Searching for a New State of Matter: True Muonium

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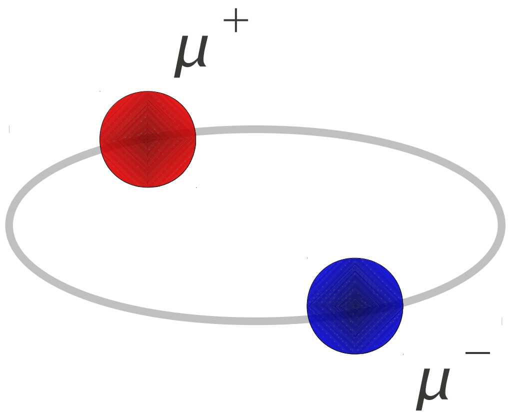
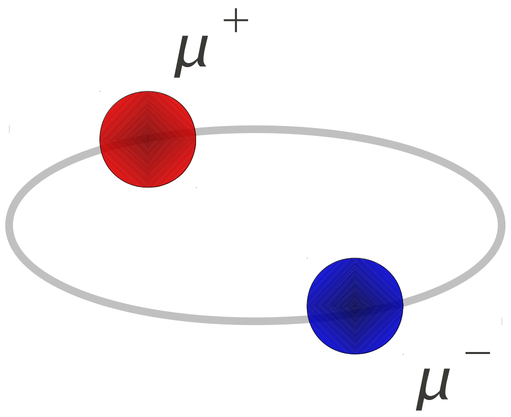
What is True Muonium?

- True muonium is a bound state of a $\mu^+\mu^-$ pair
  - "Muonium" is a bound μ^+e^- pair, tauonium is a bound $\tau^+\tau^-$ pair, and tau-muonium is a bound $\tau^\pm\mu^\mp$ pair.
- Positronium and muonium are produced and studied, but muonium, tauonium and tau-muonium have never been observed before.
- Together with $(\tau^+\tau^-)$ and $(\tau^\pm\mu^\mp)$, true muonium is the most compact pure QED system.
- True tauonium and mu-tauonium are very difficult to detect, since τ weak decay competes with the QED decay



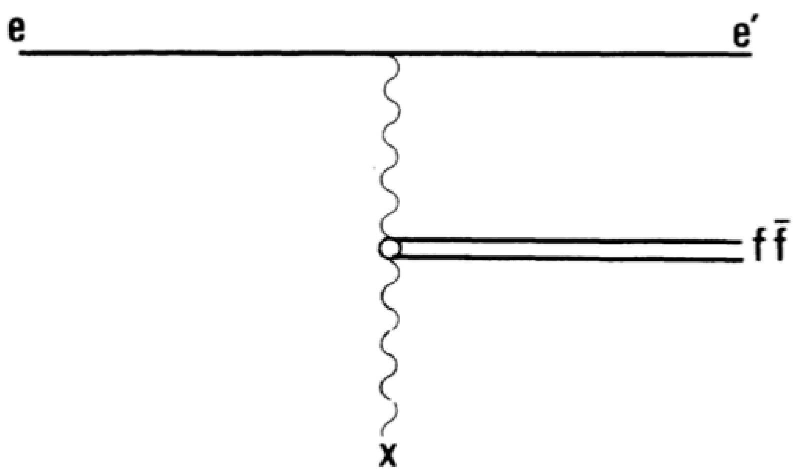
Why is True Muonium Interesting?

- Detection of true muonium would be a significant discovery and would constitute a further important test of QED.
- Unique as a laboratory for precision QED tests, and as tests of muon properties
- Further measurements of muon properties could be useful – cross-check possible explanations of the proton charge radius measurement using muonic hydrogen, and perhaps the g–2 anomaly.

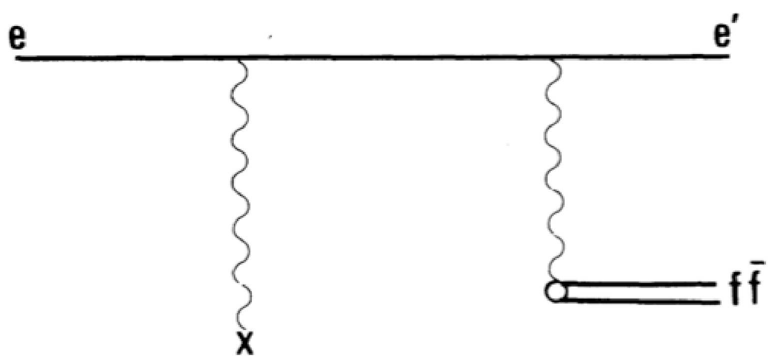


True Muonium Production

- True muonium can be produced with an electron beam on a target (like tungsten) or with a collider
- "Hydrogen-like" – has excited states characterized by quantum number n
- Binding energy: $E = -1407\,\mathrm{eV}/n^2$
- There are two spin states (n=1):

