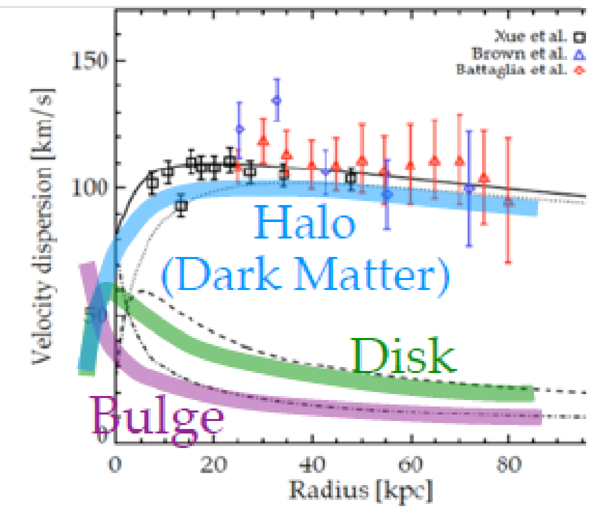
The Heavy Photon Search Experiment at Jefferson Lab

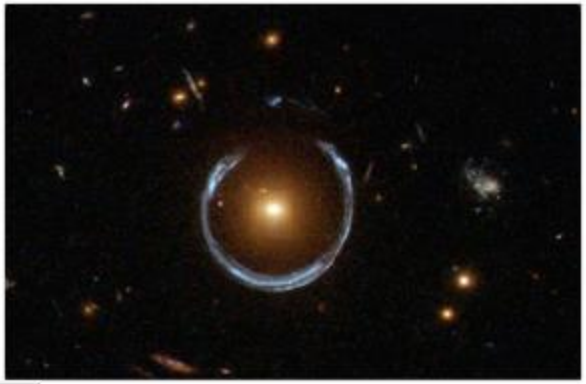
Takashi Maruyama, SLAC
For the HPS Collaboration
SLAC Summer Institute
August 10-21, 2015

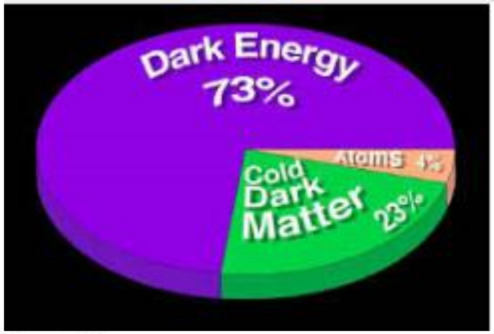
Ample evidence for Dark Matter

(Krnjaic)



Rotation curves
of spiral galaxies

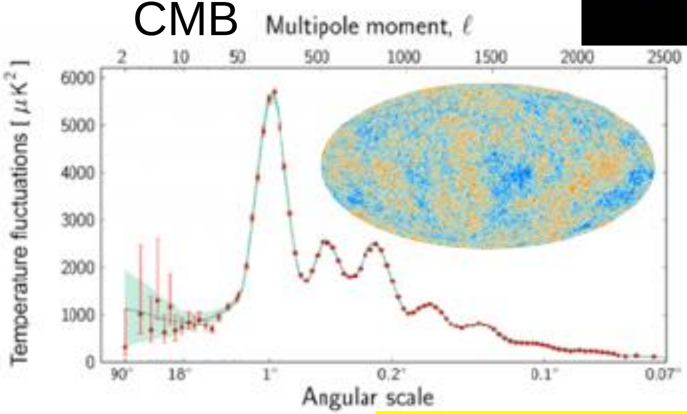




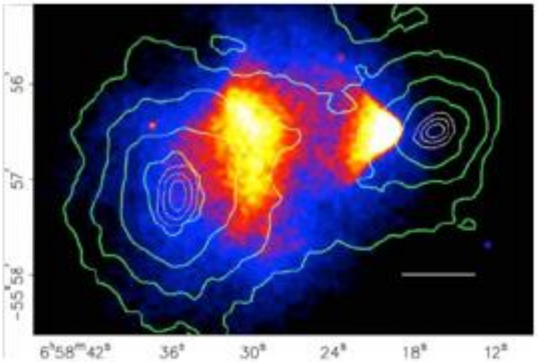
Gravitational lensing

DM Map:
PRL 115,051301 (2015)

CMB



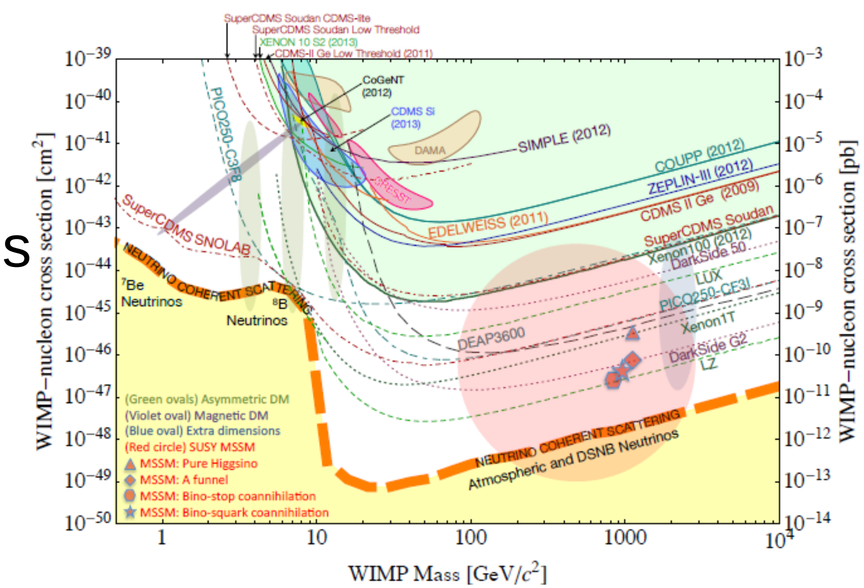
Cluster
collisions



See SSI-2014 “Shining Light on Dark Matter”

WIMP Dark Matter

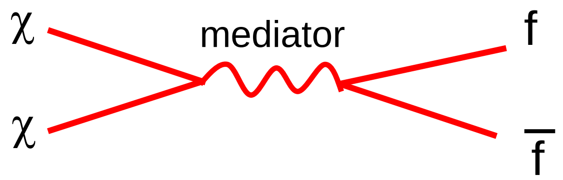
- Dark matter is Physics beyond the Standard Model.
  - Only gravitational interaction has been observed.
- WIMP miracle
  - SUSY WIMP with ~100 GeV mass was the most attractive candidate.
  - Dark matter relic density is consistent with the weak interaction scale.
- No experimental evidence
  - Direct DM detector searches
  - No SUSY at ATLAS/CMS
- Other possibilities?



Low Mass Dark Matter and Heavy Photon as a mediator

- Low mass dark matter, MeV ~ GeV.
  - Two PRL papers in the last few weeks: PRL 115, 021301 and 061301 (2015).
- Need low mass mediator
  - To be consistent with the DM relic density.

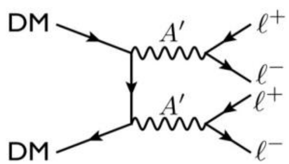
$$\Omega_{DM} \approx (\sigma v)^{-1}, \sigma v \propto \frac{m_\chi^2}{m_{med}^4}$$

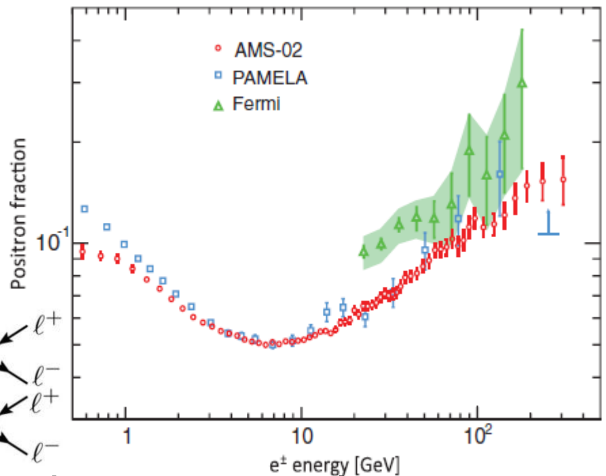


  - WIMPless miracle, PRL 101, 231301 (2008)
- HPS searches for the mediator.

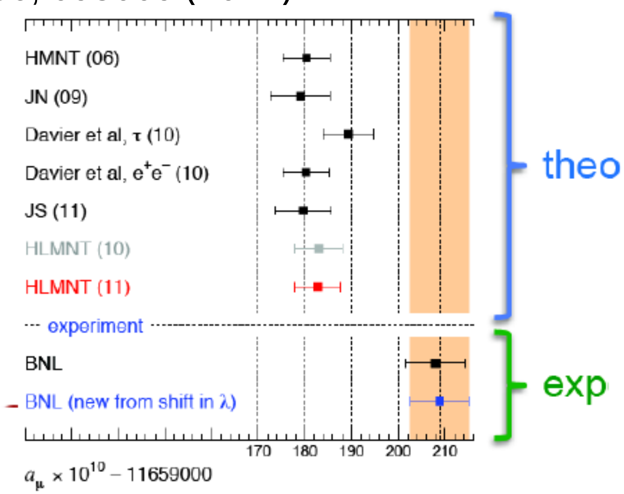
Anomalies got the heavy photon business going

- Cosmic positron excess

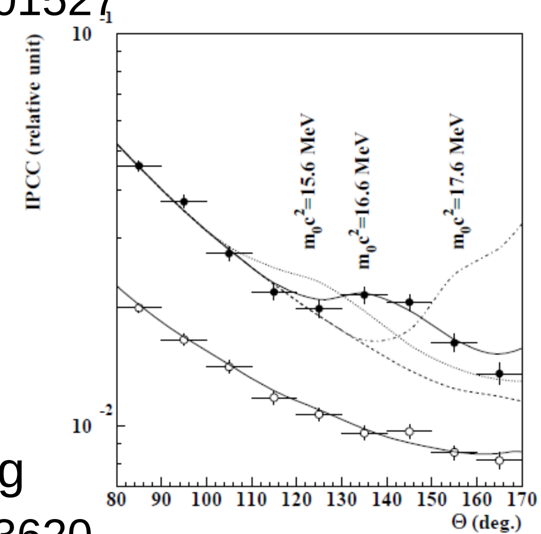




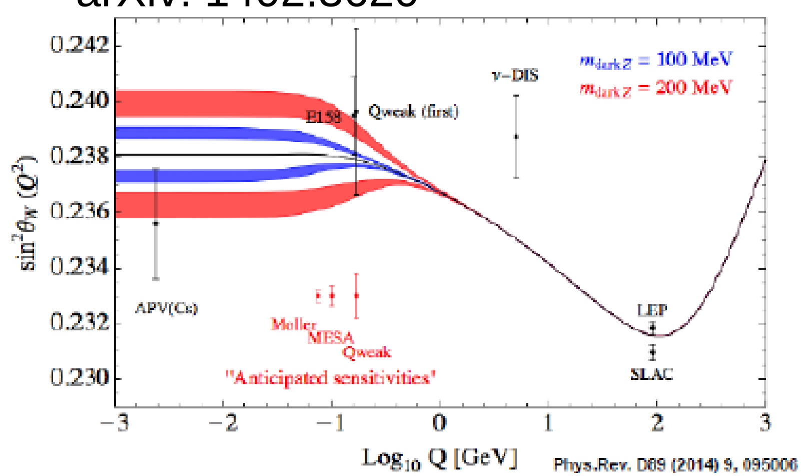
- Muon (g-2) 3.6σ anomaly
  - PR D86, 095009 (2012)



