Searching For Dark Photons at Jefferson Lab

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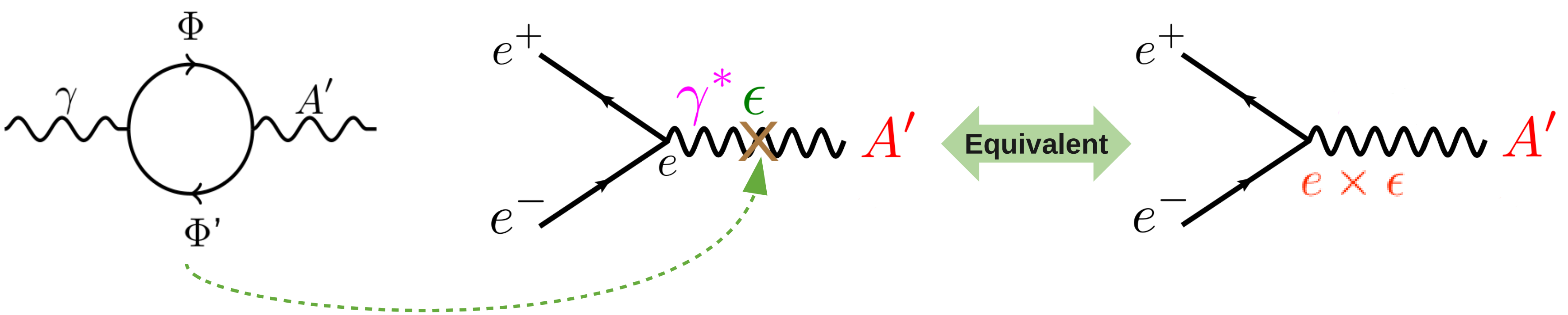
What is a "Dark Photon"?

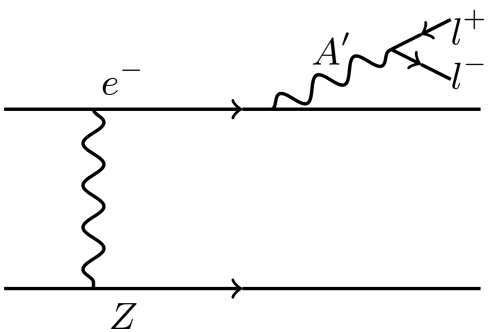
- Consider a theory in which nature contains an additional Abelian gauge symmetry, $U(1)_D$
  [Holdom, Phys. Lett.B166, 1986]

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

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

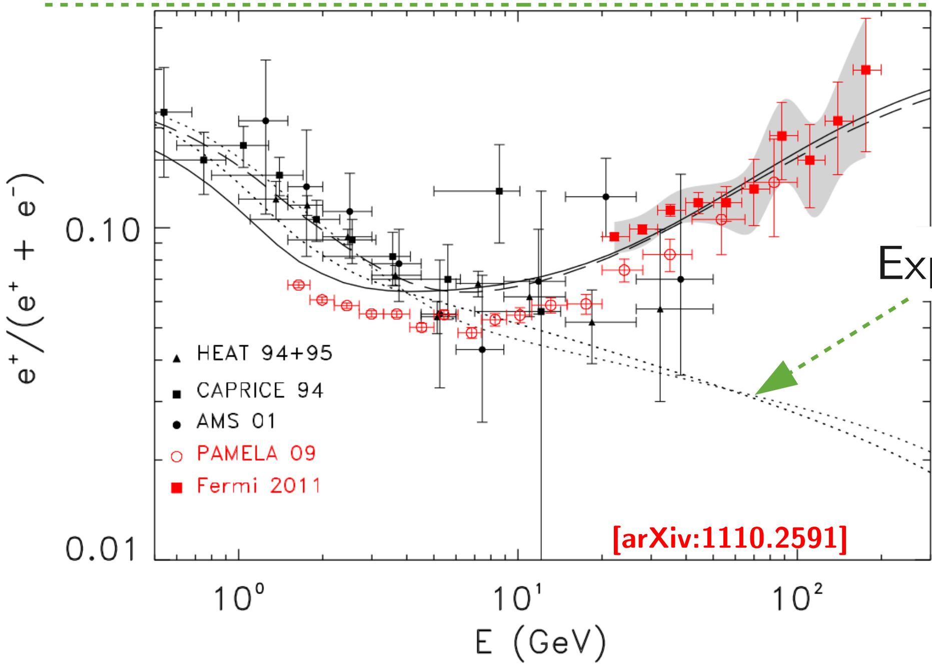


- The coupling to electric charge allows for A' production through a process analogous to bremsstrahlung



So Why Search for an Dark Photon?

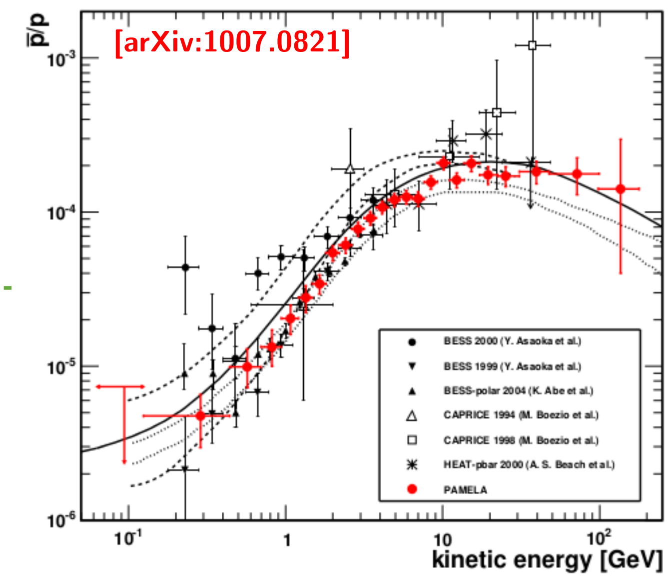
Both PAMELA and Fermi observe an excess in the positron fraction



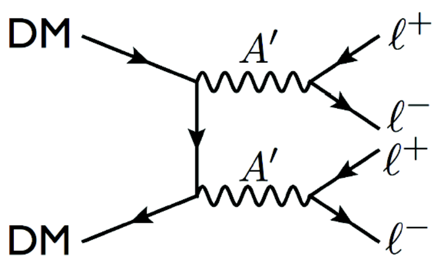
Expected

But ...

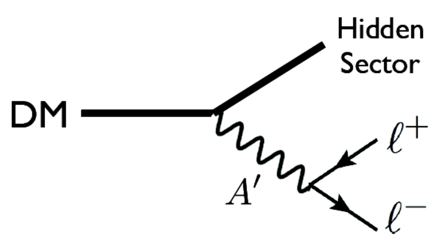
No excess anti-protons are observed



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

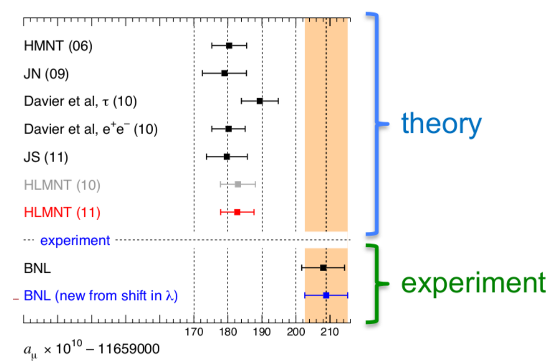


[Arkani-Hamed et. al., Pospelov & Ritz]



[Volansky & Ruderman, Essig, Schuster, Toro]

May also play a role in the anomalous magnetic moment of the muon

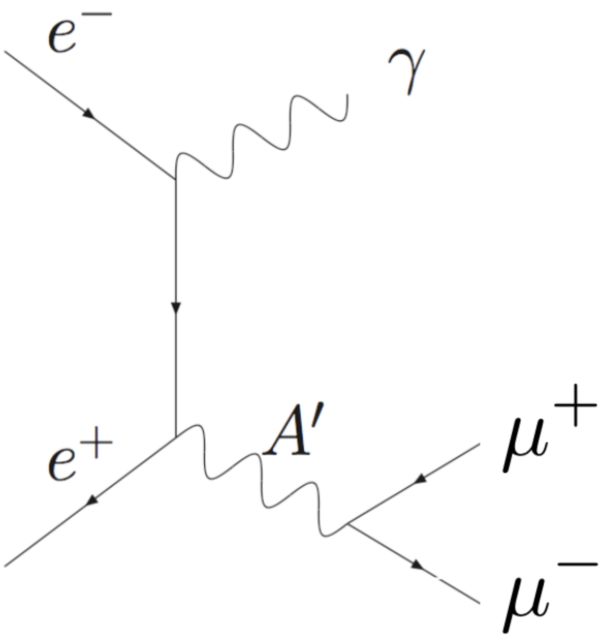


[hep-ex/0602035]

How to Search for a Dark Photon?

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

Collider

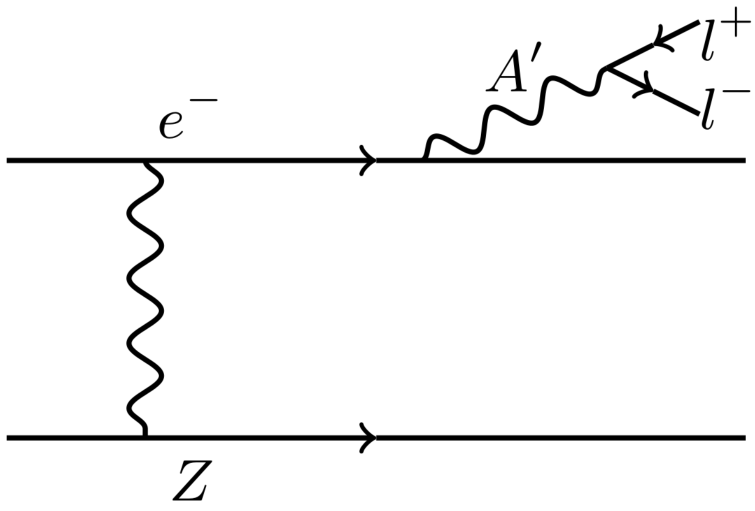


$$\sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2} \sim \mathcal{O}(10\ \text{fb})$$

$\mathcal{O}(ab^{-1})$ per ~~decade~~ **Month**

vs.