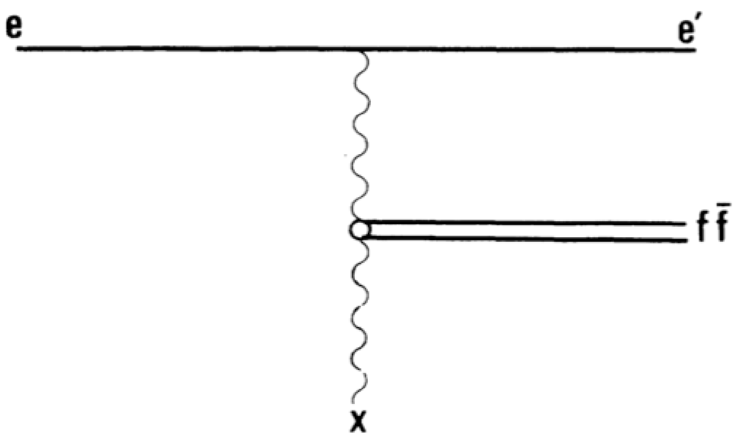


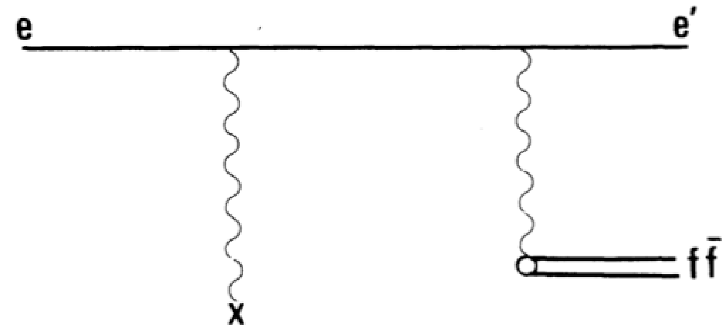
Paradimuonium, singlet state n^1S_0



Orthodimuonium, Triplet n^3S_1

True Muonium Production





Paradimuonium, singlet state n^1S_0

- Decays to 2 photons
- Lifetime = 0.602 n^3 ps
- $c\tau$ = 0.181 n^3 mm

Orthodimuonium, Triplet n^3S_1

- Decays to $e^+ e^-$
- Lifetime = 1.81 n^3 ps
- $c\tau$ = 0.543 n^3 mm

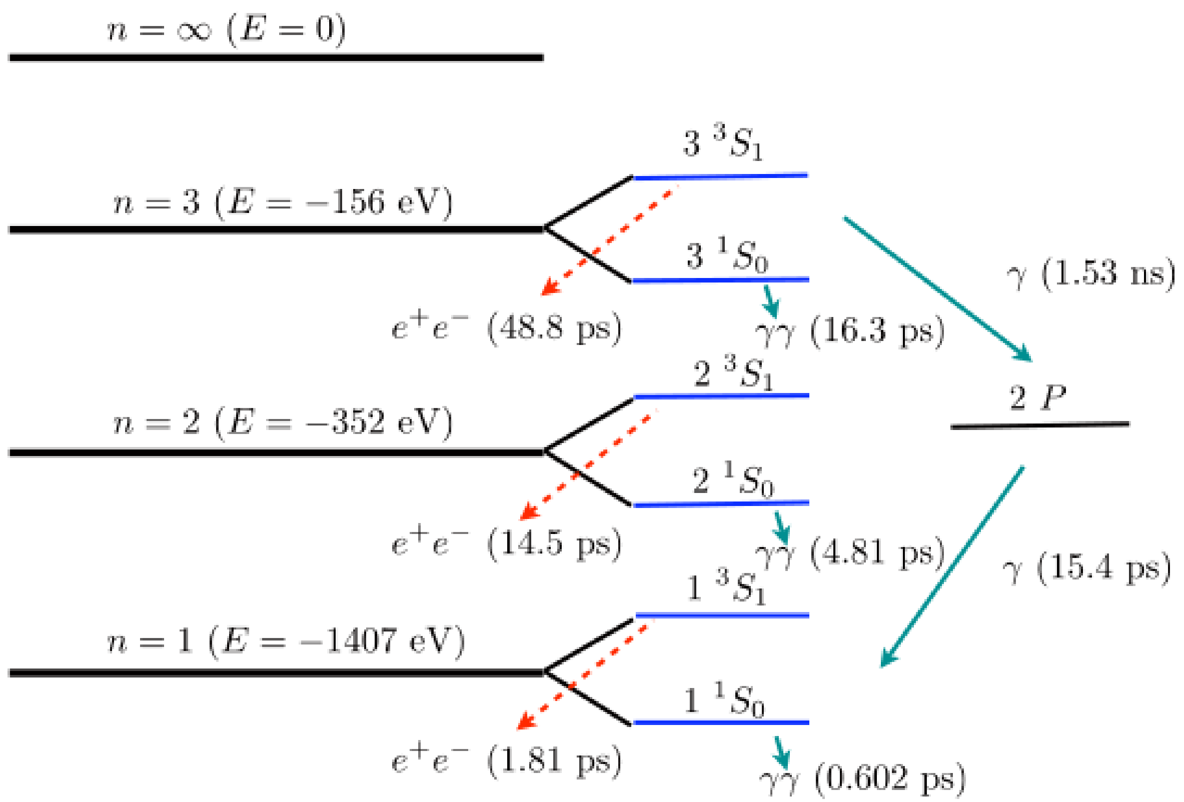
This is the one we are interested in!

Holvik and Olsen, Phys. Rev. D35 2124 (1987)

Arteaga-Romero, Carimalo, Serbo, Phys. Rev A62, 032501 (2000)

Brodsky and Lebed, Phys. Rev. Lett. 102, 213401 (2009)

True Muonium Production



(Level spacings not to scale)

- Relative to the $n = 1$ state, production cross-sections scale as $1/n^3$ – higher-n states are more difficult to produce
- Focus on $n = 1, 2$ states
- At $n = 2$, triplet and singlet S and P states are produced.

Brodsky and Lebed, Phys. Rev. Lett. 102, 213401 (2009)

True Muonium Production

- True muonium can be produced with an electron beam on a target
- Final production depends on both production and dissociation cross sections.
- Triplet production cross-section:

$$\sigma_{triplet} = 1.20\, Z^2 \frac{\alpha^7}{m_\mu^2} \left(1.79 \ln \left(\frac{E_{beam}}{m_\mu} \right) \right)$$

$$\sim 6.2\, Z^2\, 10^{-41}\, \mathrm{cm}^2 \qquad\qquad (E_{beam} = 6.6\, \mathrm{GeV})$$

- Cross-section scales like Z^2 (stay tuned for more on this topic...)

[Holvik and Olsen, Phys. Rev. D35 2124 (1987)]

True Muonium Production

But...

True muonium breaks up very easily inside the target!

- Triplet dissociation cross section is very large:

$$\sigma_{diss} \sim 1.3\, Z^2 10^{-23}\, cm^2$$

AND it scales like Z^2!

- So, only the states produced in last fraction of target will make it out of target and the total production rate is effectively independent of Z

[Holvik and Olsen, Phys. Rev. D35 2124 (1987)]

True Muonium Production

- Greater target thickness doesn't help production rate of true muonium
- Effective thickness for not breaking up in the target is

$$t_b = \frac{1}{N\sigma_{diss}} \qquad (N = \text{number of atoms/cm}^2)$$

- Note: for tungsten, t_b = 2.2 μm (0.064% r.l.), while for Carbon graphite, t_b = 190 μm (0.01% r.l.)

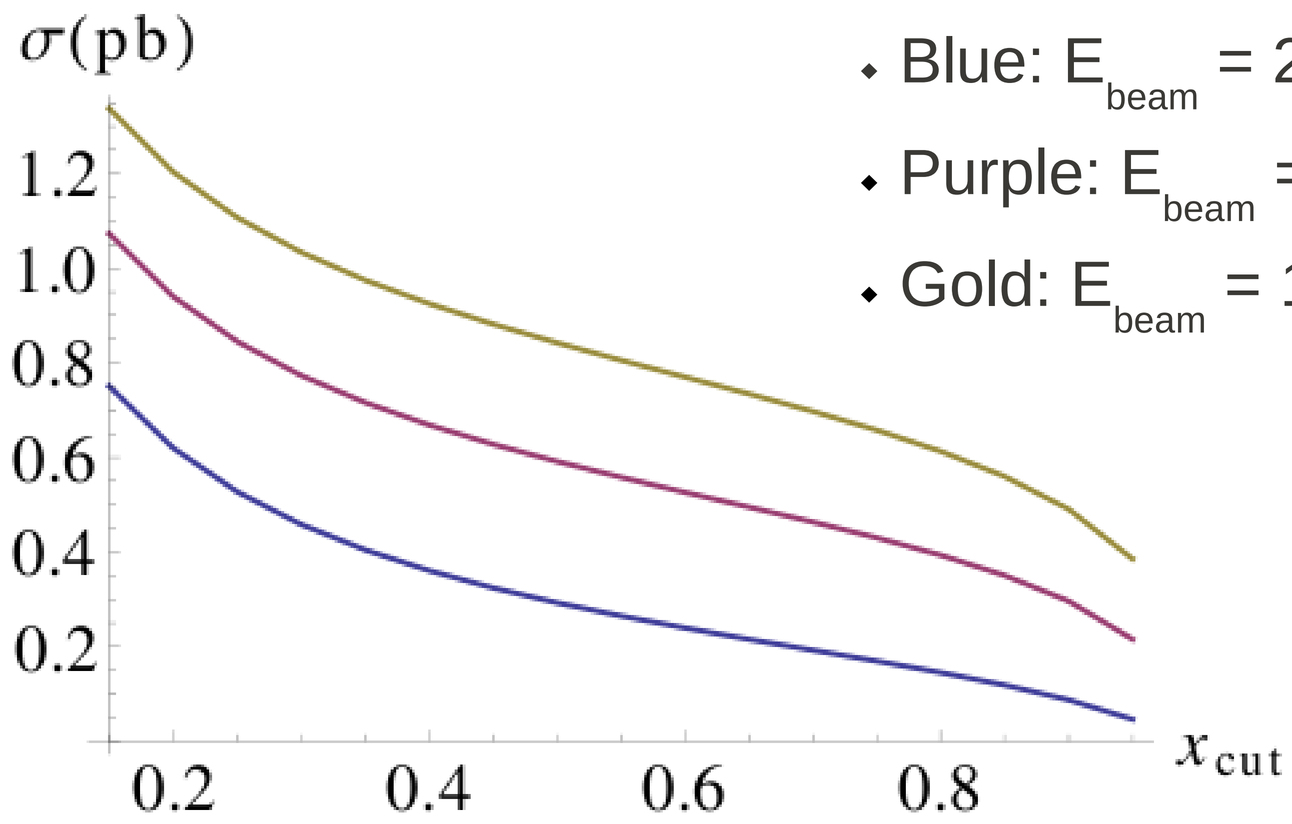
[Holvik and Olsen, Phys. Rev. D35 2124 (1987)]

