The HPS Experiment: Searching for Dark Photons at Jefferson Lab

Sarah K. Phillips

The University of New Hampshire

on behalf of the HPS Collaboration

June 1, 2012

Conference on the Intersections of Particle and Nuclear Physics 2012

An Aside: Nomenclature

There seem to be many terms for basically the same things:

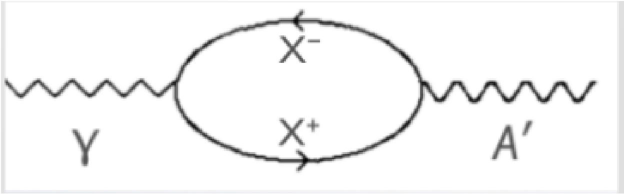
- Dark Sector = Hidden Sector = Secluded Sector
- Dark Photon = Heavy photon = A' = U-boson = …
- Coupling strength: $\epsilon^2 = k^2 = \chi^2 = \alpha'/\alpha$

Dark Photons

If there is an additional U(1) symmetry in nature, there will be mixing between the photon and the new gauge boson

Holdom, Phys. Lett B166, 1986

$$L_{U(1)'} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\epsilon}{2}V_{\mu\nu}F_{\mu\nu} + |D_\mu \phi|^2 - V(\phi)$$

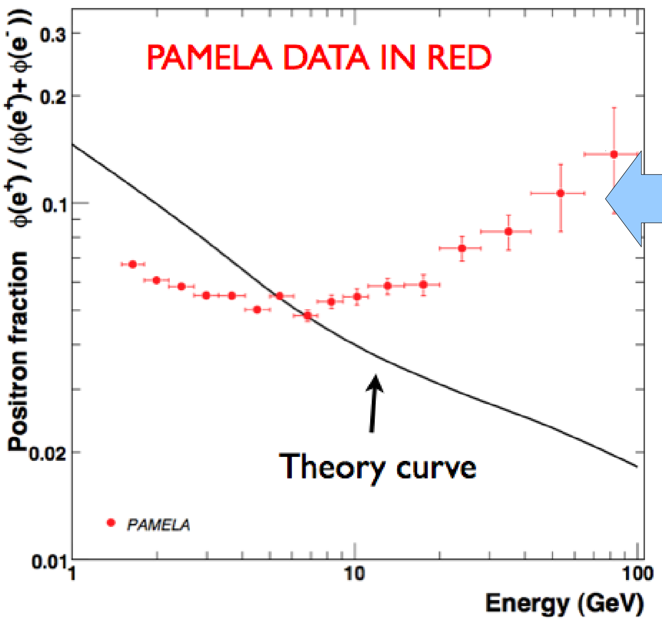


Kinetic mixing term

- Very general conclusion
- One of the few ways for a new force to communicate with the Standard Model
- Gives coupling of normal charged matter to the new "heavy photon" $q = \epsilon e$

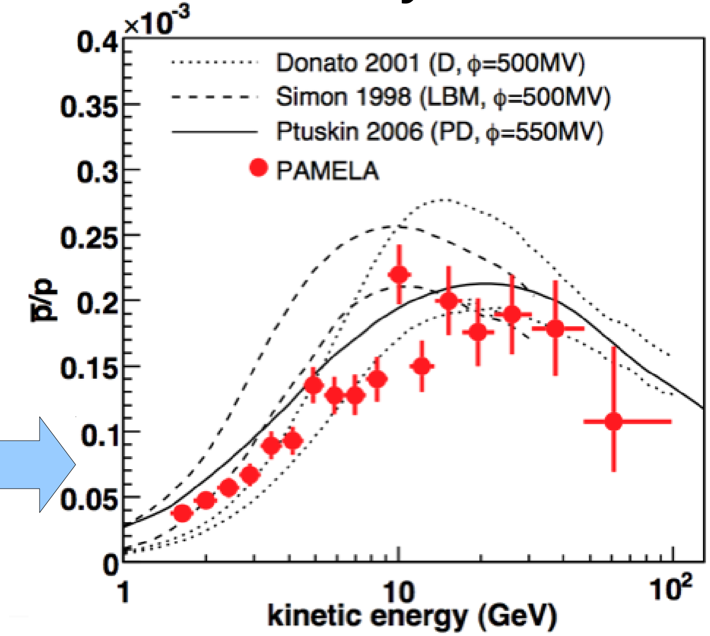
Hints from Astrophysics?

PAMELA, FERMI – energetic e+/e- cosmic rays

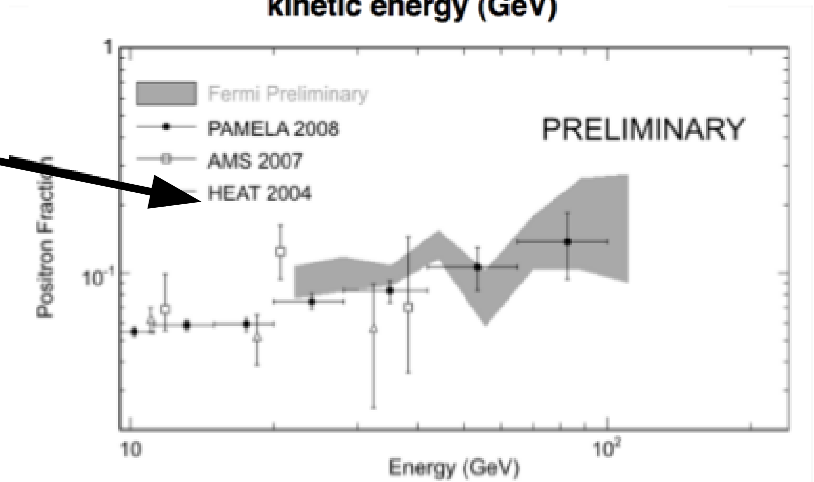


Excess in e+/e- ratio

But not in the $\bar{p}$/p ratio



FERMI sees it too!

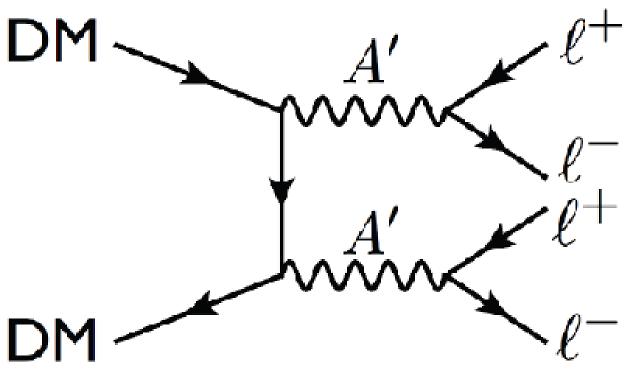


- Unknown source of high energy positrons...
- From DM annihilation through *A'*?

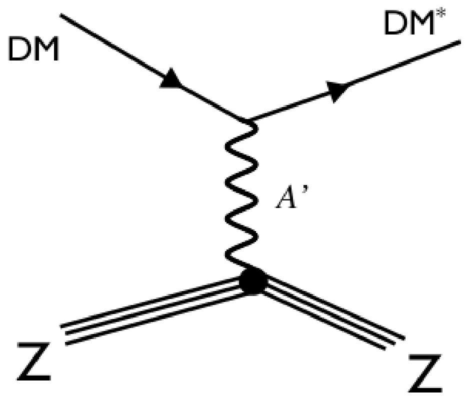
Dark Photons

- Depending on the model, the mass is in the MeV to GeV range!
- Can mediate dark matter decay and scattering!

DM decays through intermediate A'



