The Heavy Photon Search @ JLab

Maurik Holtrop
University of New Hampshire
for the HPS Collaboration.

Photon 2013, Paris, May 23rd

Art: http://yonnicolas.nl

Nomenclature

The literature has many terms for basically the same things:

Heavy Photon = A′

= Dark Photon = U-boson = Dark Force

= Light Dark Gauge Boson = Hidden Sector Photon =...

Dark Sector = Hidden Sector = Secluded Sector

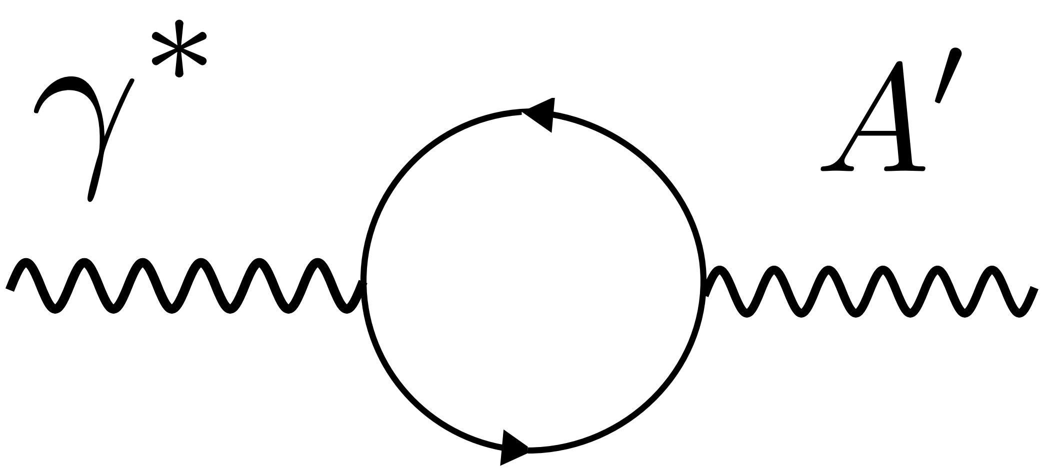
Coupling strength: $\epsilon^2 = k^2 = \chi^2 = \alpha'/\alpha$

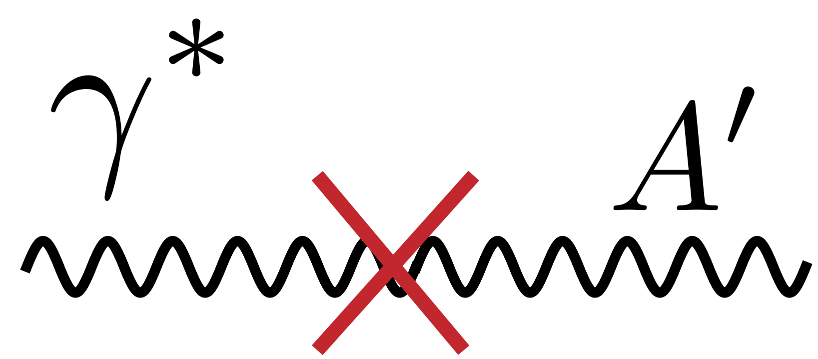
Dark Sector Gauge Boson

- Dark matter ⊂ dark sector, few portals to SM physics.
- Lots of theoretical motivation for an additional U(1)′ symmetry ⊂ dark sector ⇒ new vector boson A'
- A' will mix with SM photon through kinetic mixing.

Holdom ’86

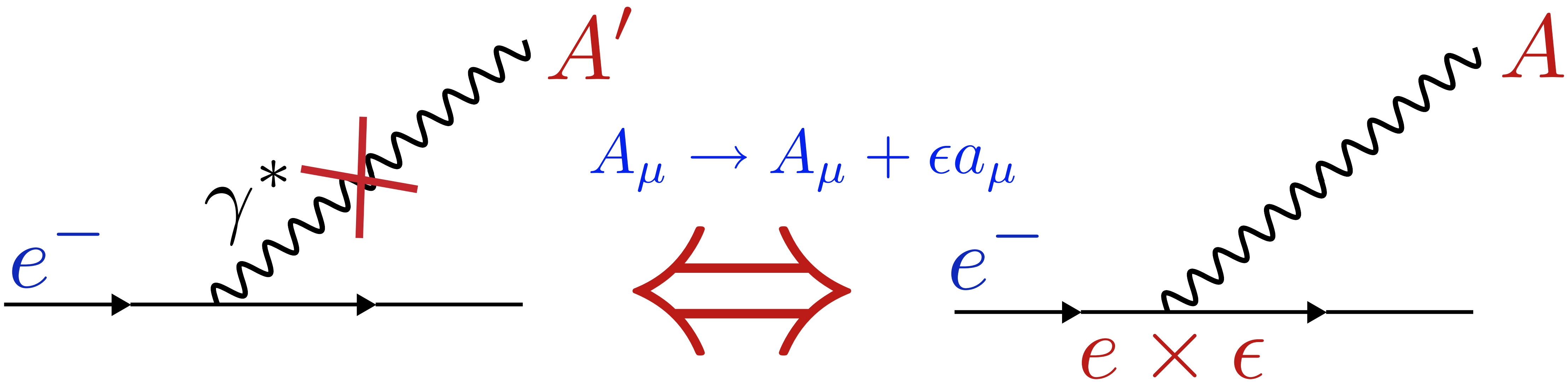
$$\Delta\mathcal{L}_{kin.mix} = \frac{\epsilon}{2} F'_{\mu\nu} F_Y^{\mu\nu}$$

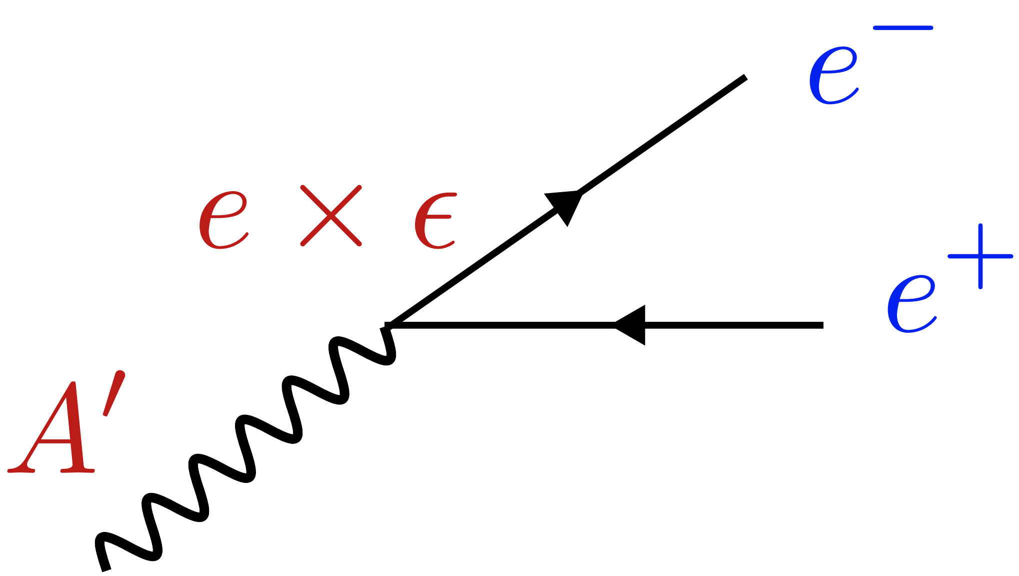




Heavy Photons

Photon mixing with A′ is equivalent to ordinary charged matter acquiring a milli-charge under the A′

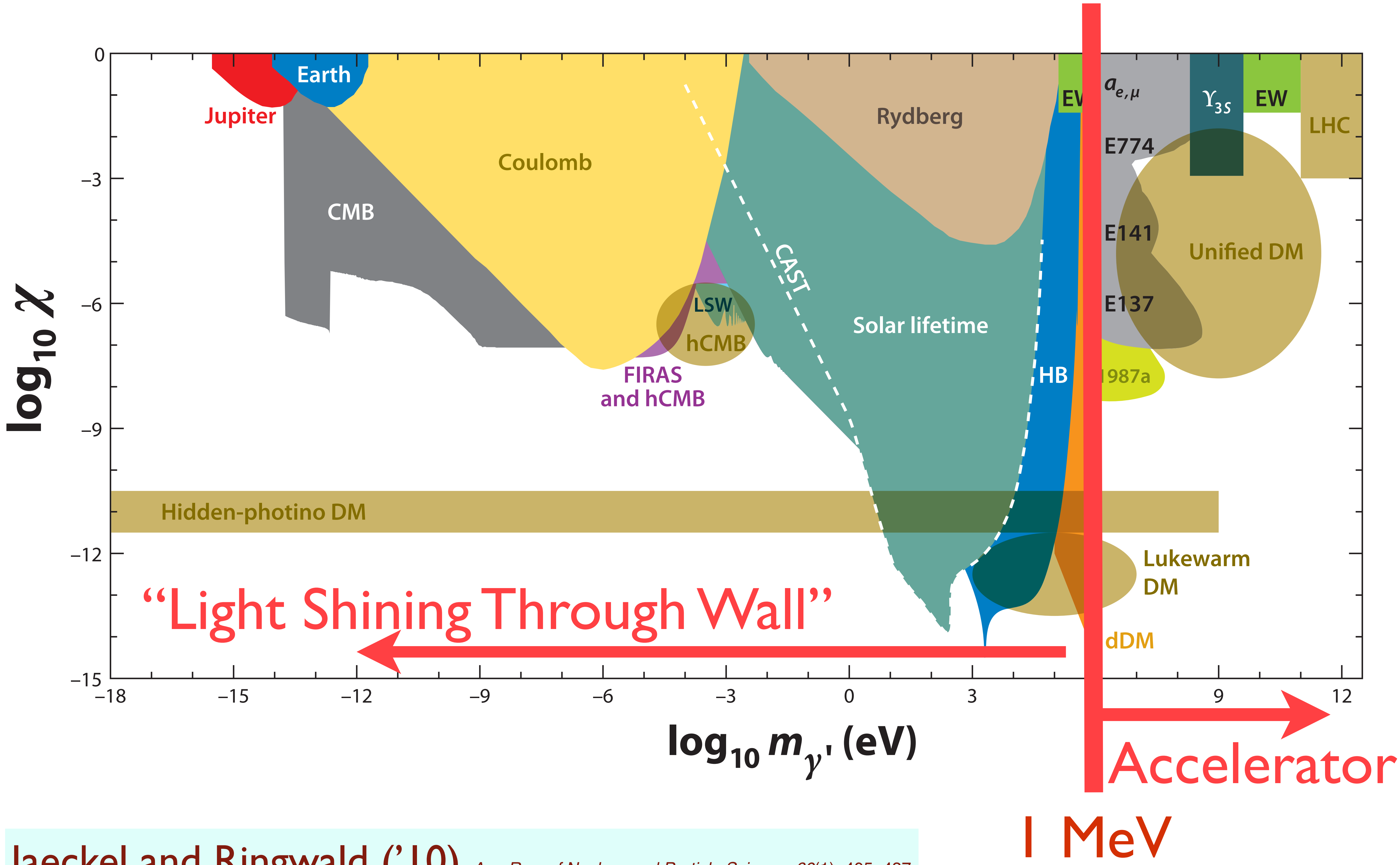




A' will pair produce

e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, ...

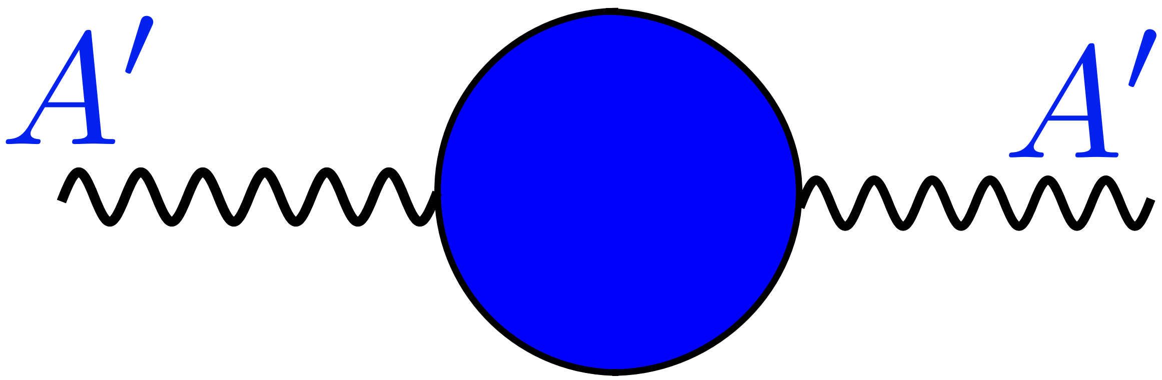
Where could it be?



Jaeckel and Ringwald ('10) *Ann.Rev. of Nuclear and Particle Science, 60*(1), 405–437

"Natural*" Coupling and Mass

✳ Depends on the model



Mass inherited from "electro-weak" scale

$$m_{A'}^2 \sim \epsilon M_W^2$$

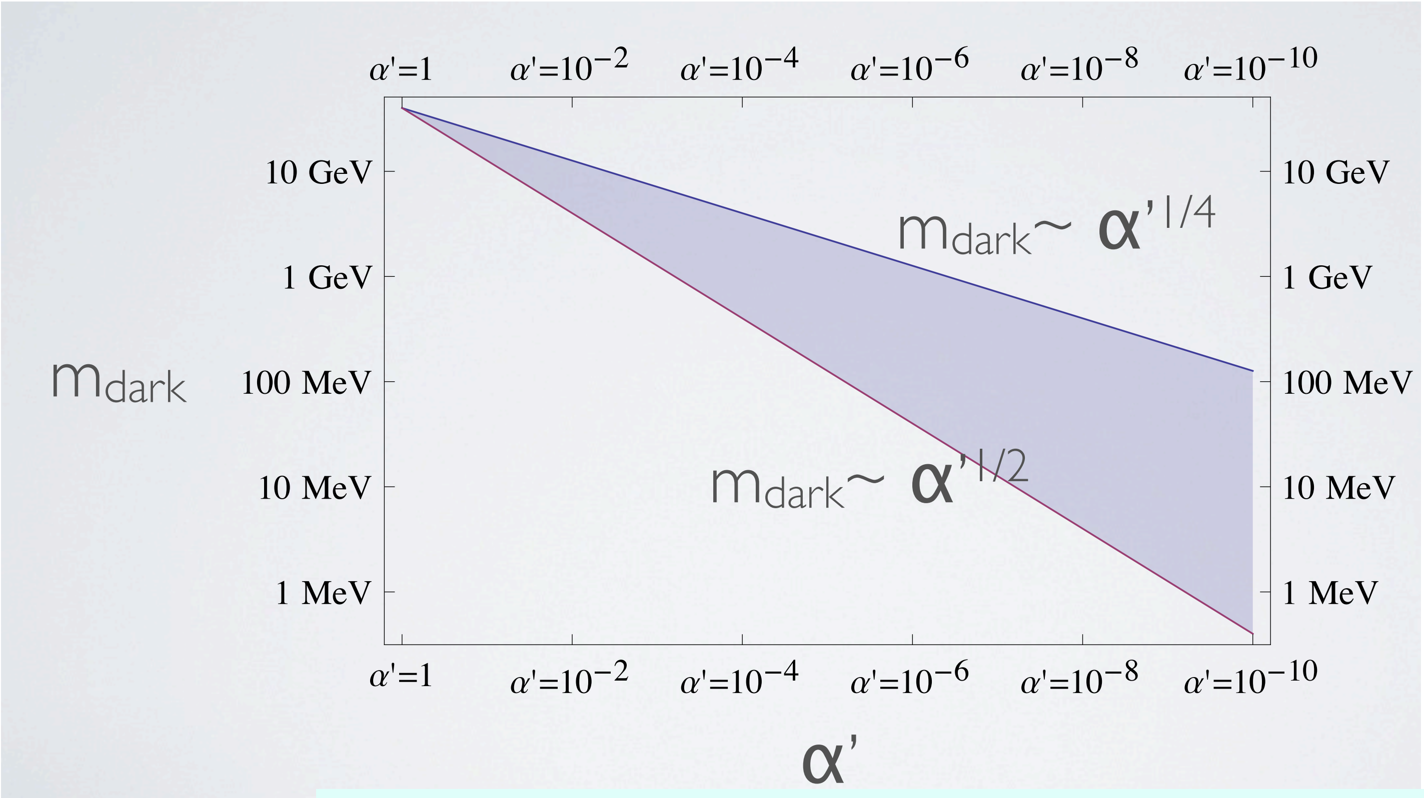
or

$$m_{A'}^2 \sim \frac{e g_D}{16\pi^2} M_W^2$$

or

Stückelberg mechanism:

$m_{A'} \sim$ meV



Neil Weiner, Intensity Frontier WS '11

Natural ε could be ~ 1 (tree level)

Or 1 < ε < 10^{-8} (loops)

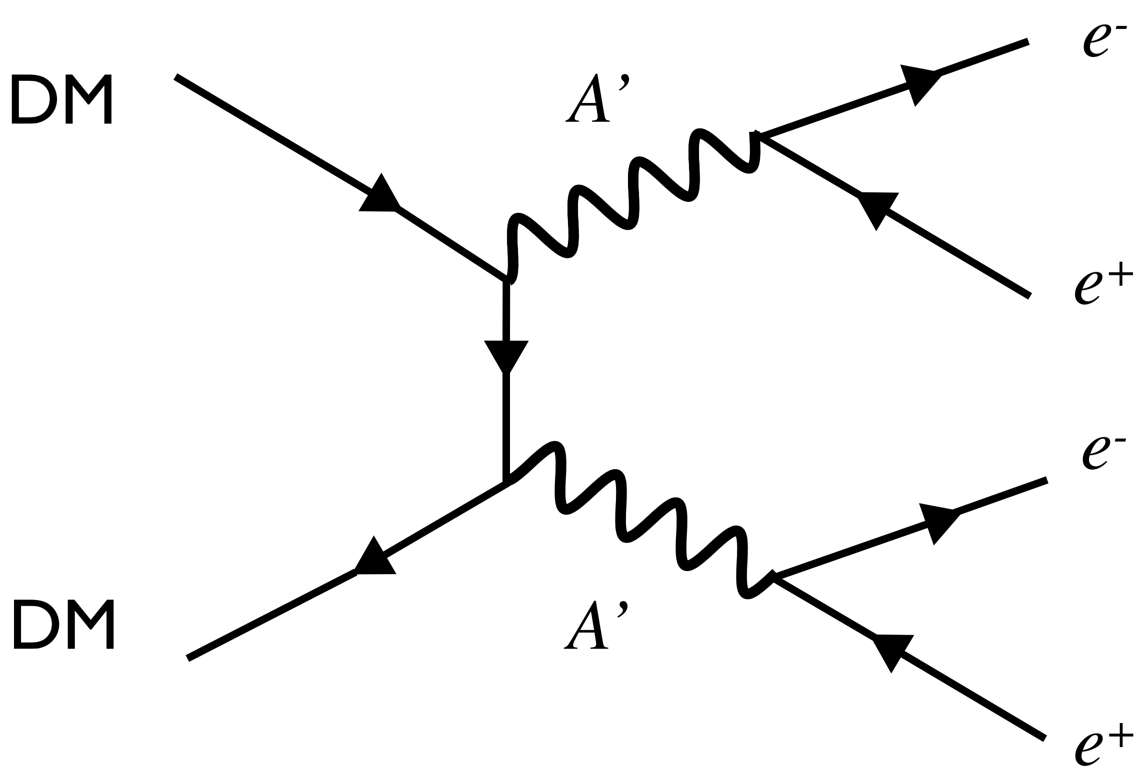
or "anything" ...

Leading to: $M_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$

See: R. Essig et al, Intensity Frontier WS '11 summary paper.

Can mediate DM decay & scattering

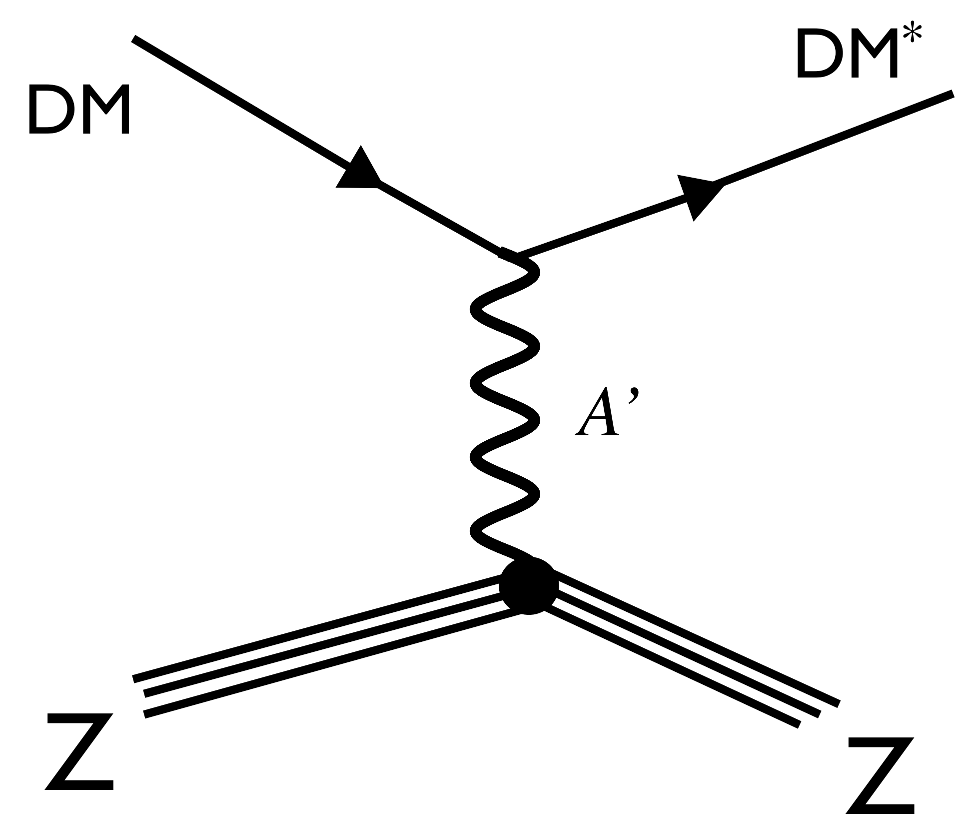
DM annihilates through intermediate A'



DM decays to A′ also possible

Pospelov, Ritz

A' mediates DM scattering

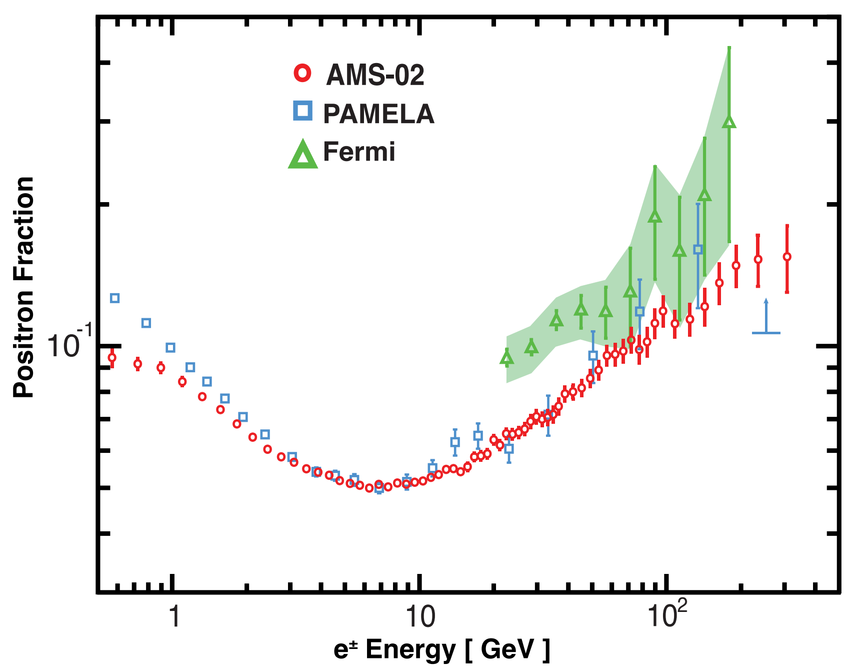


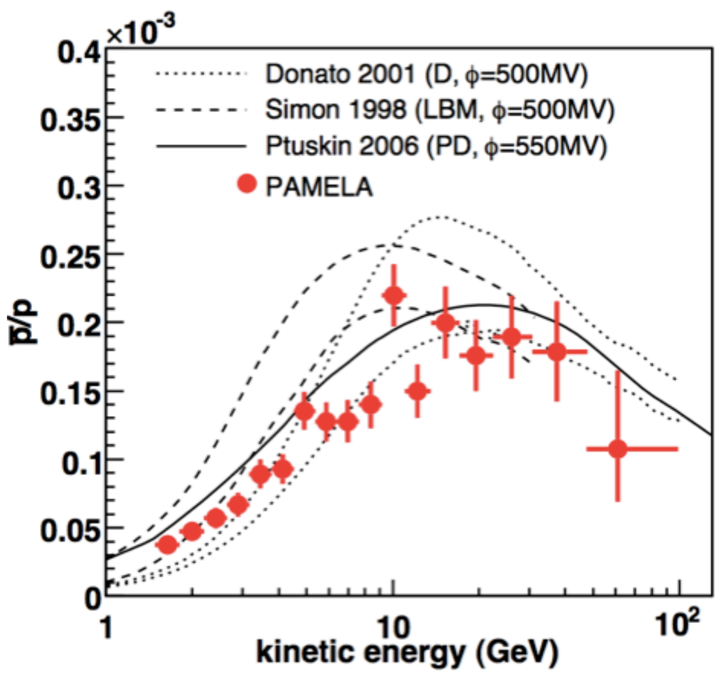
Arkani-Hamed, Finkbeiner, Slatyer, Weiner

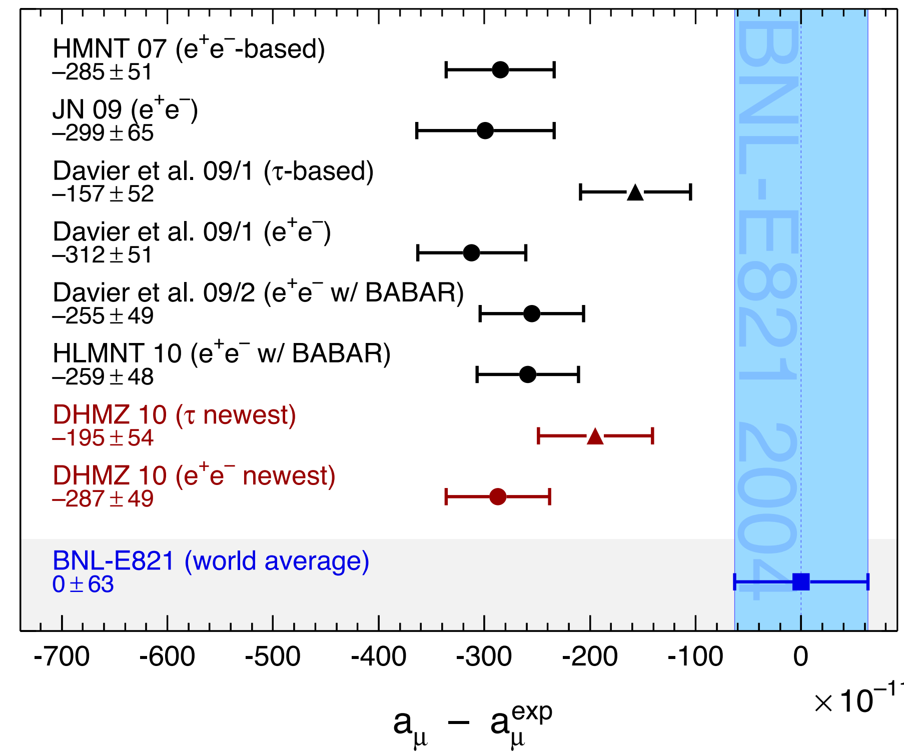
Hints from astrophysics?

