The **H**eavy **P**hoton **S**earch experiment at Jefferson Lab

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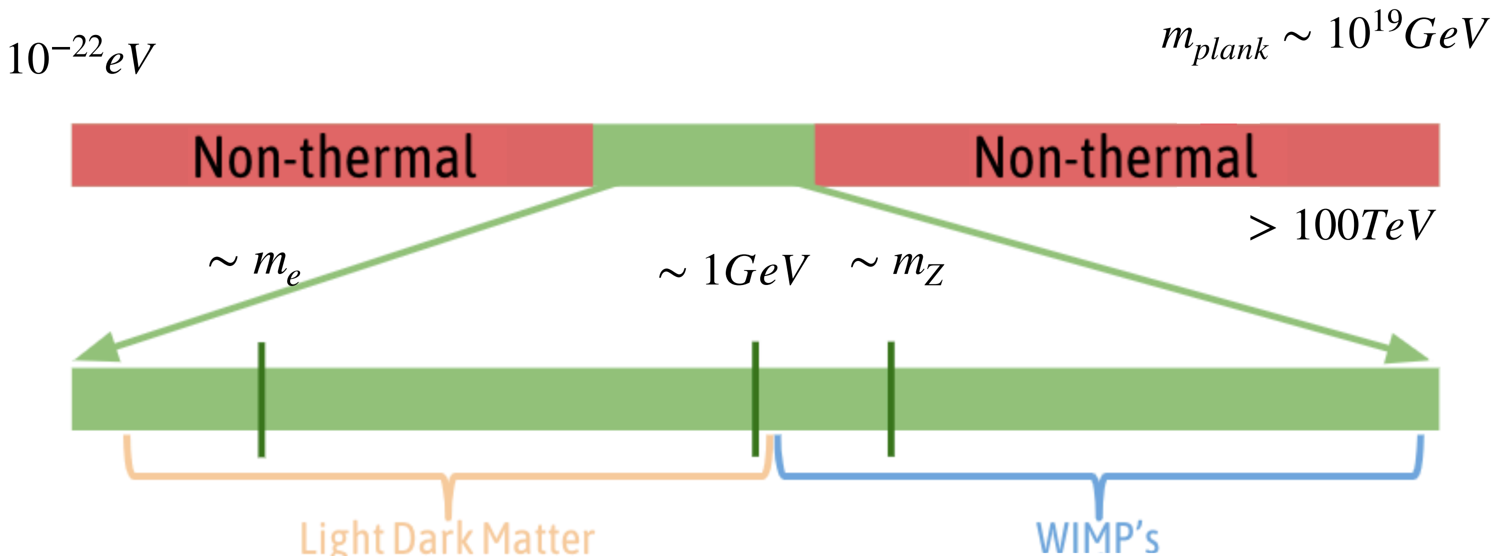
on behalf of the HPS collaboration

19/01/2023

Thermal Dark Matter

- Thermal Dark Matter (DM) originating as a relic of the hot early Universe is one of the most compelling paradigms.
- **Generic:** only non-gravitational interaction between DM and Standard Model (SM)
- **Predictive:** minimum annihilation rate $< \sigma v > \approx 10^{-26} cm^3 s^{-1}$

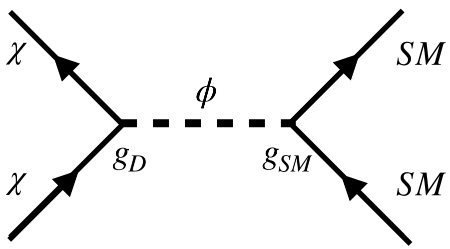


Thermal Contact implies a new mediator: Hidden sector light DM well-motivated model

Thermal freeze-out for weak scale masses. Major drive for DM search in the past years

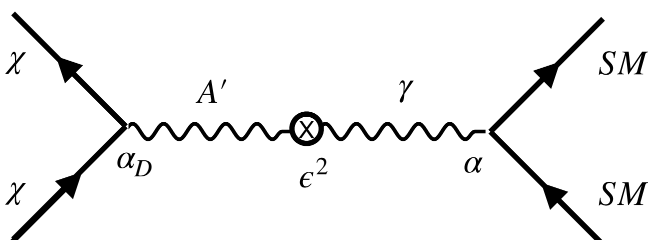
Light Thermal Dark Matter - Hidden sector

- Freeze-out scenario with Light Dark Matter (LDM) requires **new light mediator** to provide the correct relic abundance
- Dark Matter can belong to a ***"hidden sector"*** secluded from the Standard Model (SM)
- Mutual interaction mediated by a massive gauge boson

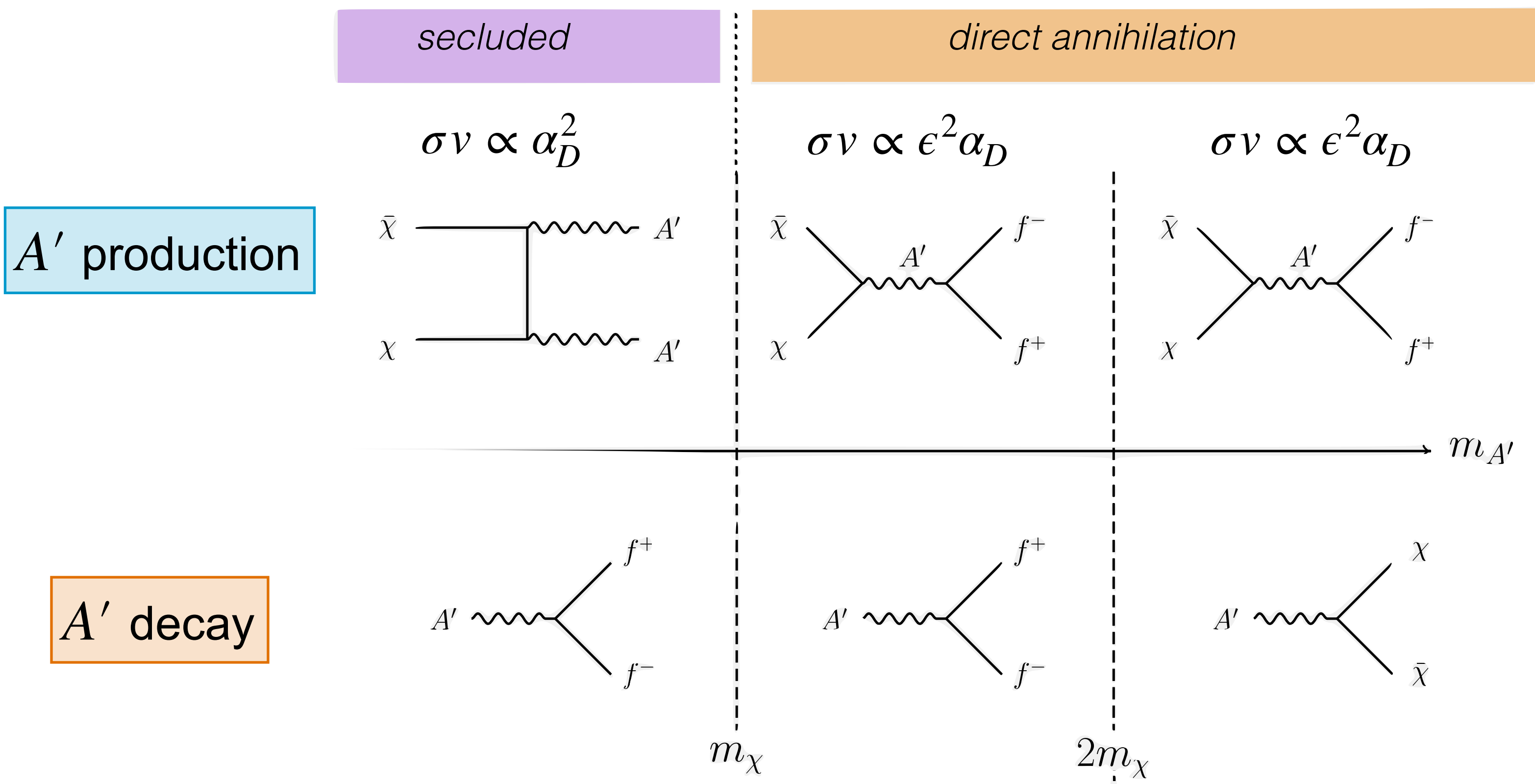


$$< \sigma v > \sim g_D g_{SM} \frac{m_\chi^2}{m_\phi^4}$$

- **Benchmark:** additional spin-one gauge boson ***"dark photon"*** A', neutral under SM, hidden $U(1)_D$ symmetry
- Kinetically mixing with SM $U(1)_\gamma$, (ϵ)

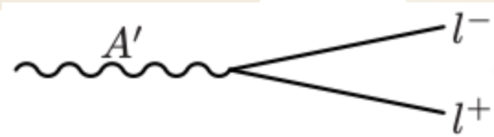


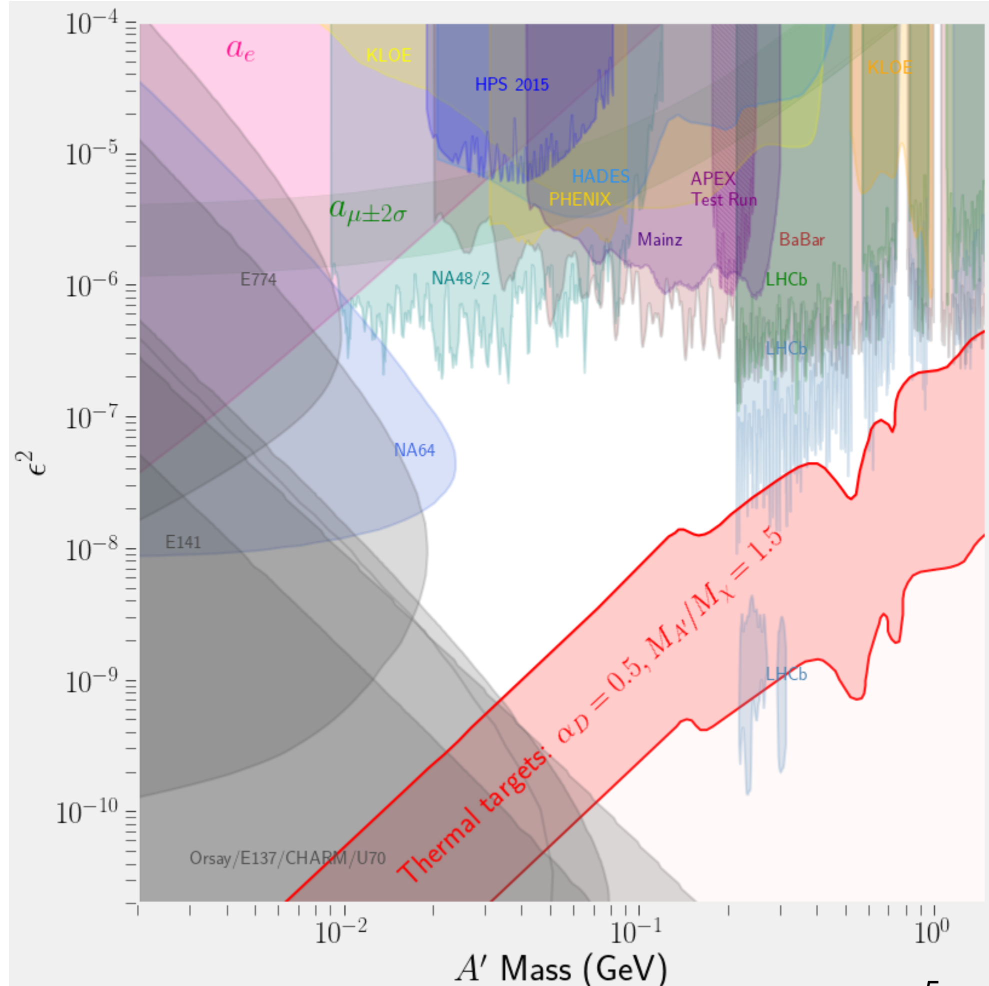
Possible dark photon signatures



visible	invisible
Prompt decay (resonance feature) Long-lived (displaced decay)	Missing … …mass …energy …momentum

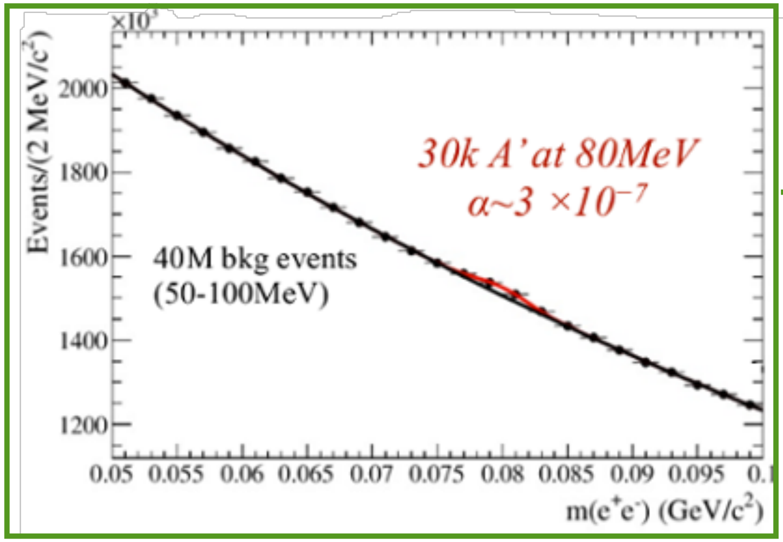
Visible Decay - Parameter space

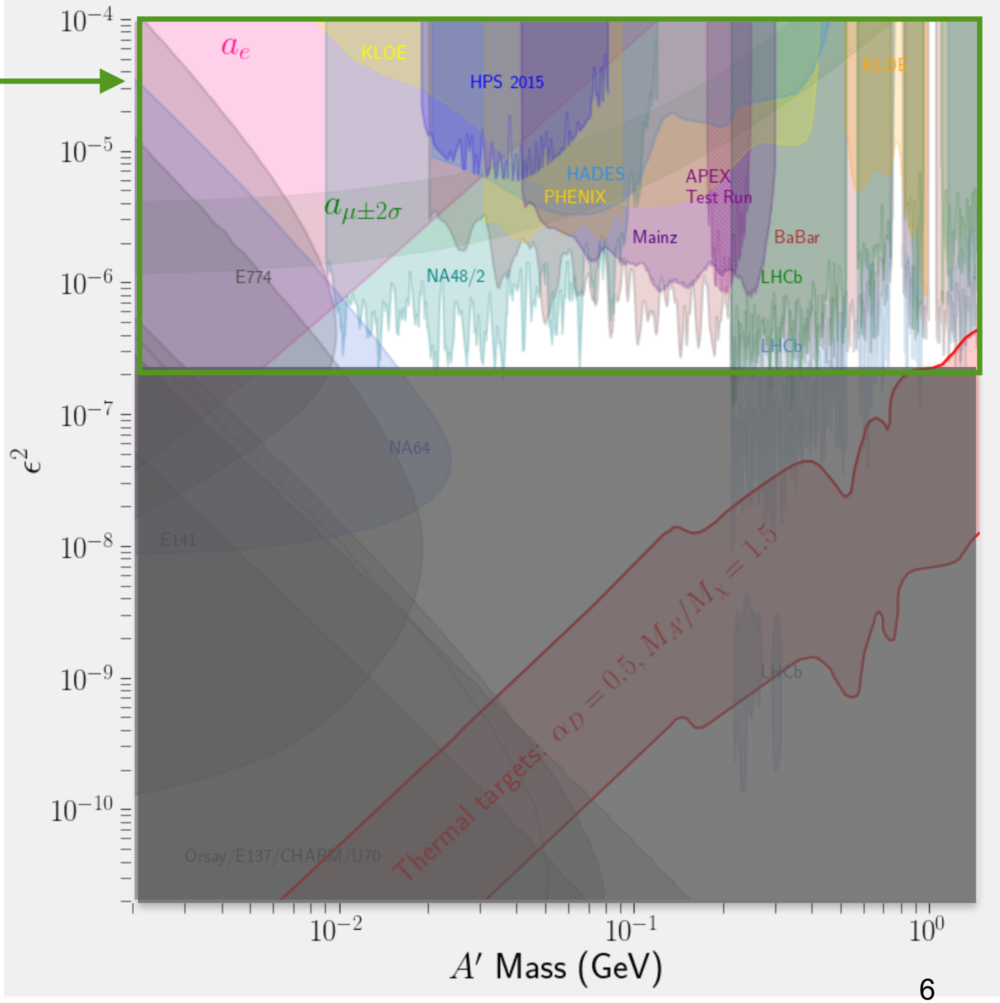




Bump Hunt search

concept simulation - not real data

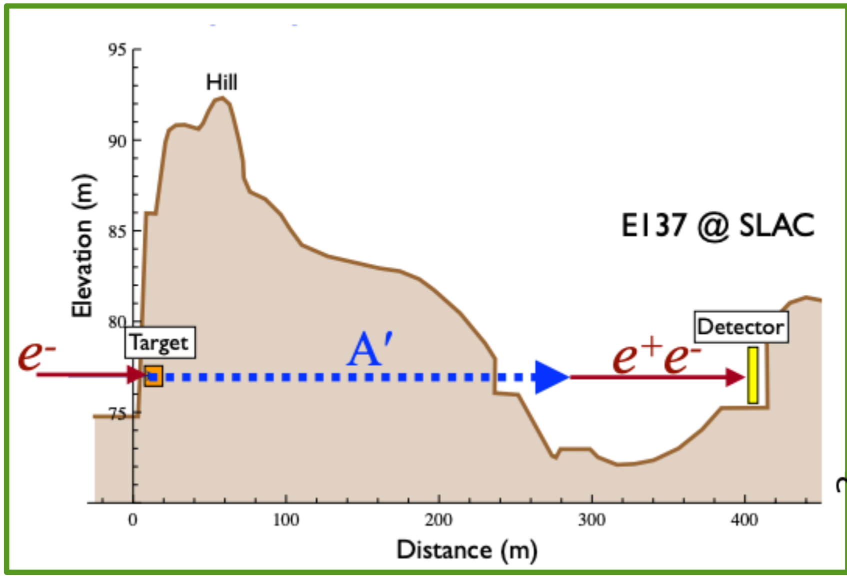


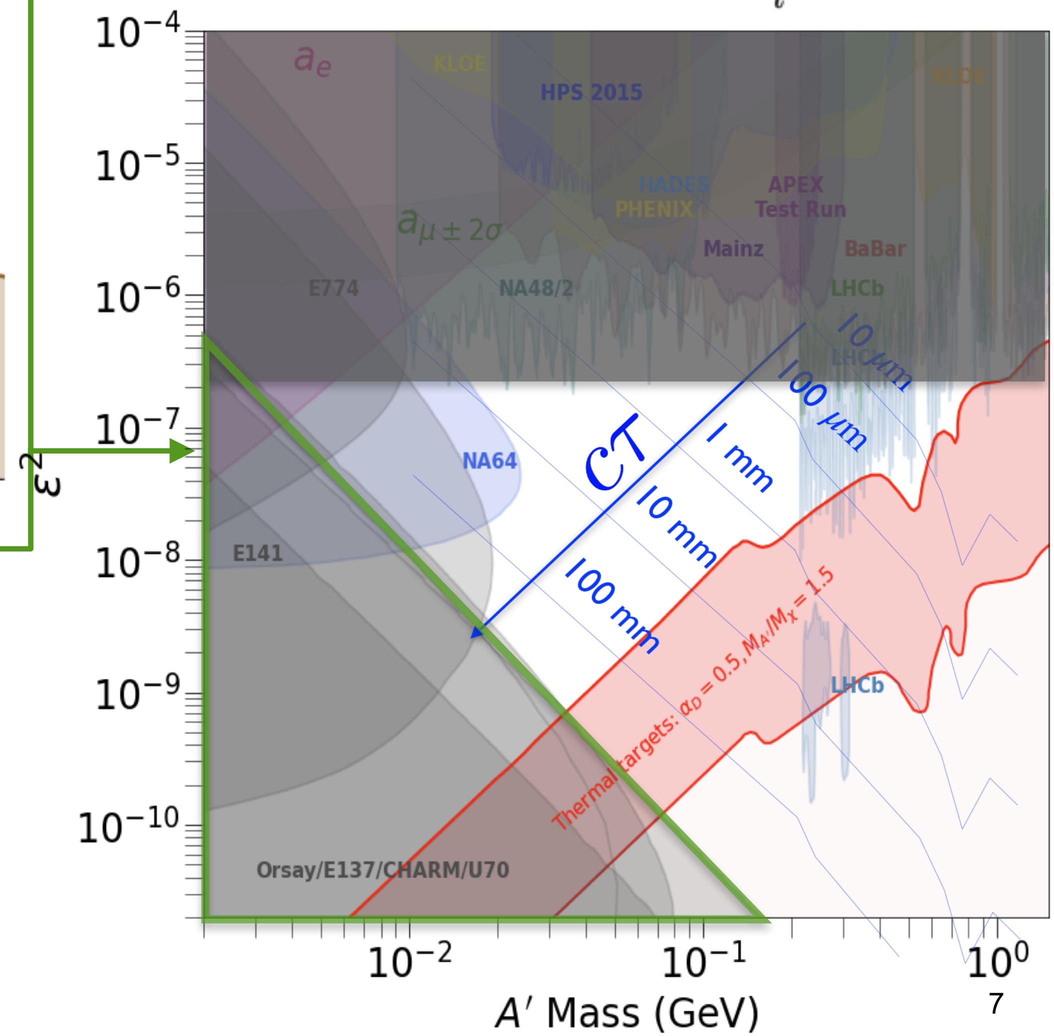


- Searches are **"Bump hunts"** for $m(l^+l^-)$ resonances
- Excess of **prompt** A' signal above continuous falling background
- The required large signal yield limits these types of searches to **"large" ϵ^2 couplings**