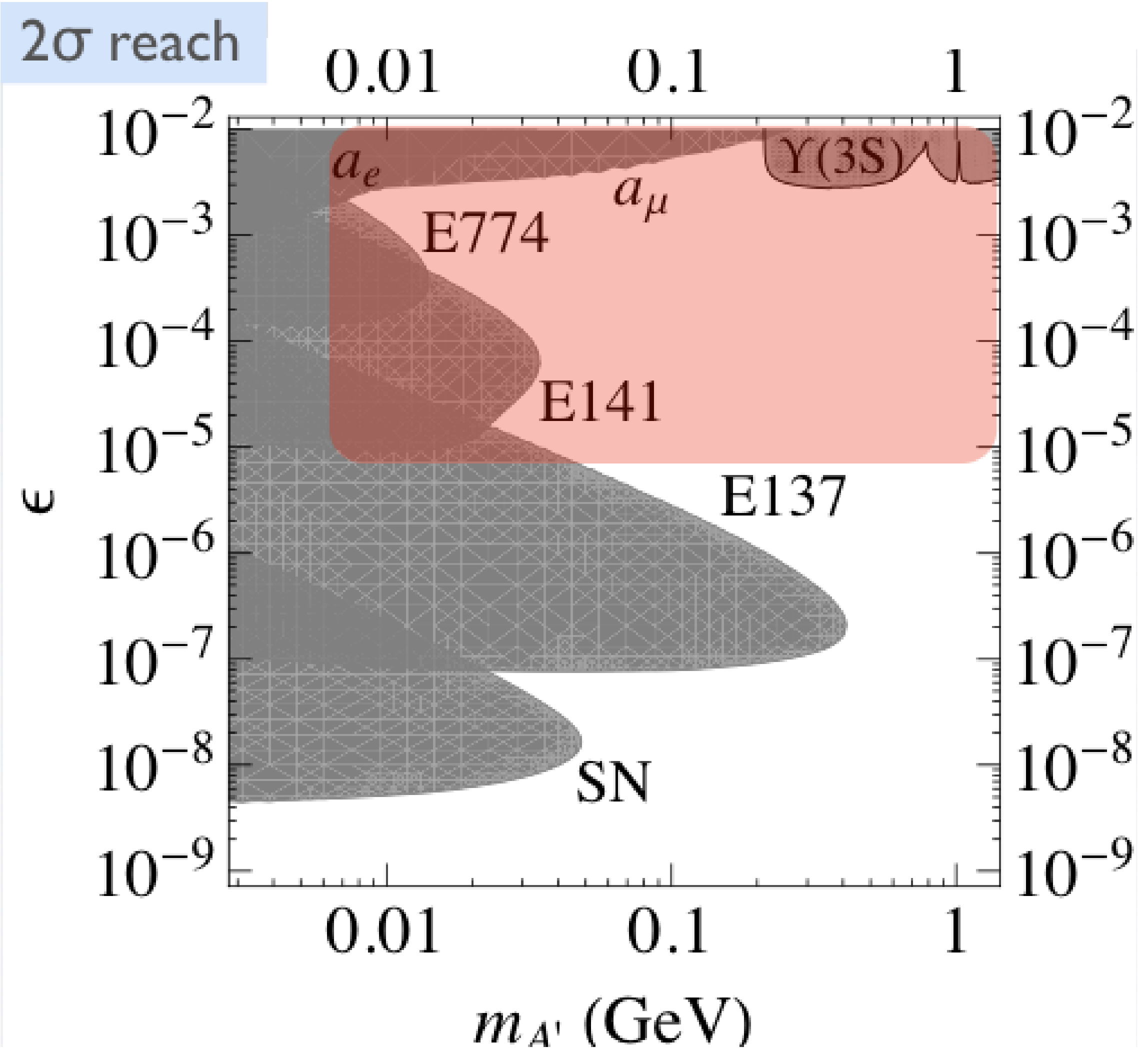
A' mediates DM scattering



N. Arkani-Hamed et al., PRD 79, 015014 (2009)
M. Pospelov and A. Ritz, Phys. Lett. B671, 391 (2009)

- New "dark force" with gauge boson ~ GeV while the dark matter particle (charged under the new force) ~ TeV
- Decays to lepton pairs (e^+e^-, $\mu^+\mu^-$) but $p\bar{p}$ decays are kinematically forbidden

Coupling-Mass Space



"Naturalness" arguments and hints from experiments seem to point to the same region in coupling-mass space:

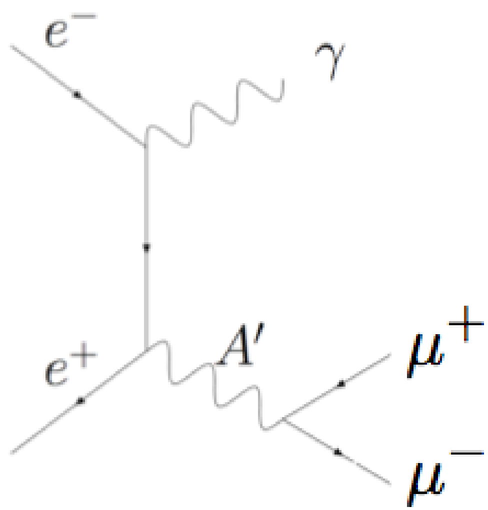
$$\epsilon \sim 10^{-2} - 10^{-5}$$
$$m(A') \sim \mathrm{MeV} - \mathrm{GeV}$$

A great place for exploration!

How to search for a dark photon?

Wherever there is a normal photon there is a dark photon...

Collider

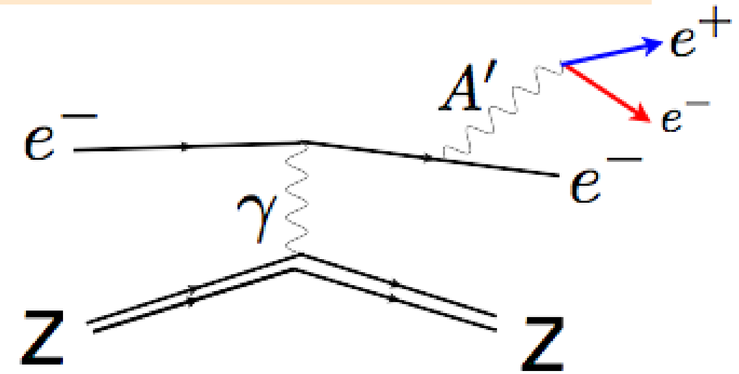


$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

$O\ ab^{-1}$ per decade

month

Fixed Target



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

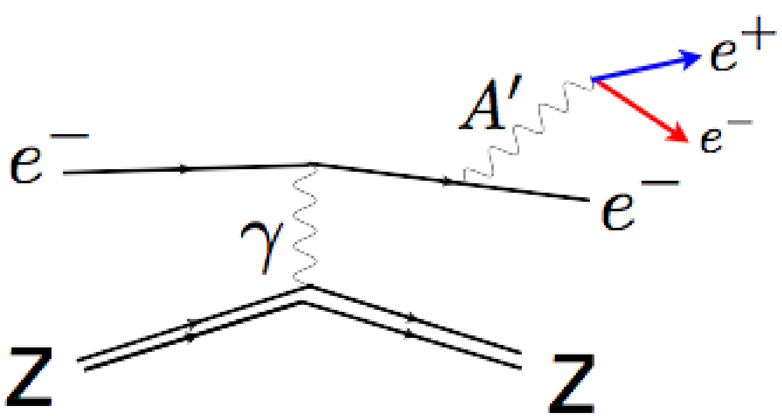
$O\ ab^{-1}$ per day

But much higher backgrounds!

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

Fixed Target Searches

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



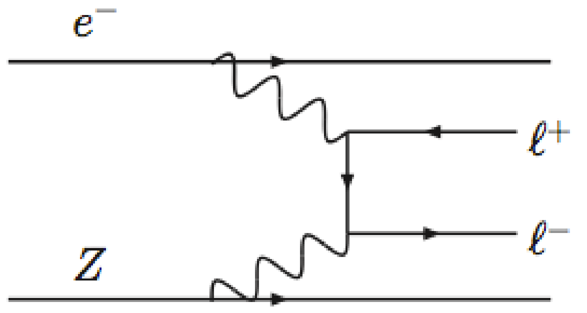
Bump Hunt:
Look for signal over background

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

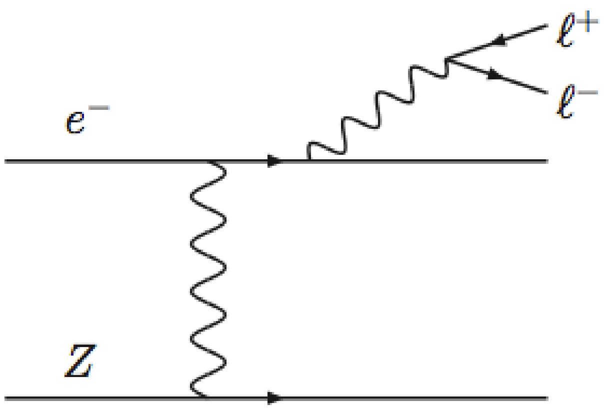
Bjorken, Essig, Schuster, Toro, Phys.Rev. D80 (2009) 075018

Background Separation

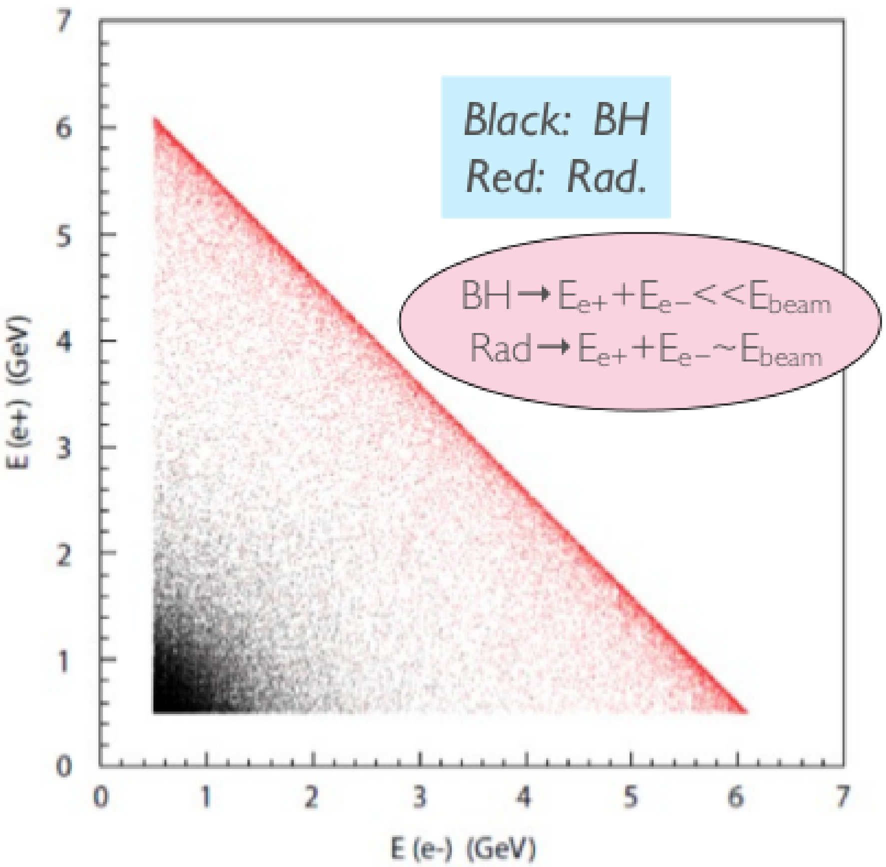
$\sigma_{B\text{-}H}$ very large $\gg \sigma_{Rad}$.
But kinematically distinct ➔
Use clever trigger to separate.