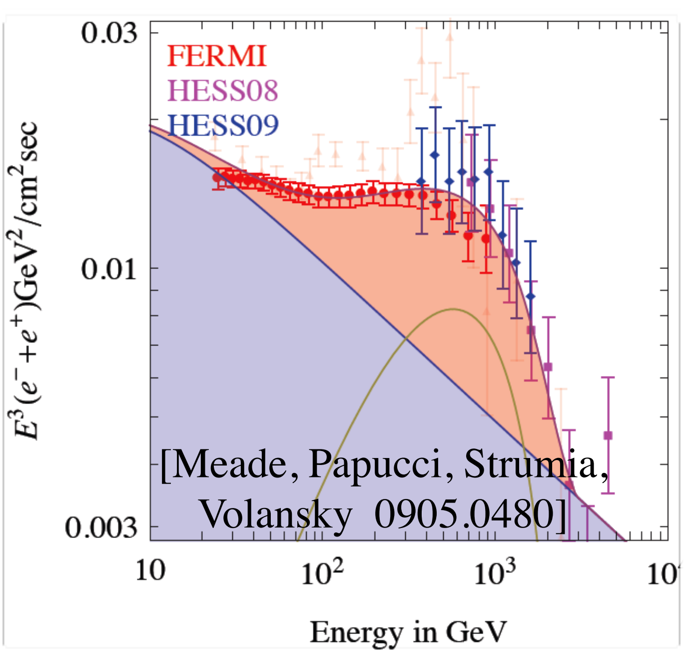
PAMELA, FERMI, AMS
Energetic e+/e- cosmic rays from DM annihilation through *A′* ?

10-100 MeV A′ could explain muon g-2 anomaly





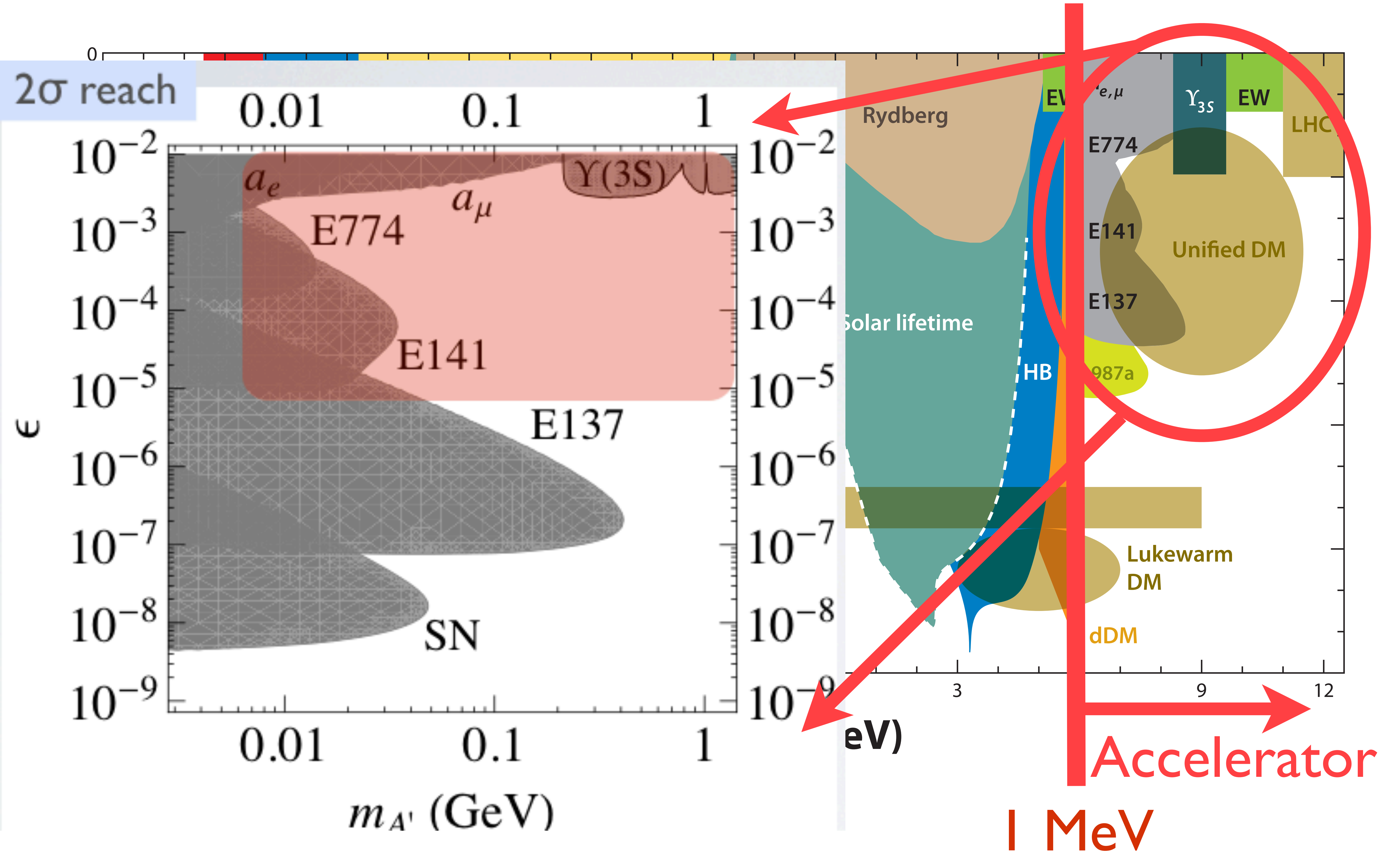




Arkani-Hamed, Finkbeiner, Slatyer, Weiner. '09 PRD 79, 015014
Pospelov and Ritz '09 PLB, 671, 391–397
Cholis, Finkbeiner, Goodenough, Weiner '09 JCAP 0912 (2009) 007

Davier, Hoecker, Malaescu, Zhang '11, Eur. Phys. J. C (2011) 71: 1515

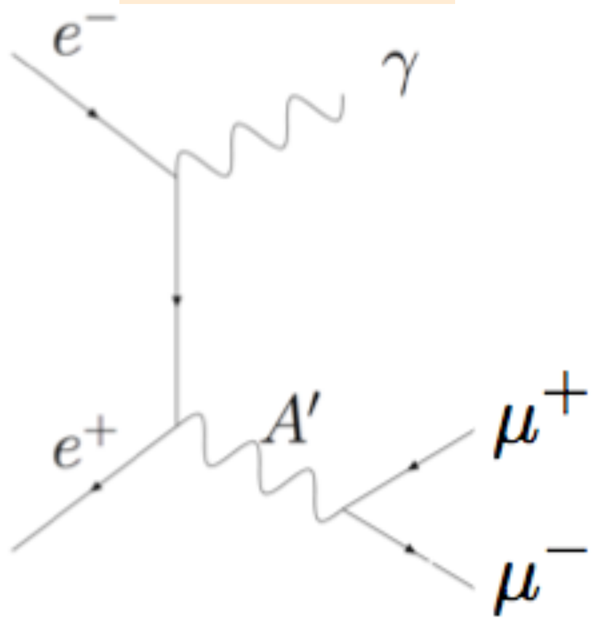
Where could it be?



How to search? $M_{A'}$>1MeV

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

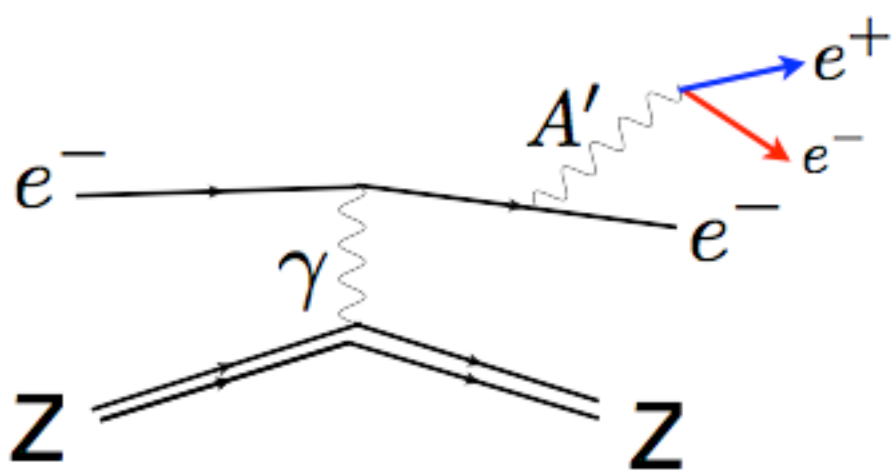
Collider



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

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

Fixed Target



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

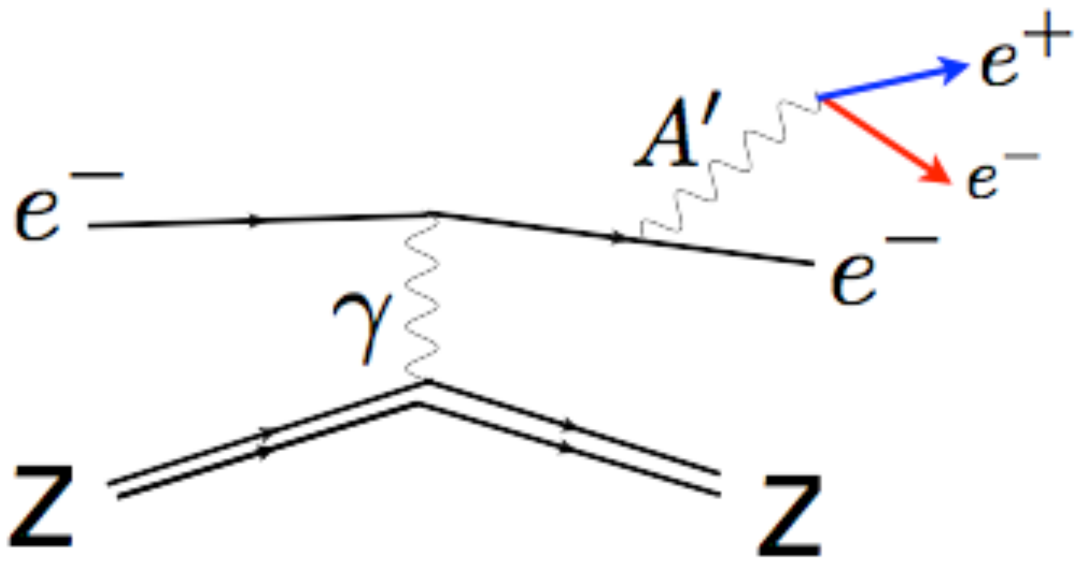
$O\ ab^{-1}$ per day

...but much higher backgrounds

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

Fixed Target Searches

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

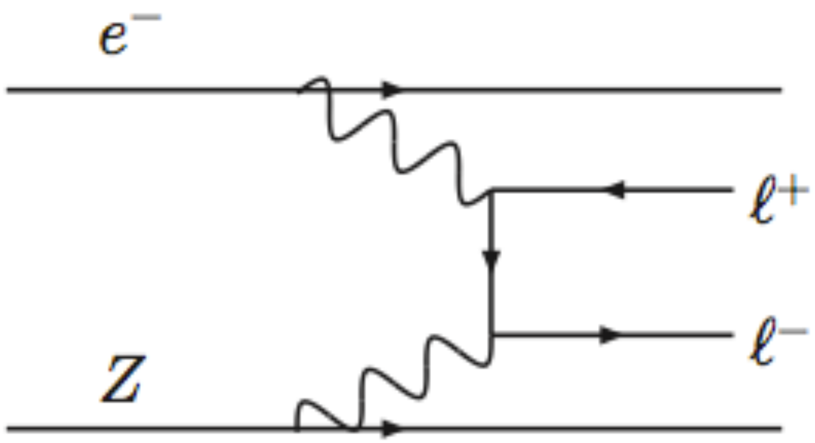


Bump Hunt:
Look for signal over background.

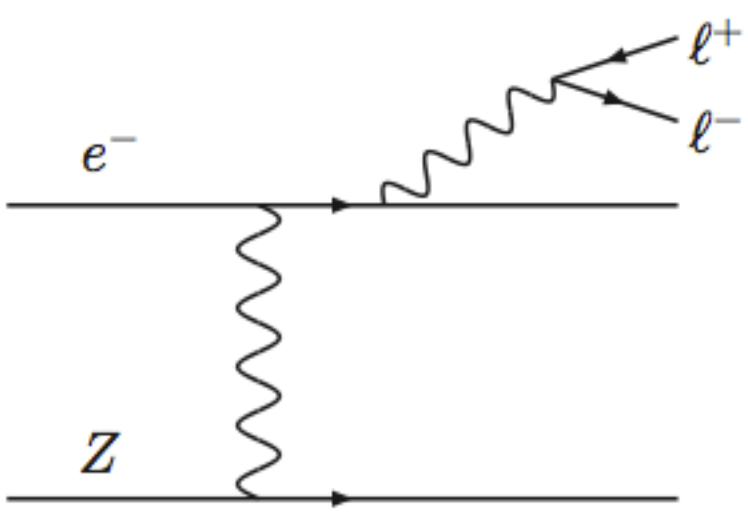
Bump Hunt + Vertexing:
Look for signal over background, reduce background with vertexing.

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

Background

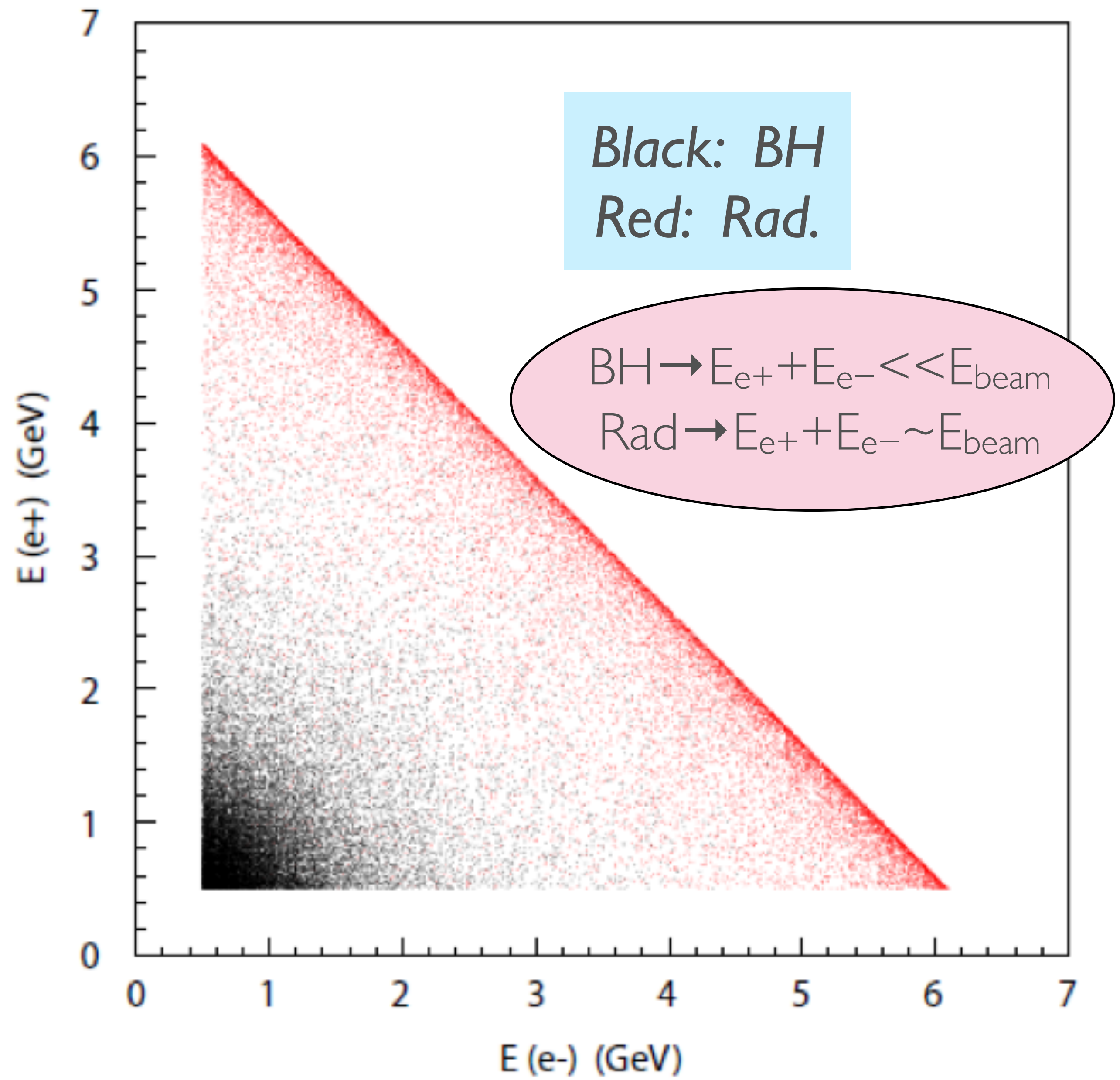


Bethe-Heitler



Radiative

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

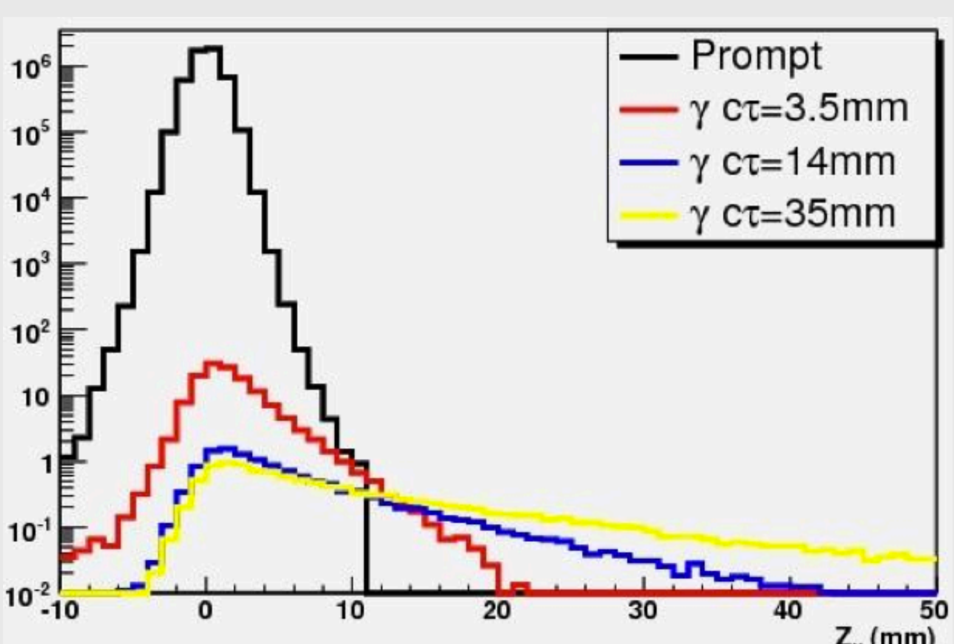


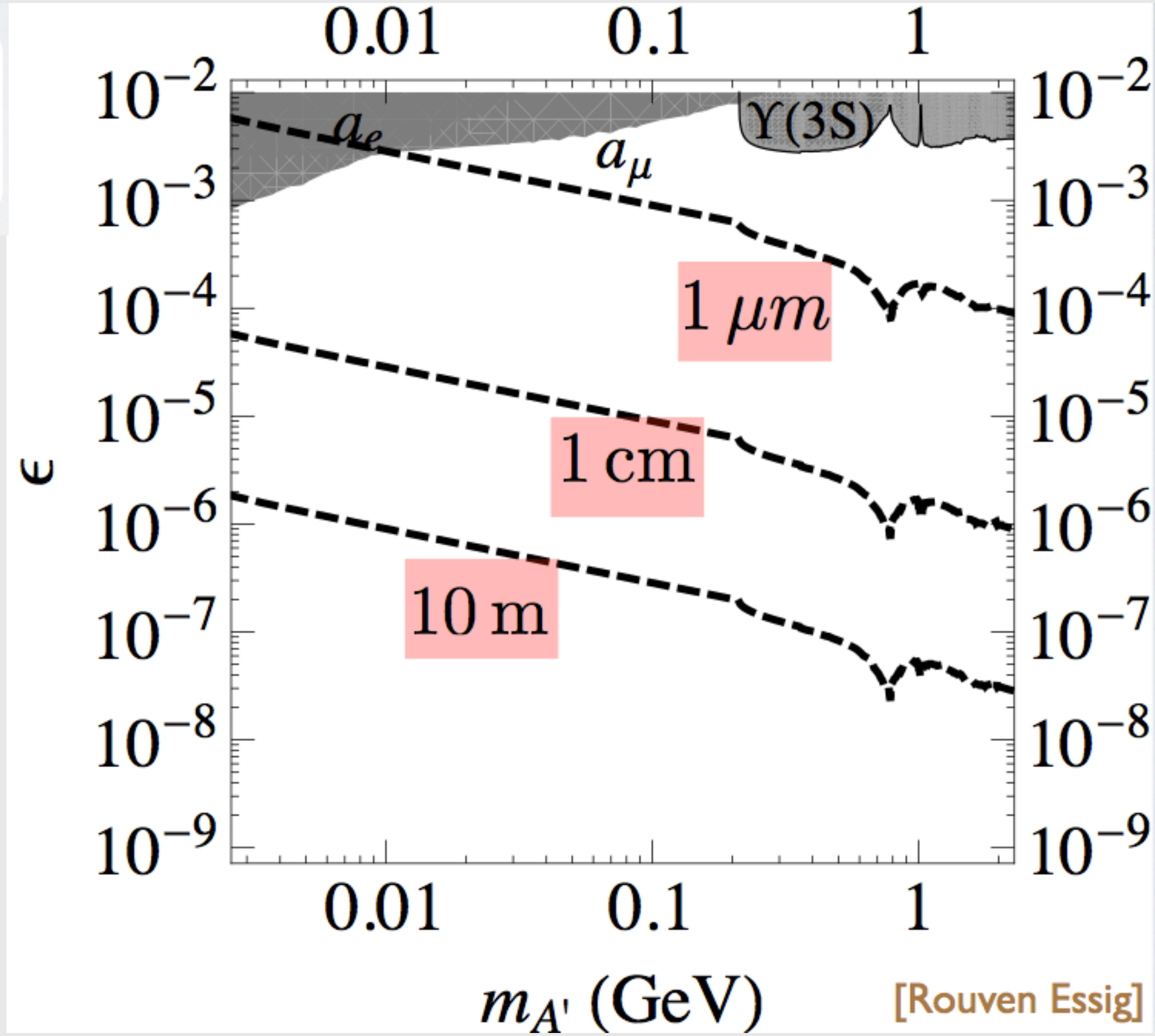
A´ lifetime

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

Lower ε, lower mass
→longer lifetime

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





True Muonium, $\mu^+\mu^-$ atom

- TM produced in target, easily dissociates, but some survive
- Long lived bound state (10 keV binding energy) decays to e^+e^-
- $M = 2\ m_\mu$, $\gamma c\tau = 35$ mm at 6 GeV
- Looks like an A', but known rate and lifetime.

