Results and Future Prospects for HPS

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on behalf of the HPS Collaboration
APS April Meeting, 2018

The Vector Portal and Kinetic Mixing

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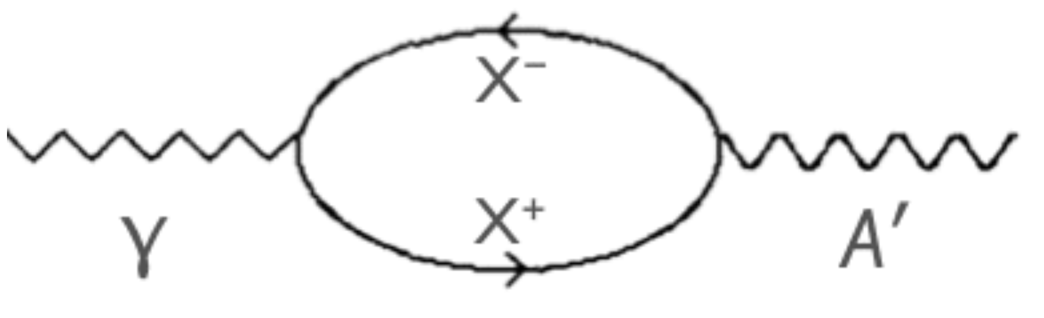
an old idea: if there is an additional U(1) symmetry in nature, there will be mixing between the photon and the new gauge boson

Holdom, Phys. Lett B166, 1986

$$\mathcal{L}_{U(1)'} = -\frac{1}{4}V_{\mu\nu}^2 - \boxed{\frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu}} + |D_\mu\phi|^2 - V(\phi)$$

Kinetic Mixing term



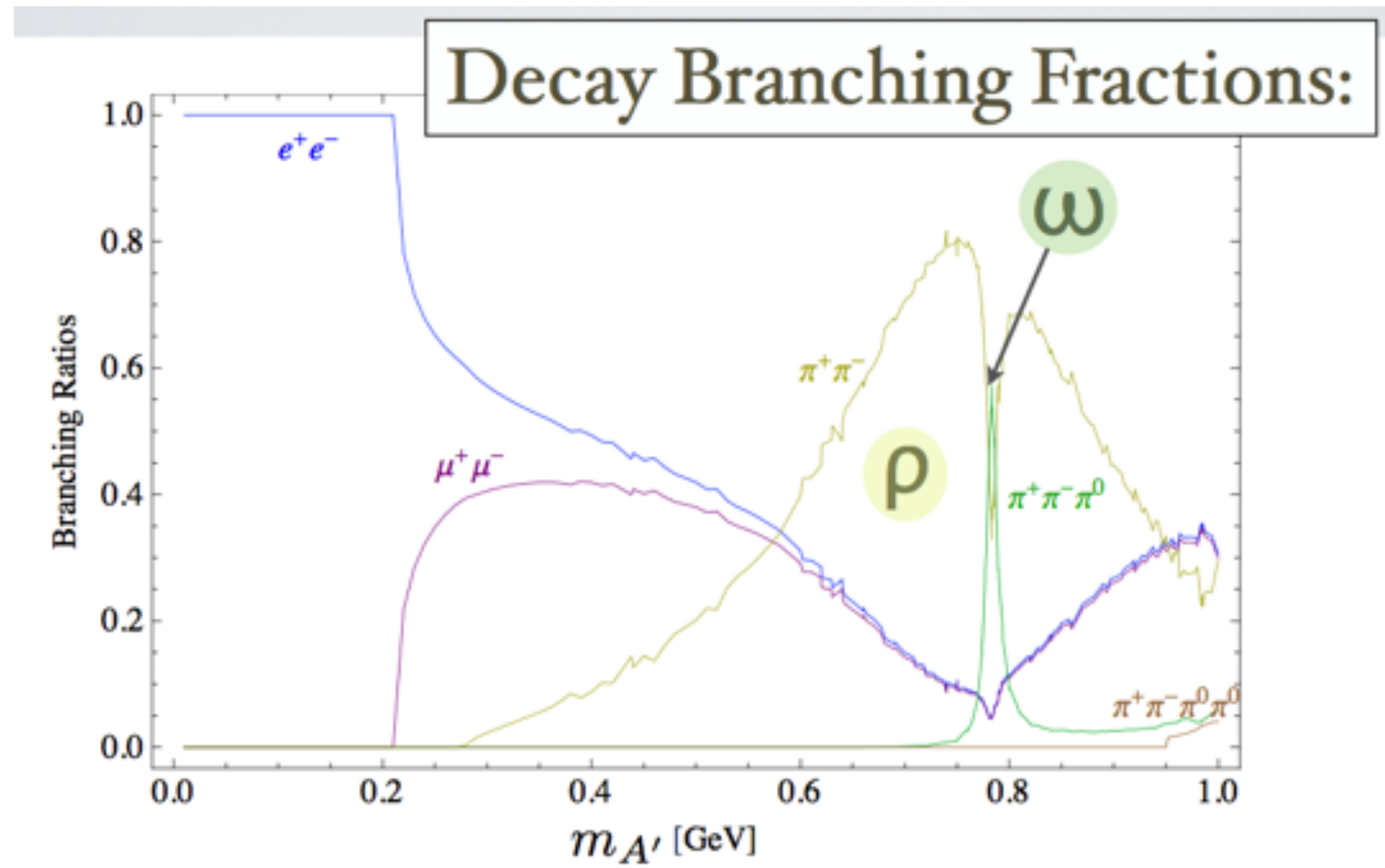
- extremely general conclusion...even arises from broken symmetries
- gives coupling of normal charged matter to the new "heavy photon" $q=\varepsilon e$
- in everything I show, I'll assume a "simple" dark sector, where the A′ is part of an Abelian gauge group…other cases are interesting too!

Decays of the A': Two Scenarios

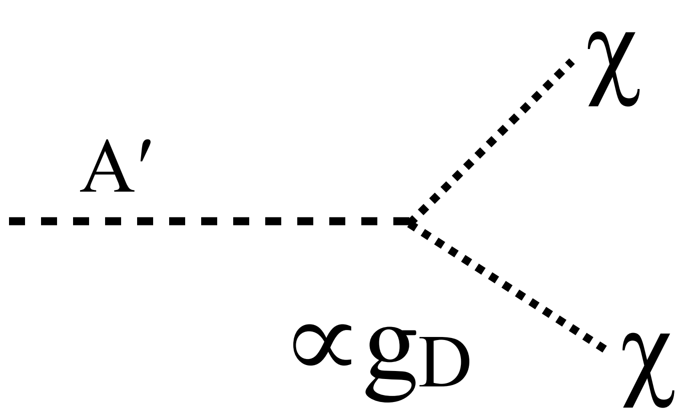
If m(A')<2m(χ)

..the A’ will decay to SM particles just like a virtual ɣ* “decays”, i.e. the ratio R!

Which means, for m(A') < GeV away from QCD resonances, a lot of lepton pairs



If m(A')>2m(χ)



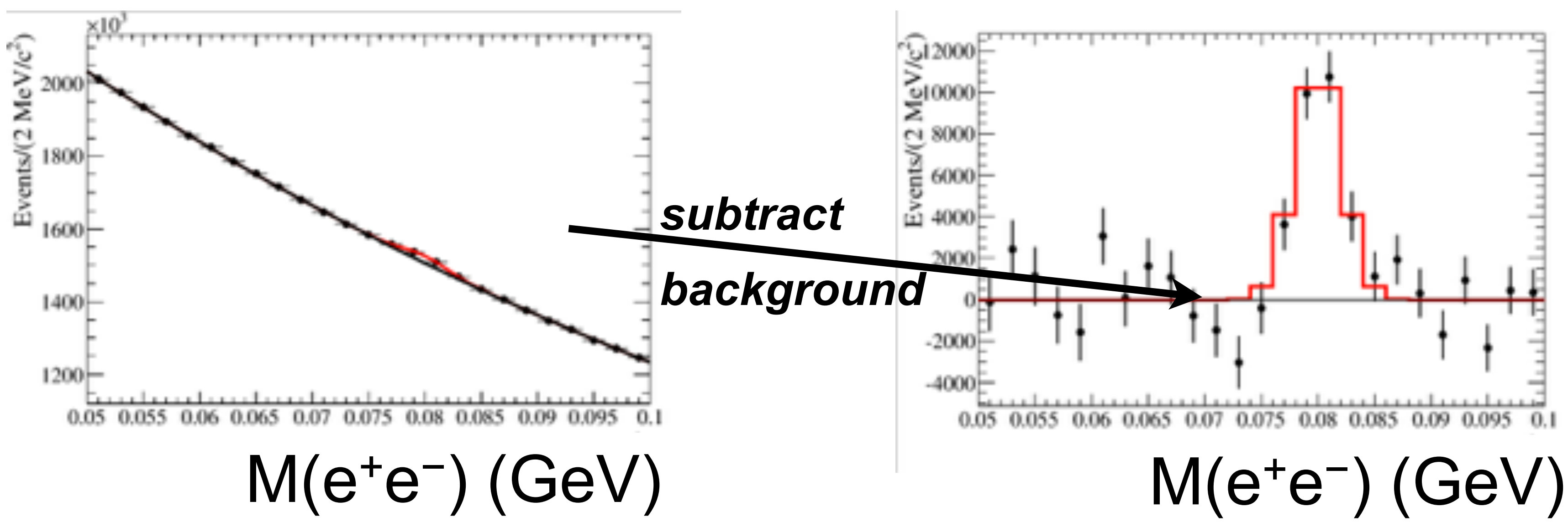
…for relatively lighter χ, A' decays into the dark sector will dominate…

the experimental picture of vector-mixed dark sectors is not complete without this scenario!

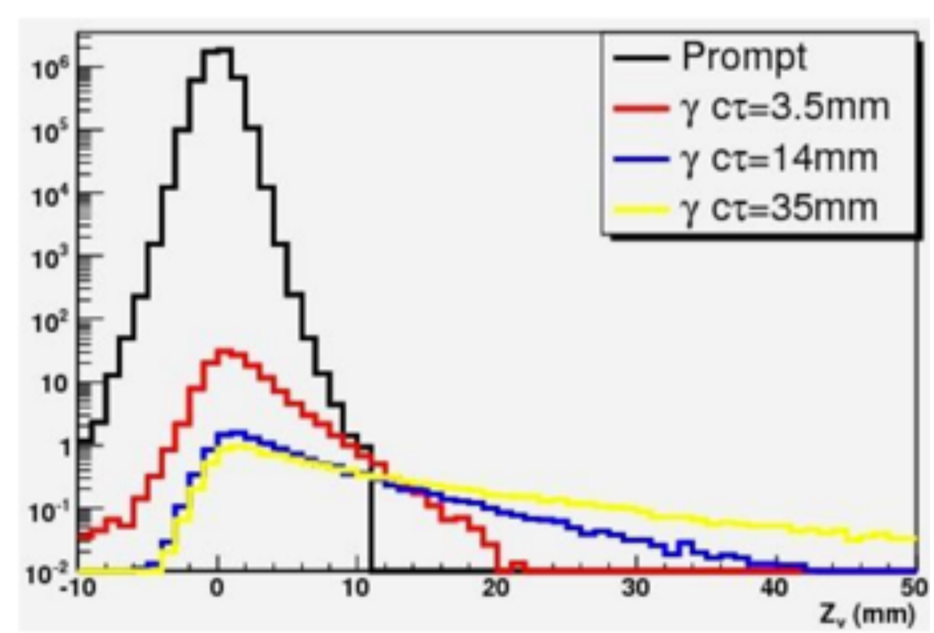
BUT, for this talk I’ll focus on visible decays

Two ways to look for a visibly decaying A'

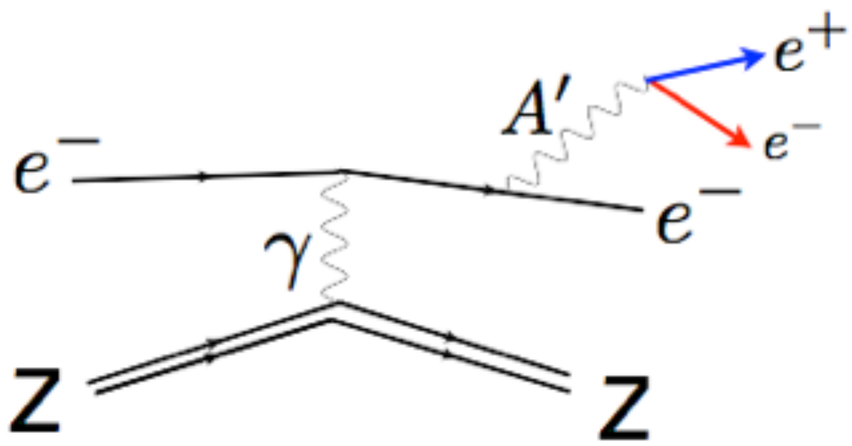
- Massive
  - when we say “dark” photon we typically also mean “heavy”
  - look for peak in the invariant mass spectrum



- Non-zero lifetime
  - some regions of parameter space will have decays that happen far from production target
  - backgrounds typically decay promptly



A' production & decay at a fixed target experiment



Production is analogous to bremsstrahlung:

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

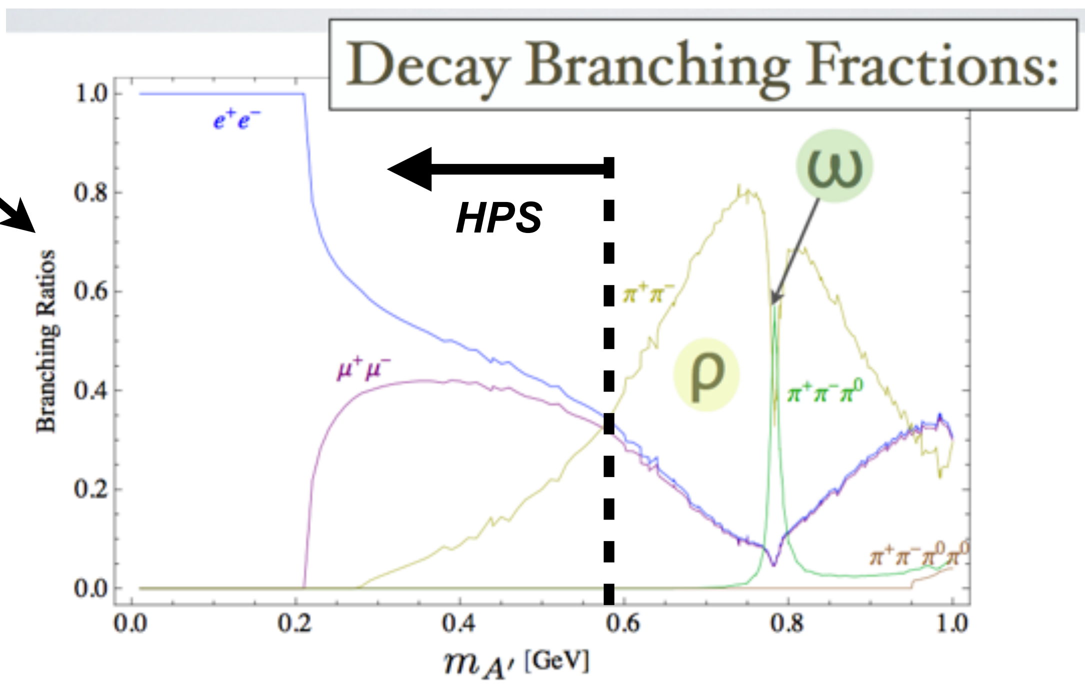
- prefers x~1 (i.e. $E_{A'} = E_{beam}$)
- small angle emission dominates

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

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

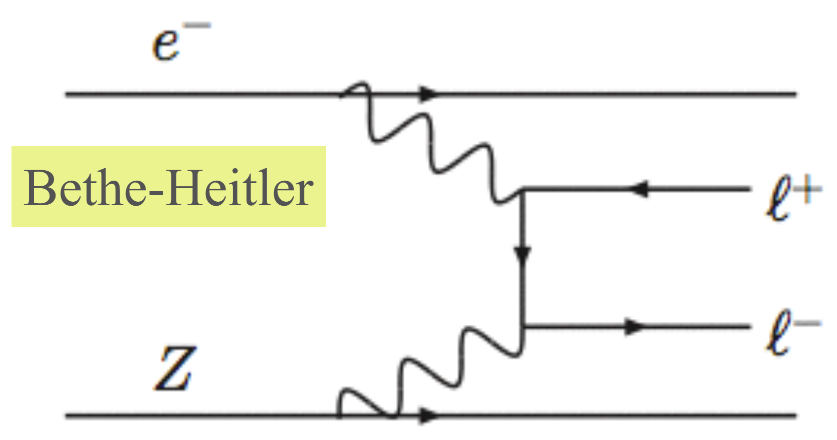
$$\ell_0 \equiv \gamma c\tau \simeq \frac{3E_1}{N_{\rm eff} m_{A'}^2 \alpha\epsilon^2}$$

