Visible dark photon searches at JLab

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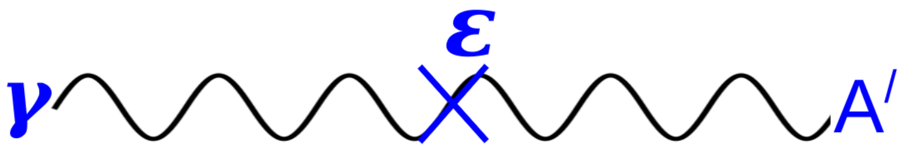
Light Dark Matter @ Accelerators (LDMA)
Apr 8 – 12, Genova, Italy

Kinetic mixing

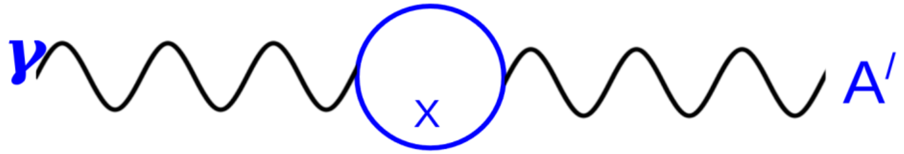
What if Nature contains an additional broken U(1) (Abelian) force mediated by a massive vector boson, A'?

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

Kinetic mixing



Induces week coupling to electric charge

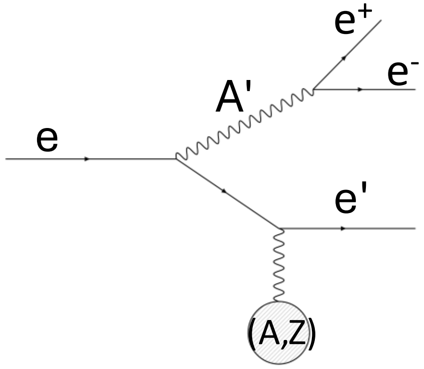


Generated by heavy particles X interacting with γ and A/

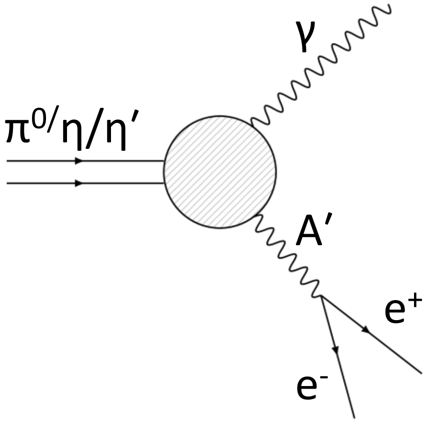
Where can A's be produced

Where you can produce photons, you can produce dark photons!

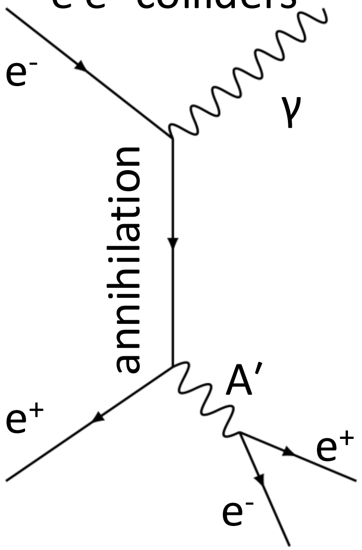
A′-strahlung

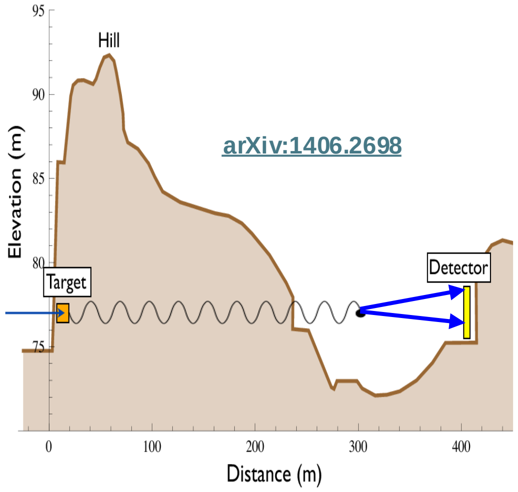


Dalitz decays of mesons $\pi^0/\eta/\eta' \rightarrow \gamma A'$



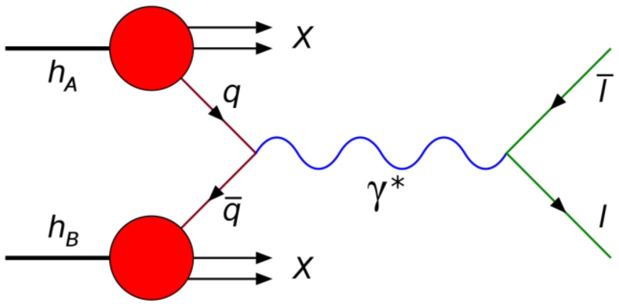
e-e+ colliders





Drell-Yan

Proton-proton collisions



In all these scenarios we assume $m_{A'} < 2m_\chi$

A' can only decay to SM particles: **Visible decay**

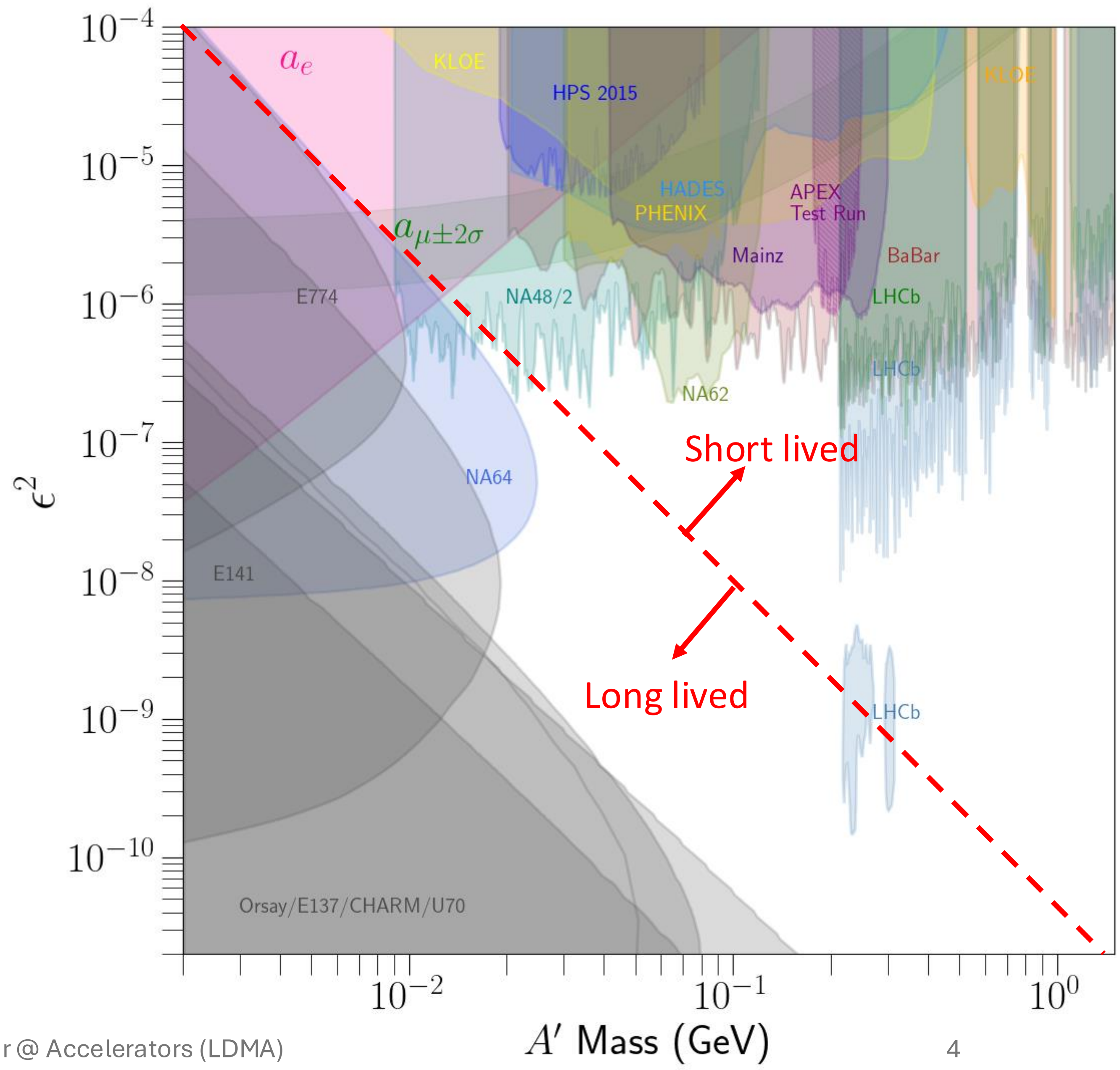
Constrains

Simplistic visible decay model has 2 parameters: $\boldsymbol{\epsilon^2}$ and $\mathbf{m_{A'}}$.

Decay length $$l_0 \equiv \gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}}$$

Depending on the mass and the mixing strength (ϵ^2) the dark photon can be short or long lived.

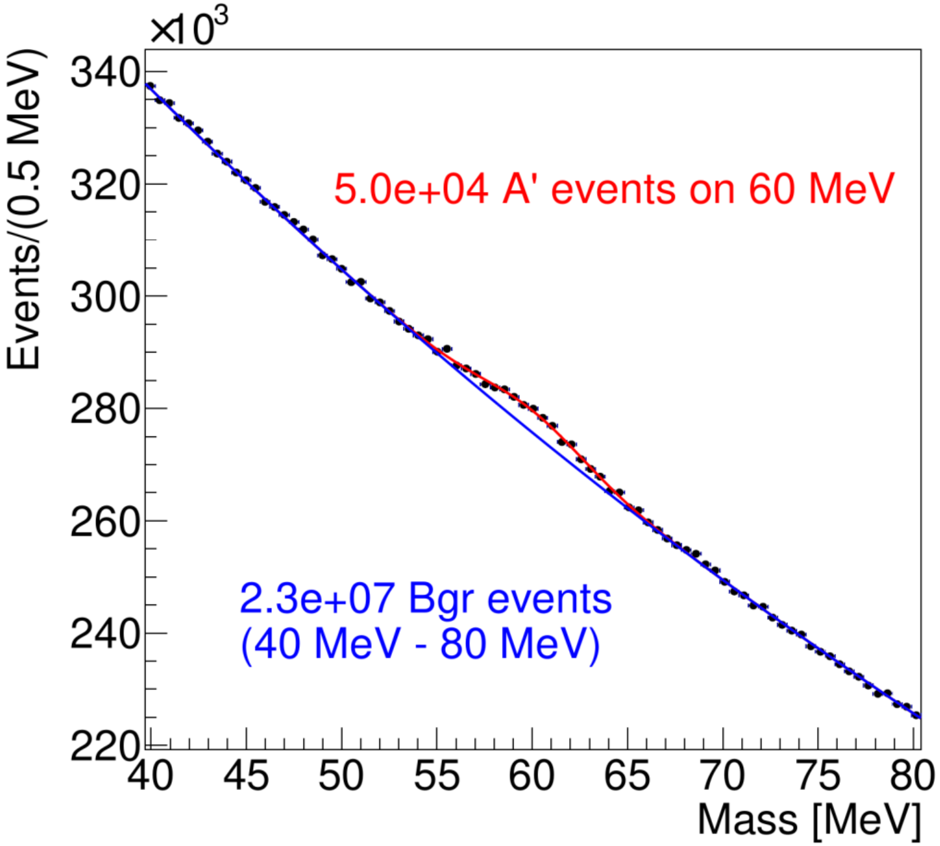
Different experimental techniques target different regions of phase space.

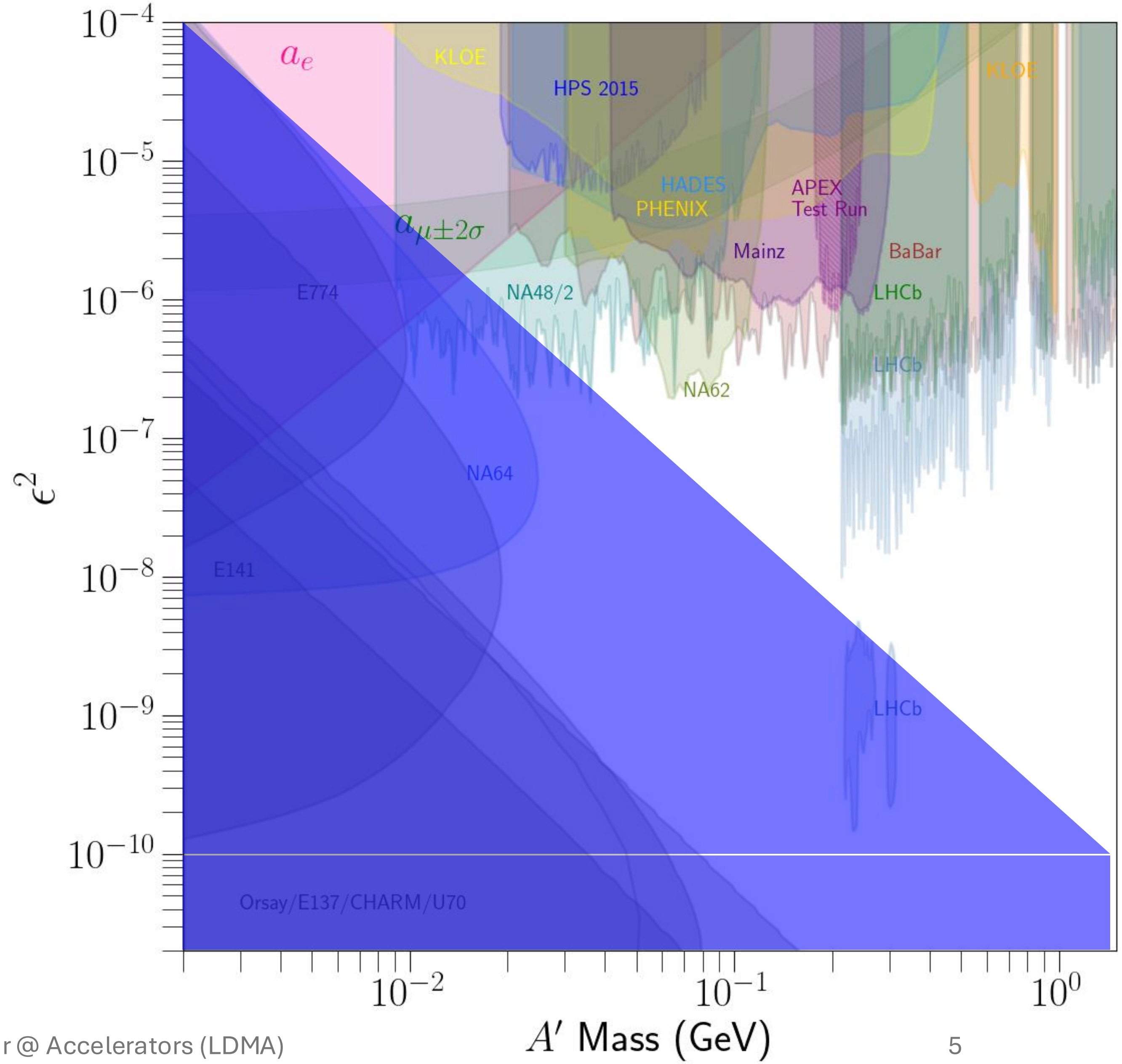


Constrains

Bump hunting

Short-lived A's manifest themselves as a bump over the copious electromagnetic background.

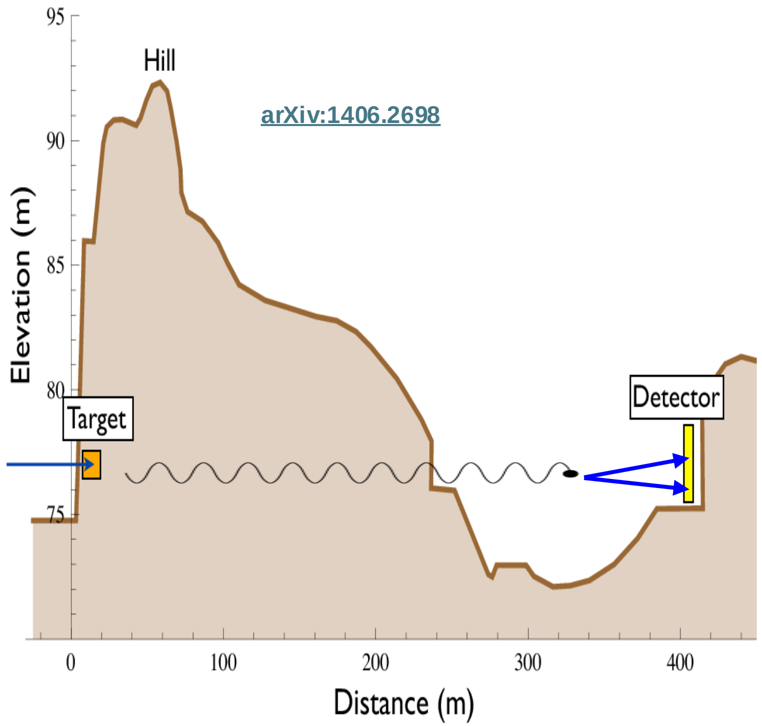


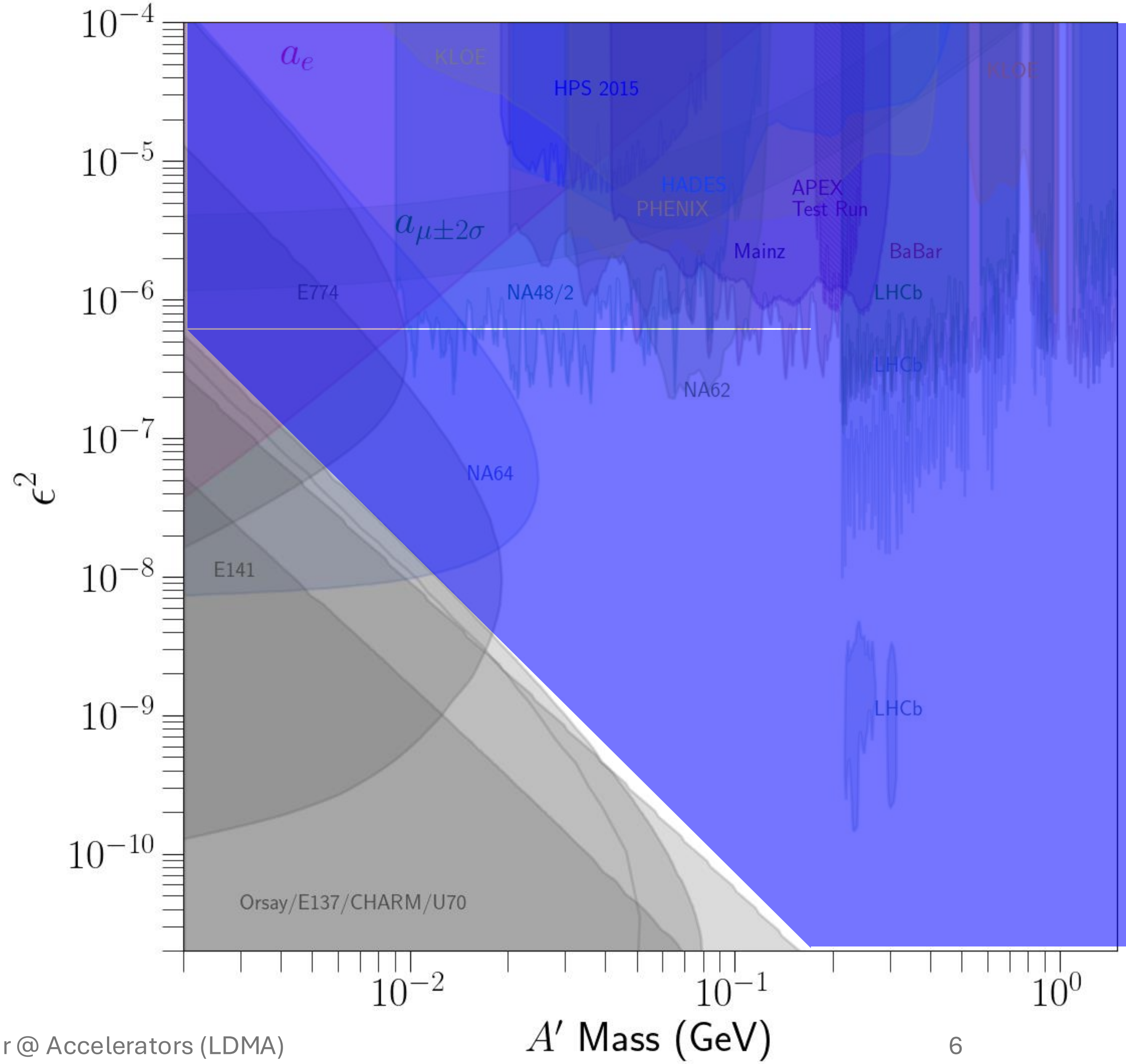


Constrains

Searching for a signal 100s of meters downstream the beam dump

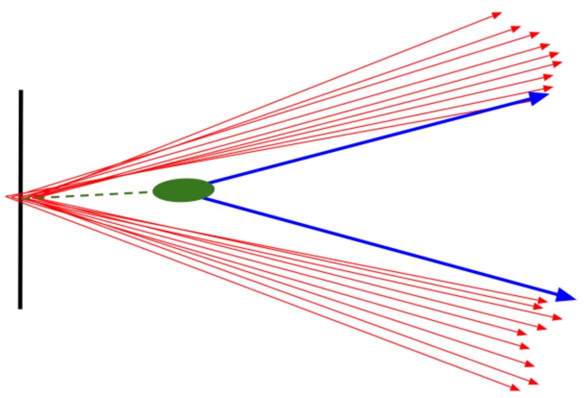
At smaller masses and smaller ϵ^2, A′ can travel 100s of meters before decaying.



