# Searching For Dark Photons at Jefferson Lab

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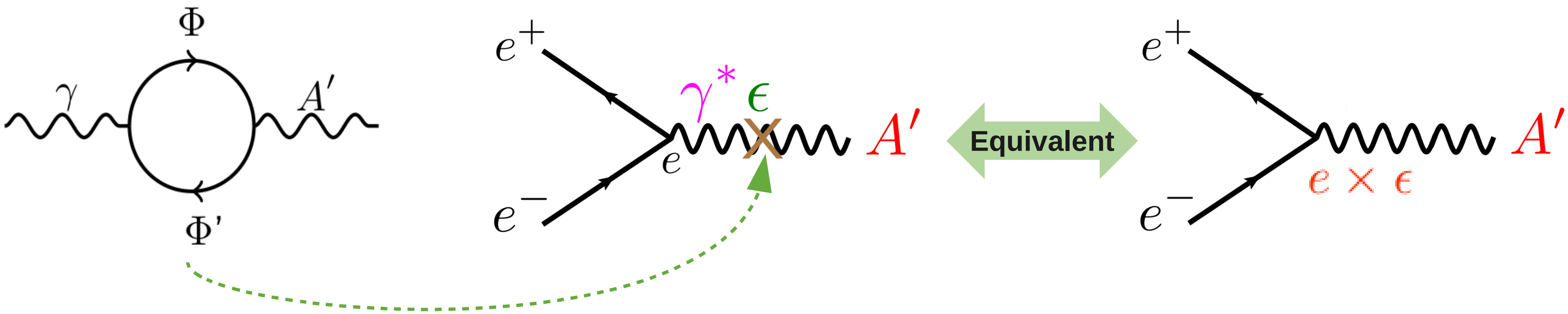
# What is a "Dark Photon"?

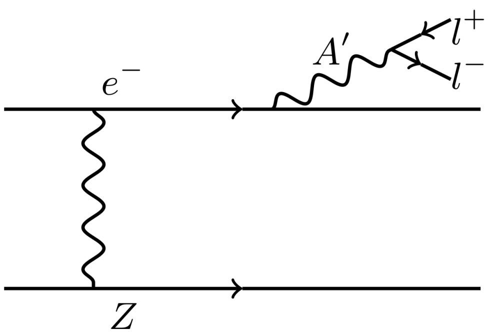
- Consider a theory in which nature contains an additional Abelian gauge symmetry, $U(1)_D$
  **[Holdom, Phys. Lett.B166, 1986]**

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

- 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 $\rightarrow$ induces small coupling to electric charge

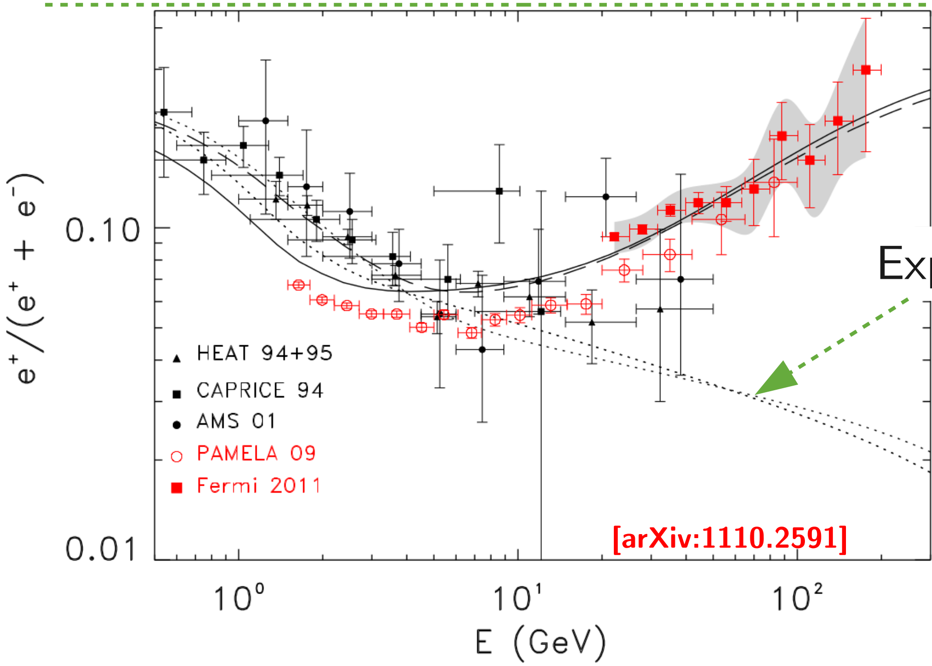



- The coupling to electric charge allows for $A'$ production through a process analogous to bremsstrahlung



# So Why Search for an Dark Photon?

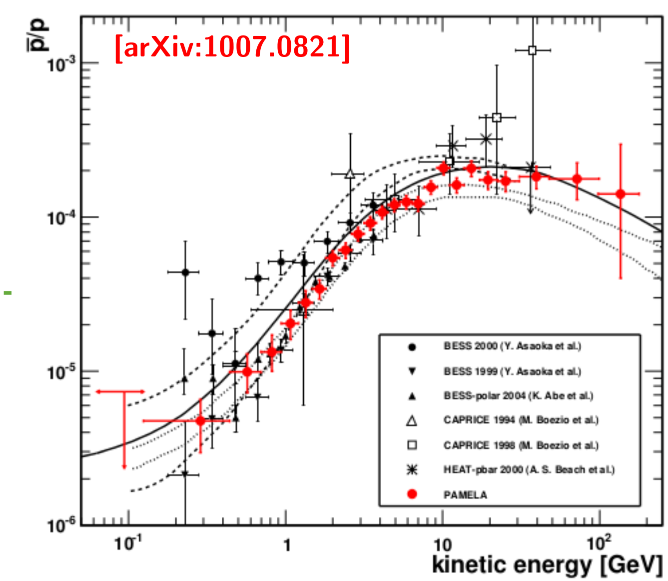
Both PAMELA and Fermi observe an excess in the positron fraction



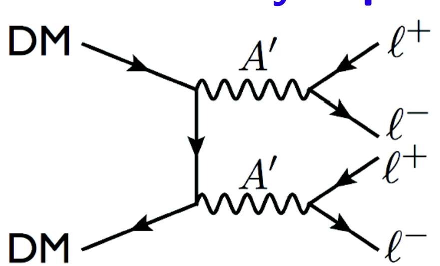

Expected

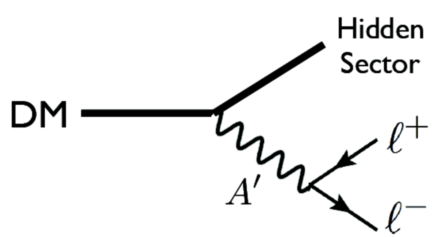
But ...

No excess anti-protons are observed




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

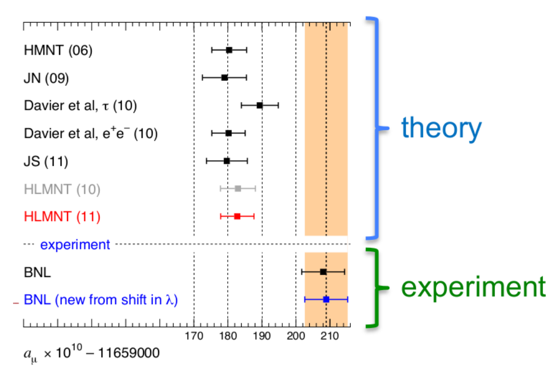



[Arkani-Hamed et. al., Pospelov & Ritz]

[Volansky & Ruderman, Essig, Schuster, Toro]

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

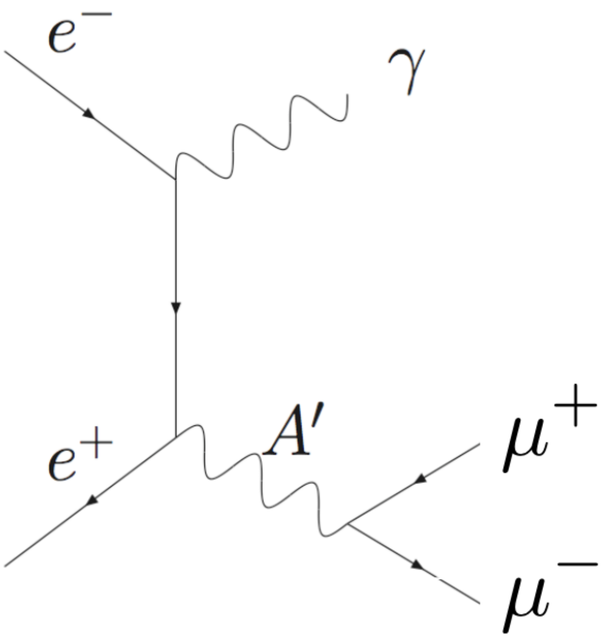



[hep-ex/0602035]

# How to Search for a Dark Photon?

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

**Collider**

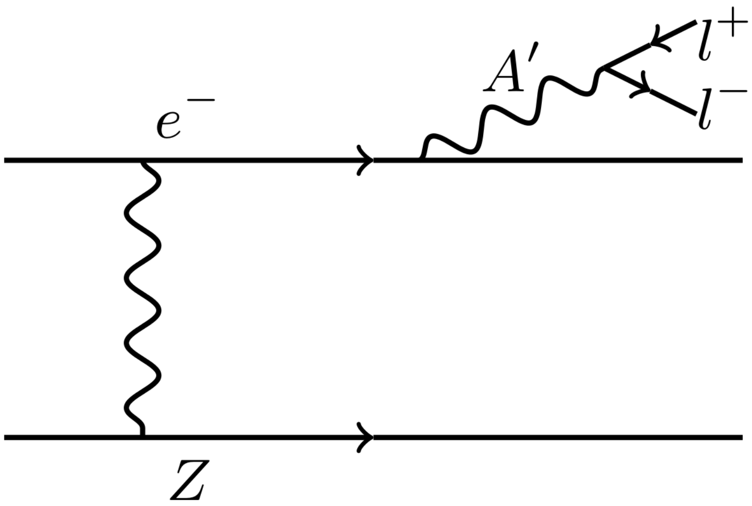



$$\sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2} \sim \mathcal{O}(10 \text{ fb})$$