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

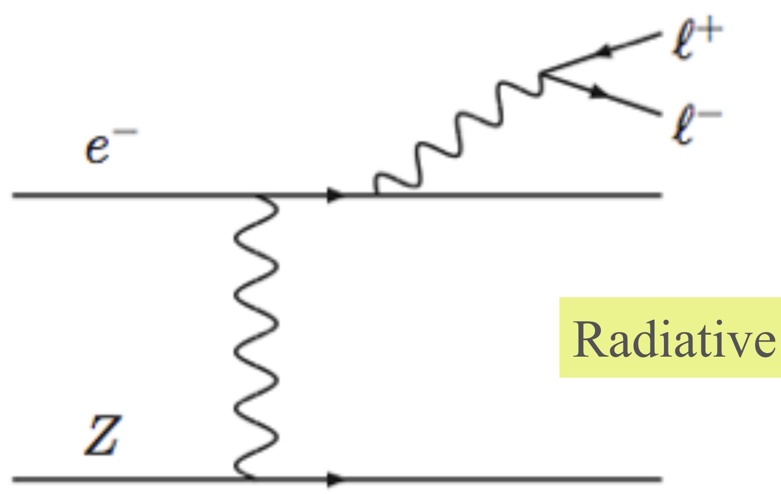


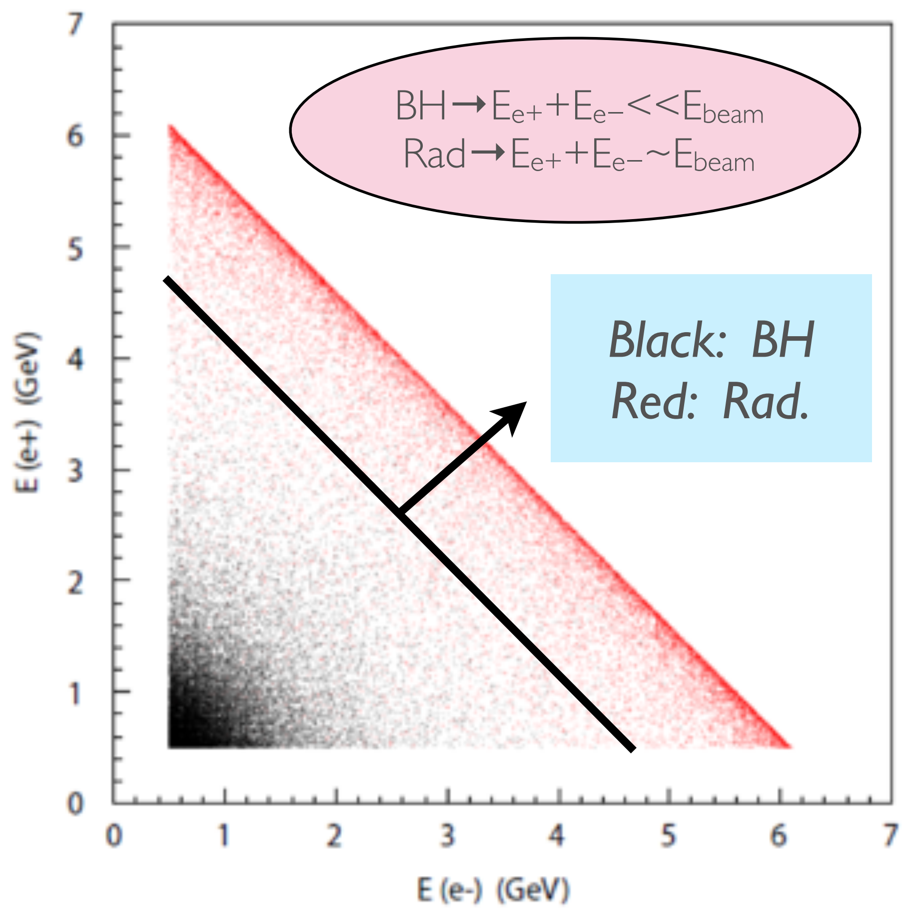
HPS is sensitive to A's with decays ~5-100mm and to e^+e^- final states.

A' backgrounds at a fixed target experiment



Two physics backgrounds, collectively known as "tridents"





- 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 (~10x 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!

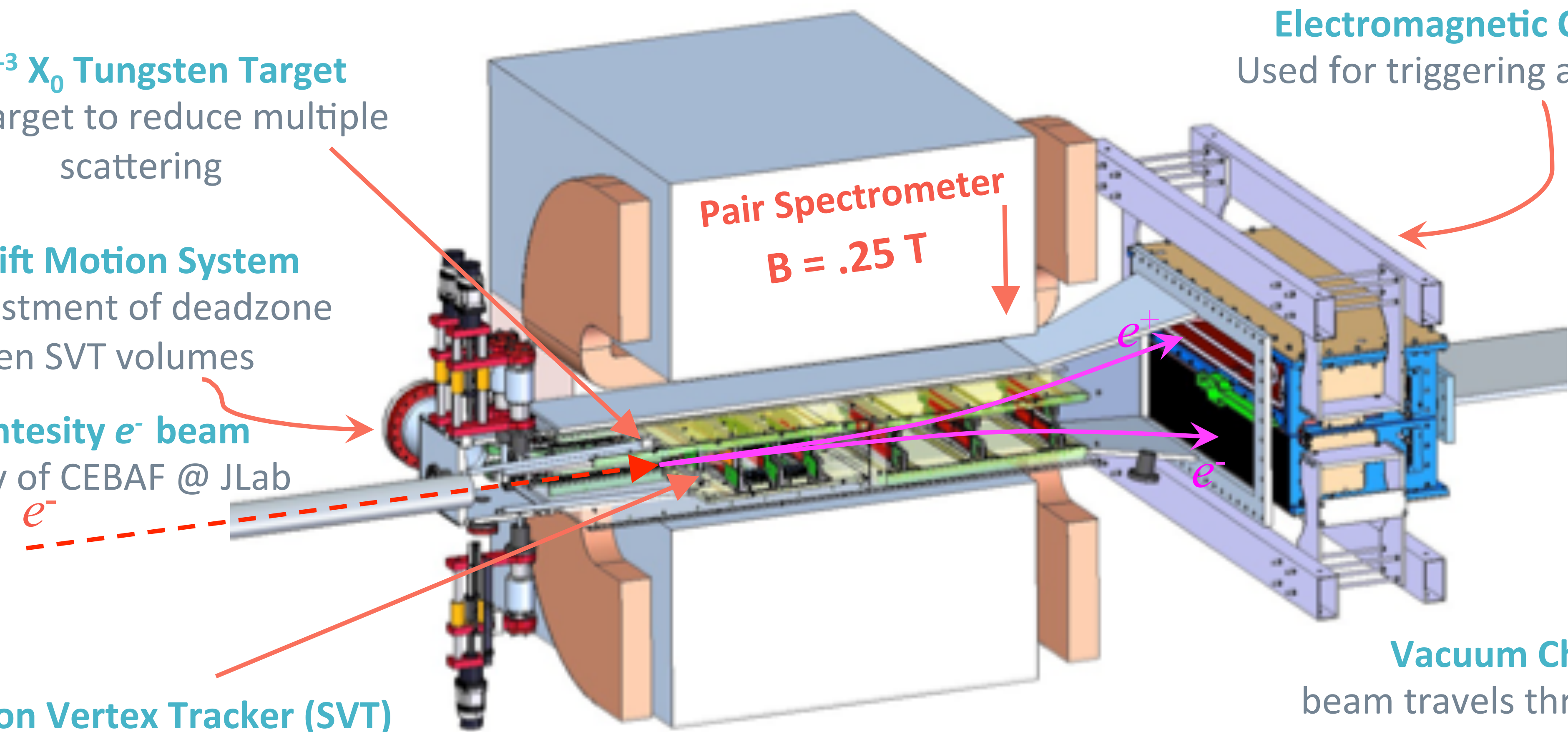
...there is one other background, which I will discuss shortly!

HPS: Heavy Photon Search Experiment

~10^{-3} X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

High intesity e^- beam
Courtesy of CEBAF @ JLab



Electromagnetic Calorimeter
Used for triggering and particle ID

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Measures momentum and vertex precisely.

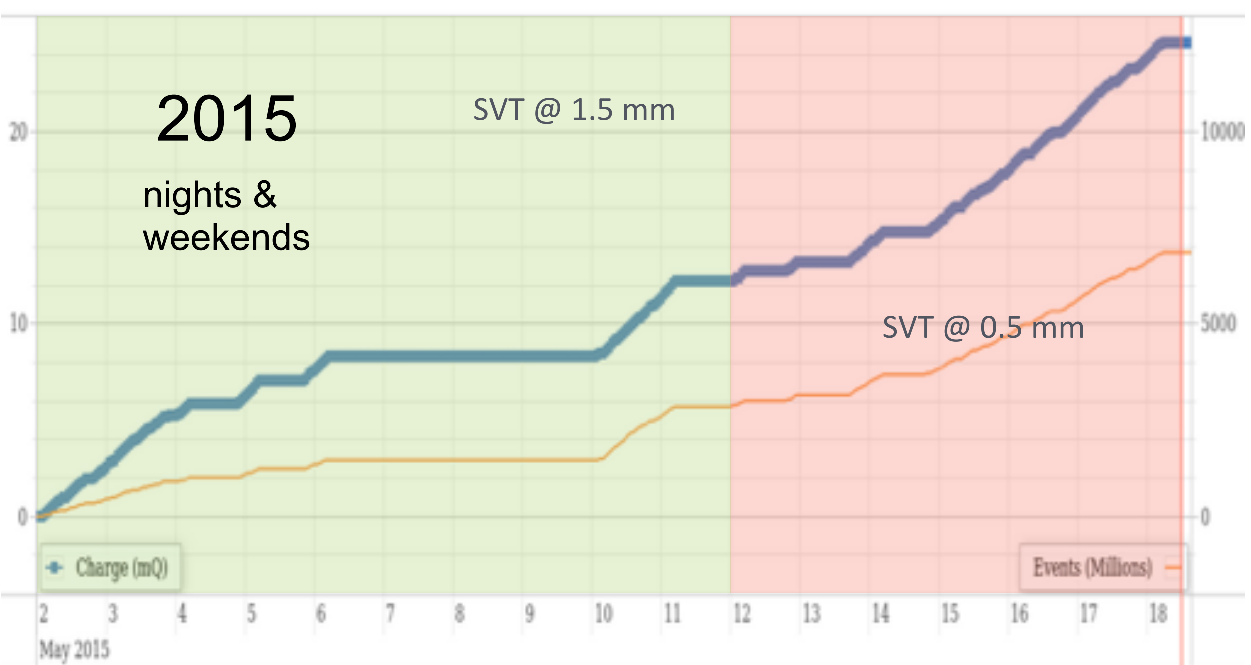
Vacuum Chambers
beam travels through vacuum in order to avoid beam-gas interactions

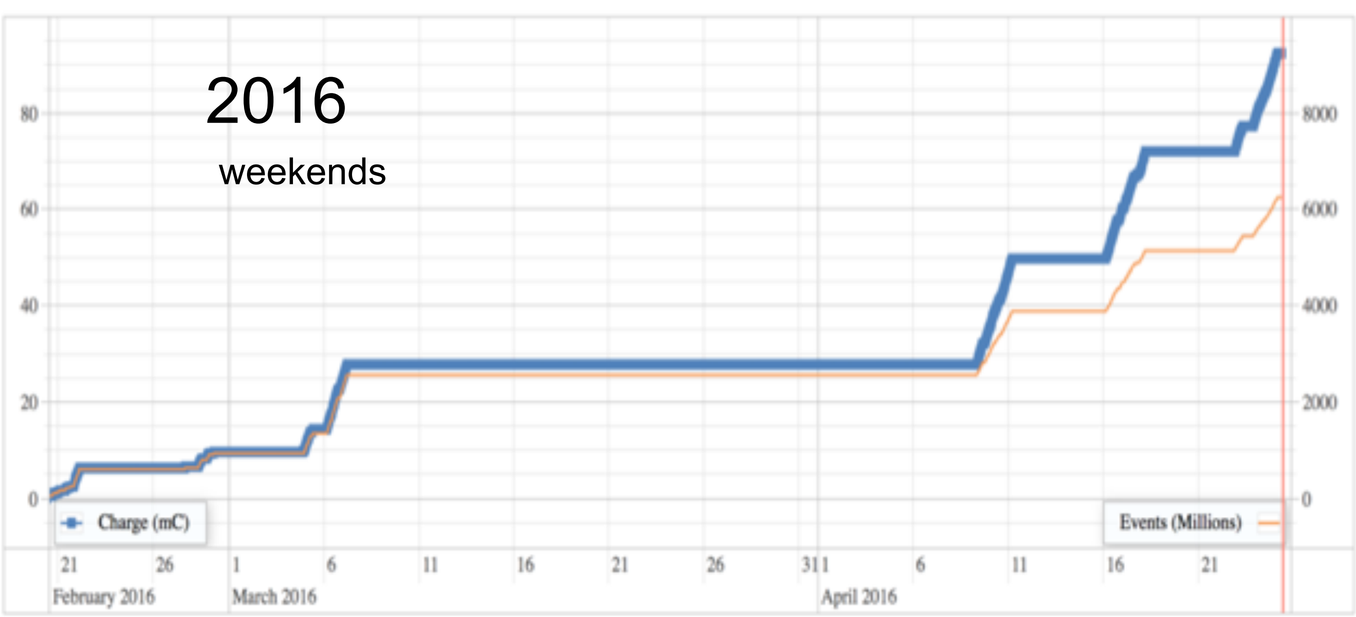
SVT + ECal DAQ capable of 50 kHz

Installed within the Hall B alcove at Jefferson Lab downstream of the CLAS12 detector

HPS Engineering Runs

- HPS has taken two runs, technically defined engineering runs but which we got some physics quality data
- In May 2015, took ***1.7 PAC days*** of data each with SVT at 0.5mm (nominal) and 1.5mm **@ *1.05 GeV***
- In spring 2016, ran **@ *2.3 GeV*** and took ***5.4 PAC days*** all with SVT at 0.5mm
- ***Analysis presented here covers 1.7 PAC days @ 1.05GeV with SVT at 0.5 mm***
- HPS has been officially approved (no more "engineering runs") for 180 PAC days
- We hope to have our next run in 201X (??? fingers crossed ???)





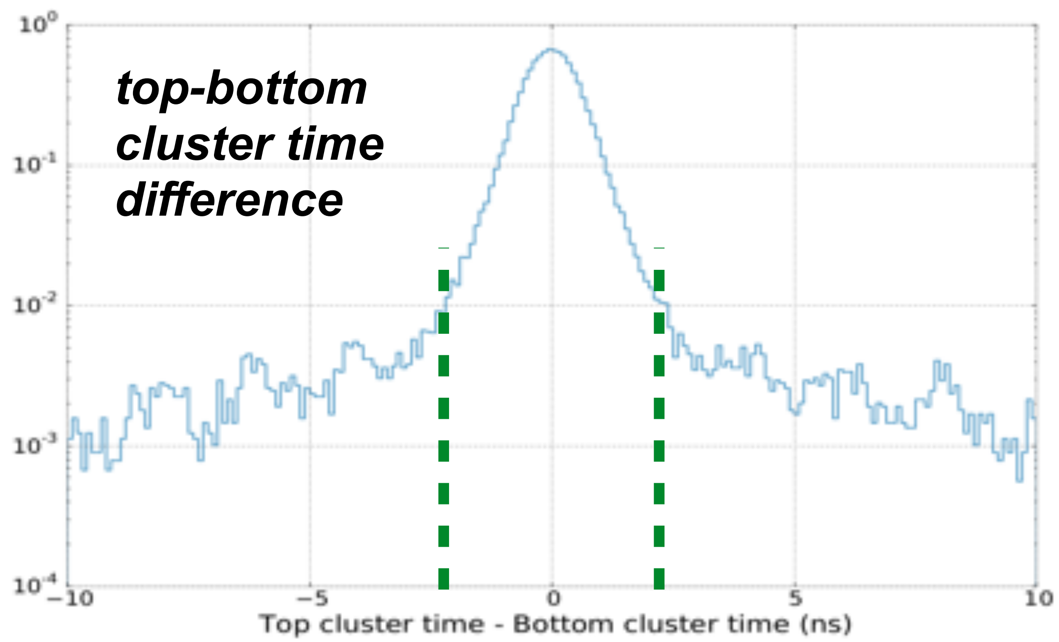
The HPS Bump-hunt Analysis

Ratio of A' to radiative rate in δm ~A' width

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

- As mentioned, A' production related to “radiative trident” production… we use this relation to relate our extracted signal yields to m(A') vs ε space
- Ingredients going into this:
  - the fraction of events in our final selected sample that are radiative events
    - use MG5 to simulate full-diagram and radiative-only tridents and then simulate detector simulation, use nominal reconstruction and cuts
  - experimental mass resolution
    - simulated with MG5-generated A' events at range of masses
- Absolute rates are not used directly, which cancels a lot of potential systematic effects!