- 16.6 MeV anomaly
  - arXiv: 1504.01527



- Moller scattering
  - arXiv: 1402.3620

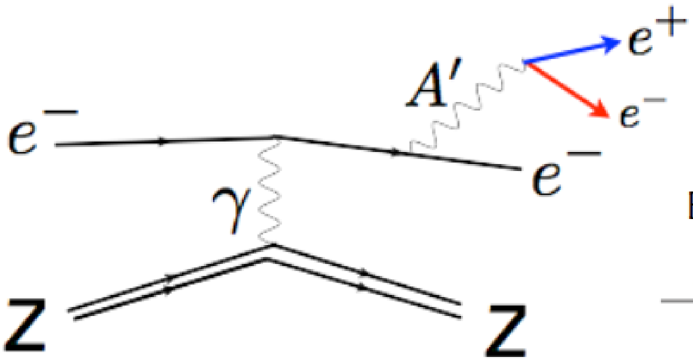


Ongoing heavy photon searches

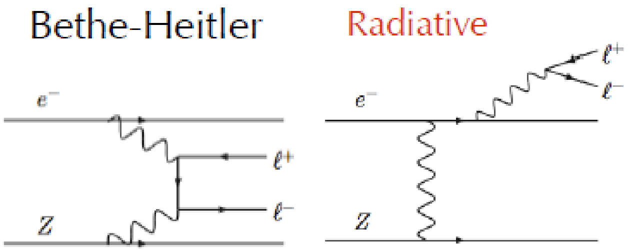
- Colliders
  - ATLAS and CMS at LHC
  - BaBar and Belle
  - KLOE at DAΦNE
  - PHENIX at RICH
  - WASA at COSY
- Fixed target
  - NA48 at SPS
  - APEX at JLab
  - HPS at JLab
  - DarkLight at JLab
  - A1 at MAMI, Mainz
  - MicroBooNE at FNAL
  - SeaQuest at FNAL (proposal)

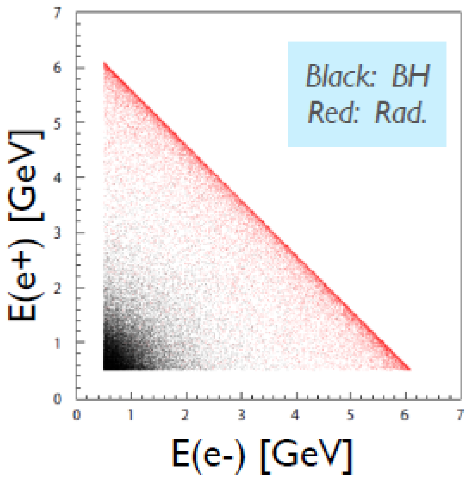
Fixed Target Searches

Look for radiated A' decay to e^+e^-, ($\mu^+\mu^-$)



$\sigma_{B\text{-}H}$ very large ≫ σ_{Rad}.
But kinematically distinct ➔
Use clever trigger to separate.





Very high luminosities:
Intensity Frontier Physics.

P. Schuster, R. Essig et al, Intensity Frontier WS '11 summary paper.

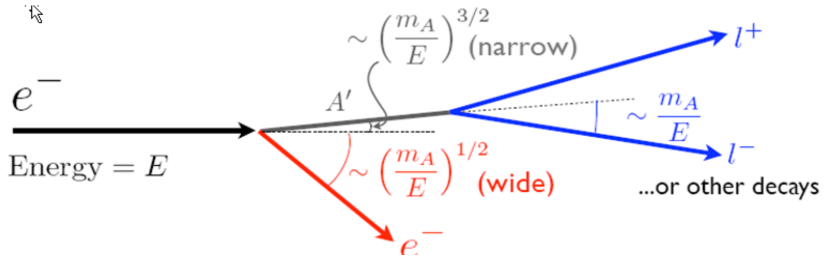
Bump Hunt:
Look for signal over background.

Bump Hunt + Vertexing:
Look for signal over background, reduce background with vertexing.

BEST: *Bjorken, Essig, Schuster, Toro, Phys.Rev. D80 (2009) 075018*

HPS Design Choices

- **A' kinematics ⇒ very forward production**

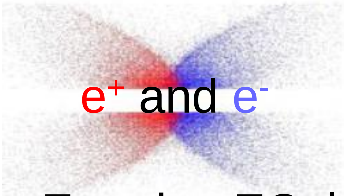


$E_{A'} \approx E_{beam}$
$\theta_{A'} \approx 0$
$\theta_{decay} = m_{A'}/E_{A'}$

- **Vertexing A' decays requires detectors close to the target**. Invariant mass is an essential signature, so good momentum/mass resolution is also required. Vertexing and bump hunting need tracking and a magnet.

Want $\Delta m/m \sim 1\%$ for bump hunt
Want $\Delta z \sim 1mm$

Beam's Eye View



Entering ECal

- **Trigger with a high rate, rad hard EM Calorimeter** Placed downstream of the magnet, it can ID e^+ and e^-.

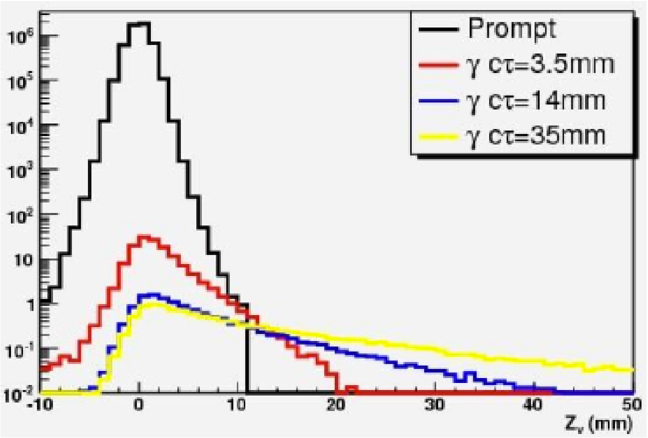
- **HPS opts for large forward acceptance/moderate currents. This requires placing sensors as close as possible to the beam.**

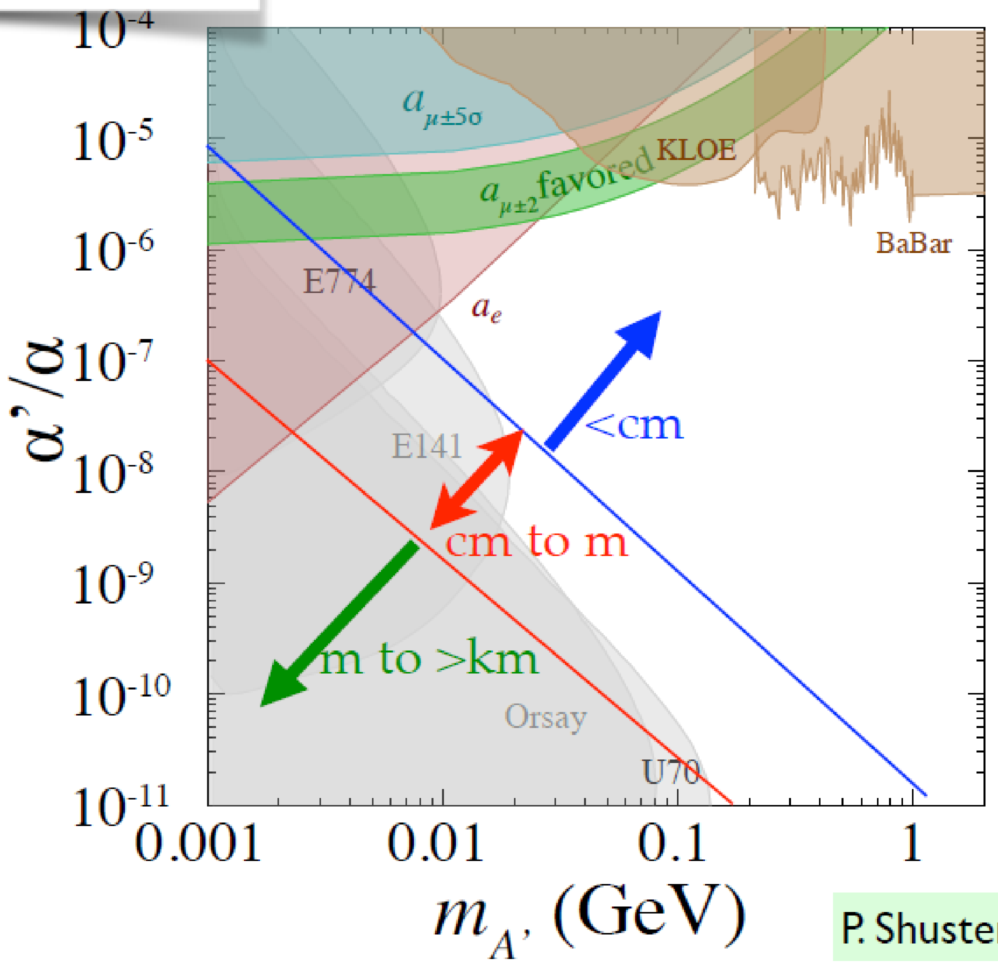
A' lifetime

$$\gamma c\tau \approx 1 \text{ mm} \left(\frac{\gamma}{10}\right)\left(10^{-8}\frac{\alpha}{\alpha'}\right)\left(\frac{100 \text{ MeV}}{m_{A'}}\right)$$

Lower α′, lower mass
→ longer lifetime

Background is all prompt
➜ Lower coupling can be reached using vertexing.





P. Shuster

Controlling Beam Backgrounds

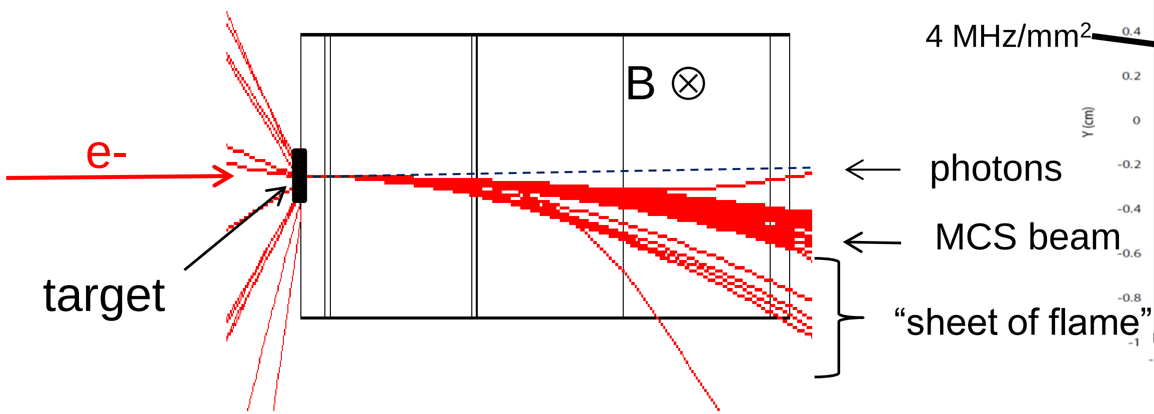
With sensors close to the beam (just ½ mm for the first Si sensor), background control, radiation damage, and beam stability become critical.