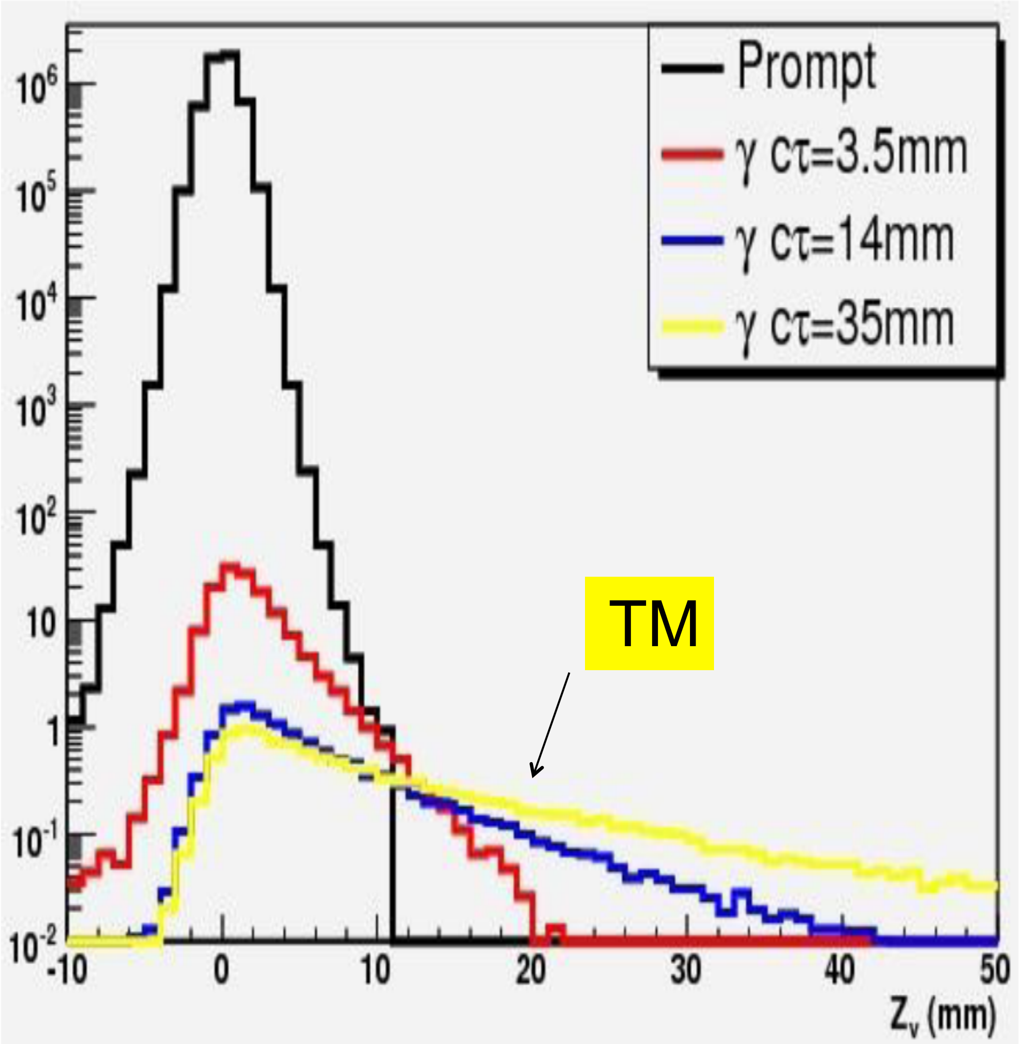
Estimated production from Philip Shuster

- Assume 6 GeV, 450 nA, 0.1% X0 target
- 1 month run
- Raw yield (1S): 180 events for x>0.8, λ> 1.5 cm
- Estimated acceptance ~ 20%

$\Rightarrow$

25 detected events, with very little background = Discovery !

Decay Length Distribution



Bamburski, Shuster 1206.3961v1

HPS Collaboration

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, A. Deur, H. Egiyan, L. Elouadrhiri, A. Freyberger, F.-X. Girod, V. Kubarovsky, 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, Durham, NH 03824

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, *INFN, Sezione di Genova, Italy*

S. Bueltmann, L. Weinstein, *Old Dominion University, Norfolk, Virginia 23529*

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

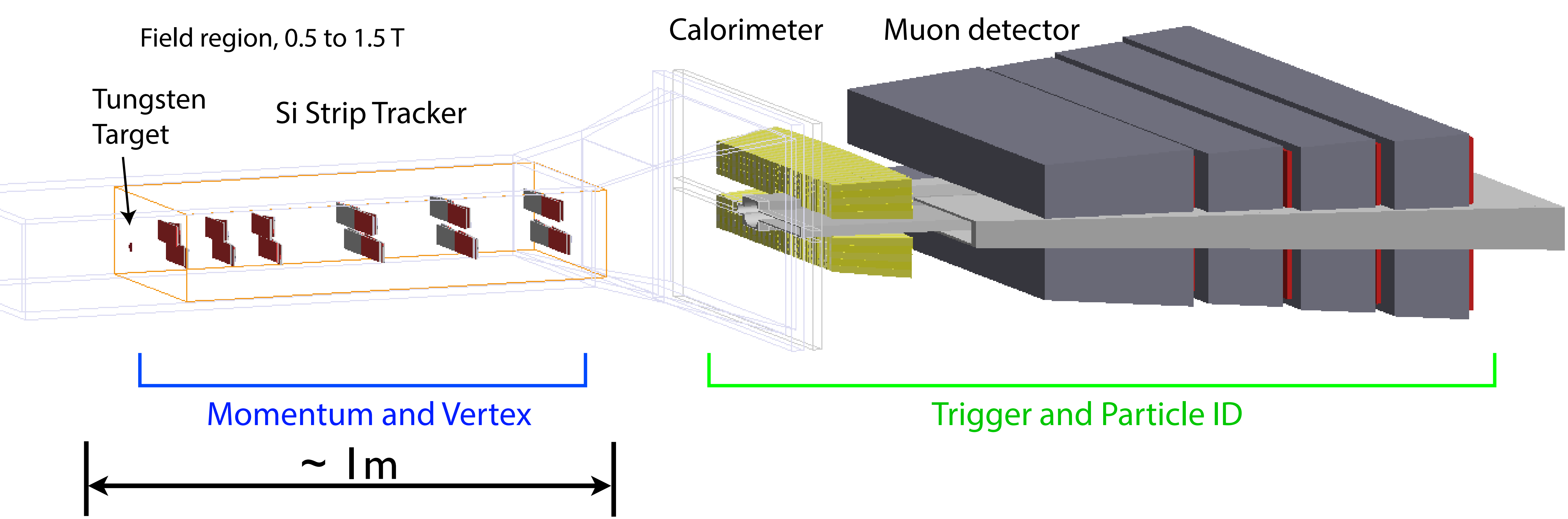
P. Stoler, A. Kubarovsky, *Rensselaer Polytechnic Institute, Troy, NY 12181*

K. Griffioen, *The College of William and Mary, Williamsburg, VA 23185*

Y. Gershtein, J. Reichert, *Rutgers University, Piscataway, NJ*

About 50 members from 16 institutions.

Heavy Photon Search

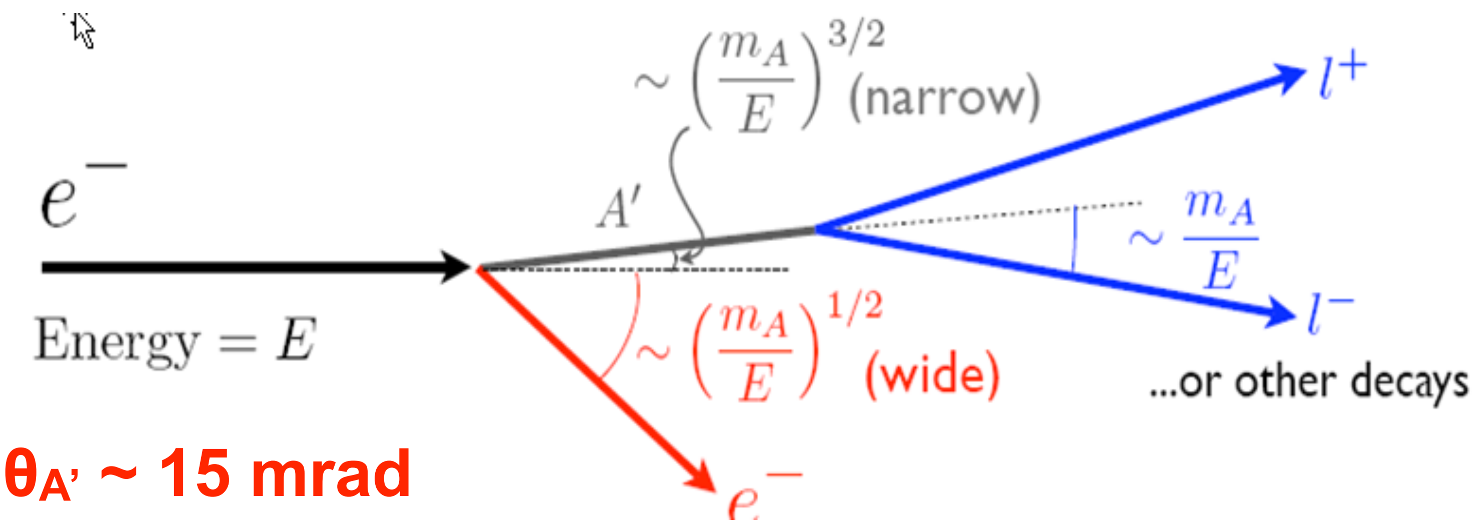


High rate, high acceptance, high mass & vertex resolution detector.
"Table top" size.
Use Jefferson Lab e^- beam in Hall B.
JLAB PAC37 January 2011 - conditional approval.
Expected data taking: commissioning 2014, production 2015

HPS Design

- A' kinematics ⇒ need good forward coverage down to ~ $\theta_{decay}/2$. This puts detectors close to the beam.

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



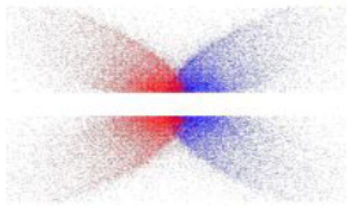
Want min $\theta_{A'}$ ~ 15 mrad

- Vertexing A' decays requires detectors close to the target. Bump hunting needs good momentum/mass resolution. Both need tracking and a magnet.

Want $\Delta m/m$ ~ 1% for bump hunt
Want Δz ~ 1mm

Beam's Eye View

e^+ and e^-



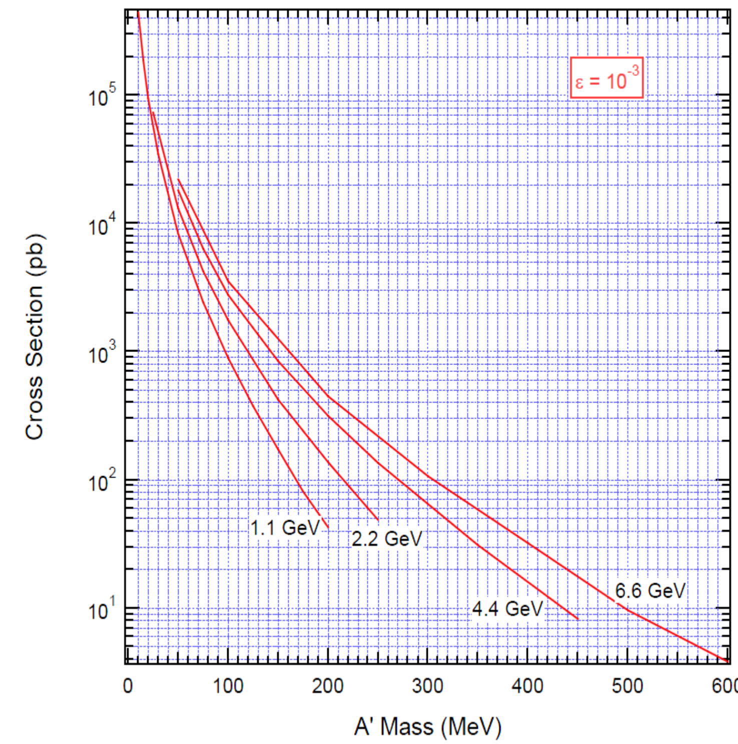
entering ECal

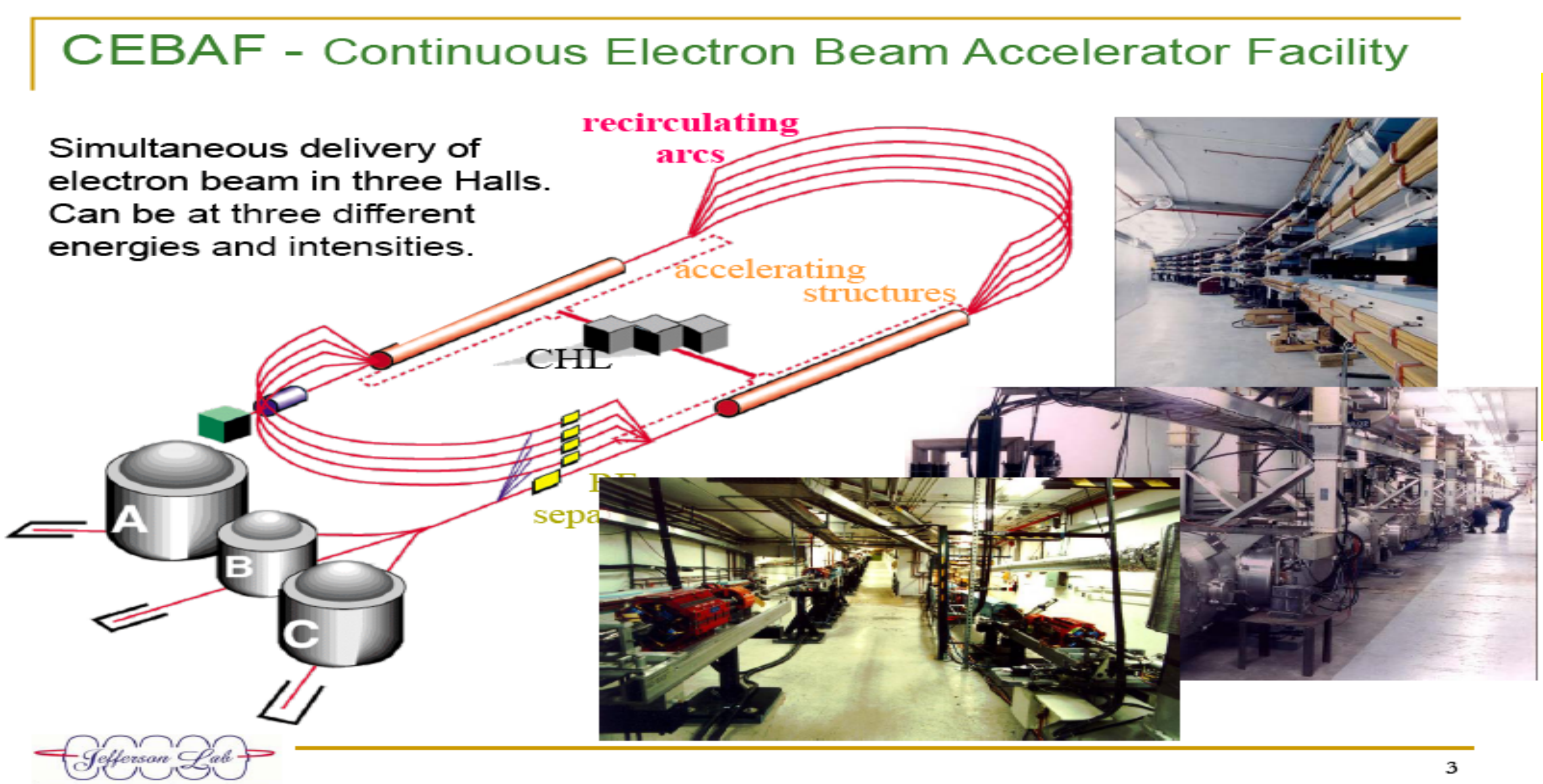
- Trigger with a high rate Electromagnetic Calorimeter downstream of the magnet to select e^+ and e^-, muon detector to select μ^+ and μ^-.

Small cross-sections, large backgrounds need high luminosity

- **How to minimize occupancy in a forward detector**
  - ✳ Maximize accelerator duty cycle
    CEBAF has **100% duty cycle!**
  - ✳ Minimize detector response times: **Fast Detectors.**
    Pulse lengths in the SVT and Ecal are ~ 60ns
  - ✳ Maximize the readout and trigger acceptance rates
    SVT has 40 MHz readout
    Ecal has 250 MHz FADC **High Rate Capable DAQ**
    Trigger can handle input every 8 ns

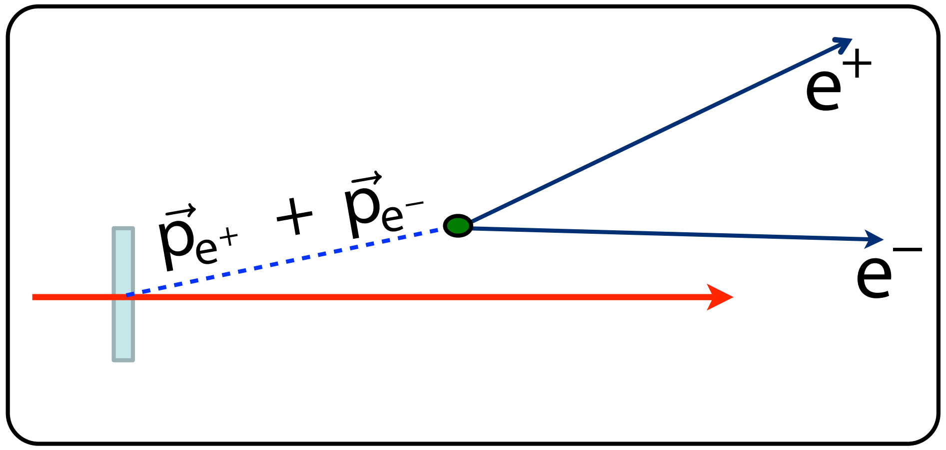
$\sigma(e^- + W \rightarrow W + A' + e^-)$



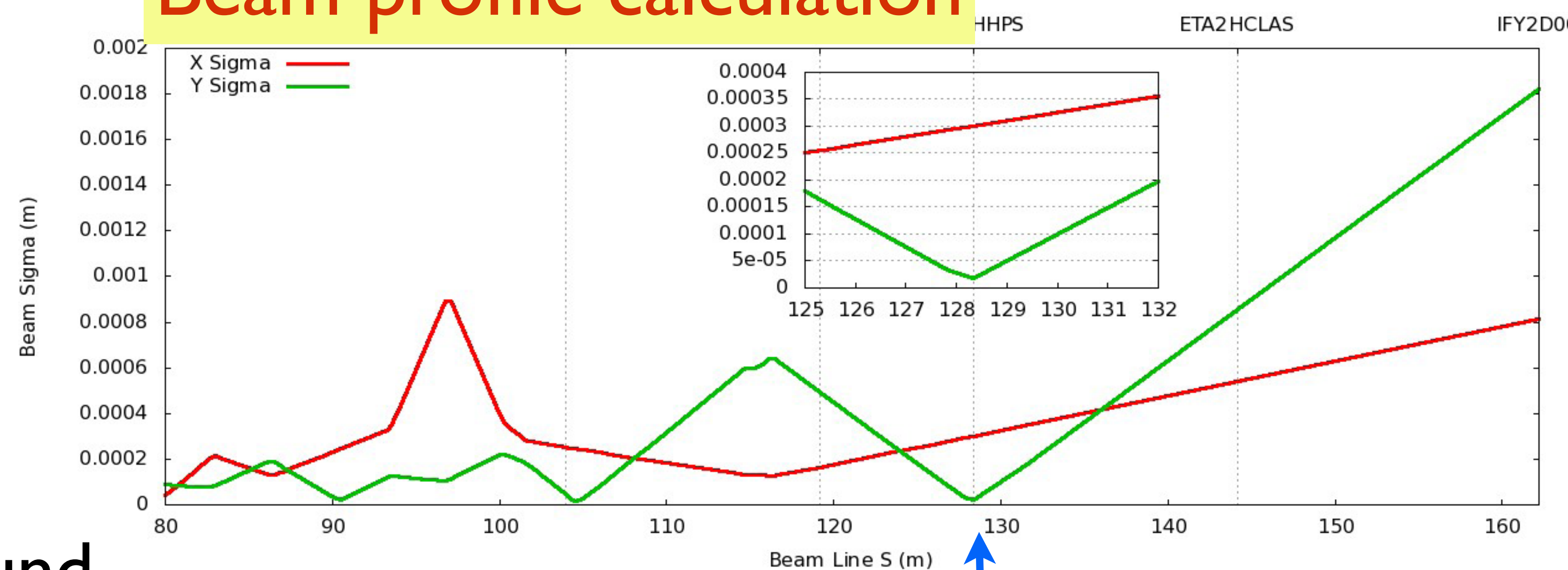


Jefferson Lab: CEBAF
E = 6 GeV (now) →
12 GeV (2014)
High currents ≤ 100 μA
Continuous! 500 MHz

Beam Quality in Hall-B



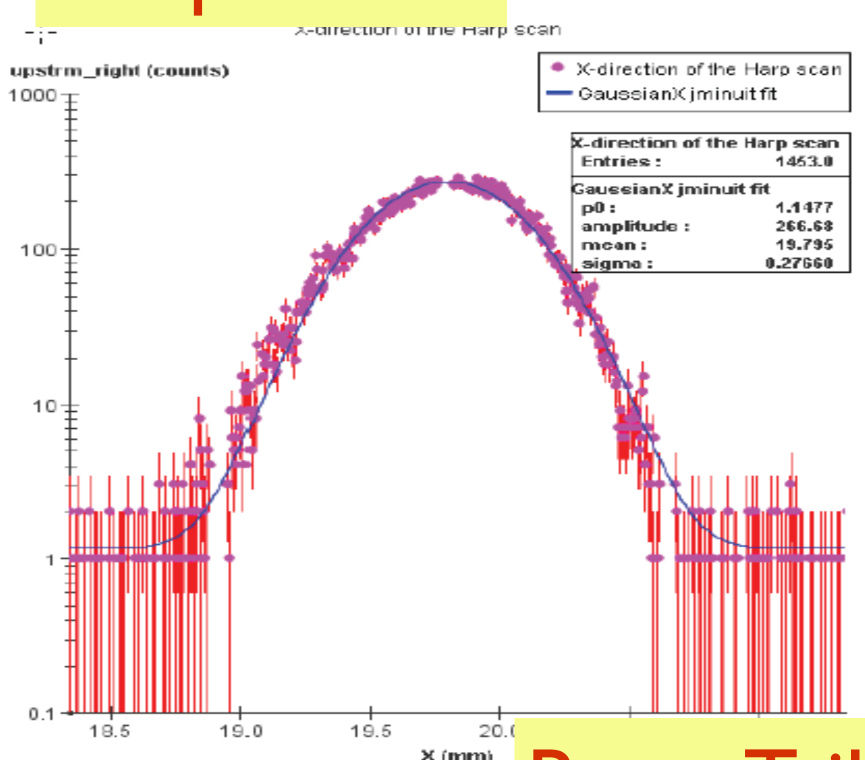
Beam profile calculation



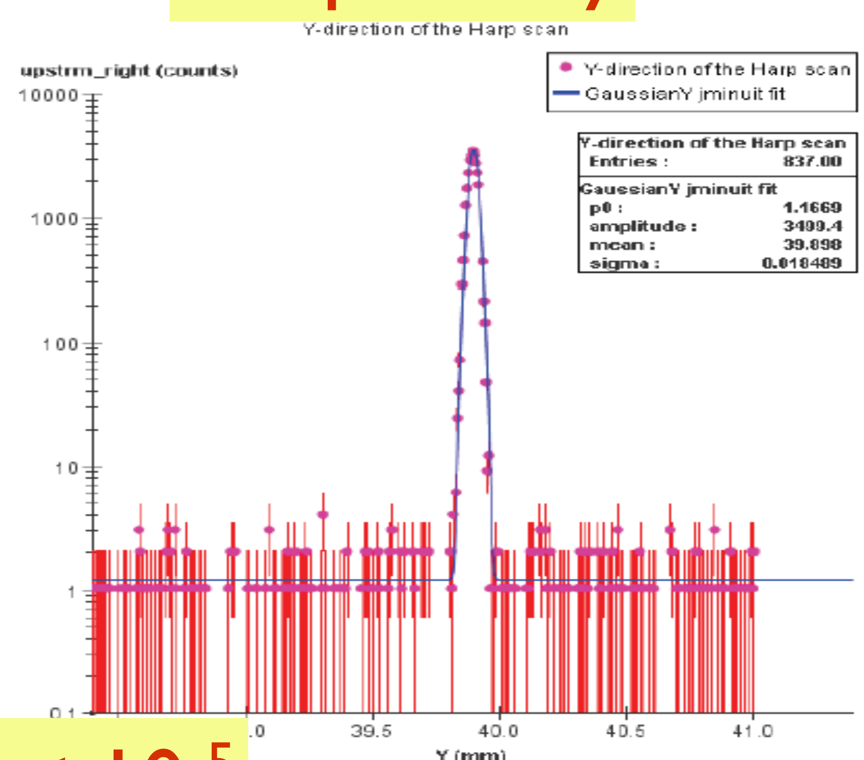
Target Location

Very low halo = low background

Harp Scan x



Harp Scan y



Beam Tail < 10^{-5}

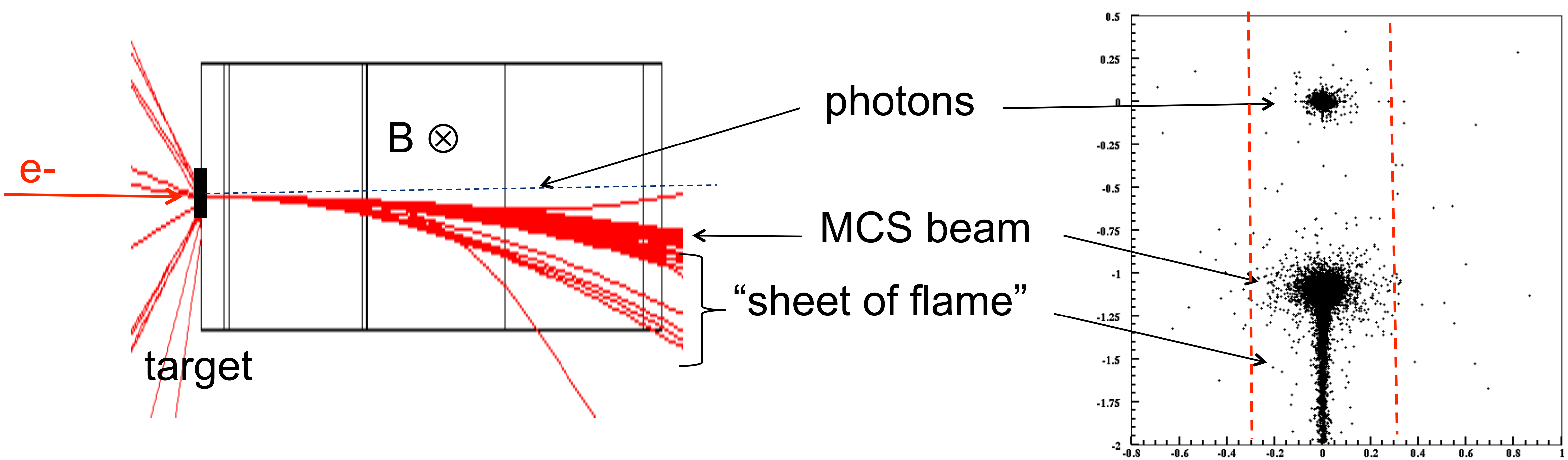
Wide beam spot in X to spread heat load.
Tight beam spot in Y helps tracking & vertexing.
I_{beam} = 1 to 500 nA

Controlling beam background

- Silicon sensors and EM Cal must be positioned as close to the beam as possible to maximize low mass acceptance. Backgrounds matter!
- **Design constraints**
  * Avoid Multiple Coulomb Scattered (MCS) beam
  * Avoid photons radiated in target
  * Avoid “sheet of flame”, the beam electrons which have radiated, lost energy, and been deflected
  * Avoid beam gas interactions.
- HPS splits detectors to avoid the “Dead Zone”, and puts SVT in vacuum.