Bethe-Heitler



Radiative

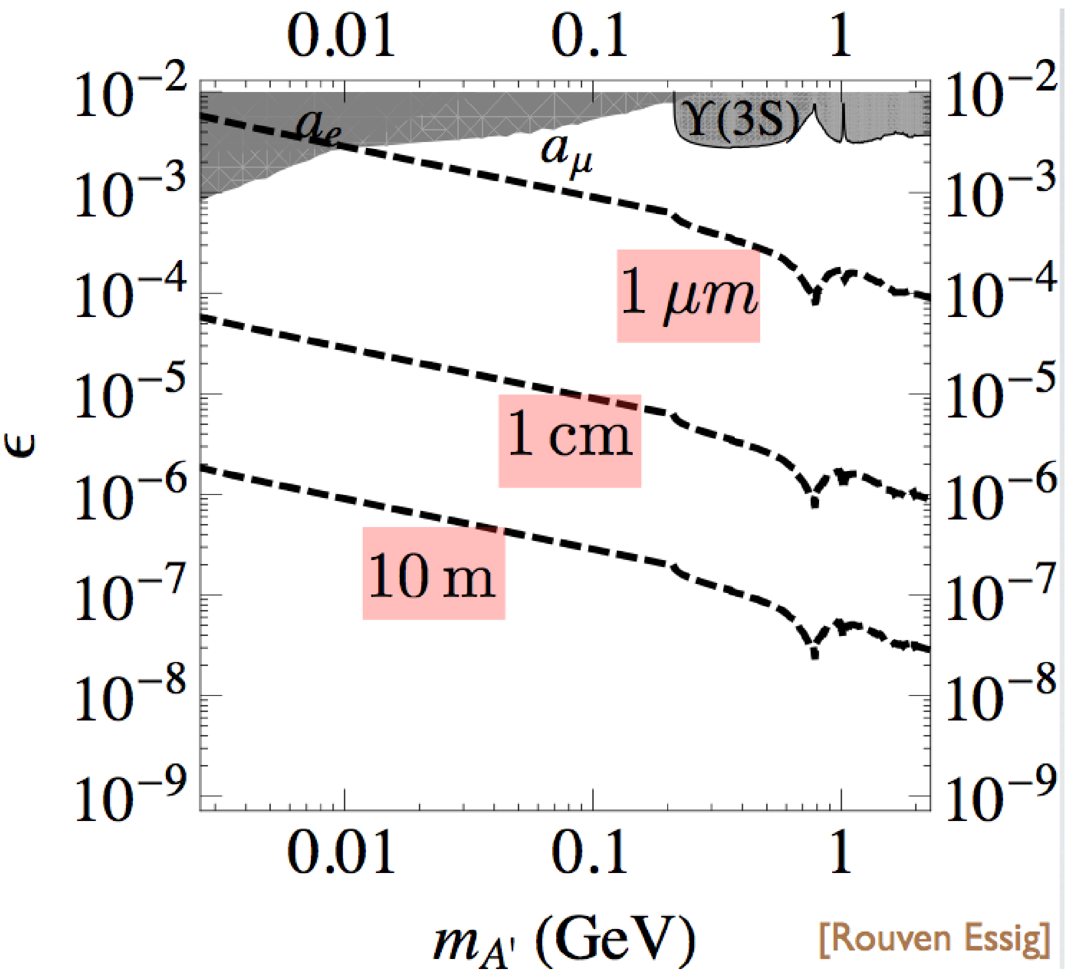


A' Lifetime

$$\gamma c\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2$$

Lower ε, lower mass
= longer lifetime

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



So, How Do We Do This?

This is what is needed:

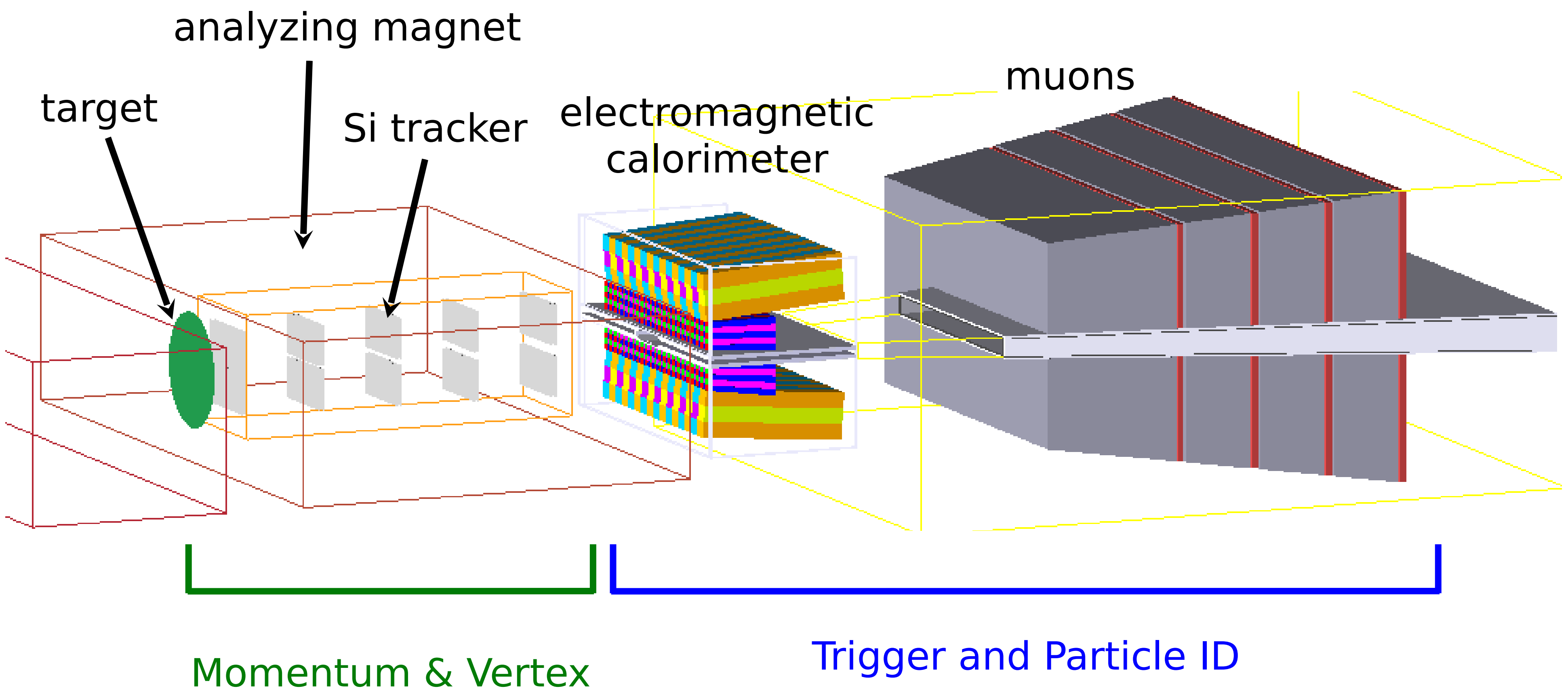
- Measurement needs to cover the low coupling ($<10^{-4}$), intermediate mass (20-1000 MeV) region
- Low rate, so need intense beam
- High background, so need high resolution and need to measure displaced vertex

The Heavy Photon Search Experiment

The Heavy Photon Search (HPS) is a new experiment in Hall B at Jefferson Laboratory to search for new dark photons in the mass range of 20 MeV/c^2 to 1000 MeV/c^2.

- About 50 members from 16 institutions; both HEP and nuclear physics!