Bump-Hunt event selection

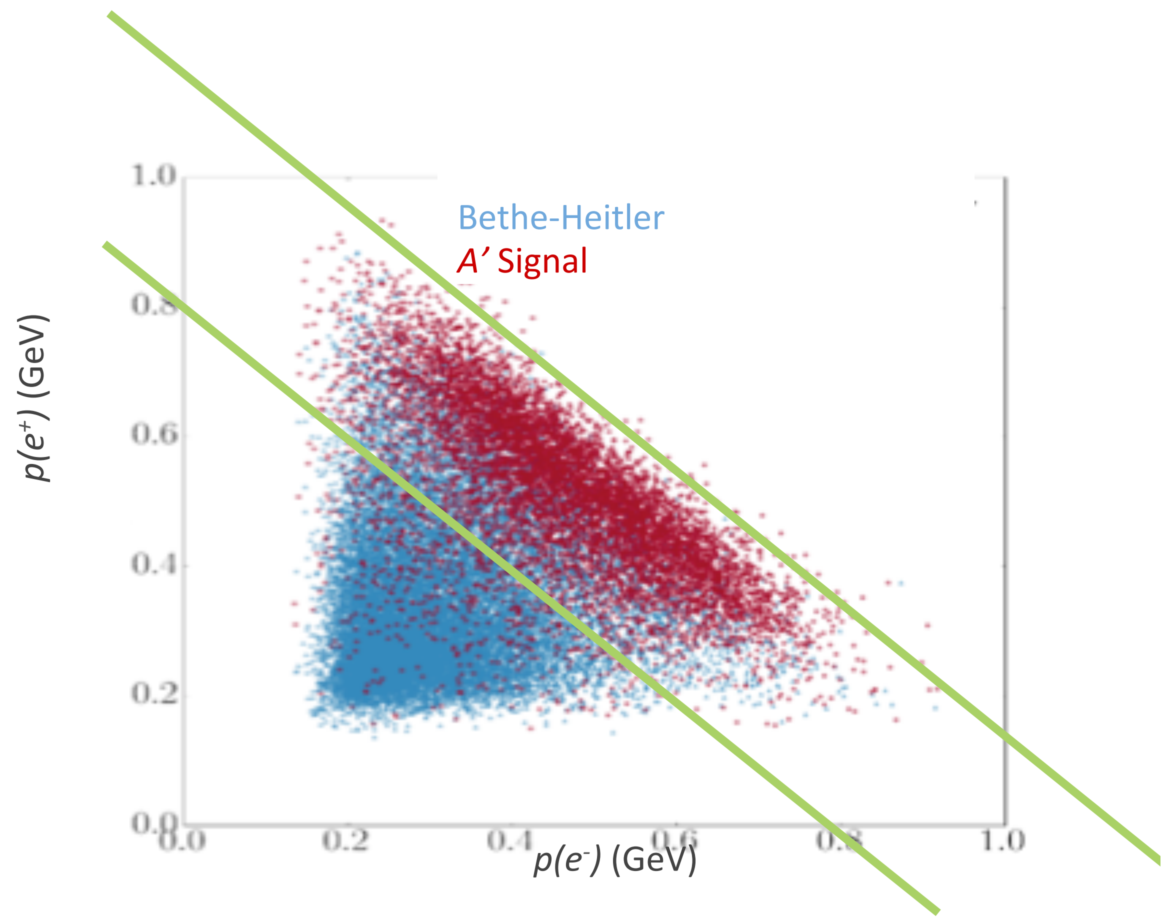


We generally to to keep the KISS approach, particularly for this first analysis:

- loose track reconstruction and track-ECal matching cuts
- ~2 sigma cut on relative ECal cluster times
  - <1% accidental e^+e^- pairs

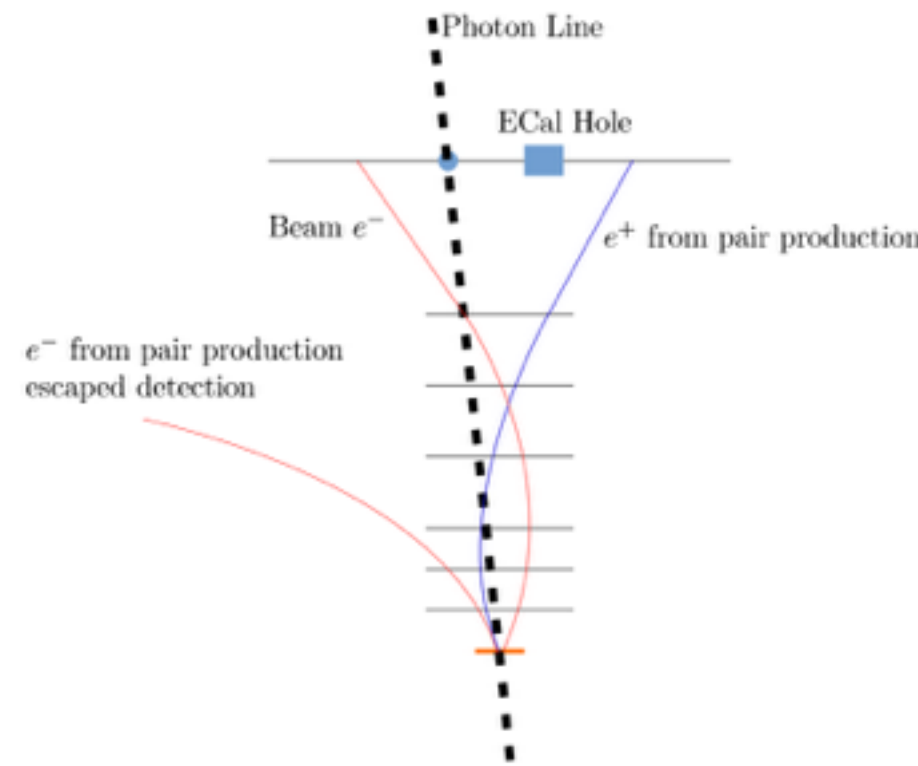
… also require that the e^+e^- momentum sum be greater than $0.8 \times E_{beam}$

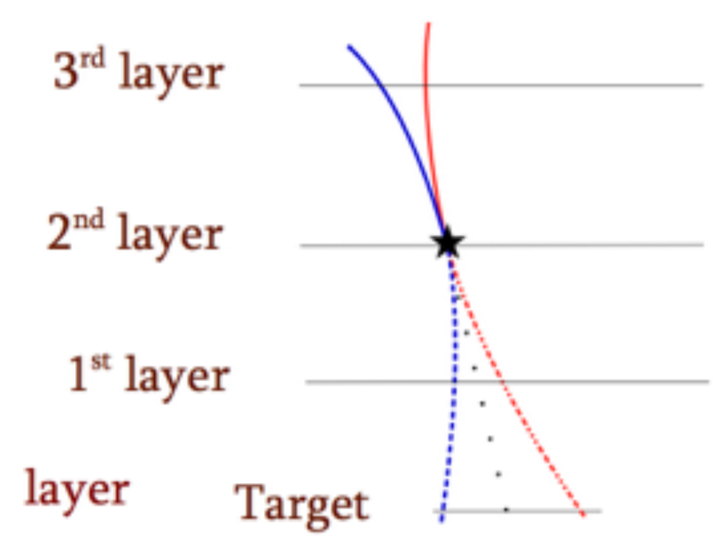
This is the single-best discriminant against BH-like trident background



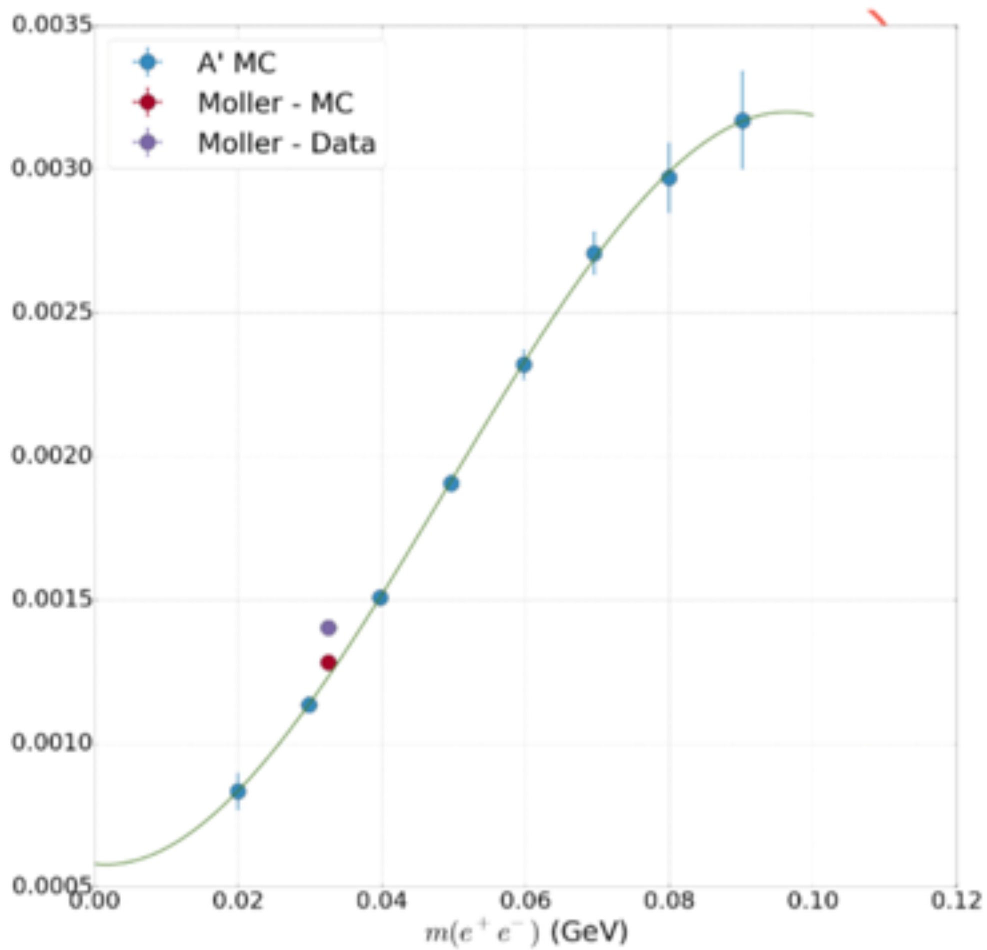
Reducing WAB gamma converted events

- One thing we missed in proposal: wide-angle Brems (WABs)!
- How could we miss this? None of the usual event generators simulate it correctly!
  - because it is expensive and the rate is "very small" (3-body)
- WAB: $e^{-}Z \rightarrow e^{-}_{\text{large } \theta}\, \gamma_{-\text{large } \theta}\, Z$
  - then, the γ converts in L1 or L2 SVT with the positron forward
  - $E(e^{-}e^{+}) \sim E_{beam}$ just like radiative tridents
- We can reduce this background quite a bit
  - require positron hits in L1
  - requirements on positron DOCA and $pT(e^{-}e^{+})$



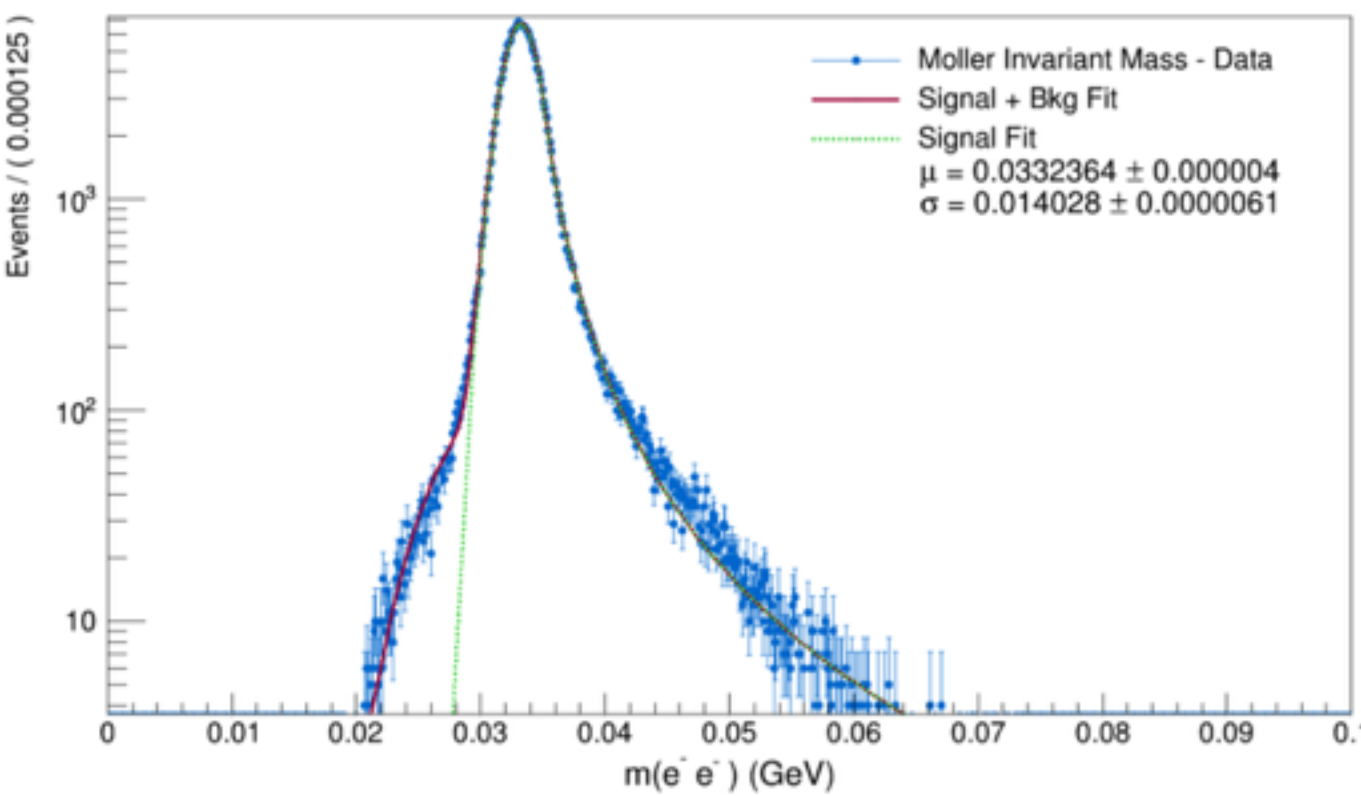


Mass resolution



Use mass resolution from MC at various A' mass hypotheses …how do we calibrate?