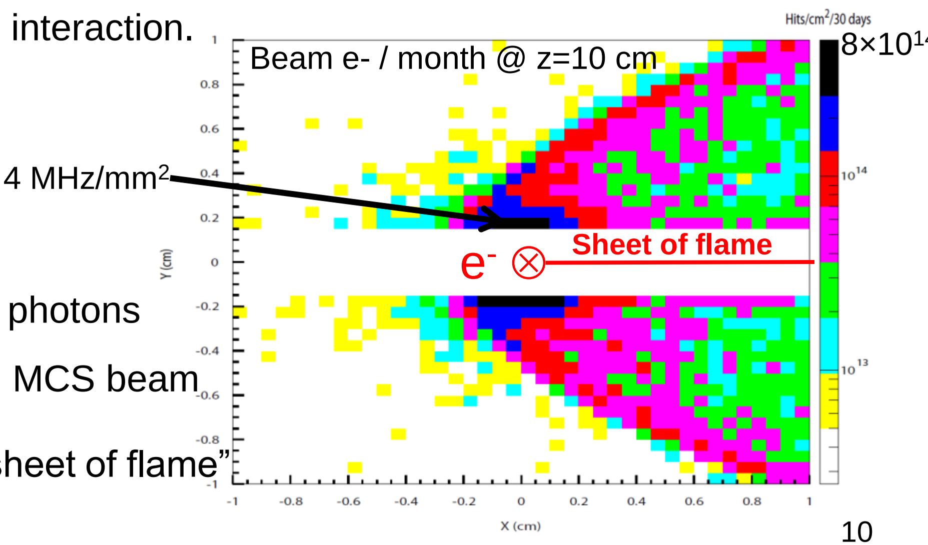
Constraints

- Avoid Multiple Coulomb Scattered (MCS) beam
- Avoid the "sheet of flame", the beam electrons which have radiated, lost energy, and been deflected in the horizontal plane by the magnet
- Avoid beam gas interactions.
- Avoid errant beam motions.

Design solutions

- Split the detectors top-bottom to avoid the beam and the "sheet of flame.
- Run the tracker in vacuum to eliminate beam gas interaction.
- Tightly collimate the incident beam.



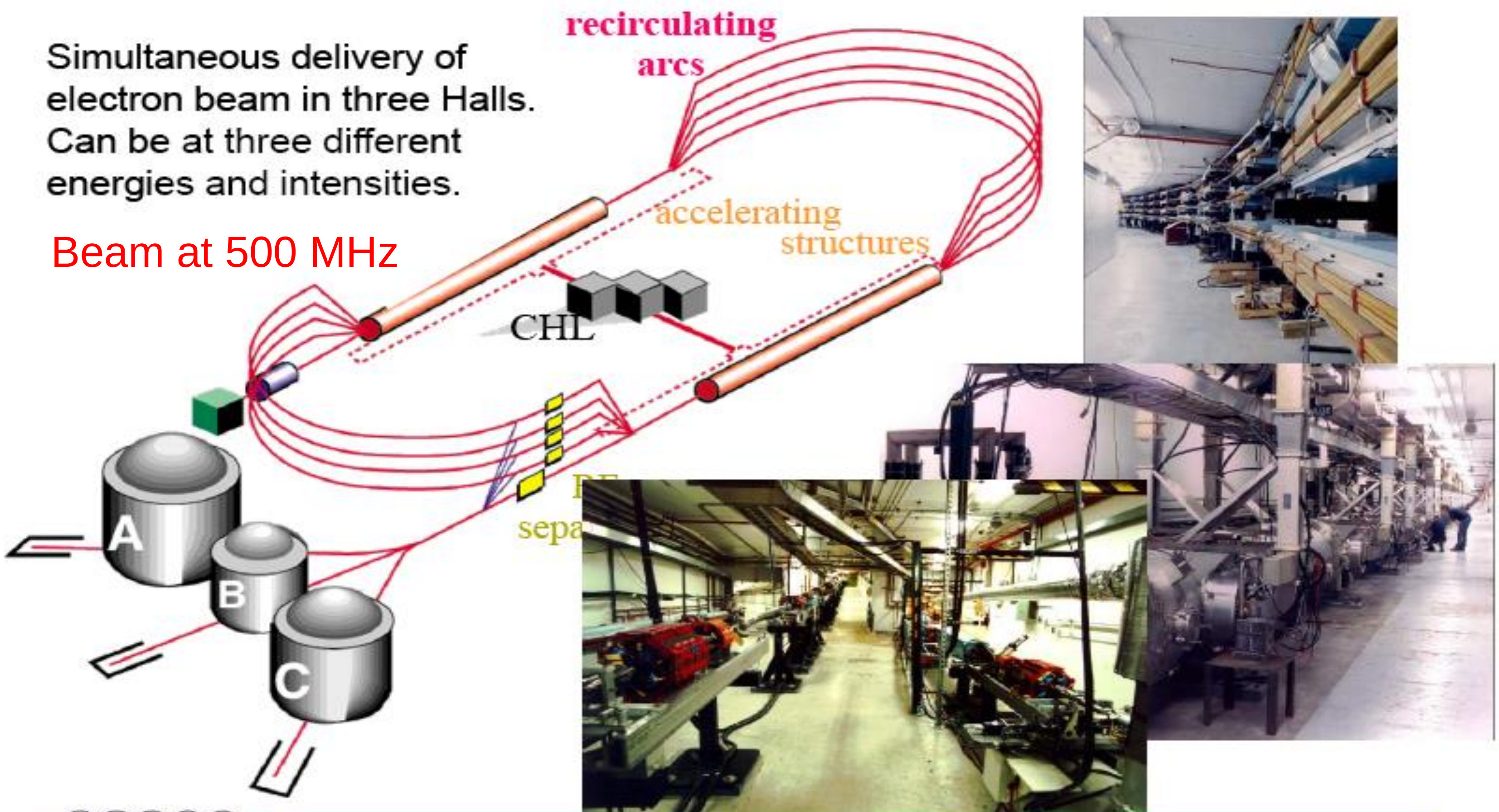


High Duty Cycle = CEBAF at JLab

CEBAF - Continuous Electron Beam Accelerator Facility

Simultaneous delivery of electron beam in three Halls. Can be at three different energies and intensities.