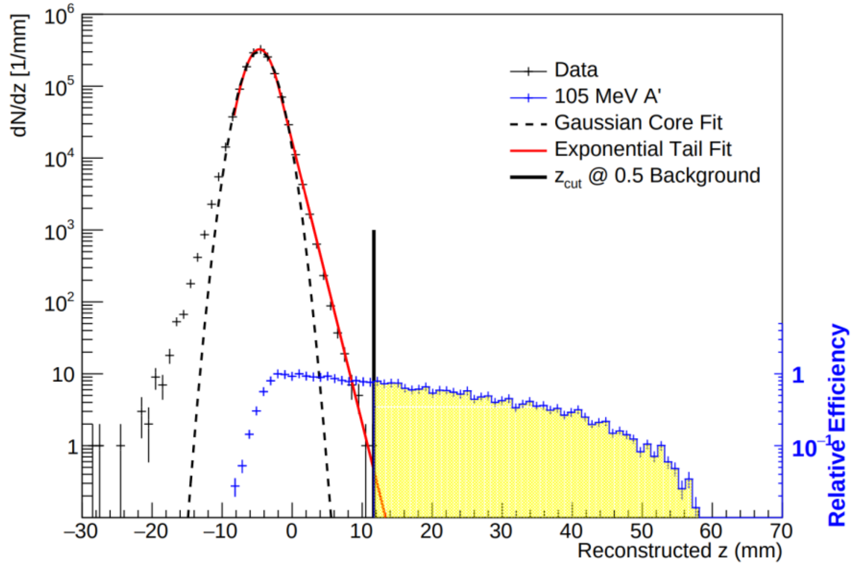


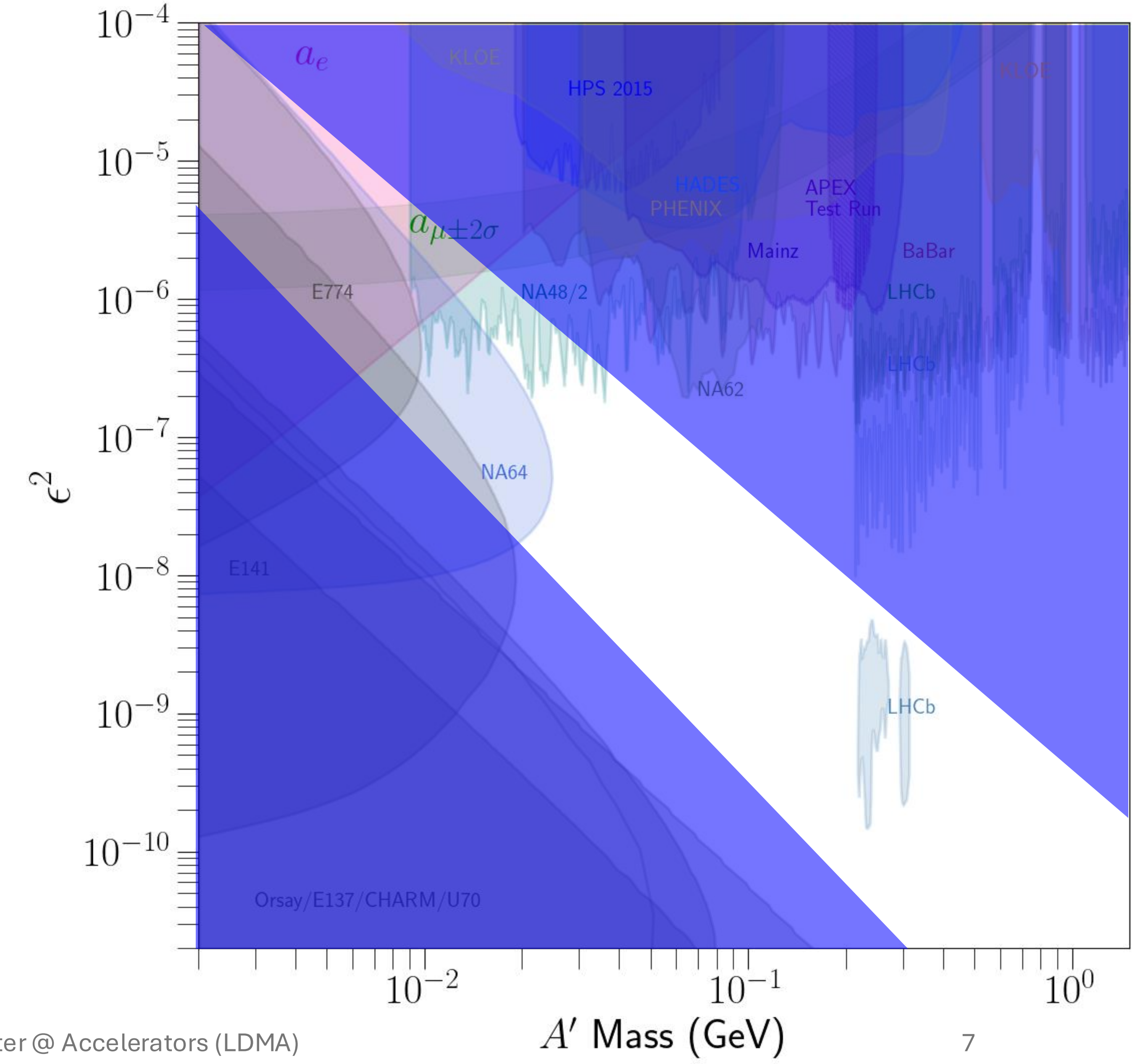
Constrains

Searching for displaced vertexes



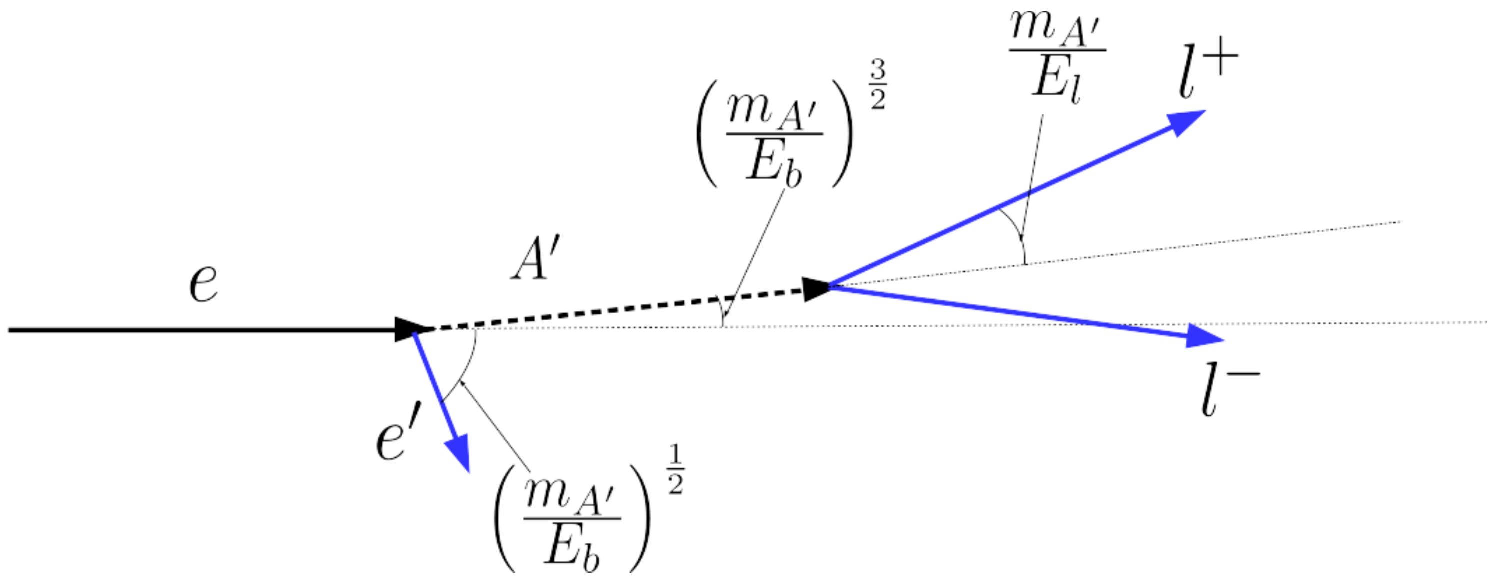
Need good vertexing detector

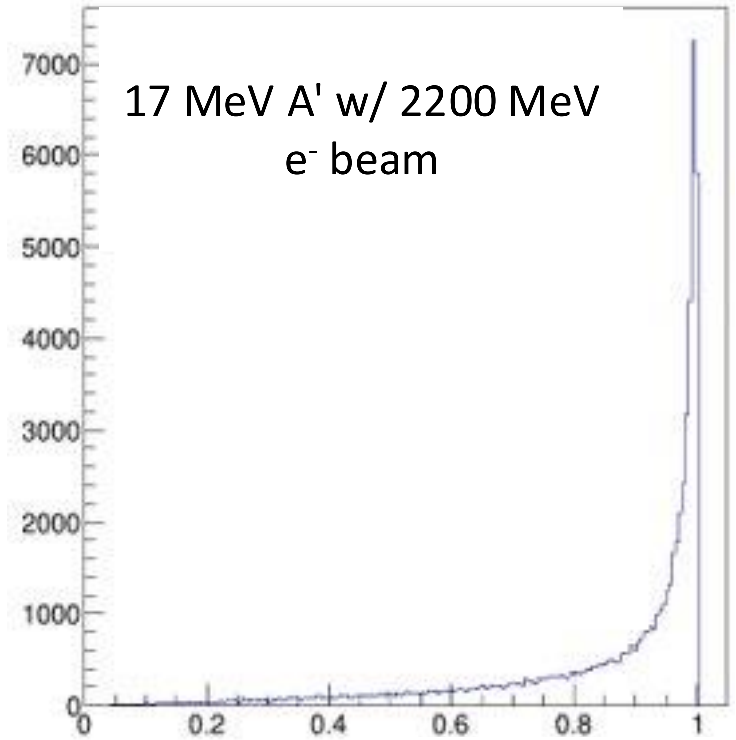




Electro-produced heavy photon kinematics on fixed targets

- Unlike Bremsstrahlung, A’ takes almost all the beam energy: $E_{A'} \sim E_b(1 - m_{A'}/E_b)$
- Peaked at forward angles: $(m_{A'}/E_b)^{3/2}$



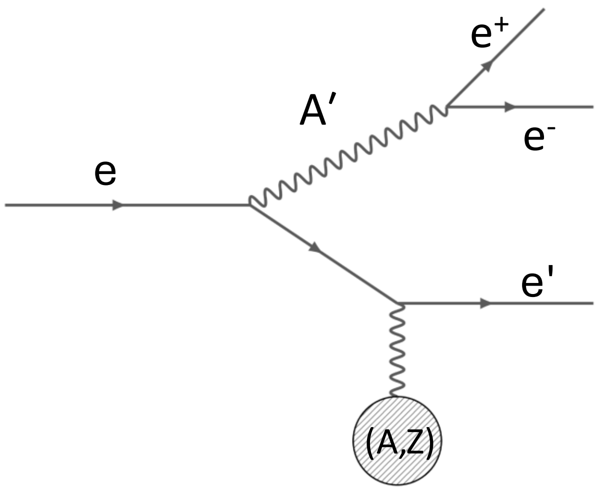


X=E(A’)/E(beam)

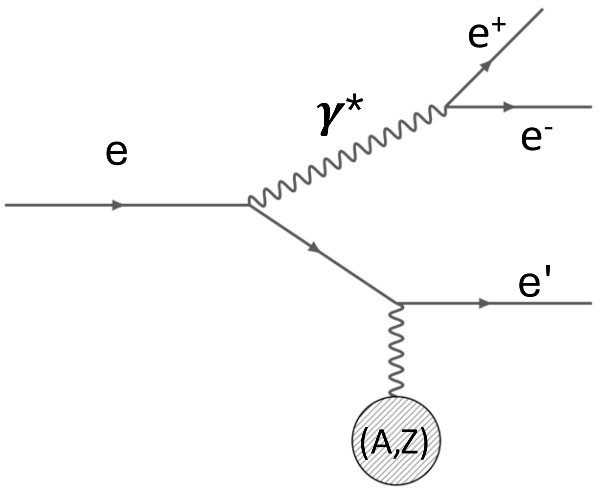
- Fixed target experiments are therefore designed to be sensitive to small angles
- Maximize acceptance for high $E_{sum} = E(l^-) + E(l^+)$

Background processes in A’ production w/ e- beam off fixed target

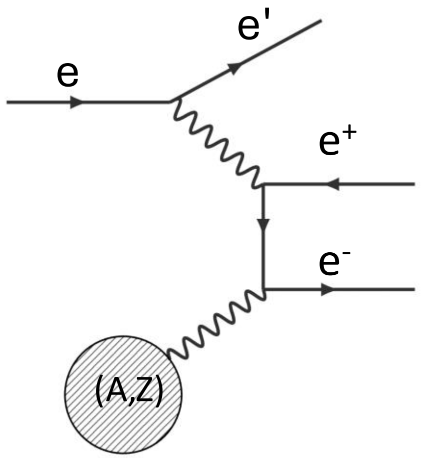
Production of A’



Radiative Tridents



Bethe Heitler

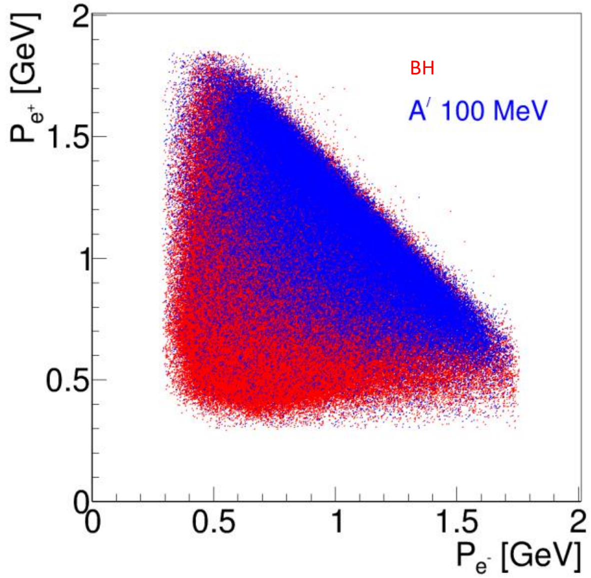


Have exactly same kinematics

$$\frac{\sigma(eA \rightarrow e'A'(\rightarrow e^-e^+))}{\boxed{\sigma(eA \rightarrow e'\gamma^*(\rightarrow e^-e^+))}} = \left(\frac{3\pi\epsilon^2}{2N_f\alpha}\right)\frac{m_{A'}}{\boxed{\delta m}}$$

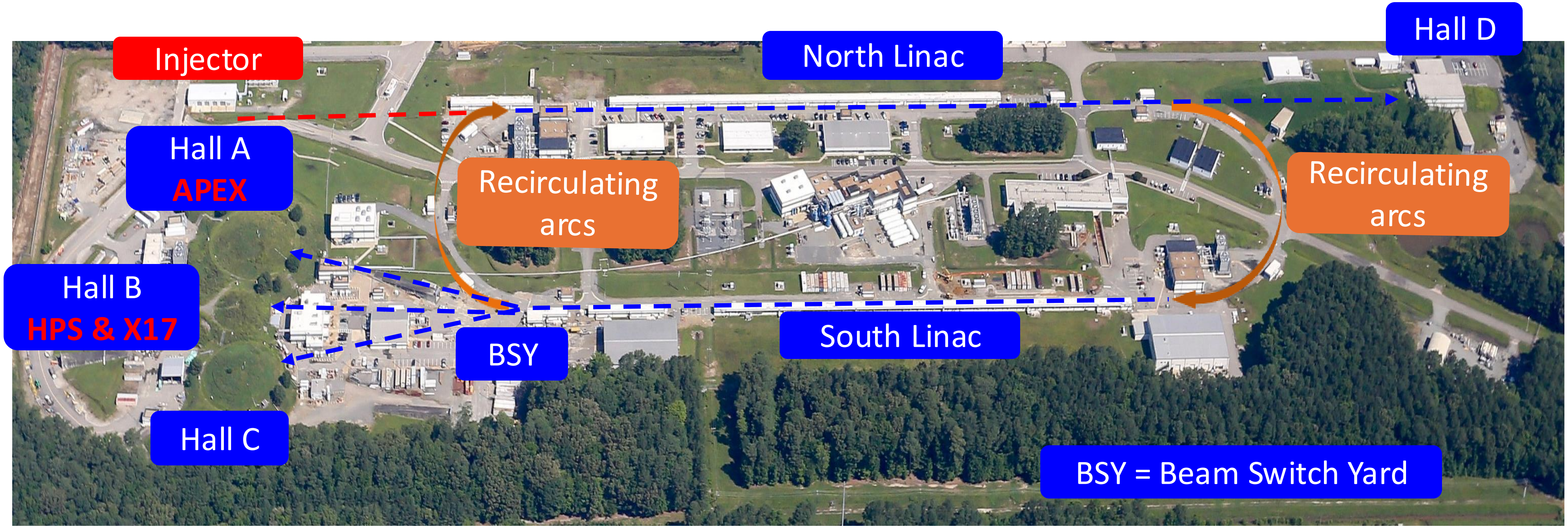
Known QED process => ε can be calculated by above ratio

