# HPS Physics Reach & Run Plan

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HPS DOE Review
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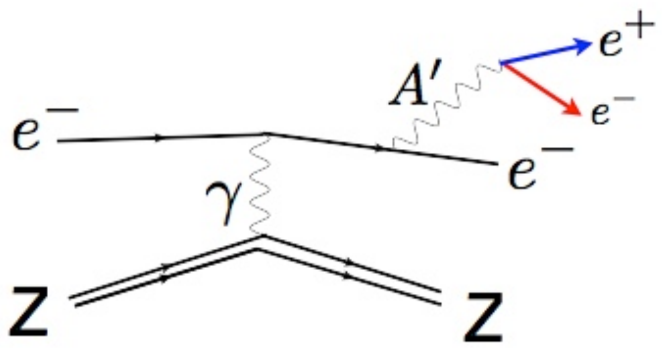
# A few opening remarks

Goal of this talk: Outline how we obtain the HPS reach in m(A') vs α' parameter space

- All resolutions etc. are from full detector simulation using GEANT4 with beam-background overlay (assume 8ns timing resolution).
- (Try to) Answer questions:
  - Why do we believe our inputs to reach?
    - Compare to test run
  - How will we validate our simulated performance with electron-beam data?

# Heavy Photon Production & Decays

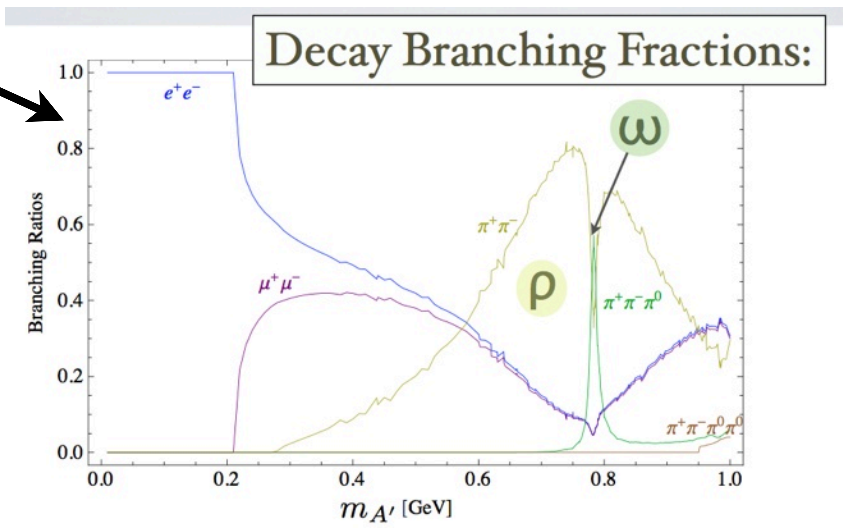



***Production*** is analogous to bremsstrahlung:

$$\frac{d\sigma}{dx} \approx \boxed{\frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}} \left(1 + \frac{x^2}{3(1-x)}\right) \mathcal{L}og$$

- prefers x~1 (i.e. $E_{A'} = E_{beam}$)
- small angle emission dominates

A' ***decays*** back to charged SM fermions with BFs taken from $R(e^+e^- \rightarrow \text{hadrons}/e^+e^- \rightarrow \mu^+\mu^-)$




The decay length depends on $m_{A'}$ and ε:

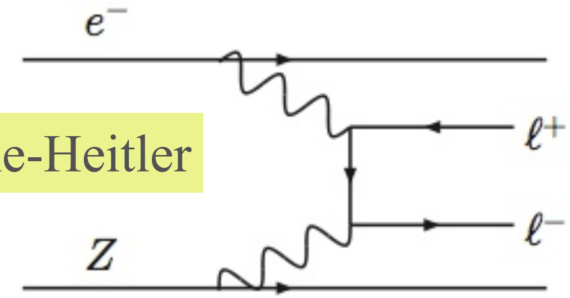
$$\ell_0 \equiv \gamma c\tau \simeq \frac{3E_1}{N_{\text{eff}} m_{A'}^2 \alpha\epsilon^2}$$

$$\simeq \frac{0.8\text{cm}}{N_{\text{eff}}} \left(\frac{E_0}{10\text{GeV}}\right)\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{100\text{ MeV}}{m_{A'}}\right)^2$$

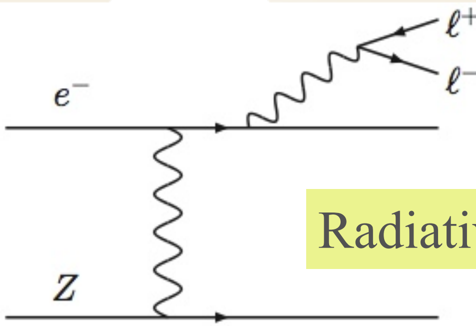
**HPS is sensitive to A's with decays ~5-100mm**

# Backgrounds to Heavy Photon Decays

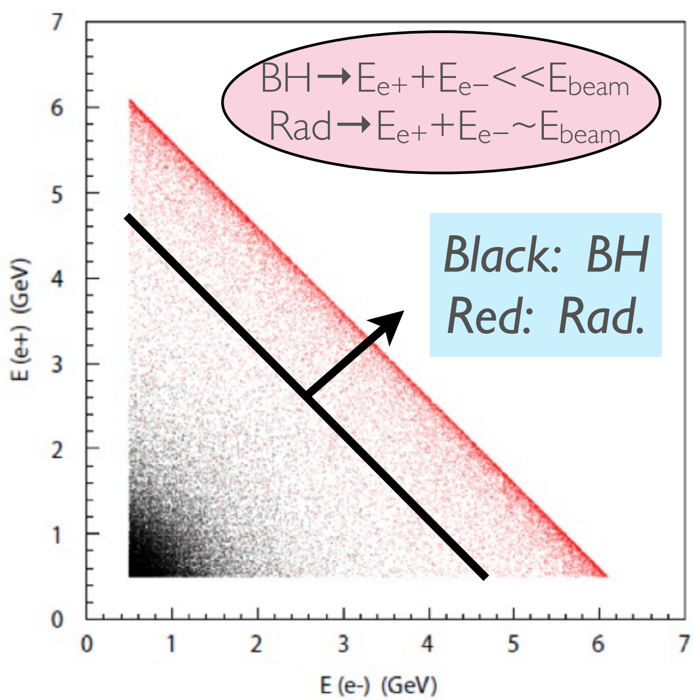
Bethe-Heitler




Two physics backgrounds, collectively known as "tridents"




Radiative



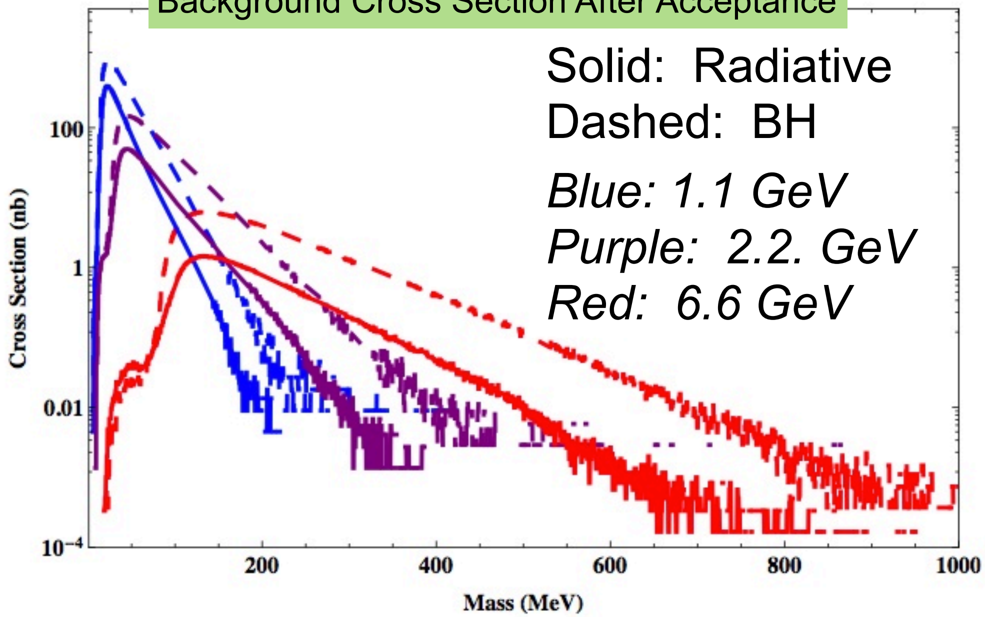

- BH and Radiative cross-sections calculated by MadGraph at NNLO
- BH cross section is huge, but dominated by
  $E(e^+)+E(e^-)<<E_{beam}$
  - this background is reducible, but still large (~2x radiative) after $E(e^+)+E(e^-)>0.8E_{beam}$
- Radiative tridents have the same kinematics as A' decays...only invariant mass & decay vertex can resolve these two
- All trident events decay promptly!