A New Calculation

- New calculation by Philip Schuster and Andrzej Banburski
- Production of $n = 2$ states not dominated by primary production, but by secondary production where $n = 1$ states scatter into 2S and 2P states before leaving the target.
- Contribution is nearly an order larger than primary production of secondary states in targets thicker than t_b
- For lead or tungsten, the total yields of 2S and 2P triplet states are about 10% that of 1S
- Work presented in April APS meeting and is about to come out in a new paper!

True Muonium Production

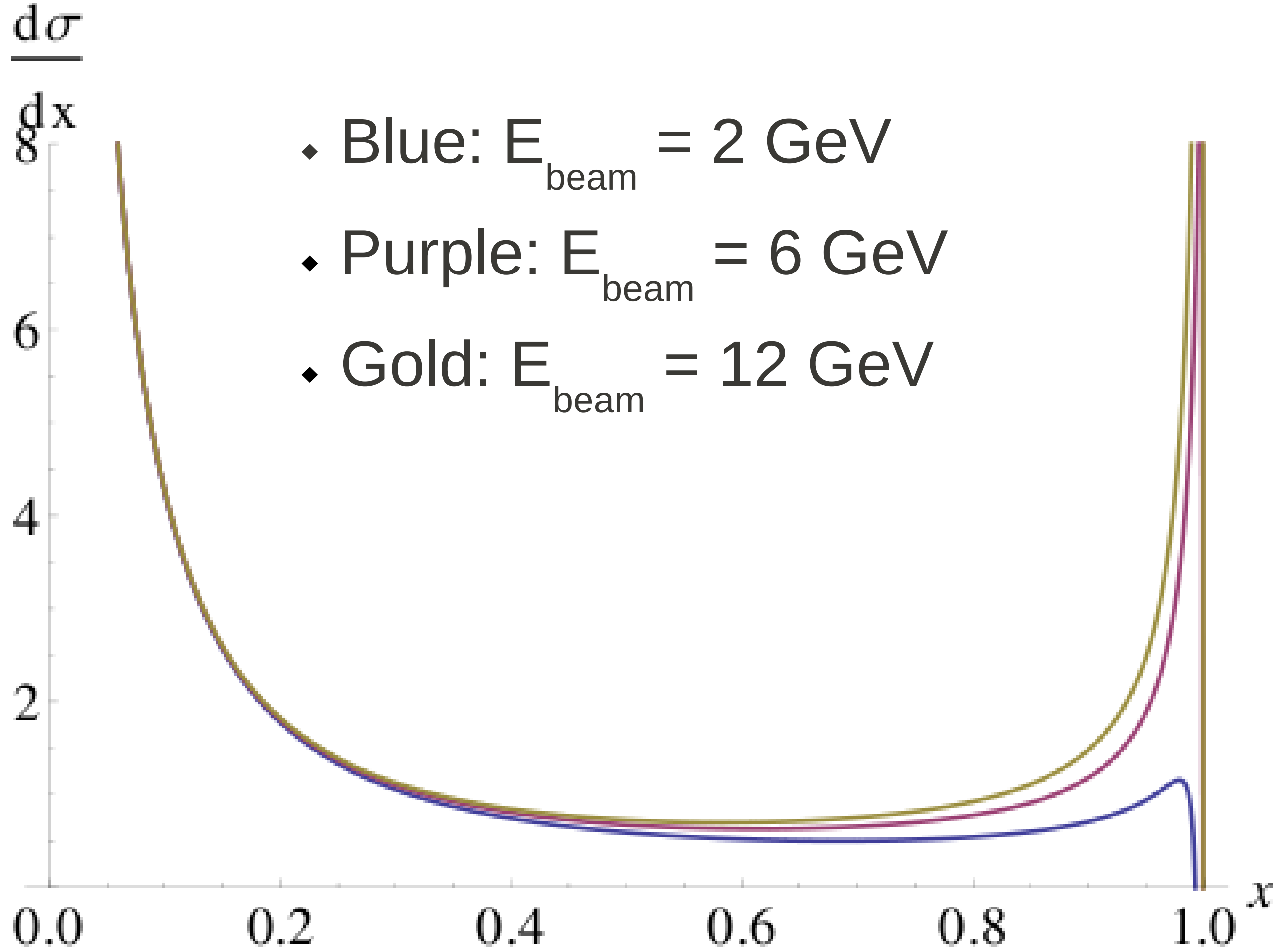
- Total primary production cross section for all *nS* states as a function of energy fraction cut (lead target)