It is critical to have a good mass resolution

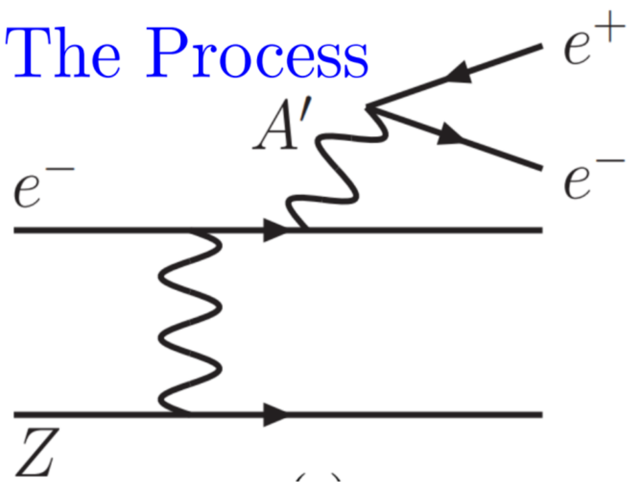


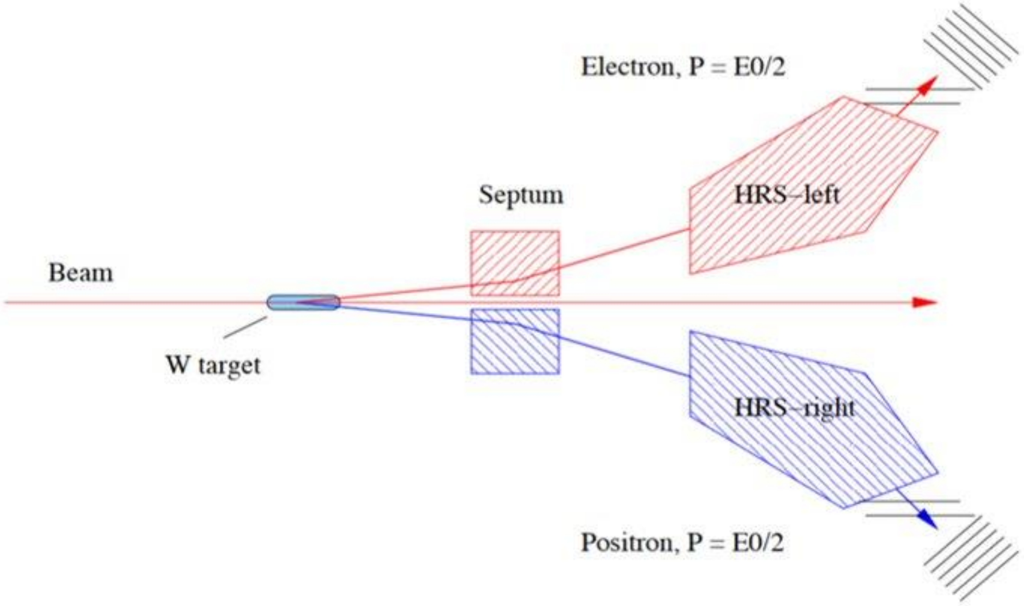
Continuous Electron Beam Accelerator Facility

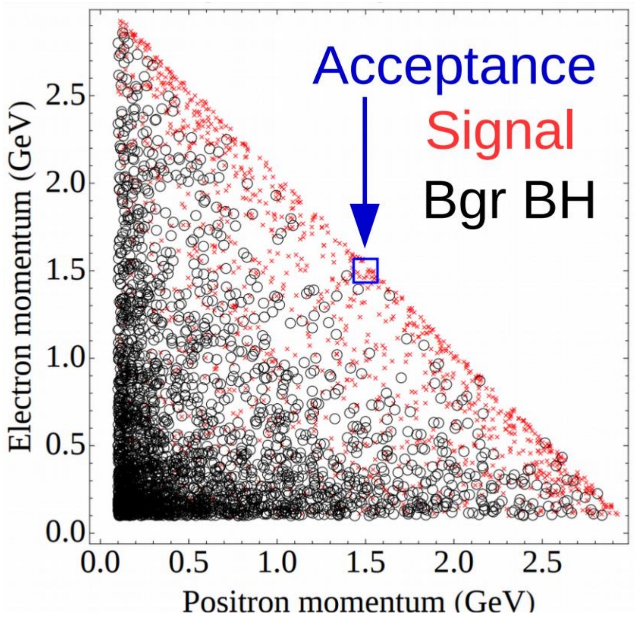
- Two parallel linear accelerators arranged in racetrack configuration.
- Simultaneous delivery of electron beam to 4 experimental halls
- Up to 11 GeV to Halls A, B and C
  - Hall-D can get 12 GeV
- High beam polarization (> 80%)
- Three approved experiments at JLab to search for visible decays of A'
  - ApEX, HPS and X17



A Prime Experiment

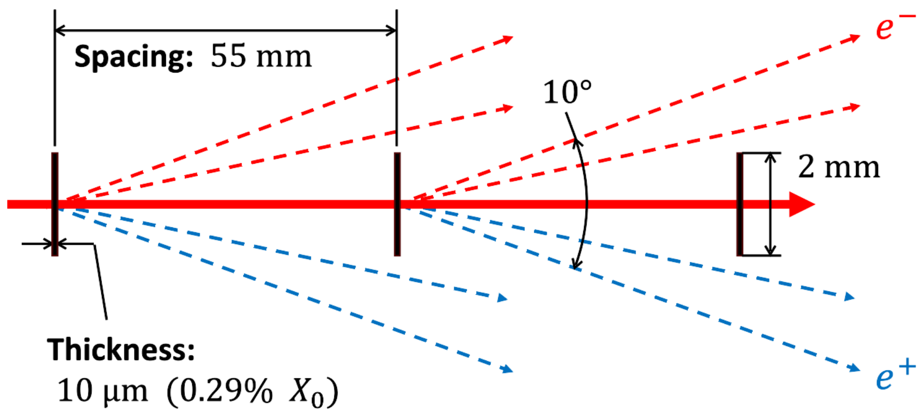




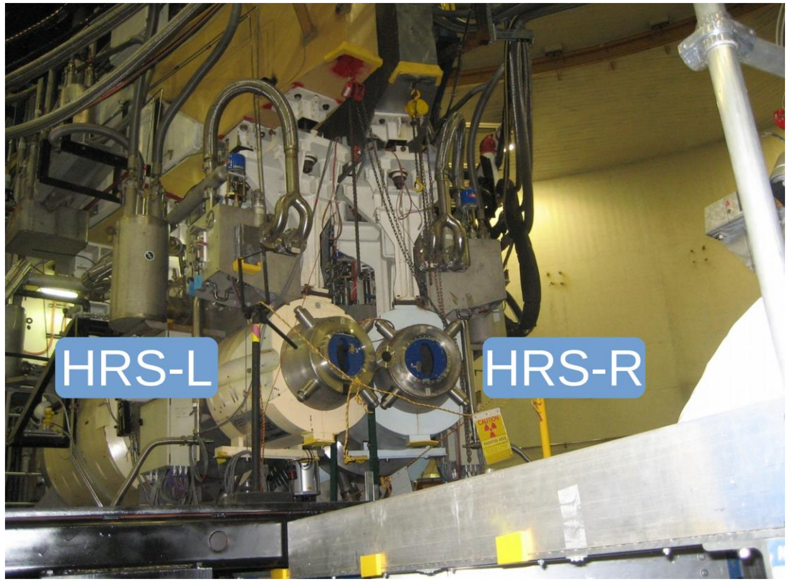


- Septum magnet allows to move average scattering angles from 12° to 5°.
- Symmetric acceptance for e^- and e^+.
  - P≈0.5*Eb
- $\delta\theta$ =0.5 mrad $\delta\phi$ = 1mrad
- Multi-foil targets: increase the mass range and reduce the multiple scattering

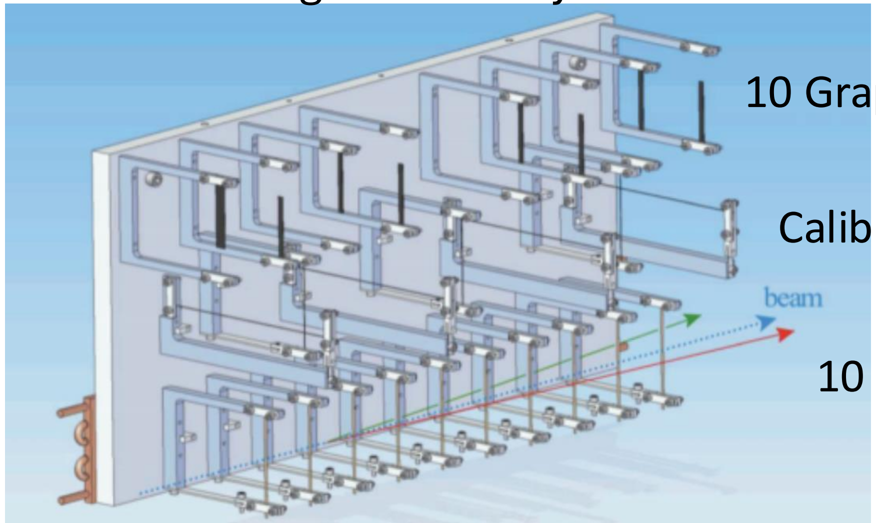
Target: ×10 Tungsten Foils



Detector components



Target assembly

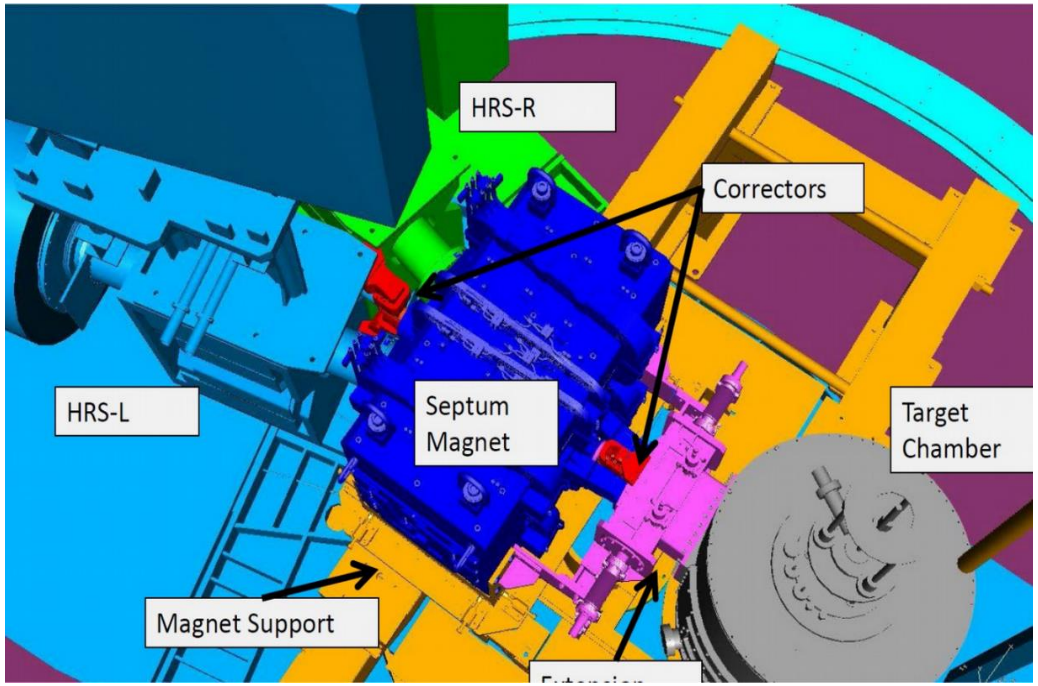


10 Graphite foils, tot 0.07% RL

Calibration of magnetic optics

10 Tungsten foils, 2.8% RL

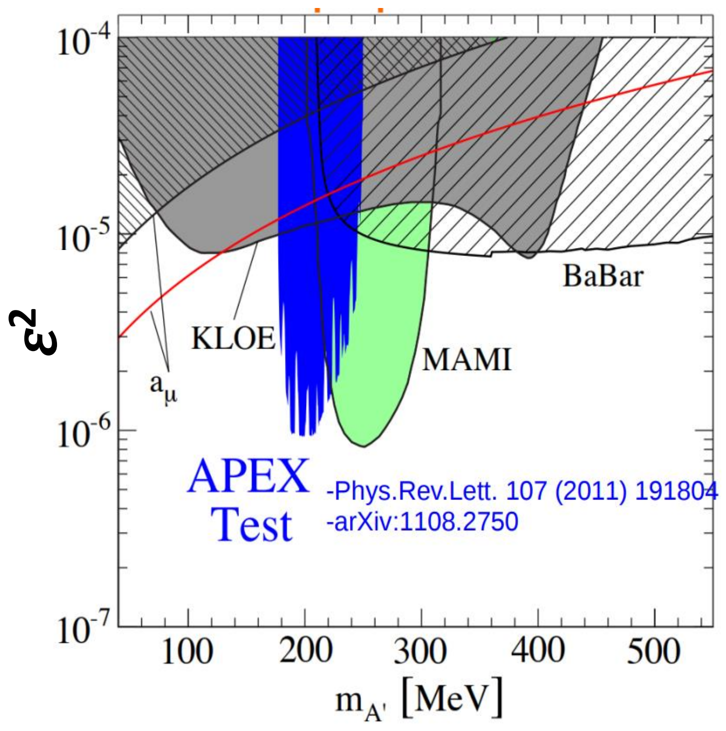
Top view



Electrons are detected in HRS-L while positrons in HRS-R

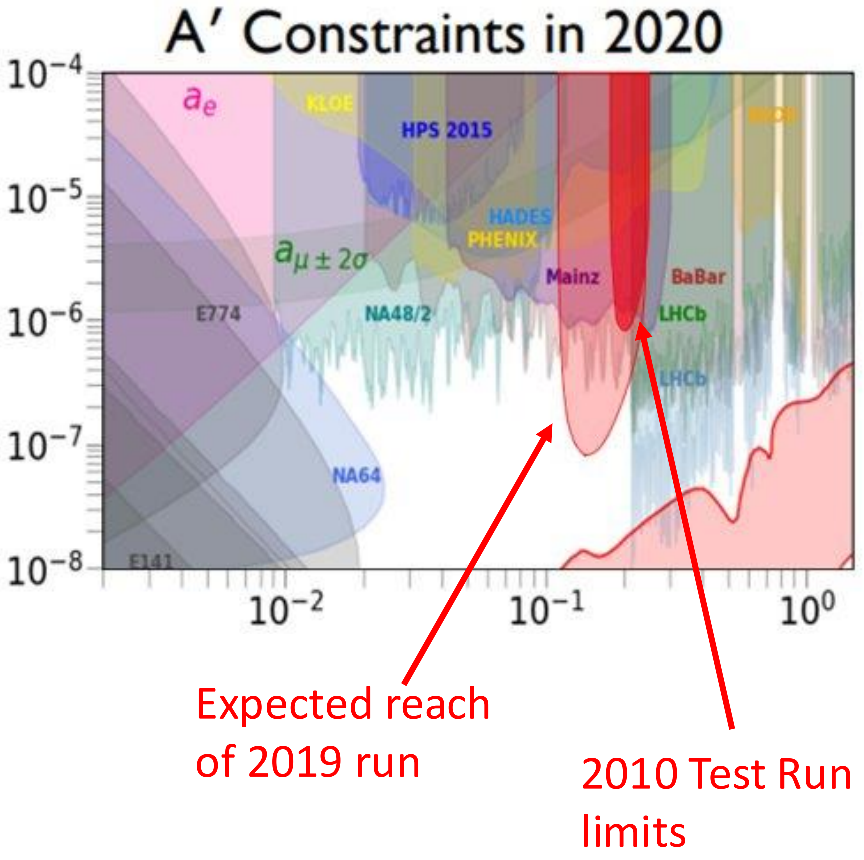
A Prime Experiment

- **2010 Test run**:
  - Eb = 2.29 GeV
  - Successfully demonstrated the concept of the experiment
  - Back in 2010 the "ε^2 vs mass" phase space was mostly empty



2019 Production Run:
- 30th January until March 10th, 2019
- ~ 34 C of accumulated charge on target for
- Eb 2.1 GeV

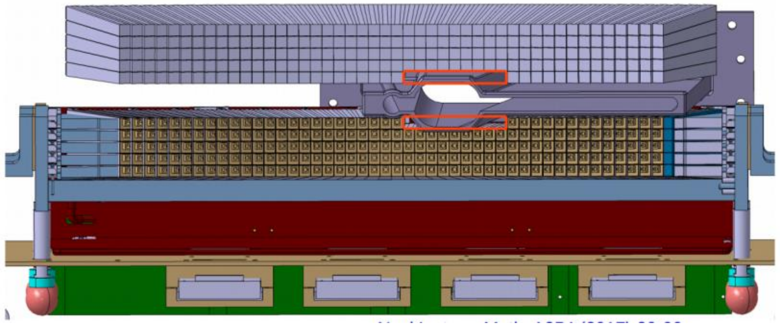
Significant territory is already excluded since 2010 approval.