# Physics Reach: Radiative & BH Backgrounds

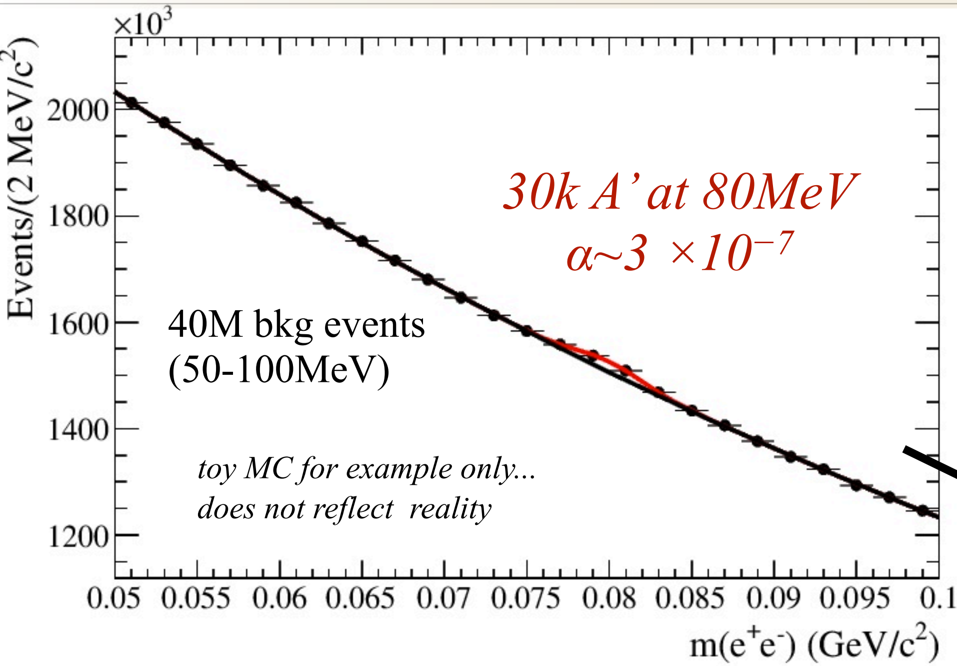
- Background cross sections calculated with MadGraph; acceptance accounted for by running generated events through detector geometry
- Signal rate obtained from radiative rate via earlier equation:

$$\frac{d\sigma(e^-Z \to e^-Z(A' \to \ell^+\ell^-))}{d\sigma(e^-Z \to e^-Z(\gamma^* \to \ell^+\ell^-))} = \left(\frac{3\pi\epsilon^2}{2N_{\text{eff}}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)$$

Background Cross Section After Acceptance



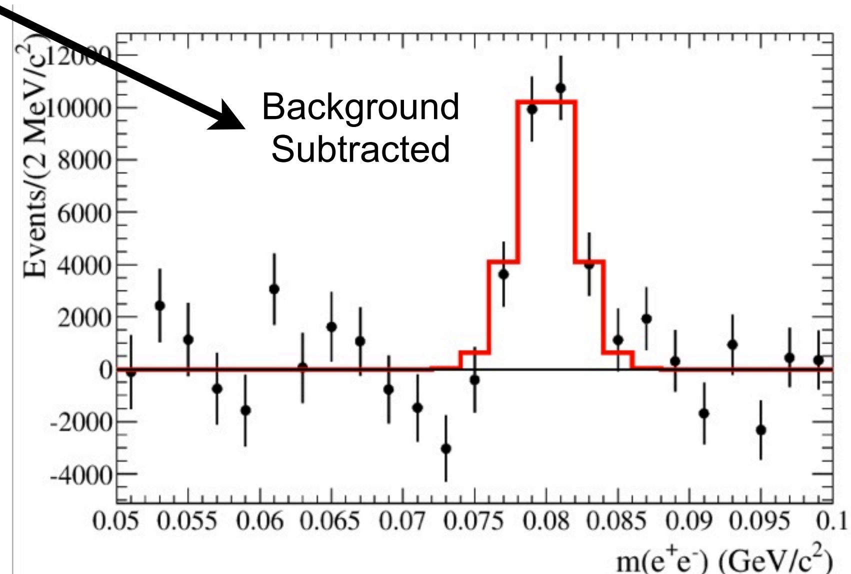
# Heavy Photon Signatures




Two types of searches, covering different coupling regions.

Pure bump hunt in $m(e^+e^-)$

$\longrightarrow$ large coupling region ($\alpha > 10^{-7}$)



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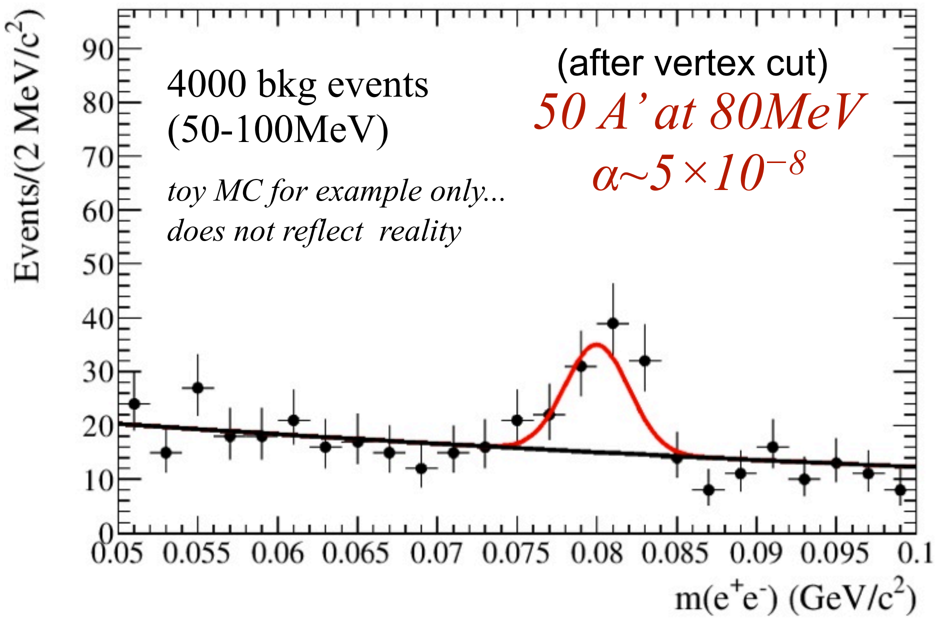
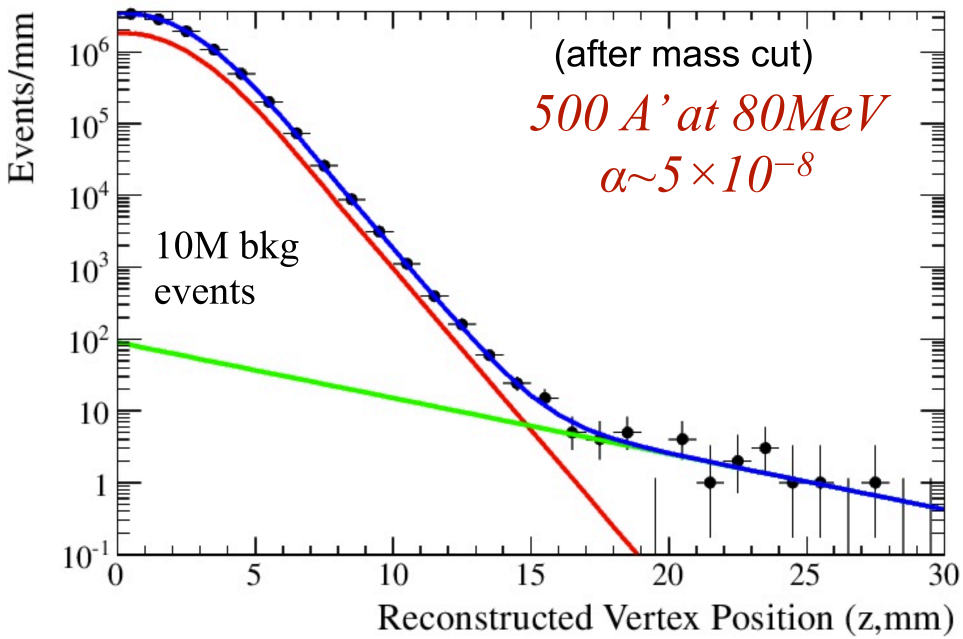
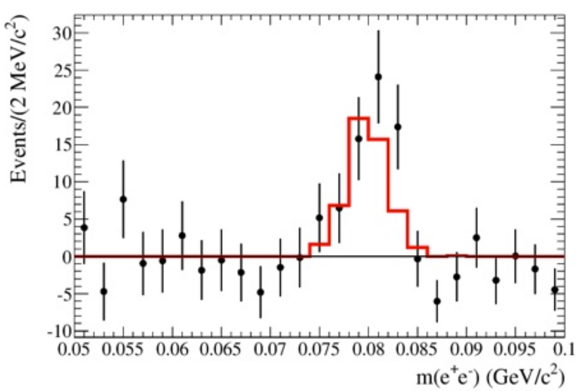