Side view

Beam’s eye view



“Dead Zone”

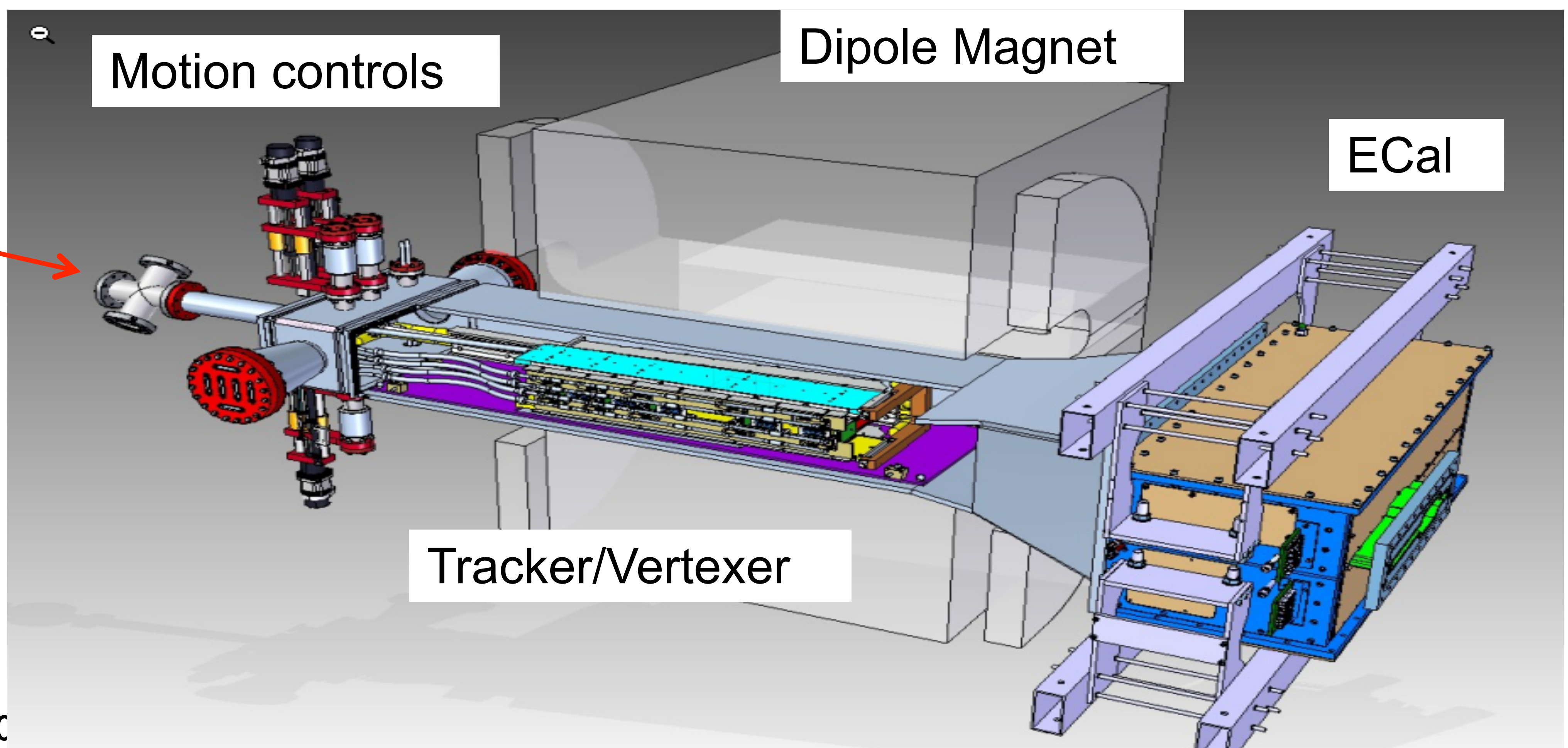
HPS Test Run

- The HPS Test Run is the first stage of HPS, **designed to demonstrate the experiment's technical feasibility**, measure backgrounds, and begin our search for heavy photons. Installed and run at JLAB during Spring 2012

- Designed to electro-produce A's on a thin W target upstream of the tracker.

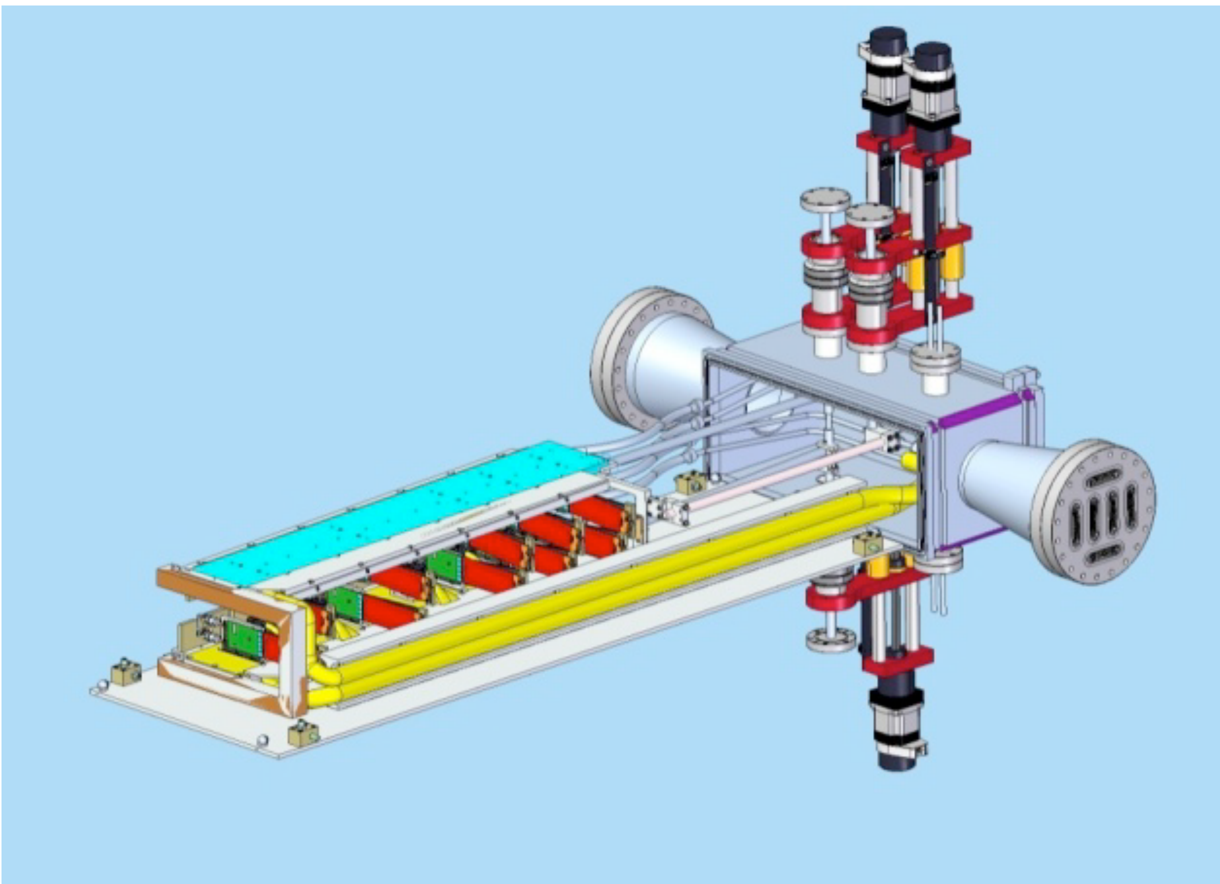
- Measure A' mass and decay point in a compact spectrometer- vertex detector placed inside a dipole magnet. Use high rate electronics.

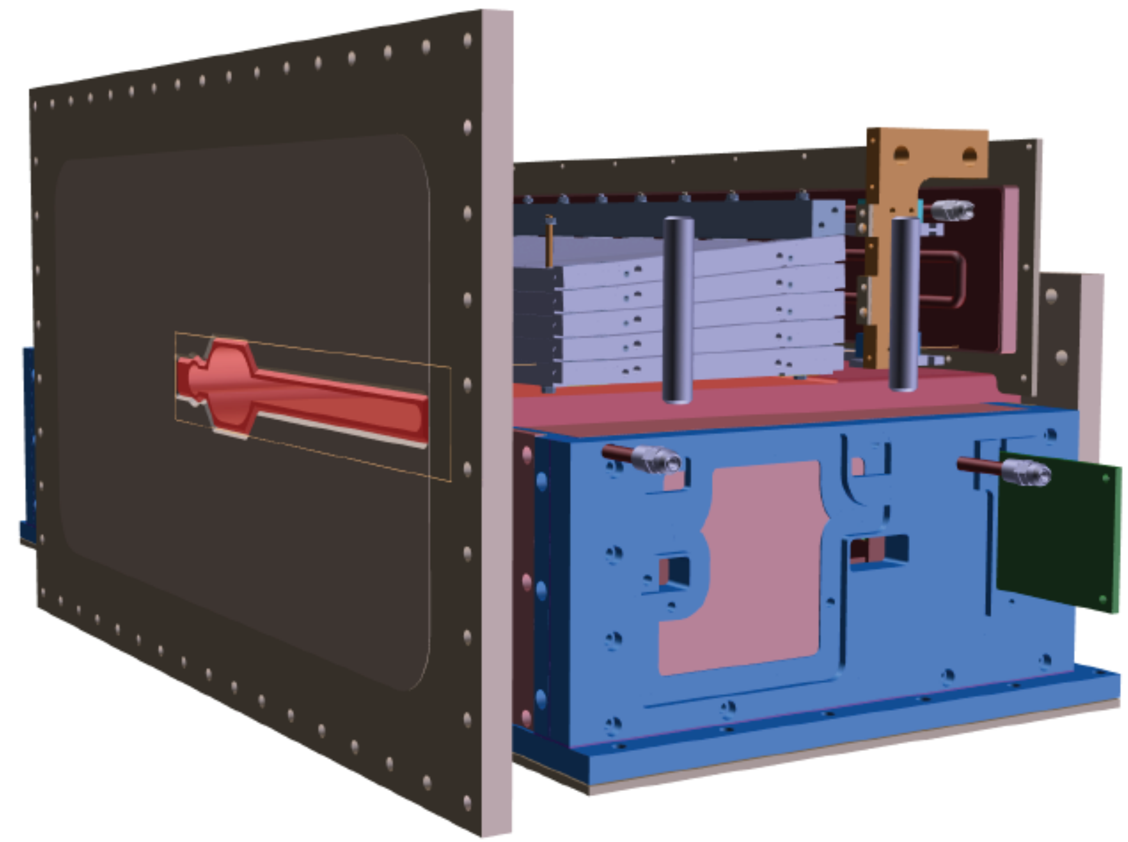
- Trigger with a fast EM Calorimeter .



Split Design

- Both the Silicon Vertex Tracker (SVT) and the Ecal are split vertically, to avoid the "sheet of flame".

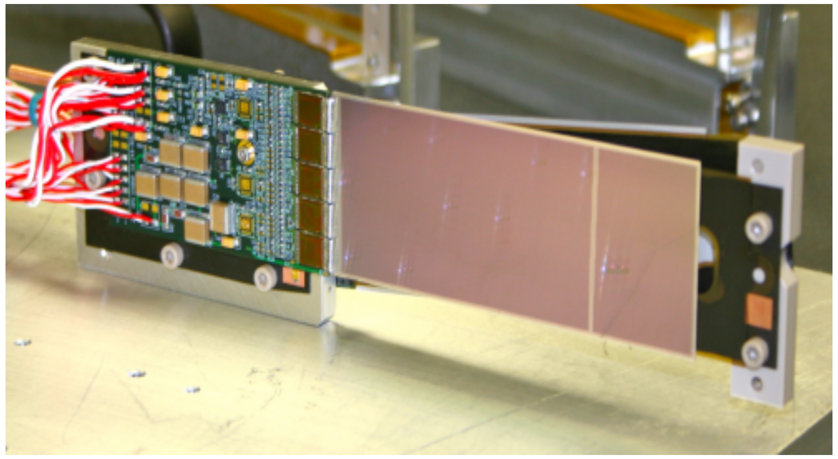


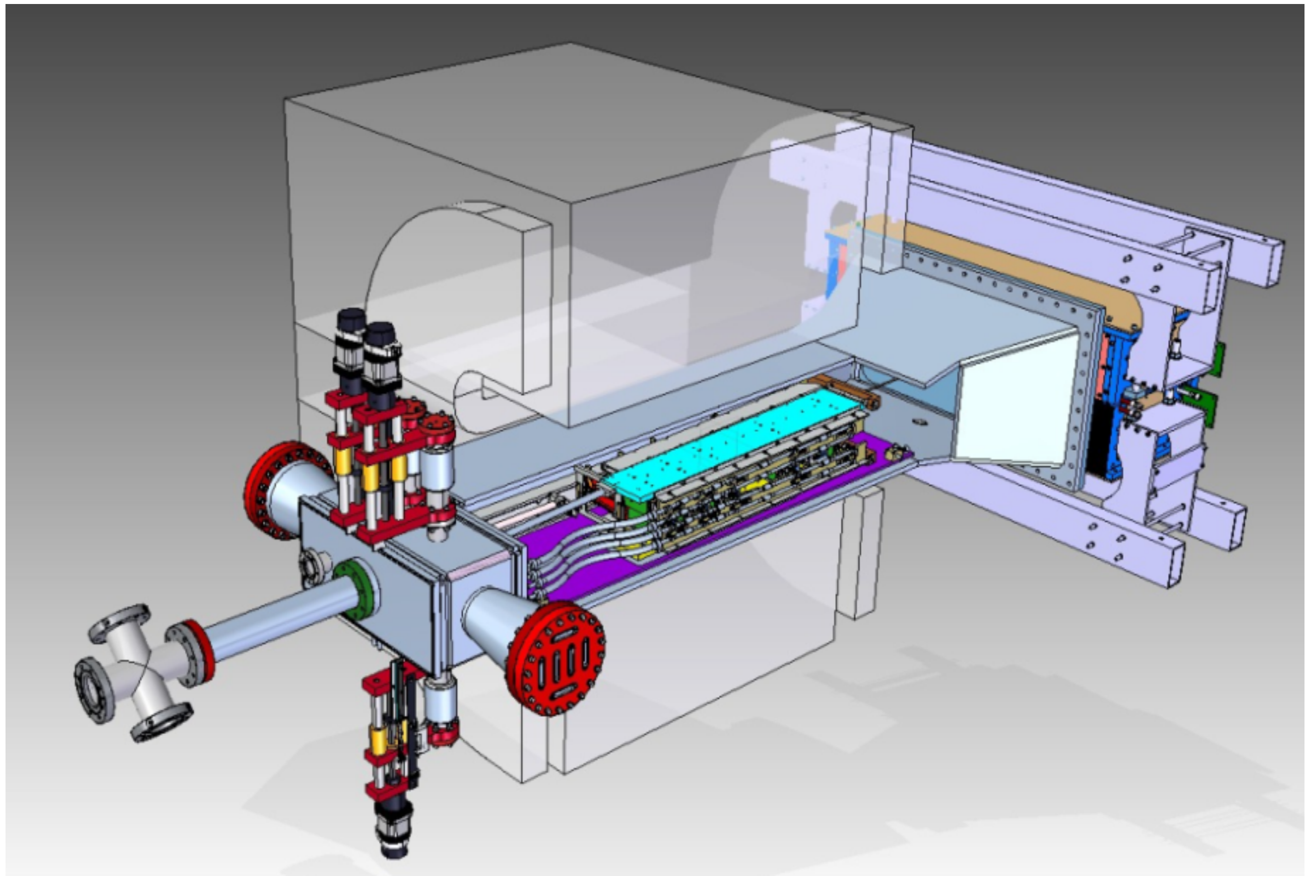


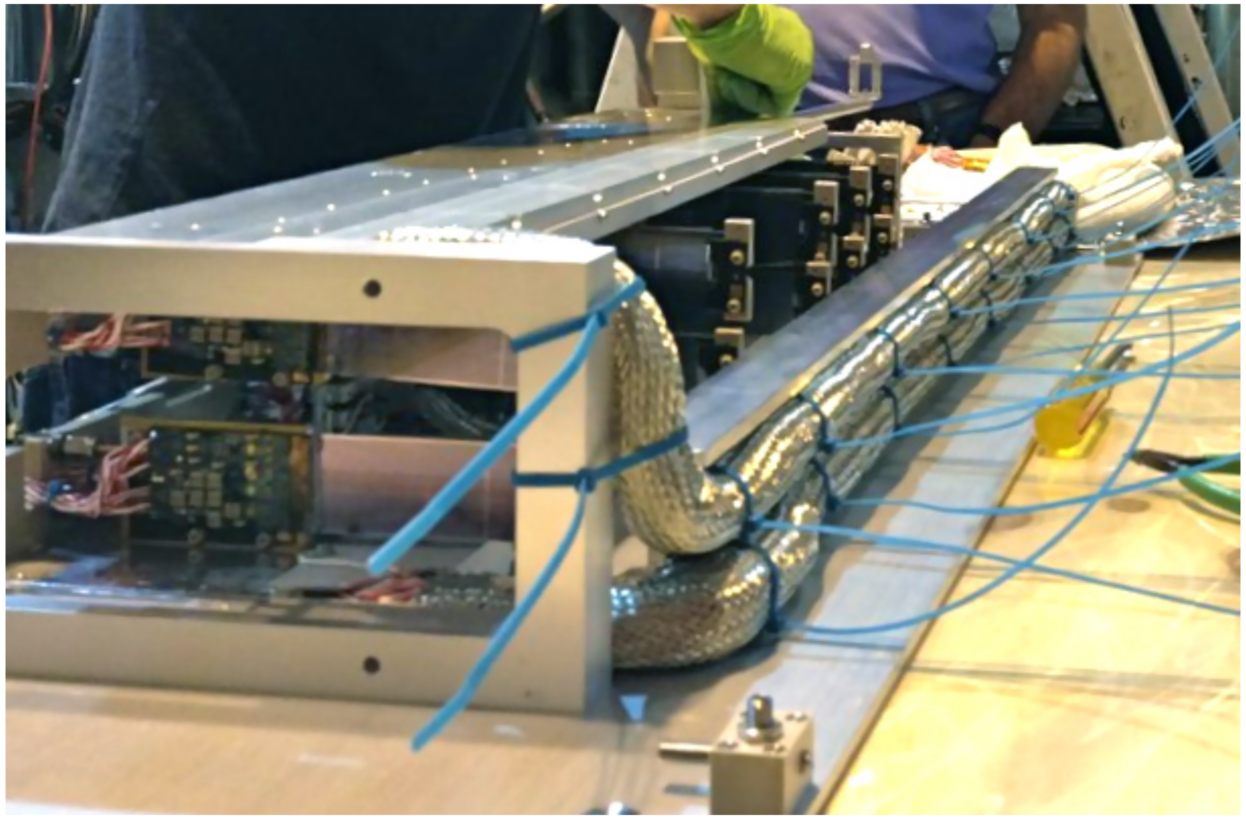
- The first layer of the SVT comes within 0.5 mm of the beam to allow acceptance at 15 mrad, so precision movers, working in vacuum, are needed to position it accurately w.r.t. the beam
- The beam passes between the upper and lower halves of the Ecal through the Ecal vacuum chamber, which accommodates the photons radiated at the target, the multiple scattered electron beam, and the "sheet of flame".