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

**vs.**

**Fixed Target**



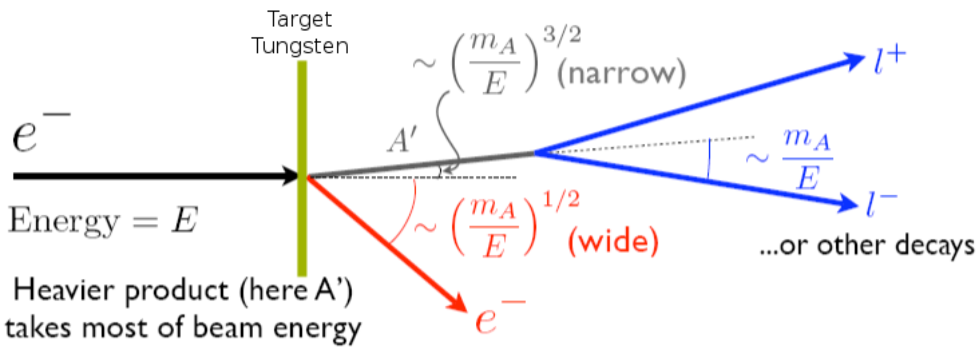

$$\sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2} \sim \mathcal{O}(10 \text{ pb})$$

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

**Fixed target experiments are ideal $A'$ hunting grounds!**

# $A'$ Fixed Target Kinematics & Backgrounds

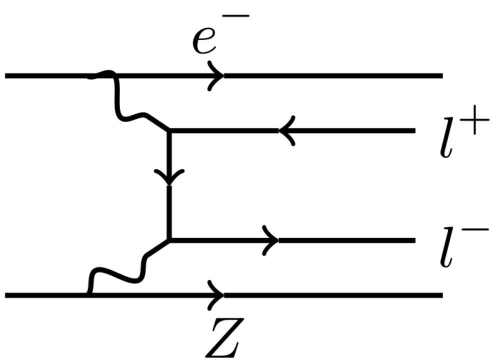
## Signal



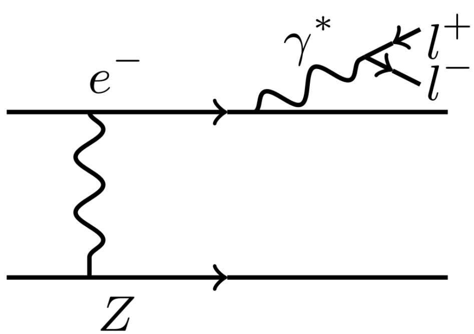

- $A'$ is produced very far forward $\rightarrow E_{A'} = E_{\text{beam}}$
- $A'$ decay products opening angle, $m_{A'}/E_{\text{beam}}$
- Long lived $A'$ will have a displaced vertex $\rightarrow$ Help in the reduction of background