Beam dump

E137 SLAC Beam Dump





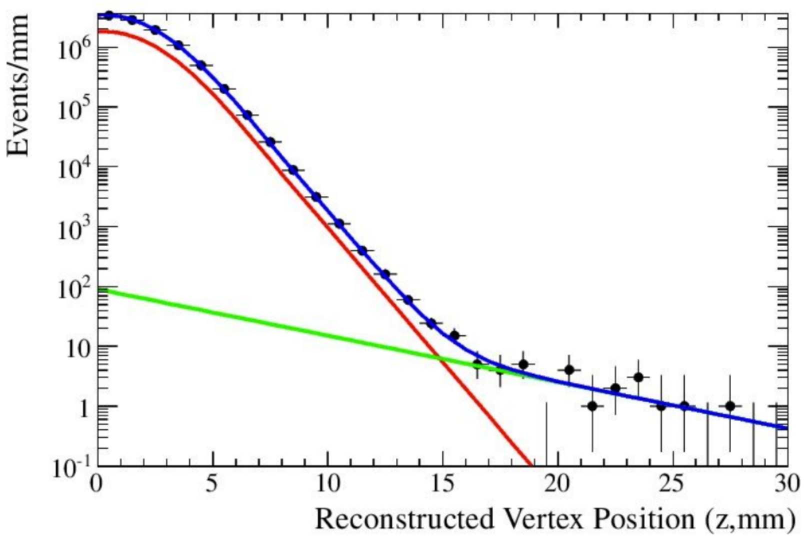
- At lower ϵ the A' becomes long-lived

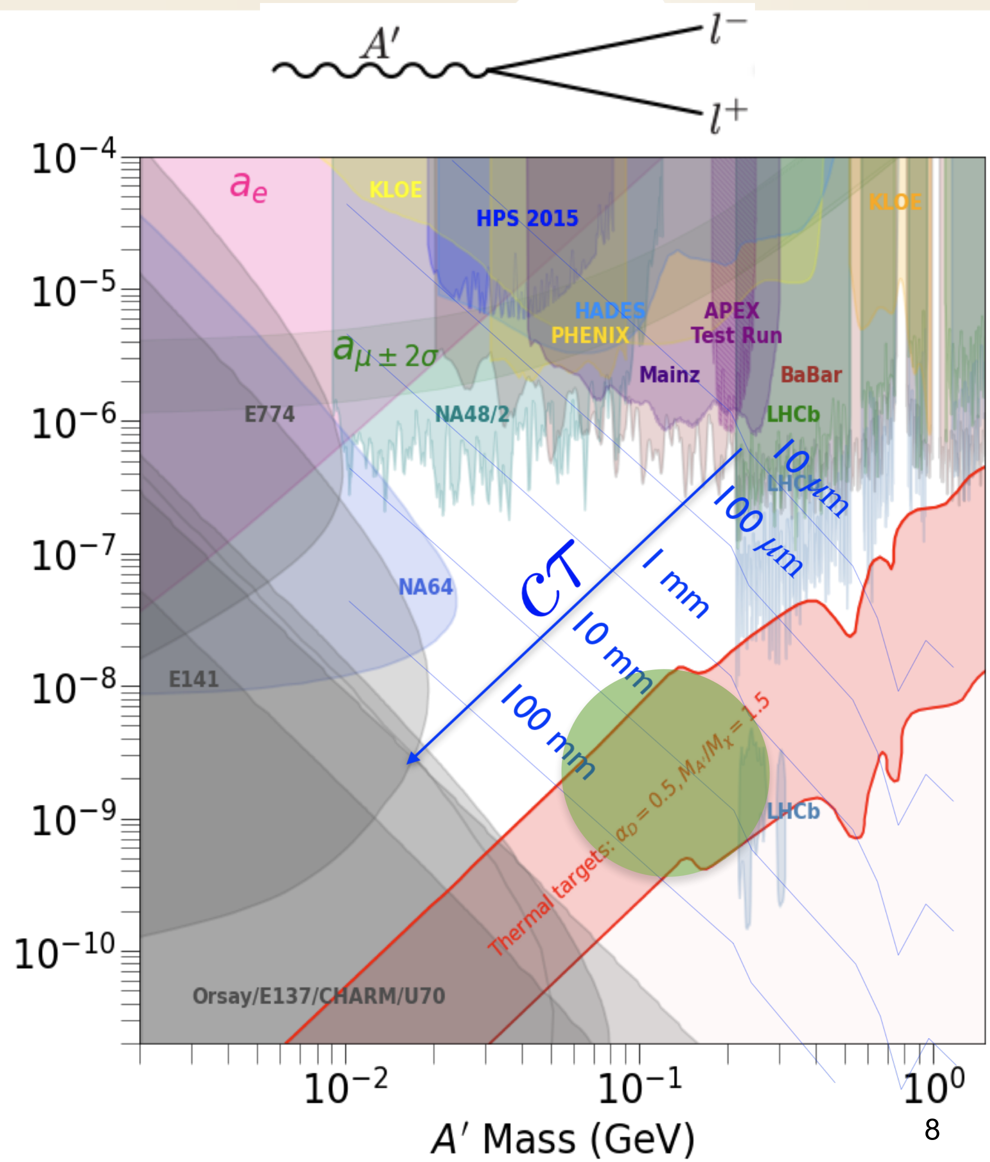
$$\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$$

- Leads to constraints from **beam dump experiments**

Displaced vertex search

concept simulation - not real data

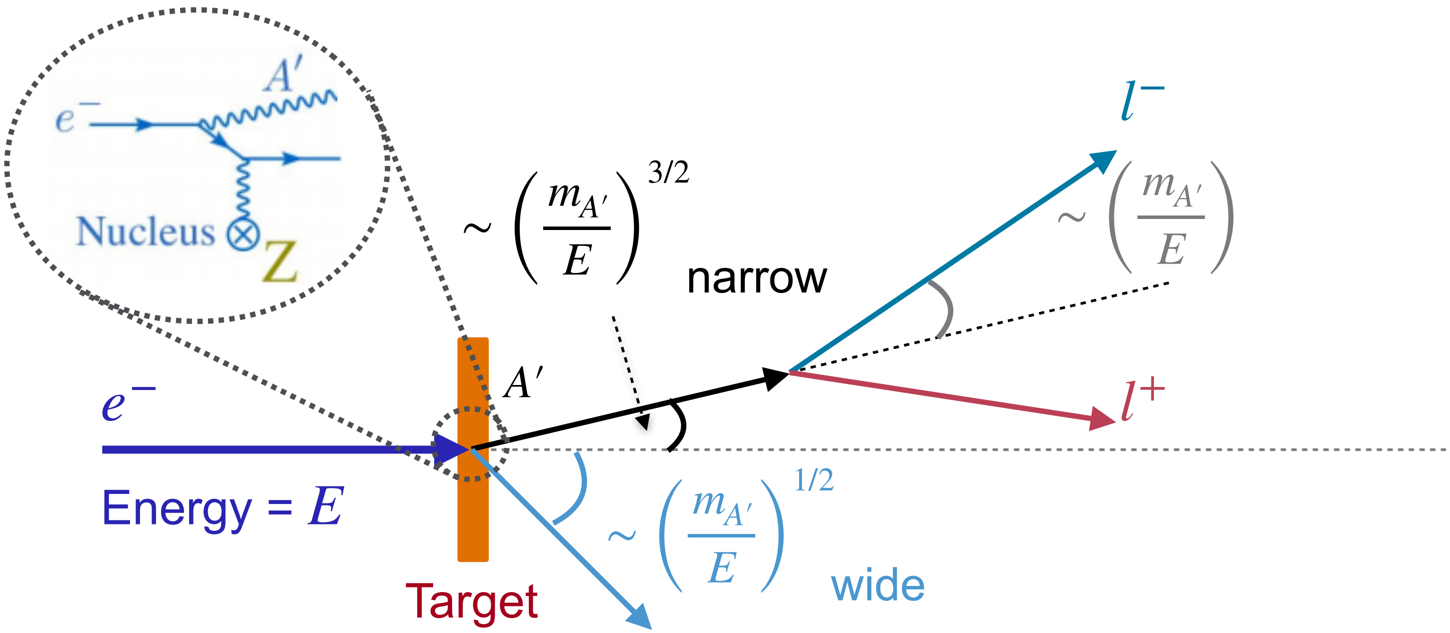




- **Fixed target experiments** search for a **displaced vertex** formed by the A' decay products.
- **Sensitive to shorter decay lengths** with respect to beam dump experiments
- Covered mass range depends on detector design and acceptance

Visible Decay - Fixed Target Experiment

- Dark Photons can be **produced via Dark bremsstrahlung** from beam electrons on a thin target
- A' production is sharply peaked at $E_{A'} = E_{beam}$ and emitted in the very forward direction
- Soft recoil electrons at large angles. A's decay into a $l^- l^+$ pair, with opening angle $m_{A'}/E_{beam}$ (~ few degrees)

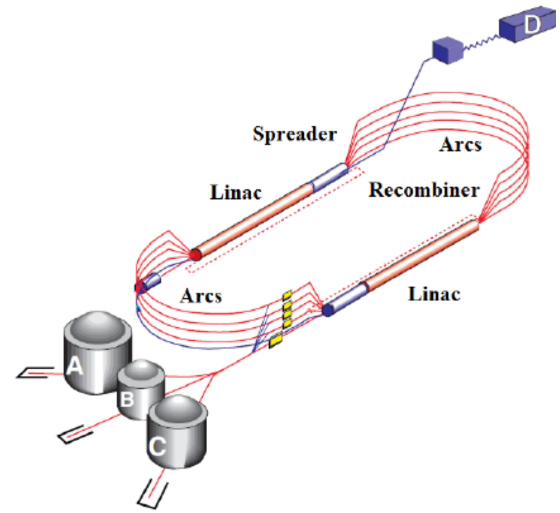


- An experiment targeting this scenario must have:
  - **Very forward acceptance** to capture A' decay products close to beam plane
  - **Calorimeter for fast trigger and precise timing information** to reject elastically scattered electrons
  - **Precise tracking system** to identify particles consistent with a decay-vertex origin.

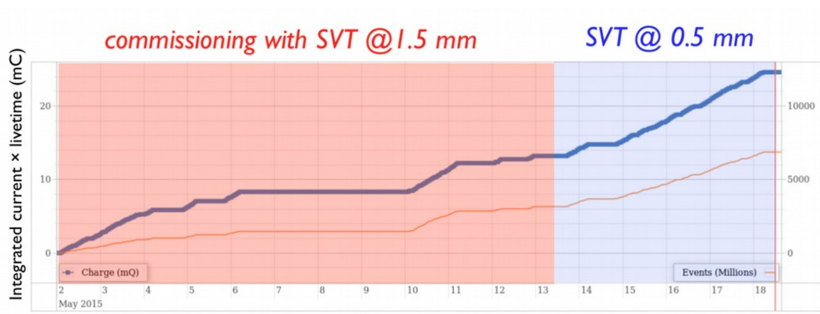
CEBAF and the HPS detector

CEBAF Accelerator at Jefferson Lab

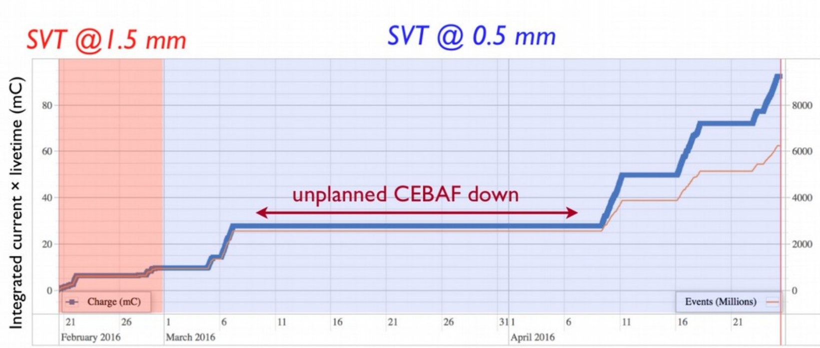
- **Superconducting RF recirculating linear accelerator**
  - 1400m length
  - High intensity continuous electron beam (500 or 250 MHz)
- Data runs performed at Jefferson Lab Hall B
  - Beam bunch every 2ns
  - Beam current up to 500 nA
  - Beam Energies: **1.06 GeV for 2015 / 2.3 GeV for 2016**



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



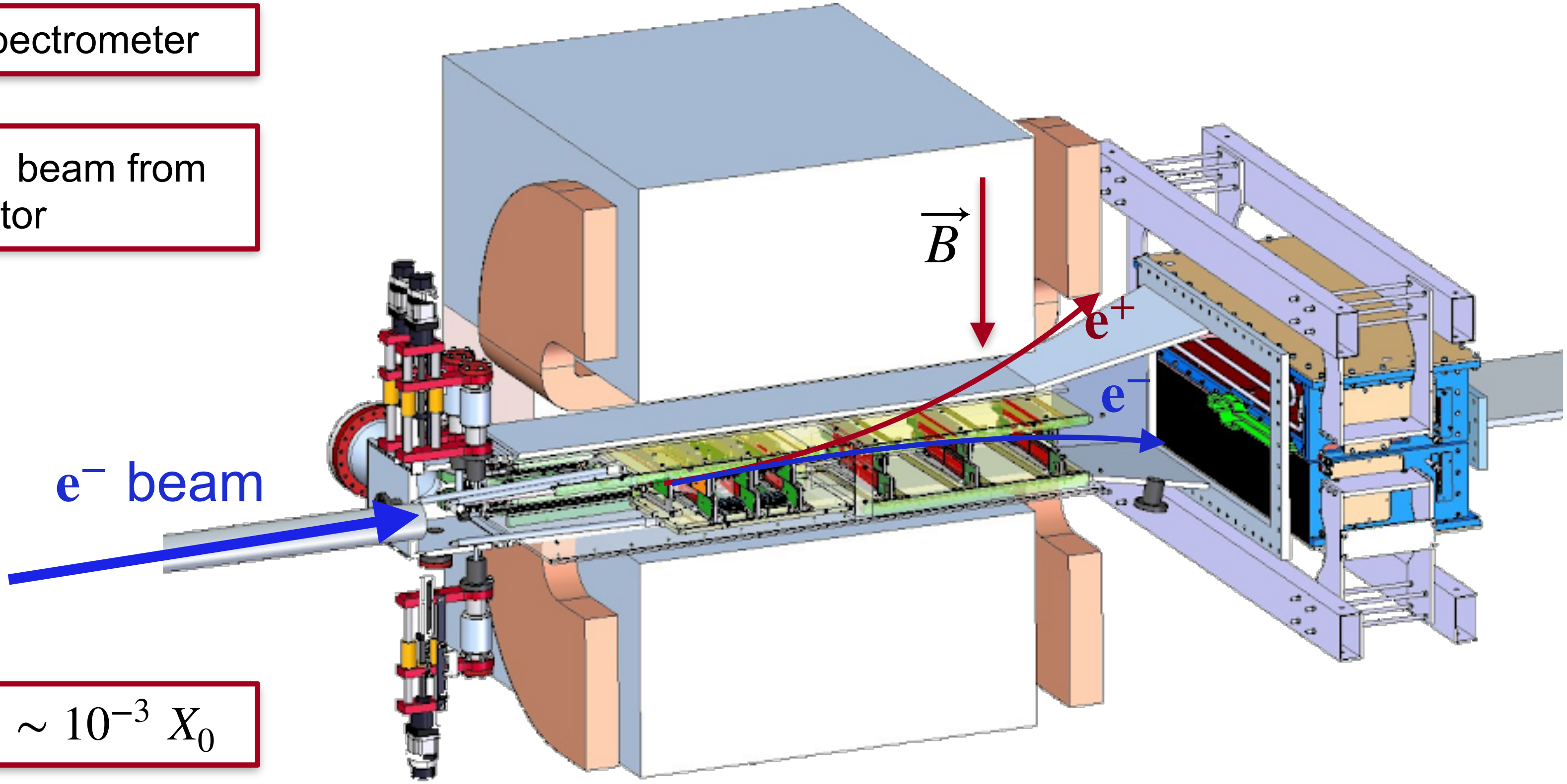
2016 Engineering Run
200 nA @ 2.3 GeV
5.4 days (92.5 mC) of physics data



The HPS Detector

Two lever arm spectrometer

High intensity $\mathbf{e}^-$ beam from CEBAF accelerator



Tungsten Target $\sim 10^{-3}\ X_0$

Linear Shift Motion System
Adjustment of Silicon Tracker opening

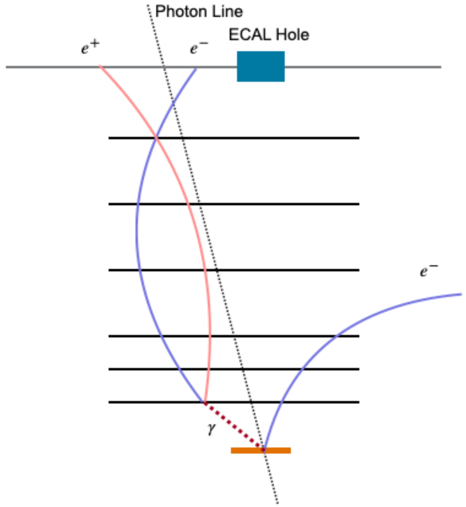
Silicon Vertex Tracker (SVT)
Split in 2 separated volumes to avoid intense flux of scattered beam electrons

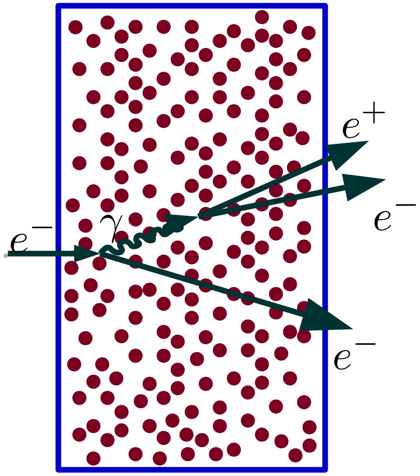
Electromagnetic Calorimeter
Triggering and ParticleID

2016 Engineering Run Bump Hunt and Displaced Vertex Analyses

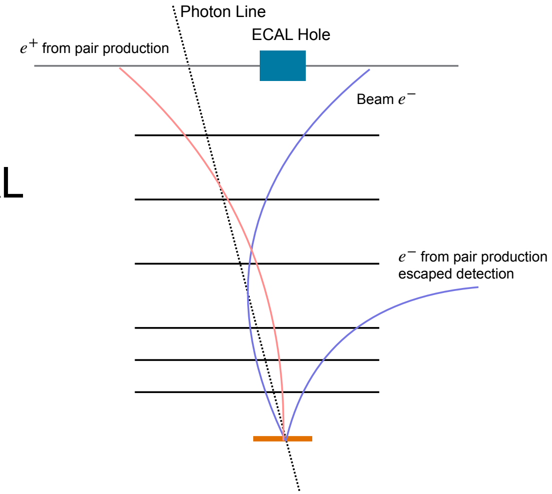
Backgrounds

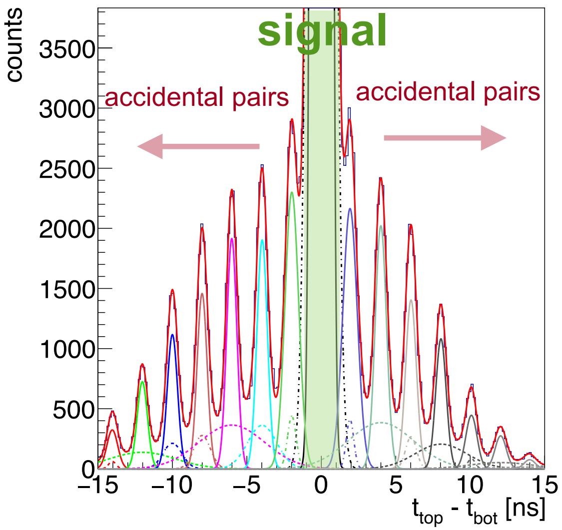
- **Wide Angle Bremsstrahlung (WAB)** events are due to photon conversions in the detector material
  - Low acceptance but huge cross-section
  - Removed by track parameters cuts and request of hits-on-track in the innermost layers



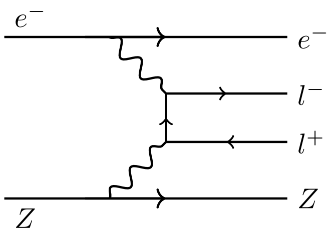


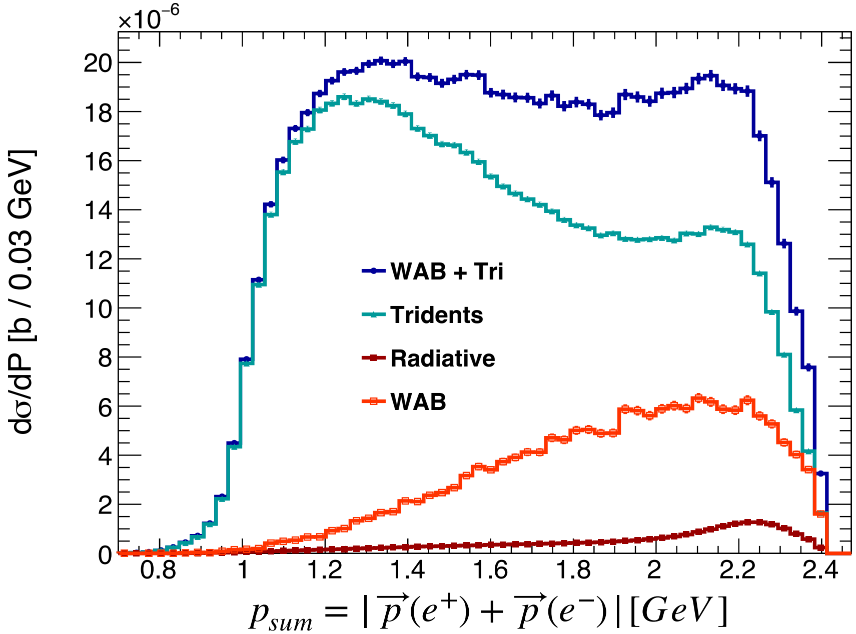
- **Accidentals** events due to random combinations of e^+ with beam electrons
- Suppressed by precise ECAL timing cuts and topological cuts used to remove elastically scattered beam electrons.

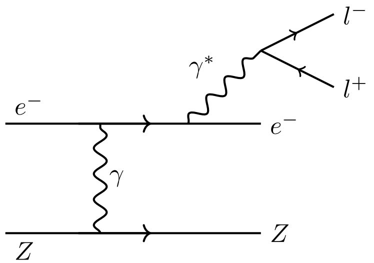




Backgrounds - Tridents







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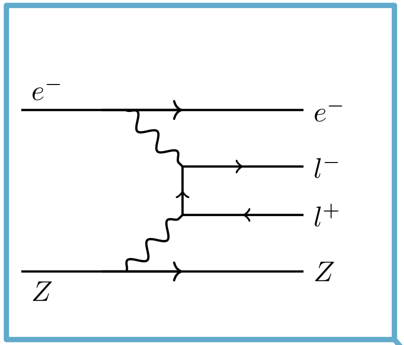
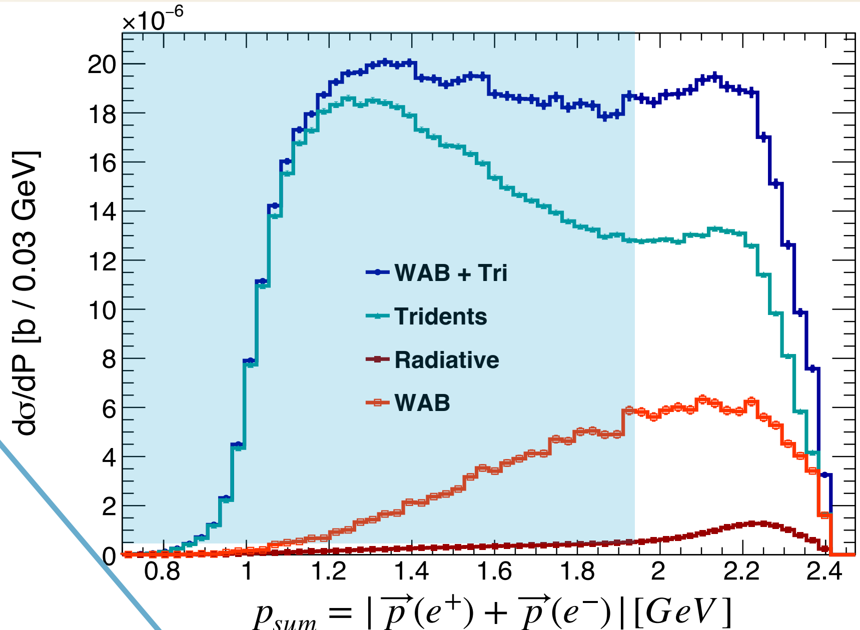
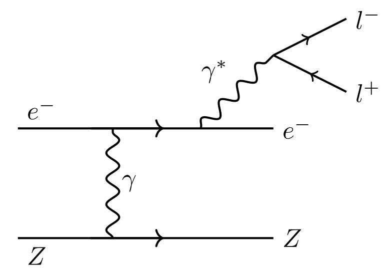
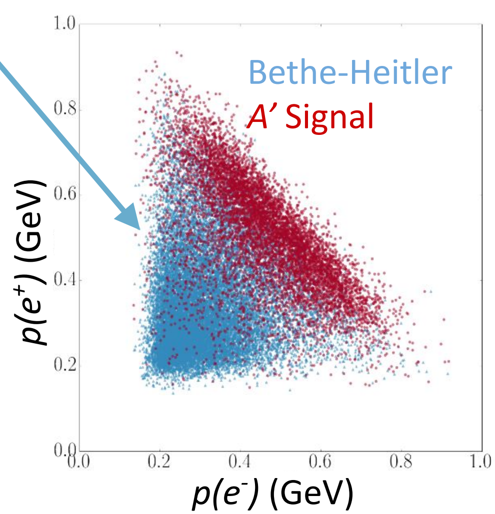






- **Bethe-Heitler** events characterized by softer final state particle momenta
- They contribute to the lower part of the p_{sum} spectrum
- **Reducible background**
- Dominate signal region due to large cross-section



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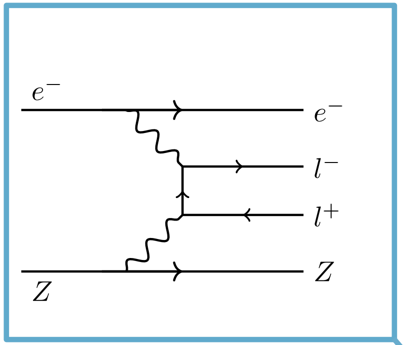