The Heavy Photon Search Experiment

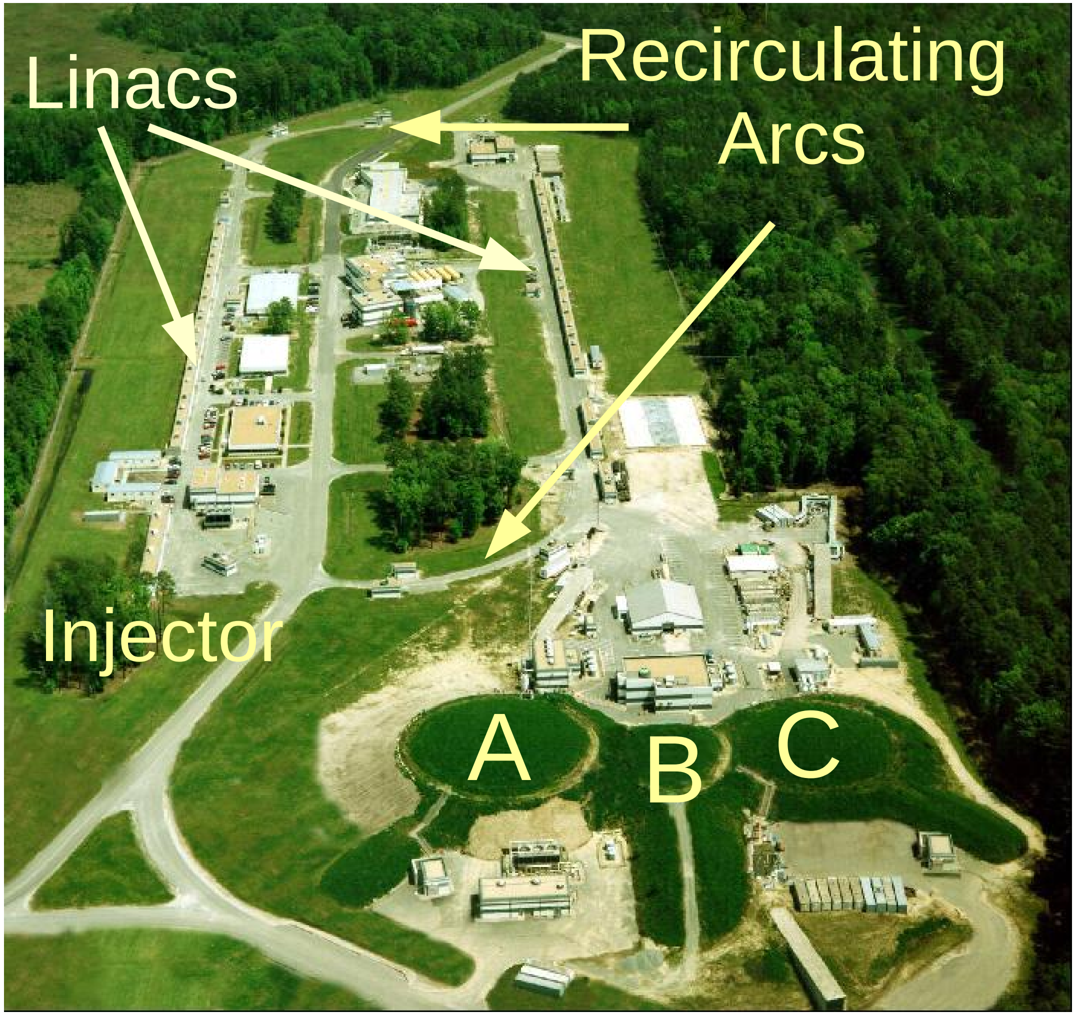


- High rate, high acceptance, high mass & vertex resolution detector to run in JLab Hall B
- JLab PAC37 January 2011 - conditional approval on test run.
- Received DOE funding to build test run apparatus; test run ran in May 2012

CEBAF at Jefferson Lab

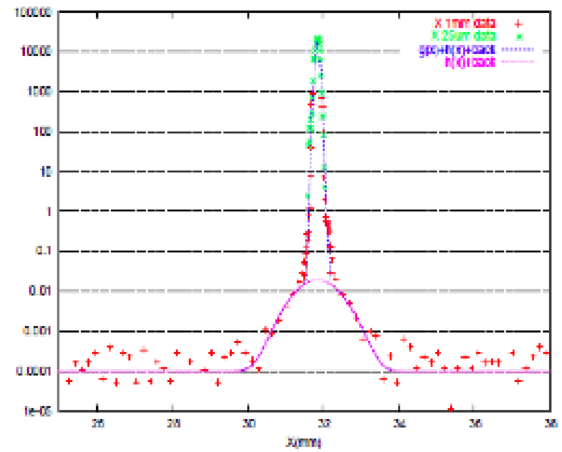
JLab: an electron accelerator facility (CEBAF) in Newport News, Virginia

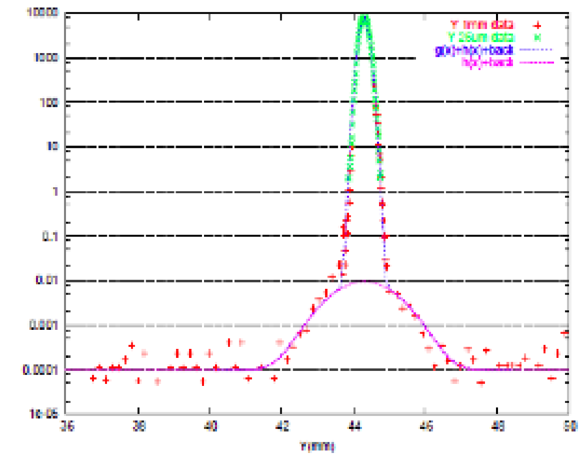
- Simultaneous delivery of beam at different energies and intensities to three experimental halls
- $E_{beam} = n \times 1.1$ GeV, $n \leq 5$ (5.5 GeV max) until May 2012
- Max design current: I_{beam}=200 μA divided among three halls
- 2 ns bunch separation; short integration times reduce ~DC backgrounds
- Energy upgrade (complete 2014) $E_{beam} = n \times 2.2$ GeV, $n \leq 5$ (11 GeV max to ABC, 12 GeV to Hall D)



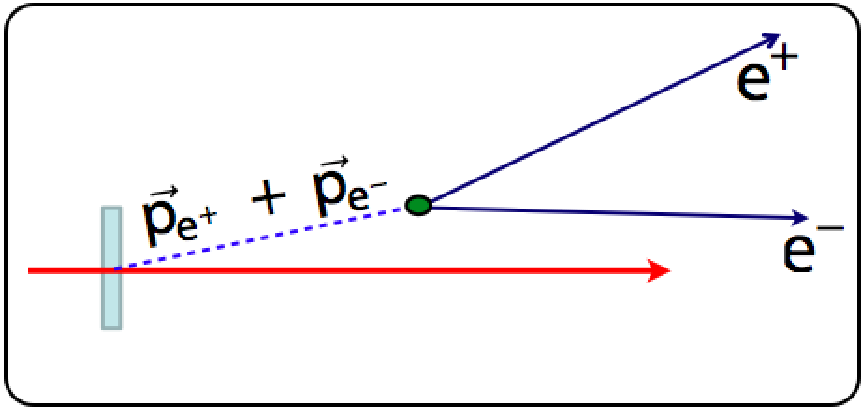
Beam Quality in Hall B

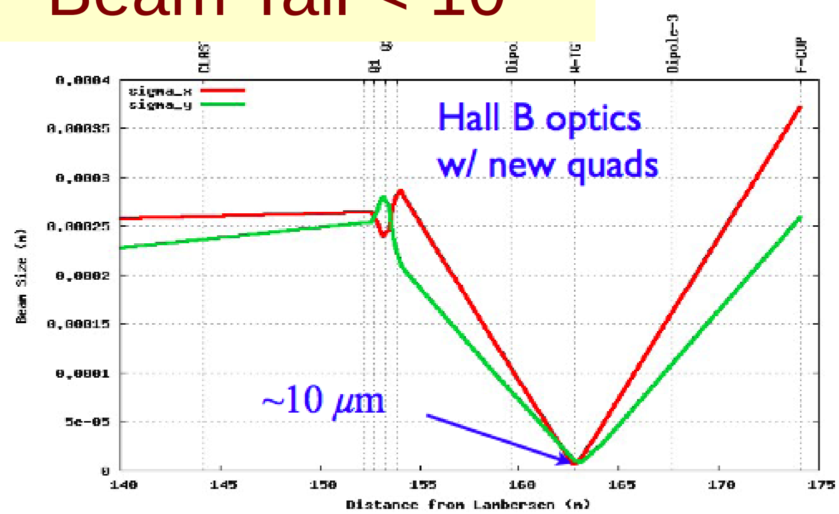
- Very stable beam
- low halo = low background
- 10 μm spot possible with additional quads; constrains A' trajectory, reducing backgrounds
- Tight beam spot helps tracking & vertex
- I_{beam} = 1 to 500 nA