Silicon Vertex Tracker

- **Si microstrip sensors readout by CMS APV25's**
  40 MHz readout
  $\sigma_x \approx 6$ μm; $\sigma_t \approx 2$-3 ns
- **Tracker has 6 (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"



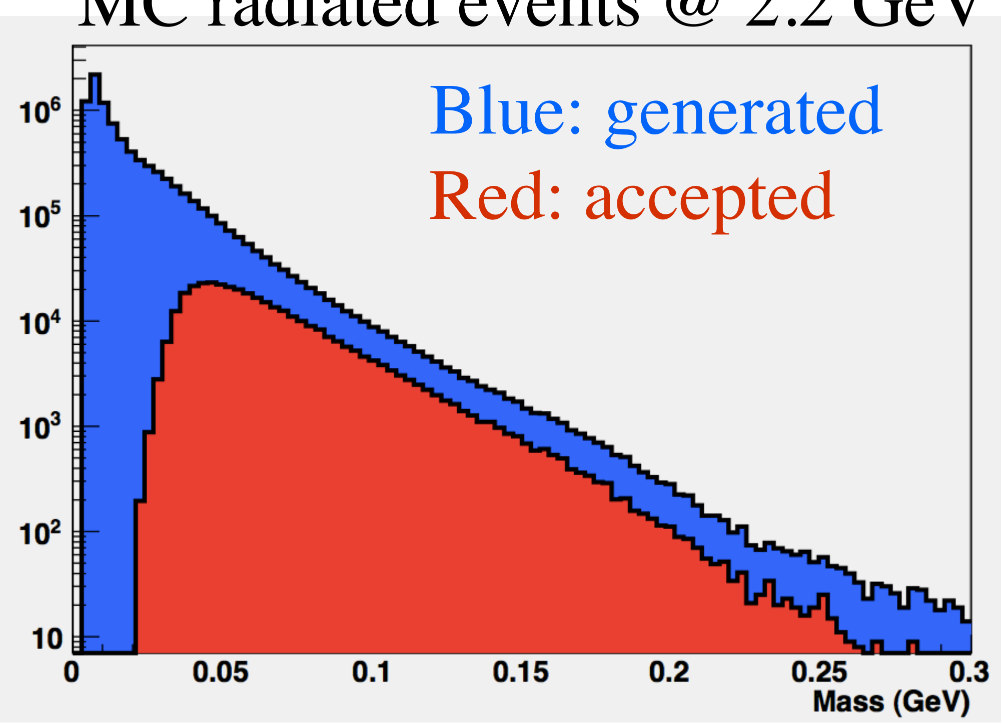


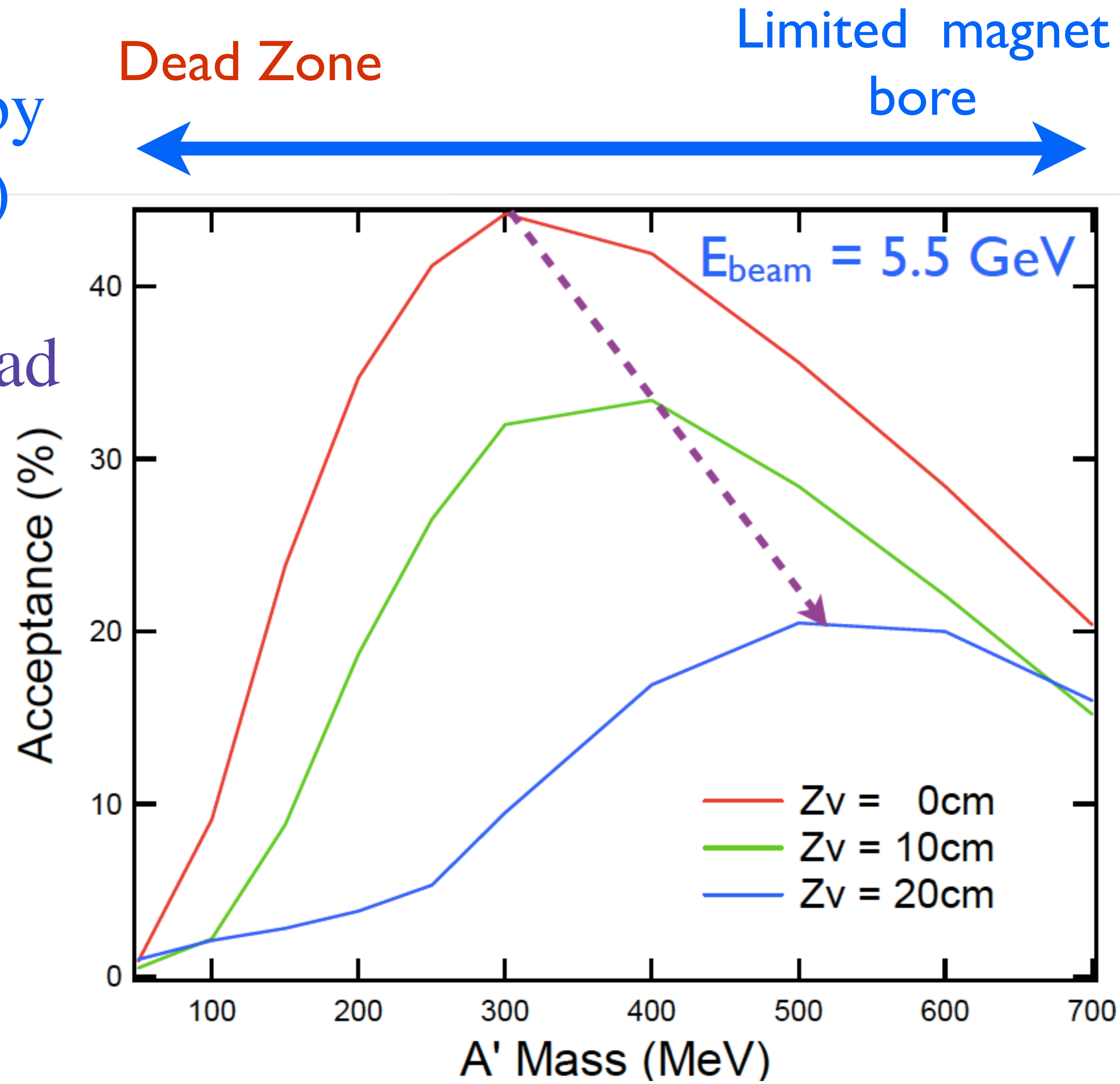


Acceptance

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

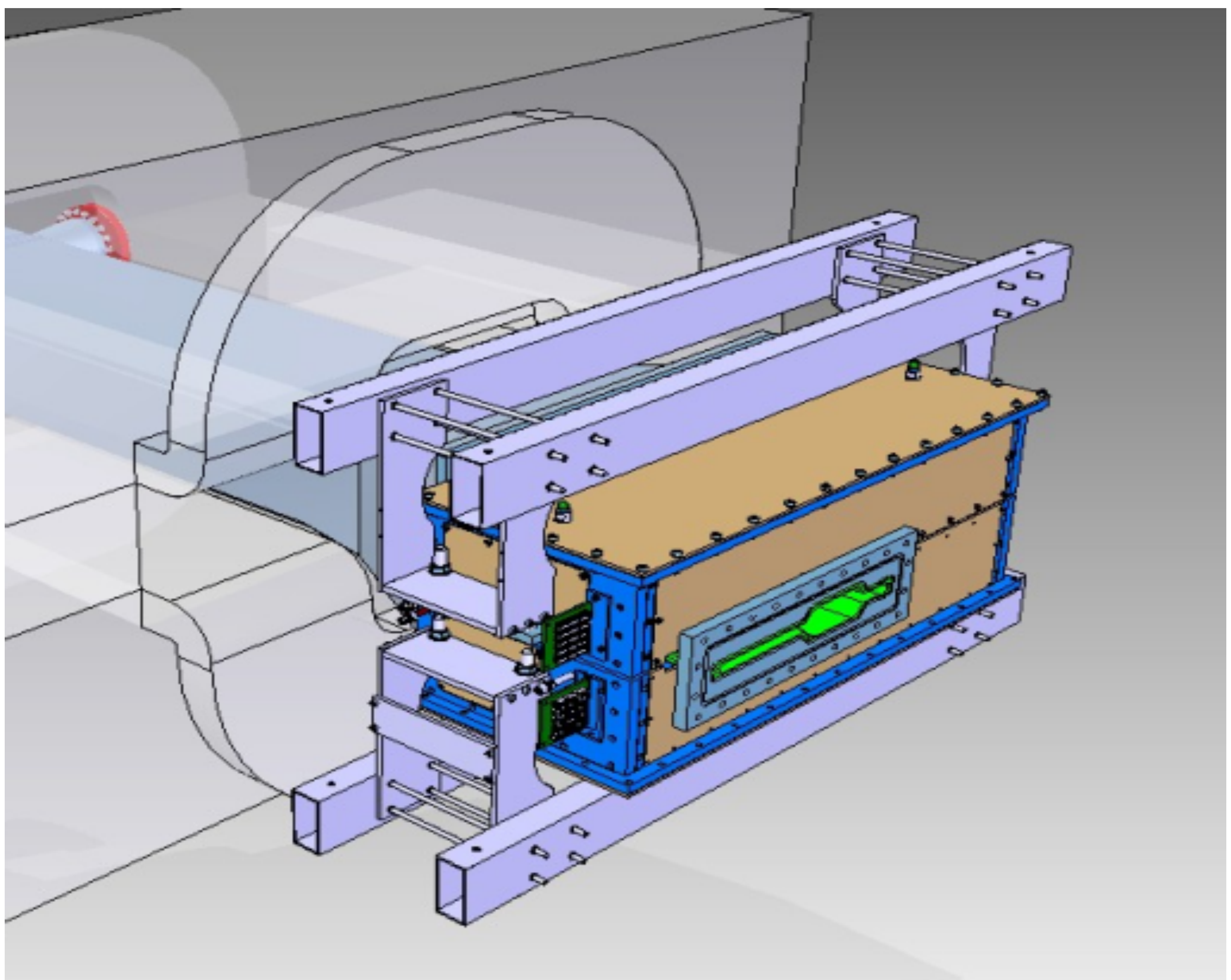
MC radiated events @ 2.2 GeV

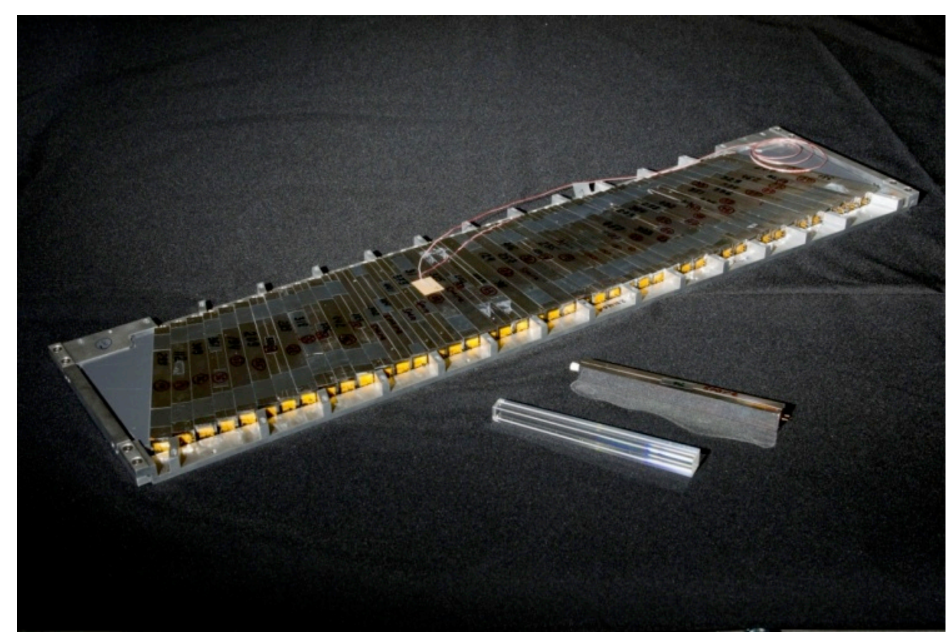




Electromagnetic Calorimeter

- 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





High Rate DAQ

- **SVT DAQ uses SLAC ATCA-based architecture**
  - * Sensor hybrids pipeline data at 40 MHz and send trigger-selected data to COB for digitization, thresholds, and formatting. COB transfers formatted data to JLAB DAQ.
  - * Record data up to 16kHz in pipeline mode. Will push this up to 50 kHz with upgrades.

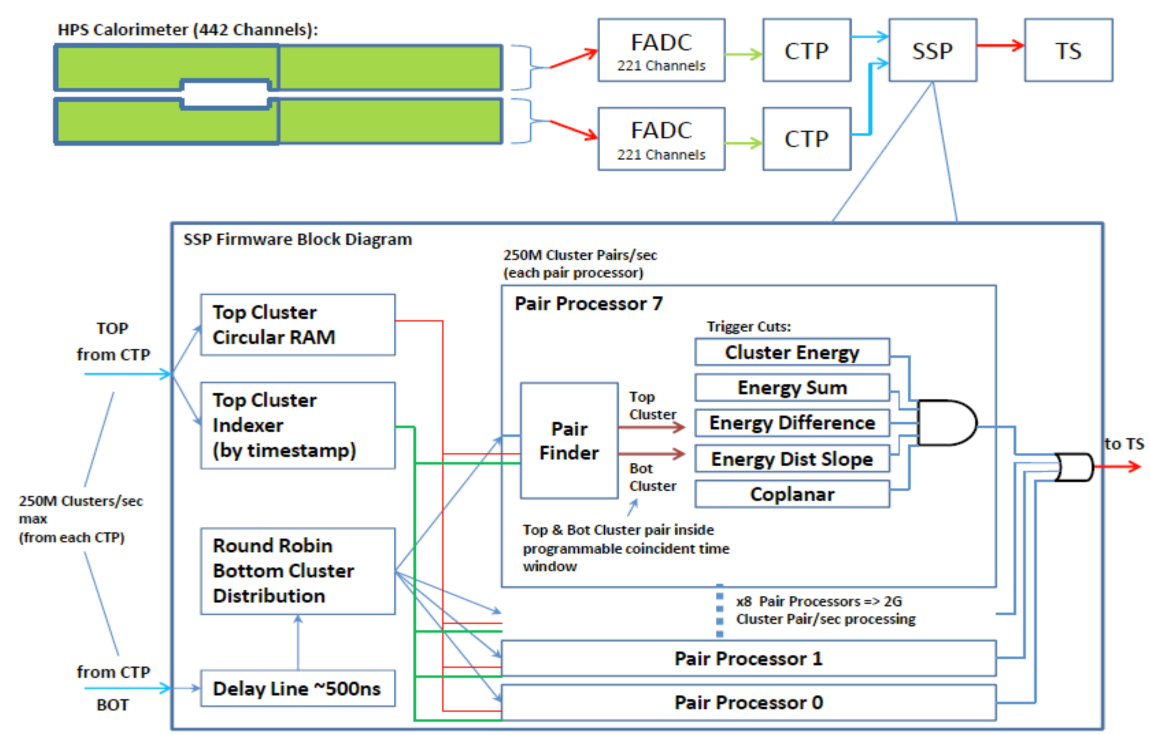
.

  - * One ATCA crate with 2 COBs handled the full HPS Test Run SVT (20 modules, ~10k channels).

Cluster on Board (COB)

- **Ecal DAQ and Trigger**
  - * Data recorded in 250 MHz JLAB FADC. PH and time transferred every 8ns to Trigger Processors.
  - * Trigger sent to SVT DAQ and FADC for data transfer.
  - * Ecal FADC and DAQ can trigger and record data up to 50 kHz.

Ecal DAQ/Trigger

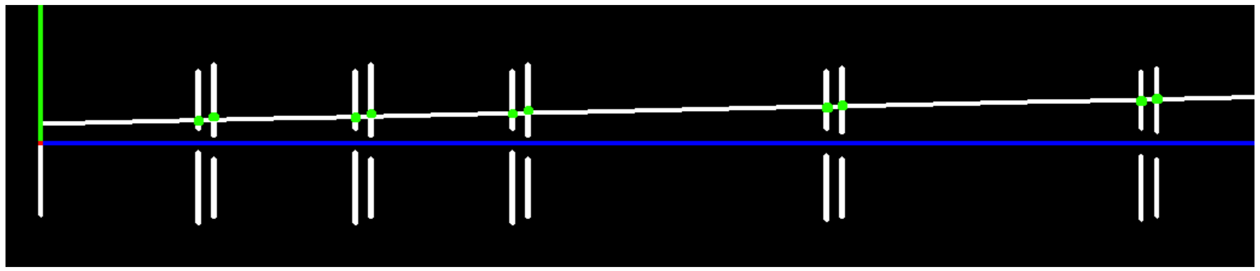


Test Run 2012

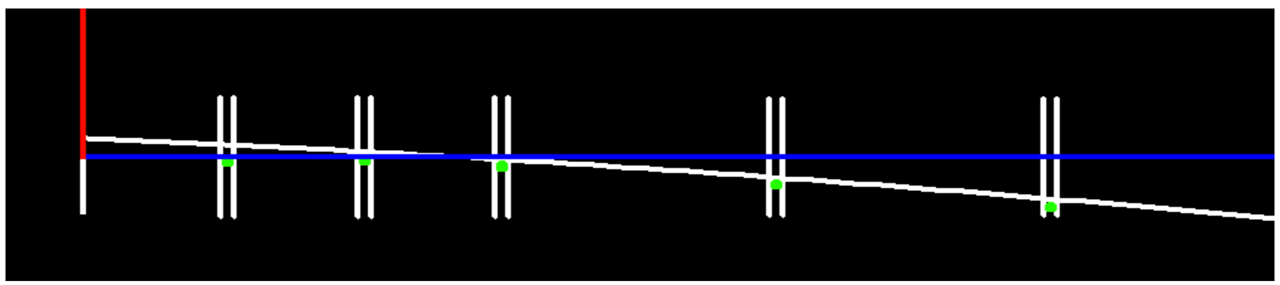
- PAC approved a test run to demonstrate technical feasibility of the experiment.
- Scheduling conflicts in Hall B prevented HPS Test Run getting a dedicated electron run. Instead, HPS Test ran parasitically with another experiment using a photon beam.
- **Photon running, with a thin conversion target** in front of HPS, let us fully commission the detector and DAQ and prove its technical feasibility
- A dedicated photon run during the last **8 hours of CEBAF-6** running, let us take high quality data for detailed performance studies, and measure normalized trigger rates.
- These data lets us make the case that HPS Test performs as advertised, and that *the **backgrounds expected in electron running are understood.***
- **PAC approves experiment, with A rating, 180 days of beam.** (But we still need to test the electron beam running)

Measured SVT Performance

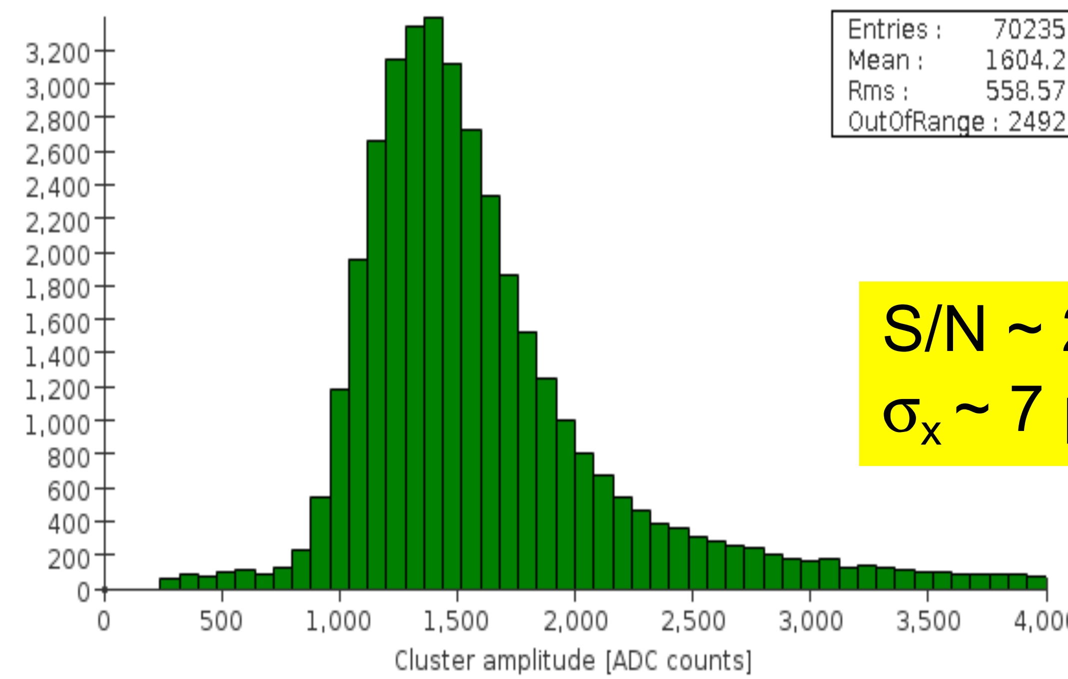
Elevation



Bend Plane



MIP Cluster PH ~ 1600 ADC counts

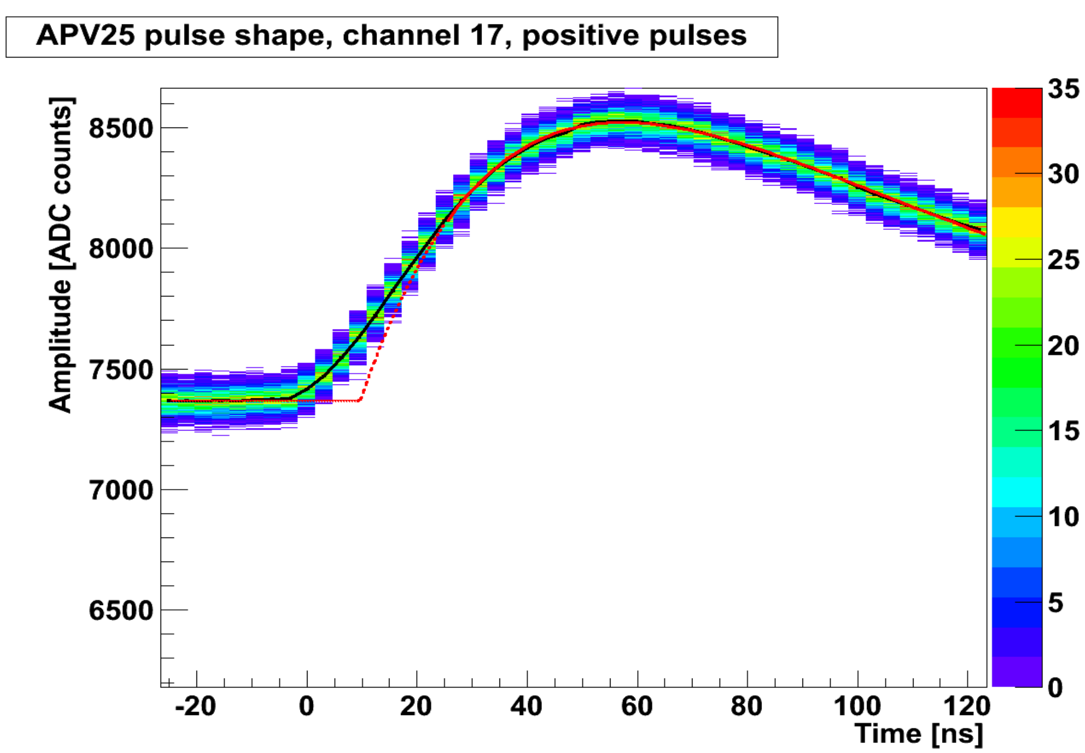


S/N ~ 20

$\sigma_x \sim 7\ \mu m$

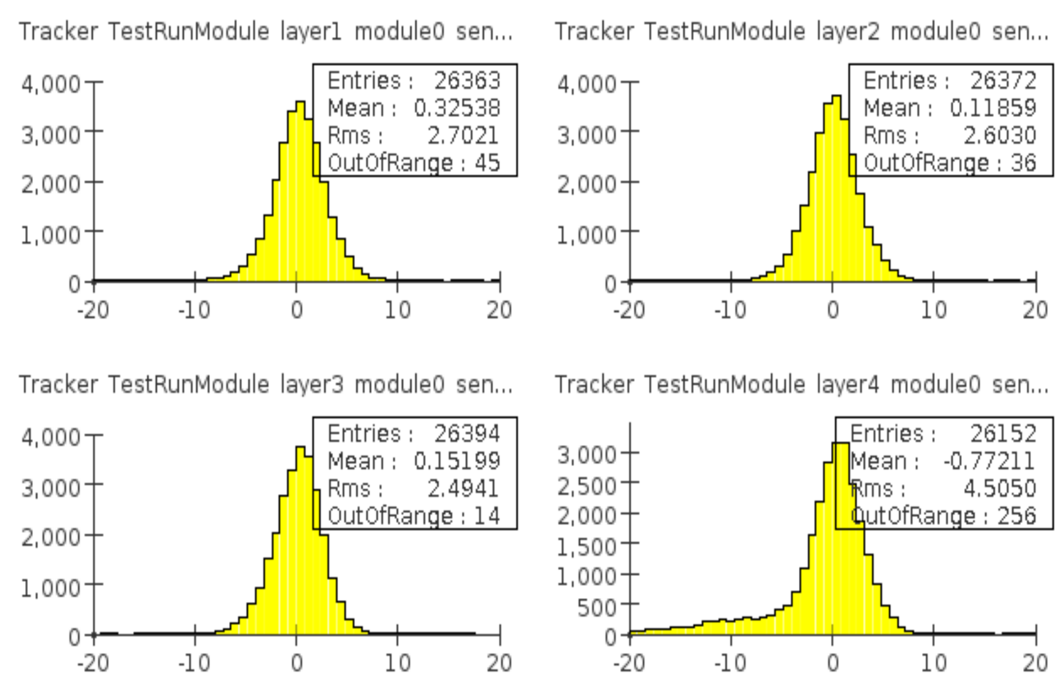
Record pulse shape in 6-25ns bins

⇒ track time



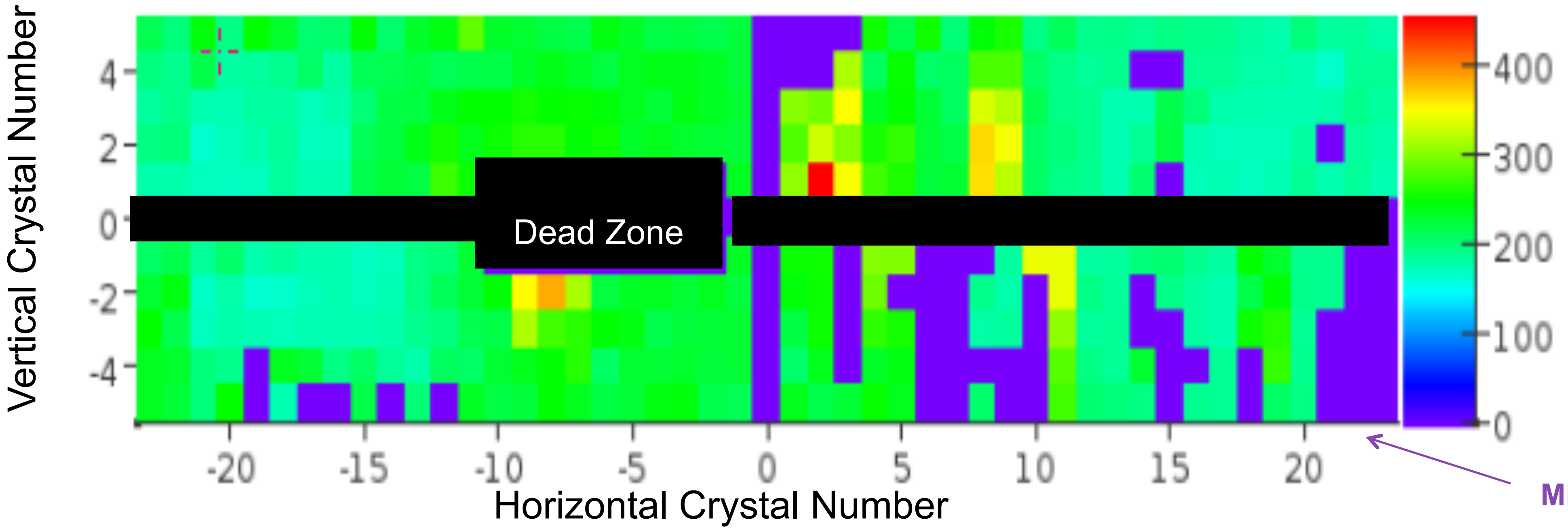
Track Time Resolution

$\sigma_t \sim 3$ ns



Measured ECAL performance

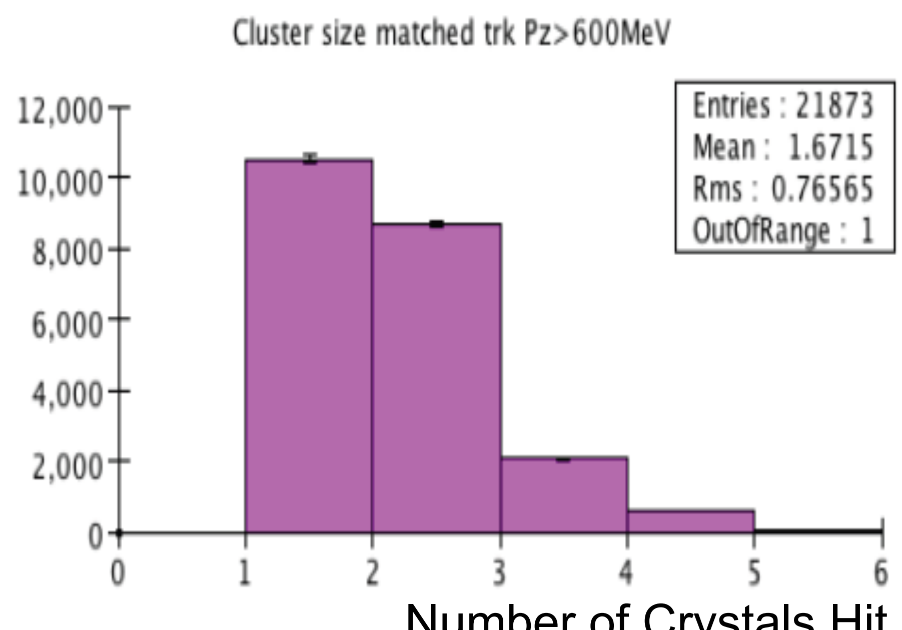
Color shows average crystal PH over Face of ECal