## Trident Backgrounds

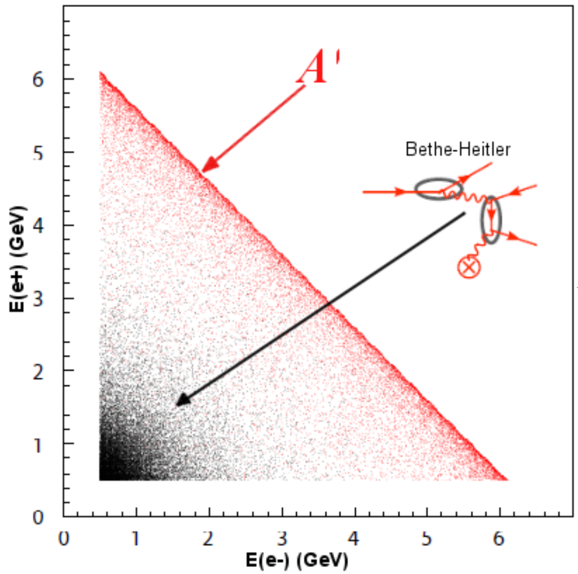
### Bethe-Heitler




### Radiative

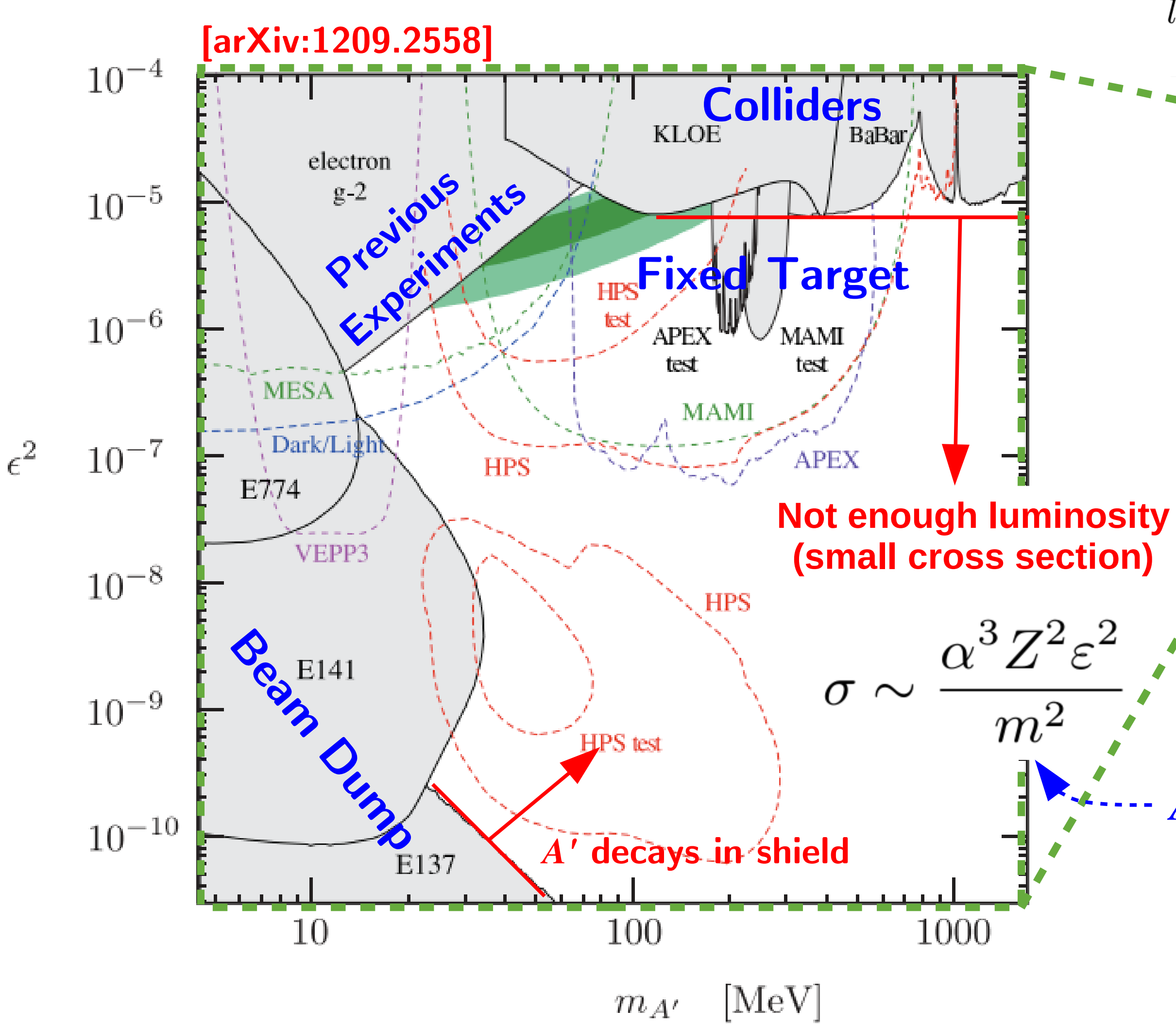



**Even after kinematic cuts, Bethe-Heitler dominates by a factor of 5!**




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

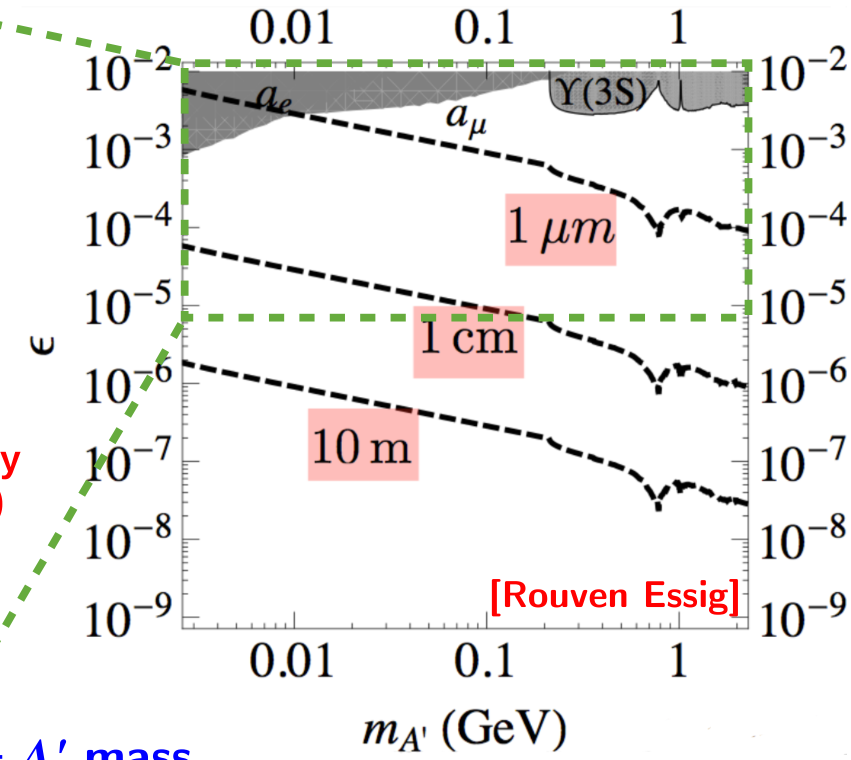
# Some Existing A' Constraints




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

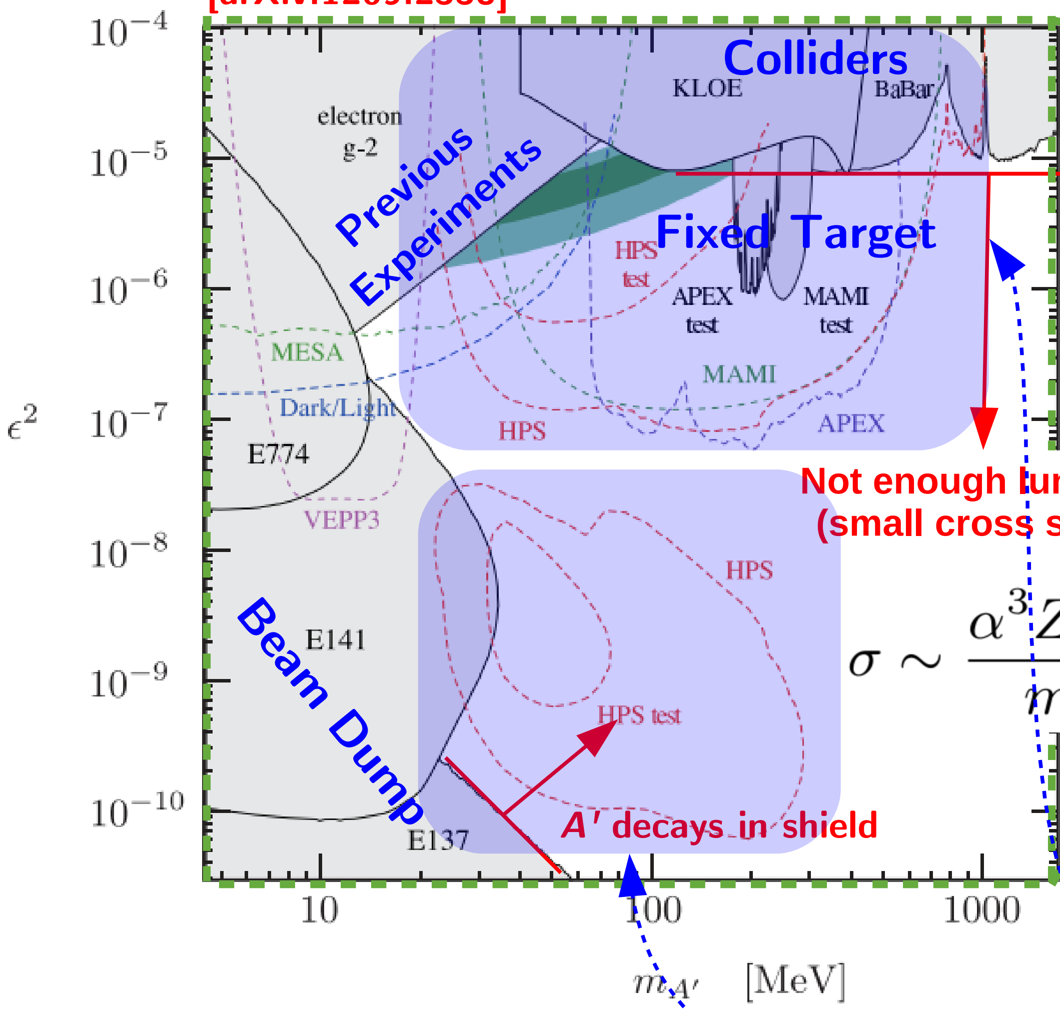
$A'$ Decay Lengths

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



# Some Existing A' Constraints

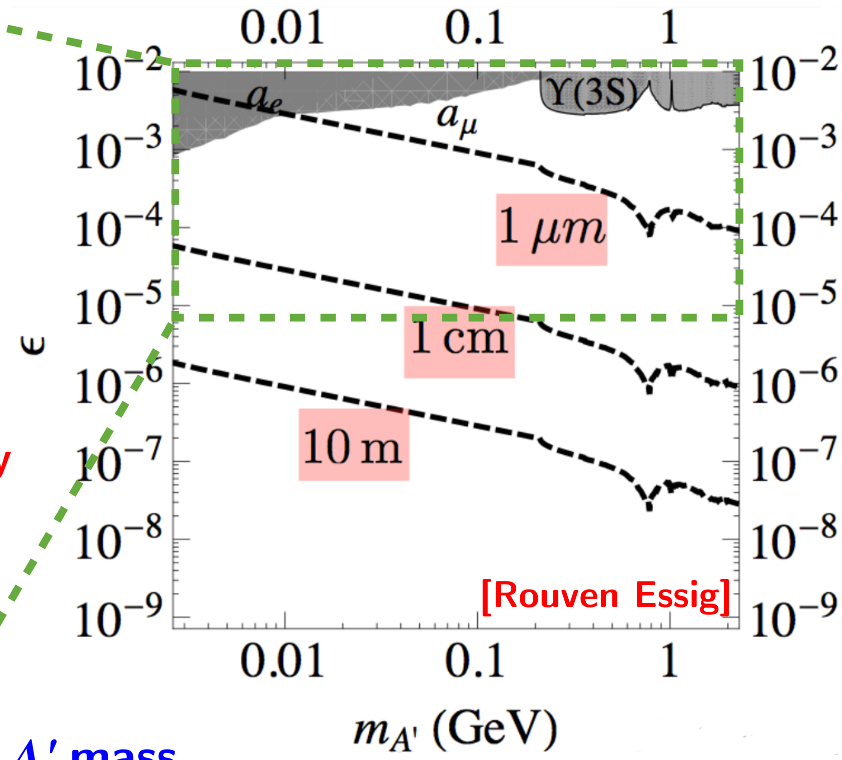
[arXiv:1209.2558]




