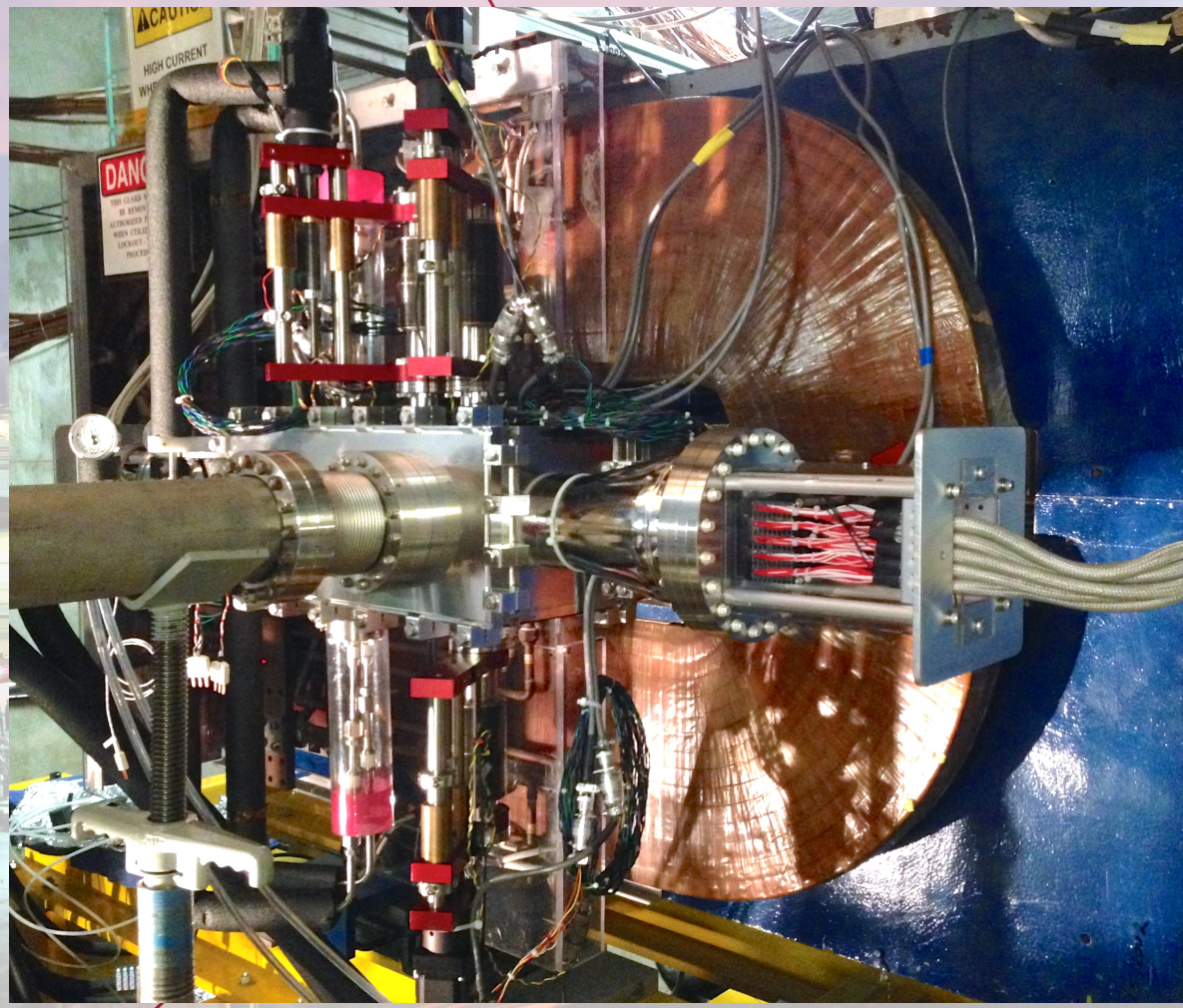
JLab A′ Searches

Tim Nelson

LDMA 2017 - Isola d'Elba

May 27, 2017



U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Dark Sectors at JLab

JLab has a broad program in dark sector physics.

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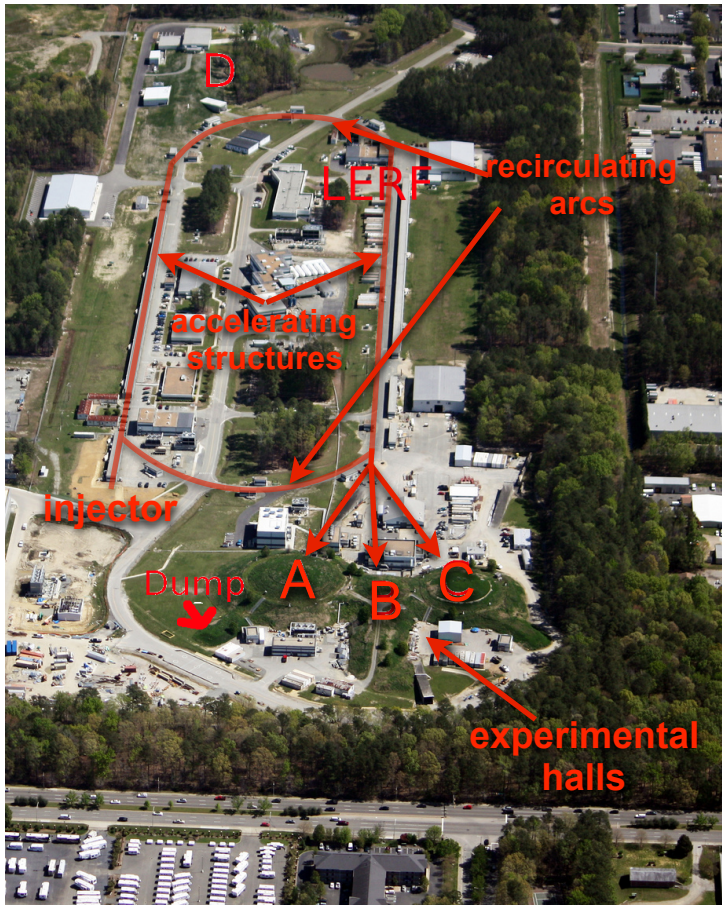
Visibly decaying A′ searches:

- APEX (A-prime Experiment) in Hall A
- HPS (Heavy Photon Search) in Hall B

Continuous Electron Beam Accelerator Facility



1-11 GeV e^-, 10 nA ~ 100 μA

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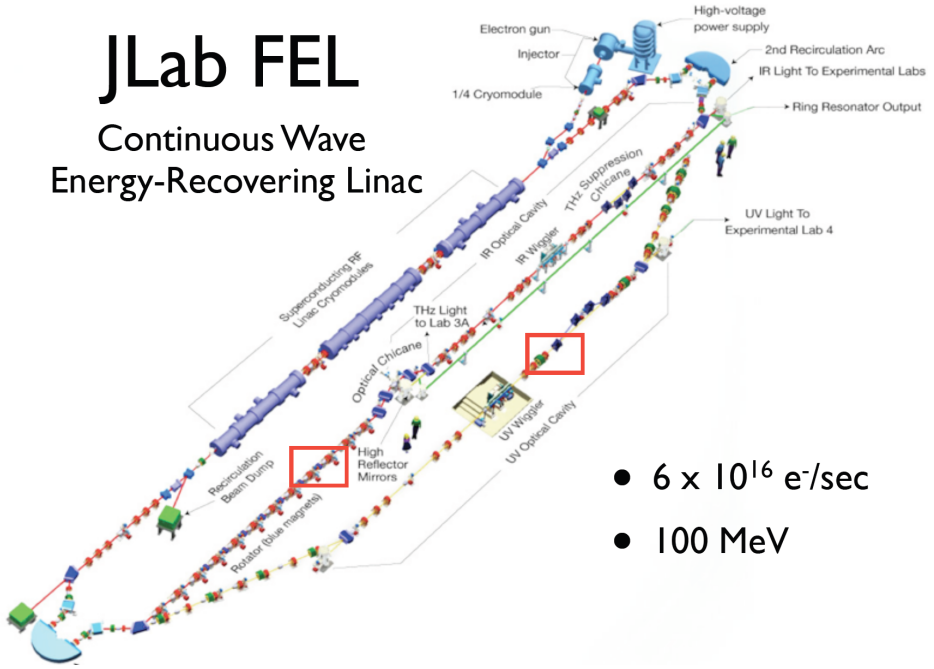
JLab FEL

Continuous Wave
Energy-Recovering Linac



- 6 x 10^{16} e^-/sec
- 100 MeV

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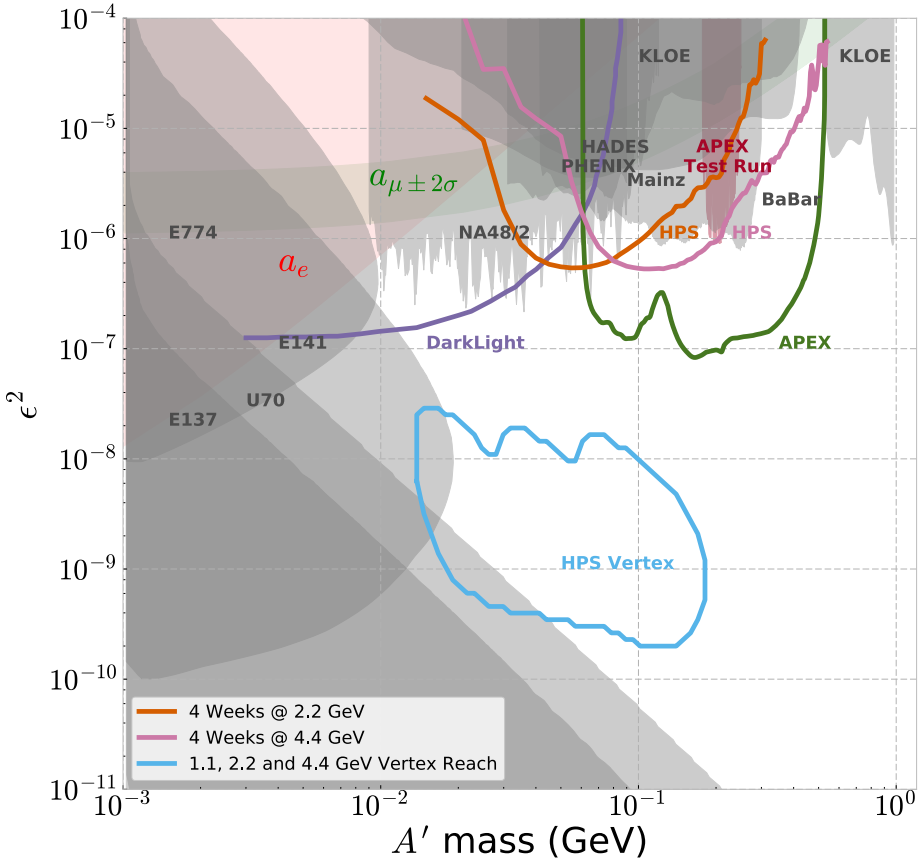

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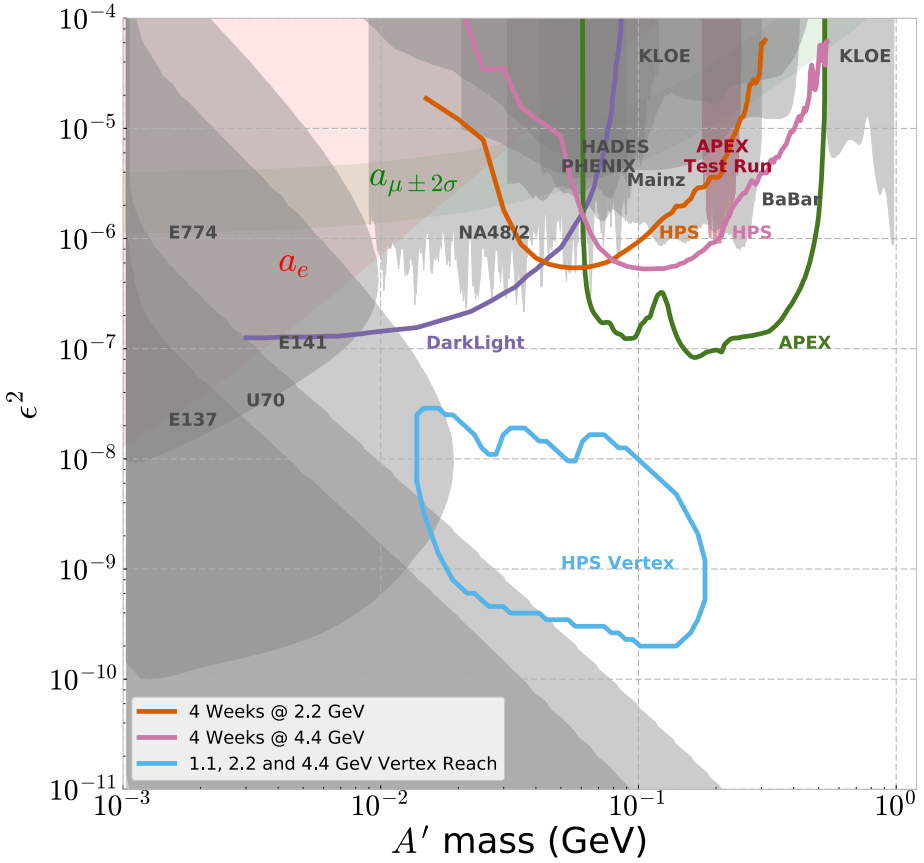
- *BDX (Beam Dump Experiment)*
- *LDMX at JLab?*



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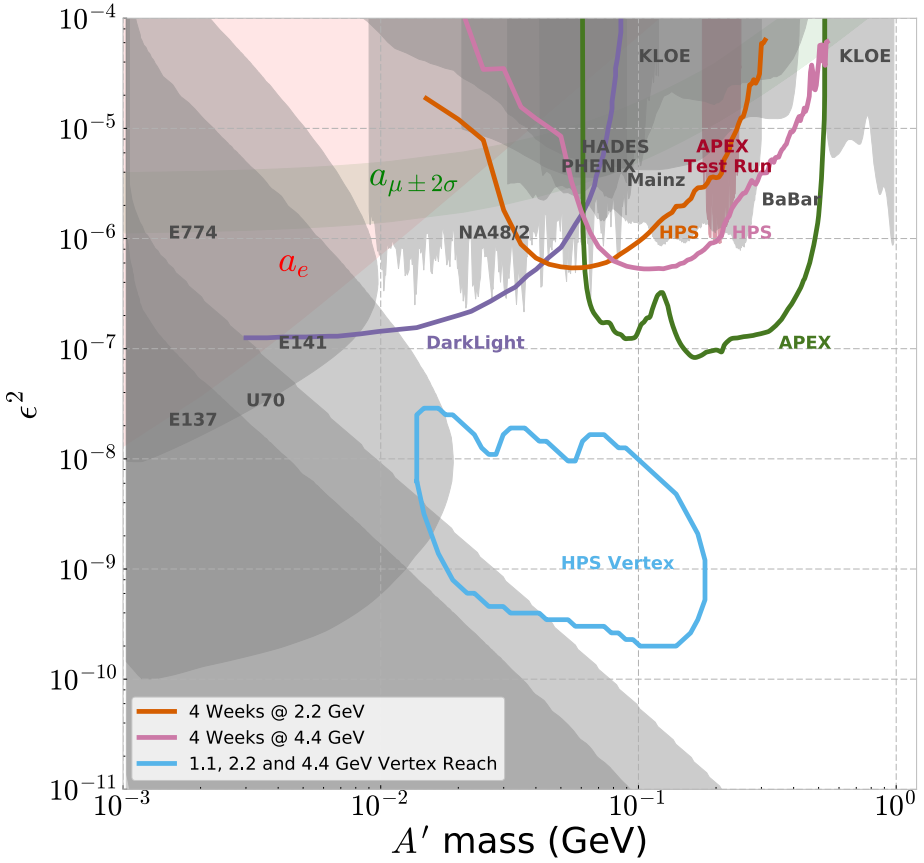
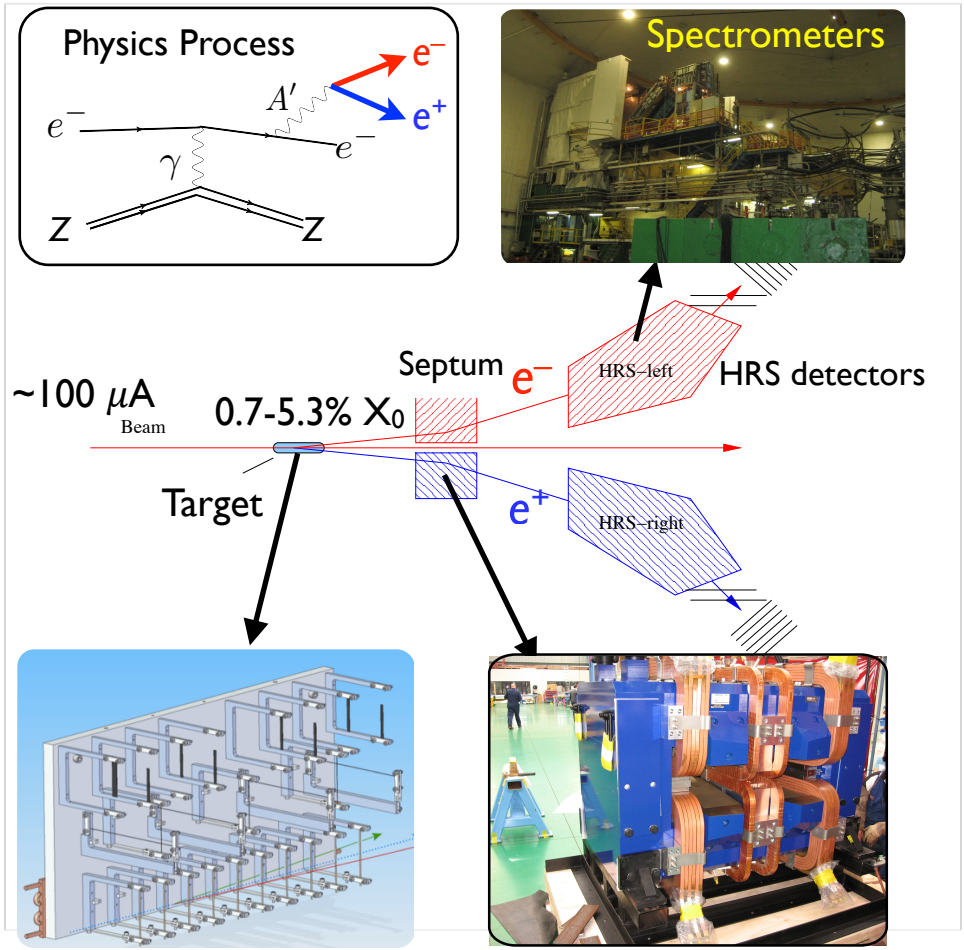


APEX

A′ search using Hall A high-resolution spectrometers (HRS)



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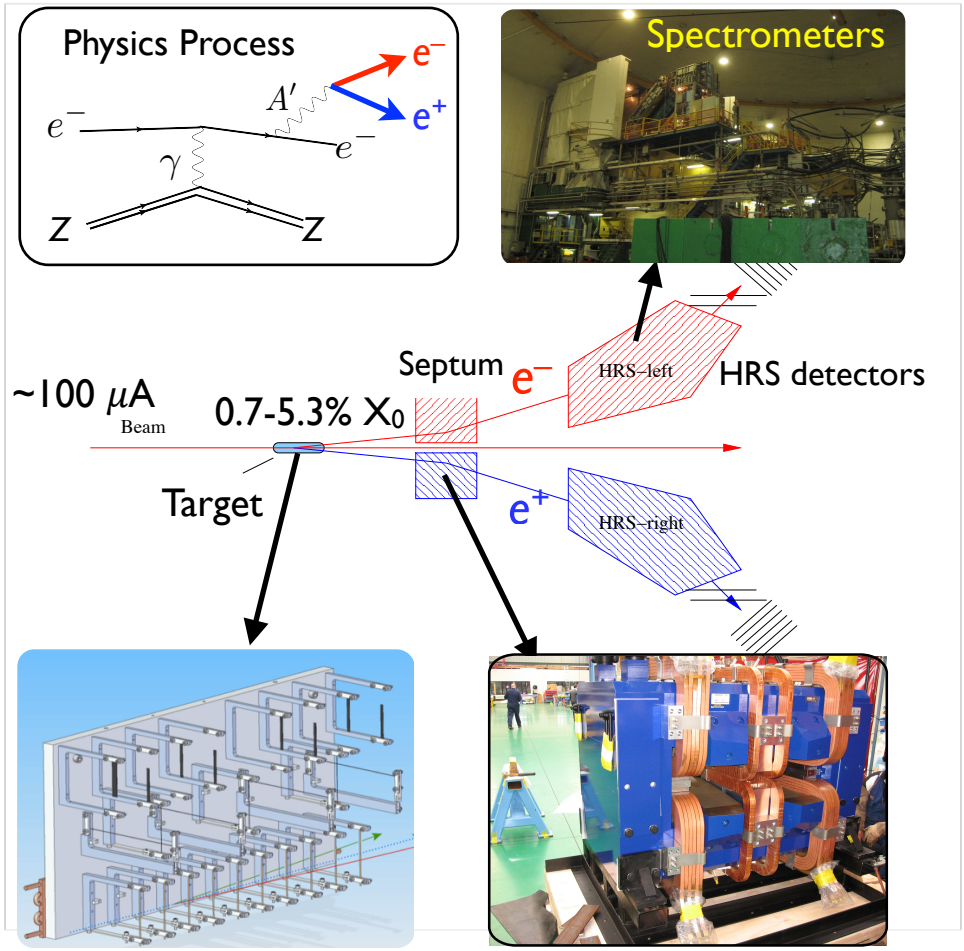
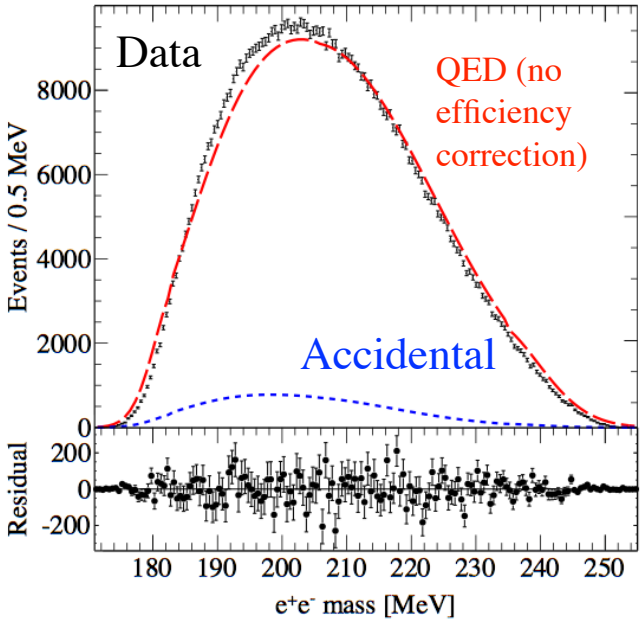


Test run (2010):

concept & technical demonstration; weekend run achieved; new sensitivity.