Luckily, at 1.05 GeV, we have a large number of Moller-scattered events in our detector ($e^-e^- \rightarrow e^-e^-$)
…these events have defined invariant mass (and well determined p vs angle)

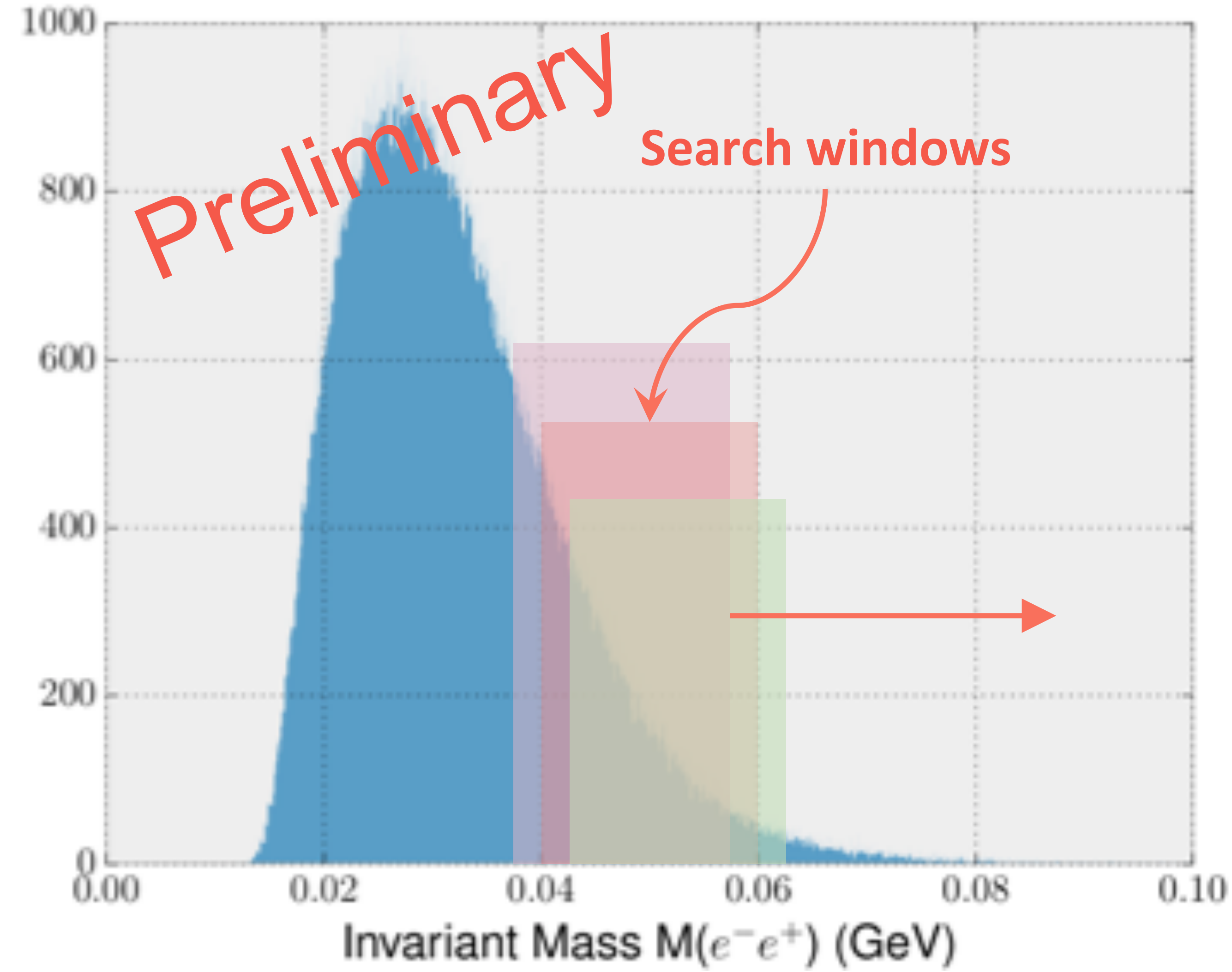


We see ~10% difference between Moller data and MC

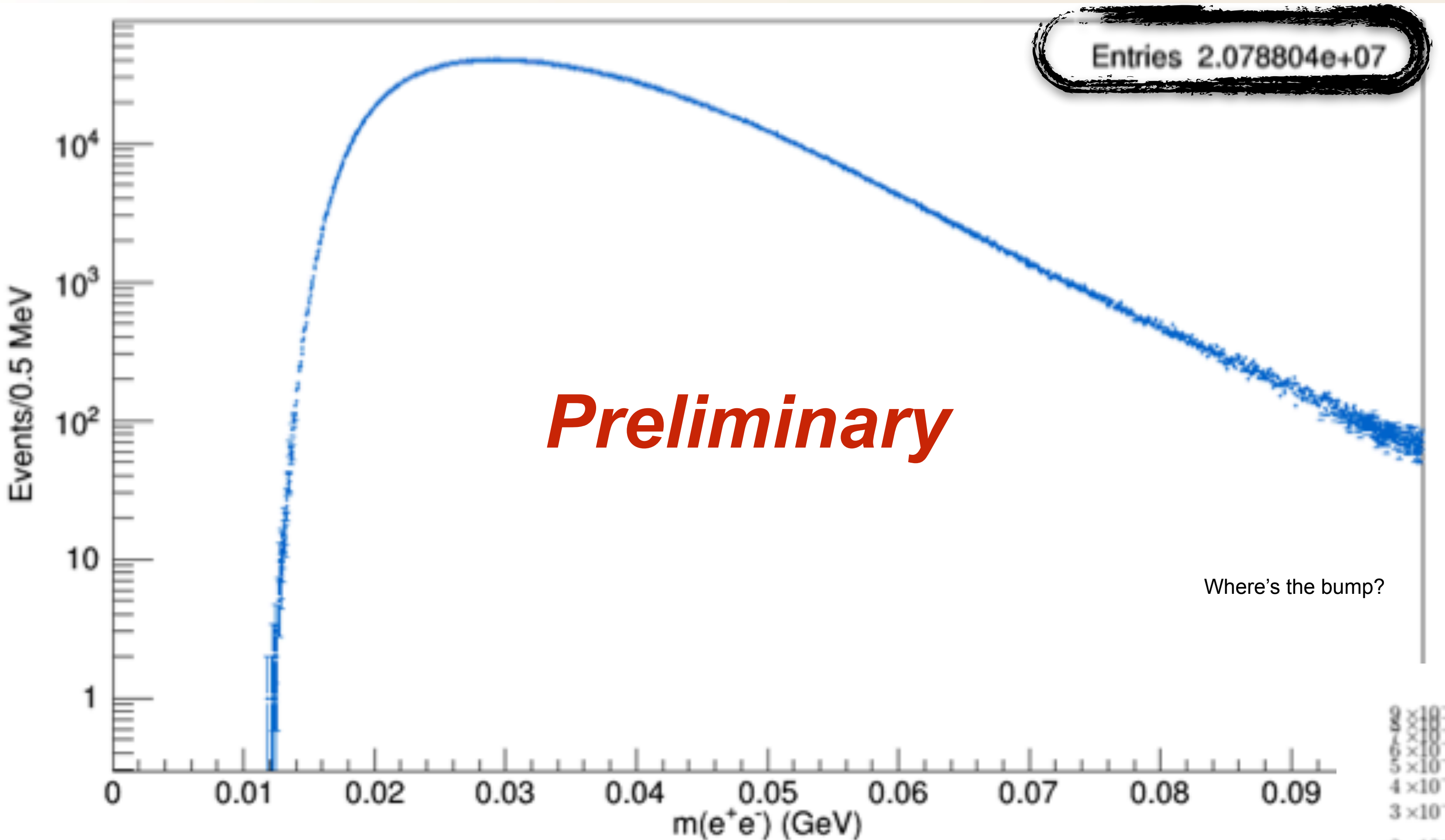
In the bump-hunt fits, actually use the MC resolution scaled up by this 10%

Mass spectrum scan

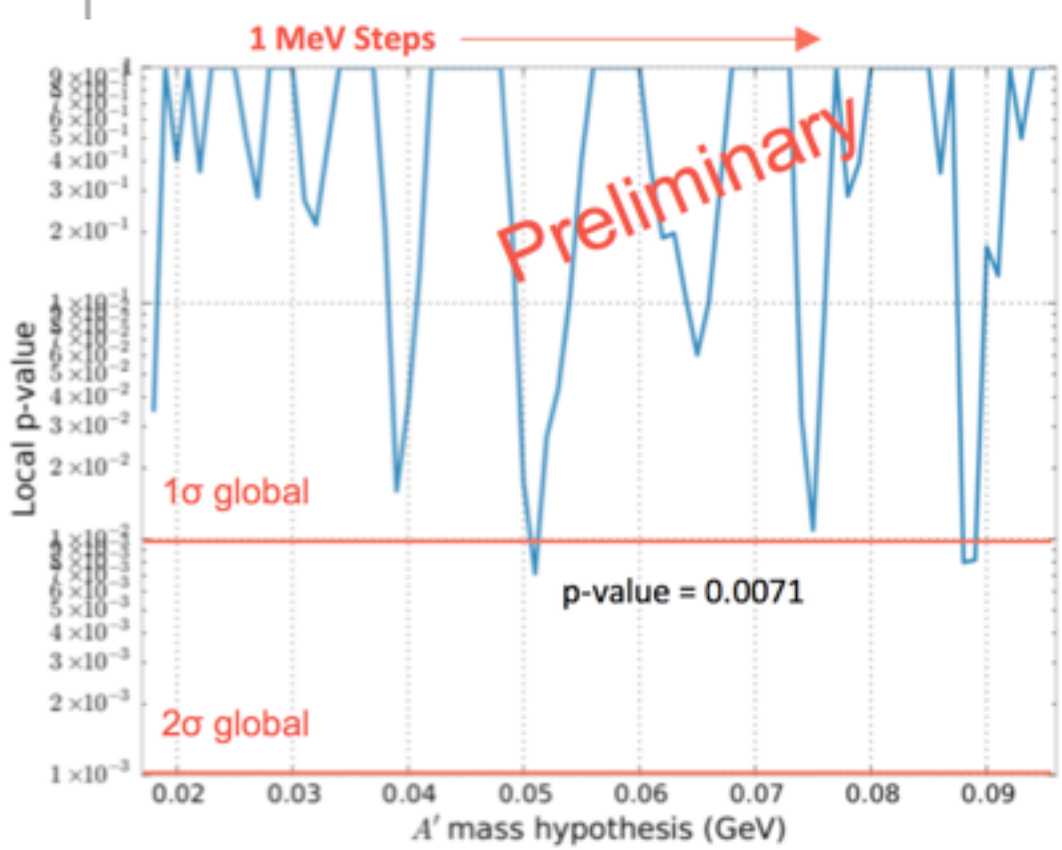
- Scan through the mass spectrum and search for a bump!
- Background: P7, parameters floating
- Signal: Gaussian, mass fixed (scanned), sigma fixed to resolution
- Search window is "many times" the resolution
- Step size: 1 MeV
- "local" signal significance found using likelihood ratio of signal+bkg vs bkg only



HPS 2015 Engineering Run invariant mass spectrum



in 1.7 days!



HUGE BUMPS!

