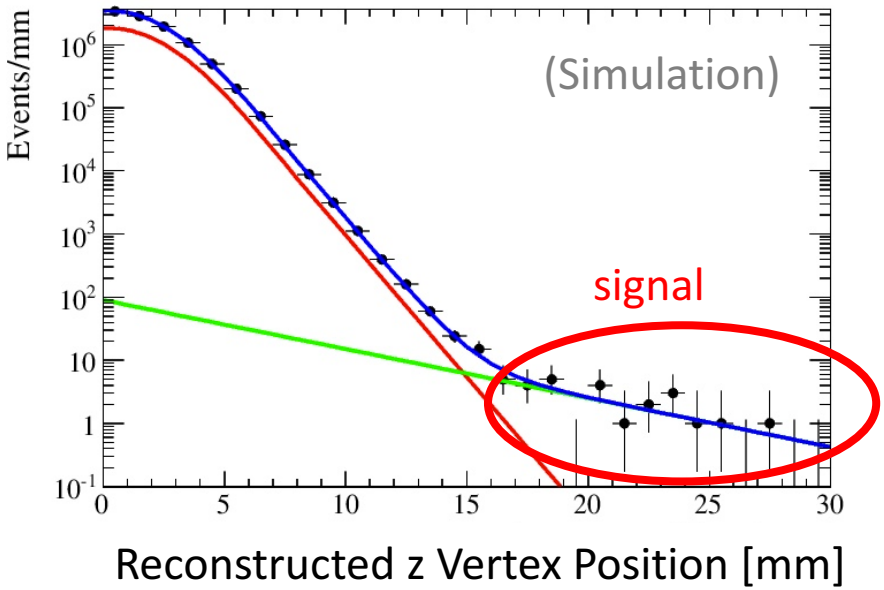
Invariant mass bump hunt:

- Large coupling, prompt decays, lots of background



Displaced vertex:

- Small coupling, long-lived decays, little/no background



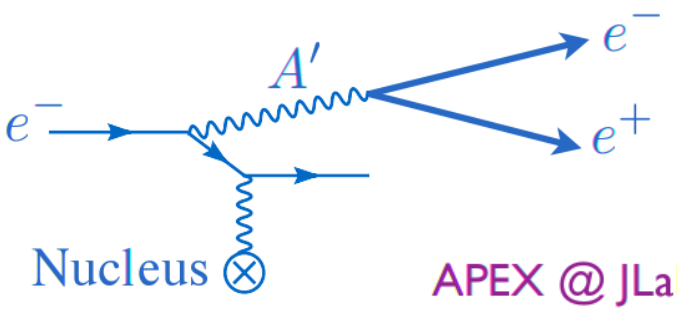
Invisible decays:

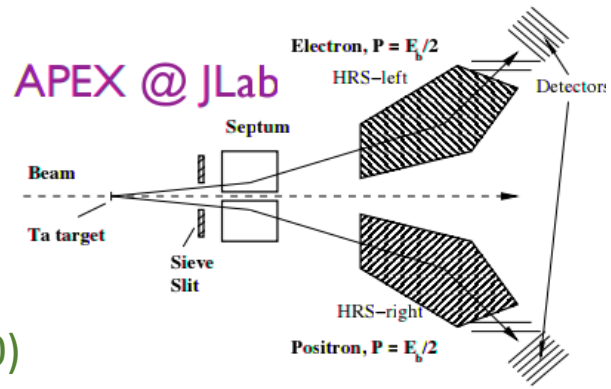
Missing mass bump hunt, allows for decay to Dark Sector

Experiments

Electron fixed target

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



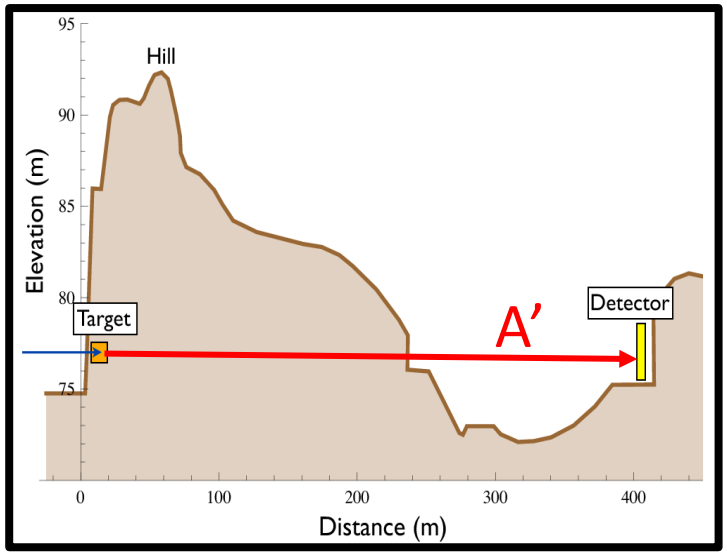


A1 at Mainz (2011)
APEX in Hall A (2010)

HPS first to vertex

DarkLight (Jlab, LERF)
APEX in Hall A (2018)
MAGIX (Mainz) (2019+)

Beam dump
(long lived A')

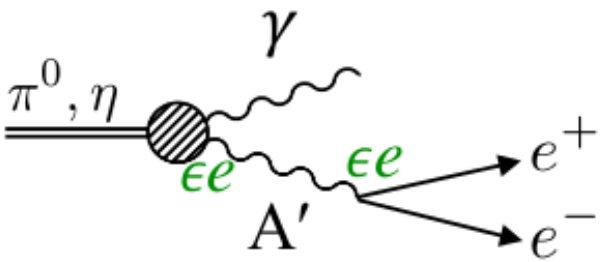


E141 and E137 at SLAC, E774 at FNL, Orsay

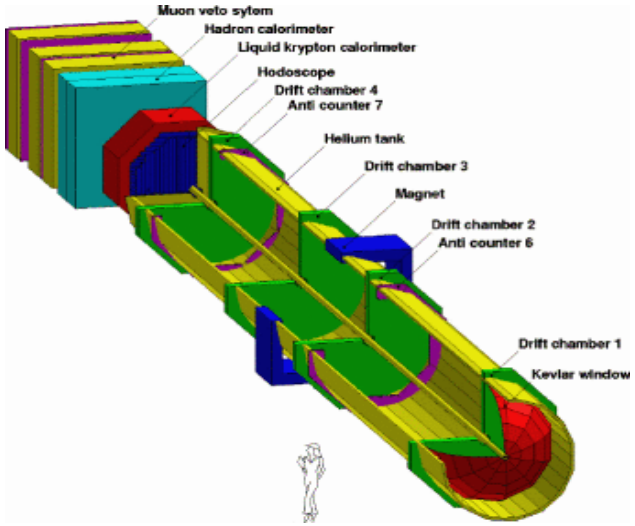
Fixed target experiments complement collider measurements
high luminosity→ sensitive to small couplings

Experiments

Proton fixed target $\sigma \sim \epsilon^2$



NA48/2 at CERN SPS



$K^{\pm}$ beam→ $\pi^{\pm}A'(\rightarrow e^-e^+)$

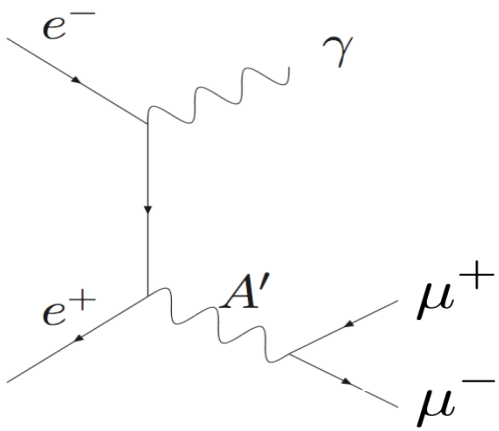
NA48/2 (2015)
HADES (2013)
U70 proton beam dump

SeaQuest (FNAL):
$\mu^+ \mu^-$ from p beam dump
Bump hunt and vertex
Test run this year

SHiP (CERN) (2026+):
CERN SPS, visible & long decay lengths

Facilities to generate heavy photons

Collider

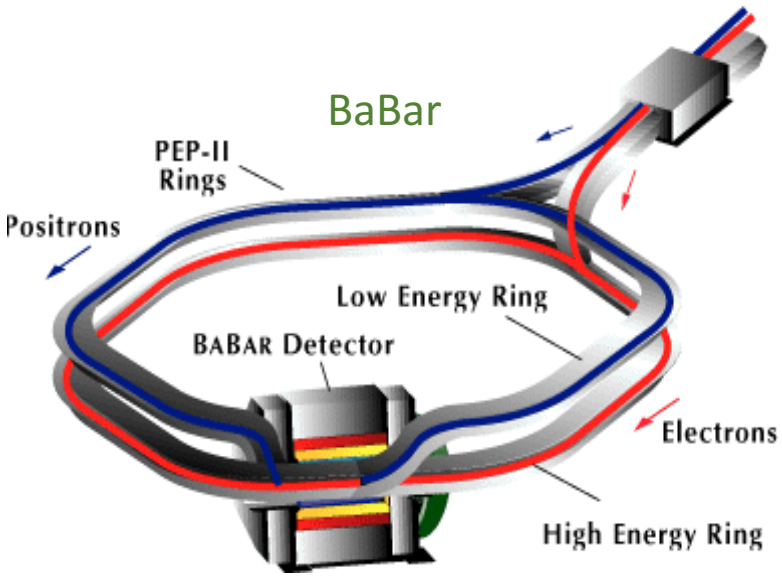


$$\sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2}$$

Good for missing mass searches

BaBar (e+e-), $\Upsilon \to \gamma A'$ (2009)
WASA (pp), $\pi^0 \to \gamma A'$ (2013)

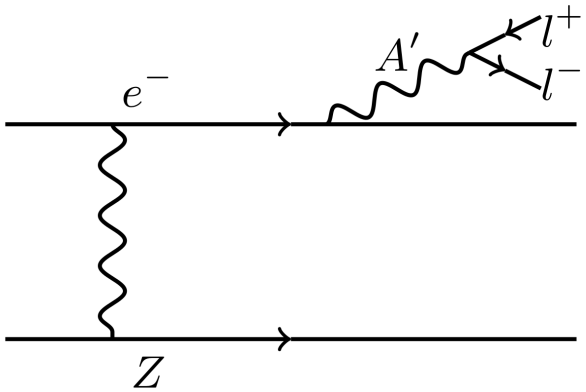
LHCb (pp), 2021+:
Triggerless operation
Rare, heavy quark decays
$D^* \to D^0 A'(e^+ e^-)$
$B \to K^* A'(\mu^+ \mu^-)$



Complements fixed target searches
Higher center of mass energy→ higher A' masses

Looking for radiated $A' \to \ell^+\ell^-$

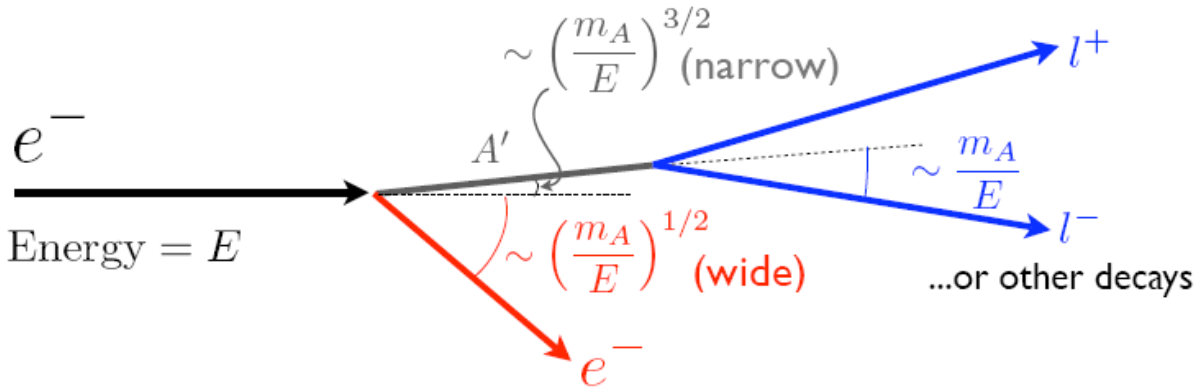
Bremsstrahlung-like reaction



- A' carries most of the beam energy
- Very small angles
- Rate suppressed by $\sim\epsilon^2 \dfrac{m_e^2}{m_{A'}^2}$

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

1 for only e+e-



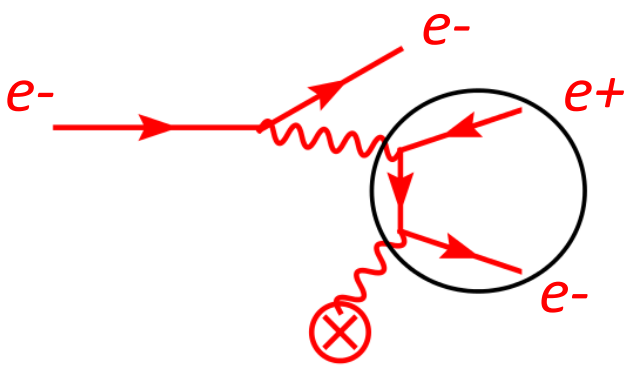
Decay length

$$l_0 \equiv \gamma c\tau \simeq \frac{0.8\ \text{cm}}{N_{eff}}\left(\frac{E_{beam}}{10\ \text{GeV}}\right)\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2$$