Heavy Photon Search

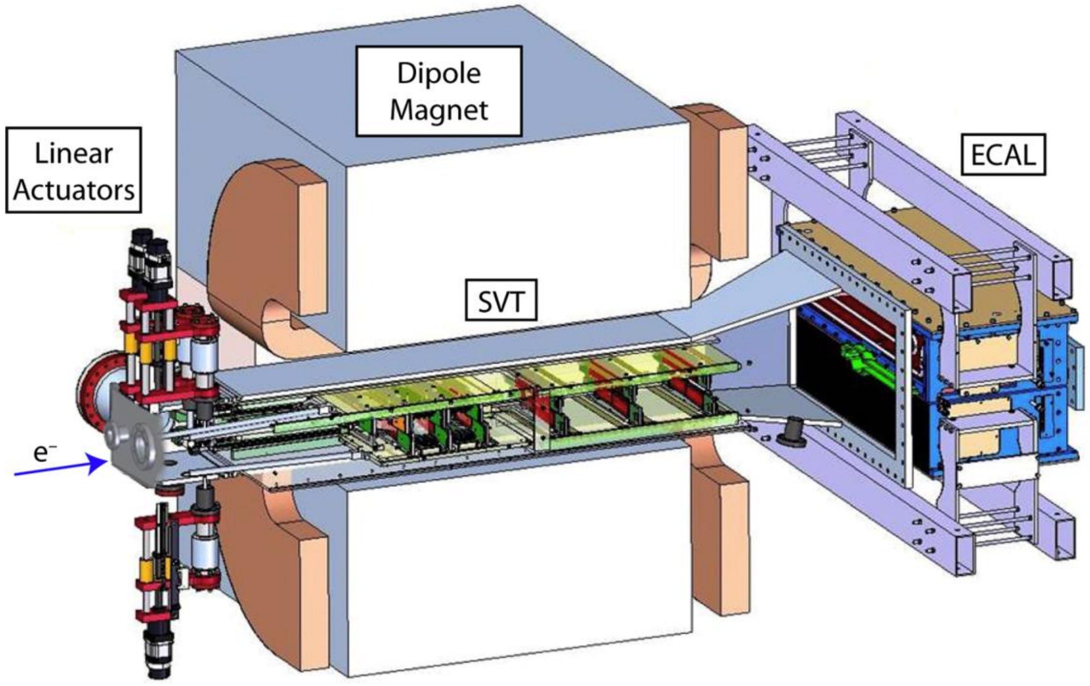
- In Hall-B
- Compact detector:
- Si. Tracker inside Dipole magnetic field
- Electromagnetic calorimeter
- Can do Bump Hunt and Displaced vertex search

ECal

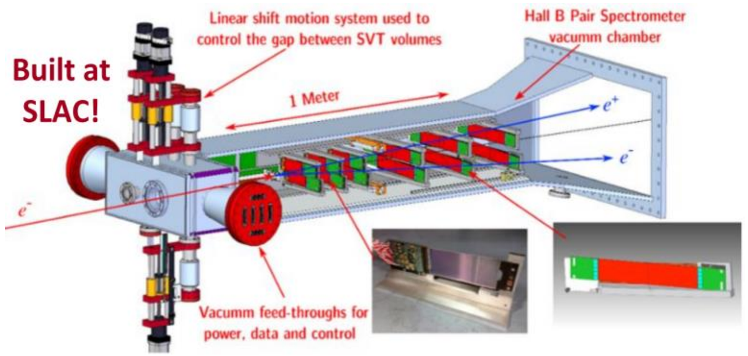


- 2 symmetric sectors
  - Top and bottom
  - In total 442 crystals
- Provide trigger
- Good timing
  - Cleans accidentals

Detector for 2015 and 2016 runs



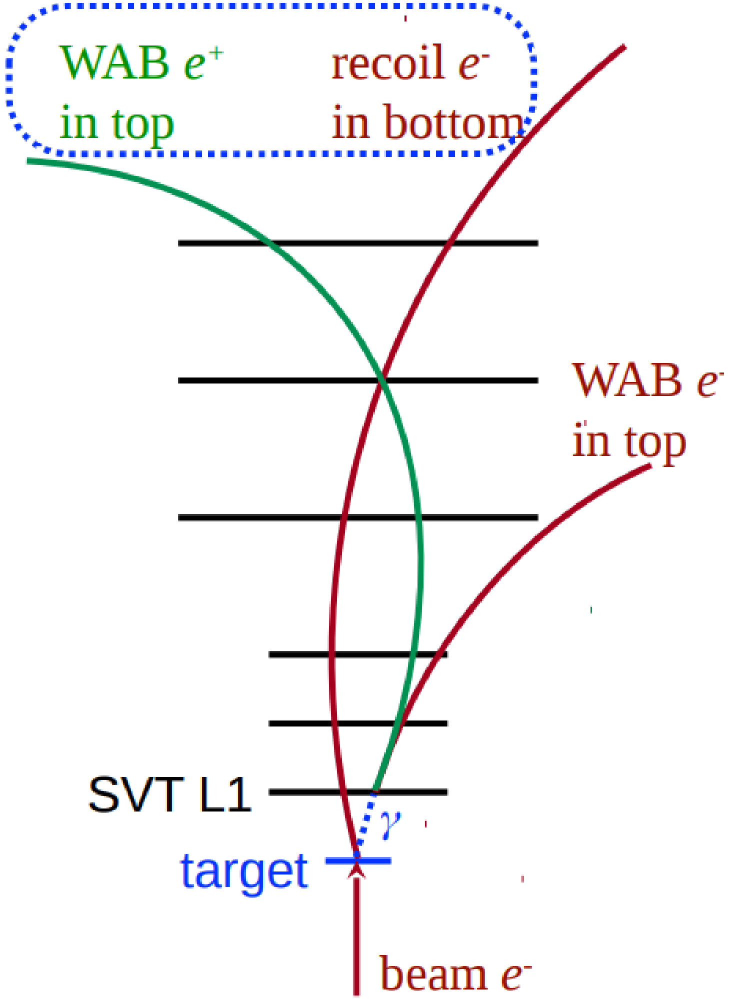
SVT

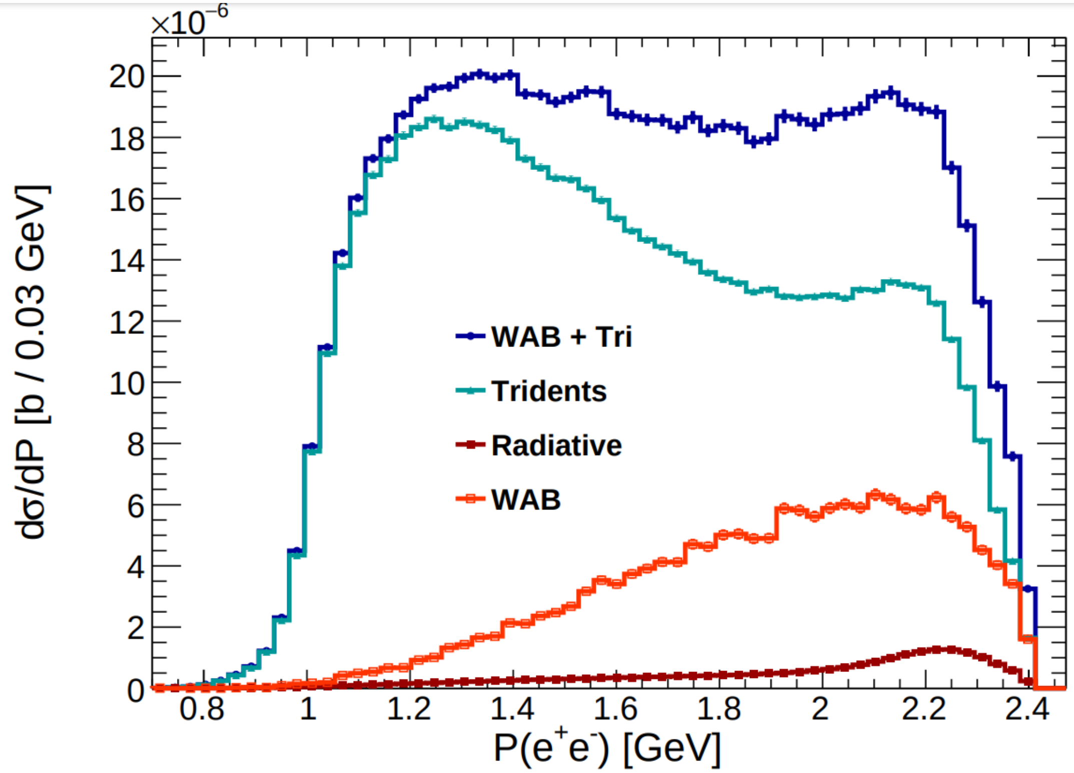


- 6 layers (2015 and 2016 runs)
- Each layer has axial and stereo strips
- Acceptance starts from 15 mrad

Wide Angle Bremsstrahlung

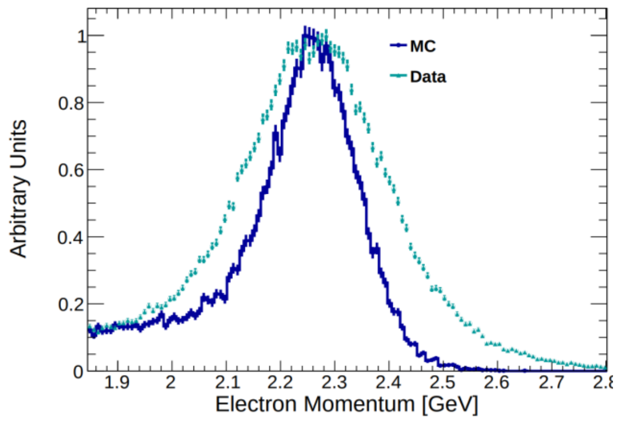
- 2 step process: Wide Angle Bremsstrahlung Then Photon conversion into e-e+ pairs can fake the trident final state.
- Most of the contributions comes from the conversion in the 1st and 2nd layers of SVT.

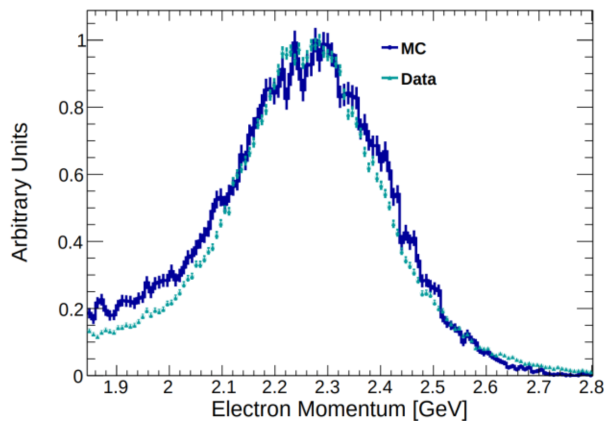




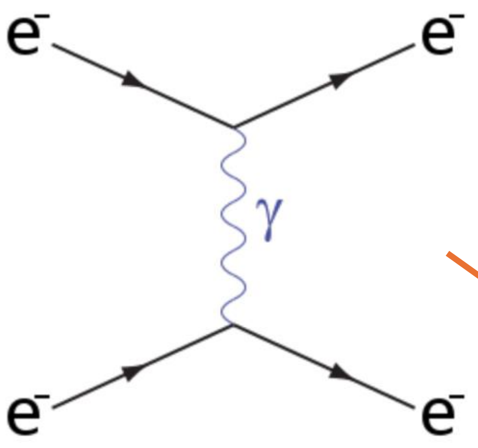
Mass resolution

- Good understanding of mass resolution is critical for "Bump Hunt" analysis
- Mass resolution of data is known in a single mass point (at Moeller mass)
- For other masses we have to rely on MC.



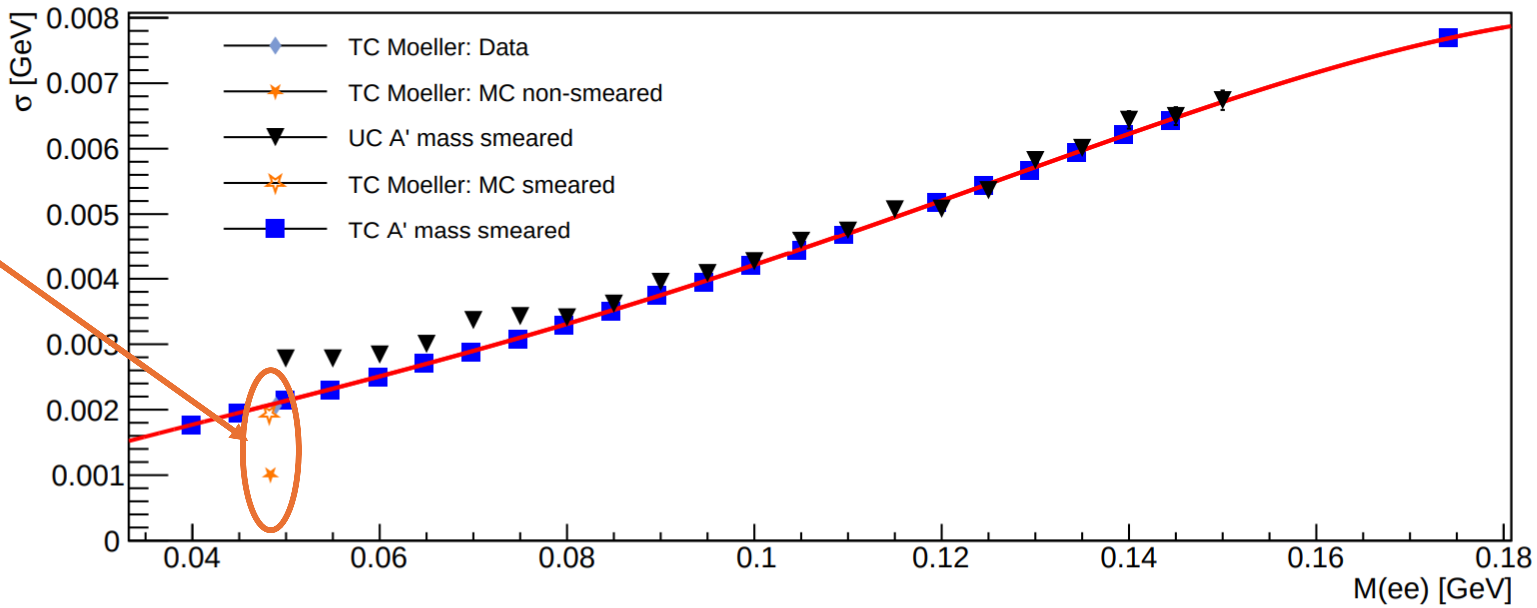


- Smear mom. resolution to match FEE width
- With just mom. smearing the width of the MC Moeller mass agrees with the data within 6%.



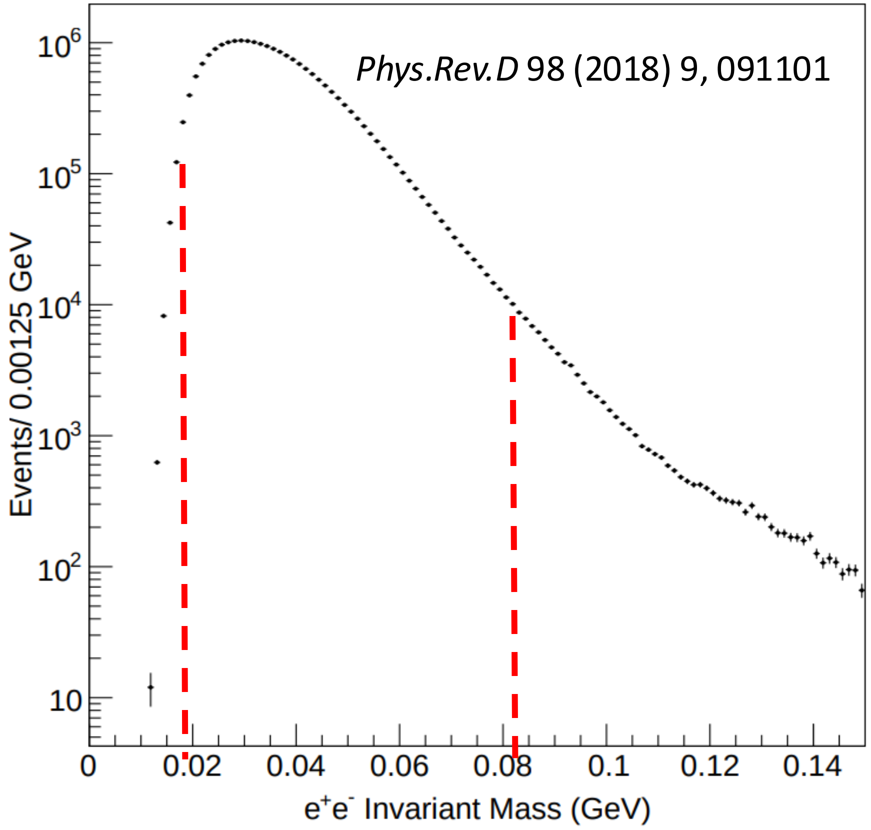
$$M(ee) \equiv \sqrt{2 \cdot E_b \cdot m_e}$$

M = 48.5 MeV for 2.3 GeV beam

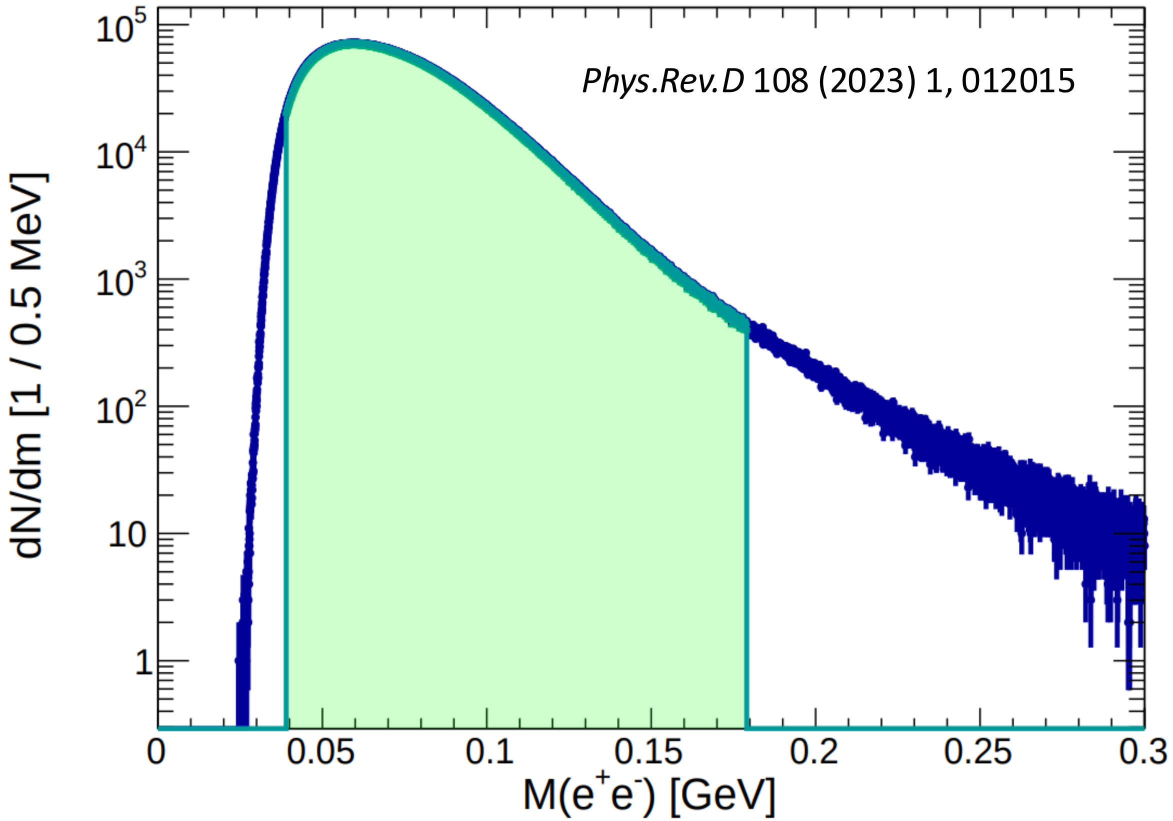


Invariant mass distributions

2015 run 50 nA beam @1.1 GeV, 1.7 days

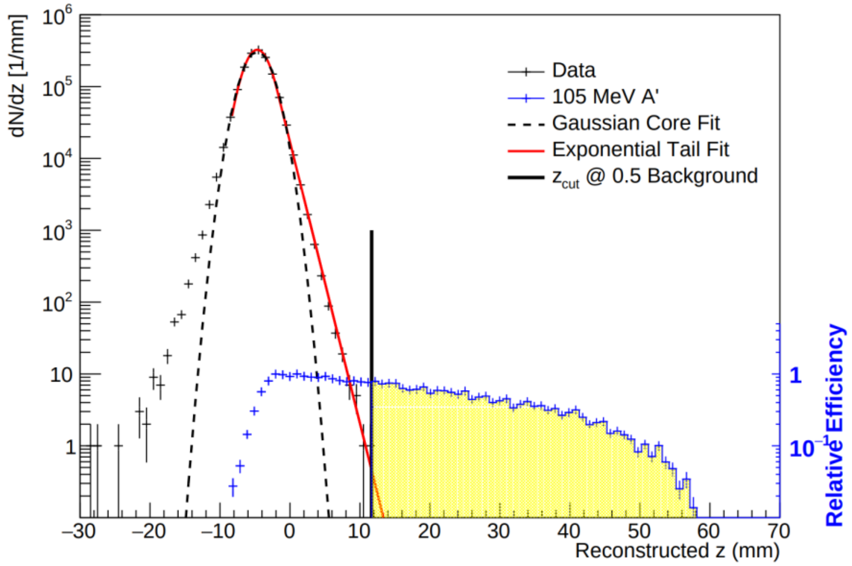


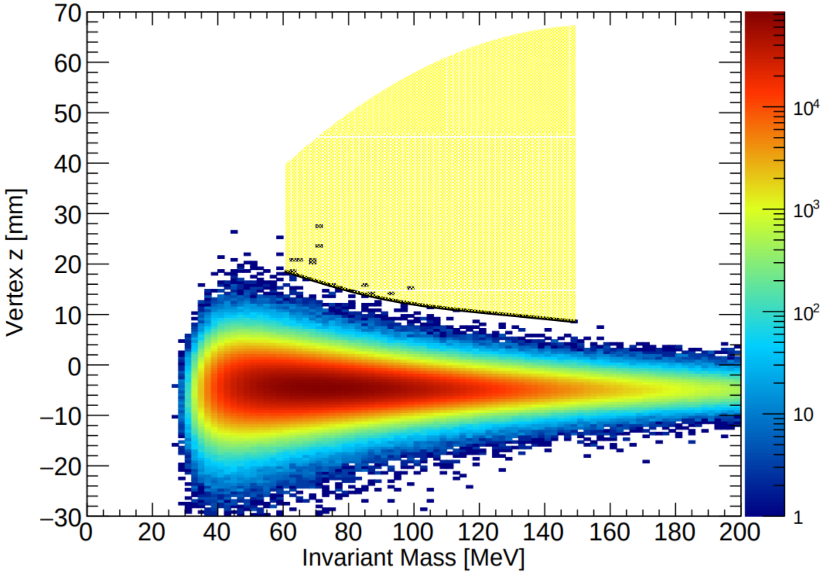
2016 run 200 nA @2.3 GeV, 5.4 days



No significant bump is found, so upper limit is set.

