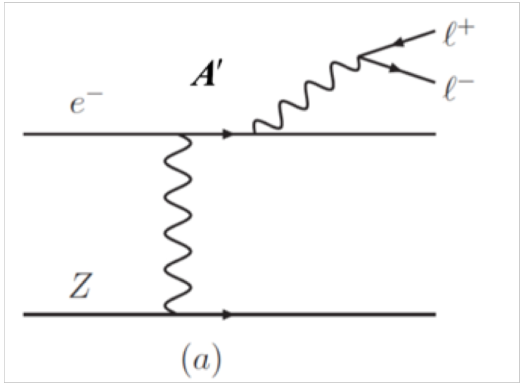
HPS Physics Analysis

Nathan Baltzell, JLAB

January 18, 2019

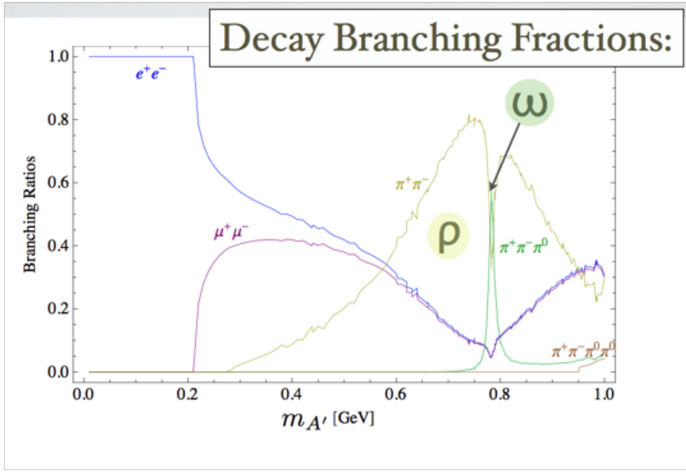
HPS Review

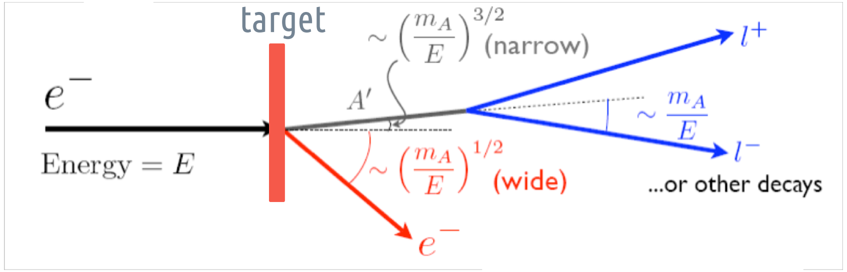
Looking for the A'



We try to produce A' via electroproduction..the A’ will decay to SM particles just like a virtual γ* “decays”, i.e. the ratio R!

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





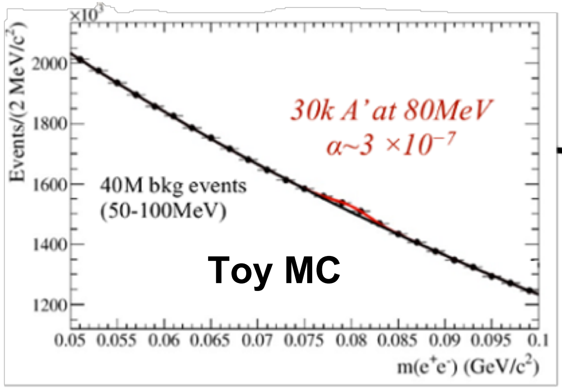
The A' (or radiative photon, same kinematics) is produced very forward, carrying almost the full beam energy → the HPS detector focuses on very forward coverage

Two Searches: Bump-hunt & Displaced Vertex

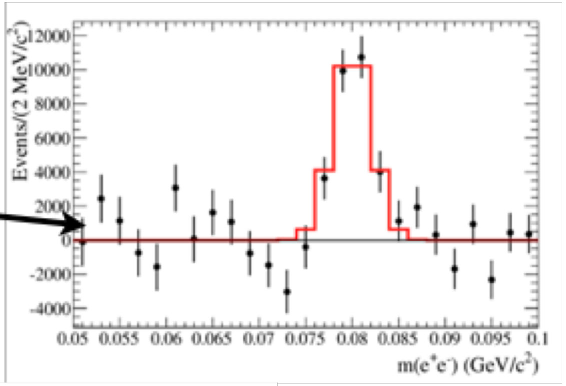
Massive

when we say “dark” photon we typically also mean “heavy”

look for peak in the invariant mass spectrum



subtract background

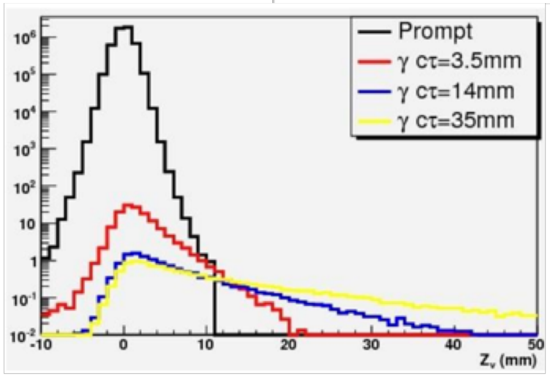


Non-zero lifetime

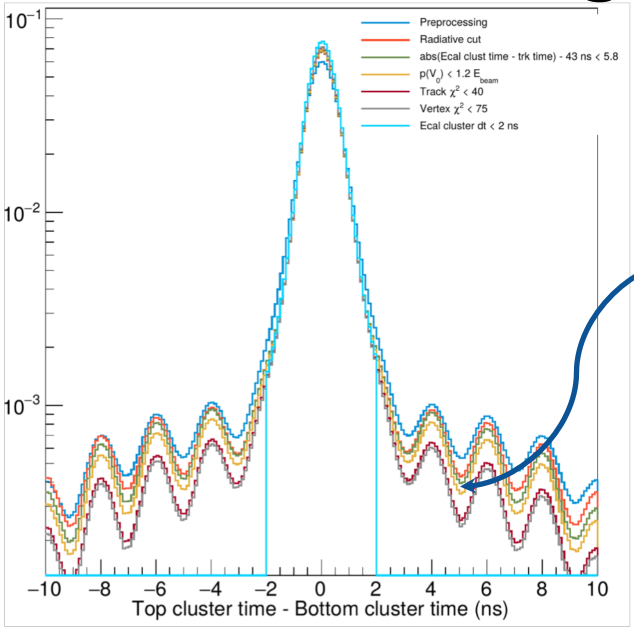
some regions of parameter space will have