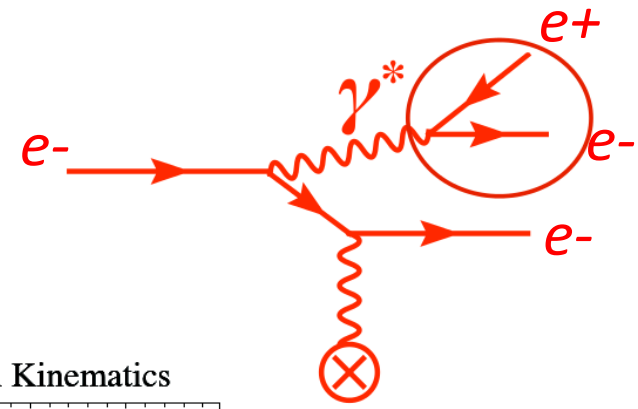
$$E_A \sim E - m_A$$
$$E_e \sim m_A$$

Physics Backgrounds: tridents

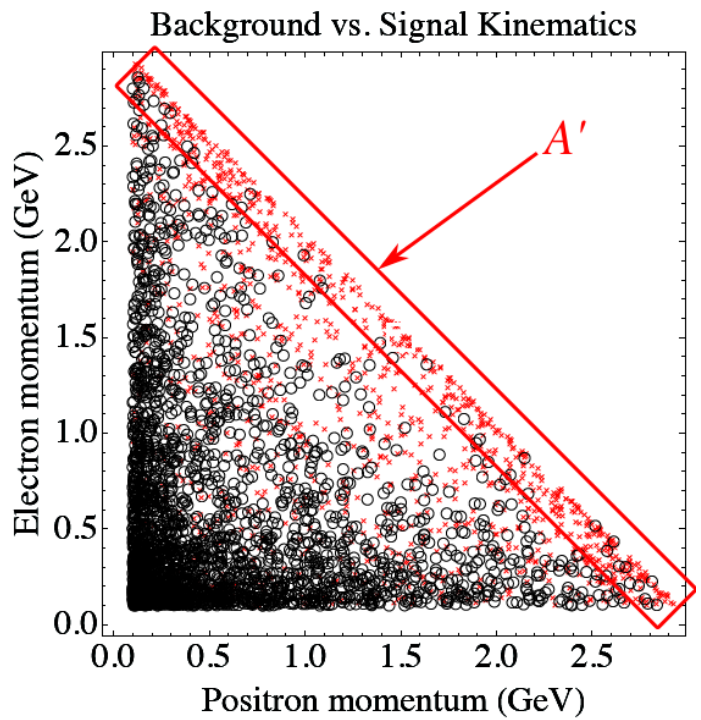
Bethe-Heitler



Radiatives

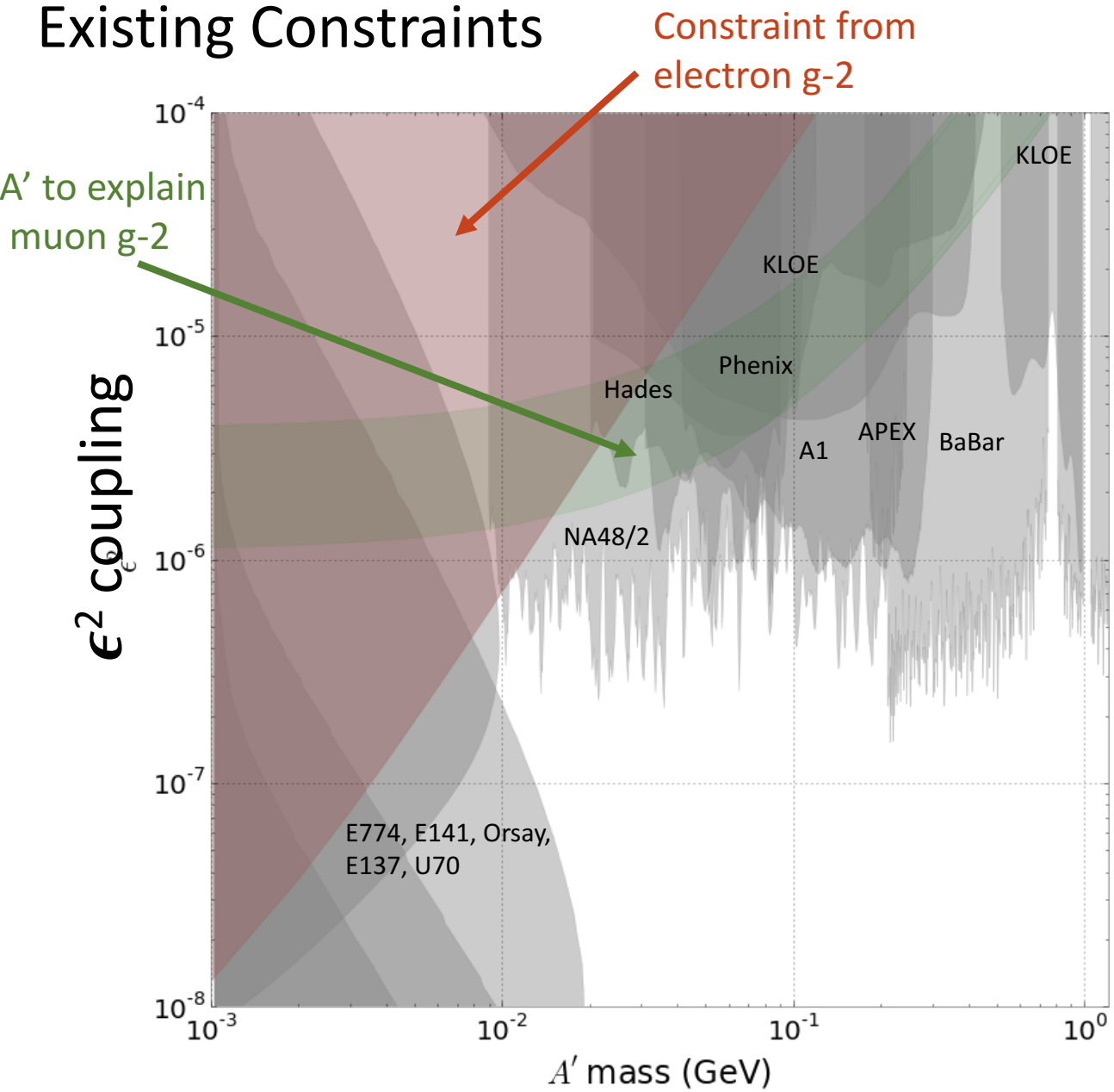


- Dominant background
- Kinematically different

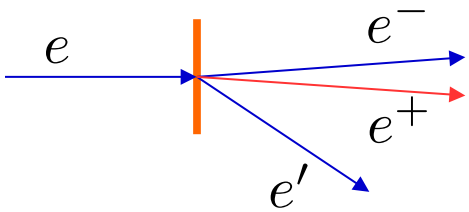


- irreducible background
- kinematics identical to heavy photon

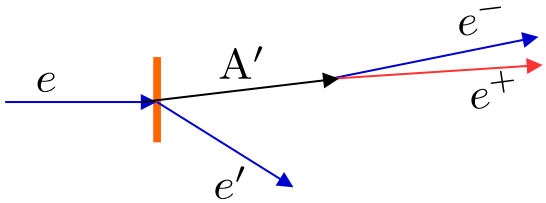
Existing Constraints



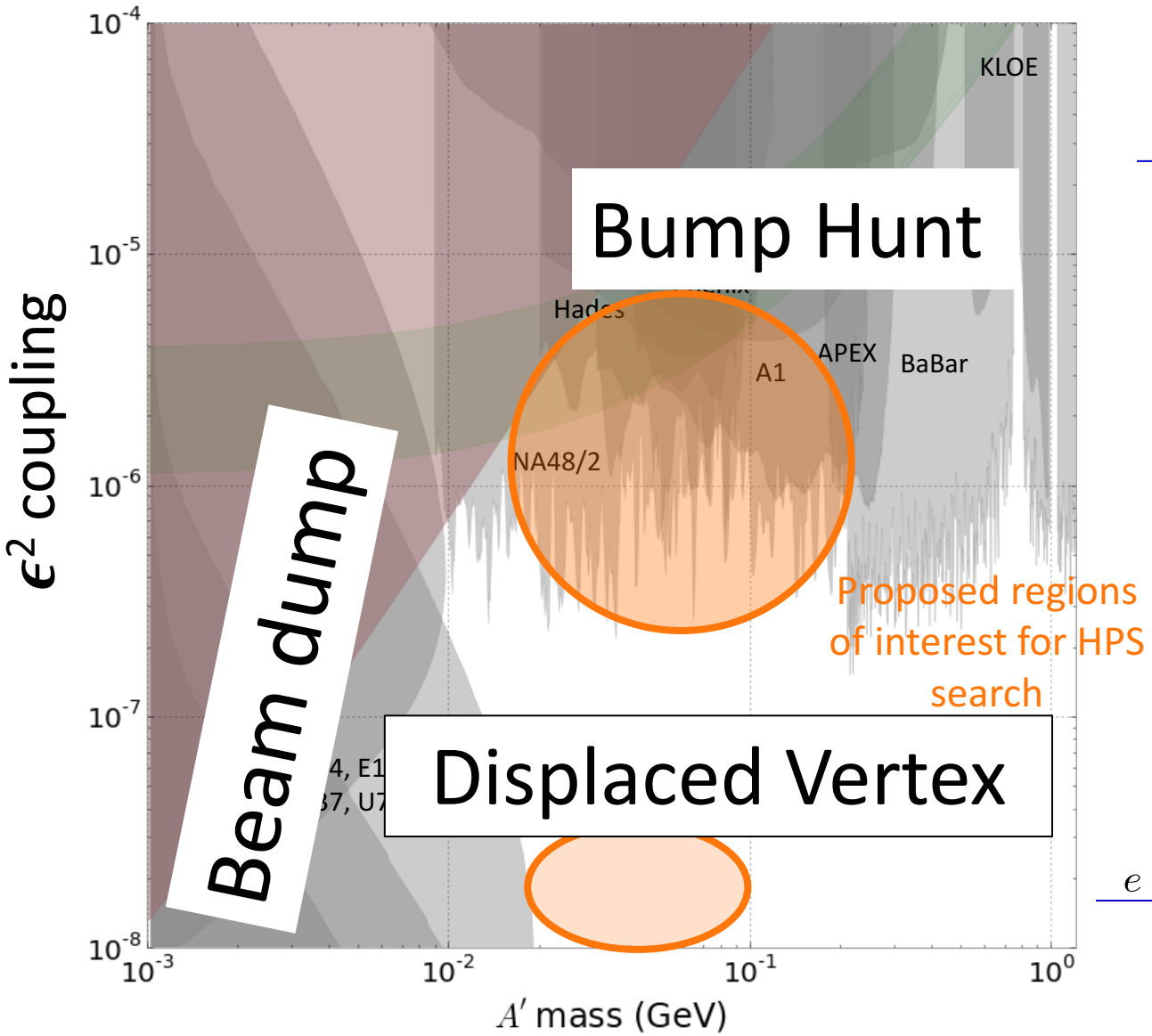
Large ϵ coupling
→ prompt decay



Small ϵ coupling
→ A' long-lived



Existing Constraints



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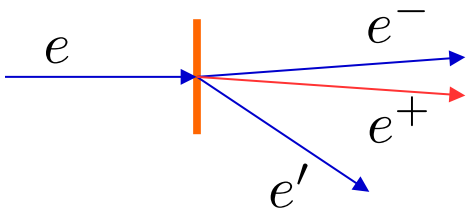

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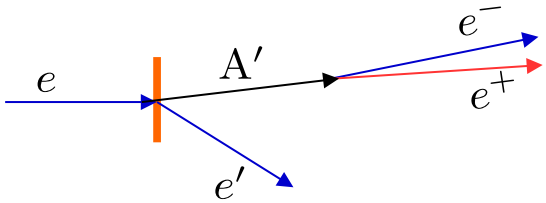
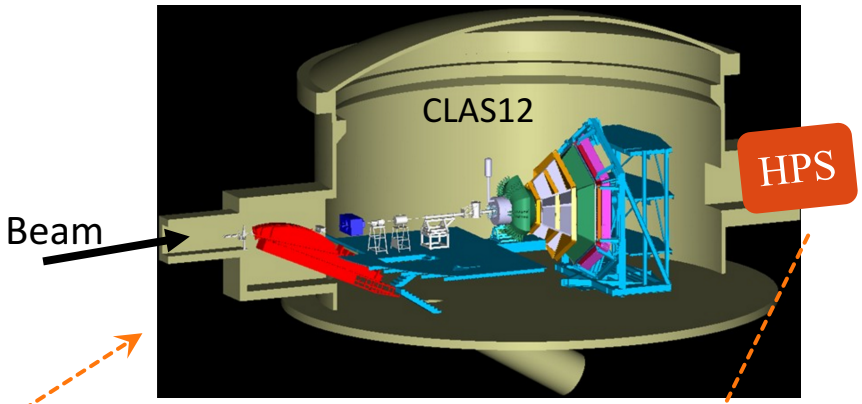


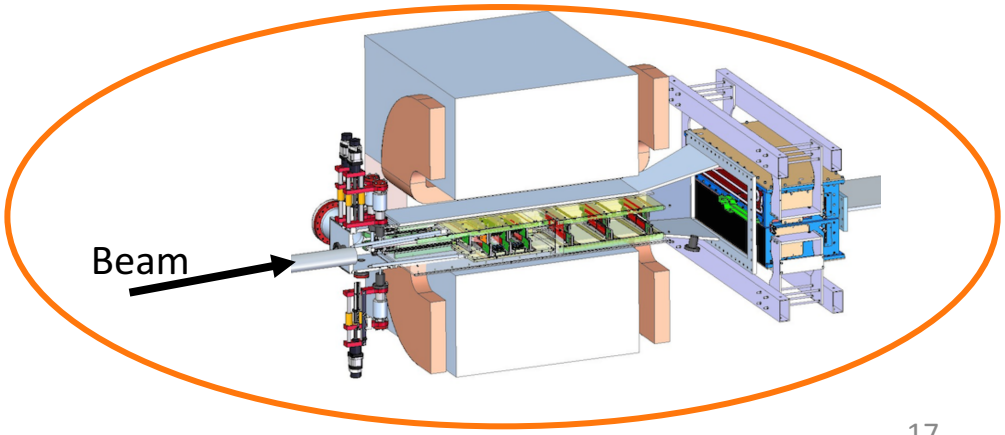
HPS in Hall B

CEBAF max energy 2.2 GeV/pass (max 5 pass)
Simultaneously deliver beam to 4 halls

