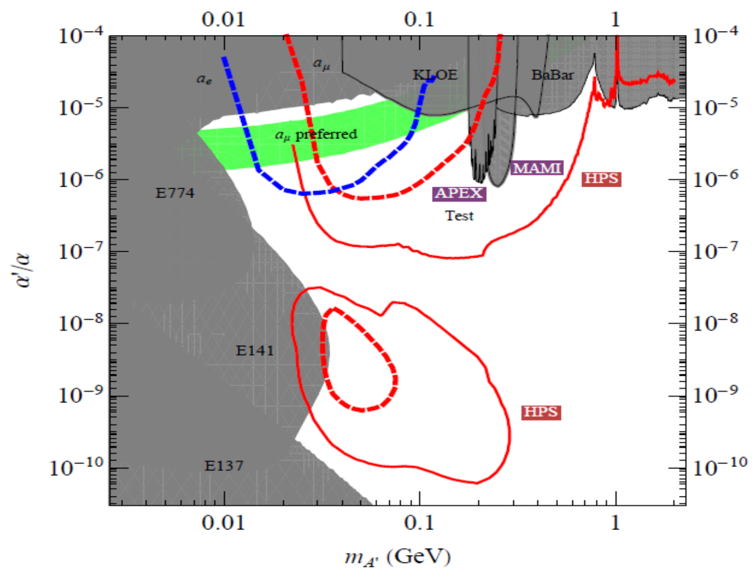
Status and Plans
Heavy Photon Search Experiment at Jefferson Laboratory



John Jaros
for the Heavy Photon Search Collaboration

Jefferson Laboratory PAC39
June 20, 2012

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(Dated: May 7, 2012)

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Busy time since PAC 37

- **PAC 37 endorsed two stage approach**, approving the HPS Test Run and conditionally approving Full HPS, awaiting Test Run results

- **HPS Test Run Proposal** reviewed by DOE HEP (3/11)

- **HPS Test Run approved** by DOE HEP (6/11)
  Funds sent to JLAB and SLAC (7/11)

- **HPS Test Run engineered, constructed, and tested** (7/11-4/12)
  Work at Orsay, JLAB, SLAC, and UCSC

- **HPS Test Run shipped, assembled, and installed at JLAB** (4/19/12)

- **HPS parasitic photon run with HDice in Hall B** allowed full commissioning of the experiment (4/26-5/17)

- **HPS dedicated photon run.** First clean beam and successful data taking for the last 8 hours of CEBAF 6!

Moving beyond Conditional Approval

PAC37 Report

Proposal: PR12-11-006 **Scientific Rating**: Unrated

Recommendation: C2, i.e. the PAC conditionally approves this proposal contingent on the success of the test run. It feels that the test run should be carried out as early as possible (ideally before the 6 GeV shutdown), so that the full experiment can be carried out in a timely manner.

Title: "Heavy Photon Search at Jefferson Laboratory"

Spokespersons: M. Holtrop, J. Jaros, and S. Stepanyan

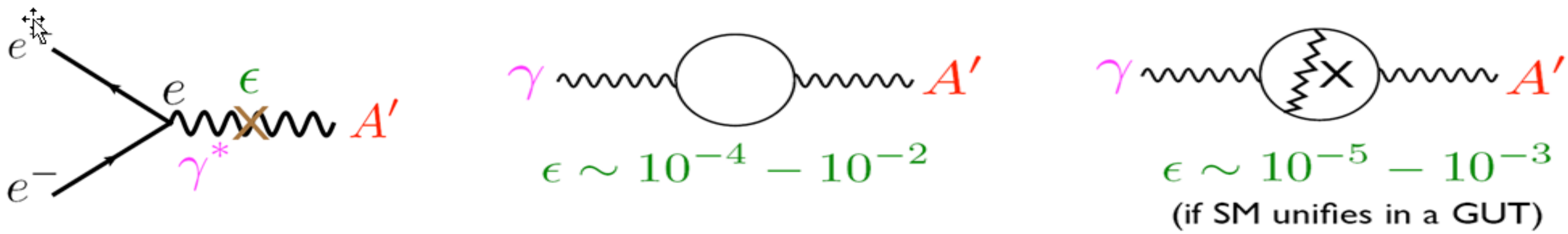
- "The PAC concurs with the need for a test run and feels that only after a successful test run that demonstrates the needed detector capabilities will full approval be appropriate."
  Test run results demonstrate that the HPS technical approach is sound, and that high rate triggering and DAQ work as required.

- "The PAC also believes that the success of the test run should be at such a level that it essentially ensures that the proposed goals would be met."
  New information on beam quality, further studies of trigger rates, and a deeper understanding of electron backgrounds, give us confidence that full HPS goals can be met.

Heavy Photon Primer

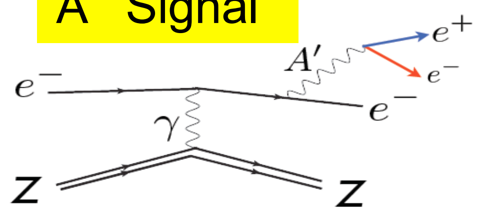
- **The Heavy Photon (A') is a conjectured U(1) force particle**, a massive vector gauge boson which couples to an analogue of electric charge.

- **A' kinetically mixes with the SM γ.** Mixing induces a weak coupling εe to electric charge, so heavy photons couple to e^+e^-, are radiated by electrons, and decay to e^+e^-

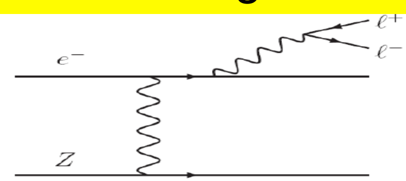


- **A' appears as a narrow e^+e^- resonance on a copious background of QED tridents**

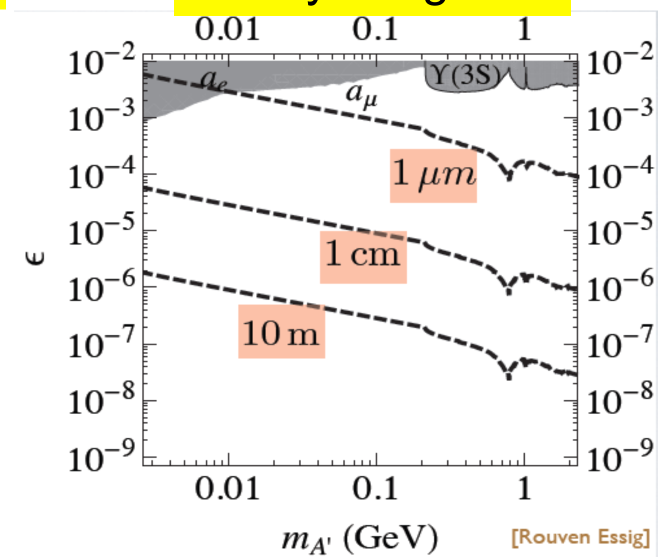
A' Signal



Trident Background



Decay Length cτ

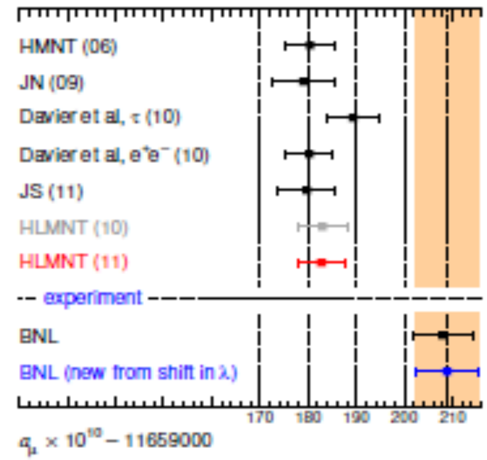


- **A' lifetime gives displaced decay vertex**

$$\gamma c\tau \sim 0.8 \text{ cm } (E_0/10 \text{ GeV})\,(10^{-4}/\varepsilon)^2\,(100 \text{ MeV}/m_{A'})^2$$

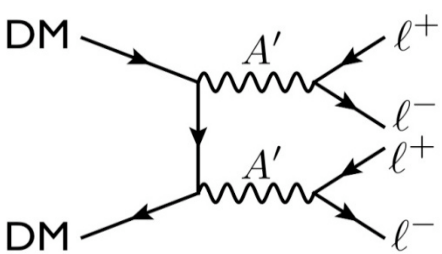
HPS Physics Motivations Alive and Well

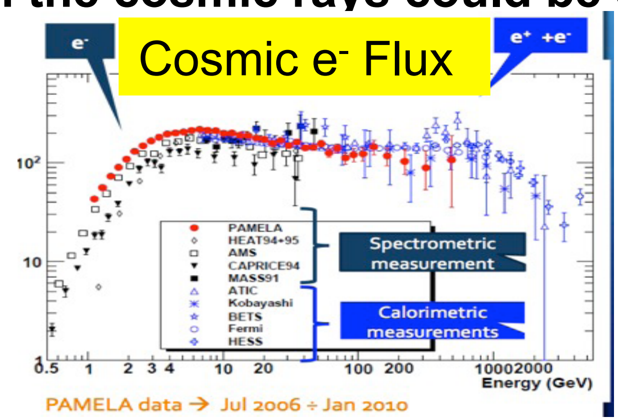
- **Are there more U(1)'s in Nature?**
  Since the SM accounts for only 4% of the universe's mass-energy, there is certainly room. Extra U(1)'s appear in BSM theories.

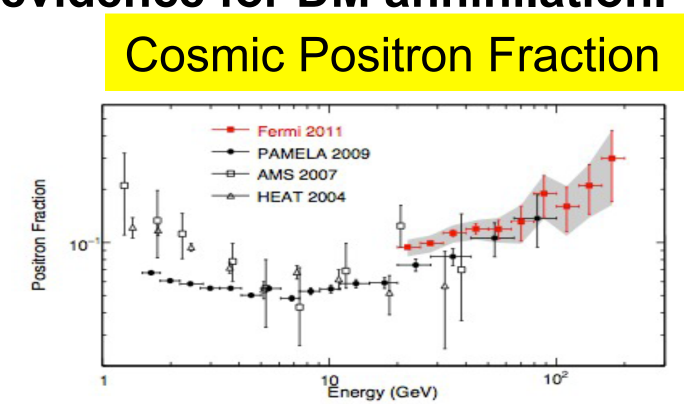


- **10-100 MeV A' could explain muon g-2 anomaly**
  Recent analysis (Davier et al., 0908.4300) shows 3.2 sigma discrepancy between theory and experiment.