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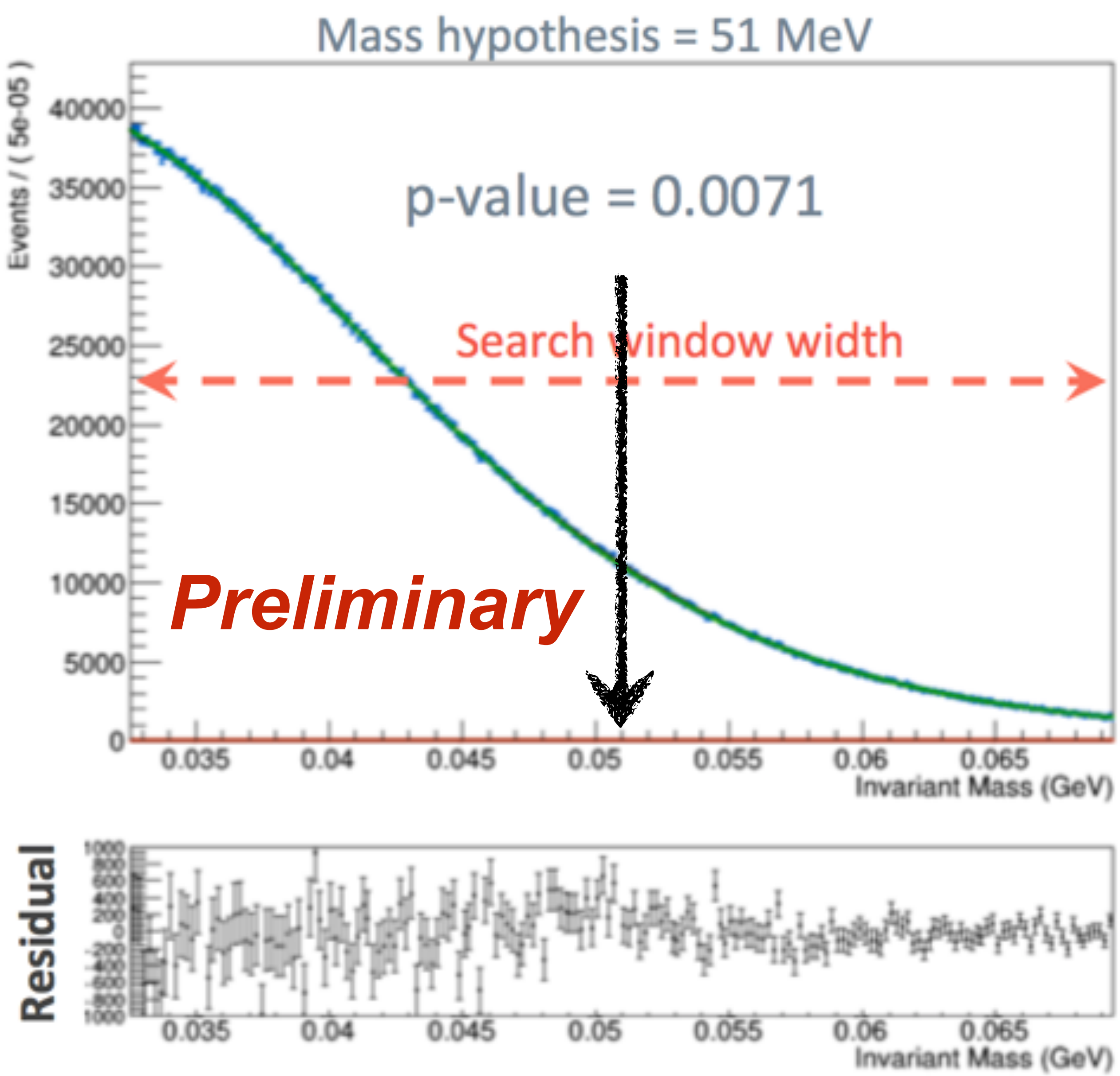
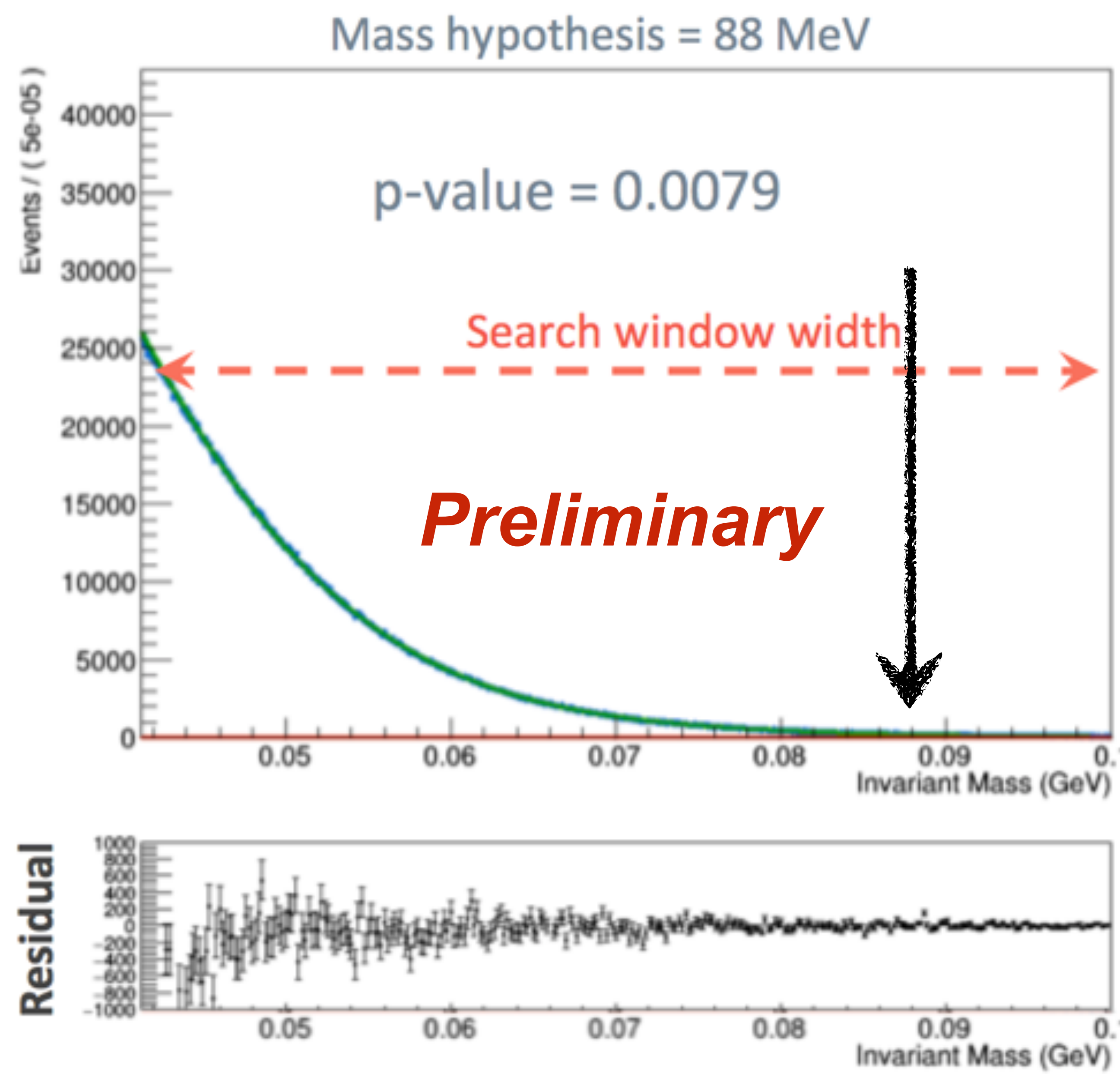
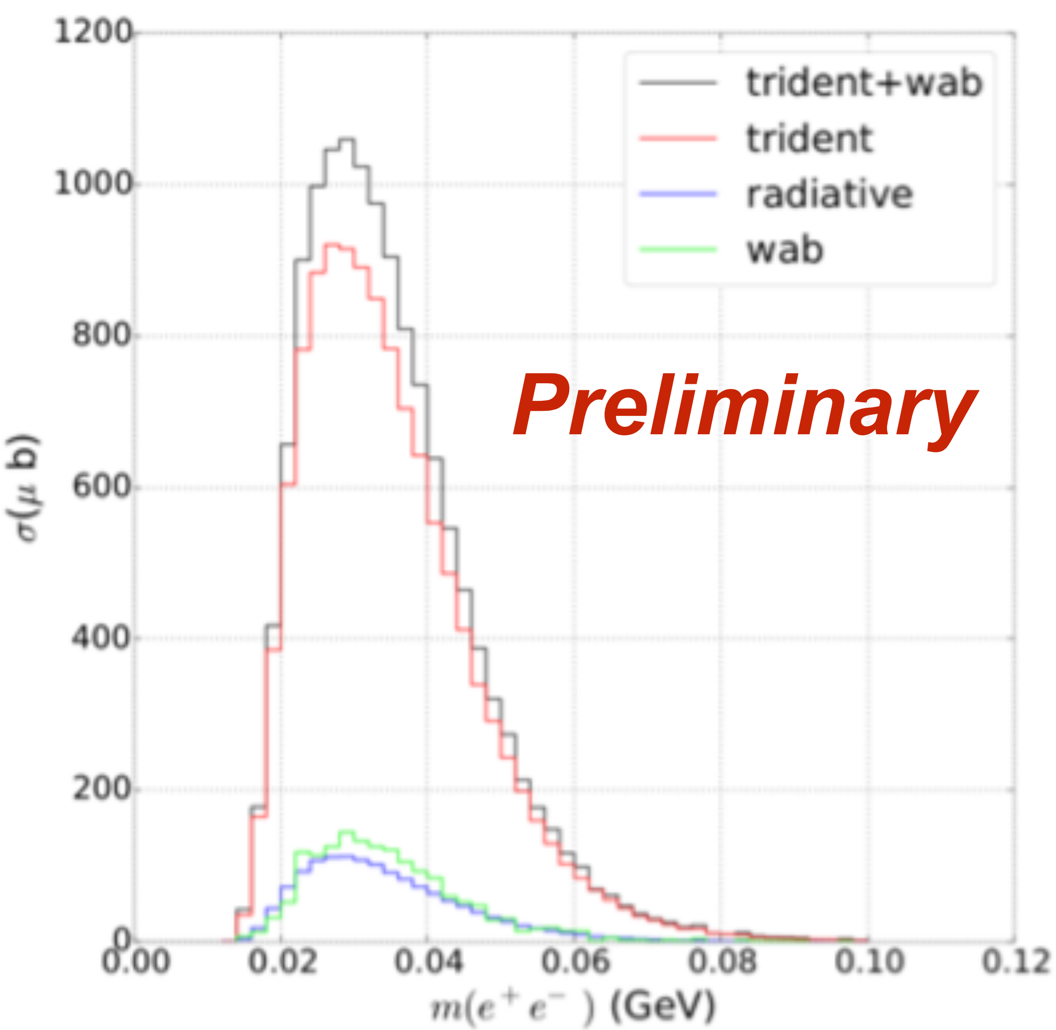
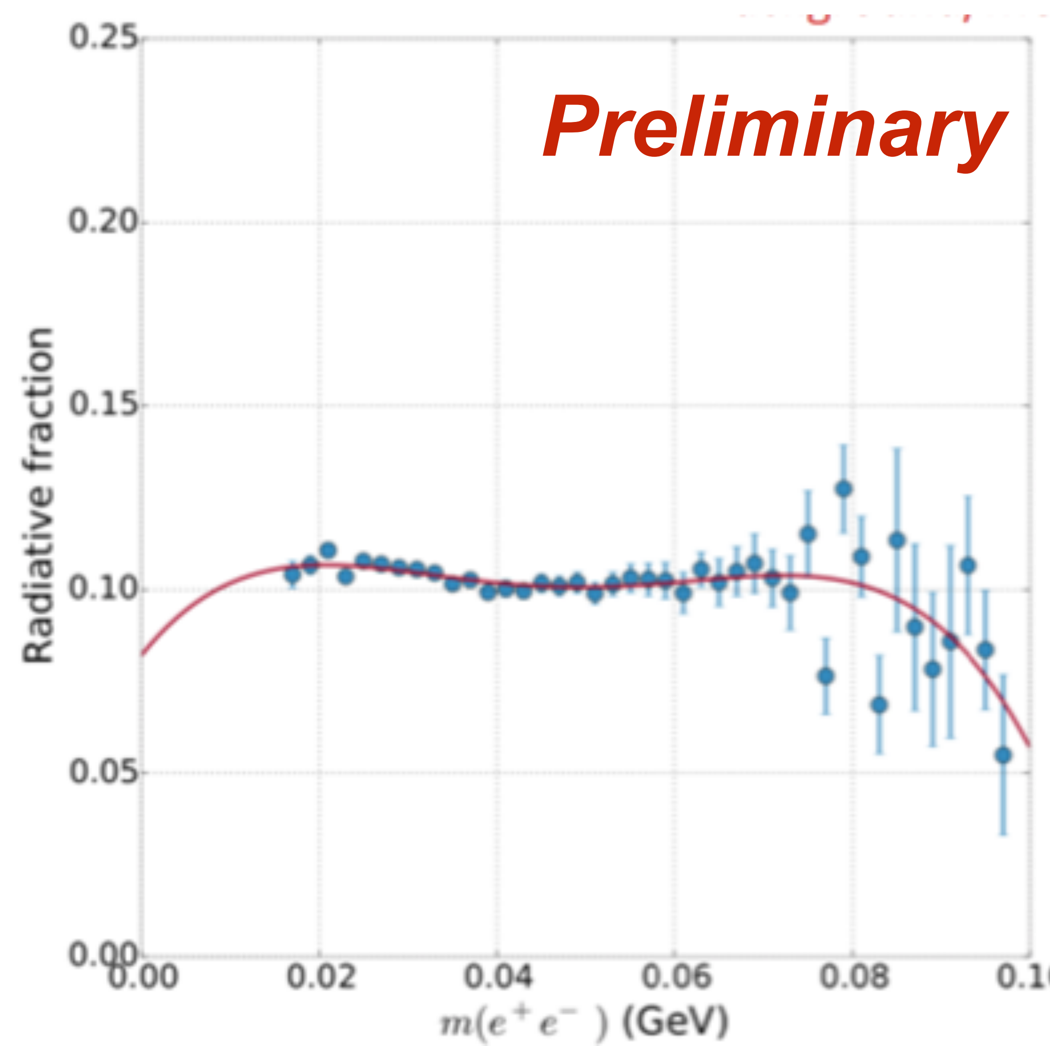




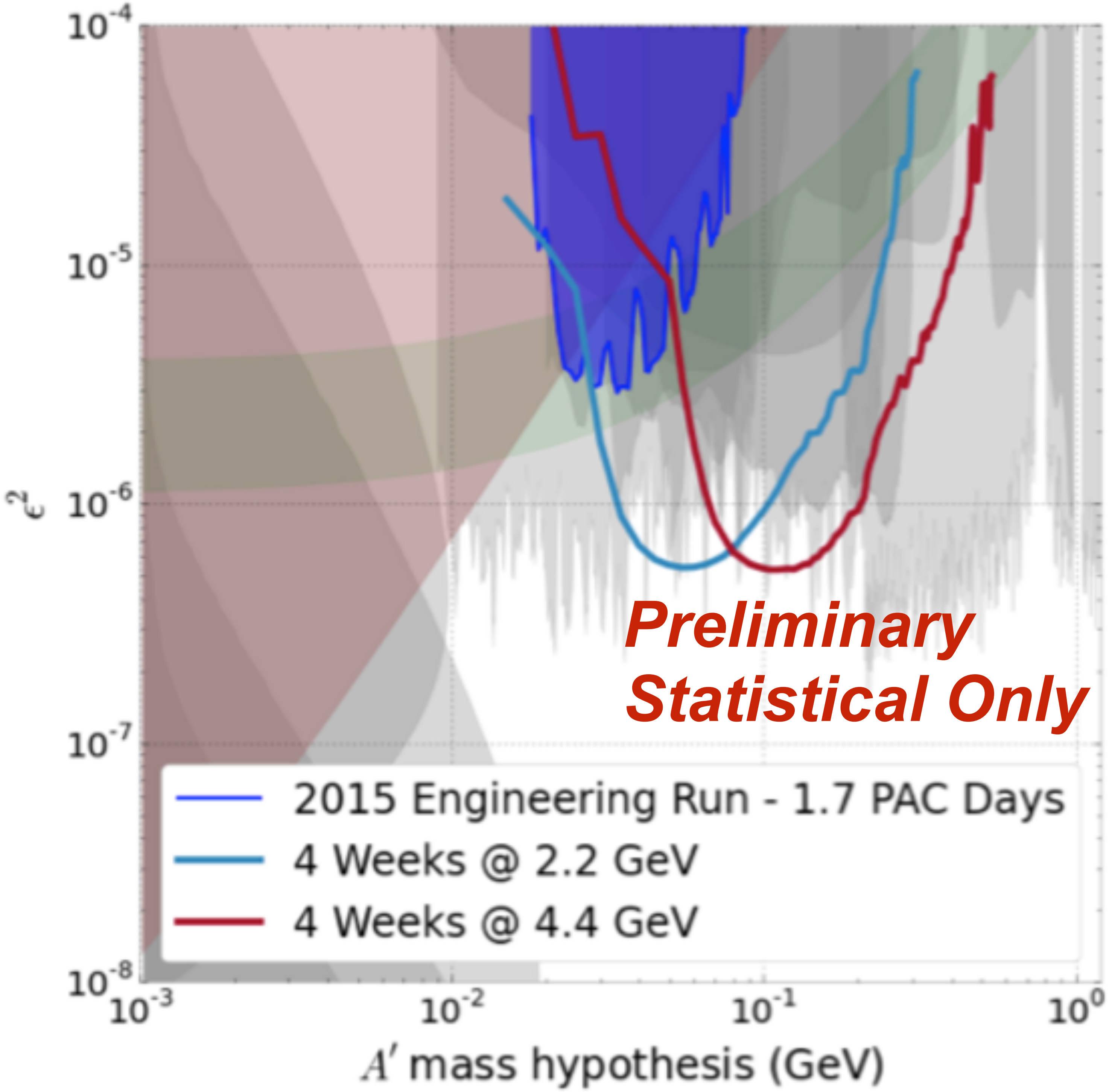
Determining the Radiative Fraction

- As mentioned, fraction of radiative events determined from MG5 + full detector simulation
- We include WAB events in our definition of "radiative fraction"





Beyond the HPS 1.05 GeV Bump-Hunt Upper Limit

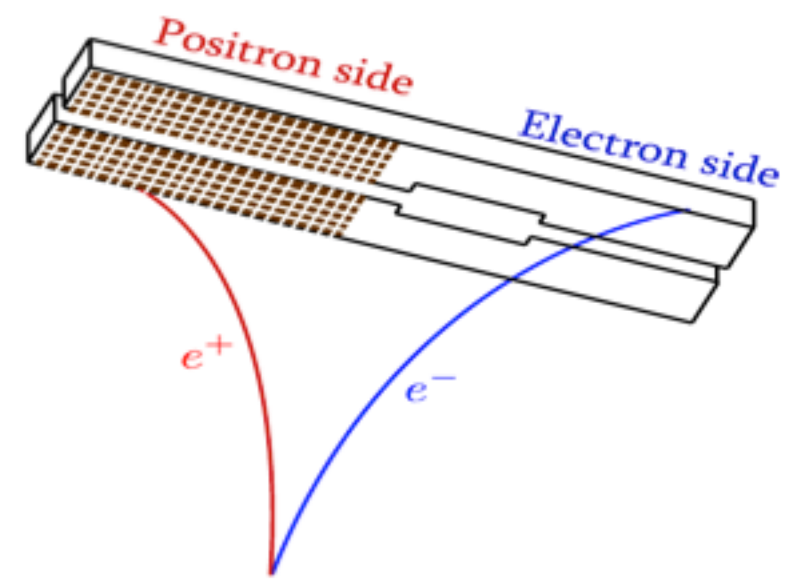


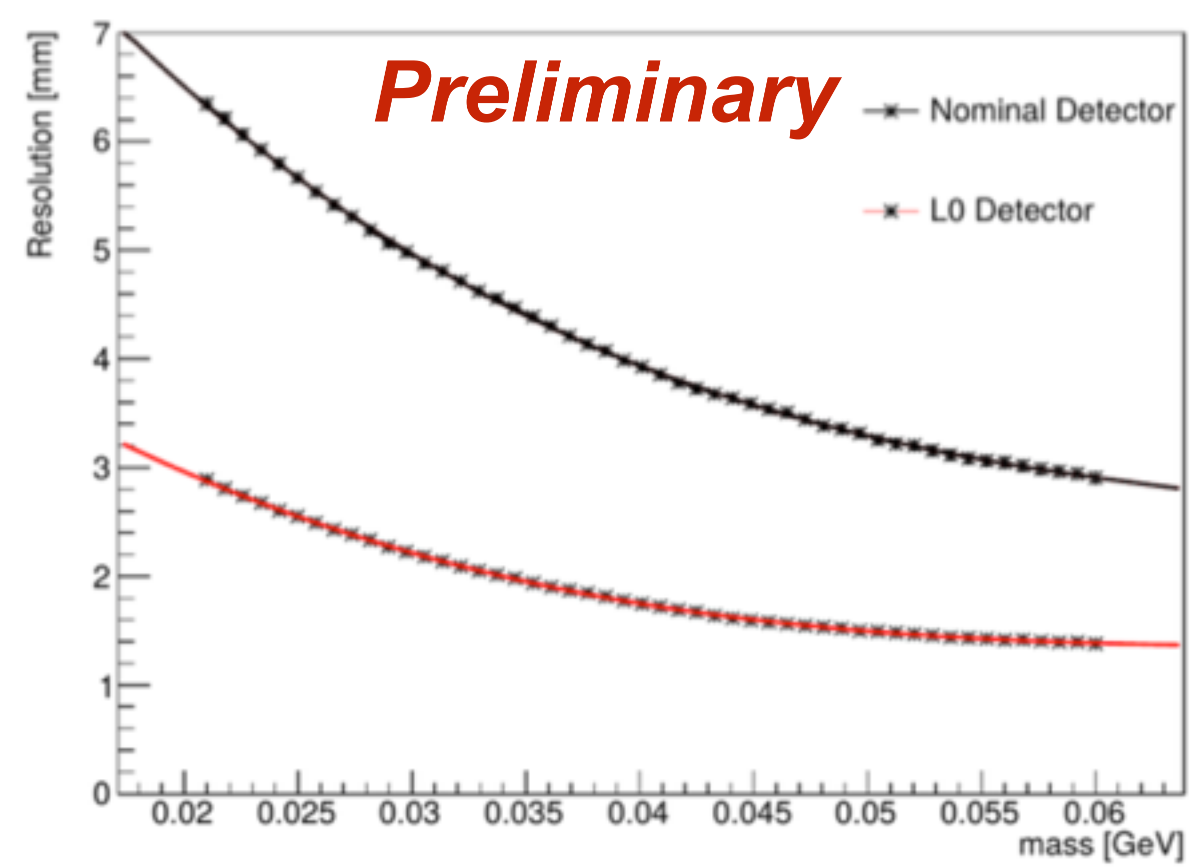
The limits for 2.2 & 4.4 GeV are simply scaled from the 1.7 days @ 1.05 GeV

Wait…why isn't this as good as you're proposal?