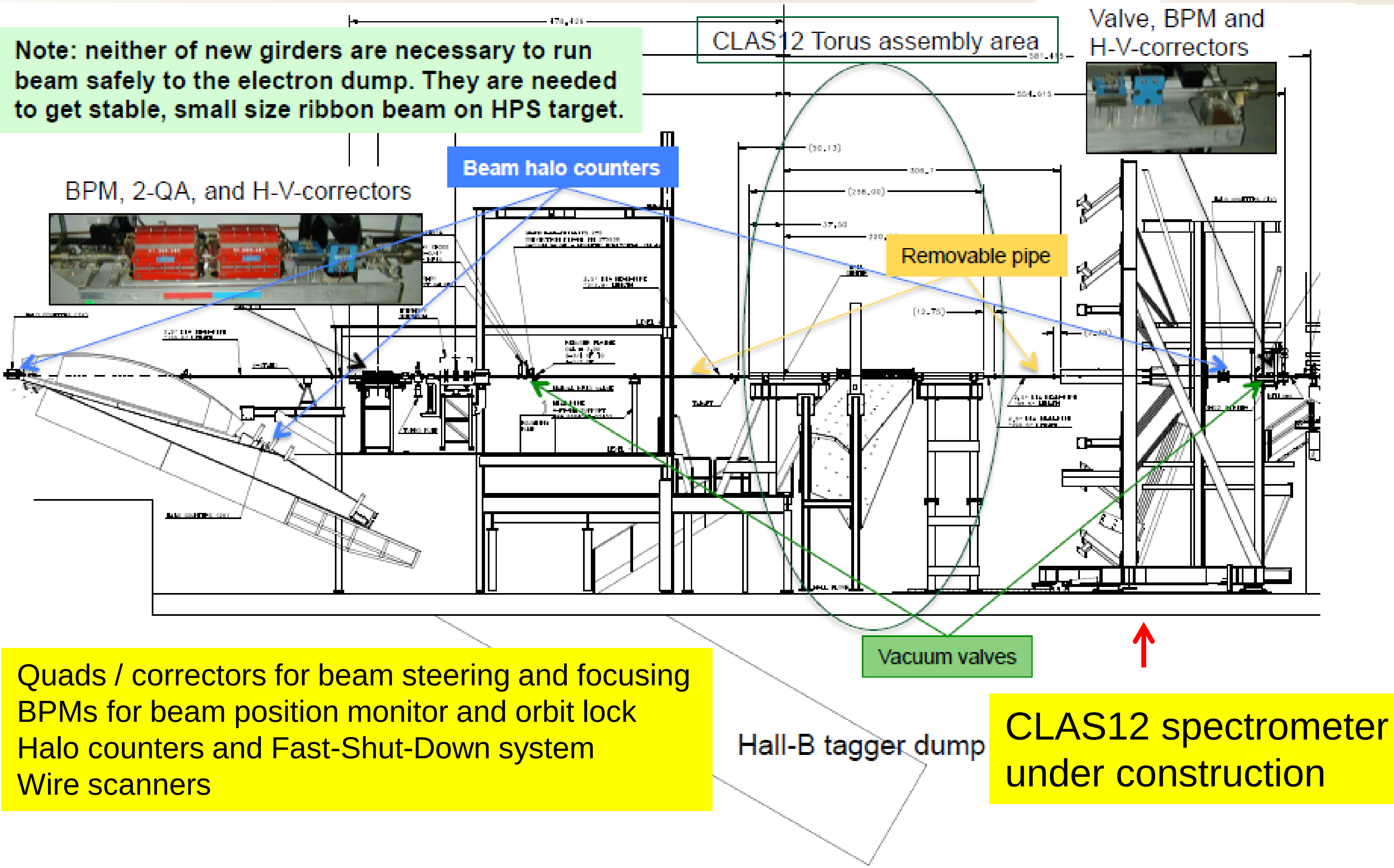
Beam at 500 MHz



Jefferson Lab
Thomas Jefferson National Accelerator Facility

Beam line in Hall B

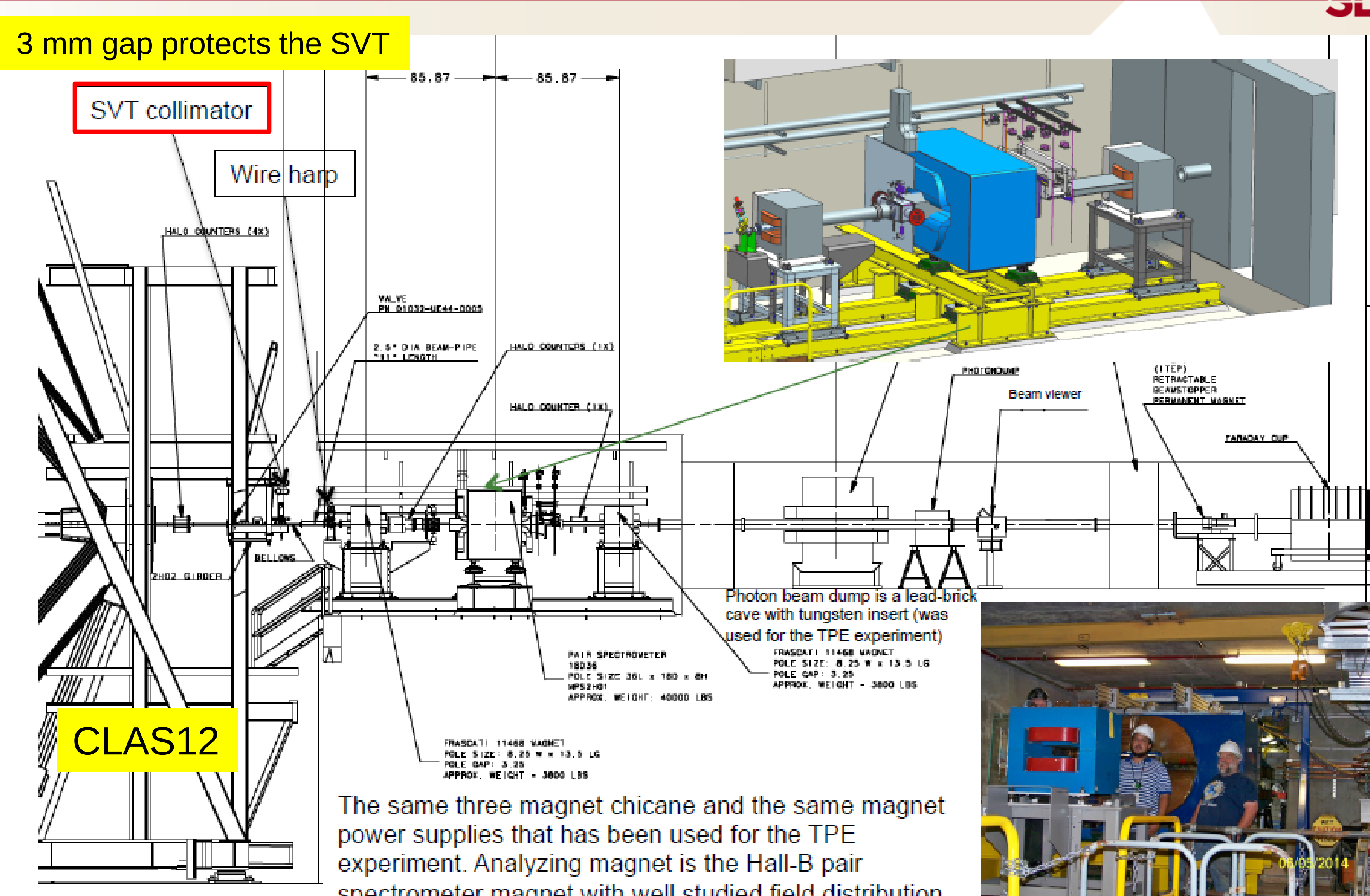
Note: neither of new girders are necessary to run beam safely to the electron dump. They are needed to get stable, small size ribbon beam on HPS target.



Quads / correctors for beam steering and focusing
BPMs for beam position monitor and orbit lock
Halo counters and Fast-Shut-Down system
Wire scanners

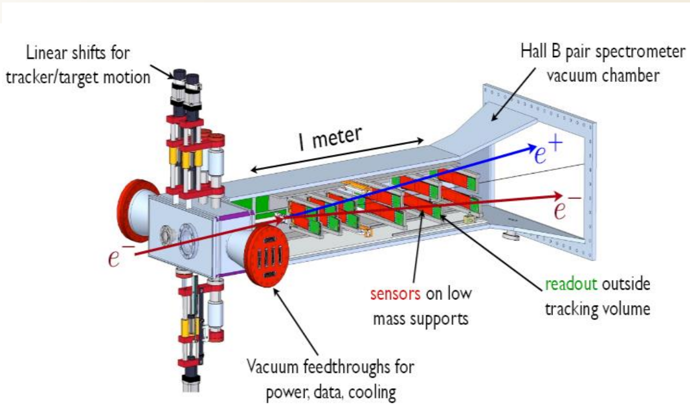
CLAS12 spectrometer under construction

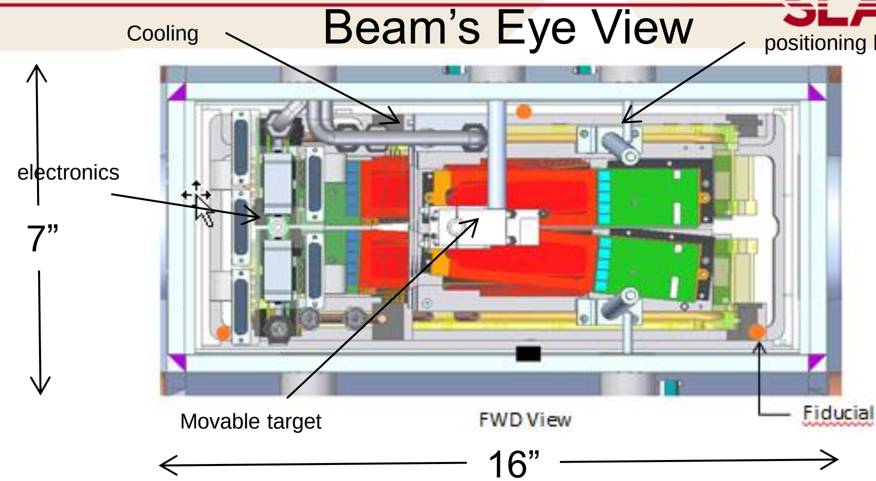
HPS in Hall B Alcove



The same three magnet chicane and the same magnet power supplies that has been used for the TPE experiment. Analyzing magnet is the Hall-B pair spectrometer magnet with well studied field distribution

HPS Apparatus: SVT



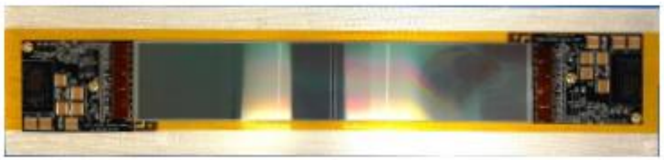
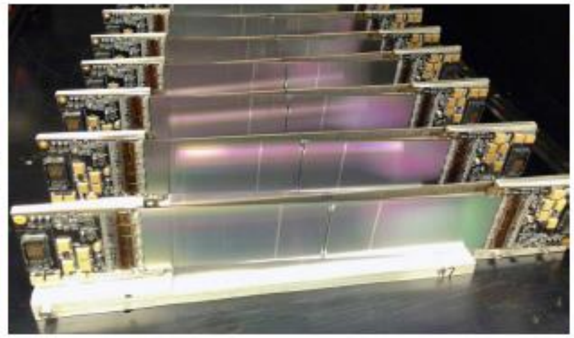
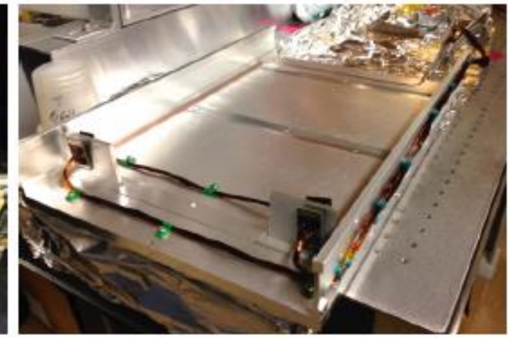
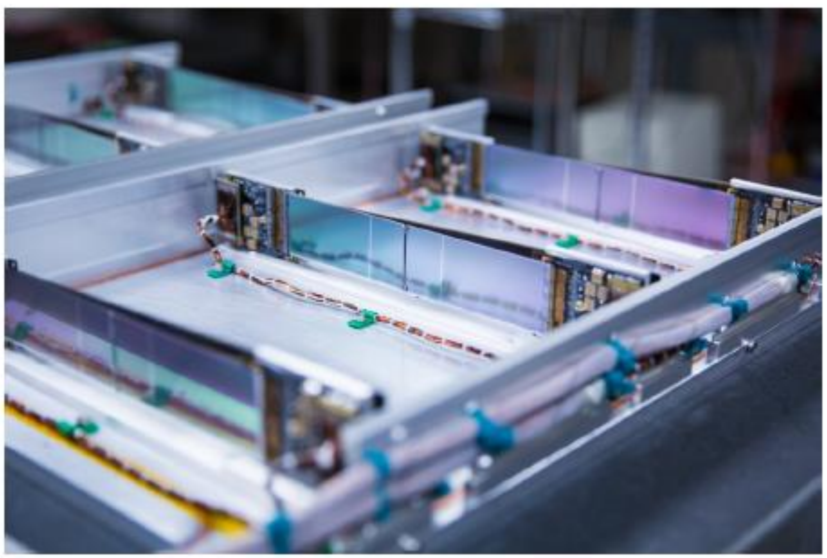


- **SVT Design:**
  - Six layers of Si modules, split top-bottom, each with two sensors: axial and stereo
  - 4x10 cm Hamamatsu microstrip sensor with 60 μm sense pitch.

- **Fast Readout**:
  - CMS APV25 chip , 40 MHz continuous amplitude sampling with 3 μsec latency.
  - Digitizing electronics and power distribution in vacuum.
  - Power and control in/data out through vacuum feedthroughs.
  - Electronics and sensors cooled < 0^0 C to remove heat and boost radiation hardness.

- **Precision Movers:**
  - Position layers 1-3 close to the beam, do wire scans, and insert targets as needed.