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

*A′* Decay Lengths

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



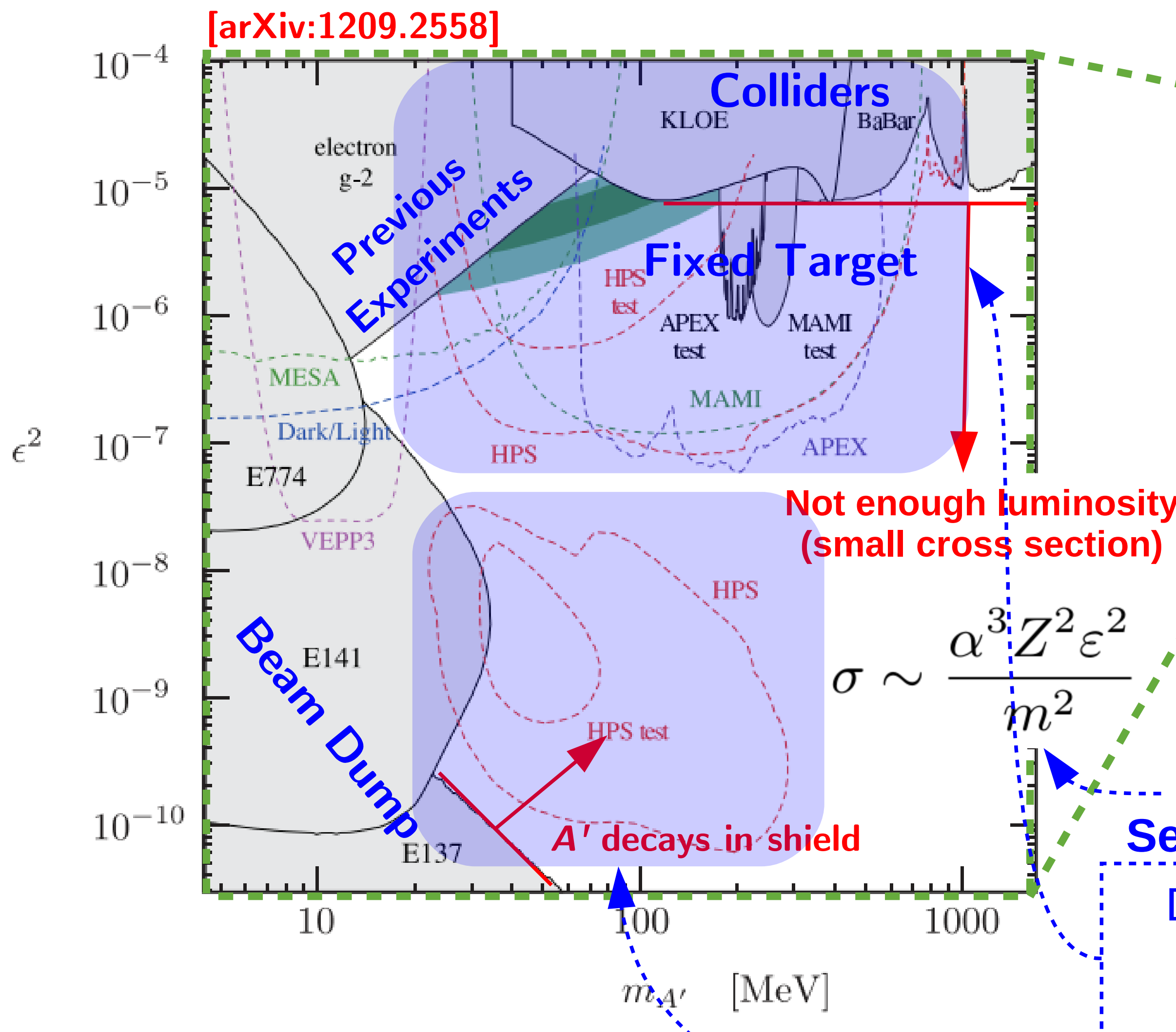

***A′* mass**

**Sensitivity to these regions will rely on**

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

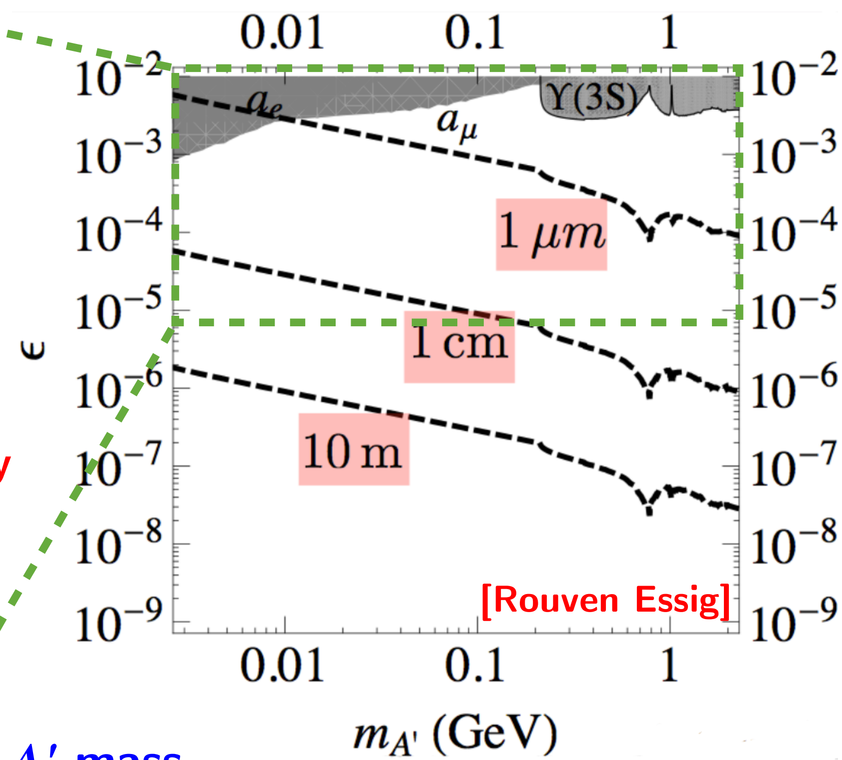
Distinguishing *A′* decay vertices as Non-prompt → Good vertex resolution

# Some Existing A' Constraints




## $A'$ 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**

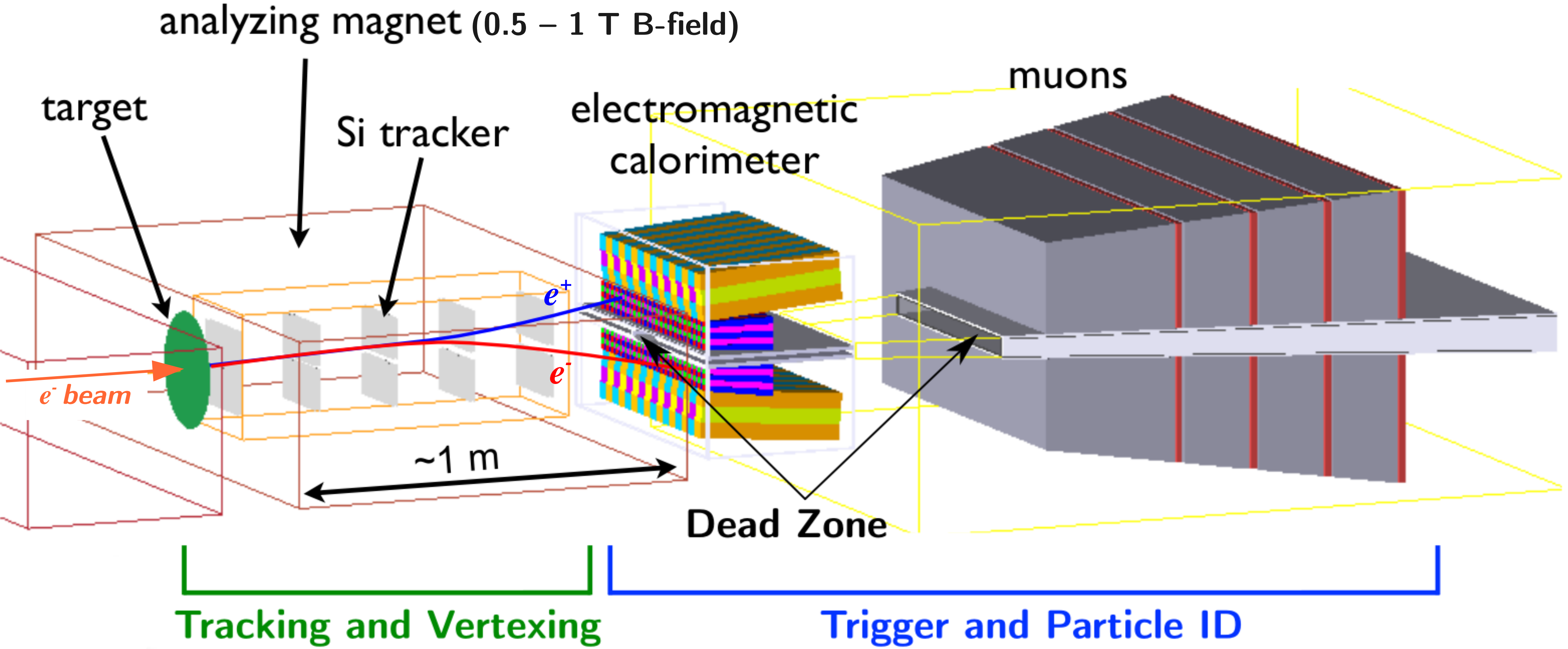
Determination of the invariant mass of the $A'$ decay products → Good mass (momentum) resolution

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

**HPS** ← **Solution**

# The HPS Experiment

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

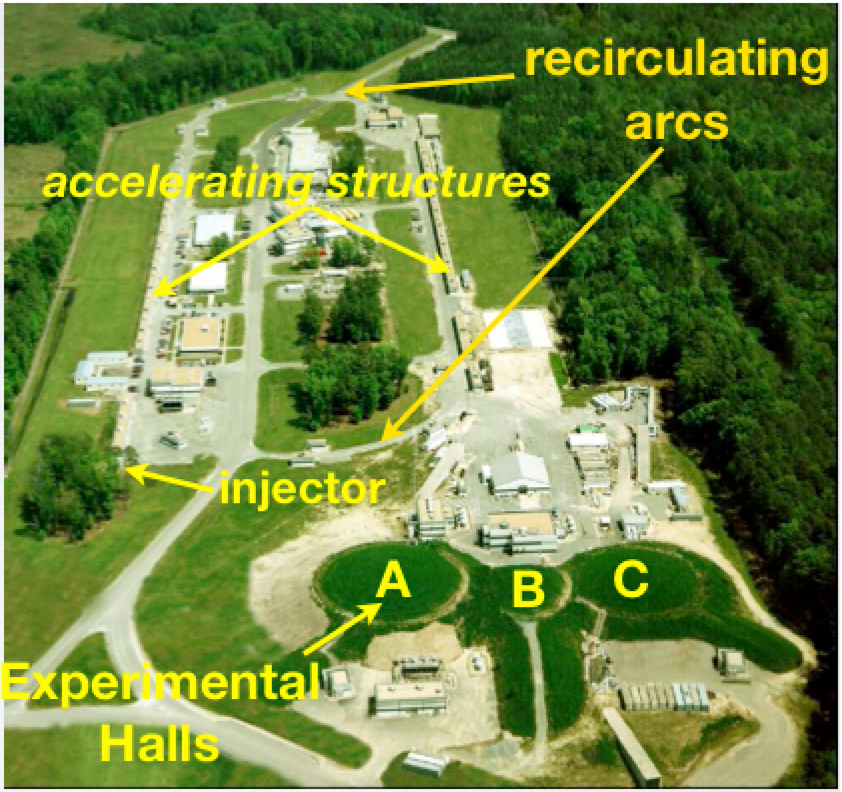


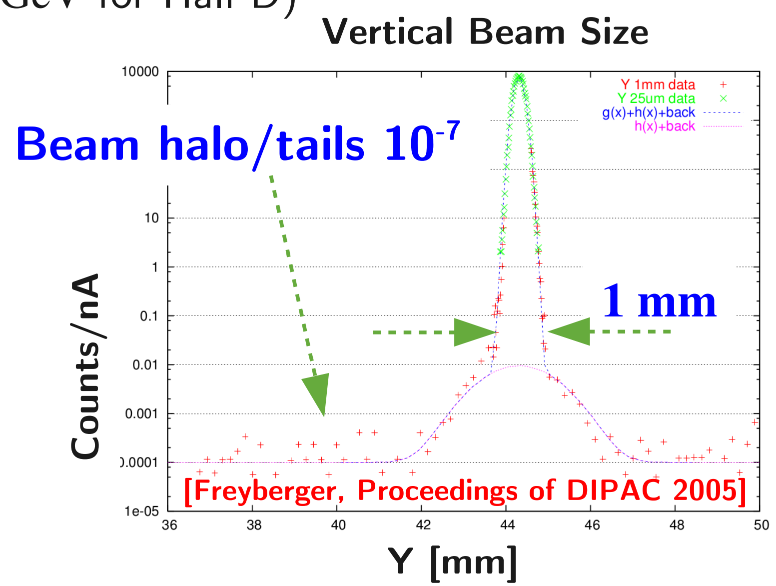

- The HPS detector will be split in half in order to avoid the "Wall of Flame" i.e. beam electrons, bremsstrahlung photons, etc.
- The HPS detector geometry is quickly evolving! Several improvements/changes are currently being explored ...