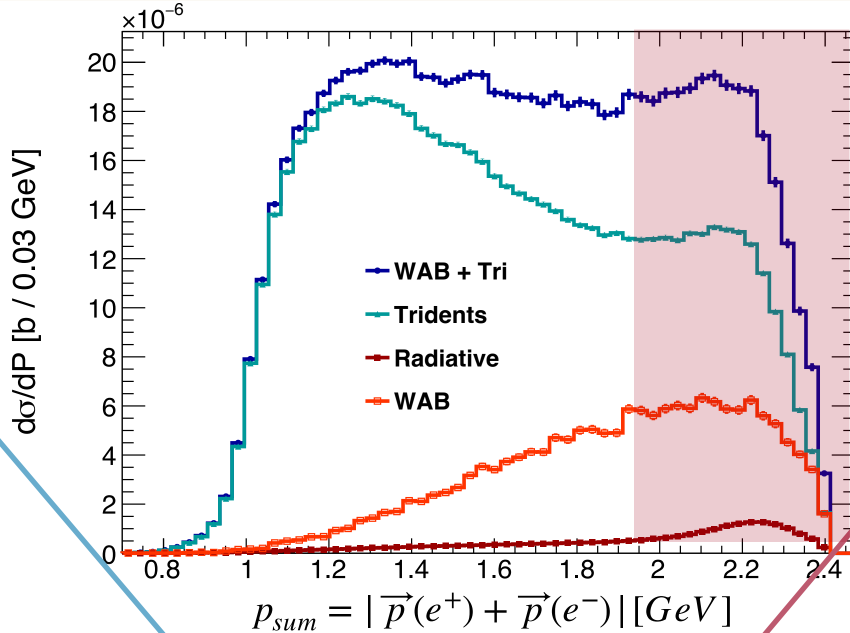

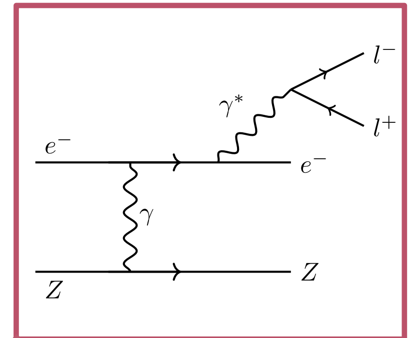

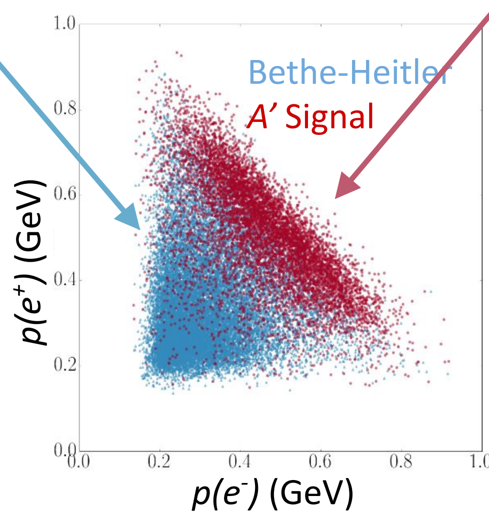

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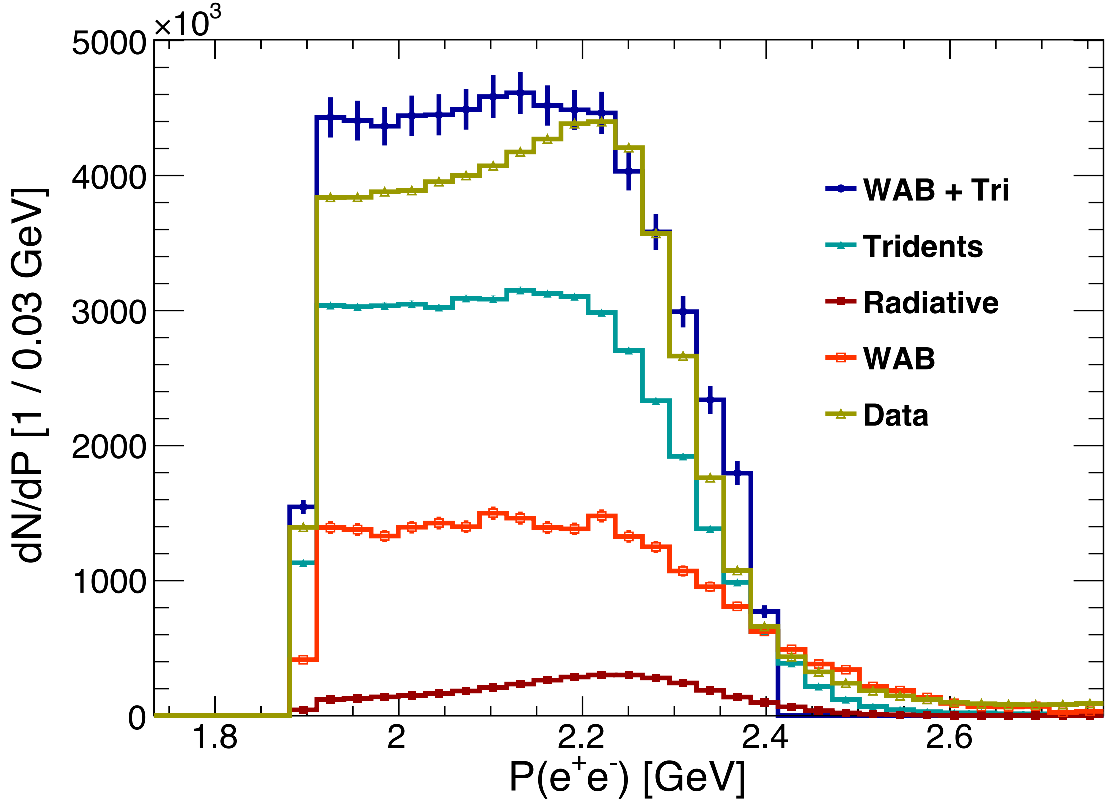
- **Radiative-tridents** identical kinematics of the A' signal
- Irreducible background
- It provides a **reference to estimate the expected A' production rate**

Event Selection Summary



- **Data and Monte Carlo in broad agreement: evidence that sample composition is understood**
- Residual discrepancies due to trigger modeling in simulation and resolution effects

Resonance Search - Radiative fraction

- The A' kinematics is identical to off-shell SM photon production
- Cross section for heavy photons at mass $m_{A'}$ is related to virtual photon of same mass by

With $N_{eff} = 1$ for mA'

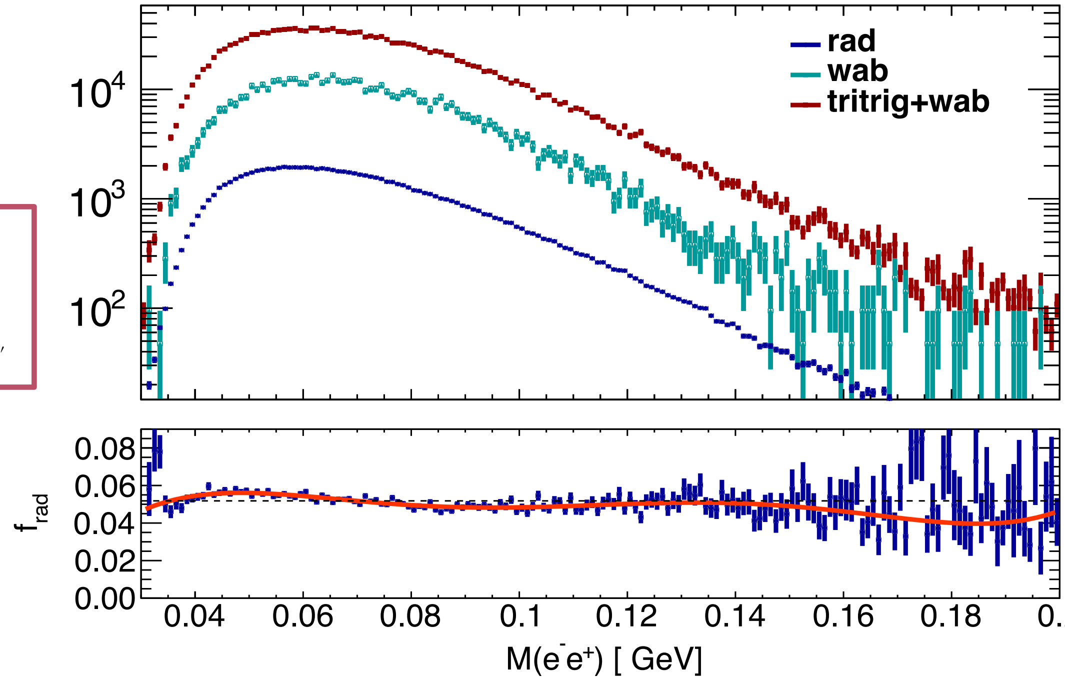
$$\boxed{\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\frac{d\sigma_{\gamma*}}{dm}\bigg|_{m=m_{A'}}}$$

PRD 80 075018

- Therefore the number of A' events:

$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2\alpha} f_{rad} \frac{dN_{bkg}}{dm_{reco}}$$

Background = tridents + WABS + beam scatters



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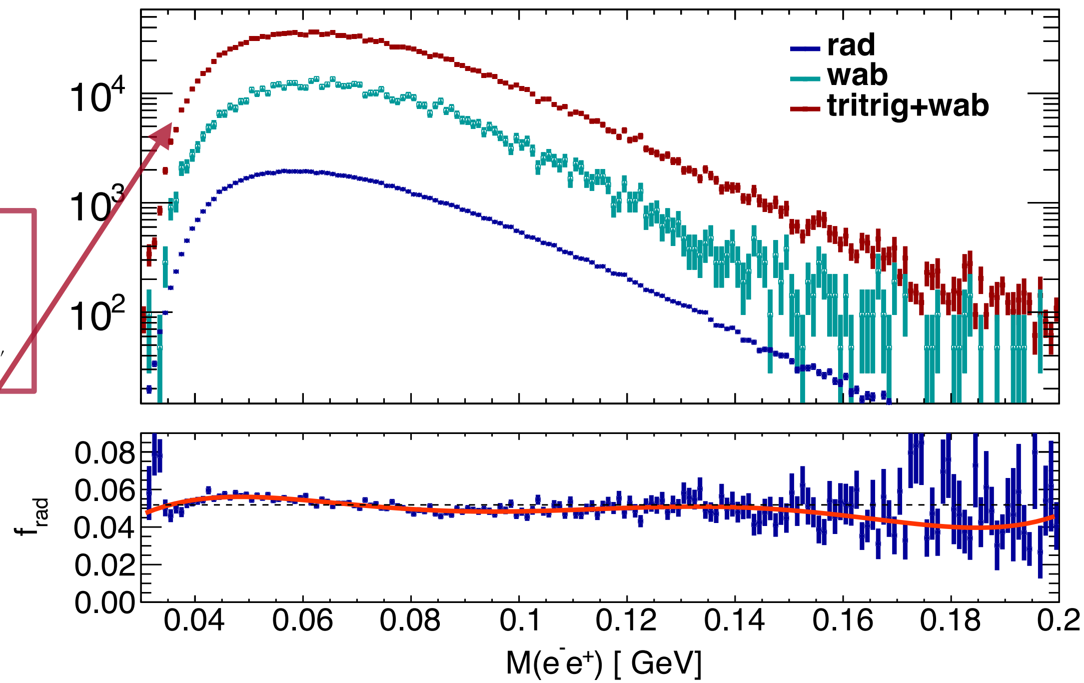
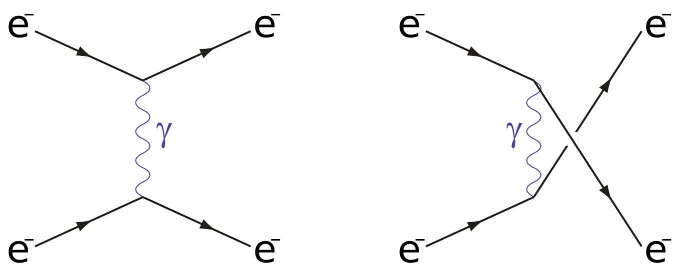


$$f_{rad} = \frac{dN_{\gamma^*}}{dm_{A'}} \bigg/ \frac{dN_{bkg}}{dm_{reco}}$$

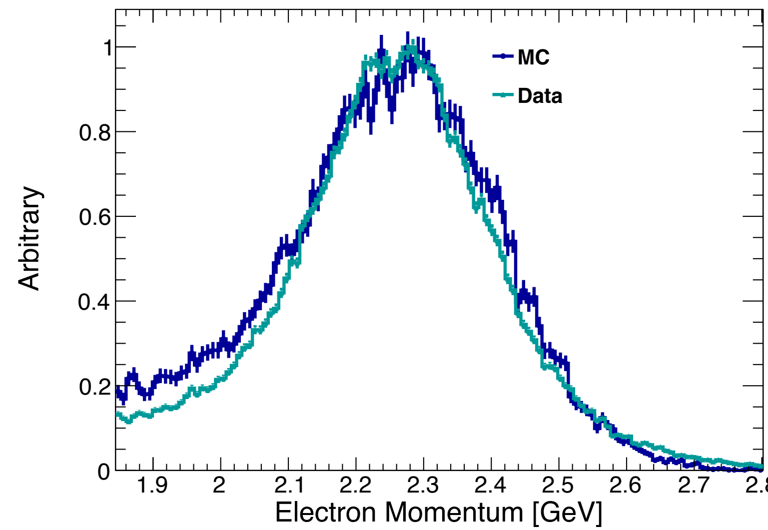
f_{rad} **radiative fraction is the ratio of radiative trident rate to total background** as function of the $m(e^+e^-)$

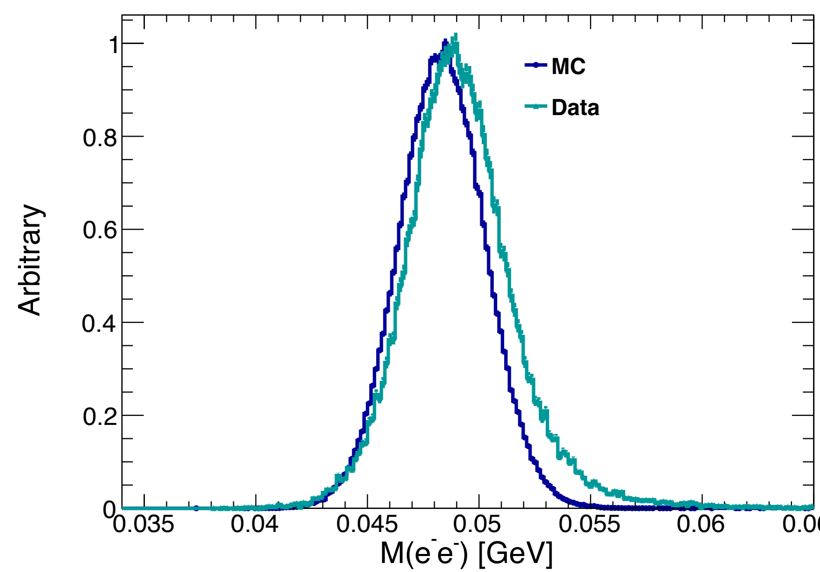
Mass calibration and resolution - Møllers



- The Møller process $e^-e^- \rightarrow e^-e^-$ is used as direct measurement of the mass resolution
- $E_{beam} = 2.3\text{GeV} \rightarrow M_{møller} = 48.5\text{MeV}$
- Uncertainty dominated by detector resolution
- Mass resolution for the e^+e^- final states (A') expected to be equivalent to the e^-e^-

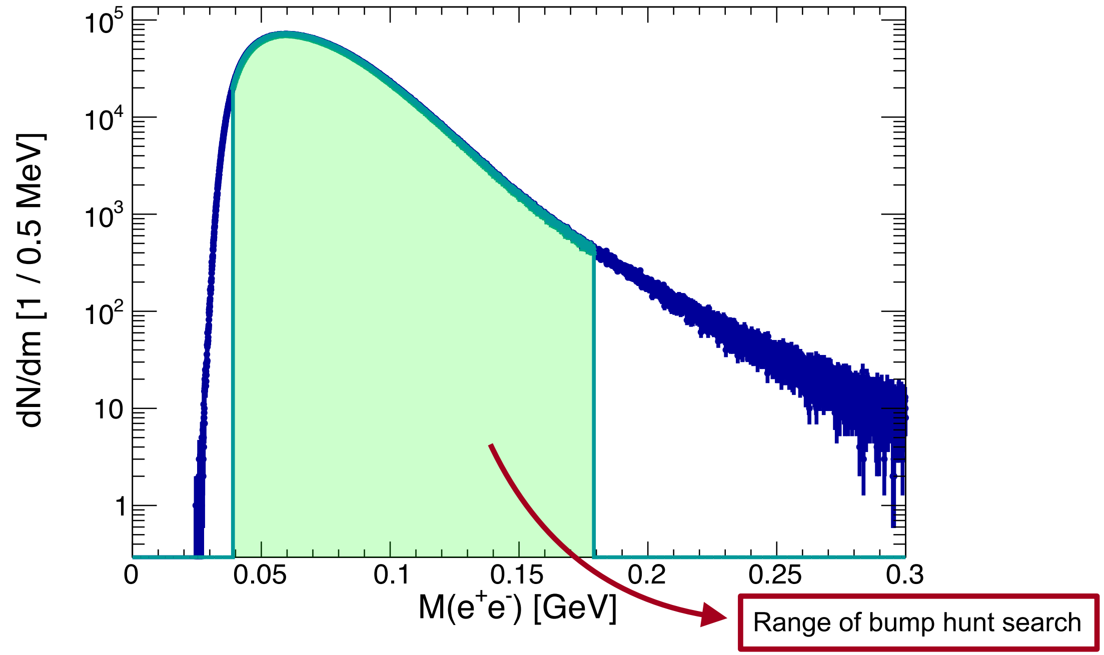
- **With the incorporation of momentum smearing, residual MC/Data mass resolution discrepancy of ~6%**

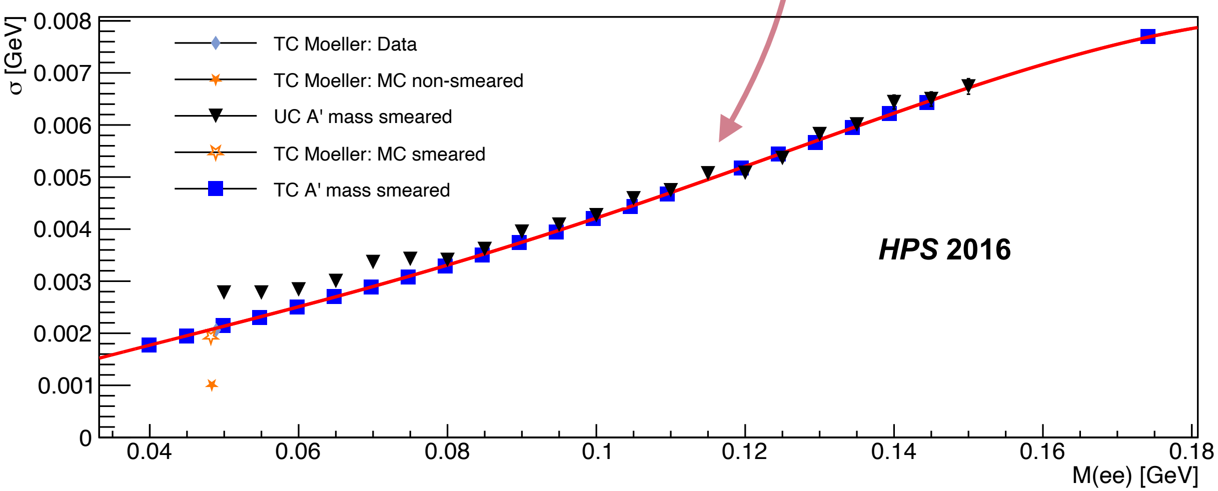




Resonance Search - Bump Hunt

- The search procedure is performed at a fixed A' mass hypothesis and is repeated over the a $m(e^+e^-)$ mass range
- Sensitivity depends on the "local" mass resolution σ_m:
  - Guide the **choice of the window size** in the spectrum scan
  - **Construct a signal shape** for the statistical fit

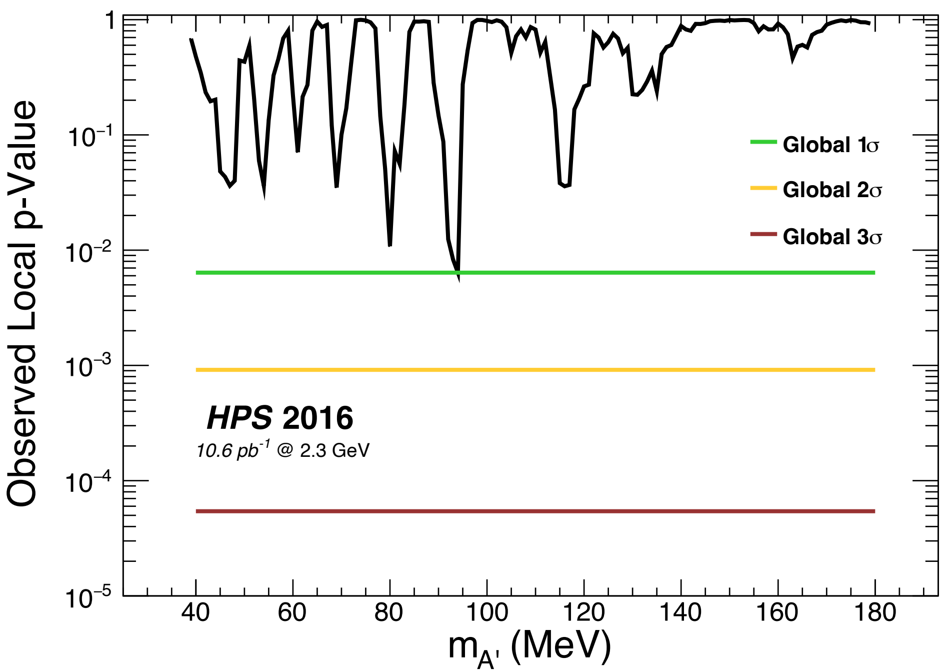


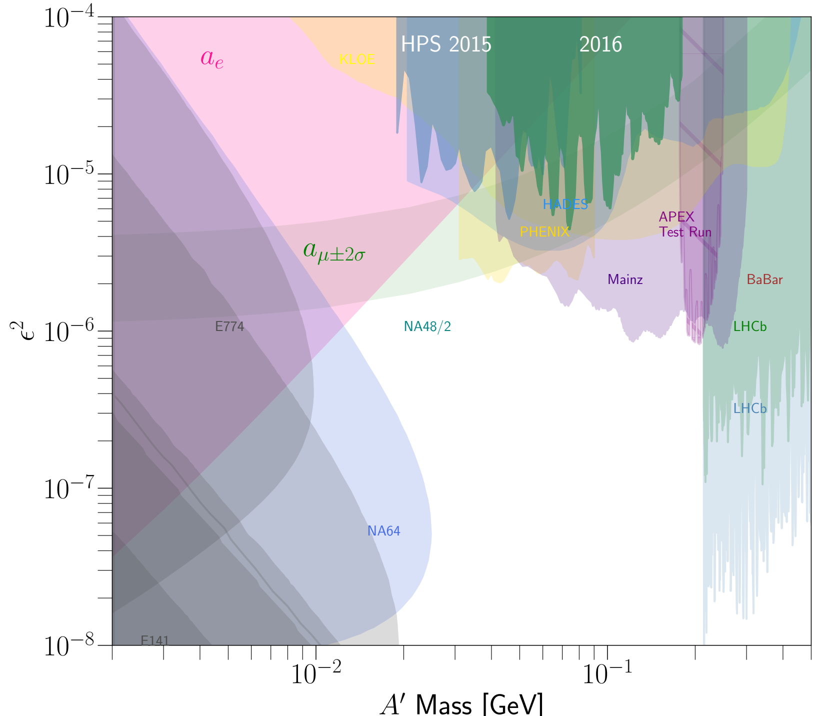


- From FEE and Møllers
- Computed for various $m_{A'}$ and interpolated

arXiv:2212.10629

Resonance search - Results





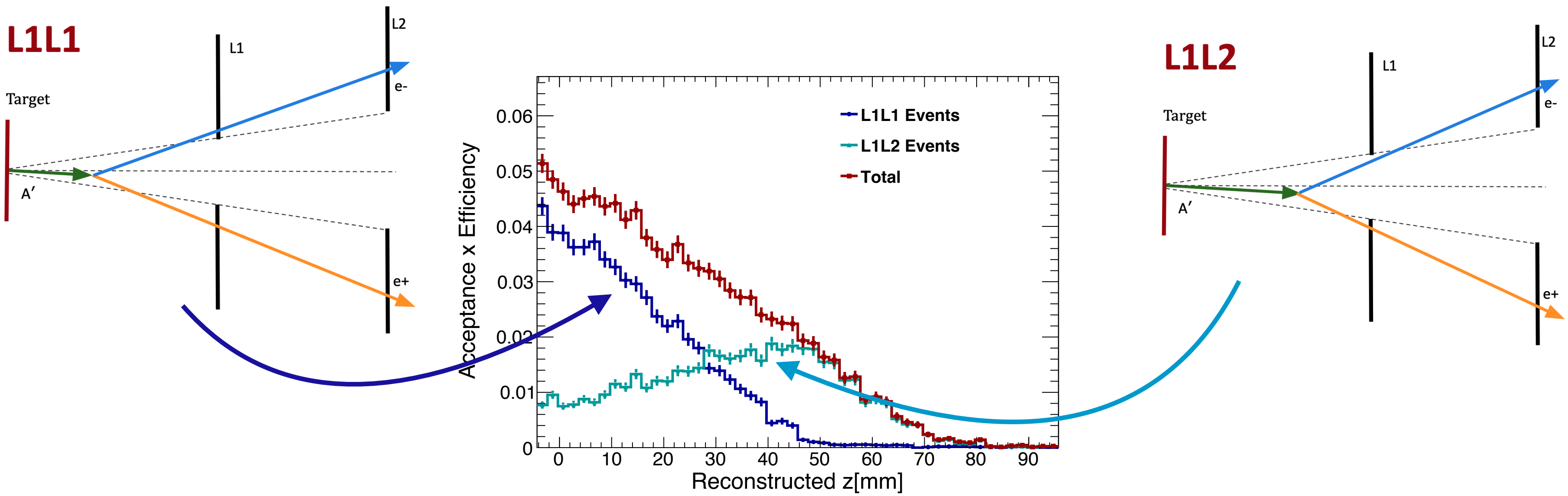
arXiv:2212.10629

- The analysis of the 2016 dataset has been completed
  - No signal observed
  - Upper Limit $\epsilon^2 = 4 \times 10^{-6}$ @ $m_{A'} = 75$ MeV
  - Results in agreement with other experiments

