Shining Light on Dark Matter
The Heavy Photon Search Experiment

Omar Moreno
on Behalf of the Heavy Photon Search Collaboration

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz
omoreno1@ucsc.edu

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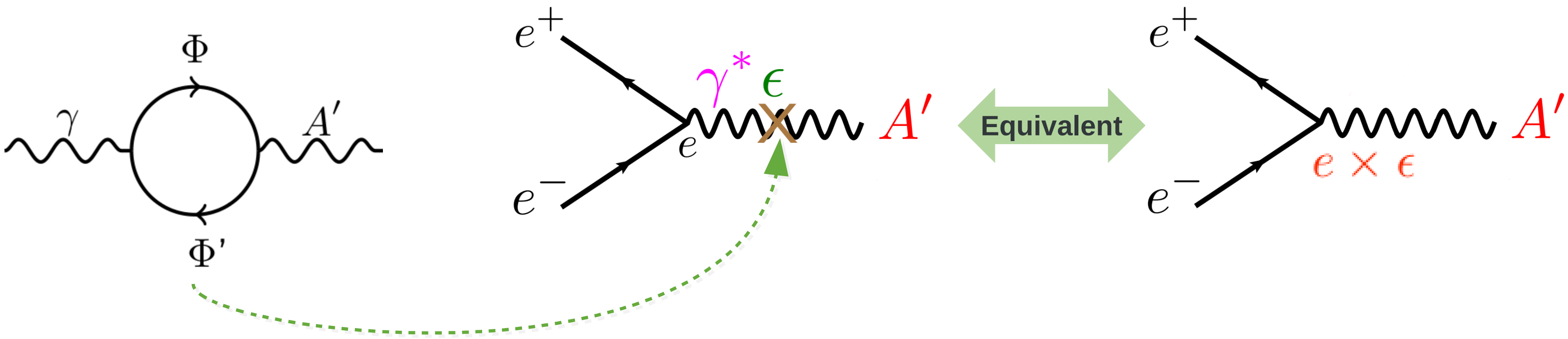
What is a "Dark Photon"?

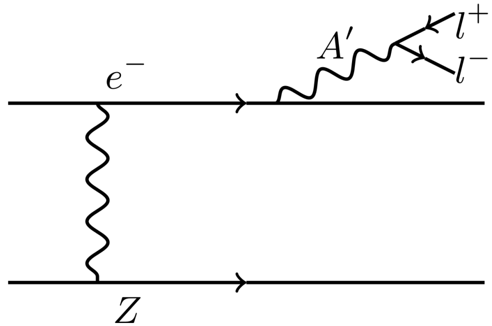
- Consider a theory in which nature contains an additional Abelian gauge symmetry, $U(1)_D$
  [Holdom, Phys. Lett.B166, 1986]

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

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

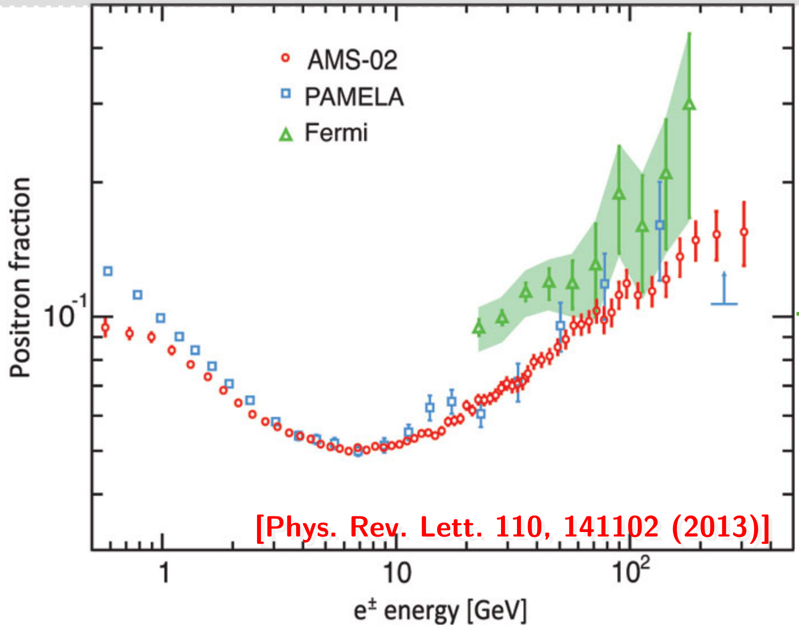


- Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets subsequently decaying to $l+l-$



Why Search for a Dark Photon?

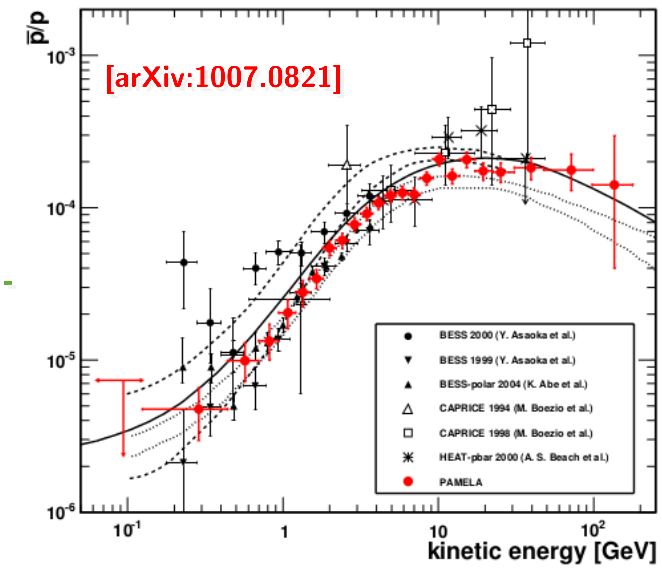
PAMELA, Fermi and AMS have observed an excess in the positron fraction



[Phys. Rev. Lett. 110, 141102 (2013)]

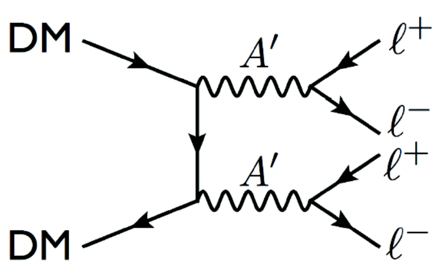
But ...

No excess anti-protons are observed

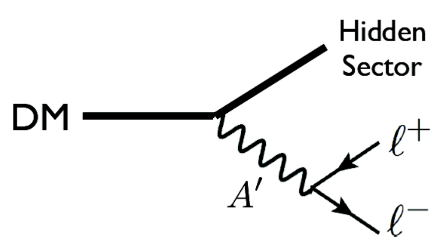


[arXiv:1007.0821]

If dark matter annihilates or decays to an A' it may explain these anomalies

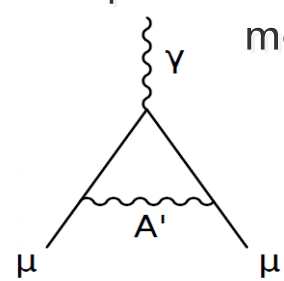


[Arkani-Hamed et. al., Pospelov & Ritz]

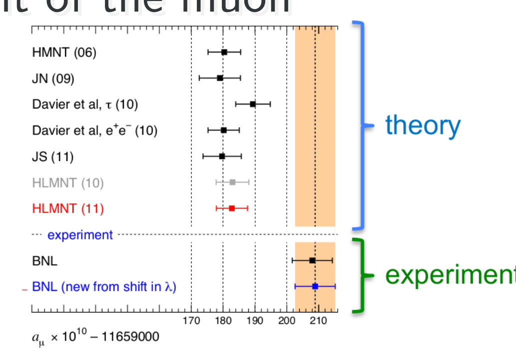


[Volansky & Ruderman, Essig, Schuster, Toro]

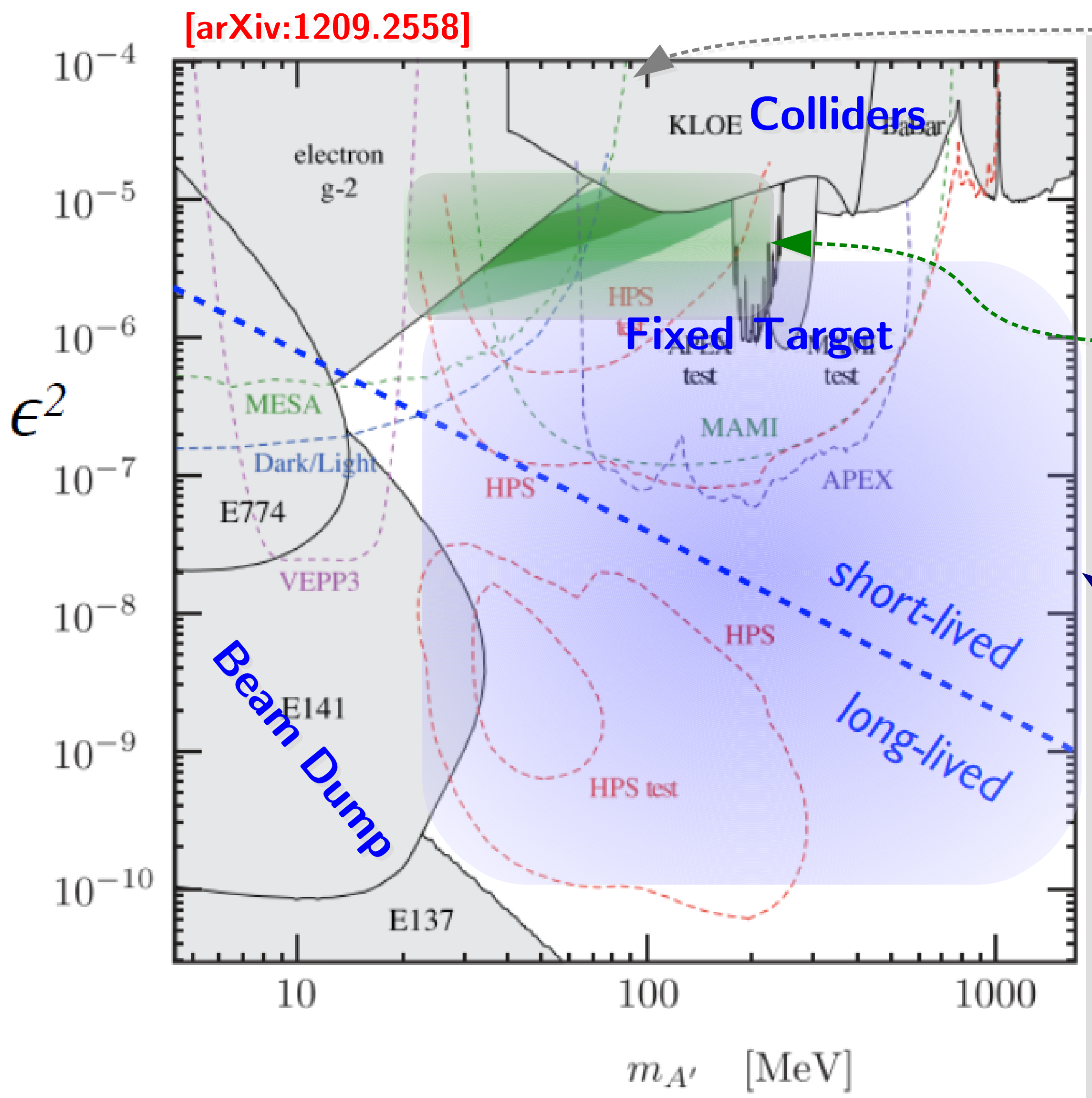
A dark photon could also provide an explanation for the anomalous magnetic moment of the muon



[hep-ex/0602035]



Where Do You Search for a Dark Photon?