# 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 $\mu$m) 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)



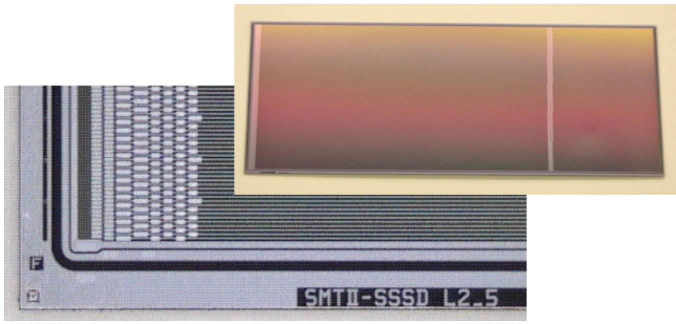




**CEBAF is ideal for this experiment**, however, schedule is not

- 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**)

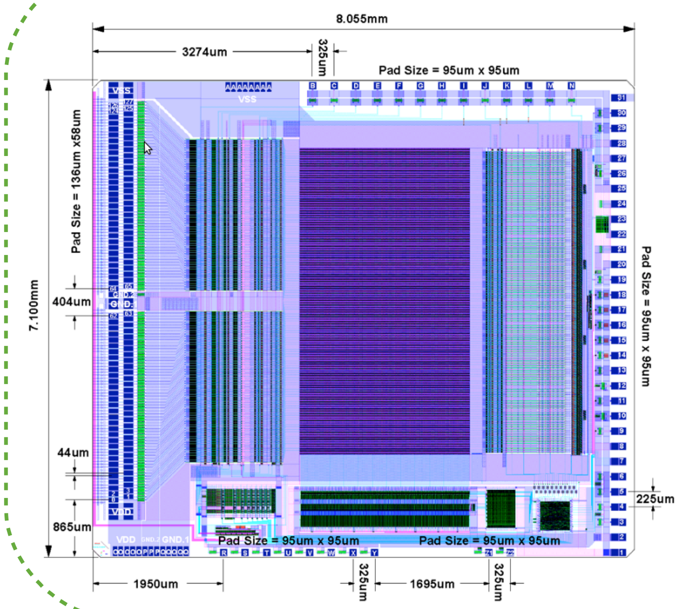
# Silicon Vertex Tracker

## D0 RunIIb sensors



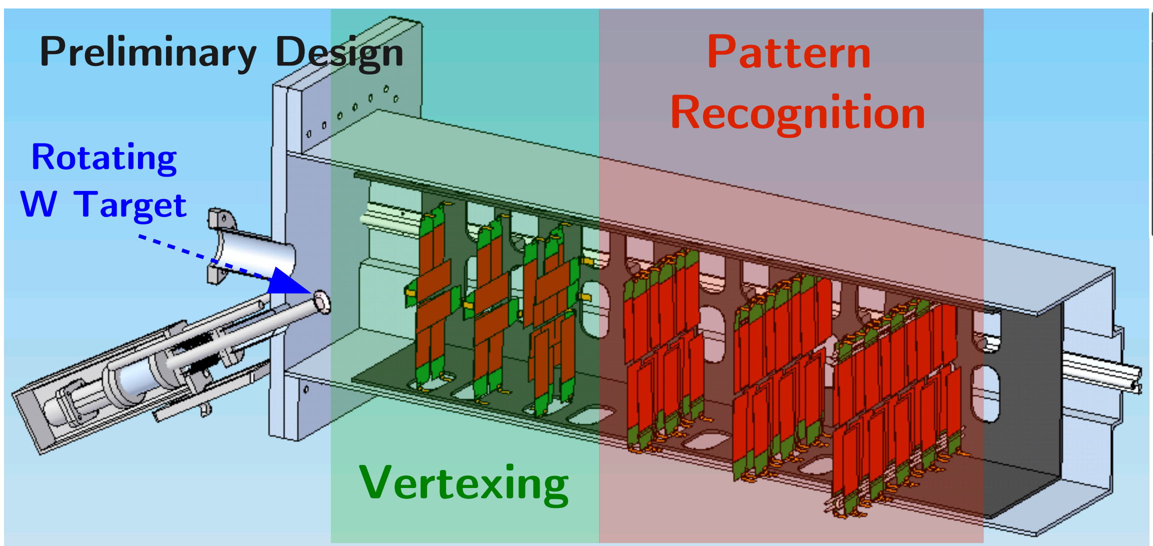

| | |
|---|---|
| Cut Dimensions (L × W) | 100 mm × 40.34 mm |
| Active Area (L × W) | 98.33 mm × 38.34 mm |
| Readout (Sense) Pitch | 60 $\mu$m (30 $\mu$m) |
| # Readout (Sense) Strips | 639 (1277) |
| Breakdown Voltage | > 350 V |
| Defective Channels | < 1% |

## APV25 Readout Chip




| | |
|---|---|
| # Readout Channels | 128 |
| Input Pitch | 44$\mu$ |
| 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



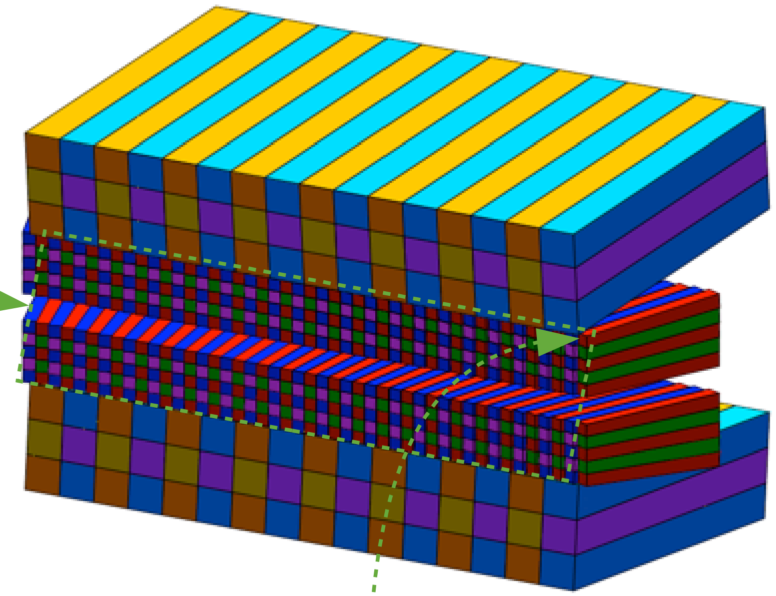

| Layer | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| z position, from target [cm] | 10 | 20 | 30 | 50 | 70 | 90 |
| Stereo angle | $90^o$ | $90^o$ | $90^o$ | 50 mrad | 50 mrad | 50 mrad |
| Bend Plane Resolution ($\mu$m) | ≈ 6 | ≈ 6 | ≈ 6 | ≈ 6 | ≈ 6 | ≈ 6 |
| Stereo Resolution ($\mu$m) | ≈ 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

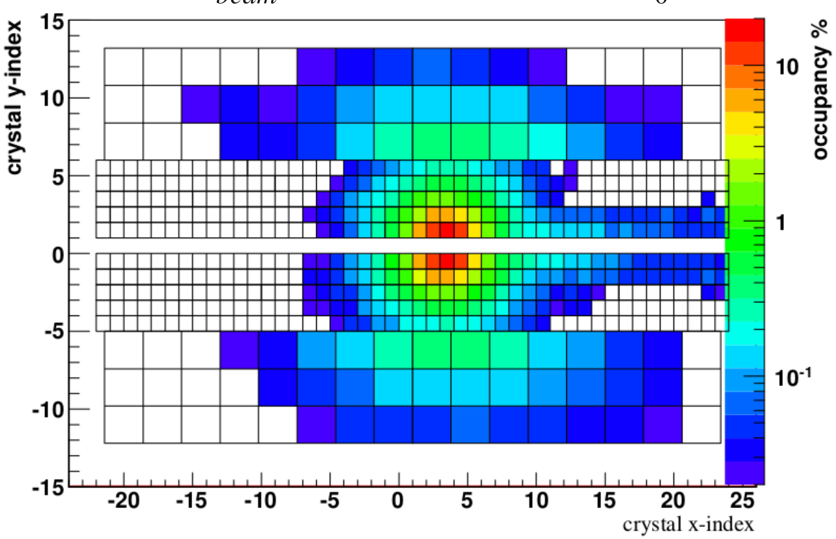
**The SVT will be comprise of 106 sensors & hybrids and 530 APV25 ASICs for a total of 67840 Channels**