- **High energy e^+/e^- in the cosmic rays could be evidence for DM annihilation.**



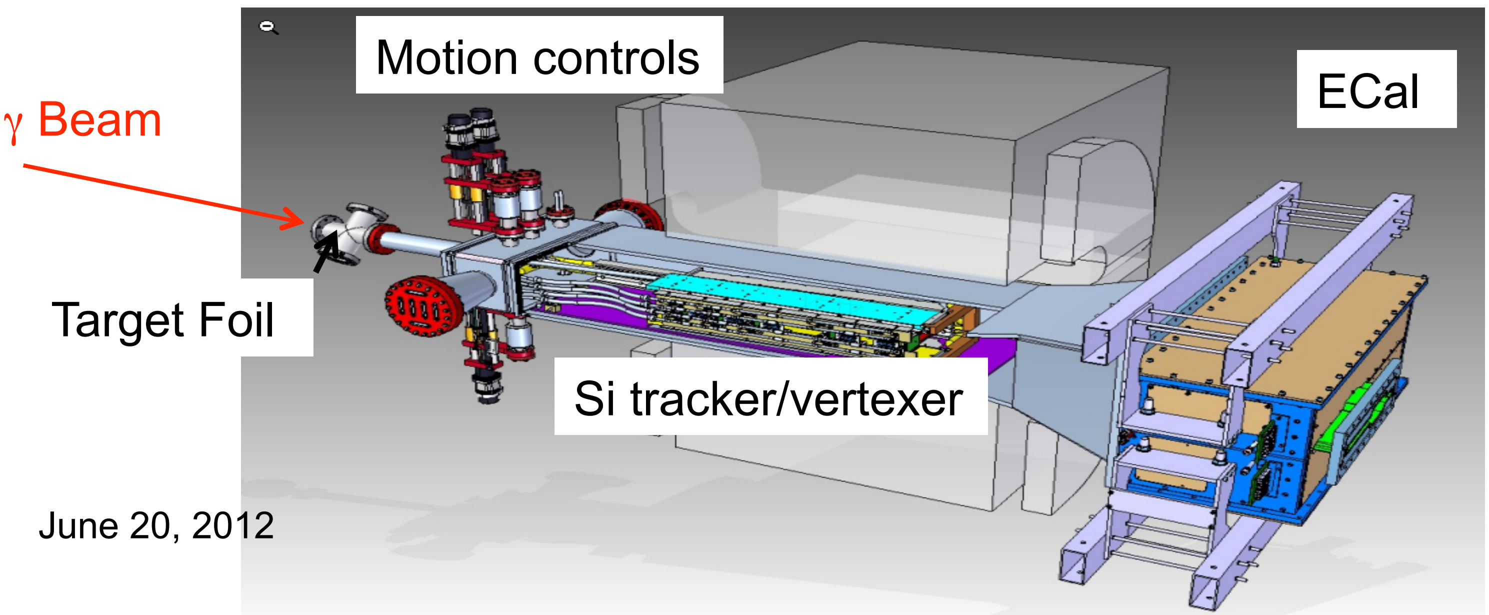




- **QED ⇒ production/decay of "true muonium" ($\mu^+\mu^-$ atom) in HPS.**
  Looks like an A' with $m_{A'} = 2m_\mu$ and finite decay length. Discoverable!

HPS Test Run Apparatus

- Forward, compact spectrometer with Si tracker/vertexer identifies heavy photon candidates with invariant mass and decay length.
- EM Calorimeter provides fast trigger and electron ID.
- Small signal cross sections and large trident backgrounds require large integrated luminosities. The 100% CEBAF duty cycle, short detector live times, and high rate DAQ keep occupancies and trigger rates manageable.
- All detectors are split above and below the beam to avoid the “wall of flame” from multiple Coulomb scattered primaries, bremsstrahlung, & degraded electrons. Beam is transported in vacuum to eliminate beam gas interactions.

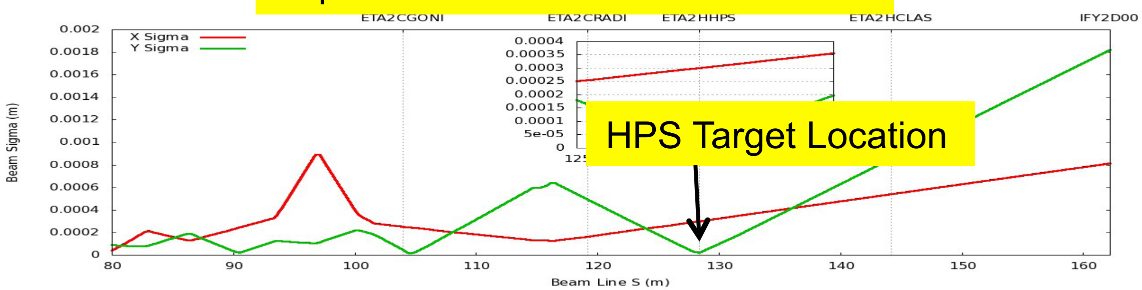


Hall B Beam Meets HPS Requirements

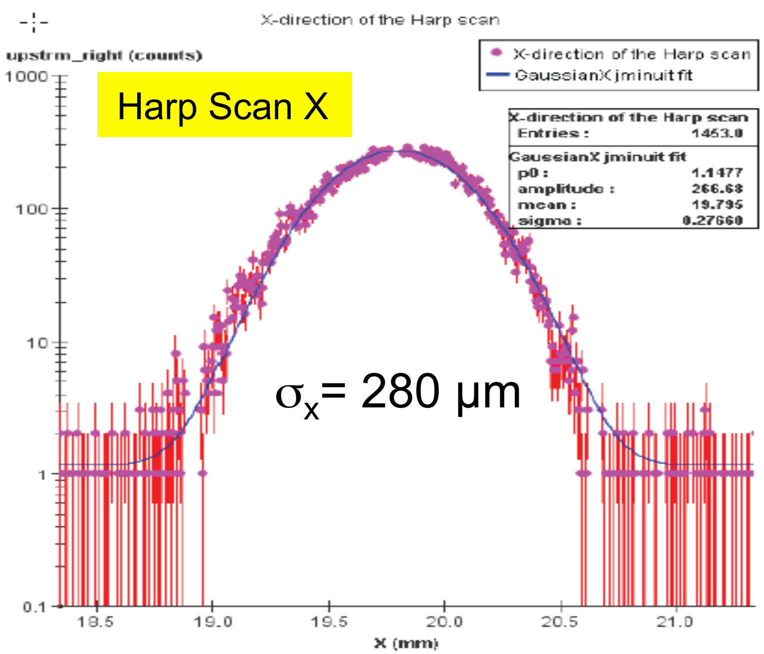
- HPS needs small, stable spots and low halo for a range of energies and beam currents.
- New beam optics from ELEGANT optimization.

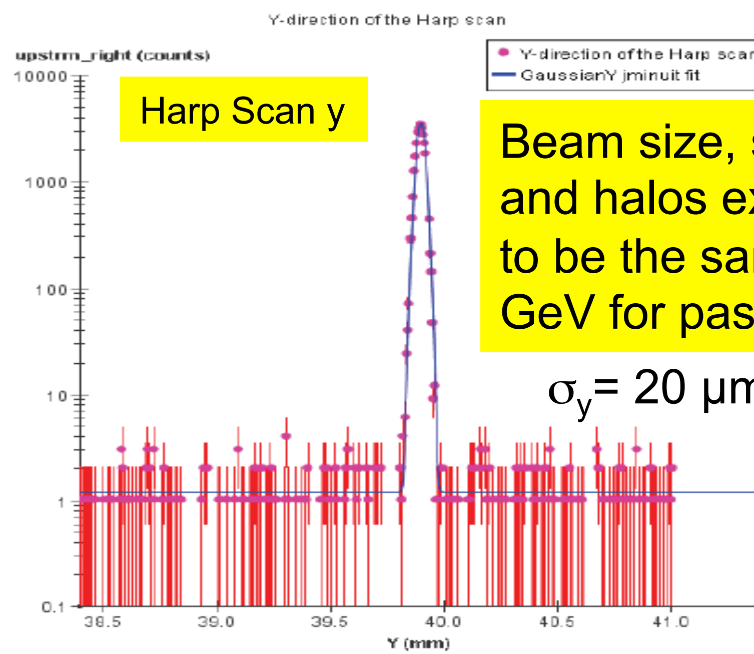
Parameter	Requirement/Expectation	Unit
E	2200	MeV
$\delta p/p$	$< 10^{-4}$	
Current	< 200	nA
Current Instability	< 5	%
σ_x	< 300	μm
σ_y	< 40	μm
Position Stability	< 30	μm
Divergence	< 100	μrad
Beam Halo ($> 5\sigma$)	$< 10^{-5}$	

Expected Beam Sizes vs Z in Hall B



- Harp scans validated these optics calculations: desired beam sizes, excellent stability, and negligible beam halo were achieved.

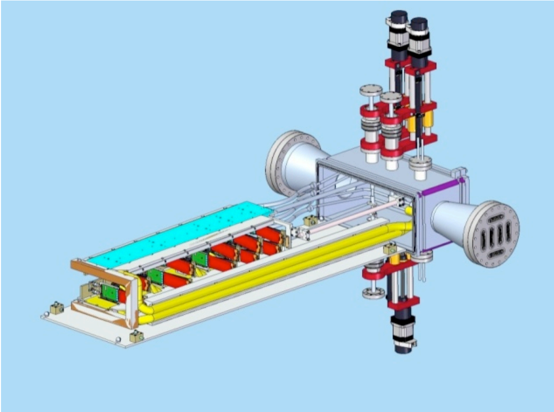


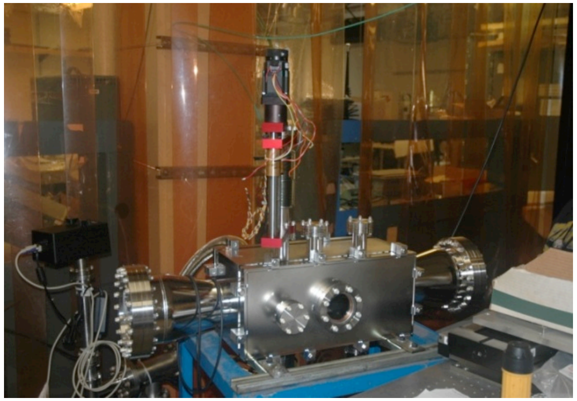


Beam size, stability, and halos expected to be the same at 12 GeV for passes 1-3.