What's next? Possible upgrades!

- We are finding out proposal reach was too optimistic…a few reasons:
  - somebody (me) got the acceptance the ECal wrong…didn't account for the electron hole
    - this cuts down low-mass acceptance by a lot!
  - didn't account for WABs (smallish effect)
  - for displaced vertices (doesn't effect bump-hunt results), assumed flat efficiency vs decay distance (up to layer 1)
- To address some of these, two proposed upgrades:
  - add a hodoscope in front of positron-side of the ECal…trigger on just positrons
    - adds a lot of low-mass acceptance, including in the ECal hole
  - add an SVT layer at 5cm (layer 0)
    - reduces vertex position resolution by ~x2





Final Thoughts/Take Home Message

- Nobody knows what dark matter is…really, nobody
- Light, thermal dark matter is really a possibility and it has not been probed in detail
  - LDM *requires* a light force carrier
- Dark/Hidden/Secluded sector physics (where LDM could live) is pretty much mainstream now
  - 10 years ago it was considered a wacky, far out idea…now we have a huge community, almost every experiment has folks working on it, and DOE is hosting workshops about what the field should do and ***build*** in the next 10 years
- HPS ***finally*** has a public result, though no new territory yet
  - Submittal of Eng. Run bump-hunt results *very soon*
  - we live & die, as an experiment, through our displaced vertex reach and we hope to have an upgraded expected reach, based on what we observe in the Eng. Run datasets, in the next few weeks/months
  - sneak peak, 1 week of beam time will not be enough … good thing we have 180 PAC-days

QED Tridents @ 1.1 GeV

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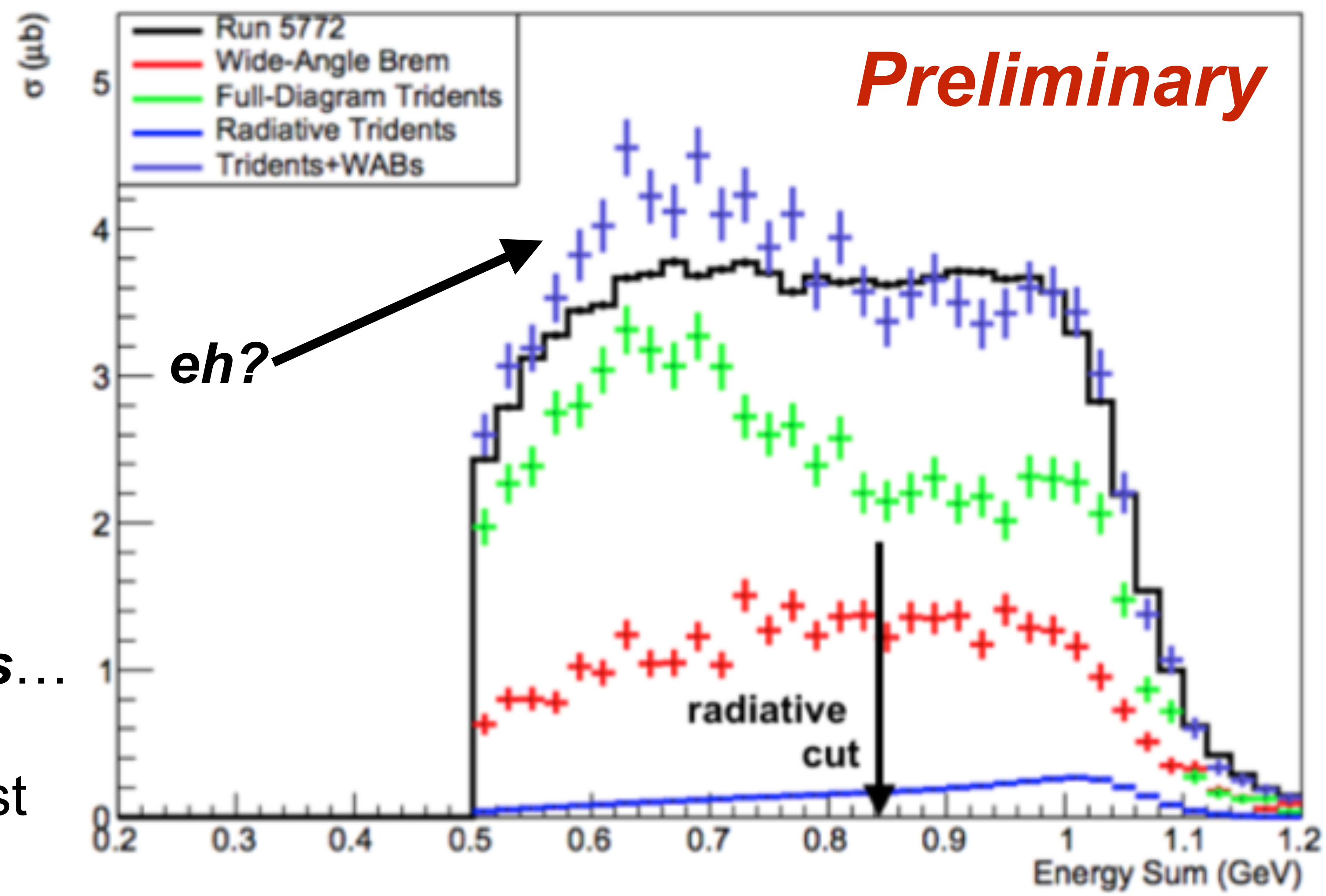
signal yield limit → (m,ε) limit requires the fraction of radiative events in the sample…***so you better believe the events you're seeing are tridents!***

we did detailed studies of the e^+e^- rates and distributions measured in our detector…***and found lots of mysteries***…

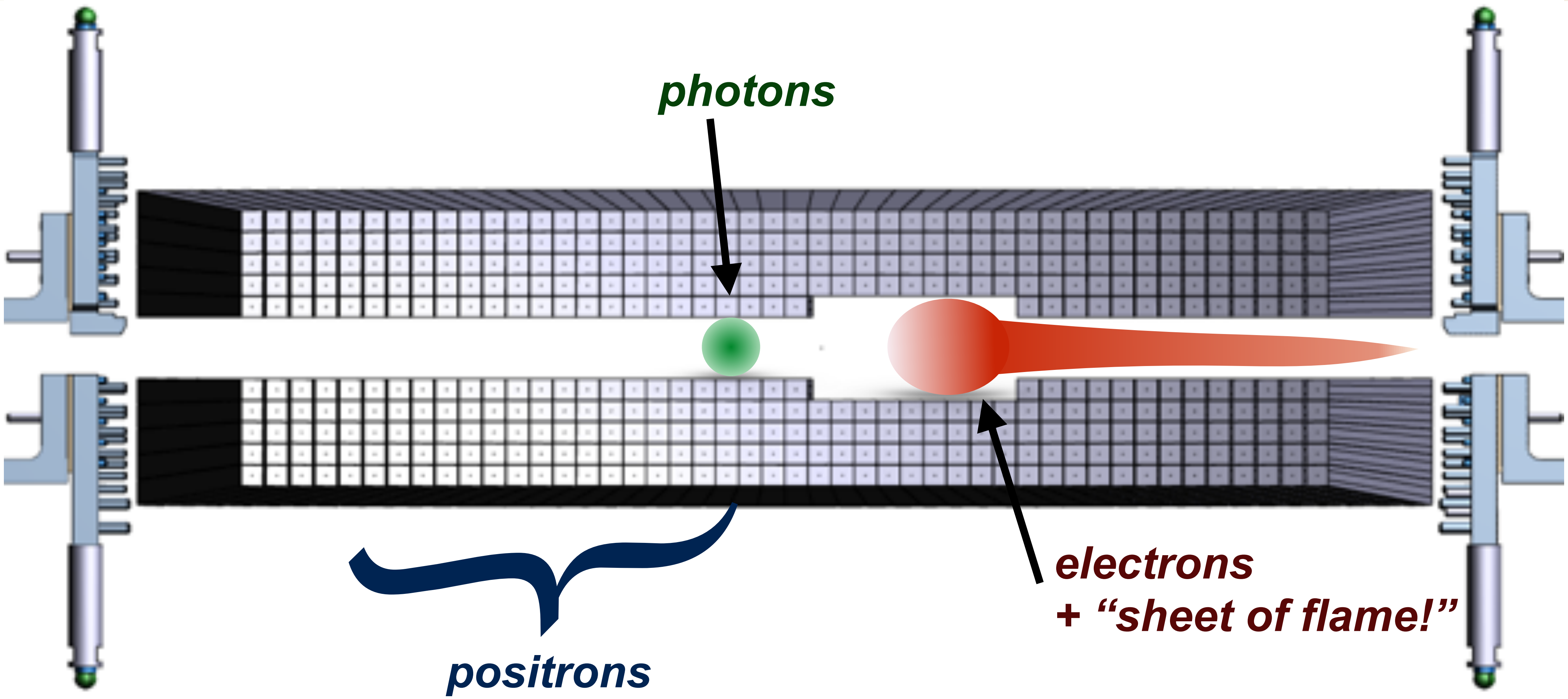
- event generators (MG4 vs MG5 vs first principles
  - alpha at 1GeV != alpha (80GeV)
- WABs
- efficiency and acceptance effects…
- ***Don't trust anything, ever***



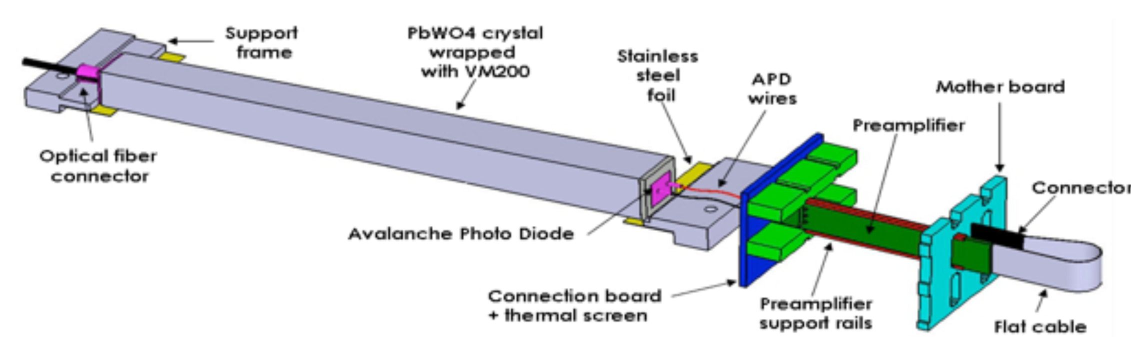
Lots of improvements made and now we believe our trident sample

Understanding this is a big part of what made it take so long to get this result out…

The HPS ECal



- ECal is 442 $PbWO_4$ crystals with APD readout
- Digitizer is JLAB-designed 250 MHz flashADC
- Used to trigger on e+e− pairs…cluster in top +bottom/left+right quadrants with ~8ns resolution



HPS Silicon Vertex Tracker (SVT)

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SVT is the key ingredient! Needs to measure momenta & vertex pairs with extreme purity in a busy environment. **Require low material & very fast.**

Si μstrip sensors

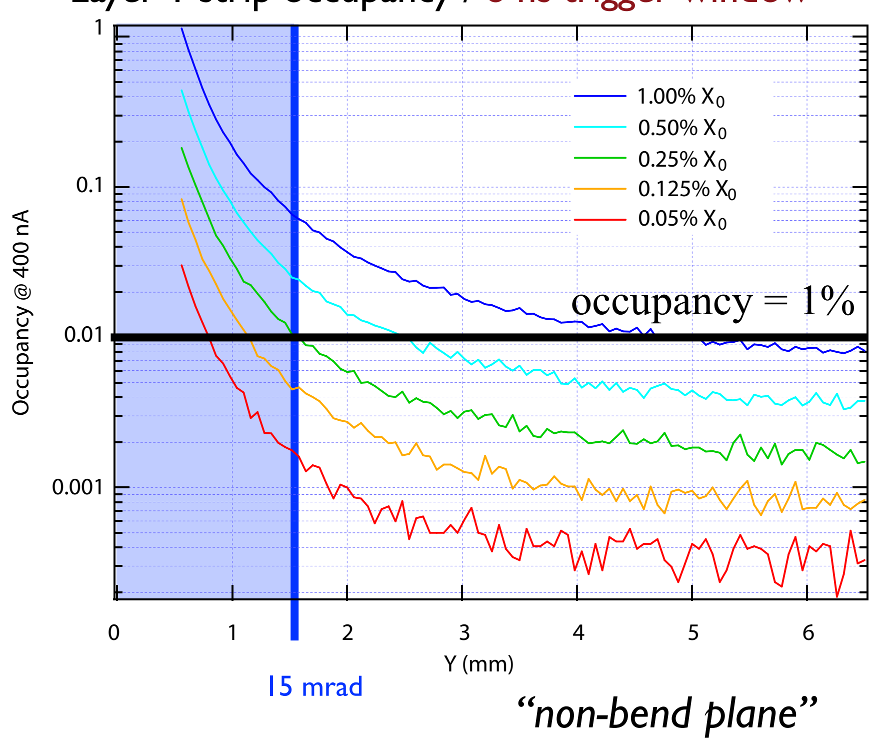
- Rad hard, thin (320μ), 60μ/30μ readout/sense pitch & $$$=Free (from RunIIb)

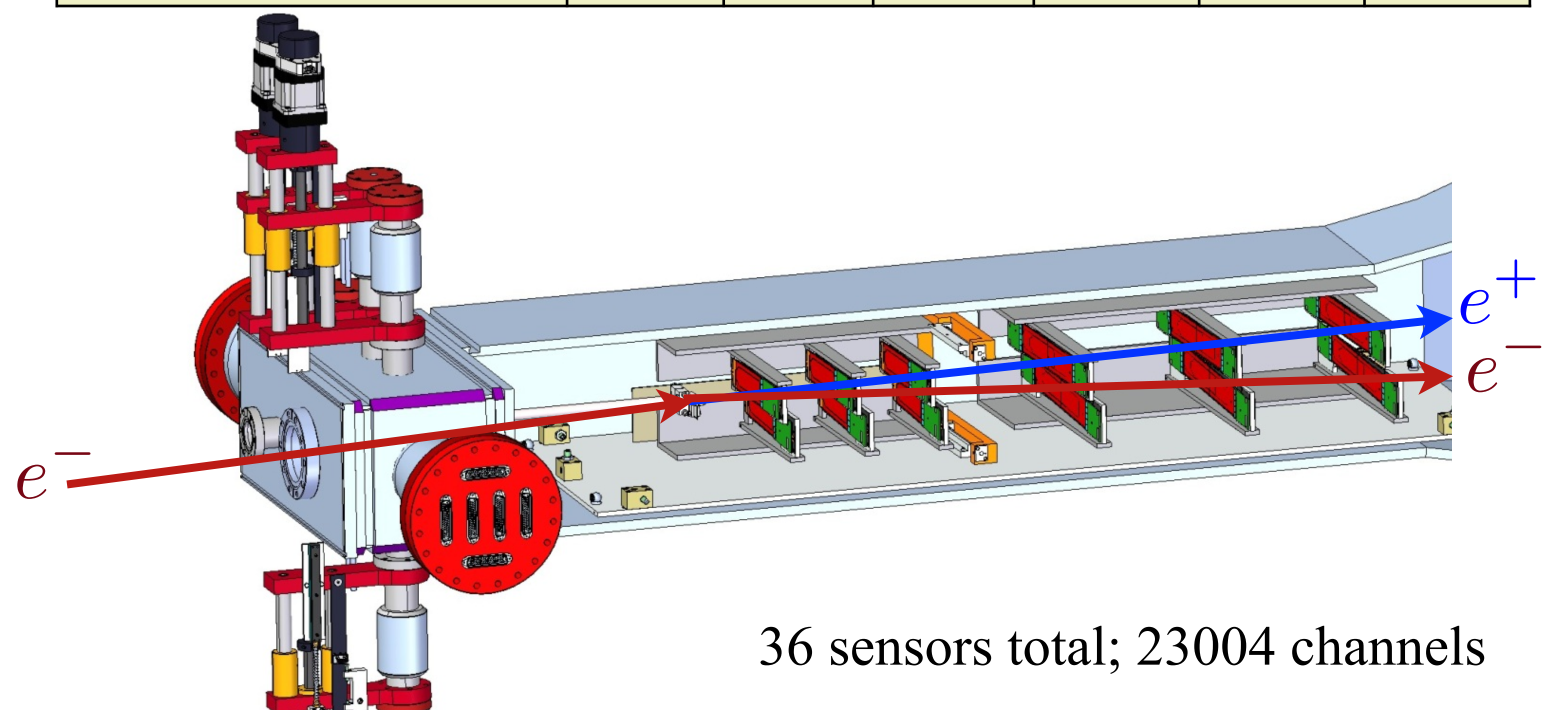
APV25 readout chip

- S/N>25 & ~2ns timing resolution

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120	≈ 120
Non-bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	4	4	4
# Stereo Sensors	2	2	2	4	4	4
Dead Zone (mm)	±1.5	±3.0	±4.5	±7.5	±10.5	±13.5