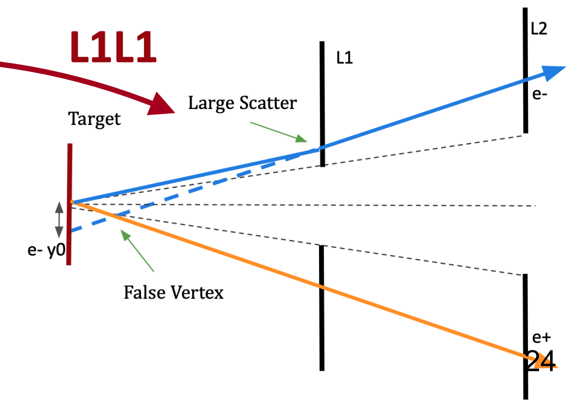
Systematic	Impact on	%	Estimated from
MC Phase space	f_{rad}	0.5-2	accidental side bands
MC process σ	f_{rad}	6.5	Madgraph
Target Position	σ_m	2.5	MC Simulation
Momentum smearing	σ_m	1.5	fit parameters variations

Displaced Vertex Search

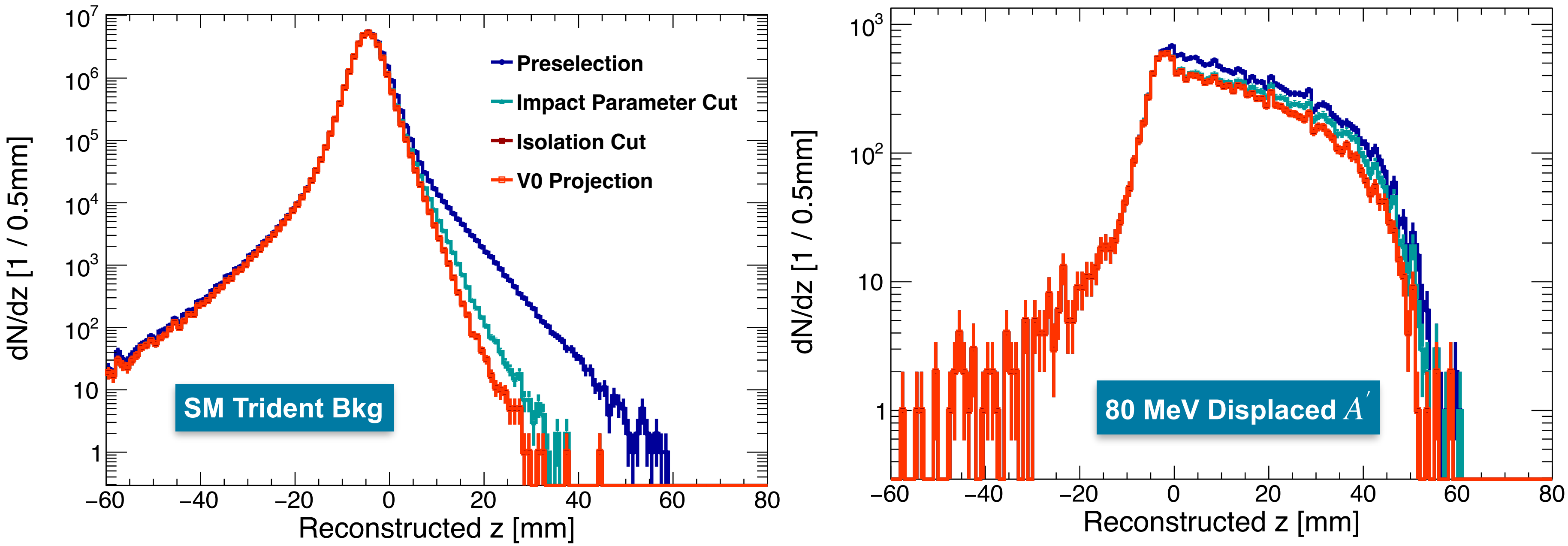
- Targeting small ϵ^2 by searching for A' that decay farther downstream wrt target (1-10cm)
- Two categories to maximize signal acceptance: L1L1 and L1L2



- Two main backgrounds at very displaced vertices:
  - **Large scattering angles** on first layers
  - **Mis-associated hits** biasing track fits



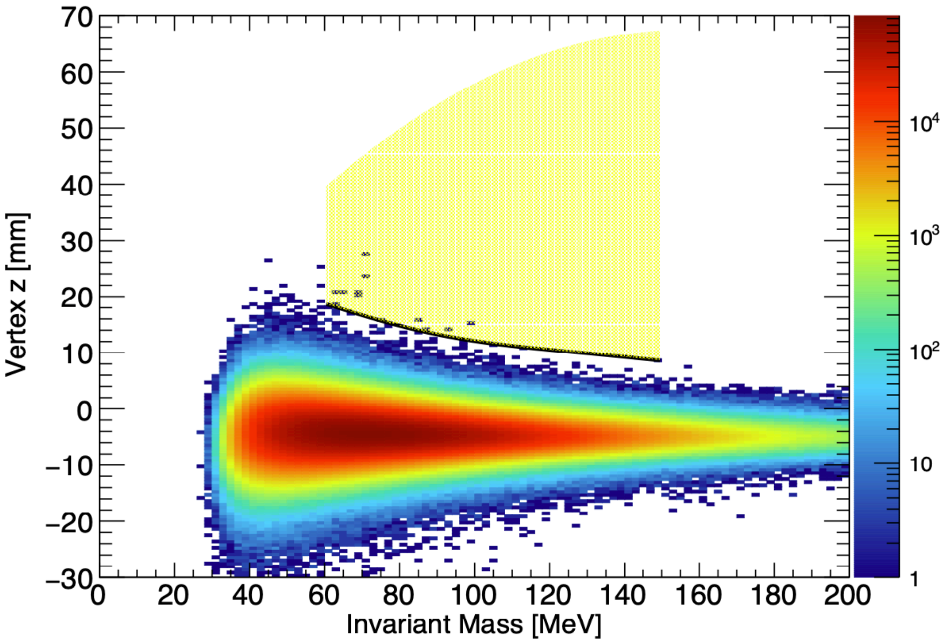
Displaced Vertex Search - Event Selection



- Background largely dominated by prompt decay vertex reconstruction resolution, scattering, tracking errors
- Tracking requirements driven by the signal topology are employed to reduce background and are successful in reducing the high-z tail

Displaced Vertex Search - Signal Region

- Analysis structured to define a signal region with “no-background“
- Reconstructed vertex z location vs $m(e^+e^-)$ distribution is sliced in overlapping bins

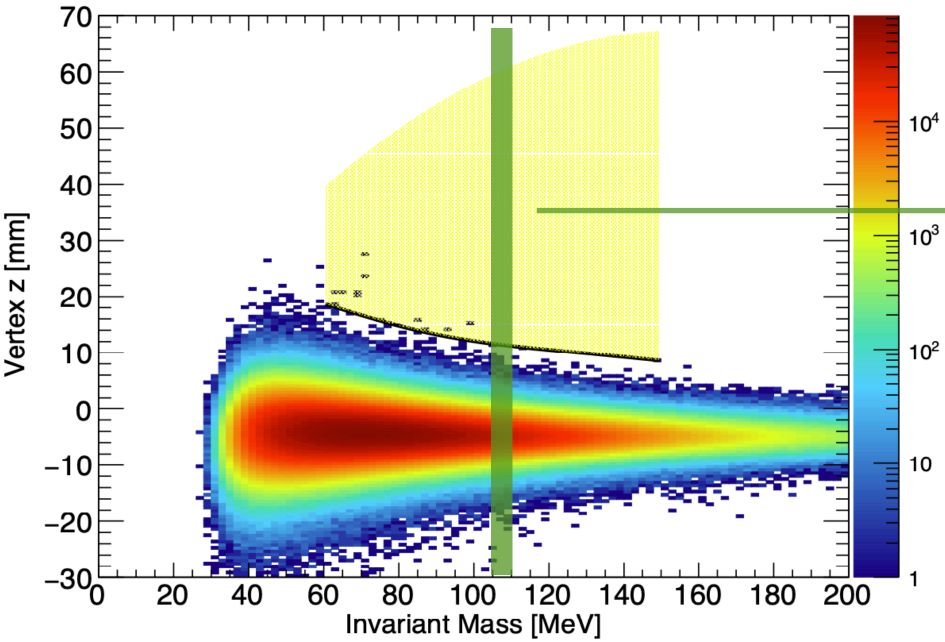


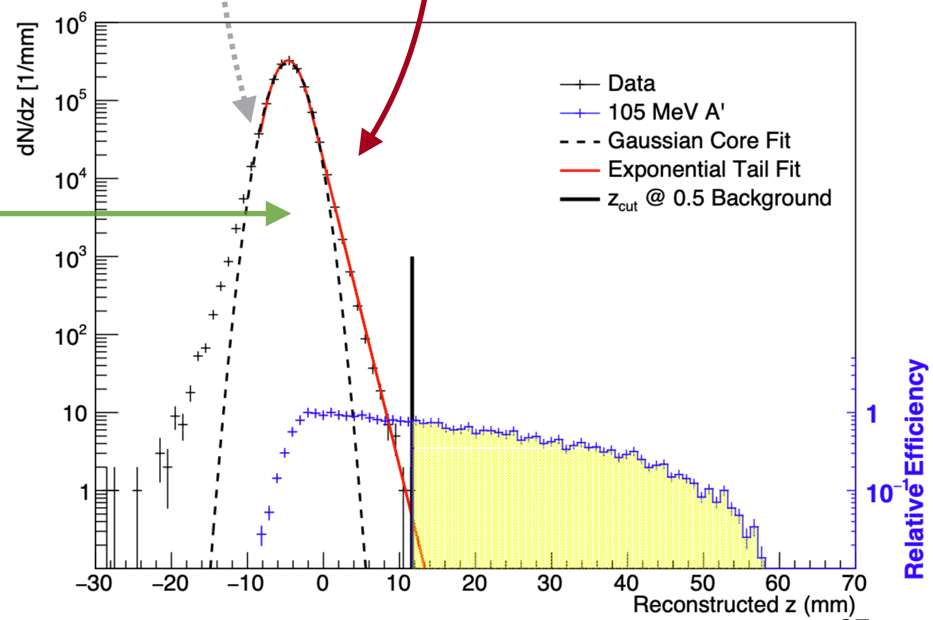
Displaced Vertex Search - Signal Region

- Analysis structured to define a signal region with “no-background“
- Reconstructed vertex z location vs $m(e^+e^-)$ distribution is sliced in overlapping bins
- 1D vertex z location is fit with Gaussian core + exp tails.
- **Signal region defined by vertices with $z \geq z_{cut}$**

$$F(z) = \begin{cases} Ae^{-\frac{(z-\mu_z)^2}{2\sigma_z^2}}, & \text{if } \frac{z-\mu_z}{\sigma_z} < b \\ Ae^{-\frac{b^2}{2} - b\frac{z-\mu_z}{\sigma_z}}, & \text{if } \frac{z-\mu_z}{\sigma_z} \geq b \end{cases}$$

$$0.5 = \int_{z_{cut}}^{\infty} F(z)dz$$

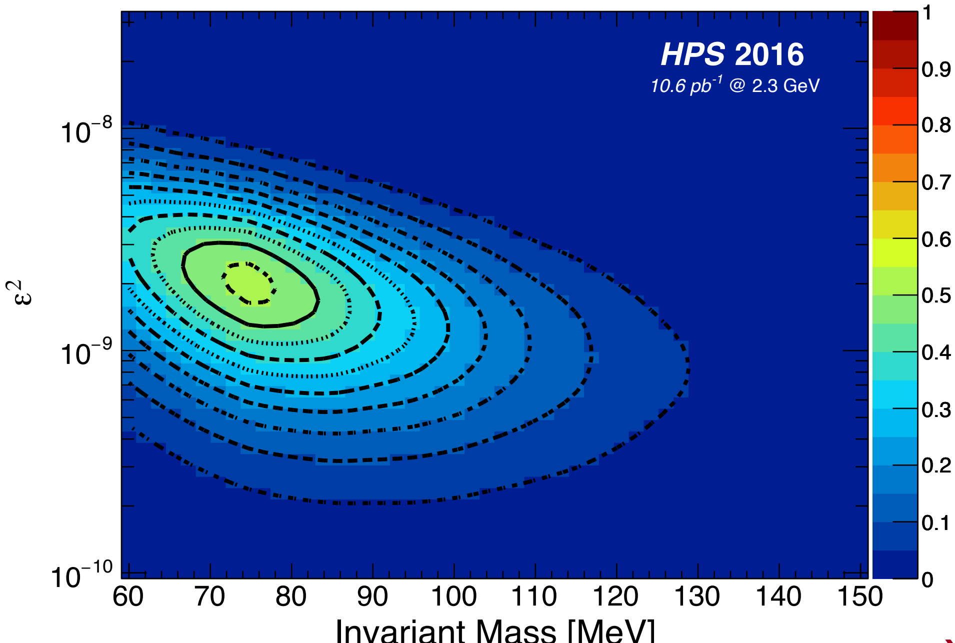


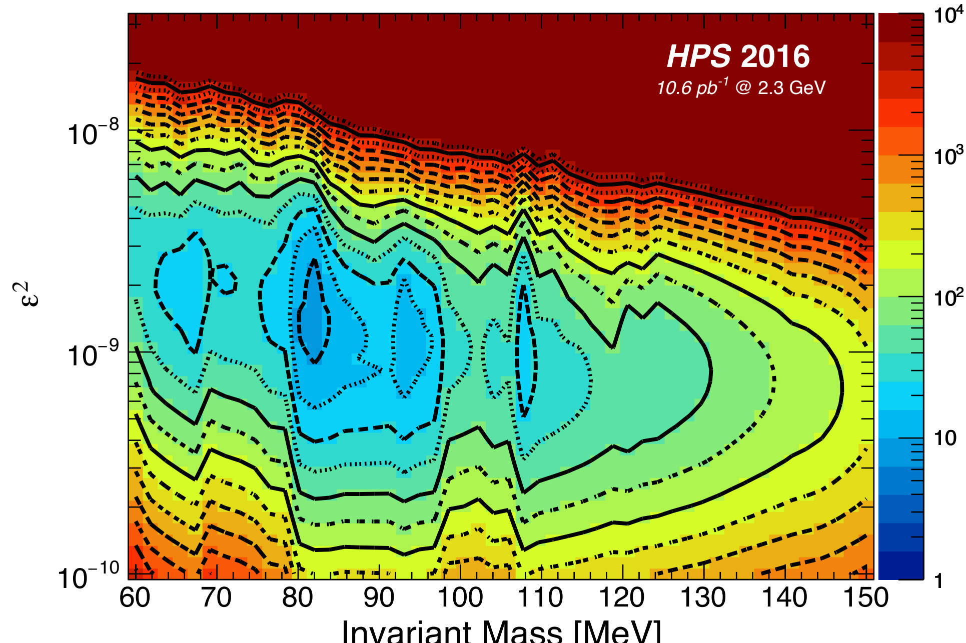


Displaced Vertex Search - Results

- Expected A' signal rate computed past z_{cut} ~ 0.5 events for 2016

- Used Optimum Interval Method (OIM) to set an upper limit on ϵ^2 from expected rate
- Common procedure employed when the source of background is unknown





arXiv:2212.10629

Combination best limit

$$m_{A'} = 80 \text{ MeV } \epsilon^2 = 1.7 \times 10^{-9} \rightarrow 7.9 \times \sigma_{A'}$$

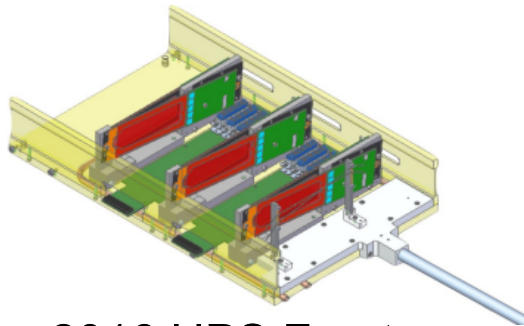
https://arxiv.org/pdf/physics/0203002.pdf

2019 and 2021 Data Run

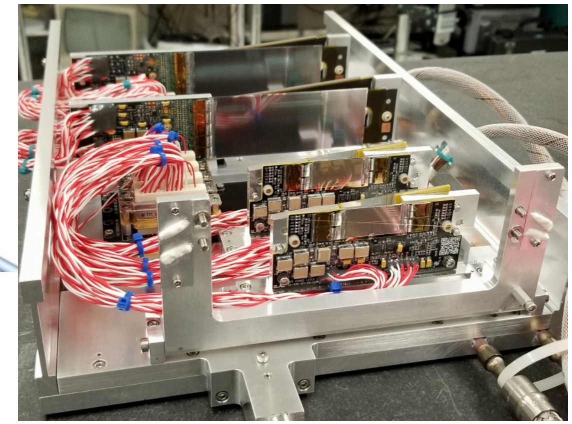
The 2019 and 2021 datasets

SLAC

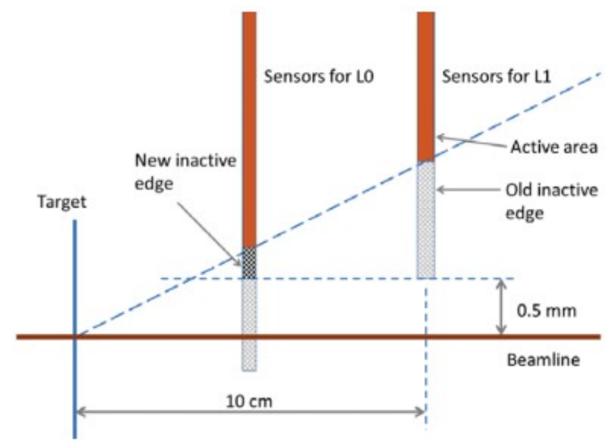
- HPS took 2 additional **data runs in 2019 and 2021:**
  - 2019: $E_{beam} = 4.55\ GeV$ @ 100nA for a $L_{int} =\ 128$ pb^{-1}
  - 2021:
    - $E_{beam} = 3.74$ GeV @ 168 pb^{-1}
    - $E_{beam} = 1.94$GeV for Møllers
- Upgrades done to improve sensitivity to long lived dark photons:
  - First layers of the SVT moved closer to the beam plane: **increase acceptance to low mass dark photons**
  - Additional thin layer to the SVT: **improved vertex resolution and reconstruction efficiency**
  - Implemented positron only trigger using a hodoscope: **allow recover of sensitivity due to ECAL hole**



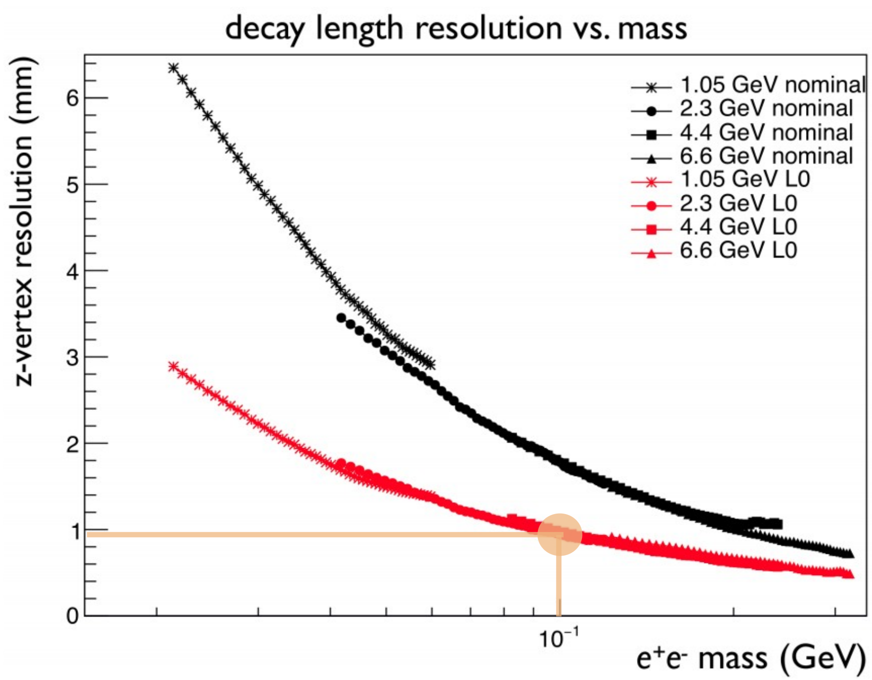
2016 HPS Front

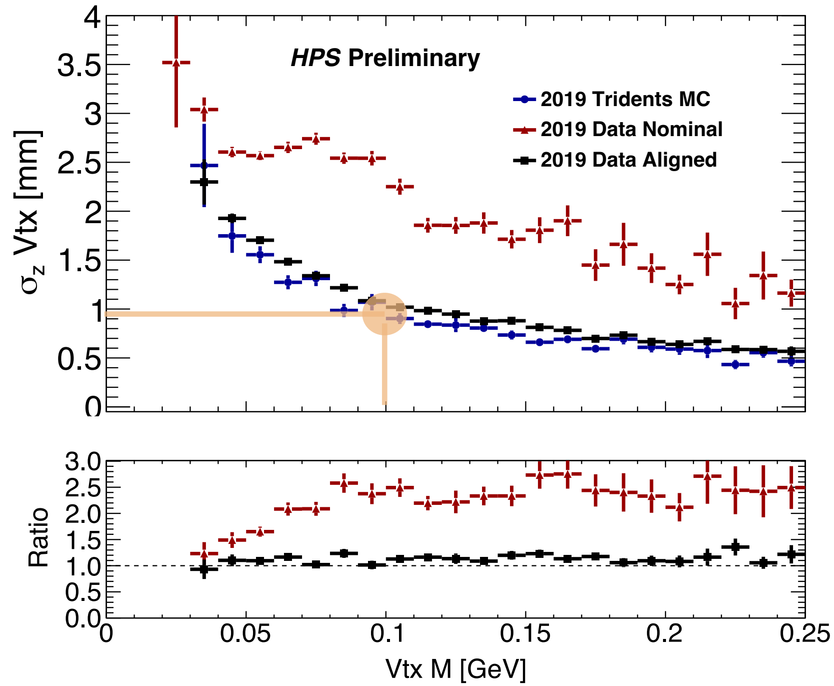


z-Location [mm]	Axial	Stereo
Top Ly0	38.15	45.97
Top Ly1	88.15	95.97
Bottom Ly0	61.85	54.03
Bottom Ly1	111.85	104.03