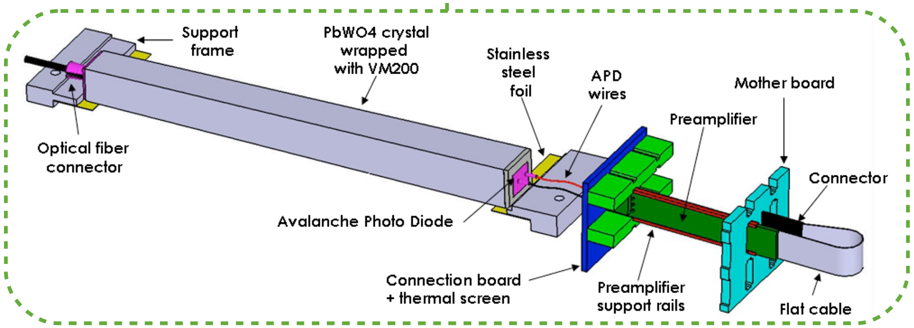
# Trigger – Hybrid Calorimeter

- 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



6.6 GeV, $I_{beam}$ = 400 nA, 0.25% $X_0$ target



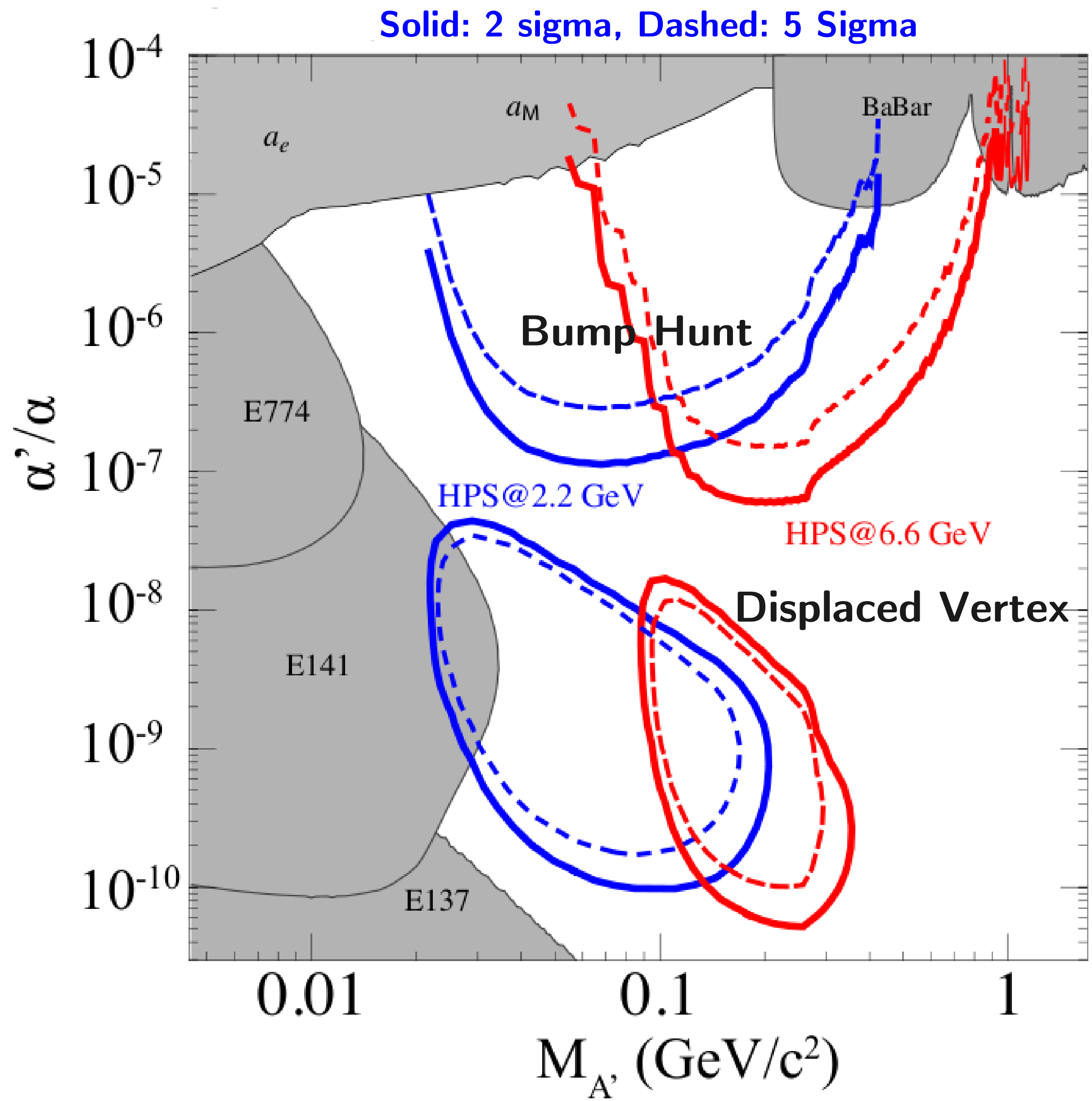



# HPS Reach

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

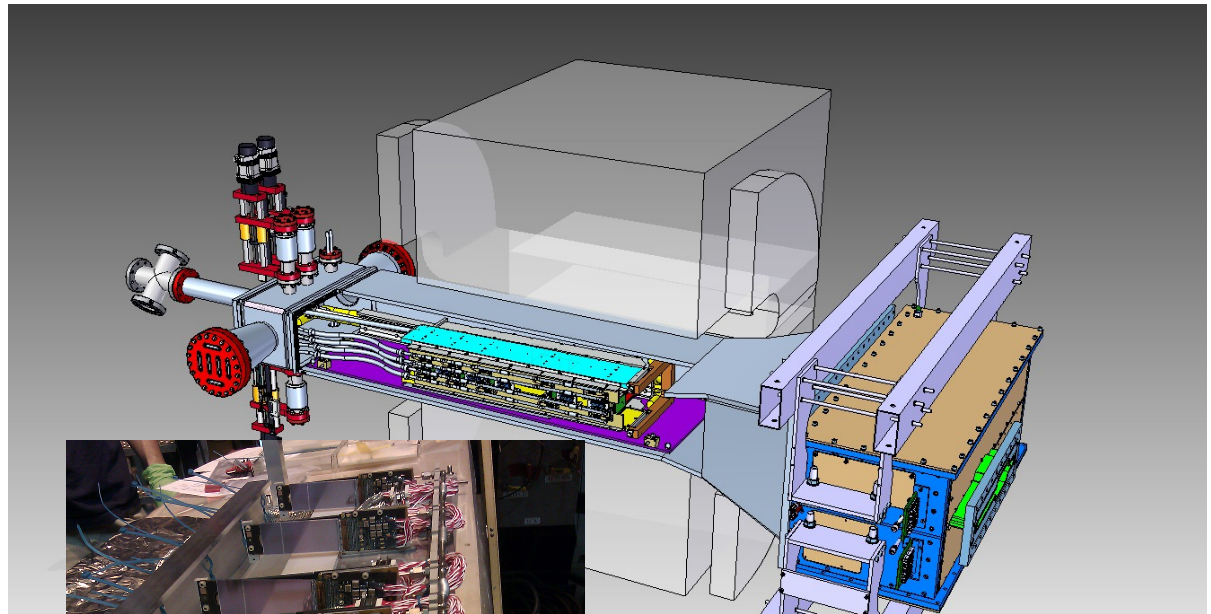
Beam = 6.6 GeV @ 450 nA
Target = 0.25%$X_0$

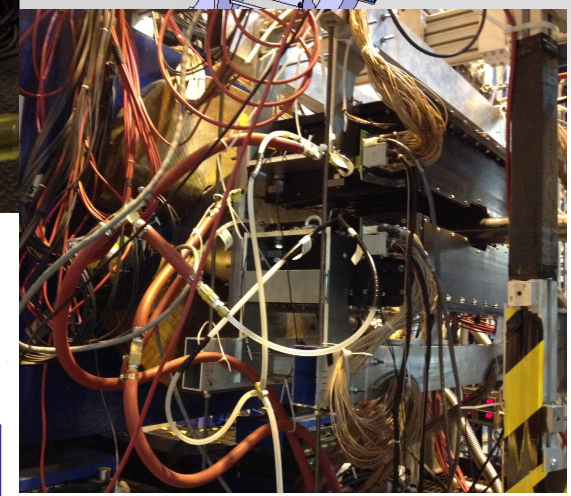
**Assumes 3 months of running at each energy**



# 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 19$^{th}$ 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**



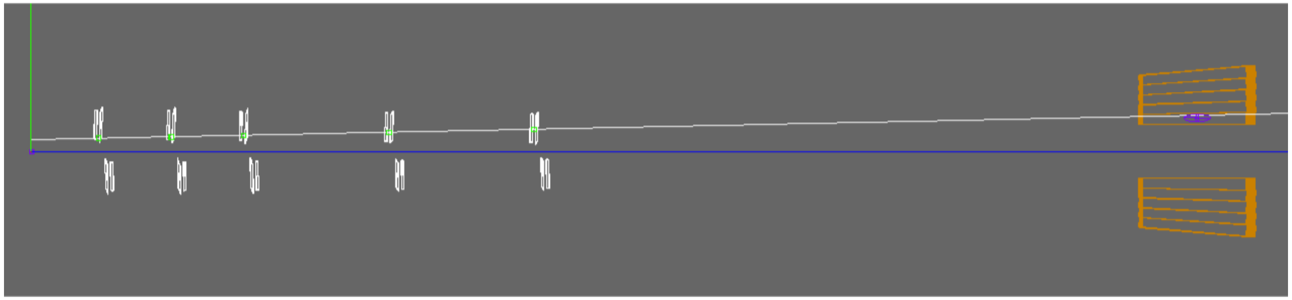


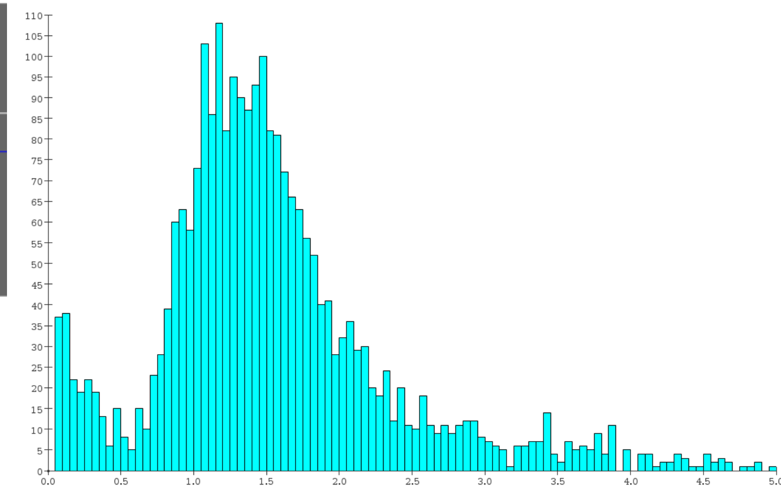
Short photon beam run
(last hours of CEBAF 6GeV era!)

