Search for a Long-Lived Heavy Photon with the Heavy Photon Search Experiment

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Introduction

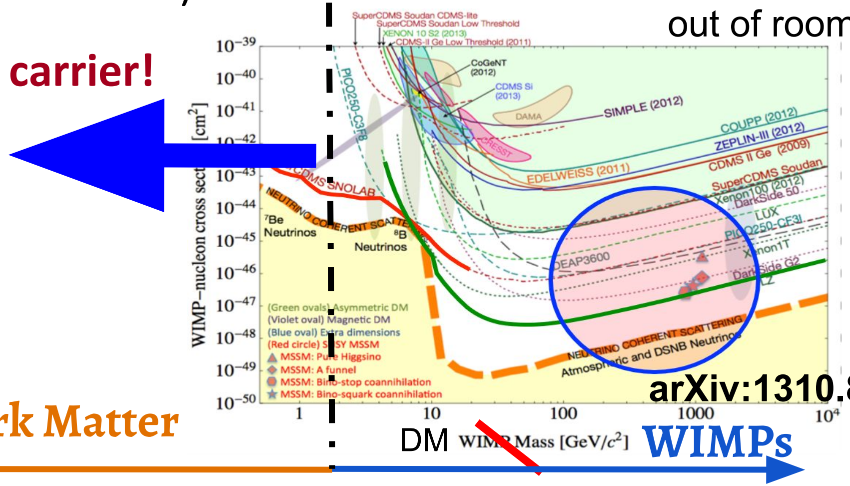
- A heavy photon (or dark photon, or A’) is a **hypothetical vector boson** that couples to electric charge
- The Heavy Photon Search (HPS) is a **fixed target experiment** at Jefferson Lab dedicated to searching for this hypothetical vector boson, an A’
- HPS uses two distinct methods to search for A’s - a **resonance search** and a **displaced vertex search** (focus on vertex search)

Lighter dark matter requires a **new, light force carrier!**

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Rightarrow m_\chi \gtrsim 2\text{GeV}$$

“Lee-Weinberg Bound”

WIMPs are running out of room!



arXiv:1310.8327

Heavy Photon Primer

- Suppose nature contains an **additional Abelian gauge symmetry** U'(1) (analogous to EM)

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

Heavy Photon Primer

- Suppose nature contains an **additional Abelian gauge symmetry** U’(1) (analogous to EM)
- This gives rise to a **kinetic mixing term** where the SM photon mixes with a new gauge boson (an A’) through interactions of massive fields (i.e. a “vector portal”)

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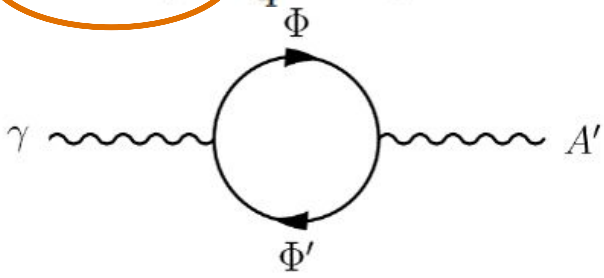

Heavy Photon Primer

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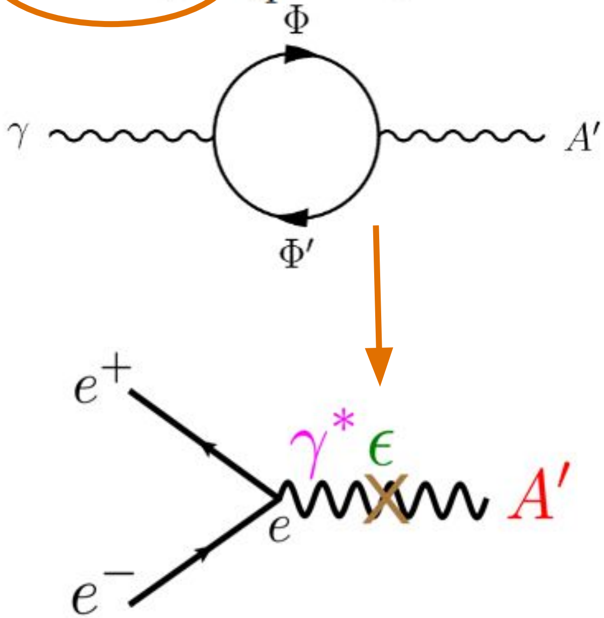
- This gives rise to a **kinetic mixing term** where the SM photon mixes with a new gauge boson (an A’) through interactions of massive fields (i.e. a “vector portal”)
- Induces a weak effective coupling of εe to SM fermions

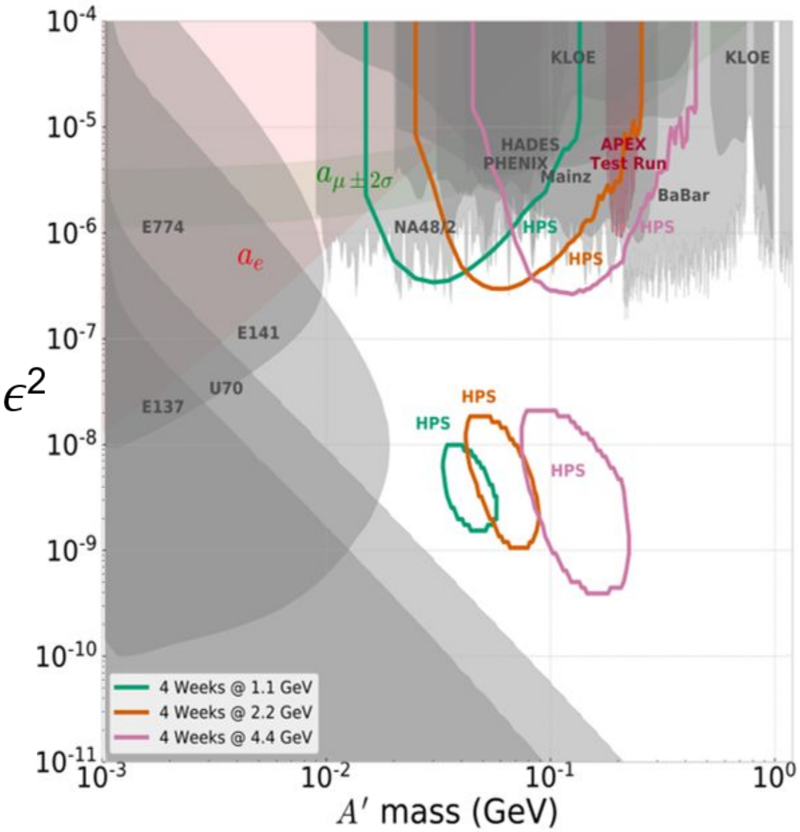
$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} \ln\left(\frac{m_\Phi}{m_{\Phi'}}\right) \sim 10^{-3} - 10^{-1}$$

- GUT theories motivate log(ε) ~ -5 to -3

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

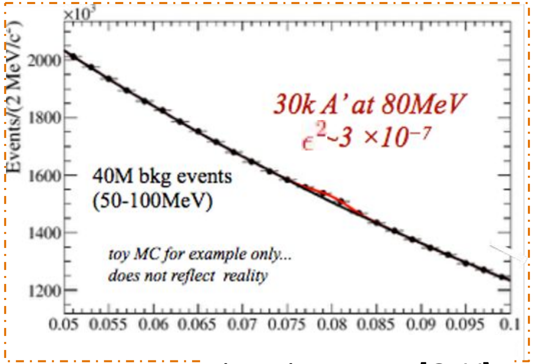


Heavy Photon Signatures in HPS

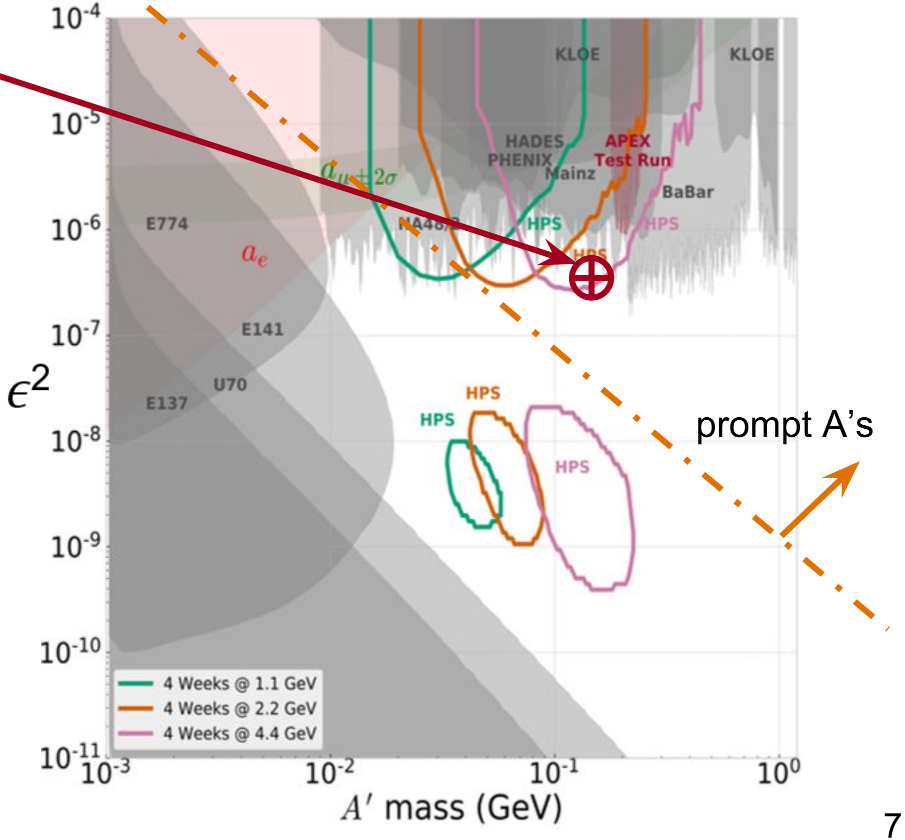


Heavy Photon Signatures in HPS

“Large” signal, huge QED background (**bump hunt**)



invariant mass [GeV]



prompt A's

Heavy Photon Signatures in HPS

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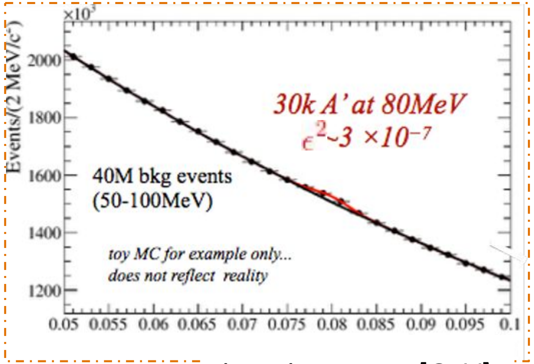
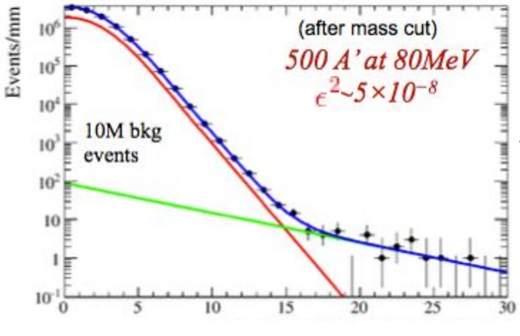
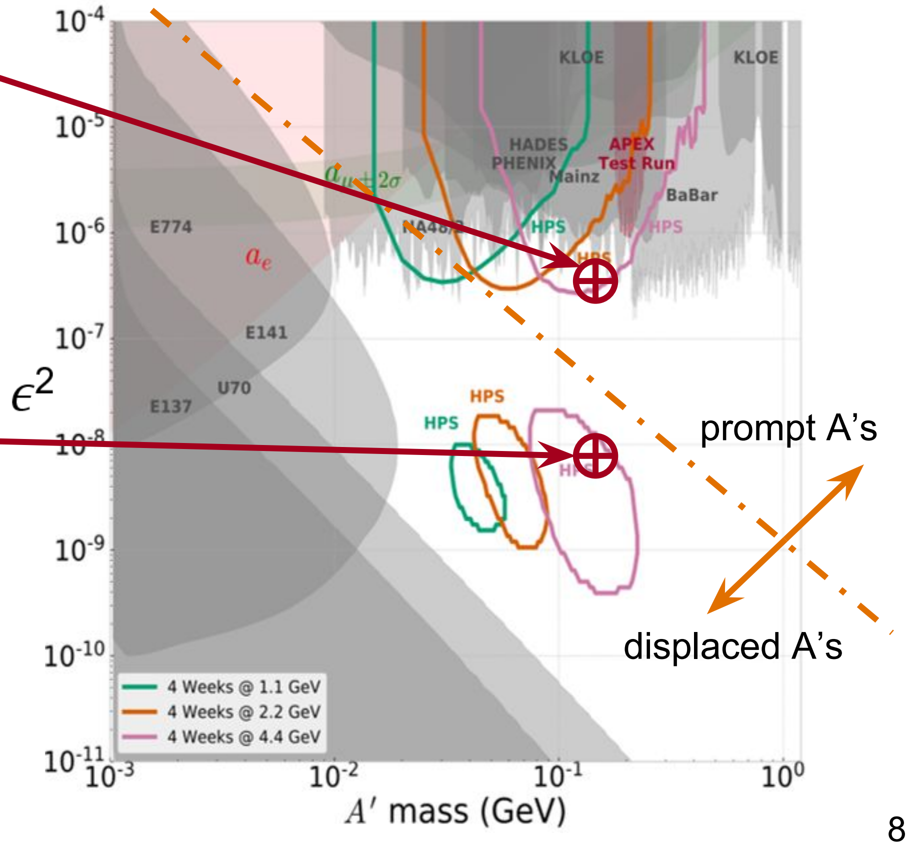