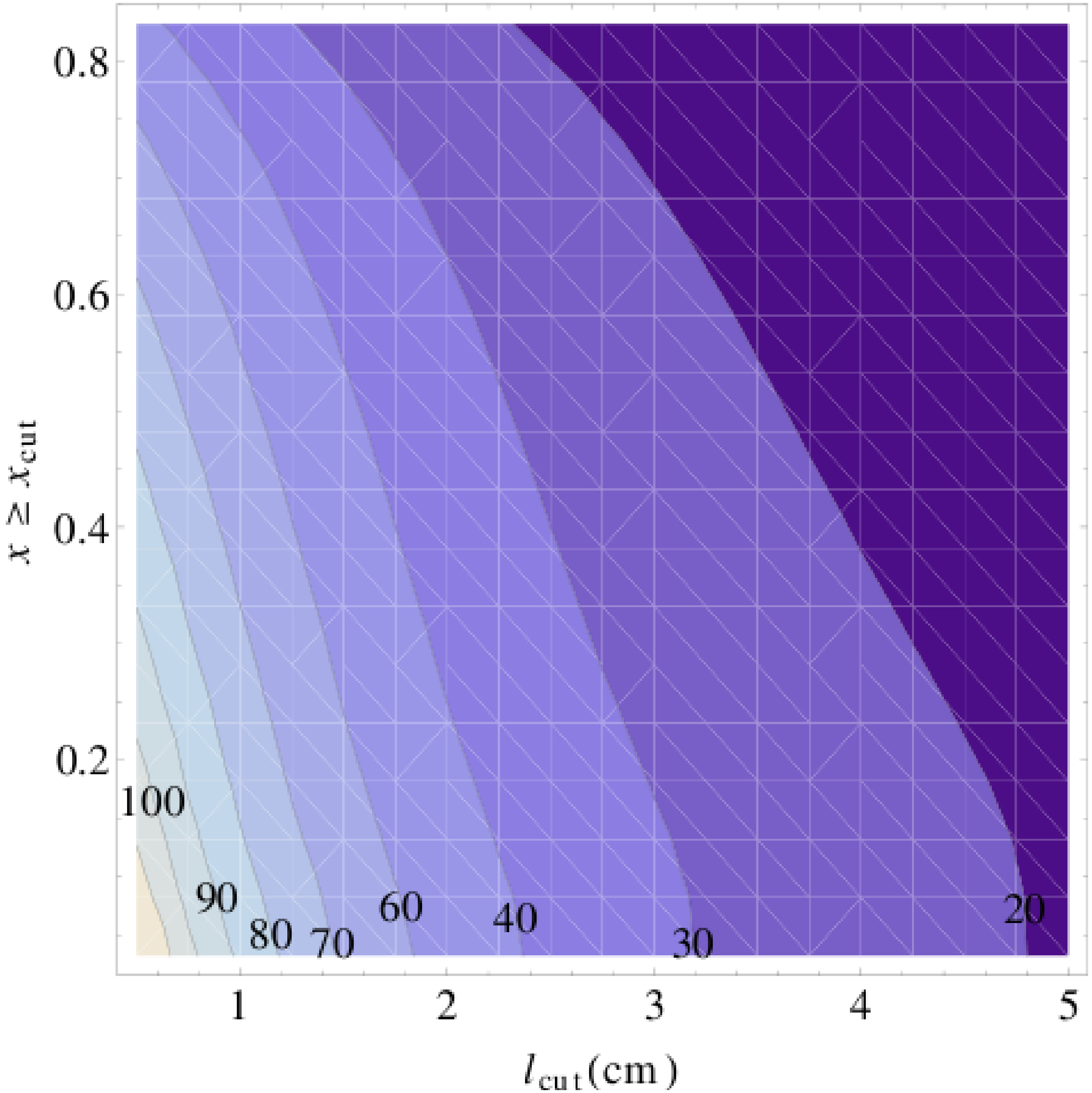
- Blue: E_{beam} = 2 GeV
- Purple: E_{beam} = 6 GeV
- Gold: E_{beam} = 12 GeV

True Muonium Production

- Differential cross section for for primary production for all *nS* states as a function of energy fraction (lead target)



True Muonium Yield in HPS



- Total yield for 1*S*, 2*S*, and 2*P* decays as energy fraction cut versus displaced vertex cut
  - In units of 10^{-18} N_e (N_e is the number of electrons on the target)
  - E_{beam} = 6.6 GeV
  - Lead target

TM Search

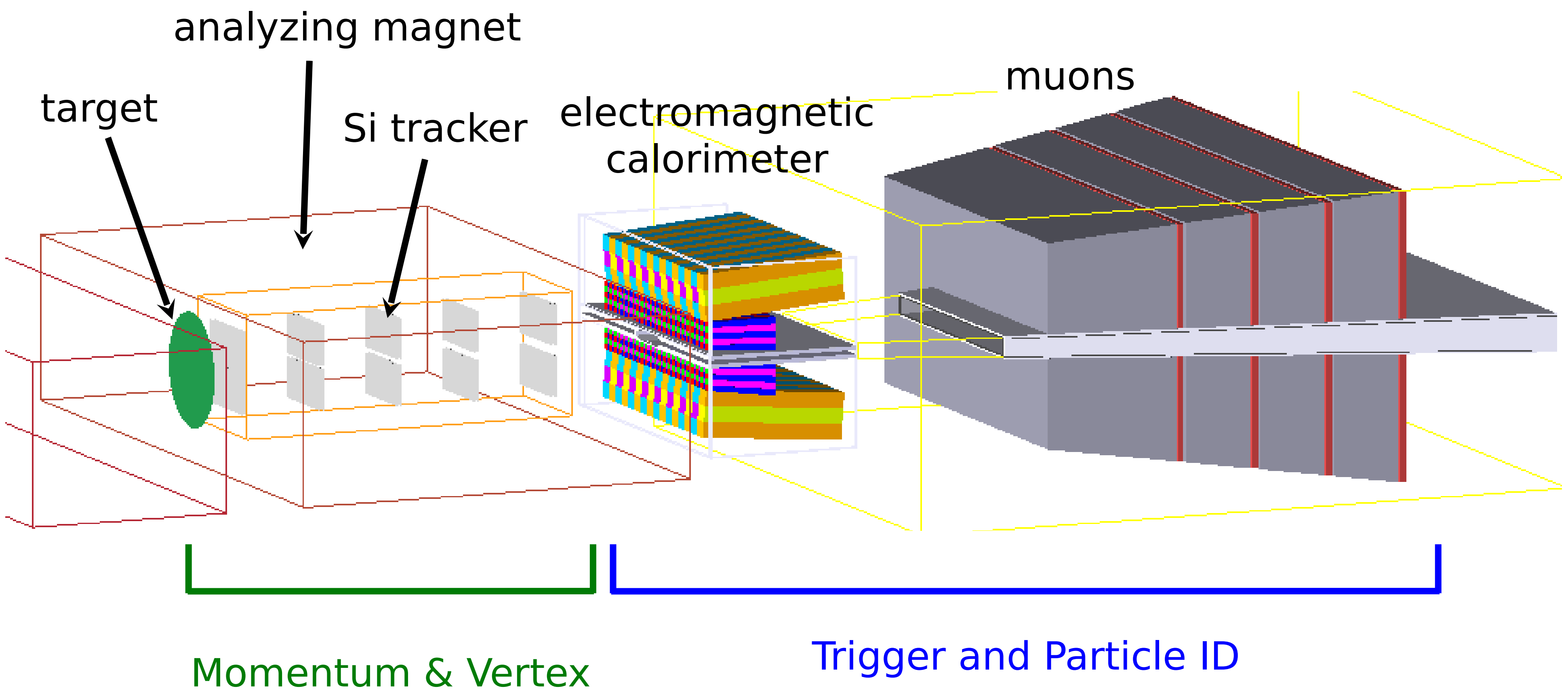
- A true muonium search is like the one HPS will do for heavy photons with separated vertices, requiring a vertex cut at about 1.5 cm to reject almost all of the QED background events
- Precise search window: search for a resonance at 2 m_{μ}
- Additional cut on the total energy of the e^+e^- pair $E_{e-} + E_{e+} > 0.8\, E_{beam}$ will also be required for triggering.
- The vertices near the cut of 1.5 cm will be dominated by the 1*S* state, while a tail of vertices extending out beyond a few cm is dominated by 2*S* and 2*P*.