decays that happen far from production target

backgrounds (typically) decay promptly



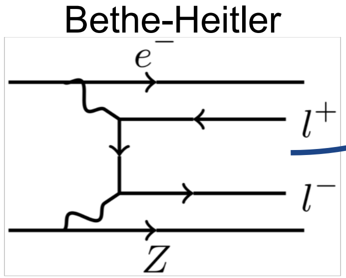
A' Search Backgrounds

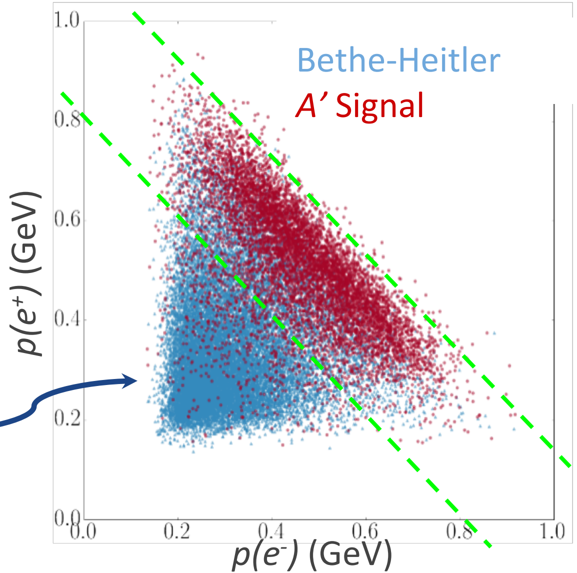


We generally try to keep a simple approach, particularly for this first analysis:
loose track reconstruction and track-ECal matching cuts
~2 sigma cut on relative ECal cluster times
<1% accidental e^+e^- pairs

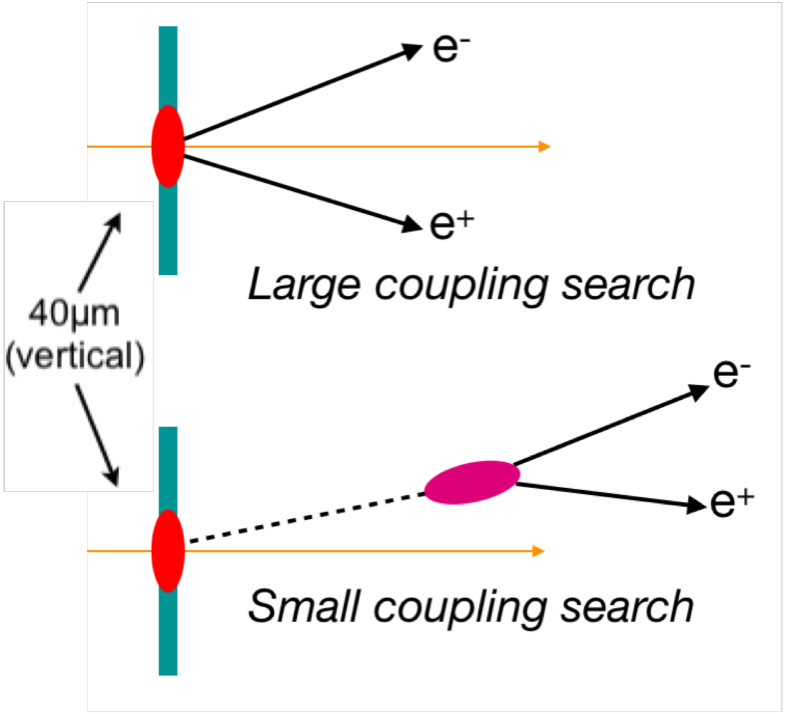
… also require that the e^+e^- momentum sum be greater than $0.8\times E_{beam}$

This is the single-best discriminant against Bethe-Heitler trident background...





Fitting the Vertex



two types of searches → two vertex 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

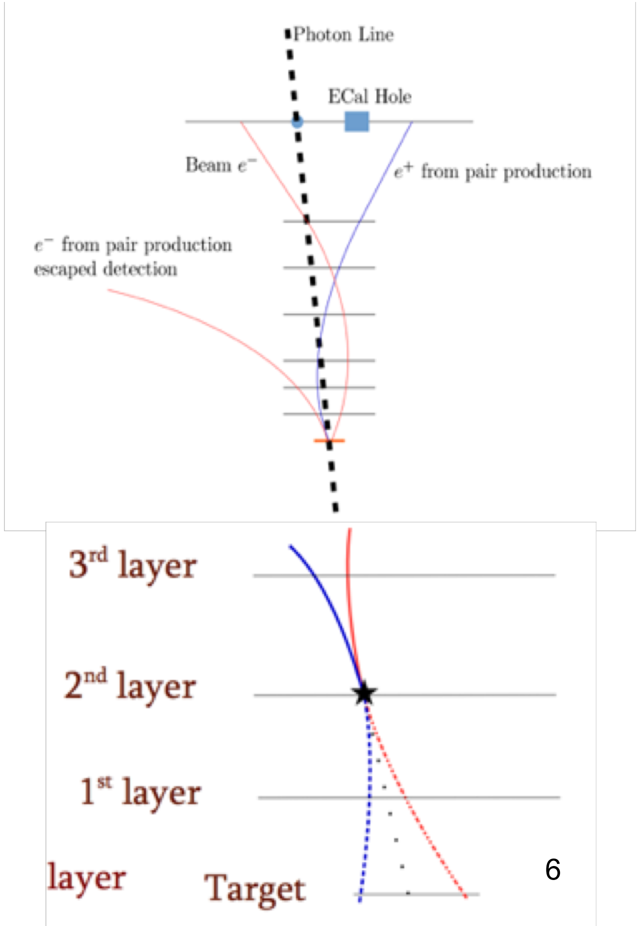
Small coupling A's decay outside of target → point decay products back to target

- good at removing poorly reconstructed tracks

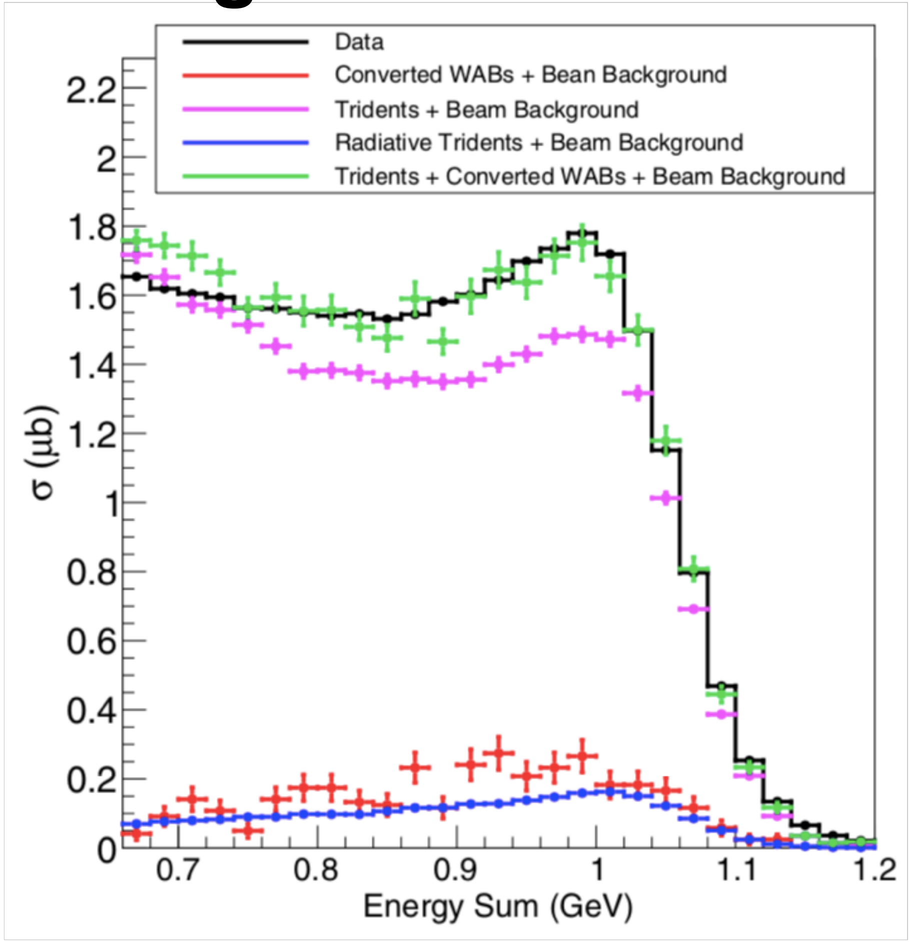
An unexpected background: Wide-Angle Bremsstrahlung