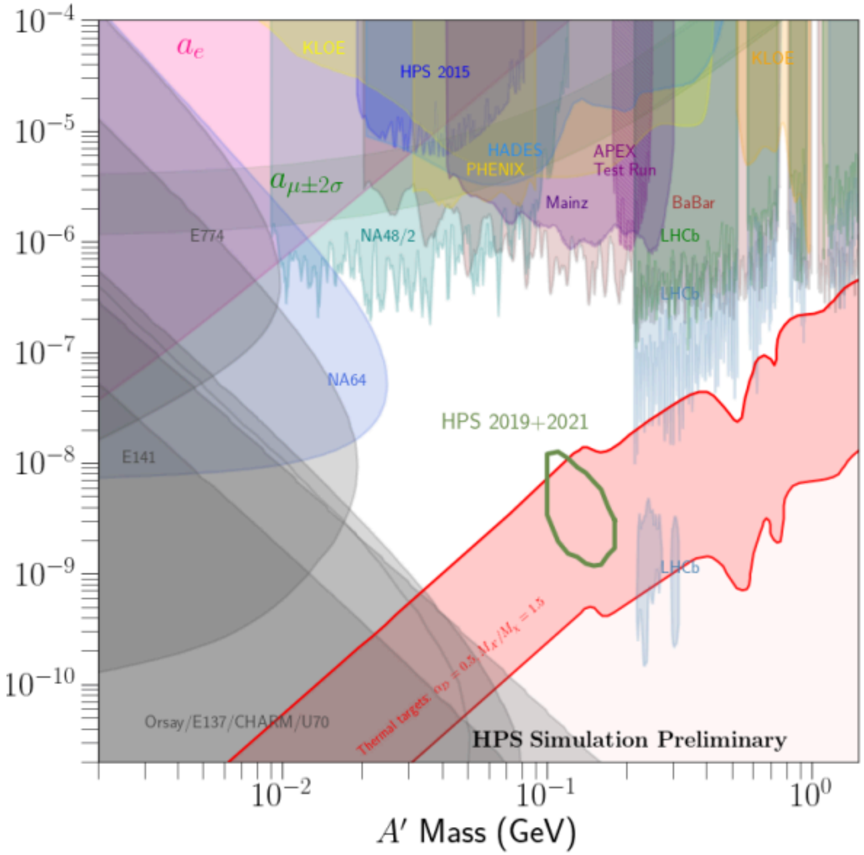
Detector performance - Vertexing

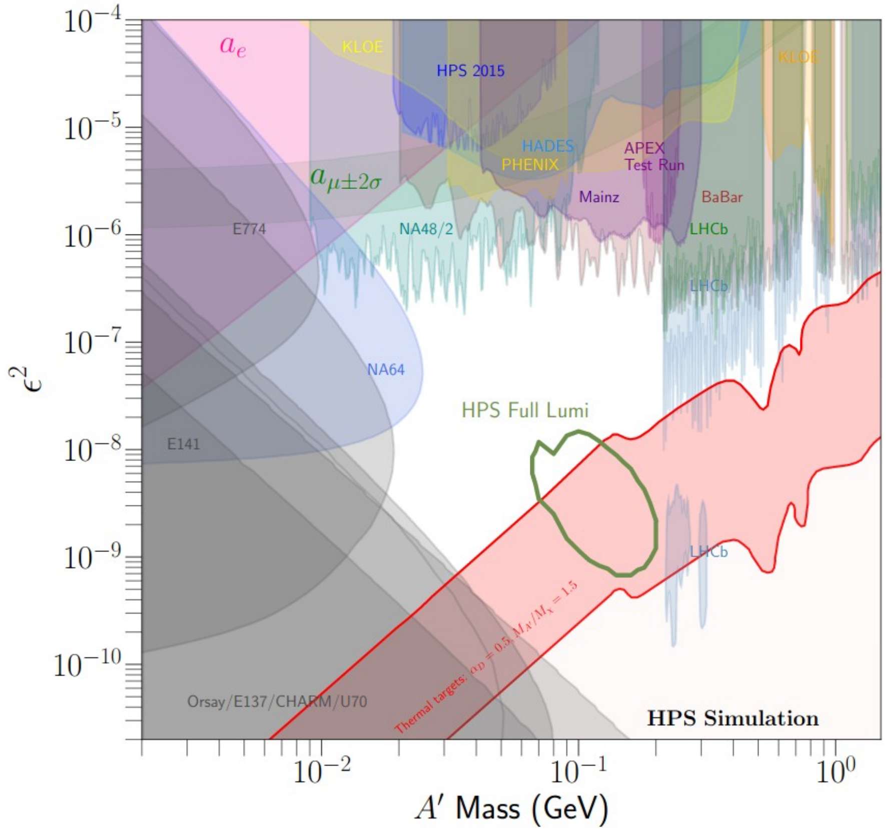




- Preliminary studies show that HPS reconstruction is able to achieve simulated design performance

Future prospects





- New reach estimates for analysis using full detector simulation show clear reach in the thermal relic target band in the parameter space

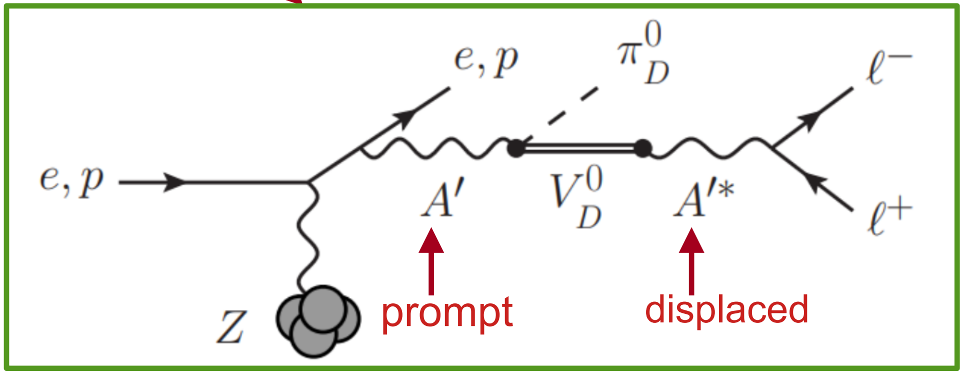
Sensitivity to Strongly Interacting Massive Particles

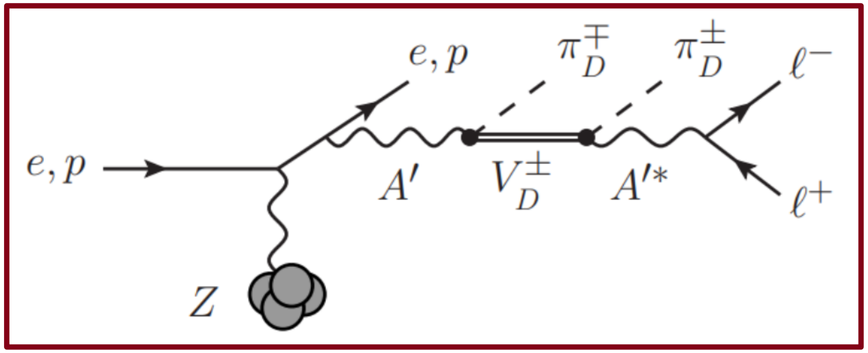
Strongly Interacting Massive Particles (SIMPs)

- Assume QCD-like strongly-coupled hidden sector (HS) neutral under SM forces
- HS contains dark pions (π_D) and heavier dark vector mesons (V_d) analogous to SM
- **Visible 2-body** and **3-body** decays expected arXiv:1402.5143
- Model can predict thermal relic abundance

Fixed target experiments well suited to detect long-lived V_D resonant decay to two leptons

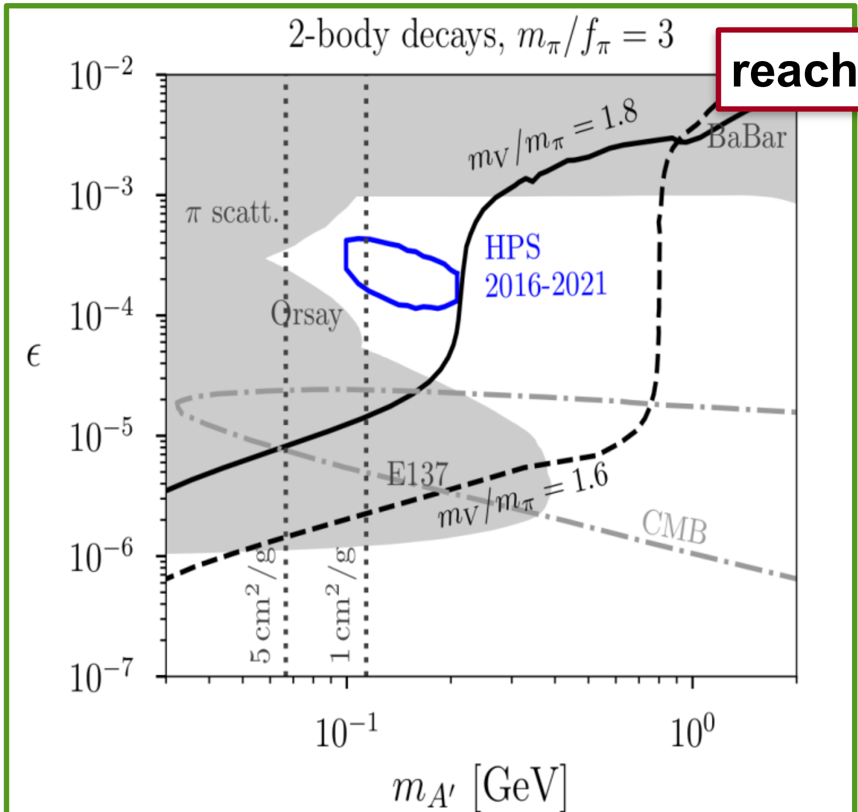
missing energy



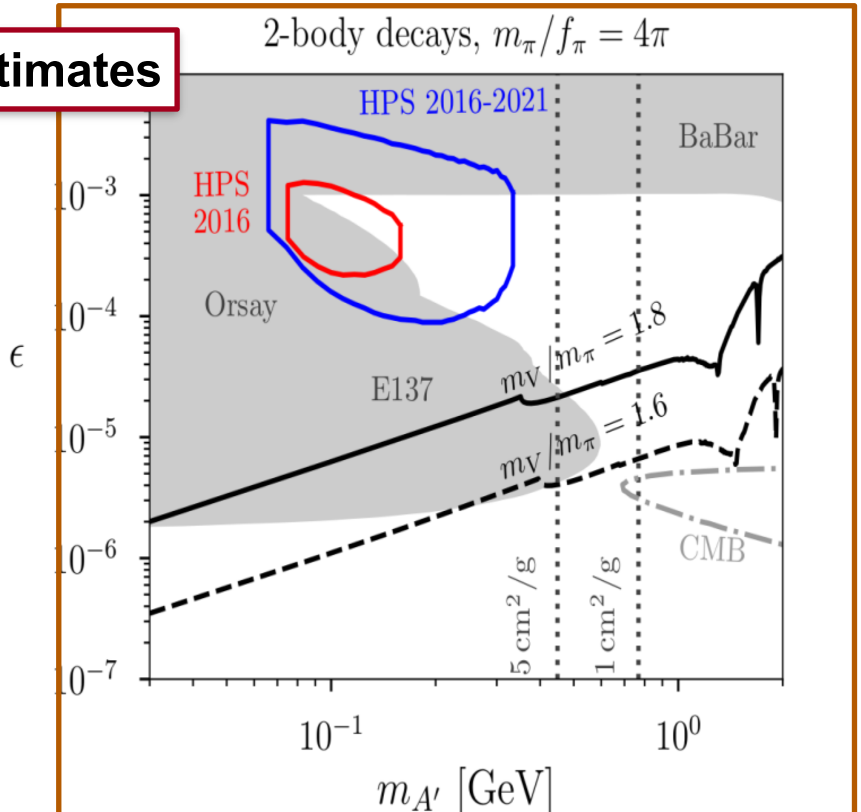


Strongly interacting Dark Matter

- HPS performed SIMP **reach estimates** for the **2016 run (red)** and combined runs **2016-2021 (Blue)**
- Mass ratios are fixed to $m_{A'}/m_\pi = 3$, $m_V/m_\pi = 1.8$ and α_D=0.01
- Assume only 2-body decays are visible (conservative)
- Two benchmark cases **minimum** and **maximum** $BR(A' \to \pi_D V_D)$
- HPS has unique sensitivity to thermal targets for both benchmarks



reach estimates

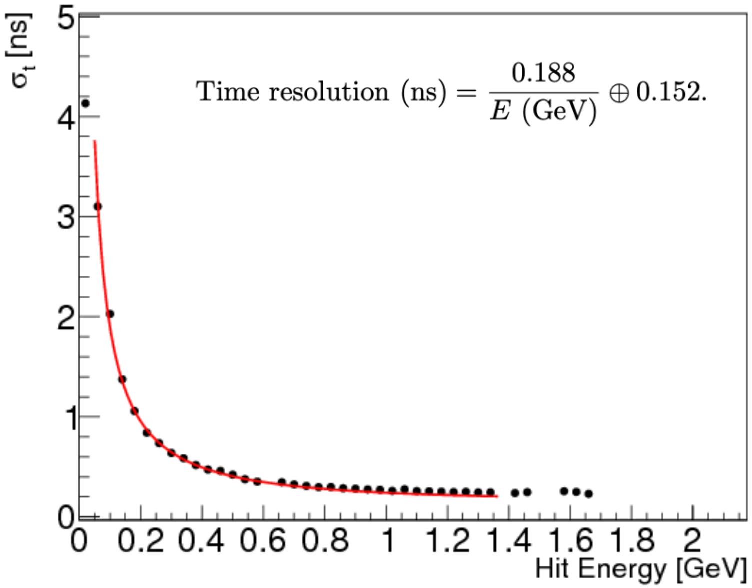


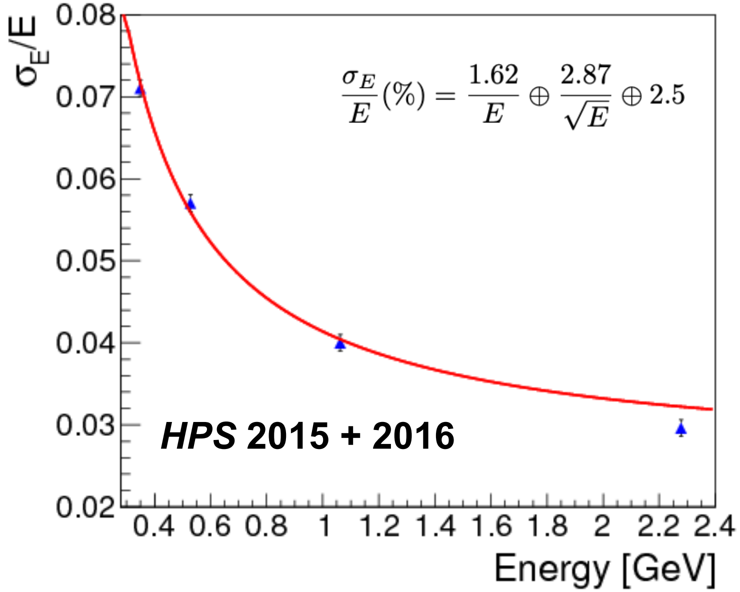
Conclusions

- Thermal relic dark matter in the sub-GeV range is motivating a worldwide search program for dark photons
- **HPS experiment has been designed to search for dark photons** with masses and couplings of particular interest for thermal relic dark matter.
- **HPS successfully took and completed the analysis of 2 engineering runs (2015 and 2016)**, refining analysis techniques. No signal observed so far. Results submitted to PRD.
- Bump-hunt search confirmed 2015 exclusion, first displaced vertex analysis.
- **HPS also has sensitivity to other dark sector scenarios**, such as SIMPs, beginning with the 2016 dataset
- 2019 and 2021 datasets are currently being calibrated and analyzed and are expected to provide significant reach in the thermal relic band in of the $(m_{A'}, \epsilon)$ parameter space

Backup

ECAL Performance plots



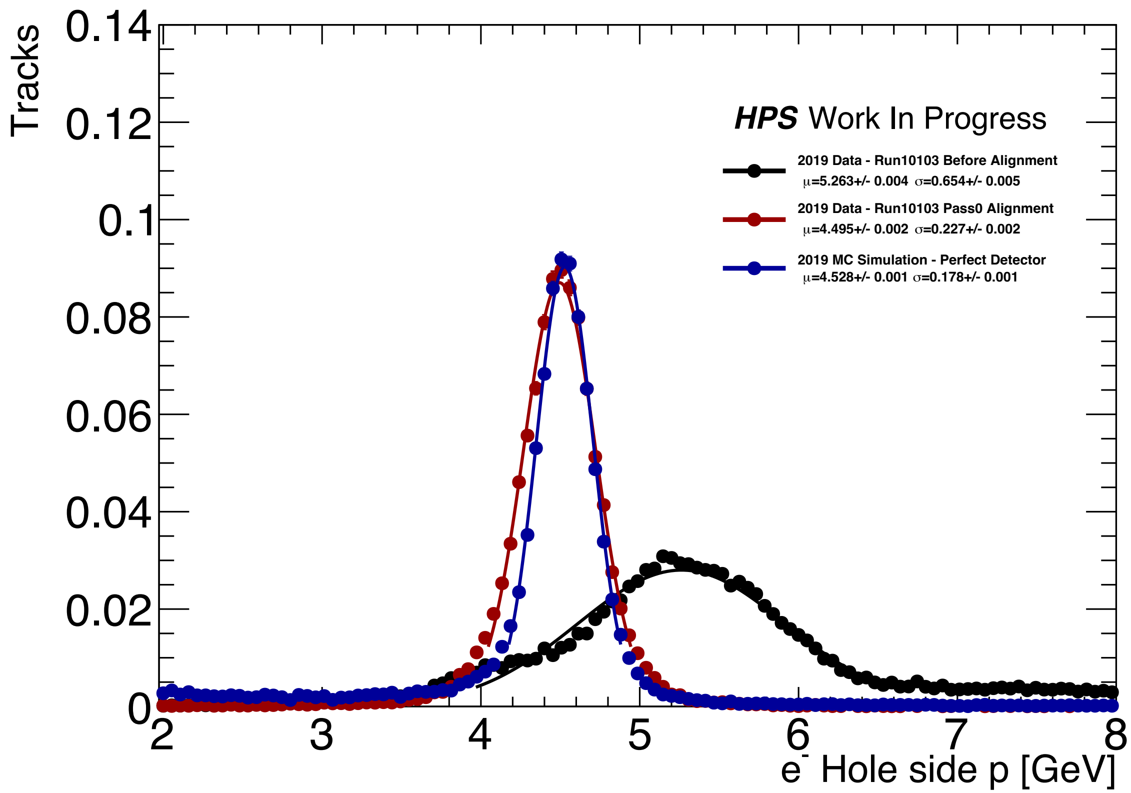


- HPS is a high-rate experiment (1MHz/crystal)
  - Time calibration is a key element for efficient removal of accidentals
- RF and cluster-wise time walk corrections
  - Resolution **better** than 4ns intrinsic FADC sampling period

- Energy calibration extracted from FEEs and wide angle bremsstrahlung events
- Correction of edge effects

arXiv:1610.04319

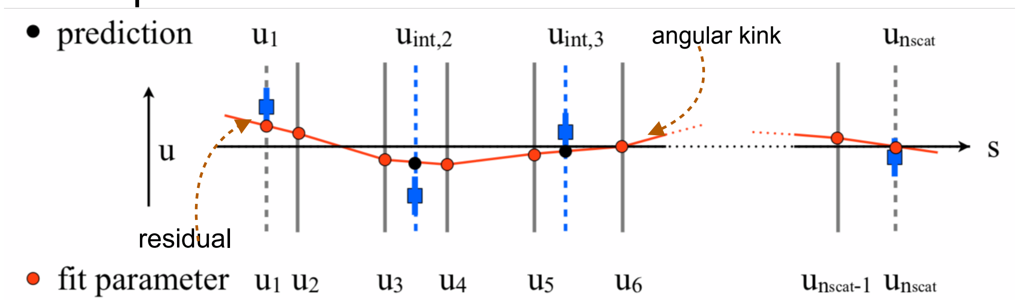
SVT Performance - Momentum Scale and Resolution

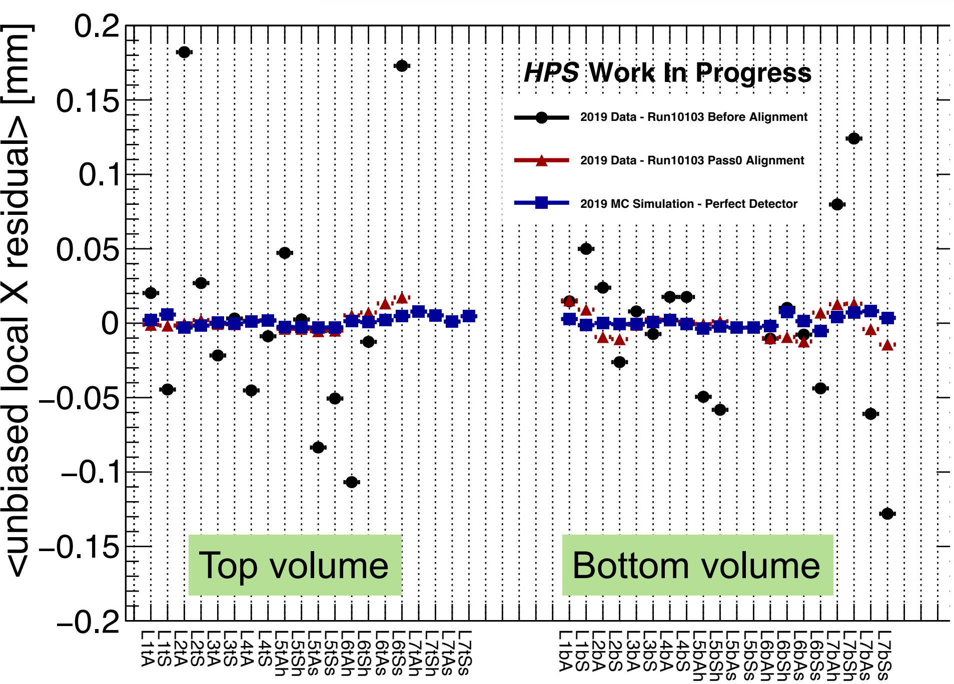


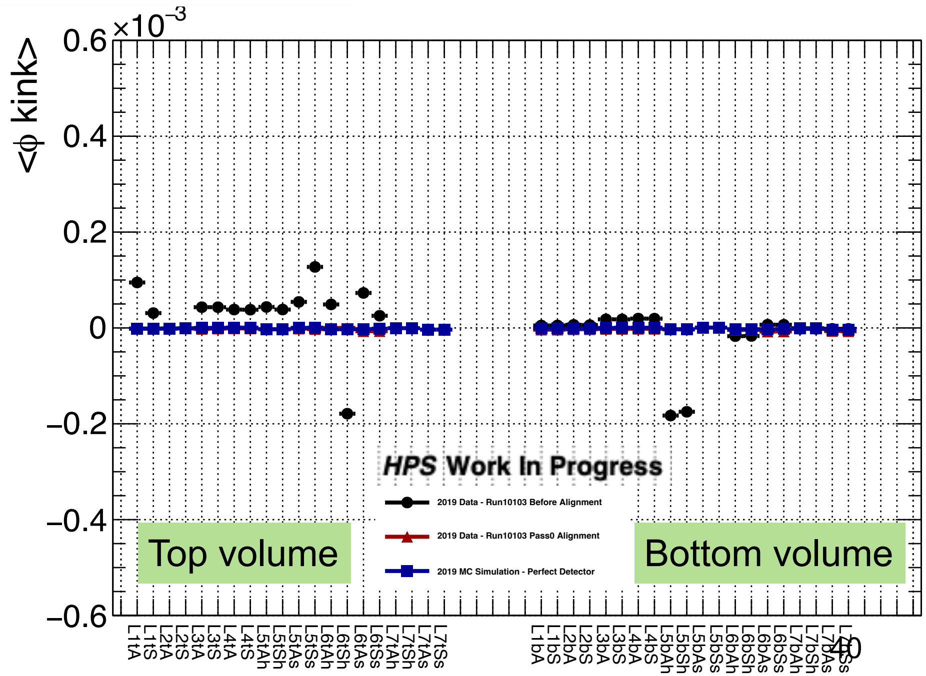
- Elastically beam scattered electrons are used to align the SVT with momentum scale constraint
- New techniques reach better Data/MC agreement in momentum distribution with respect previous analysis