Small signal, very little background (**vertex search**)



$$\gamma c \tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$$



The Heavy Photon Search Experiment

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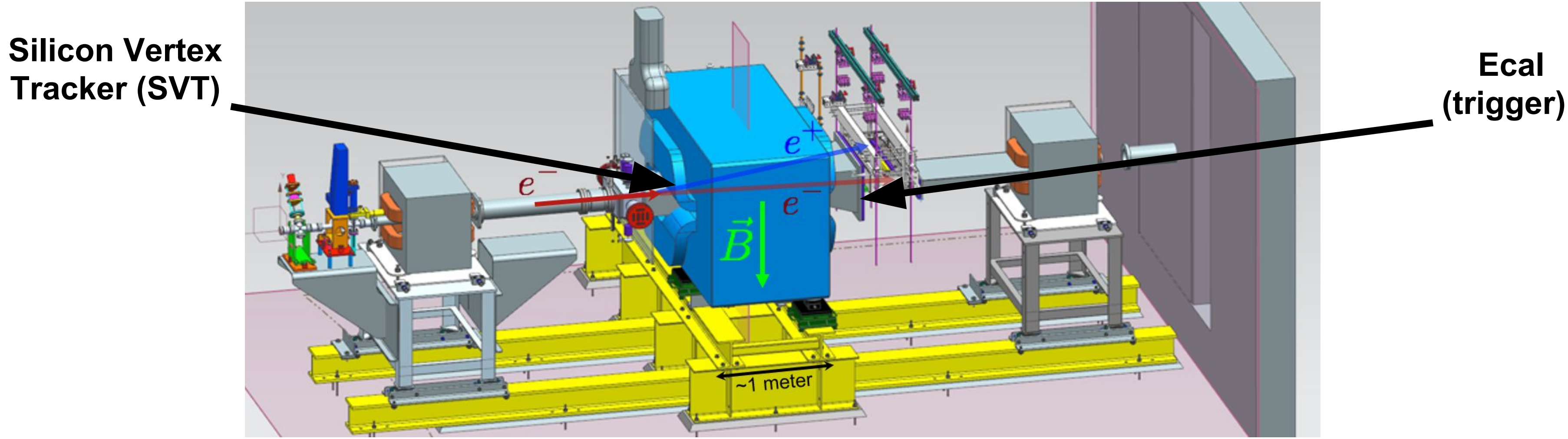
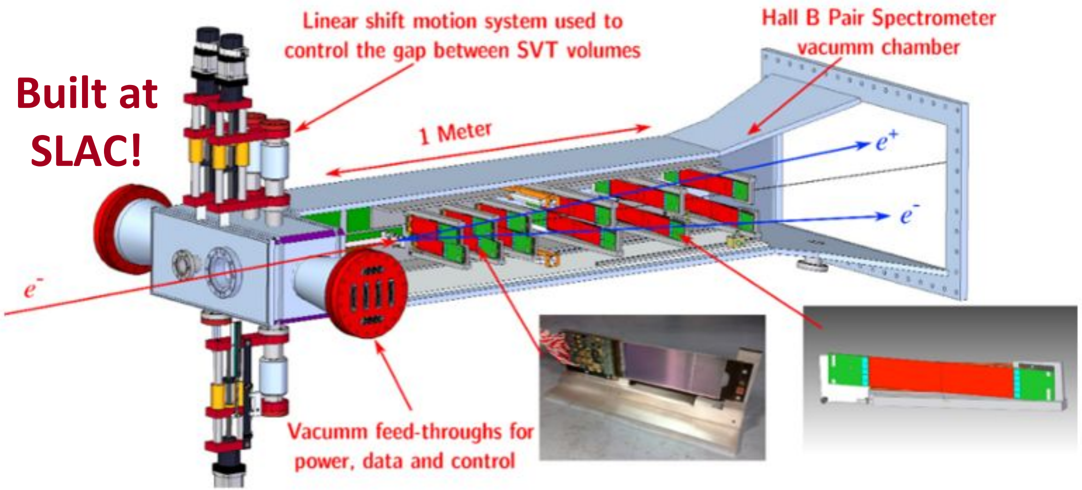
- HPS is a **fixed-target experiment** for **visibly decaying dark photons** using the CEBAF electron beam (1-6 GeV) in Hall B at Jefferson Lab
- Very forward A's can be produced in a process **analogous to Bremsstrahlung** in a thin W foil $x = \frac{E_{A'}}{E_{beam}} \sim 1$
- Large dipole magnet spreads e+e- pairs and provides momentum measurement

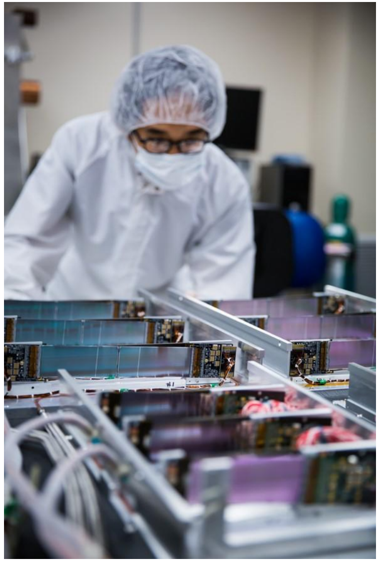


Silicon Vertex Tracker

- SVT measures trajectories of e+e- and **reconstructs mass and vertex position**
- 6 layers of silicon microstrips (~0.7% radiation length per layer)
- Each layer has axial/stereo strips (100 mrad) for 3D hit position
- SVT is split to avoid "sheet of flame"; Also, very large scattered beam backgrounds!
- Silicon is very close to beam for good forward coverage

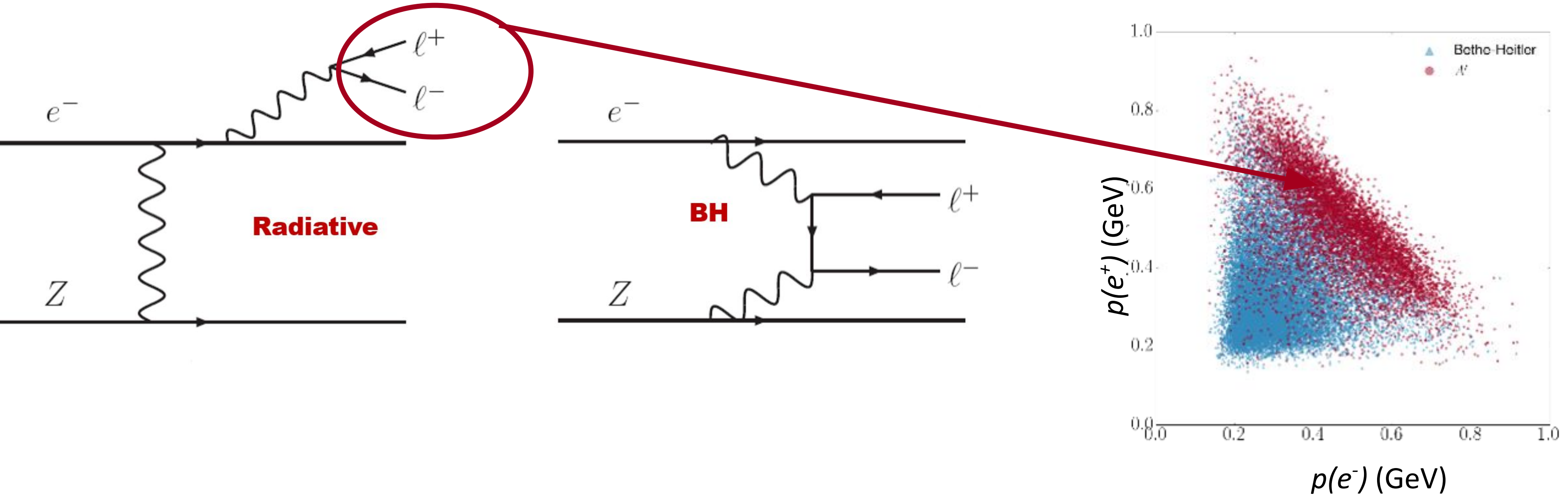
Built at SLAC!





Trident Backgrounds

- **Radiative tridents** have identical kinematics to A’s, so constitute an irreducible background



Trident Backgrounds

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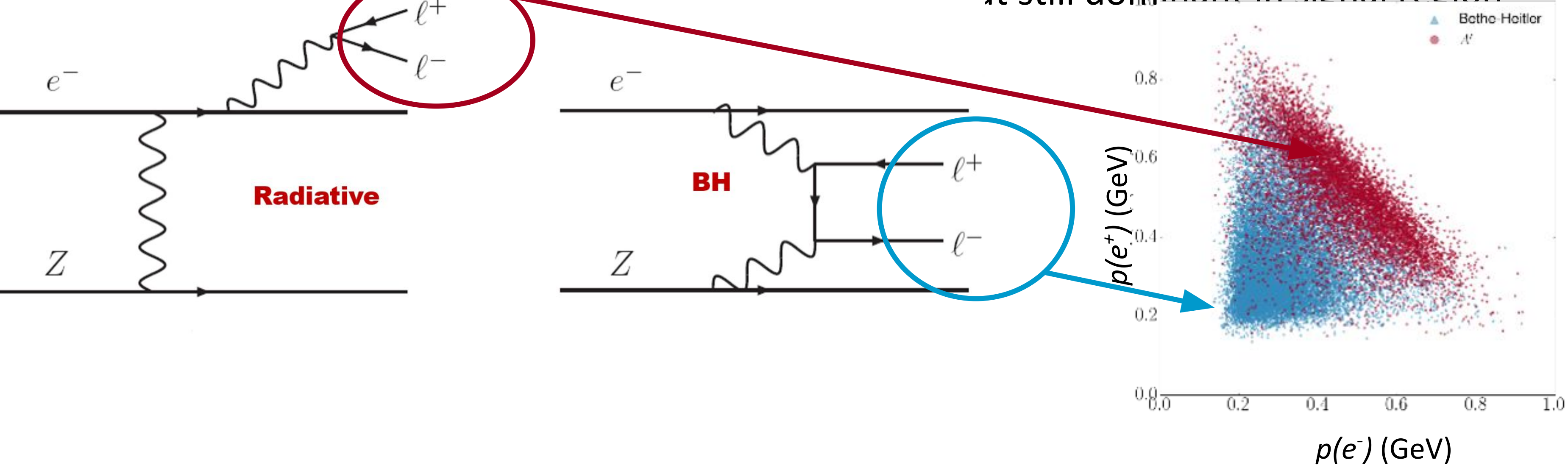
- **Bethe-Heitler (BH) tridents** have softer e+e- pairs, but still dominant in signal region