2D search in mass & vertex position (z)

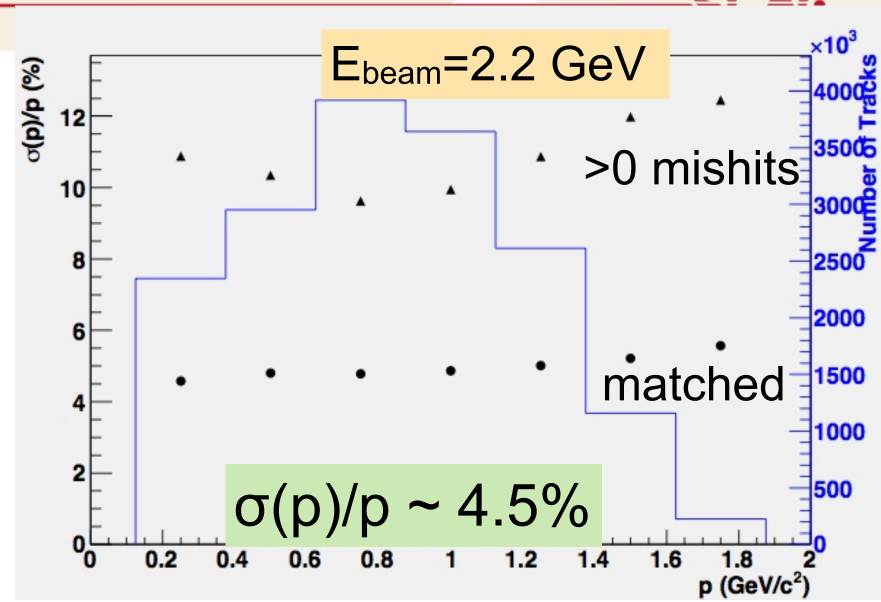
$\longrightarrow$ small coupling region ($\alpha \sim 10^{-8} - 10^{-10}$)

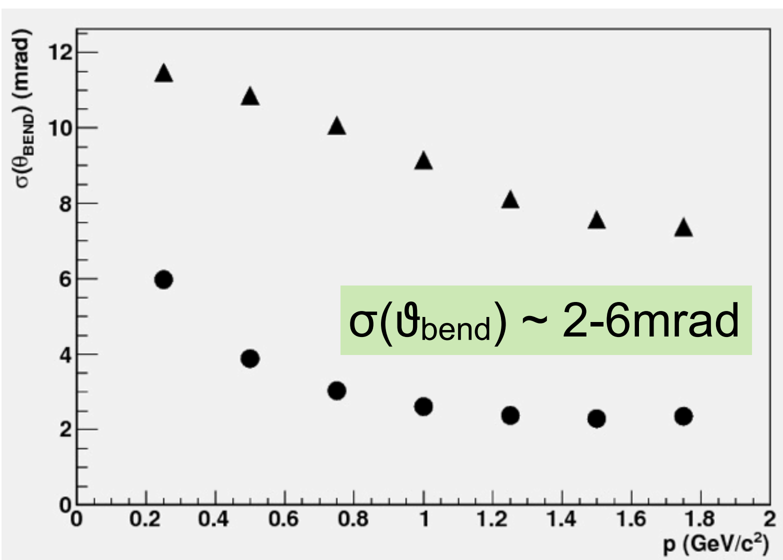
# Mass Resolution:  Momentum & Angular Resolution

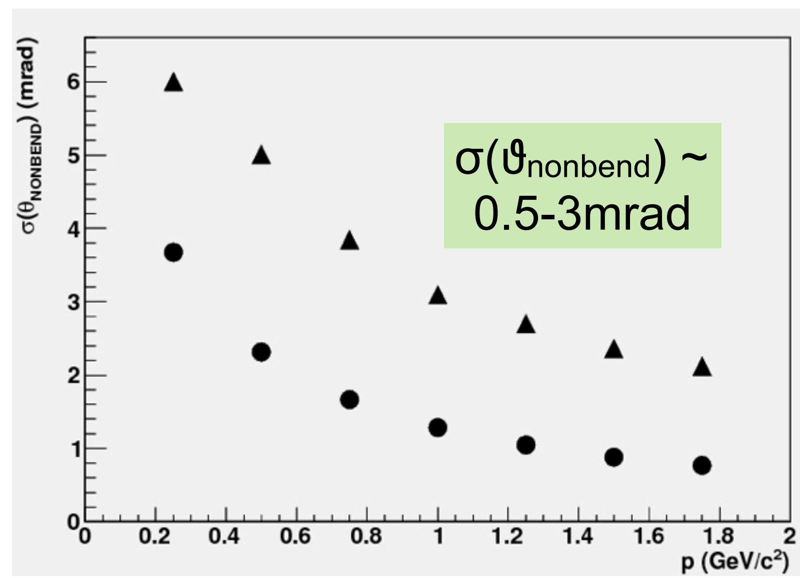
$$M = 2p_{e^+}p_{e^-}(1 - cos\theta)$$

$$\left(\frac{\Delta M}{M}\right)^2 \sim \left(\frac{\Delta p}{p}\right)^2 + \left(\frac{\Delta \theta}{\theta}\right)^2$$

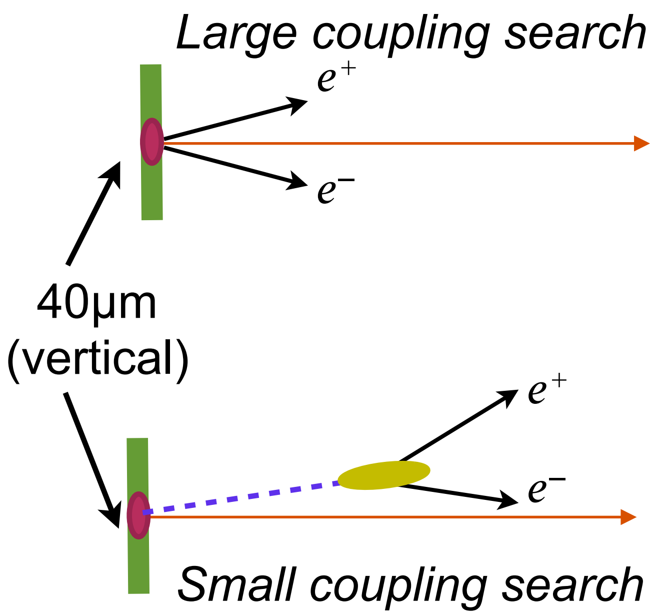
- momentum resolution→ material throughout whole tracker & ∫L×B
- angular resolution→ material in first few layers



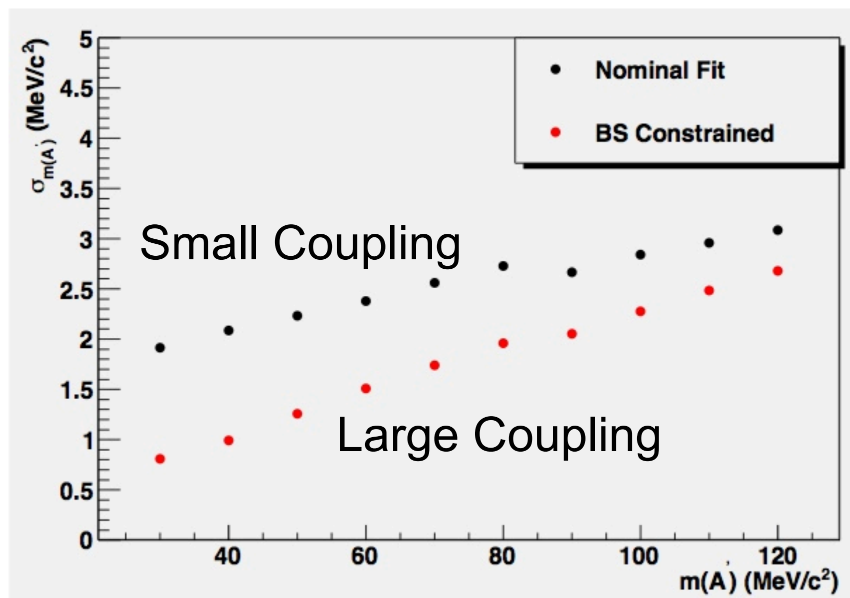



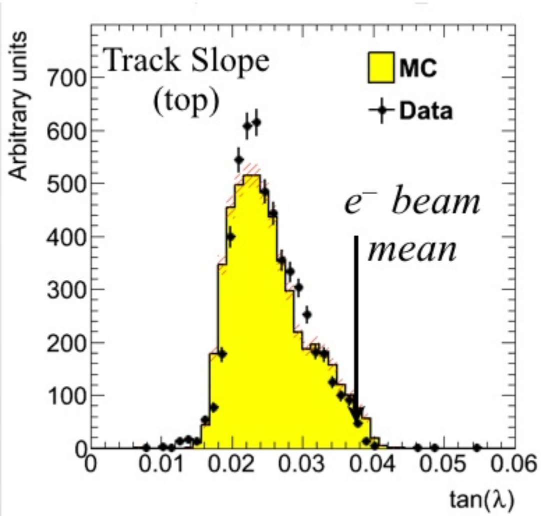
# Mass Resolution: Bump-Hunt vs Vertexing