Fixed Target



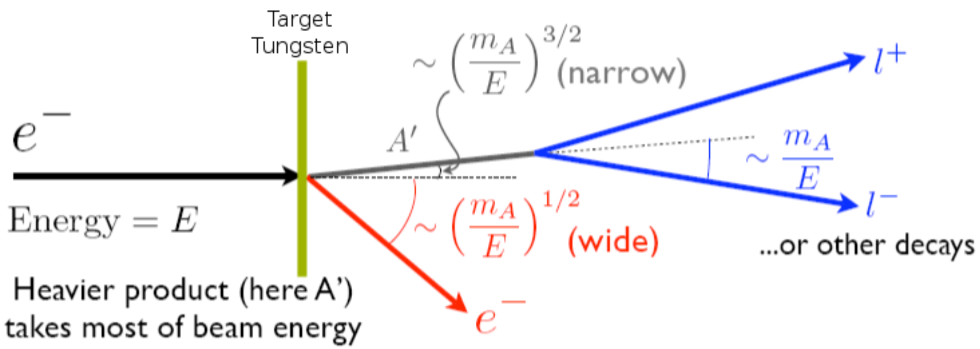
$$\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2} \sim \mathcal{O}(10\ \text{pb})$$

$\mathcal{O}(ab^{-1})$ per day

Fixed target experiments are ideal A' hunting grounds!

A' Fixed Target Kinematics & Backgrounds

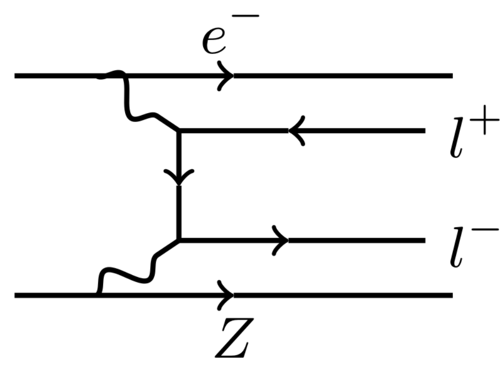
Signal



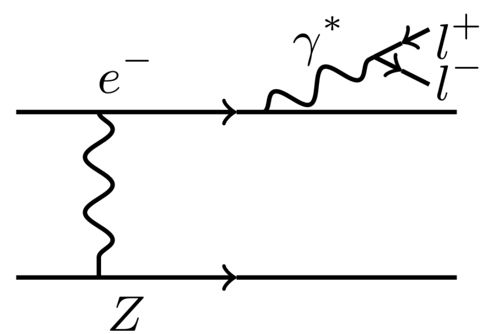
- A' is produced very far forward $\rightarrow E_{A'} = E_{beam}$
- A' decay products opening angle, $m_{A'}/E_{beam}$
- Long lived A' will have a displaced vertex $\rightarrow$ Help in the reduction of background

Trident Backgrounds

Bethe-Heitler

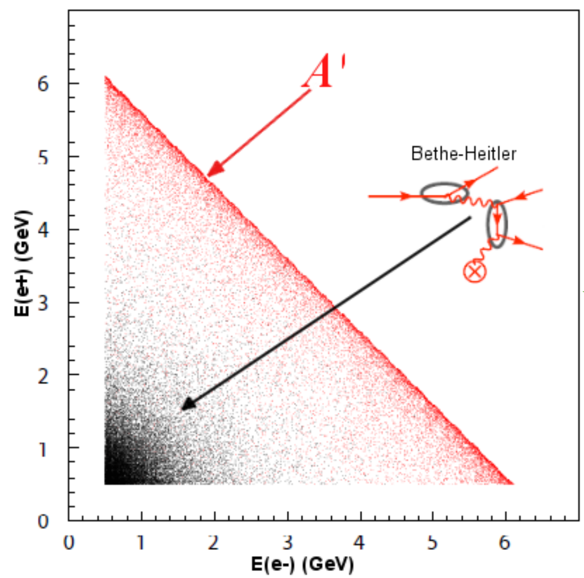


Radiative

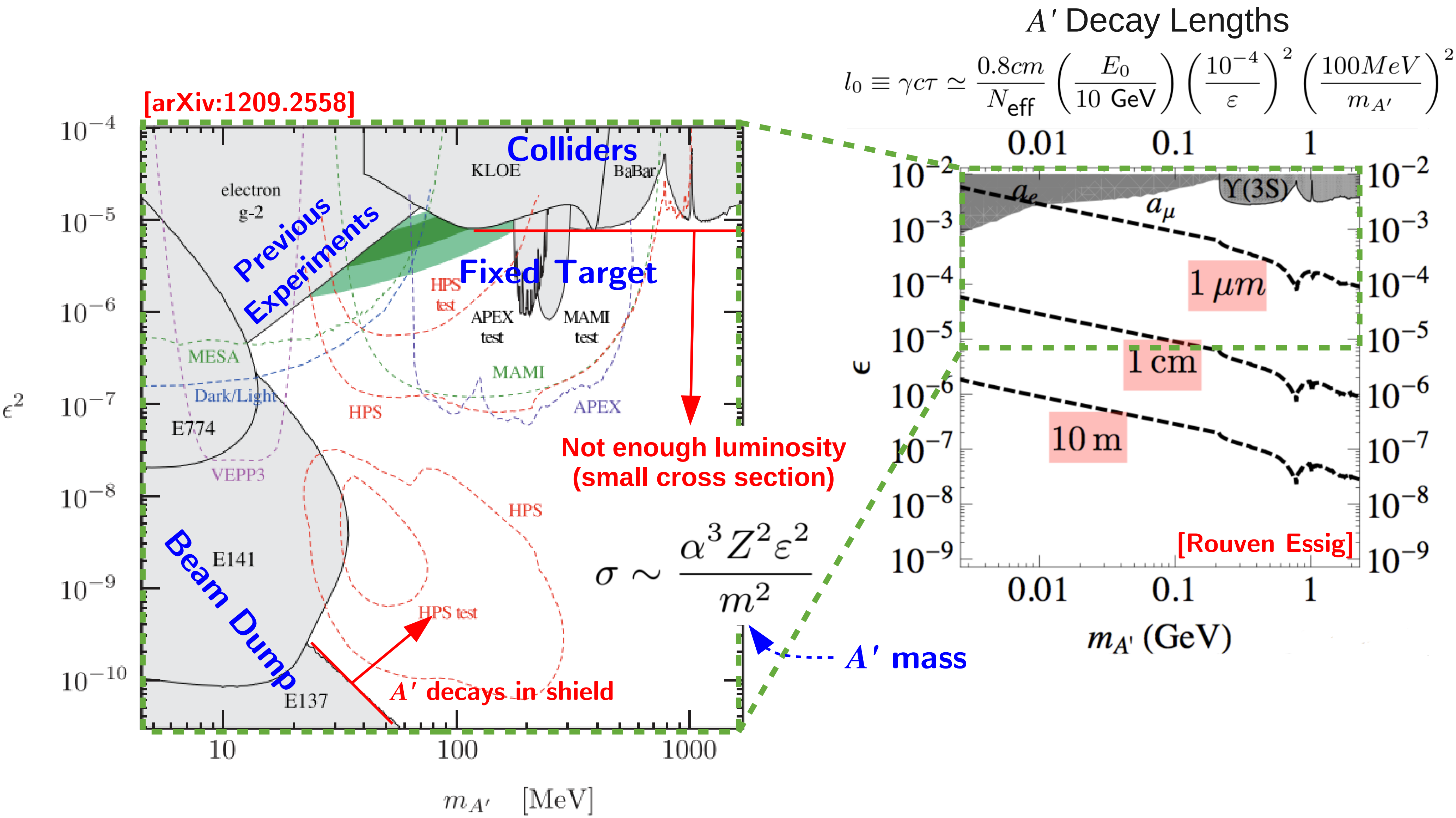


- Bethe-Heitler cross section is much larger than radiative but is kinematically distinct
- Radiative and A' signatures are kinematically **identical**

Even after kinematic cuts, Bethe-Heitler dominates by a factor of 5!



Some Existing A' Constraints



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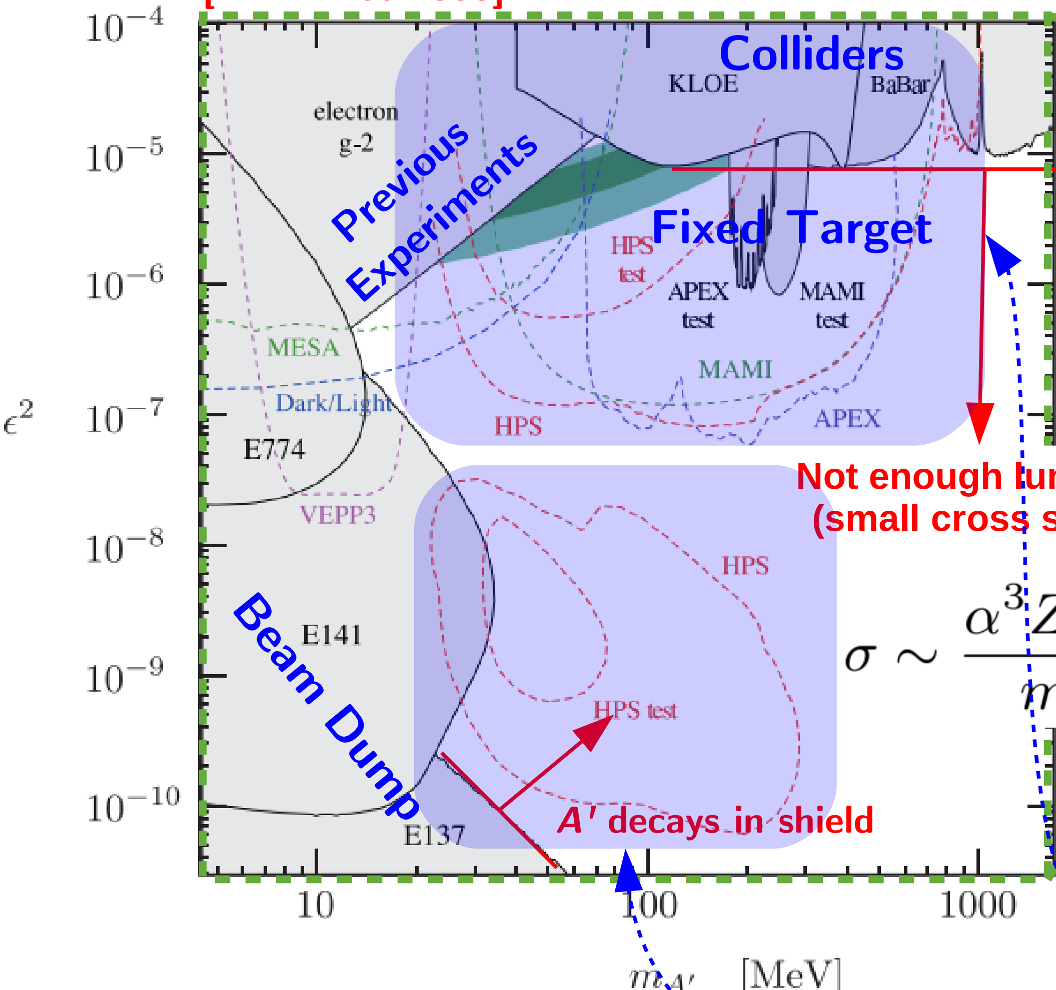
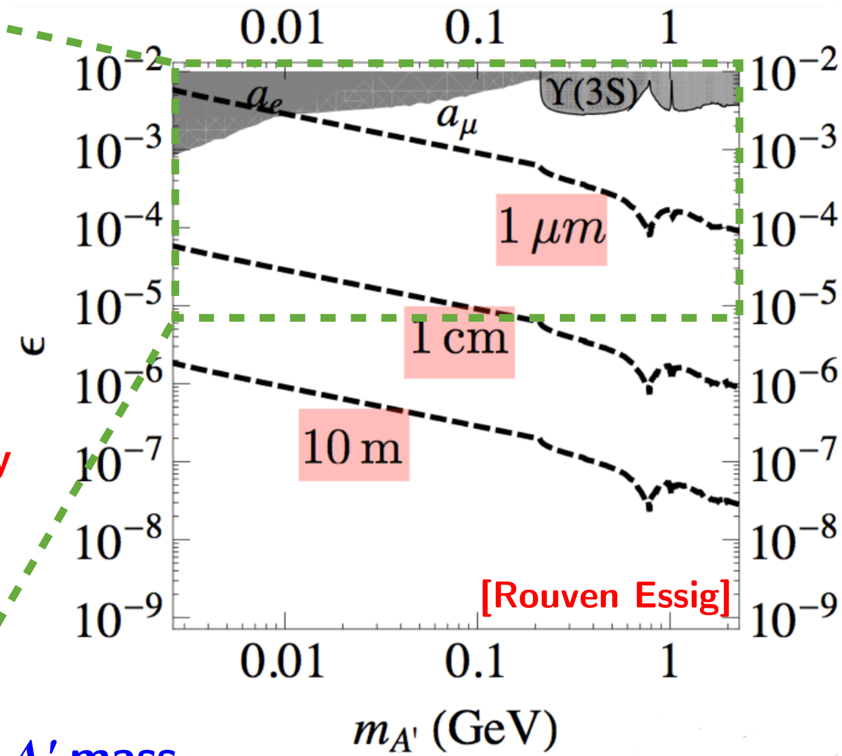