Displaced Vertex Search





- Background is parametrized as Gaussian + Exponential tail
- Z cut is determined to have 0.5 Bgr event
- Limits are set using the Optimum Interval Method
- No exclusion in 2016 data
- Highest sensitivity is obtained for $m_{A'}$ = 82 MeV and $\boldsymbol{\varepsilon}^2 = 1.710^{-9}$,
  - A′ cross section is scaled by x7.9

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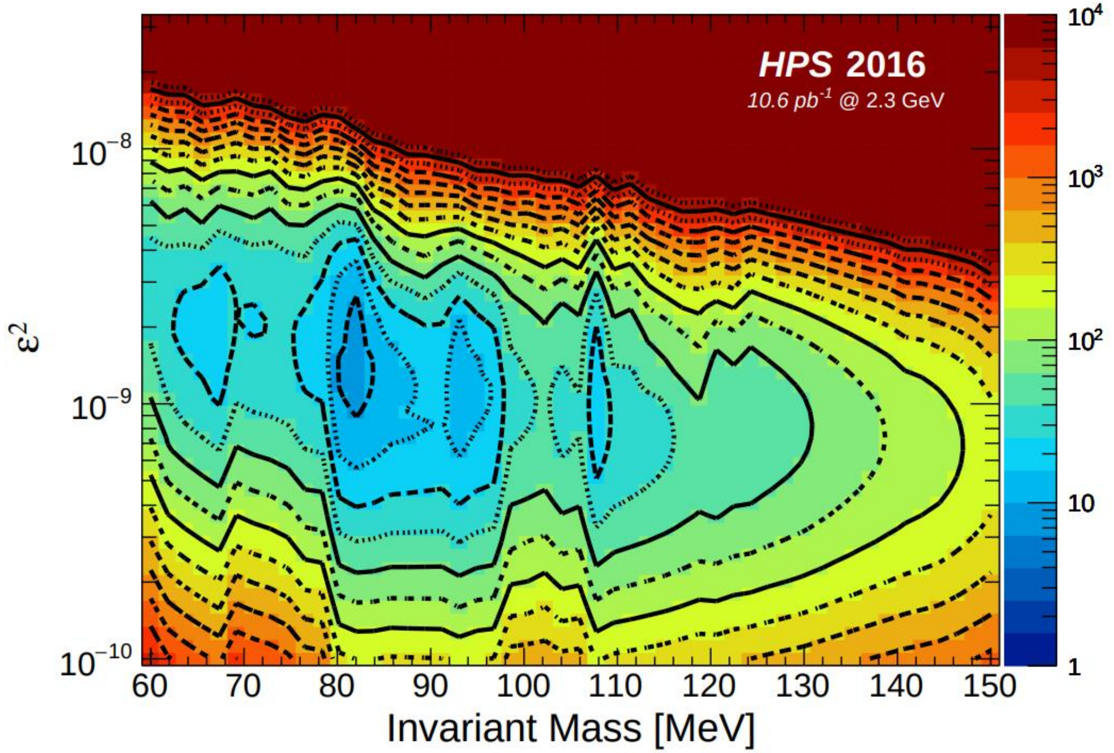
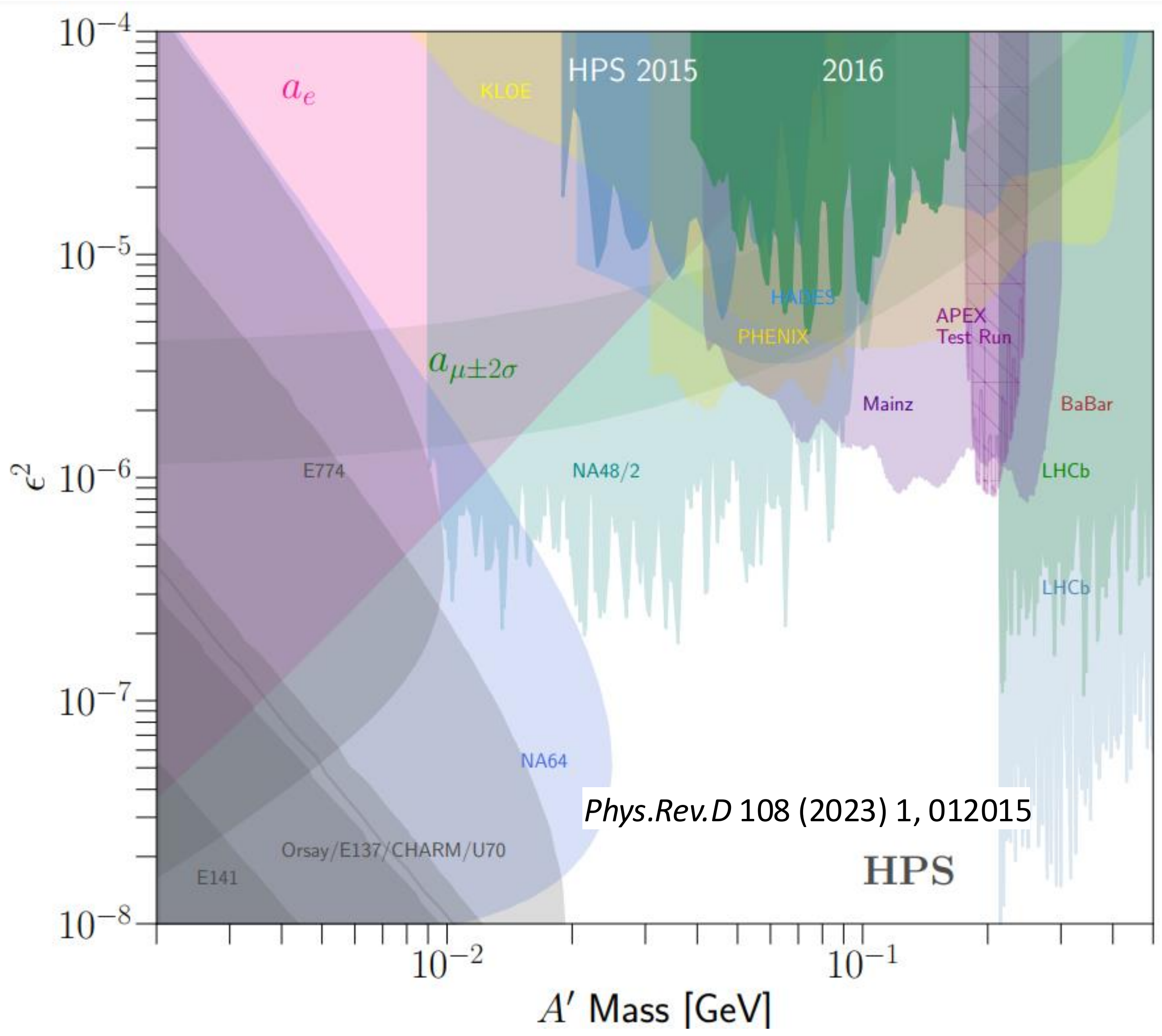


2015 and 2016 Engineering run limits

- HPS is approved for 180 days of running.
- Two opportunistic engineering runs
  - On weekends and/or after work hours
  - 2015 Engineering Run 50 nA @ 1.06 GeV 1.7 days (10 mC) of physics data
  - 2016 Engineering Run 200 nA @ 2.3 GeV 5.4 days (92.5 mC) of physics data
- The statistics from engineering runs is not enough to test uncharted territory, however it we have learned a lot
  - Backgrounds
  - Developed analysis procedures
  - Detector performance and limitations which lead to two upgrades (next two slides)
    - Addition of a new tracking layer
    - Single arm trigger



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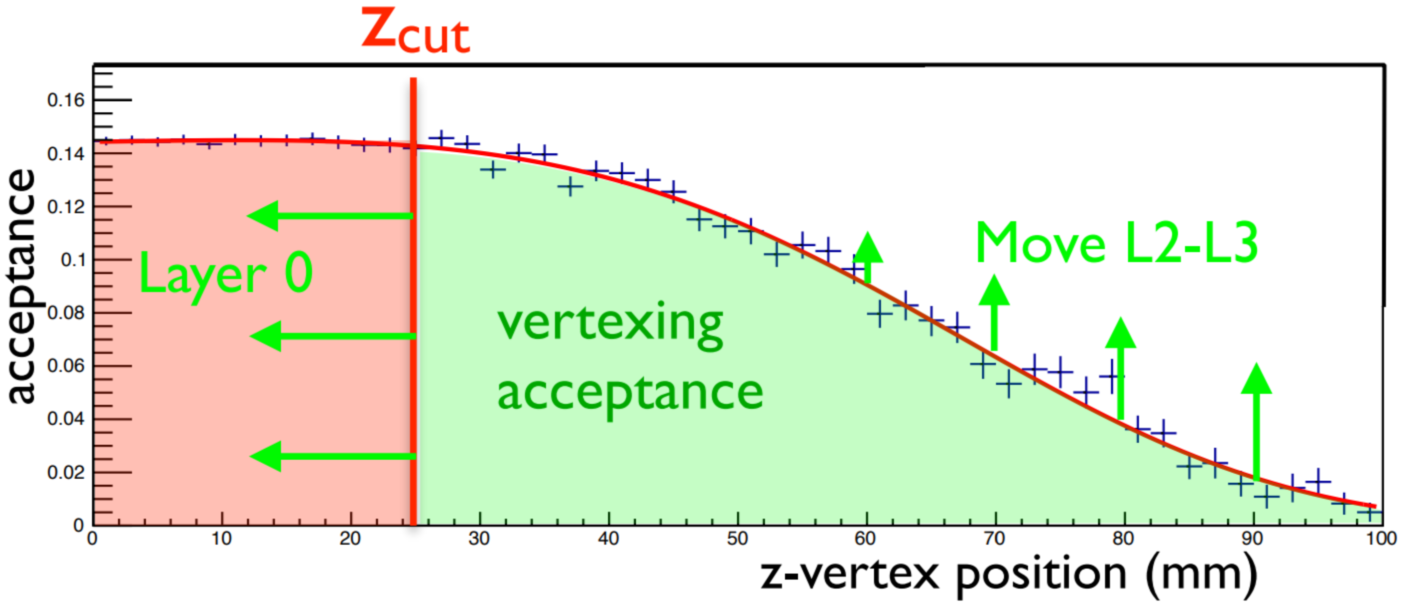
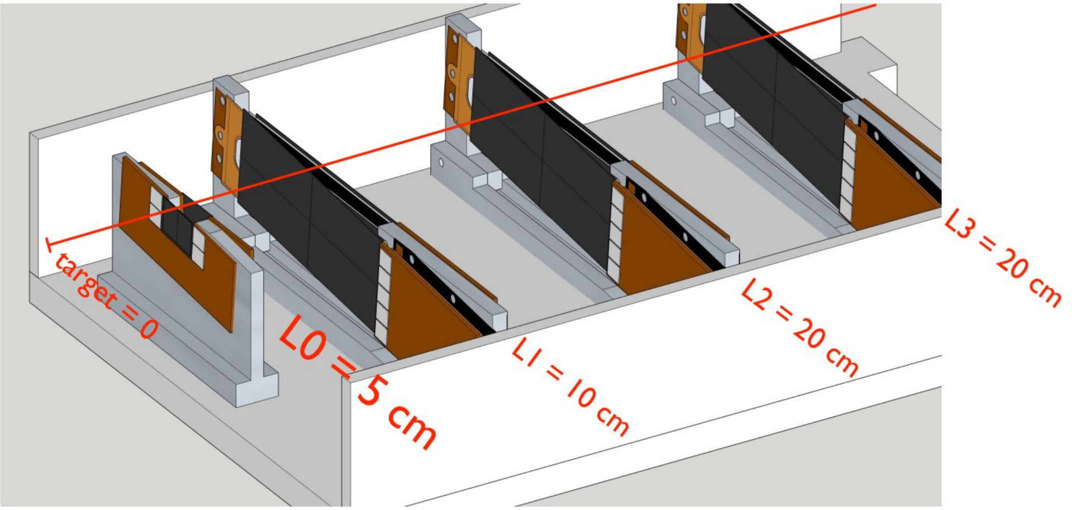
SVT upgrade

-Adding a new thin SVT layer at 5 cm downstream of the target, will significantly improve the vertexing resolution

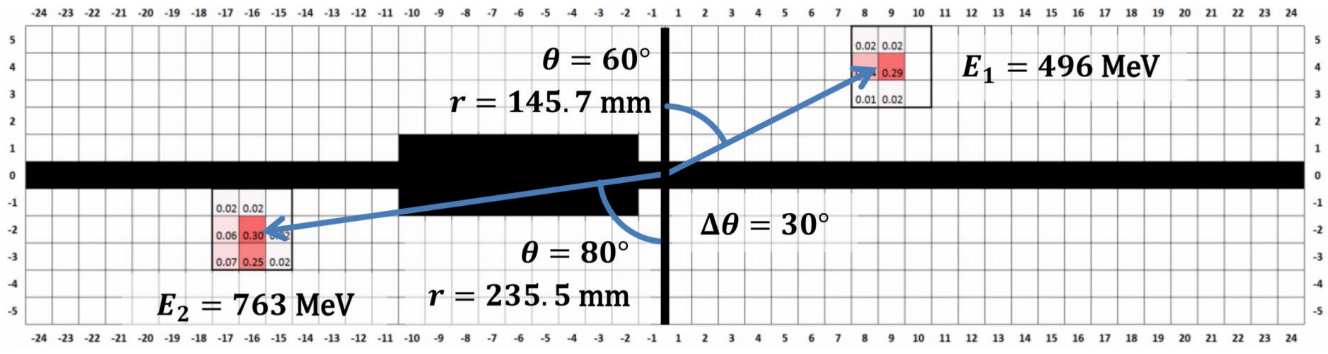


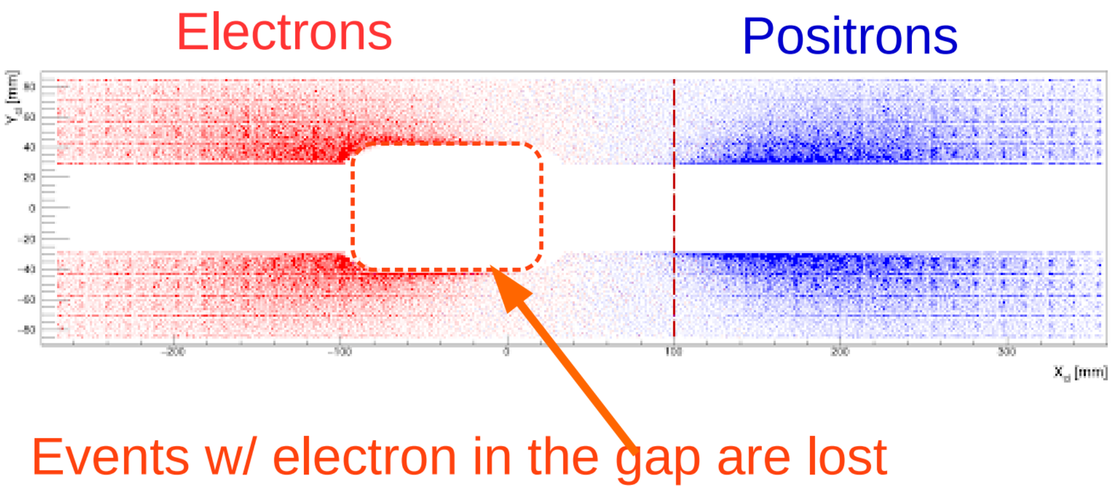
-Moving SVT Layers 2-3 closer to the beam increase the acceptance for longer lived A's

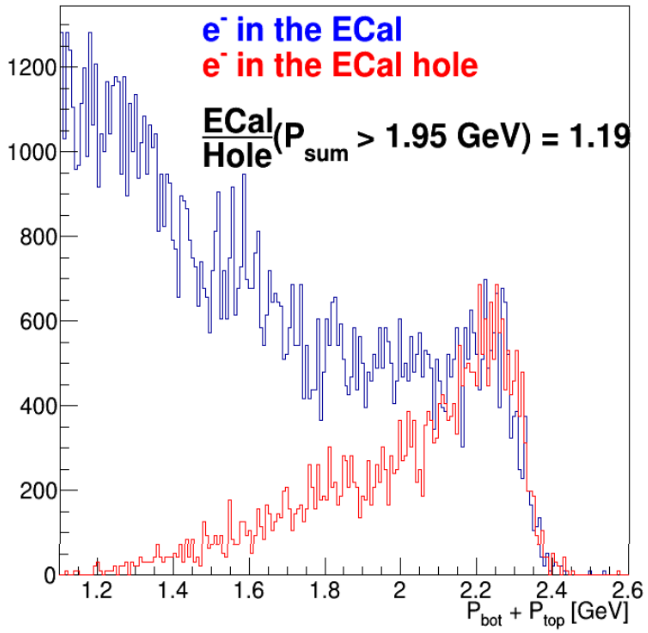


Trigger upgrade

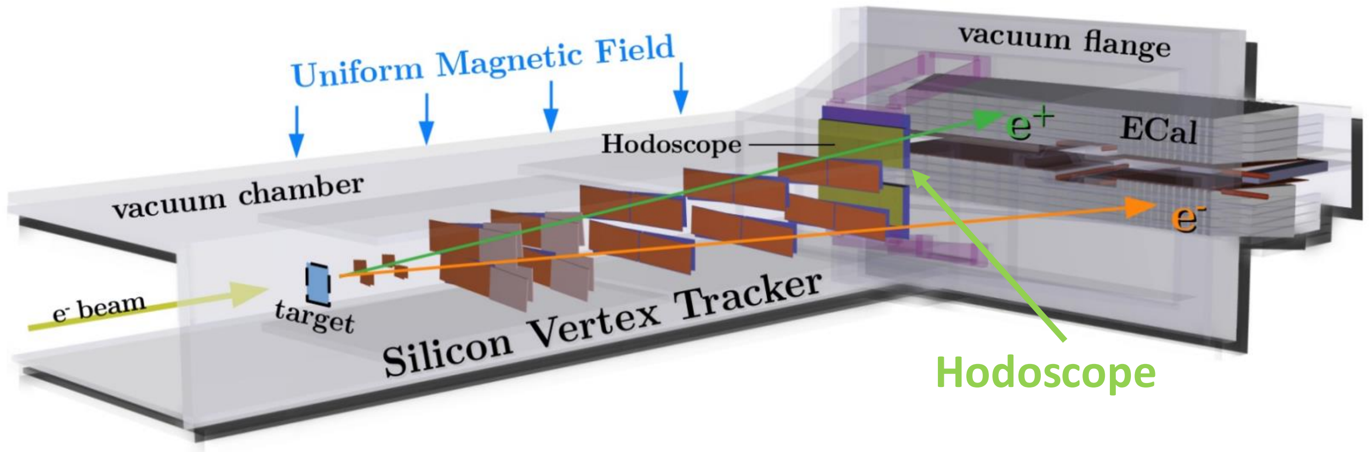
2015 and 2016 run trigger required coincidence of two clusters: one in e- side another in e+ side.