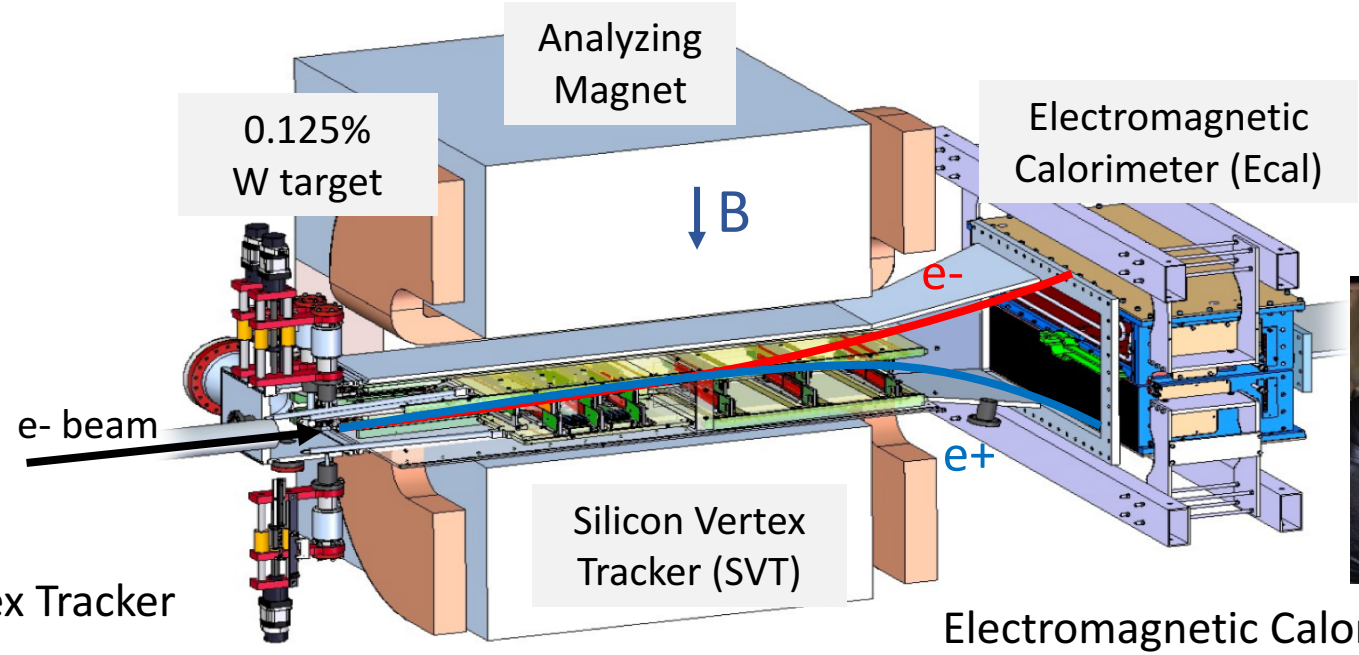
Jefferson Lab, CEBAF

Hall B

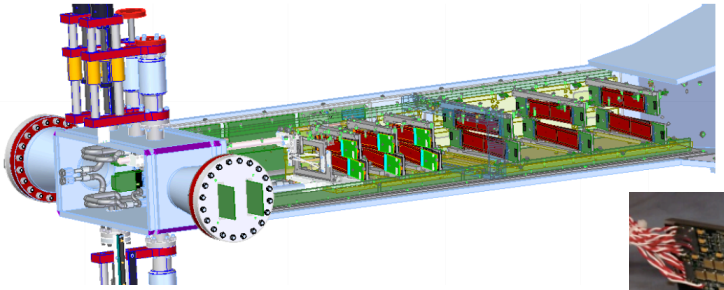




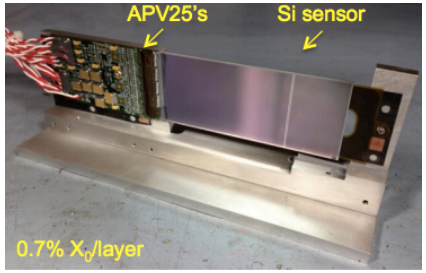
HPS Detector



Silicon Vertex Tracker

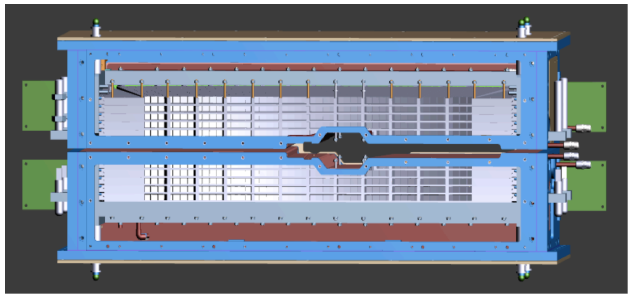


SVT active area
0.5 mm from beam!



- Measures particle trajectories
- Momentum and vertex

Electromagnetic Calorimeter



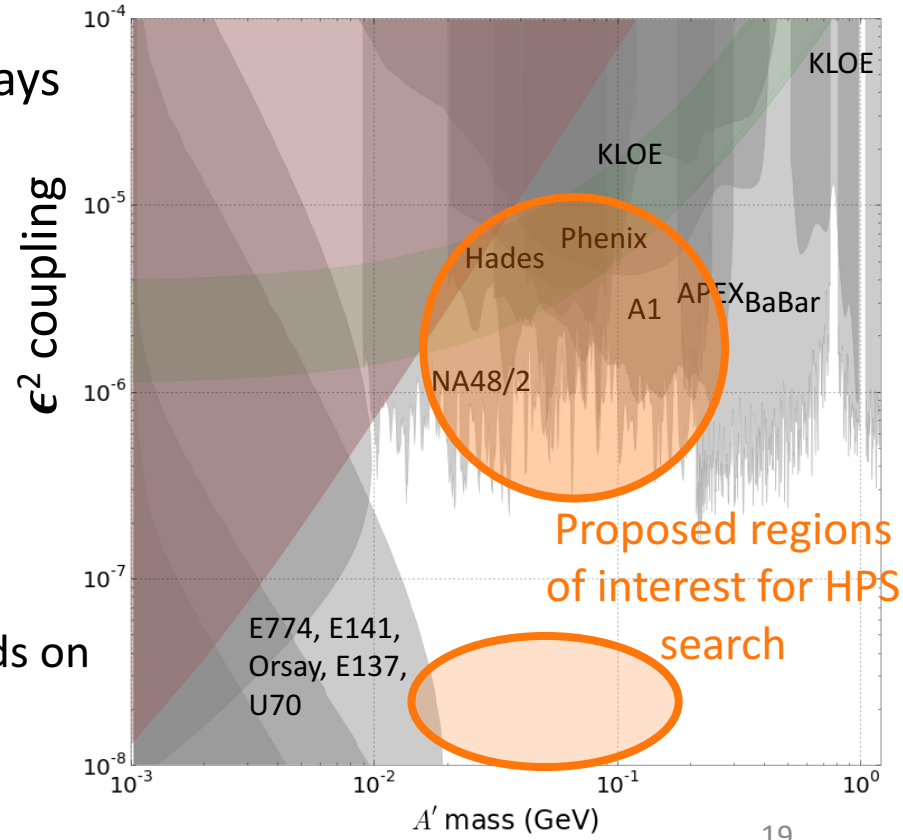
- Triggers events
- Measures particle energy
- Resolution: 4%/√E

HPS Experimental Goals and Considerations

HPS is sensitive to heavy photons with both **prompt** and **displaced** decay vertices
→ Small mass resolution for bump hunt to fight backgrounds
→ Small vertex resolution and minimal tracking material to reduce scattering

Maximize acceptance for low mass A' decays
→ Close to the beam

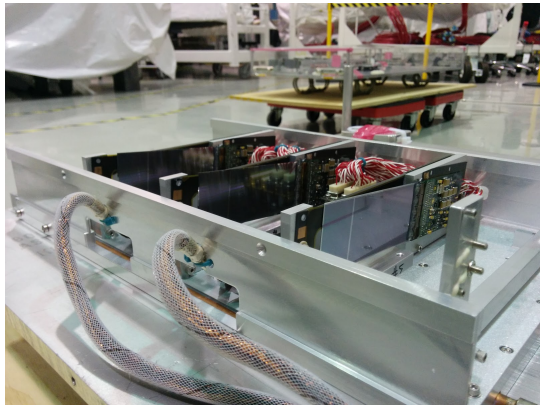
HPS approved to run for 180 beam days

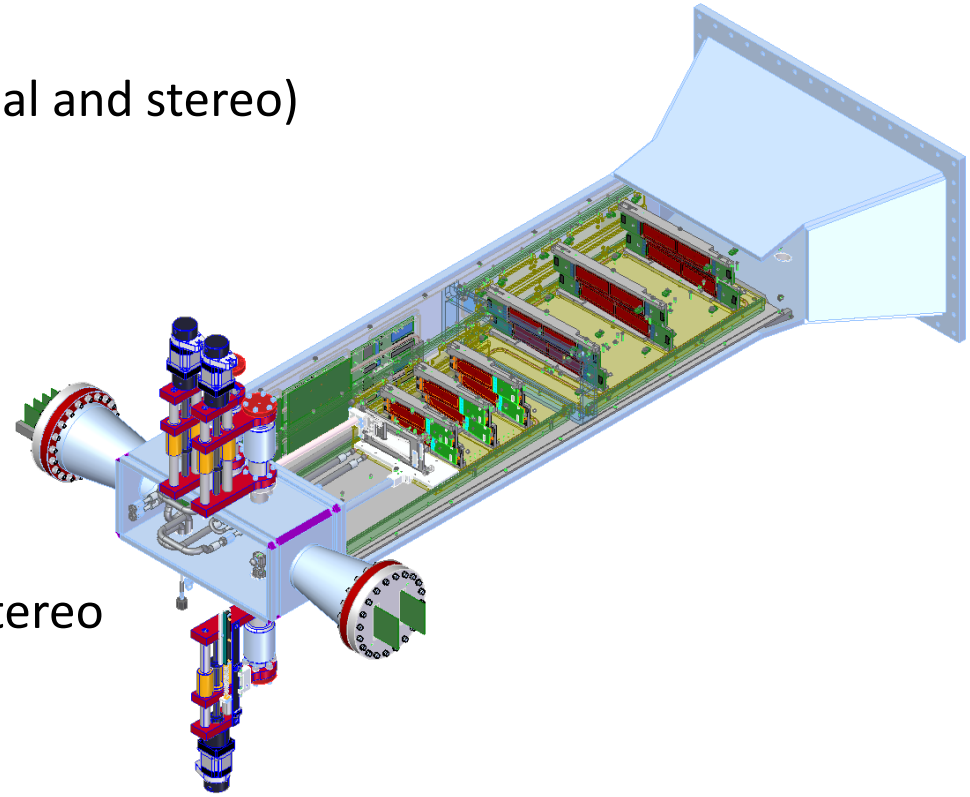


Actual HPS sensitivity depends on beam time and energy

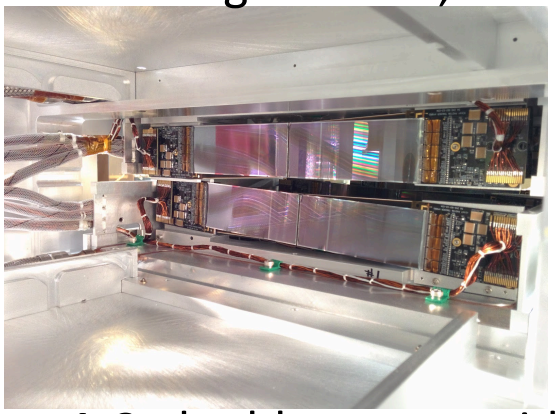
Silicon Vertex Tracker

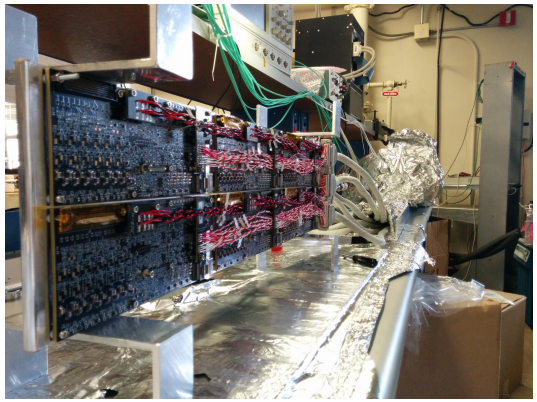
- Six layers of Si microstrip sensors (axial and stereo)





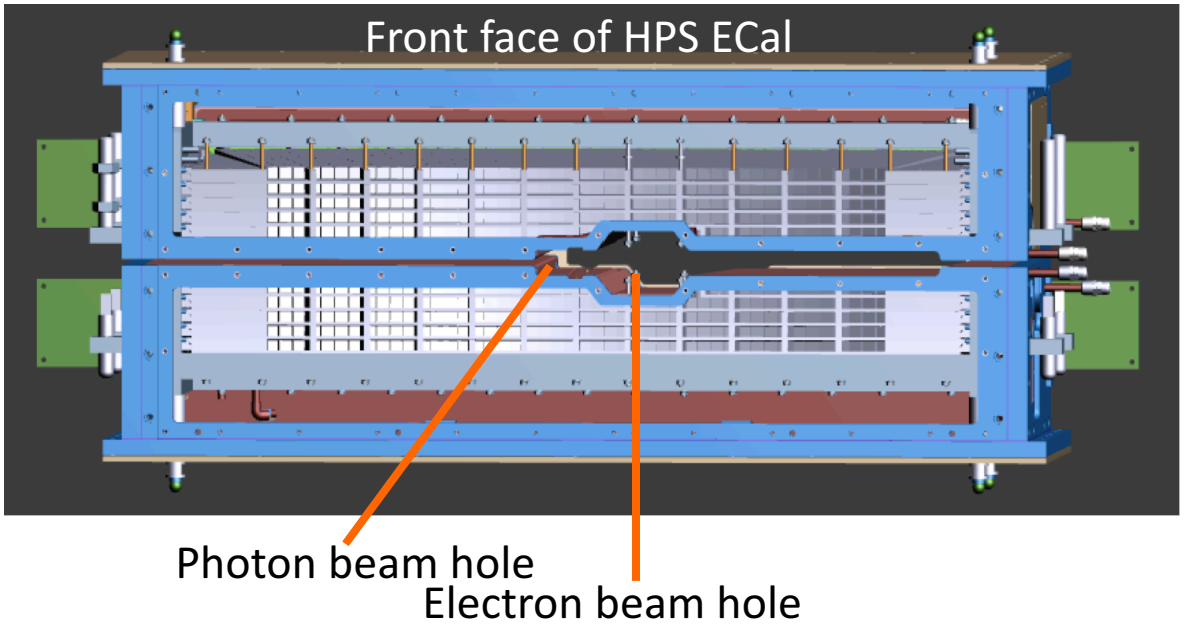
- Layers 1-3: single sensor, 100 mrad stereo



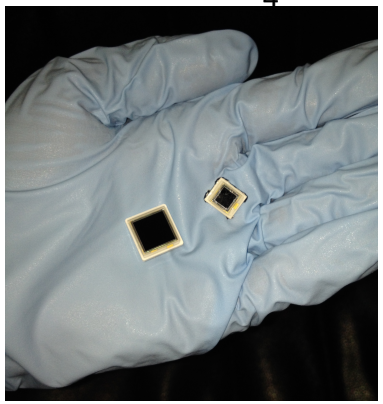


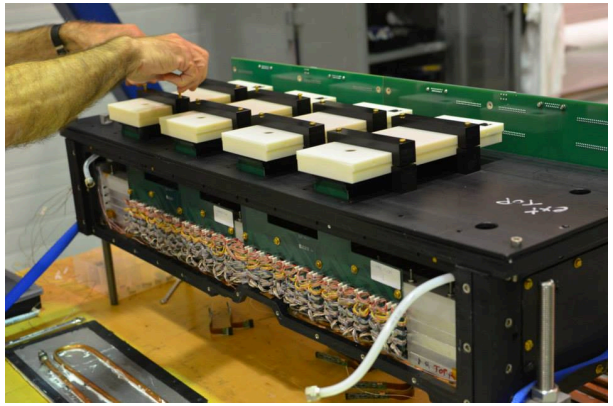
- Layers 4-6: double sensor wide, 50 mrad stereo
- 36 total sensors
- 180 APV25 chips
- 23,004 channels

Electromagnetic Calorimeter

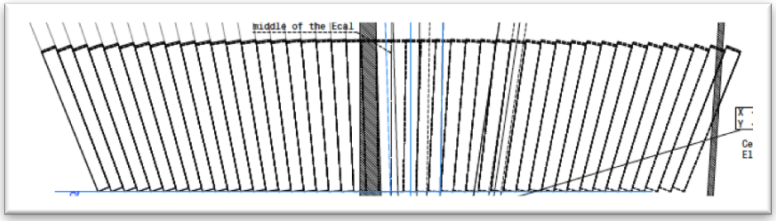


- 442 $PbWO_4$ scintillating crystals re-used from CLAS Inner Calorimeter





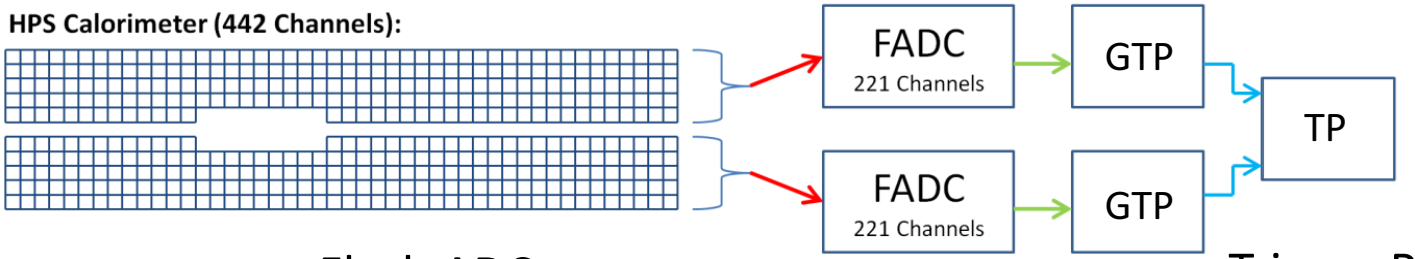
Bird's eye view



- Large Area Avalanche Photo Diodes (APD) for readout (10x10 mm^2)
- Light Monitoring System
- Gap between top and bottom half to allow for "sheet of flame"