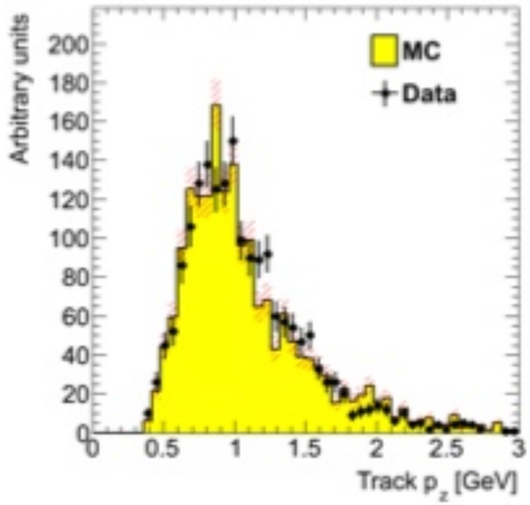


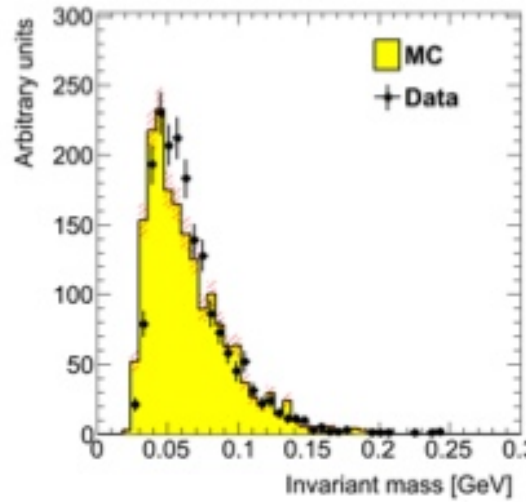

- two types of searches → two kinematic fits → two mass resolutions
  - Large coupling A's decay in the target → constrain the $e^+$ & $e^-$ to originate from beamspot
    - very good constraint on angles
  - Small coupling A's decay outside of target → point decay products back to target
    - good at removing poorly reconstructed tracks



# Test Run: Angles, Momentum, and Mass

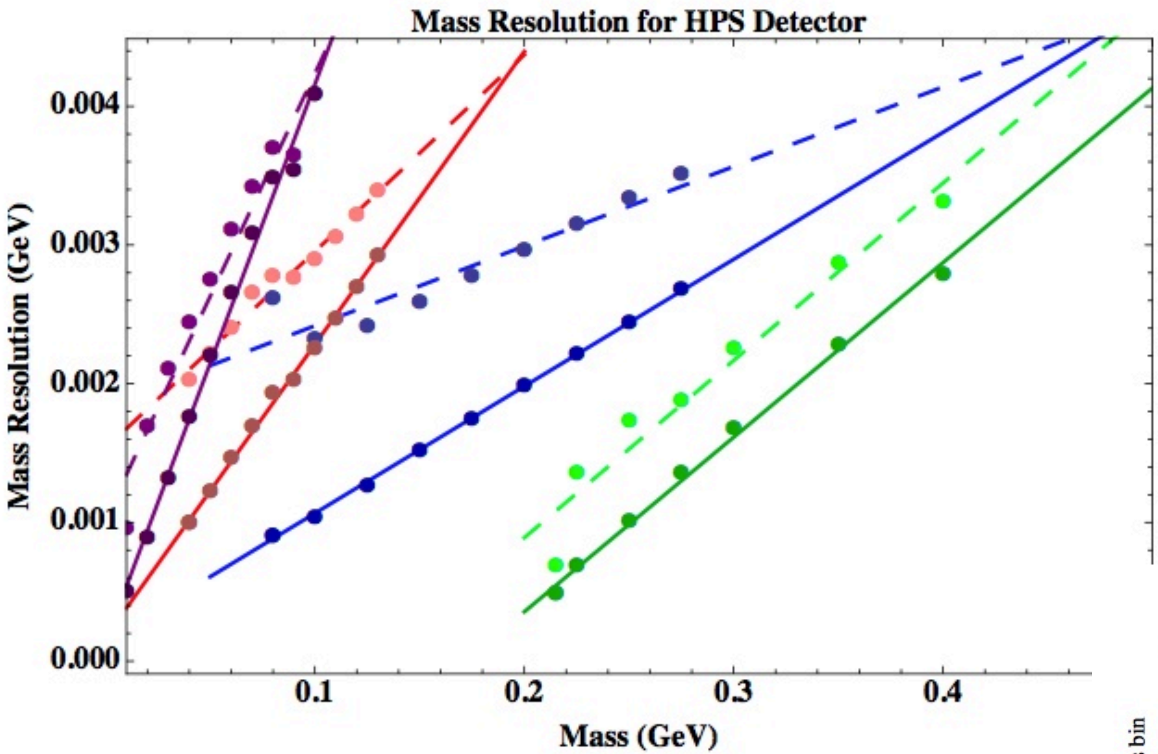



- No direct checks of momentum or angular resolution from test run
  - best we can do is compare MC with data
  - we can do is compare the e+e− pairs we observed with simulation
- Reasonably good agreement in track direction, momentum, and pair invariant mass
- For full run we can calibrate on:
  - fully reconstructed tridents (recoil nucleus carries very little energy)
  - MS beam electrons
  - bootstrap from the ECAL

# Physics Reach: Mass Resolution

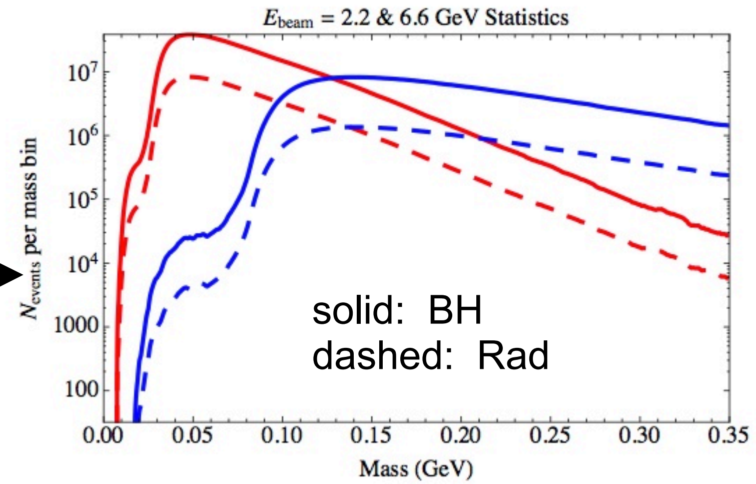



Lighter: resolution for vertexing reach
Darker: resolution for bump-hunt-only reach

Purple: 1.1 GeV
Red: 2.2 GeV
Blue: 6.6 GeV (electrons)
Green: 6.6 GeV (muons)

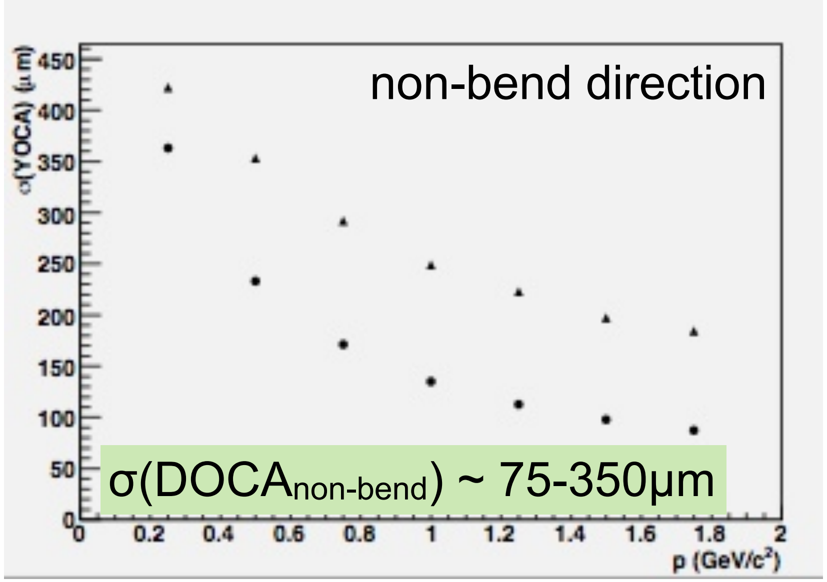
# of events (in expected run)/mass bin →