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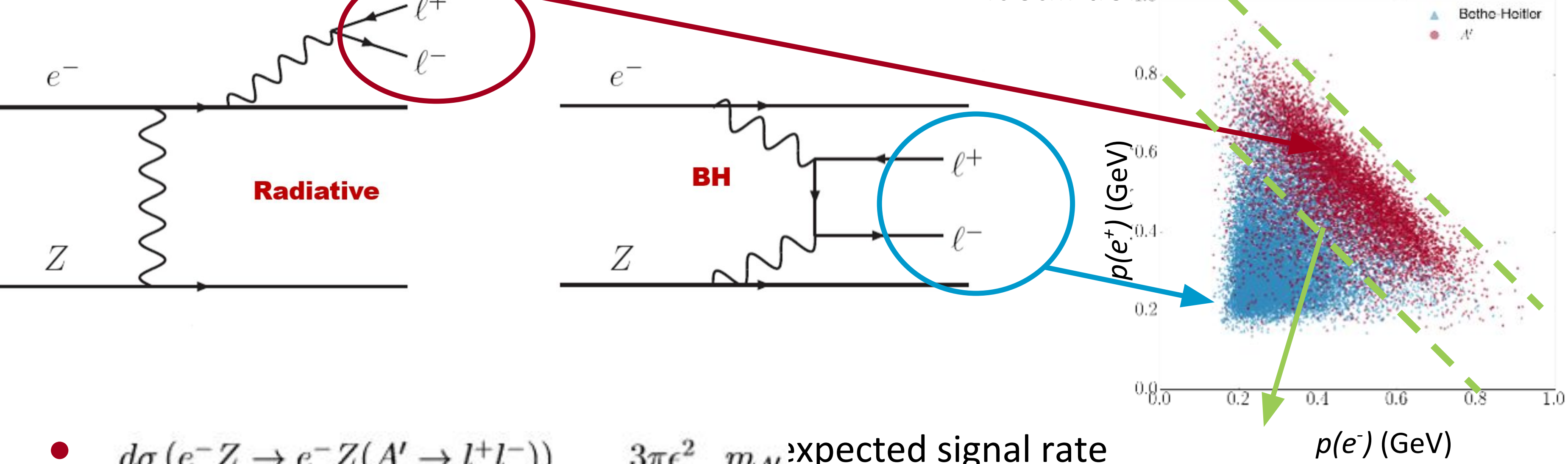
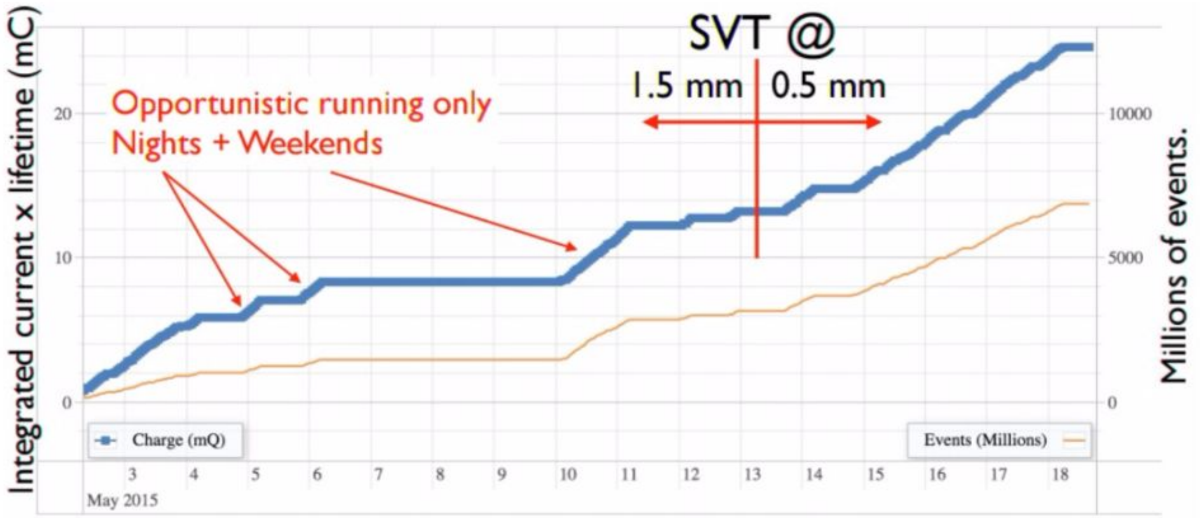


- $$\frac{d\sigma\,(e^-Z \to e^-Z(A' \to l^+l^-))}{d\sigma\,(e^-Z \to e^-Z(\gamma^* \to l^+l^-))} = \frac{3\pi\epsilon^2}{2N_{eff}\alpha}\frac{m_{A'}}{\delta m}$$ expected signal rate

Require $0.8E_{beam} < p(e^+e^-) < 1.2E_{beam}$ greatly reduces fraction of BH background

2015 & 2016 Engineering Runs



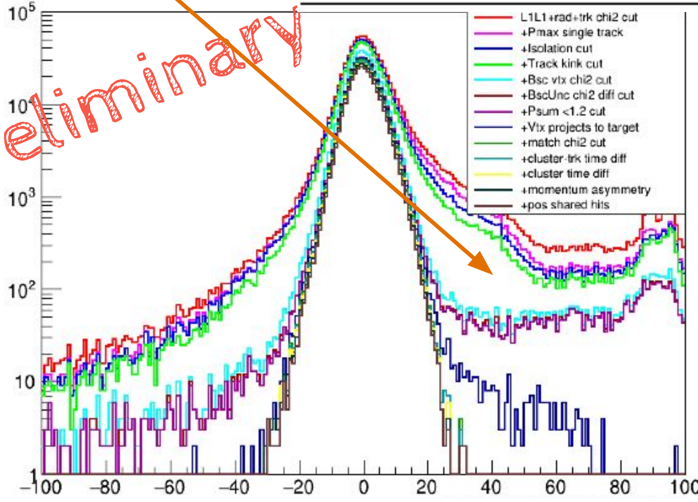
Data Run	Beam Energy (GeV)	Beam Current (nA)	Beam Time (days)	Total Charge (mC)	SVT Position (mm)
2015 Engineering Run	1.05	50	1.7	10	0.5
2016 Engineering Run	2.3	200	5.4	92.5	0.5

Event Selection

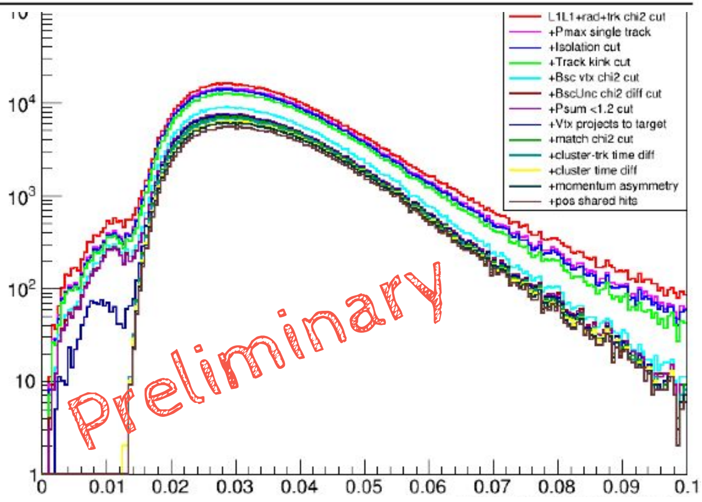
Cut type	Cut	Cut Value	%cut	%cut core	%cut tails
track	Fit quality	track $\chi^2/dof < 6$	24	–	–
track	Max track momentum	$P_{trk} < 75\% E_{beam}$	11	9	20
track	Isolation		4	1	14
track	kinks in L1 and L2	9	7	16	
vertex	beamspot constraint	bsc$\chi^2 < 10$	28	22	57
vertex	beamspot - unconstrained	bscχ^2-unc$\chi^2 < 5$	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!



unconstrained z vertex [mm]

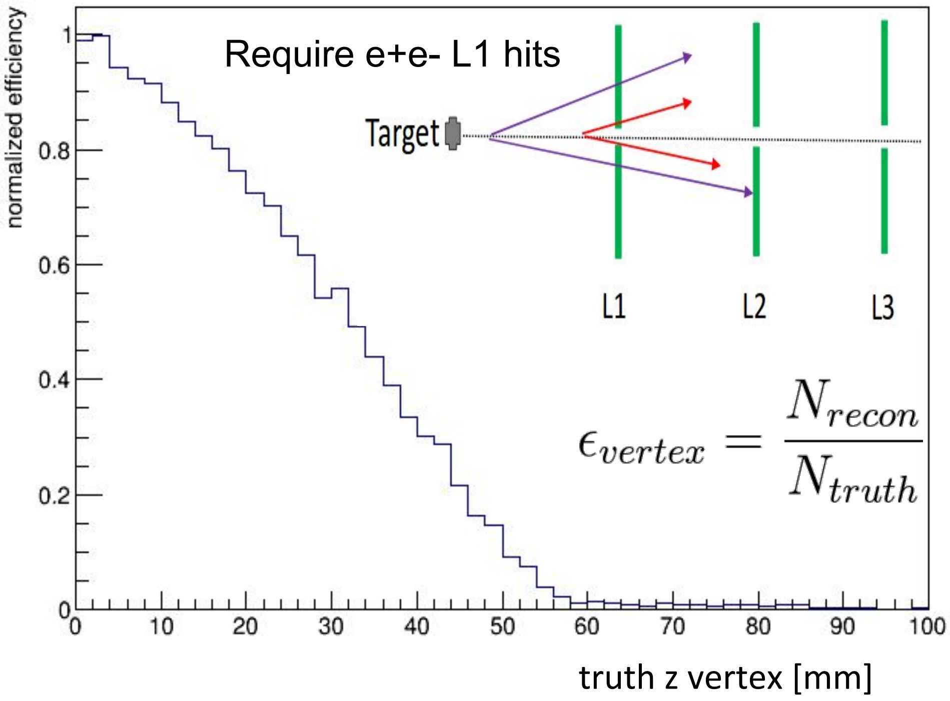


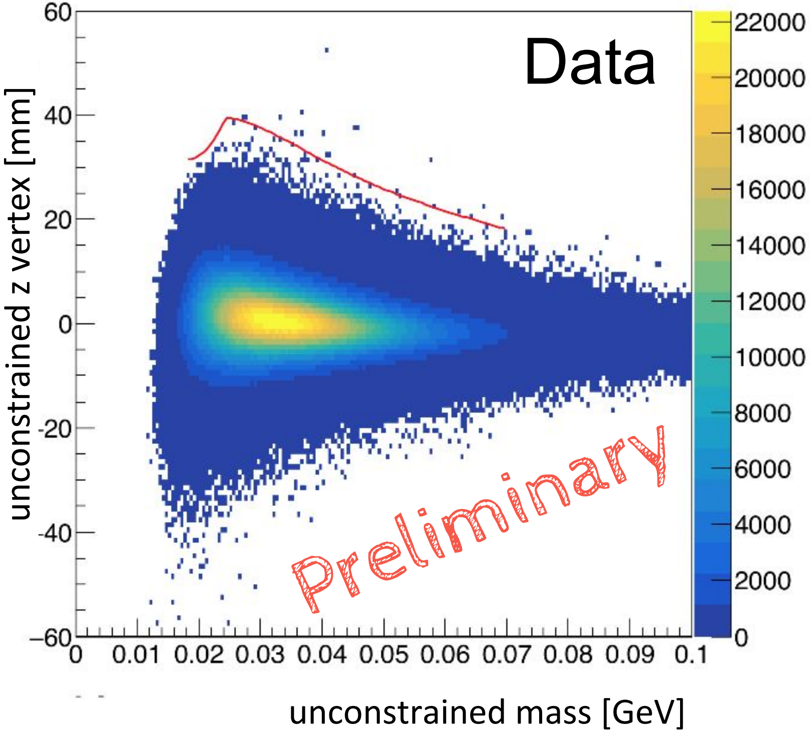
unconstrained mass [GeV]