One thing we missed in the 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”
  - WAB: $e^{-}Z \rightarrow e^{-}_{\text{large } \theta}\, \gamma_{\text{large } \theta} Z$
- Gives HPS a large e-γ contribution to trigger rate, and a significant background when the γ converts in L1 or L2 SVT and the positron is forward
  - $E(e^{-}e^{+}) \sim E_{beam}$ just like radiative tridents
- We learned how to largely remove this background …
  - e.g. requirements on hits in L1, vertexing DOCAs, transverse momentum
  - ~80% reduction, leaving ~10% of our radiative e+e- from WAB



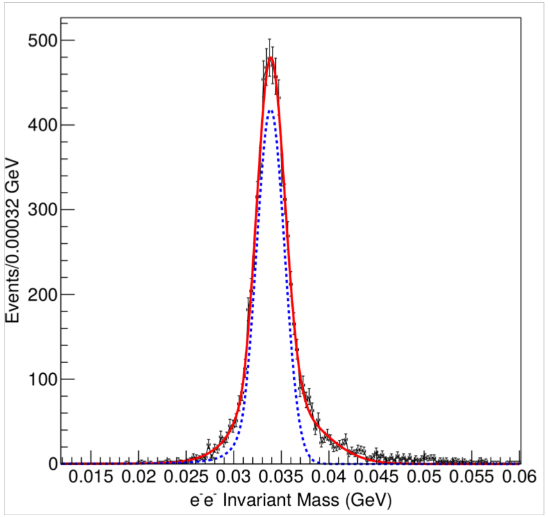
A' Search Backgrounds



MC-Data agreement for the 2015 run

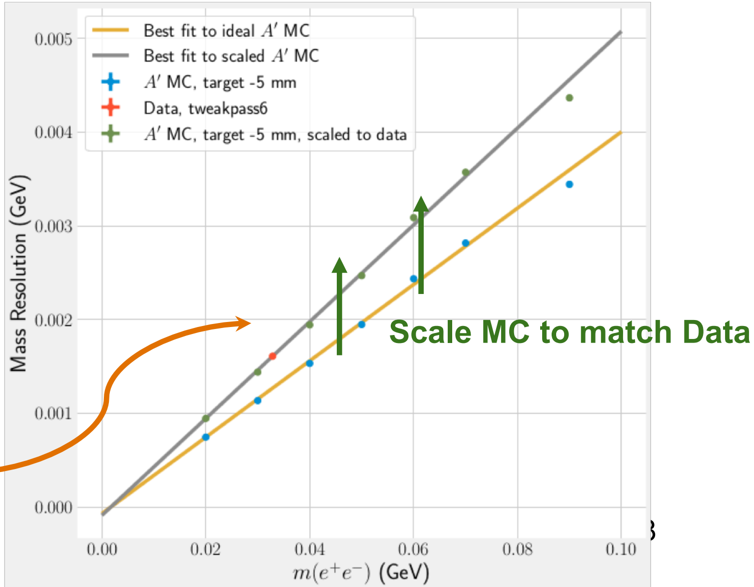
(published with the bump-hunt paper last year)

Mass Resolution (Bump-hunt)



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)