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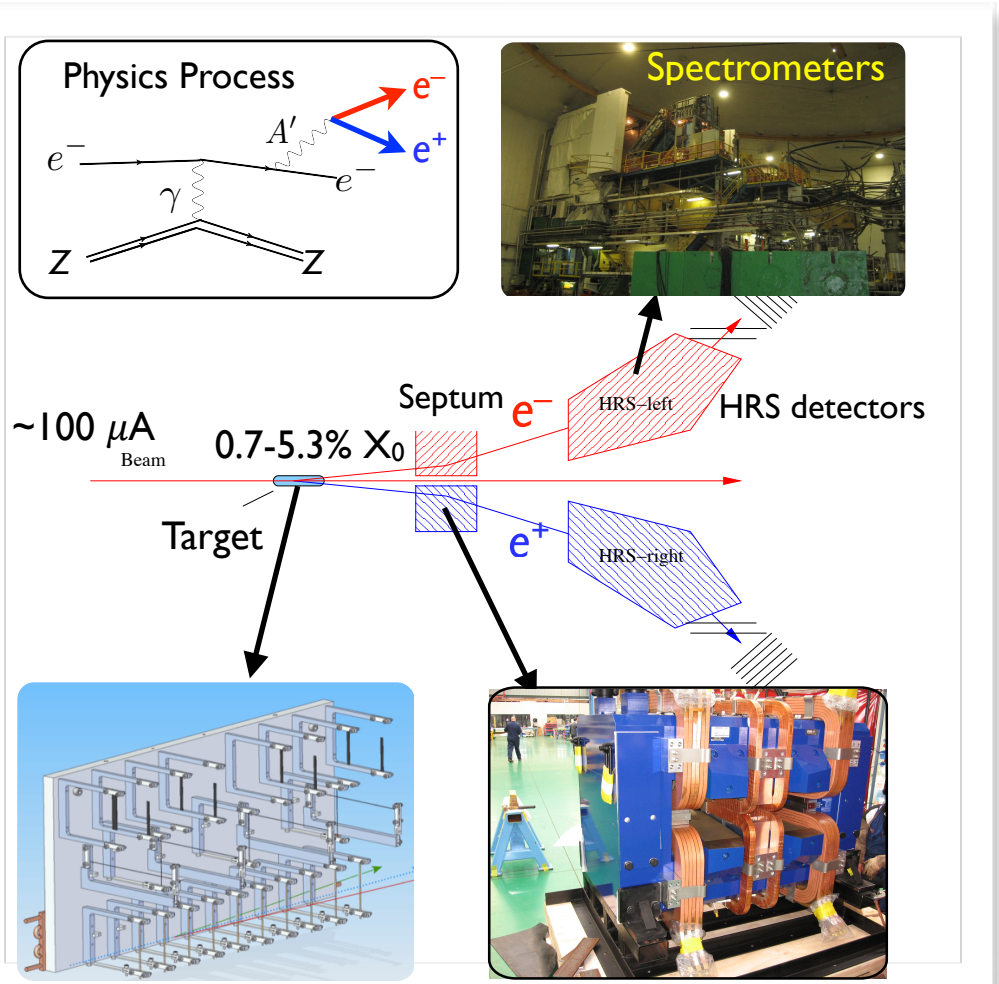

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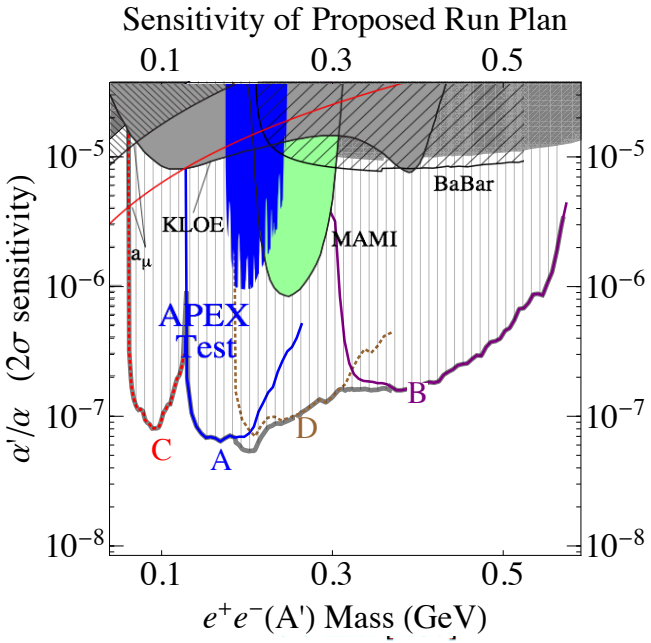

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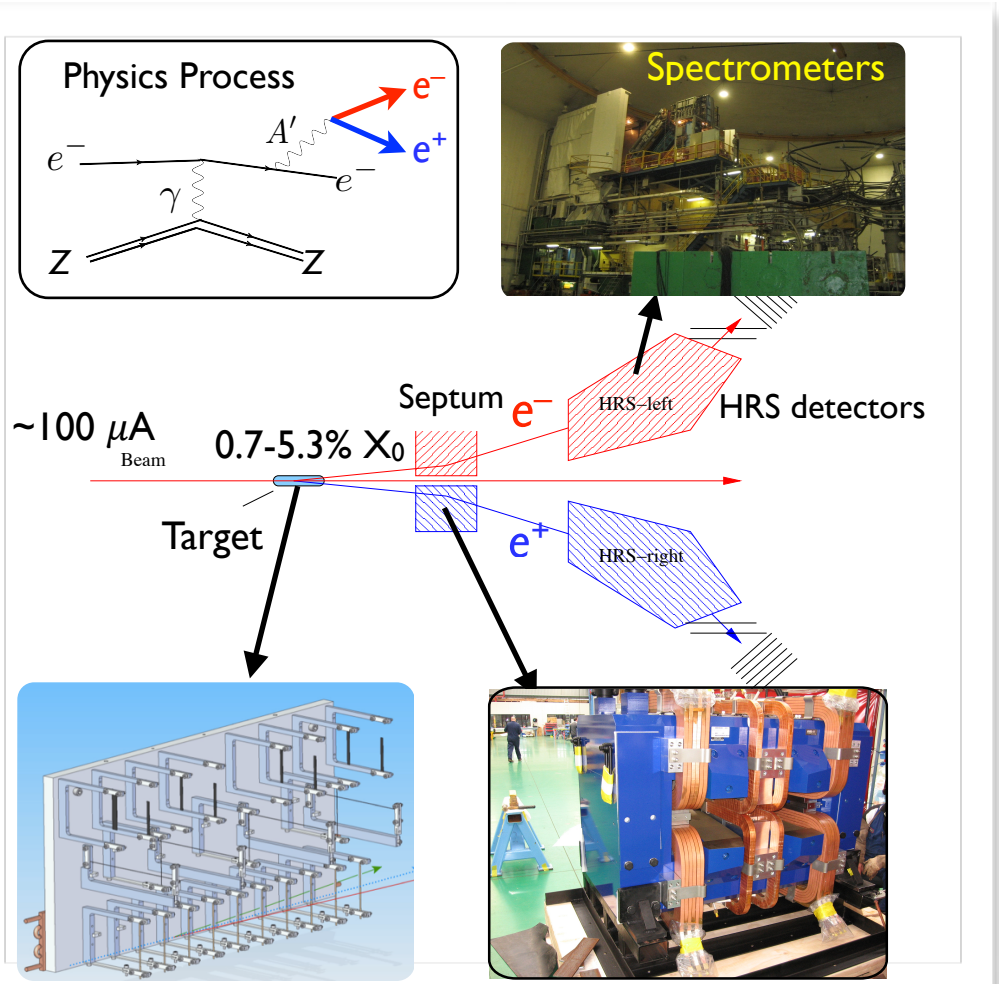

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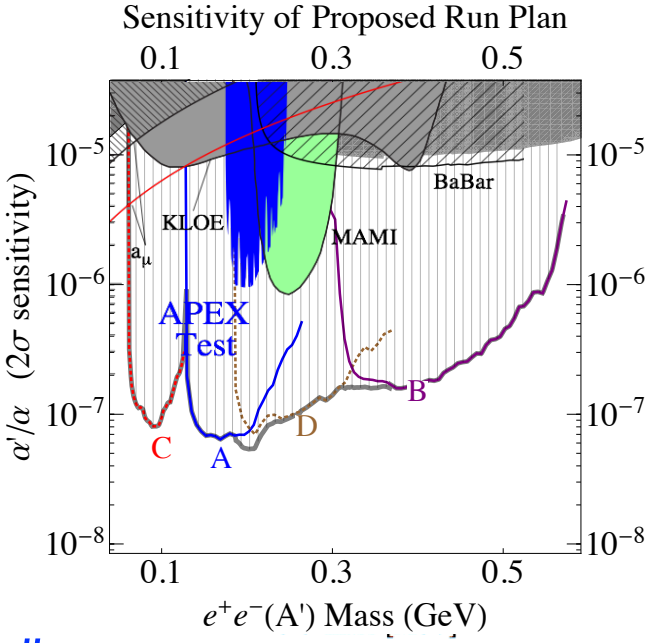
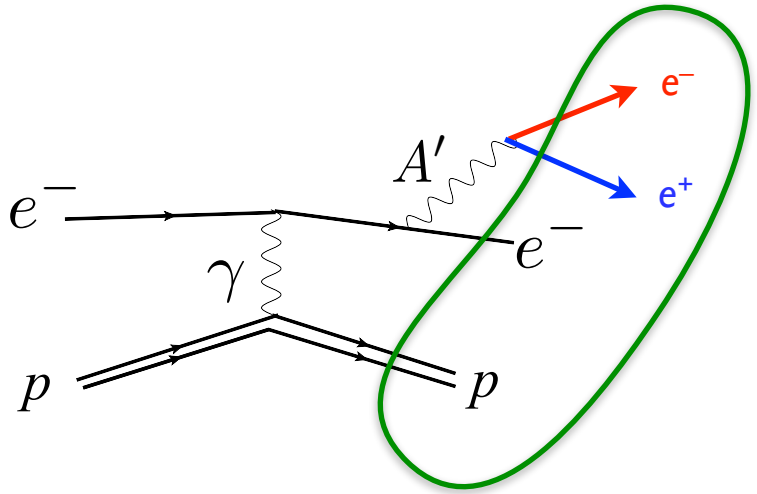


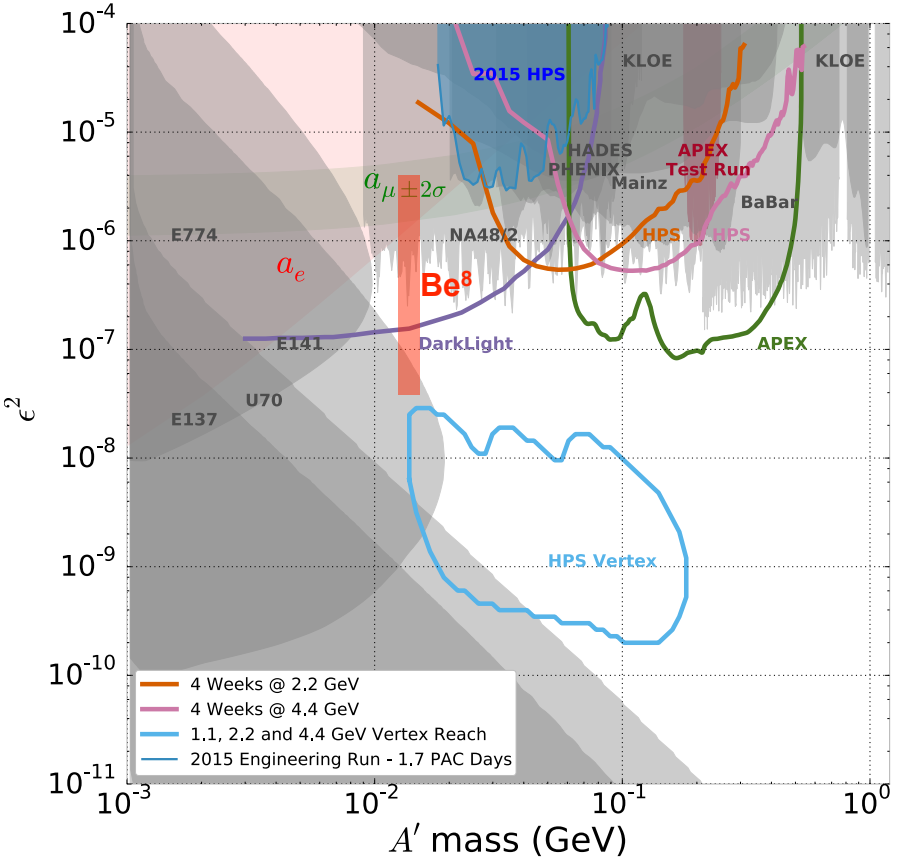
Full run:

PAC approved and prioritized, funded, projected to run ~2018. Optimized septa magnet constructed. Smaller beam line items funded and HRS detectors ready.

Darklight

5 mA, 100 MeV e^- on few×10^{19}/cm^2 H_2 gas target:





complete reconstruction of final state allows sensitivity to invisible decays also

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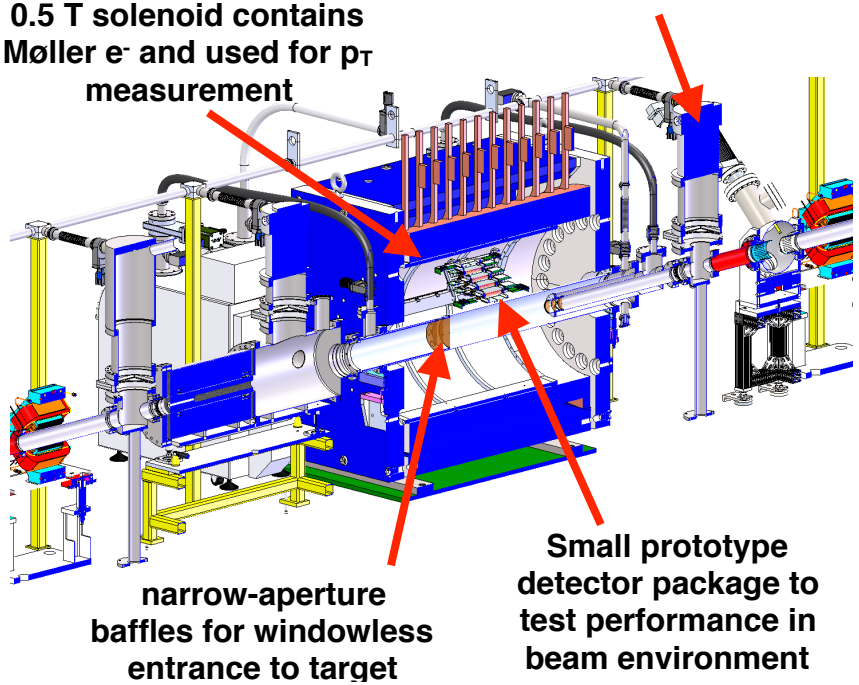

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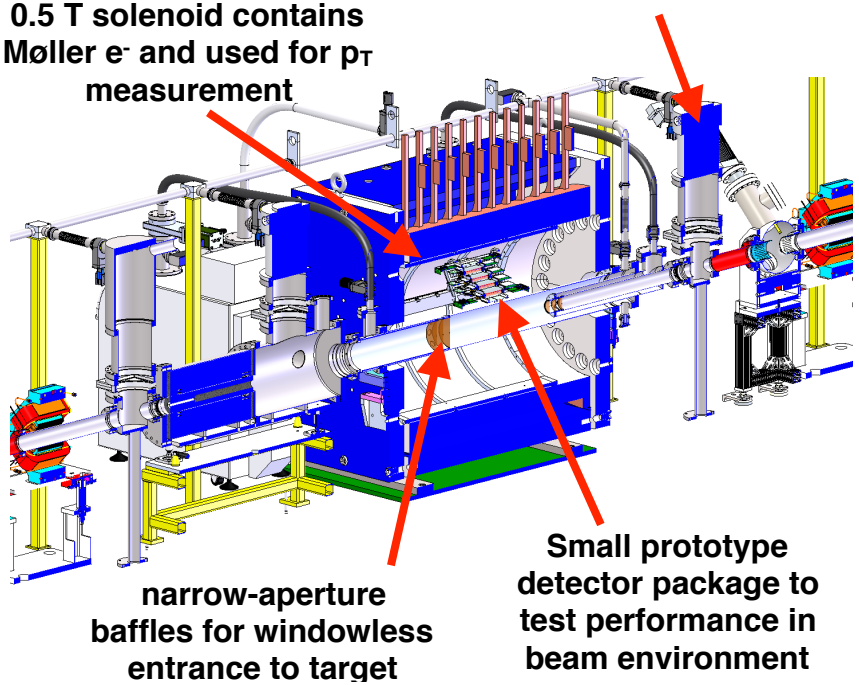
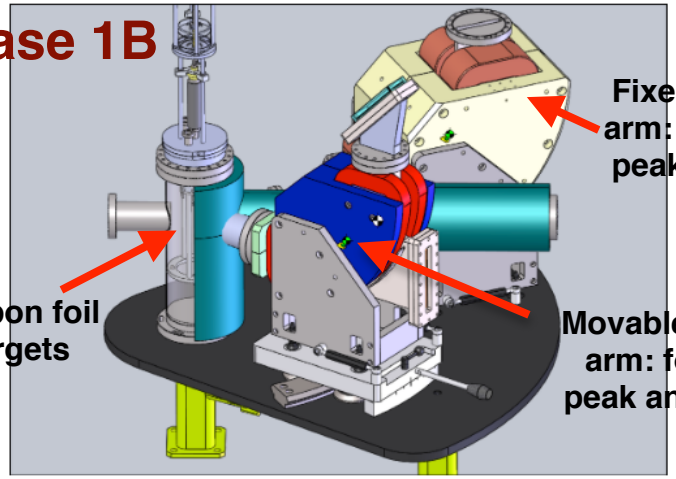


Phase 1B



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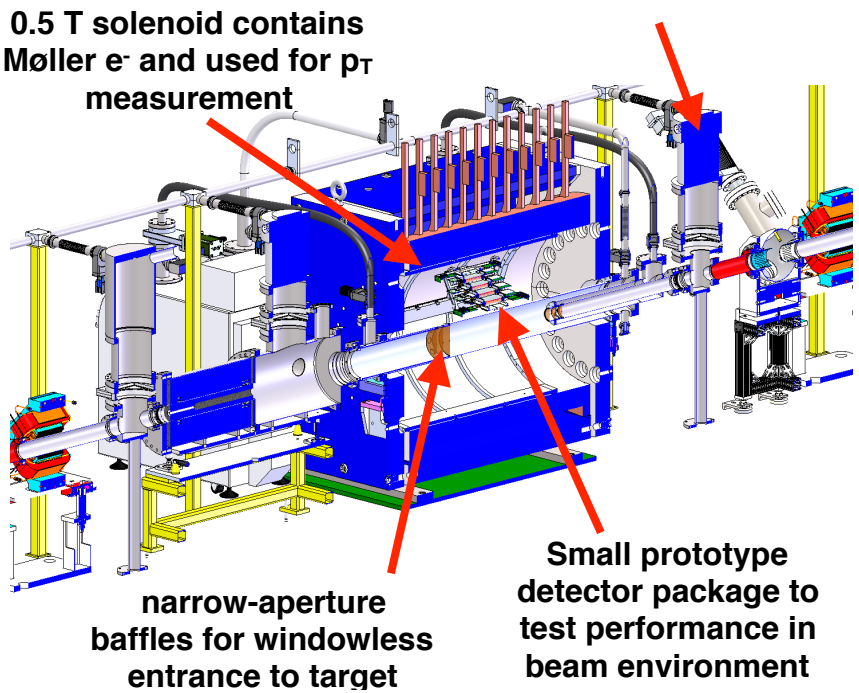
Phase **1C**: Proof-of-principle detector focused on low A' mass

Phase 1A



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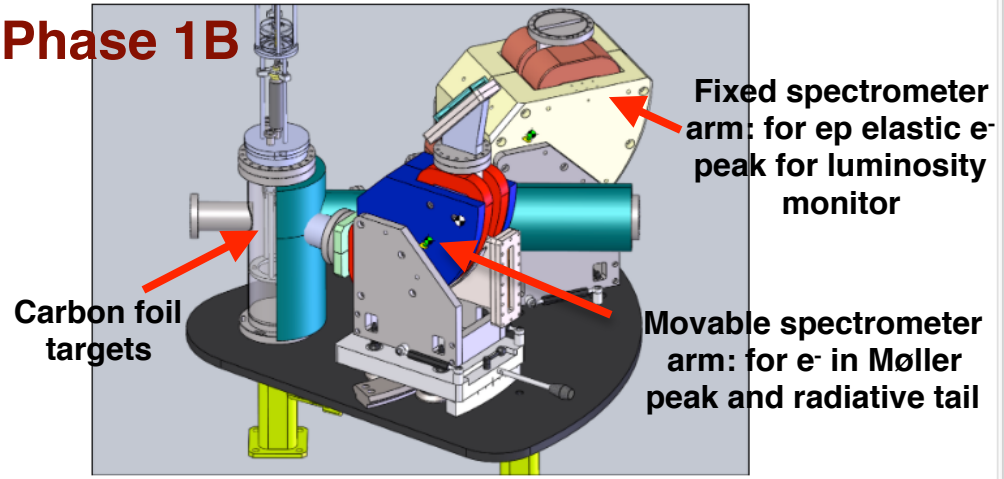
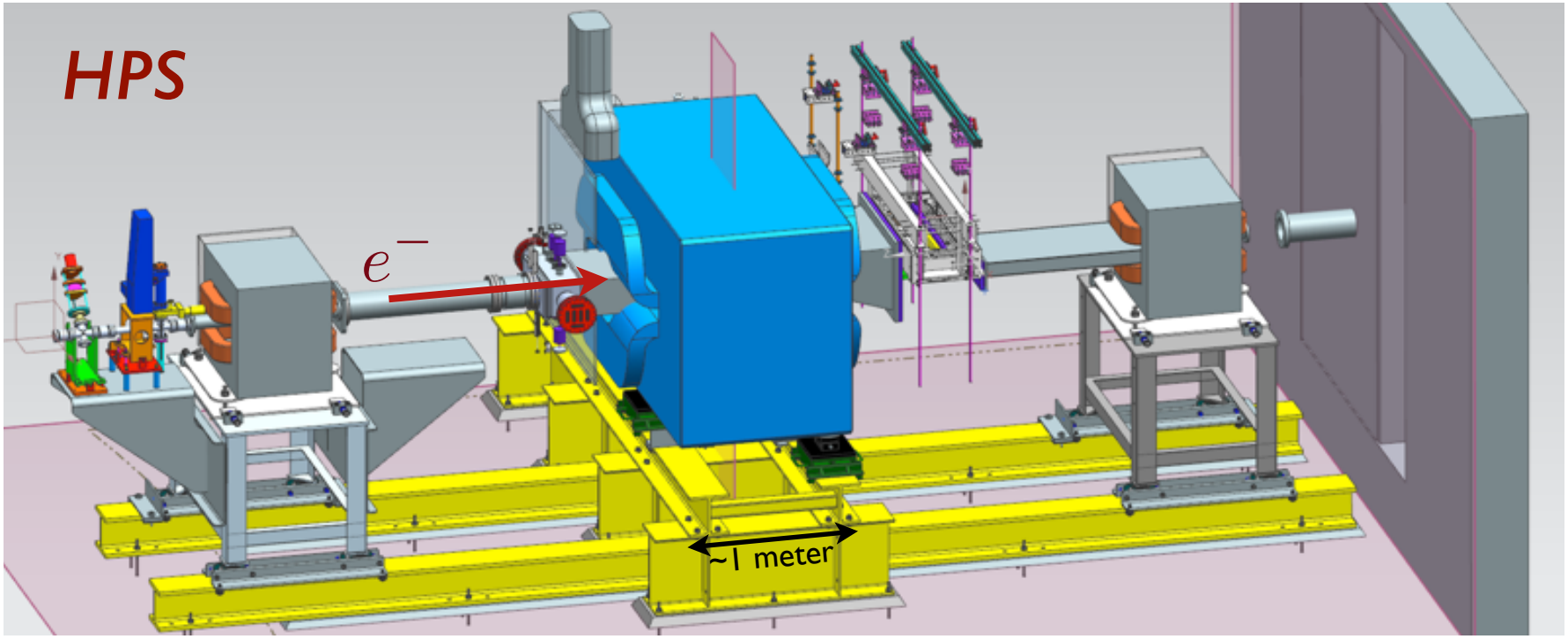


The Heavy Photon Search Experiment

HPS is a fixed-target search for visibly decaying hidden photons using ~10^{19} e^- of CEBAF (1.1–6.6 GeV) beam in Hall B at JLab.