| 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 |

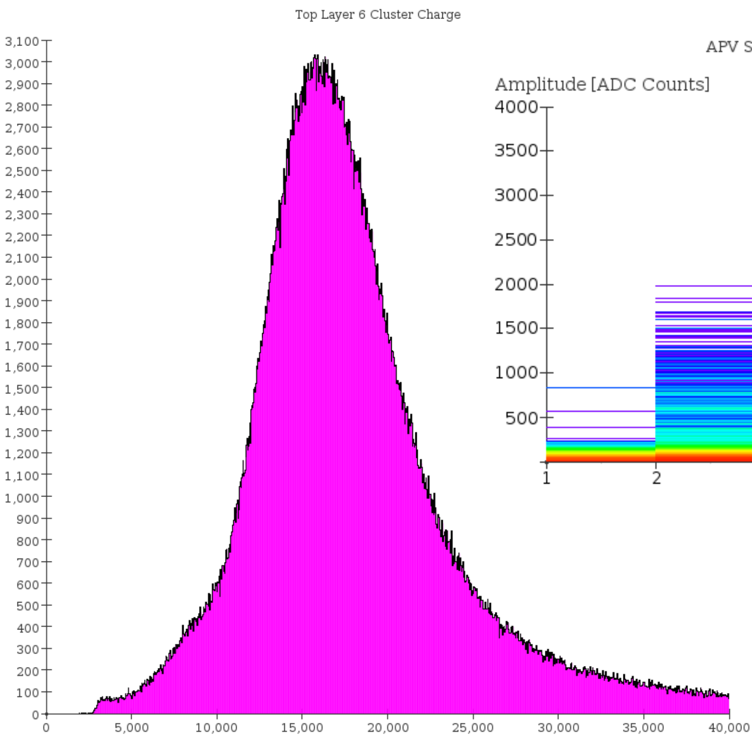
# Test Run Performance

Y-Z view of a track

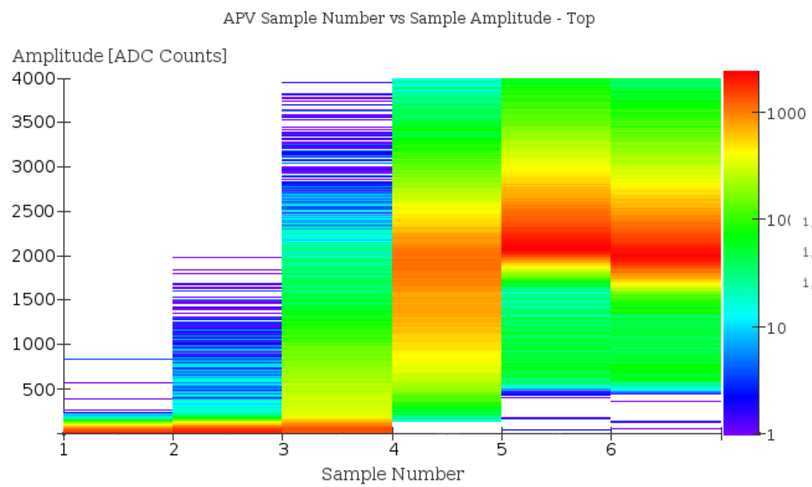


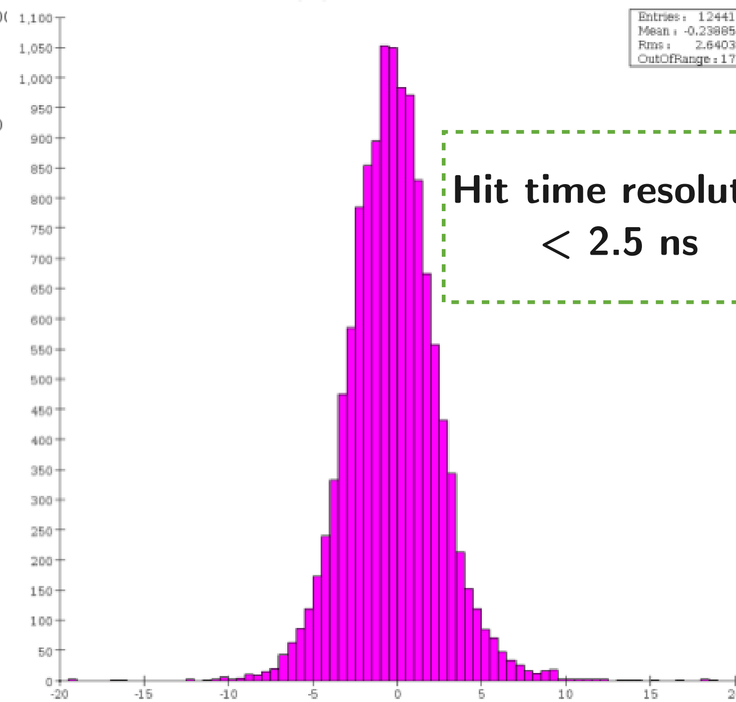


Momentum [GeV]




Cluster Charge [e-]




Hit time resolution
$< 2.5$ ns

Hit Time - <Hit Time> [ns]

**Analysis of Test Run data is still ongoing**
**$\rightarrow$ Comparison to full simulation is beginning**

# HPS Collaboration

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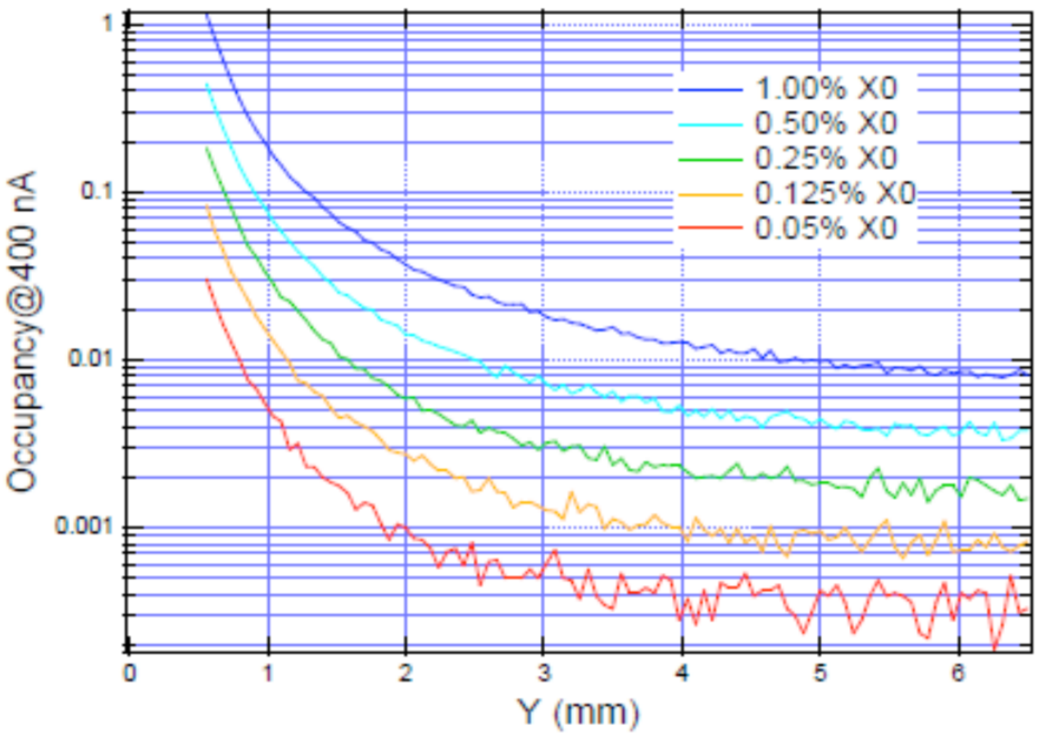
(Dated: May 7, 2012)