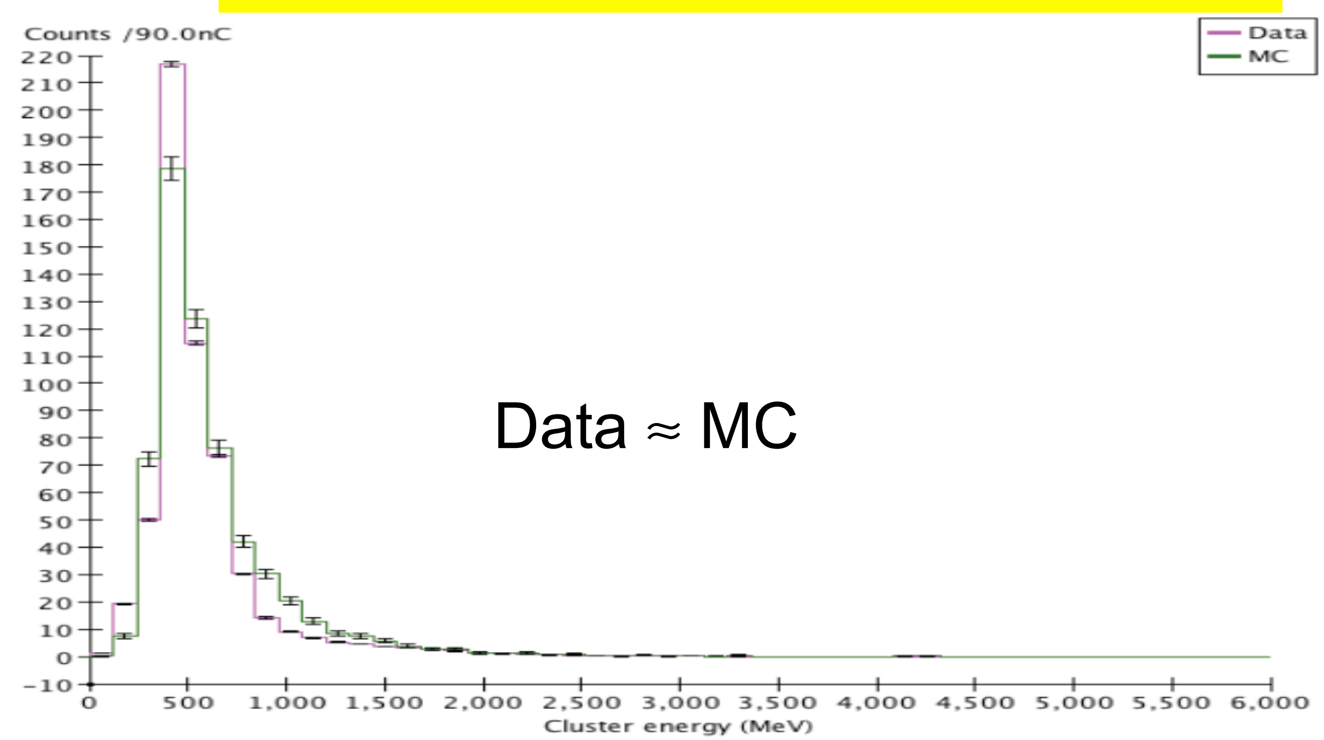
Missing Channels

* ECAL upgrade planned before next running.

Cluster Size for tracks with p>0.6 GeV/c



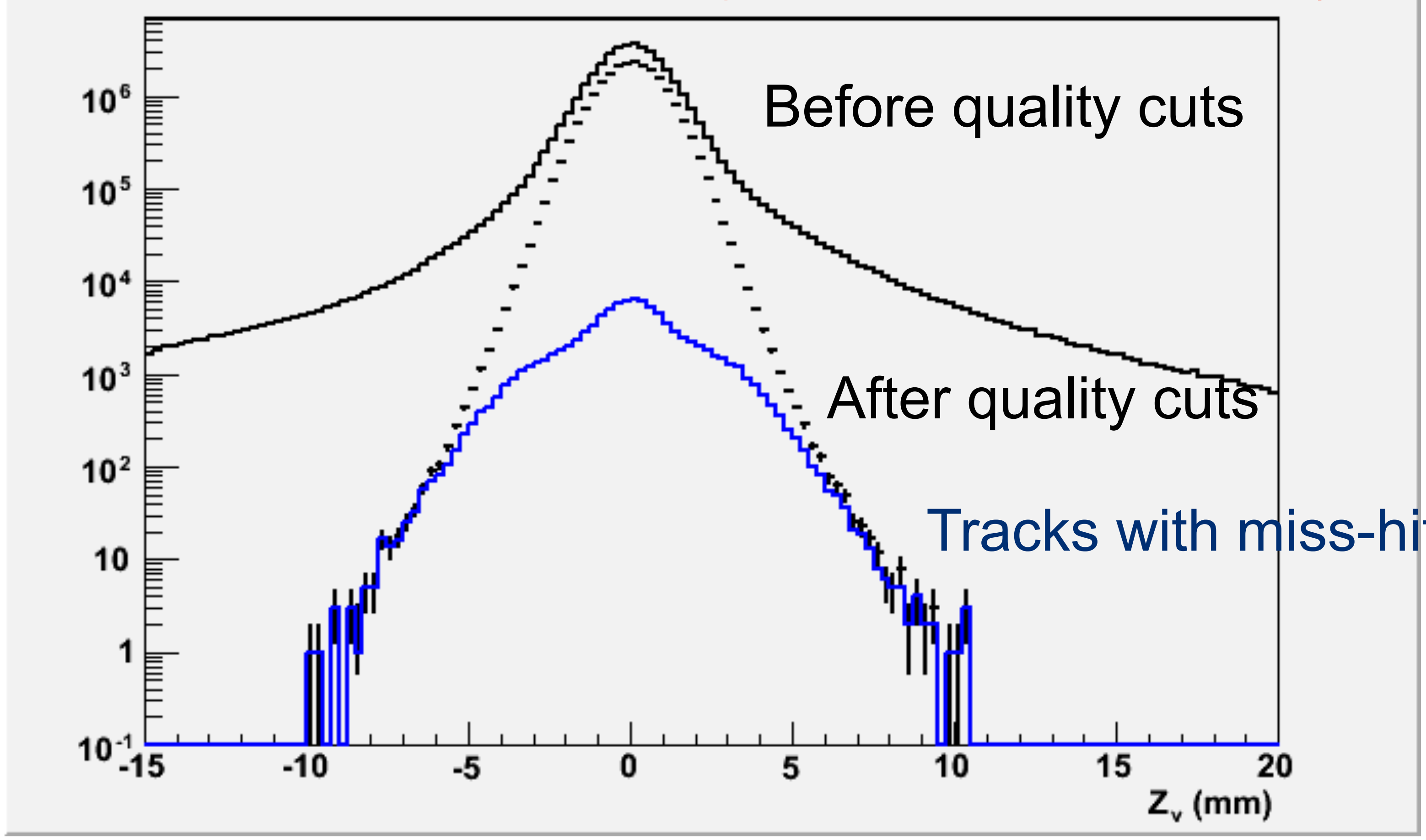
Cluster Energy Data/MC



Simulated Vertexing Performance

- Accurate knowledge of SVT occupancy gives us confidence that stand alone pattern recognition will work in the presence of realistic backgrounds.
- Simulated tracking efficiency is ~ 98% with beam backgrounds included. Only 5% of tracks have miss-hits, which can cause vertex tails, and spoil reach.
- Track quality, vertex quality, and trajectory cuts nearly eliminate vertex tails.

Vertex Resolution along the beam direction, Z_v

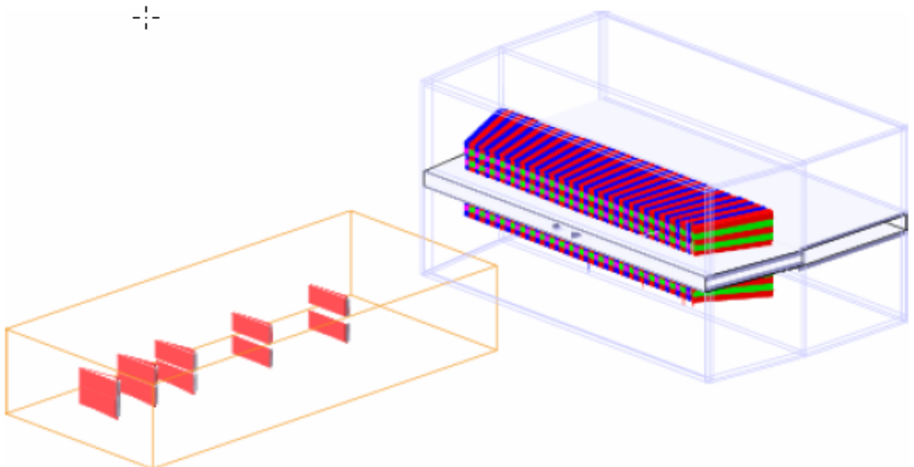


$m_{A'}$= 200 MeV
E_{beam}= 5.5 GeV

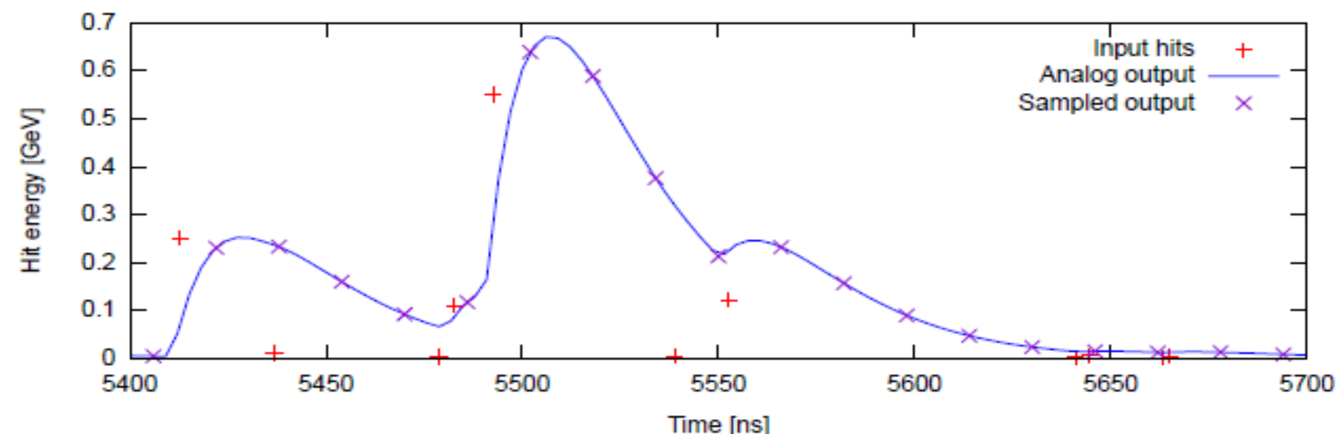
Simulated Trigger Rate.

- **Full GEANT4 simulation of detector, with EGS5 input events.**
- **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



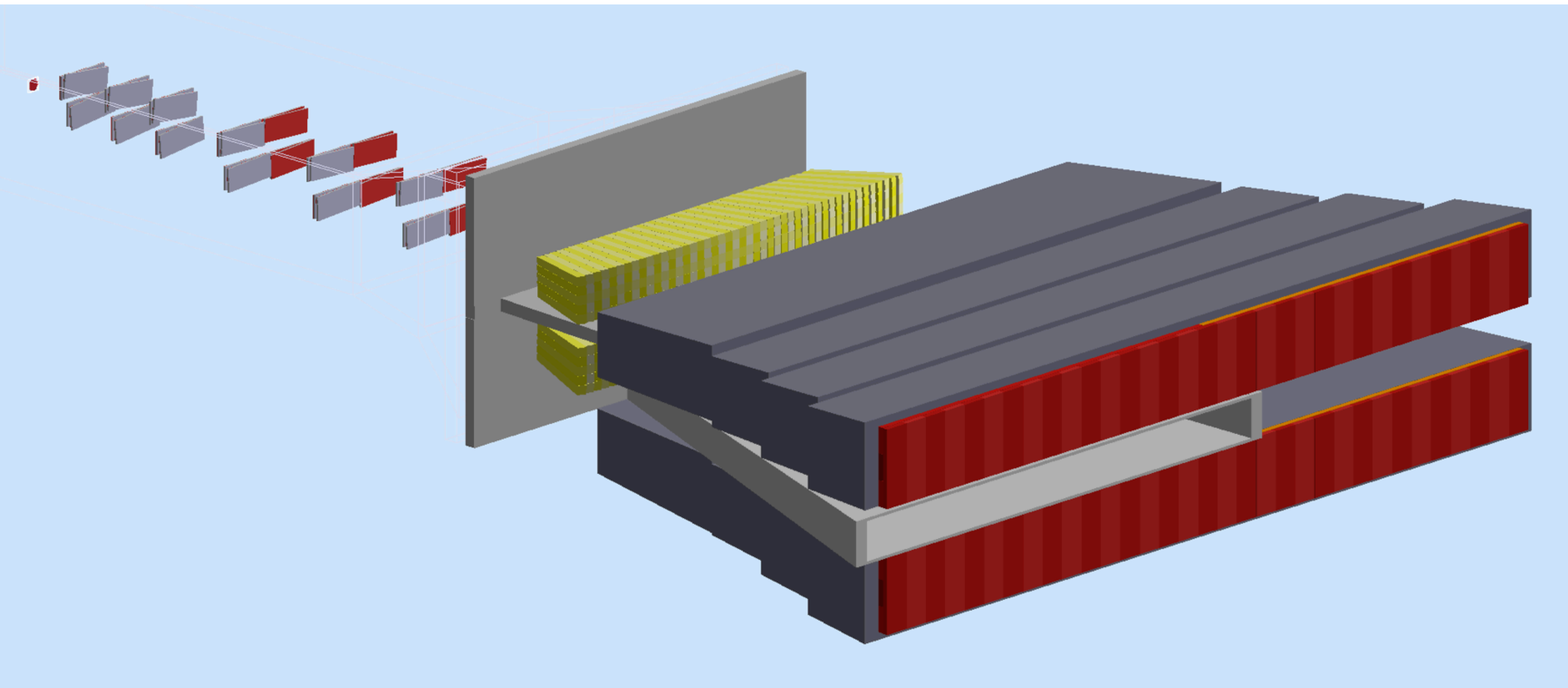
- **Performance at 2.2 GeV (200 nA)**
  *35 kHz trigger rate, compatible with previous estimate

  * 1% of useful events are affected by pileup

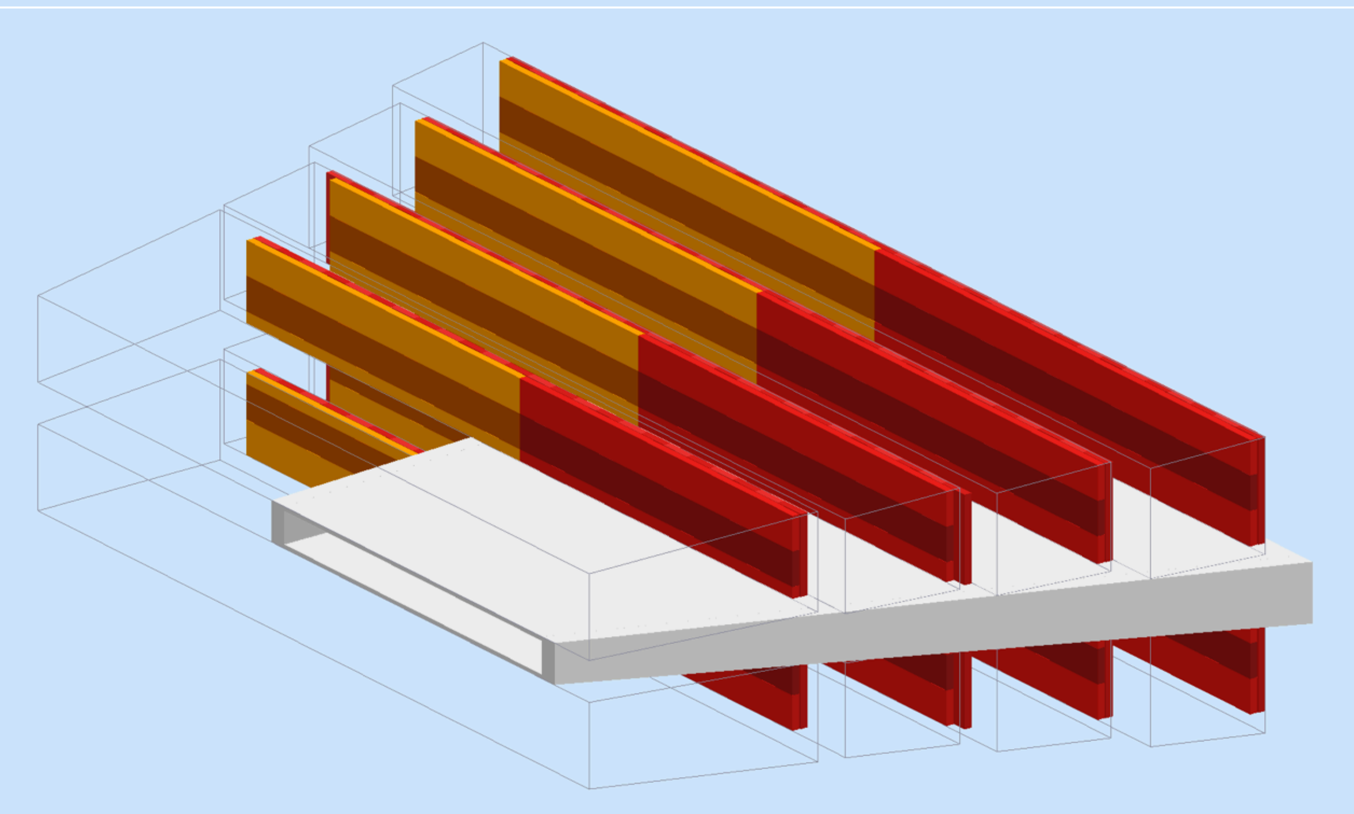
- **HPS trigger rates under control**

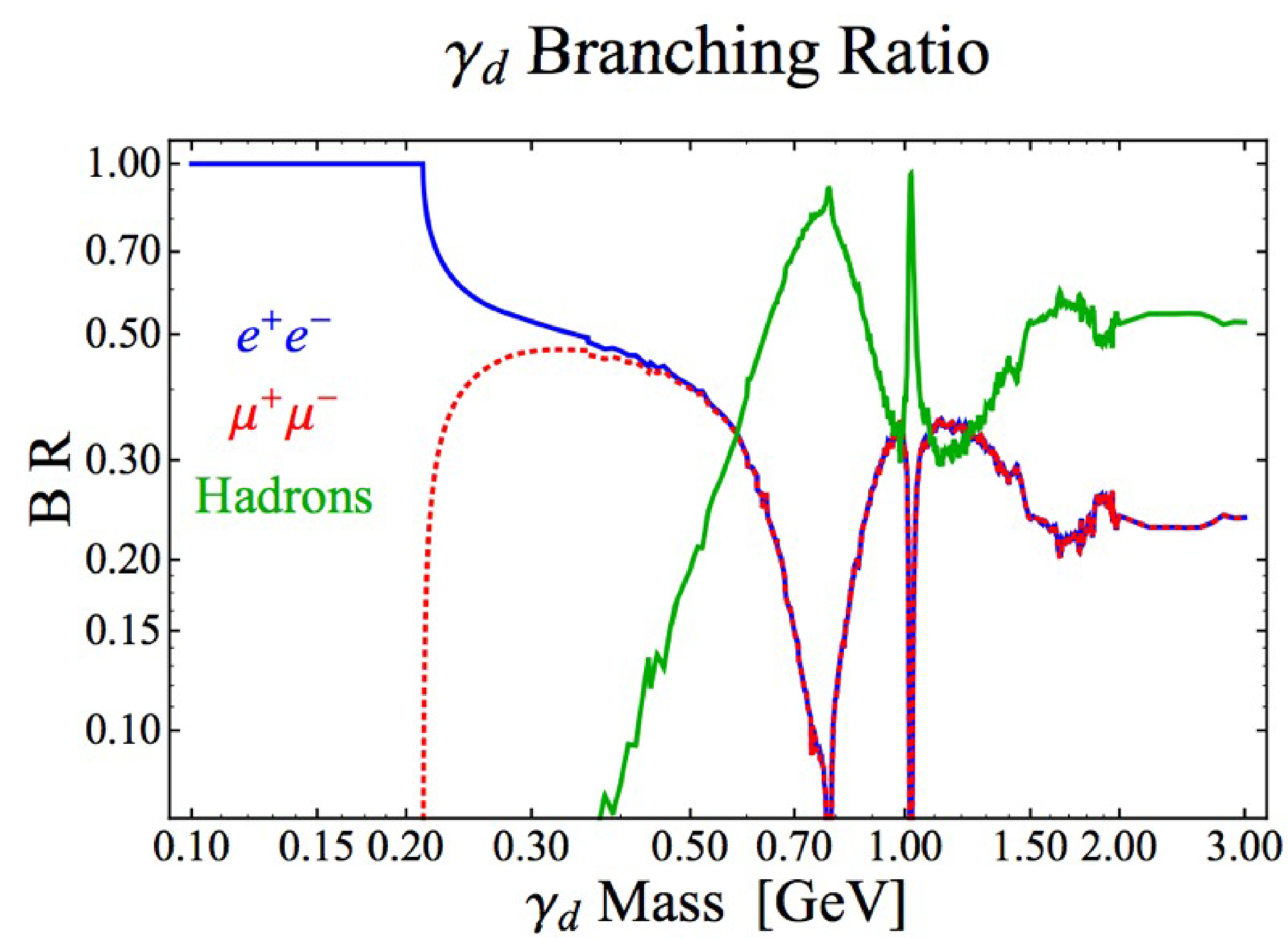
Trigger cut	75 MeV/c^2 A' acceptance	Background rate
Pairs of clusters in opposite quadrants	59.5%	1.8 MHz
Cluster energy between 100 MeV and 1.85 GeV	45.1%	725 kHz
Energy sum less than E_{beam}	45.1%	431 kHz
Energy difference less than 1.5 GeV	45.1%	386 kHz
Energy-distance cut	36.1%	80 kHz
Clusters 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

Muon Detector Design

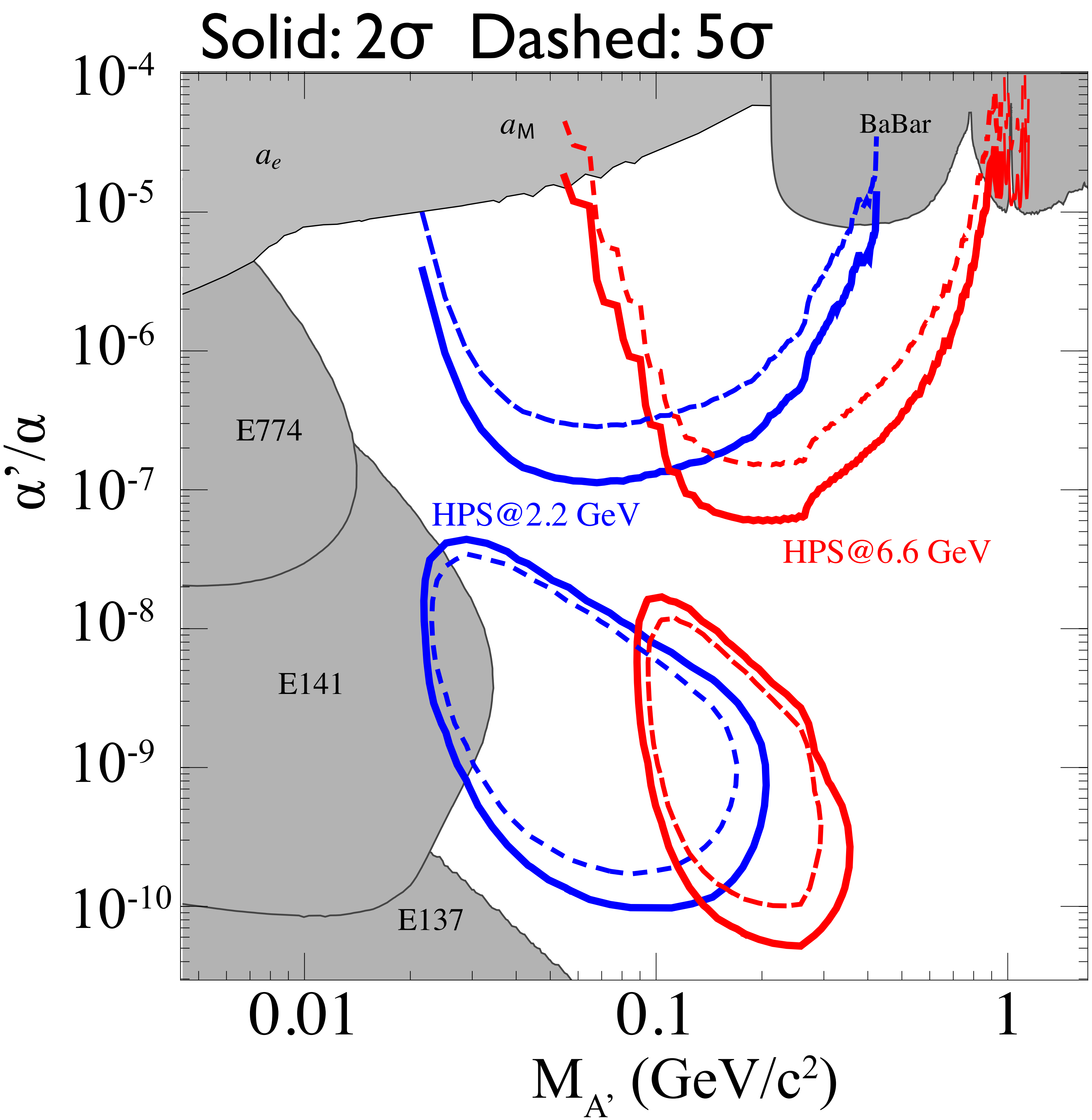


Add a segmented muon detector behind ECAL for muon trigger.
Adds a second channel to look for high mass A' decays.