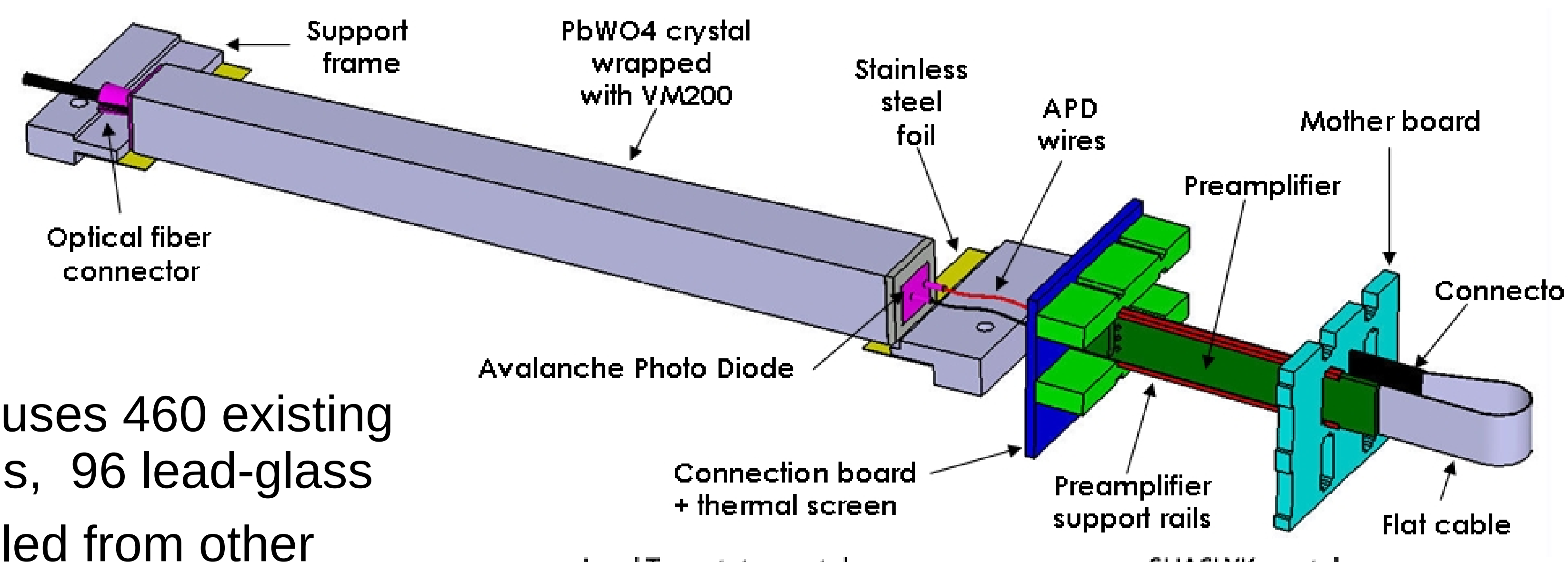


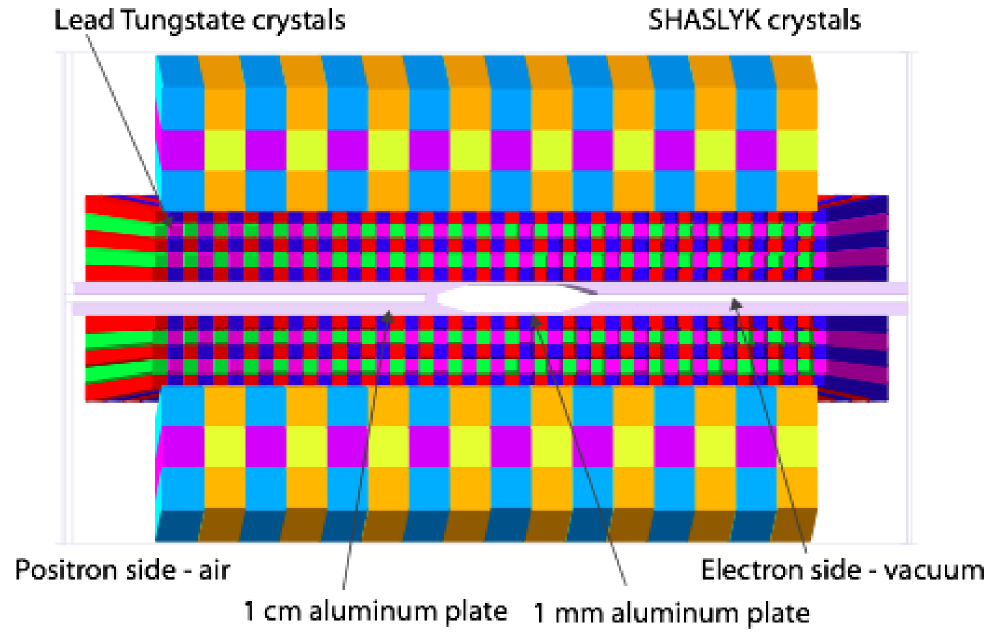
Beam Tail < 10^{-5}





Calorimeter and Trigger



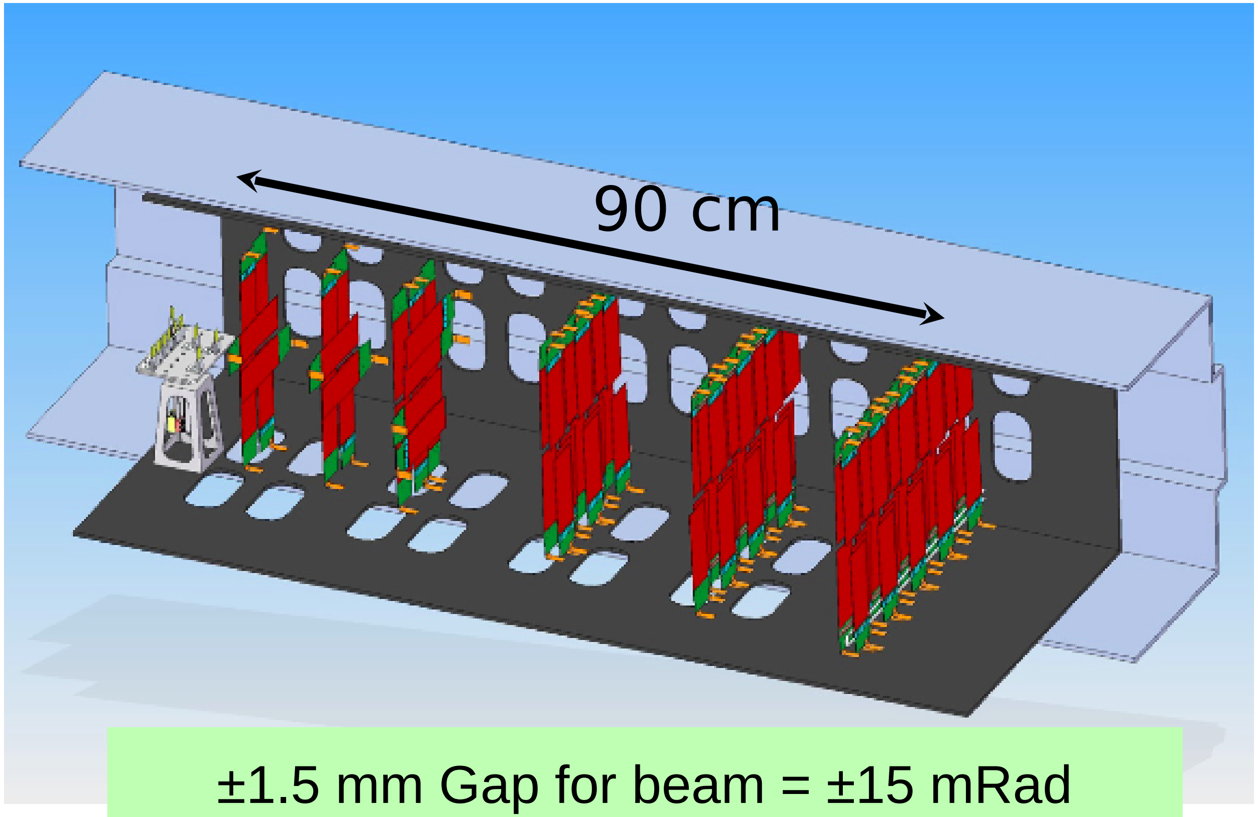


- Hybrid design uses 460 existing $PbWO_4$ crystals, 96 lead-glass crystals (recycled from other experiments!)
- Flash-ADC readout at continuous 250 MHz
- FPGA based trigger logic: Reduces two cluster background trigger rate from ~4 MHz to ~20 kHz, by using unique A’ signature.
- Keep high A’ acceptance.

Tracker

Requirements:

- Forward angular coverage gives large acceptance (1000x two spectrometers)
- High Rate capable = 25 MHz
- Thin (reduce M.S.)
- Robust, movable, replaceable, operate in vacuum
- Excellent hit resolution
- Cost is acceptable.



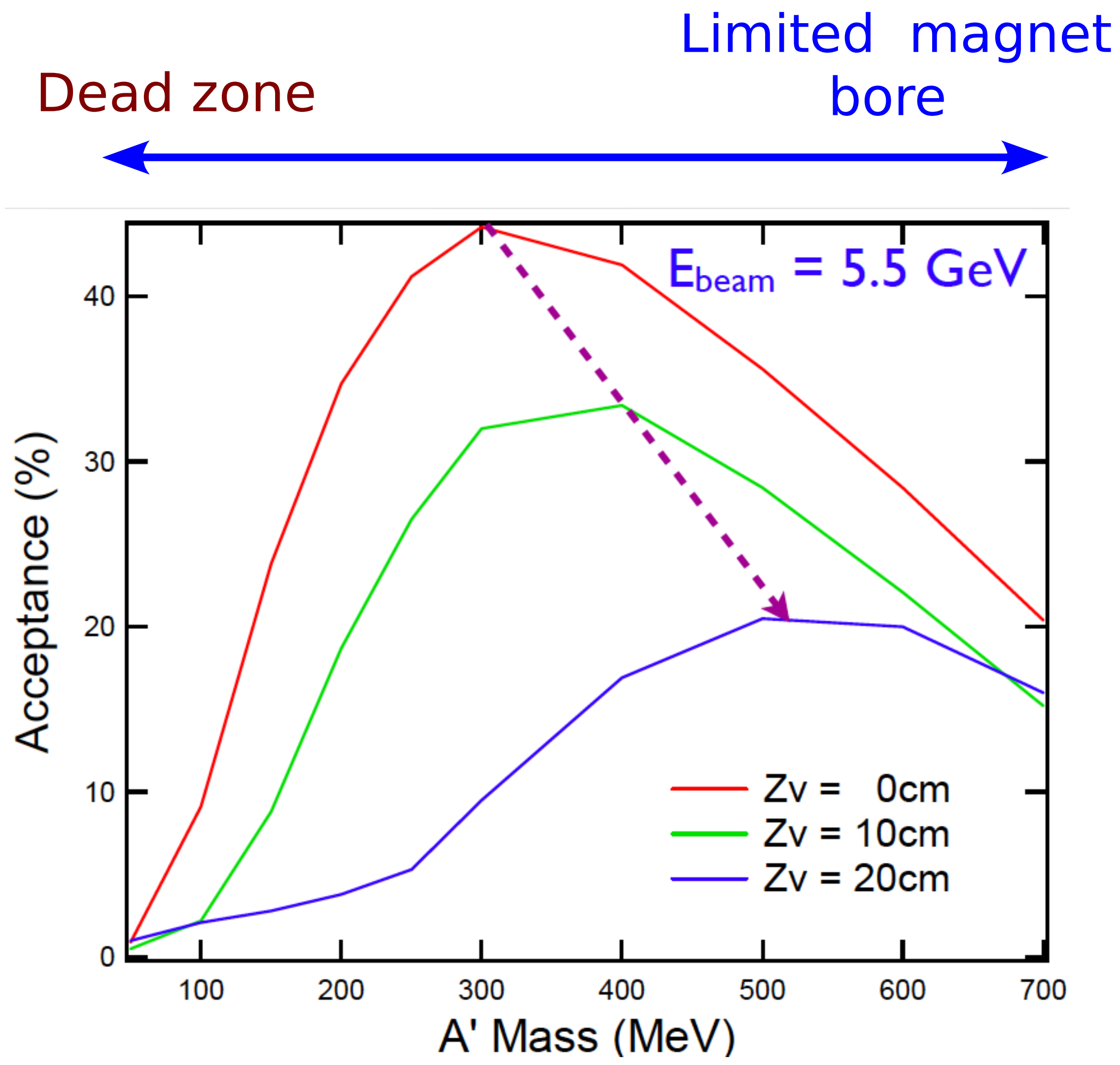
±1.5 mm Gap for beam = ±15 mRad
Small “dead zone” in acceptance