Vertex Analysis Final Selection

*Vertex resolution is limited by multiple scattering

40 MeV A' Normalized Acceptance*Efficiency





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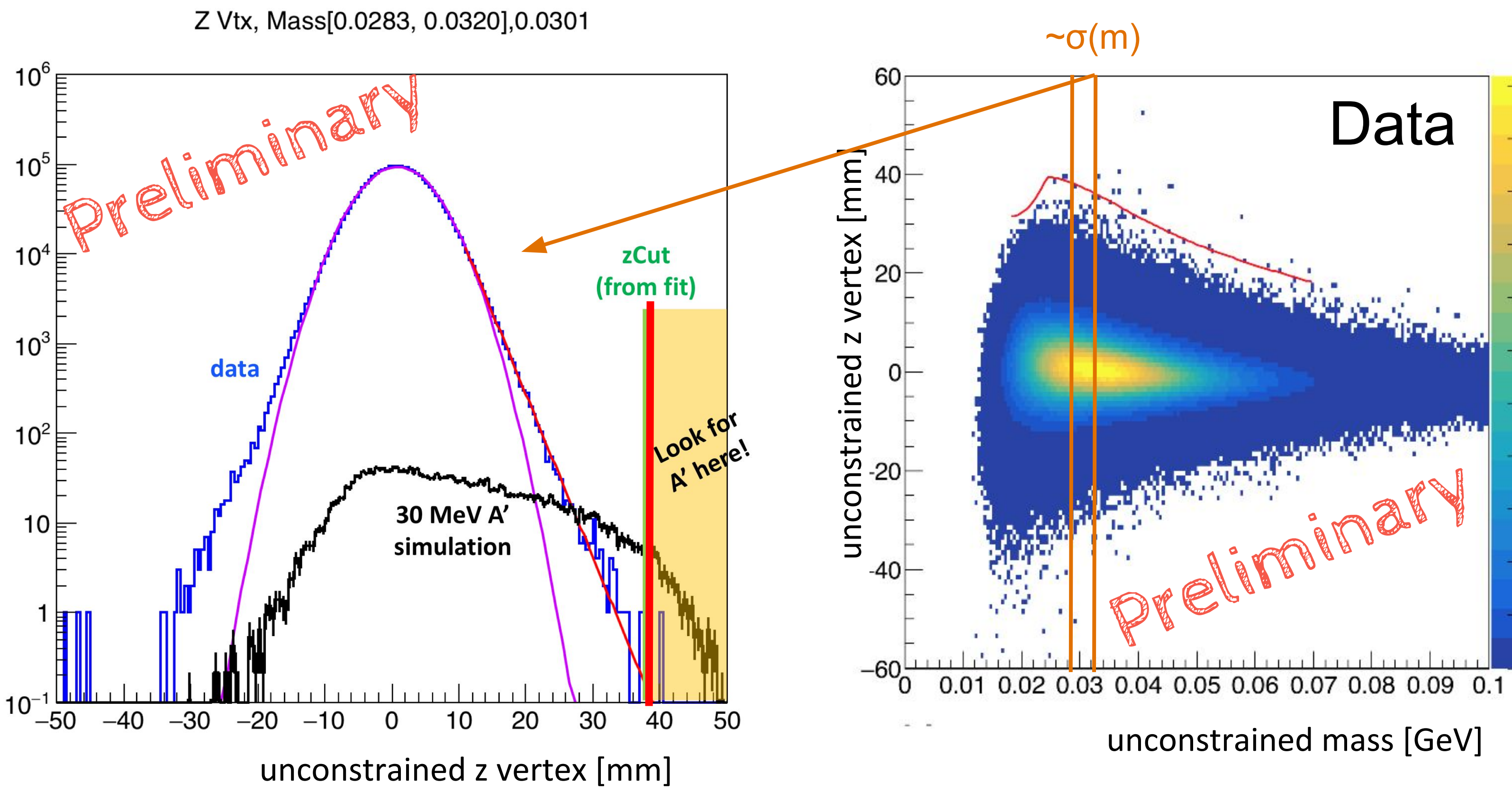

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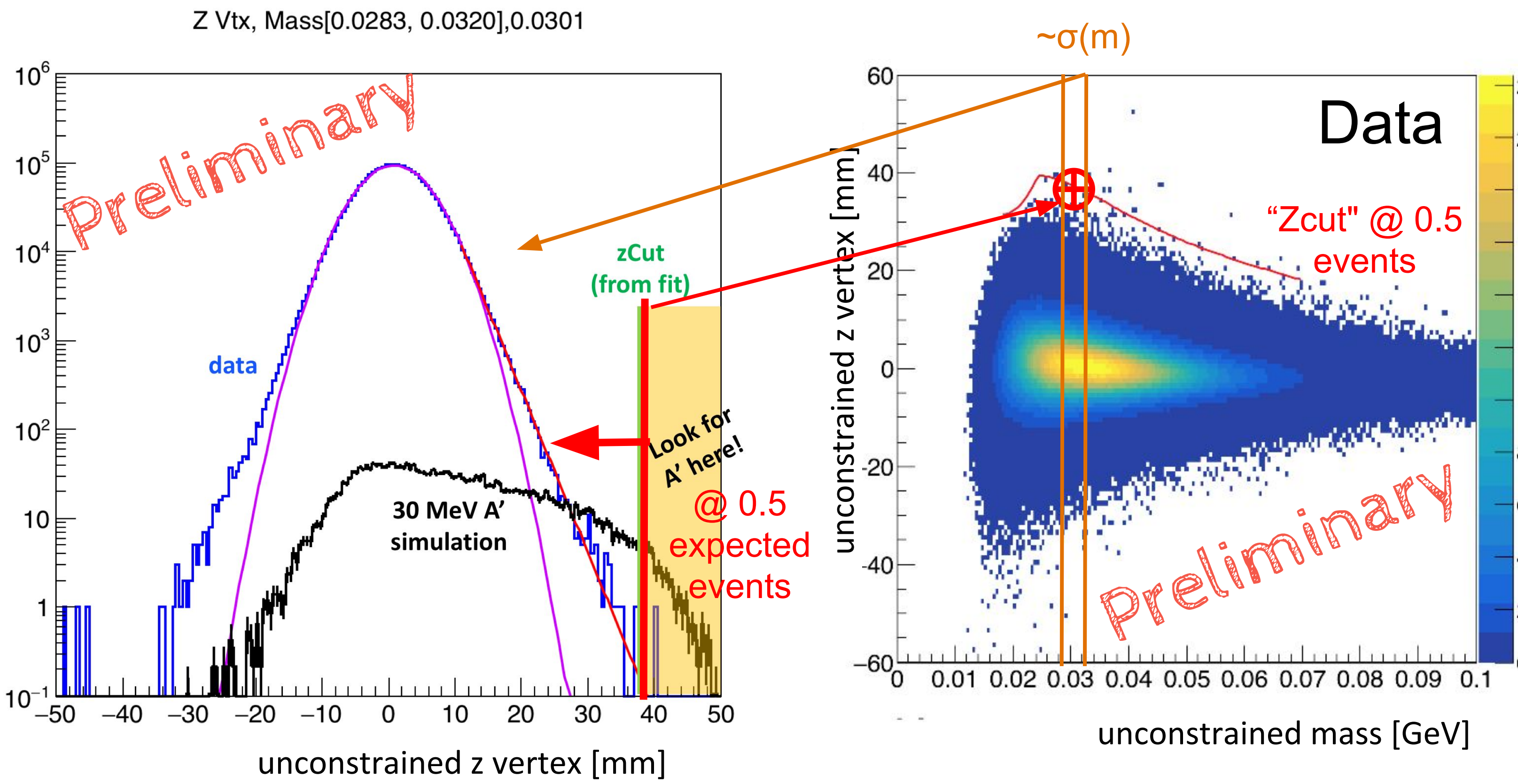

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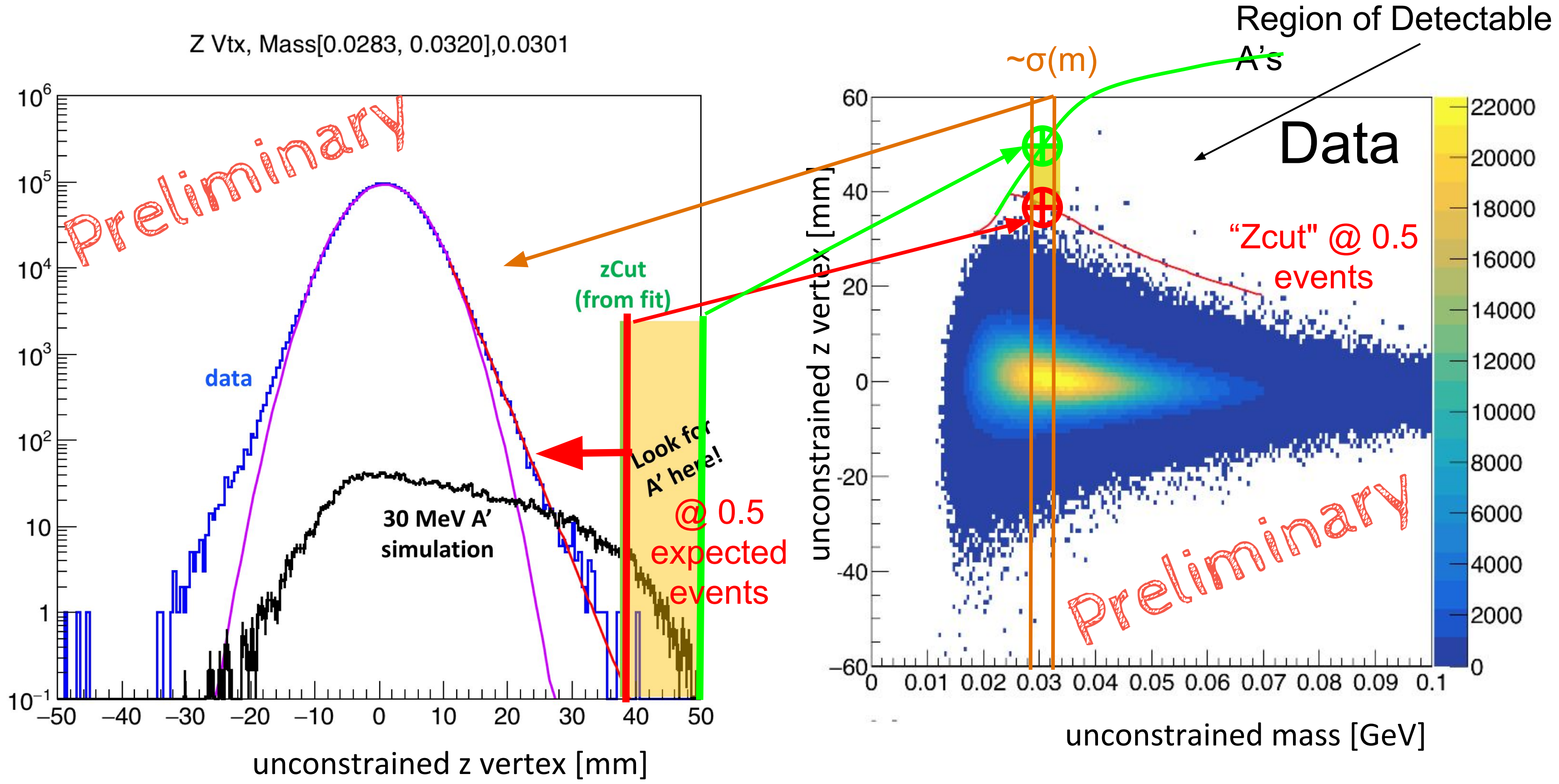