Alignment performance - Unbiased Residuals

- Initial misalignments up to 200um recovered by current alignment procedure across all detector
- Residual misalignment from first calibration pass ~ 10um, work in progress
- Angular kinks as expected from MC ideal simulation



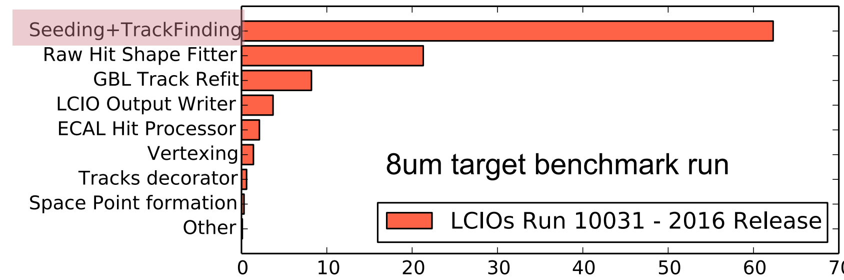


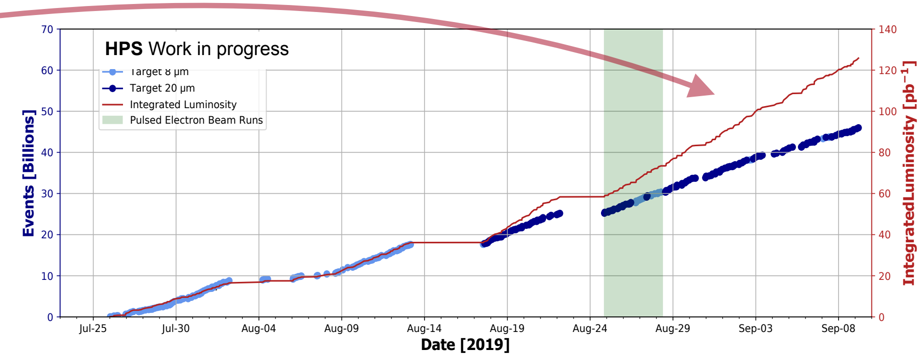


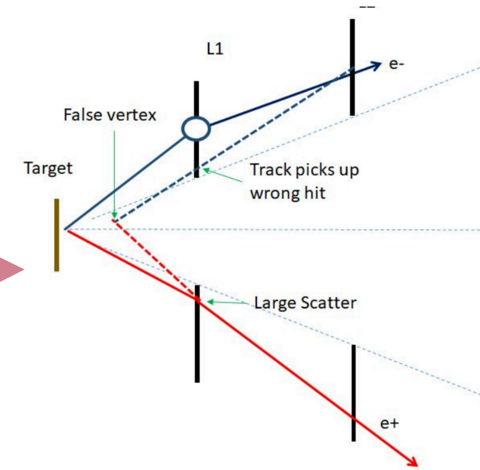
2019 Data Run - Reconstruction Upgrades

Track reconstruction upgrades

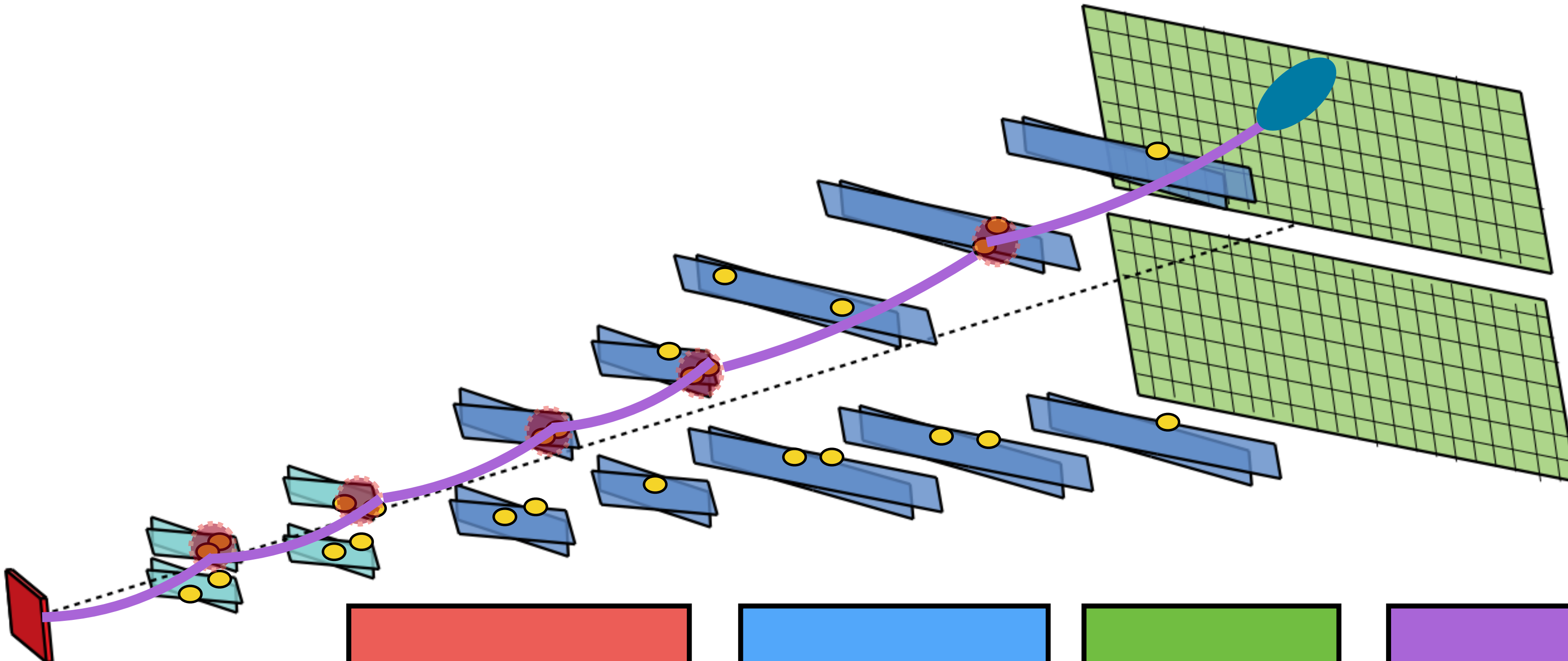
- The 2019 dataset is about **10x the integrated luminosity** with respect to the 2016 dataset
- Track reconstruction time takes **60%** of event reconstruction time
  - The thicker target $20\mu m$ will lead to even higher processing time
- **Single side** dead sensors or single side hit-**inefficiency cause the loss of the full hit**
  - In 2019 Ly 5 bottom axial sensor in positron bending side defective
- Current tracking doesn't provide any metric to reduce **hit-on-track mis-association**
  - Complicated background of vertex analysis that needed ad-hoc post-track fit topological cuts





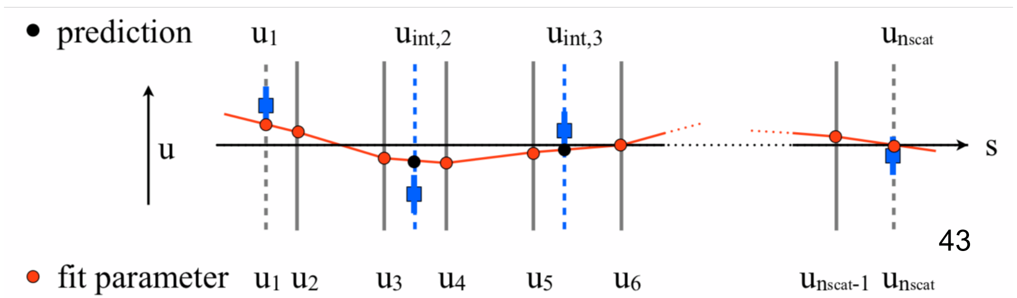


Tracking Upgrade - Legacy Track Reconstruction



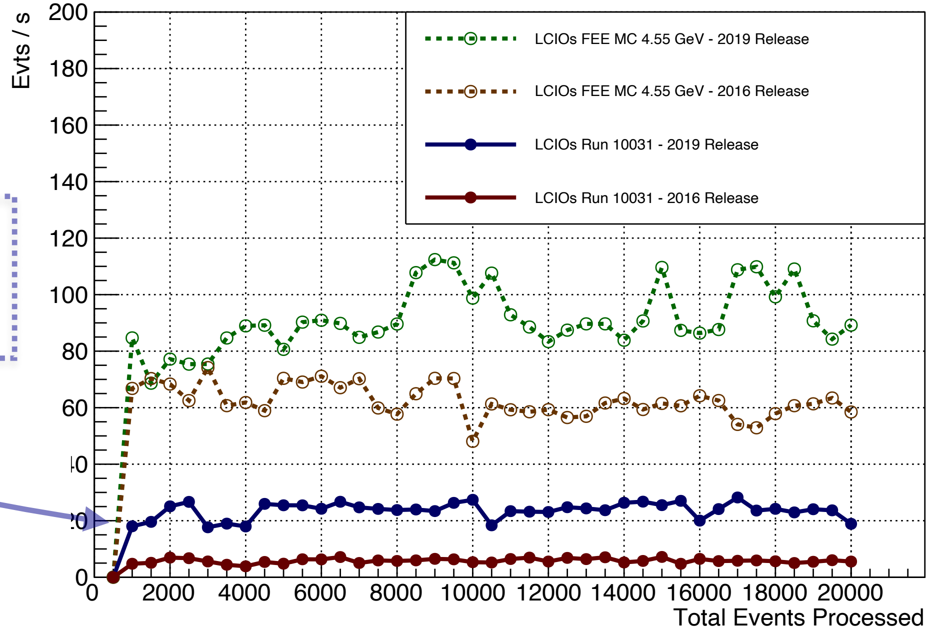
2D Clustering → 3D Space Points → Seed Finding (global Chi2) → Tracks (global Chi2) → GBL Refit

- General Broken Line
  - Multiple Scattering treatment
  - Alignment derivatives for Millepede II

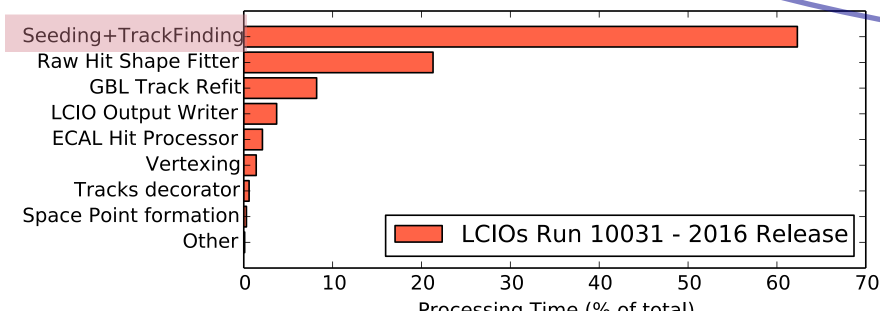


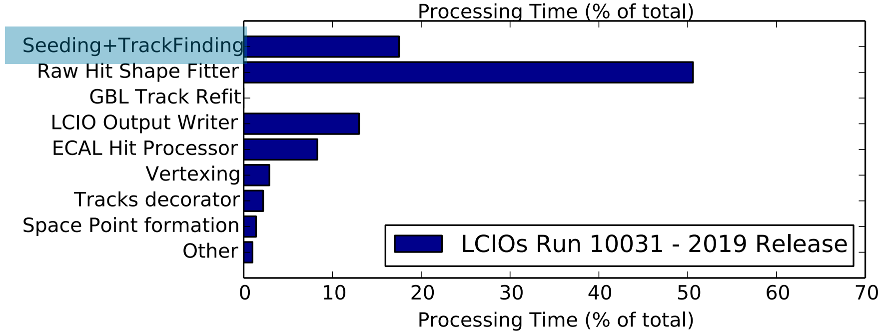
New Tracking - Computing Time

- New tracking procedure had the largest impact on cutting off the total processing time
- Track finding and fitting reduced from 60% to 20% of event reconstruction time
- With additional software optimisation techniques obtained a x5 speed up of event reconstruction (event dependent) in Data



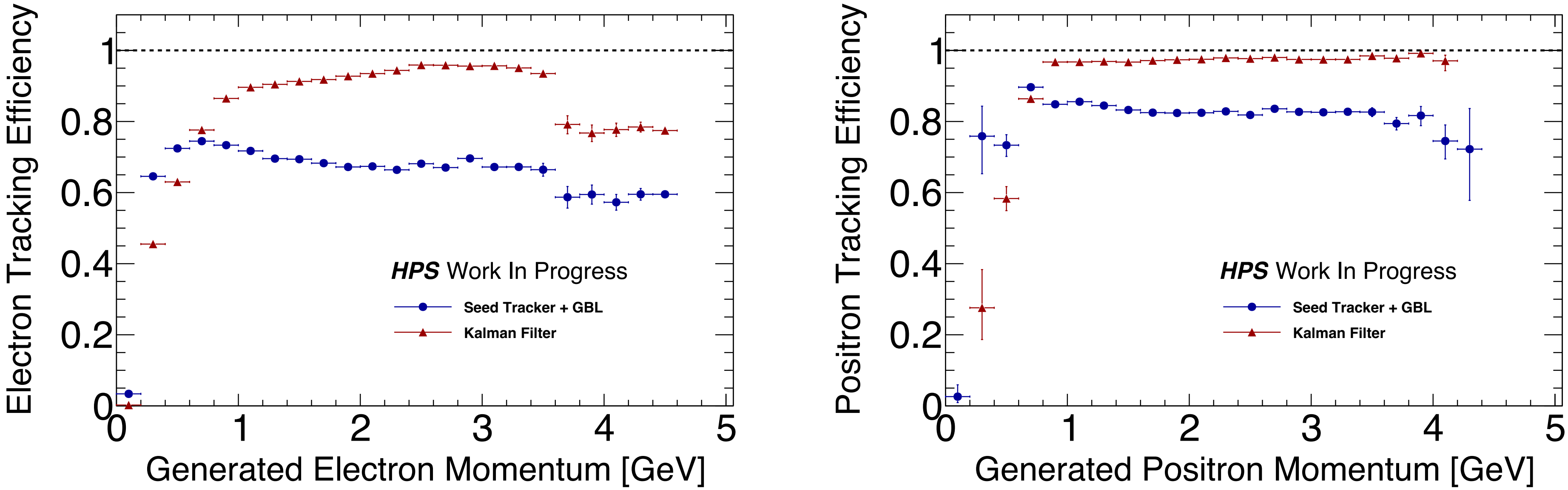
x5





- Pile-up responsible of lower processing time for physics analysis with respect to single-track events:
  - **Strip-hit signal shape fitting** for cluster charge/time estimation
  - **Pattern recognition combinatorics**

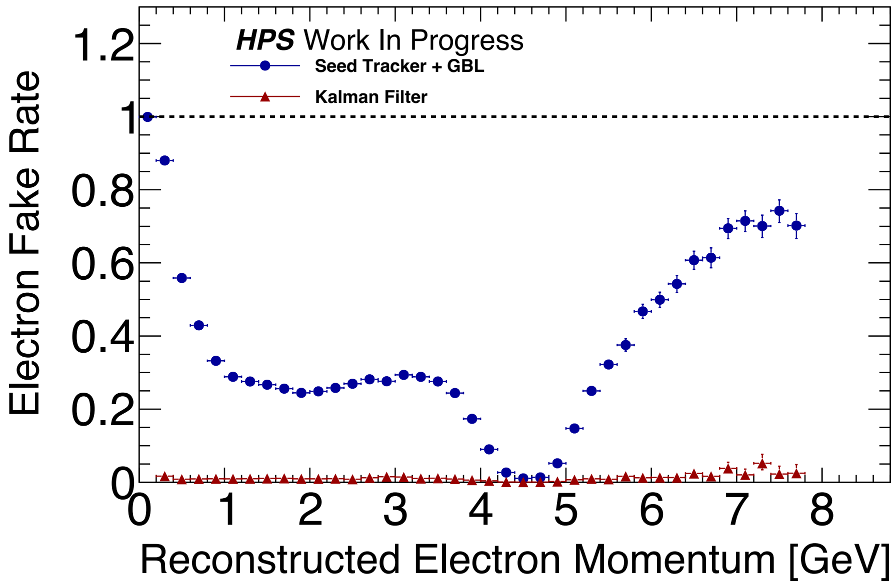
New Tracking - MC Simulation Distributions

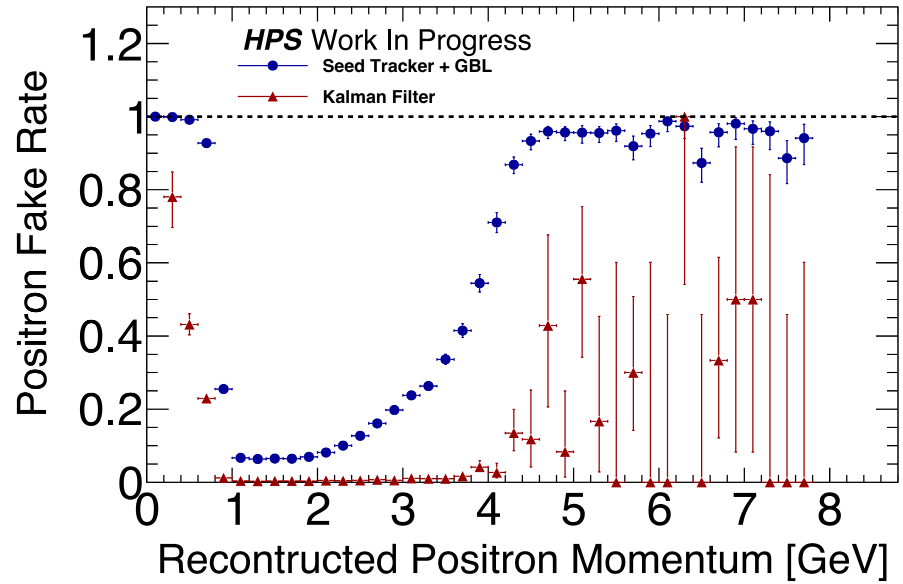


$$\epsilon(p_{truth}) = \frac{N^{recoTrack}_{matched}(p_{truth})}{N_{trackableMCP}(p_{truth})}$$

- $N^{recoTrack}_{matched}$ are the tracks required to have TrackP > 0.8
- The efficiency to find “high-quality” tracks is up to **>85% (>95%) for e^- (e^+)** across the physics range. Legacy tracking ranges between **70-75% (~85%) for e^- (e^+)**.
- Drop close to beam energy for e^- due to large fraction of generated beam scattered electrons hardly reconstructable at high-purity

New Tracking - MC Simulation Track Efficiency

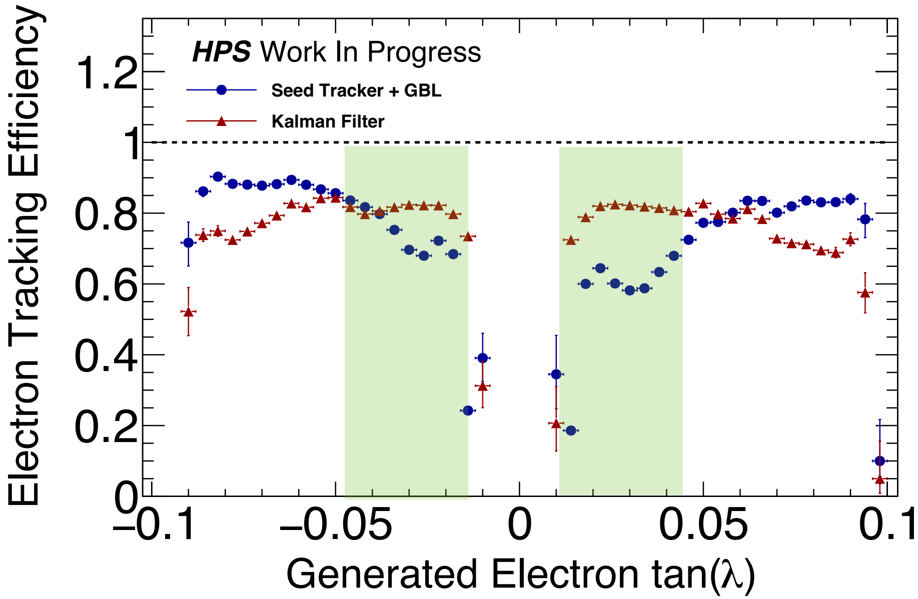


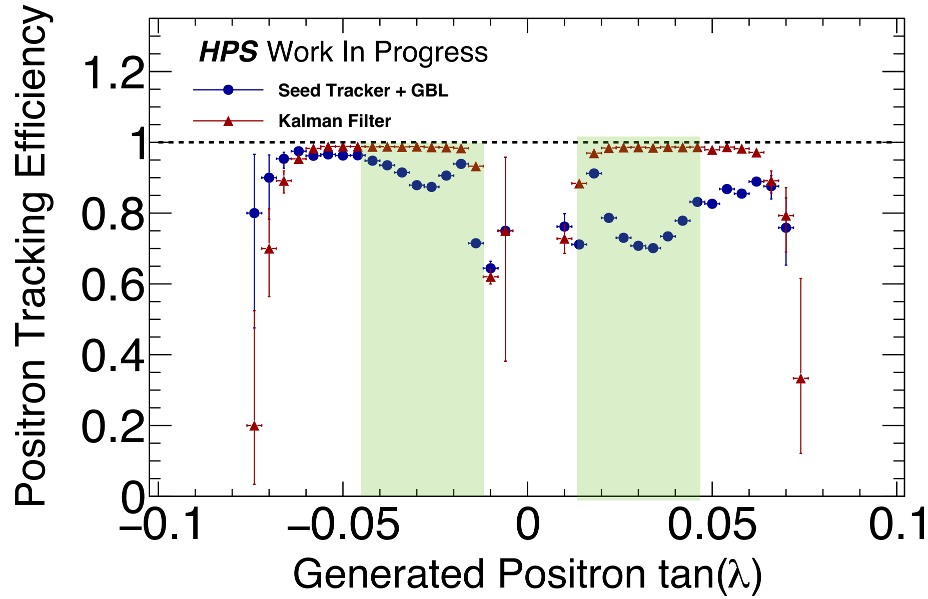


$$fake(p_{trk}) = \frac{N^{fakeTrack}(p_{trk})}{N^{recoTracks}(p_{trk})}$$

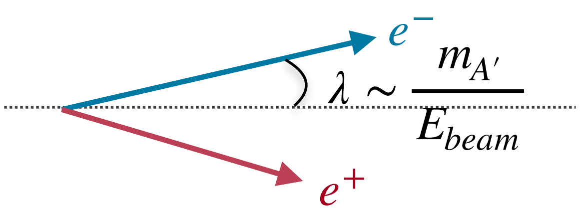
- $N^{fakeTrack}$ are the tracks with TrackP < 0.8
- Dip at 4.5 GeV for e^- due to large amount of elastically reconstructed electrons.
- Low momenta tracks have very poor quality and likely to be fake
- Fake rate ~30% (>10%) for e^- (e^+) across momentum spectrum for legacy tracking, **<2% for new tracking**