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!

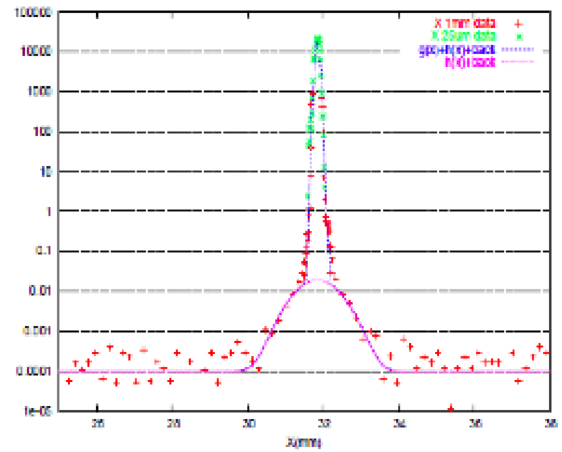
The Heavy Photon Search Experiment

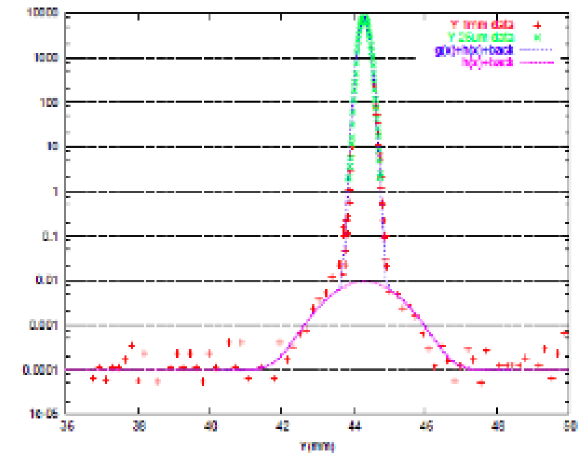


- High rate, high acceptance, high mass & vertex resolution detector to run in JLab Hall B
- JLab PAC37 January 2011 - conditional approval on test run.
- Received DOE funding to build test run apparatus; test run ran in May 2012

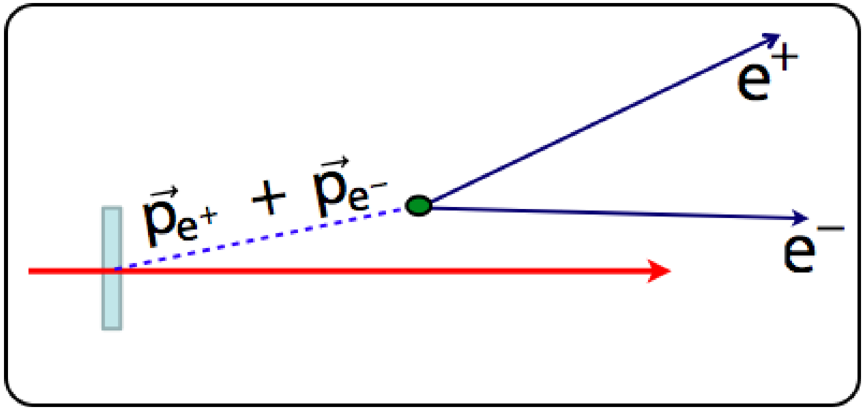
Beam Quality in Hall B

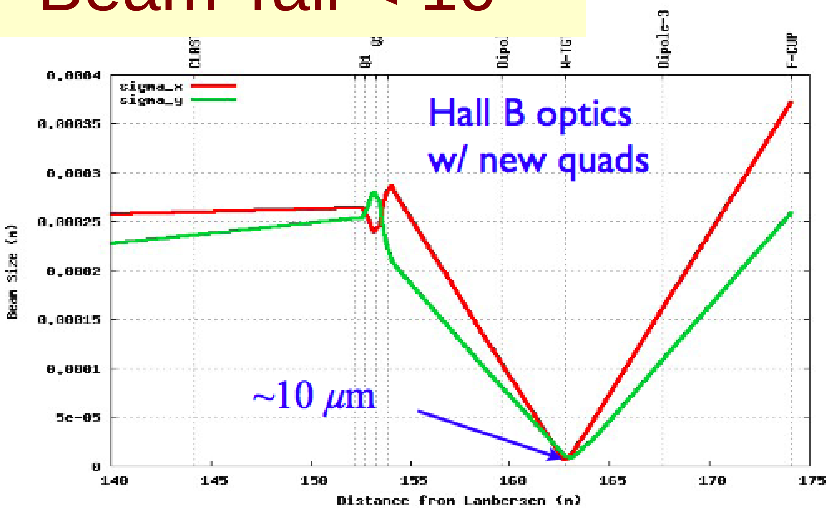
- Very stable beam
- low halo = low background
- 10 μm spot possible with additional quads; constrains A' trajectory, reducing backgrounds
- Tight beam spot helps tracking & vertex
- I_{beam} = 1 to 500 nA