Additional Backgrounds Beyond Zcut

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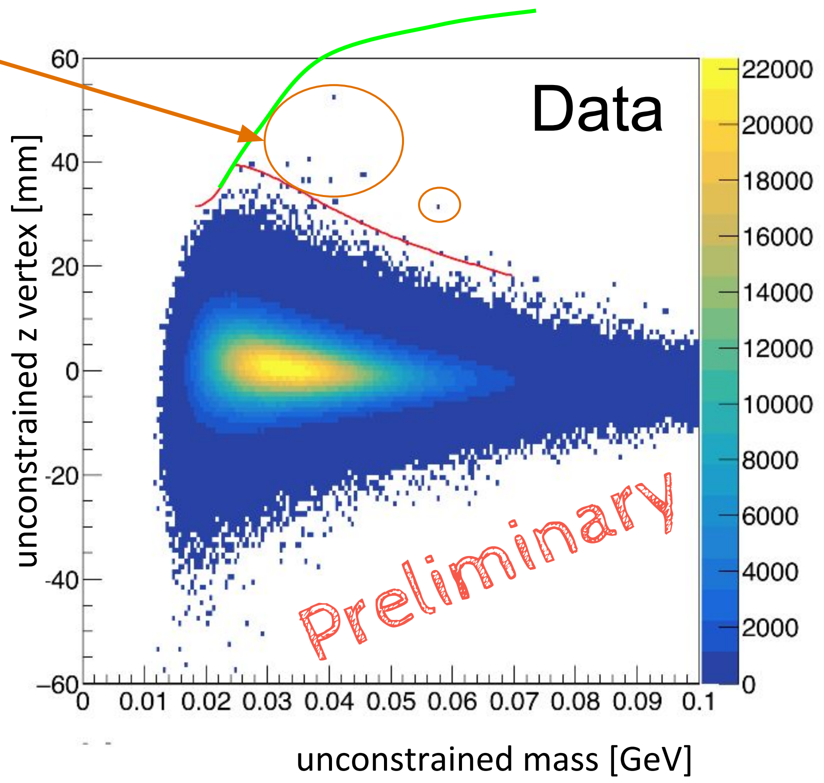
- We have vertices past zcut that are inconsistent with what we expect from our background fit (below)

$$F\left(\frac{z - z_{mean}}{\sigma_z} < b\right) = Ae^{-\frac{(z - z_{mean})^2}{2\sigma_z^2}}$$

$$F\left(\frac{z - z_{mean}}{\sigma_z} >= b\right) = e^{-\frac{b^2}{2} - b\frac{z - z_{mean}}{\sigma_z}}$$

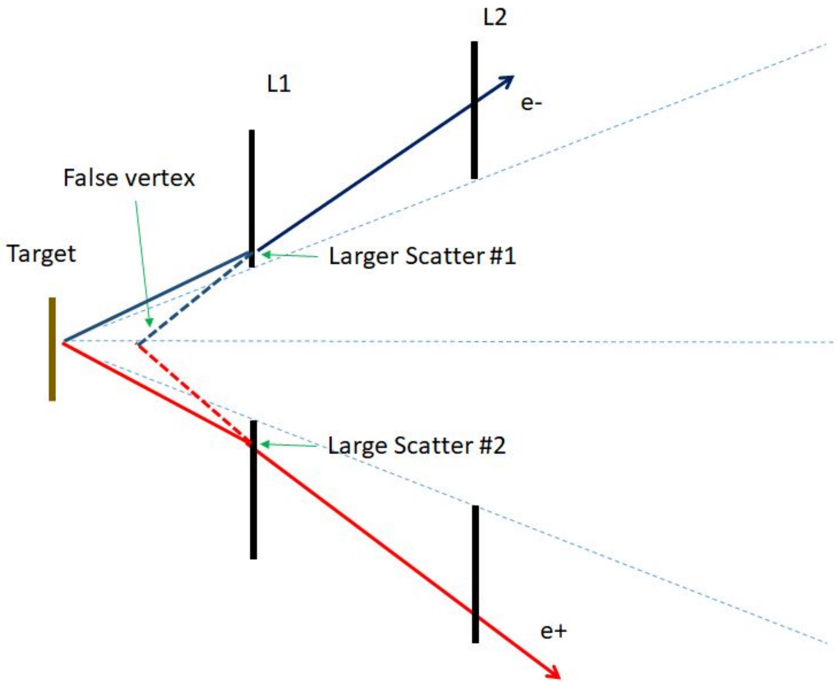
Gaussian Core + Exponential Tail

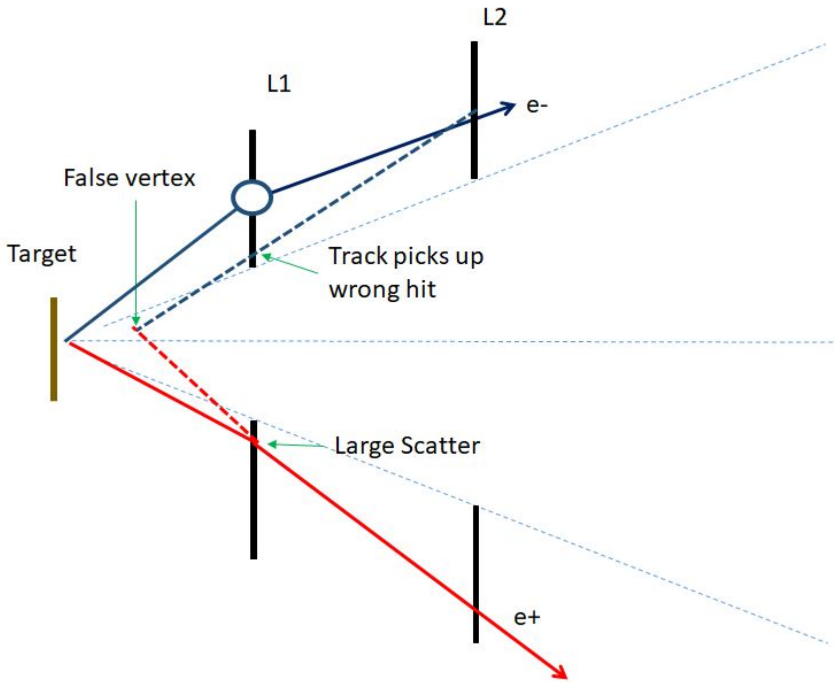


- MC sees roughly a similar number and pattern of such backgrounds
- **MC lets us see the source of these backgrounds**

Additional Backgrounds Beyond Zcut

- Measurement is limited by multiple scattering, but events past zcut are mainly due to rare double **large Coulomb scatters** (left) and picking up the **wrong L1 hit**





Optimum Interval Method

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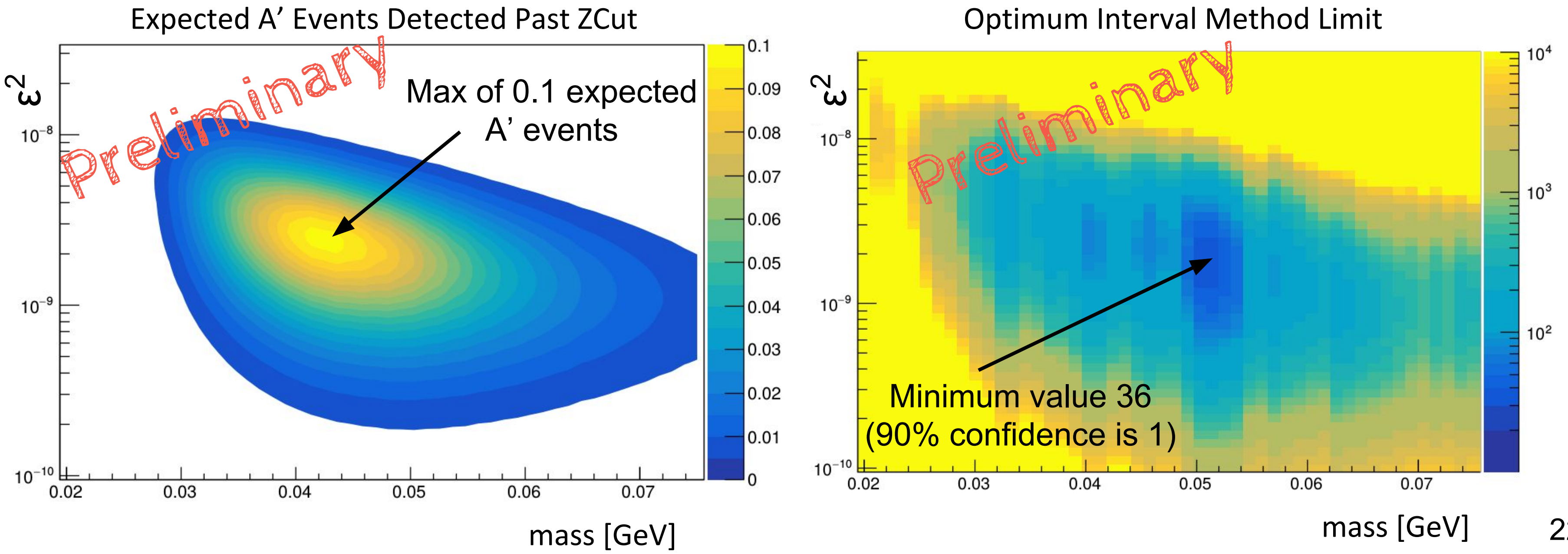
- Optimum Interval Method is ideally used for small signal where signal shapes are known, but background is not sufficiently known (HPS, direct DM detection, etc.)

arXiv:physics/0203002v2



Vertex Search

- Vertex search technique works!
- No sensitivity for minimal A' model with 2015 data at 1.05 GeV **(only 1.7 PAC days)**

But…

Vertex Search

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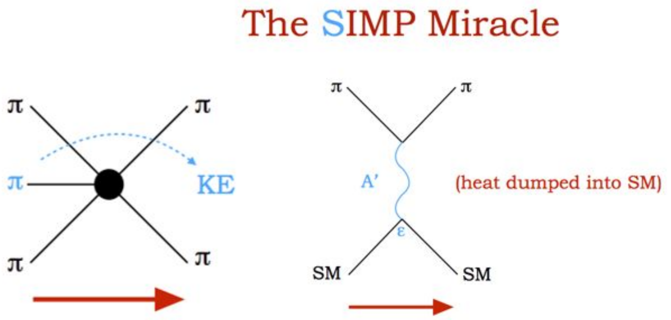
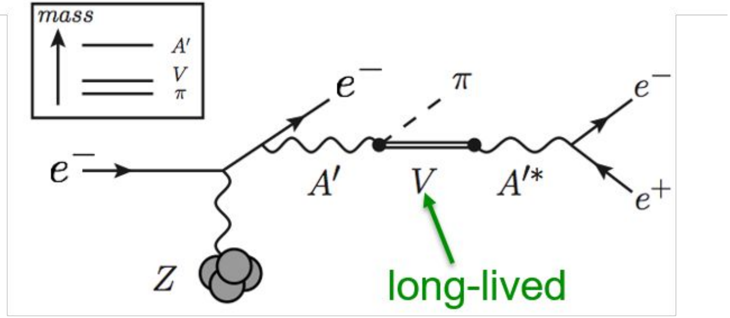
But…