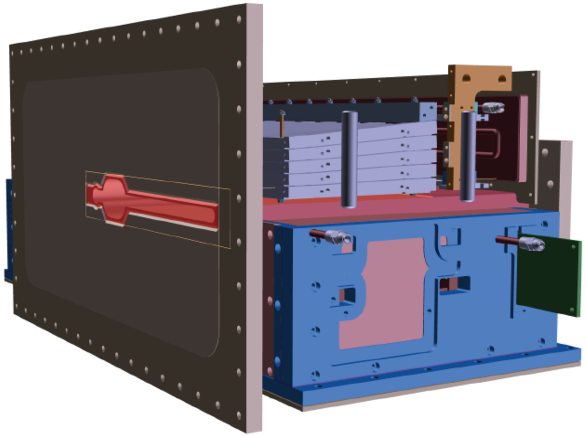
Beamline Components Tested

- SVT Vacuum Box provides data/power vacuum feedthroughs for SVT electronics, motion systems for the SVT and target, and coolant feedthroughs for heat removal.



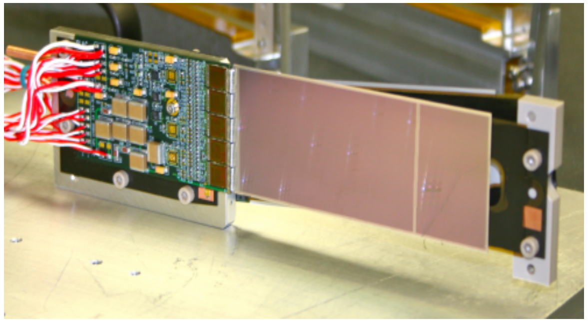


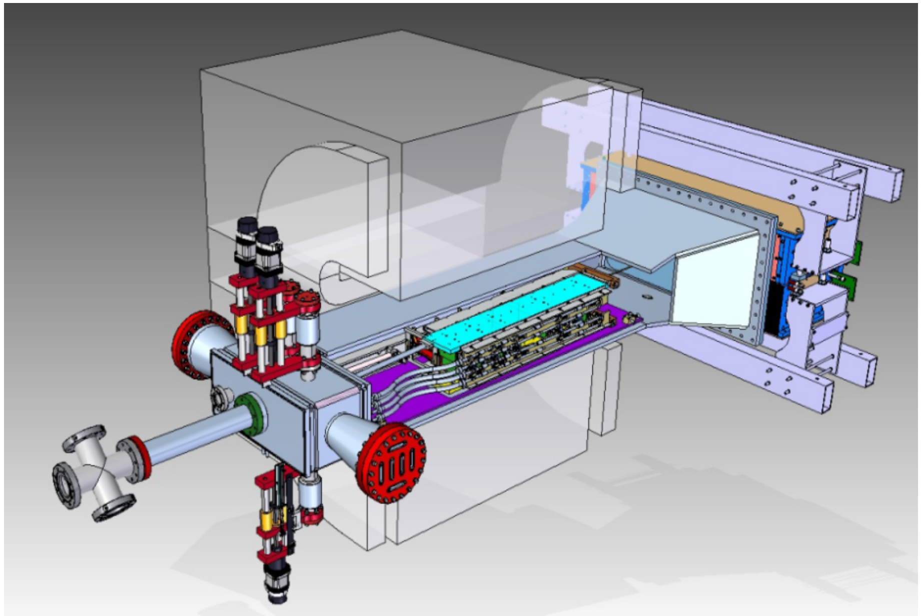
- Ecal vacuum chamber, needed for electron running, has been built and vacuum tested. Ready to go.

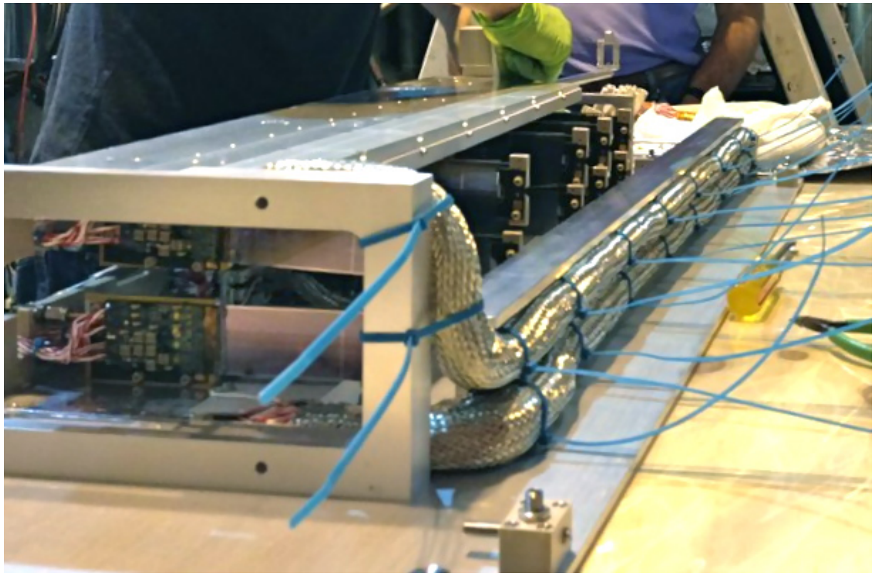


Silicon Vertex Tracker (SVT)

- **Si microstrip sensors readout by CMS APV25's**
  - 40 MHz readout
  - $\sigma_x \approx 6\ \mu m$; $\sigma_t \approx 2\text{-}3$ ns
- **Tracker has 5 layers, each axial + stereo**
  - Measures track momentum and trajectory
  - Placed inside Hall B pair spectrometer magnet
  - Resides in vacuum to minimize beam backgrounds
  - Split top and bottom to avoid beam and "wall of flame"

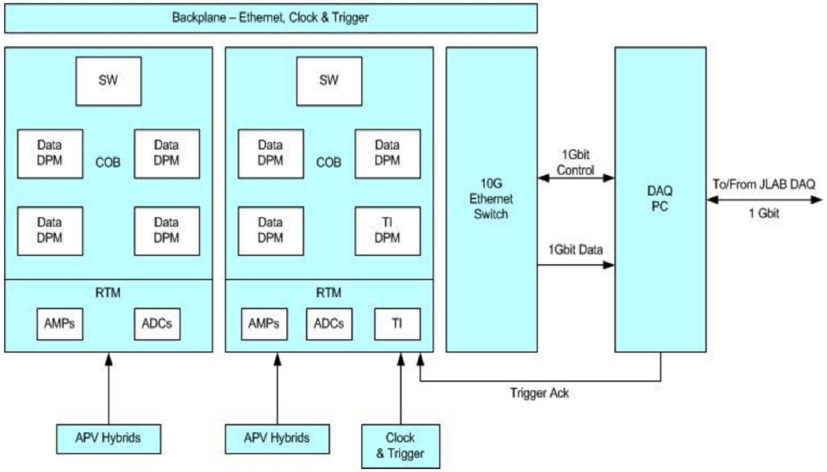






SVT DAQ

- **SLAC ATCA-based architecture provides high speed readout**
  Sensor Hybrids pipeline data at 40 MHz, send selected data when triggered
  RTM board amplifies and digitizes selected data
  COB board applies thresholds, formats, and transfers data to JLAB DAQ

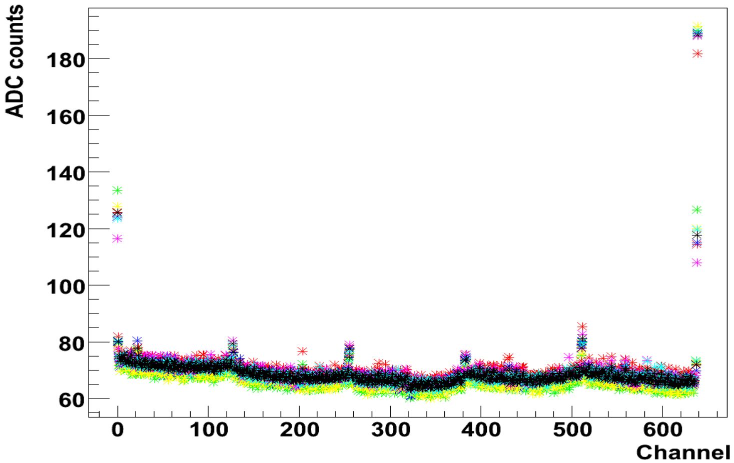


COB Module

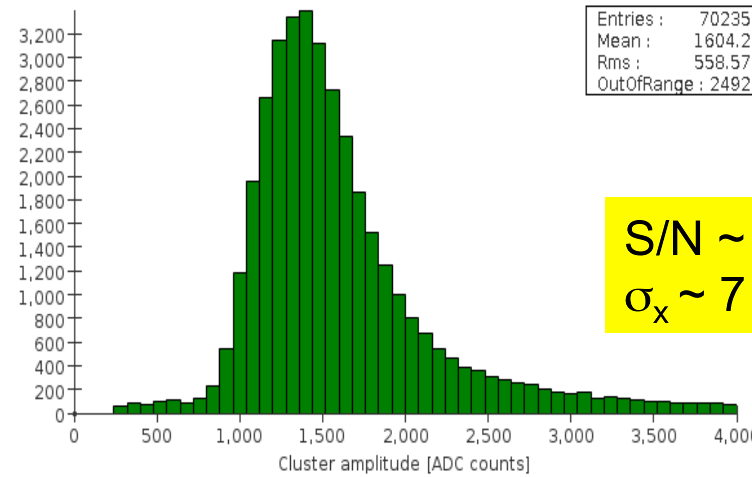
- **Performance**
  Recorded data at 2 kHz in ROC LOCK mode (adequate for photon run)
  Recorded data at 16 kHz trigger rate in PIPELINE mode
- **Straightforward to boost capability to 50 kHz**
  Develop APV buffer to store triggered events
  Change 1 Gbit links to 10 Gbit links
  Move readout controller software to COB