Build Using:

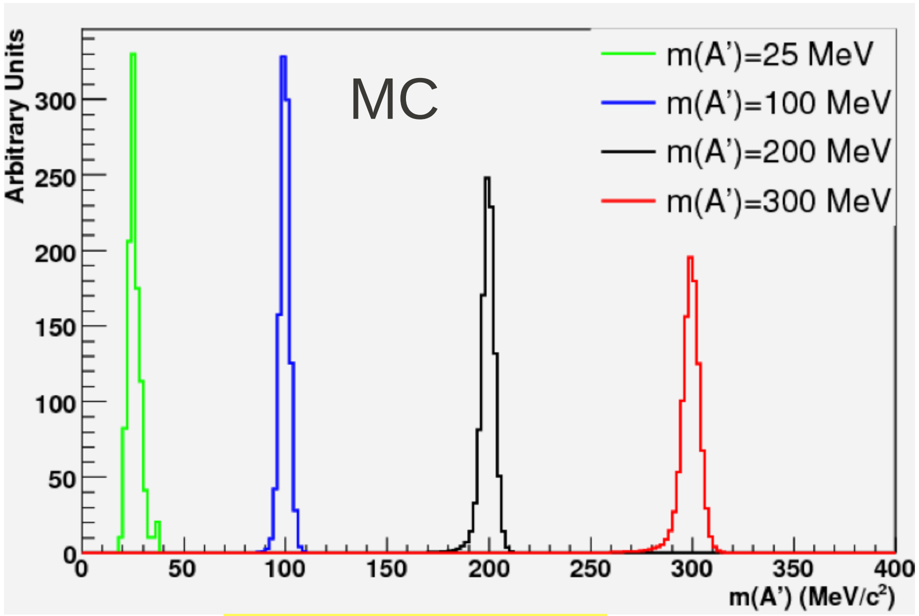
- Si Microstrip detectors (106, thin, leftover from Tevatron Run IIb)
- AVP25 readout chip (67840 channels, from CMS, S/N~34, timing ~ 2ns)
- Cooling outside tracking volume. (~0.5% X_0 per layer)

Tracker Acceptance

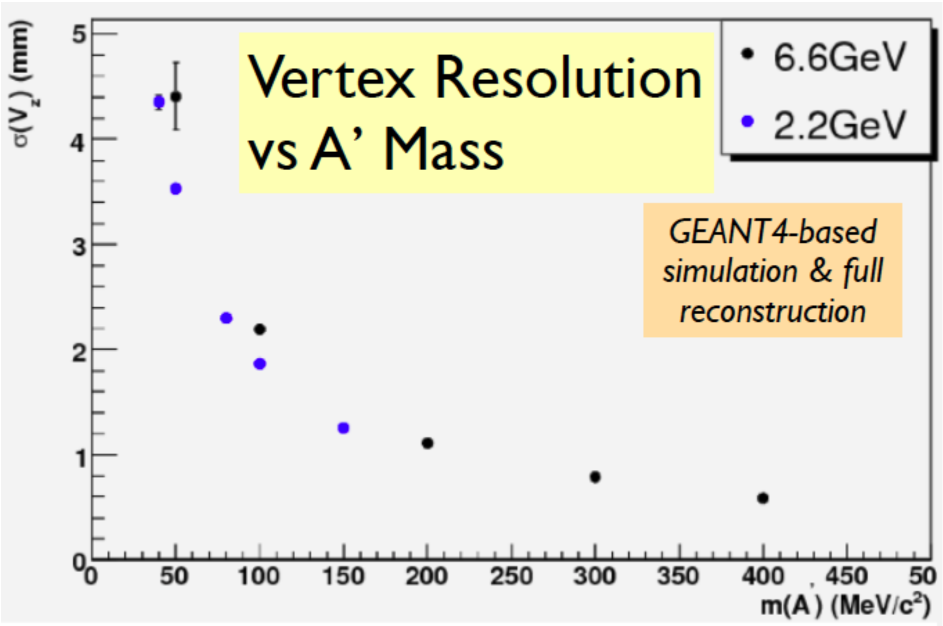
- At small A’ mass, dead zone limits acceptance
- At large A’ mass, limited by size of layers 5,6
- Increased z-vertex displacement increases dead zone