Triggering events

General Trigger Processor
- Builds 3x3 clusters
- Reports time, energy, and position to TP

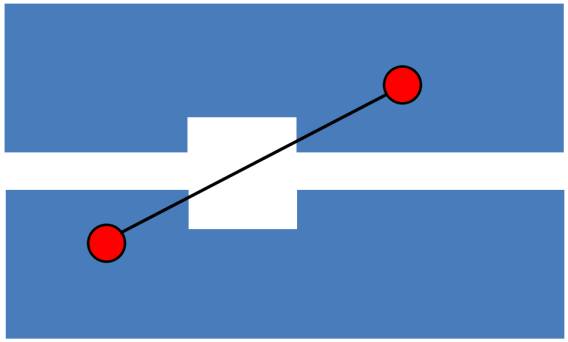


Flash ADC
- Samples Ecal crystals at 250 MHz
- If threshold crossing, reports integrated amplitude and time to GTP

Trigger Processor
- Applies a topological selection to clusters
- Makes trigger decision

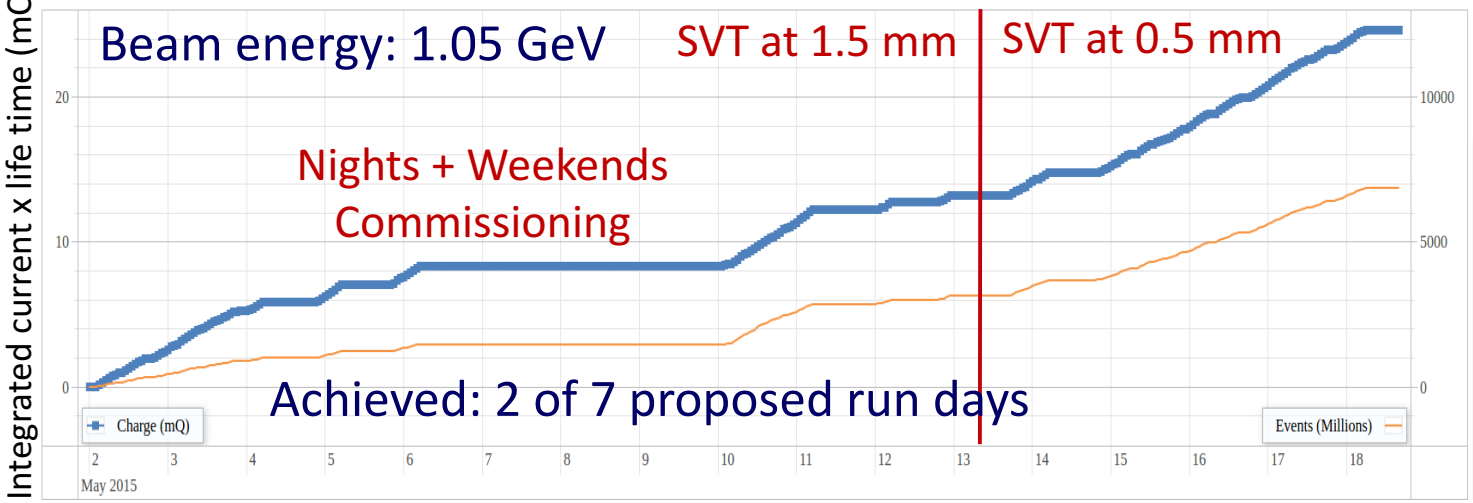
Consider topologies and optimize for heavy photon signal:

- Cluster energy sum
- Cluster energy difference
- Time coincidence
- Cluster size
- Cluster energy
- Coplanarity
- Energy-distance

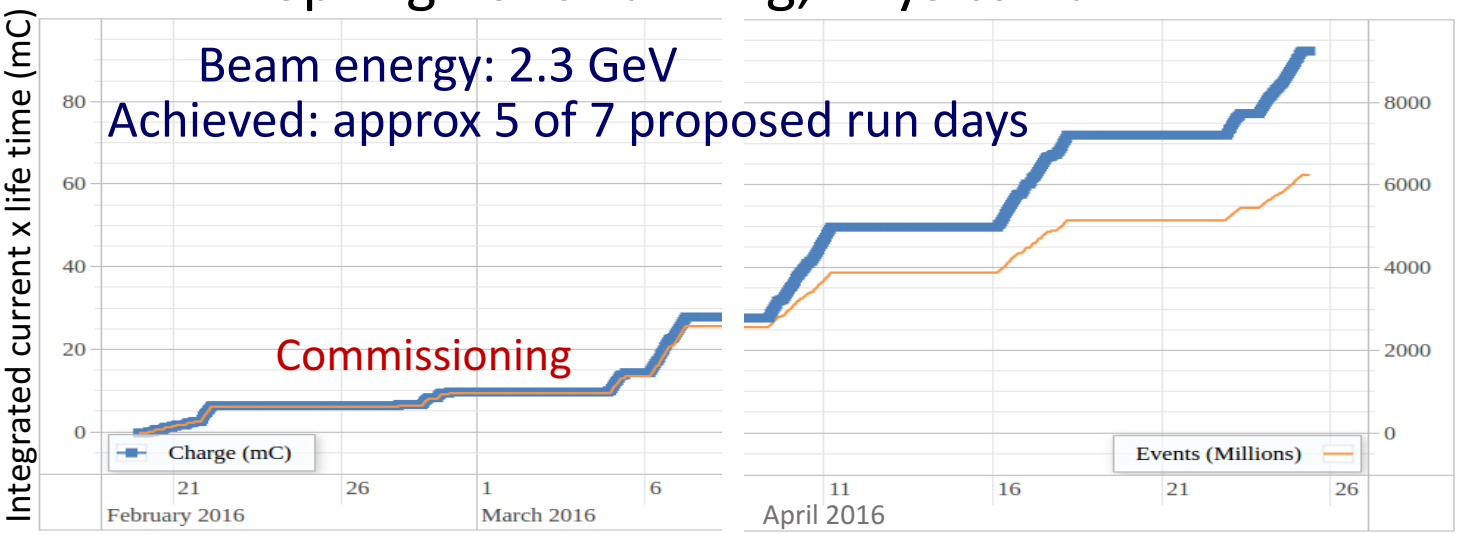


HPS Running

Spring 2015 running, Engineering Run



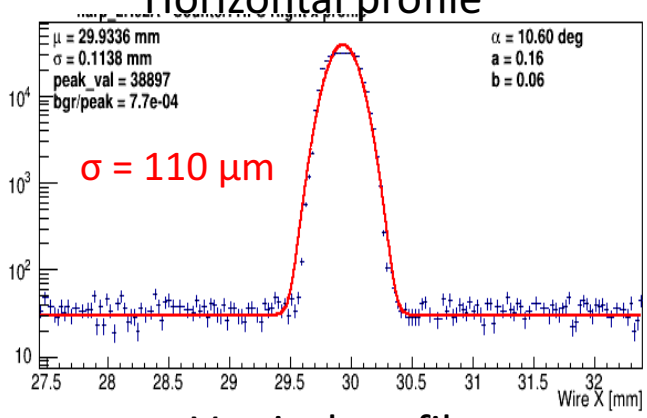
Spring 2016 running, Physics Run



High quality beam:

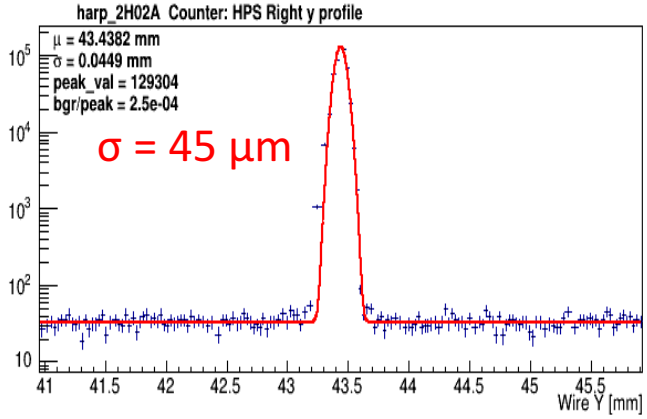
- Asymmetric beam profile
- Prevent potential overheating of target
- Small in vertical size for precise vertex reconstruction

Horizontal profile



First layer of SVT at ± 0.5 mm from the beam!