Full Experiment Reach



Blue:

Beam = 2.2 GeV@200 nA

Target = 0.125%

Red:

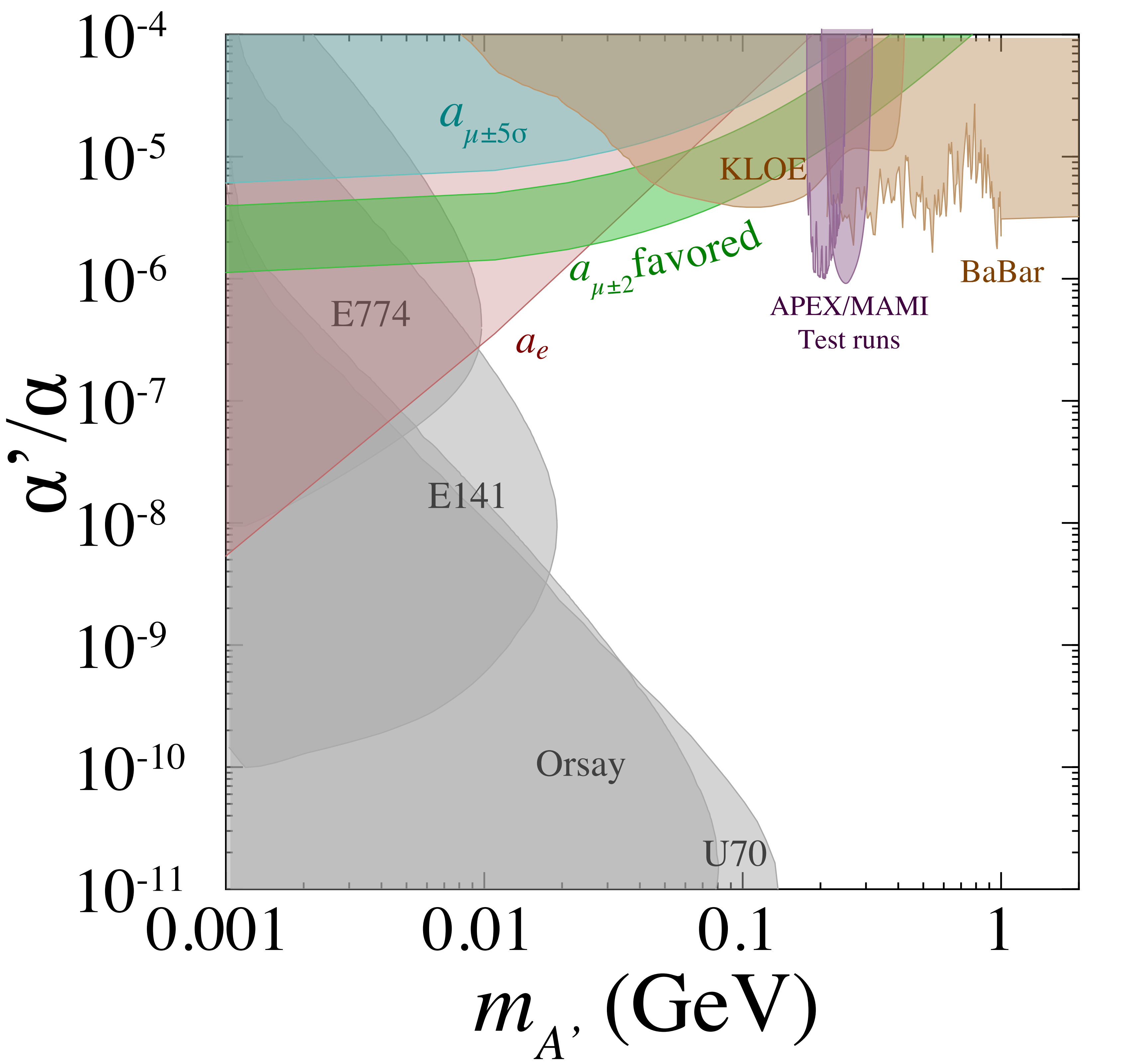
Beam = 6.6 GeV@450 nA

Target = 0.25%

3 months of running each energy = 180 days

Gray areas, excluded regions (2011)

Updated Limits

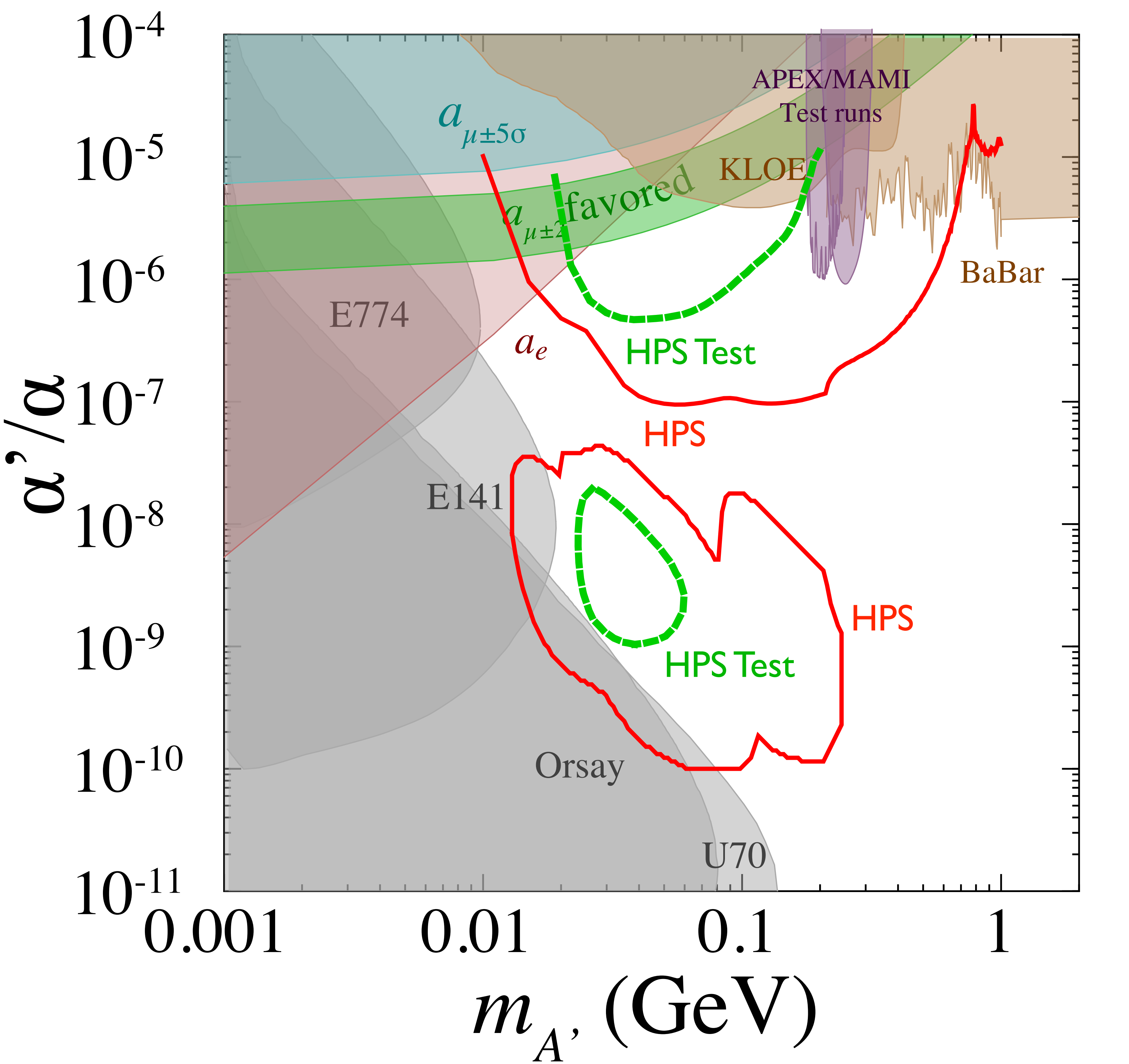


The improved a_e and improved limits from KLOE reduce g_μ-2 favored region.

Green band is the region favored by a A′ explanation of the g_μ-2 anomaly.

Pospelov ’08

Commissioning Run Reach



Green dashed:

2.2 GeV, 200 nA

0.125% X_0 target

~1 week of data.

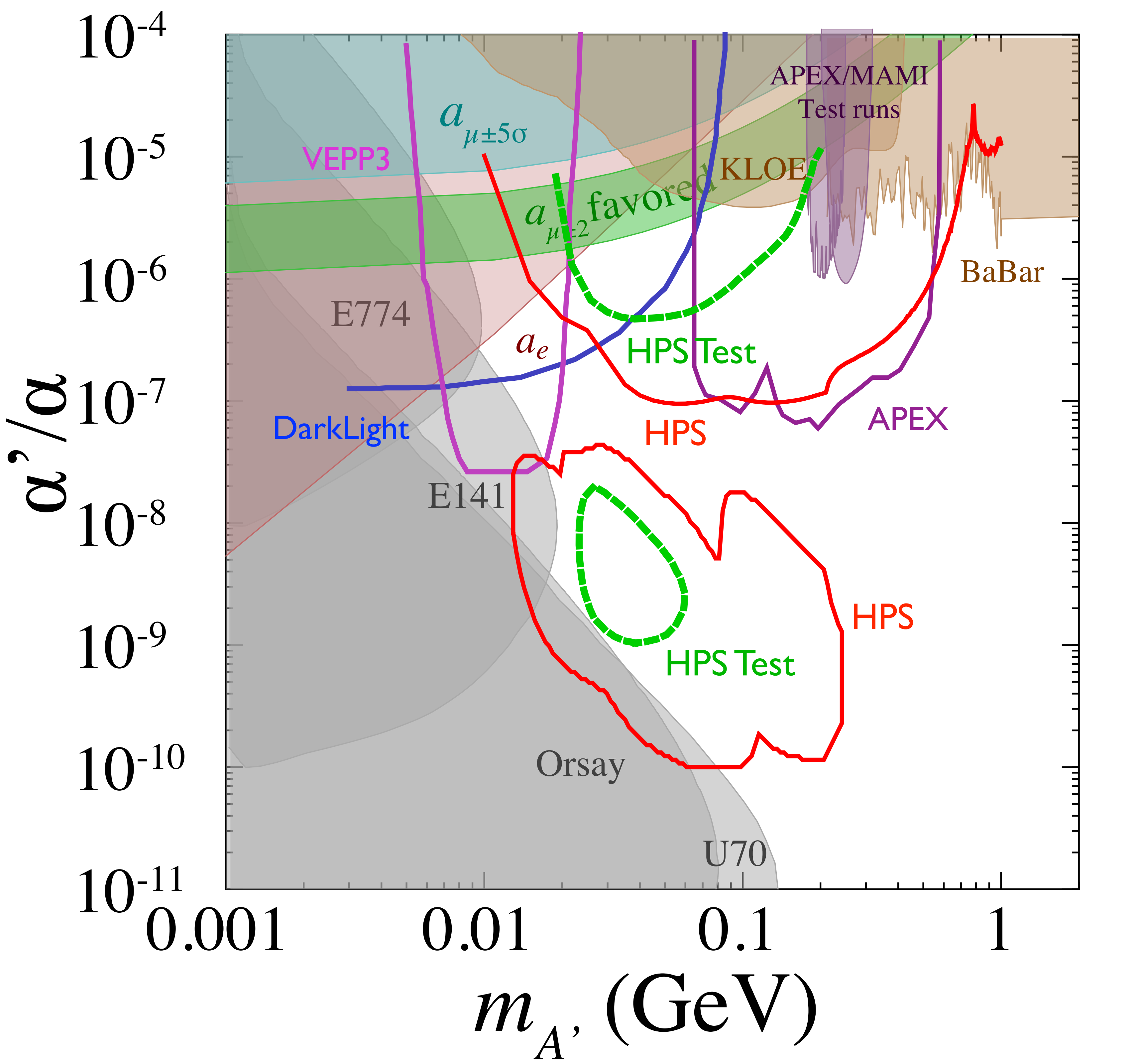
Red line:

2.2 GeV, 200 nA

6.6 GeV, 450 nA

180 days of data.

Other Experiments...



APEX - Jlab Hall-A & **Mainz A1**

~ same region as APEX. Using spectrometers.

DarkLight - Jlab FEL

Using internal "active" target recoil detector.

Not shown:

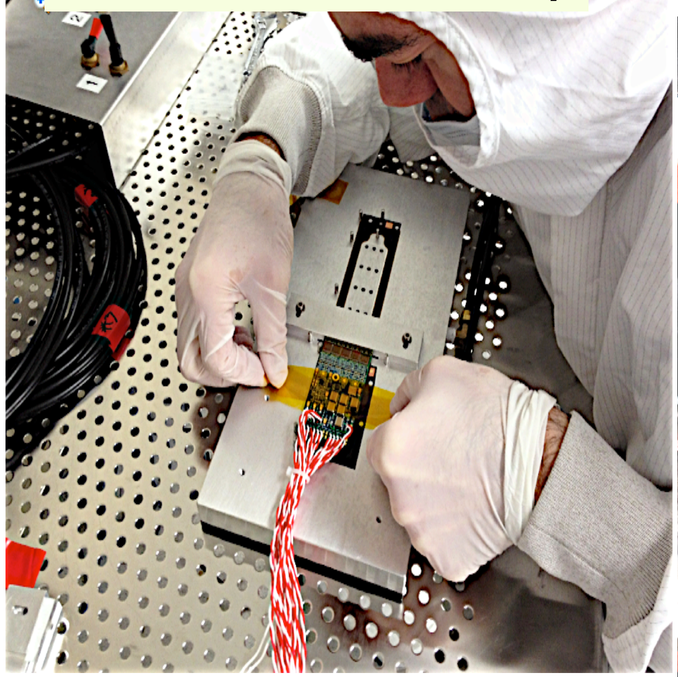
Babar, BELLE, KLOE, BES, SuperB, D0, Atlas, CMS,...

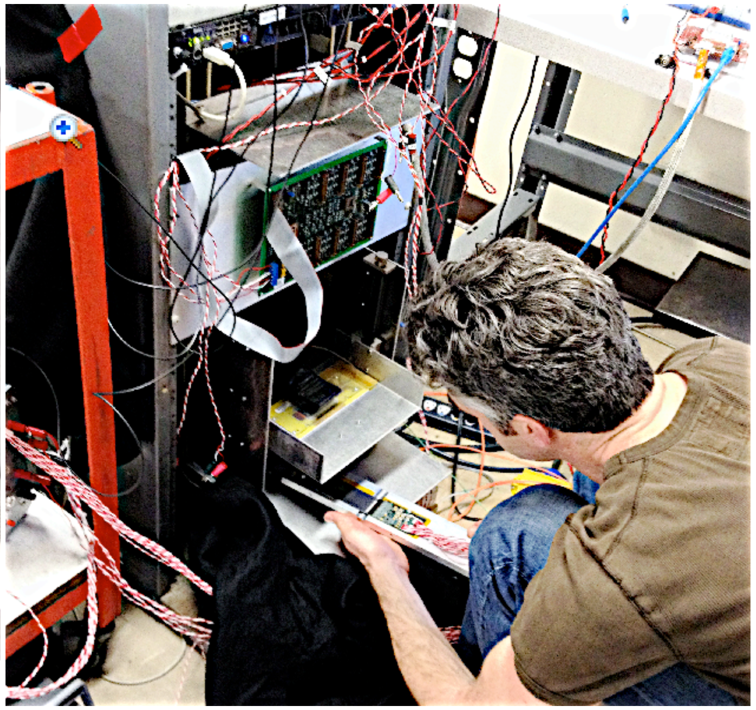
Next Steps

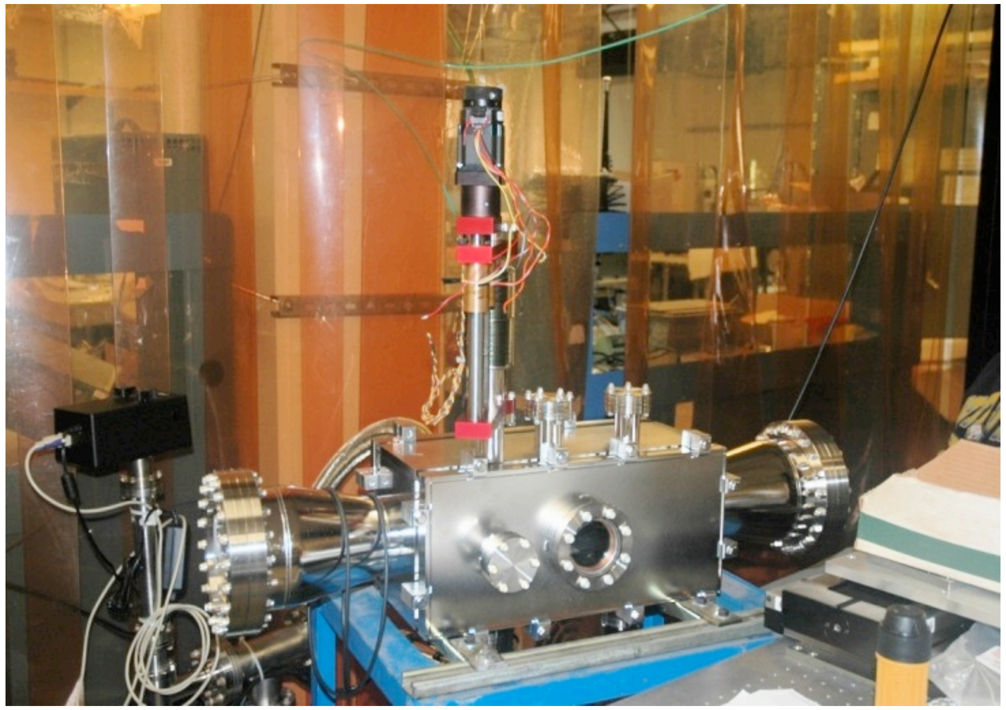
- **Upgrade the test run detector** to handle high intensity e- beams for longer periods.
- **Funding** proposal for upgrade submitted to DOE. Funding proposal for muon detector submitted to NSF.
- Design of upgraded detector started, construction starting soon.
- If funded, installation commissioning and data taking of **commissioning run in Fall 2014**.
- Good prospects for **extended data run in 2015**.

Conclusions

- ✳ The Heavy Photon Search at Jlab is an ambitious experiment looking for the A′, a heavy U(1) vector boson.
- ✳ Challenging experiment.
- ✳ Excellent reach, excellent discovery potential.
- ✳ Detector is being upgraded for 2014/15 run.


SVT Module assembly


SVT cosmic tests

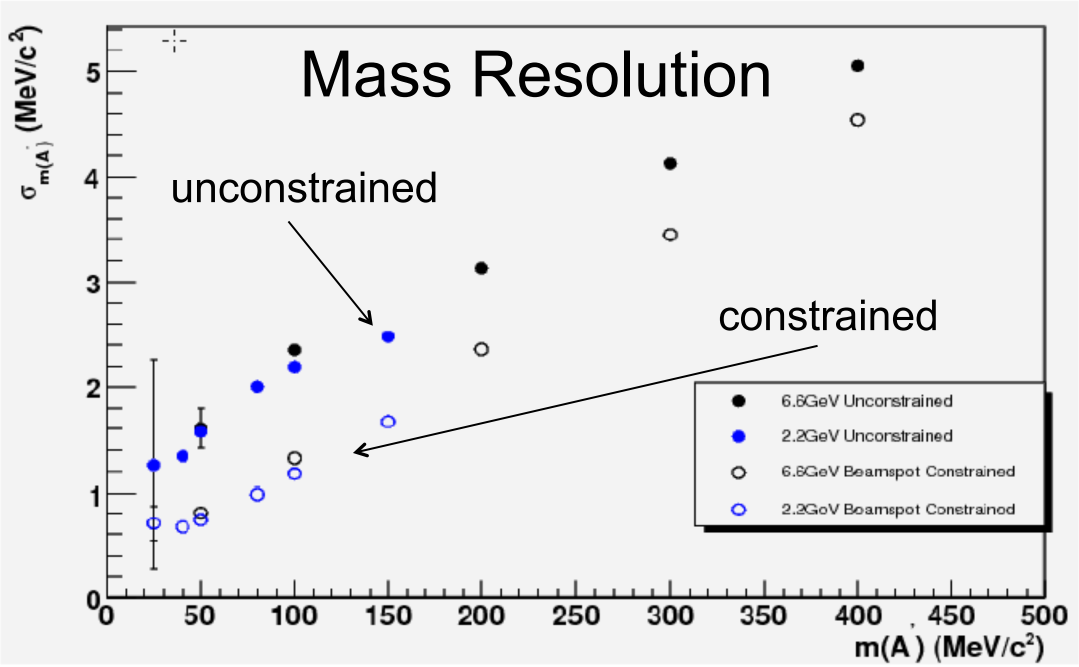

Vacuum system

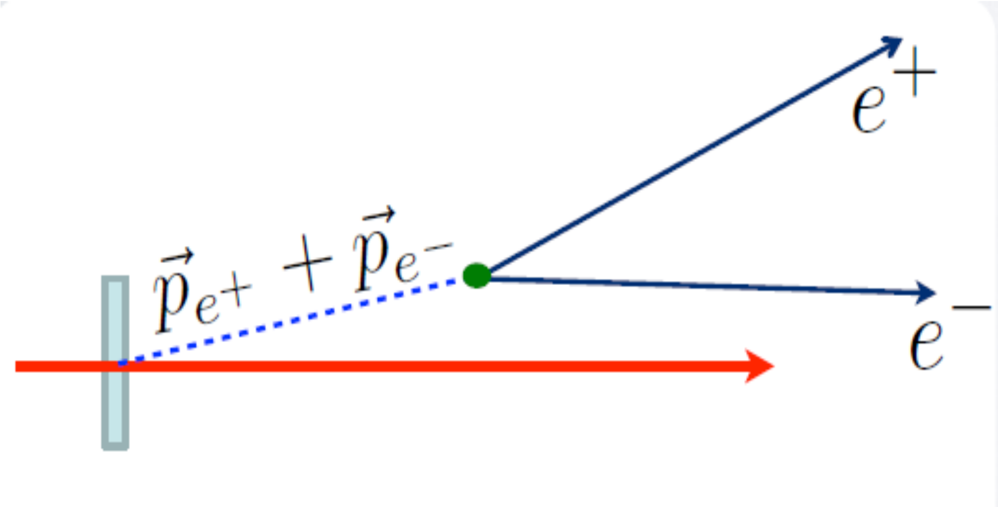

Tracker module

Extras

Optimize: target, current & beam size

- **Minimize target thickness (4-8 μm) and boost beam current (few x 100 nA)** This minimizes the multiple coulomb scattering (MCS) tails which dominate tracker occupancy and trigger rates.
- **Minimize Beam Spot Size.**
  Small beam spots help define track angles and improve mass resolution in the bump hunt region, and improve vertex resolution and reduce vertex tails.