Present limits set by beam dump, fixed target test runs and collider experiments

Favored region which could account for the μ g-2 anomaly

Favored region if the excess in the cosmic ray positron flux is due to dark matter annihilating to dark photons

$\varepsilon^2 \sim 10^{-4} - 10^{-10}$

$m_{A'} \sim$ MeV – GeV

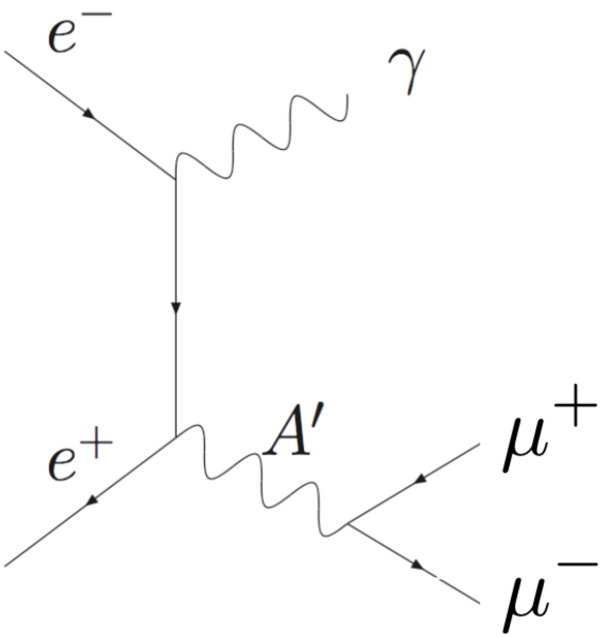
From cosmic results

$m_{A'} < 2\, m_p = 2$ GeV

How Do You Search for a Dark Photon?

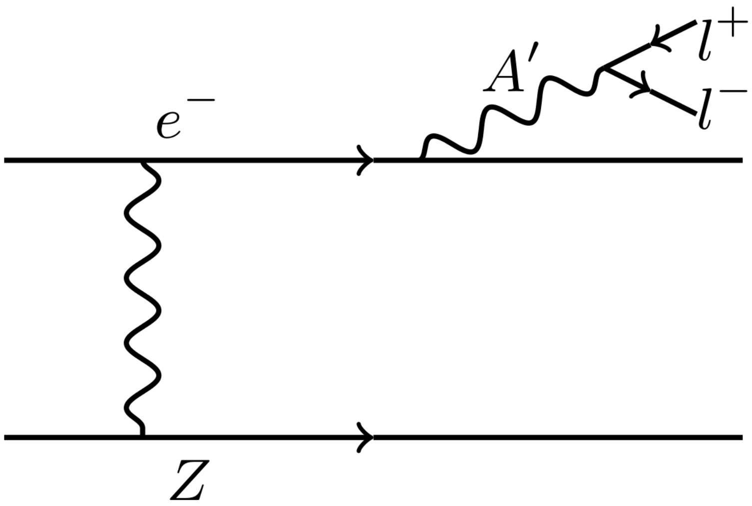
[Bjorken, Essig, Schuster, Toro, Phys. Rev. D80 (2009) 075018]

Collider



vs.

Fixed Target



Low Energy

$$\sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2} \sim \mathcal{O}(10 \text{ fb})$$

High luminosity

~$O(100)$ events/month

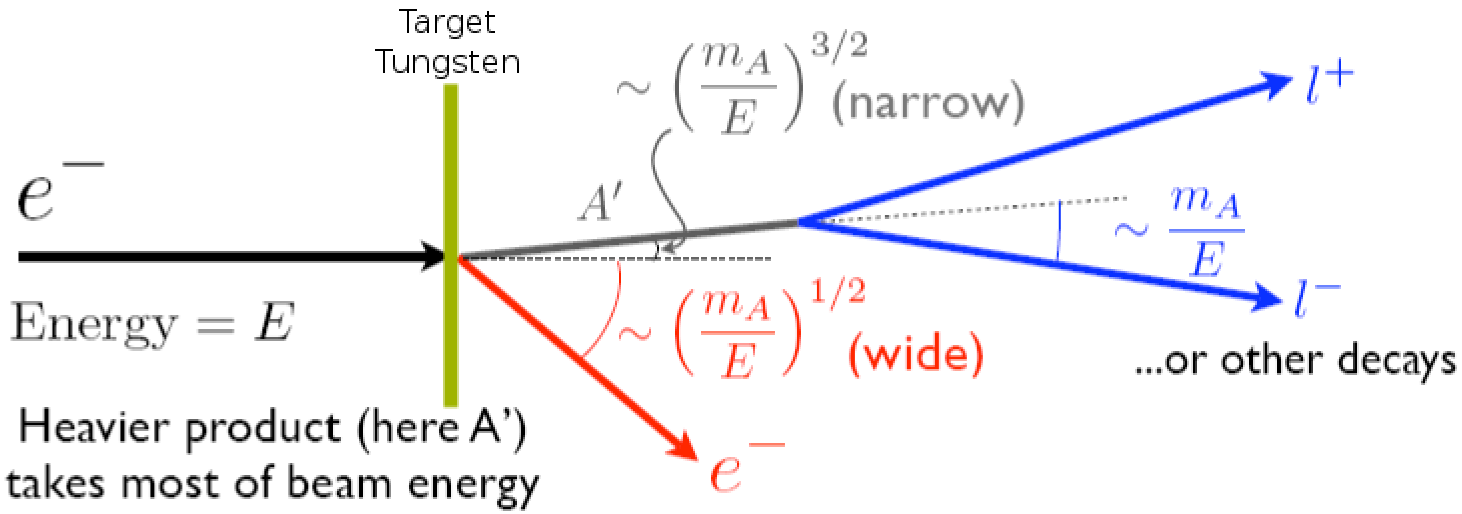
$$\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2} \sim \mathcal{O}(10 \text{ pb})$$

~$O(1000)$ events/day

… But much higher backgrounds

Fixed target experiments are ideal *A′* hunting grounds!

A' Fixed Target Kinematics

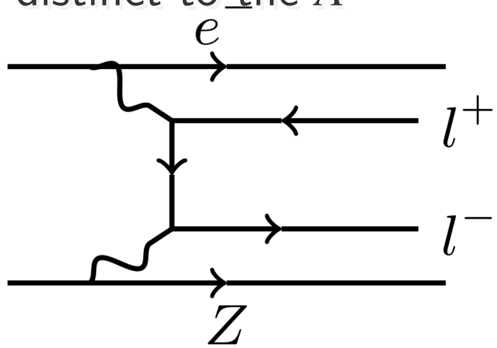


- Even though A' particles are produced by a process analogous to ordinary photon bremsstrahlung, the rate and kinematics differ in several key ways
  - The A' productions cross section is suppressed relative to photon bremsstrahlung by a factor of $m_e^2 \varepsilon^2 / m_{A'}^2$
  - **The A' is produced very forward**, opening angle of it's decay products is ~ $m_{A'}/E_{beam}$
  - The A' will take most of the incident beam energy
  - Long lived A' will have a displaced vertex $\rightarrow$ Will help cut down prompt backgrounds

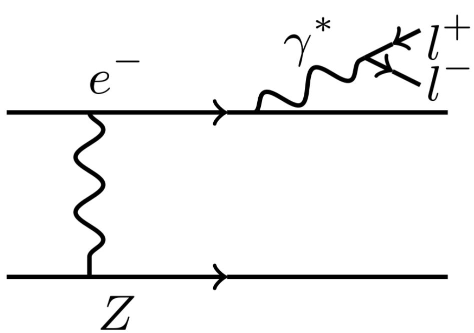
A' Fixed Target Backgrounds

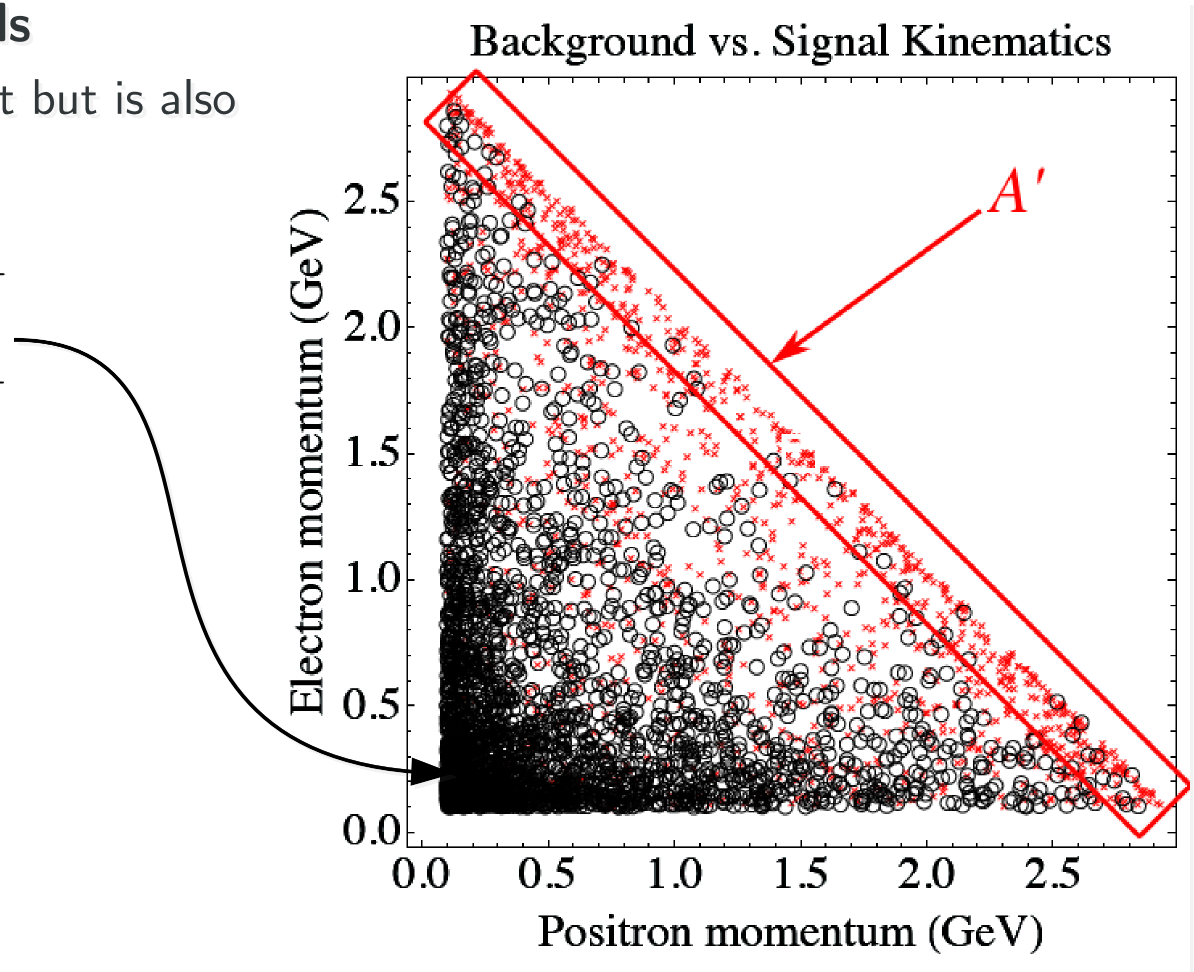
QED Trident Backgrounds

- Bethe-Heitler background is dominant but is also kinematically distinct to the A'