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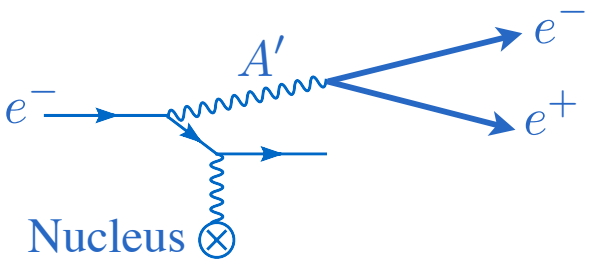
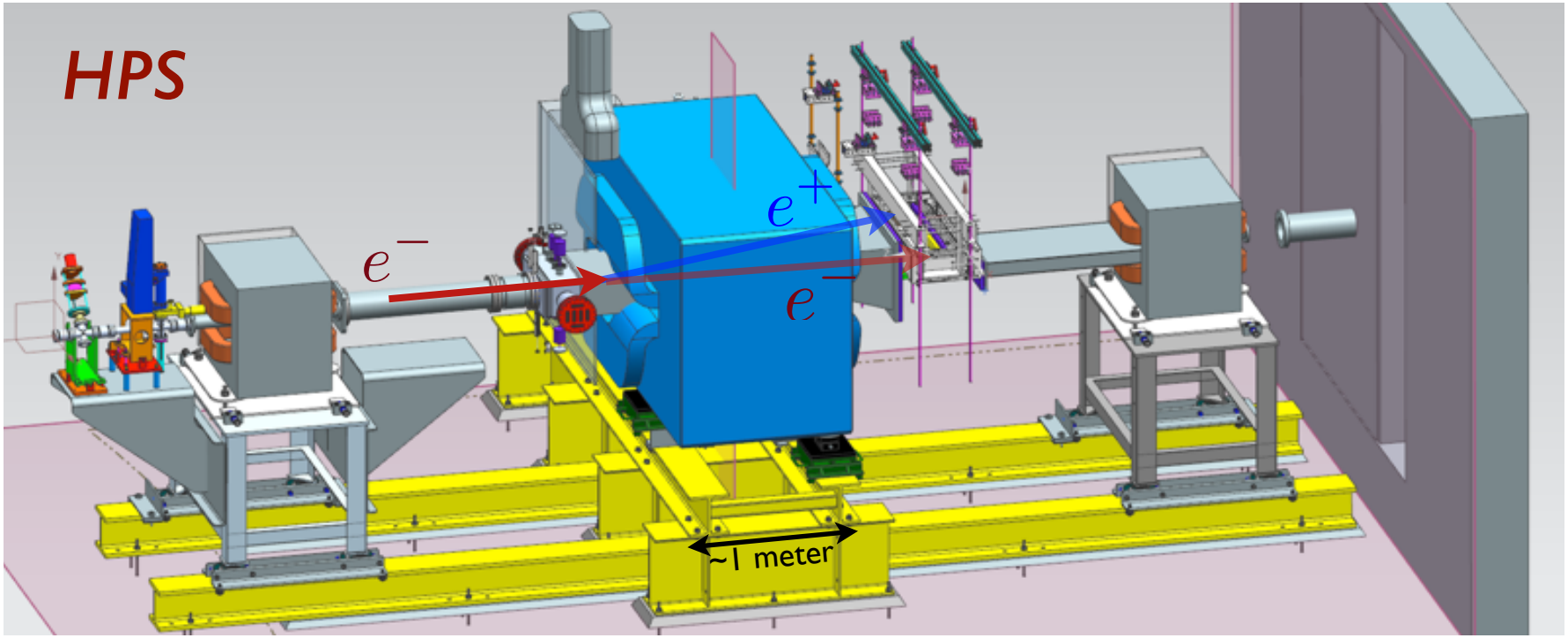
dark bremsstrahlung in thin (0.125% - 0.25% X_0) tungsten foil





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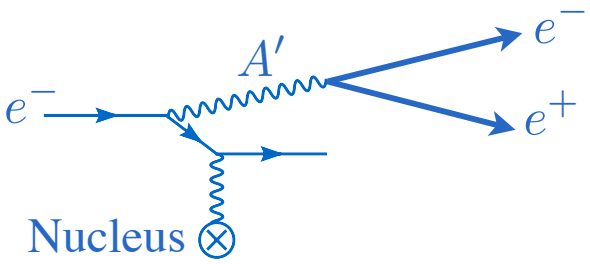

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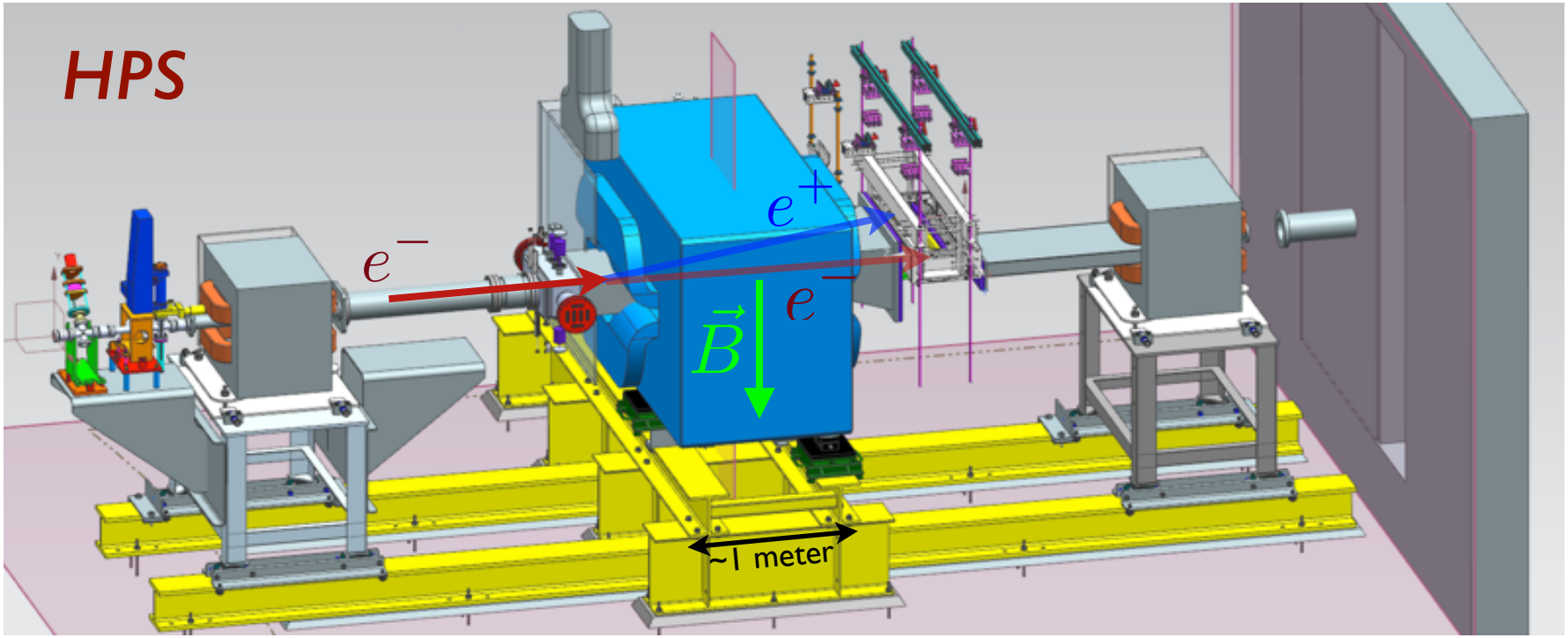
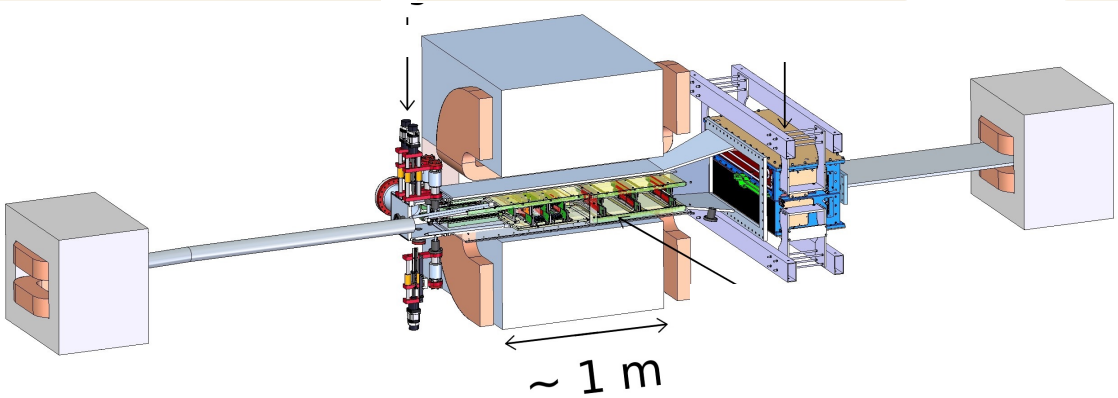
dipole magnet spreads out e^+e^- pairs, enables momentum measurement



Key Components of HPS



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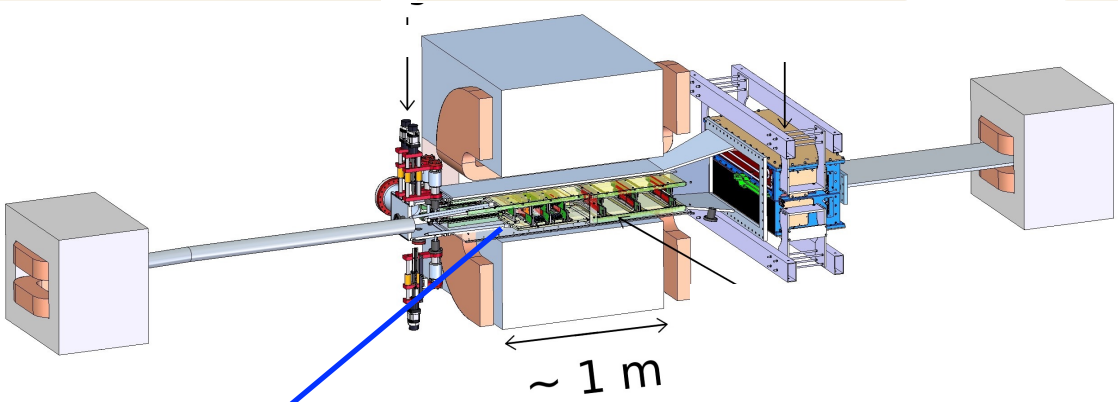
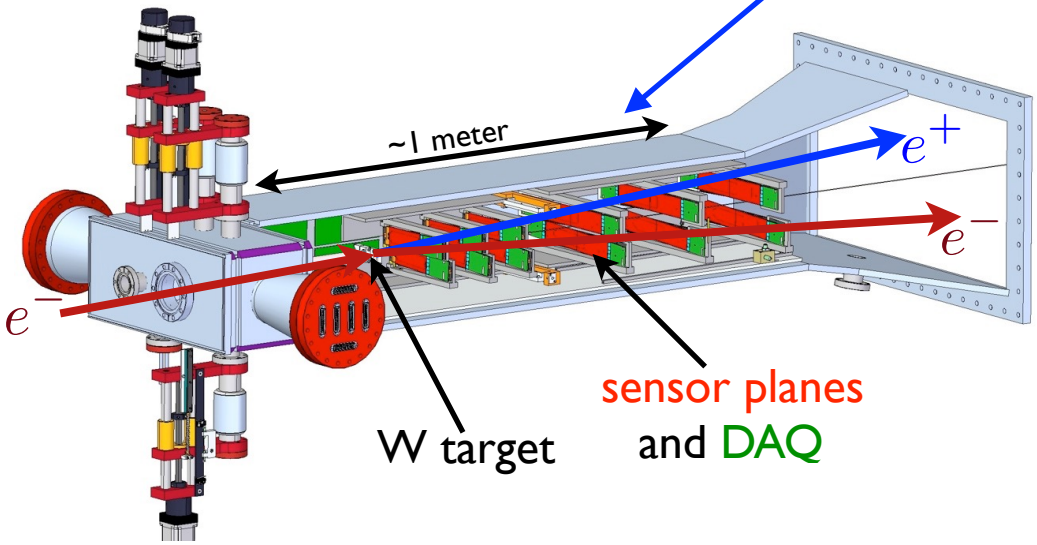


Silicon Vertex Tracker
Built at SLAC



SVT measures trajectories of electrons to reconstruct e^+e^- mass and ***vertex position***.

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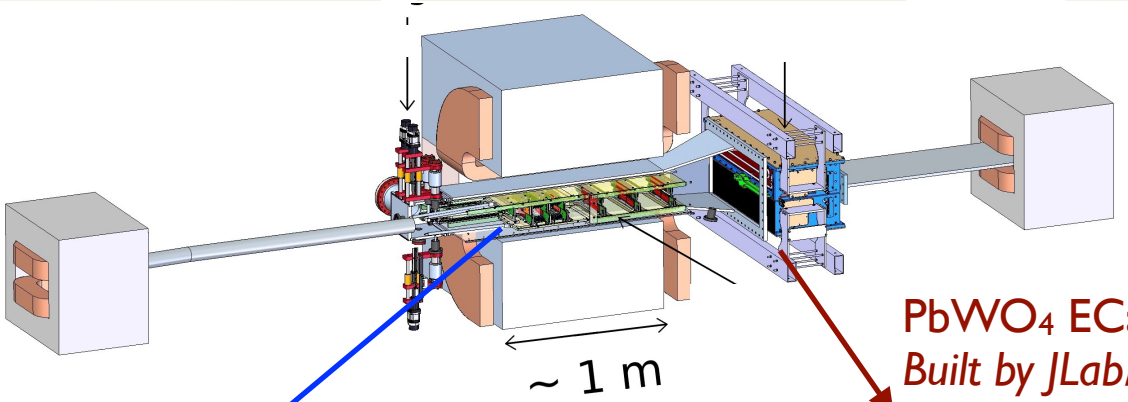

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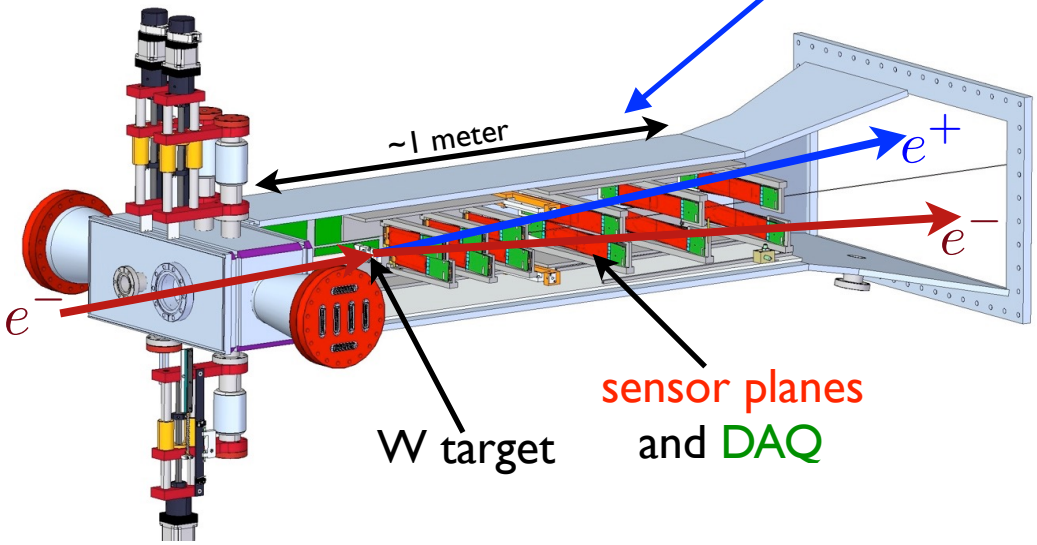
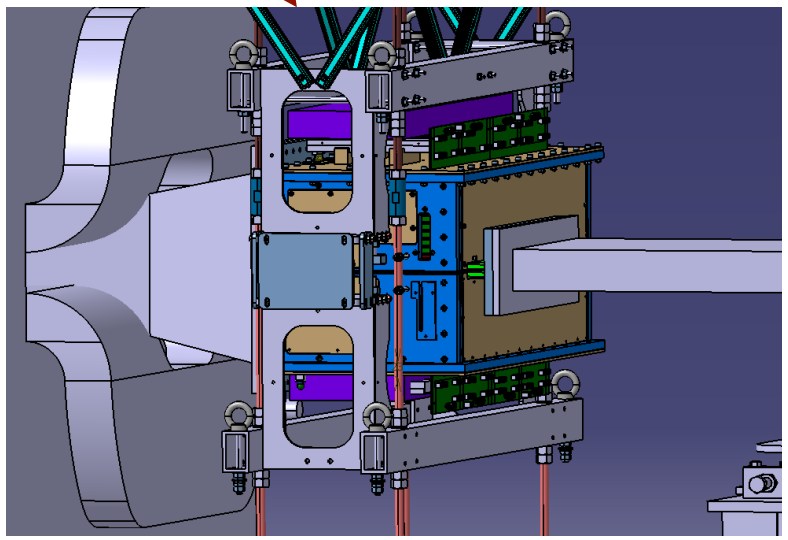
PbWO$_4$ ECal
Built by JLab/Orsay/INFN





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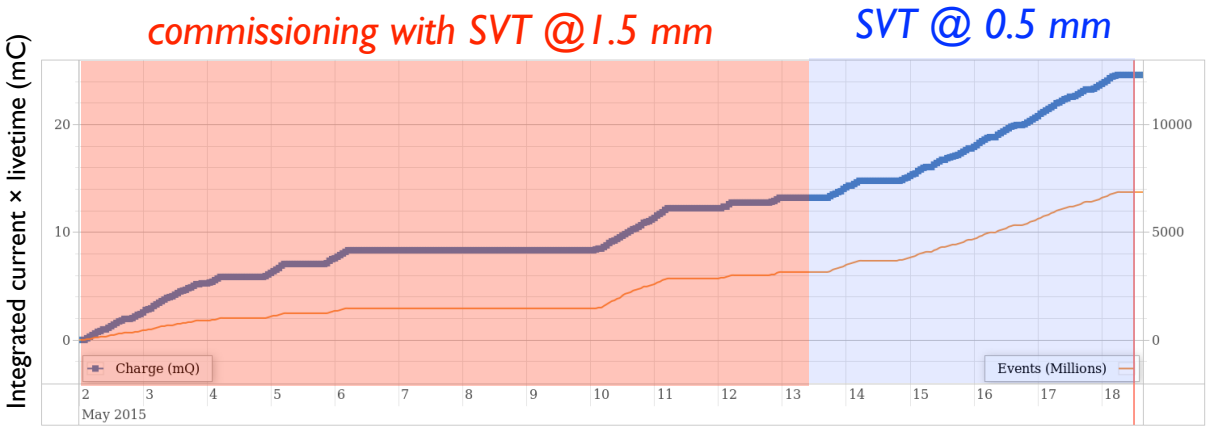
ECal provides e^+e^- trigger with precision timing to reject single e^- backgrounds.

2015 and 2016 Engineering Runs

2015 Engineering Run

50 nA @ 1.06 GeV

1.7 days (10 mC) of physics data



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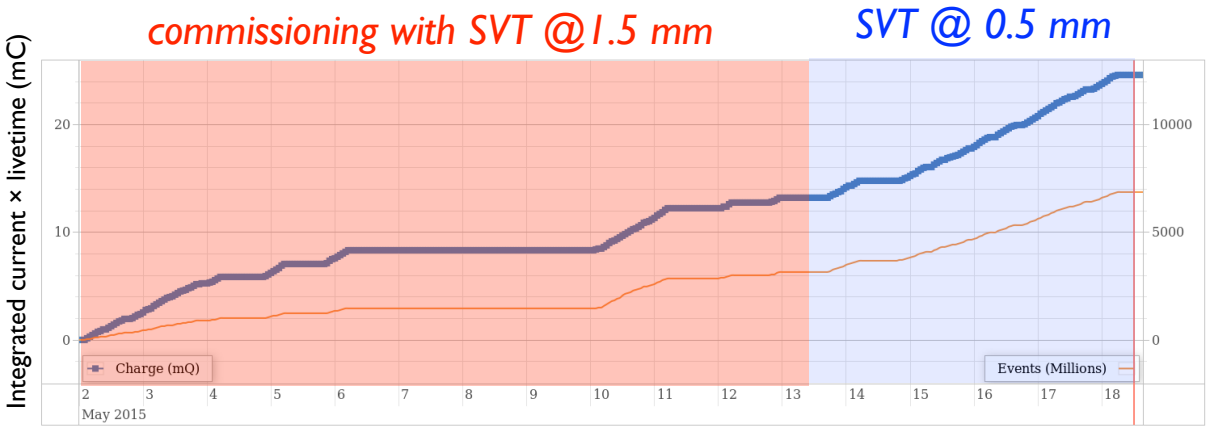

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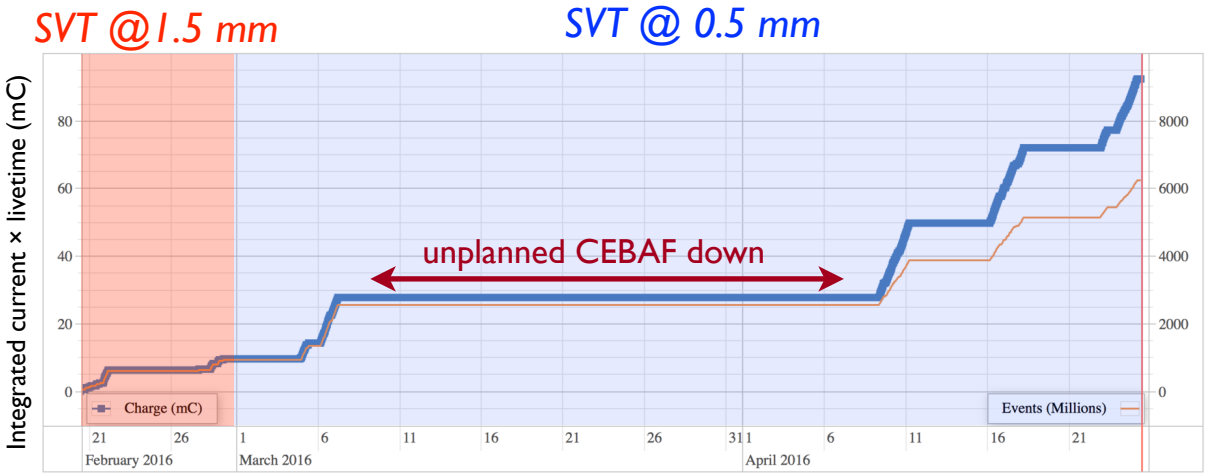

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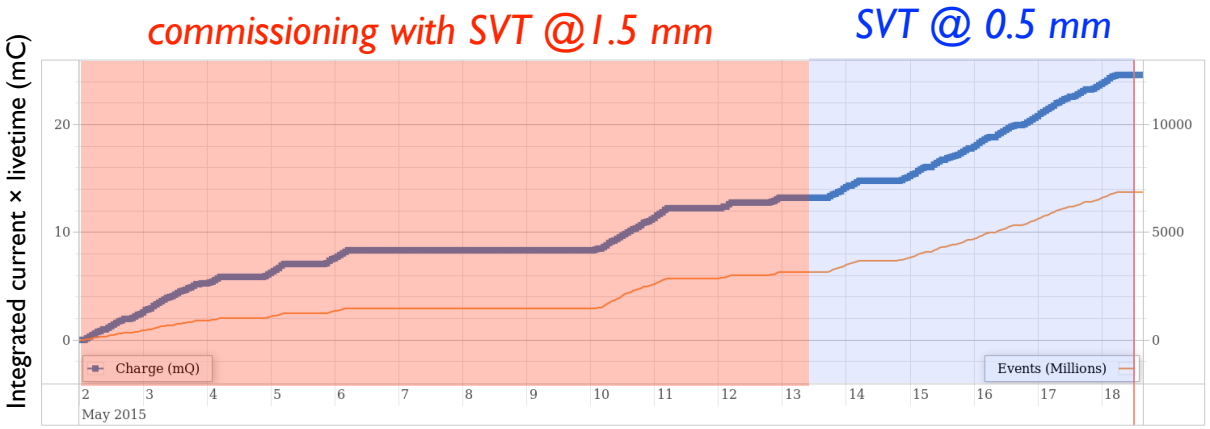