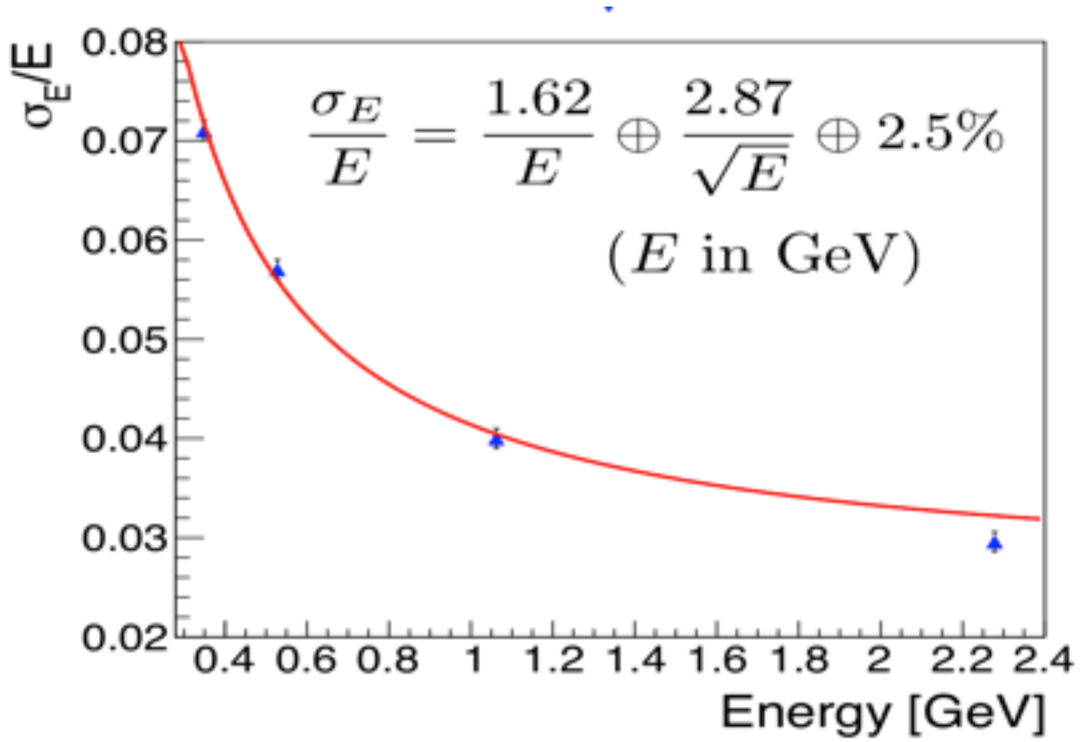
Layer 1 strip occupancy / 8 ns trigger window



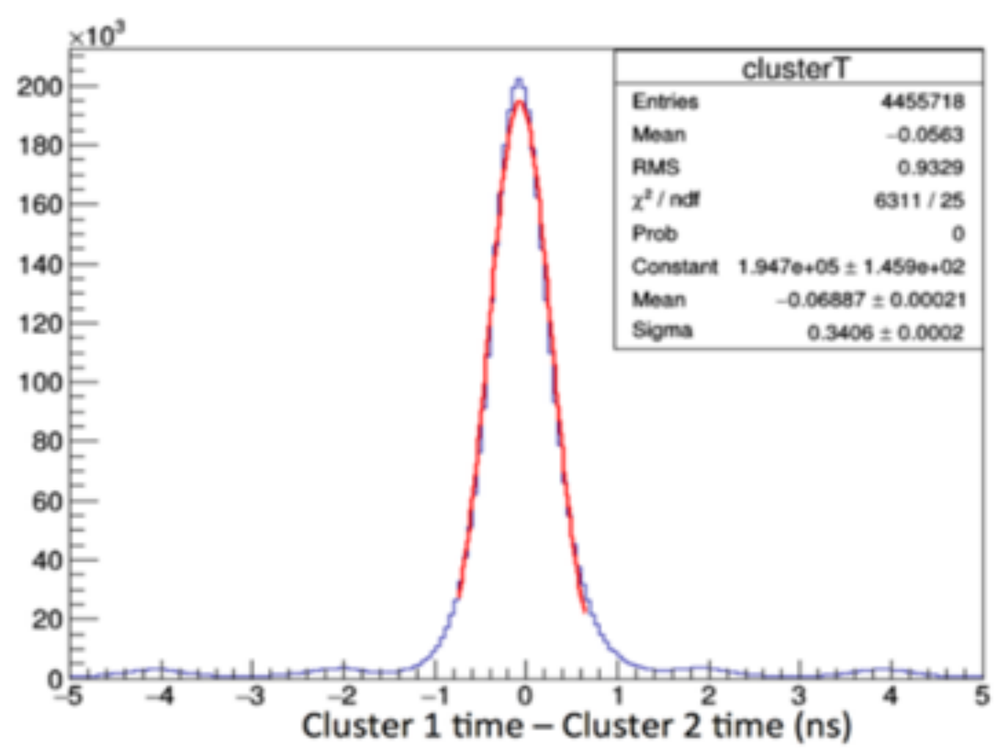


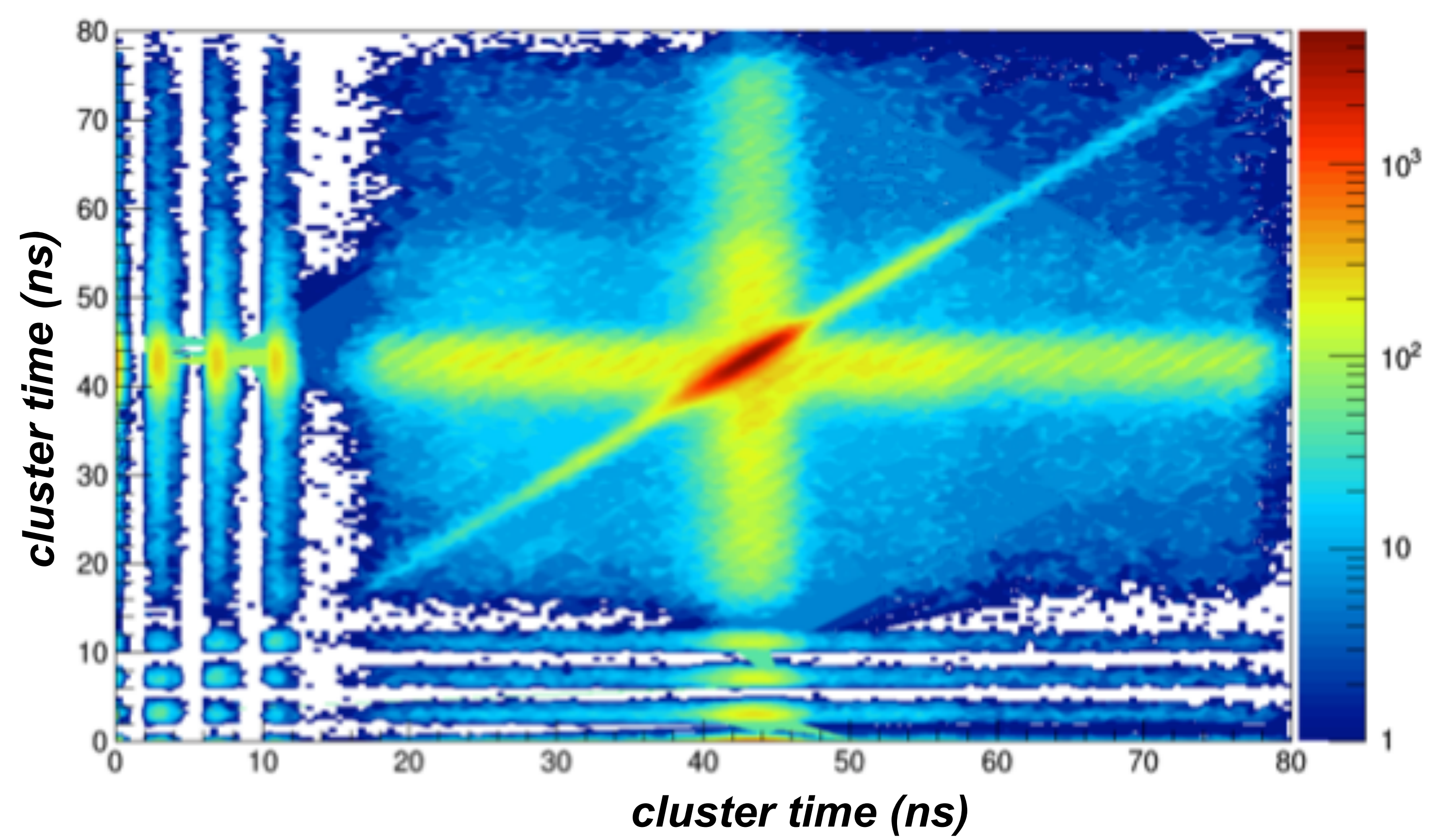
36 sensors total; 23004 channels

ECal & Trigger performance from 1.05 GeV run



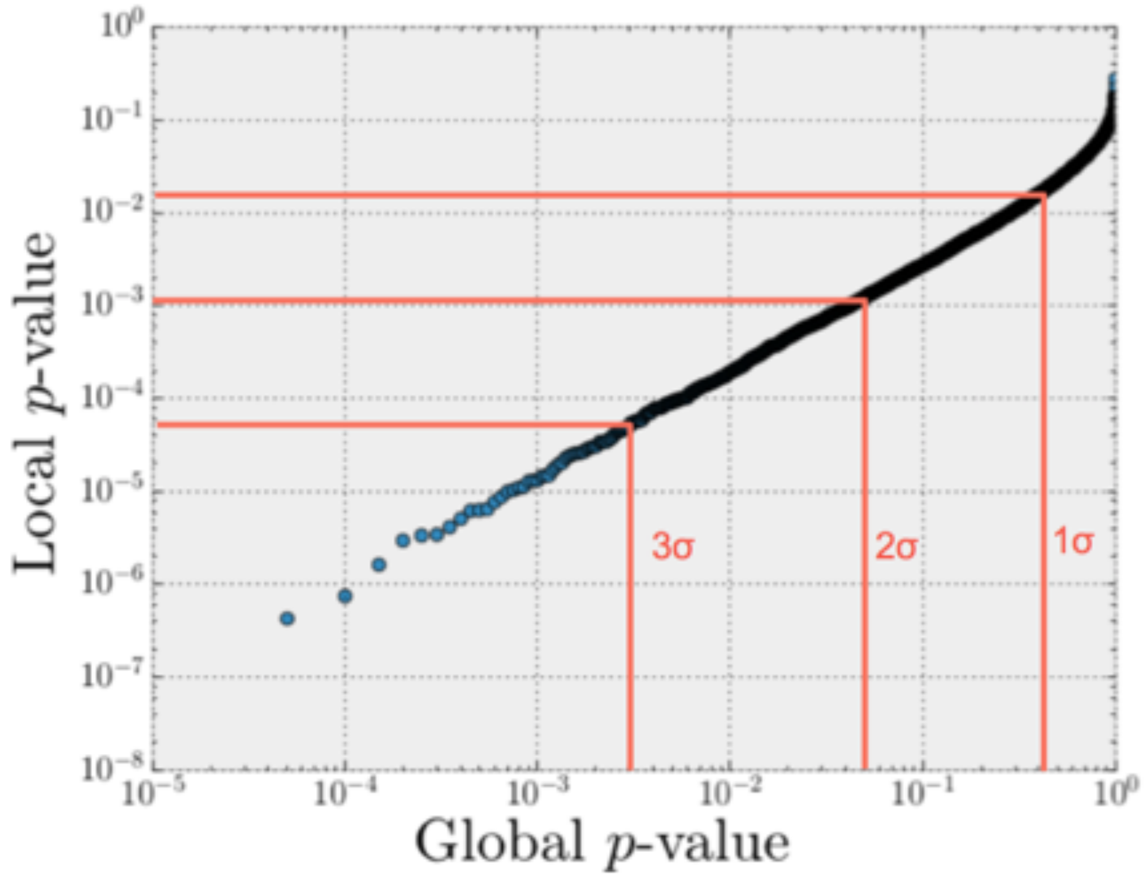
- ECal performed as expected!
  - <2ns relative cluster time resolution
  - reasonable energy resolution (as expected given the design)
- trigger/DAQ capable at >100kHz running, though SVT occupancy considerations max us out at ~20kHz