$$\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2}$$

A' Decay Lengths

$$l_0 \equiv \gamma c\tau \simeq \frac{0.8cm}{N_{\text{eff}}} \left(\frac{E_0}{10\ \text{GeV}}\right) \left(\frac{10^{-4}}{\varepsilon}\right)^2 \left(\frac{100MeV}{m_{A'}}\right)^2$$



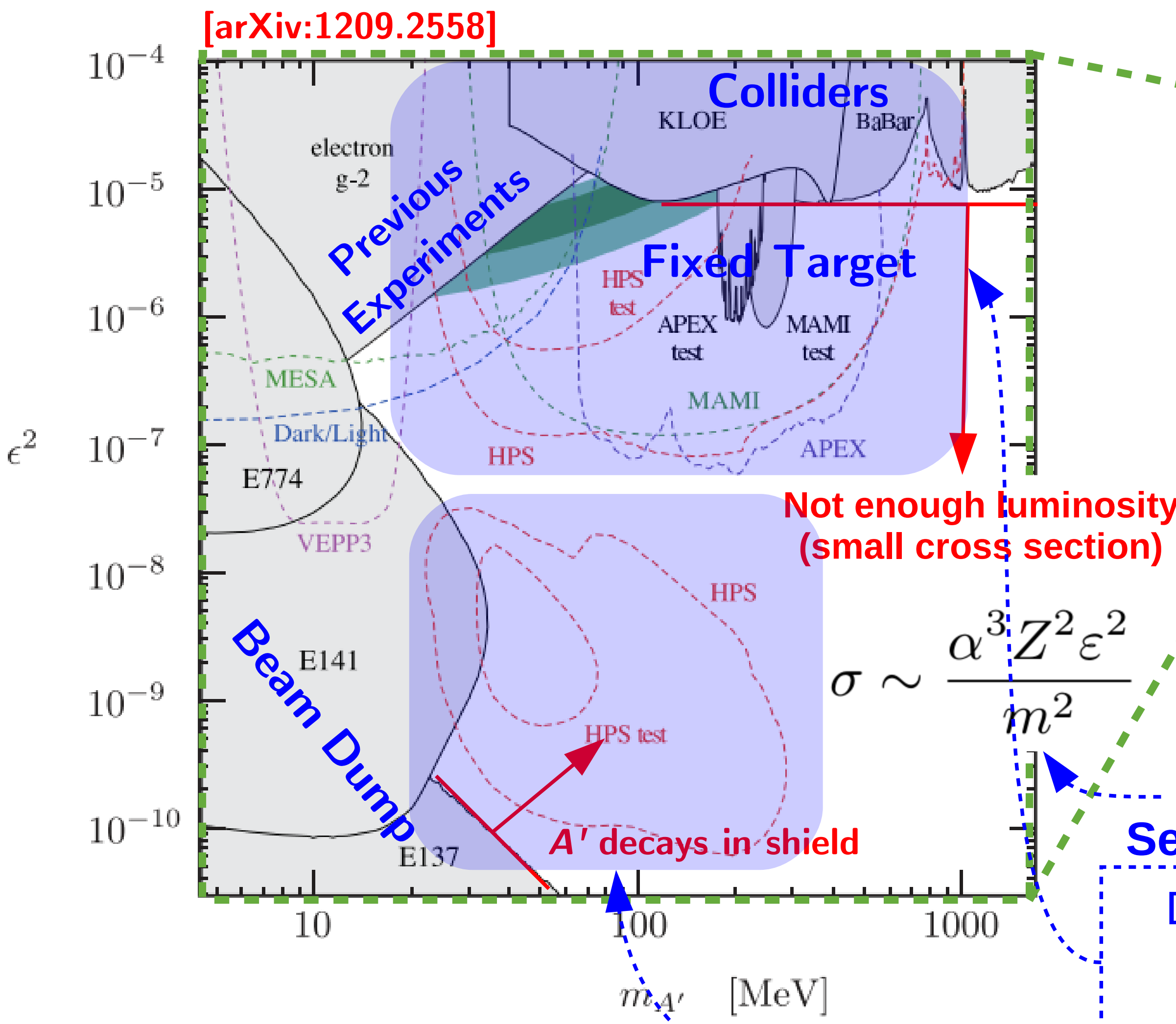
A' mass

Sensitivity to these regions will rely on

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

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

Some Existing A' Constraints



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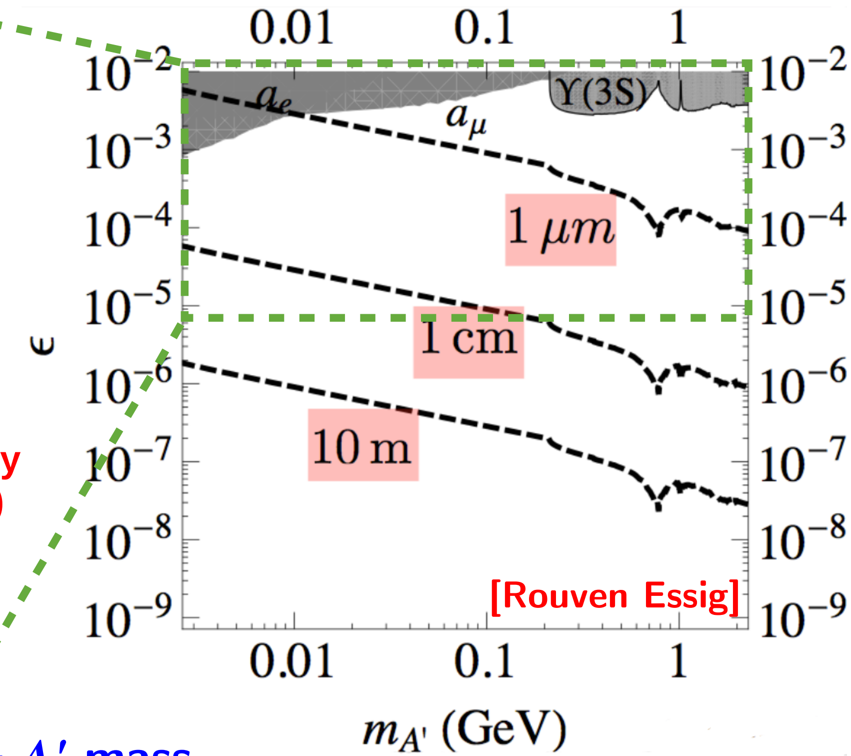