New Tracking - MC Simulation Track Efficiency



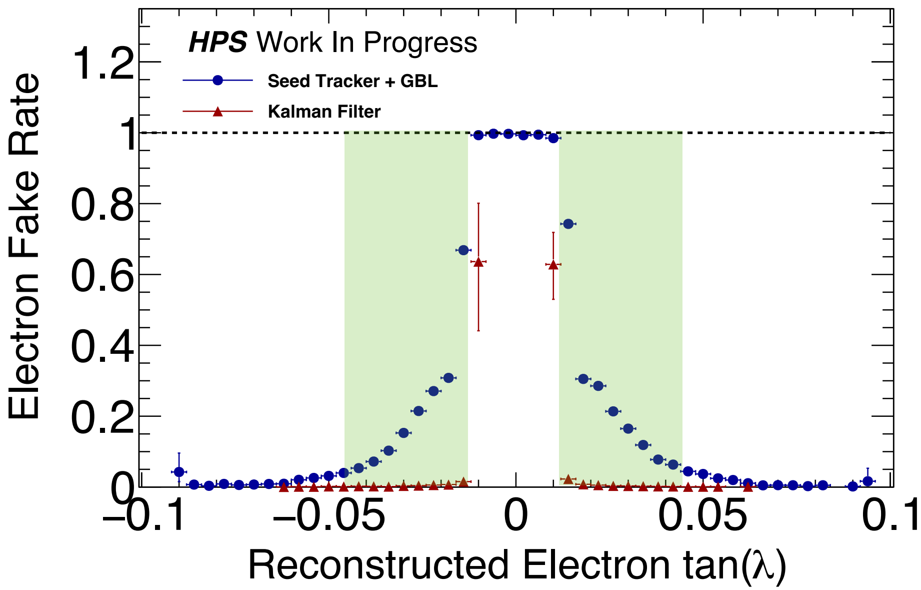


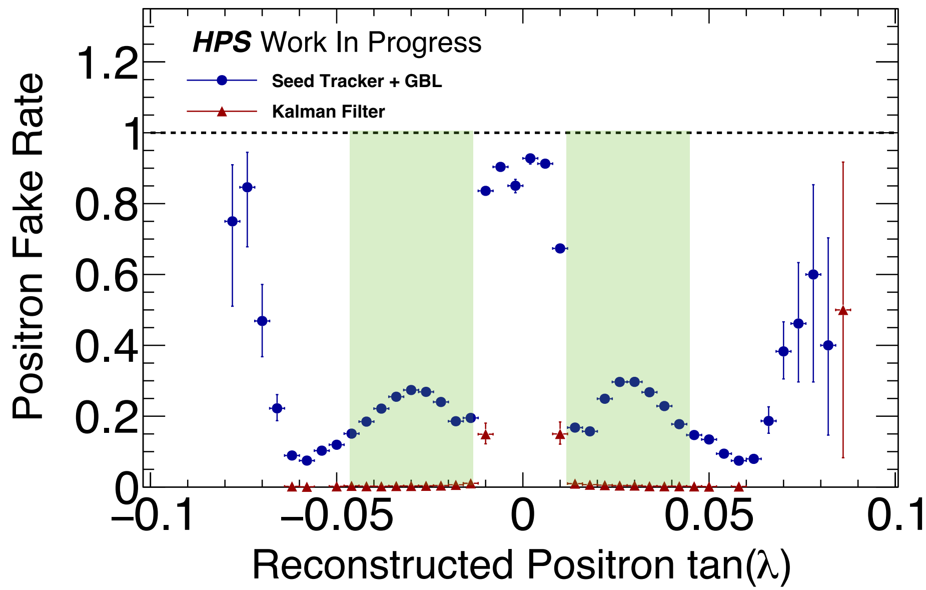
$$\epsilon(p_{truth}) = \frac{N_{matched}^{recoTrack}(p_{truth})}{N_{trackableMCP}(p_{truth})}$$



- $N_{matched}^{recoTrack}$ are the tracks required to have TrackP > 0.8
- The A' daughters are produced at very small angles from the beam plane.
- New tracking algorithms show much better high-quality reconstruction in physics region of interest

New Tracking - MC Simulation Fake Rate





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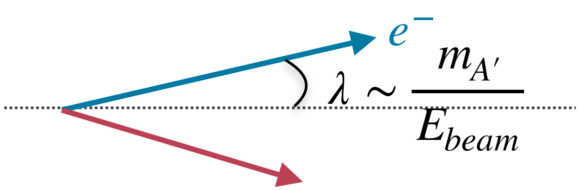

- $N^{fakeTrack}$ are the tracks with TrackP < 0.8
- Legacy tracker leads to several tracks with dip angle mis-reconstructed
- >30% (20%) legacy e^- (e^+) tracks have poor quality in the region of physics interest
- Fake rate is well below 2% for new tracking

Search for Dark Matter - Dark Photons

- Growing interest in the search of new forces mediated by sub-GeV scale force carrier
  - Could play essential role in DM physics
  - Complement to the search of new physics at higher ranges, e.g. LHC…

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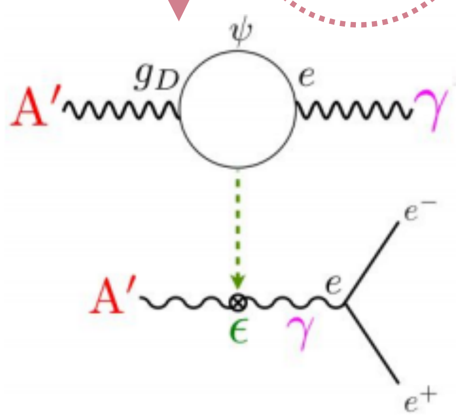
- DM features ↔ Hidden Sector
- **Heavy Photons** A' canonical example of new force coupling to DM
  - New spontaneously broken “dark” $U(1)'$ symmetry
  - Kinetic terms induced mixing to the SM photon $\rightarrow$ ϵe coupling to SM fermions

kinetic term

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

PRL B166, 1986



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  - New spontaneously broken “dark” $U(1)'$ symmetry
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A's circumvent the **“Lee-Weinberg Bound”** which requires dark matter mass > 2 GeV for interactions through weak SM bosons

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

kinetic term

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{\epsilon}{2} F^Y_{\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\nu\mu} F'_{\nu\mu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

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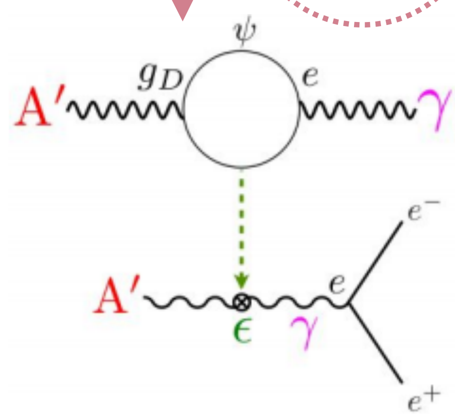
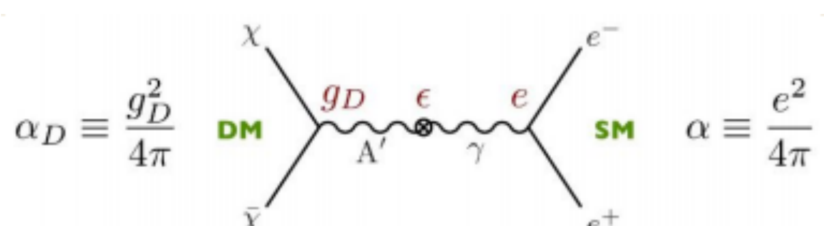


2 Parameter Model:
Mass of A' and ε

$$\epsilon \sim \frac{e g_D}{16\pi^2} \log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$



If one or both U(1) in GUT, ϵ as small as $\sim 10^{-7}$

Backup - Signal Rate - Displaced Vertex

SLAC

- A' kinematics are identical to virtual photon production, and the cross section for heavy photons of mass $m_{A'}$ can be related to virtual photons of the same mass by [arxiv:0906.0580]
  - $\sigma_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha} \frac{d\sigma_{\gamma^*}}{dm_{l^+l^-}}|_{m_{l^+l^-}=m_{A'}}$ ← All following calculations are for mass slice $m_{A'}$
- Number of events for both processes are given by:
  - $N_{\gamma^*} = \mathcal{L}\sigma_{\gamma^*}\epsilon_{\gamma^*}A_{\gamma^*} = \mathcal{L}\sigma_{\gamma^*}\phi_{\gamma^*}$
  - $N_{A'} = \mathcal{L}\sigma_{A'}\epsilon_{A'}A_{A'} = \mathcal{L}\sigma_{A'}\phi_{A'}(\epsilon^2)$ ← Combined acceptance and efficiency into one term
  - Displaced decay of A' leads to an acceptance/efficiency dependence on lifetime
- Re-writing top equation in terms of number of A' events:
  - $N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\epsilon_{vtx}\frac{dN_{\gamma^*}}{dm_{A'}}$
  - where $\boxed{\epsilon_{vtx} = \frac{\phi_{A'}(\epsilon^2)}{\phi_{\gamma^*}}}$ ("efficiency vertex") is ratio of combined detector acceptance and efficiency for A' and virtual photon decays into charged particles

SLAC

Expected Signal (Radiative Fraction)

- Expected signal proportional to radiative trident production rate

$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\epsilon_{vtx}\frac{dN_{\gamma^*}}{dm_{A'}}$$

Not measurable in data

- Relate Radiative Tridents to Background:
  - $\frac{dN_{\gamma^*}}{dm_{A'}} = f_{rad}\frac{dN_{bkg}}{dm_{reco}}$
  - where $\boxed{f_{rad} = \frac{dN_{\gamma^*}}{dm_{A'}} / \frac{dN_{bkg}}{dm_{reco}}}$ ("radiative fraction") is ratio of selected MC radiative trident events to MC background (WAB + Tridents)
- The expected signal is now related to the radiative fraction by

$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\epsilon_{vtx}f_{rad}\frac{dN_{bkg}}{dm_{reco}}$$

Backup - Signal Rate - Displaced Vertex

SLAC

- The last piece needed for the expected signal is the “efficiency vertex”
  - $N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\epsilon_{vtx}f_{rad}\frac{dN_{bkg}}{dm_{reco}}$ $\quad$ $\boxed{\epsilon_{vtx} = \frac{\phi_{A'}(\epsilon^2)}{\phi_{\gamma^*}}}$

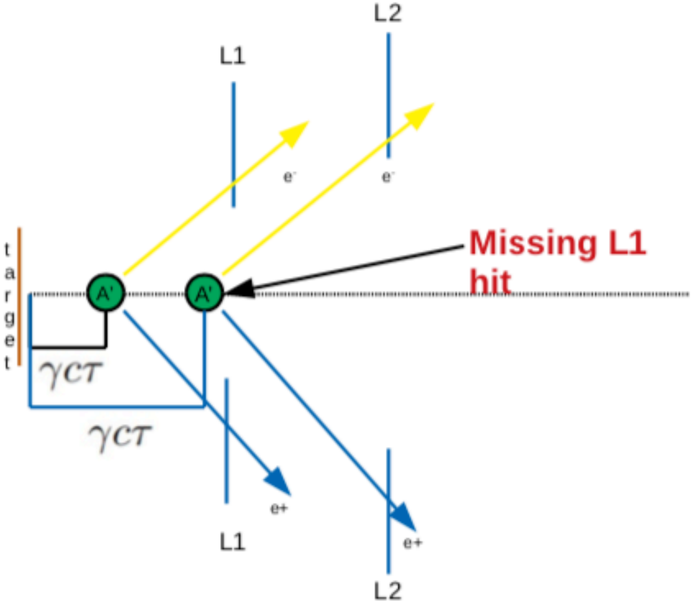
- Write acceptance/efficiency terms as integral of decay probability distribution multiplied by fraction of generated events that pass selection F(z)

- For virtual photons:
  - $\phi_{\gamma^*} = \int_{z_{tar}}^{\infty} \delta(z) F(z)dz$

Prompt decay of virtual photons

- For heavy photons:
  - $\phi_{A'}(\epsilon^2) = \int_{z_{tar}}^{\infty} p(\epsilon^2, z)F(z)dz$

Probability distribution depends on A' decay length



Backup - Signal Rate - Displaced Vertex

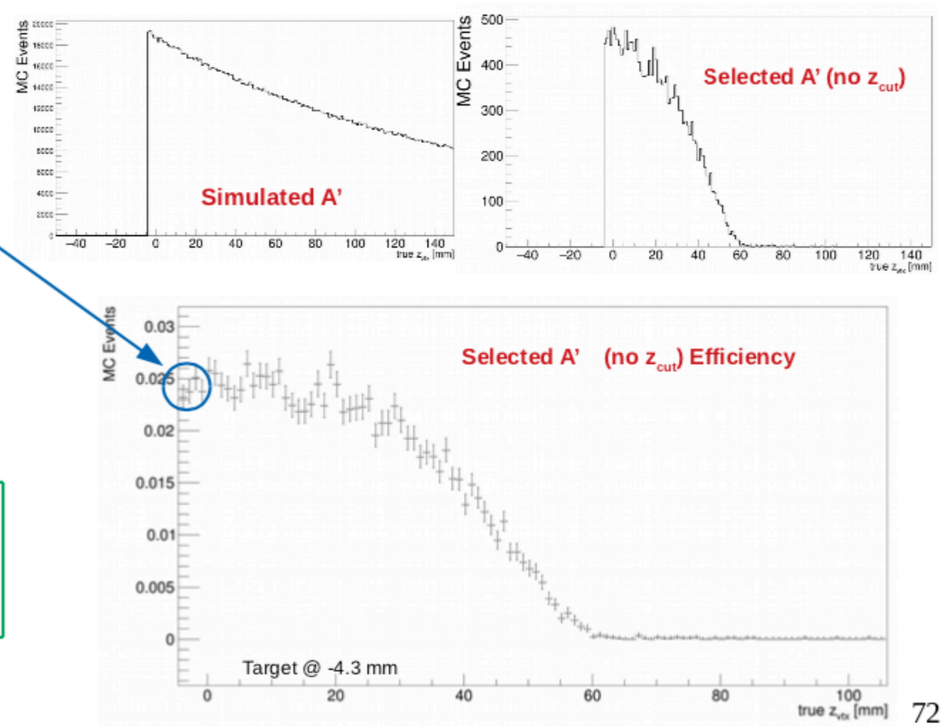
- For virtual photons, add scaling factor β, and define fraction of events passing selection at the target F(z=target) = 1
  - $$\phi_{\gamma^*}\beta = \int_{z_{tar}}^{\infty} \delta(z)\beta F(z)dz = 1$$
- Simplifies efficiency vertex
  - $$\epsilon_{vtx} = \frac{\phi_{A'}(\epsilon^2)}{\phi_{\gamma^*}} \longrightarrow \epsilon_{vtx} = \beta\phi_{A'}(\epsilon^2)$$
- Include scaling factor in A' efficiency/acceptance integral
  - $$\beta\phi_{A'}(\epsilon^2) = \int_{z_{tar}}^{\infty} p(\epsilon^2, z)\beta F(z)dz$$
- A' will travels distance z before decay, according to lifetime [arxiv:0906.0580]
  - $$\gamma c\tau \approx \frac{0.8cm}{N_{eff}}\left(\frac{E_0}{10GeV}\right)\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{100MeV}{m_{A'}}^2\right)$$
- Probability distribution in z for A', normalized to 1 when integrated from target → ∞
  - $$p(\epsilon^2, z) = \frac{\exp\frac{(z_{tar}-z)}{\gamma c\tau}}{\gamma c\tau}$$

$$\boxed{\epsilon_{vtx} = \int_{target}^{\infty} \frac{\exp\frac{(z_{target}-z)}{\gamma c\tau}}{\gamma c\tau}\beta F(z)dz}$$

Backup - Signal Rate - Displaced Vertex

- Efficiencies taken from histograms for simulated A’ true z_{vtx} and selected A’ (no z_{cut}) true z_{vtx}
- β is the efficiency for prompt decays, so average of first 3 bins at target = β
- Recall: Calculations are done for a particular $m_{A'}$, so efficiencies re-calculated for every A’ mass

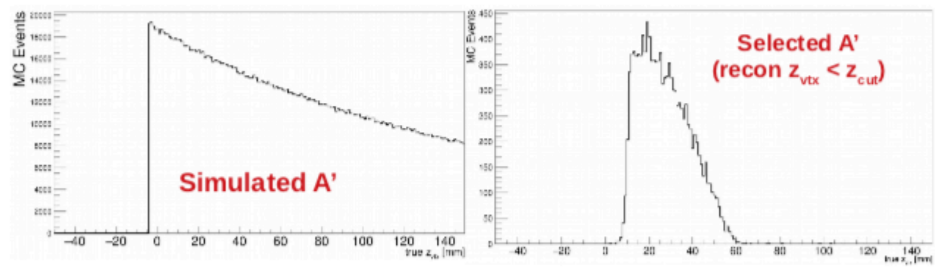
$$\epsilon_{vtx} = \int_{target}^{\infty} \frac{\exp\frac{(z_{target}-z)}{\gamma c\tau}}{\gamma c\tau} \beta F(z) dz$$

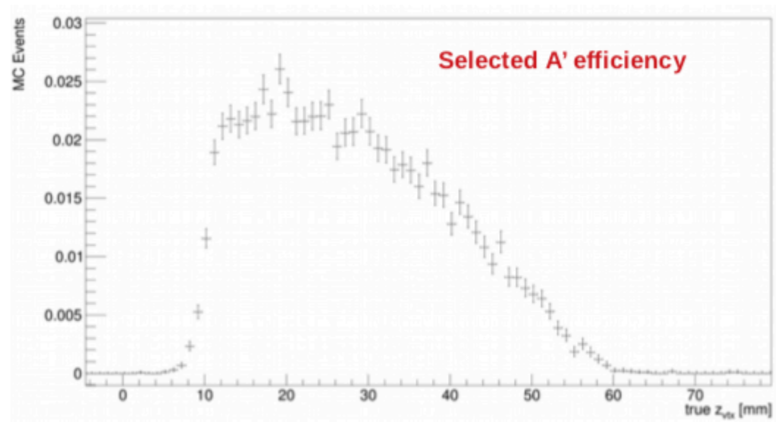


Backup - Signal Rate - Displaced Vertex

- Efficiencies taken from histograms for simulated A' true z_{vtx} and selected A' true z_{vtx}
  - Only selected A' vertex where reconstructed $z_{vtx} < z_{cut}$ are included
- F(z) = Efficiency(z)
- Integral evaluated as sum over bins in z
- Efficiency Vertex calculated for every $m_{A'}$, ε^2

$$\epsilon_{vtx} = \int_{target}^{\infty} \frac{\exp\frac{(z_{target}-z)}{\gamma c\tau}}{\gamma c\tau}\beta F(z)dz$$





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Backup - Signal Rate - Displaced Vertex

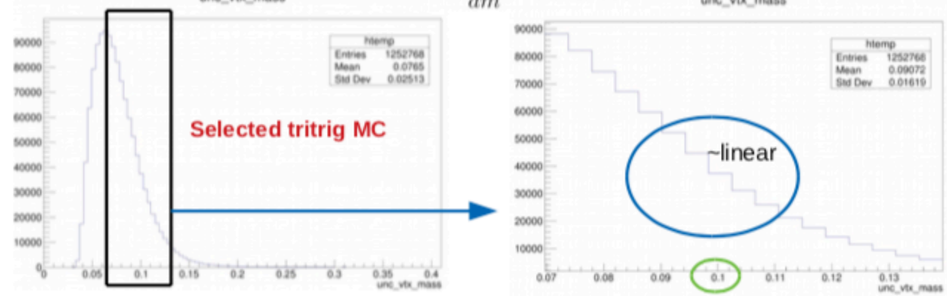
- The last thing needed for the expected signal is the background rate

$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\boxed{\epsilon_{vtx}}\boxed{f_{rad}}\boxed{\frac{dN_{bkg}}{dm_{reco}}}$$

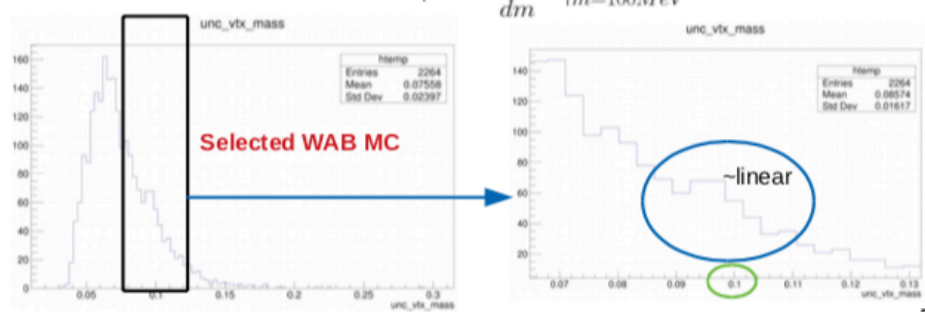
- Background = (tridents + WABS + beam)
- Take tritrig & WAB MC reconstructed and selected events. For $m_{A'}$, select mass window centered on $m_{A'}$ with width in linear region
- Count luminosity corrected background events within mass window, and divide by number of mass bins to get

$$\boxed{\frac{dN_{bkg}}{dm_{reco}}}$$

Example: $\frac{dN_{tridents}}{dm}|_{m=100MeV}$



Example: $\frac{dN_{WAB}}{dm}|_{m=100MeV}$



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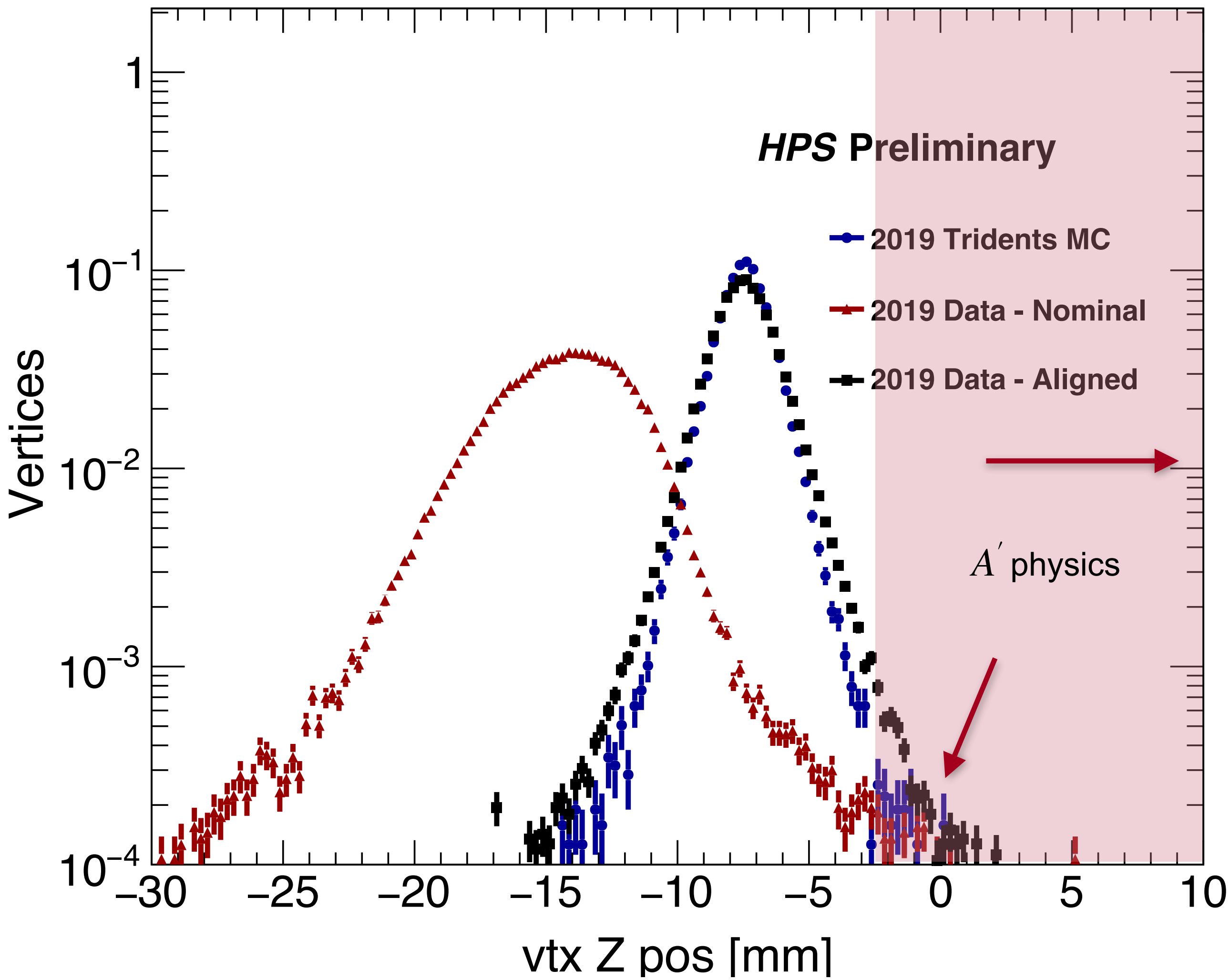
Vertex distribution