Tracker Performance: all channels work

Pedestal ~ 70 ADC counts



MIP Cluster PH ~ 1600 ADC counts

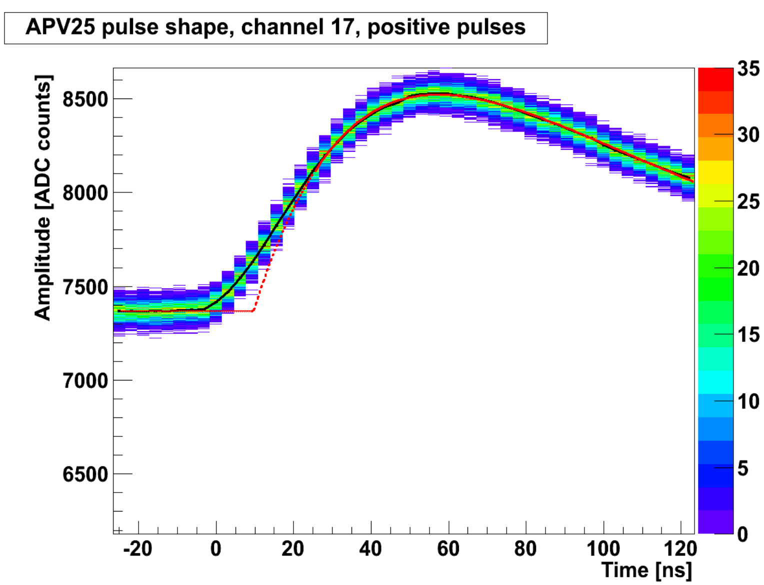


S/N ~ 20

$\sigma_x \sim 7\ \mu m$

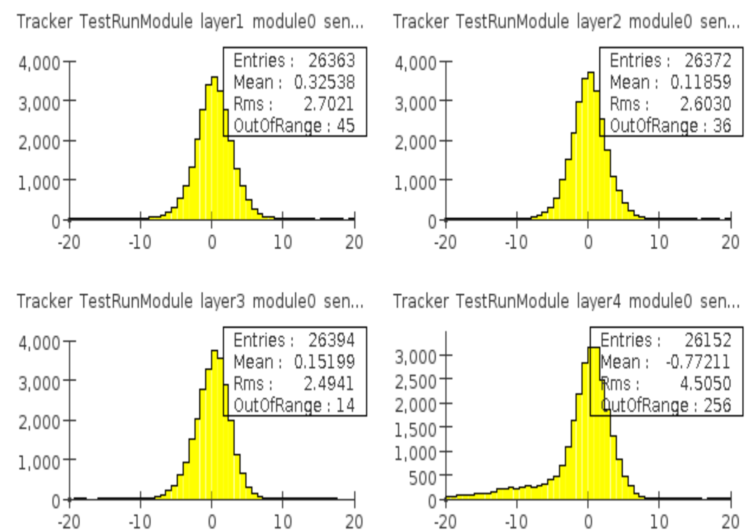
Record pulse shape in 6-25ns bins

$\Rightarrow$ track time

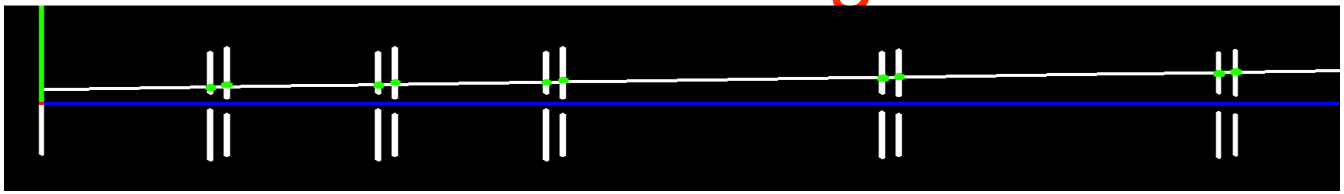


Track Time Resolution

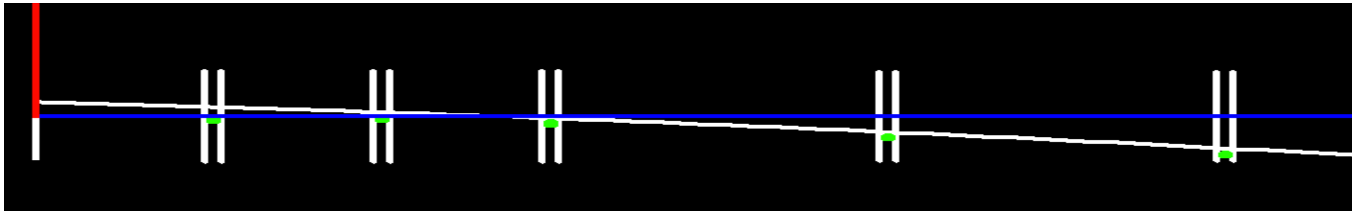
$\sigma_t \sim 3$ ns



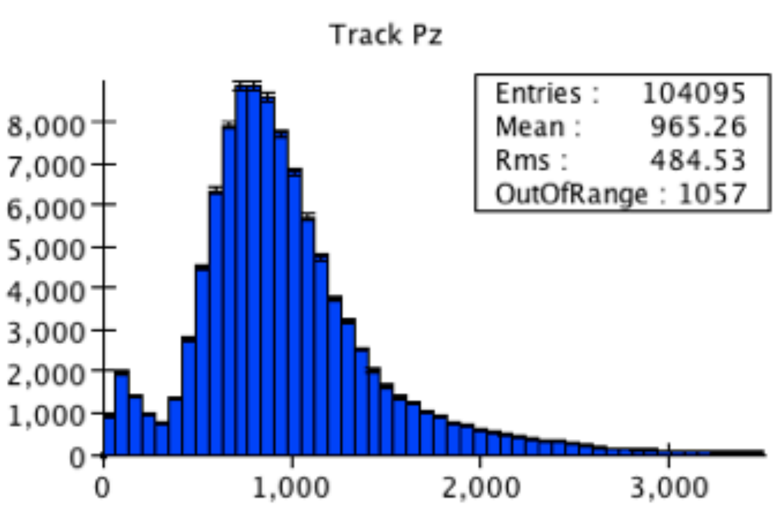
Tracking Works



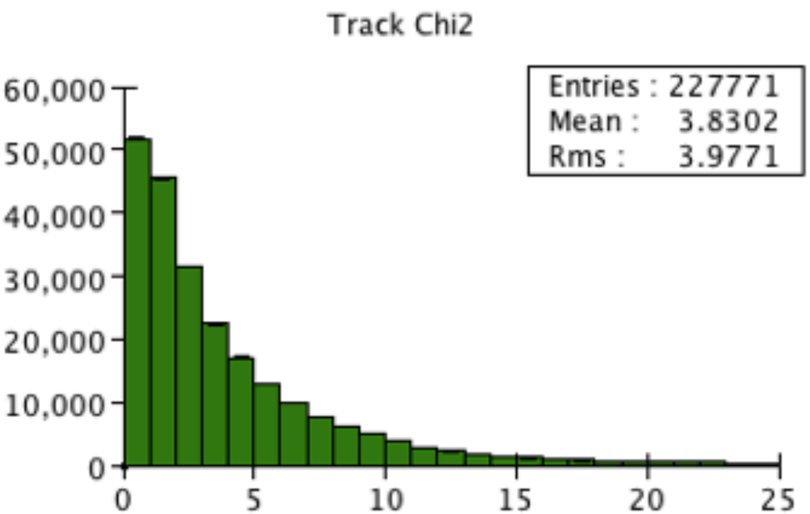
Elevation



Bend Plane



Momentum in MeV/c →

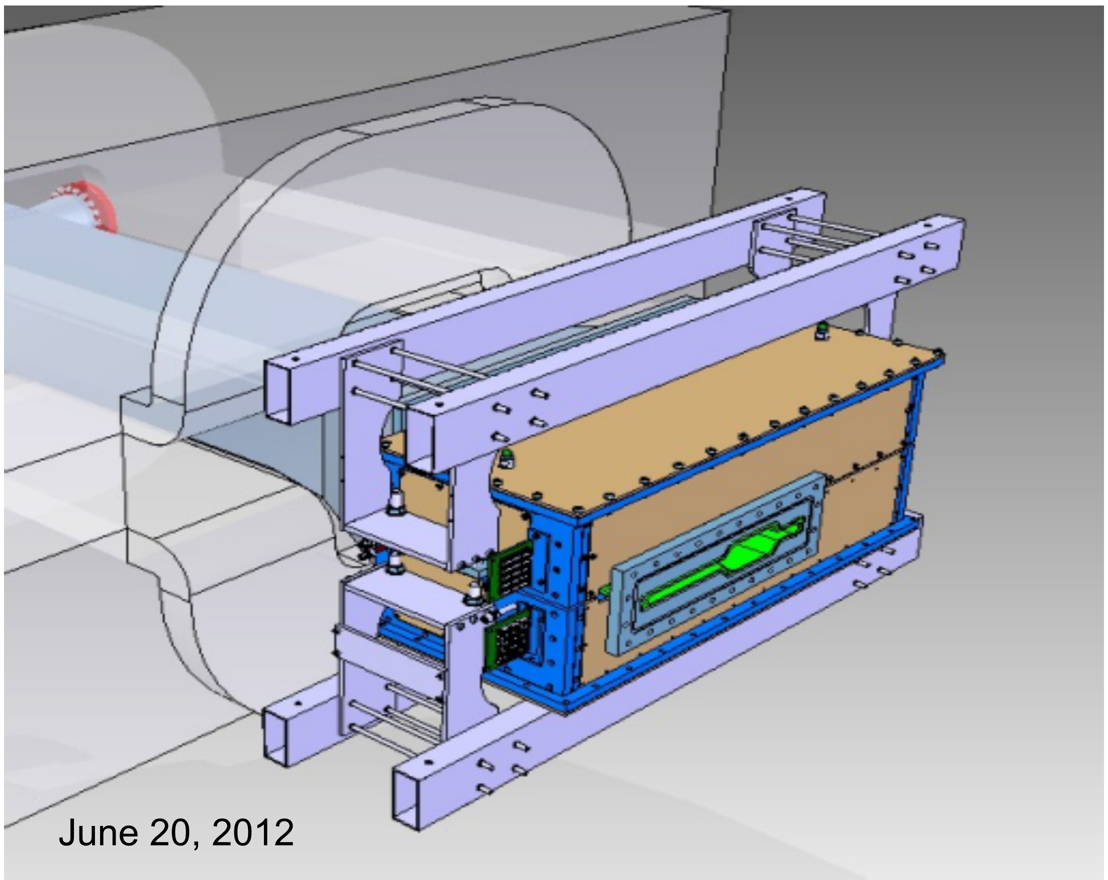


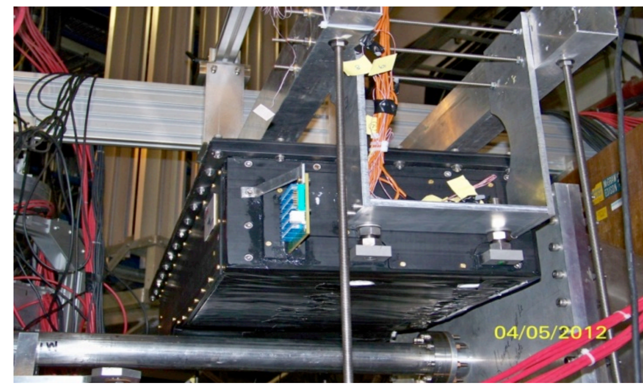
$\chi^2 \rightarrow$

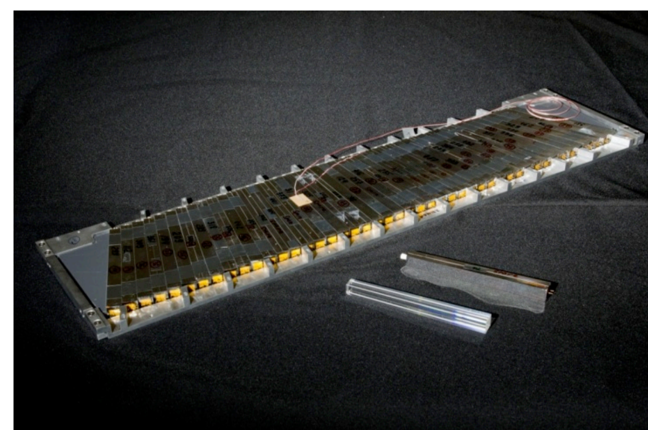
- Refined Alignment, Non-uniform B field maps, Kalman fits, Momentum and Vertex Resolution Studies Underway

Electromagnetic Calorimeter

- Ecal consists of top and bottom modules, each arranged in 5 layers , with 442 lead-tungstate ($PbWO_4$) crystals in all.
- Crystals are readout with APDs and preamplifier boards
- Data is recorded in 250 MHz JLAB FADC
- Thermal enclosure holds temperature constant to ~1^{o} F to stabilize gains

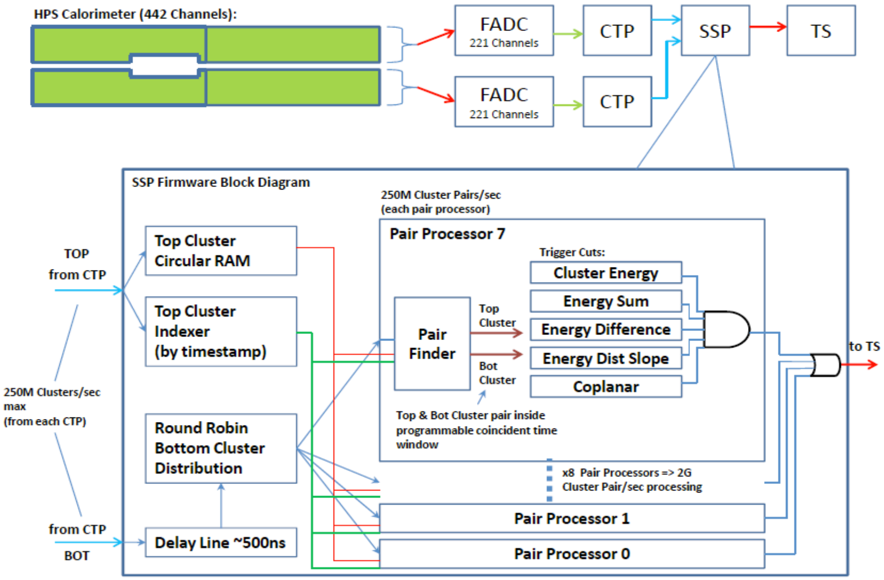