- Radiative background is irreducible



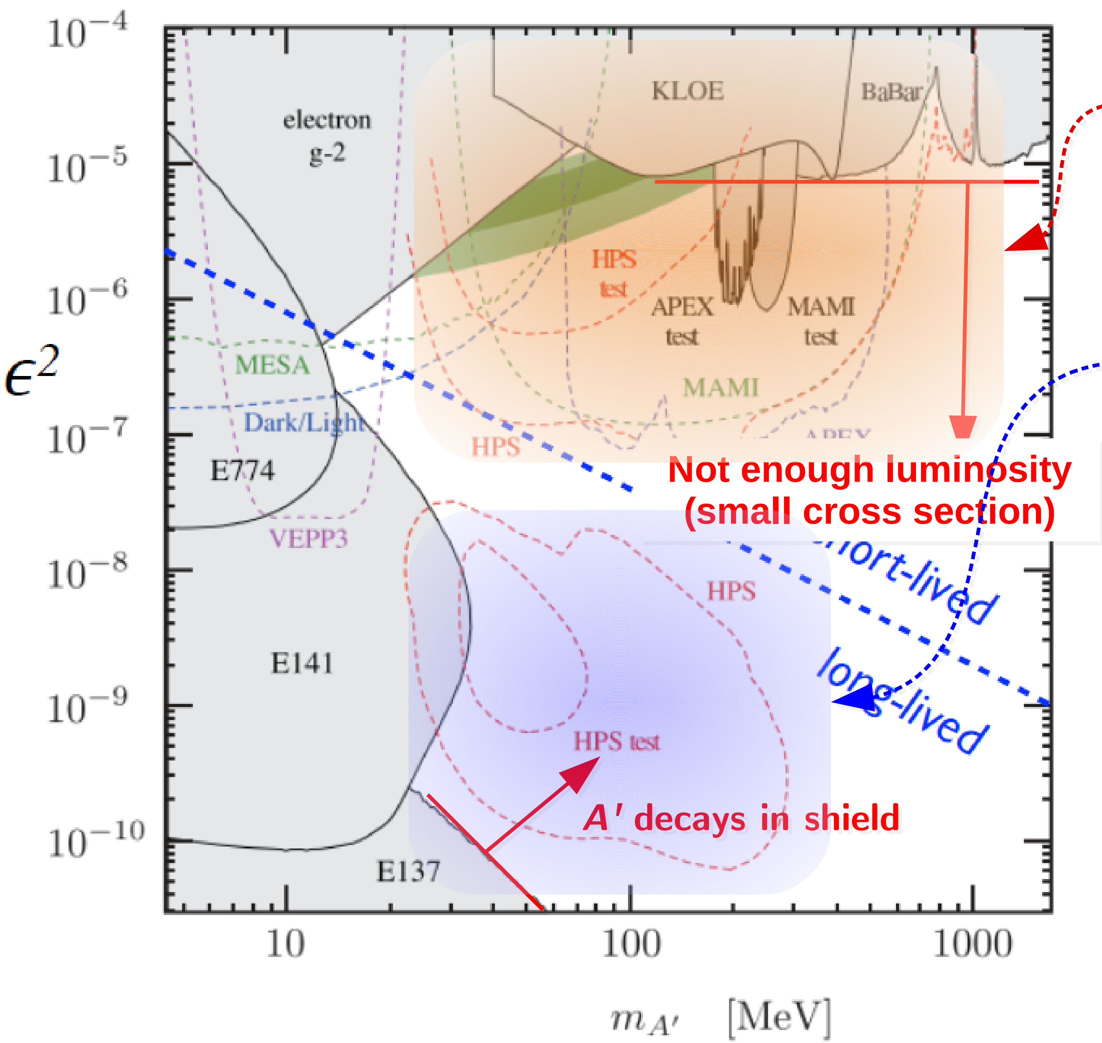


Beam Backgrounds

- Forward production of A' necessitates placing the detector very close to the beam making beam backgrounds an issue
  - Coulomb scattering in the target
  - Secondary particle production: bremmsthrahlung and delta-rays
  - Pair conversion of bremmsthrahlung photon

HPS Design Considerations

- Maximizing the acceptance for A' requires placement of the detector as close to the beam as possible → Occupancy will be very high so a fast readout and trigger system will be required



Bump Hunt

Determination of the invariant mass of the A' decay products → Good mass (momentum) resolution

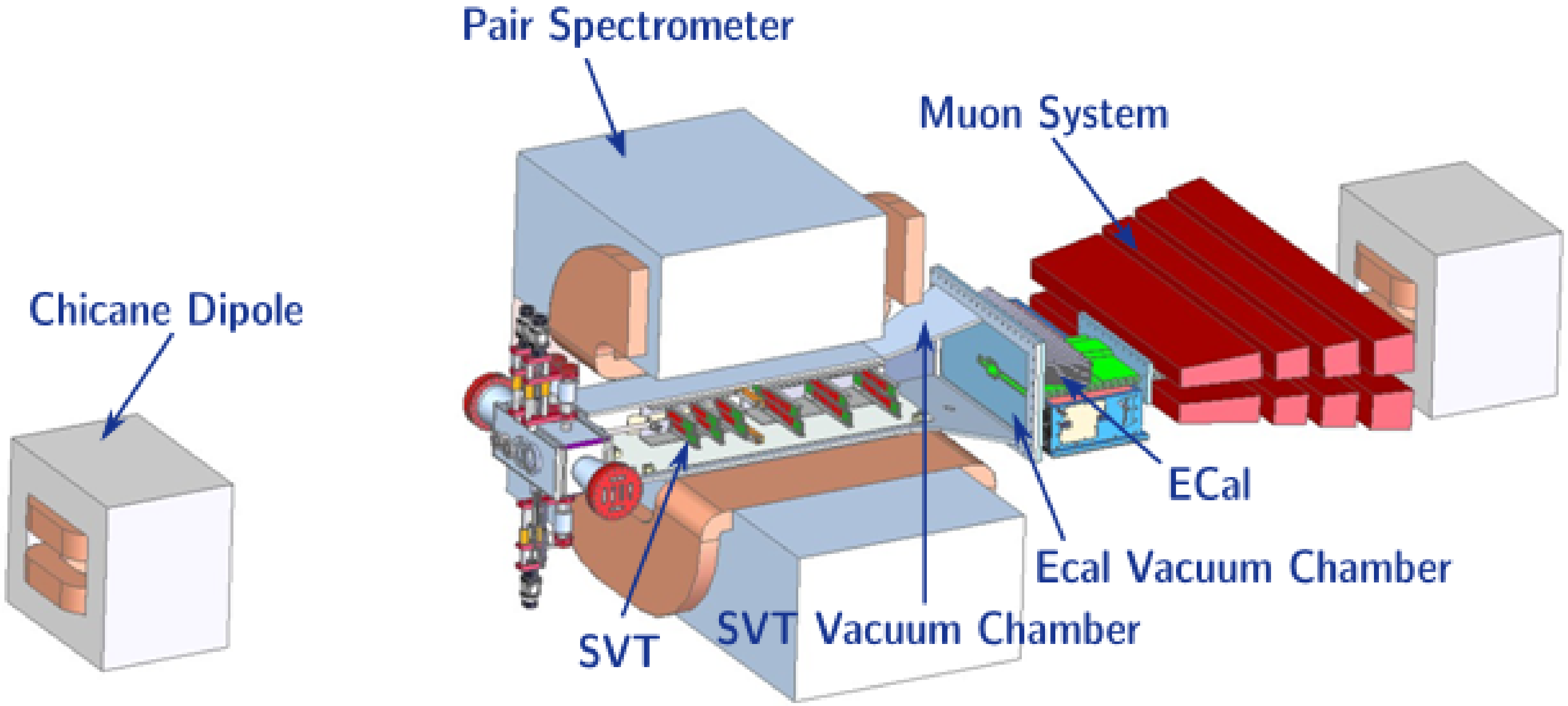
Displaced Vertex + Bump Hunt

Distinguishing A' decay vertices as Non-prompt → Good vertex resolution

- Both will 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 cross section will require a high luminosity beam

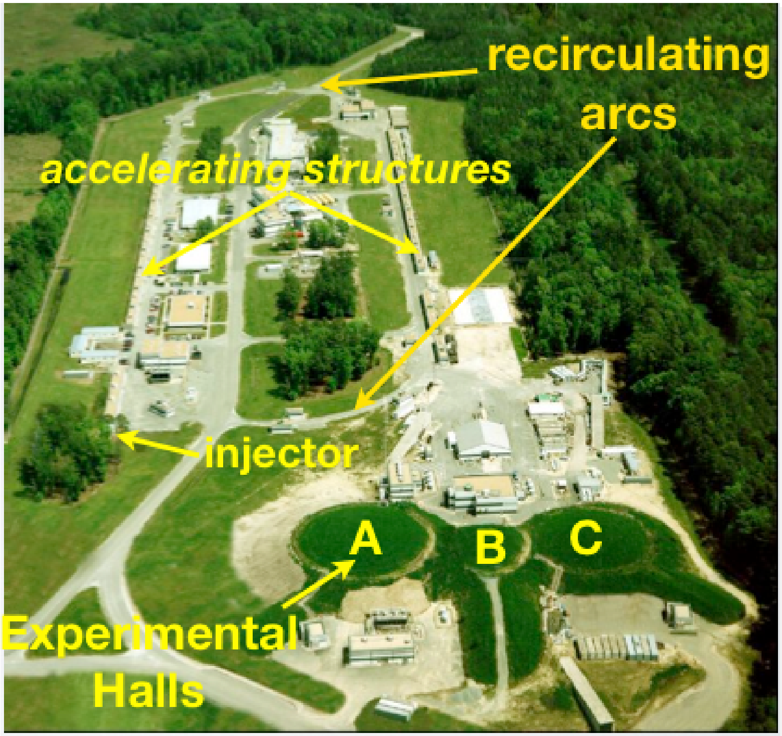
The HPS Experiment

- The HPS Experiment will make use of a compact large acceptance forward spectrometer consisting of a silicon microstrip tracker and lead tungsten electromagnetic calorimeter → A muon ID system will be included in an upgrade