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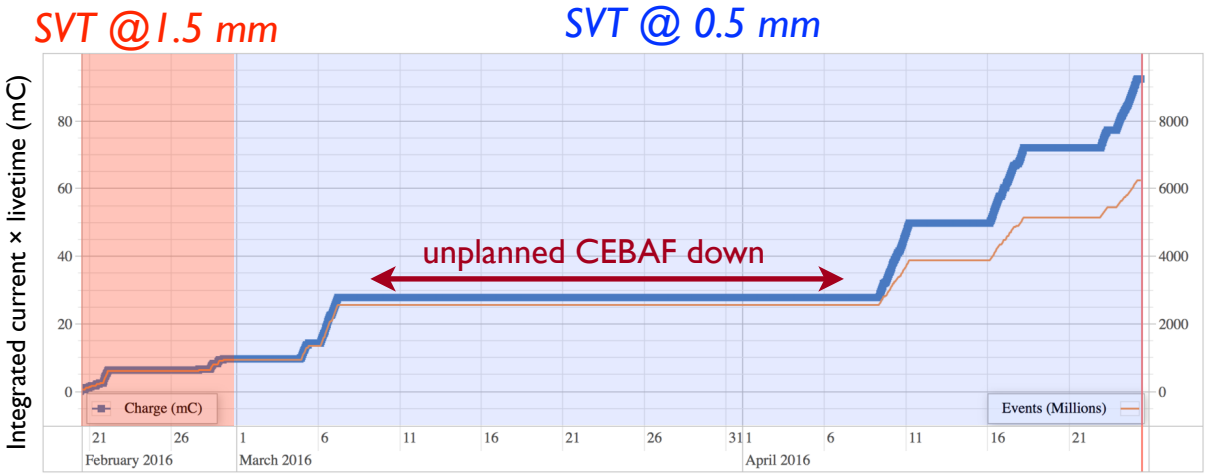
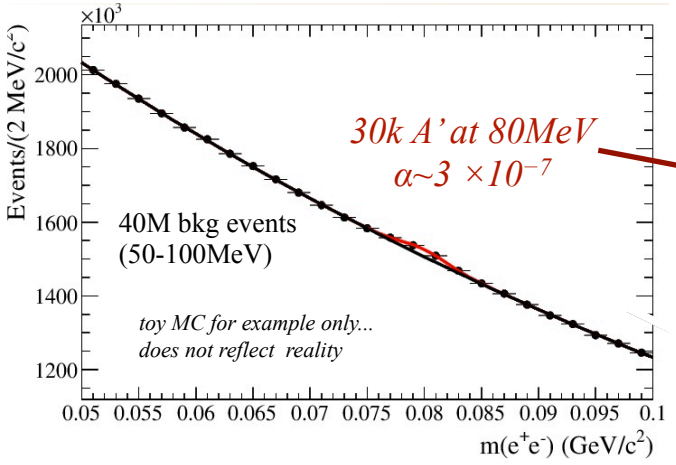
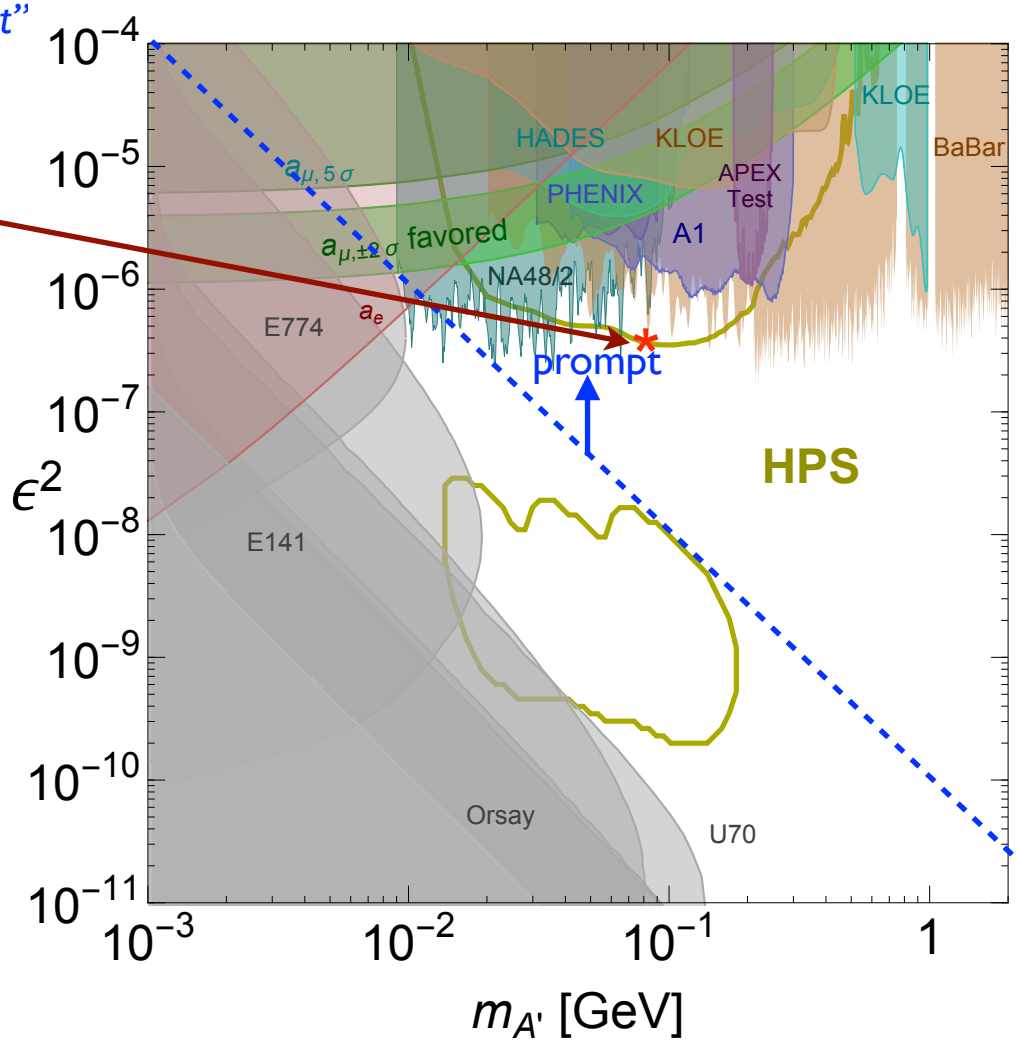


HPS is approved for 180 days of beam time: HPS is just getting started.

HPS Signal Sensitivities

*Large signal, **huge** SM background "bump hunt"*





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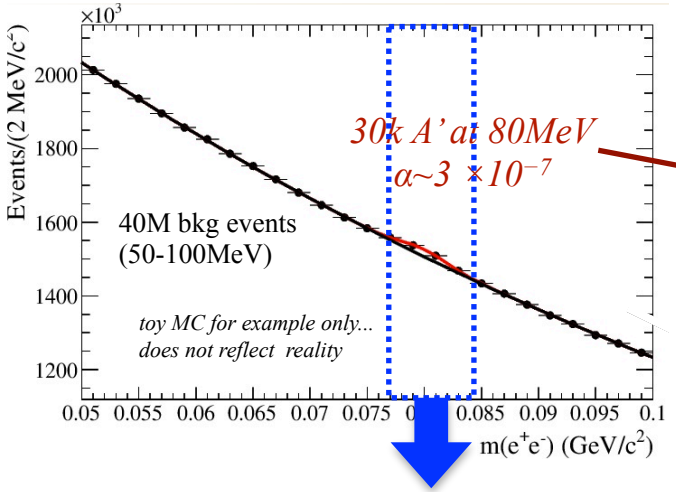

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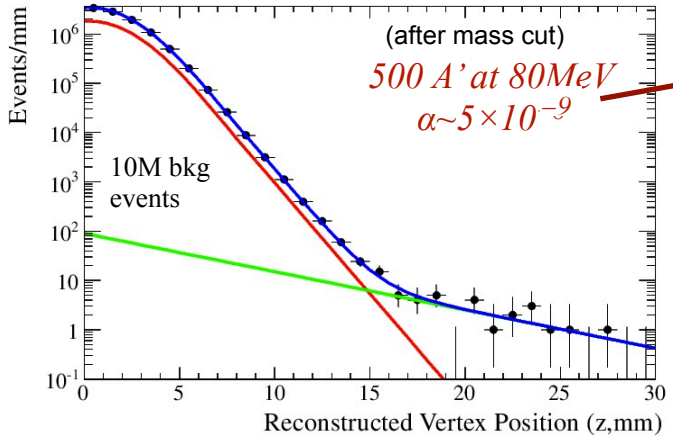

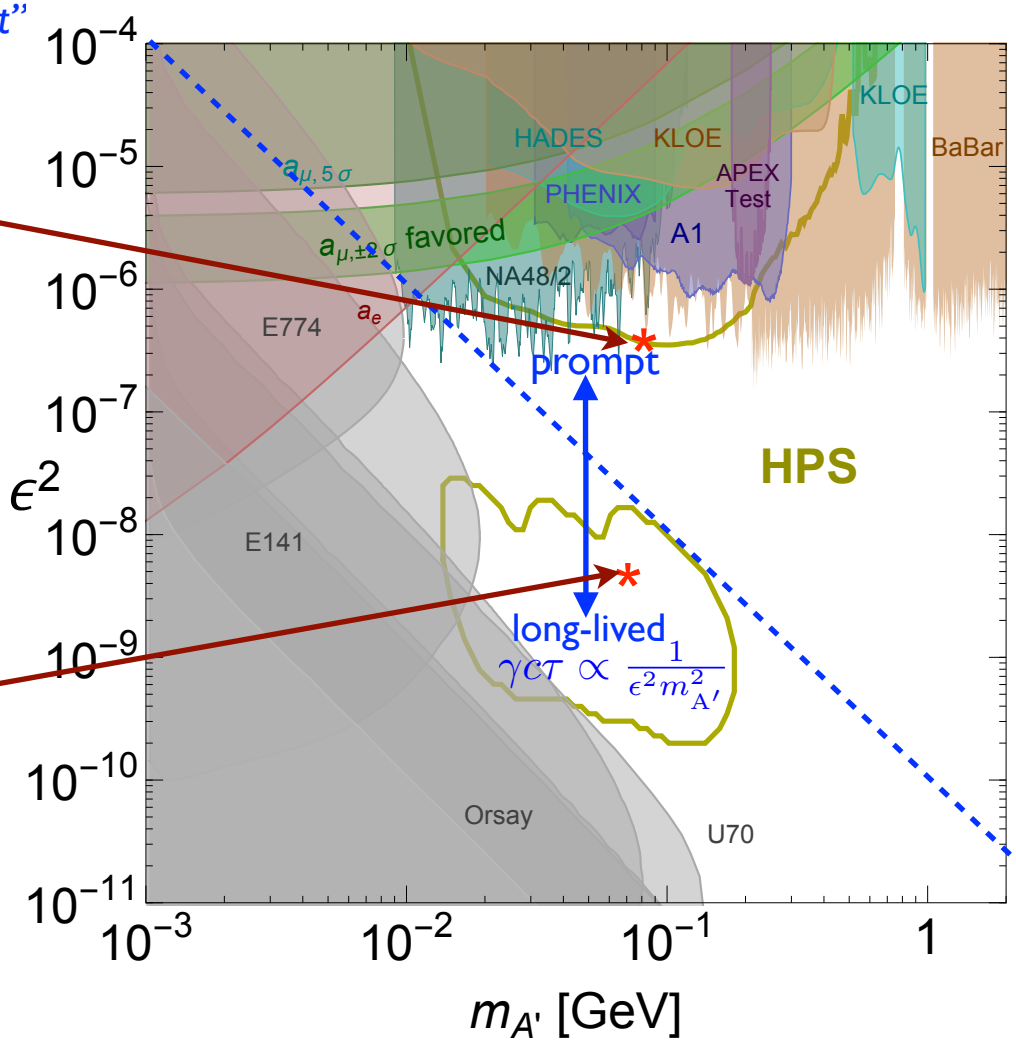

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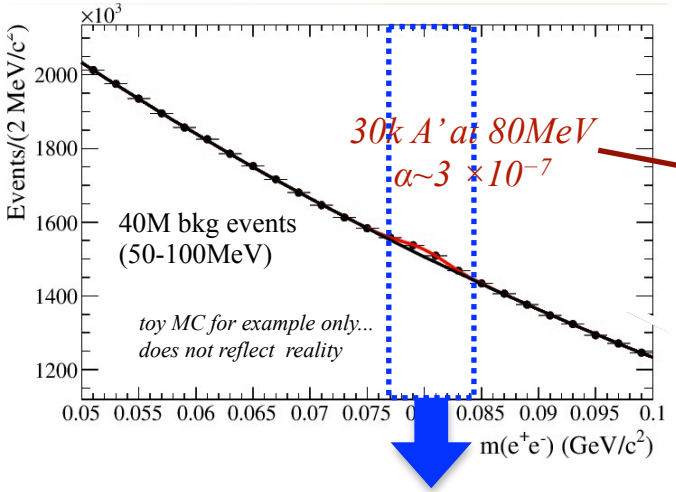

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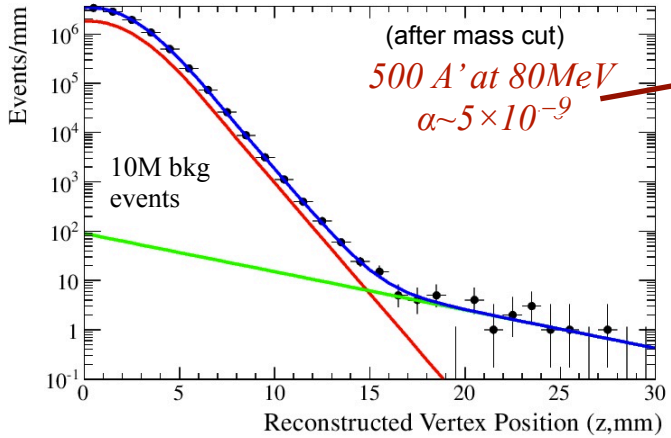

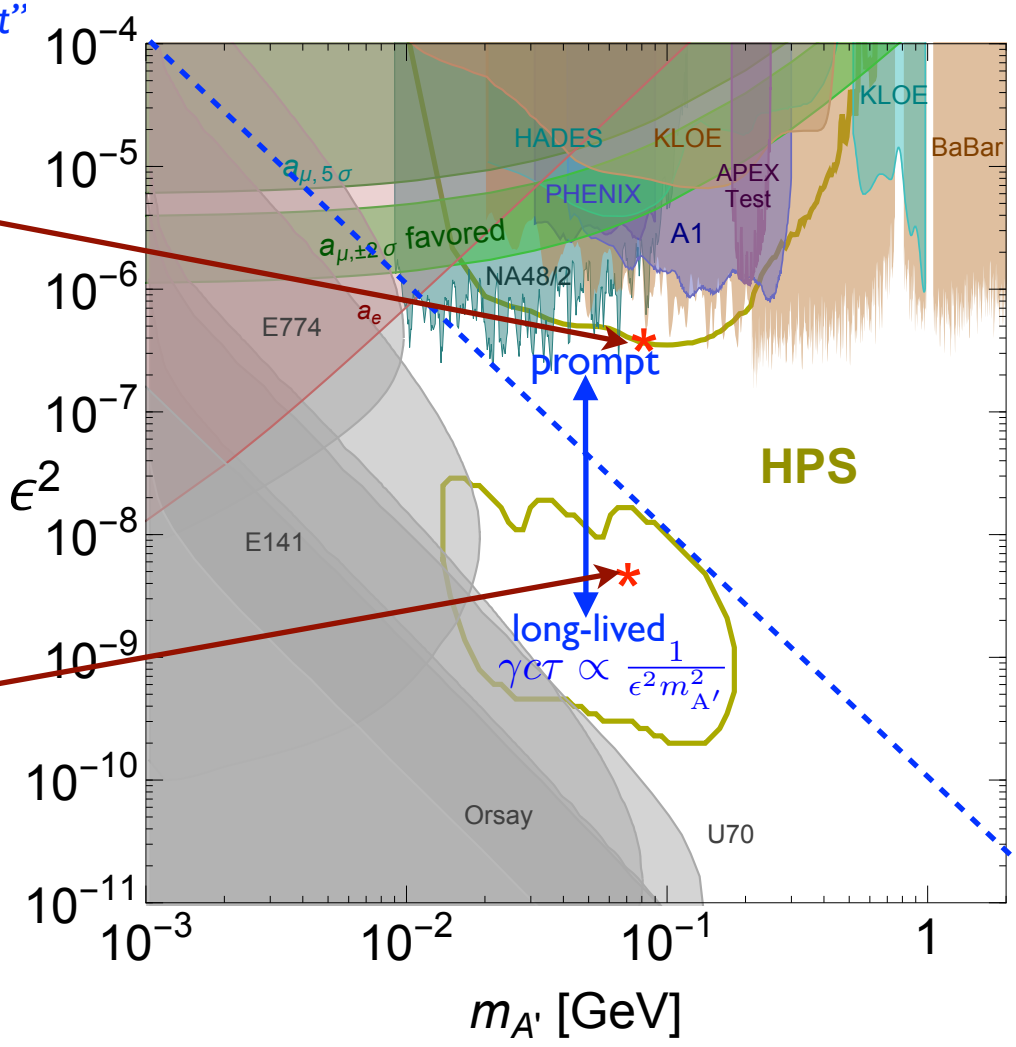

Leads to two separate analyses, *"resonance search"* and *"vertexing search"*

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Fully unblinded results were presented for the first time at JLab on 5/3.

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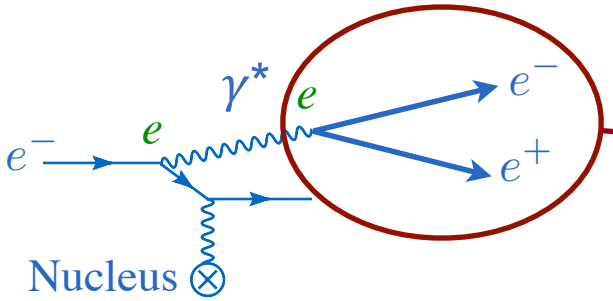
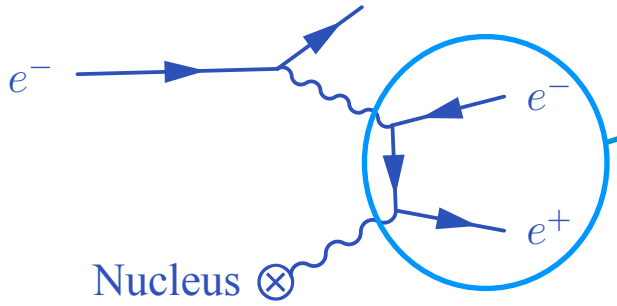
Analysis of 2016 data is waiting while we learn from the 2015 run.

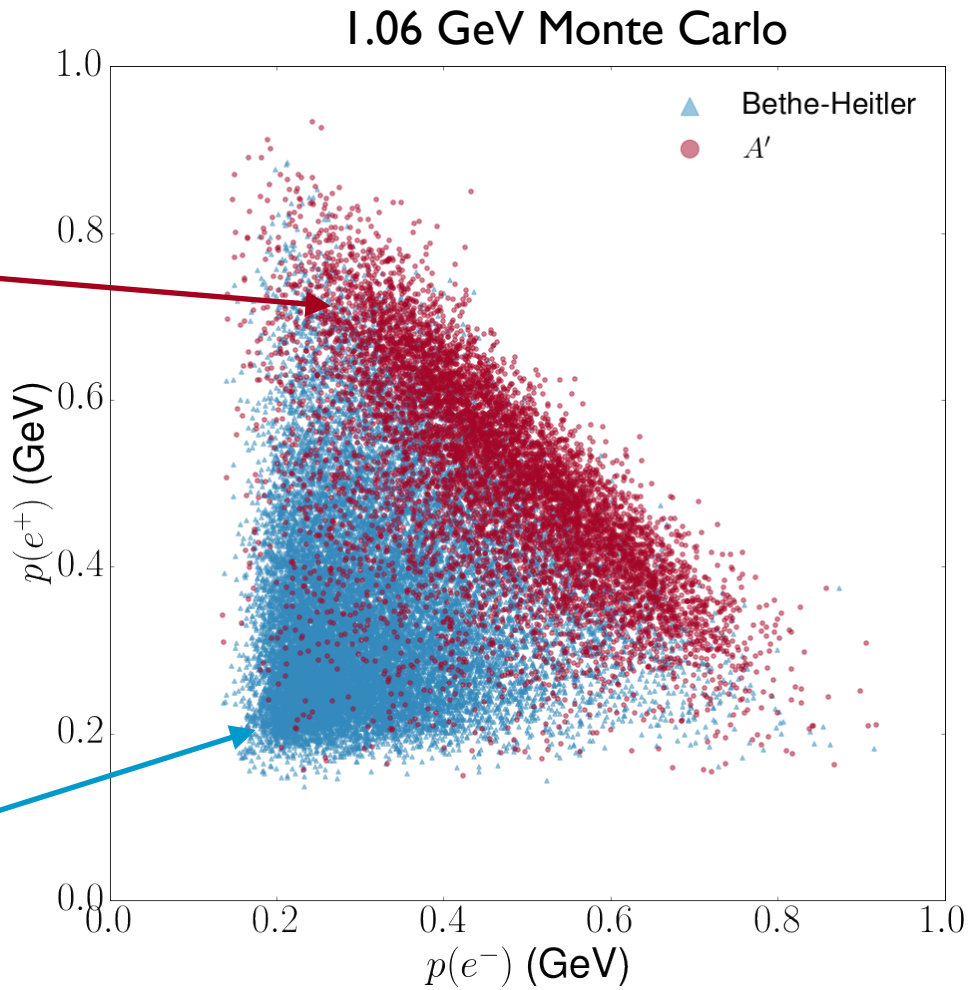
2015 @ 1.06 GeV: Trident Backgrounds

Virtual photon tridents have identical kinematics for given $m(e^+e^-) \Rightarrow$ irreducible



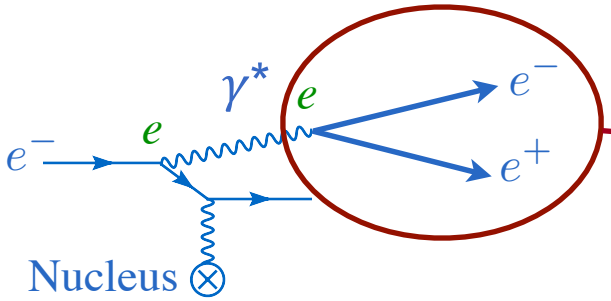
Bethe-Heitler tridents are kinematically different but still dominant in signal region (normalization here is arbitrary)



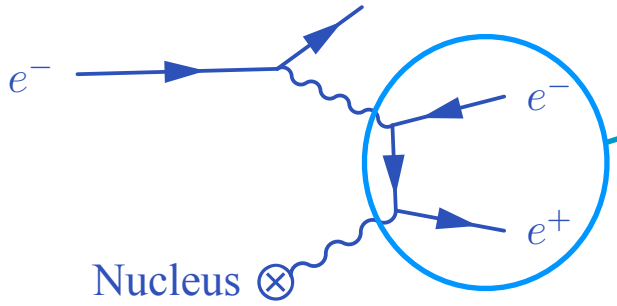


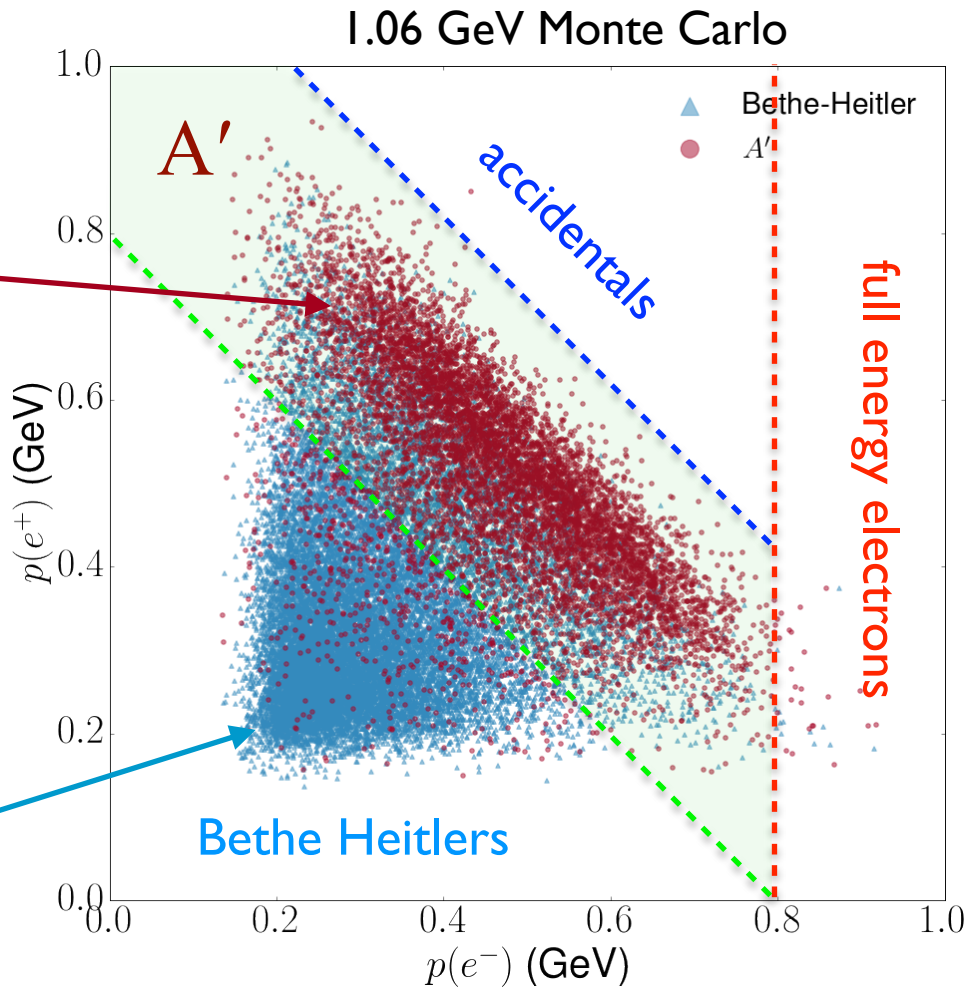
2015 @ 1.06 GeV: Trident Backgrounds

Virtual photon tridents have identical kinematics for given $m(e^+e^-) \Rightarrow$ irreducible

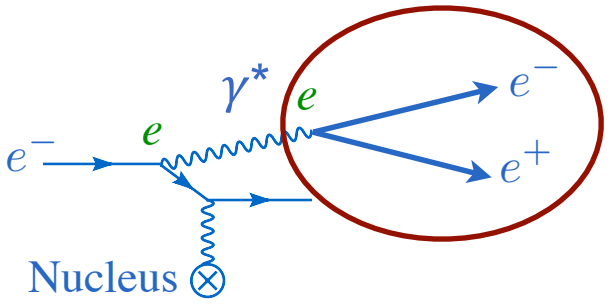


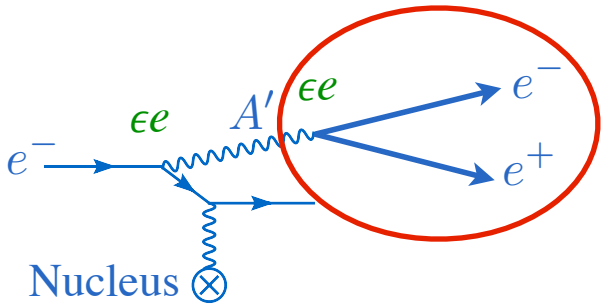
Bethe-Heitler tridents are kinematically different but still dominant in signal region (normalization here is arbitrary)





2015 @ 1.06 GeV:
Trident Backgrounds





Radiative trident background provides an absolute reference for expected signal yields.