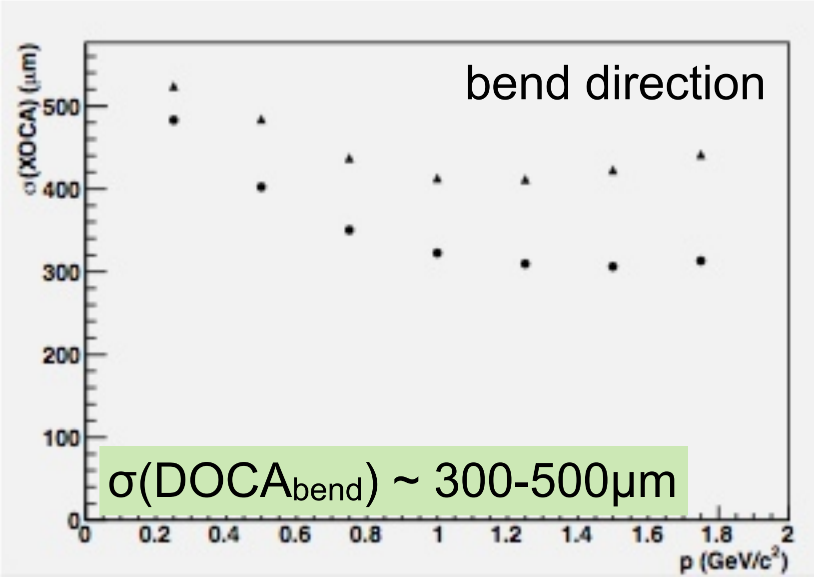
mass bin == 2.5σ



# Vertex Resolution:  Position Resolutions

- For small coupling region, remove trident background by selecting A' decays displaced from the target
  - On a per-track basis, the vertex resolution depends on how well we know the trajectory of the track near the decay vertex (of course, related to angular resolution)
  - Better resolution in non-bend vs bend due to the orientation of strips
    - Only need narrow beam in non-bend direction



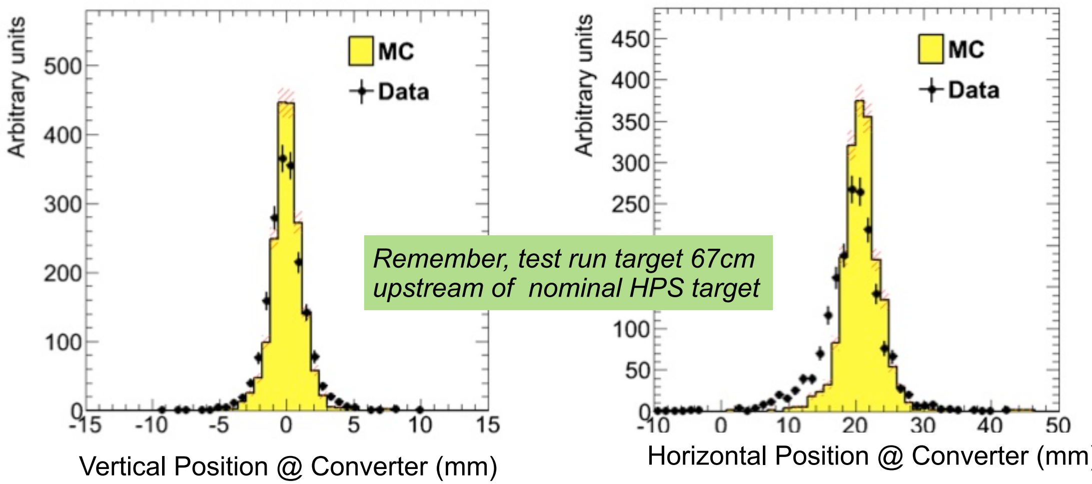



# Resolution: Test Run & Alignment

Vertical and horizontal positions at target

- from test run, we've performed global alignment using pairs

- no track-based alignment done yet...expect this is the difference seen between MC and data resolutions



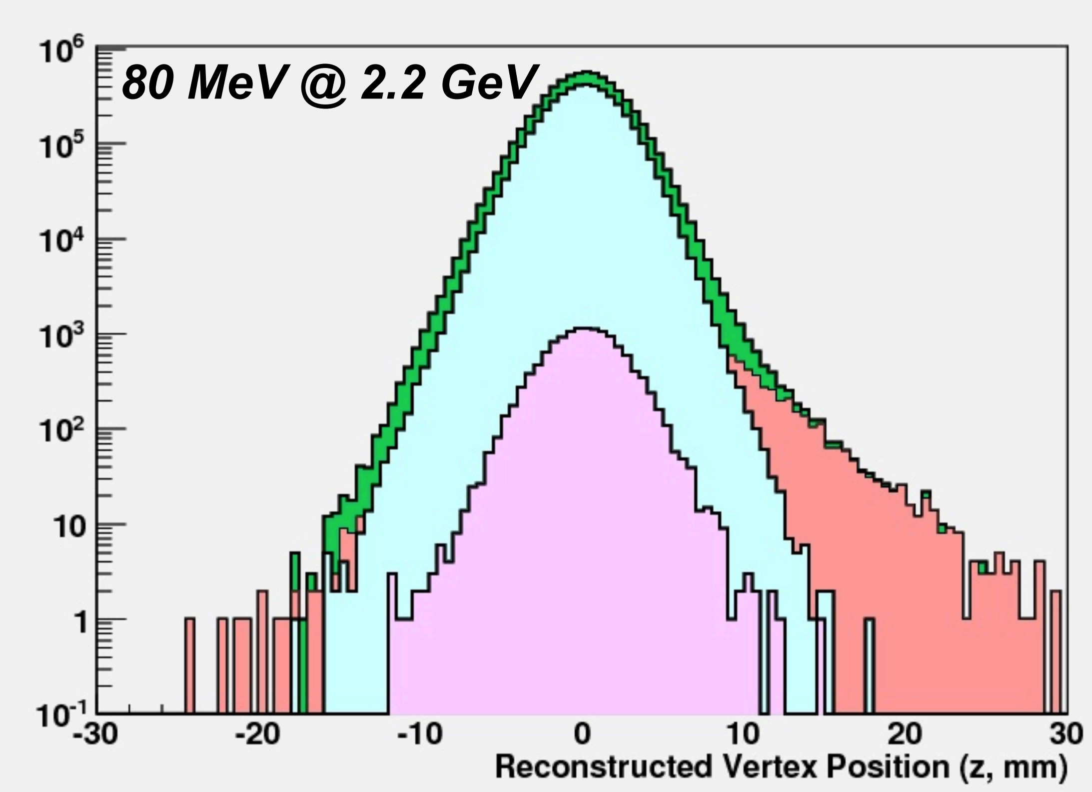

- For the electron run:
  - ~billions of electrons to perform track-based alignment
  - ~hundred millions of $e^+e^-$ pairs from tridents
  - ~millions triplets with known kinematics
- will give us plenty of events to perform needed alignment calibrations

# Vertex Resolution

- Vertex position of $e^+e^-$ pairs is determined

- dark green: "reasonable" cuts ... e.g. track $chi^2$, vertex $chi^2$ etc
- dark red: >0 hits not matched to the true $e^+$ or $e^-$ ; "mishits"

- light green: all pairs after isolation cut
- light red: mishits after isolation cut