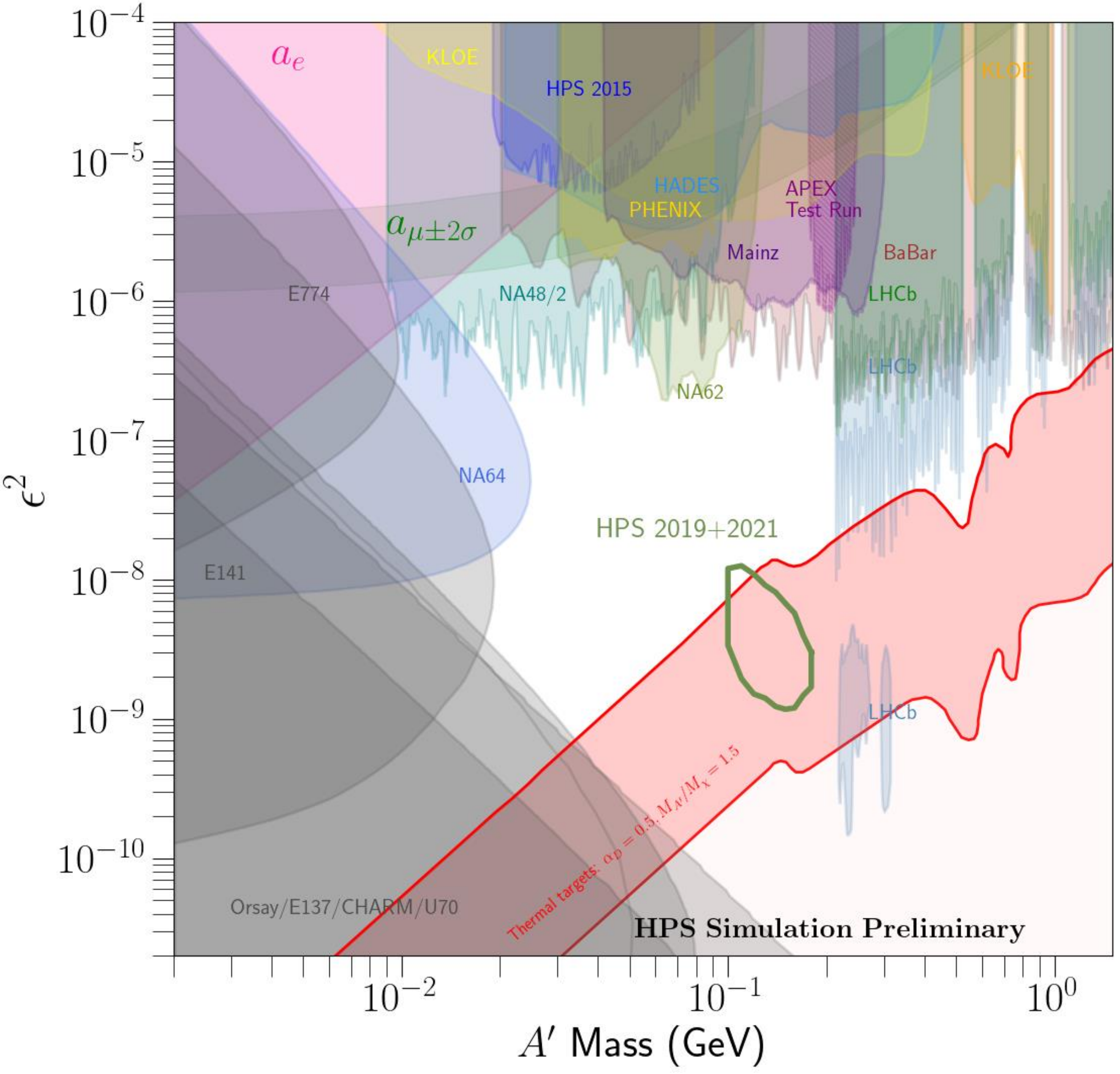




- Significant number of events have electron going to the ECal hole
- A new hodoscope is built on the positron side: and the new trigger is a coincidence between the hodoscope and cluster in the positron side.



2019 and 2021 Runs



Two physics runs are completed with the upgraded detector.

2019 run

- Eb = 4.55 GeV
- Lumi = 128 pb-1
- Target 8μm and 20 μm W foils

2021 run

- Eb = 3.74 GeV
- Lumi = 168 pb-1
- Target: 20 μm W foil

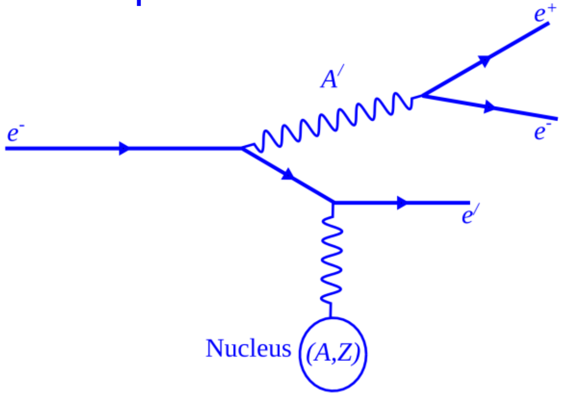
Results are expected soon…

The X17 experiment

- Validate existence or establish an experimental upper limit on the electroproduction of the hypothetical X17 particle claimed in several ATOMKI low-energy proton-nucleus experiments.
- Search for a dark photon in the mass range M ∈ (3 MeV - 60 MeV) through it's $\mathbf{A^{/} \rightarrow e^{-}e^{+}}$ decay.

$$e^{-} + Ta \rightarrow e^{-}\, e^{-}\, e^{+}$$

A' production



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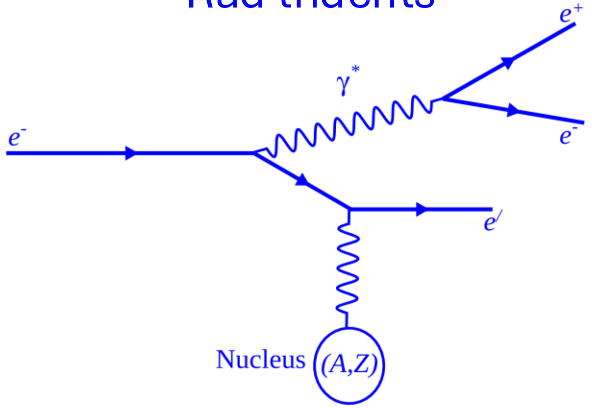
Rad tridents



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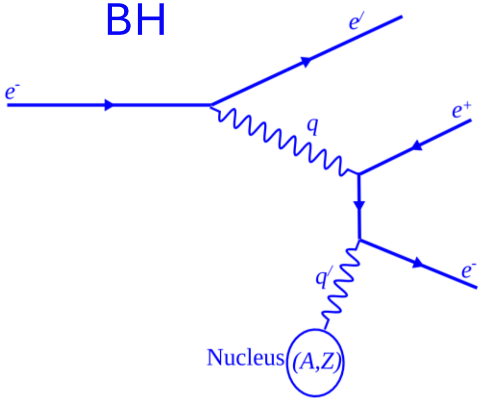
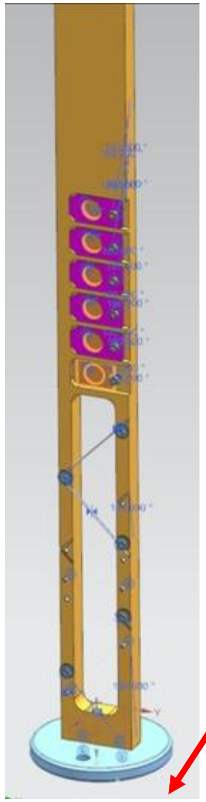
BH

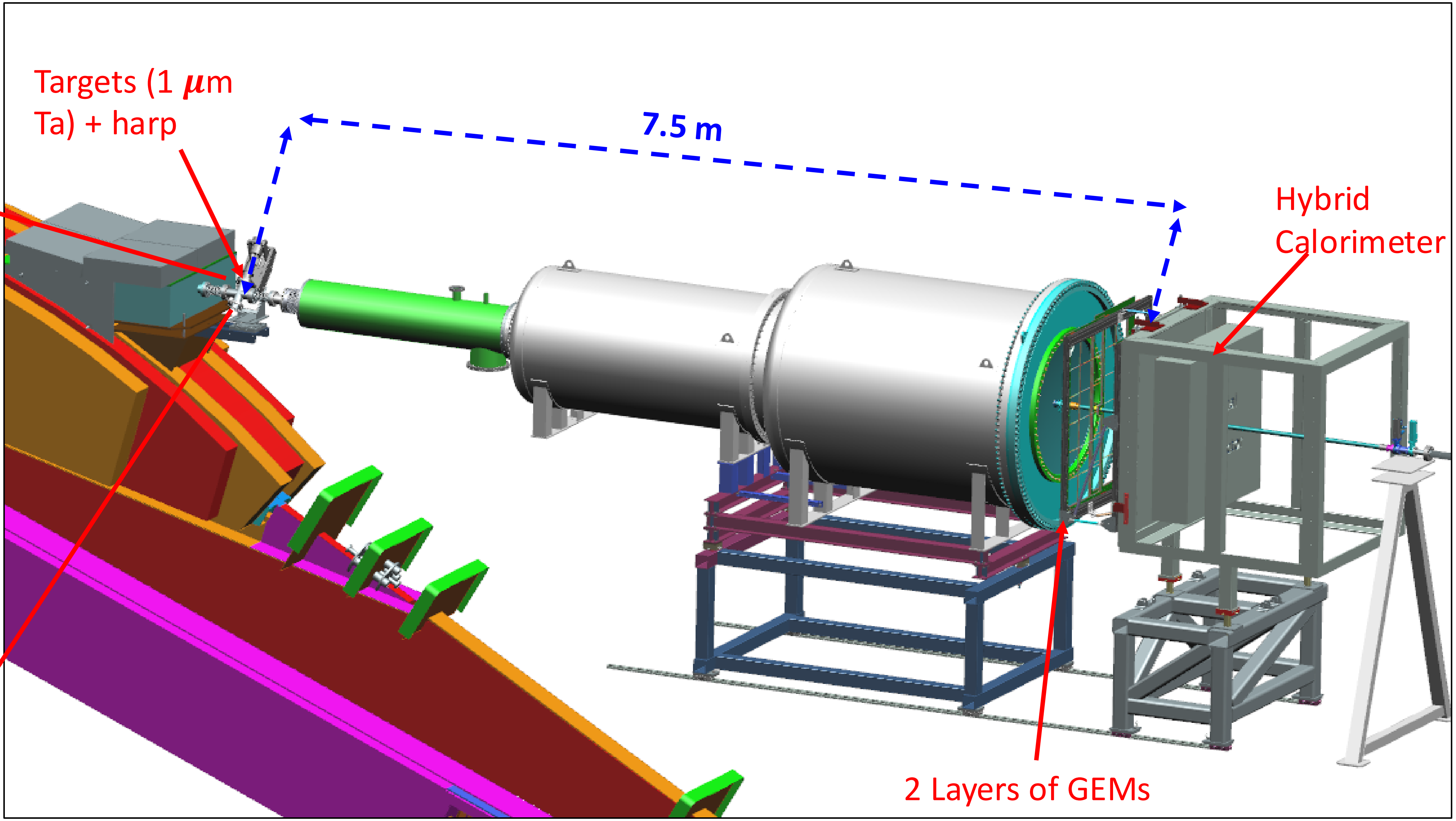


- **Detection of all three final state particles e', e^{-} and e^{+}.**
- **Magnetic-spectrometer-free experimental setup.**
  - Particle energies are measured with a PbWO4 part of HyCal calorimeter.
  - Two-layers GEMs allow to suppress photon background.
  - GEMs also allow to cut charged tracks originating from the beam pipes.
  - High resolution calorimeter along with GEMs provide good precision target constrained mass resolution.

Beamline and detectors

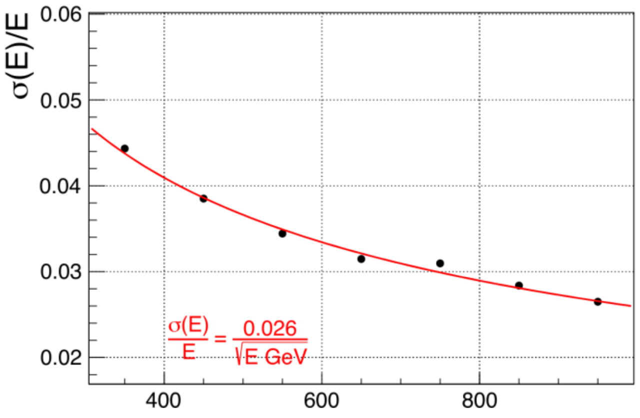
From Bob Miller's presentation



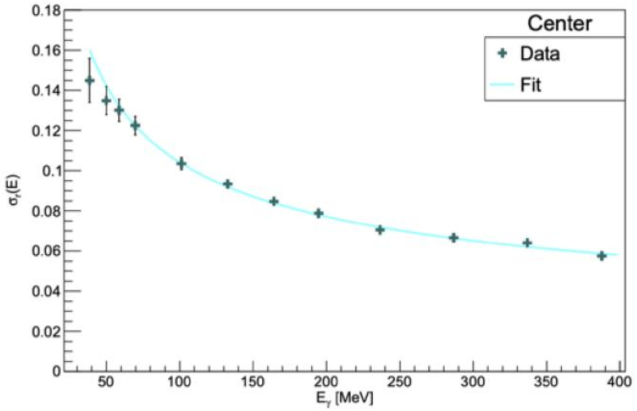


HyCal calorimeter

PrimEx measurement



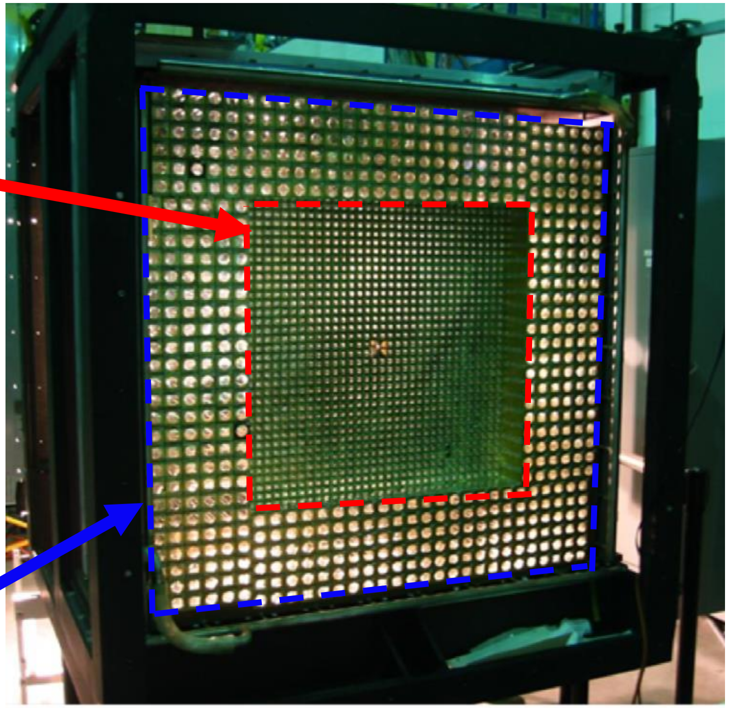
Mainz experiment



Outer part of the HyCal will not be used for X17

Lead Tungstate: PbWO4: inner part

- Provide trigger
- 2.05 × 2.05 cm^2 x 18 cm (20 X0)
- 34 × 34 square matrix
- Inner 2x2 crystals are removed
- In addition, two Innermost layers will not be used
- Full azimuthal coverage
- Very forward angles (0.47° - 3.78°)
- **σ**E/E = 2.6%/√E
- **σ**xy = 2.5mm/√E



Lead glass

- 3.82x3.82 cm^2 x45 cm
- 576 crystals
- Will not be used for the X17 experiment

Will be read out by fADC250

GEMs

- To Veto/select neutrals
- Being currently build in UVA
- 2 layers displaced wrt each other by 40 cm
- Double GEMs to reduce the material budget
- 123 cm X 123 cm
- A hole 4 cm x 4x cm to allow beam pipe to pass through
- Better than 100 um position resolution
  - PRad achieved 70 um resolution