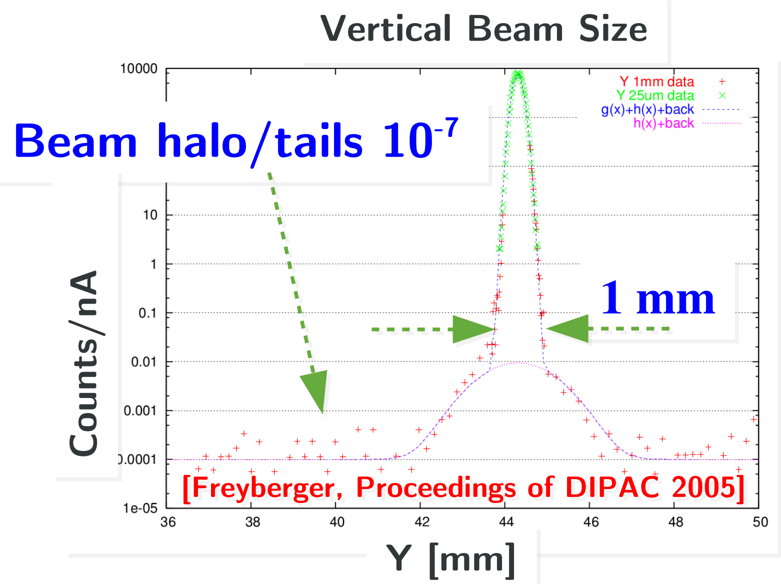
- Si tracker will be placed in vacuum in order to avoid backgrounds due to beam gas interactions
- The HPS detector will be split in half, creating a "dead zone", in order to avoid the "Wall of Flame" i.e. beam electrons that have been dispersed by the magnet
- The tracker planes are retractable allowing the dead zone to be adjusted

CEBAF @ Jefferson Lab



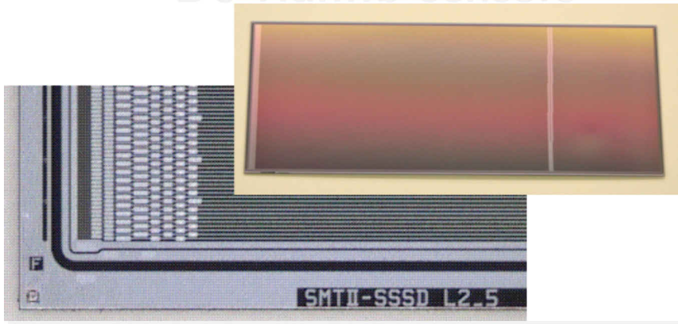
Continuous **E**lectron **B**eam **A**ccelerator **F**acility

- Simultaneous delivery of electron beams at different energies and intensities to three experimental halls
- Energy upgrade currently underway and expected to be completed in 2014
- E_{beam} = n x 2.2 GeV, n < 6 up to a maximum of 11 GeV
- Beam delivery is nearly continuous: 2 ns bunch structure
- Able to provide small beam spot which will help improve vertexing



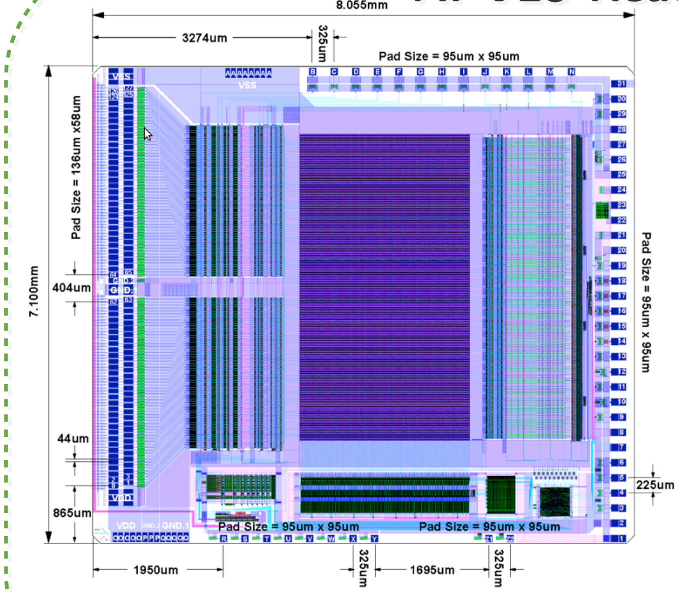
Silicon Vertex Tracker

D0 RunIIb sensors



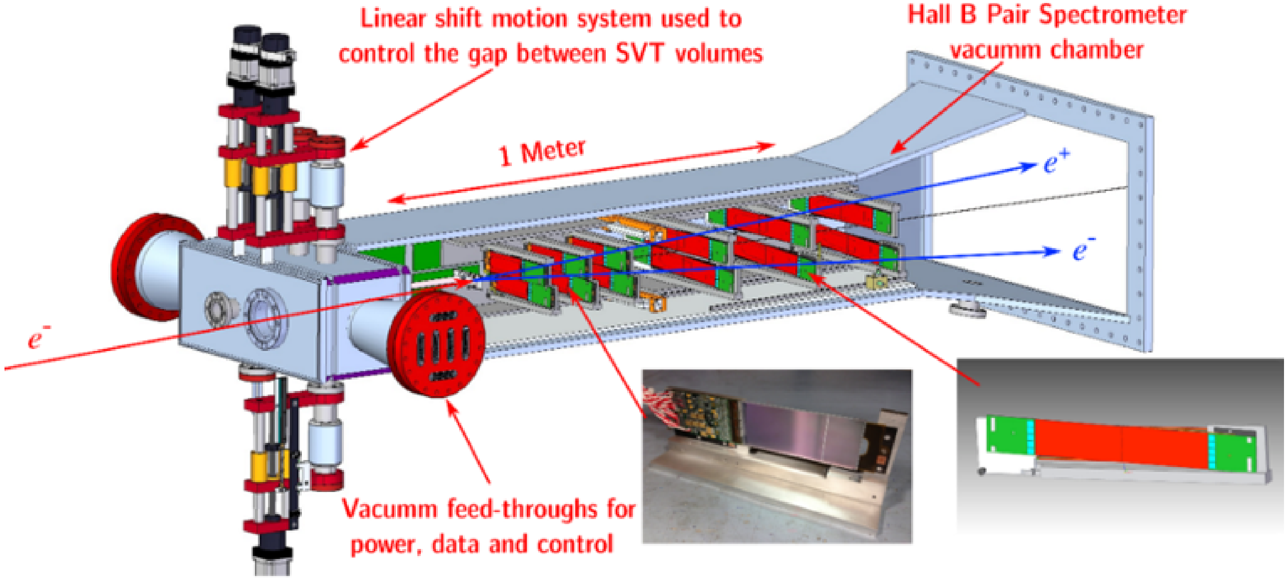
Cut Dimensions (L × W)	100 mm × 40.34 mm
Active Area (L × W)	98.33 mm × 38.34 mm
Readout (Sense) Pitch	60 μm (30 μm)
# Readout (Sense) Strips	639 (1277)
Breakdown Voltage	> 350 V
Defective Channels	< 1%

APV25 Readout Chip



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

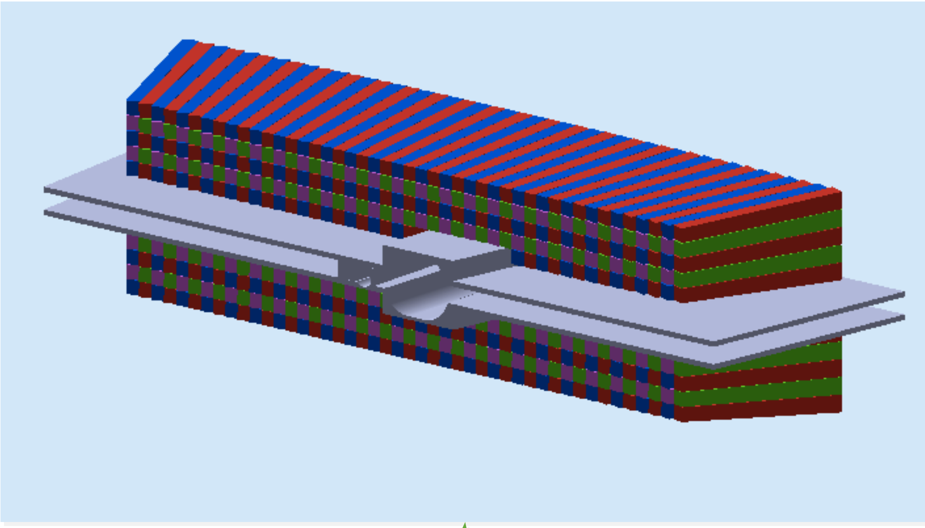
- 40 MHz nominal readout, 50 MHz possible
- Low noise: S/N > 25
- High radiation tolerance
- "Multi-peak" readout
- t_0 resolution approx. 2 ns will help reduce pileup

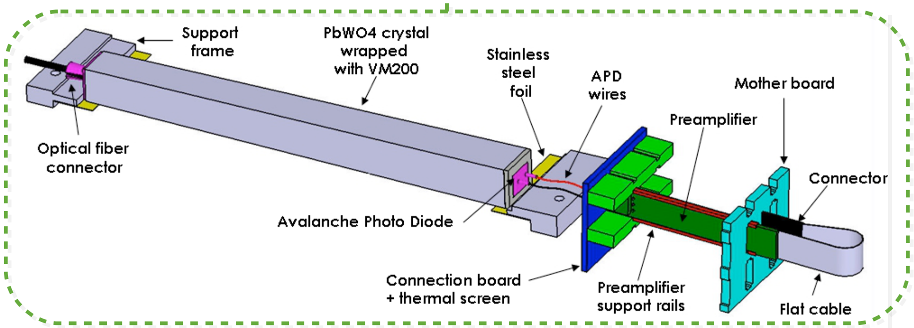


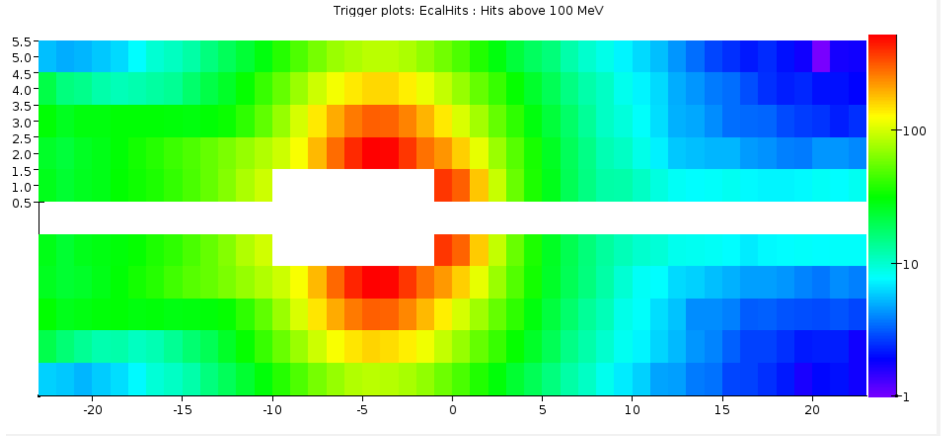
- Thin layers in order to reduce multiple scattering ($0.7\%X_0$/layer)
- Layers 4-6 are double width in order to match calorimeter acceptance
- Total of 36 sensors & hybrids
- 180 APV25 chips
- 23004 channels