Vertical profile

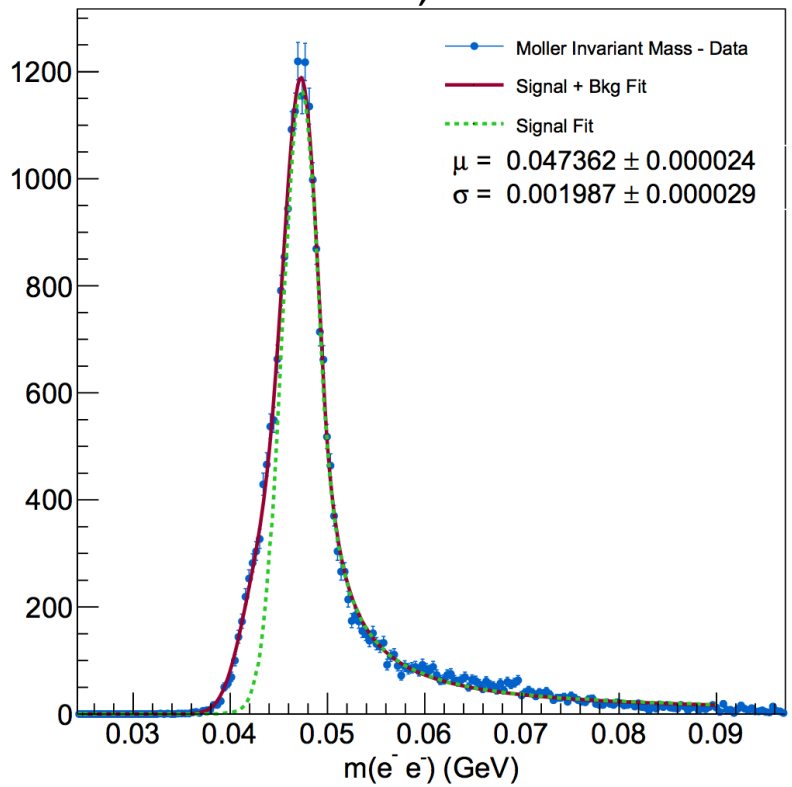


Fast Shut-Down if halo counter rates too high, cuts off beam in 5 ms

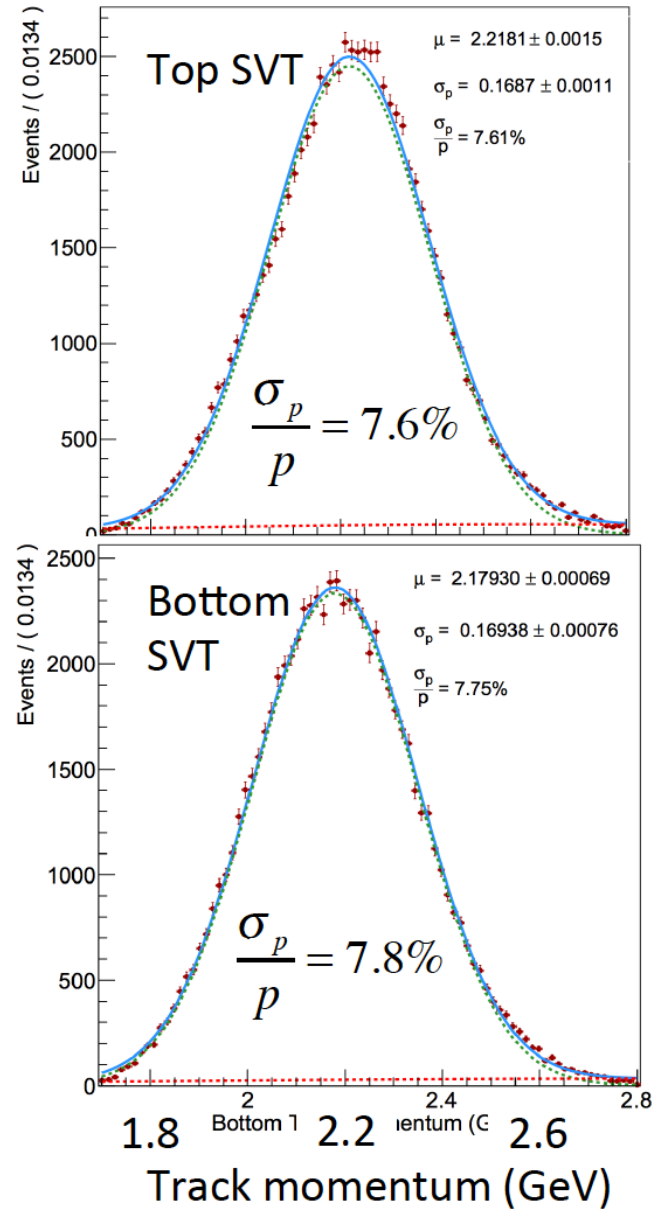
SVT Performance

- Consistent with proposal

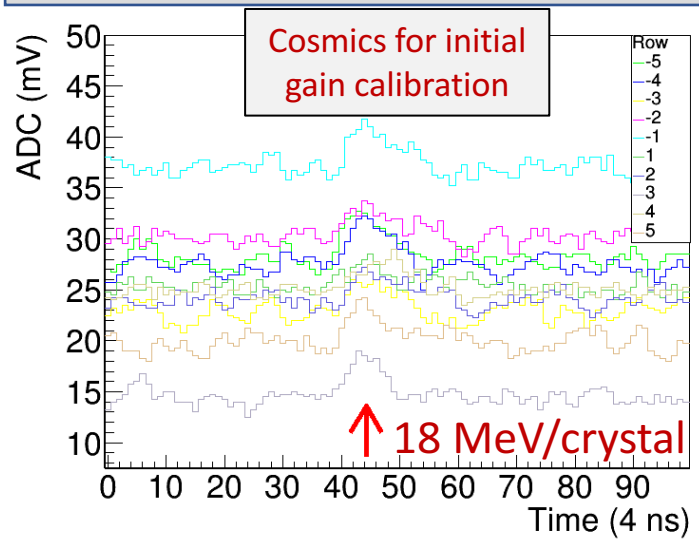
Moller Mass, initial data

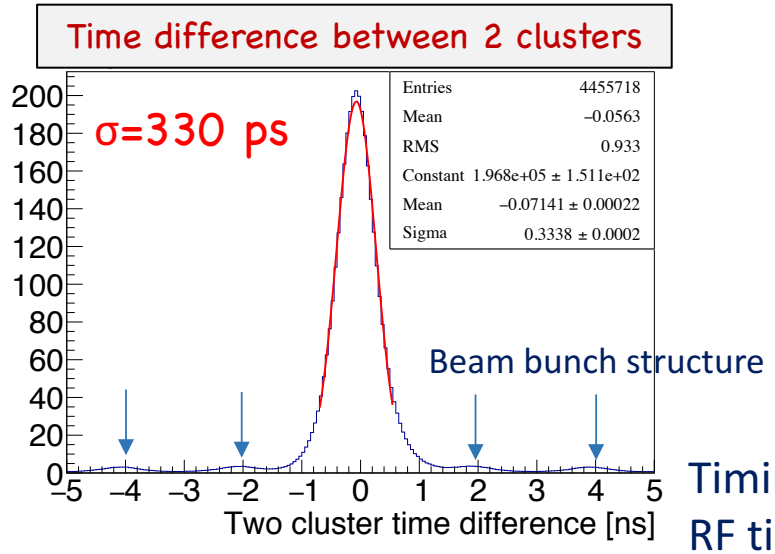


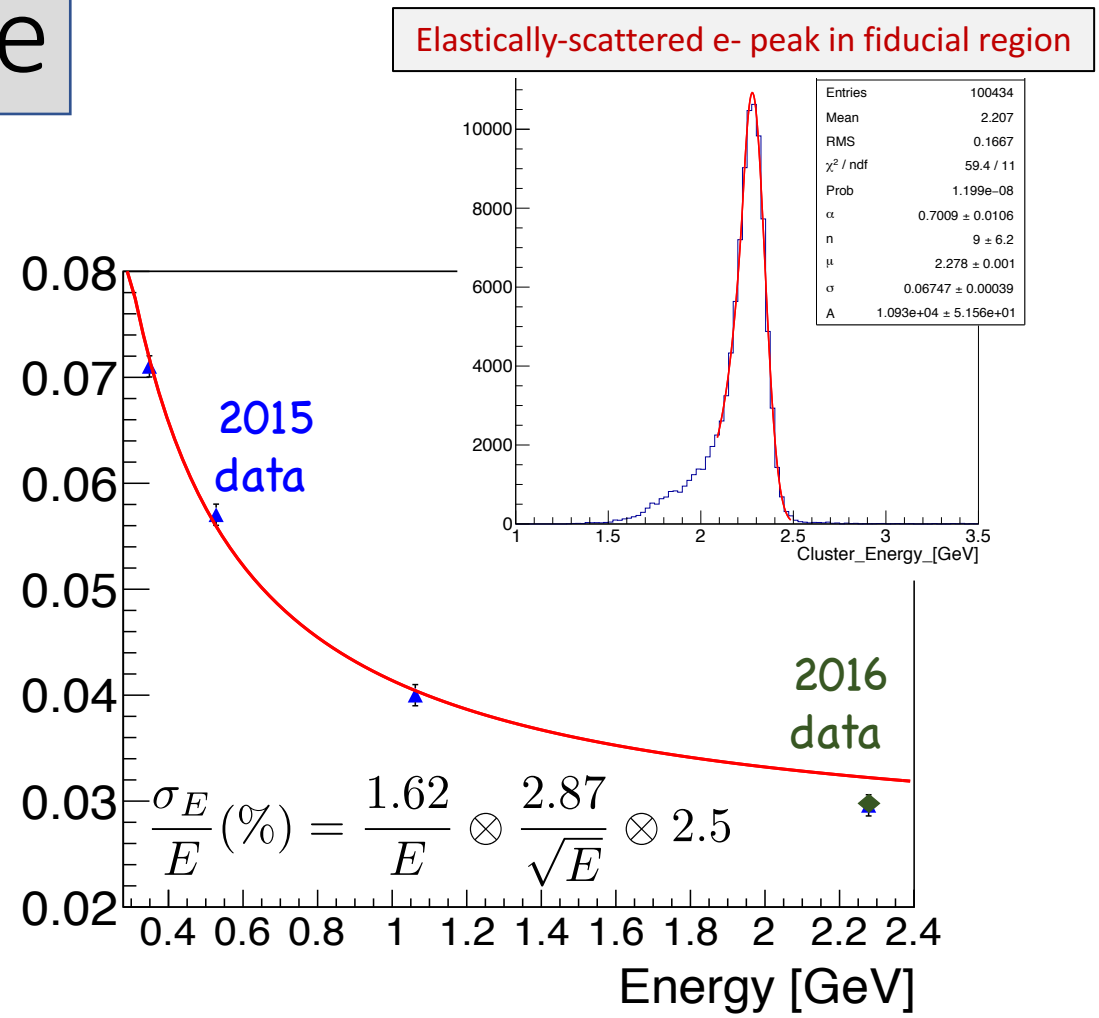
Elastic scattering, initial data



Ecal Performance

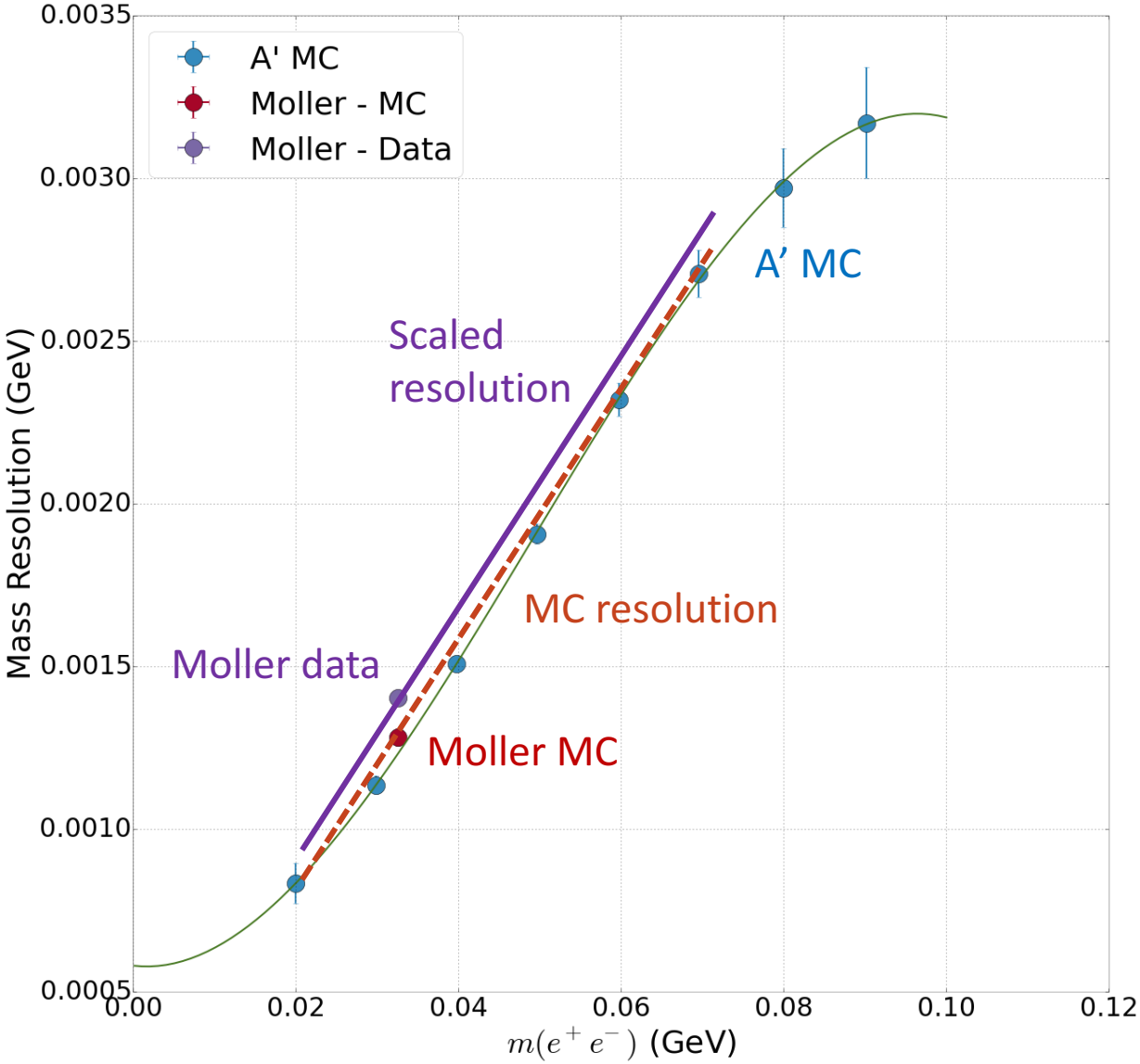






Timing offsets were calibrated using RF time from accelerator

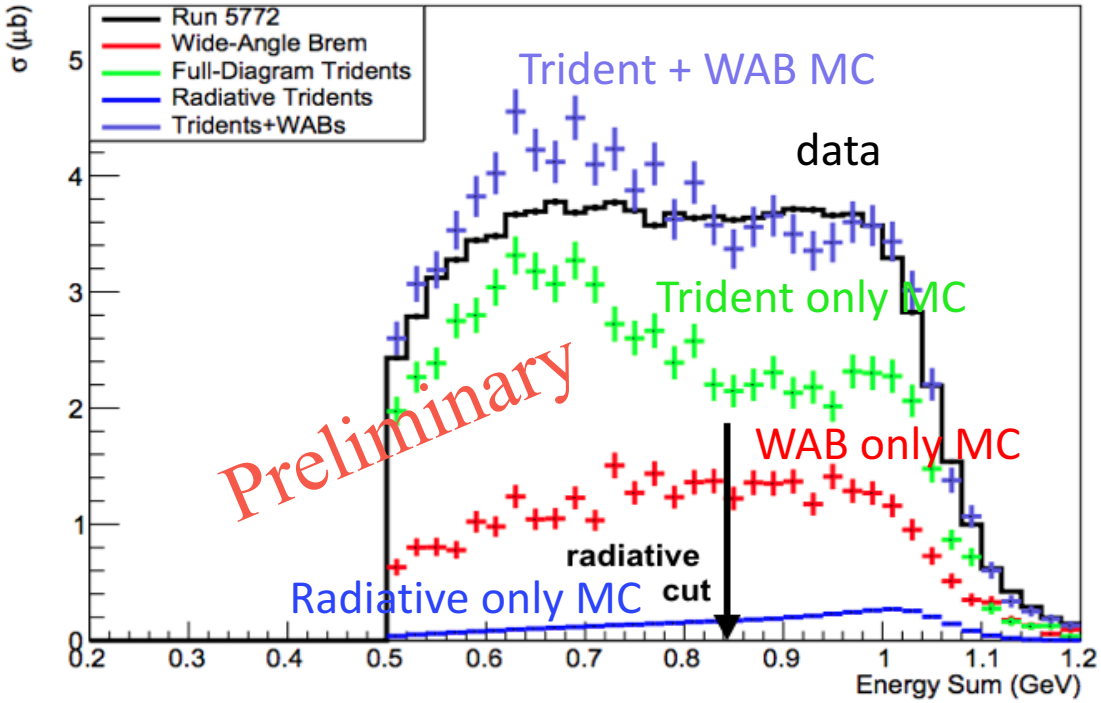
Mass resolution



Agreement with Simulation

Need good agreement in order to calculate amount of radiative tridents in final sample

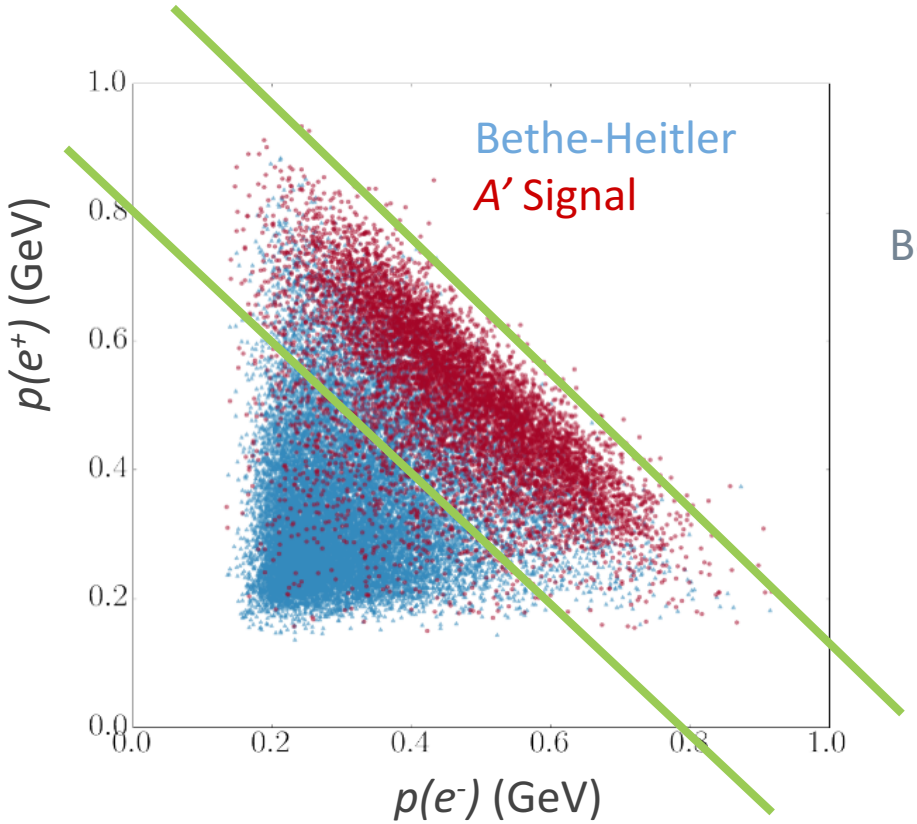
- Additional significant background: Wide Angle Bremsstrahlung (WAB), $e^{-}\gamma$
- Agrees at high energy sum
- Differences at lower energy sum are being studied



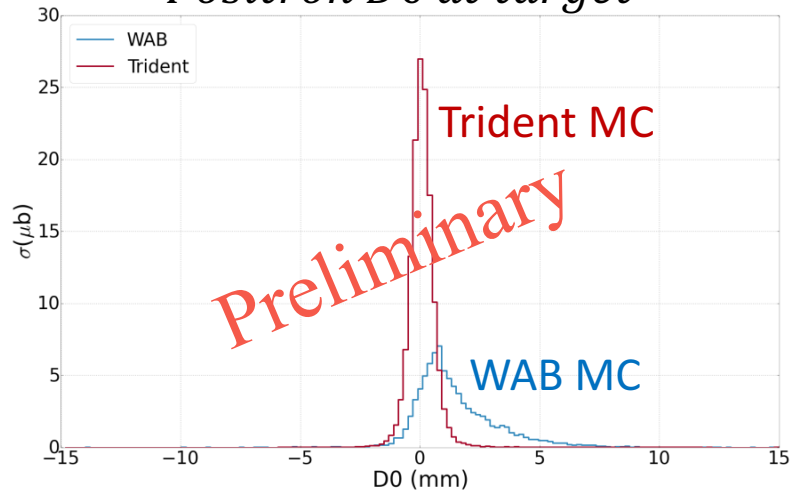
Bump hunt event selection and backgrounds