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

2015 @ 1.06 GeV:
Wide Angle Bremsstrahlung Background

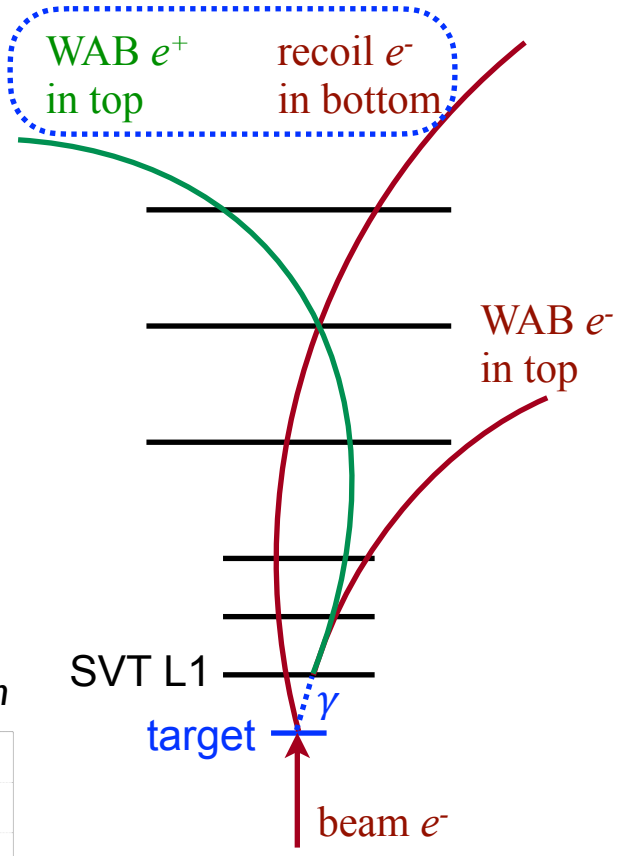
Converted bremsstrahlung in SVT (esp. Layer 1) are common, but pairs are in same hemisphere.

Recoils are often too soft, wide for acceptance

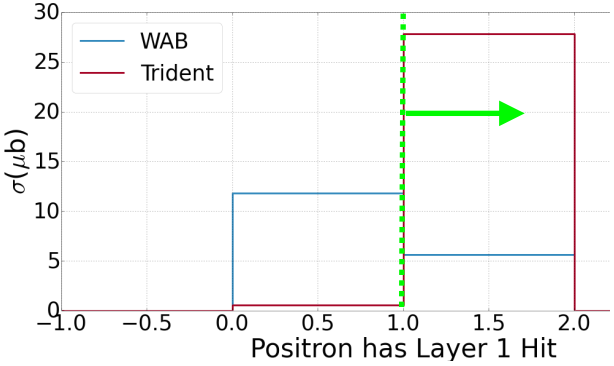
Occasionally recoil makes a candidate with a conversion positron in opposite hemisphere: rate is similar to tridents.

EGS5 does not simulate angular distribution of recoils.

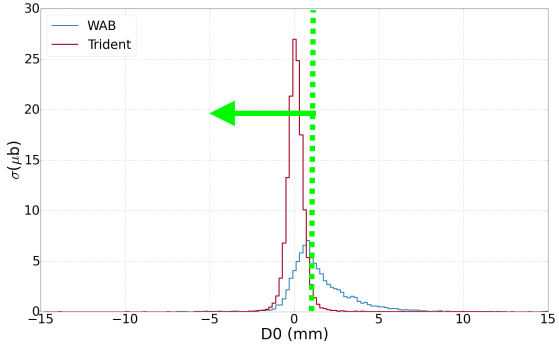
Simple cuts eliminate ~80% with minimal loss of signal.



e^+ *has Layer 1 hit*

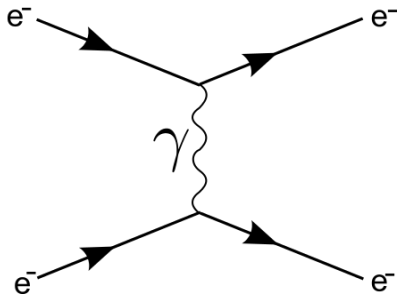


e^+ *distance of closest approach*

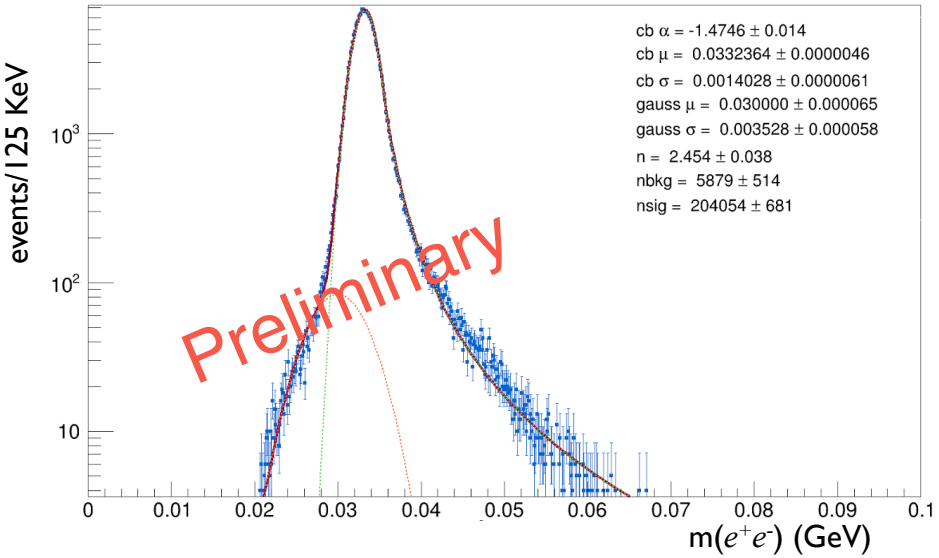


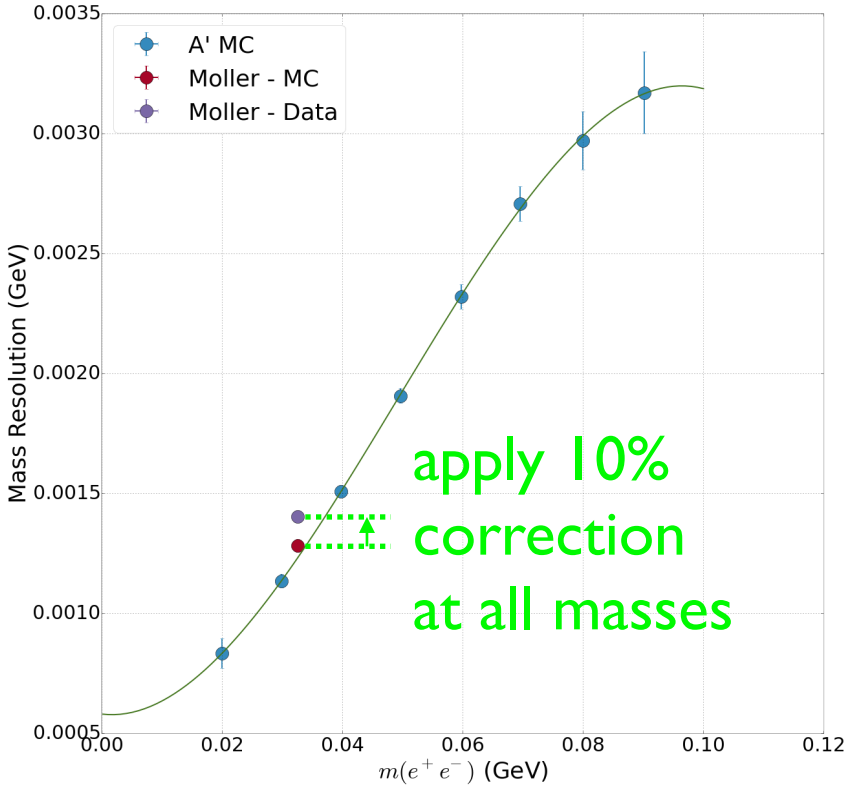
2015 @ 1.06 GeV: Mass Resolution

Normalize mass resolution using Møller pairs

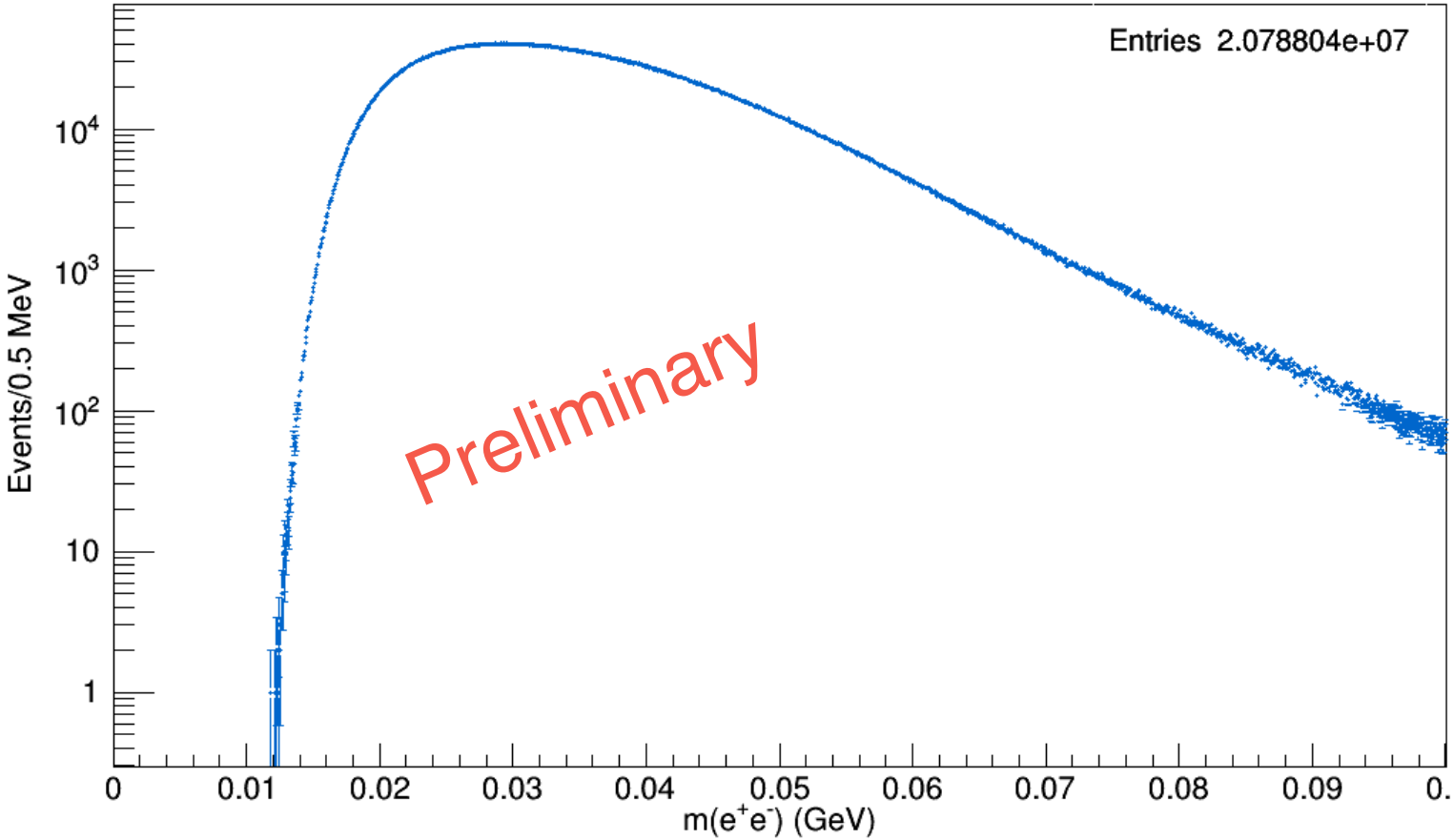


$$E_{\mathrm{CM}} = \sqrt{2 m_e E_{\mathrm{beam}}}$$





2015 @ 1.06 GeV: Resonance Search

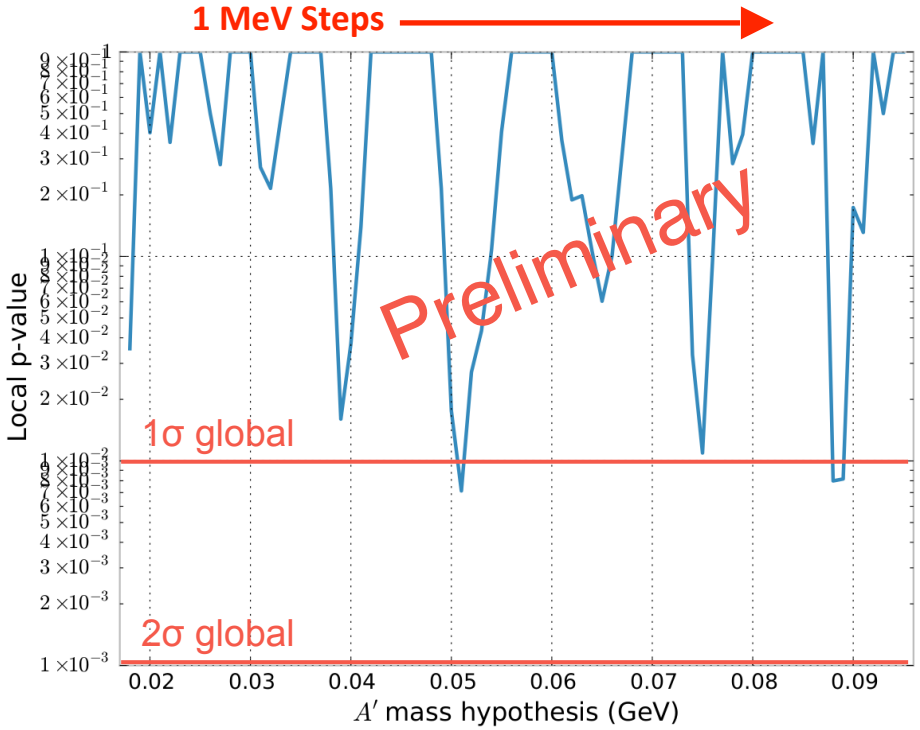


Scan mass spectrum in search windows between 17-90 MeV

Perform likelihood fit in each window with Gaussian signal and polynomial background.

2015 @ 1.06 GeV:
Resonance Search Fit Results

no significant excess observed.



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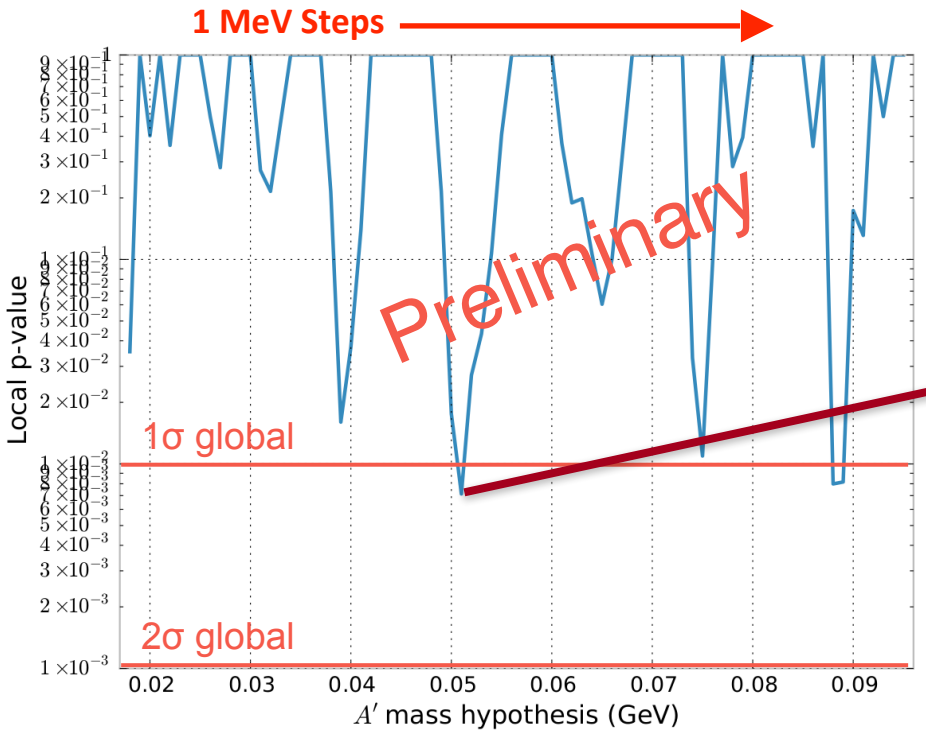
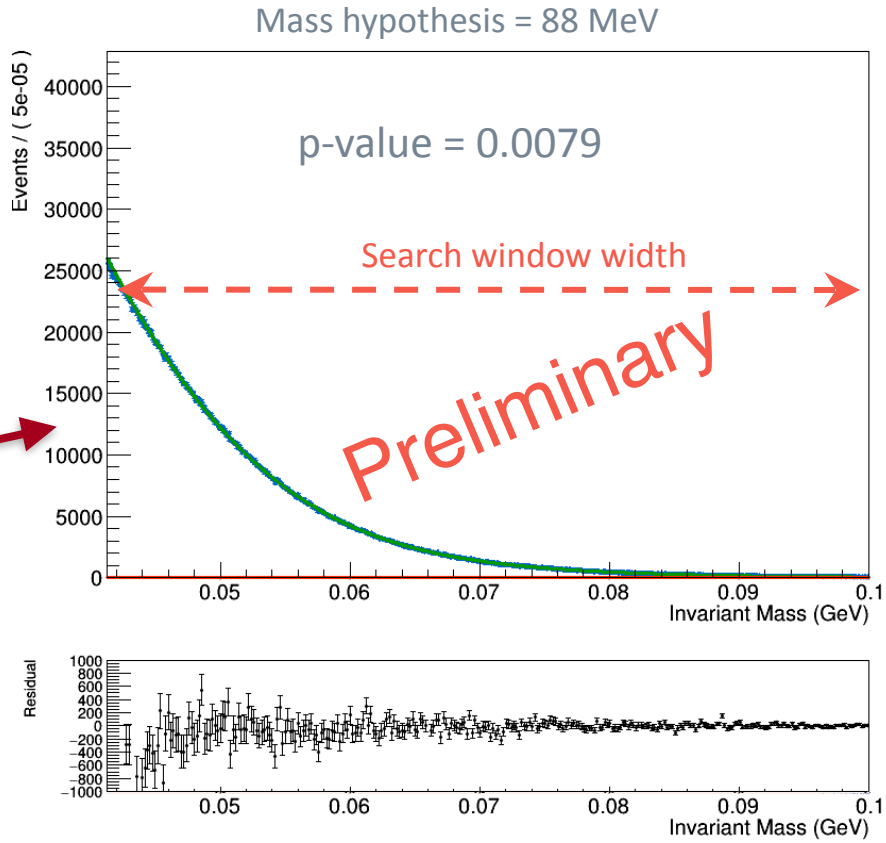
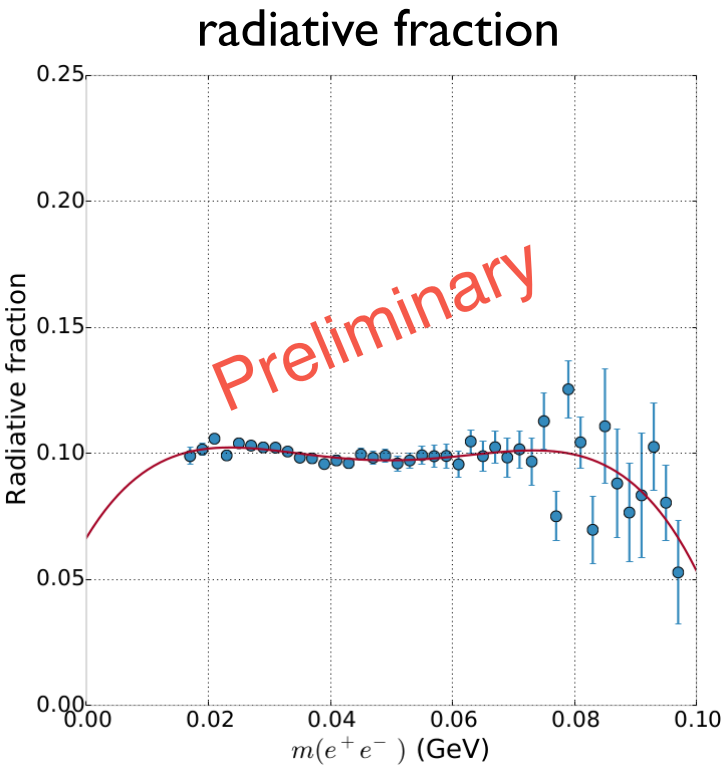
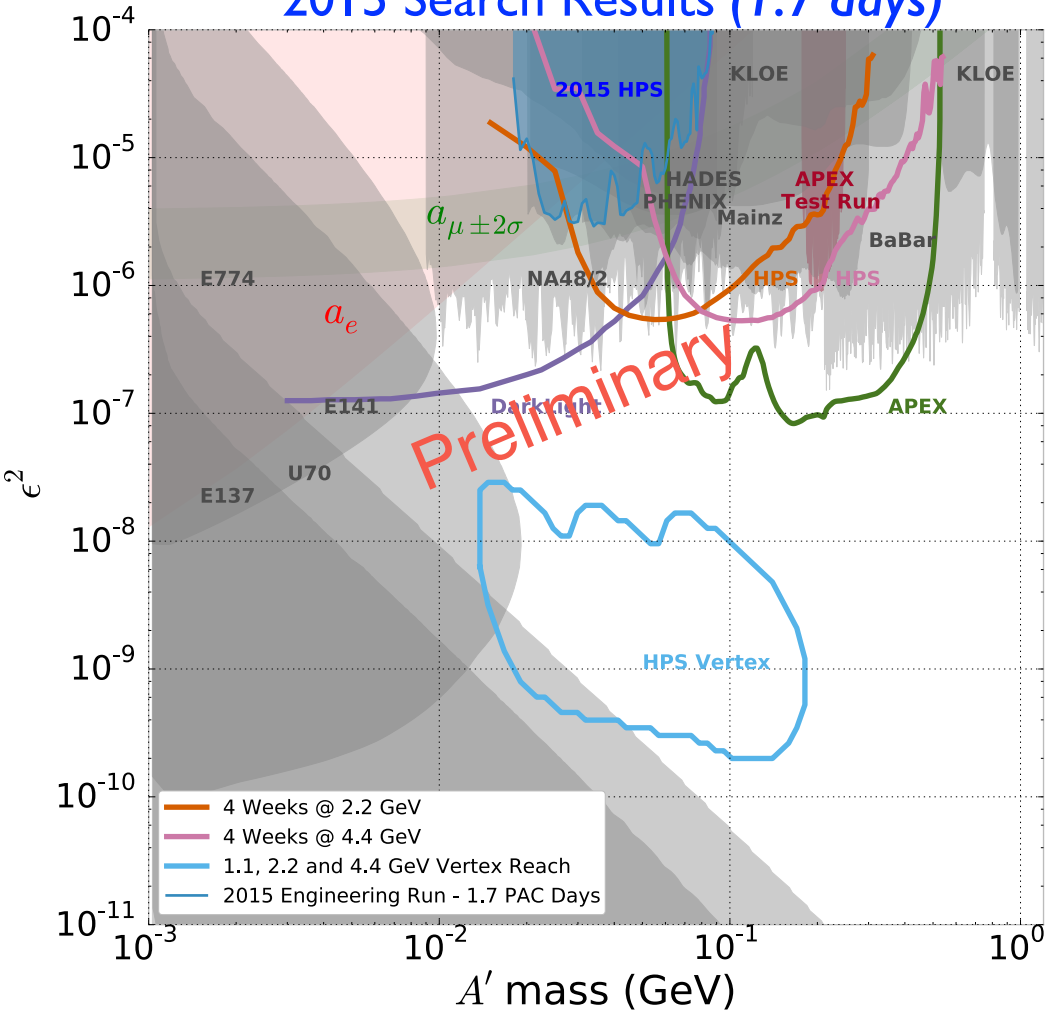




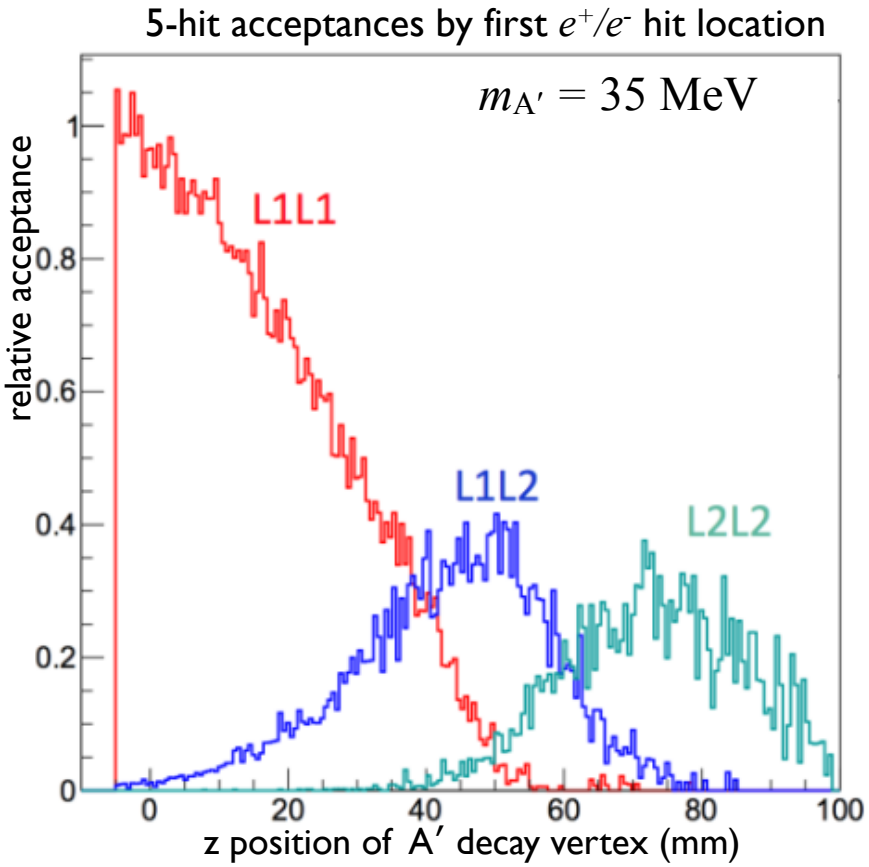
2015 @ 1.06 GeV:
Resonance Search Results





6.4% 2015 @ 1.06 GeV: Vertexing Search

First analysis of 2015 data for thesis, using 6.4% (2.6 hours) of data, required hits in SVT Layer 1 for both tracks: only part of acceptance.