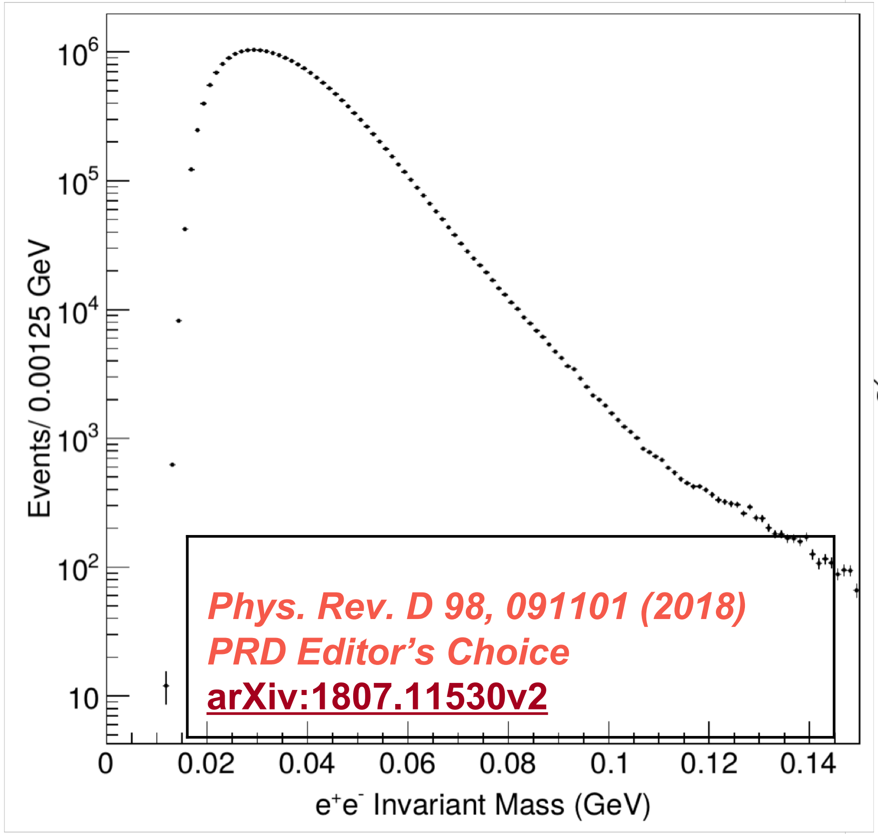


We see ~10% difference between Møller data and MC

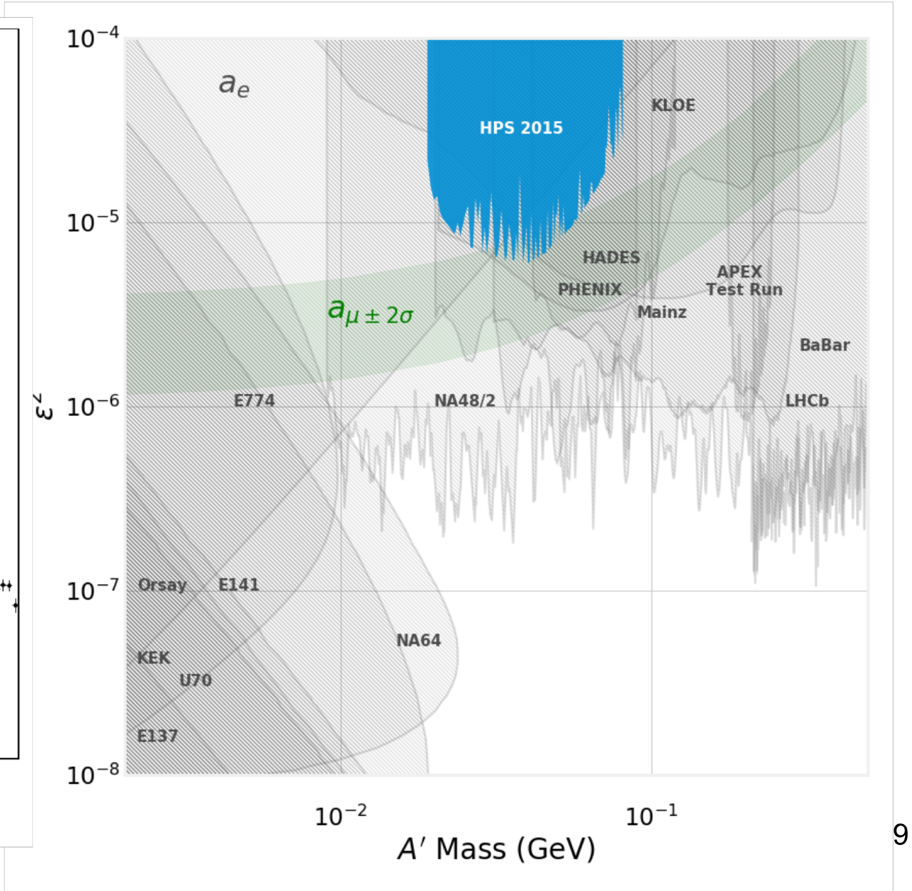
- Discrepancy between data and Møller Monte Carlo is due to mismatch of momentum resolutions

In the bump-hunt fits, actually use the MC resolution scaled up by this 10% so that this systematic is already folded into the result

2015 Data Bump-Hunt Results



Phys. Rev. D 98, 091101 (2018)
PRD Editor's Choice
arXiv:1807.11530v2

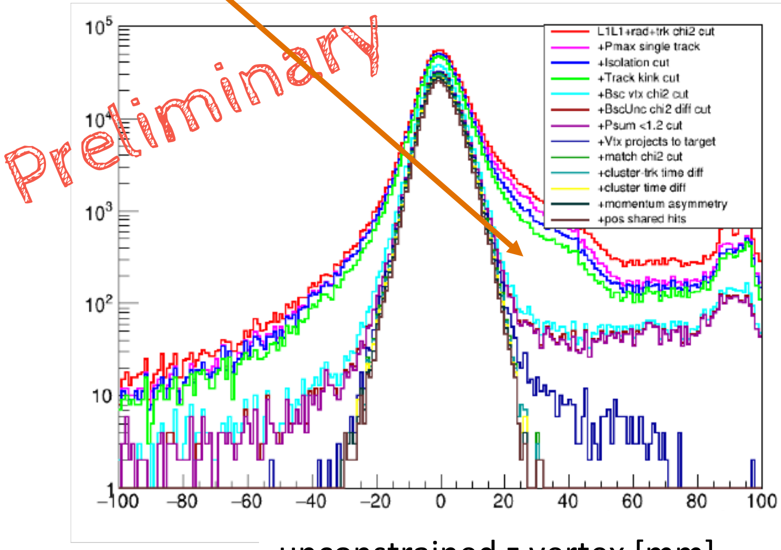


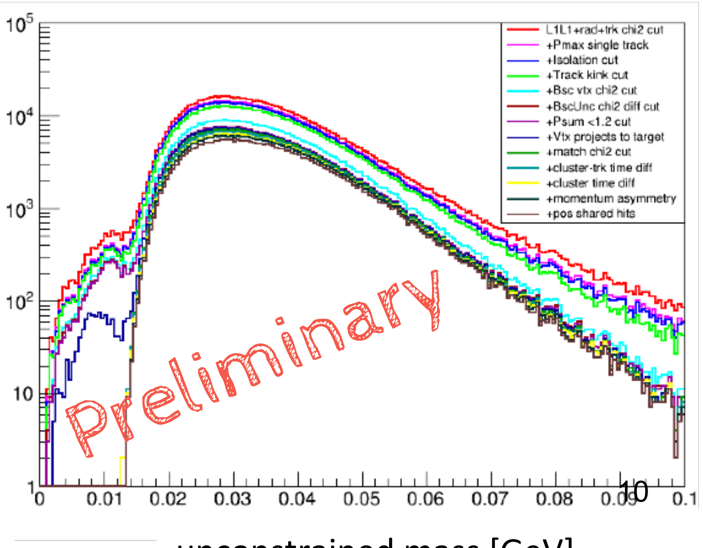
2015 Displaced Vertex Analysis

Cut type	Cut	Cut Value	%cut	%cut core	%cut tails
track	Fit quality	track $\chi^2/dof < 6$	24	–	–
track	Max track momentum	$P_{trk} < 75\%E_{beam}$	11	9	20
track	Isolation		4	1	14
track	kinks in L1 and L2	9	7	16	
vertex	beamspot constraint	bsc$\chi^2 < 10$	28	22	57
vertex	beamspot - unconstrained	bscχ^2-unc$\chi^2 < 5$	15	15	15
vertex	maximum P_{sum}	$< 115\%E_{beam}$	0.5	0.5	0.8
vertex	vertex projects to target	elliptical $3\sigma_{x,y}$	2	1	16
ecal	Ecal SVT matching	$\chi^2 < 10$	5	4	10
ecal	track Ecal timing	< 4ns	4	4	5
ecal	2 cluster time diff	< 2ns	6	6	9
physics	momentum asymmetry	< 0.5	3	3	5
event	max shared hits in e^+ track	< 5 shared hits	9	9	10

Goal is to reduce/eliminate backgrounds at large z

Tracking and vertexing work very well!