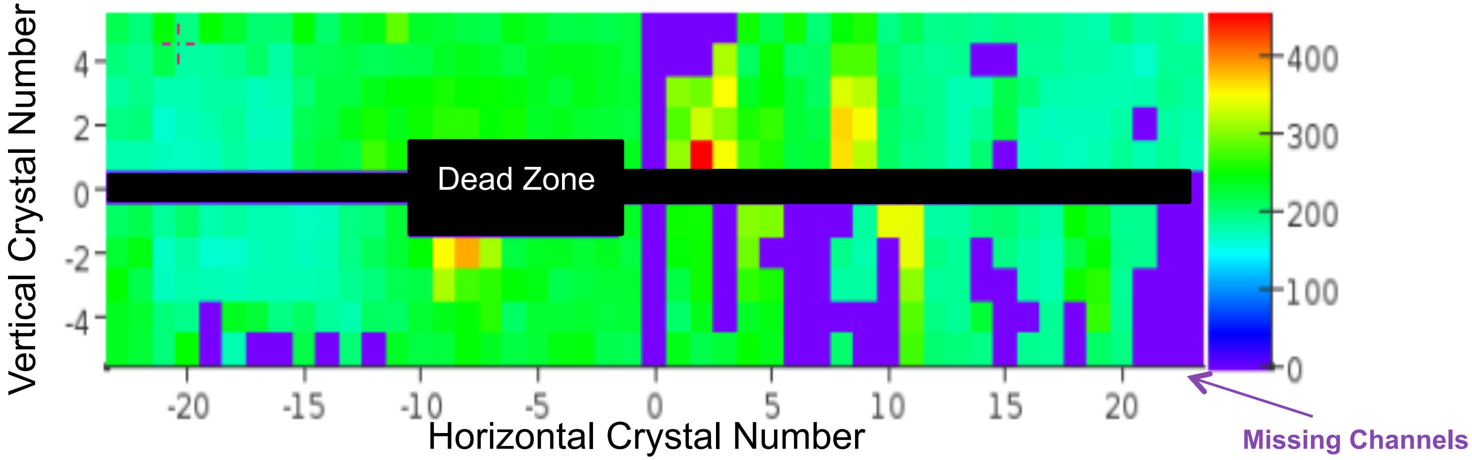
Ecal DAQ and Trigger

- **250 MHz FADC**
  Sends 5 bit PH and 3 bit time info from each channel to Crate Trigger Processor (CTP)
  On receiving trigger, sends integrated 12 bit PH for pulses > 73 MeV to DAQ
- **CTP Trigger**
  Looks for 3 x 3 clusters over threshold (> 270 MeV) in 8 ns window
- **SSP Sub-System Processor**
  Applies trigger criteria and creates readout trigger signal (single cluster for photon run).
- **Performance**
  Ecal FADC and DAQ can trigger and record data up to 50 kHz.

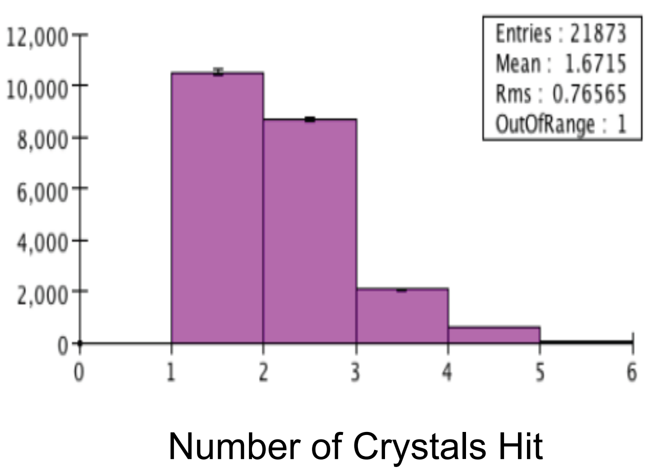


Ecal Performance

Color shows average crystal PH over Face of ECal



Cluster Size for tracks with p>0.6 GeV/c



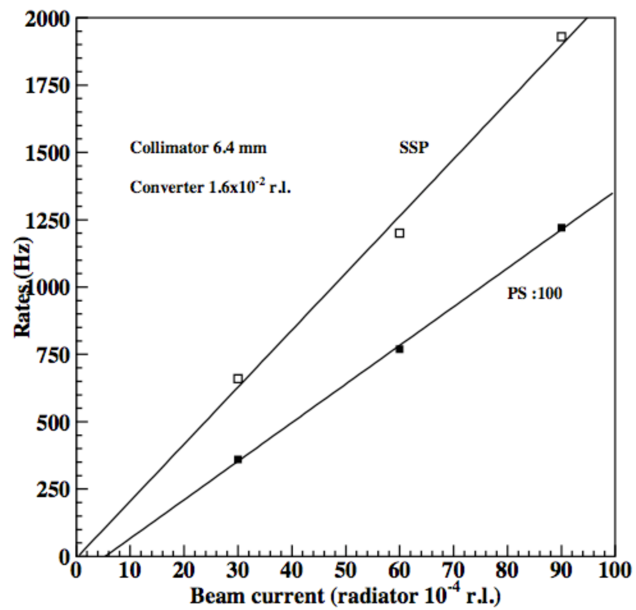
Number of Clusters/Event

Horizontal Crystal Number

Trigger Performance

- Timing of individual crystal hits is known to 4ns, with small channel to channel offsets.
- 8 ns coincidence window is fully efficient for trigger
- Experiment required top OR bottom Ecal clusters with E_{clus} > 270 MeV deposited. This catches all conversion pairs that hit the Ecal.
- Trigger rates are proportional to target thickness and beam current in the dedicated runs.