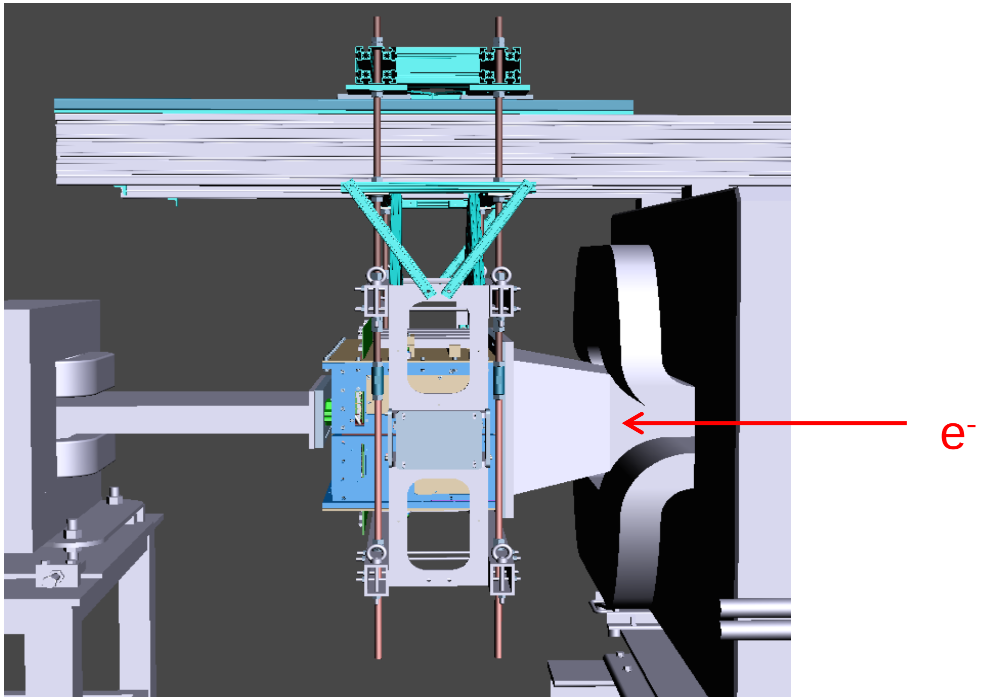
SVT Assembly at SLAC

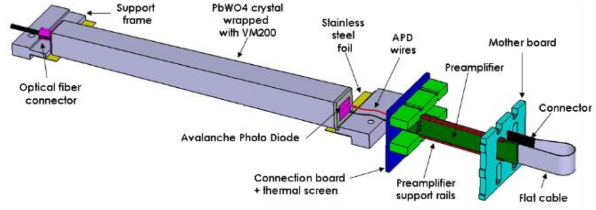

HPS Apparatus: ECal

- Top and bottom modules
  - 5 layers each
  - 442 lead-tungstate ($PbW0_4$) crystals in all
- APD readout through custom preamplifiers
- Data recorded with 250 MHz 12 bit FADCs
- A thermal enclosure to keep crystal temperature constant to ~1^0F to stabilize gains.

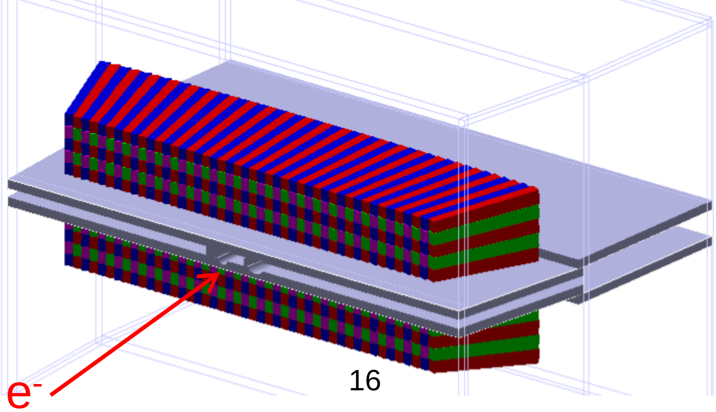
Ecal is downstream of SVT & magnet



$PbWO_4$ crystal with APD and preamp



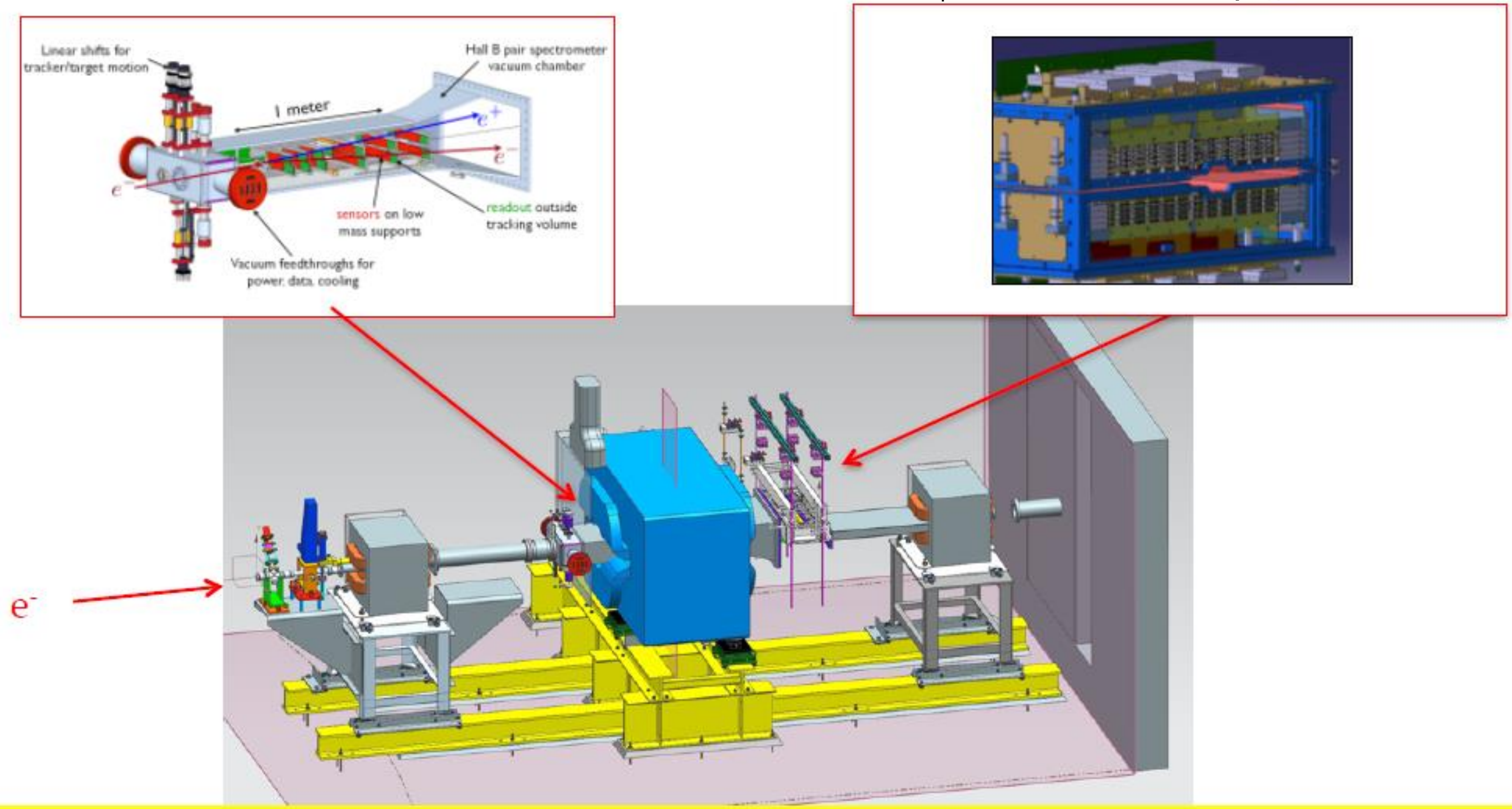
Crystals are arrayed above and below the Ecal vacuum chamber



HPS Setup in Hall B Alcove

Si Vertex Tracker Installed Feb 23, 2015

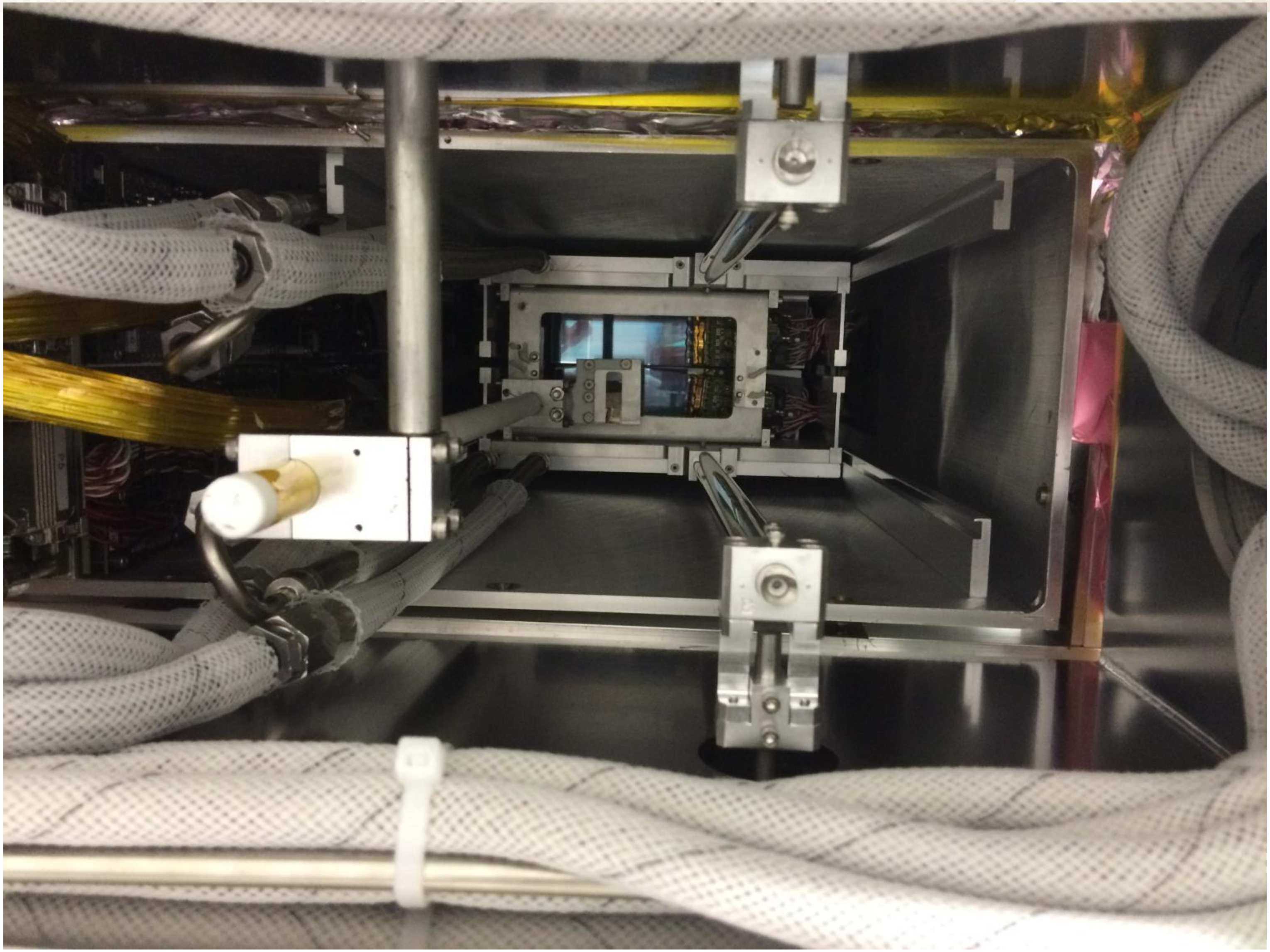
$PbWO_4$ ECal Installed September, 2014



A magnet chicane directs the CEBAF 12 electron beam onto a W foil, producing heavy photons. They decay to e^+e^- pairs, which are measured by the Si vertex tracker inside an analyzing magnet. A $PbWO_4$ ECal provides a fast trigger.