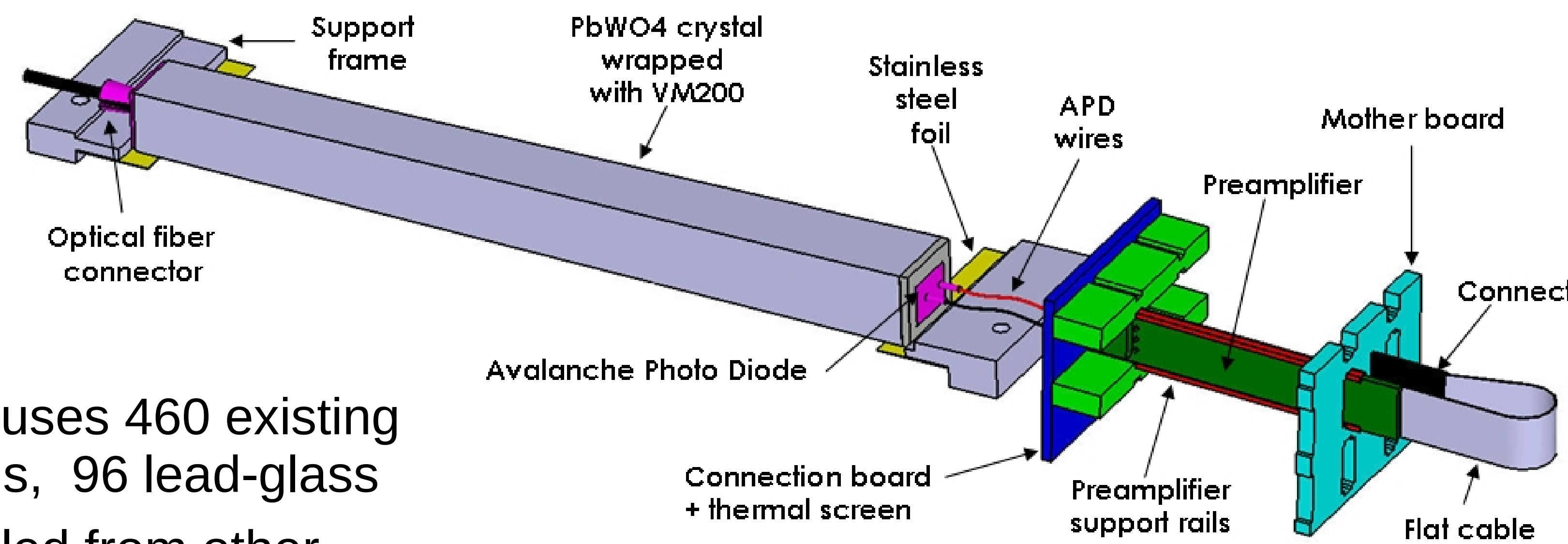


Beam Tail < 10^{-5}

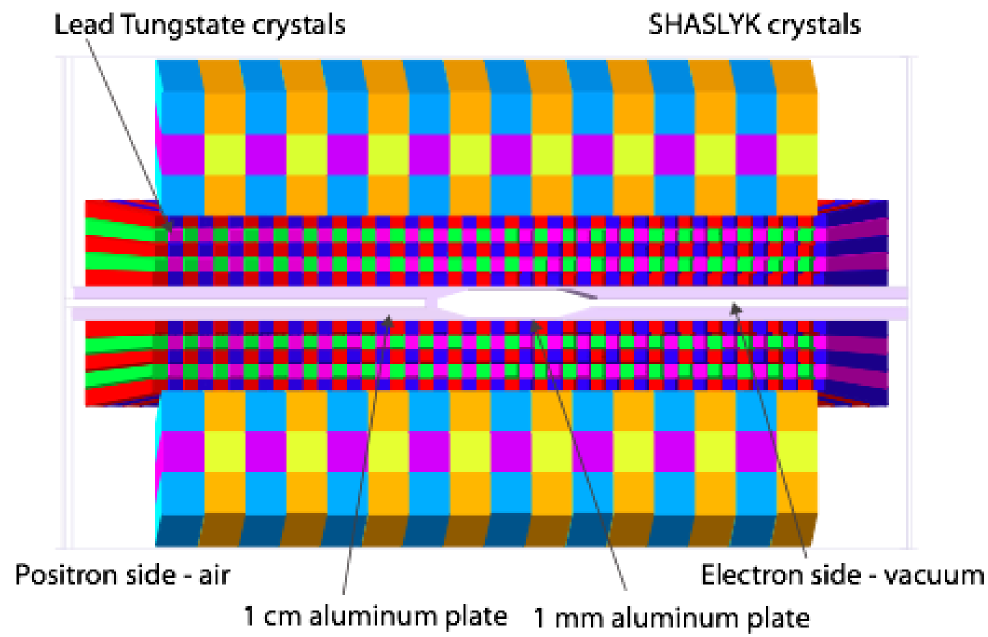




Calorimeter and Trigger



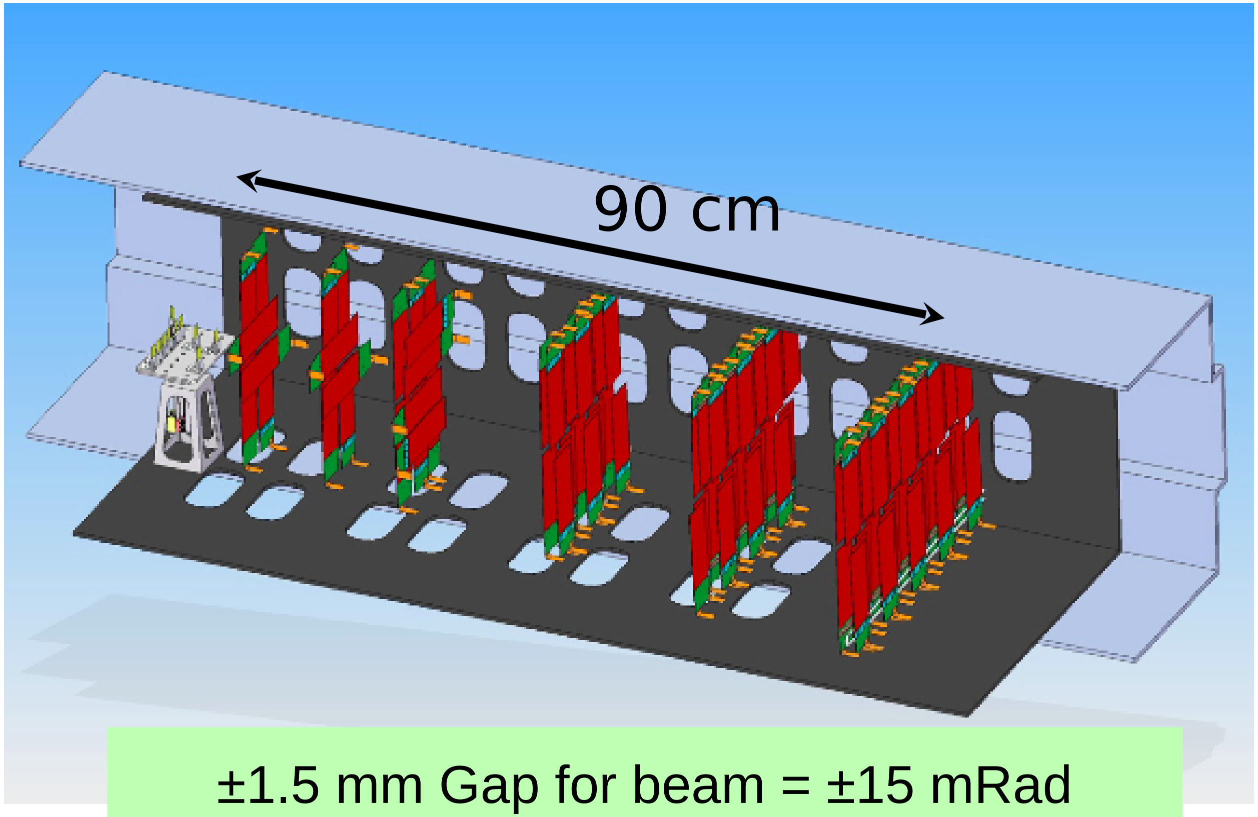
- Hybrid design uses 460 existing $PbWO_4$ crystals, 96 lead-glass crystals (recycled from other experiments!)
- Flash-ADC readout at continuous 250 MHz
- FPGA based trigger logic: Reduces two cluster background trigger rate from ~4 MHz to ~20 kHz, by using unique A' signature.
- Keep high A' acceptance.



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.