Trigger Rates ∝ Beam Current



Compare recorded trigger bits to offline analysis of Ecal data

Expectation Based on Ecal data

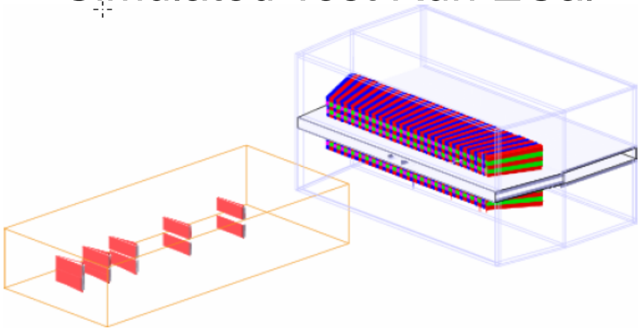
Trigger Bit Data

	Neither	Top	Bottom	Both
Top Fired	774	270003	2	1654
Bottom Fired	125	2	224070	1259
Both Fired	0	5	6	2953

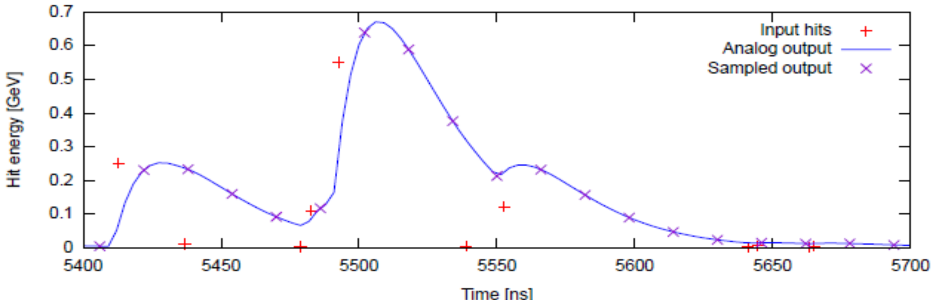
Refined Trigger Simulation Studies

- **Event pile-up and Ecal pulse width effects** have been added to the GEANT4 simulation of the HPS trigger.

Simulated Test Run ECal



Full time development of Ecal Pulses included



- **Performance at 2.2 GeV (200 nA)**
  *35 kHz trigger rate, compatible with previous estimate

  * 1% of useful events are affected by pileup

- **HPS trigger rates under control**

Trigger cut	75 MeV/c^2 A' acceptance	Background rate
Pairs of clusters in opposite quadrants	59.5%	1.8 MHz
Cluster energy between 100 MeV and 1.85 GeV	45.1%	725 kHz
Energy sum less than E_{beam}	45.1%	431 kHz
Energy difference less than 1.5 GeV	45.1%	386 kHz
Energy-distance cut	36.1%	80 kHz
Clusters coplanar to within 35°	35.3%	46 kHz
Not counting double triggers	34.4%	43.8 kHz
Applying trigger dead time	18.8%	34.8 kHz

HPS Technical Readiness

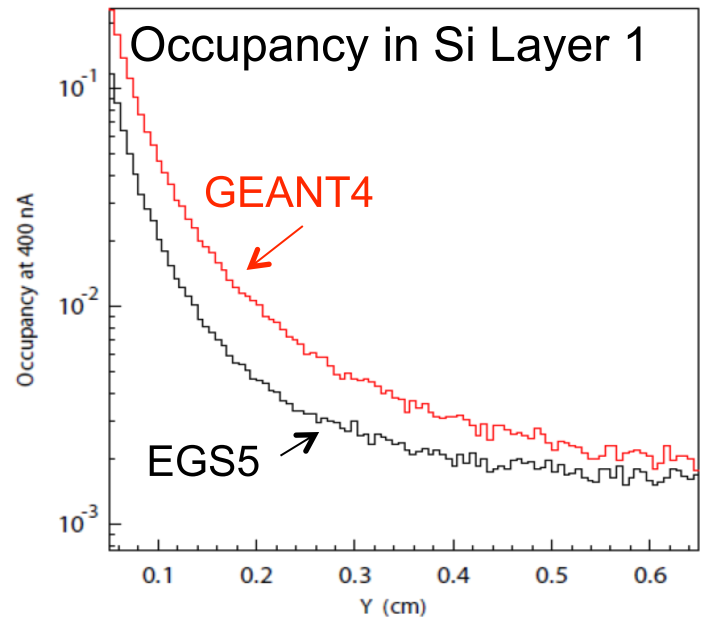
- CEBAF beam and new Hall B beamline optics have met HPS beam requirements
- Sophisticated tracking and calorimeter hardware has been built, installed, and successfully commissioned
- High Rate DAQ built and commissioned for SVT (ATCA) and Ecal (FADC250)
- High rate FADC trigger successfully implemented and tested
- Full MC trigger studies, including pulse width and pileup, confirm trigger rate estimates for full HPS

"Needed detector capabilities" have been demonstrated.

What else is needed to "ensure that HPS goals can be met" ?

Key: Tracker Occupancies and Trigger Rates

- **HPS can succeed if tracker and occupancies and trigger rates are manageable** in high luminosity running.



- **EGS5 and GEANT4 predictions for tracker occupancies and trigger rates differ by ~x2.** This discrepancy made us question the validity of these simulations generally.

- **Multiple Coulomb Scattering (MCS) of beam electrons passing through the HPS target is the principal cause of both tracker occupancies and Ecal trigger rates.** Simulation shows that this background far overwhelms any other .

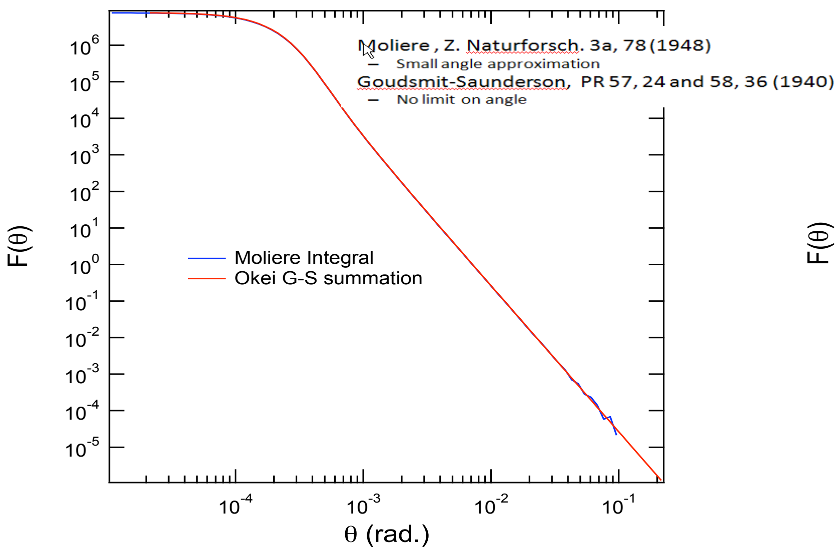
- **Understanding Multiple Coulomb Scattering is thus tantamount to understanding the backgrounds in HPS.**

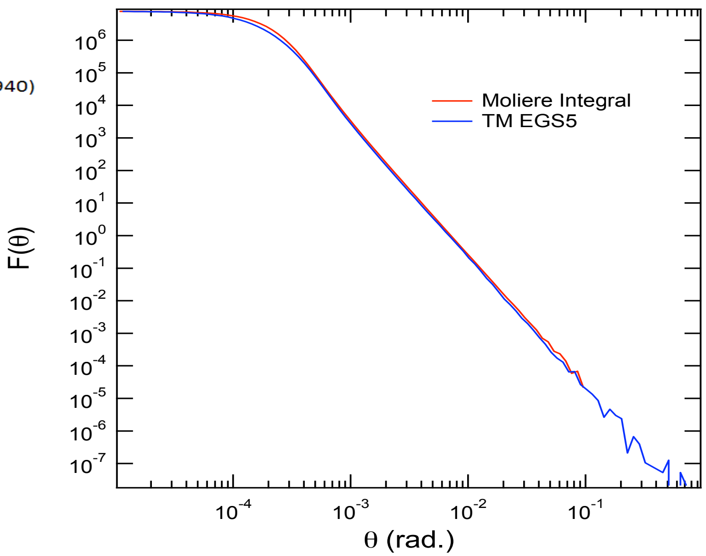
Understanding Multiple Coulomb Scattering

- **Further investigation** has shown the EGS5 calculation in very good agreement with MCS theory and the GEANT4 result in conflict with it. The inaccuracy in GEANT4 is due to time saving approximations and appears at θ > few mrad.

Moliere and Goudsmit-Saunderson provide formal MCS theory and agree

EGS5 agrees with Moliere & G-S

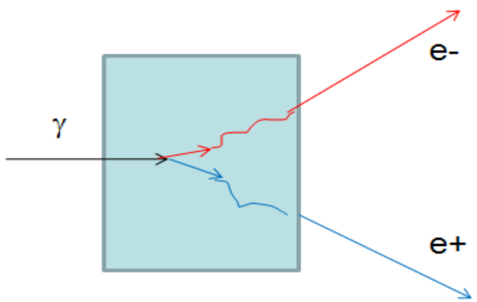




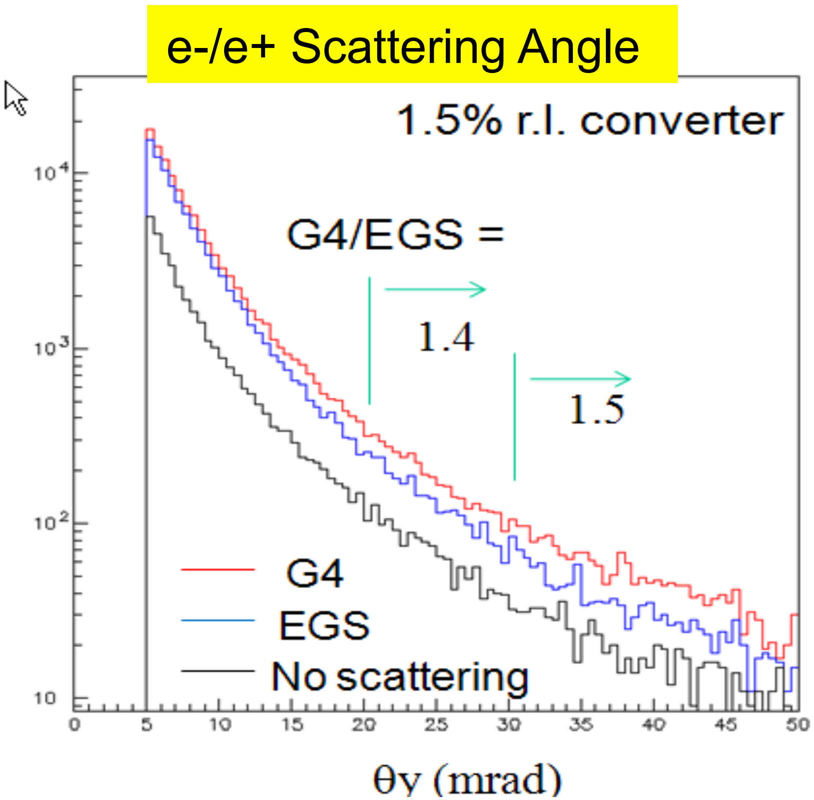
- **MCS *should be* well-understood, and is. EGS5 is right.**
- **Estimates of occupancies and trigger rates based on EGS5 simulation are solid. We are confident HPS goals can be met.**