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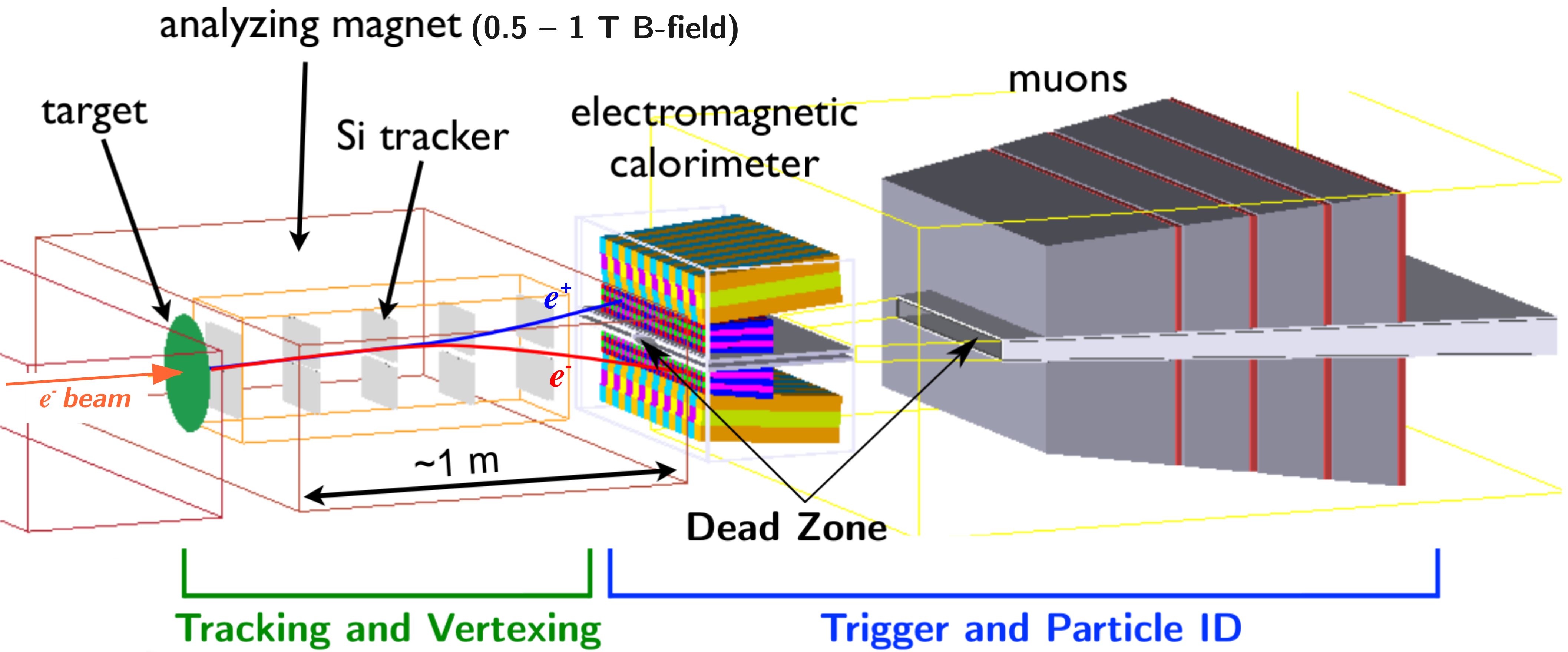
HPS ← **Solution**

The HPS Experiment

- The HPS Experiment will make use of a compact large acceptance, **vertex** detector capable of handling high rates

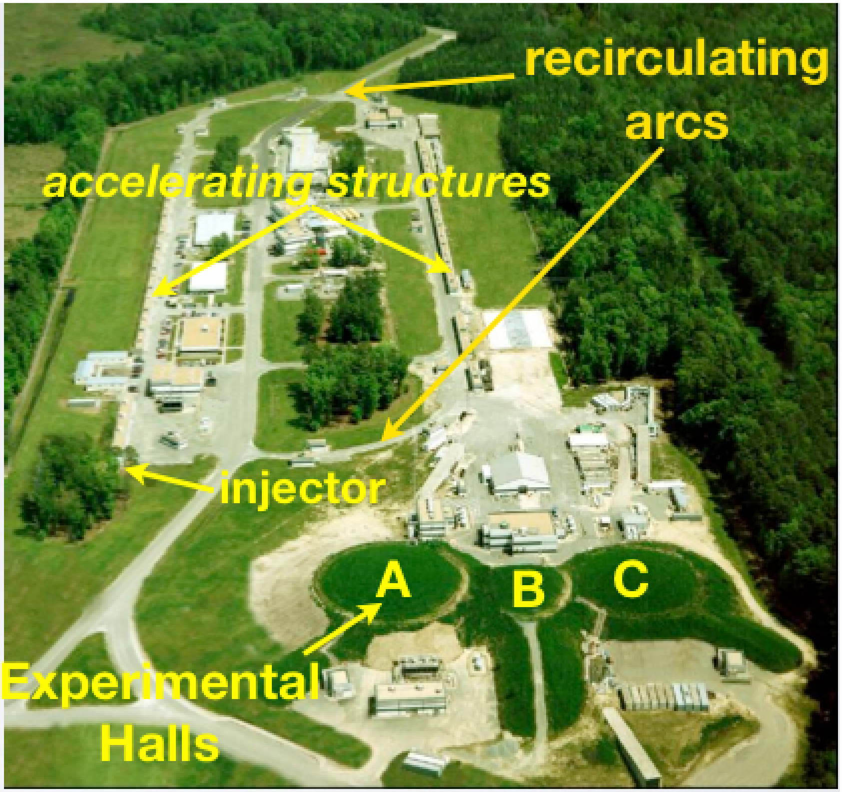


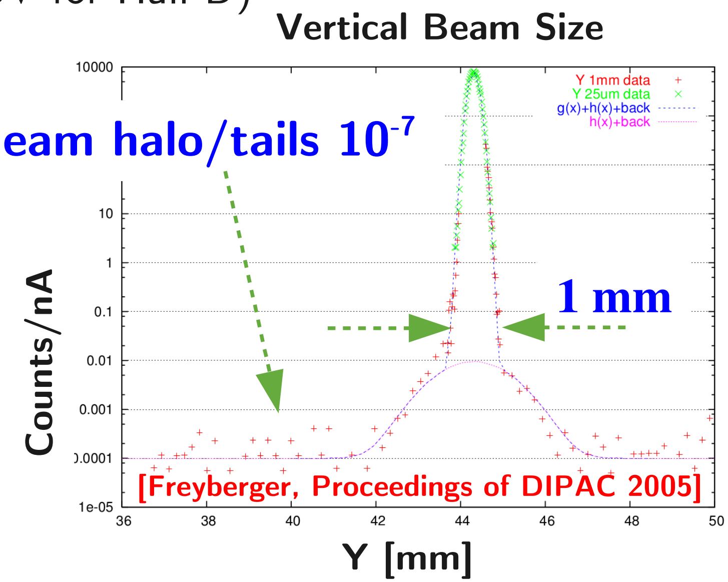
- The HPS detector will be split in half in order to avoid the "Wall of Flame" i.e. beam electrons, bremsstrahlung photons, etc.
- The HPS detector geometry is quickly evolving! Several improvements/changes are currently being explored ...

CEBAF @ Jefferson Lab

Simultaneous delivery of electron beams at different energies and intensities to three experimental halls

- E_{beam} = n x 1.1 GeV, n < 6 up to a maximum of 5.5 GeV (until May 2012)
- **Hall A, C:** $I_{beam} < 100\ \mu A$, **Hall B:** $I_{beam} < 800$ nA
- Beam delivery is nearly continous: 2 ns bunch structure
- Able to provide small beam spot (<30 μm) which will help improve vertexing
- Energy upgrade expected to be complete in 2014 E_{beam} = n x 2.2 GeV, n < 6 up to a maximum of 11 GeV (12 GeV for Hall D)



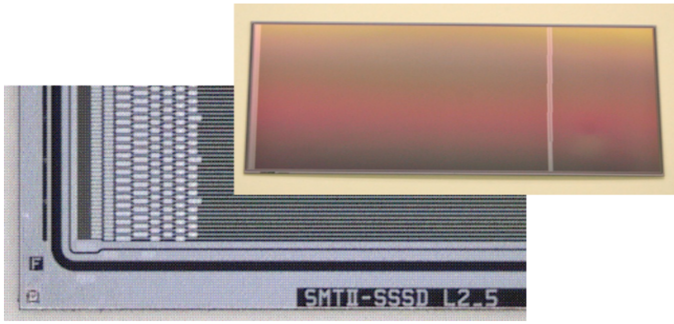


CEBAF is ideal for this experiment, however, schedule is not

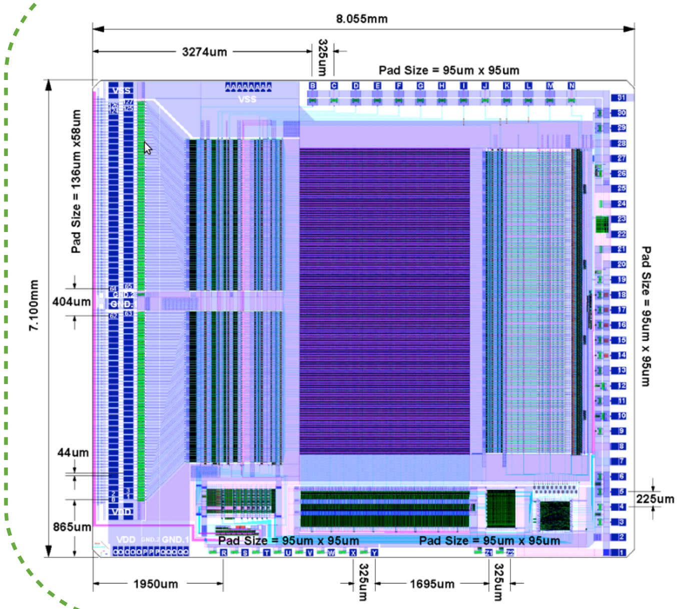
- Beam is down until 2015 for 12 GeV upgrade
- Aim is to run using first beam with possible commissioning run in late 2014 (**Will make use of existing Test Run detector**)

Silicon Vertex Tracker

D0 RunIIb sensors



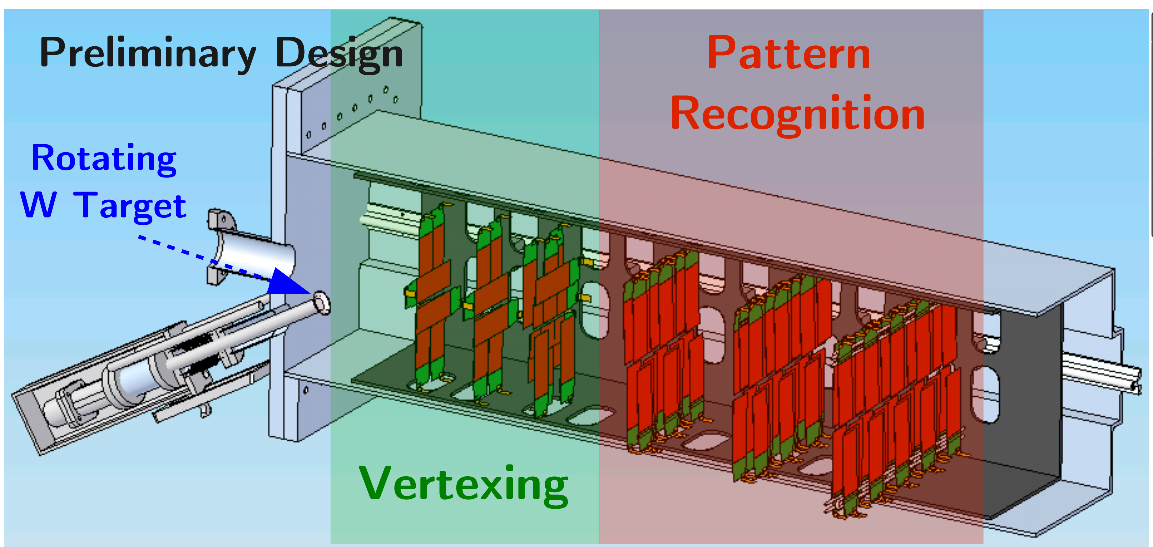
Cut Dimensions (L × W)	100 mm × 40.34 mm
Active Area (L × W)	98.33 mm × 38.34 mm
Readout (Sense) Pitch	60 μm (30 μm)
# Readout (Sense) Strips	639 (1277)
Breakdown Voltage	> 350 V
Defective Channels	< 1%