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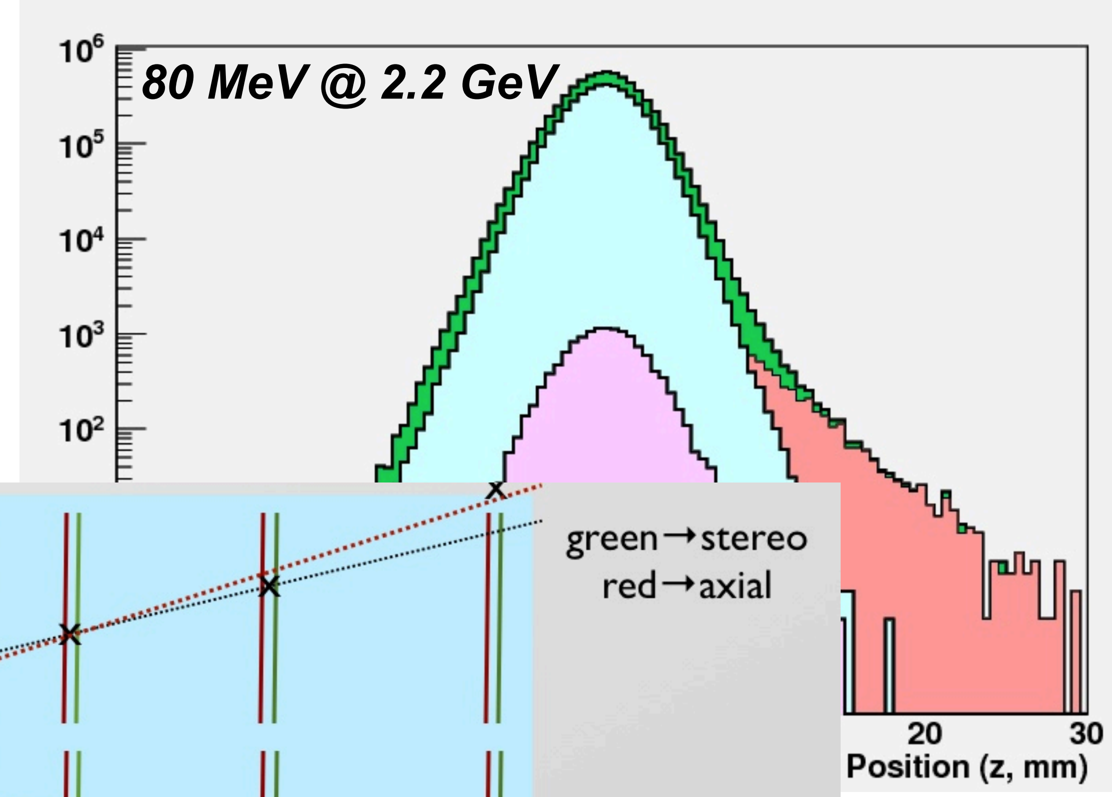