Ecal

- Comprised of 460 PbWO4 crystals
- Used for triggering and electron ID
- FADC readout at 250 MHz $\rightarrow$ allows for a narrow trigger window (8 ns)
- FPGA based trigger selection (Two clusters along with some constraints on their energy and geometry) reduces background trigger rate from 3 MHz to 27 kHz
- Trigger and DAQ capable of a rate of > 50 KHz







HPS Experimental Reach

2014

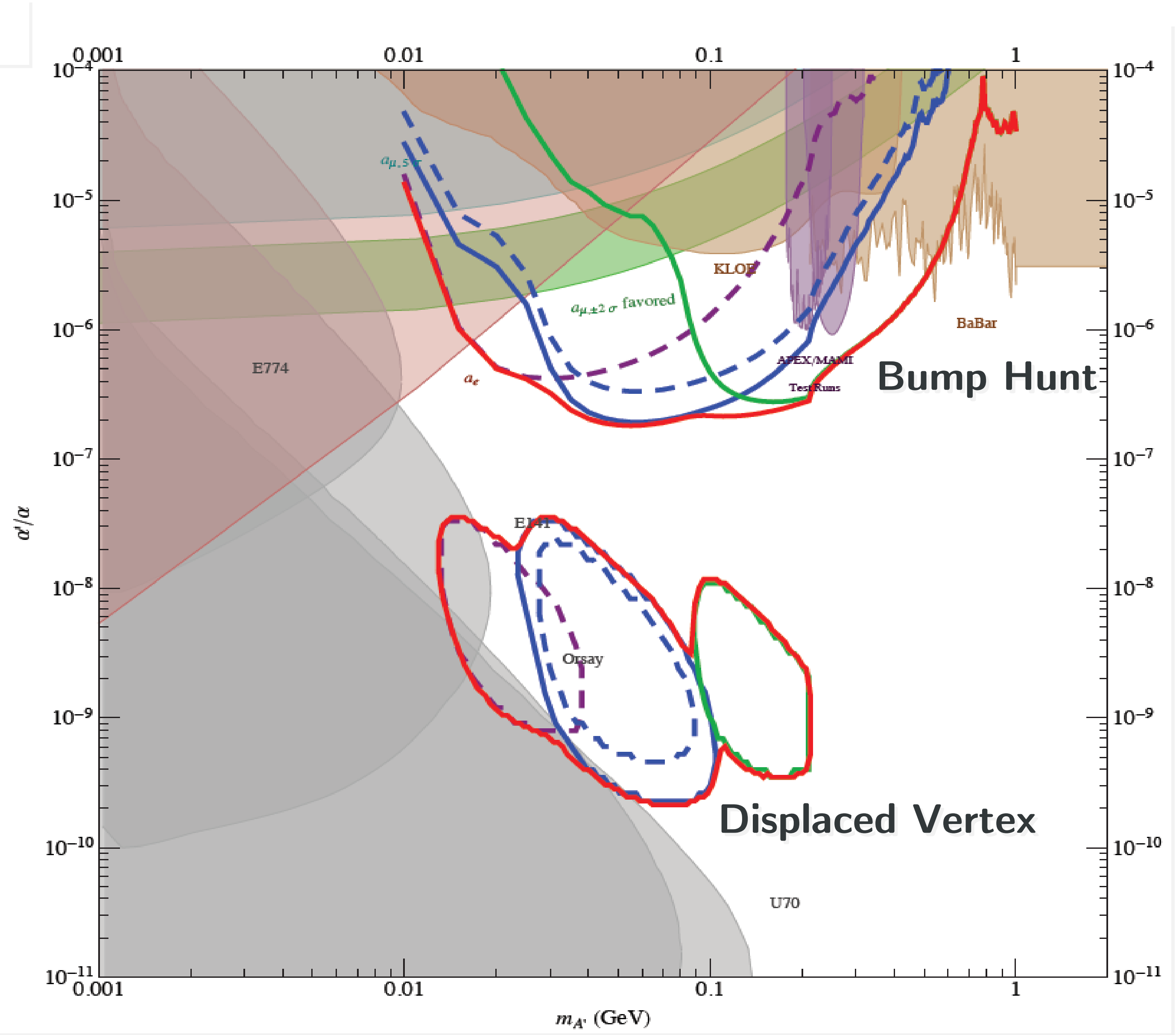
1 Week @ 1.1 GeV

1 Week @ 2.2 GeV

2015

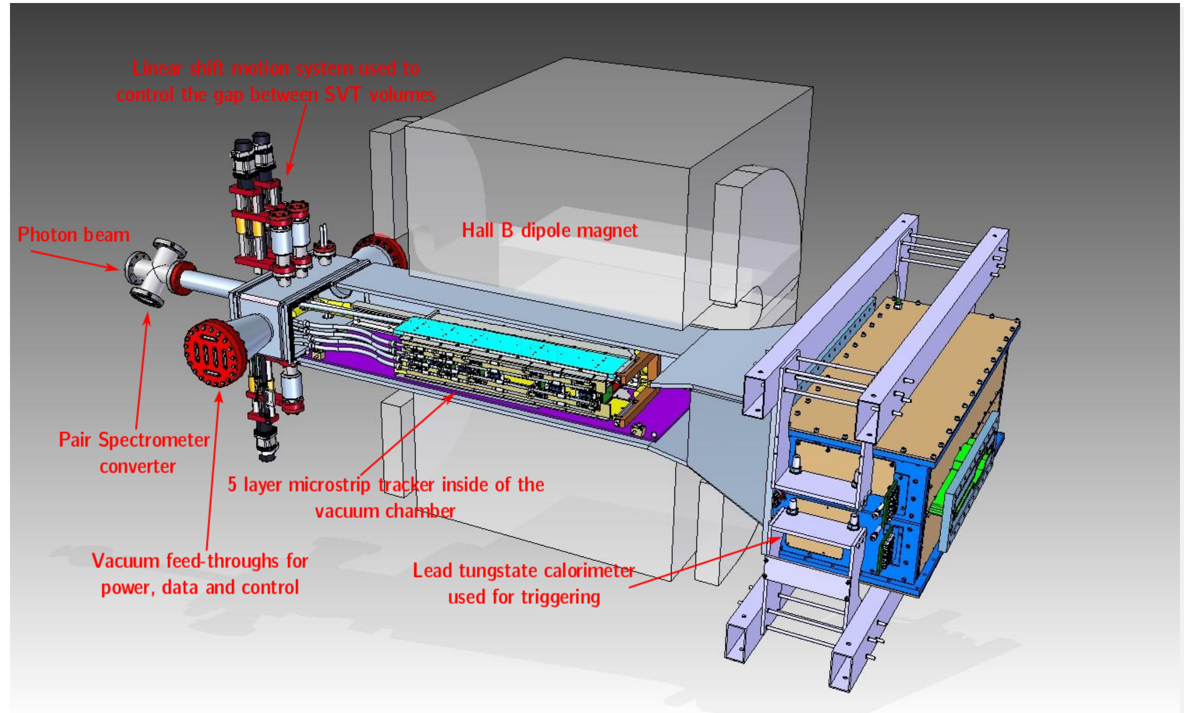
3 Weeks @ 2.2 GeV

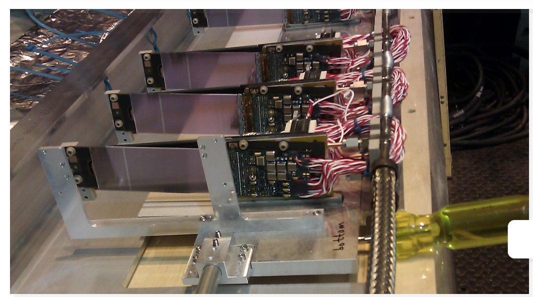
3 Weeks @ 6.6 GeV

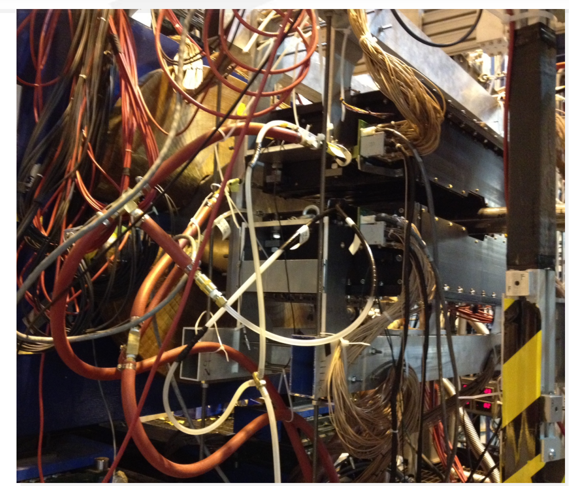


Proof of Principle: The HPS Test Run

- **Determined that occupancies and trigger rates have been well modeled and are manageable, and demonstrated detector performance estimates were reasonable**
  - Also capable of search for dark photons
- Used a scaled down version of the HPS detector
  - 5 Si tracker layers with two sensors per layer
  - Same Ecal as full run
  - The muon chamber was absent
  - Use existing Beamline elements
- Was installed in Hall B in May of 2012
- Scheduling conflicts prevented a run with an electron beam → Ran parasitically using a photon beam
- Dedicated photon run was used to determine if trigger rates were well modeled



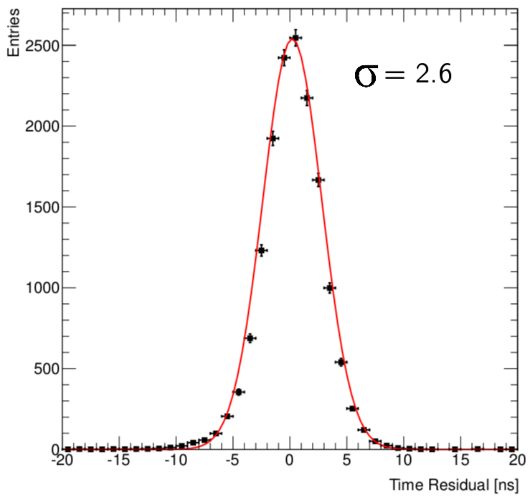


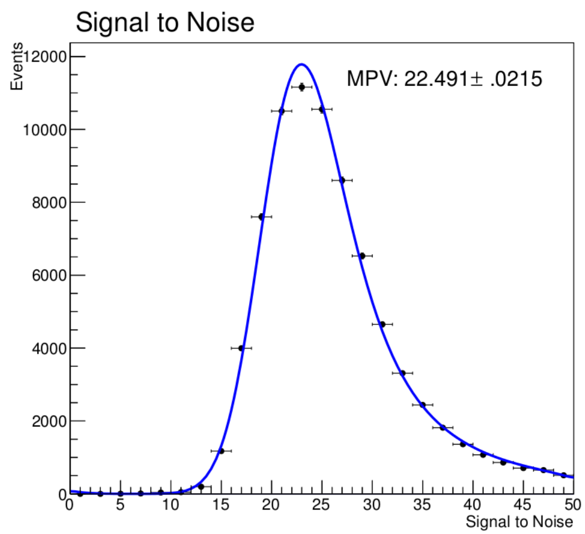


Short photon beam run
(last hours of CEBAF 6GeV era!)