APV25 Readout Chip

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

- 40 MHz readout
- Low noise: S/N > 25
- High radiation tolerance
- "Multi-peak" readout
- t_0 resolution approx. 2 ns

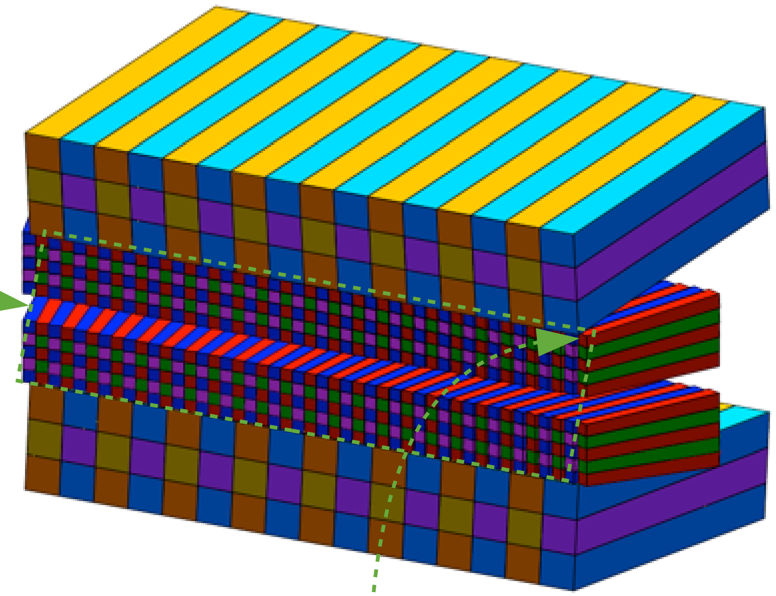


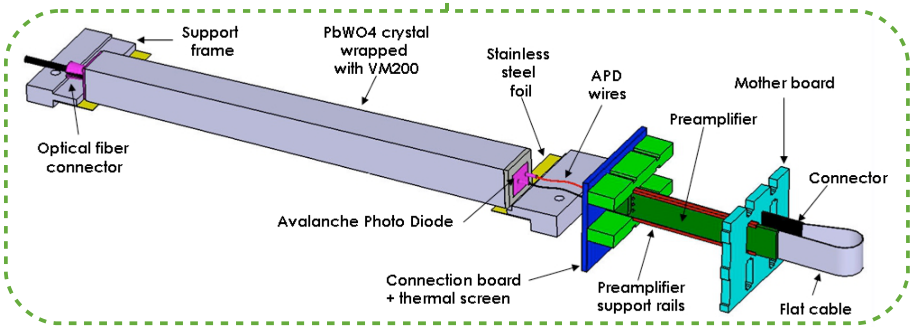
Layer	1	2	3	4	5	6
z position, from target [cm]	10	20	30	50	70	90
Stereo angle	90^o	90^o	90^o	50 mrad	50 mrad	50 mrad
Bend Plane Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
Stereo Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 120	≈ 120	≈ 120
# Bend Plane Sensors	4	4	6	10	14	18
# Sterep Sensors	2	2	4	10	14	18
Dead Zone [mm]	± 1.5	± 3.0	±4.5	±7.5	±10.5	±13.5

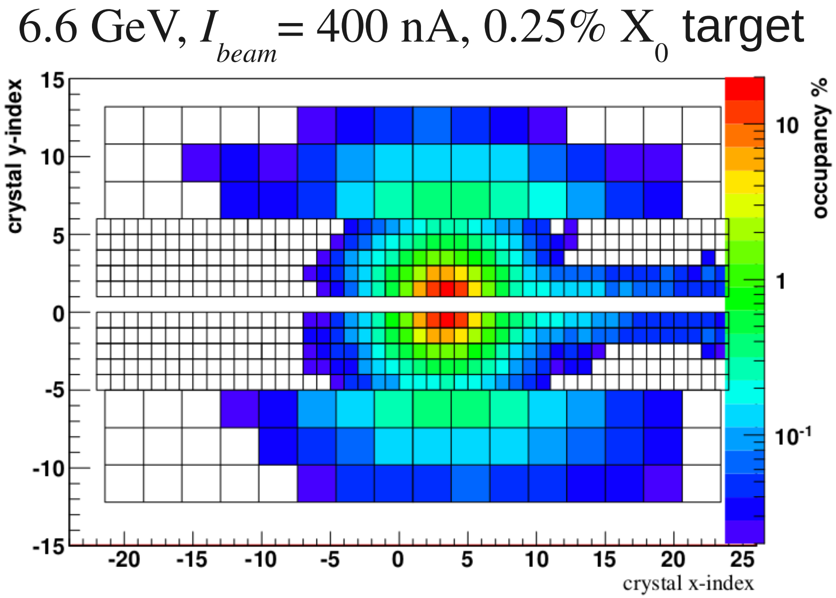
- Thin layers in order to reduce multiple scattering ($0.7\%X_0$/layer)
- Bend plane measurements in all layers (for momentum)
- 90 degree stereo will be used for vertexing

Trigger – Hybrid Calorimeter

- Hybrid design comprised of 460 existing PbWO4 crystals and 96 lead-glass crystals
- FADC readout at 250 MHz → allows for a narrow trigger window
- FPGA based trigger selection (Two clusters along with some constraints on their energy and geometry) reduces background trigger rate from 3 MHz to 27 kHz
- Trigger and DAQ capable of a rate of > 50 KHz