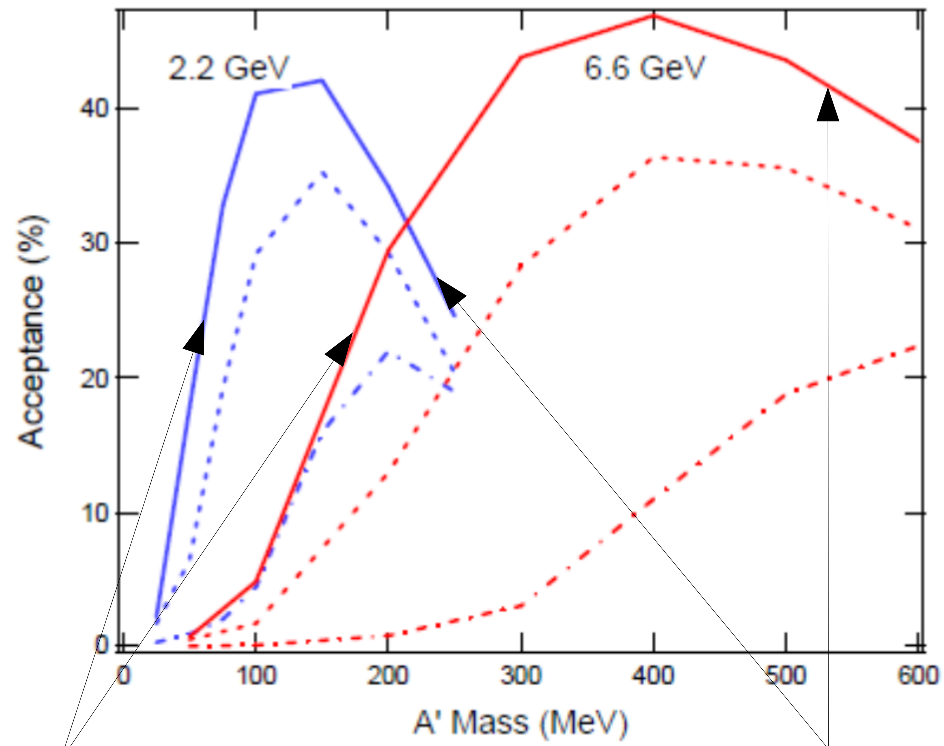
# Backup

# 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




Dead Zone Limited

Transverse size of SVT Limited

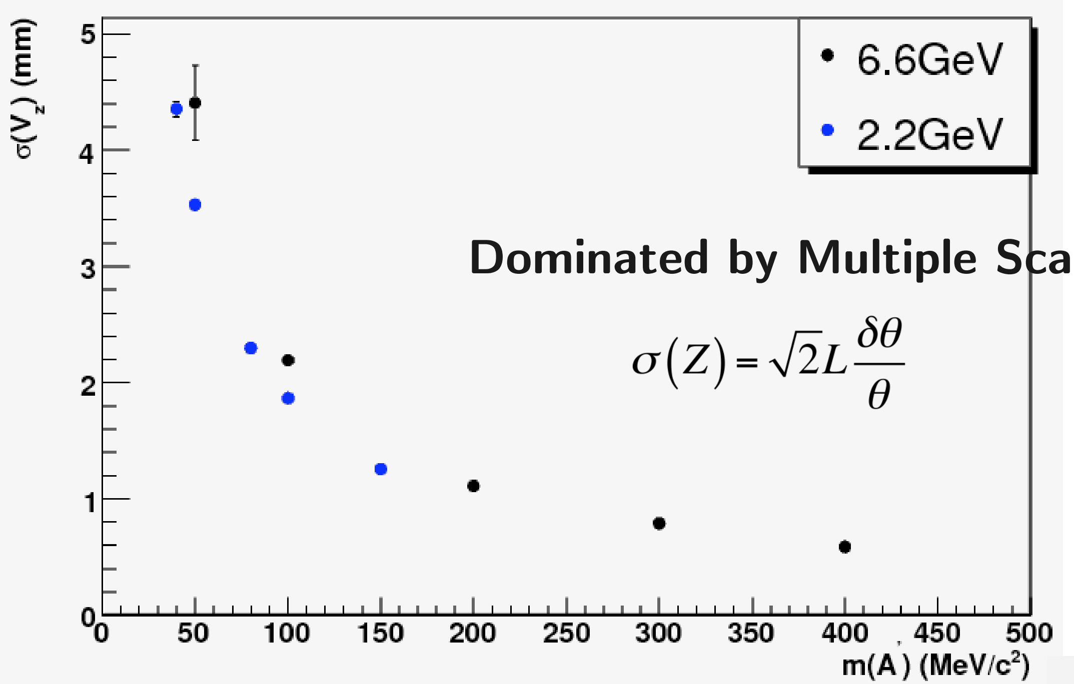
——— Decay at Target

- - - - - - Decay at 10 cm

·–·–·– Decay at 20 cm

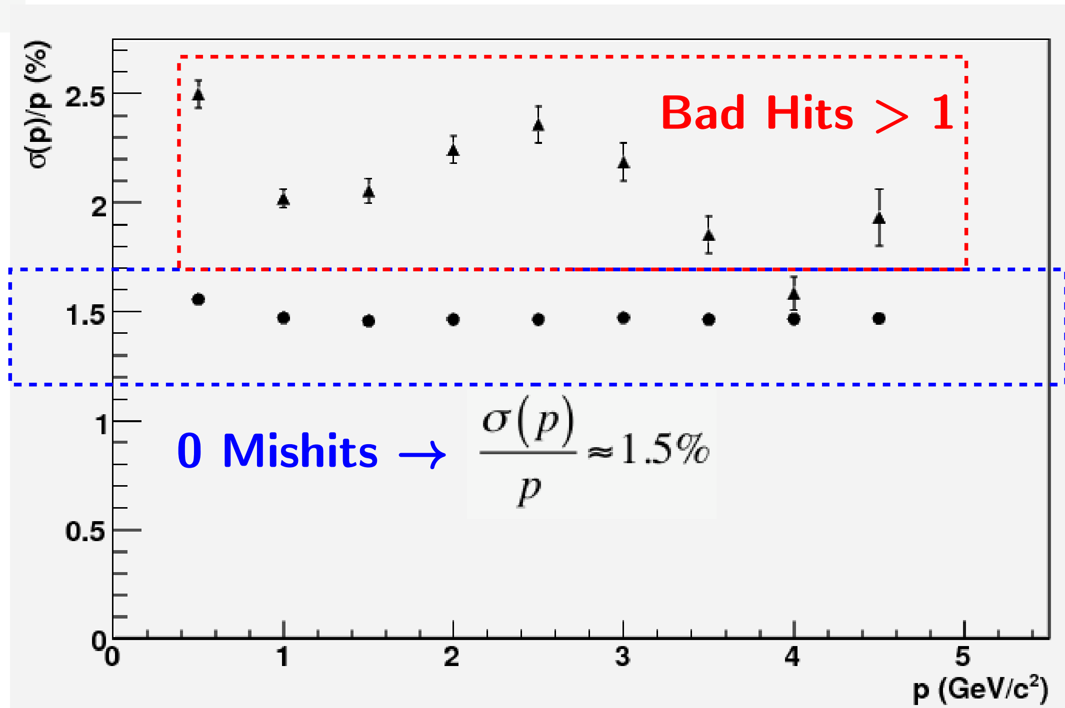
Acceptance is calculated by requiring the $e^+e^-$ to hit the first five layers

# Mass and Vertex Resolution



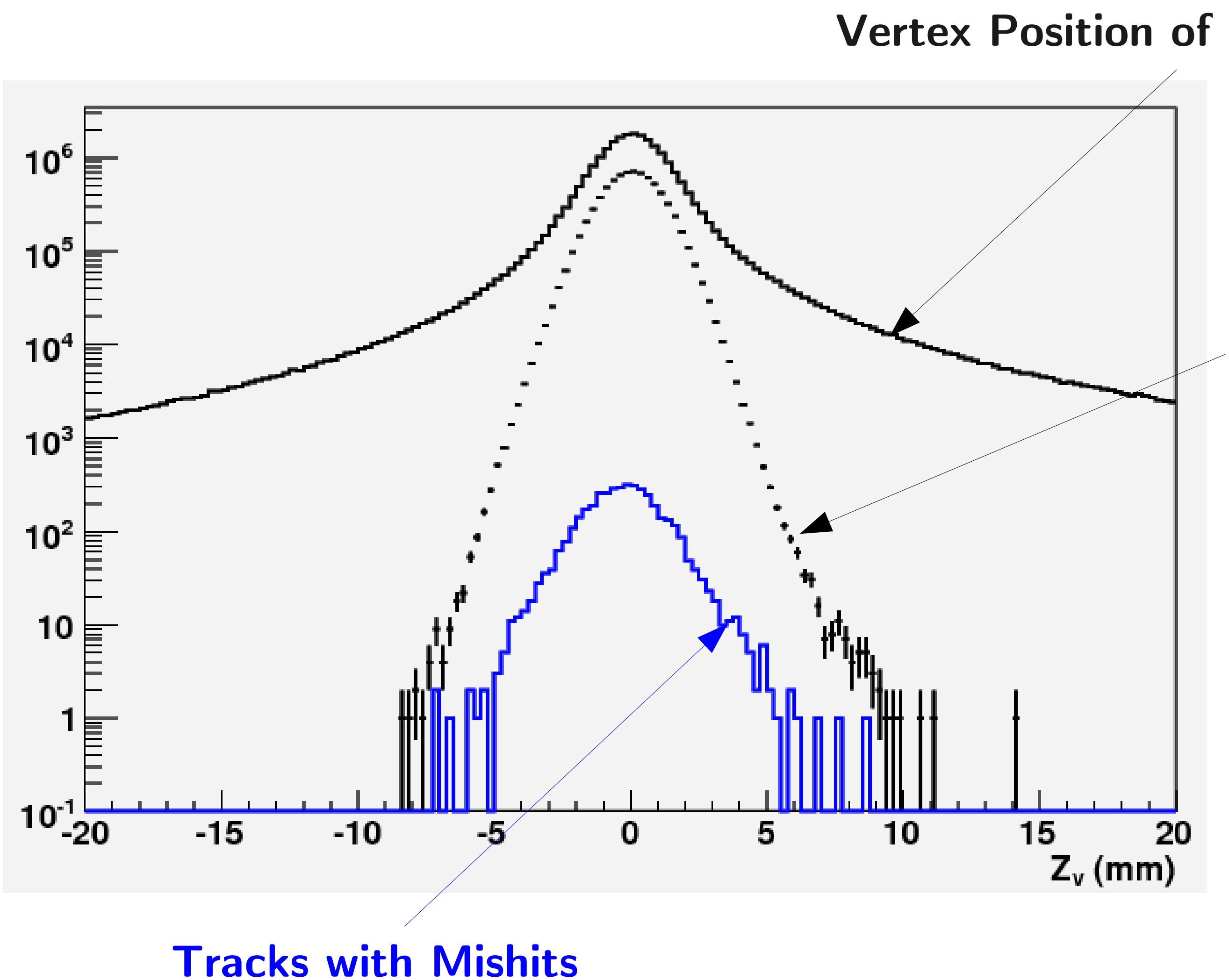

**Dominated by Multiple Scattering**

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




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

# Mass and Vertex Resolution




**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