Target thickness (rad. len)	# Events	Approx. trigger rate (Hz)
no target	0.6M	0.3k
0.18%	2M	0.4k
0.45%	1M	0.6k
1.6%	1.5M	1.9k

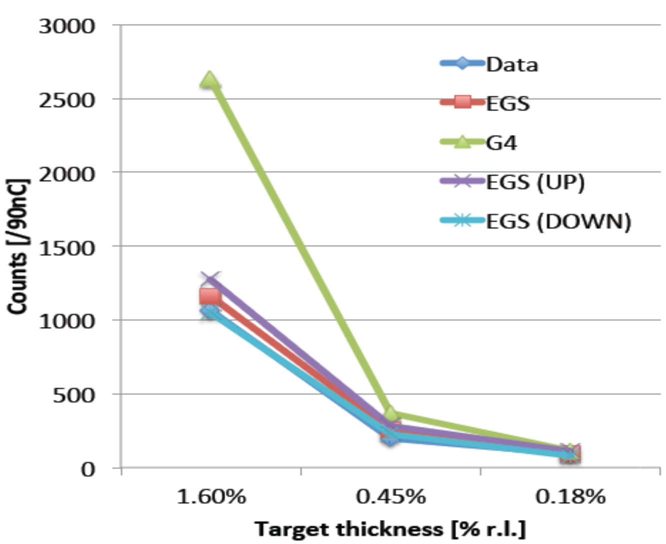
Test Run Performance



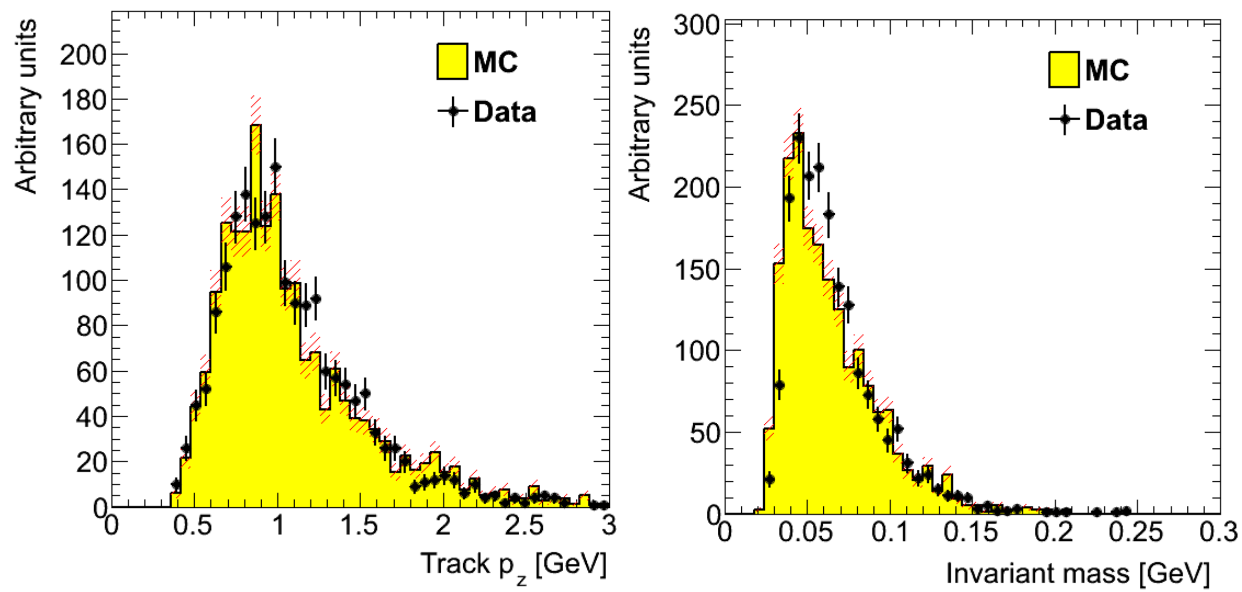


- 98% of 12780 SVT channels were operational
- Signal to noise ratio ~ 23 which implies is consistent with a 6 um spatial resolution
- T0 resolution was found to be 2.6 ns
- Hit efficiencies > 99%
- SVT aligned to within 300 μm

Trigger rates are well understood

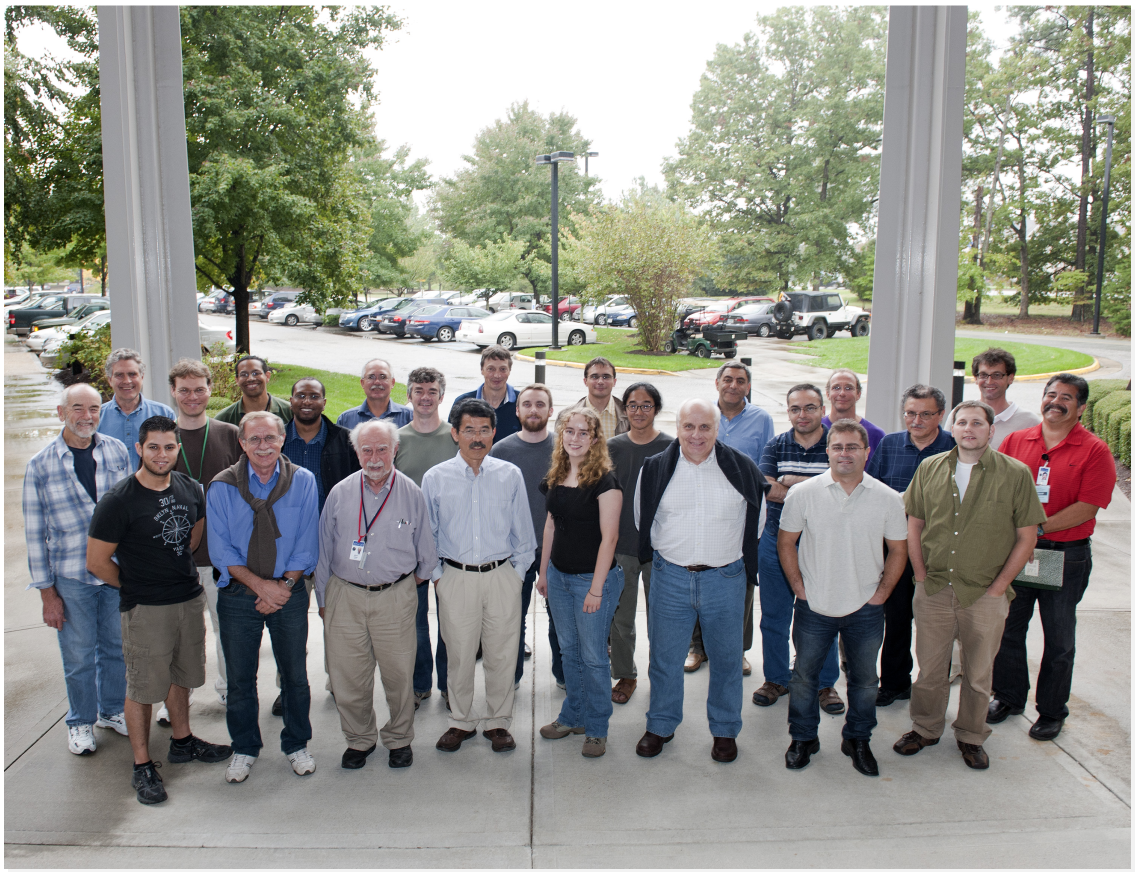


Achieved very good agreement between data and MC



HPS is ready for electrons!

HPS Collaboration



P. Hansson Adrian, C. Field, N. Graf, M. Graham, G. Haller, R. Herbst, J. Jaros[a], T. Maruyama, J. McCormick, K. Moffeit, T. Nelson, H. Neal, A. Odian, M. Oriunno, S. Uemura, D. Walz

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

A. Grillo, V. Fadeyev, O. Moreno

University of California, Santa Cruz, CA 95064

W. Cooper

Fermi National Accelerator Laboratory, Batavia, IL 60510-5011

S. Boyarinov, V. Burkert, A. Deur, H. Egiyan, L. Elouadrhiri, A. Freyberger, F.-X. Girod, V. Kubarovsky, Y. Sharabian, S. Stepanyan[a,b], M. Ungaro, B. Wojtsekhowski

Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

R. Essig

Stony Brook University, Stony Brook, NY 11794-3800

M. Holtrop[a], K. Slifer, S. K. Phillips

University of New Hampshire, Department of Physics, Durham, NH 03824

A. Fradi, B. Guegan, M. Guidal, S. Niccolai, S. Pisano, E. Rauly, P. Rosier and D. Sokhan

Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France

P. Schuster, N. Toro

Perimeter Institute, Ontario, Canada N2L 2Y5

N. Dashyan, N. Gevorgyan, R. Paremuzyan, H. Voskanyan

Yerevan Physics Institute, 375036 Yerevan, Armenia

M. Khandaker, C. Salgado

Norfolk State University, Norfolk, Virginia 23504

M. Battaglieri, R. De Vita

Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dell'Universita, 16146 Genova, Italy

S. Bueltmann, L. Weinstein

Old Dominion University, Norfolk, Virginia 23529

G. Ron

Hebrew University of Jerusalem, Jerusalem, Israel

P. Stoler, A. Kubarovsky

Rensselaer Polytechnic Institute, Department of Physics, Troy, NY 12181

K. Griffioen

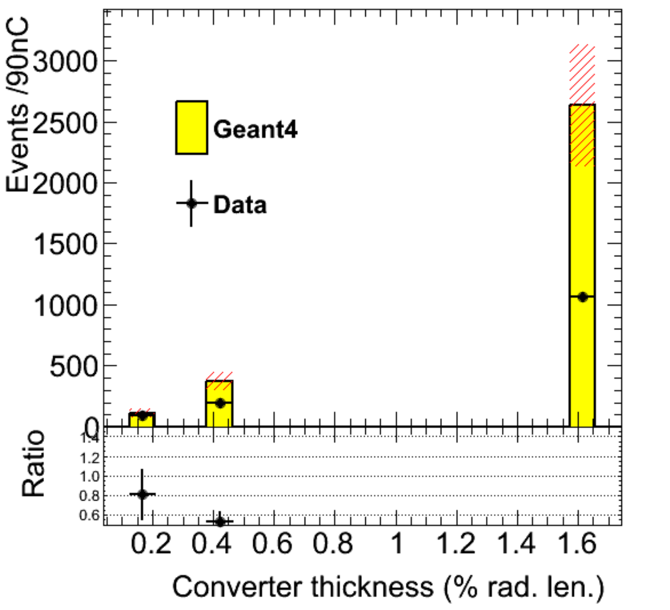
The College of William and Mary, Department of Physics, Williamsburg, VA 23185