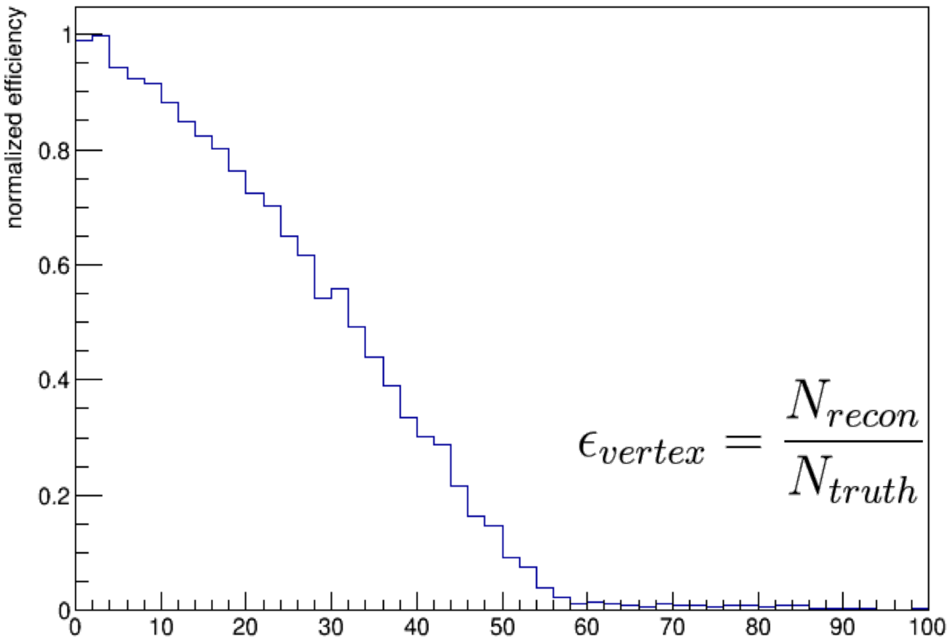




2015 Displaced Vertex Analysis: Vertex Z vs Mass

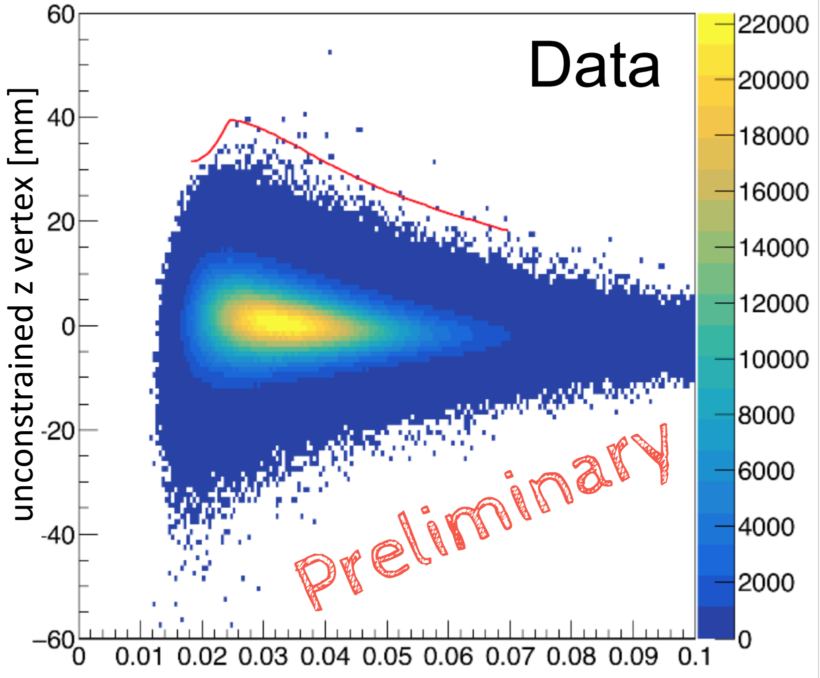
*Vertex resolution is limited by multiple scattering

40 MeV A' Normalized Acceptance*Efficiency



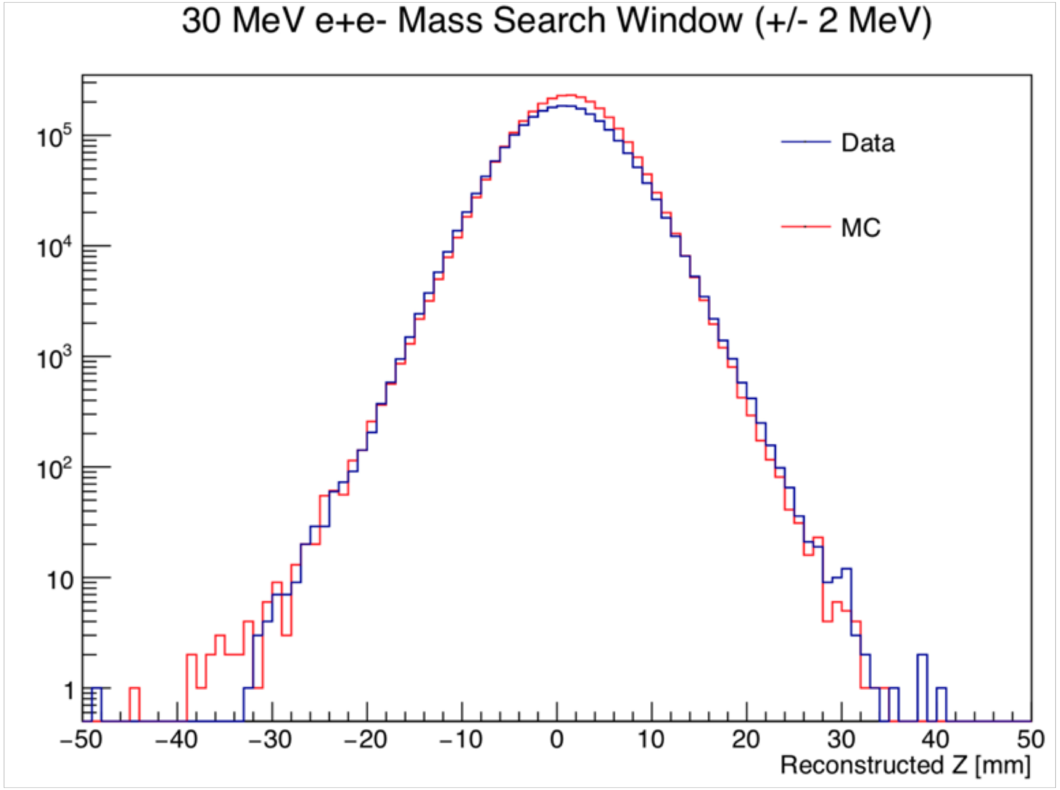
$$\epsilon_{vertex} = \frac{N_{recon}}{N_{truth}}$$

truth z vertex [mm]

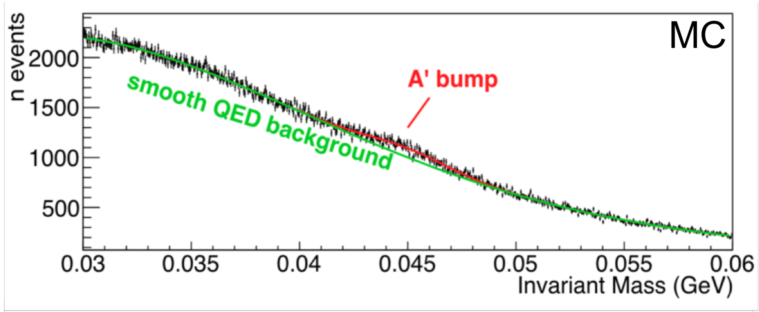


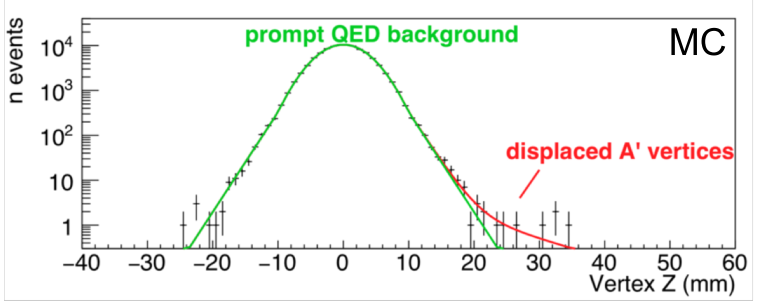
unconstrained mass [GeV]