Cuts:

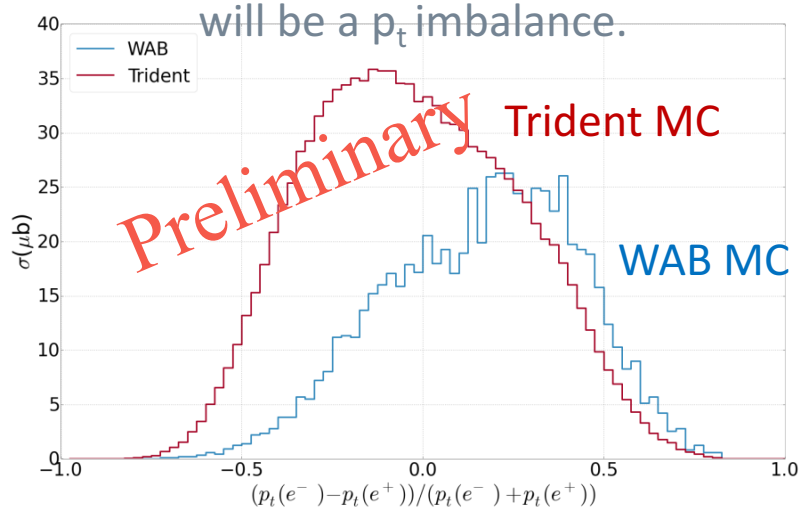
- Track Quality
- Target-Constrained Vertex Quality
- Timing (2 beam buckets)
- Track-Ecal cluster matching



Positron D0 at target

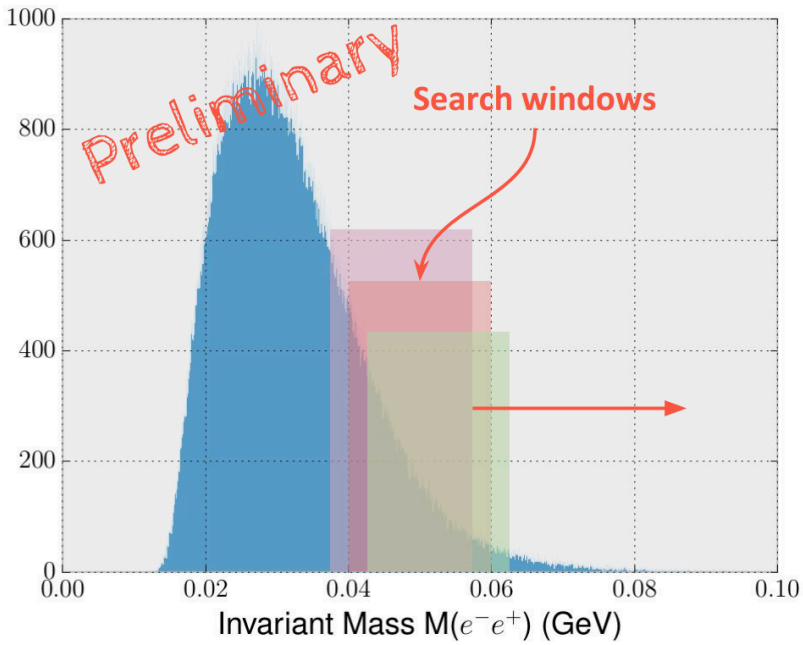


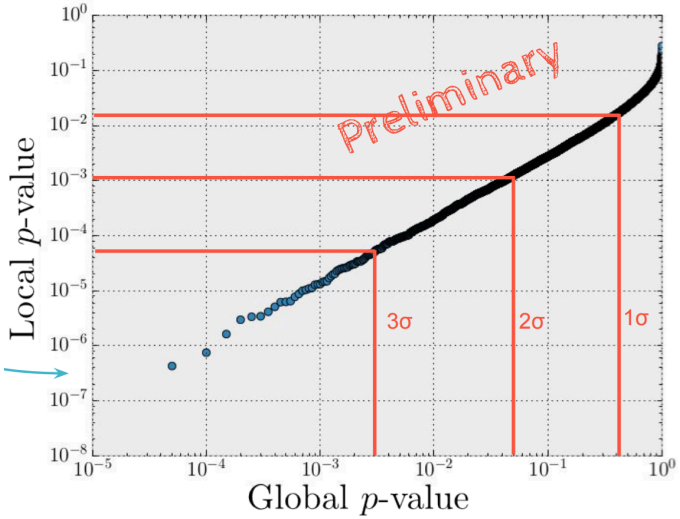
Because the conversion electron is missing there will be a p_t imbalance.



$$(p_t(e^-) - p_t(e^+))/(p_t(e^-) + p_t(e^+))$$

Bump hunt procedure

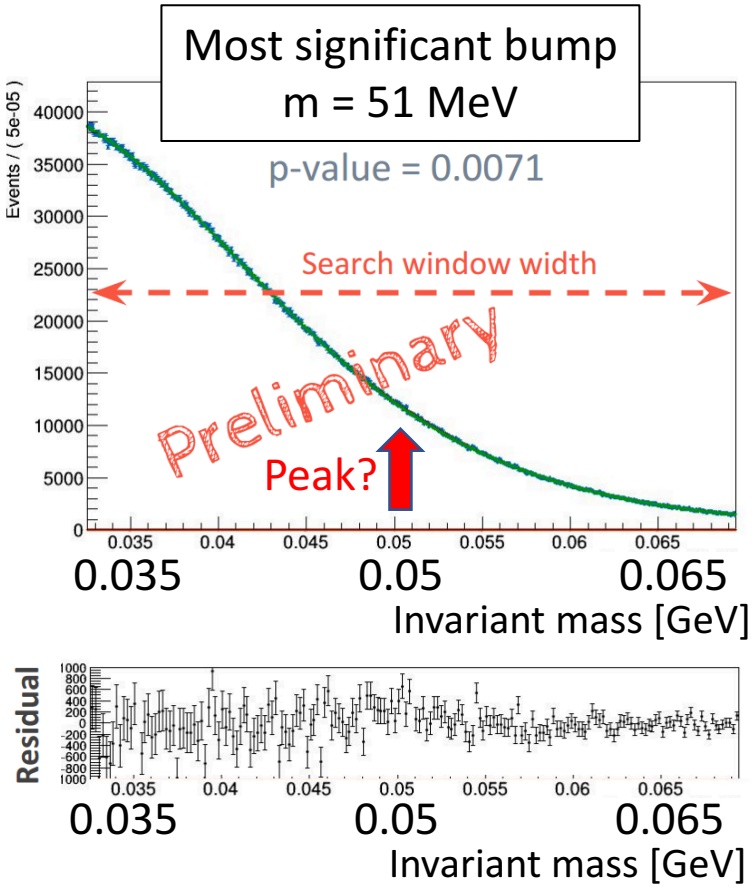


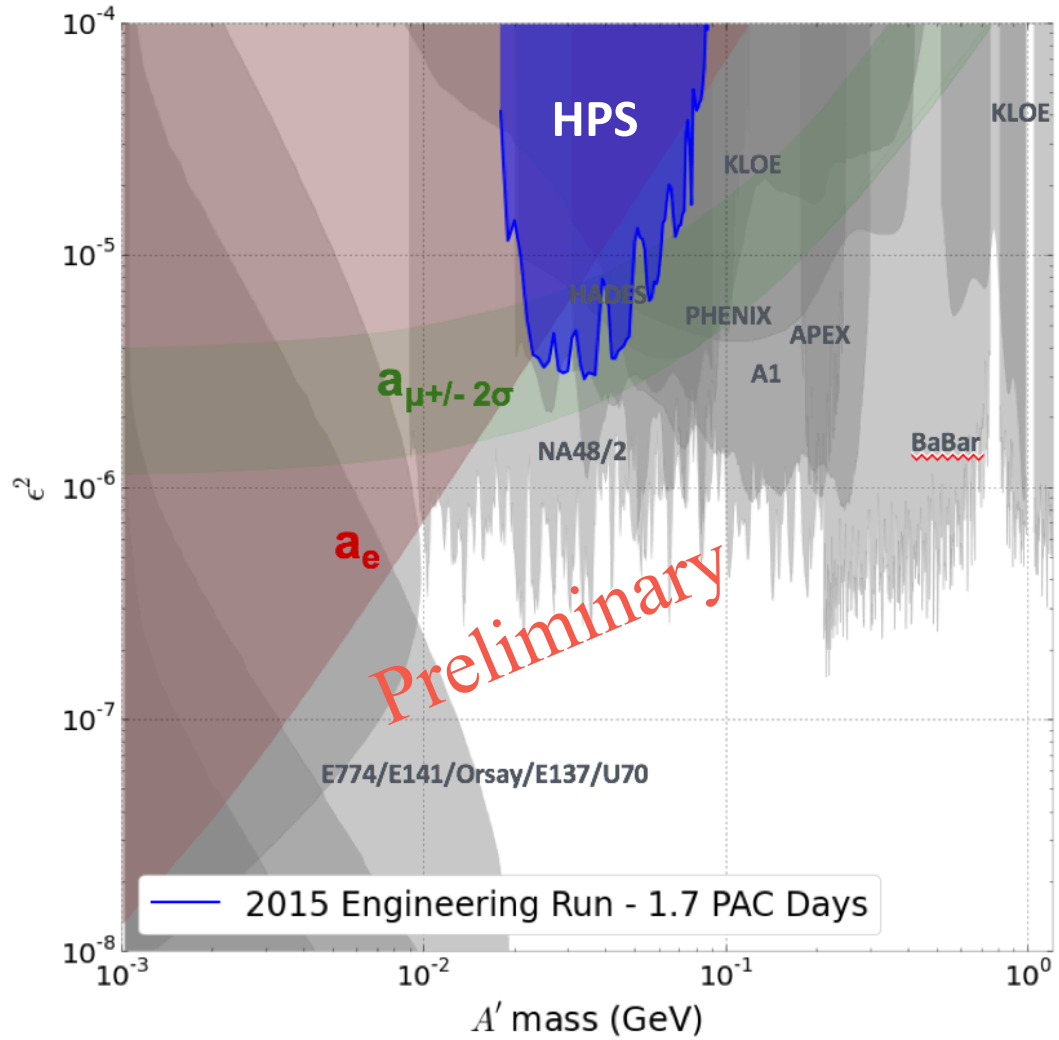


- Fix Gaussian peak width σ_m
- Optimal search window size from pseudo-experiments:
  - 11 σ_m at the edges
  - 17 σ_m in the center
- Scan window in 1 MeV steps from 18 to 95 MeV
- Fit a **Gaussian** plus a **7th order Chebyshev polynomial**
- Likelihood ratio from S+B vs B fits
- Translate the signal upper limit into the coupling-mass phase space

Account for Look Elsewhere Effect!

Bump hunt results





Search for heavy photons with displaced vertices

Procedure:

- Scan in bins of 2.8 σ_m from 20 to 70 MeV
- Fit vertex distribution with **Gaussian** plus **Exponential** to determine zCut, fewer than 0.5 background events beyond
- Either
  - Look for events beyond zCut [discovery!]
  - Calculate expected events beyond zCut (90% CL exclusion region for n > 2.3)

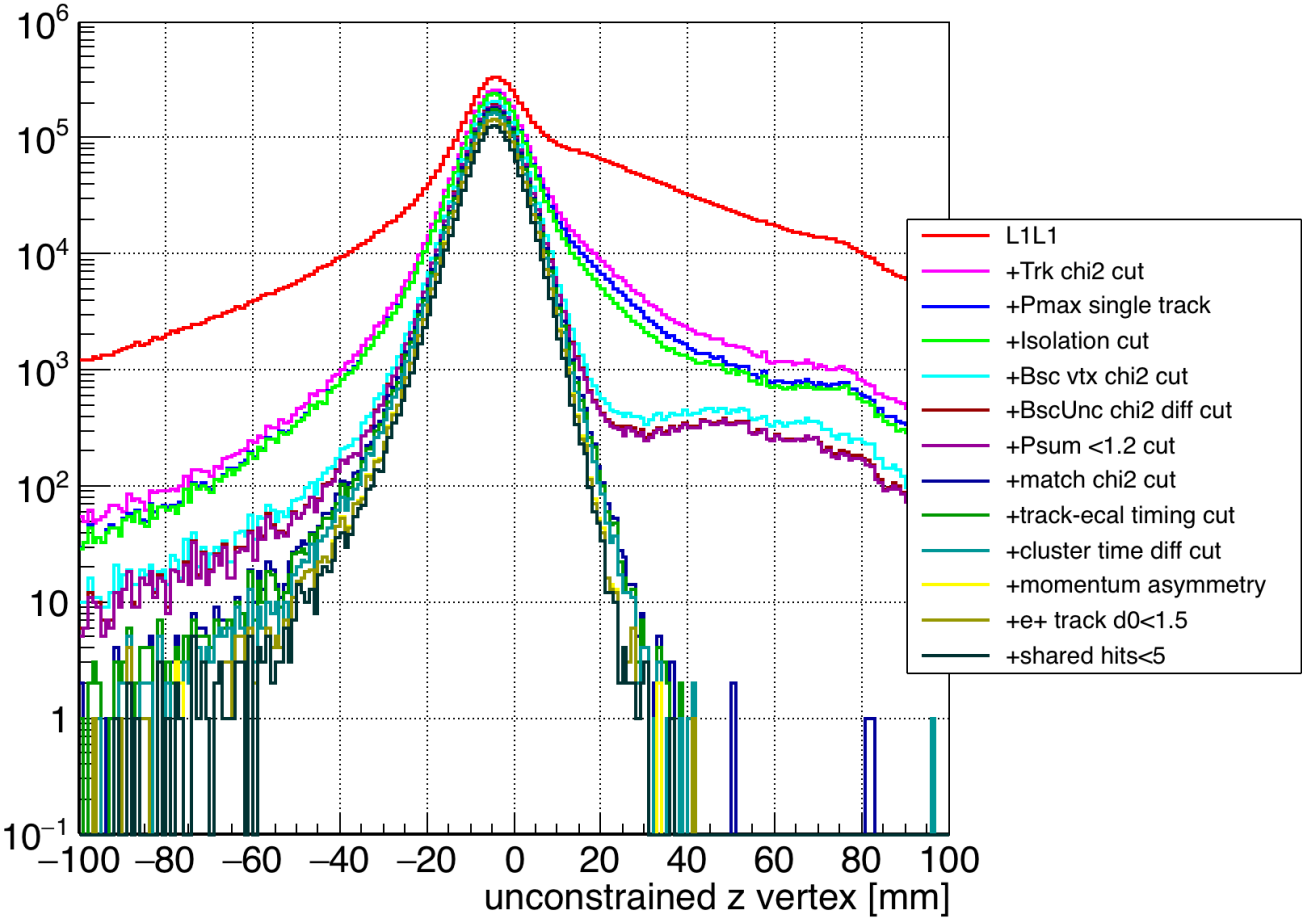
84% A' signal in mass bin

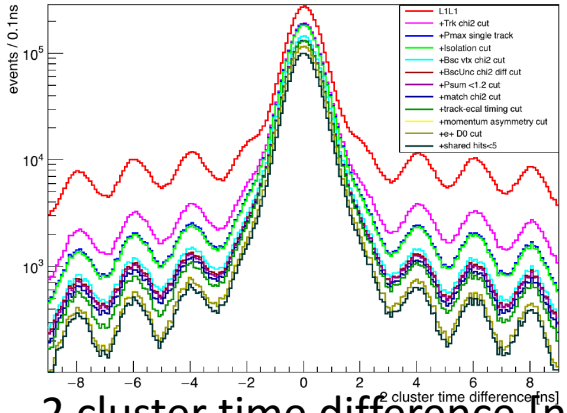
$$S_{bin,zCut} = \underbrace{\left(\frac{N_{rad}}{N_{tot}}\right) N_{bin} \left(\frac{3\pi\epsilon^2}{2N_{eff}\alpha}\right) \left(\frac{m_{A'}}{\delta m_{A'}}\right)}_{\text{A' yield in mass bin}} \epsilon_{bin} \underbrace{\int_{zCut}^{zMax} \frac{e^{-ztgt-z/\gamma c\tau}}{\gamma c\tau} \epsilon_{vtx}(z, m_{A'}) dz}_{\text{Fraction of events beyond zCut we can reconstruct (includes inefficiencies and acceptance effects)}}$$