1. **Possibly sensitive to Strongly Interacting Massive Particles** (SIMPs) in both 2015 and 2016 datasets
2. **Small upgrade projects** will be installed at start of 2019 (new tracking layer + upgraded trigger)
3. **95% of data is still to come!** (including 8





arXiv:1402.5143

Upgraded HPS Reach at 4 Weeks of Beam

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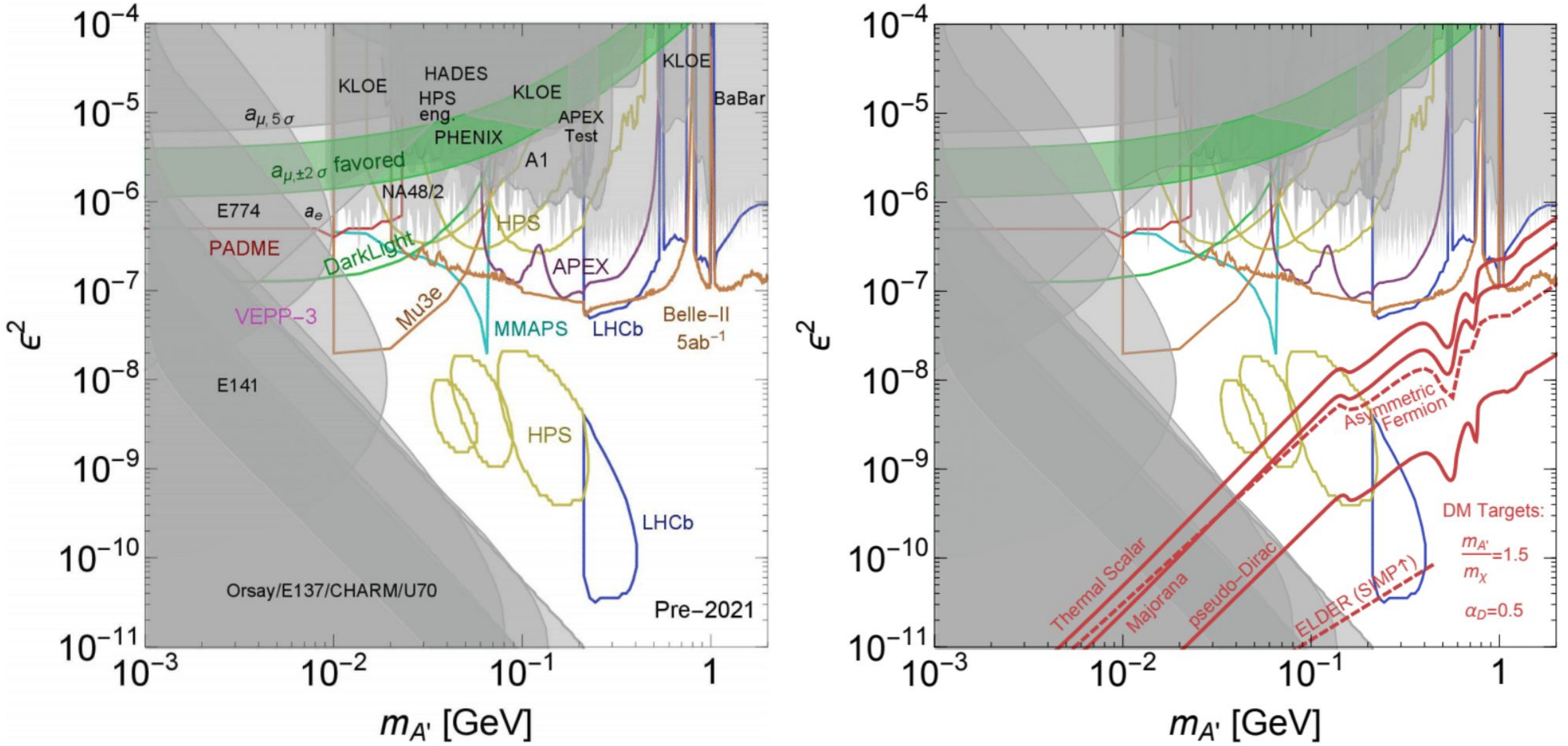


*Reach plots made for expected 2.3 detected A' events and assumes 0.5 background events per mass bin

Conclusion

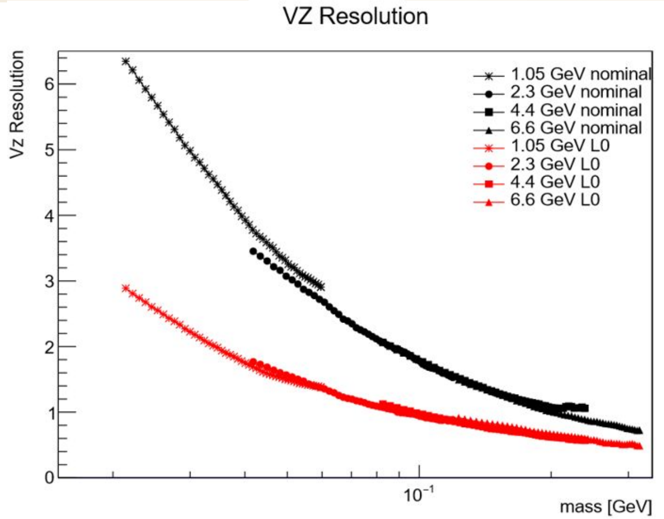
- Heavy photons are well-motivated as the force which mediates LDM-LDM and LDM-SM interactions
- **HPS has successfully run** at two different beam energies (1.06 GeV in 2015 and 2.3 GeV in 2016)
- **Displaced vertex search technique works for HPS!**
- Bump hunt results from 2015 are public (reported in another session)
- Many more upcoming analyses to come out including 2016 vertexing, 2016 bump hunt, and possibly SIMPs
- HPS upgrades are small projects but provide dramatic improvements (construction underway, installation in early 2019)
- **HPS is on the JLab run schedule for 8 weeks at 4.4 GeV in 2019 with upgrades!**

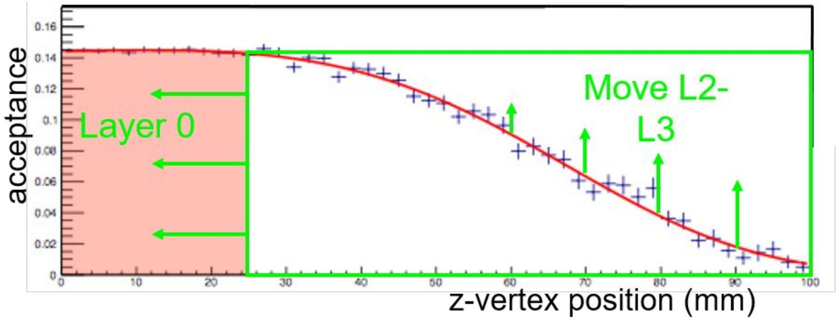
Questions?


HPS Collaboration
May 3 - 5, 2017
Jefferson Lab • Newport News, VA

HPS Upgrades

- **Add a tracking layer** (Layer 0) between target and current first layer
  - Dramatically improves vertex resolution, hence the vertex reach
- **Move L2-L3** slightly towards beam
  - Improves acceptance for longer-lived A's





HPS Upgrades

SLAC

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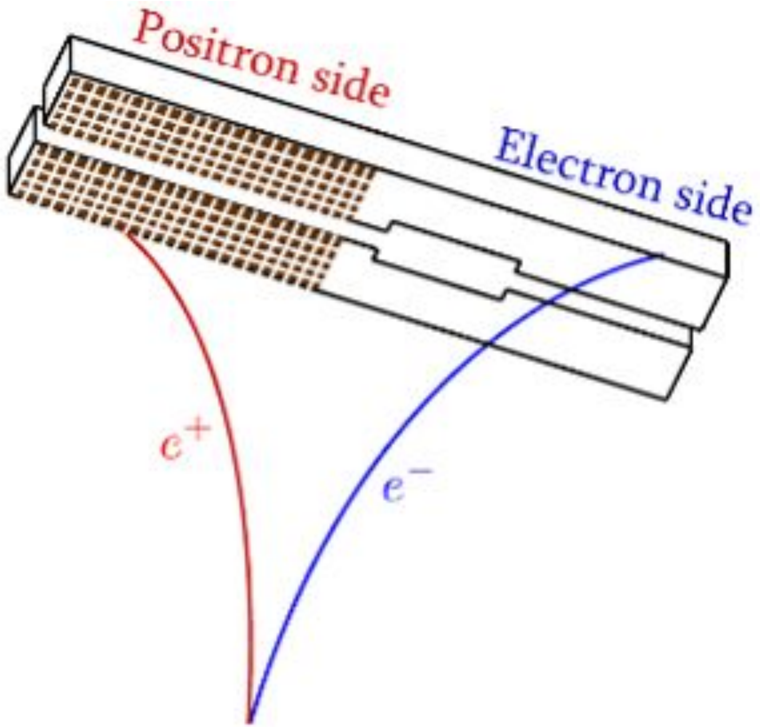
  - Dramatically improves vertex resolution, hence the vertex reach
- **Move L2-L3** slightly towards beam
  - Improves acceptance for longer-lived A's
- **Add positron hodoscope** inside vacuum chamber
  - Reduces acceptance losses in the "Ecal hole"
- Relatively simple. Construction underway, installation in early 2019



HPS Detector

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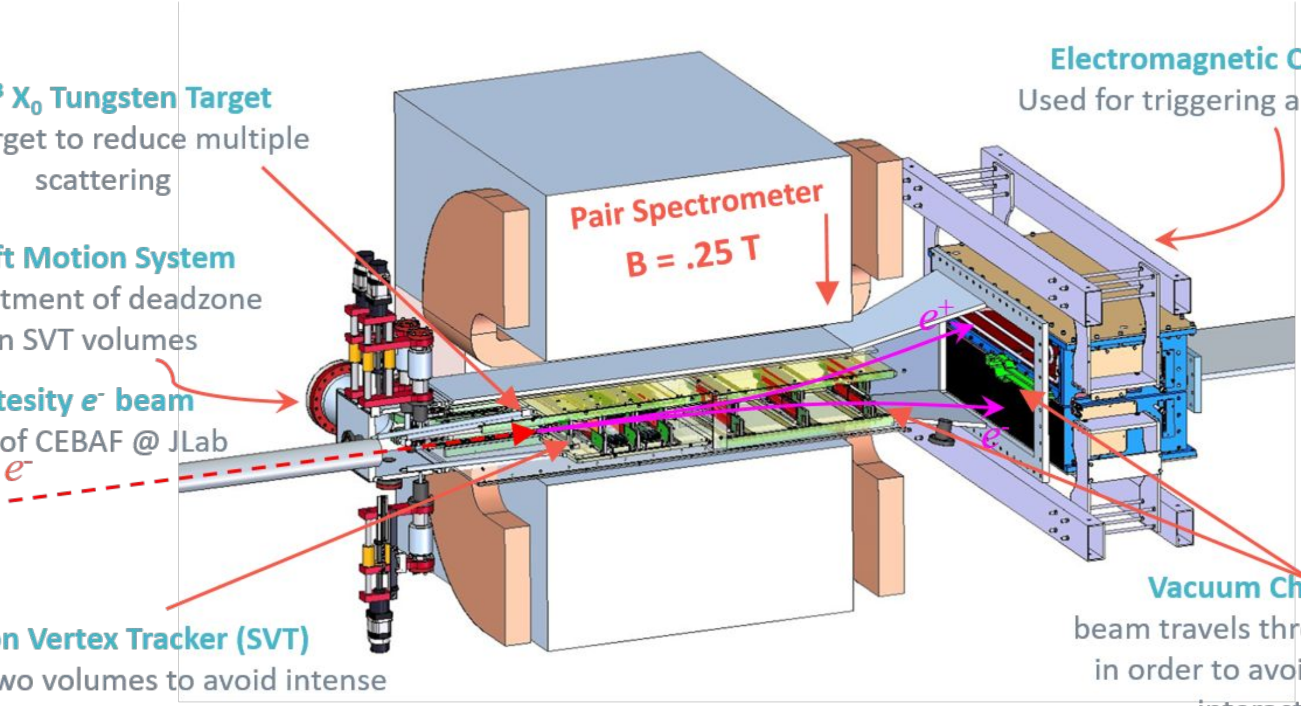
$\sim 10^{-3}$ X_0 Tungsten Target
Thin target to reduce multiple scattering

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.