Vertex Z Position Data/MC Comparison



In the bulk, data and the MC agree very well; but on the +Z tails, there is an excess in data above MC



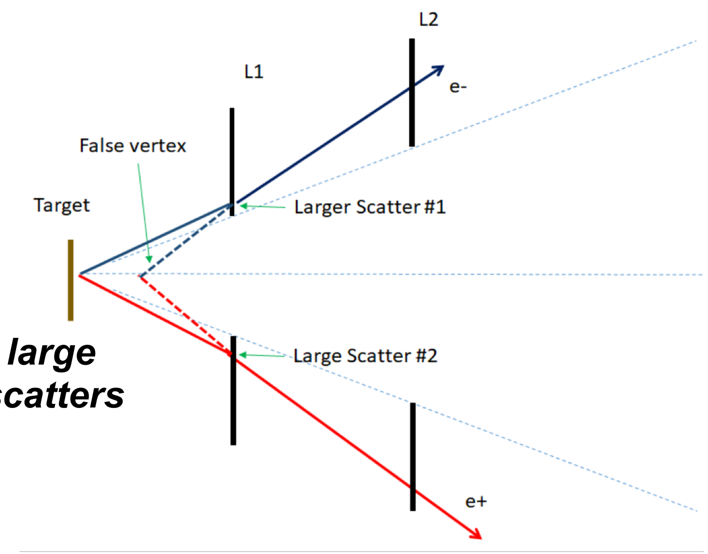


Sources of Excess Displaced Events

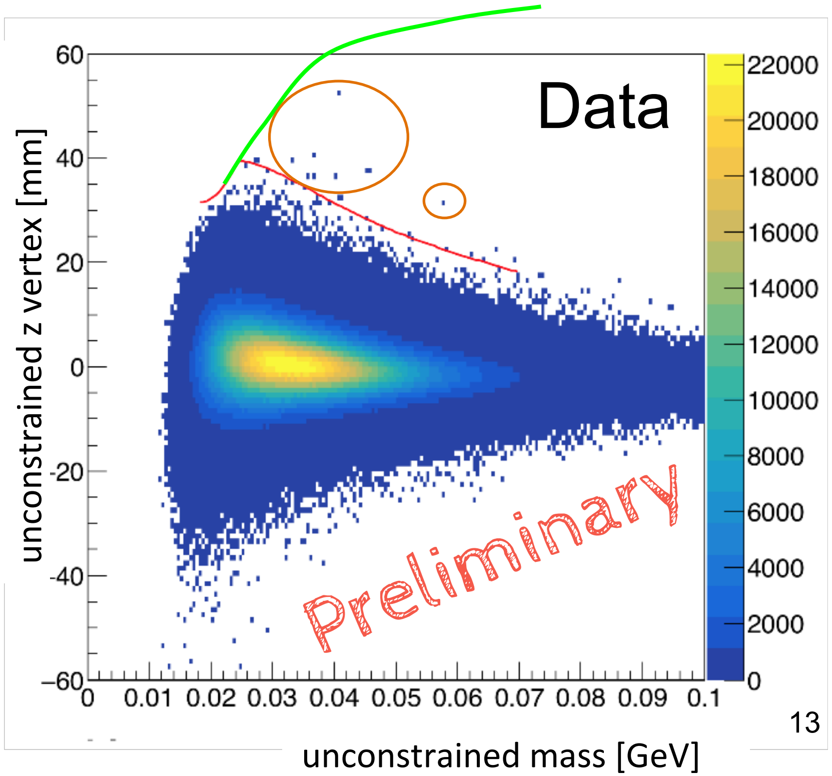
In the 1.05 GeV data, we found some unanticipated excess of very large Z events.

- Events where **both** the electron and positron have a large angle scatter in L1
- Events where one of the tracks has a large angle scatter and the other has an incorrectly assigned hit in L1
- Trident production in dead silicon

Large MC samples are helping to understand and develop techniques to reduce them. Also multivariate techniques, machine learning.



double large angle scatters

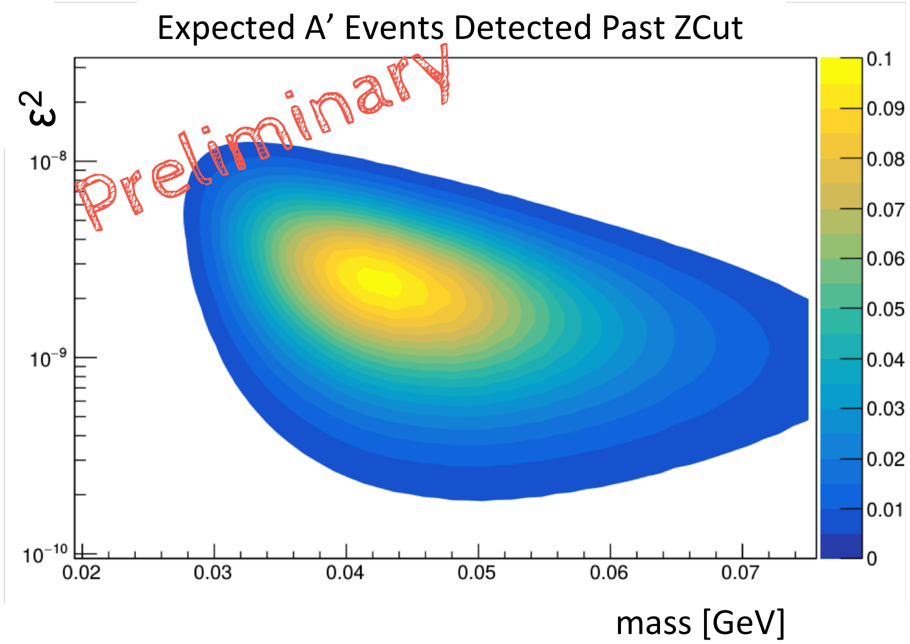


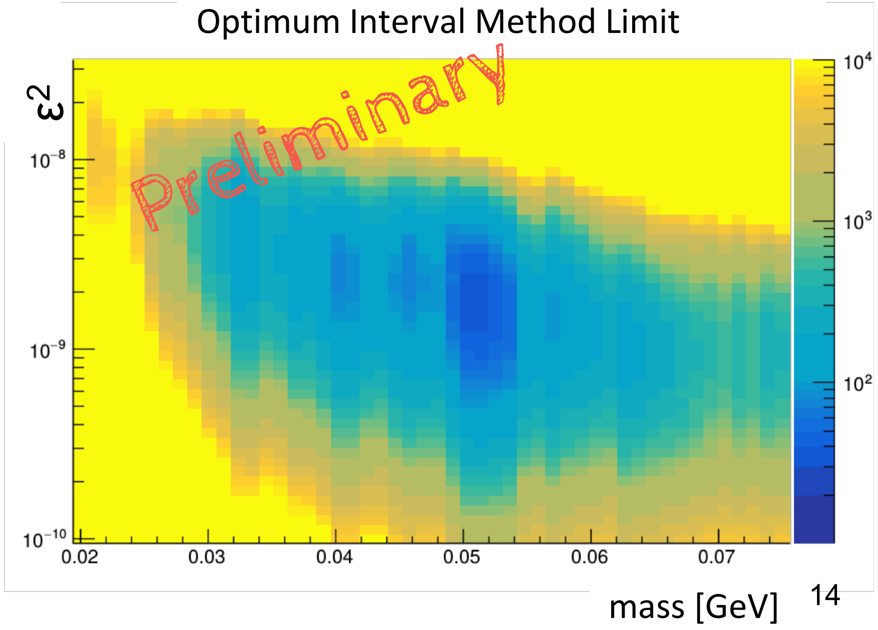
2015 Displaced Vertex Analysis Results

Despite the small amount of data in 2015, we still calculate

- the number of A′ events expected (left)
- the 90% confidence upper limit, where less than 1 is exclusion (right)