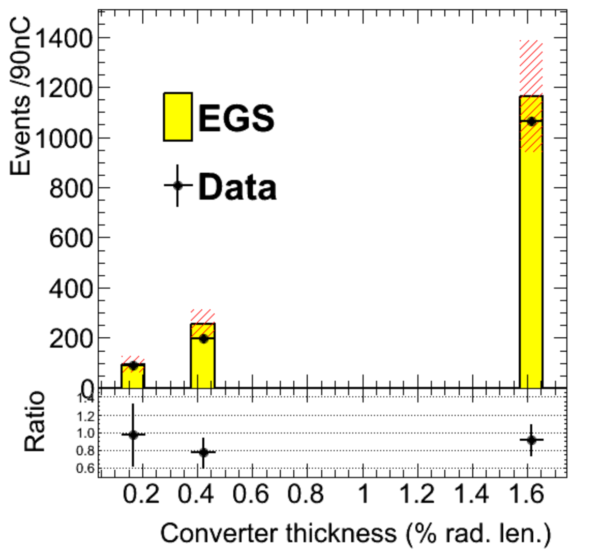
(Dated: May 7, 2012)

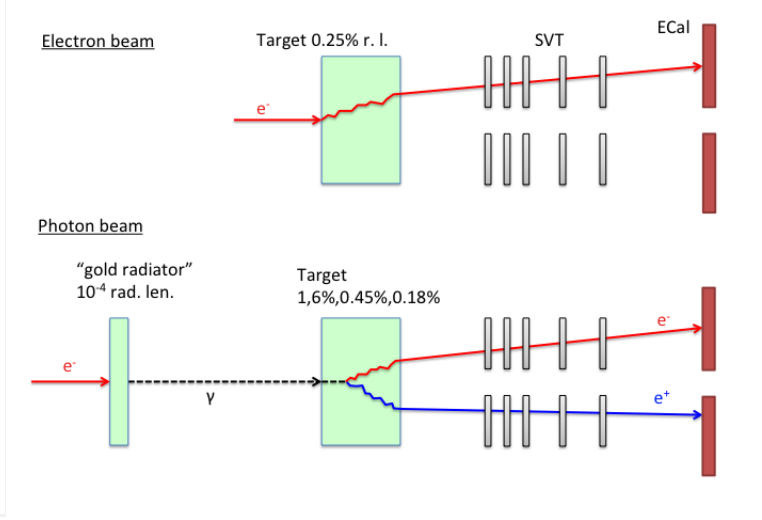
Backup

Multiple Coulomb Scattering

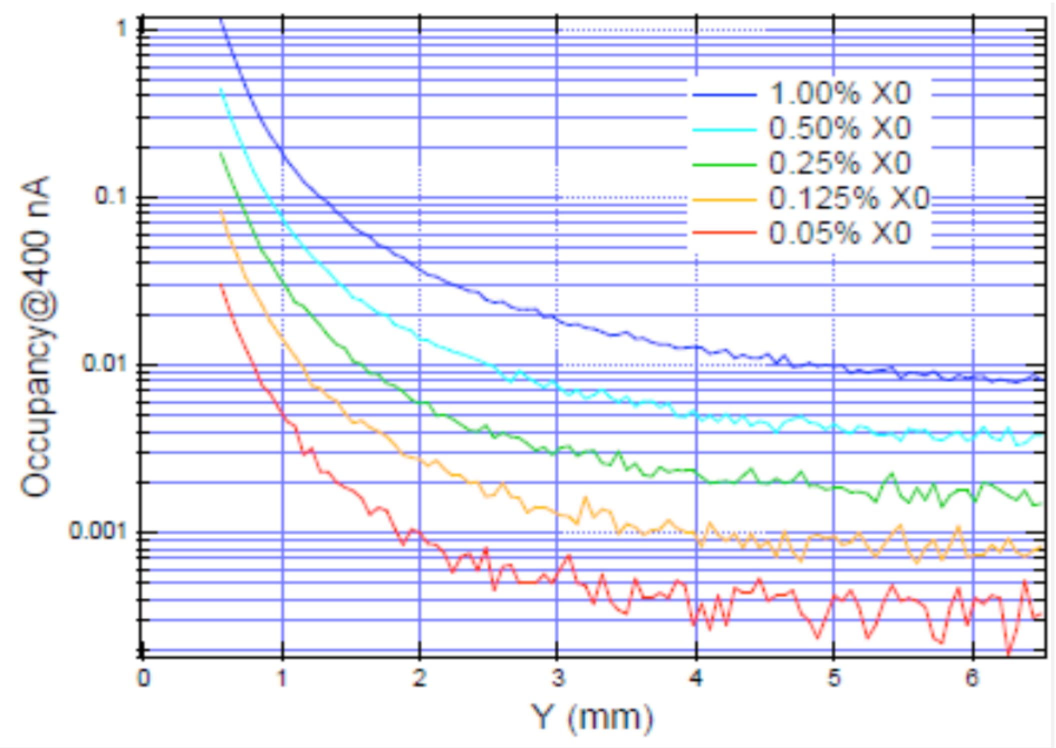
- The dominant source of occupancy for the HPS experiment will come from multiple Coulomb scattered beam electrons into large angles
- The multiple Coulomb scattering rate at large angles is overestimated by Geant 4 by a factor of two as compared to EGS5
- Measurement of the angular distribution of the pair produced electron and positron can be used to test which model of multiple Coulomb scattering is correct
- Comparing total rates observed during the dedicated run to those expected from simulation reveals that **EGS5** agree with the test run data to within 10%



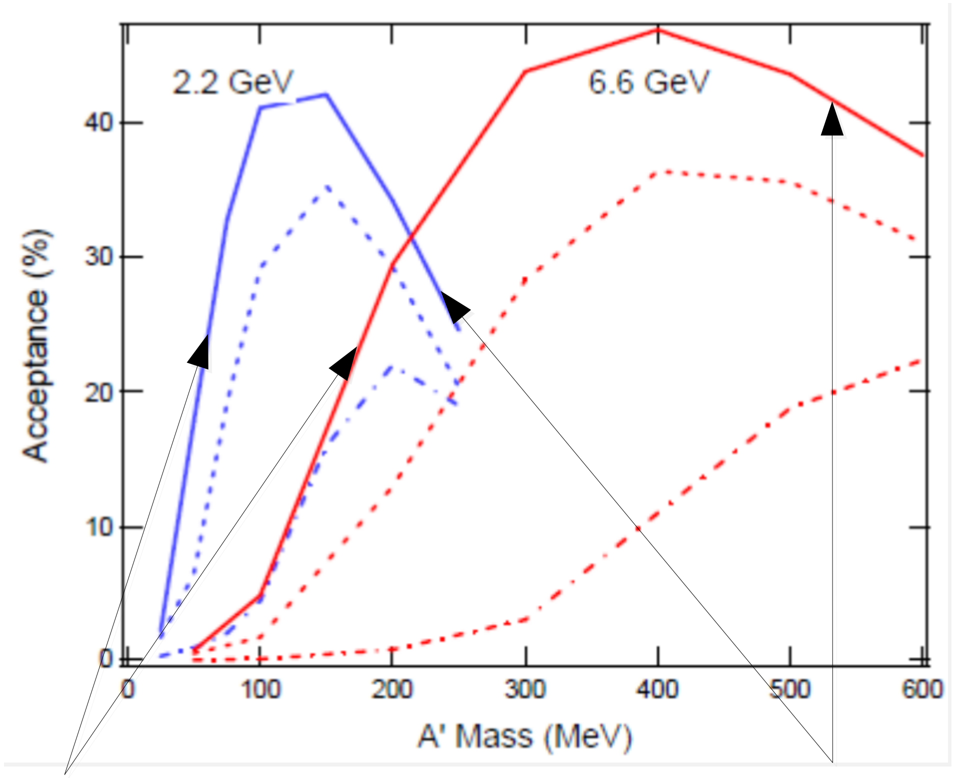




SVT Performance



Dead Zone chosen such that the occupancy at Layer 1 is approx. 1%



A' production rate is proportional to the product of the beam current and the target thickness $\rightarrow$ Prefer to run using a thinner target and higher currents in order to reduce multiple scattering