Photo of PRad GEMs

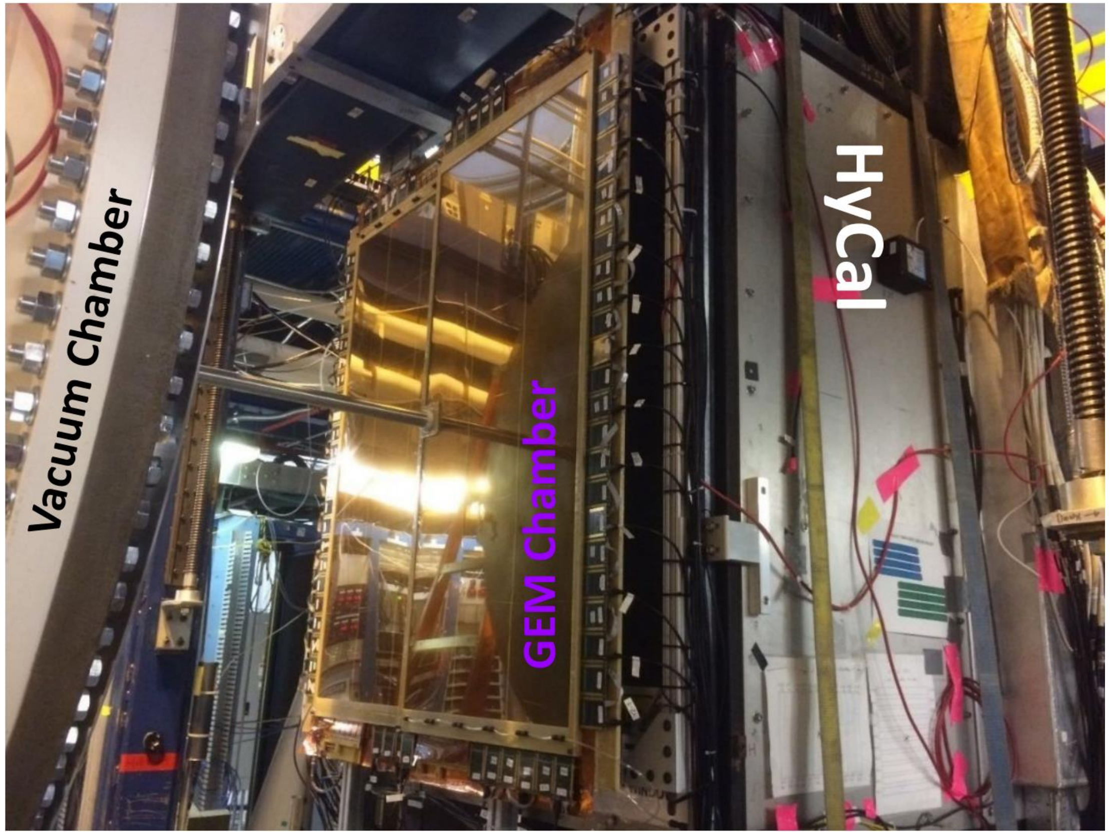
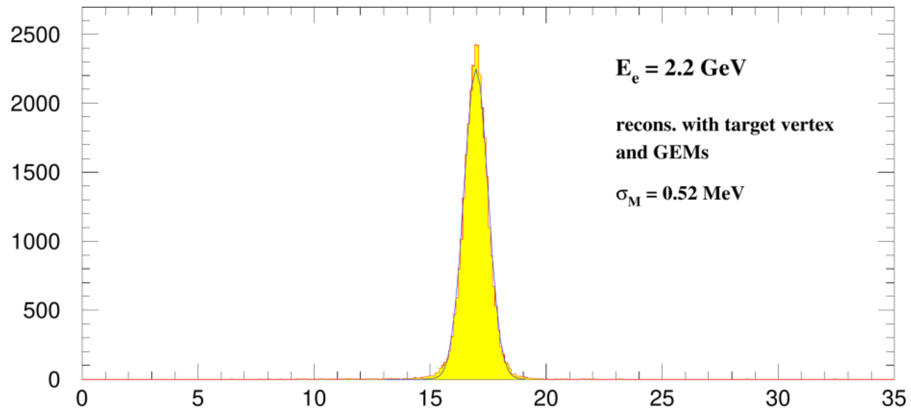


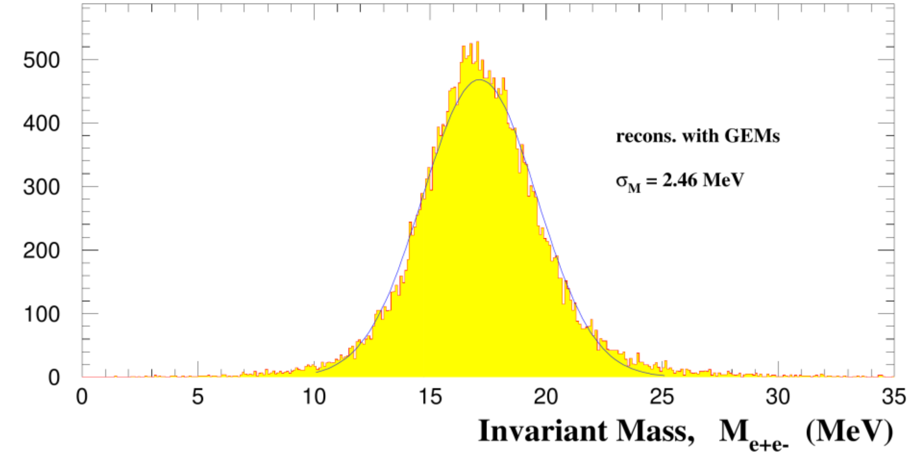
Photo from Xinzhan Bay

Experimental resolutions

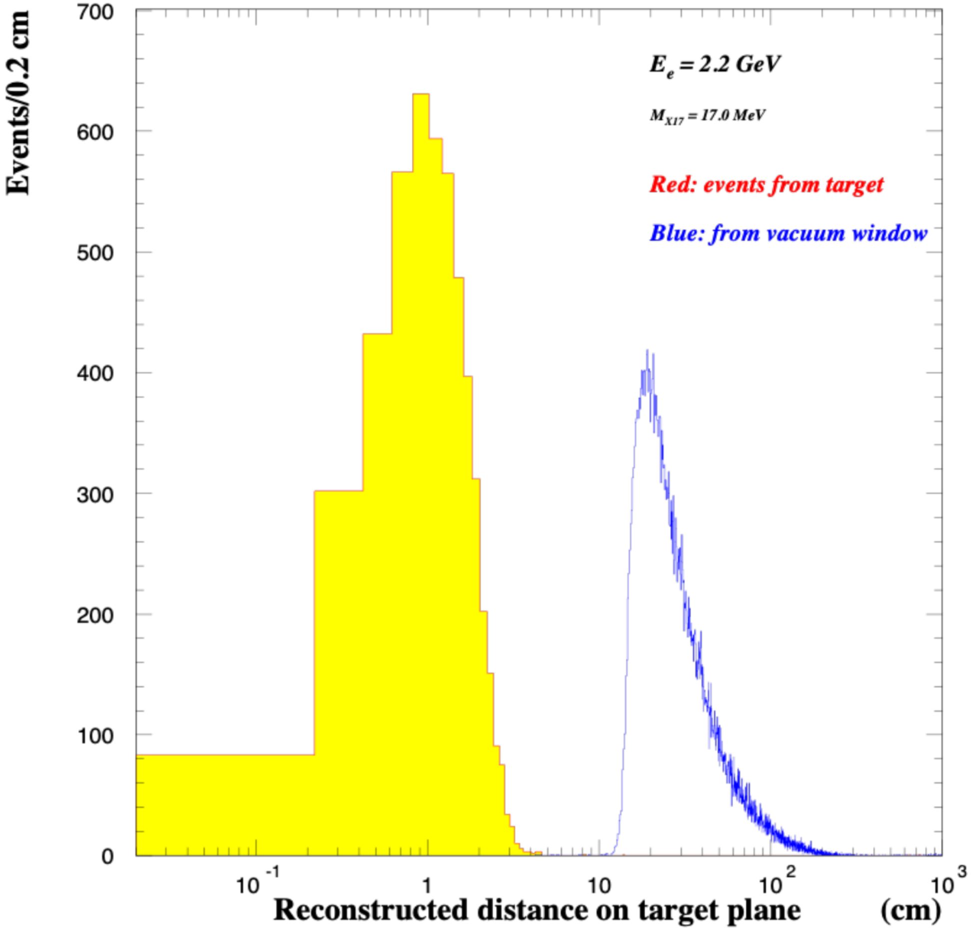
Target constrained mass resolution



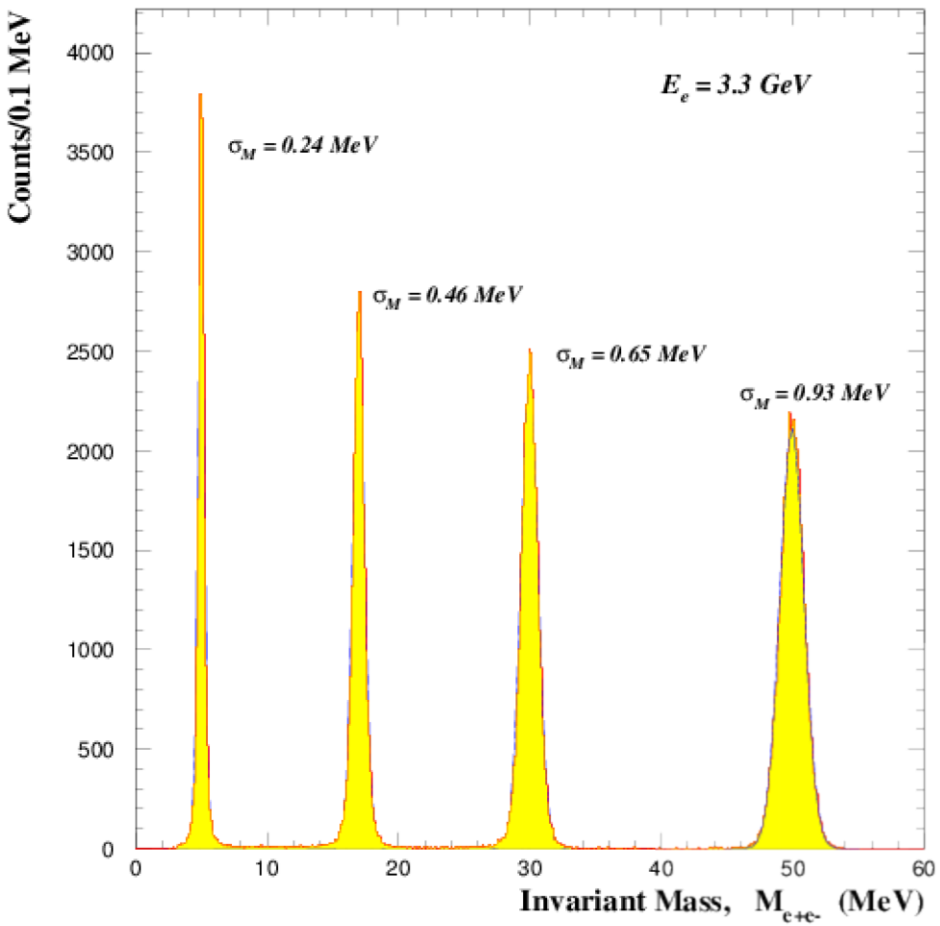
Unconstrained mass resolution

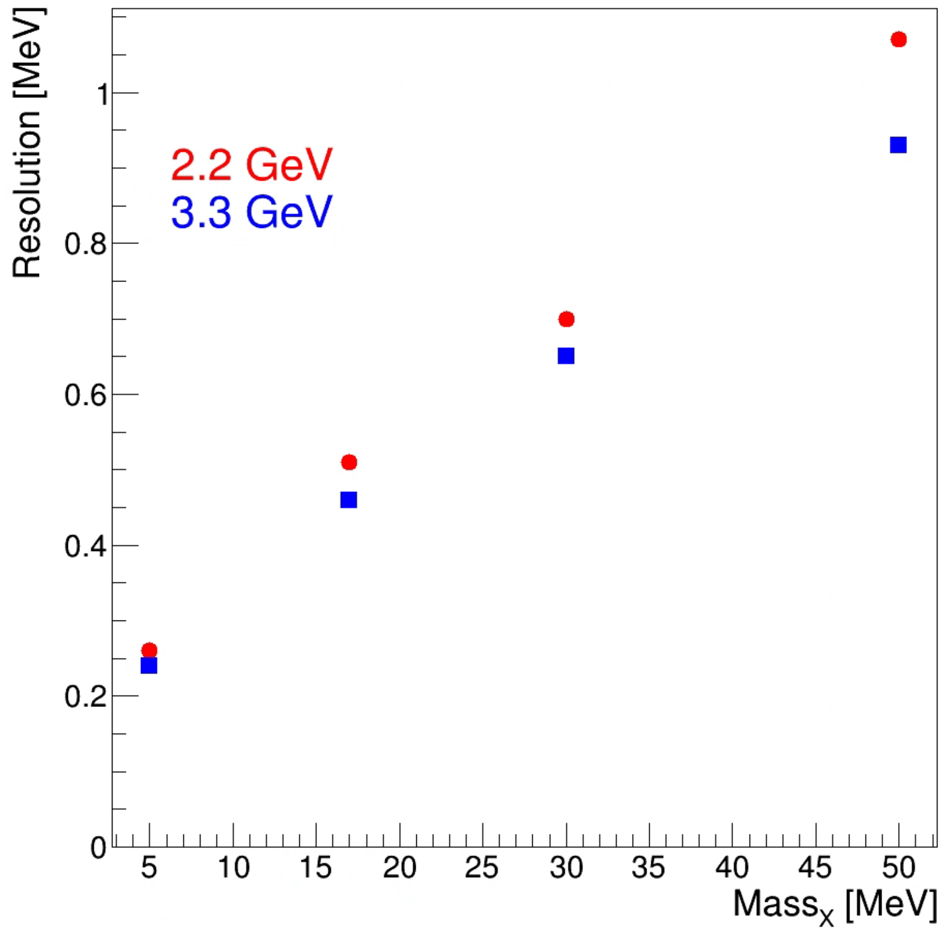


Particles originating from the vacuum window will be effectively cleaned.



Mass resolutions





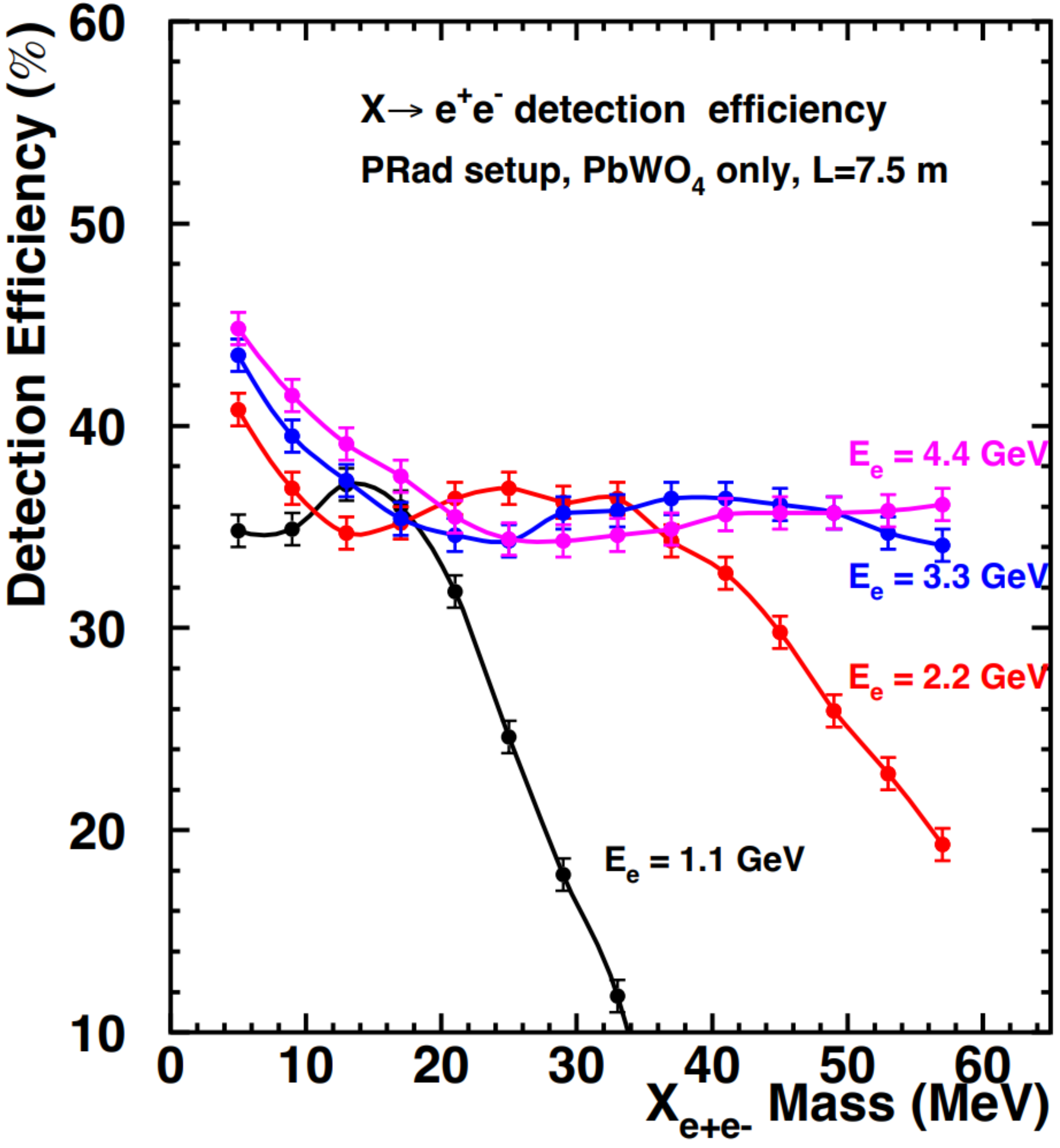
Detector efficiency

Acceptance calculation:

- Electron angle generated (0°-3°)
- Energy 30 MeV to few 100 MeV
- A' decayed into e^-e^+ isotopically in CM frame then boosted to lab frame.

- Note: A' here is not generated with the same kinematics as Radiative Photons. This can have significant impact on the acceptance calculation.
- The re-evaluation of the acceptance is in progress.