Results shown at ICHEP 2018 and **arXiv:1812.02169**



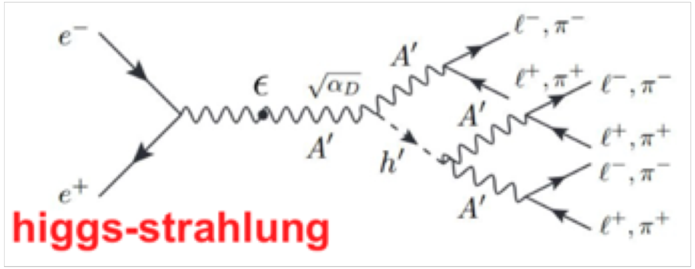


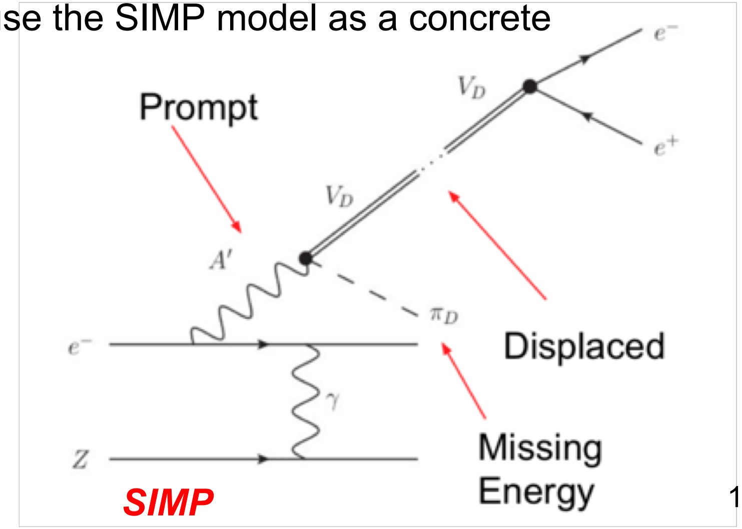
Status & Schedule for 2016 Physics Results

- We are currently focused on getting the 2016 bump-hunt and displaced vertex searches out
  - The aim is to get the analysis finished by ~April, prior to the major ramp up for summer 2019 data taking; review and publication will follow
  - We have the benefit of having the 2015 analyses to use as templates; follow these taking into account any peculiarities in 2016 datasets.
  - Led by Matt Solt (vertexing) and Rafayel Paremuzyan (bump-hunt)
- We expect to include some incremental analysis improvements to 2016 results as well:
  - Include tracks with first hit in L2 (L1L2, L2L2 combinations)
  - Improved handling of track-hit isolation to help reduce mis-hits in tracks
  - Incorporate machine learning techniques with the hope of efficiently removing the high-z background

Generalized Displaced Vertex Search & SIMPS

- There are numerous other light dark-sector models beyond the vanilla U(1) A′ models
  - “Higgsed” models, inelastic, strongly-interacting massive particle (SIMPs)
- These models typically have high(er) multiplicity final states and regions of parameter-space with non-prompt decays to di-leptons
- HPS is particularly well equipped to search for the displaced decays from these models; the primary change in strategy is to relax the $E(e^+e^-)$ requirement
- While the plan is to generalize this search, we use the SIMP model as a concrete target





2016 Projected SIMP Reach

The SIMP model has relavant 6 parameters:

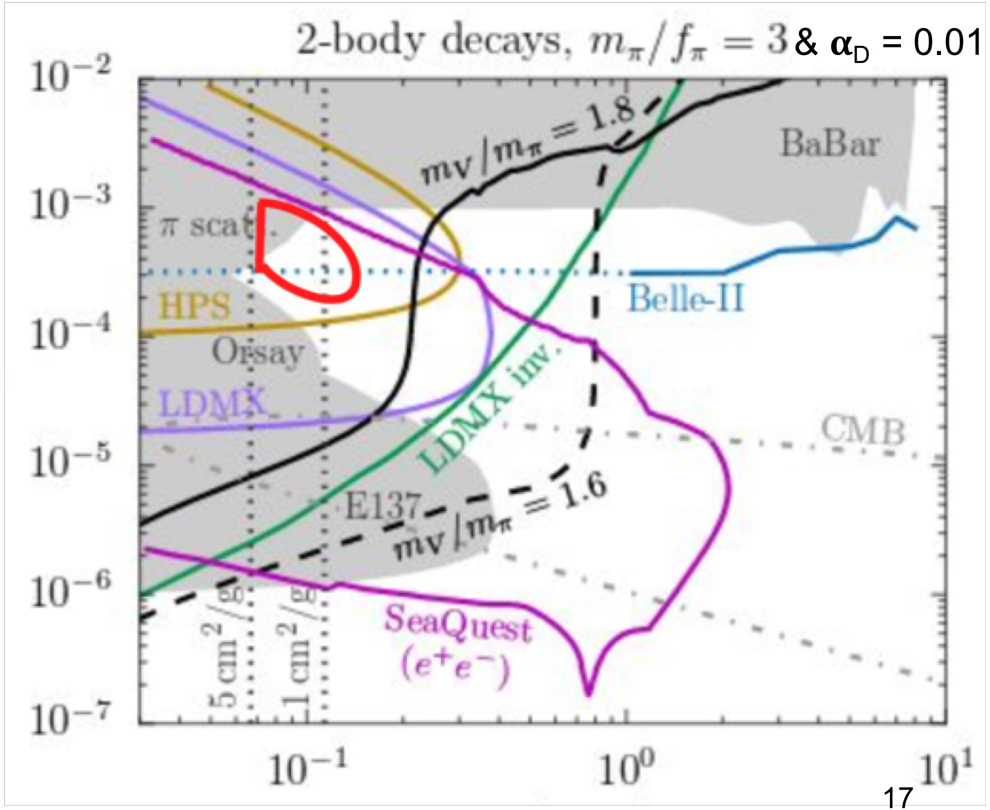
- 3 masses: A′, π_D, V_D
- Coupling between dark sector particles: α_D
- Dark pion decay constant f_π
- SM-DS mixing parameter ε

Fix mass ratios: $m_{A'}:m_V:m_\pi$ = 3:1.8:1 (to compare with public reach plots)

Look in SM-DS coupling (ε) vs m(A′) with various m_π/f_π and α_D values.