——— Decay at Target

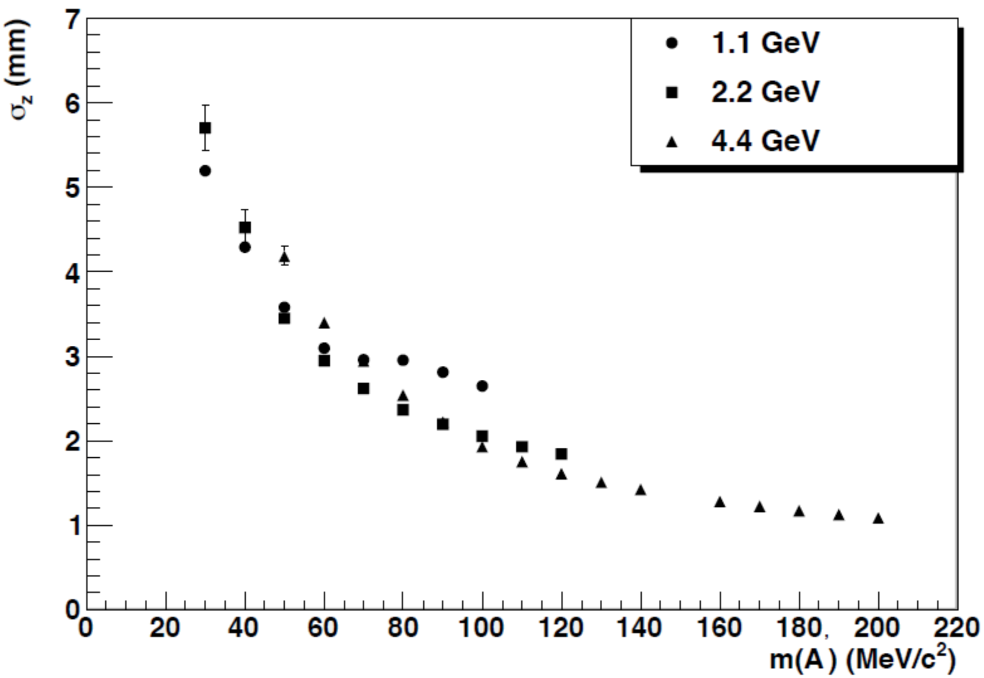
- - - - - Decay at 10 cm

·· — — — ·· Decay at 20 cm

Acceptance is calculated by requiring the e^+e^- to hit the first five layers

Mass and Vertex Resolution

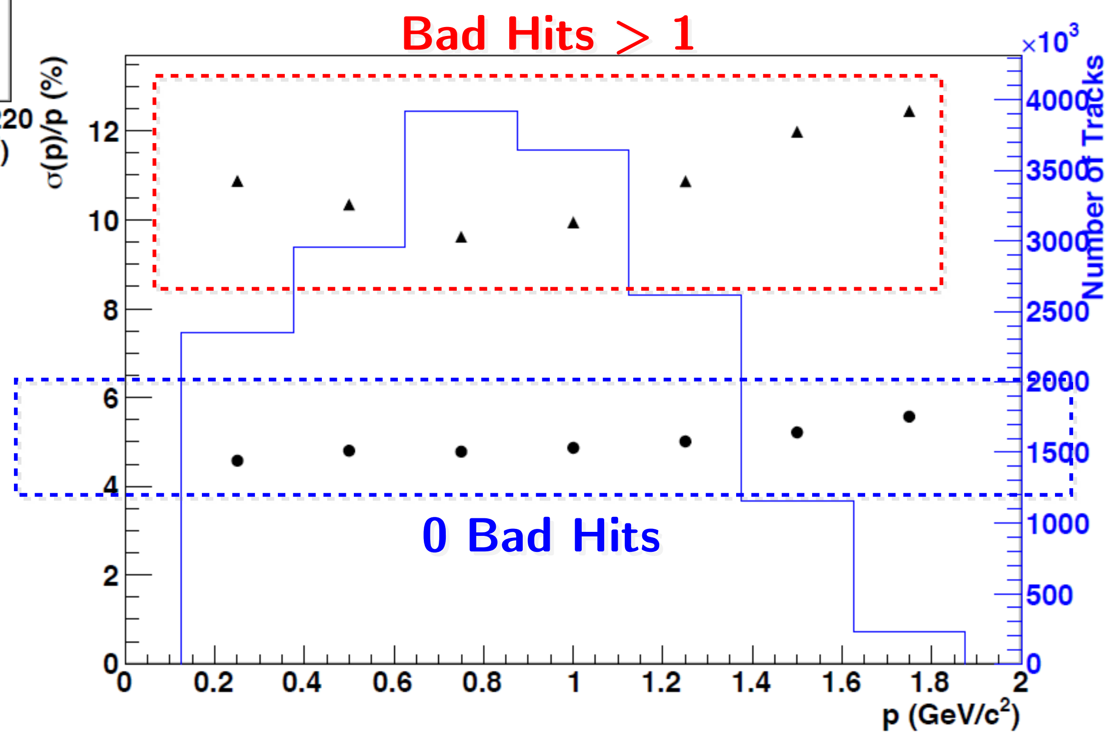
Vertex Resolution



Dominated by Multiple Scattering

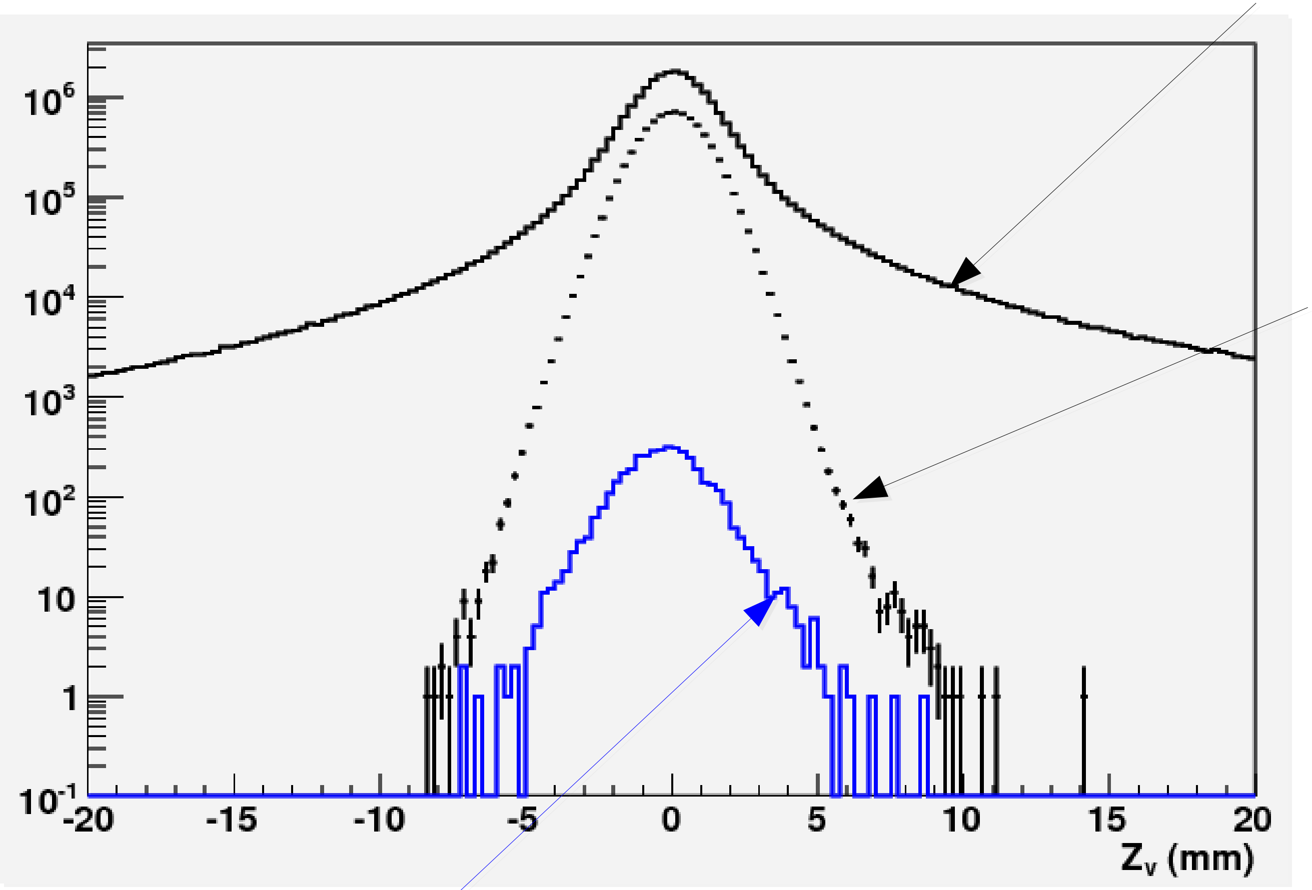
$$\sigma(Z) = \sqrt{2}L\frac{\delta\theta}{\theta}$$

Mass Resolution



Mass and Vertex Resolution

Vertex Position of Prompt Decays



Tracks with Bad Hits

Event selection

- Track $X^2 < 20$
- $p(A') < E_{beam}$
- $|V_x| < 400$ μm and $|V_y| < 400$ μm
- Cluster isolation in Layer 1 >500 μm
- Vertex X^2<15

These cuts have not been optimized

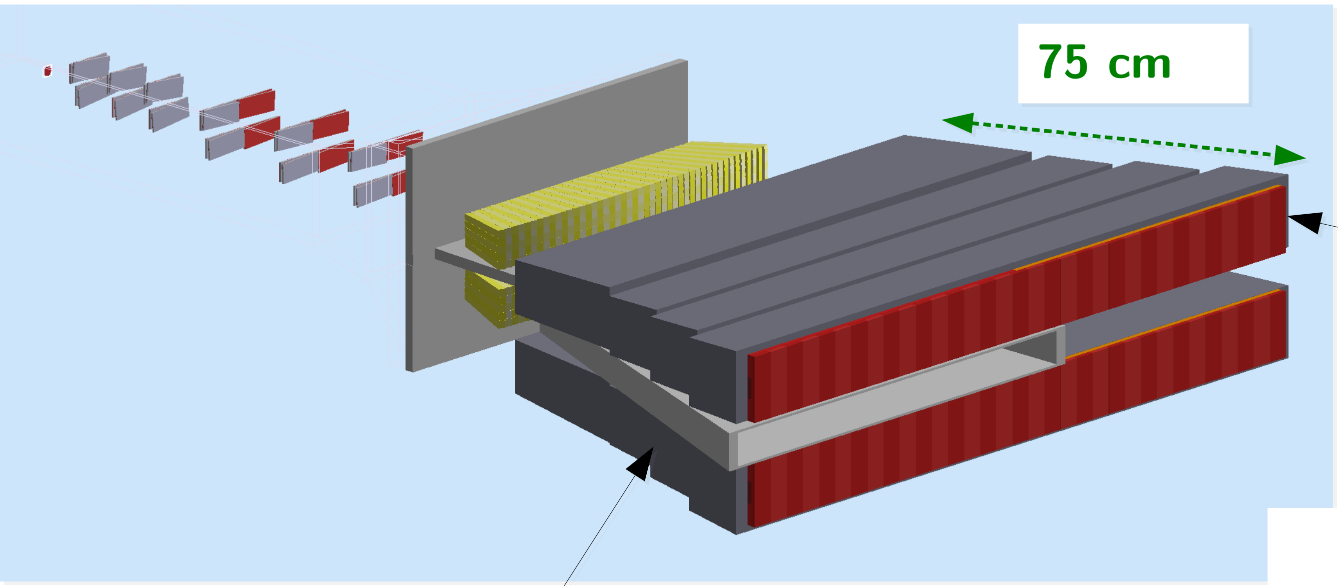
Trigger Rates

Trigger Cut.	200 MeV/c^2 A′ Acceptance	Background Acceptance	Background rate
Events with least two opposite clusters	42.35%	2.30%	2.9 MHz
Cluster energy > 500MeV and < 5 GeV	44.25%	0.123%	154 kHz
Energy sum <= E_{beam}*sampling fraction	44.25%	0.066%	82.5 kHz
Energy difference < 4 GeV	44.20%	0.062%	77.5 kHz
Lower energy - distance slope cut	43.46%	0.047%	58.8 kHz
Clusters coplanar to 40°	42.33%	0.0258%	32.3kHz
Not counting double triggers	38.58%	0.0210%	26.3 kHz

Trident Rates after trigger cuts are applied

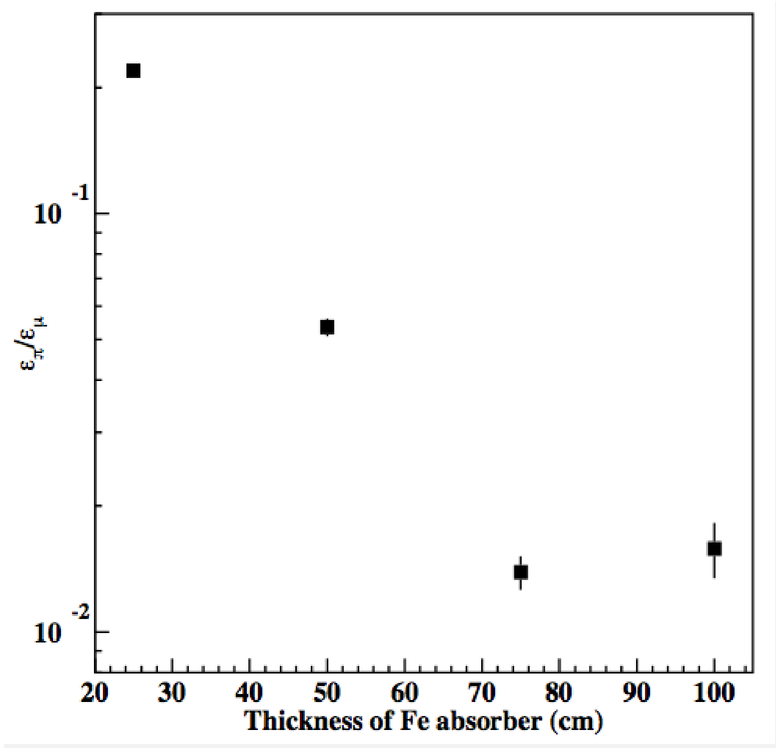
Trident	Estimated trigger rate
Coherent trident	
Bethe-Heitler	7.8 kHz
Radiative	130 Hz
Incoherent trident	180 Hz

Muon Detector



Sci. Hodoscopes 1.5 cm

Iron Absorber
30 cm + 3x15 cm



Closing the Gaps