Cross-check

- **Analysis of HPS Test Run data** taken during our dedicated run provides an additional crosscheck.
- **Compare the observed trigger yield with that simulated by EGS5.**
- **These yields depend on the pair opening angle distribution, and are sensitive to the tails of multiple Coulomb scattering**



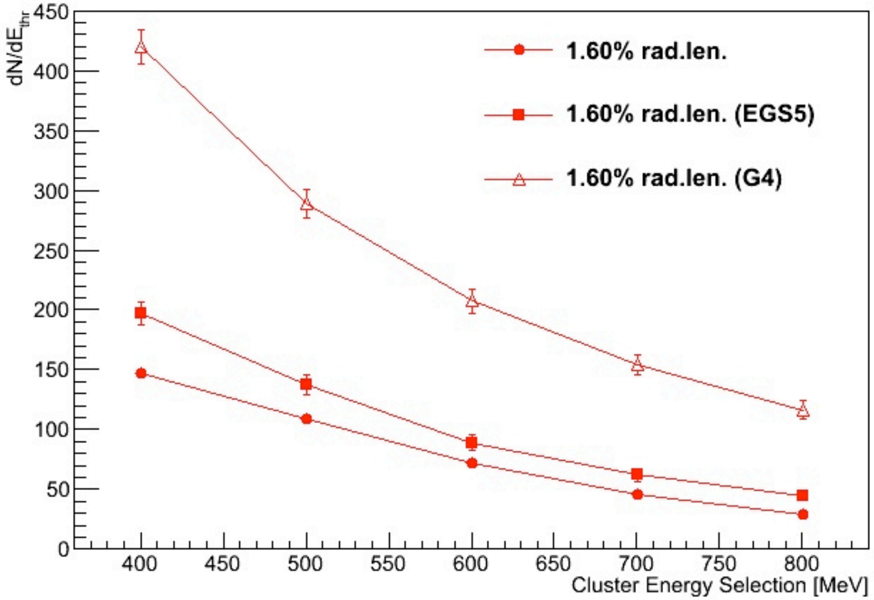
e+e- are not produced at 0 deg.
$\theta \sim m_e/E_\gamma$, but has a long tail.



Preliminary Result: EGS5 OK

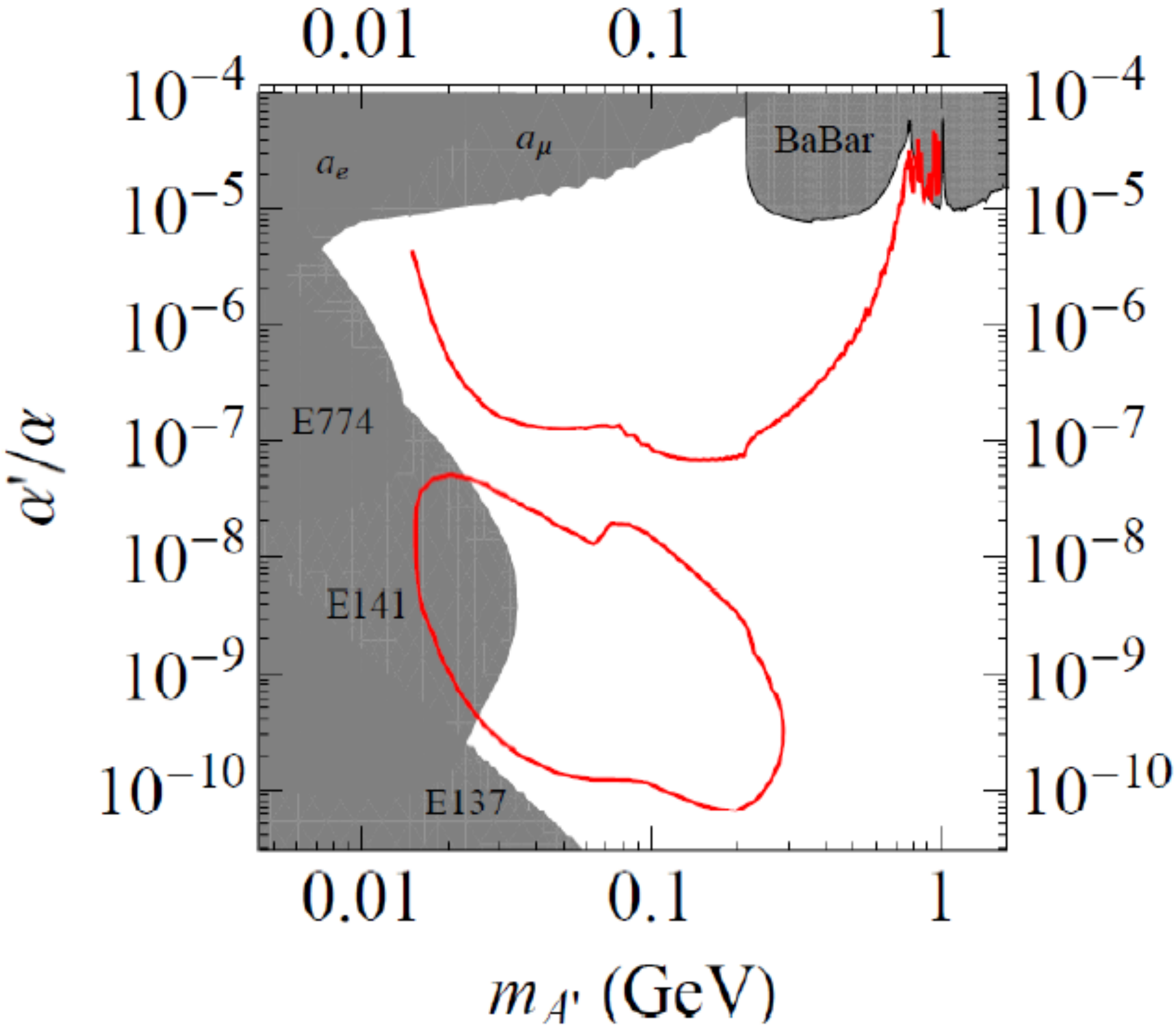
- **Measure triggering rate into Ecal acceptance (θ > 20 mr)**
  90% of this rate is due to electrons/positrons from photon conversion.
- **Require "good" Ecal region** (uniform gain, few bad channels, avoid boundaries)
- **Corrections**
  * account for DAQ dead time (< 15%)
  * subtract target empty run
- **Caveats** : First look at data; many systematics to study; lots to do

Triggers/90 nC vs Cluster Energy Threshold Top Ecal



- Similar agreement for 0.18 and 0.45% X_0 targets
- Threshold dependence as predicted
- Bot Ecal data is ~ factor 2 lower