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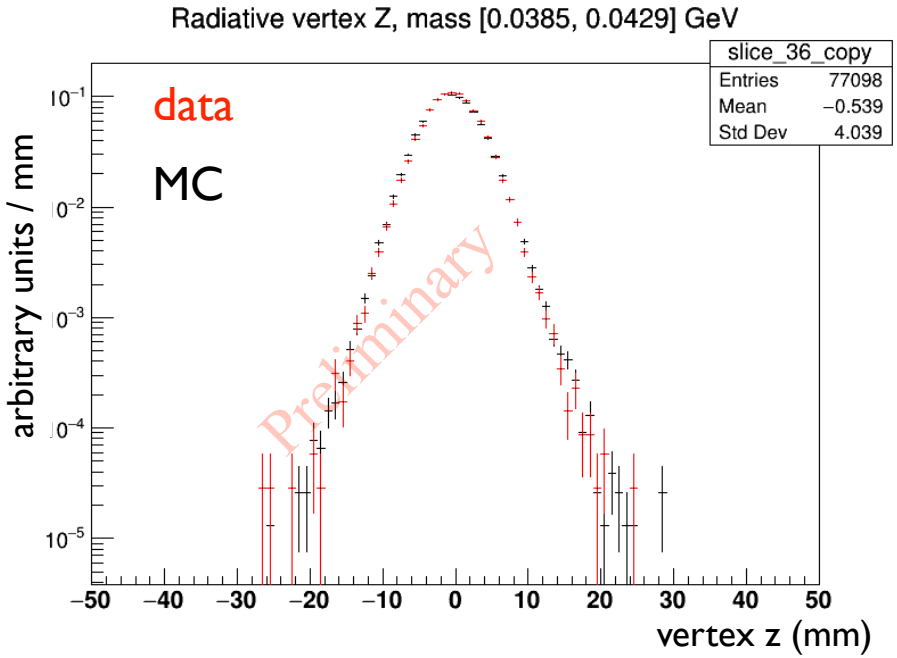
Plot v_z in mass slices and verify data/MC agreement in single slice.



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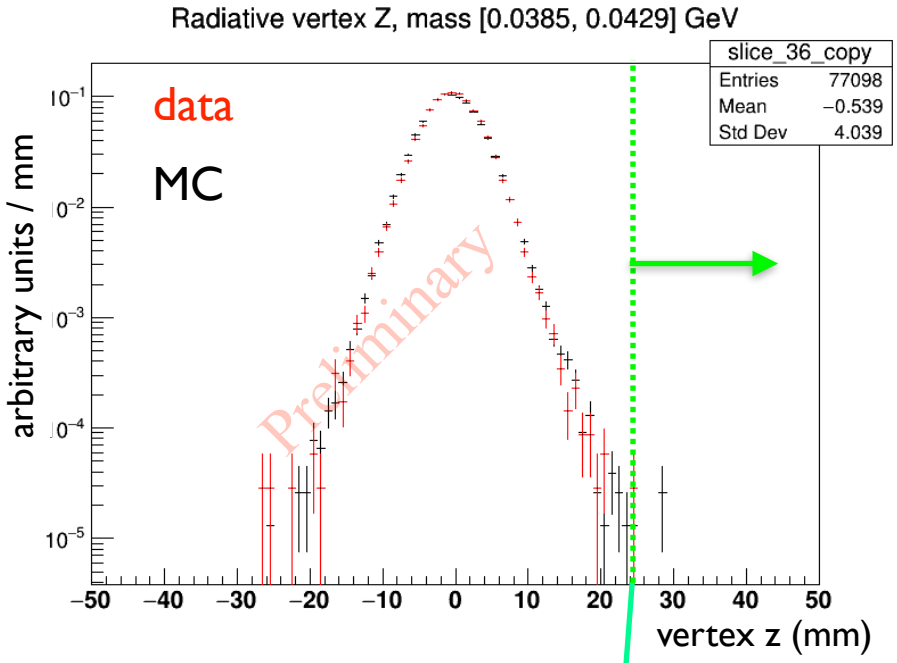
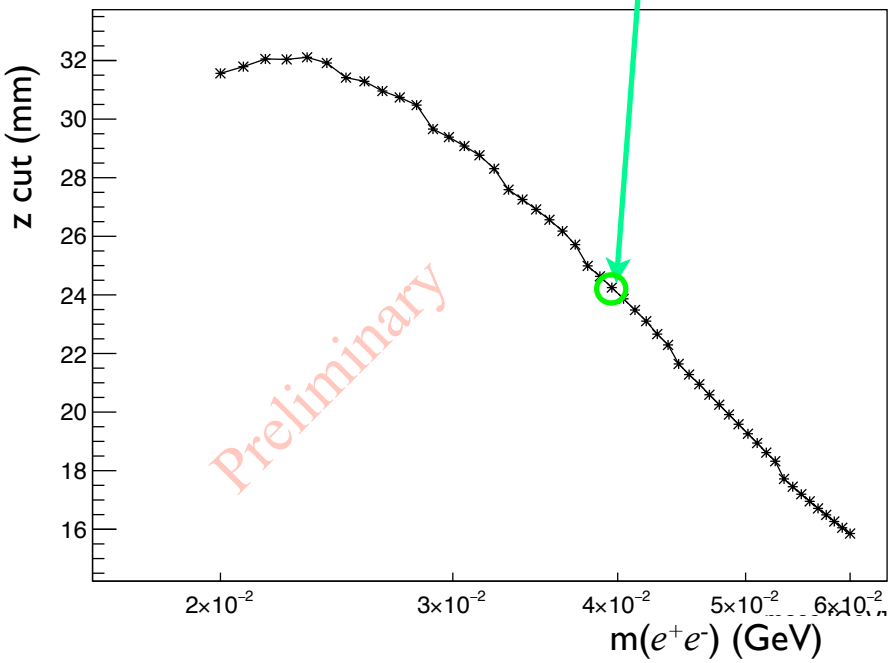
Use MC to fit background as gaussian+exponential tail at each mass, determine zcut to expect 0.5 events background for z>zcut.





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A few unexpected background-like events were observed above the z cut.

These have obvious tracking anomalies and similar events can be eliminated in the full sample.

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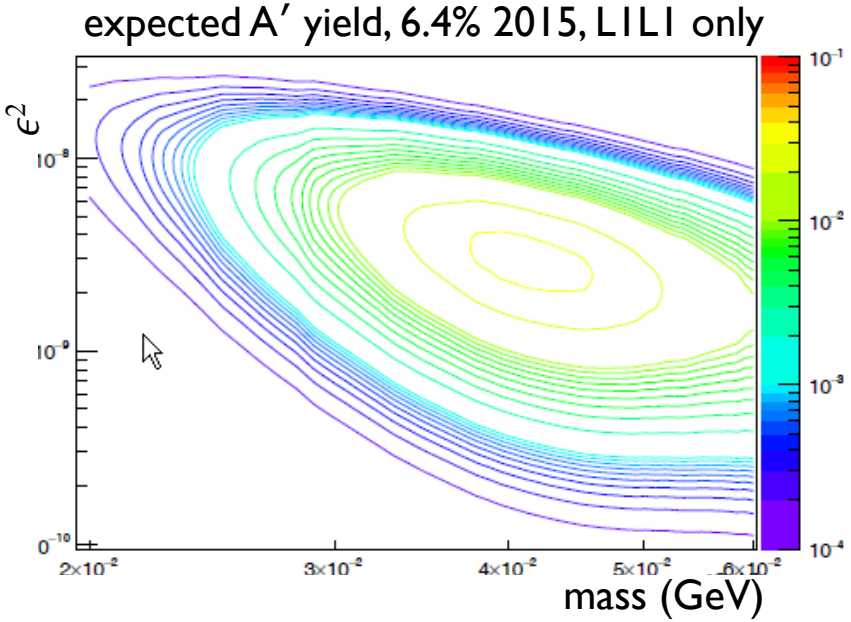

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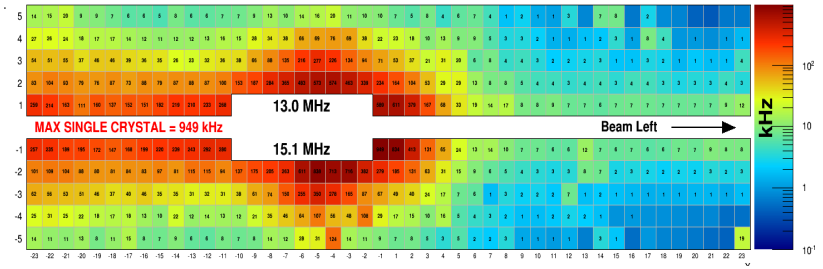

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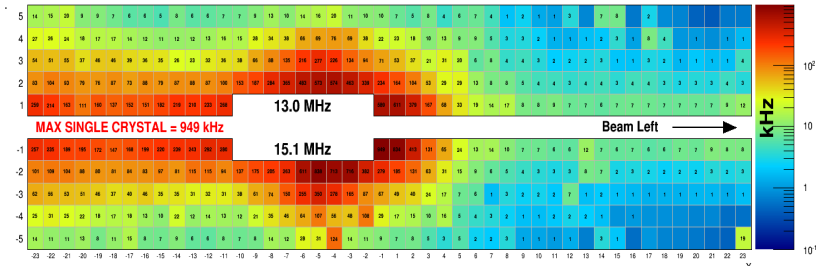
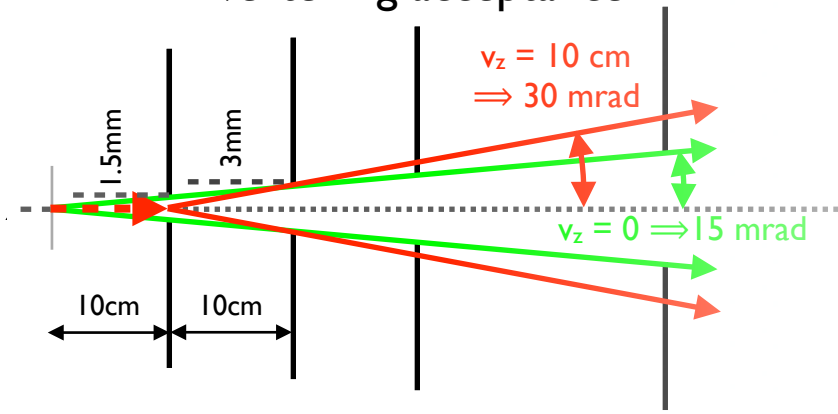


vertexing acceptance



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These primarily affect low-mass tail of HPS acceptance, more important for vertex search than the resonance search.

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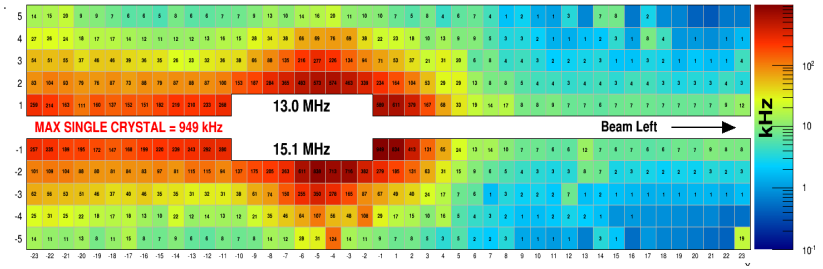

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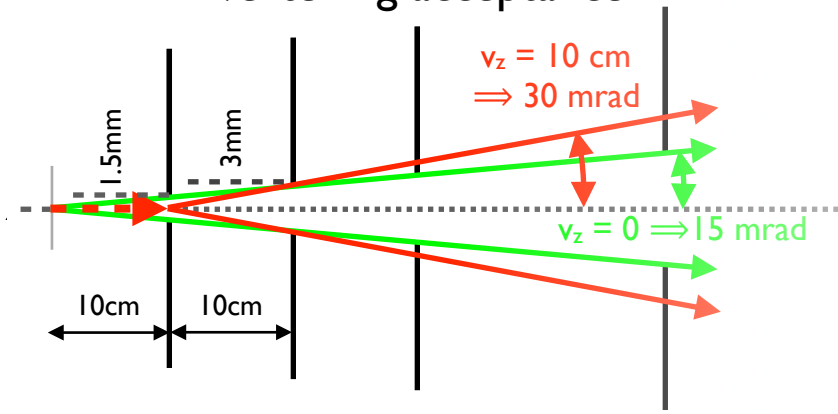

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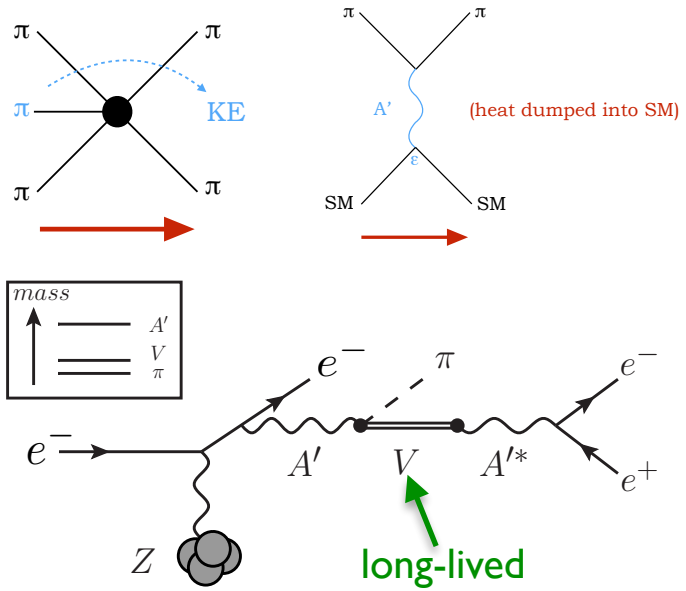
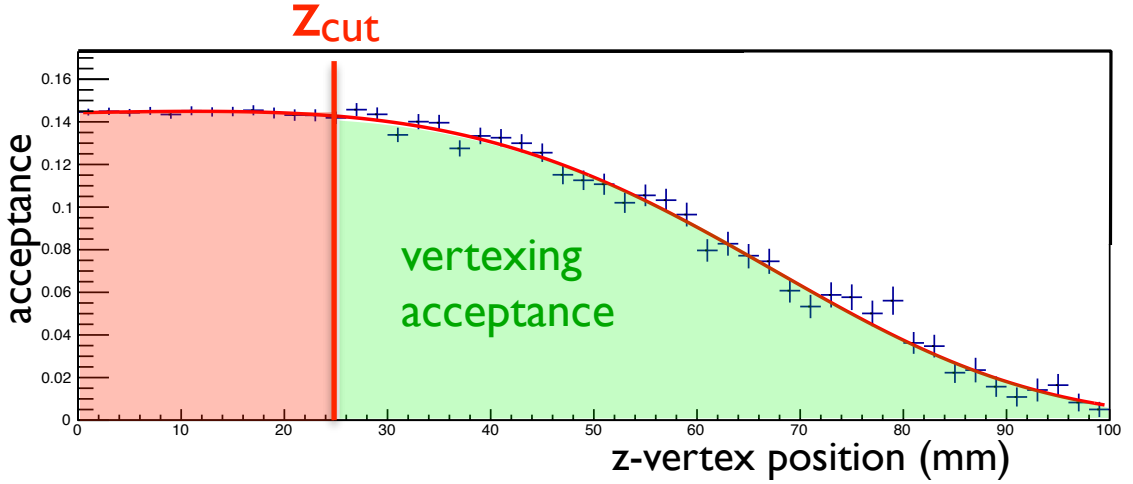
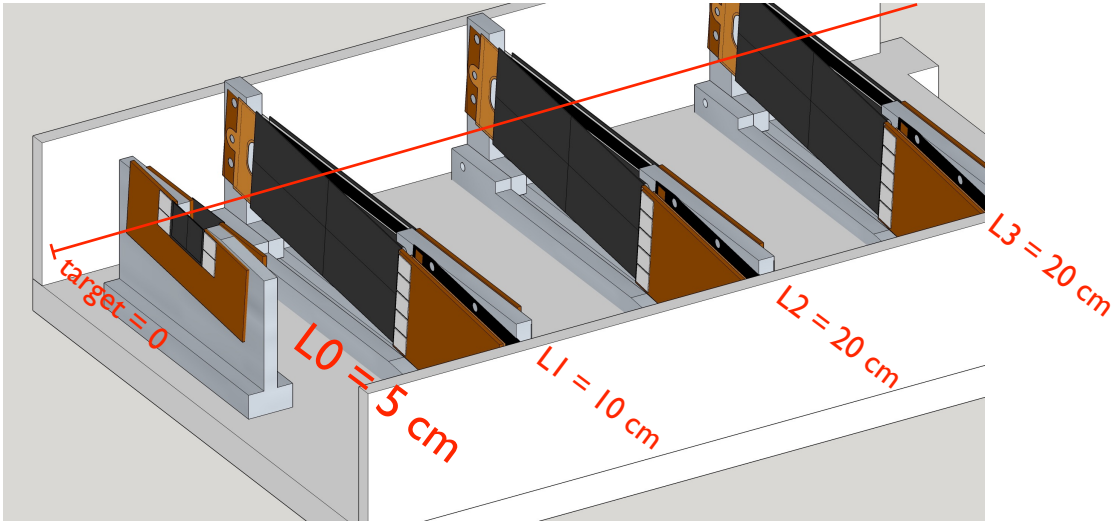
The SIMP Miracle



Models with strong dynamics in dark sector (SIMPs) decouple the $\alpha\epsilon^2$ production rate from expectation of long-lived decays. Assessing sensitivity with 2015 data.

HPS Upgrades



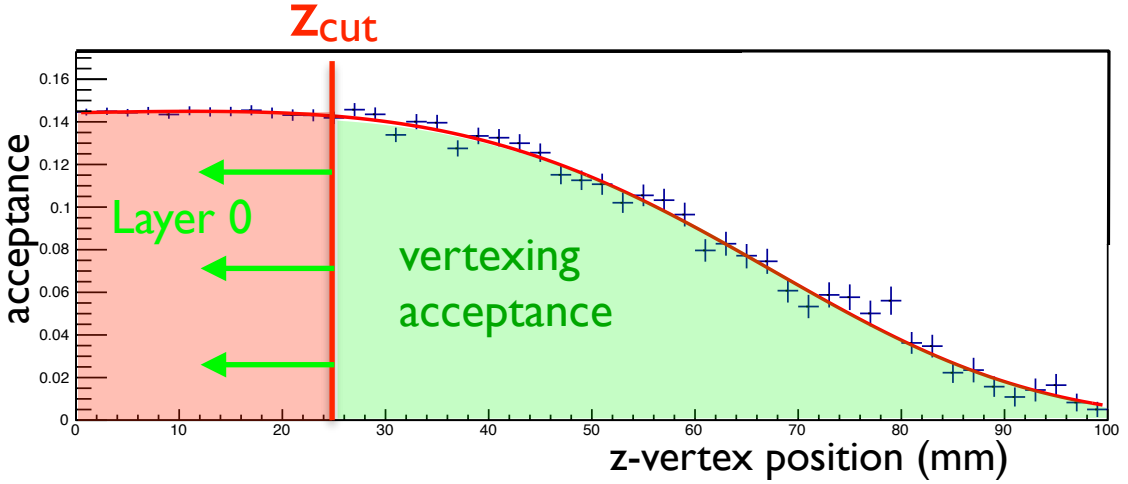


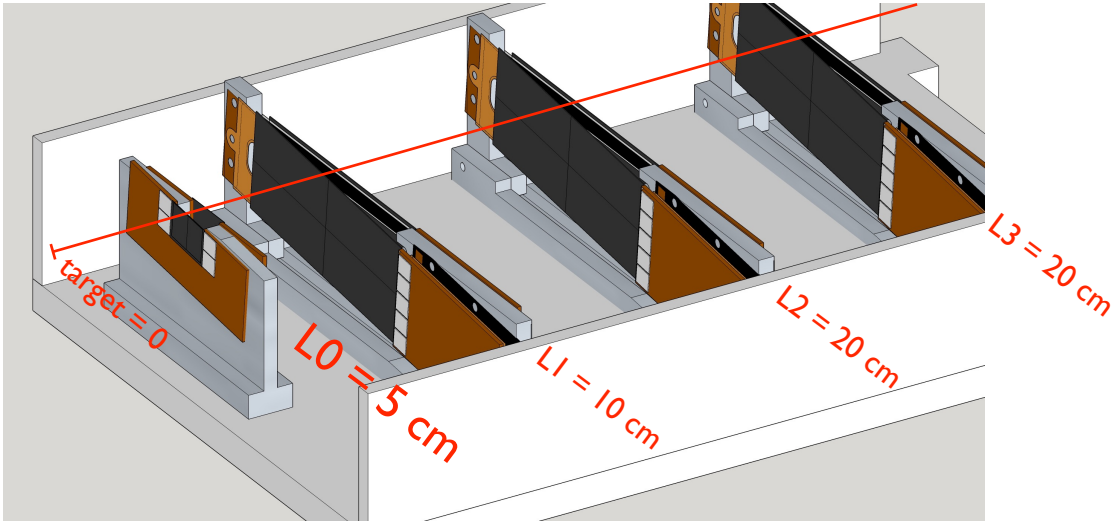
HPS Upgrades

Previously planned:

Add a thinned, slim-edge SVT "Layer 0" at z=5 cm

⟹ large factor increase in yields for (exponentially decaying) A′





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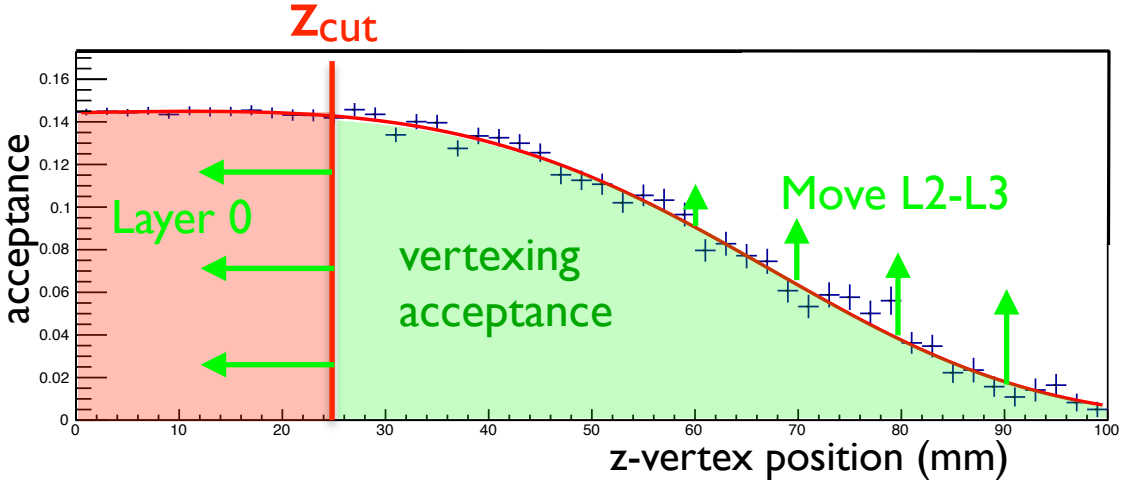
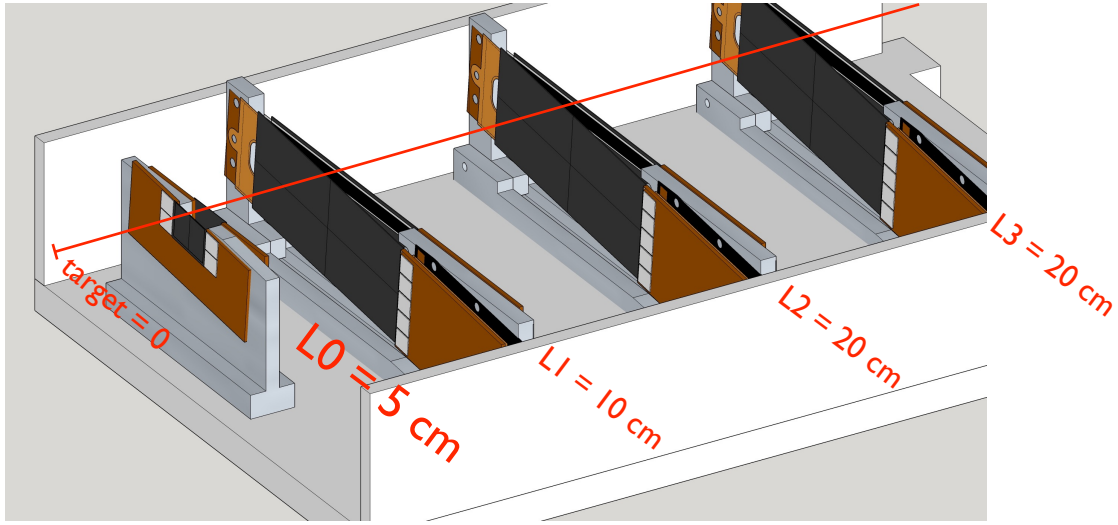


In response to acceptance issues:

Move SVT L2,L3 slightly inwards

⟹ increased yields for longer-lived A′



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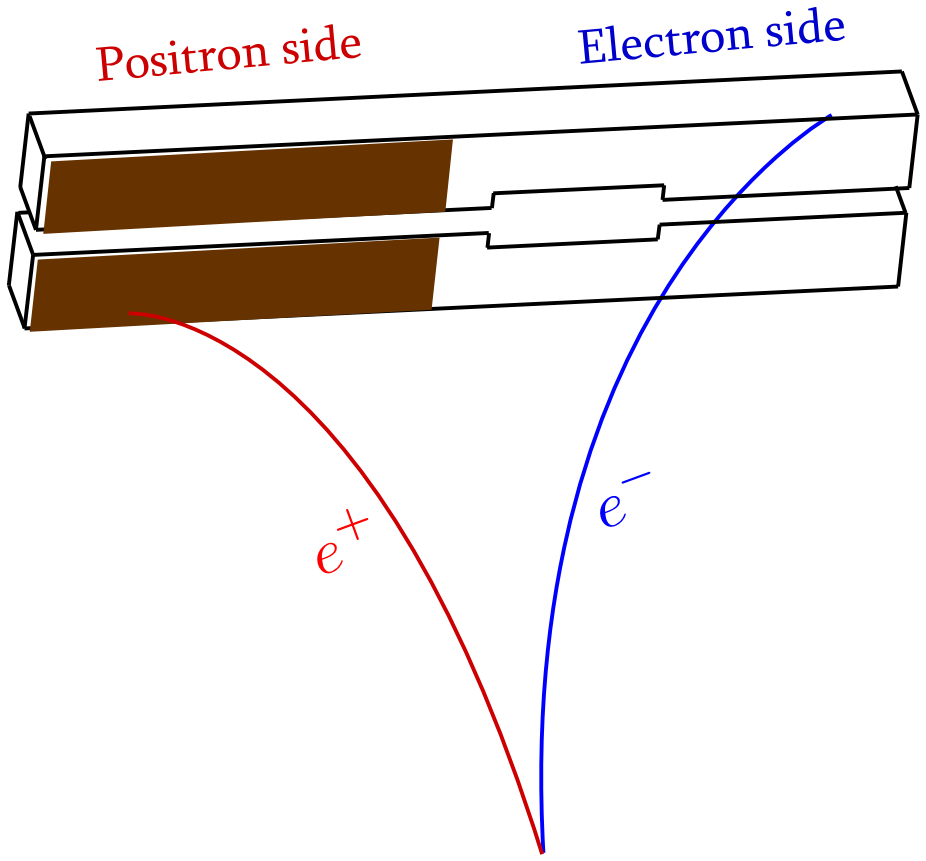
⟹ increased yields for longer-lived A′

Add positron hodoscope inside vacuum chamber

⟹ positron-only trigger eliminates losses in ECal hole



HPS Summary and Outlook

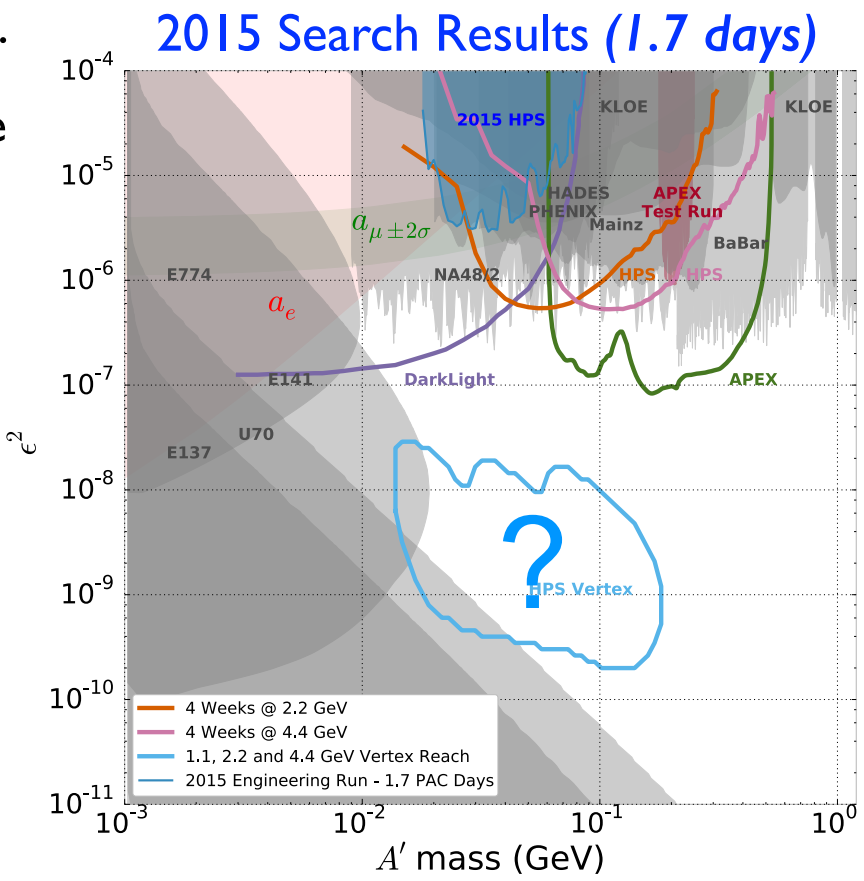
HPS has first results from the resonance search with 2015 Engineering Run (1.7 days).

Vertexing search is ongoing but will not have sensitivity for minimal A' with 2015 data.

Assessing vertex reach for upgraded detector: initial results are very encouraging but reach studies are not yet completed.
Hope to match or exceed proposal reach.

Upgrade is very small project:
Plan to have it in place for next run.

HPS will run periodically at JLab from 2018-2020 as beam time is available:
a long run is expected in 2018.



95% of data taking is yet to come!

JLab Summary and Outlook

JLab has had a pioneering role in the development of the experimental program in dark sector physics

Together, APEX, Darklight, and HPS together will have broad sensitivity to visibly-decaying dark photons by ~2020.

All three experiments will make further progress in the coming year, with significant physics runs expected for APEX and HPS.

With the possibility of BDX and LDMX at JLab, JLab may be the center for dark sector physics in the USA for years to come.

Extra Slides

Beam Backgrounds

Signal kinematics demand acceptance close to beam

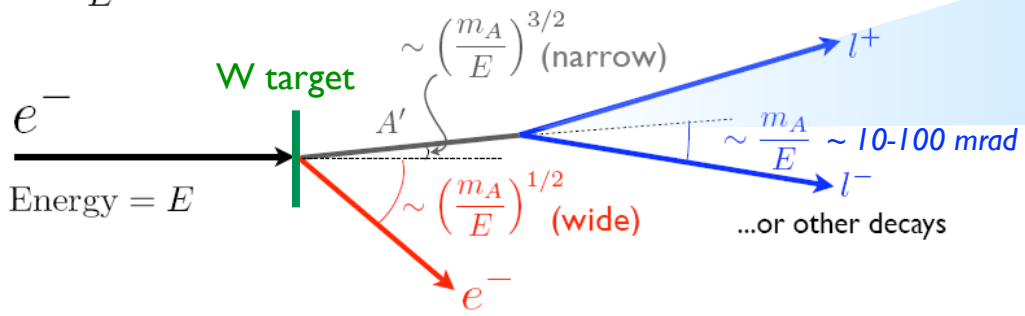
…where scattering in target creates extreme background.

A′ signal

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2(1-x)/x}$$

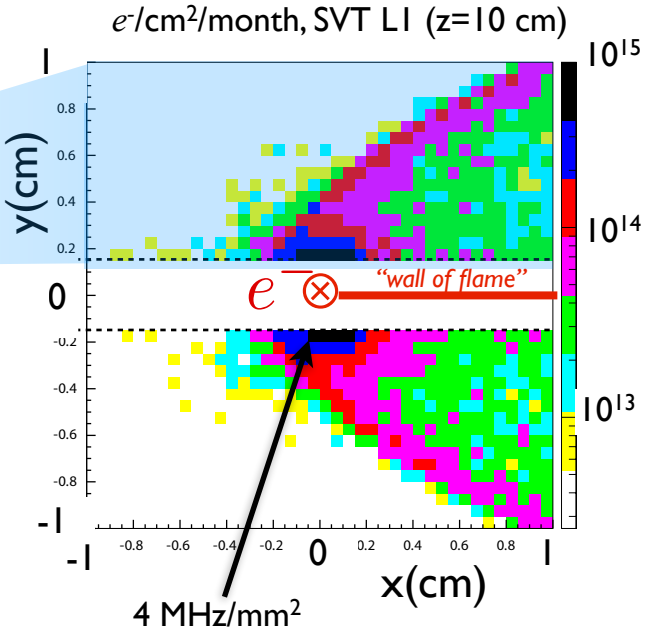
$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung



A′ takes most of beam energy

Scattered Beam Background

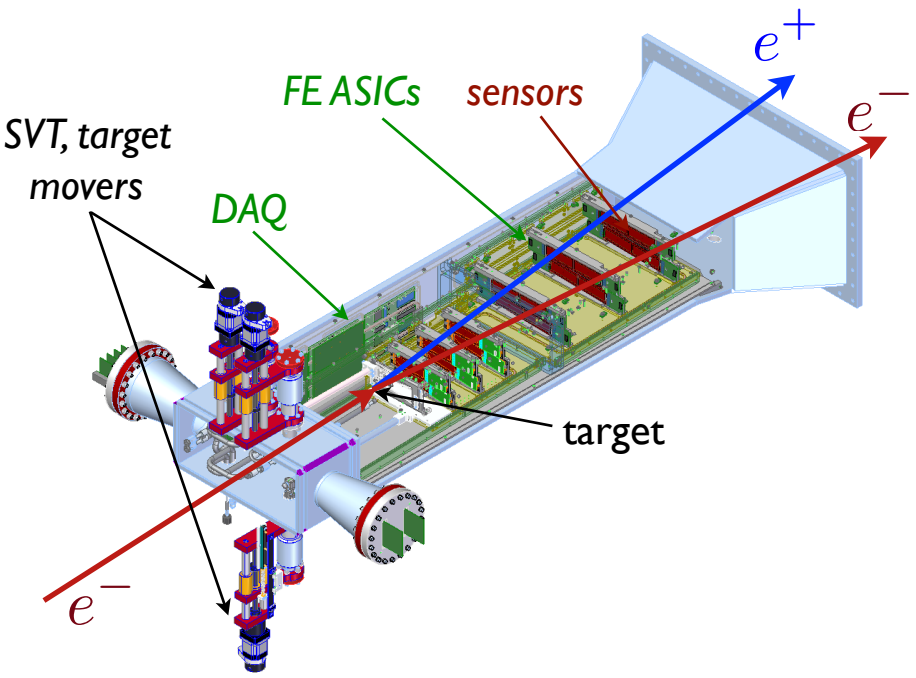


Detector split above/below beam plane with acceptance down to +/- 15 mrad.

Challenges for occupancies, data rate, radiation tolerance, detector safety (edge of SVT L1 500 μm from beam axis)

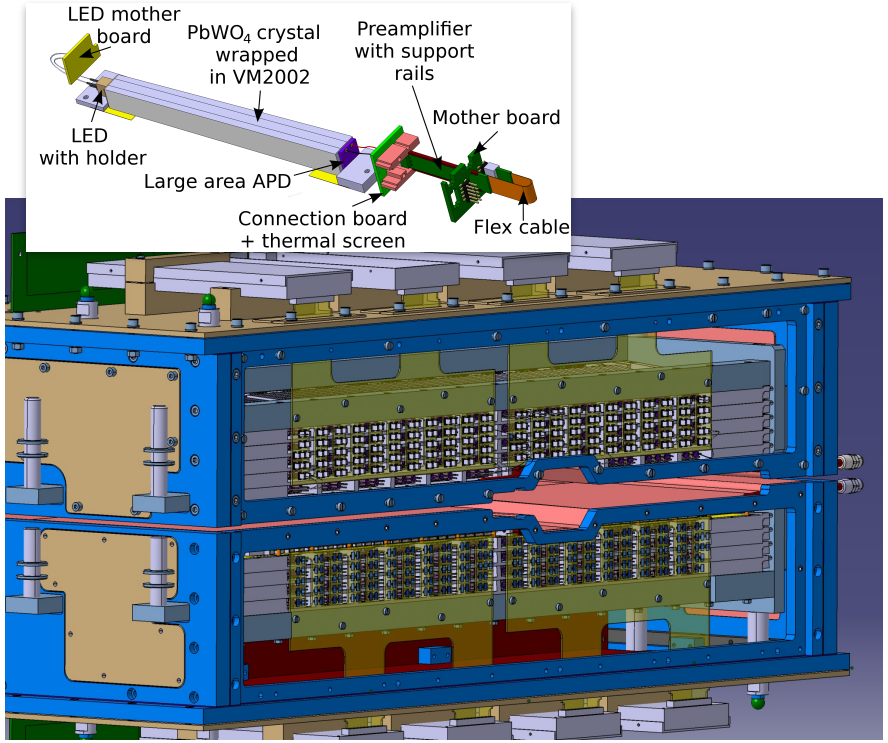
ECal trigger for e^+e^- in opposite hemispheres with ~ns time resolution and similar time resolution in SVT are critical to reduce rates and occupancies in combination with CEBAF 2 ns bunch timing.

HPS Detector



SVT

- 6 layers, 0.7% X_0/layer, in beam vacuum
- $\sigma_y = 6\ \mu m$, $\sigma_x = 60(120)\ \mu m$ in L1-3 (L4-6)
- $\sigma_t = 2$ ns (offline)
- 50 kHz max trigger rate
- >100 gb/sec max data rate
- L1-3 vertically retractable from beam



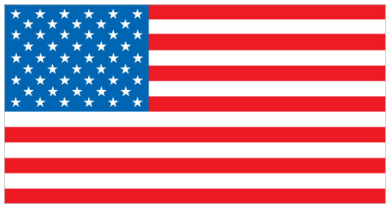
ECal

- 442 $PbWO_4$ crystals w/ LAAPD readout
- $\sigma_E = \frac{4\%}{\sqrt{E}}$ @ 1 GeV
- $\sigma_t = 8$ ns (trigger), <1 ns (offline)
- >100 kHz max trigger rate

The HPS Collaboration

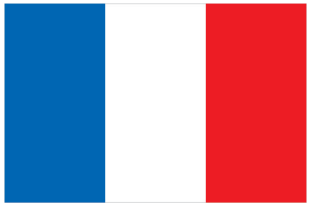
HPS has become increasingly diverse, but ATLAS/CMS it's not!

SLAC (15)
JLab (15)
ODU (4)
UNH (4)
UCSC (3)
William & Mary (2)
Stony Brook (1)
Idaho U. (1)
FNAL (1)



INFN Catania (4)
INFN Genova (4)
INFN Rome (2)
INFN Sassari (2)
INFN Torino (2)
INFN Padova (1)

Orsay (7)
Saclay (1)



Yerevan (3)

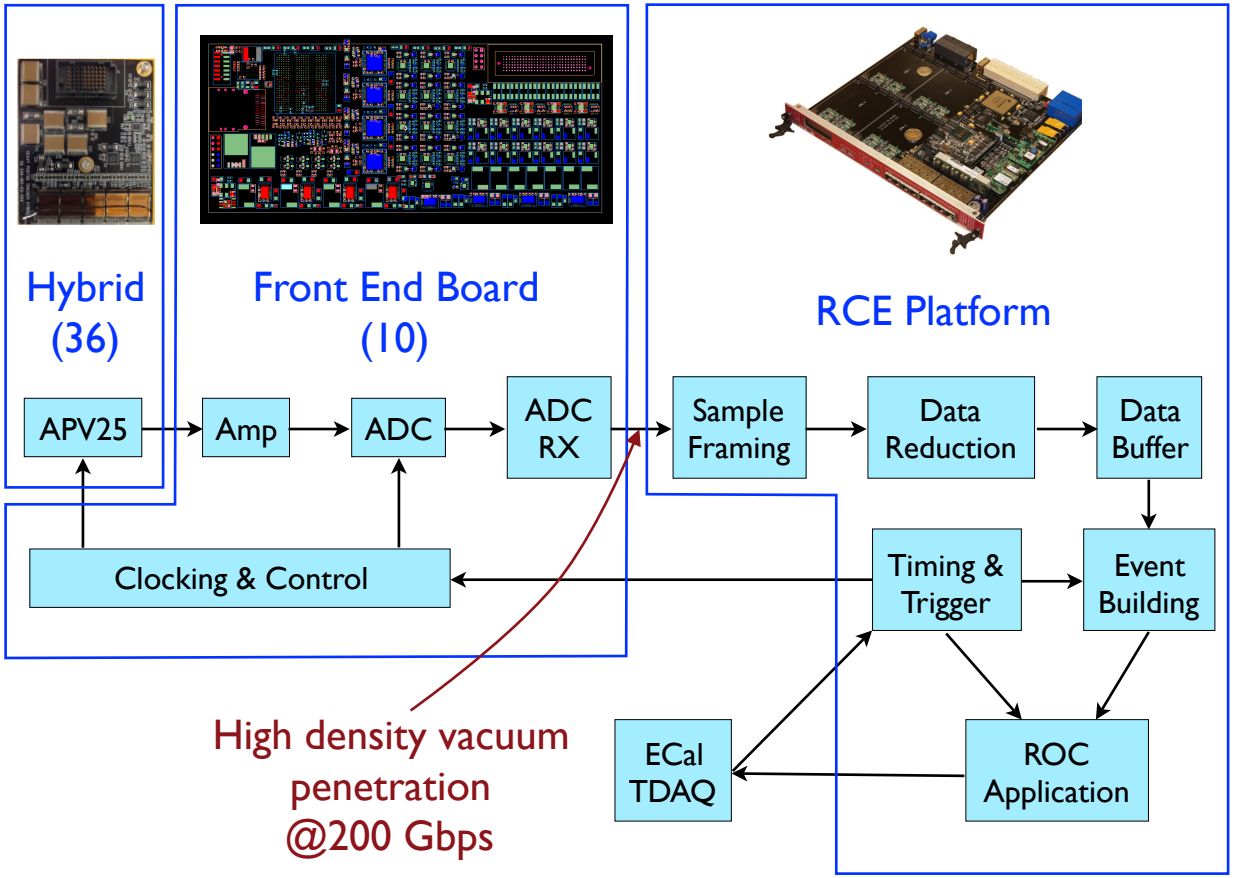
Glasgow (2)

SVT DAQ

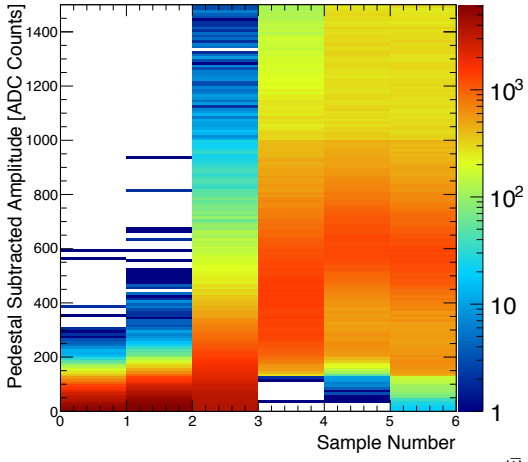
Based upon SLAC RCE platform (ATLAS upgrade, DUNE, LSST…)

Some unique challenges too…

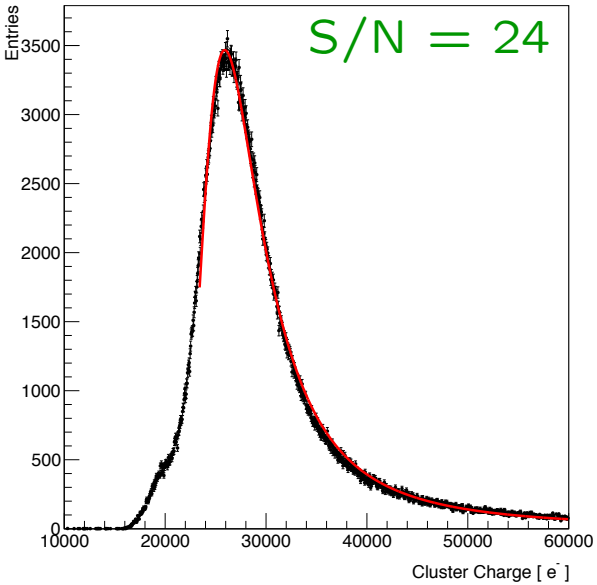
- CMS APV25 multi-peak readout for 2 ns time resolution
- In-vacuum ADC, voltage generation and power distribution/control on very dense Front End Boards
- Vacuum penetration for digital signals via high-density PCB through flange w/ external optical conversion.
- Supports trigger rates up to 50 kHz, raw data rates in excess of 100 gbit/sec.