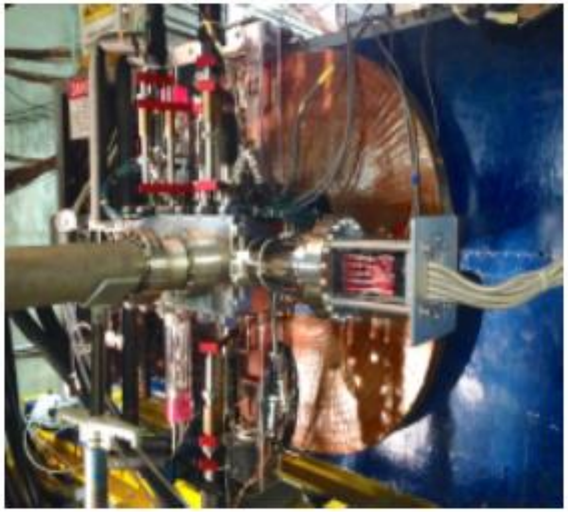
https://confluence.slac.stanford.edu/display/hpsg/Heavy+Photon+Search+Experiment

Beam's Eye View of the SVT



Spring 2015 Engineering Run

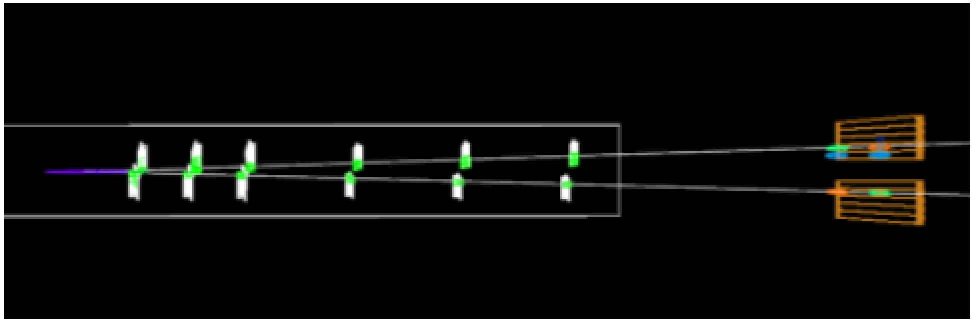
Opportunistic run: other Halls had a priority and the 12 GeV work was carried out during week-day day shift.



- Installed SVT end of February
- Commissioned Hall B beamline March-April
  - Calibrated bpms & established orbit locks
  - Set up SVT Protection Collimator
  - Checked beam position stability
- CEBAF down for two weeks after power outage
- Commissioned Trigger and Integrated SVT DAQ late April
- Explore SVT backgrounds as moved SVT closer to beam
- Production running at 1.5 mm started May 1
- Production running at 0.5 mm started May 12
- Run ended May 18th.

Layer 1 silicon sensors are just 0.5 mm above and below beam. Min. opening angle is $\theta y = 15$ mrad.

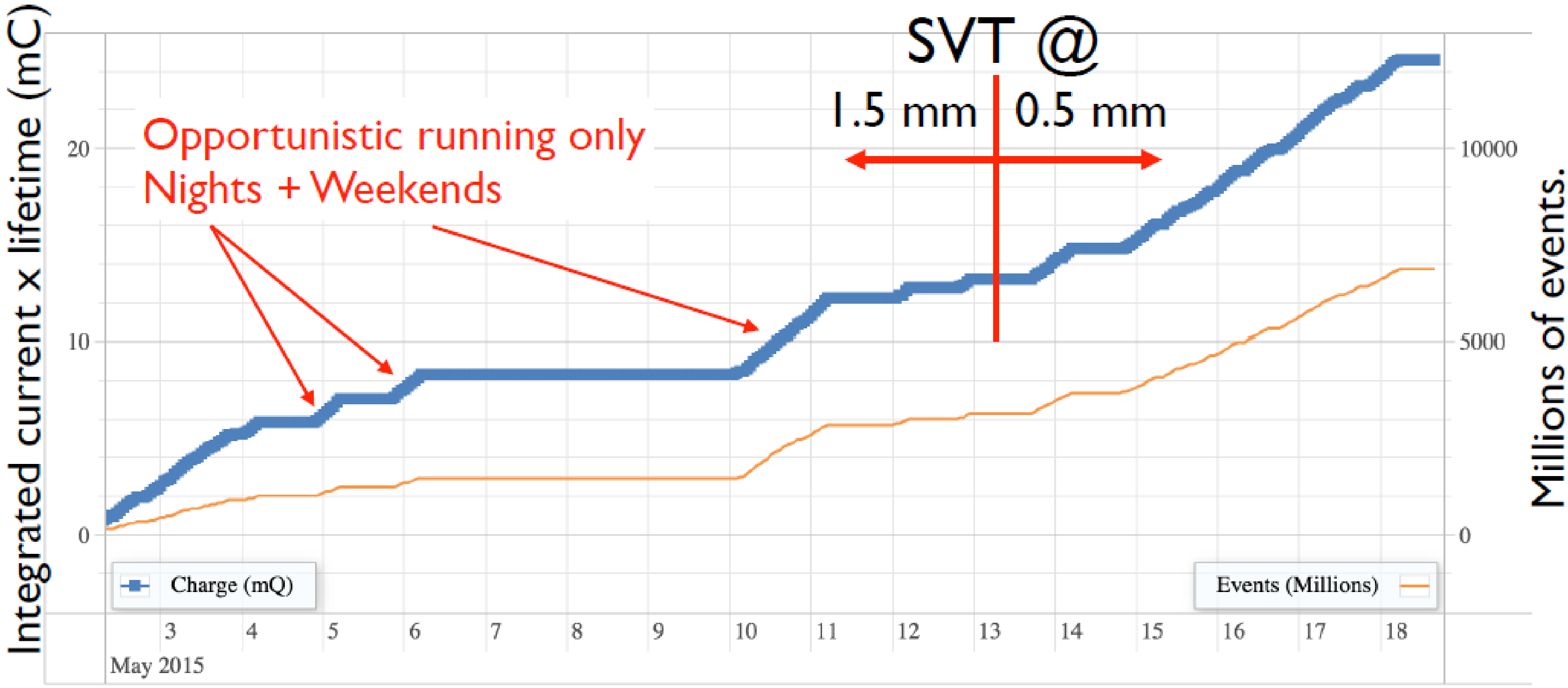
Run 5623
Event 62



1 GeV Run, Charge on Target

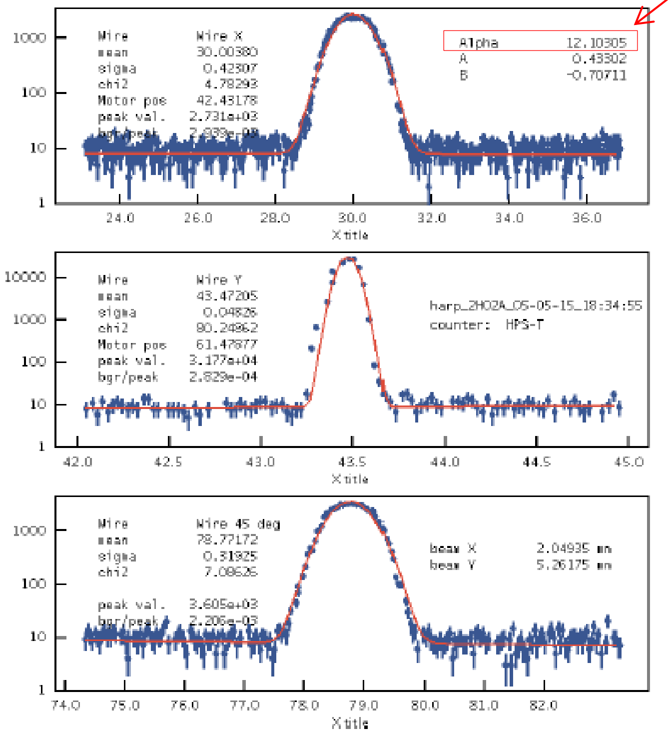
SLAC

Proposal: 1 full week of 50 nA beam on target, 30mC
Achieved: ~10 mC with SVT at 1.5mm, 10 mC at 0.5 mm



Beam Quality

Small skewness



X,Y and 45 degree beam profiles. May 5th, 2015

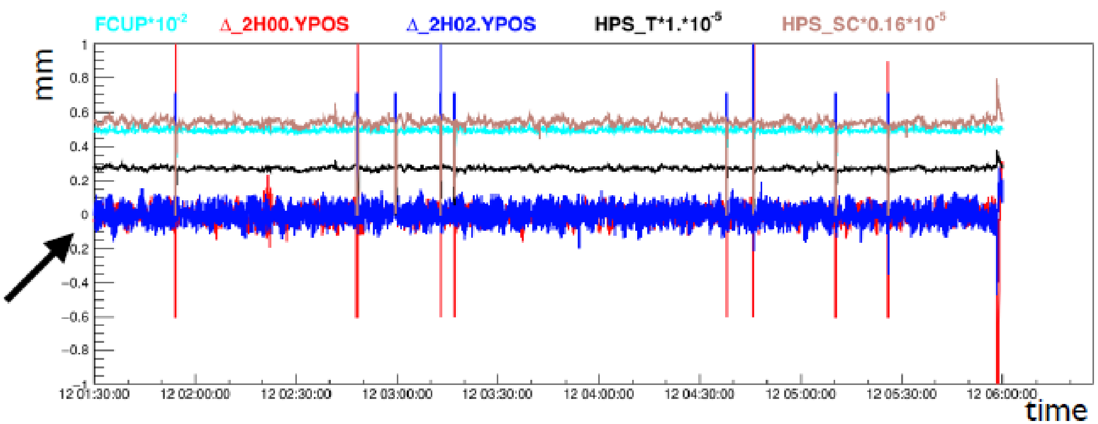
Very stable beam on May 12th.

HPS requires a very high quality beam, with very low halo.

σ_X ~ 300 to 500 μm - To spread heat load.

σ_Y ~ 15 - 50 μm - To help vertexting & tracking.

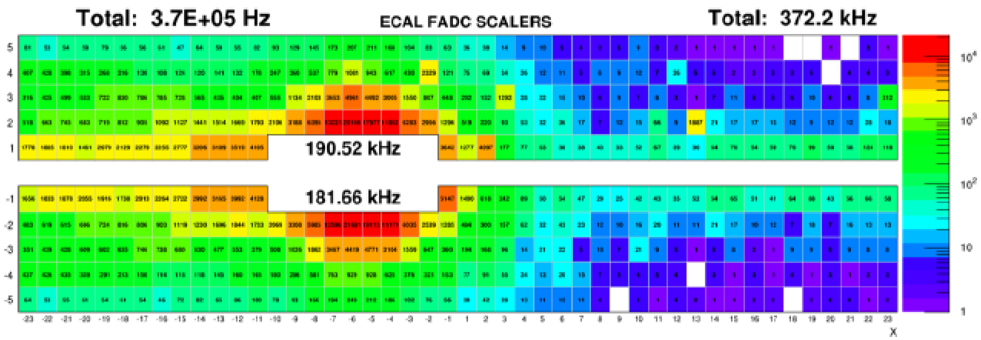
The beam also needs to be very stable over time. A Fast Shut-Down stops the beam in <10 ms, if halo counters register above threshold counts.