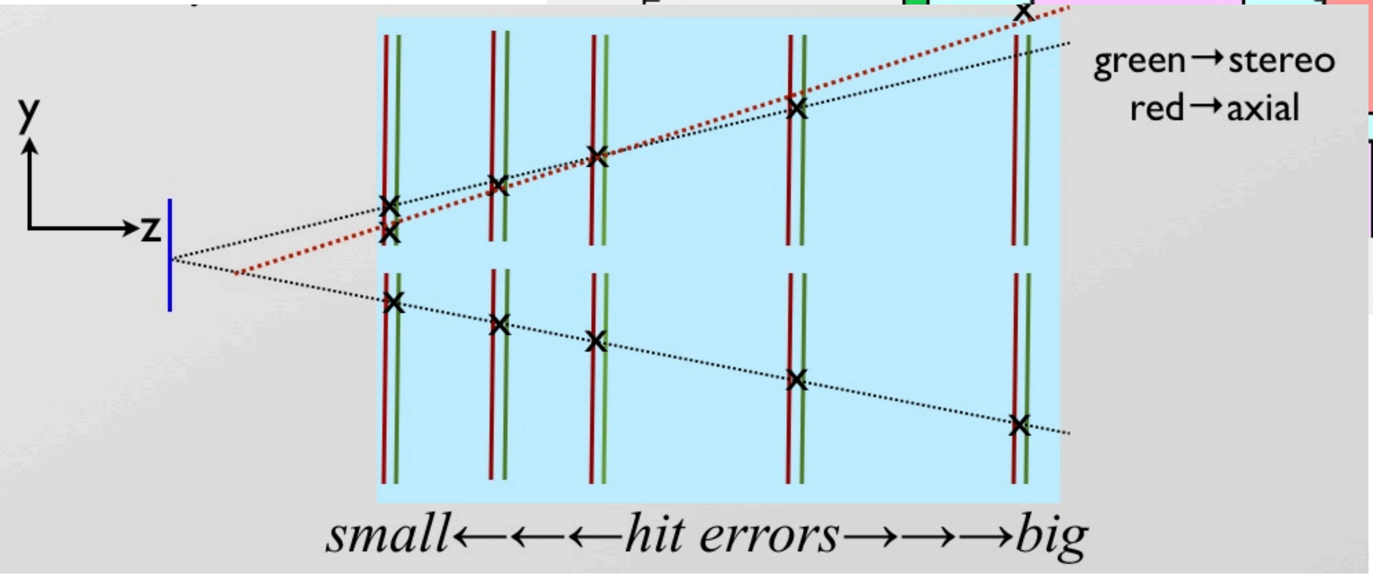

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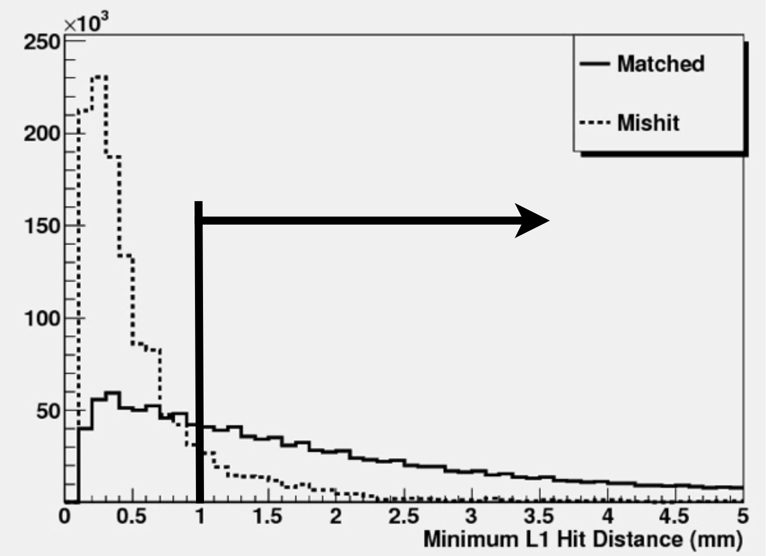
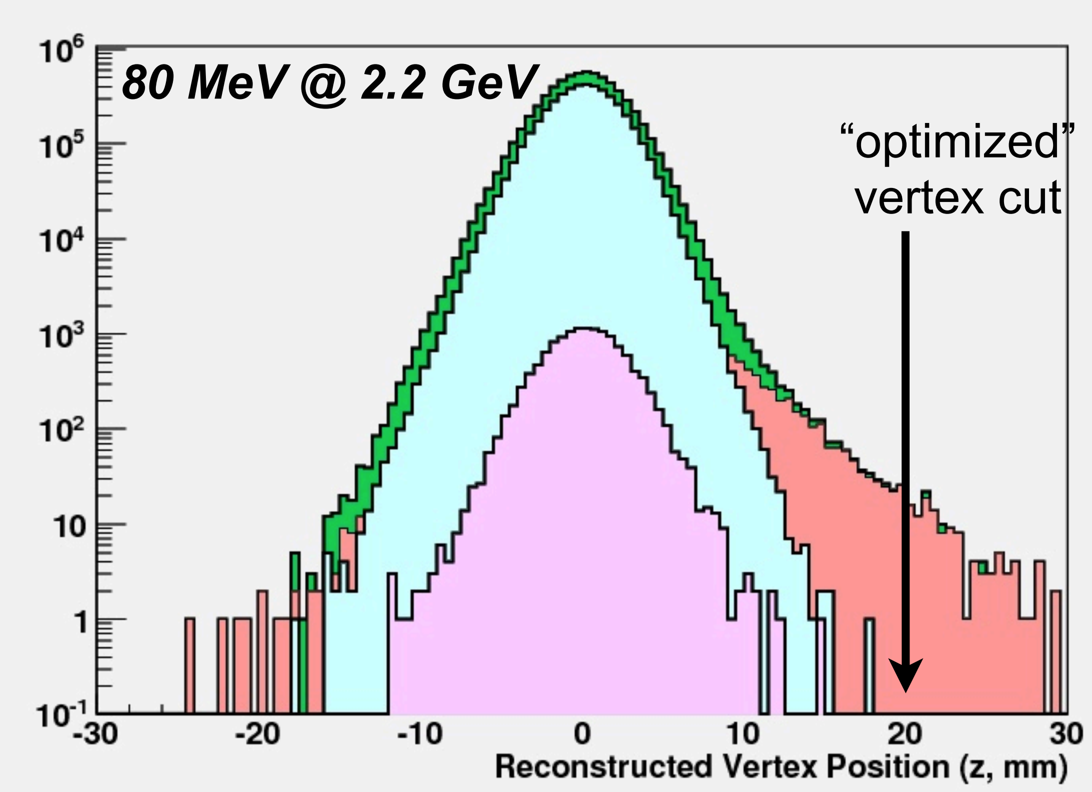
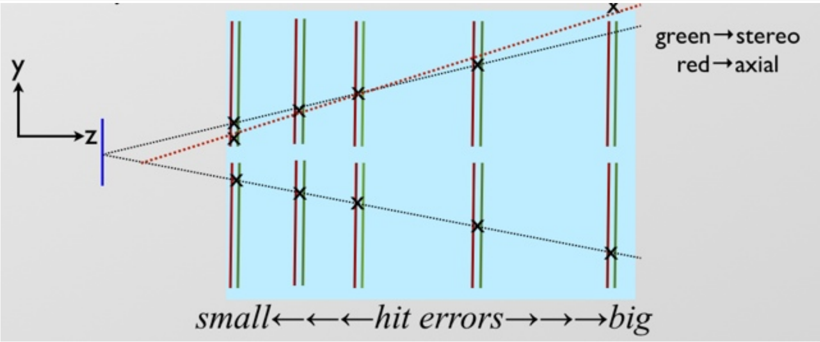
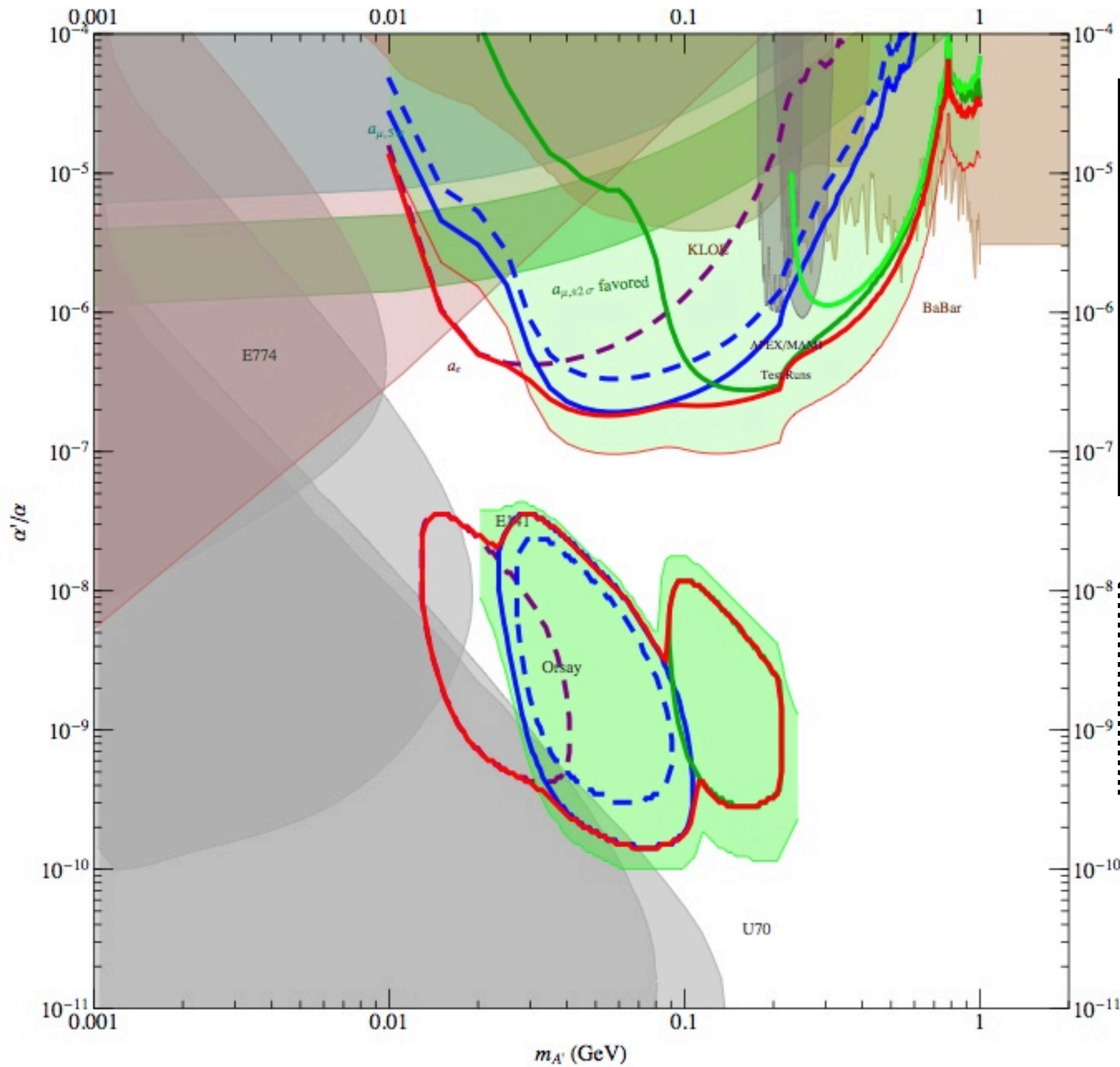


# Physics Reach & Run Plan




Commissioning Run (dashed):

1 week with 50nA @ 1.1 GeV
1 week with 200nA @ 2.2 GeV

Production Run (solid):

2 weeks with 200nA @ 2.2 GeV
2 weeks with 450nA @ 6.6 GeV

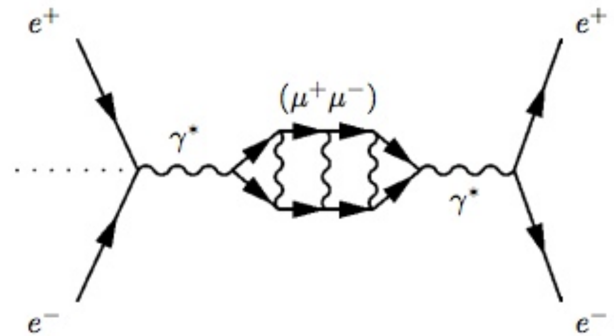
Shaded green:

3 months with 200nA @ 2.2 GeV
3 months with 450nA @ 6.6 GeV

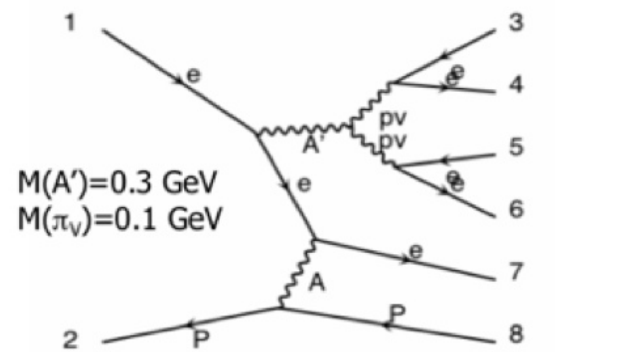
*time given is beam time*

# Other Physics Topics with HPS Detector

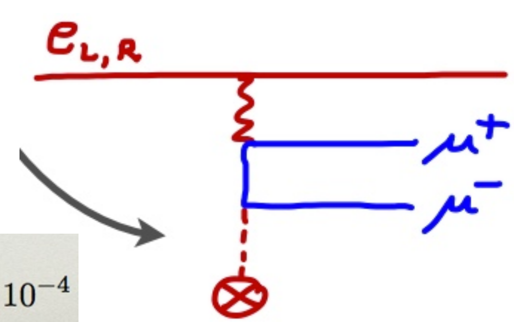
•true muonium: $\mu^{+}\mu^{-}$ bound state
•same signature as an A' at di-muon mass
•expect 10-20 accepted events (after vertex cut → no background)




- non-abelian or “higgsed” dark sector could give rise to events with many leptons in final state
- high multiplicity events with many mass peaks




•according to Pospelov et al., MeV-scale force carrier could explain muonic Hydrogen anomaly...could also induce polarization-dependent muon-trident rate



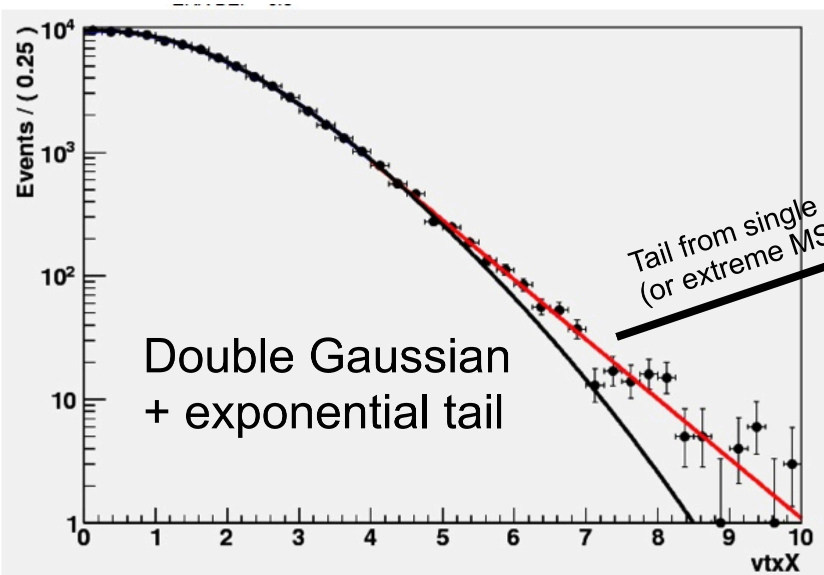

$$\delta = \frac{A_L(\mu^+\mu^-) - A_R(\mu^+\mu^-)}{A_L(\mu^+\mu^-) + A_R(\mu^+\mu^-)} \sim 10^{-3} - 10^{-4}$$