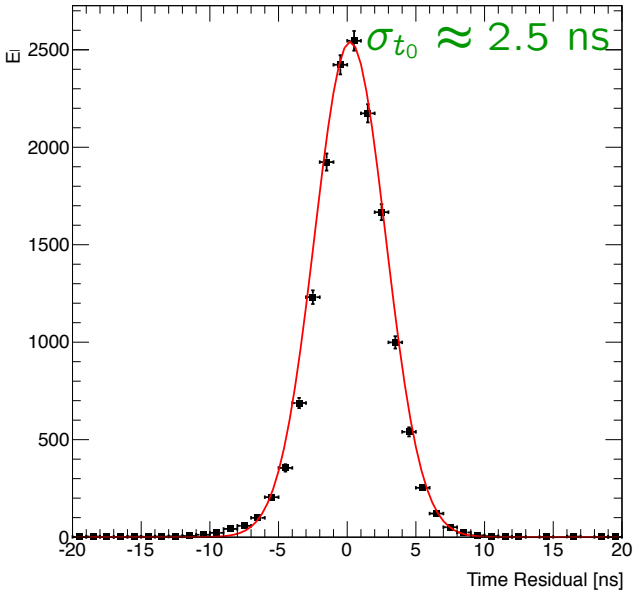
SVT Amplitude and Time Reconstruction



Cluster Charge Reconstruction



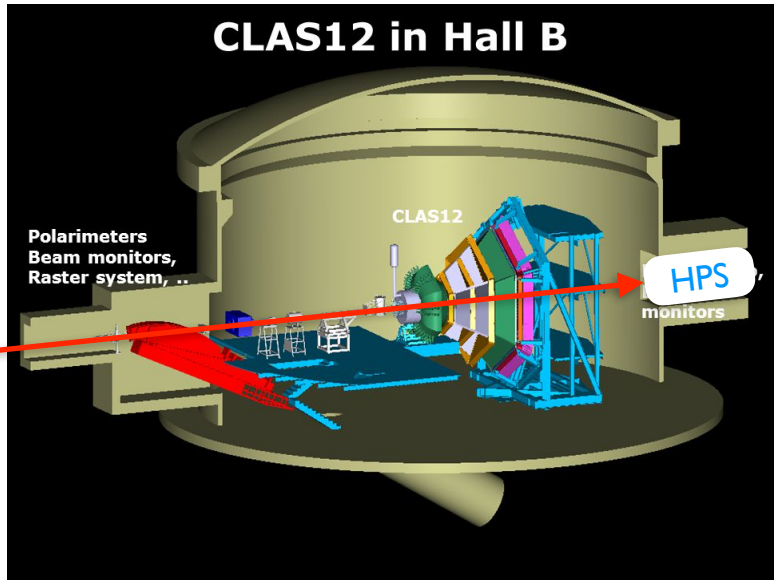
Hit Time Reconstruction

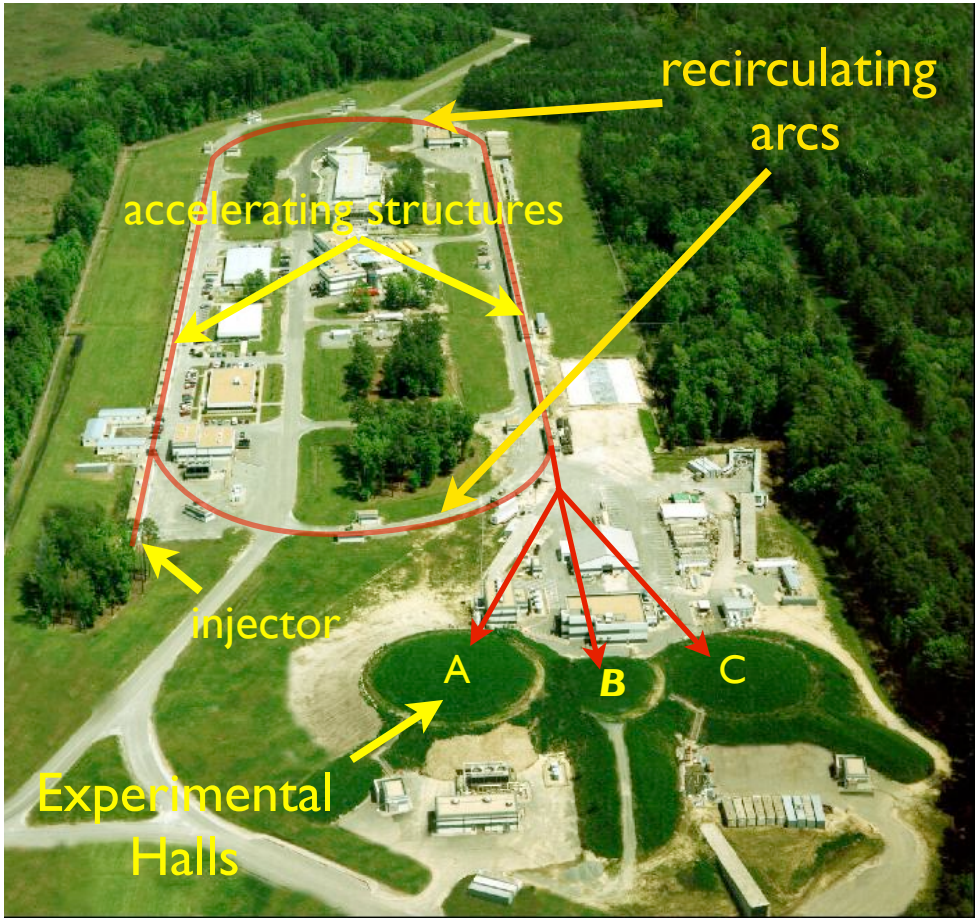


Hall B at JLab CEBAF

Simultaneous beam to multiple halls with 2 ns bunch separation

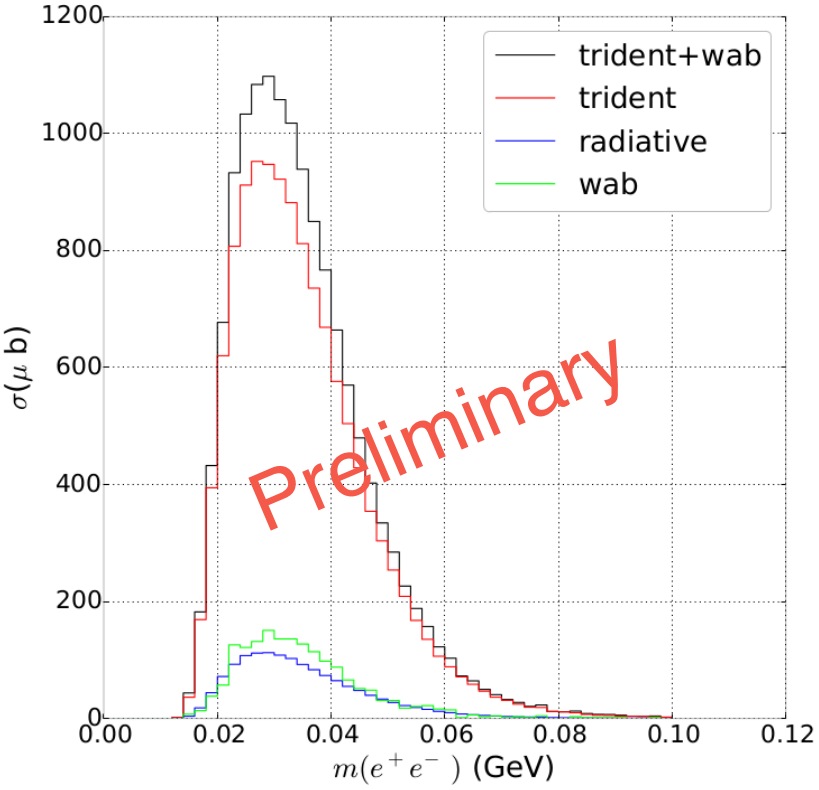
- E_{beam} = n×2.2 GeV, n≤5 (11 GeV Max)
- I_{beam} < 500 nA (Hall B) ~ 10000 e^-/bunch

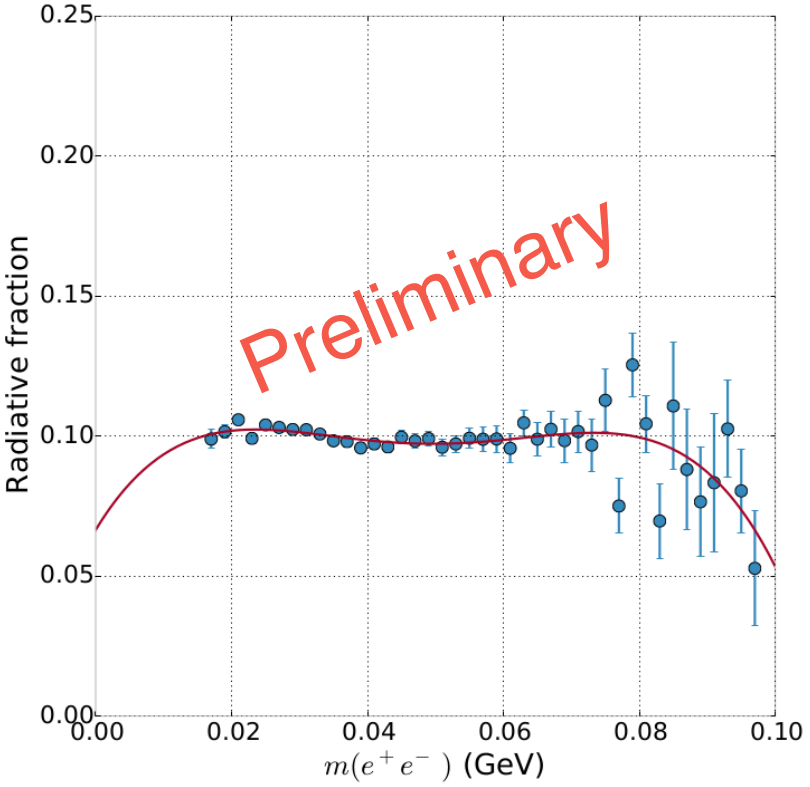




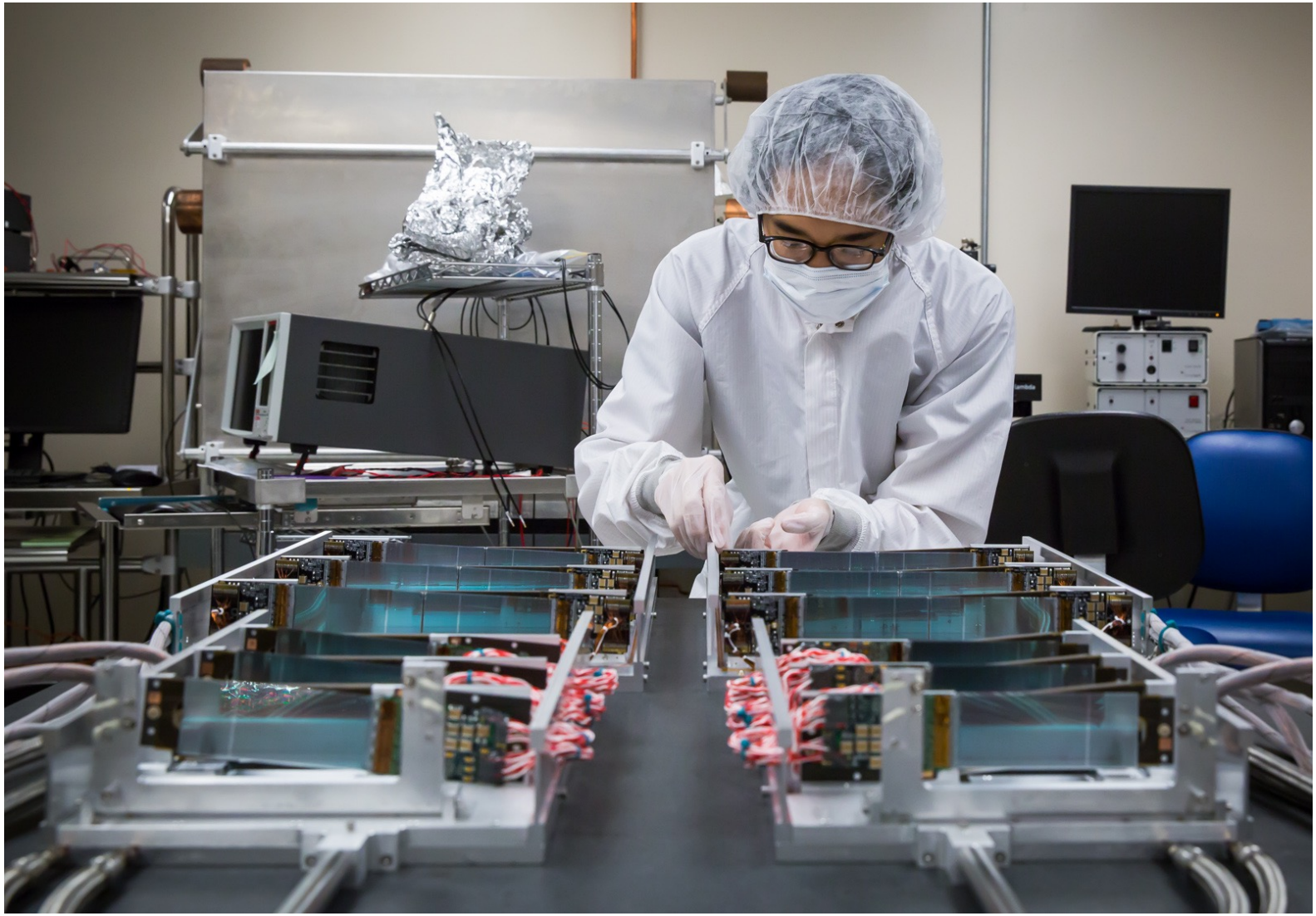
Radiative Fraction

~10% of total yield are radiative tridents

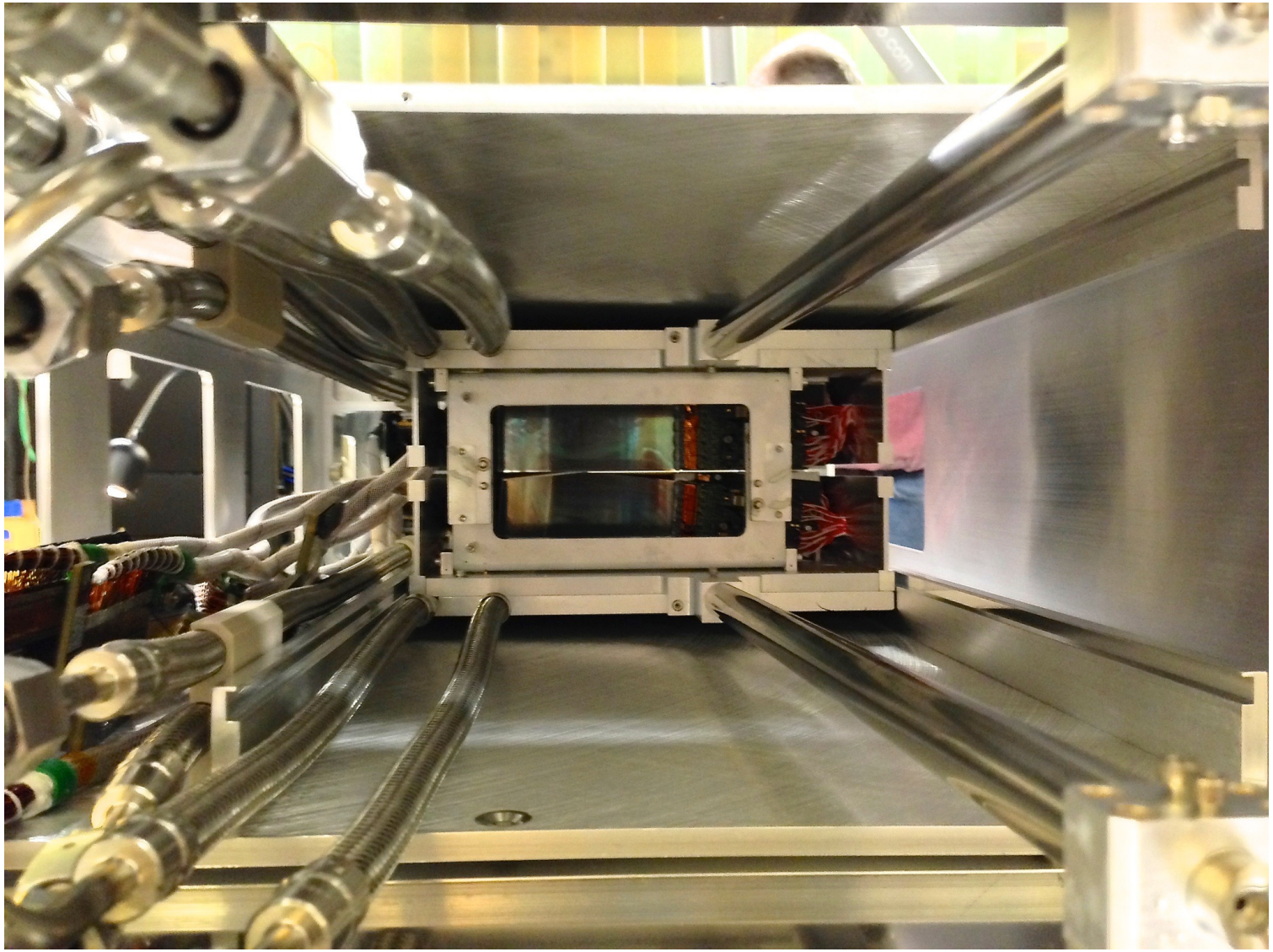




HPS SVT

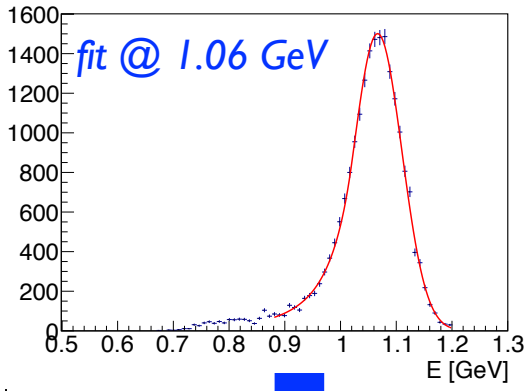


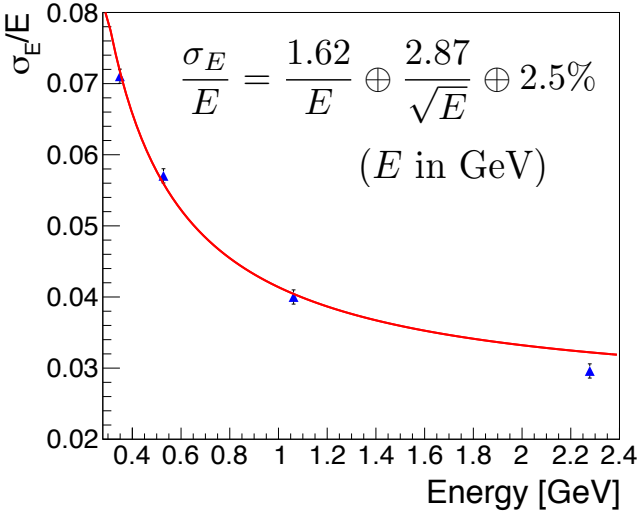
HPS SVT



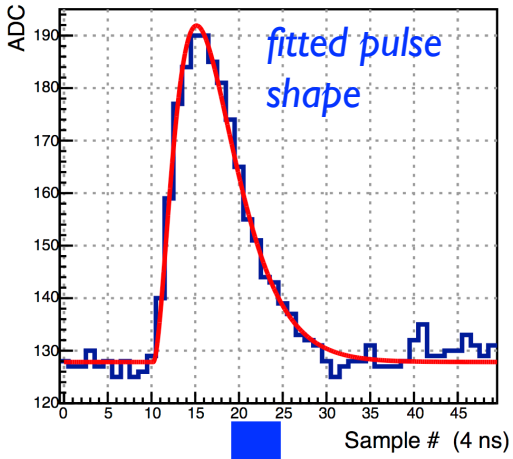
ECal Performance

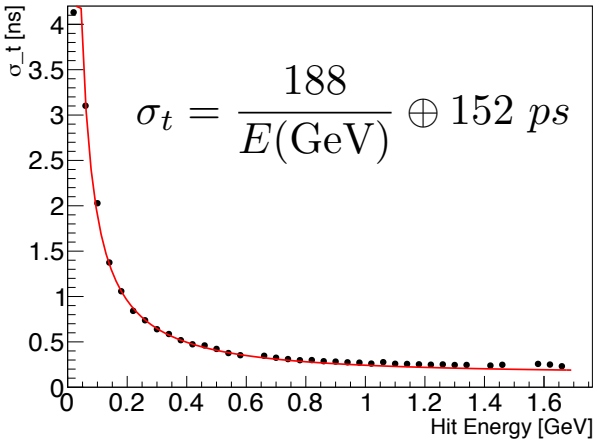
cluster energy resolution





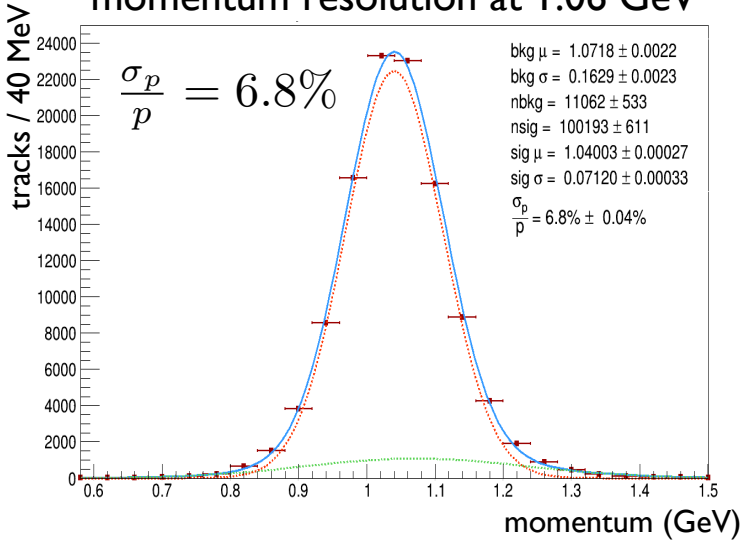
single-crystal time resolution



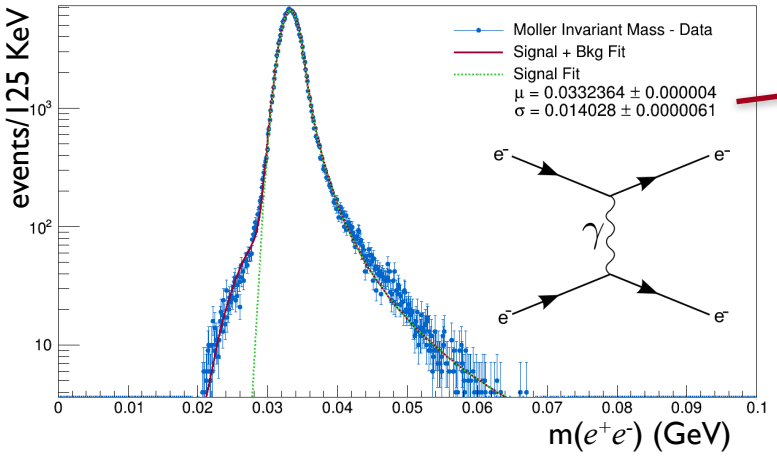


SVT Performance

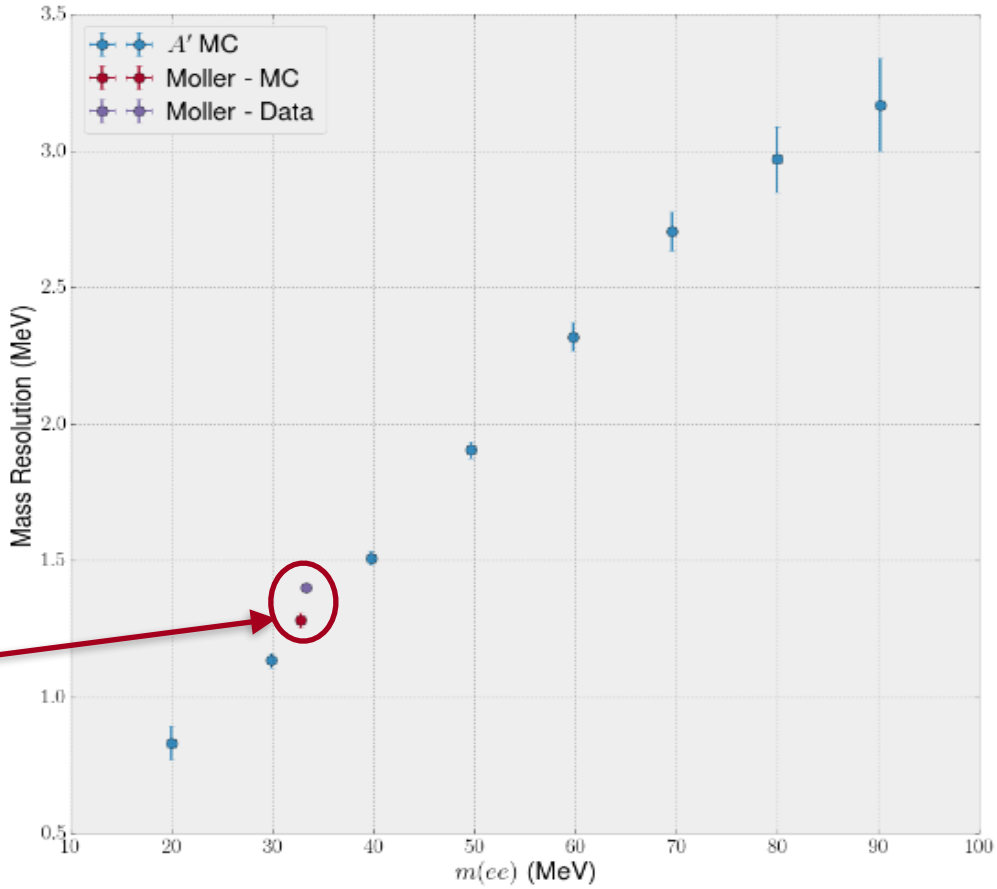
momentum resolution at 1.06 GeV



mass resolution @ $E_{\mathrm{CM}} = \sqrt{2m_e E_{\mathrm{beam}}}$



mass resolution data/mc comparison



Dark Photons in 2021?