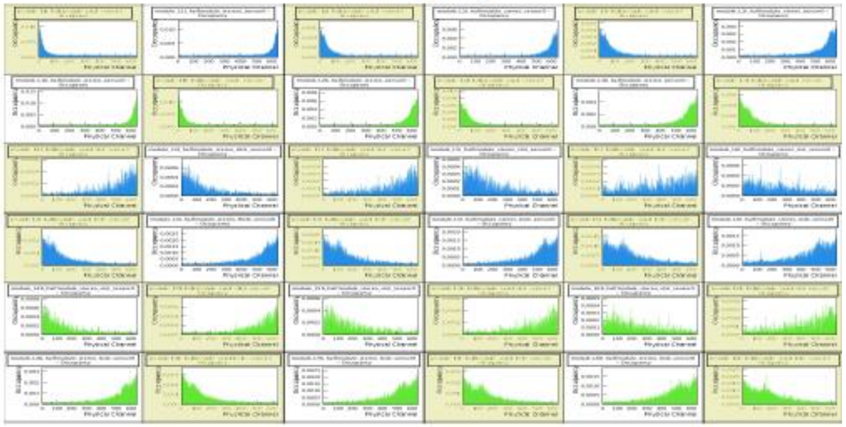
Online data quality

SLAC

ECal single rates



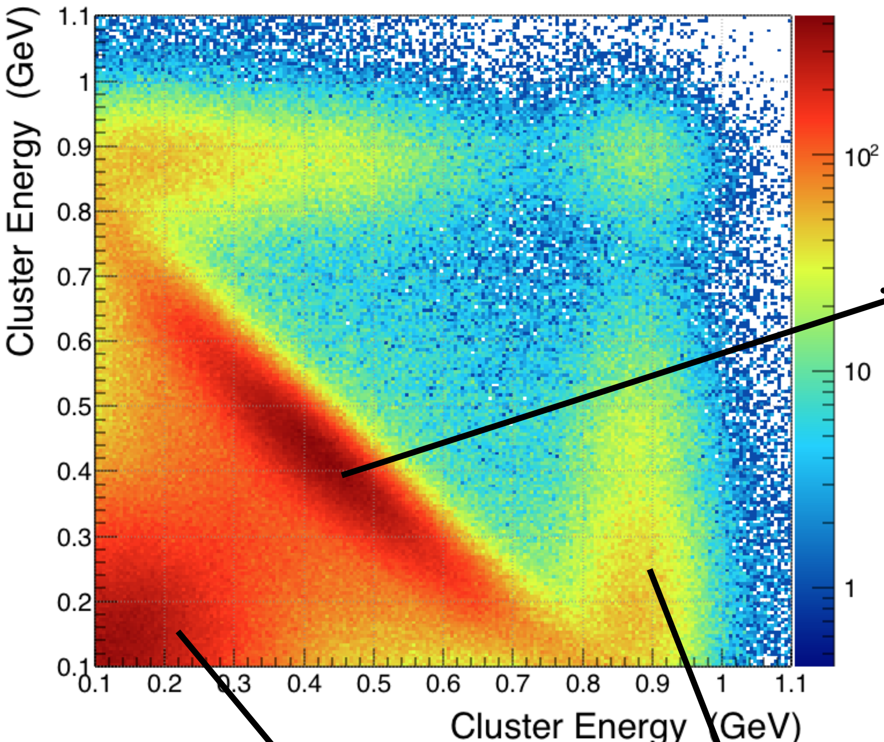
SVT Occupancy



Trigger rates

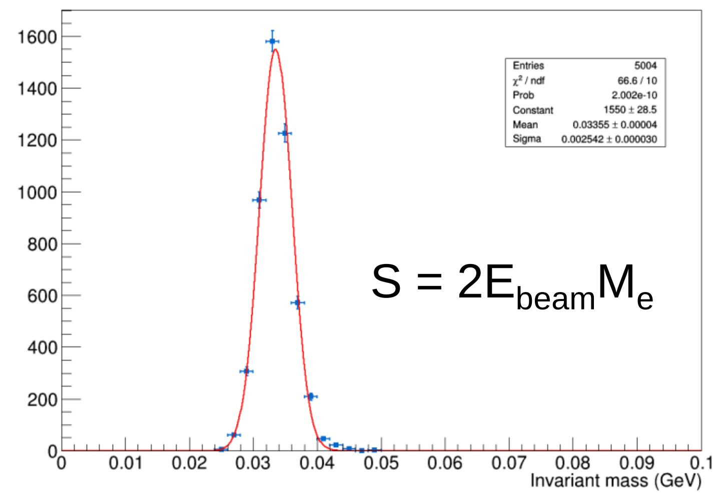
In good agreement with simulations.

Two Cluster Events



Mollers

invariant mass - mollers



$S = 2E_{beam}M_e$

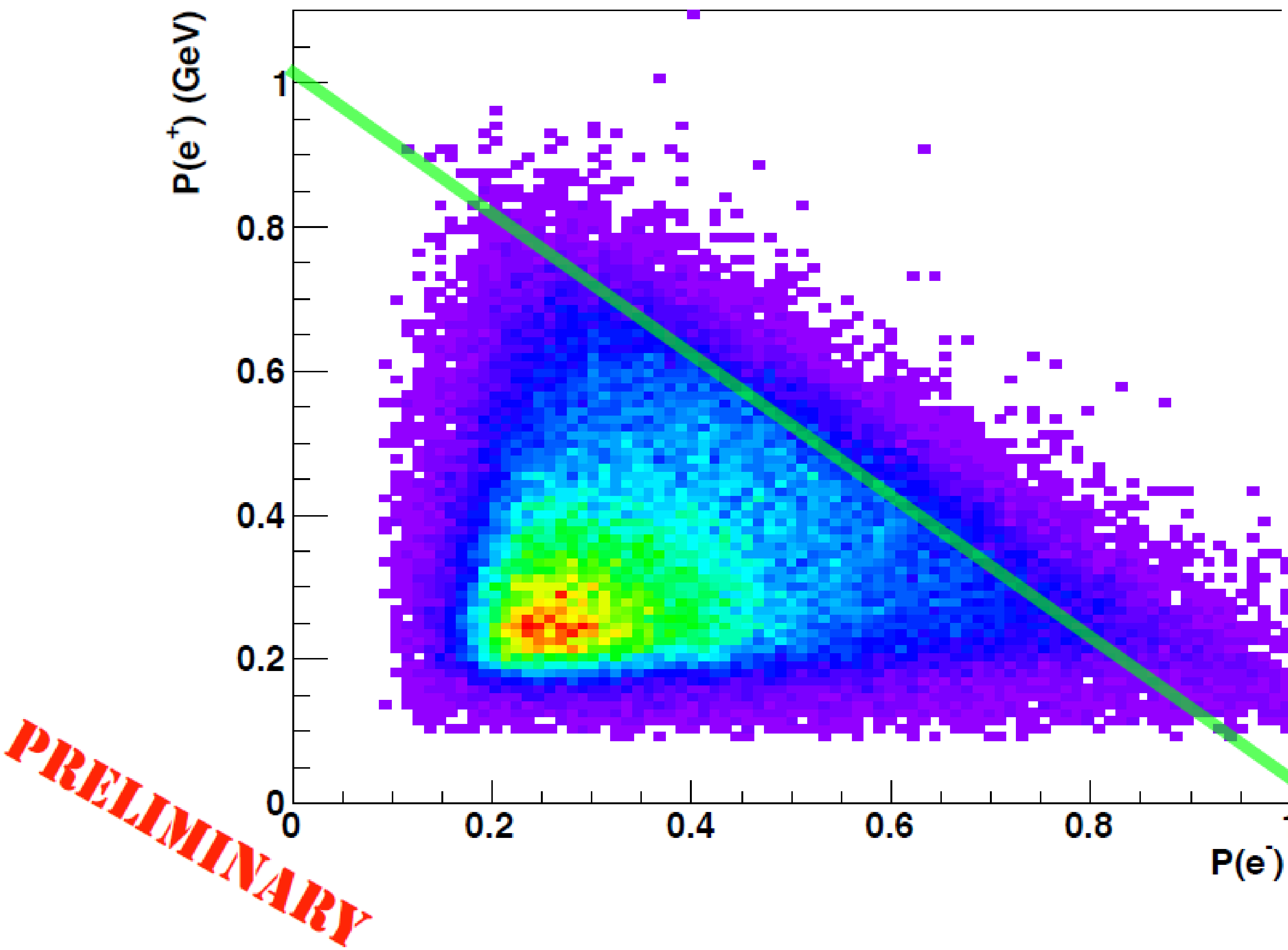
- Momentum/energy calibration
- Mass resolution

Tridents

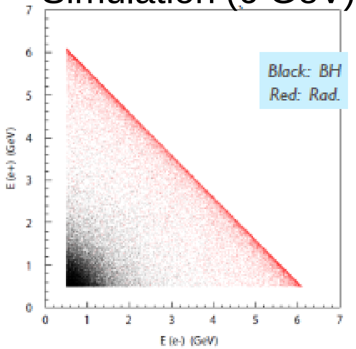
Beam background

Tracked Pairs at 1.5 mm

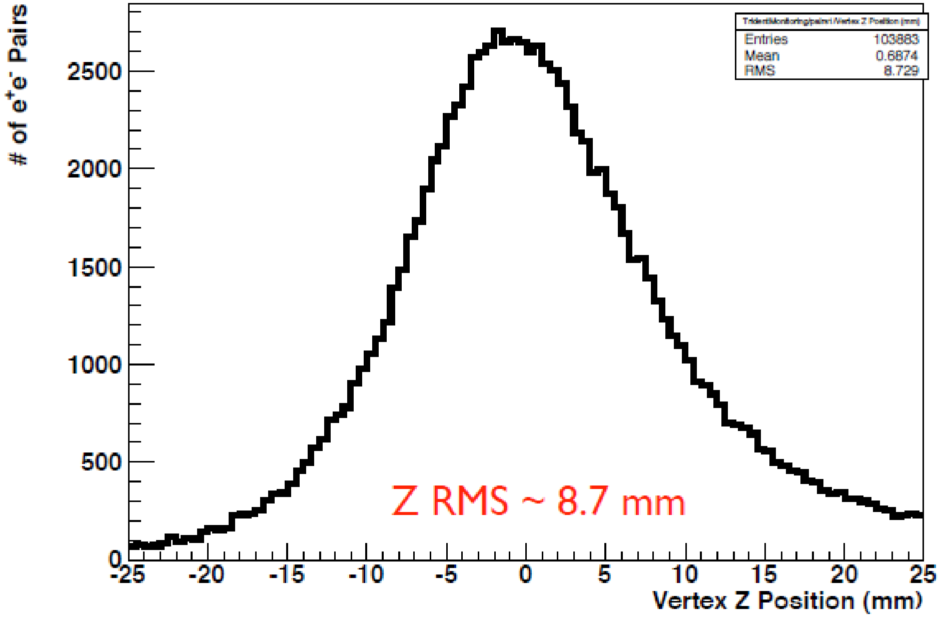
A' candidates have Pe+ + Pe- ~ Pbeam = 1.05 GeV



Simulation (6 GeV)