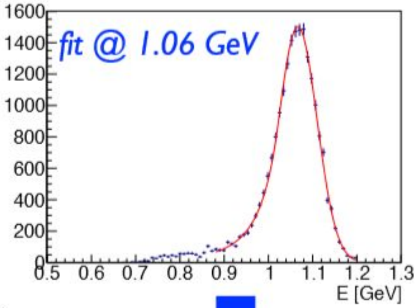
Vacuum Chambers
beam travels through vacuum in order to avoid beam-gas interactions

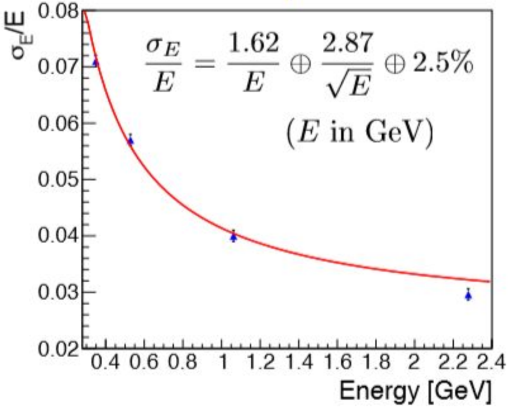
SVT + ECal DAQ capable of 50 kHz

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

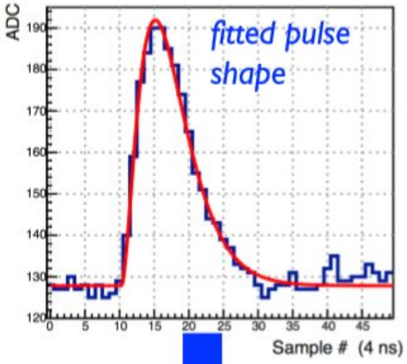
Ecal Performance

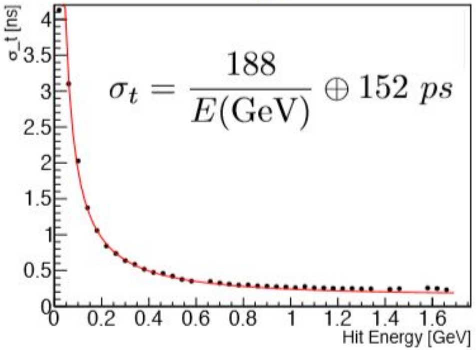
cluster energy resolution





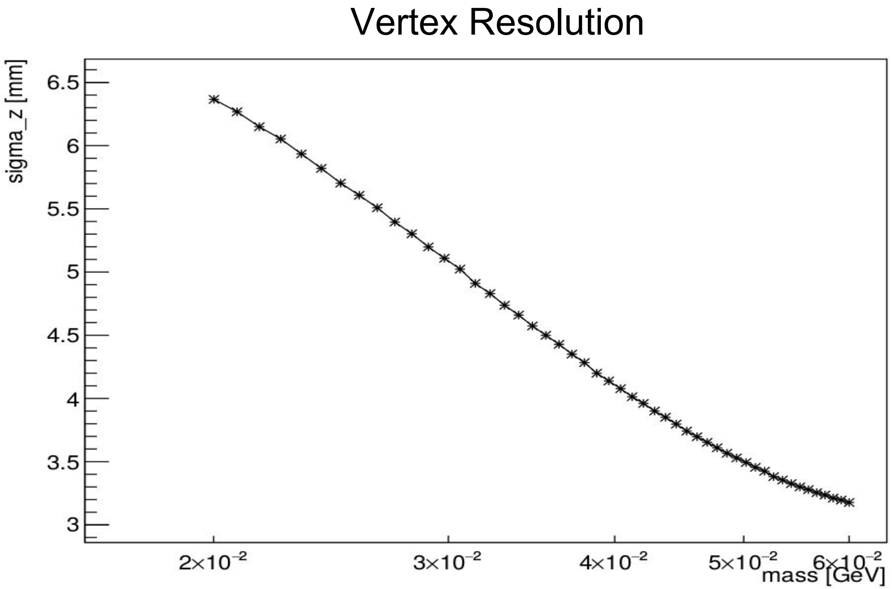
single-crystal time resolution

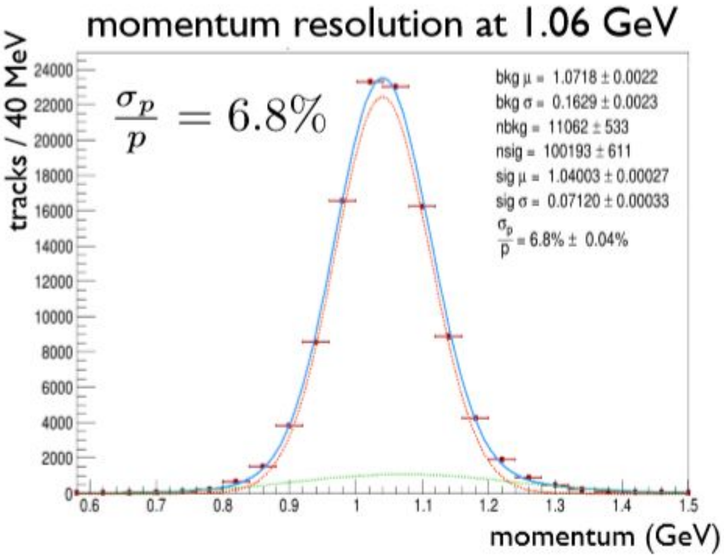




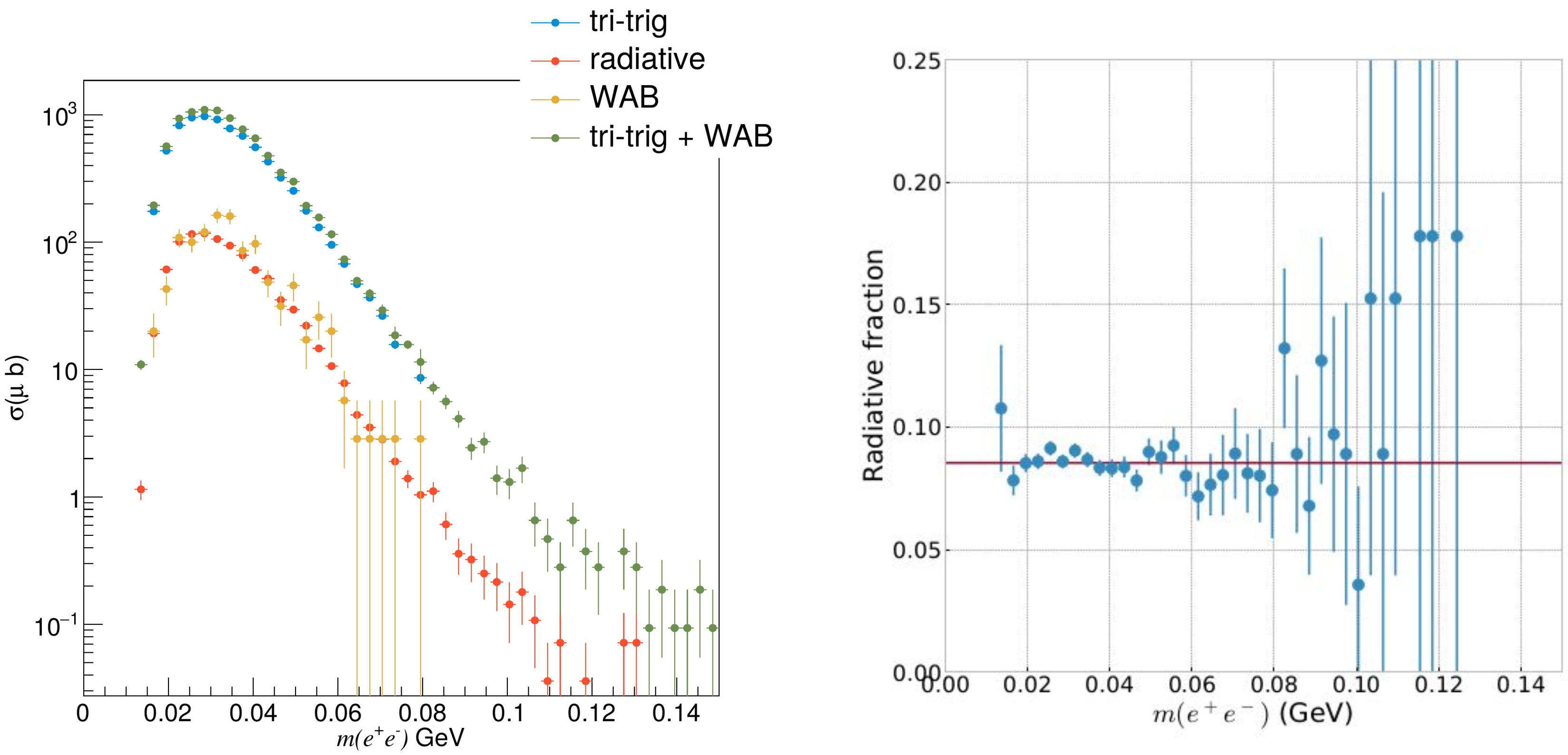
Slide courtesy of Tim Nelson

SVT Vertex and Momentum Resolution





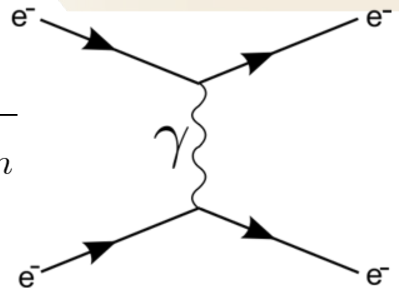
Radiative Fraction

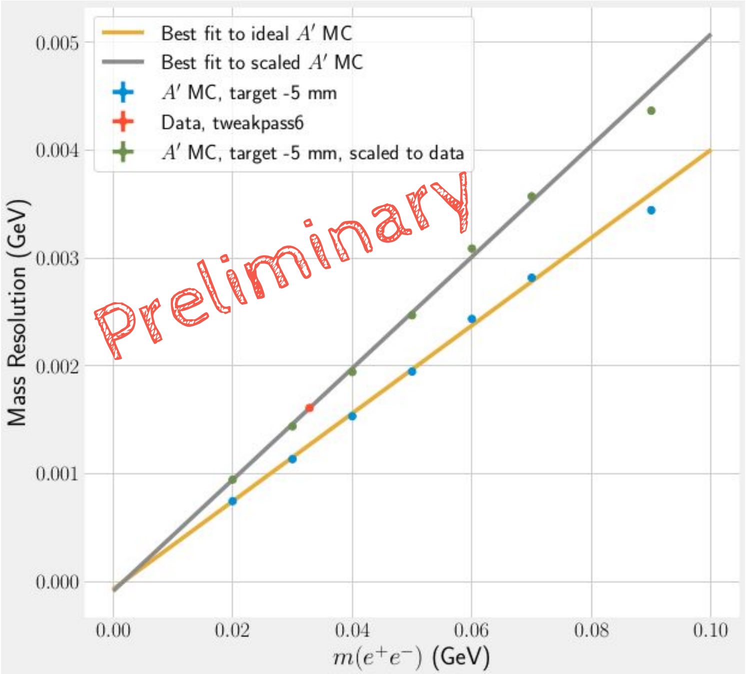


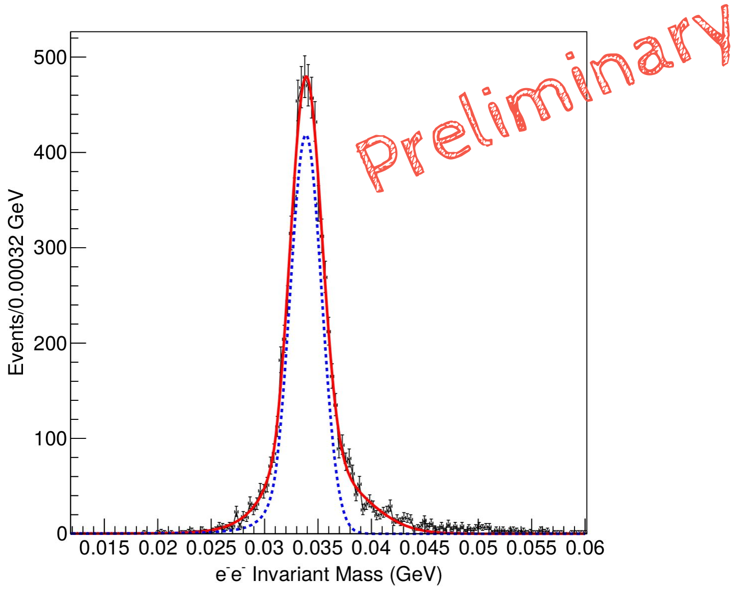
HPS Mass Resolution

- Mass resolution is linear (from A' MC), normalize to Moller pairs

$$E_{CM} = \sqrt{2 m_e E_{beam}}$$





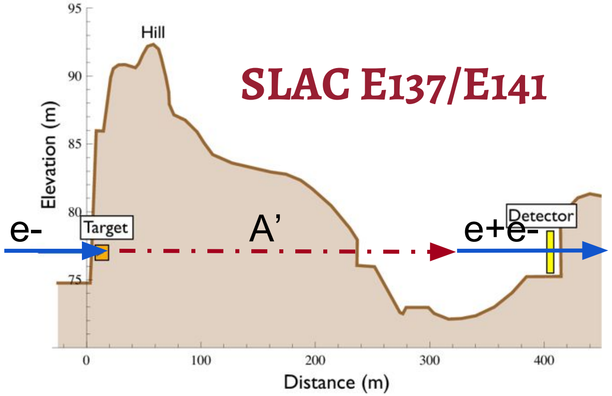


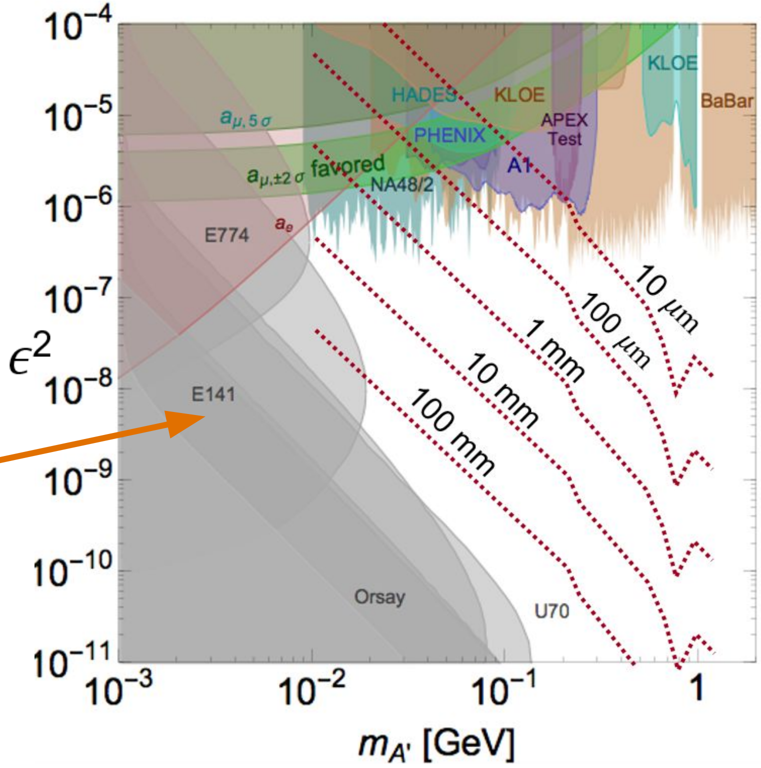
Existing Heavy Photon Constraints

- Large coupling searches are generally **"bump hunts"** for $m(l^+l^-)$ resonances
- A's with small coupling are **long-lived**

$$\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$$