- **Beam Stability and Halo**
  Since detectors are close to the beam, beam stability is at a premium, and beam halo must be minimized.

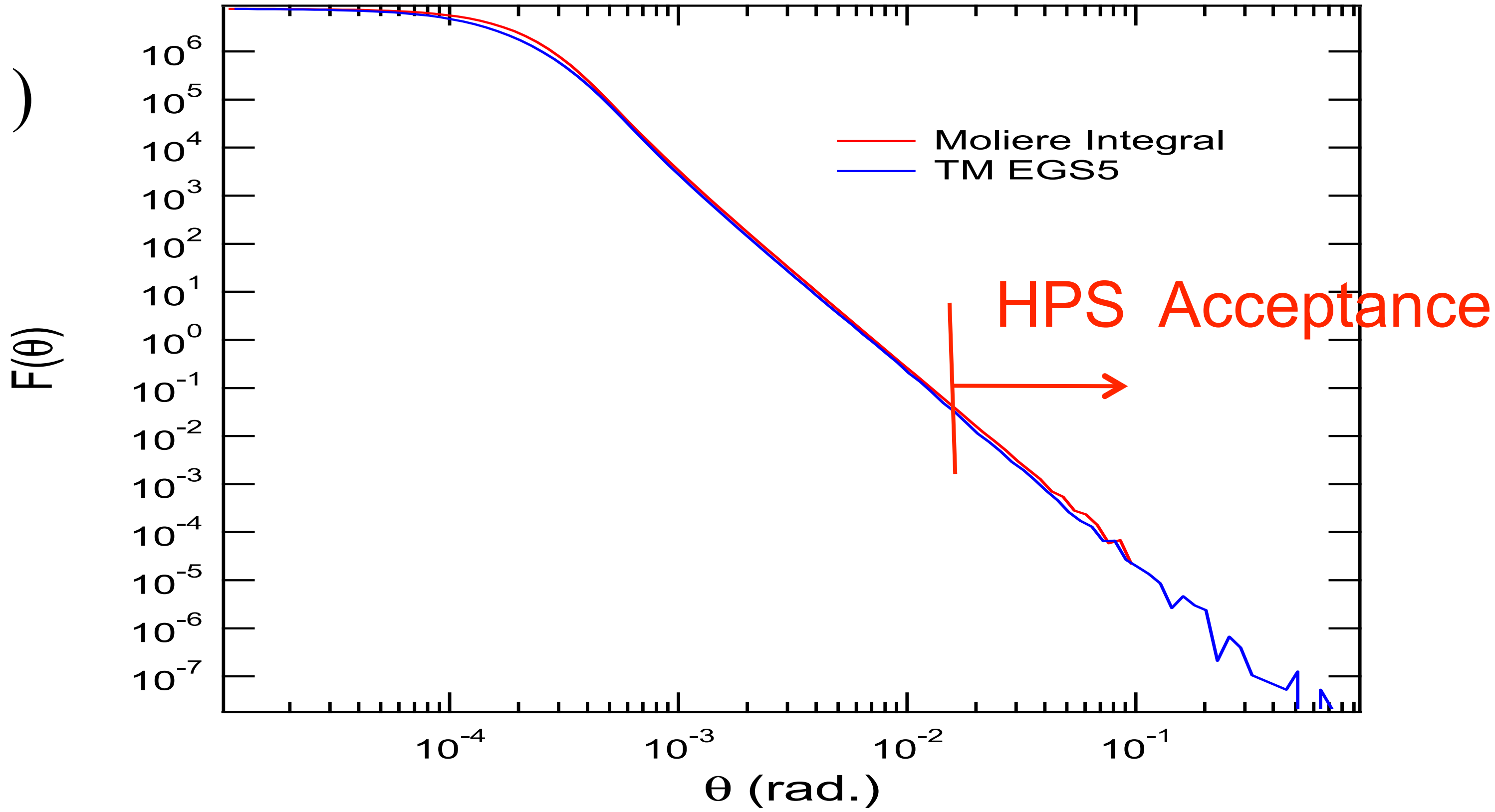
Is HPS ready for electron beams?

- **Full Monte Carlo simulation shows MCS of beam electrons is the principal HPS background**
  The tails of the multiple Coulomb scattering of beam electrons in the target hit the innermost layers of the tracker and Ecal and are the principal cause of tracker occupancy and ECal trigger rate.

- **EGS5 simulations accurately describe MCS tails from thin targets.**
  They agree with formal MCS Theory (Moliere, and Goudsmit-Saunderson) and available thin target data. (Not true for GEANT4!)

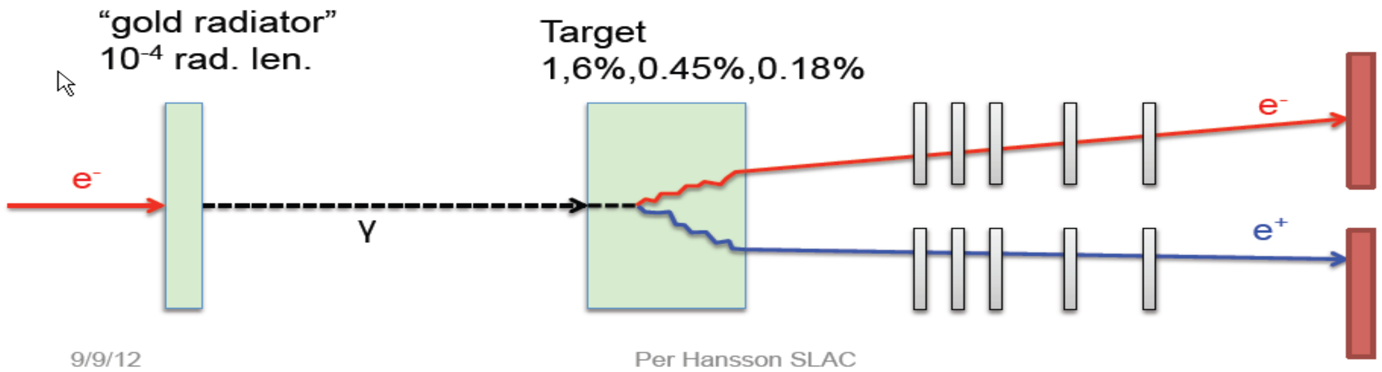
$$\frac{d\sigma}{d\Omega} \approx F(\theta) 2\pi d(\cos\theta)$$

Moliere integral vs. EGS5



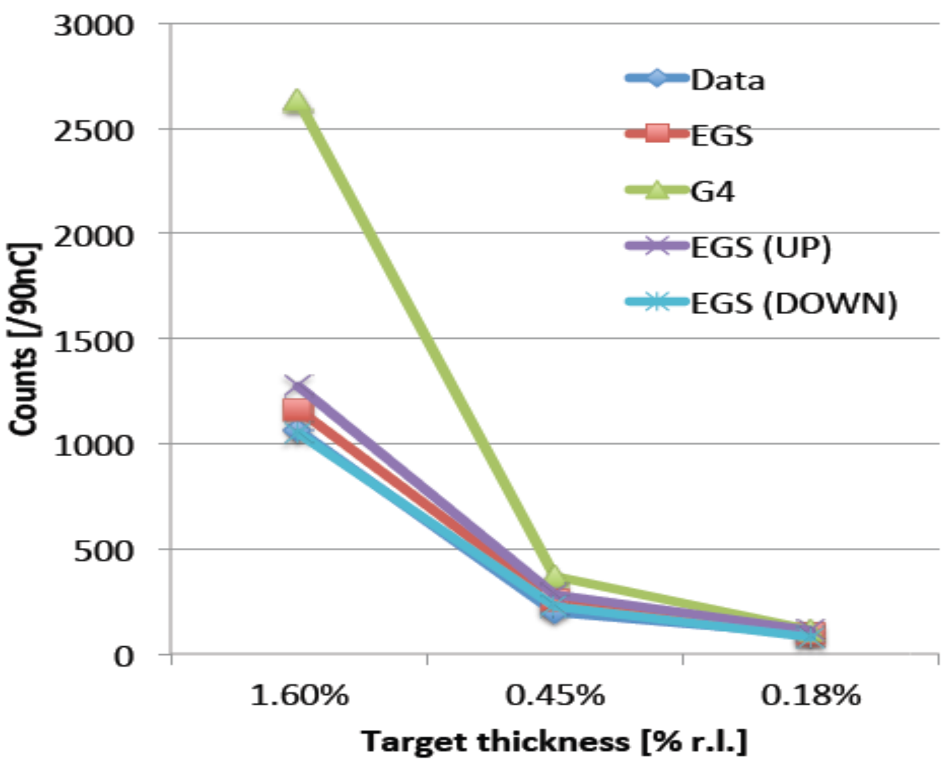
YES, HPS is ready!

- Photon conversions in the test run produce pairs whose angular distribution depends on two effects, of roughly equal importance:
  1) pair opening angle distribution
  2) Multiple Coulomb Scattering of electrons through the target



- With a photon beam incident, the HPS trigger rate is almost entirely due to pair production in the target. The observed rate is given by the pair angular distribution, integrated over the Ecal acceptance.

Trigger Rate Data agrees with EGS5 simulation.



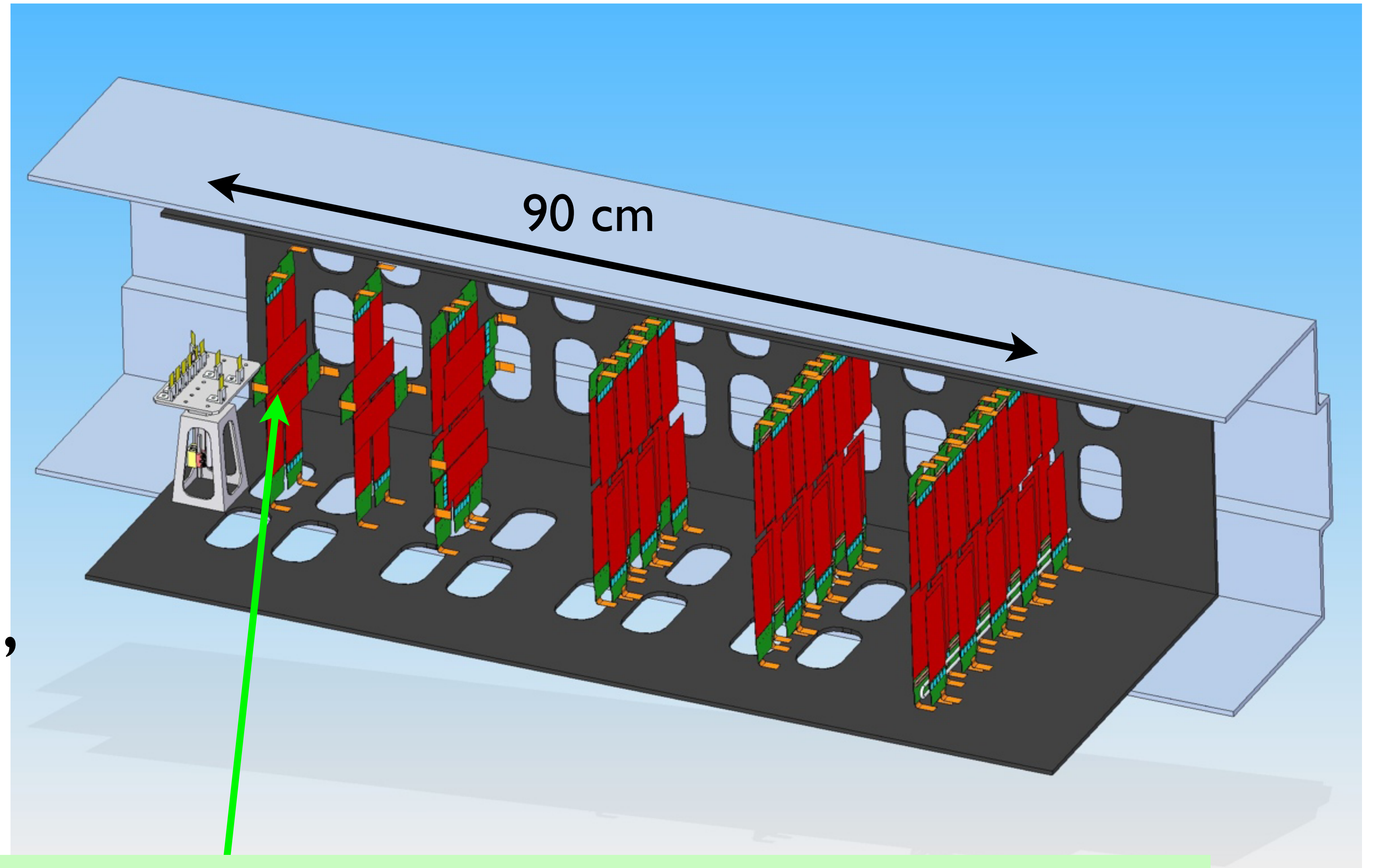
Background estimates using the EGS5 simulation are reliable.

HPS ready for e- beams

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.

Using:

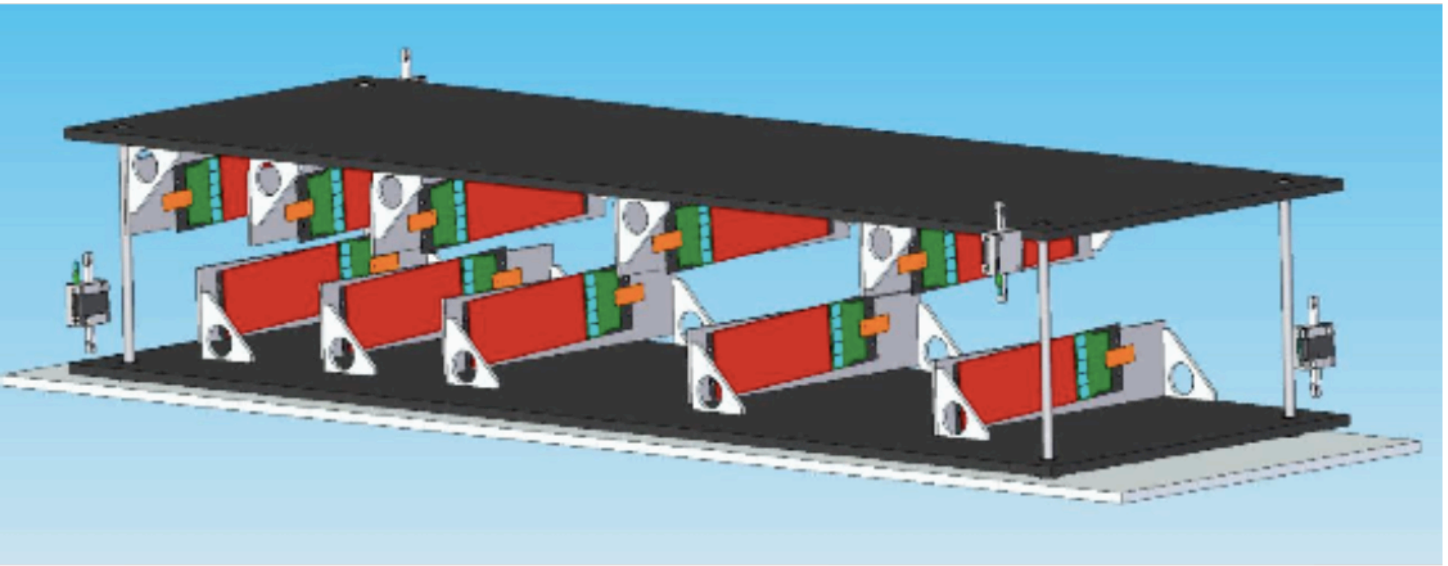
Si Microstrip detectors (106, thin, leftover from Tevatron run IIb)

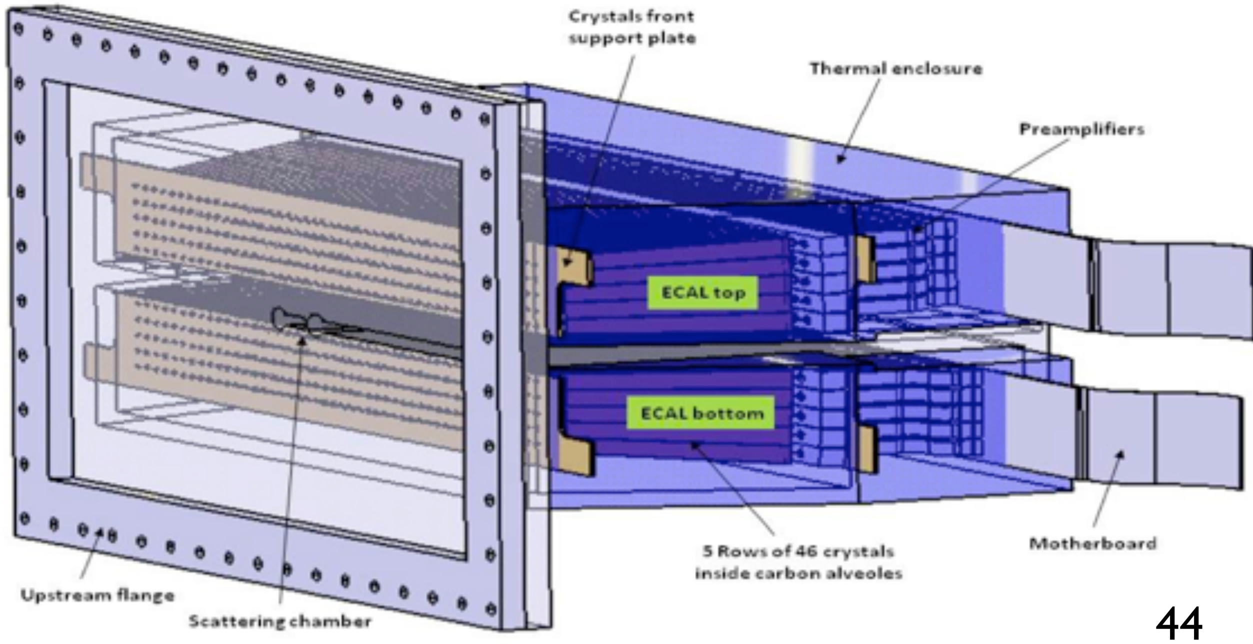
AVP25 readout chip (67840 channels, from CMS, S/N~25, timing ~ 2ns)

Cooling outside tracking volume. (~0.5% X_0 per layer)

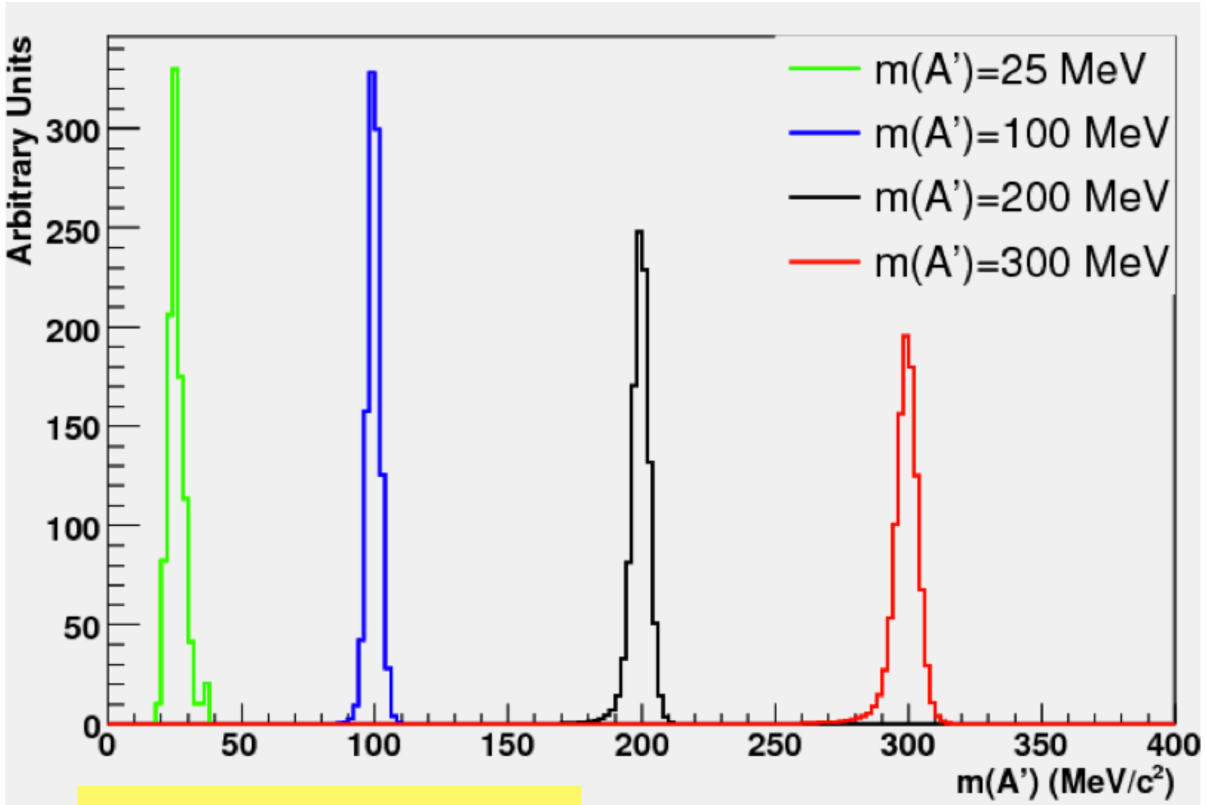
Test Run

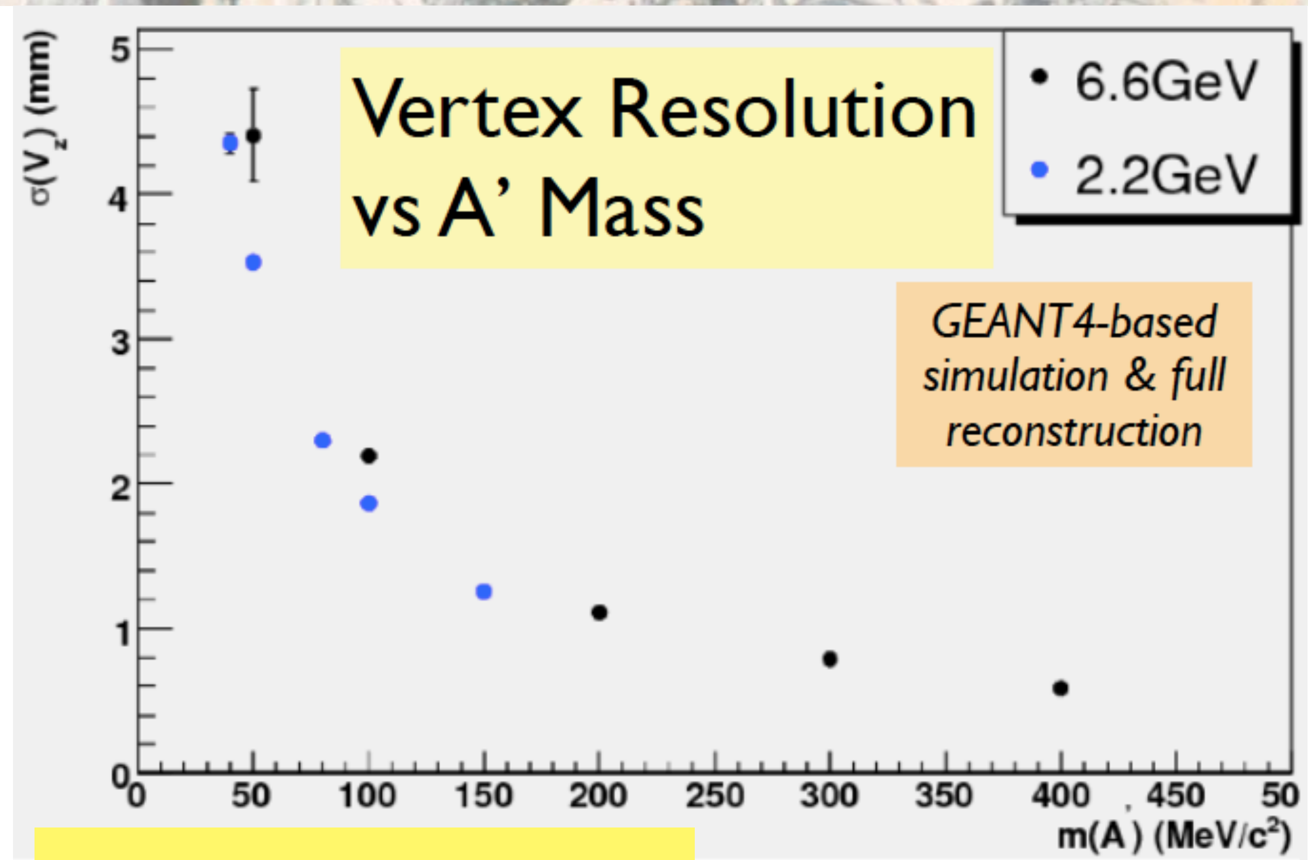
* Test the equipment & methods before building full system
* Cheaper & Faster to build.
* Reduced size tracker and calorimeter (no muons)
* Verify background estimates, SVT & Ecal occupancies, trigger algorithm, DAQ performance.
* Run before Jlab 12 GeV upgrade this summer.





Tracker Resolution (MC)





$\Delta m/m \sim 1\%$

$\Delta z \sim 1$ - 4 mm

Mass resolution dominated by M.S.

Beat down prompt tails to ~ 0

Tails dominated by fake tracks.