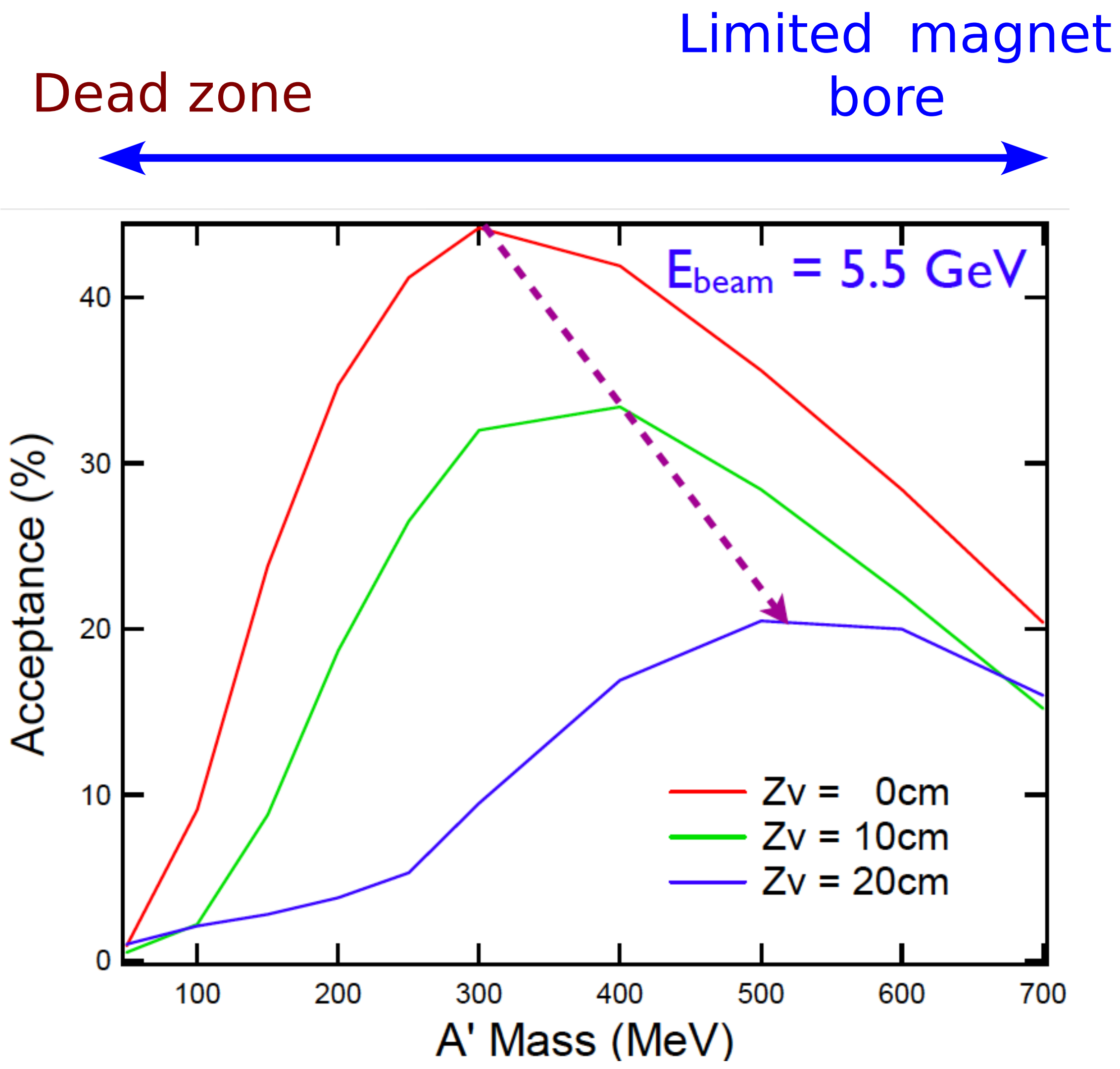
±1.5 mm Gap for beam = ±15 mRad
Small "dead zone" in acceptance

Build Using:

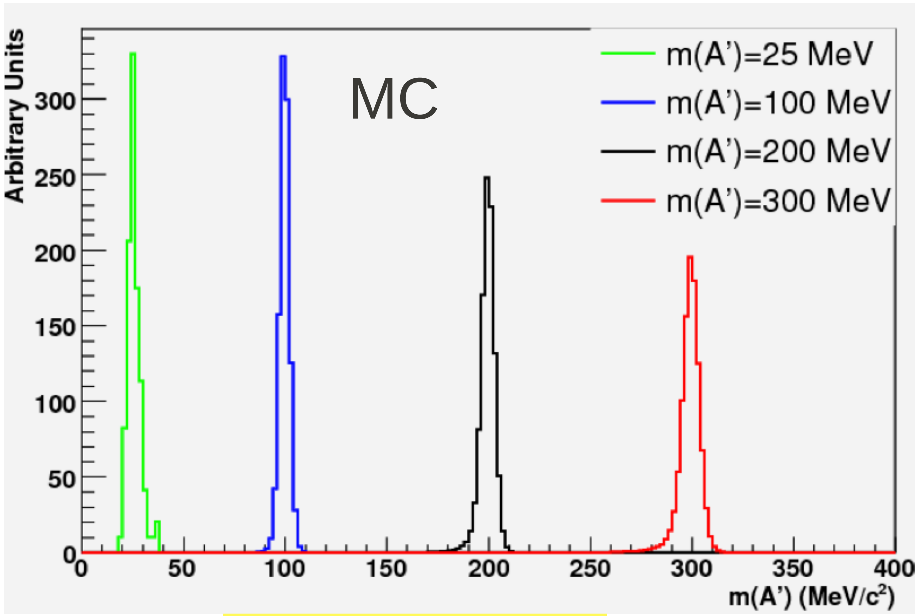
- Si Microstrip detectors (106, thin, leftover from Tevatron Run IIb)
- AVP25 readout chip (67840 channels, from CMS, S/N~34, timing ~ 2ns)
- Cooling outside tracking volume. (~0.5% X_0 per layer)

Tracker Acceptance

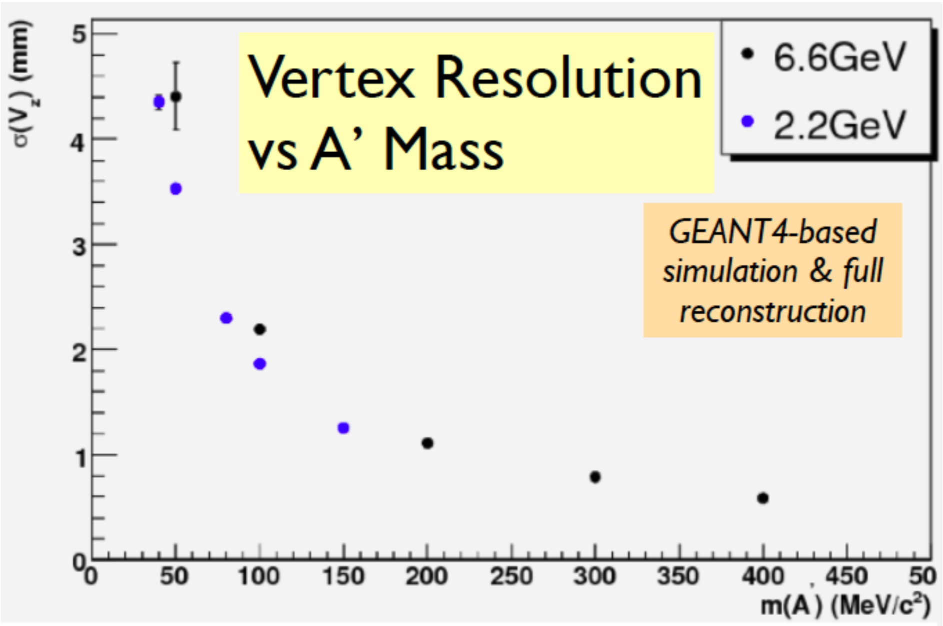
- At small A' mass, dead zone limits acceptance
- At large A' mass, limited by size of layers 5,6
- Increased z-vertex displacement increases dead zone