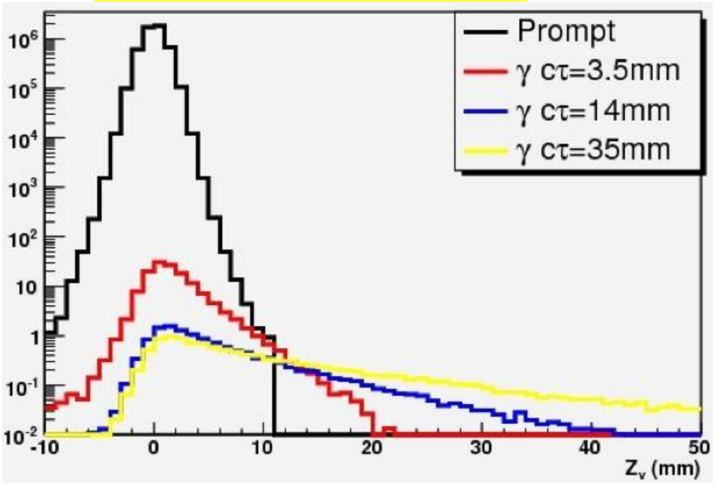
Tracker Resolution



Δm/m~1%

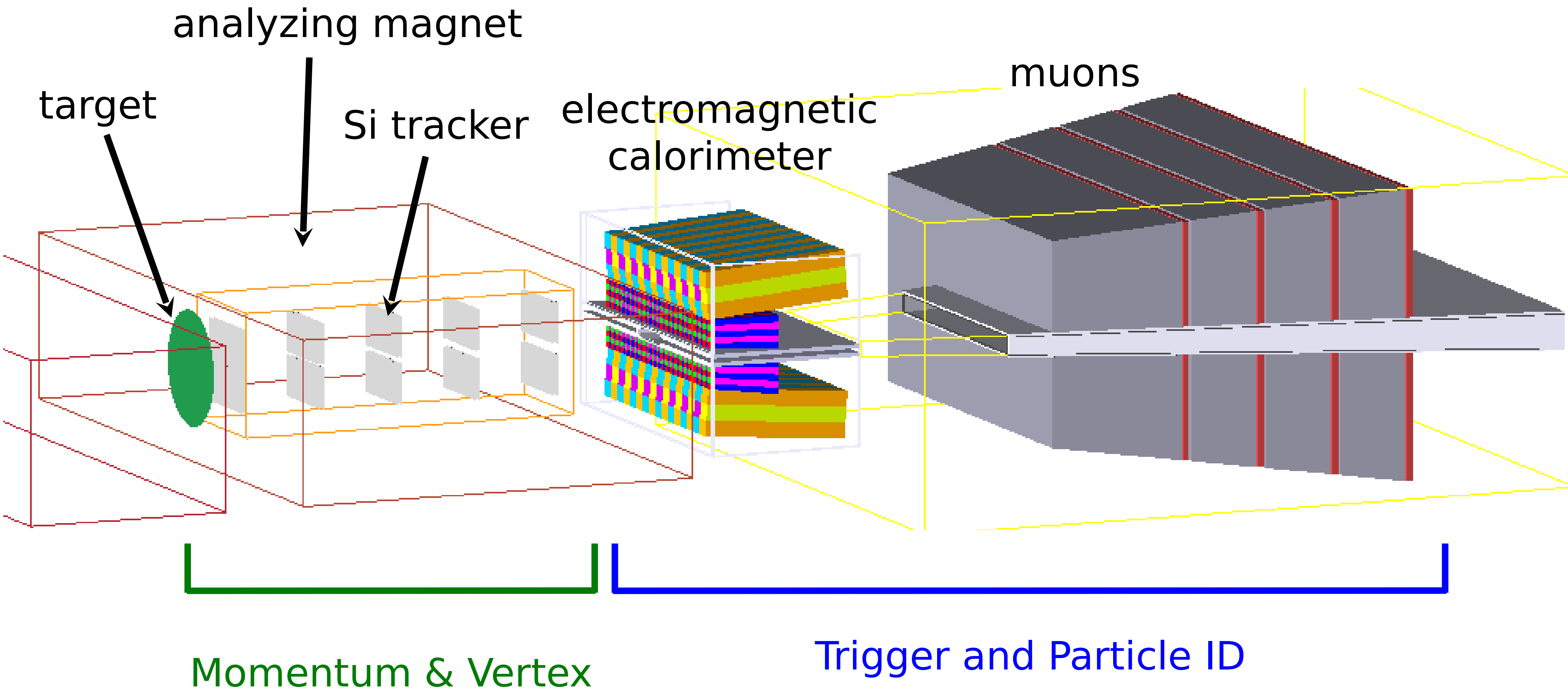


Δz ~1 - 4 mm



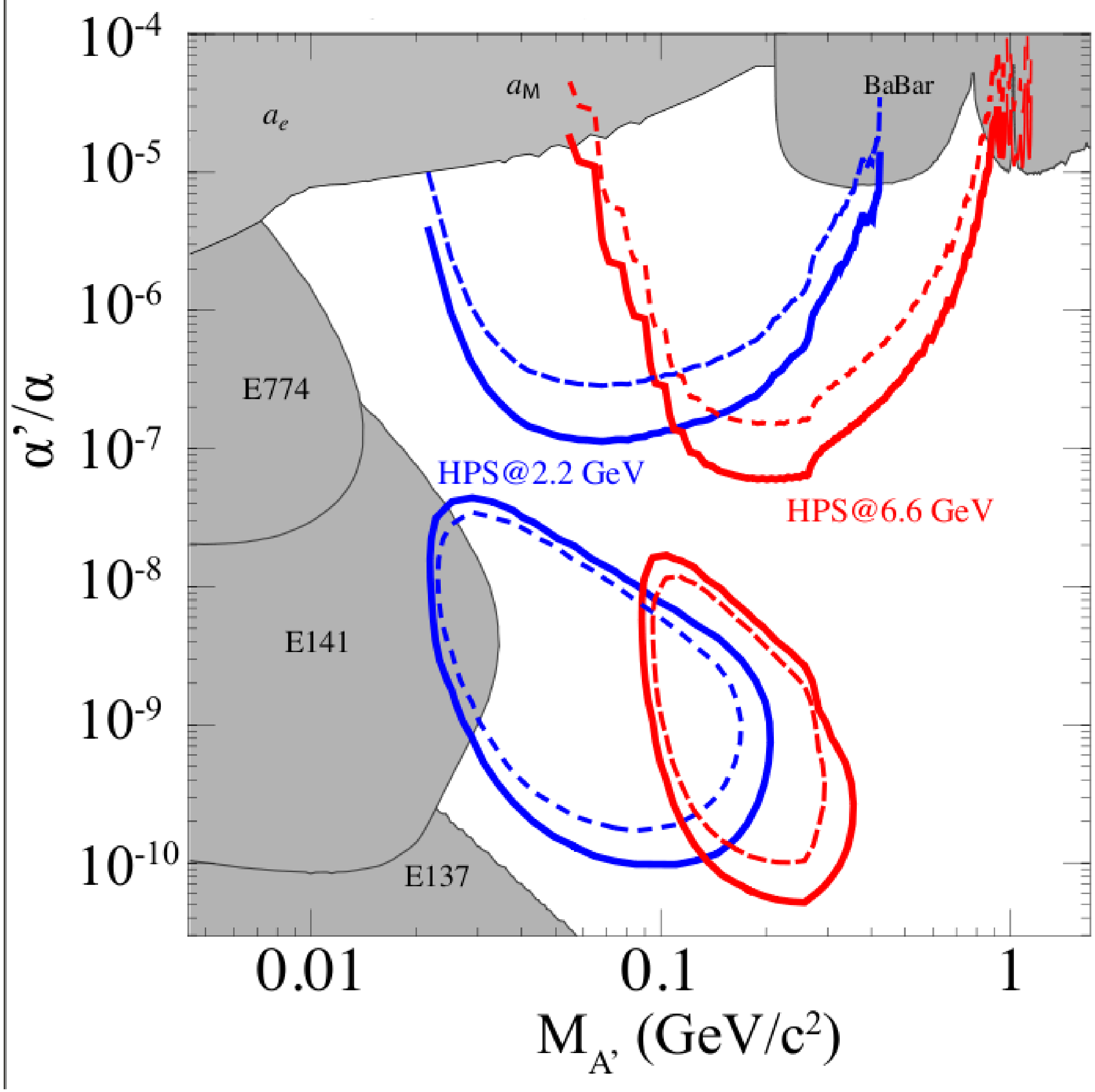
- Mass resolution dominated by multiple scattering
- Prompt tails to ~ 0 quickly; greater sensitivity further out.

Muon Detector



- Located about 2m from the target
- Iron absorbers – 30 cm + 3 $\times$ 15cm
- Four segmented hodoscopes, 1.5 cm thick

HPS Reach



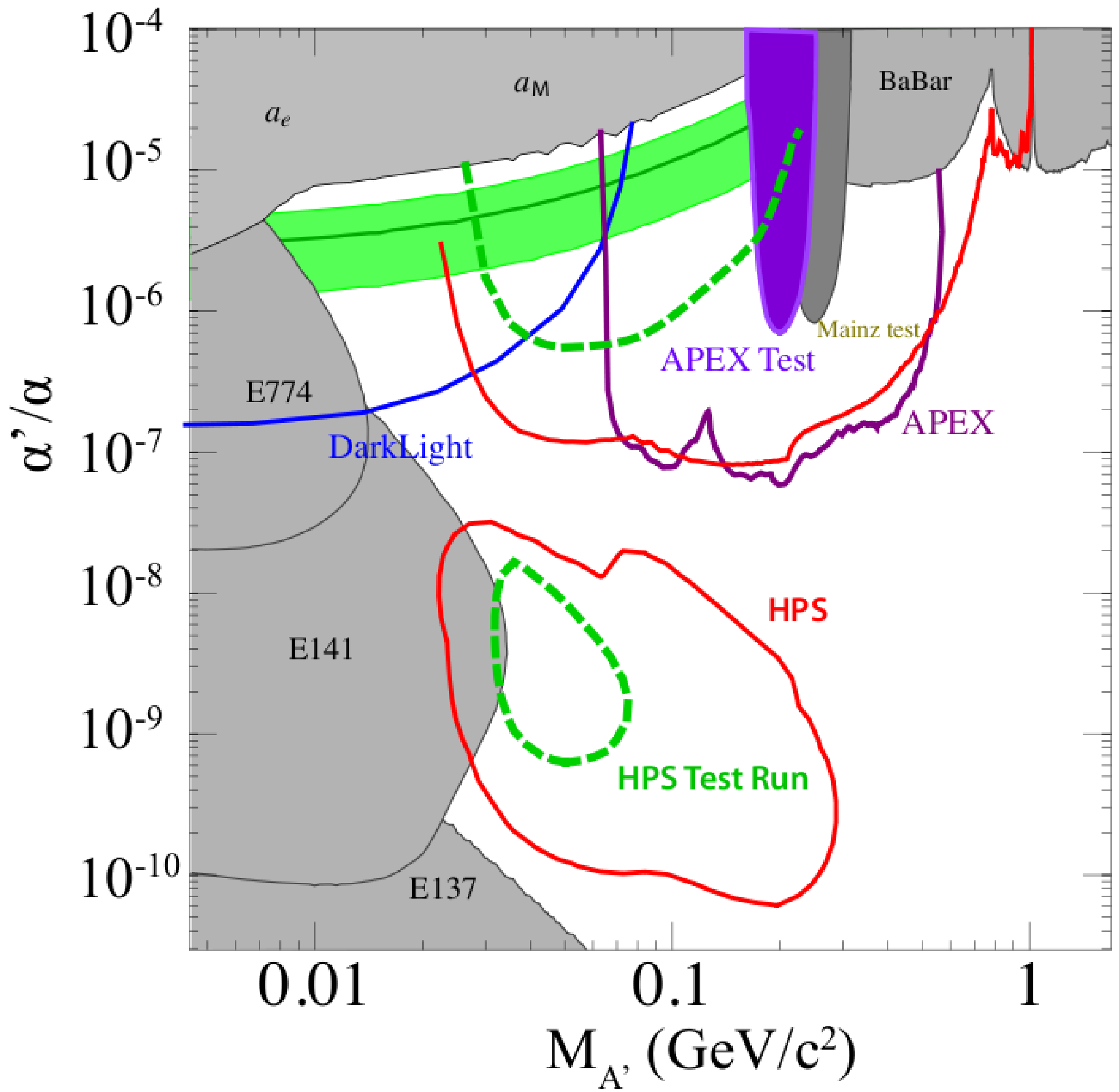
Blue:
Beam = 2.2 GeV at 200 nA
Target = 0.125%

Red:
Beam = 6.6 GeV at 450 nA
Target = 0.25%

3 months of running each energy = 180 days

Solid: 2σ Dashed: 5σ

Other Experiments



Many experiments in the works to look for Dark Forces!

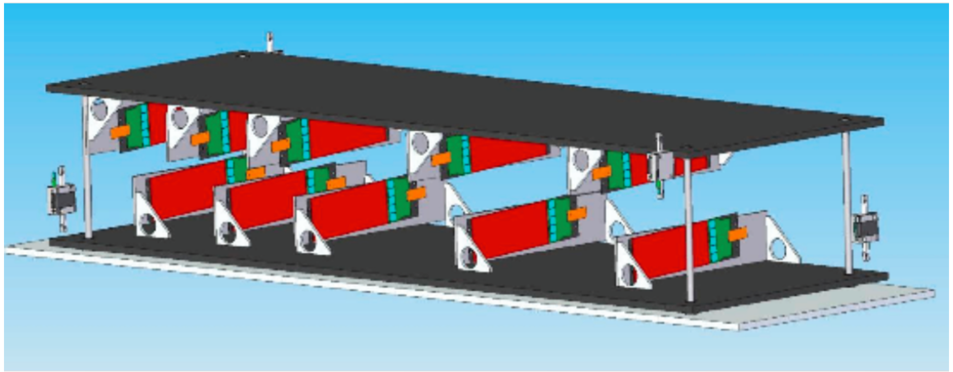
APEX – JLab Hall A & **Mainz A1** ~ same region as APEX; Uses spectrometers.