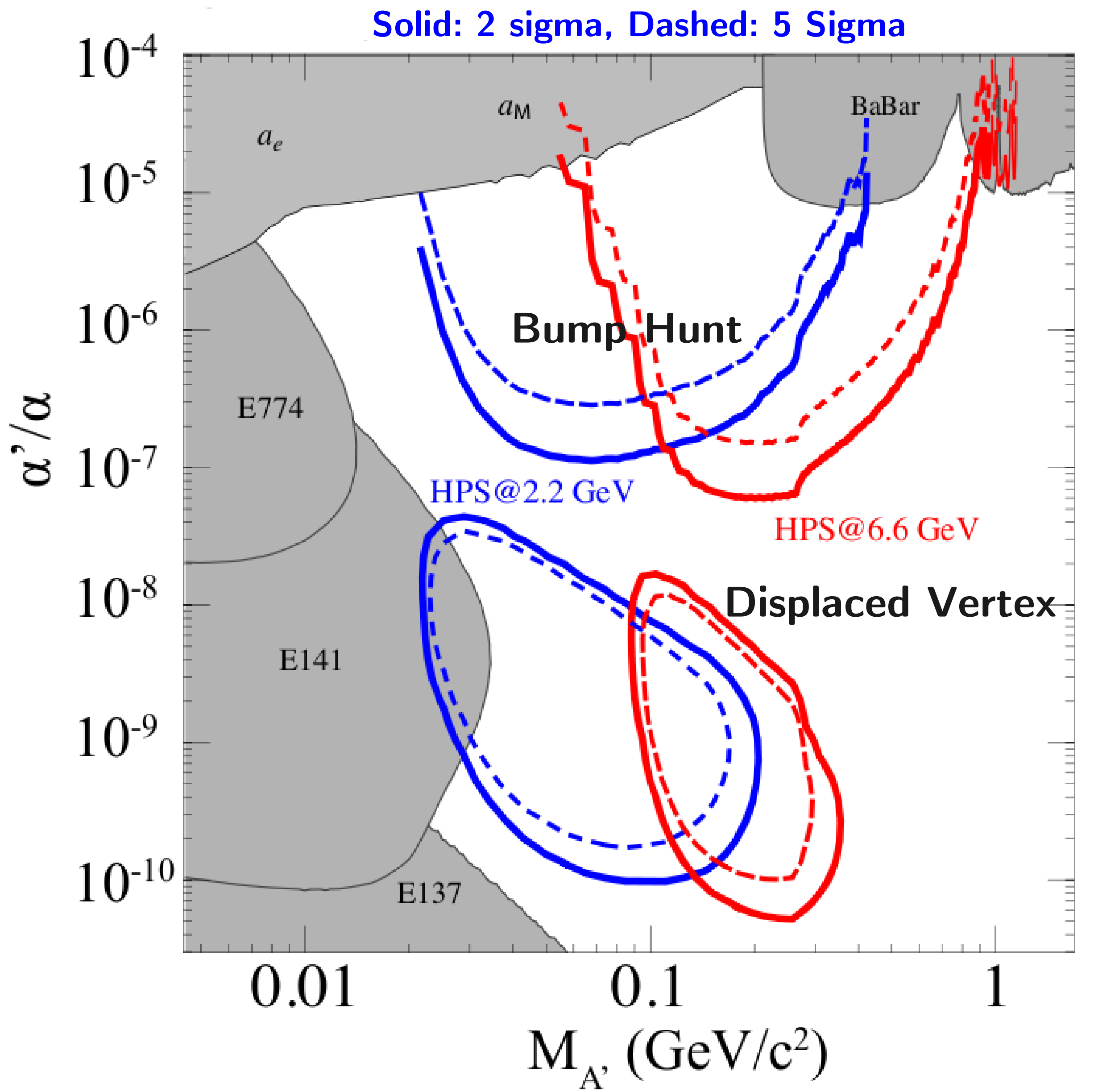


HPS Reach

Beam = 2.2 GeV @ 200 nA
Target = 0.125%X_0

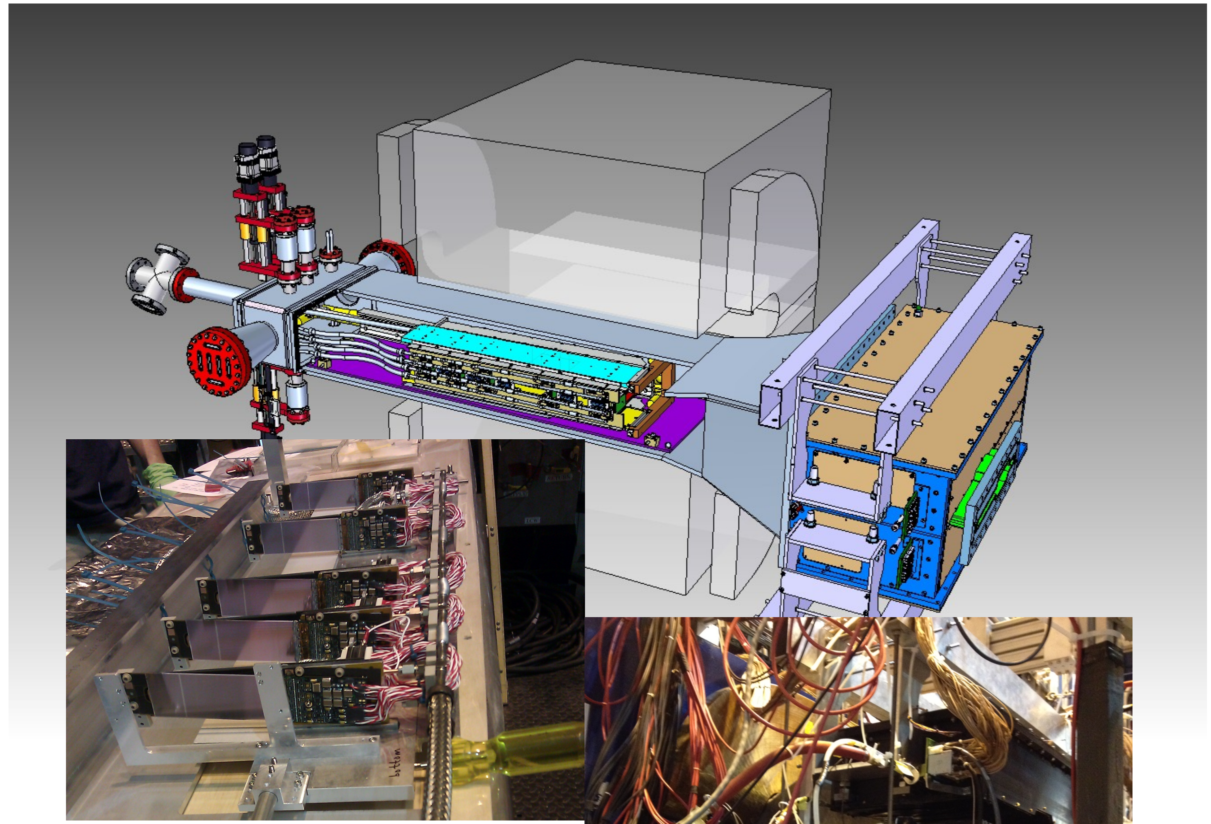
Beam = 6.6 GeV @ 450 nA
Target = 0.25%X_0

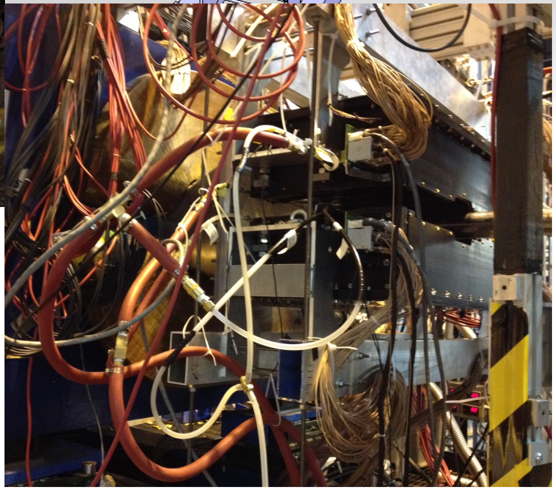
Assumes 3 months of running at each energy



The HPS Test Run

- The aim was to **determine if the occupancies and trigger rates have been well modeled and are manageable, as well as to show if detector performance estimates were reasonable**
- Used a scaled down version of the HPS detector
  - 5 Si tracker layers with two sensors per layer (1 axial, 1 stereo)
  - Only use the inner crystals of the Ecal
  - The muon chamber was absent
  - Use existing beamline elements
- HPS Test Run was installed on April 19th and **successfully** ran until the CEBAF shutdown
  - SVT design was conceived, built and installed in less than 14 months!
  - Scheduling conflict prevented running using electrons → **Ran parasitically using a photon beam instead**

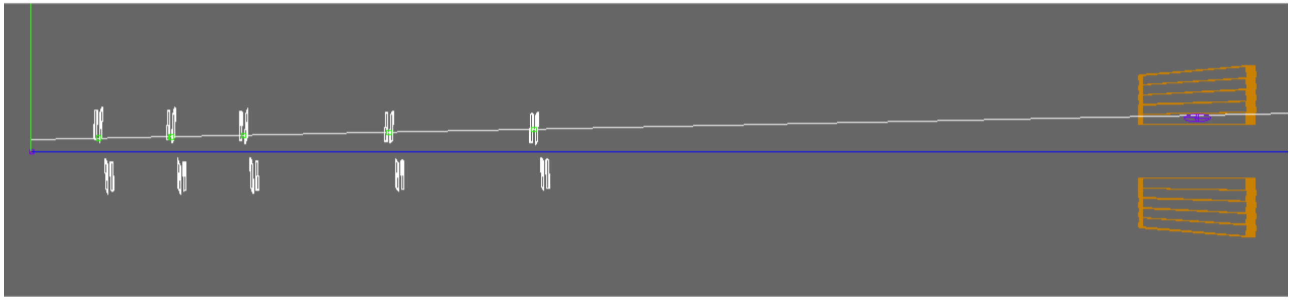


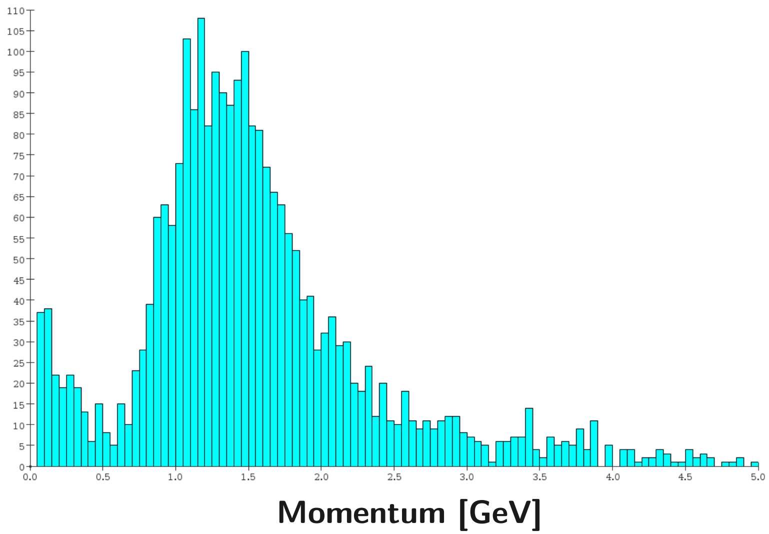


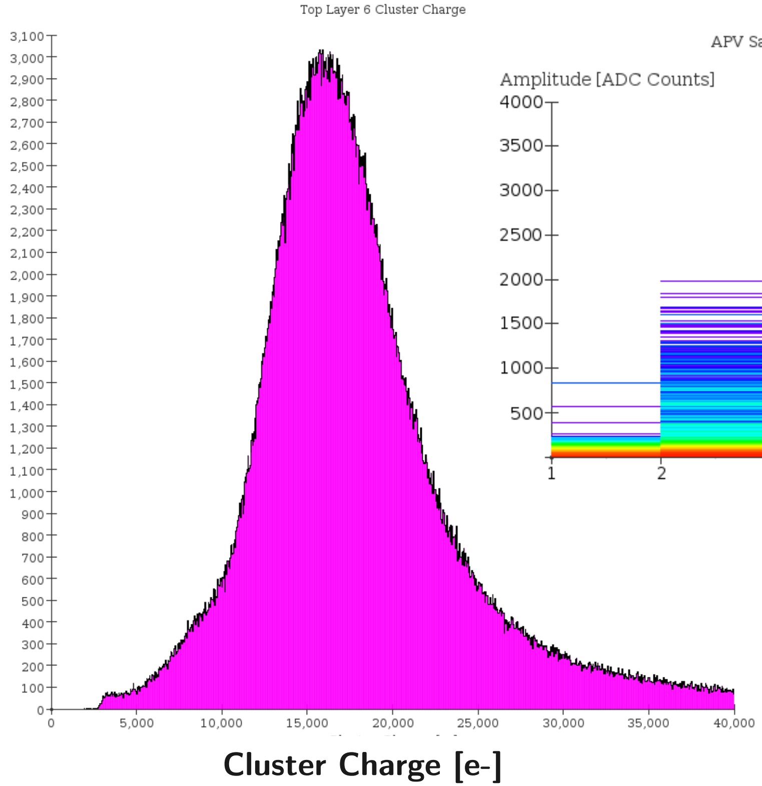
Short photon beam run
(last hours of CEBAF 6GeV era!)