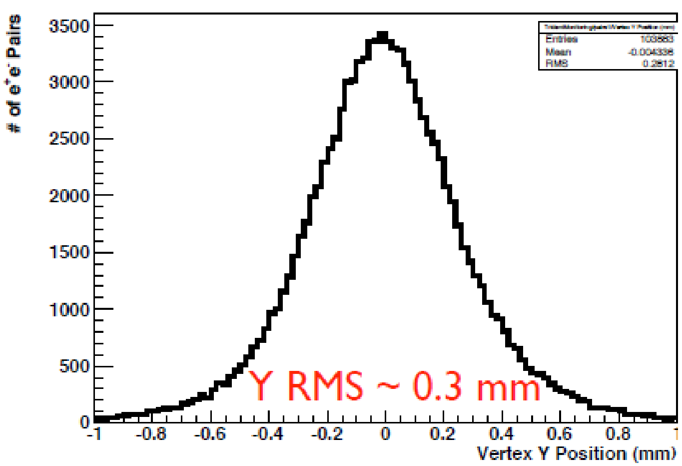
Pairs Vertex at the Target

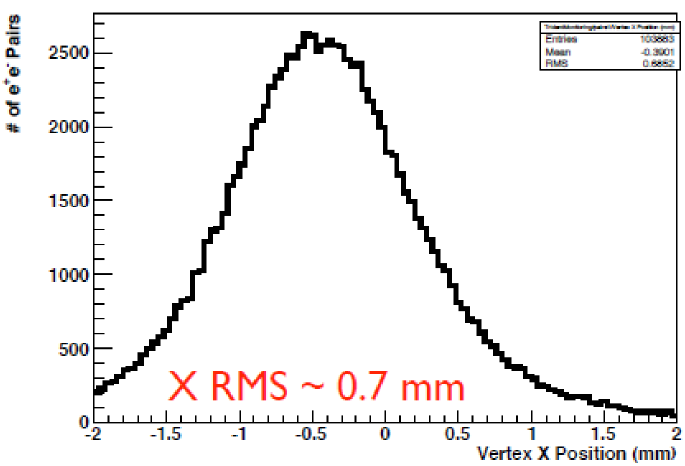


Z-vertex is critical for the experiment.

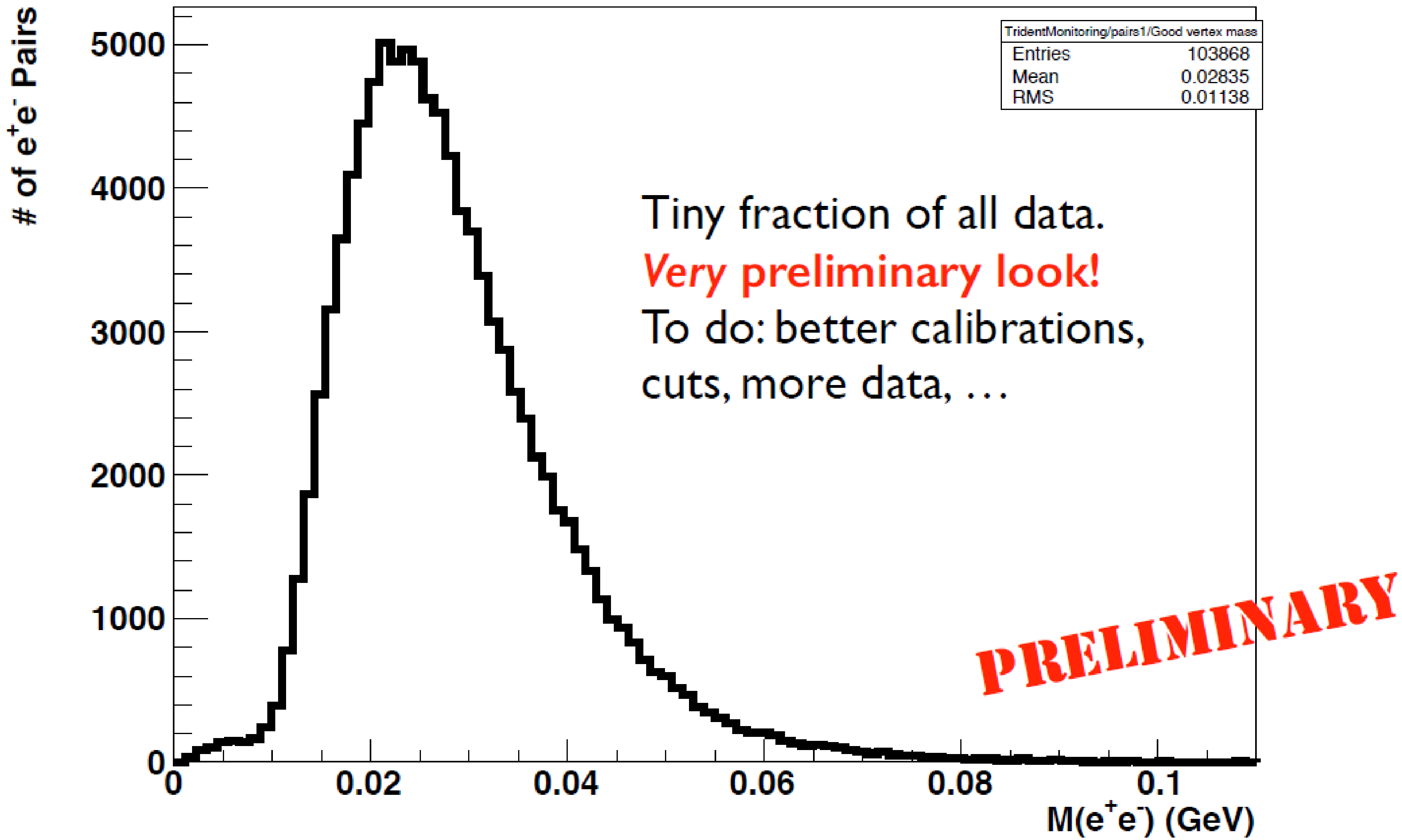
- Also the hardest @ 15 mrad.
- Requires very good SVT alignment (not yet done!)

PRELIMINARY

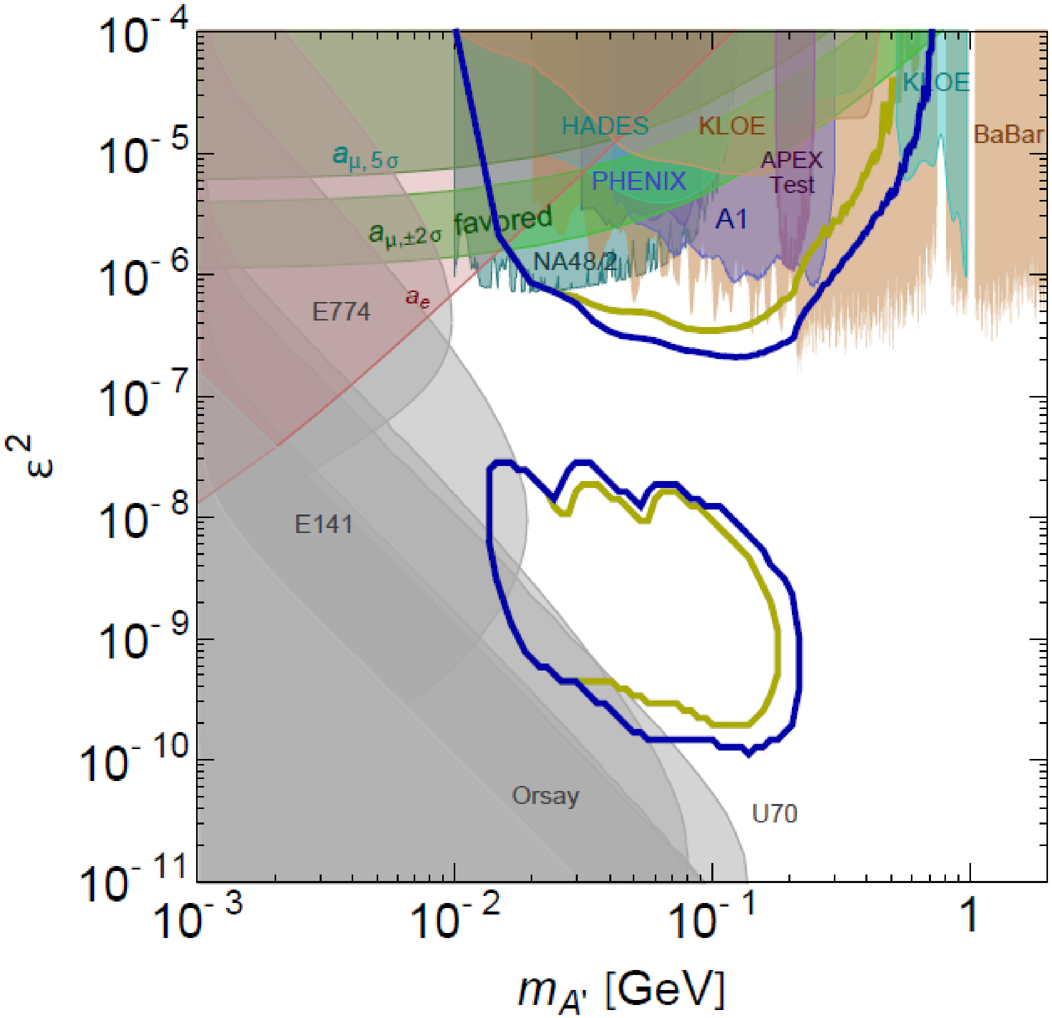




Pairs Mass Distribution



Full HPS Reach



Near term Running (Yellow)

1 week with 50nA @ 1.1 GeV
1 week with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV

Additional Running (Blue):

2 weeks with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV
3 weeks with 450nA @ 6.6 GeV

Times are “PAC” times = Calendar time/2

Opportunistic run Fall 2015
TBD Spring 2016

Summary

- We have roughly 1/3 PAC week with Si at 0.5 mm
  - 15 mrad acceptance
- Beamline, ECal, Trigger and SVT all worked well
  - Beam background and trigger rates are consistent with simulations.
- Lots of work to do ..
  - Check Trident Yield in the data
  - ECal energy calibration
  - SVT alignment
  - Understanding the vertex tails
- But a physics result may be in reach

HPS Collaboration
JLAB + SLAC + FNAL + IPNO Orsay + INFN Genova + Universities
(+ New Collaborators at Glasgow and INFN Catania, Torino, Sassari, Roma)

P. Hansson Adrian, C. Field, N. Graf, M. Graham, G. Haller, R. Herbst, J. Jaros*†, 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, C. Cuevas, A. Deur, H. Egiyan, L. Elouadrhiri, A. Freyberger, F.-X. Girod, S. Kaneta, V. Kubarovsky, N. Nganga, B. Raydo, Y. Sharabian, S. Stepanyan[†], 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[†], K. Slifer, S. K. Phillips

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

R. Dupre, M. Guidal, S. Niccolai, E. Rauly, and P. Rosier

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

D. Sokhan

School of Physics & Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland, UK

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

Idaho State University, Pocatello, Idaho 83209

M. Battaglieri, R. De Vita

Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dellÚniversita, 16146 Genova, Italy

S. Bueltmann, L. Weinstein

Old Dominion University, Norfolk, Virginia 23529

G. Ron

Hebrew University of Jerusalem, Jerusalem, Israel

A. Kubarovsky

University of Connecticut, Department of Physics, Storrs, CT 06269

K. Griffioen

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

Y. Gershtein, J. Reichert

Rutgers University, Department of Physics and Astronomy, Piscataway, NJ 08854

(Dated: May 6, 2013)