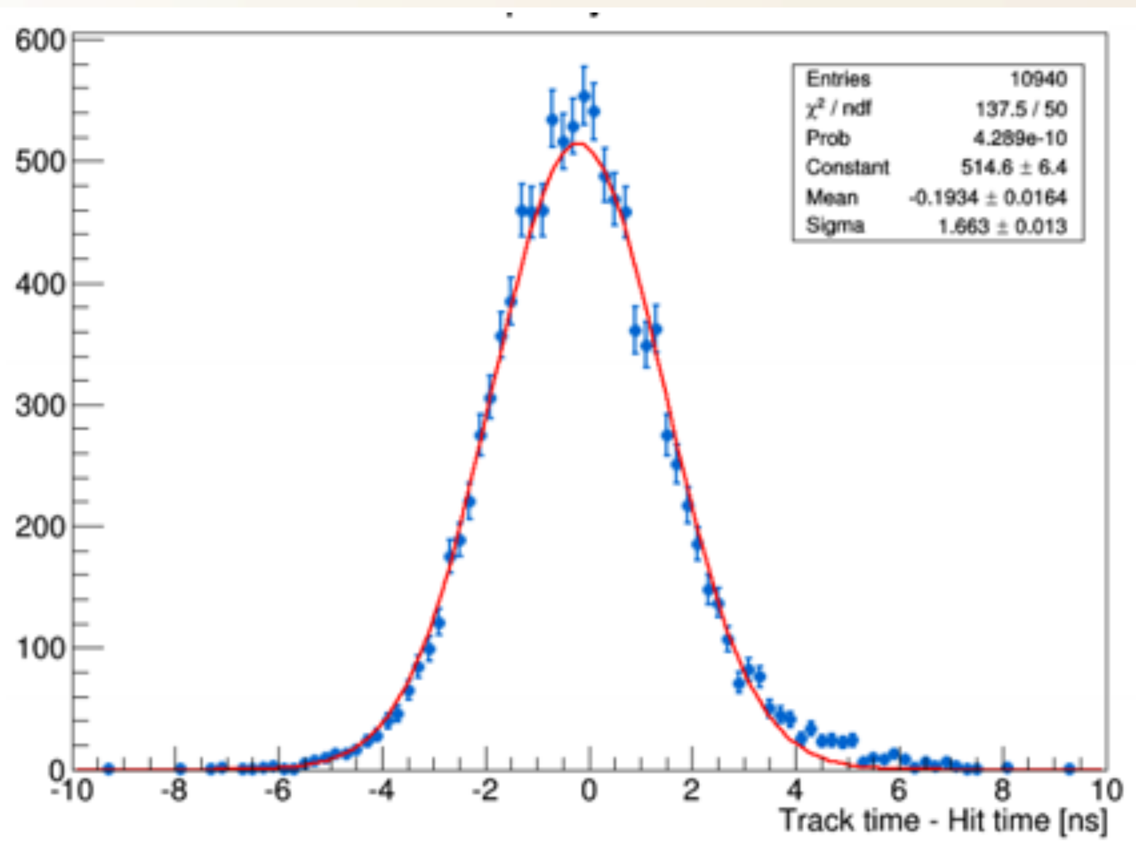


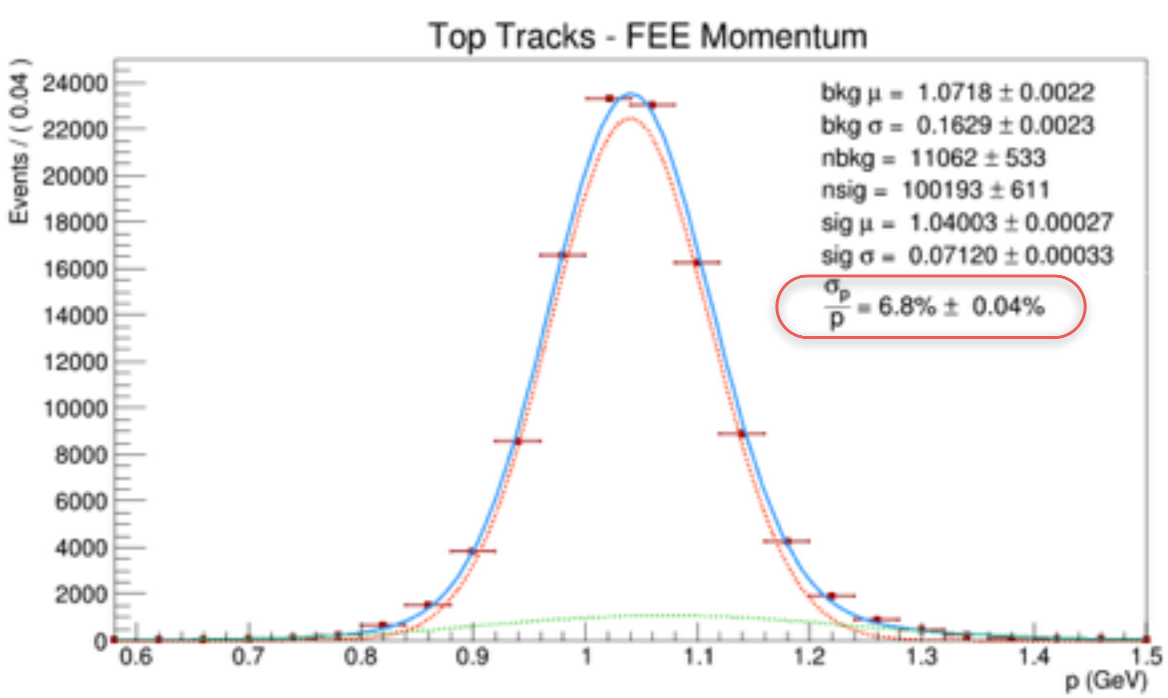
Accounting for look-elsewhere effect

- When you're doing a scan like this, must ask the right questions
- "What is the probability I see a signal significance fluctuation of at least X% given the scan I'm doing"
- We account for this by doing a bunch of toy experiments, scanning, and plotting the p-value of the largest fluctuation
- Correct the "X-sigma" criteria for this effect

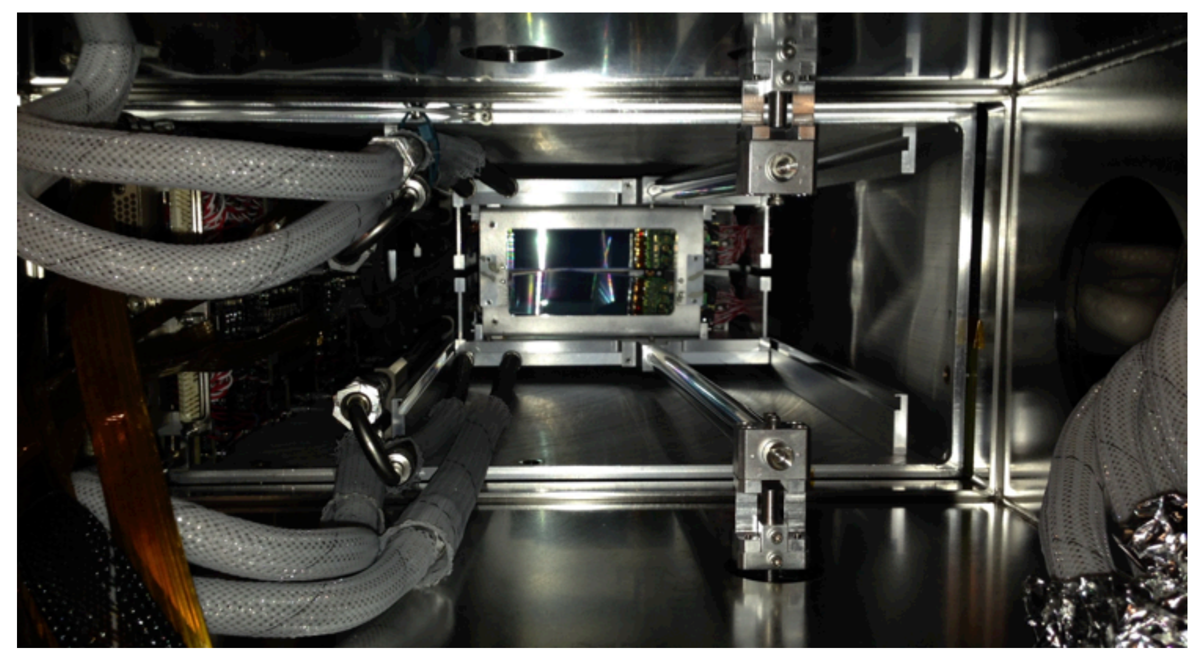


HPS SVT Performance from 1.05 GeV run





- SVT also performed well!
  - <<1% dead or noise channels
  - <2ns relative cluster time resolution
  - momentum and angular resolution as expected (dominated by MS)
  - occupancies roughly as expected from MC

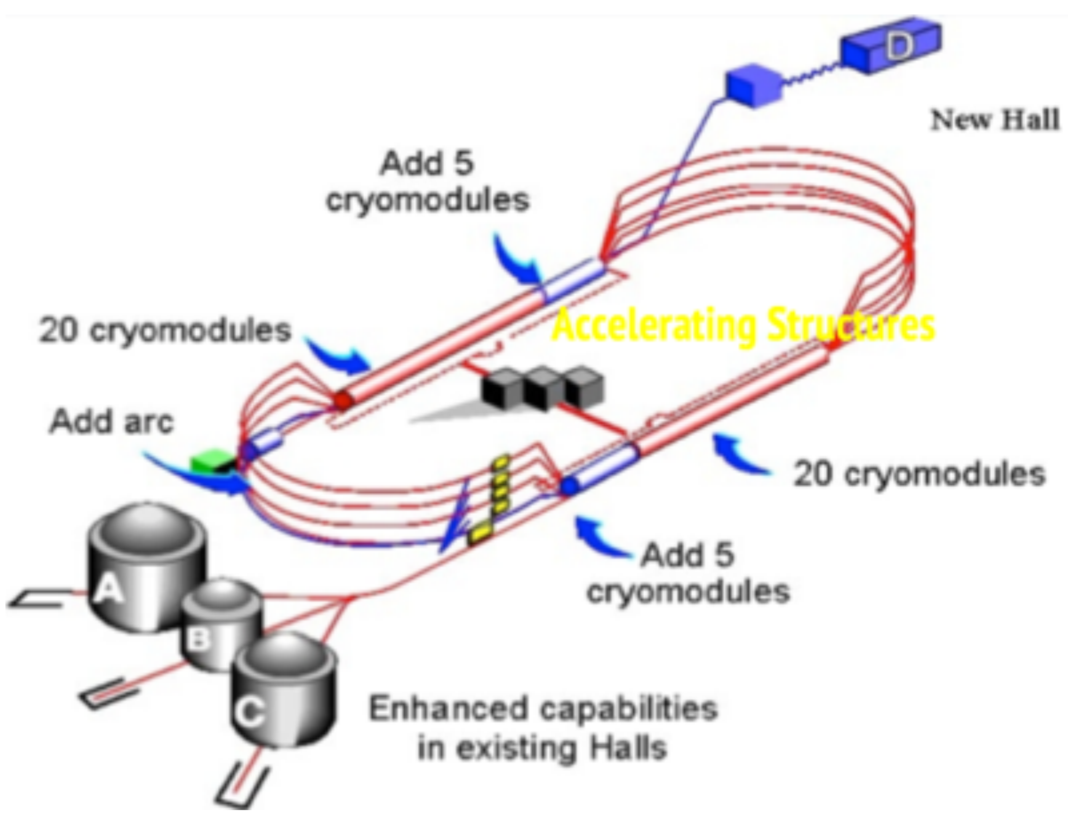


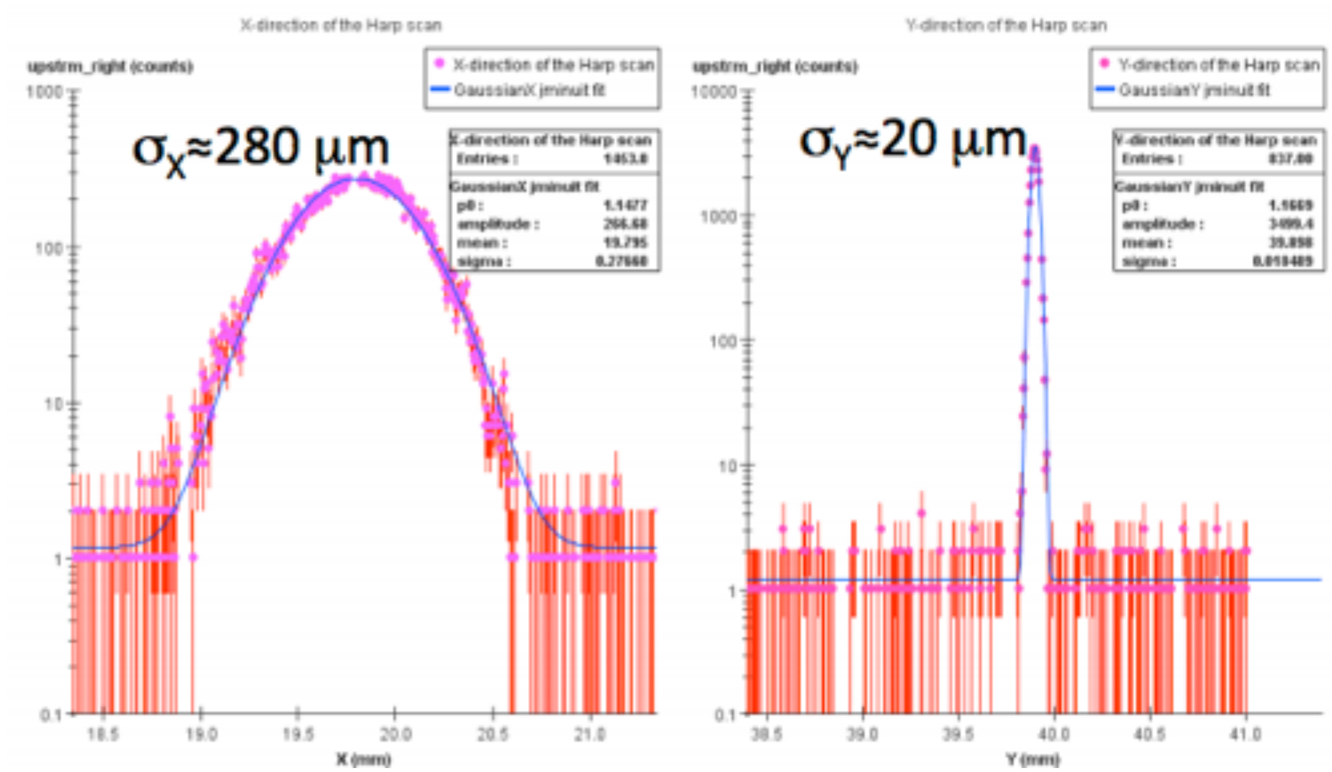
beam's-eye view of the SVT (looking downstream)

CEBAF and Hall-B @ JLAB

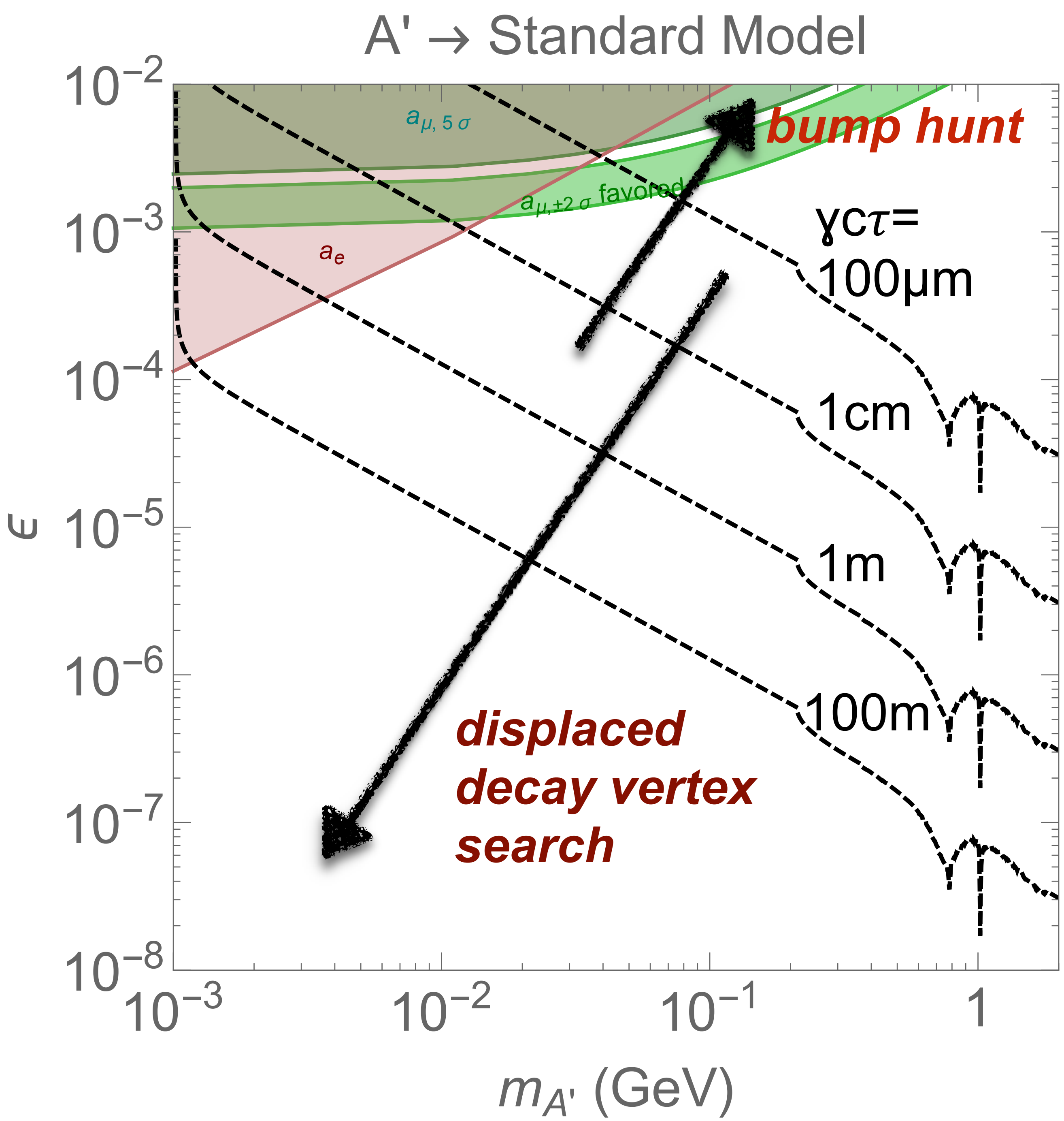
HPS sits in an alcove in ***JLAB Hall-B***…behind CLASS, in front of beam dump

- energy: ***1.1-11.1 GeV***
- current: up to ~***700nA***
- roughly CW…***2ns*** bunch spacing
- can focus beamspot ~ ***300μ*** × ***20μ*** at target with small beam halo
  - small beamspot lets us use the IP as a constraint for long-lived decay search





Two (roughly) complimentary types of searches



thinking about direct searches…

if (γcτ<~100 μm) bump-hunt;

if (γcτ > 1 m) displaced decay/“light shining through wall”;

…some mushy middle where both handles are useful;