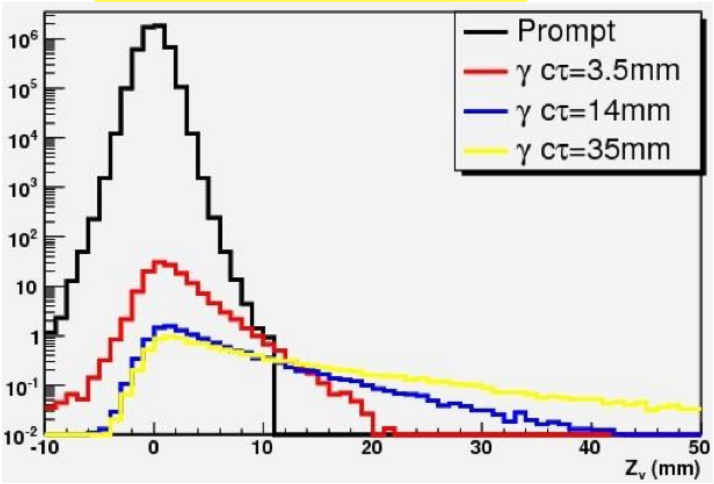
Tracker Resolution



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

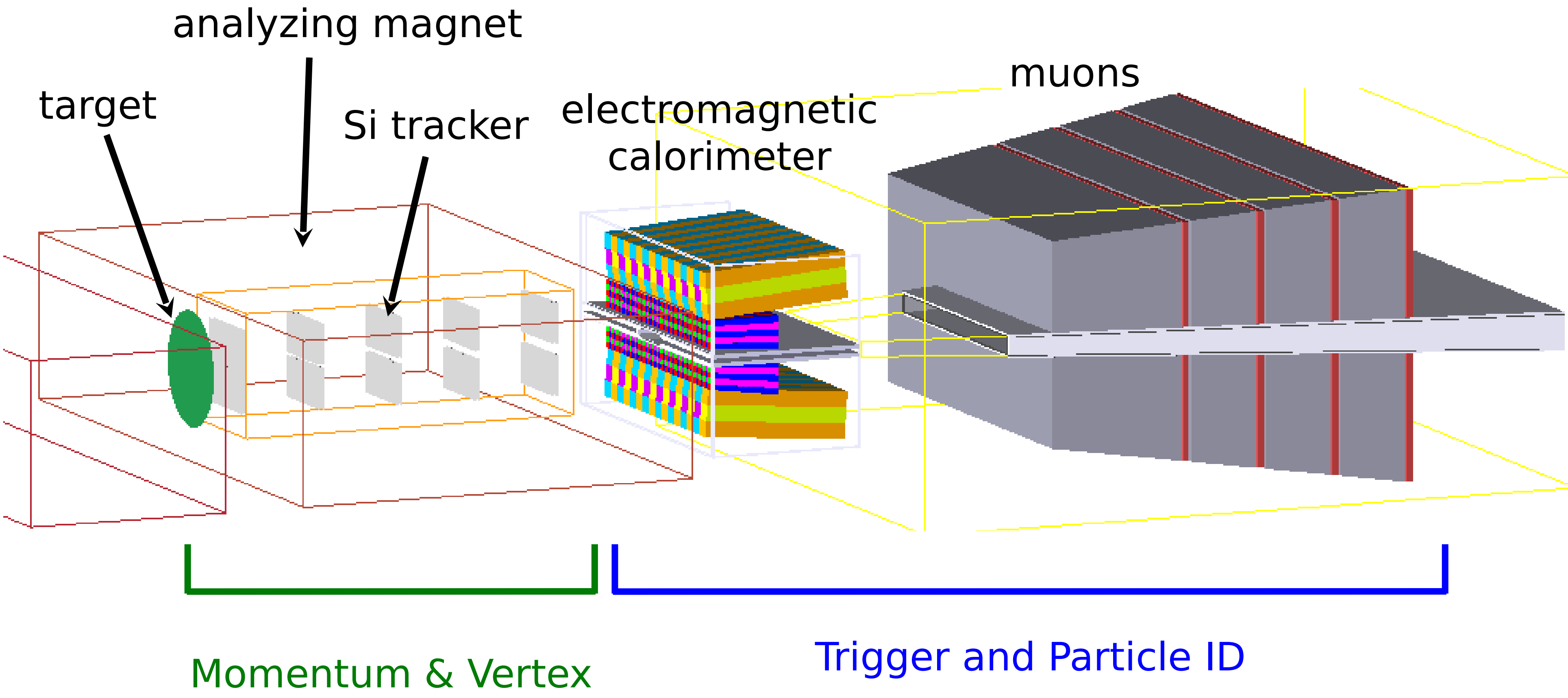


$\Delta z \sim 1 - 4$ mm



- 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

What Will I Do With This Grant?

- With a separated vertex search, we expect to see about 60–100 true muonium events (acceptance parameterization roughly estimated).
- What if we could produce enough to measure various properties?
  - Lifetimes are sensitive to physics that couples to leptonic currents. With enough statistics, could do a measurement of the lifetimes of the 1S, 2S, and 2P states
  - With a dedicated target, dissociation cross-sections as a function of energy could be studied
  - With sufficient quantities, a Lamb shift measurement could be possible, which may constrain explanations of the proton charge anomaly.
  - Work is ongoing to explore these possibilities.

What Will I Do With This Grant?

The production rate can be increased, but would require a different target.

- The production rate scales linearly with both the current and the number of target foils (spaced by 2 or more cm, so true muonium decays between foils).

Goals:

- A simulation has been started for this! Need to complete it and use it to design a dedicated target and to optimize for true muonium production; develop this into a separate proposal.
- Build this target.
- Great project to get students involved in!

Summary

HPS will be a great place to detect true muonium!

- If we observe it, it will be a fun discovery.
- Use this grant to design a build a target optimized for true muonium so we can do measurements of its properties

"Who doesn't want to see a new form of matter that no one's ever seen before?"

— Dr. Stanley Brodsky

Many thanks to Philip Schuster, Rouven Essig, and Andrzej Banburski, and the HPS Collaboration for their support of this endeavor.

Backup Slides

Excited States

- Seeing the n=2 state (which has a $c\tau$ = 0.44 cm) will be more difficult, as we would produce only 10% as many of these states as of the 1S states. However, the large boosted decay length would increase the efficiency for detecting separated vertices, and many decays would be virtually background free, so that even a small number may be sufficient for detection.

Old Total Production Rate

Triplet production rate:

$$Rate = 0.021\left(1.79\ln\left(\frac{E_{beam}}{m_{\mu}}\right) - 6.12\right) I\,(mA)$$

- For running conditions of E_{beam} = 6.6 GeV, 450 nA beam current, 3 months (~7.8×10^{6} s) and a single foil:

95 n=1 events, with a decay length of about 1.7 cm.

- The search requires a vertex cut at about 1.5 cm to reject almost all QED background events, then searching for a resonance at 2 m_{μ}.

- Accounting for efficiencies, we would expect to see about 10 true muonium events (acceptance parameterization is uncertain at the 50% level).