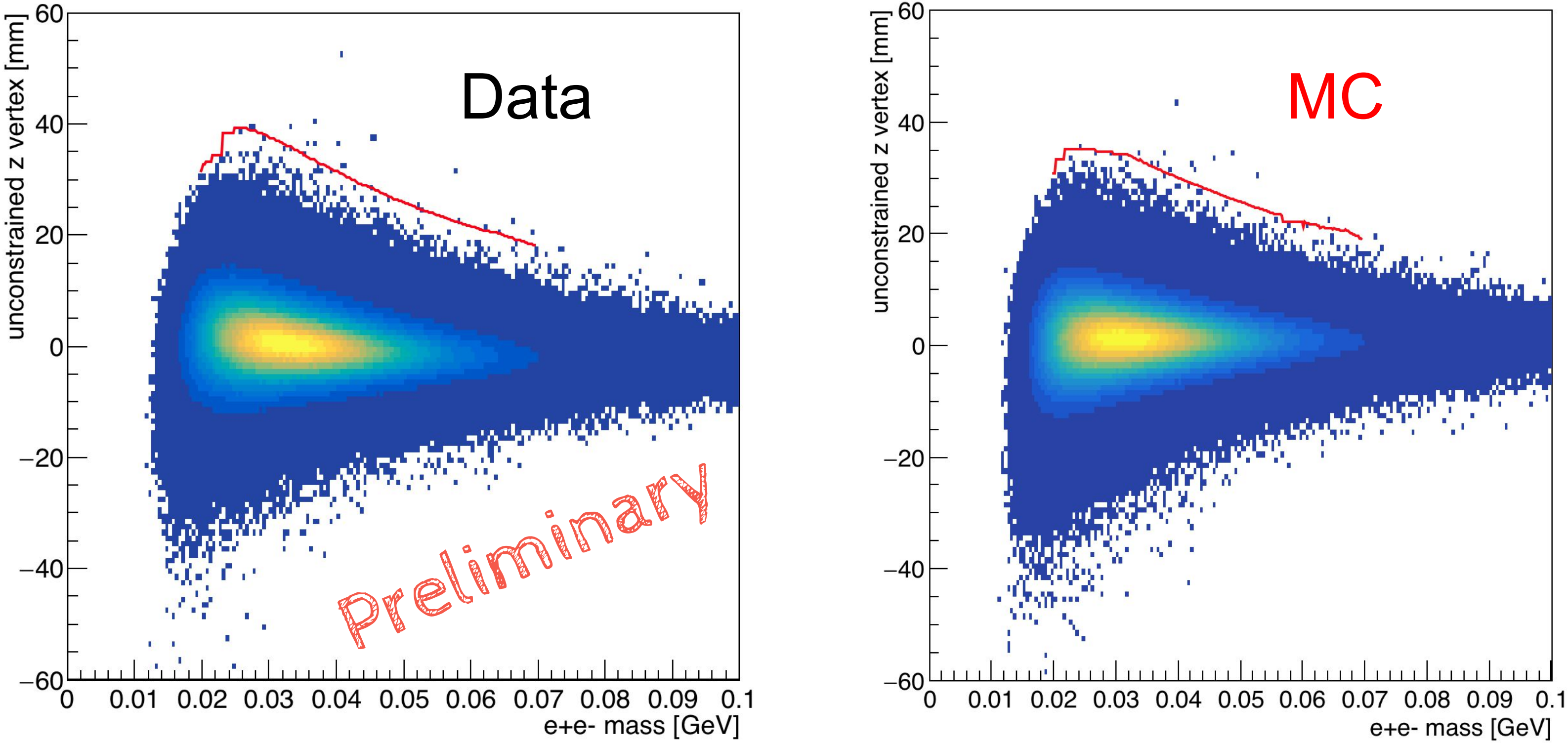
- Constraints from "beam dump" experiments are possible



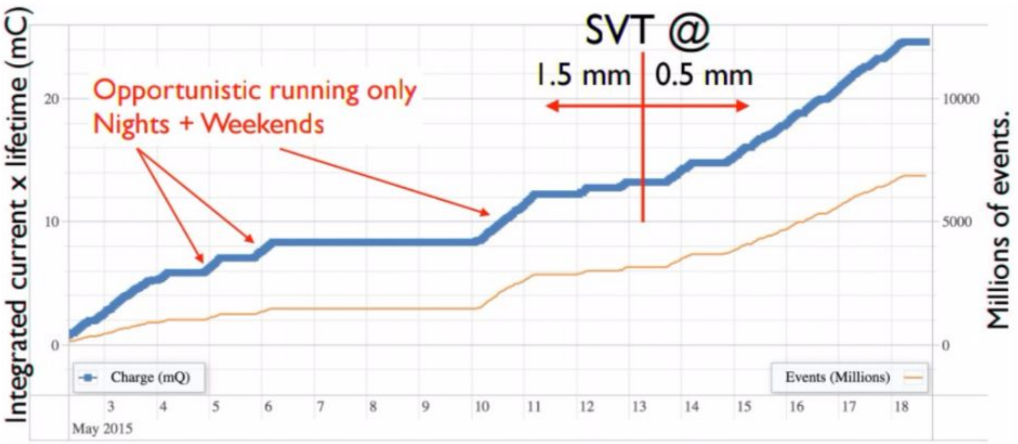


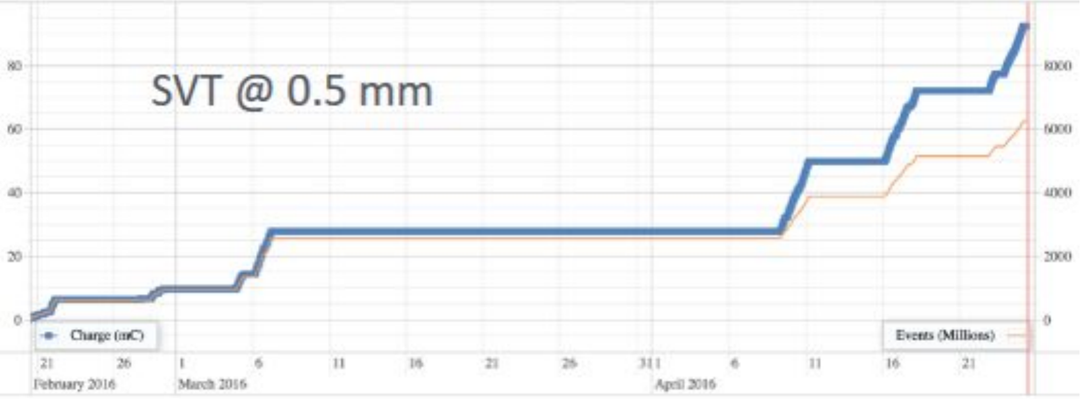
Comparison with MC

- Data (left) and MC (right) have reasonable agreement at equivalent luminosity



2015 & 2016 Engineering Runs





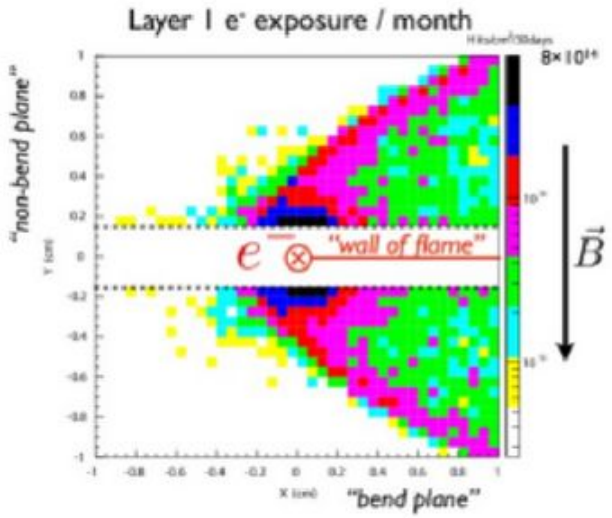
2015 Engineering Run
50 nA at 1.06 GeV
1.7 days (10 mC) of physics data

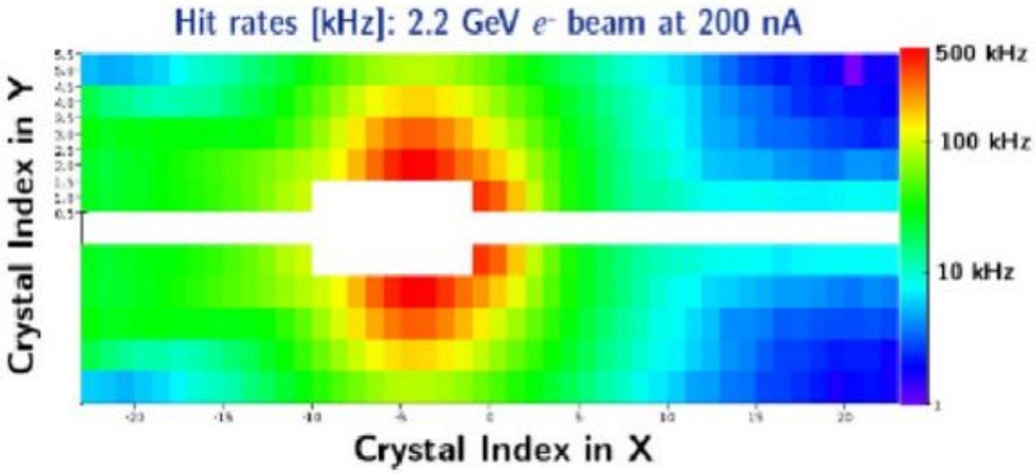
2016 Engineering Run
200 nA at 2.3 GeV
5.4 days (92.5 mC) of physics data

180 days of data taking approved by JLab PAC!

Beam Backgrounds

- Background is dominated by **electron scattering in the target**
- Detector (vertical) acceptance down to +/- 15 mrad (which means L1 of SVT is **0.5 mm from beam axis!**)
- This provides challenges for occupancies, data rates, and radiation tolerances





Jefferson Laboratory and CEBAF

- JLab (Newport News, VA) has the Continuous Electron Beam Accelerator Facility (CEBAF) that can simultaneously deliver intense electron beams of different energies to 4 experiment halls
- 1.1 or 2.2 GeV per pass up to 12 GeV and 2 ns bunch pulse
- **Provides small, stable beam spot with minimal halo**