We predict that we should have significant reach for the SIMP model; in some regions of parameter space (that are not yet ruled out) we'd observe thousands of signal events.

2016 Run: 2.2 GeV, ~5 days, non-upgraded detector



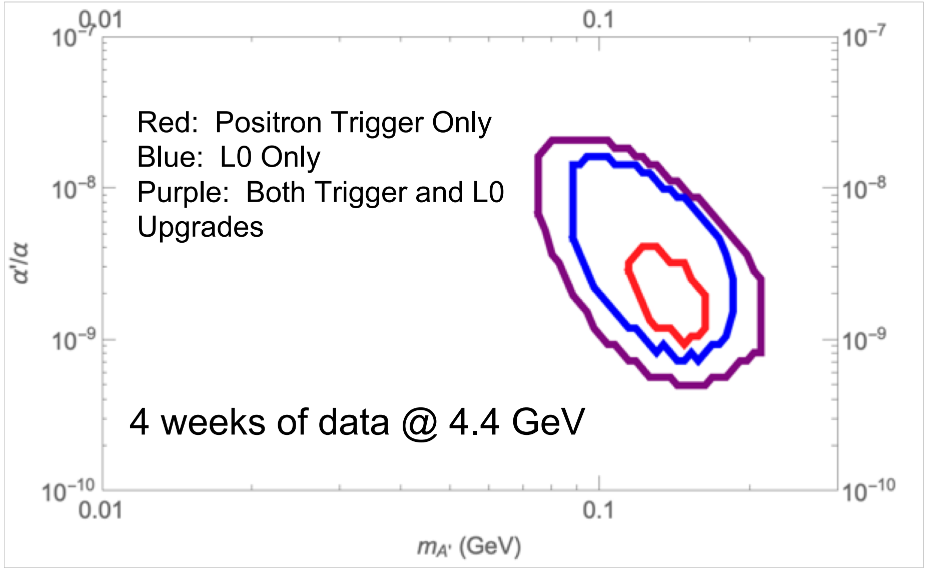
2019 & Beyond: Effects of Detector Improvements

Both the SVT L0 and hodoscope positron trigger are vital for getting significant reach in the 2019 run. Each separately add reach but together they are very powerful.

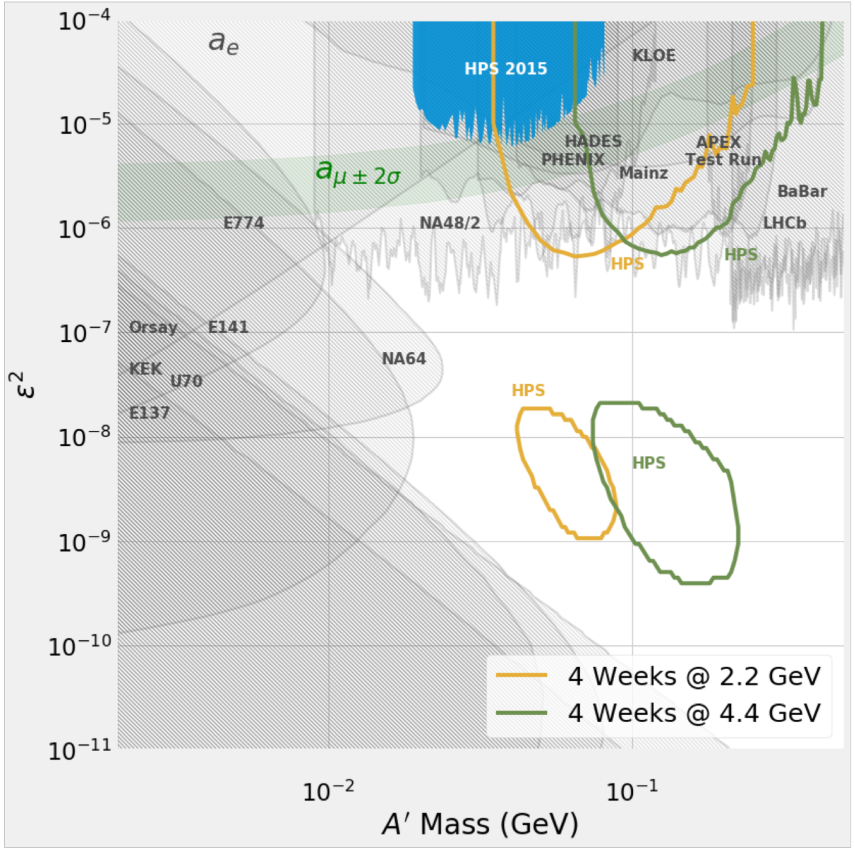
Positron trigger→ adds large amount of low-ϑ efficiency lost in ECal hole

L0 → improved vertex resolution; short decay lengths

Reaches shown here, and everywhere in this talk, are for events with tracks having hits in the first SVT layer; relaxing this gives us reach for longer lived A′s (lower couplings) but, since we have not demonstrated we can do this yet, it's not included.



2019 & Beyond: Effects of Detector Improvements II



Keys to Getting 2019 Results Out Promptly

- It's taken a long time to get the engineering run data pubic/published; there was much we needed to understand about the detector and the data:
    - Correct MC generators are crucial!
        - WABs (dominating the trigger rate) and converted WABs (significant contribution to e^+e^- events) was unexpected and took some time to understand (EGS5).
        - Trident production normalization, running coupling α and nuclear form factor approximations, were incorrect for HPS (Madgraph4/5).
    - Procedure for SVT alignment has taken time to nail down; we think we have that now
    - The specific, detailed, coded, debugged analysis chains weren't there
- We understand the 1.1 and 2.2 GeV data quite well now and also what it takes to go from data-on-tape to data-for-analysis
    - We expect that the limiting factor will be actual computing time for the event reconstruction of the ***full*** data set (~few months) -- alignment, calibration, analysis tuning will be done quickly on select runs but data processing time will likely dominate

Beyond 2019

- Next run: 4 weeks at ~2.2 GeV -- significant vertexing reach to be covered here
- After that:
  - We will re-evaluate 6.6 GeV reach with detector upgrades
    - Estimated with pre-upgrade design before we had real data; need to revisit it
    - 6.6 GeV beam energy brings some new wrinkles:
      - $\mu\mu$ and **ππ** final states become important … muon detector?
      - “True-muonium” starts to be produced in significant (detectable?) amounts
        - True-muonium is bound state of $\mu^+\mu^-$; decay products (e^+e^-/γγγ) and lifetime depends on the state produced
        - No one has actually observed this before! Many SM tests have been done with positronium and muonium (bound state of μe)

Summary

- HPS has made public our first two results from the 2015 engineering run (1.1 GeV) and will soon do the same for the 2016 (2.2 GeV) run as well
  - Unfortunately, due to detector realities and the small amount of data collected, we see/don't expect significant reach with the data we've taken
- The upgrades we are currently working on are crucial
  - Positron trigger→ increased low-angle acceptance
  - SVT L0 (and other) upgrades → improved vertex resolution, increased low-angle acceptance
- We have a solid analysis foundation but we plan to continually improve and optimize our techniques as the understanding of the data and detector grows; this will allow us to both quickly turn around the data→public results and get the most out the data we collect