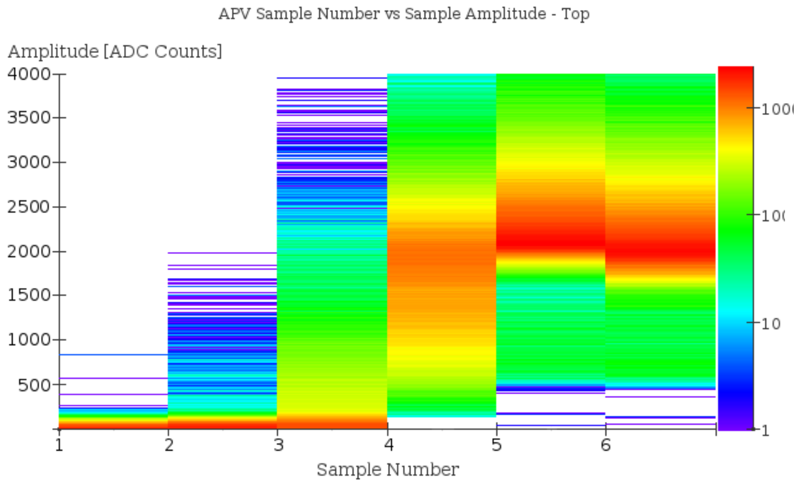
Target thickness (rad. len)	# Events	Approx. trigger rate (Hz)
no target	0.6M	0.3k
0.18%	2M	0.4k
0.45%	1M	0.6k
1.6%	1.5M	1.9k

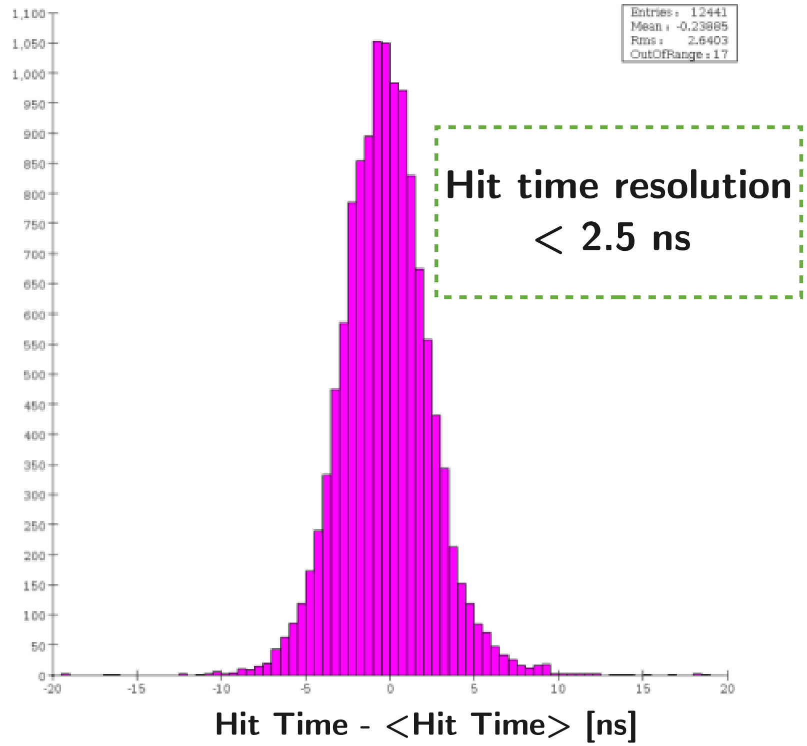
Y-Z view of a track









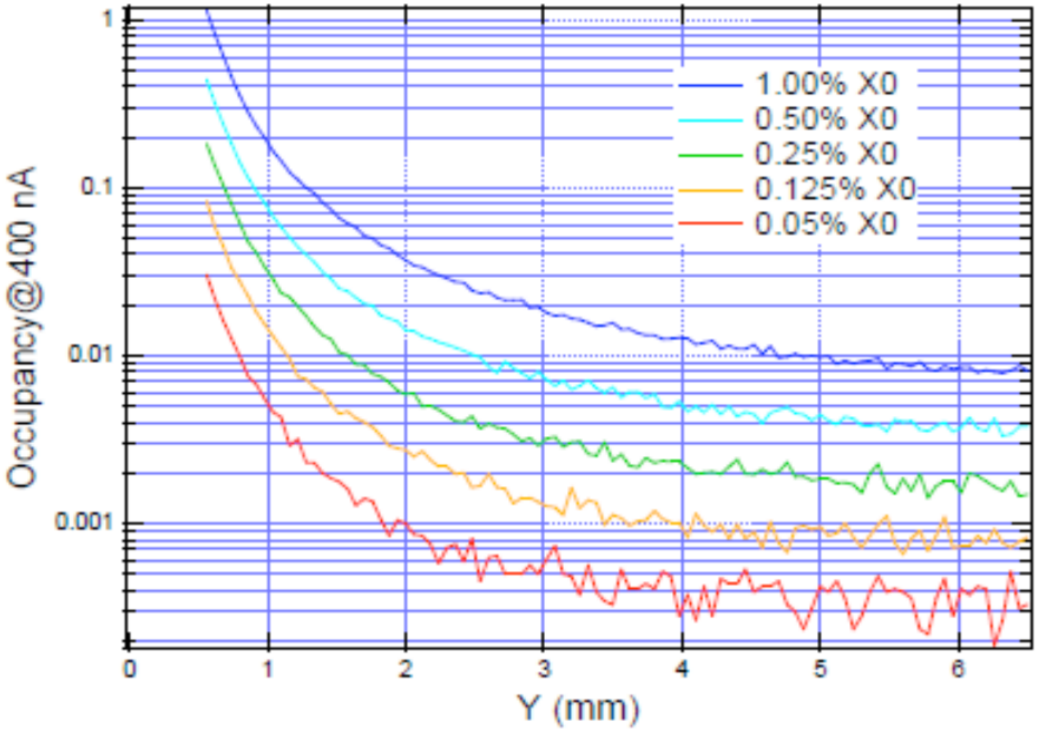


Analysis of Test Run data is still ongoing
→ Comparison to full simulation is beginning

HPS Collaboration

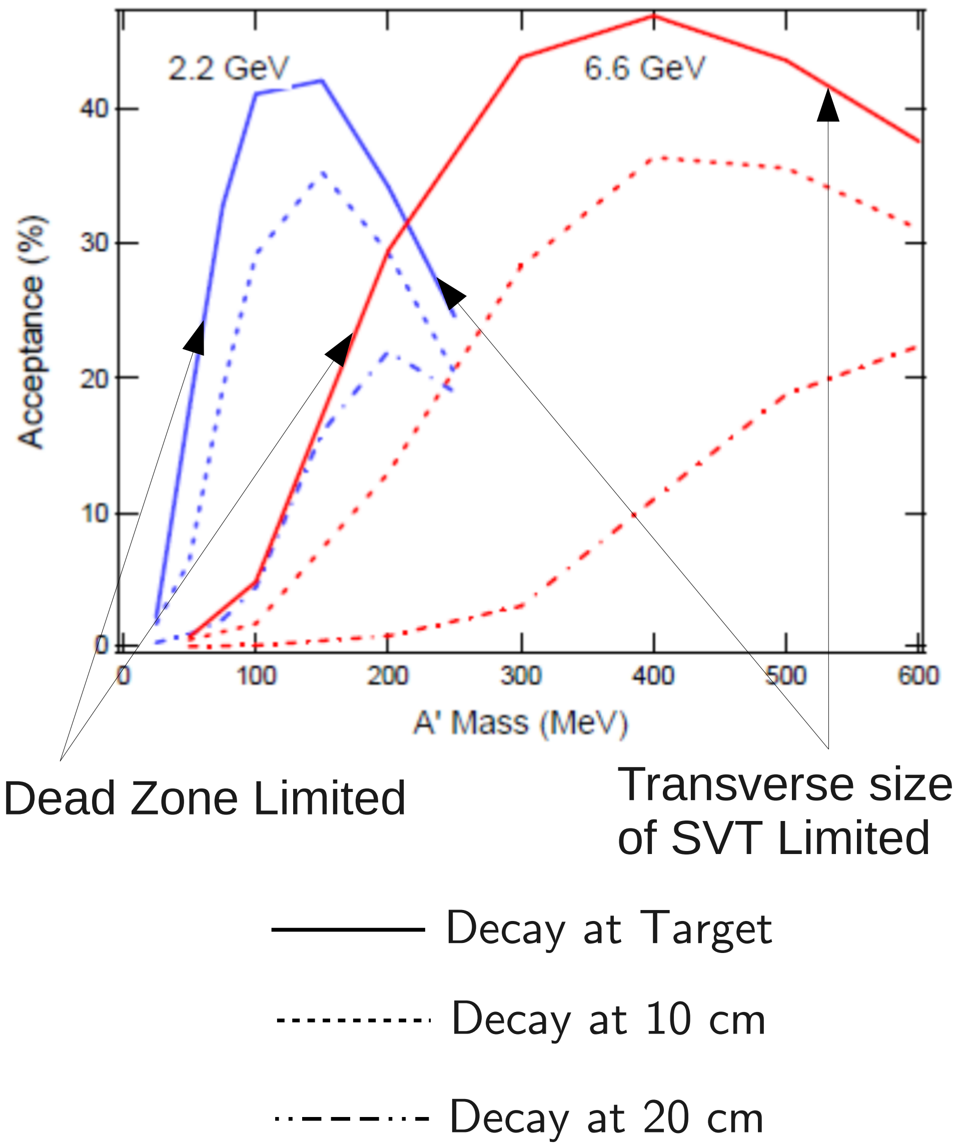
Backup

SVT Performance



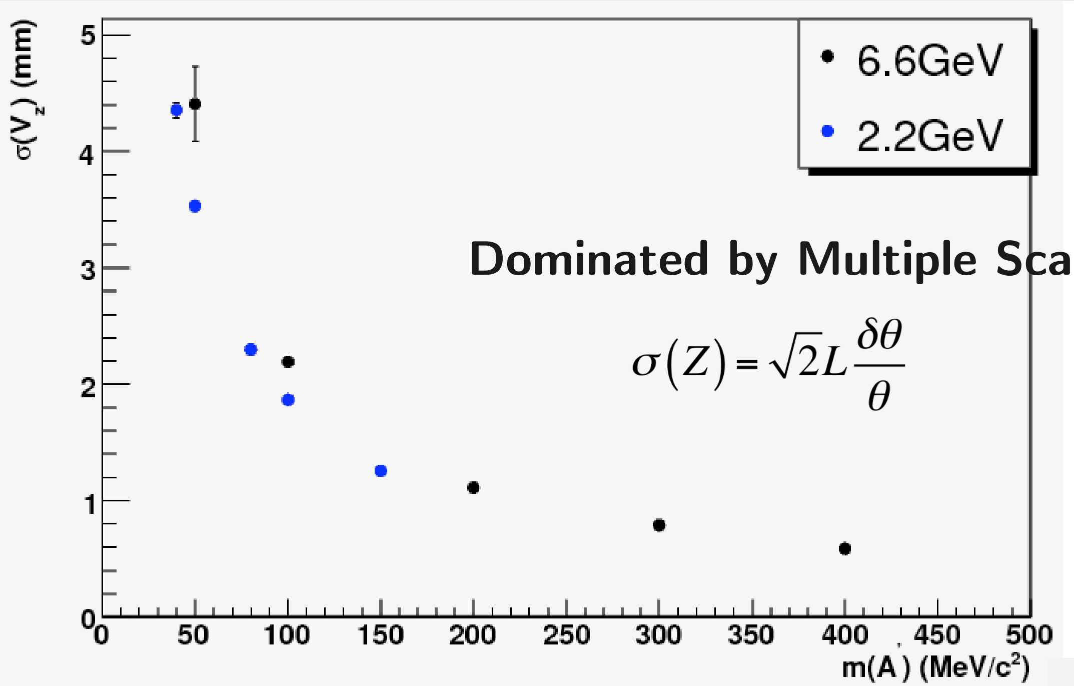
Dead Zone chosen such that the occupancy at Layer 1 is approx. 1%