HPS - 2015 Engineering Run Published Results

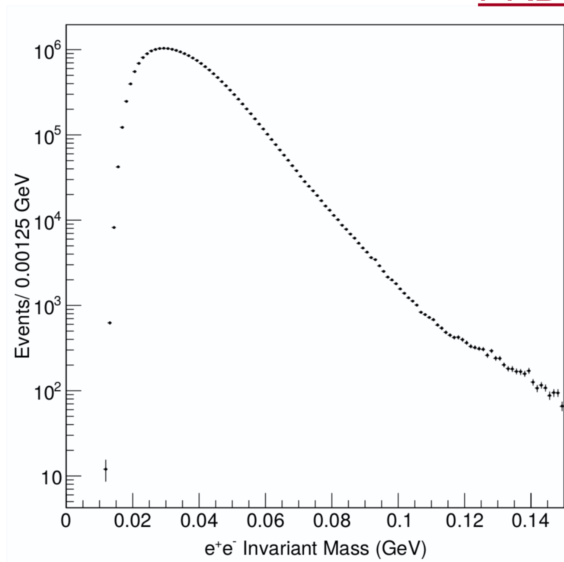
SLAC

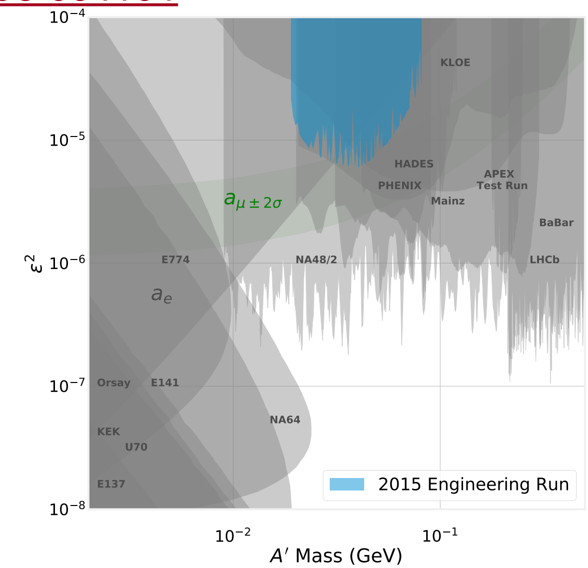
[PRD 98 091101]

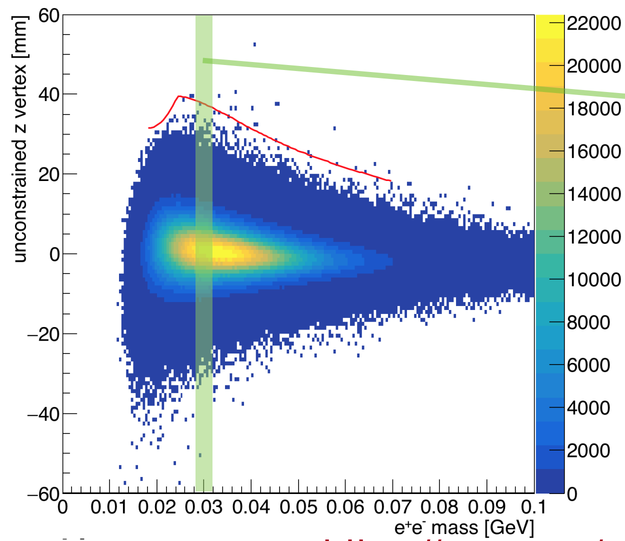
- Both 2015 Engineering run resonance and displaced vertex analysis are completed
  - Important benchmark for tracker and calorimeter performance
- No resonance found on the $m(e^+e^-)$ invariant mass
  - Upper limits $\epsilon^2 > 6 \times 10^{-6}$
- Displaced Vertex analysis
  - Look for vertices at displaced z location wrt target position
  - No sensitivity
  - Best upper limit:

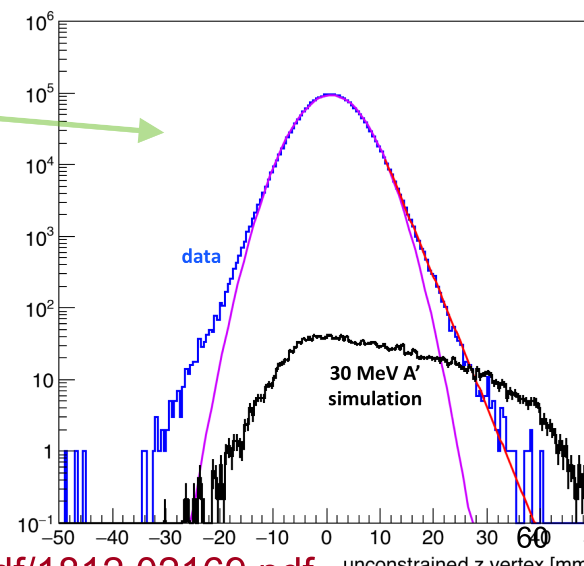
$35.7 \times \sigma_{A'}$

$m_{A'} = 51.4$ MeV, $\epsilon^2 = 1.7 \times 10^{-9}$





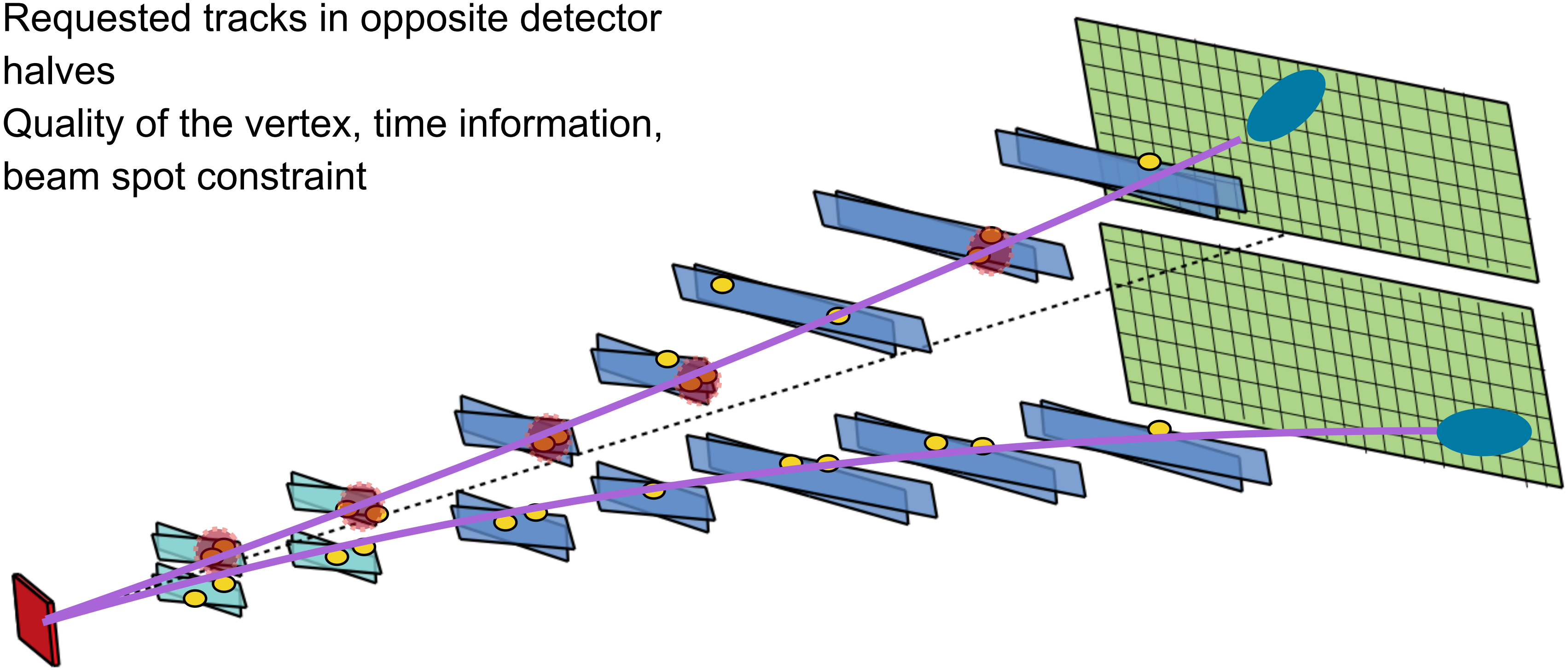




[https://arxiv.org/pdf/1812.02169.pdf]

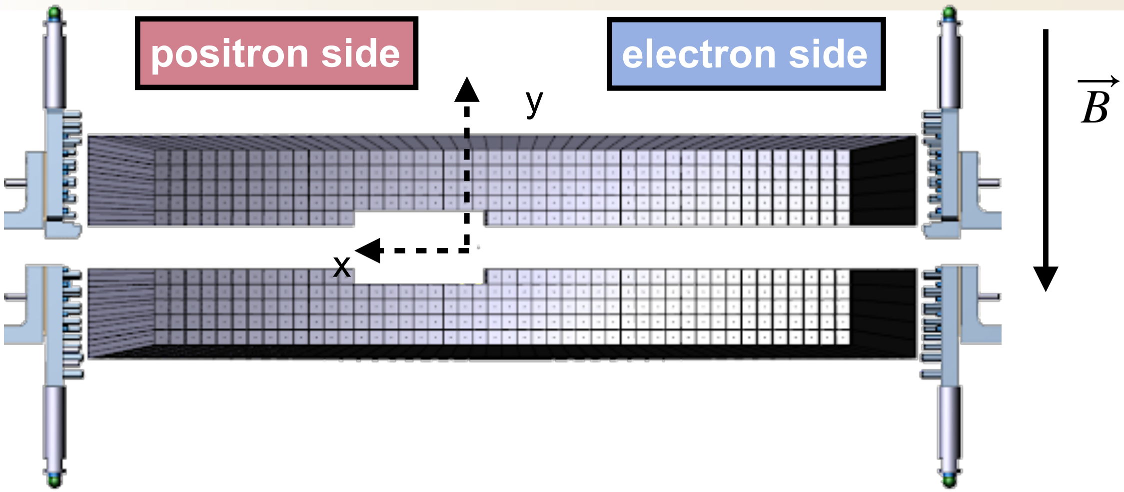
Track and Vertex Reconstruction

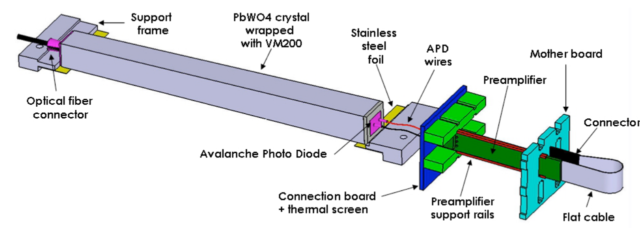
- Requested tracks in opposite detector halves
- Quality of the vertex, time information, beam spot constraint



2D Clustering → 3D Space Points → Seed Finding (global Chi2) → Tracks → Final State Particles

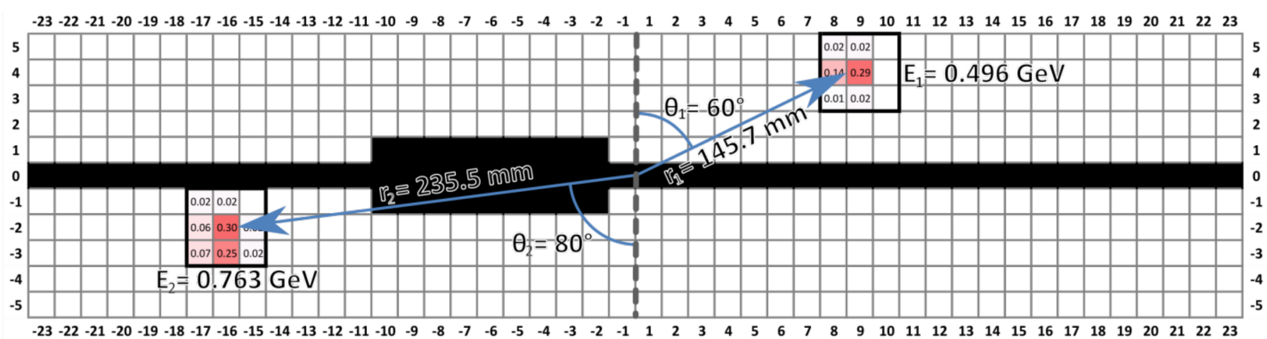
Electromagnetic calorimeter





- 442 $PbWO_4$ crystals coupled to avalanche photodiode readout (2 identical halves of 5x46 cells)
- Cells: 16cm long, front face 13x13 mm²
- σ_E/E @ 1.06 GeV (@2.2 GeV) $\sim 4\,\%\,(3\%)$
- σ_t @ $E \geq 200$ MeV ≤ 1 ns
- $\sigma_{pos} \sim 1-2$ mm

- Readout at 250 MHz allowing for 8ns trigger window
- Trigger and DAQ at rate > 100 kHz
- Physics trigger menu' composed by **coincidence pairs** in opposite halves of ECal
- Readout architecture of the SVT limits the readout rate to 50 kHz

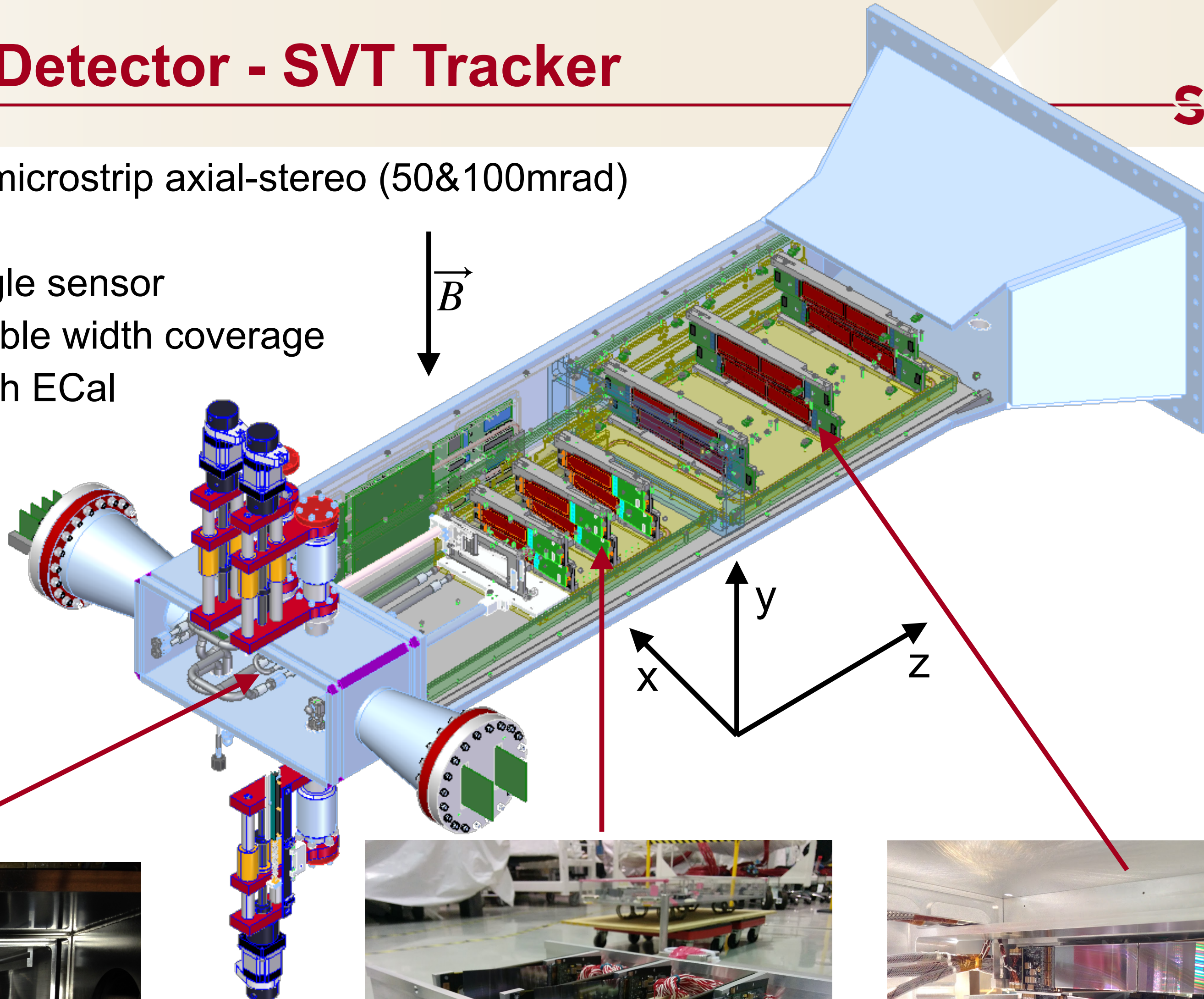


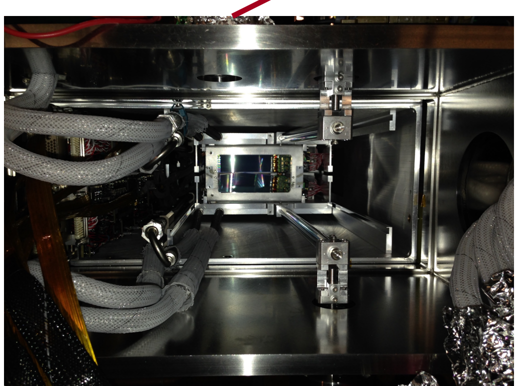
- **Coplanarity cut:**

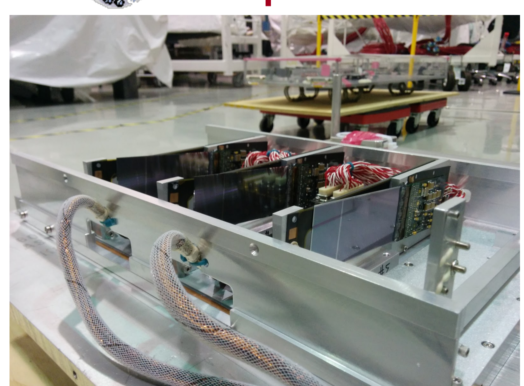
  - $e^+ - e^-$ pair are bent in opposite directions on the same plane

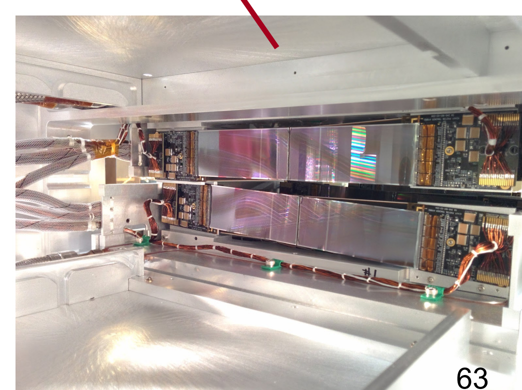
The HPS Detector - SVT Tracker

- Six Layers of Si microstrip axial-stereo (50&100mrad) modules
  - Layer 1-3: single sensor
  - Layer 4-6: double width coverage for better match ECal acceptance
- 36 Sensors
- 180 APV25 chips
- 23,004 channels in total

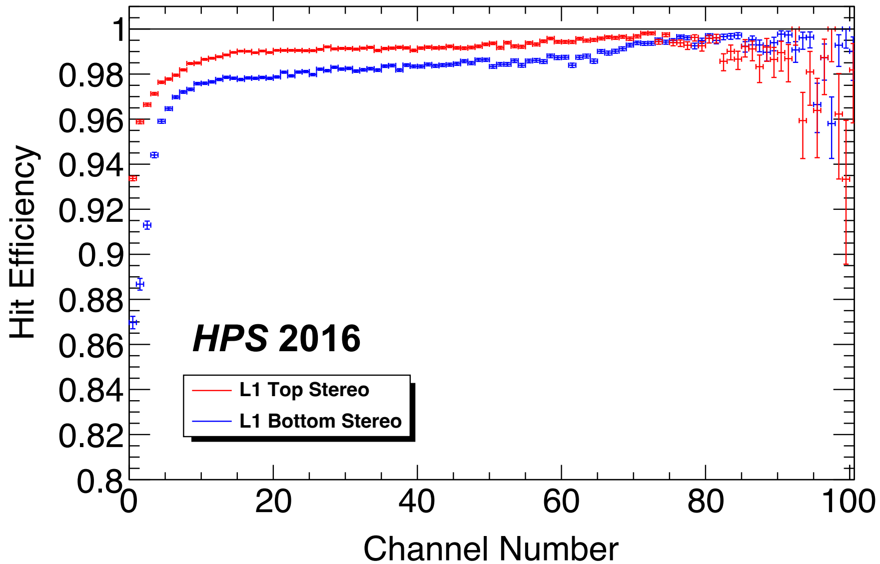


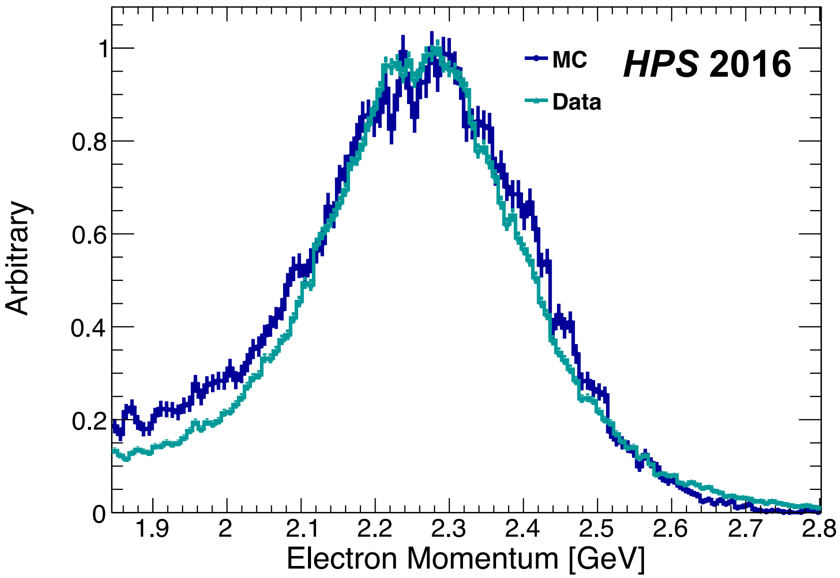






SVT Detector Performance





- Hit-efficiency > 90% across the whole SVT detector
- Slightly worse in inner edges of innermost layers (close to electron beam)
  - Track extrapolation error
  - High pile-up conditions

- Momentum scale and resolution from elastically scattered full beam electrons (FEEs)
- Multiple scattering dominated
- MC Fee momentum is smeared to match data distribution with smearing factor Σ (1.3 - 1.6) depending on track selection criteria