- Trigger configuration:
  - Total energy sum in calorimeter: $\Sigma E_{clust} > 0.7 E_{beam}$.
  - 3 clusters in PbWO4 calorimeter;
  - each cluster energy: 30 MeV < Eclust < 0.8xEbeam (rejects the elastic scattered electrons)



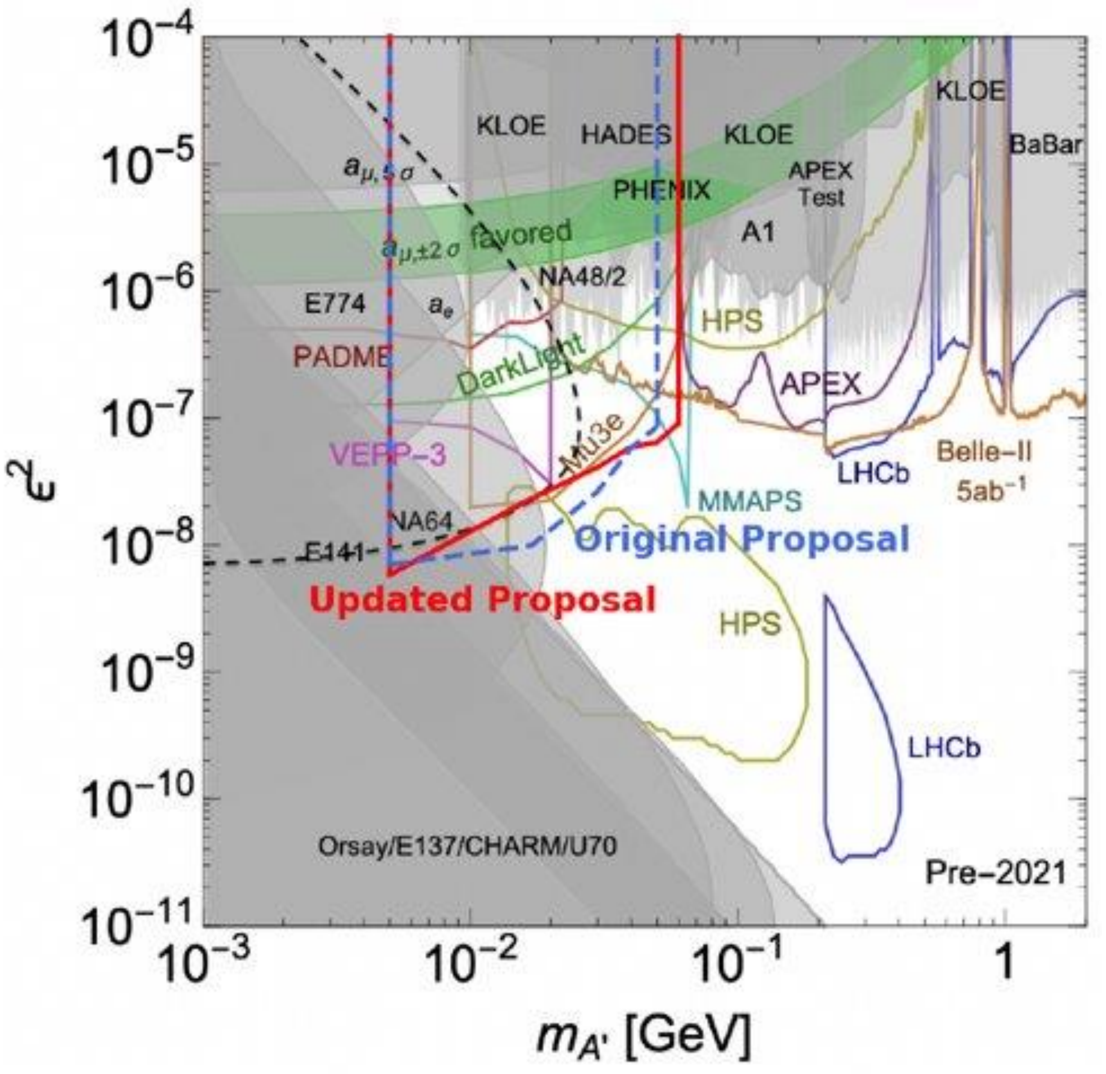
Initial proposal was submitted for 2.2 GeV and 3.3 GeV beam energies, however 3.3 GeV being non-standard CEBAF energy, we will run with 2.2 and/or 4.4 GeV energies.

Exclusion limit

- Limits are calculated for 20 days w/ 2.2 GeV beam and 30 days 3.3 GeV beam

- Note: as mentioned earlier, acceptances are being re-evaluated with using MADGRAPH5 A' generator.
  - This will change the limit

$$\epsilon^2 = \frac{N_{A'}}{N_e C T \epsilon^2 \frac{m_e^2}{m_{A'}^2}}$$



This experiment is highly likely to run early 2026.

Summary

- JLab has a broad dark photon search program
  - APEX, HPS and X17
  - Search is through A'-Strahlung
  - Searches include both "Bump hunt" and "Displaced Vertex"
  - All experiments probed and/or will probe uncharted territories
- New publications and data taking are expected soon.

Backup

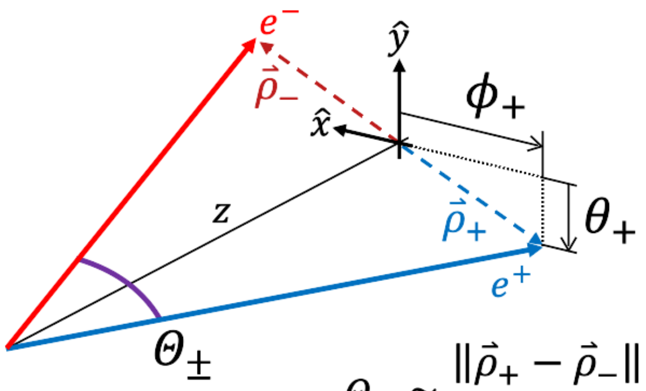
Seth Hall's slide

A' Invariant Mass Resolution

- **Objective:** minimize $\left(\frac{\sigma_m}{m}\right)^2$:

$$\left(\frac{\sigma_m}{m}\right)^2 = \left(\frac{\sigma_p}{p}\right)^2 + 0.5\left(\frac{\sigma_{\Theta_\pm}}{\Theta_\pm}\right)^2$$

$\sim 2 \times 10^{-4}$ $\qquad$ $\sigma_{\mathrm{HRS}}^2 + \sigma_{\mathrm{MS}}^2$



$$\Theta_\pm \approx \frac{\|\vec{\rho}_+ - \vec{\rho}_-\|}{z}$$

σ_{HRS} - HRS angular resolution
Previously reported for APEX (mrad)
[*J.Williamson*, PhD Thesis]:

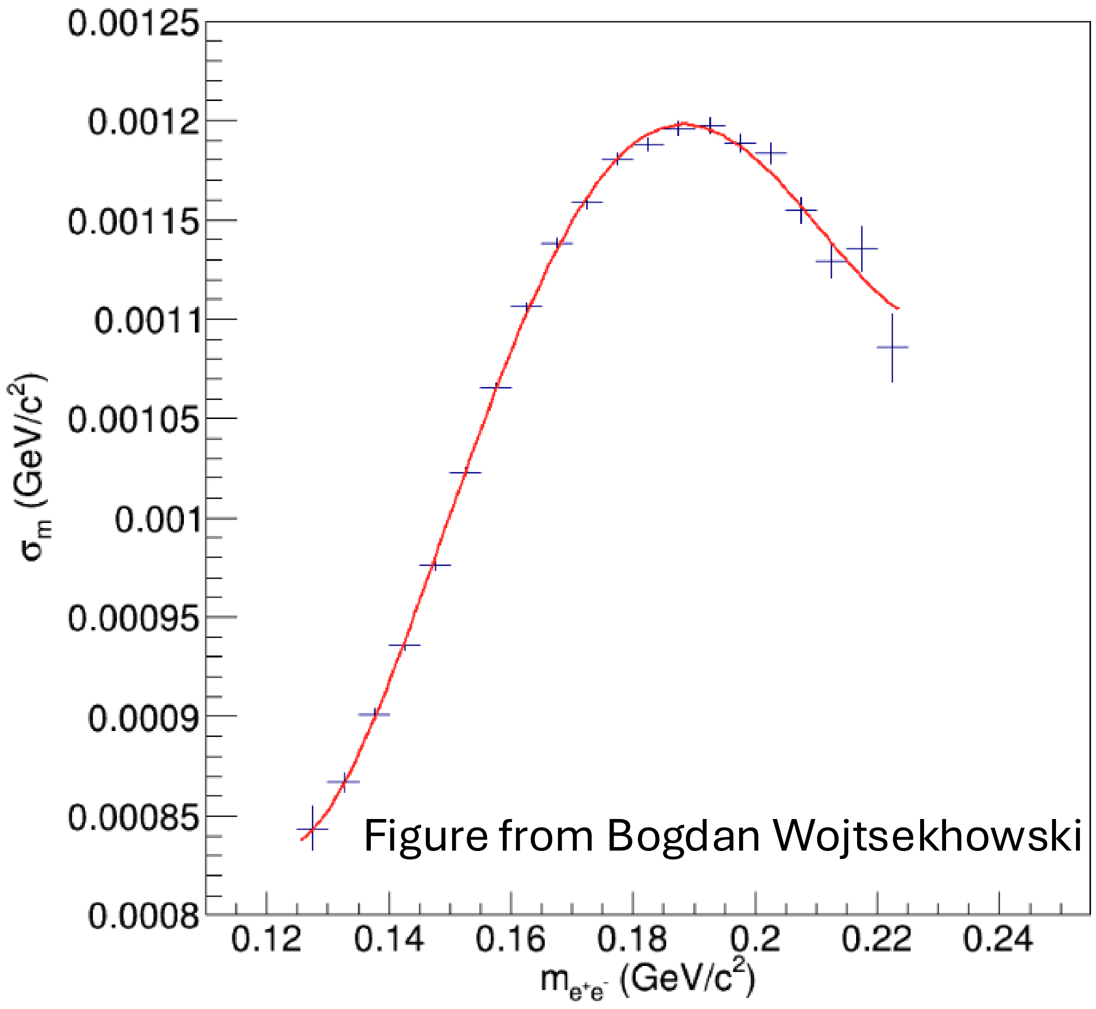
$$\frac{\sigma_{\Theta_\pm}}{\Theta_\pm} \sim \left(\frac{0.5\ \mathrm{mrad}}{175\ \mathrm{mrad}}\right)$$

	LHRS	RHRS
σ_θ	1.74	1.94
σ_ϕ	0.56	0.59

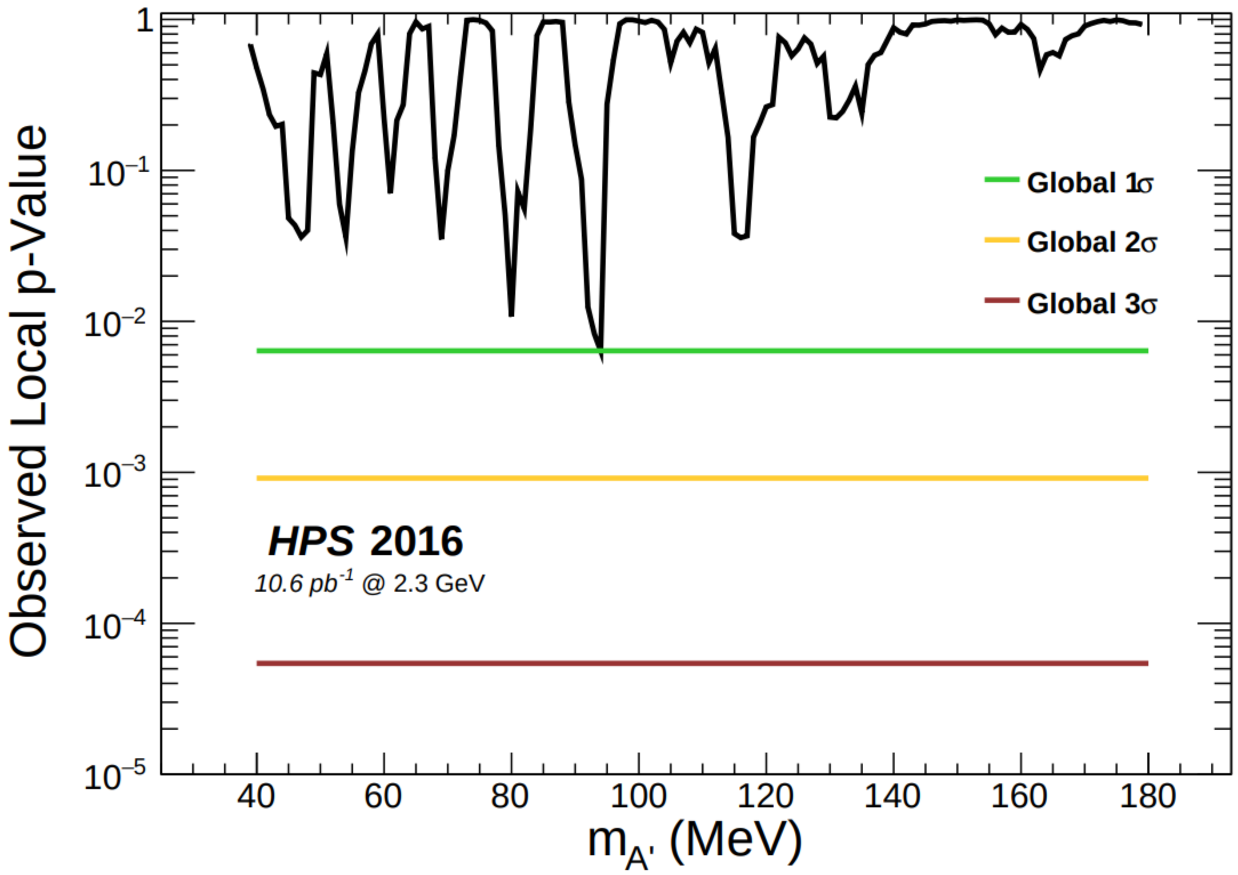
$|\theta| < 2.6$

σ_{MS} - Multiple-Scattering contribution

Mass resolution for APEX 2019 run



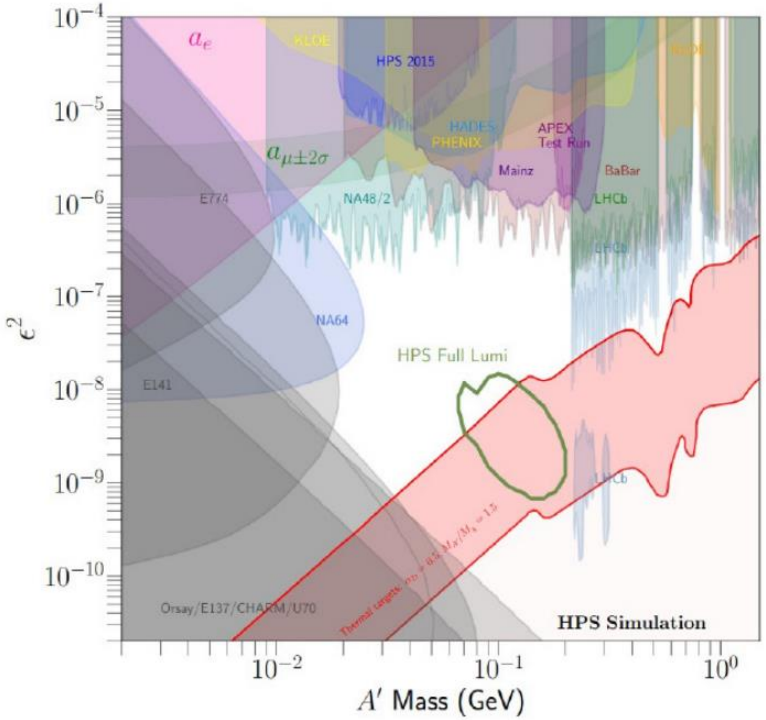
P-value


Observed Local p-Value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
40
60
80
100
120
140
160
180
$m_{A'}$ (MeV)
Global 1σ
Global 2σ
Global 3σ
HPS 2016
10.6 pb^{-1} @ 2.3 GeV

Slide from A. Filippi's presentation

Future prospects

- New reach estimates for analysis using the full upgraded detector and the allocated run-time show clear reach in the thermal relic target band
  - Sensitivity region more than doubled as compared to 2016 data-set
  - The sensitivity grows almost linearly and does not saturate at the end of the approved beam-time



- HPS is approved for 180 PAC days of running
- So far (up to 2021): 75 days

Data run	Beam Energy (Gev)	Beam Current (nA)	Luminosity (pb^{-1})	Beam Time
2015 Engineering run	1.05	50	1.17	1.7 d
2016 Engineering run	2.3	200	10.7	5.4 d
2019 Physics run (w upgrade)	4.55	150	122	4 w
2021 Physics run (w upgrade)	3.7	120	168	4 w

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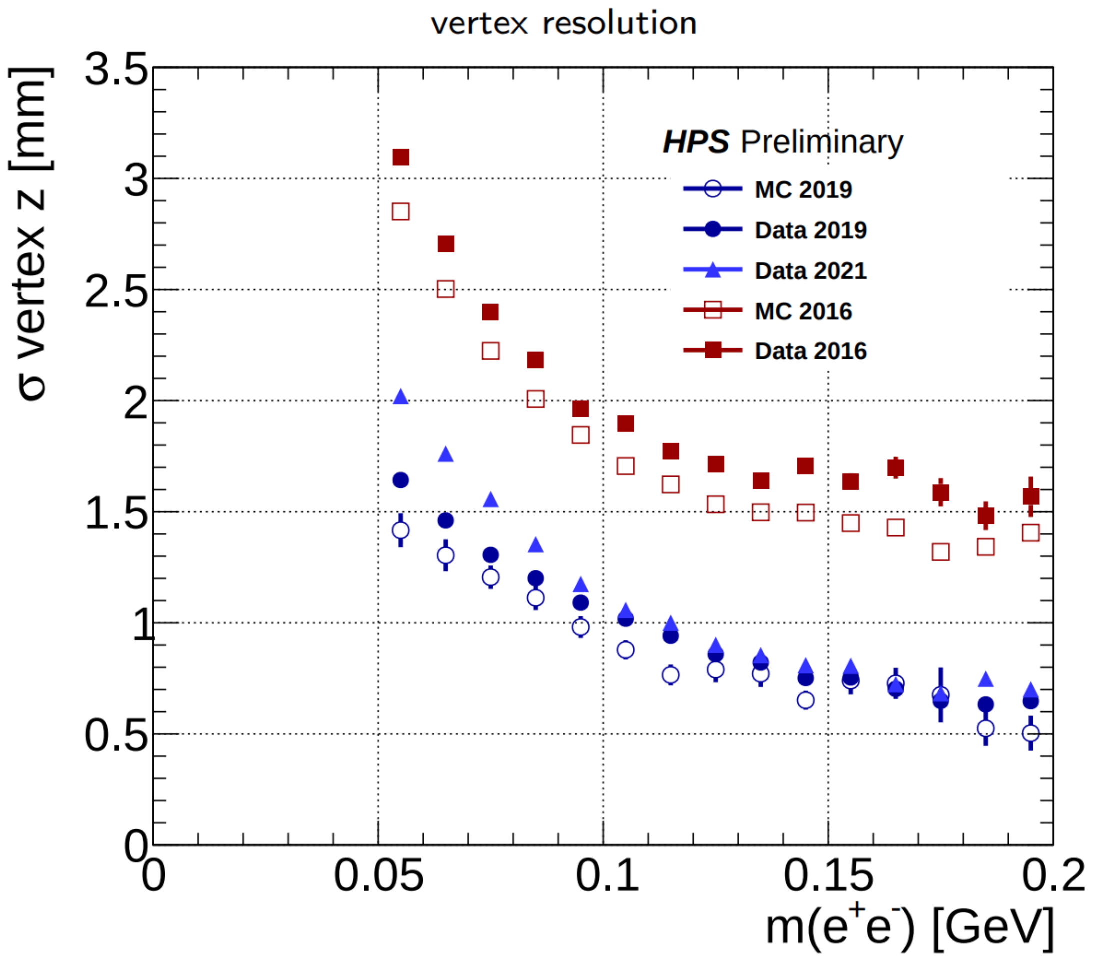
vertex resolution
σ vertex z [mm]
3.5
3
2.5
2
1.5
1
0.5
0
0.05
0.1
0.15
0.2
m(e+e-) [GeV]
HPS Preliminary
MC 2019
Data 2019
Data 2021
MC 2016
Data 2016

Window Adapter in Orange

- 1 Meter Diameter Window
- 0.020” Thick Aluminum

- 15 mm Diameter Window at Center
- 30 micron Thick Aluminum