The HPS Test Run has ensured that the goals of full HPS can be met



Full HPS

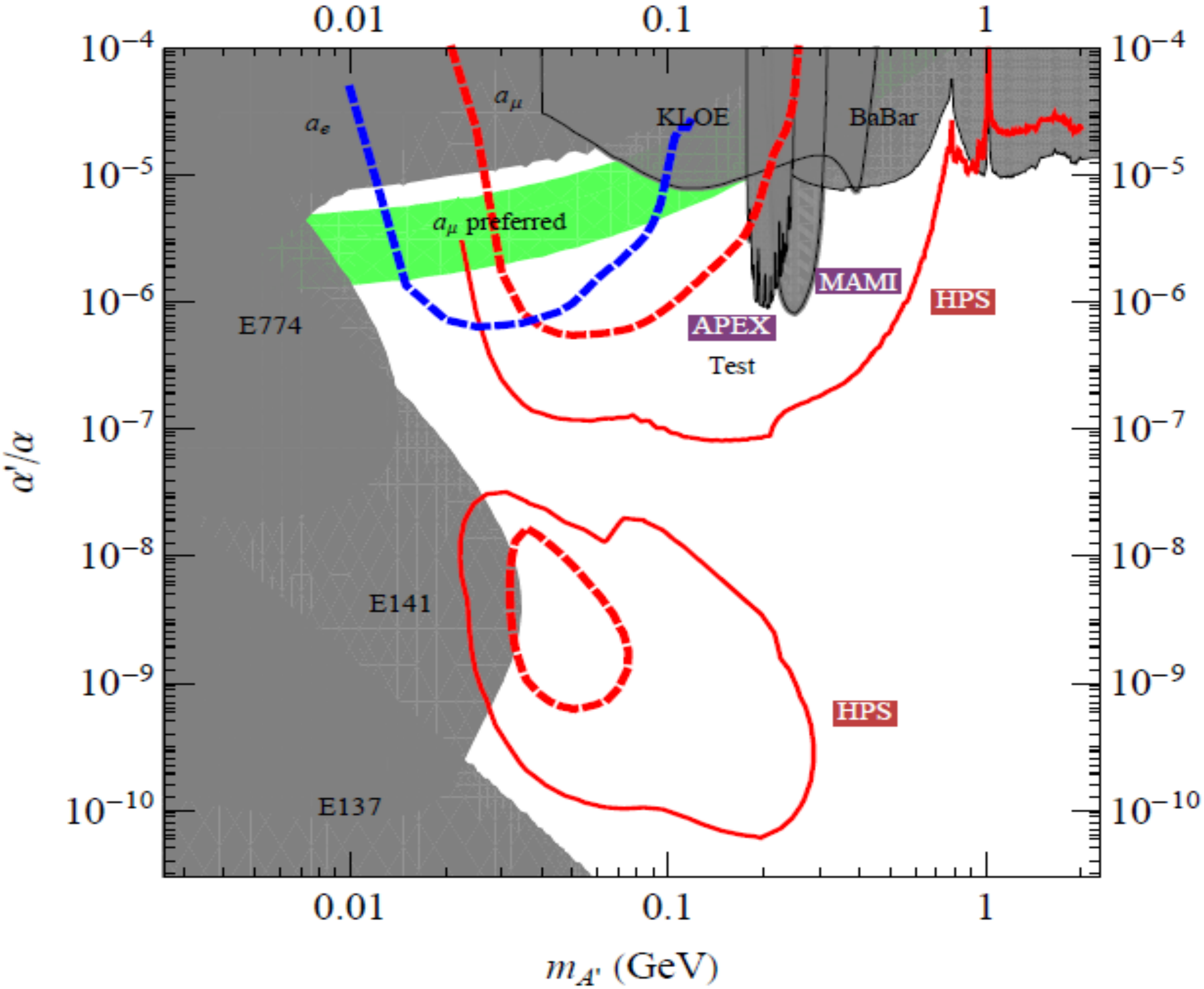
2.2 GeV 3 months

6.6 GeV 3 months

Conclusions

- The HPS Collaboration has successfully designed, built, installed, and commissioned the HPS Test Run Experiment in record time.
- Detector and DAQ capabilities needed for full HPS have been demonstrated.
- A thorough understanding of multiple Coulomb scattering of beam electrons ensures that occupancies and trigger rates for full HPS are under control, and that the goals of full HPS can be met. The test run result confirms this.
- We seek full approval in order to proceed to securing funding and beginning engineering and construction by Summer 2013. This will let us be ready for running at CEBAF12 in 2015.
- Timely approval is needed for HPS to remain competitive in this exciting search for new physics at the Intensity Frontier.

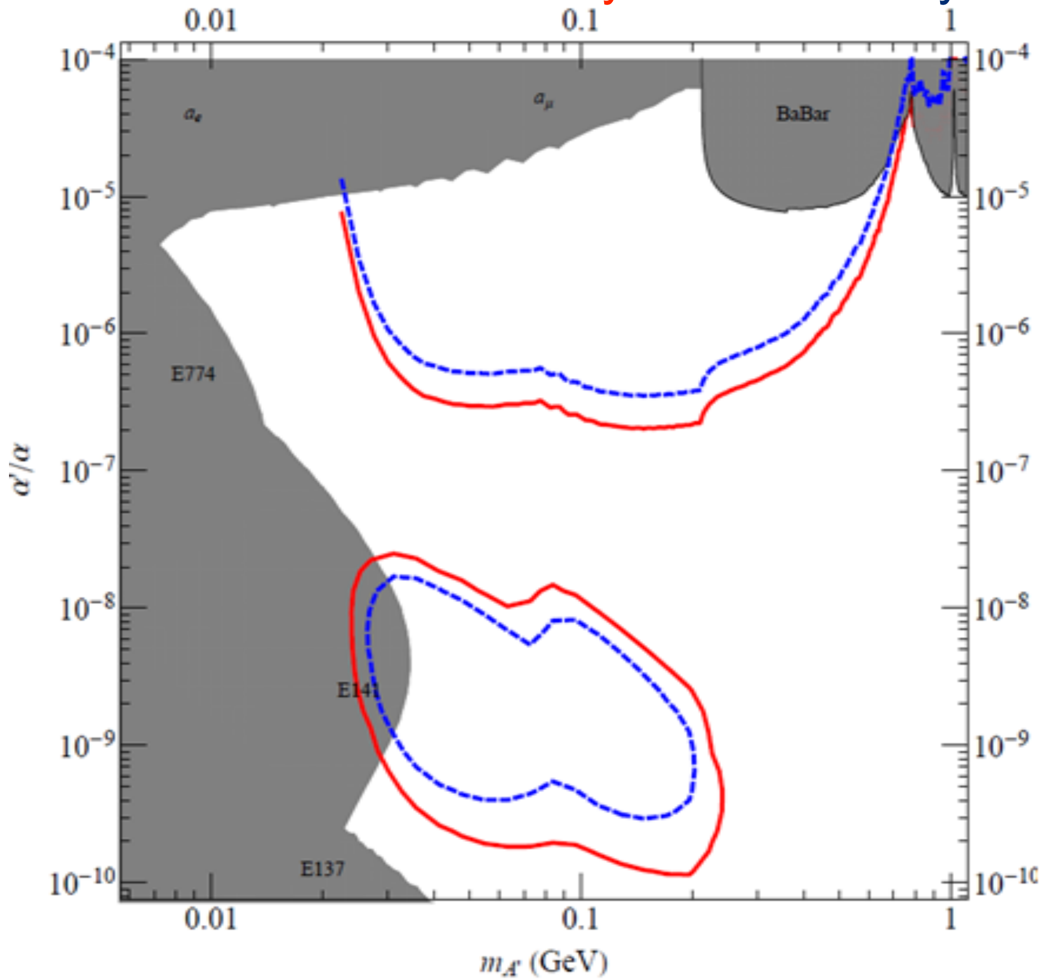
HPS Backup Slides


0.01
0.1
1
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
a_e
a_μ
KLOE
BaBar
a_μ preferred
MAMI
HPS
APEX
Test
E774
E141
E137
HPS
α'/α
$m_{A'}$ (GeV)

Sensitivity of Reach Estimate

Modest changes in accumulated in luminosity will not make or break the experiment.

5σ Reach Full luminosity 1/3 Luminosity



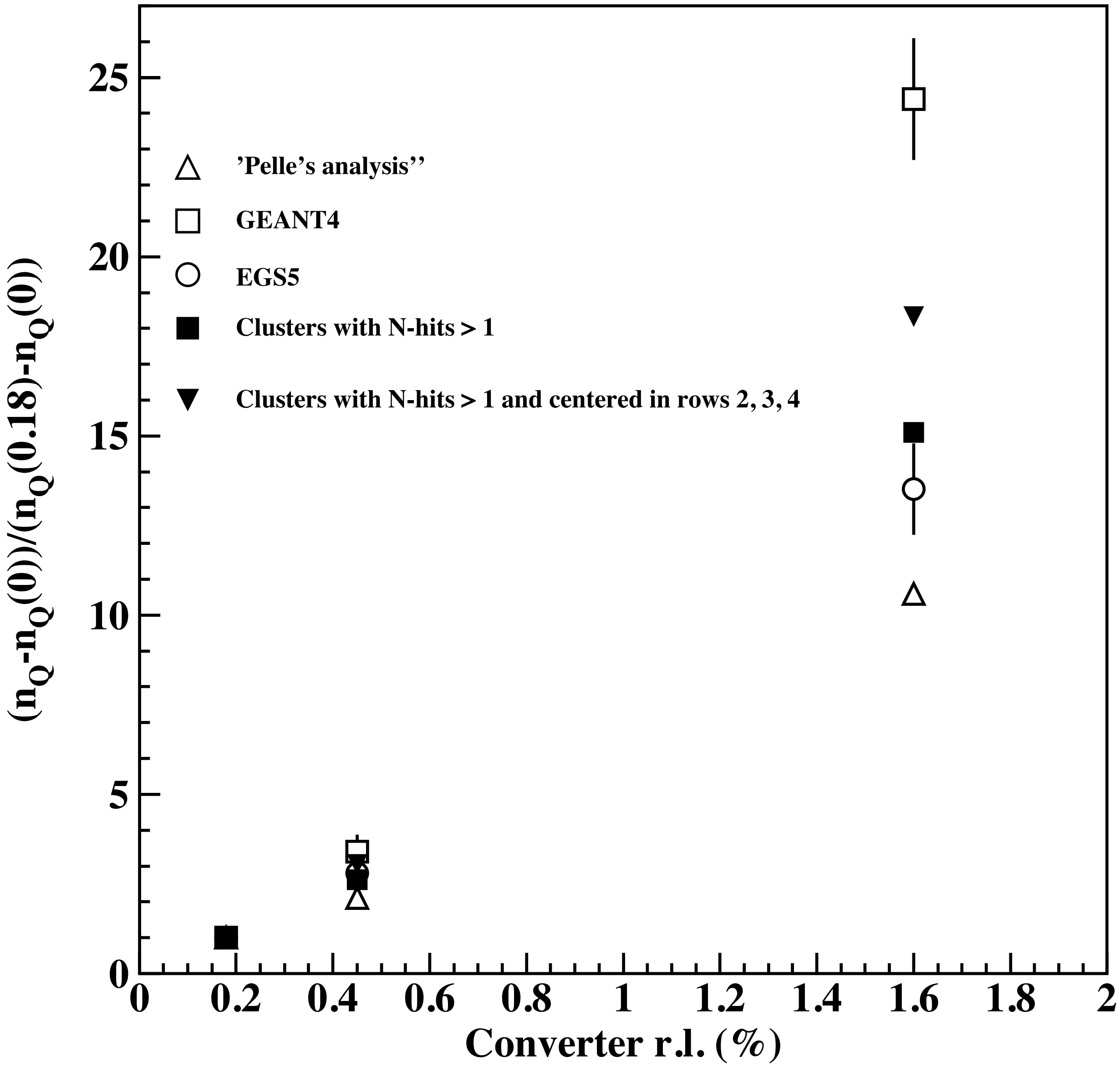
Trigger Performance

- Trigger bits register if top or bottom Ecal module triggered
- Trigger FPGA code has been fully simulated, allowing a comparison of actual triggering with an off-line analysis based on observed hits in the Ecal.
- Bottom Line: Trigger Works! Some fine points to investigate.

Expectation Based on Ecal data

Trigger Bit Data

	Neither	Top	Bottom	Both
Top Fired	774	270003	2	1654
Bottom Fired	125	2	224070	1259
Both Fired	0	5	6	2953



’Pelle’s analysis’’
GEANT4
EGS5
Clusters with N-hits > 1
Clusters with N-hits > 1 and centered in rows 2, 3, 4
$(n_Q-n_Q(0))/(n_Q(0.18)-n_Q(0))$
Converter r.l. (%)
0
5
10
15
20
25
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2