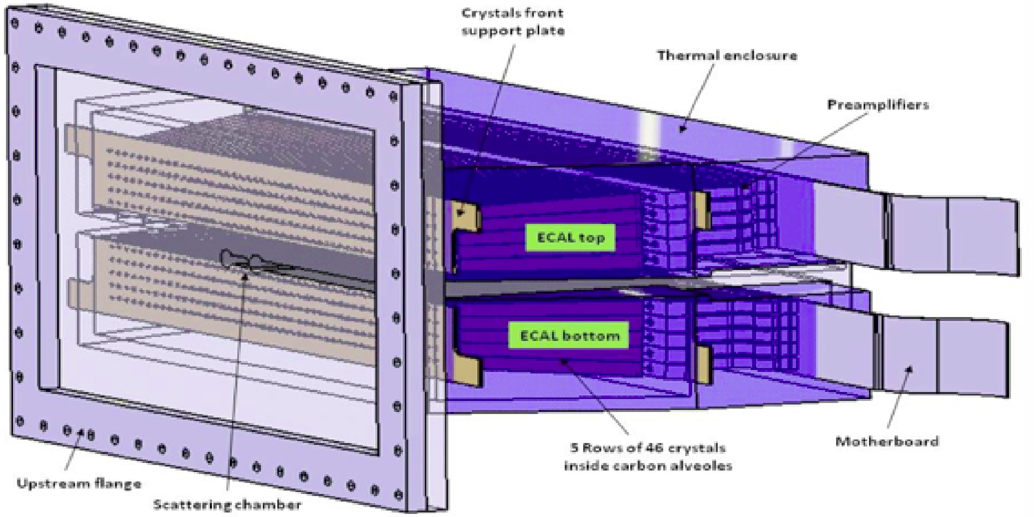
DarkLight – JLab FEL Using H_2 gas target, recoil detector.

Not shown:
VEPP-3, BABAR, BELLE, KLOE, BES, SuperB, D0, Atlas, CMS,...

HPS Test Run

- Goal: Test the concept and methods before building full system in a physics environment
- Reduced size tracker and calorimeter (no muon detector)
- Verify background estimates, SVT & Ecal occupancies, trigger algorithm, DAQ performance
- Run before JLab shutdown for 12 GeV upgrade this May; ran parasitically with HDIce experiment in Hall B



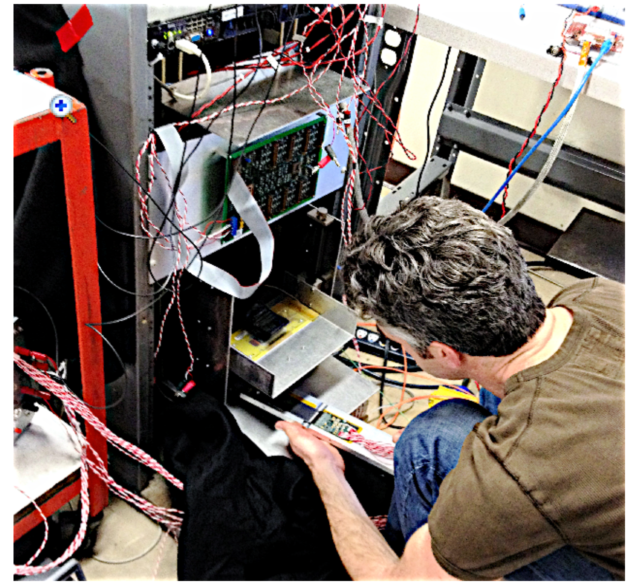


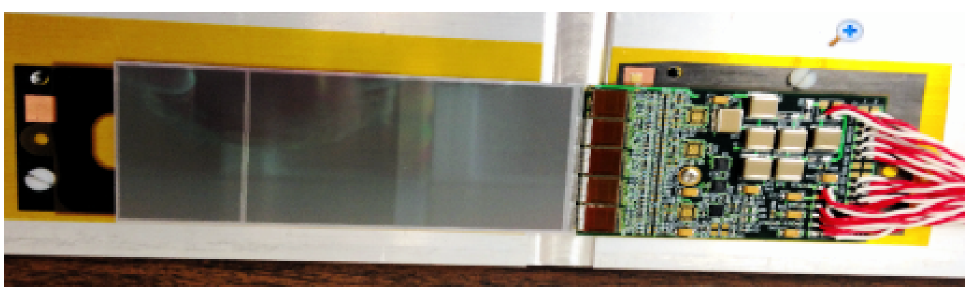
SVT and Vacuum Chamber

Tracker and vacuum chamber preparations for the test run.

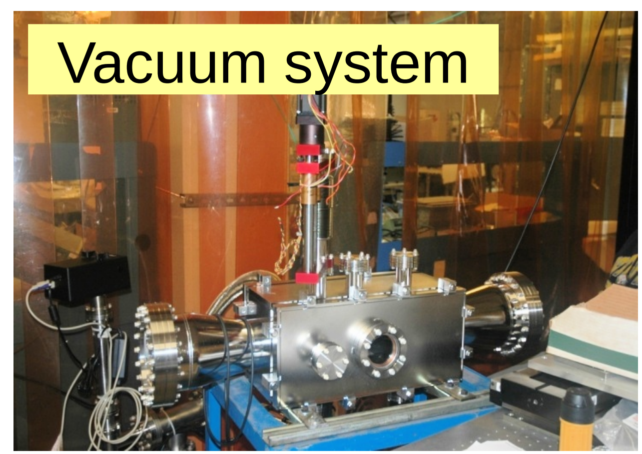
SVT Module assembly

SVT cosmic tests





Tracker module



Vacuum system

HPS Test Run

- Just finished running on May 18th! Data analysis is in progress...
- Technical challenges were met successfully
- Analysis ongoing to show that trigger rates and tracker occupancies agree with simulations
- Results will be submitted to JLab PAC39 to get approval for full HPS run

In Summary

There has been a lot of interest in the dark sector lately!

- There are compelling reasons to look for the A'
- The Heavy Photon Search at JLab is a challenging experiment looking for dark photons.
- HPS has unique capability to probe intermediate couplings; complimentary to other efforts
- Just completed a successful test run
- Full experiment will run in Jefferson Lab's Hall B after the accelerator comes back up after the upgrade in 2014.

Thanks to Matt Graham, Maurik Holtrop, and Tim Nelson for plots and figures

HPS Simulation

Simulation uses tools developed for lepton collider studies

- GEANT4-based simulation package, “SLIC”
- Signal and trident background events are simulated using MadGraph
- Beam backgrounds generated using GEANT single particle gun
- Java-based digitization and reconstruction, “lcsim,” includes detailed simulation of silicon response; fast, robust track finding; and track/vertex fitting packages: used for ILC, CLIC, ATLAS upgrade and Muon Collider studies.

The HPS Collaboration

About 50 members from 16 institutions.

HEAVY PHOTON SEARCH

DM

A. Grillo, V. Fadeyev — *University of California, Santa Cruz, CA*

M. Ungaro — *University of Connecticut, Department of Physics, Storrs, CT*

W. Cooper — *Fermi National Accelerator Laboratory, Batavia, IL*

A. Micherdzinska — *The George Washington University, Department of Physics,Washington, D*

G. Ron — *Hebrew University of Jerusalem, Jerusalem, Israel*

M. Battaglieri, R. De Vita — *INFN, Sezione di Genova, 16146 Genova, Italy*

M. Holtrop (Co-Spokesperson), K. Slifer, S. K. Phillips — *University of New Hampshire, Department of Physics, Durham, NH*

M. Khandaker, C. Salgado — *Norfolk State University, Department of Physics, Norfolk, VA*

S. Bueltmann, L. Weinstein — *Old Dominion University, Department of Physics, Norfolk, VA*

A. Fradi, B. Guegan, M. Guidal, S. Niccolai, S. Pisano, E. Rauly, P. Rosier and D. Sokhan — *Institut de Physique Nucleaire d'Orsay, 91405 Orsay, France*

P. Schuster, N. Toro — *Perimeter Institute, Ontario, Canada N2L 2Y5*

P. Stoler, A. Kubarovsky — *Rensselaer Polytechnic Institute, Department of Physics, Troy, NY*

R. Essig, C. Field, M. Graham, G. Haller, R. Herbst, J. Jaros (Co-Spokesperson), C. Kenney, T. Maruyama, K. Moffeit, T. Nelson, H. Neal, A. Odian, M. Oriunno, R. Partridge, S. Uemura, D. Walz — *SLAC National Accelerator Laboratory, Menlo Park, CA*

S. Boyarinov, V. Burkert, A. Deur, H. Egiyan, L. Elouadrhiri, A. Freyberger, F.-X. Girod, V. Kubarovsky, Y. Sharabian, S. Stepanyan (Co-Spokesperson), B. Wojtsekhowski — *Thomas Jefferson National Accelerator Facility, Newport News, VA*

K. Griffioen — *The College of William and Mary, Department of Physics, Williamsburg, VA*

N. Dashyan, N. Gevorgyan, R. Paremuzyan, H. Voskanyan — *Yerevan Physics Institute, 375036 Yerevan, Armenia*

HPS Test Run ECal