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



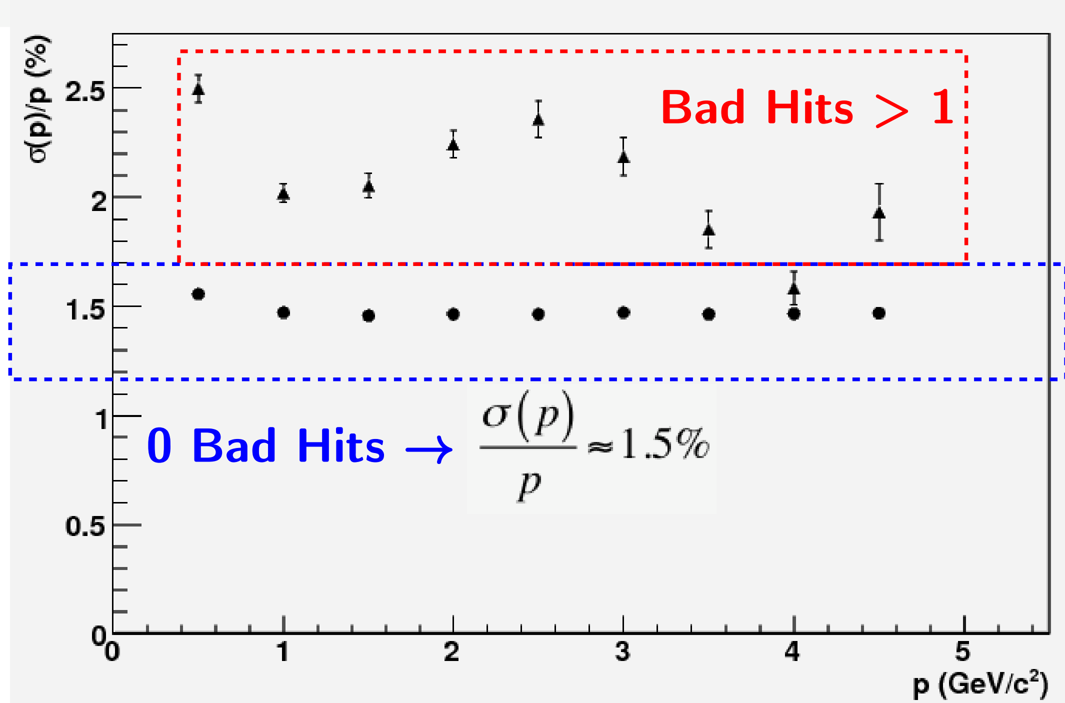
Acceptance is calculated by requiring the e^+e^- to hit the first five layers

Mass and Vertex Resolution



Dominated by Multiple Scattering

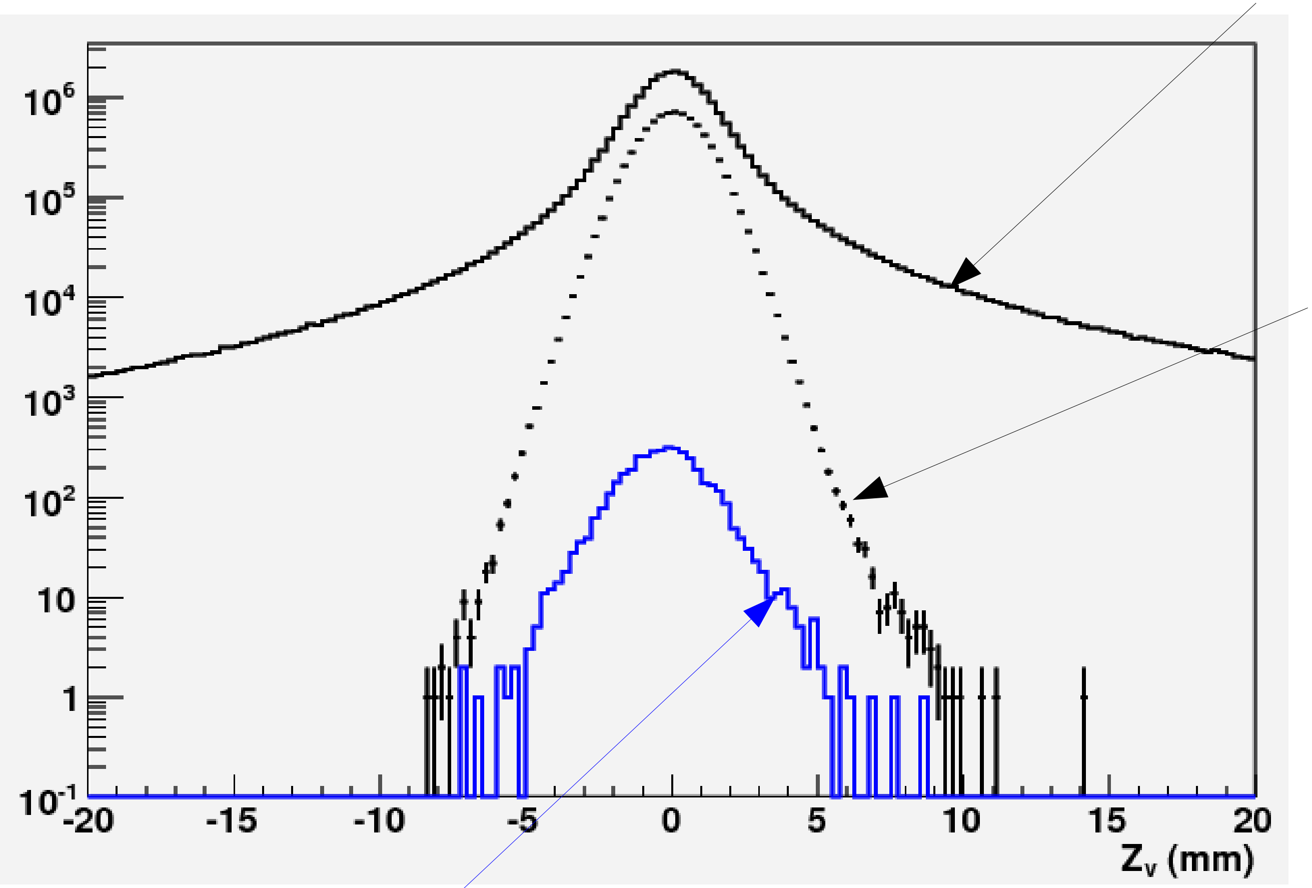
$$\sigma(Z) = \sqrt{2}L\frac{\delta\theta}{\theta}$$



$$\frac{\sigma(p)}{p} \approx 1.5\%$$

Mass and Vertex Resolution

Vertex Position of Prompt Decays



Tracks with Bad Hits

Event selection

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

These cuts have not been optimized

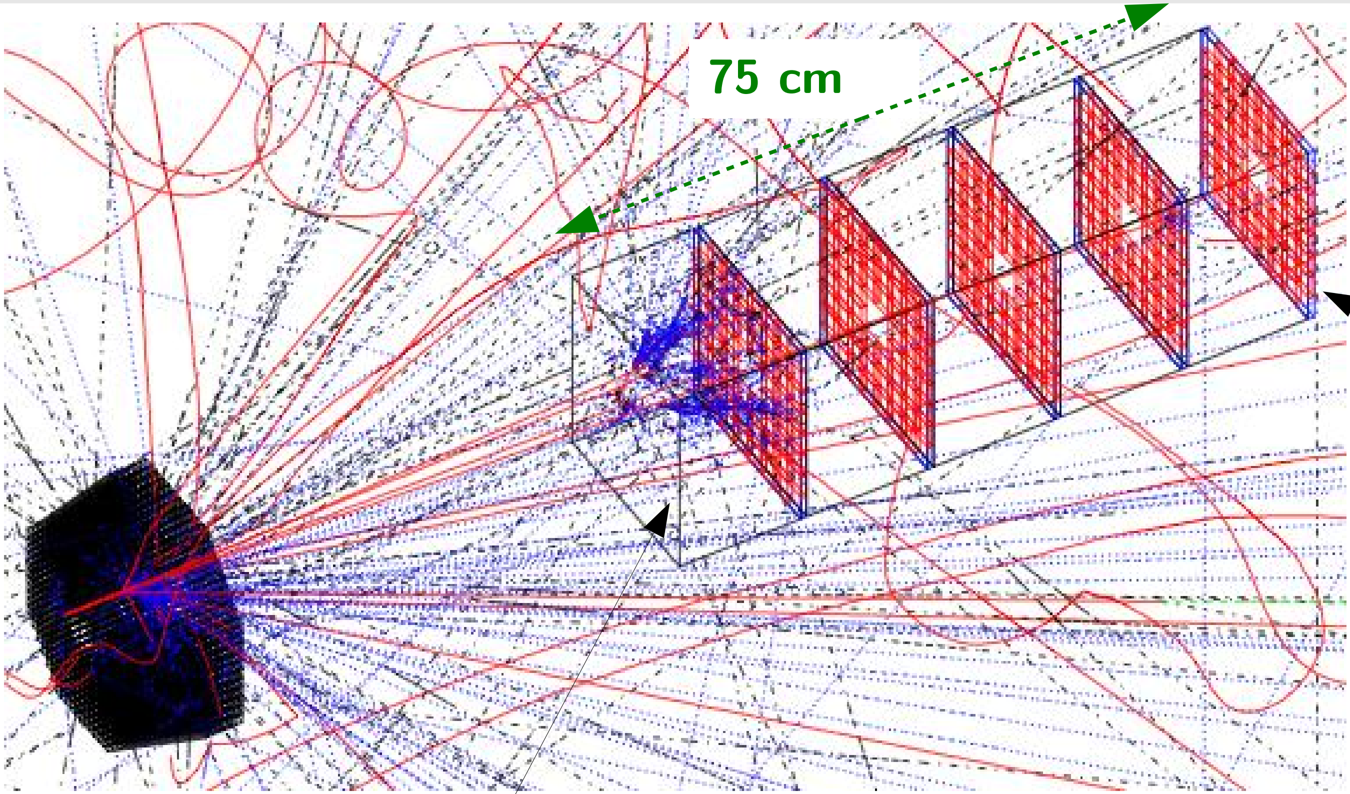
Trigger Rates

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

Trident Rates after trigger cuts are applied

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

Muon Detector



Sci. Hodoscopes
1.5 cm

Iron Absorber
30 cm + 3x15 cm