# Summary

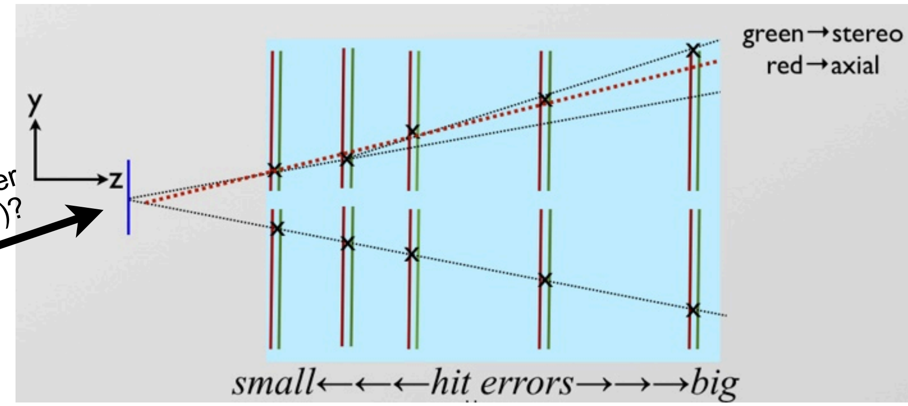
HPS will search an interesting and unique region of heavy photon parameter space

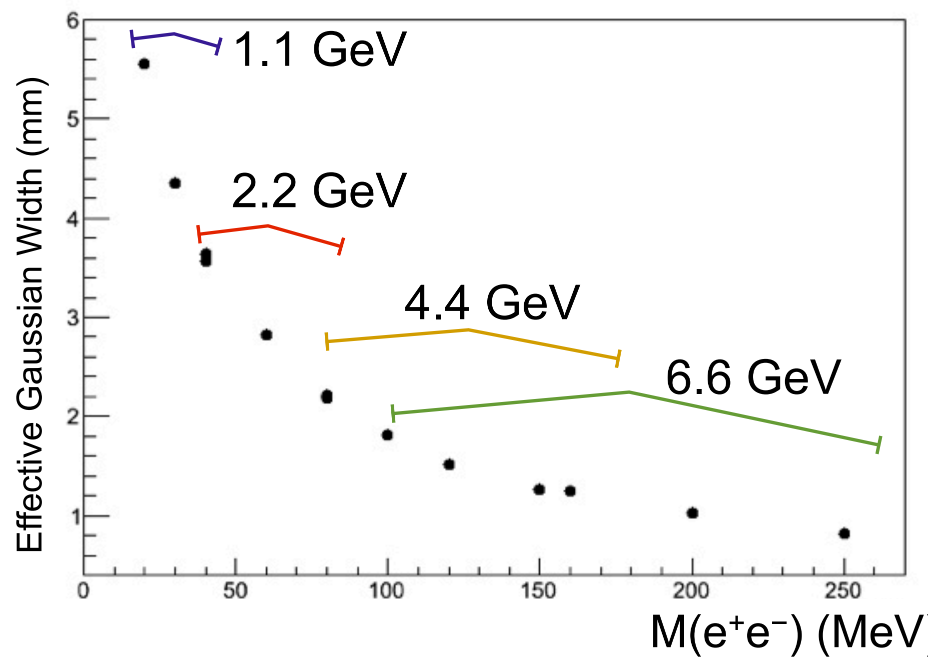
- We've calculated our expected reach using a full, realistic detector simulation
- To the extent possible, the test run verified our expected performance
- The key performance parameters can all be verified using electron data
  - the background rates and vertex resolution can be taken directly from sideband data
- Still room for improvements from simple (improved data analysis) to easy (lighter targets at 11 GeV) to more advanced (muon detector, pion ID)

# Vertex Resolution:  Closer Look




Tail from single scatter
(or extreme MS tails)?




Vertex resolution should be:

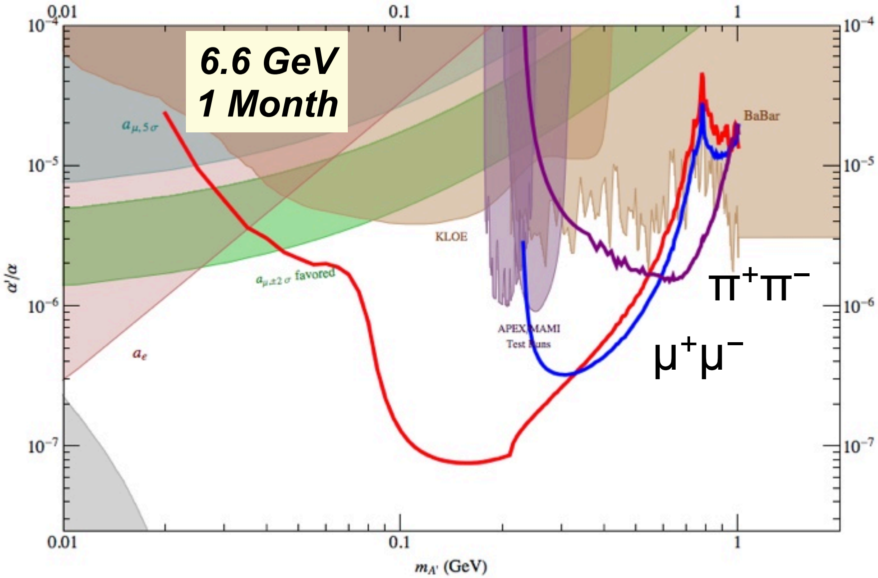
$$\Delta z \sim 2\Delta\theta_{track}/\theta_{open} \times L$$

...so mass/energy scaling should go as:

$$\Delta z(m, E) \sim (1/E) \times (E/m) \sim (1/m)$$

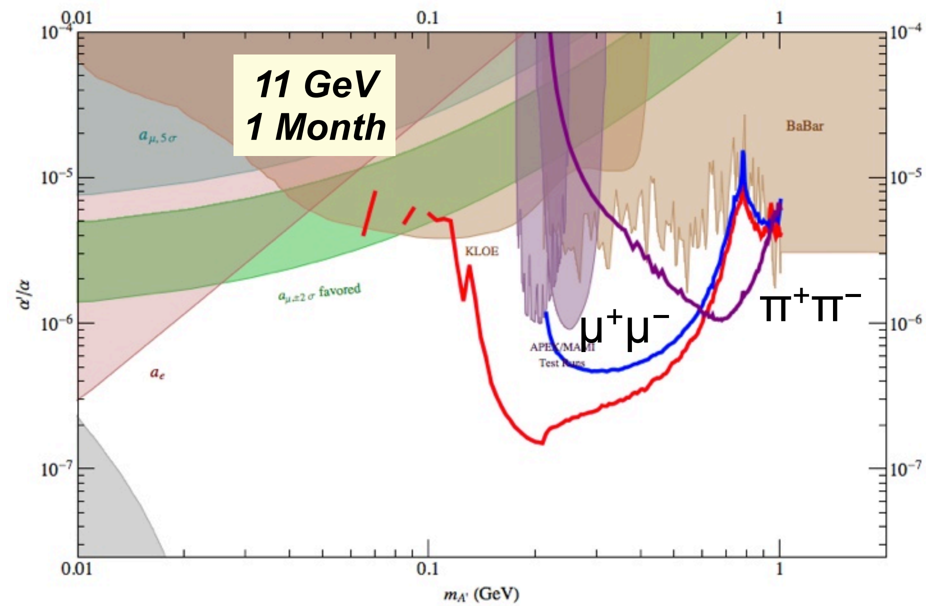
The tail also scales (roughly) with mass.

# Physics Reach:  Further Improvements




The "cliff" that occurs at ~300 MeV @ 6.6 GeV is mostly due to acceptance

...however, even at 11 GeV (and accounting for di-muon/di-pion events) there is still a steep fall > 500 MeV due to loss of coherence → can be improved by using lower Z target



# Physics Reach: Vertex Displacement Cut

- For the reach calculation, make vertex displacement cut where # of background events <0.5
  - For a real data analysis, we will be more sophisticated

***Blue: displacement cut; Red: $\gamma c\tau$ for $\alpha=10^{-8}$***