Displaced vertex event selection

Cuts:

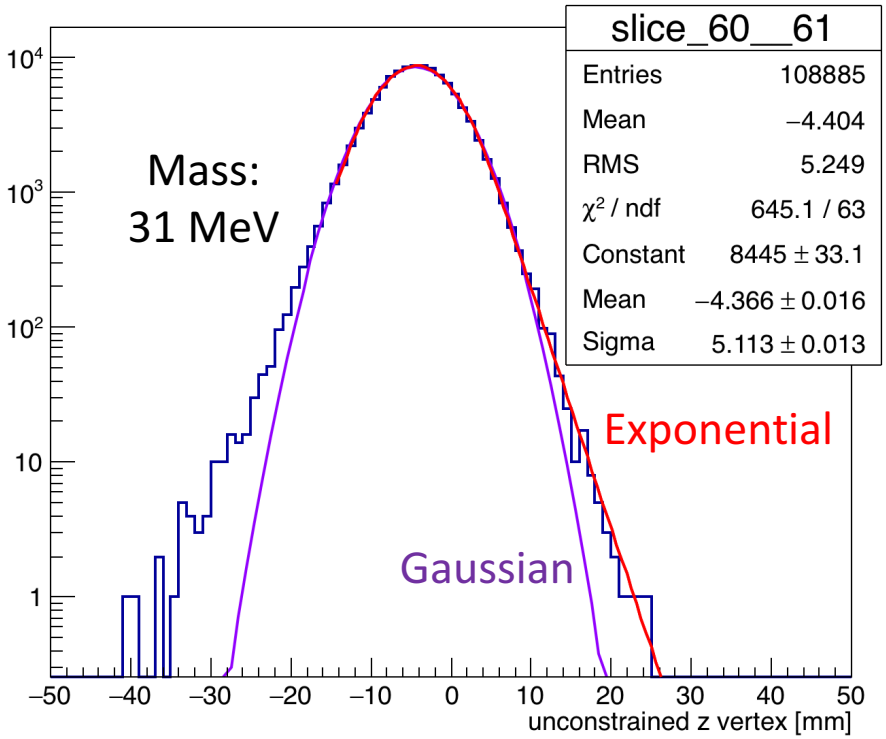
- Track Quality
- Unconstrained Vertex Quality
- Timing (2 beam buckets)
- Track-Ecal cluster matching
- Isolation cut
- Difference between Beamspot constrained and Unconstrained vertex quality

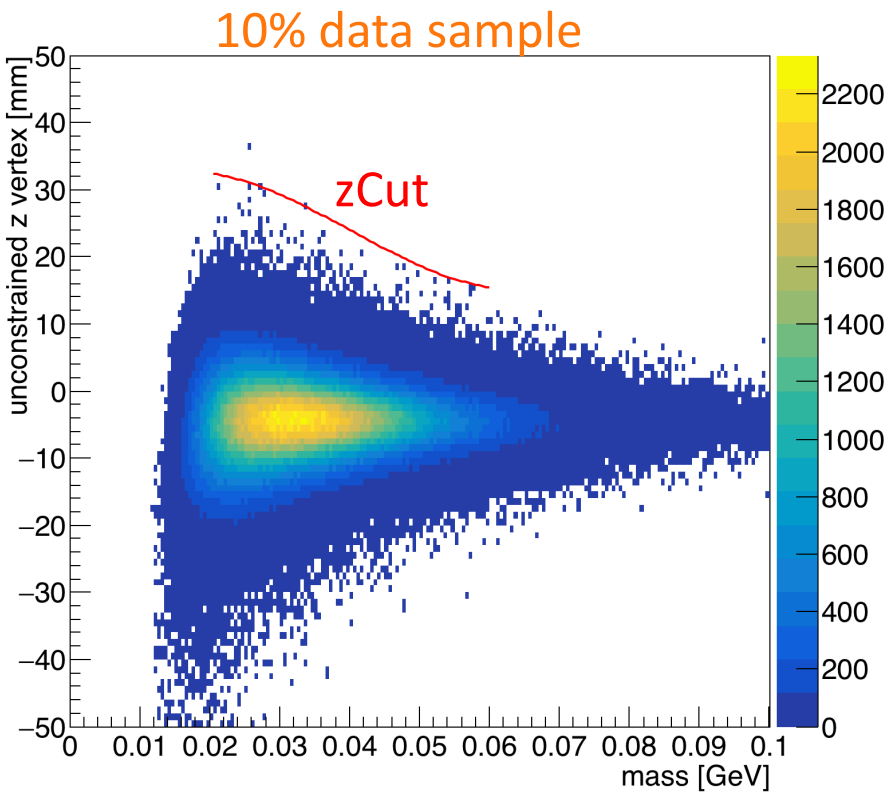




2 cluster time difference [ns]

Searching for A' with detached vertex





$$F(z < b) = Ae^{-\frac{(z - z_{mean})^2}{2\sigma^2}}$$

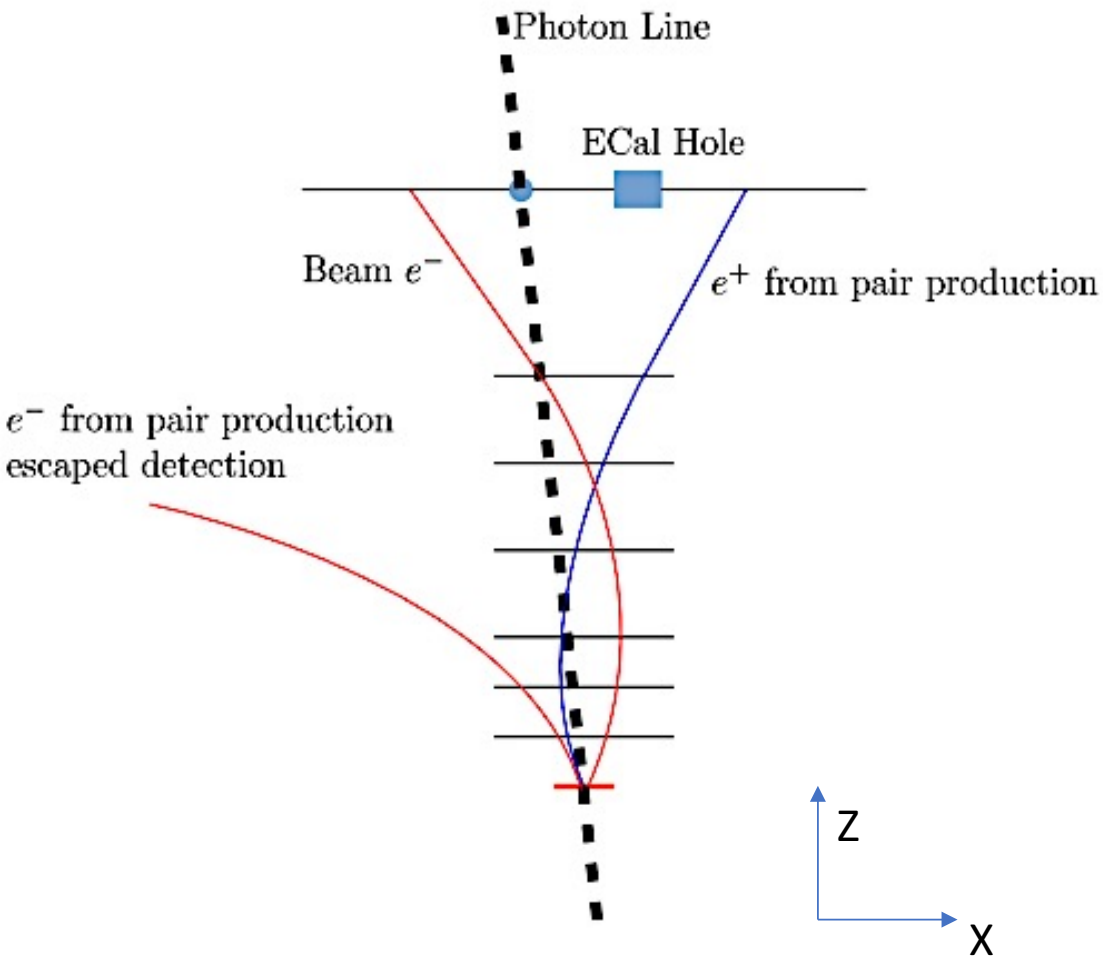
$$F(z > b) = Ae^{-\frac{b^2}{2\sigma^2} - \frac{z - z_{mean} - b}{l}}$$

Validated vertex procedure

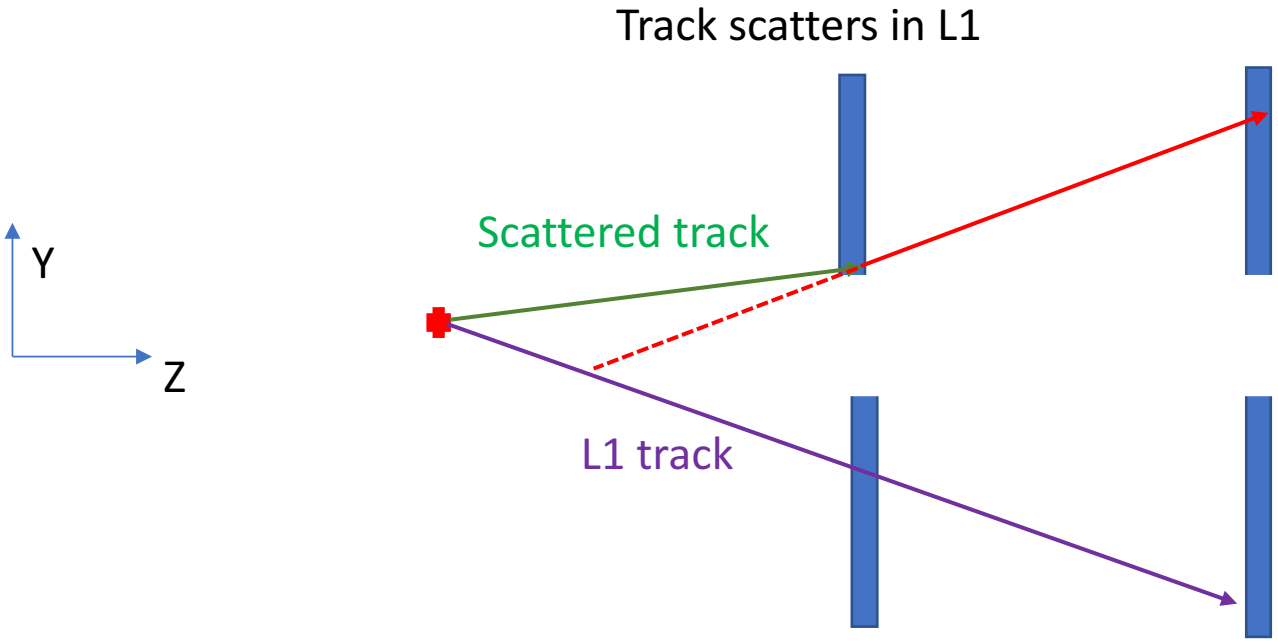
Extra background at high z

Backgrounds from wide angle bremsstrahlung

$e^-\gamma \rightarrow e^-e^+e^-$



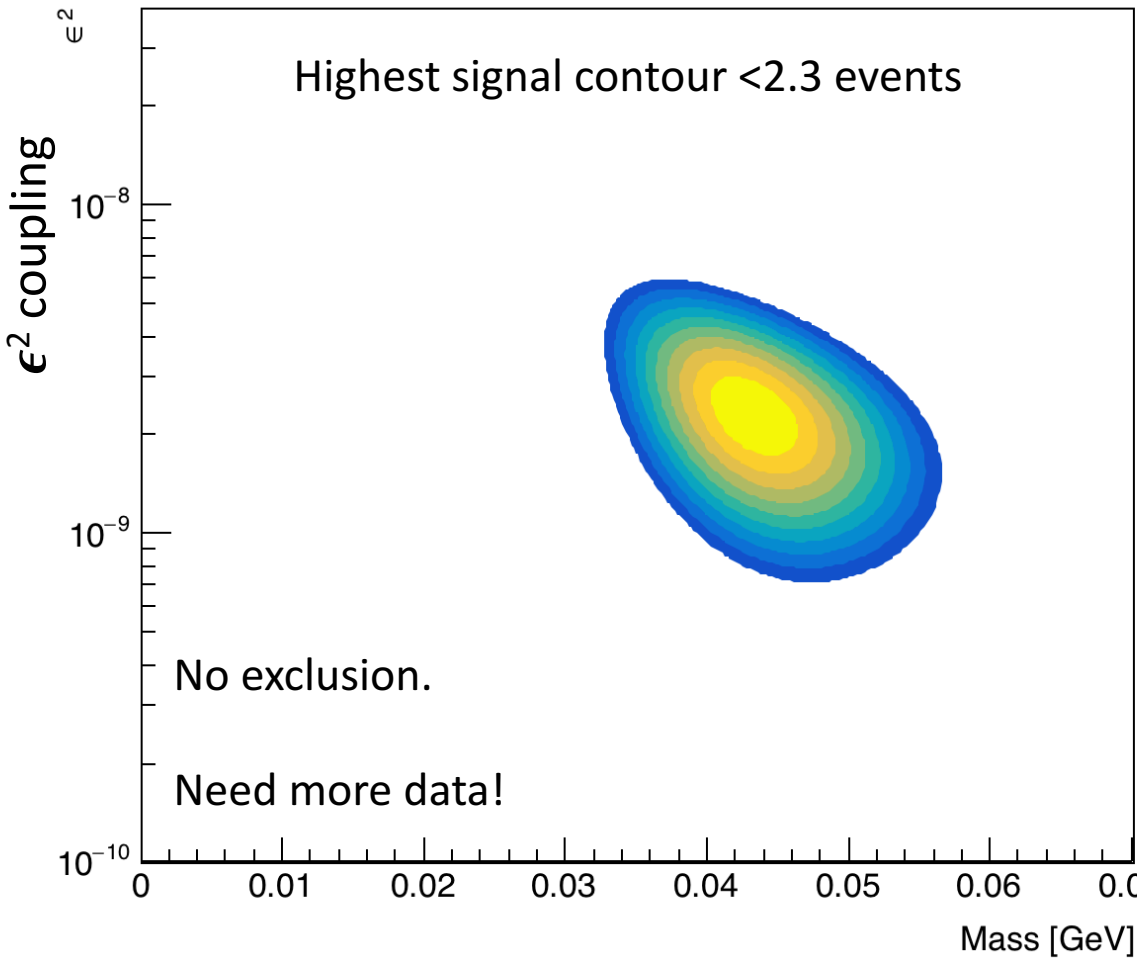
Backgrounds from scattering



Reduce backgrounds:

- Layer 1 requirement for both tracks
- Hit isolations in first two layers

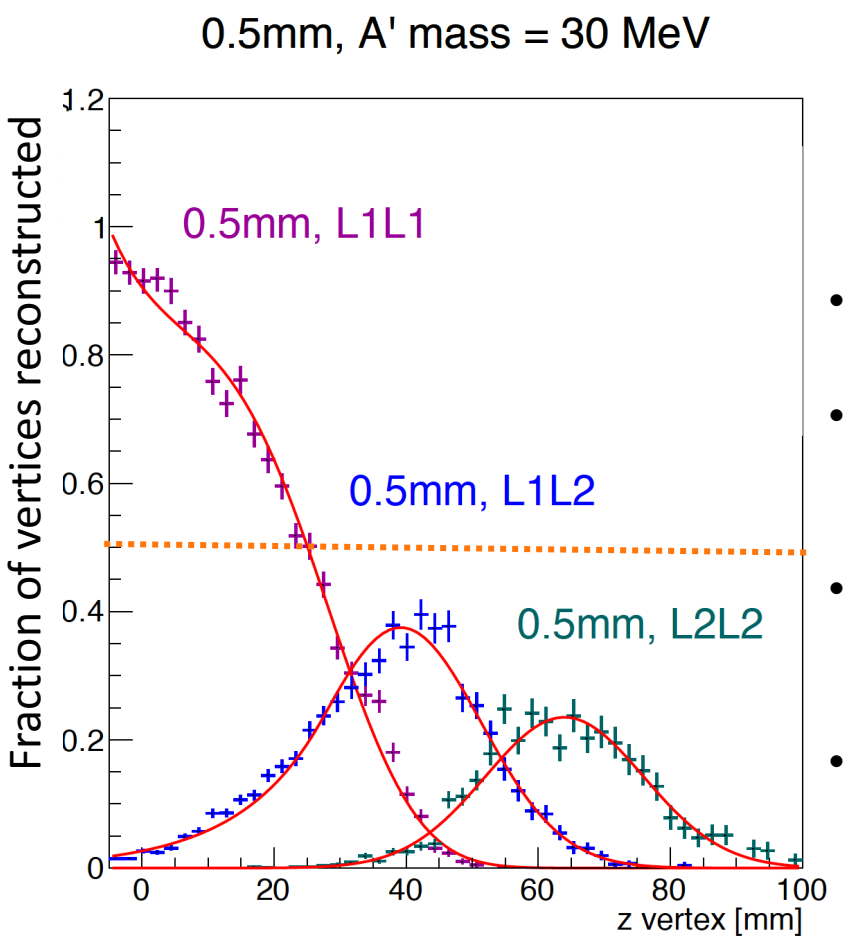
Expected signal count:
SVT at 0.5 mm, both tracks through Layer 1

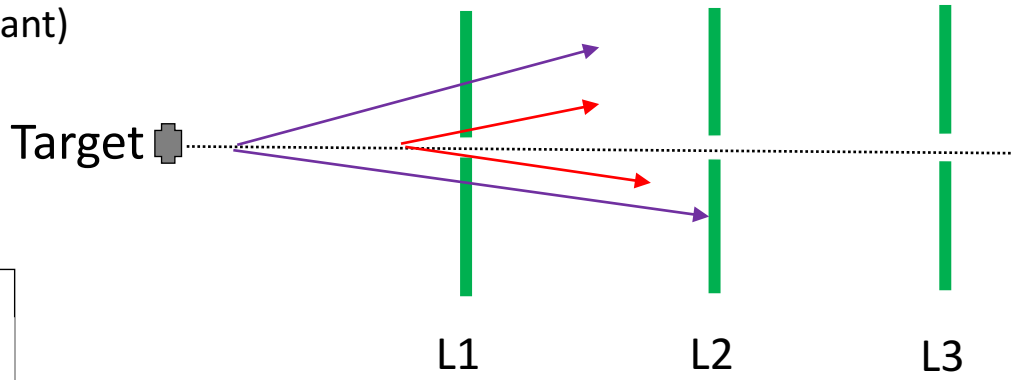


Why didn't we exclude anything?

Separate datasets from 1 GeV Engineering Run:

- Both tracks pass through 1st layer (significant)
- One track misses 1st layer
- Both tracks miss 1st layer



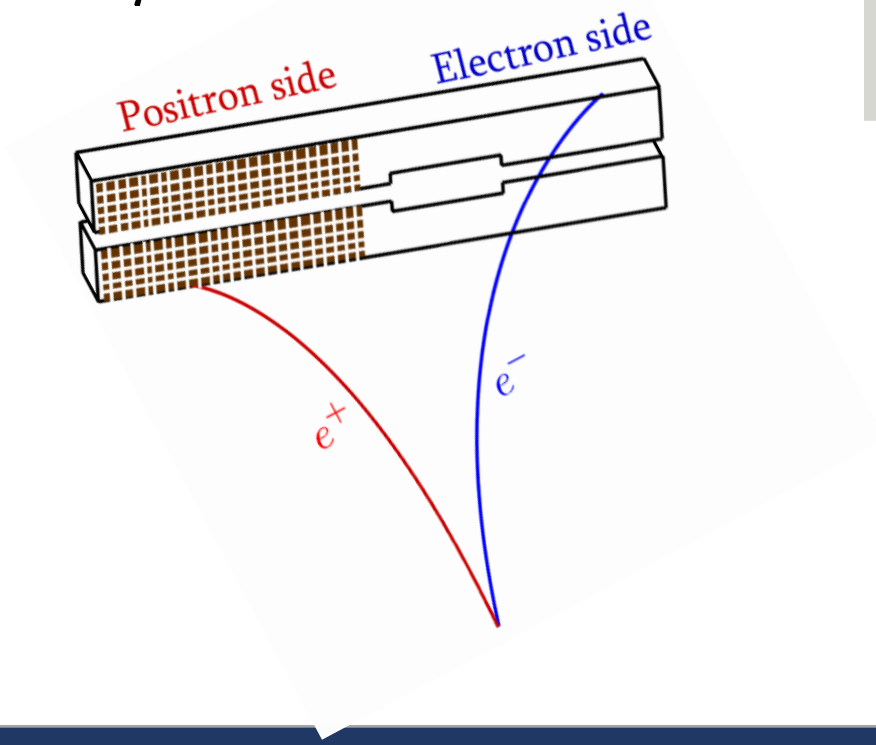


- Only two days of beam time
- Proposal assumed 0.5 constant efficiency to 10 cm
- Initial projections omitted beam hole in calorimeter
- Need more data!!

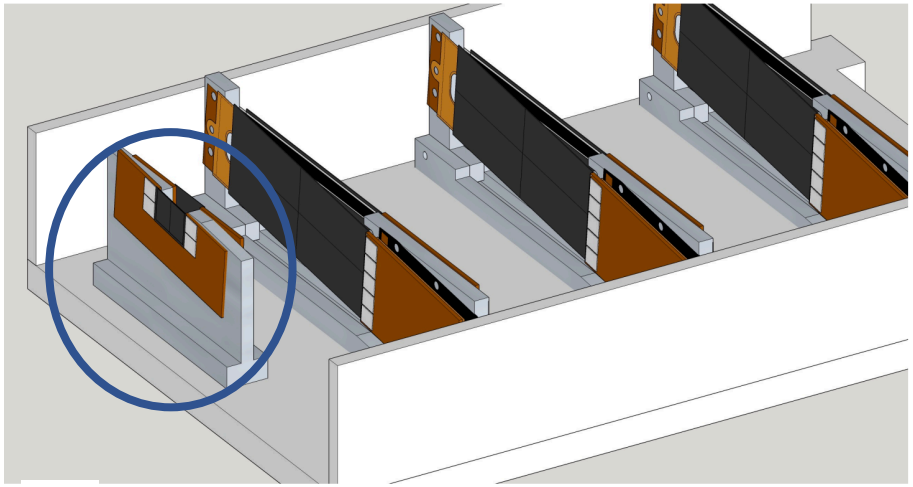
Future upgrades

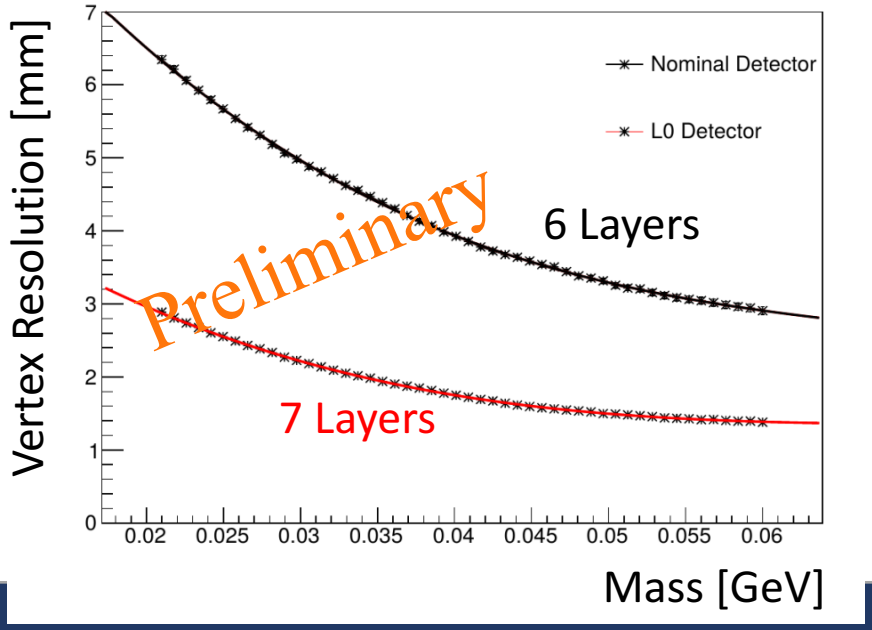
Hodoscope on positron side of Ecal:

- Keeps events where e- lost in hole
- Reduce WAB triggers from $e^{-}\gamma$



Add SVT layer at 5cm





Summary

Great “table top” nuclear physics experiment!

Successful running

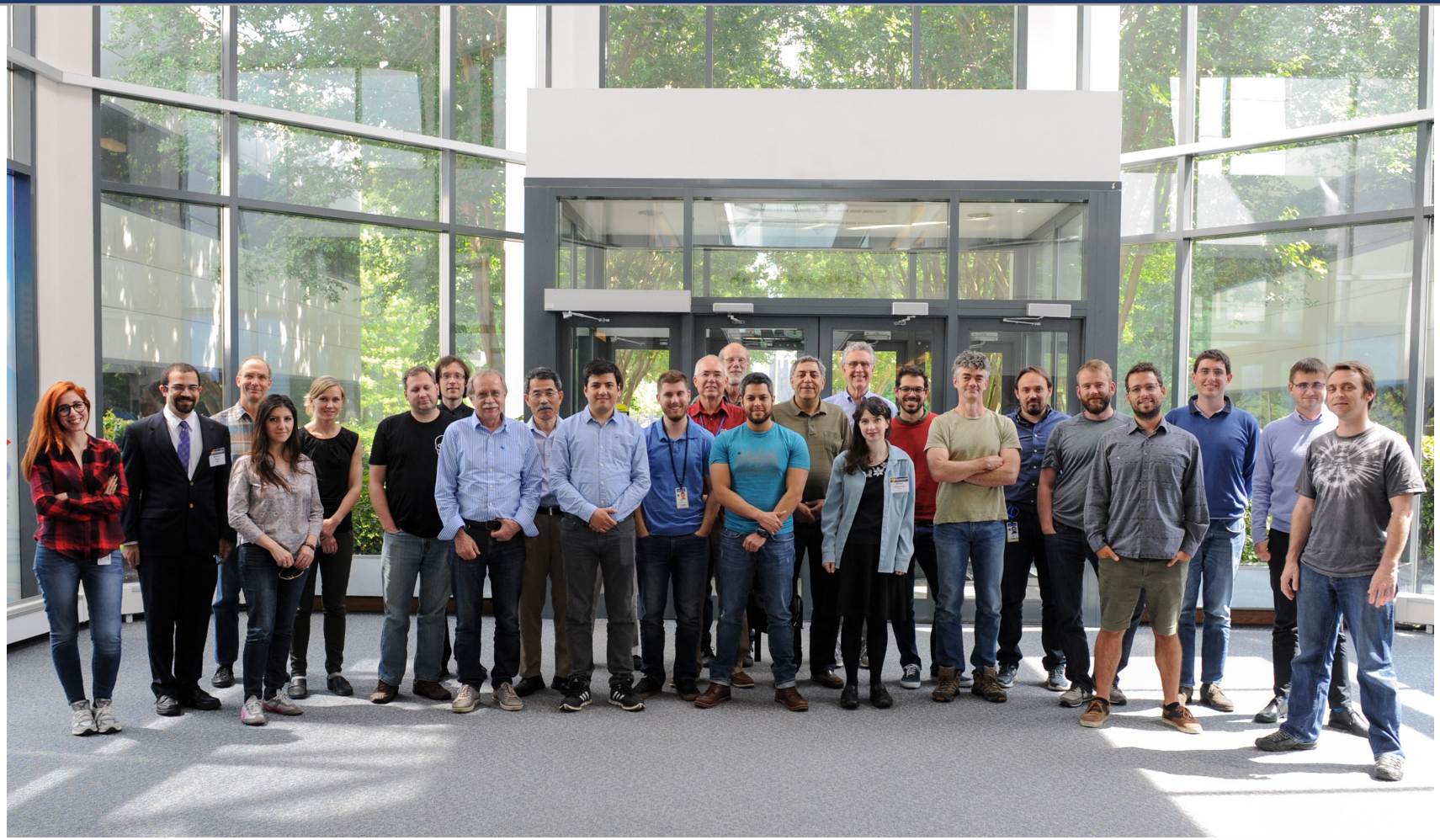
- Engineering Run at 1GeV in 2015: commissioned detectors, first analyses
- Physics Run at 2.3 GeV in 2016: analyses underway

Recently released bump hunt results
Paper in progress

NIM articles accepted

- Beamline: **arXiv:1612.07821**
- Electromagnetic calorimeter: **arXiv:1610.04319**

Upgrade planning in progress
Future running in 2018!



Thanks!

HPS Collaboration

May 3 - 5, 2017

Jefferson Lab • Newport News, VA