The Heavy Photon Search Experiment
Summary and Recent Developments For 2019 Data Run

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SCIPP
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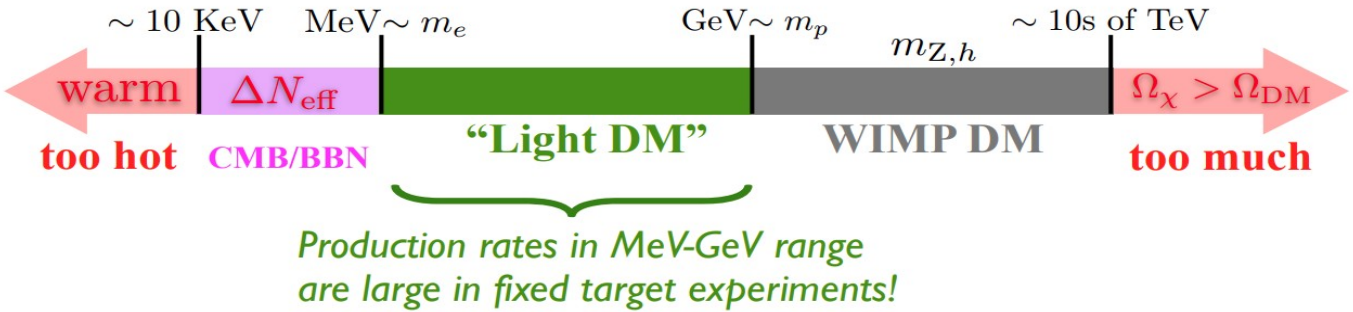
Introduction

- Interest growing in thermal **light (sub-GeV) dark matter** candidates, which require new light gauge boson
- The Heavy Photon Search (HPS) is a **fixed target experiment** at **Jefferson Lab** focused on detecting the heavy photon (A'), a finite-lifetime mediator connecting SM→Dark-Sector
- HPS utilizes a **mass resonance search** and a **displaced vertex search**
- After 2015+2016 Engineering Runs, analysis driven upgrades have been implemented for **2019 Data Run**, showing expected improvements to the A' displaced vertex search



2015 published results → Search for a Dark Photon in Electro-Produced e+e- Pairs with the Heavy Photon Search Experiment at JLab

Search for Dark Matter – Dark Photons

Assume an **additional $U_D(1)$ gauge symmetry** gives rise to a **new gauge boson (A')**

Kinetic mixing leads to coupling of A' to SM photon

Induces weak effective coupling of εe to SM fermions

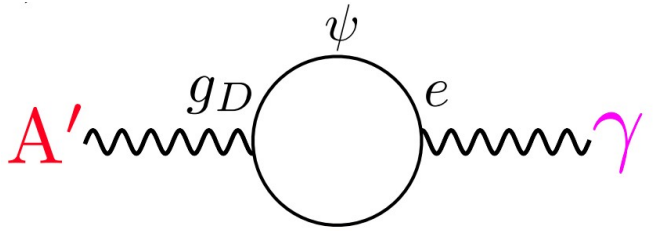
$$\epsilon \sim \frac{e g_D}{16\pi^2} log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$

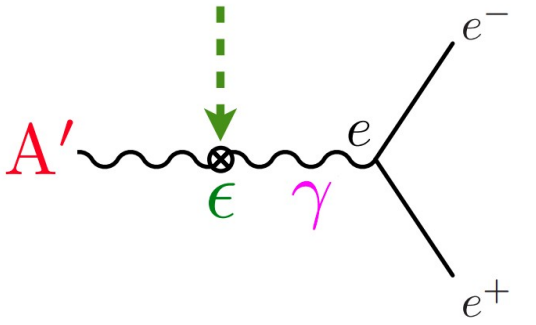
Assume $M_{A'} < 2M_\chi$ & $M_{A'} < 2M_\mu$

A' decay → $e^+ e^-$

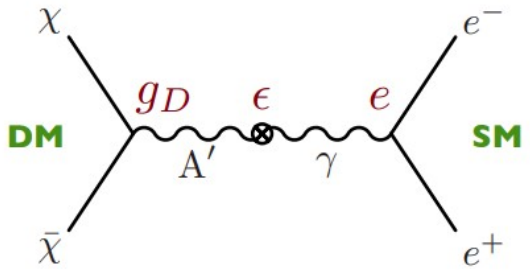
Kinetic mixing

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F_Y^{\mu\nu} F_{Y,\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} \epsilon F'^{\mu\nu} F_{Y,\mu\nu}$$





$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$



$$\alpha \equiv \frac{e^2}{4\pi}$$

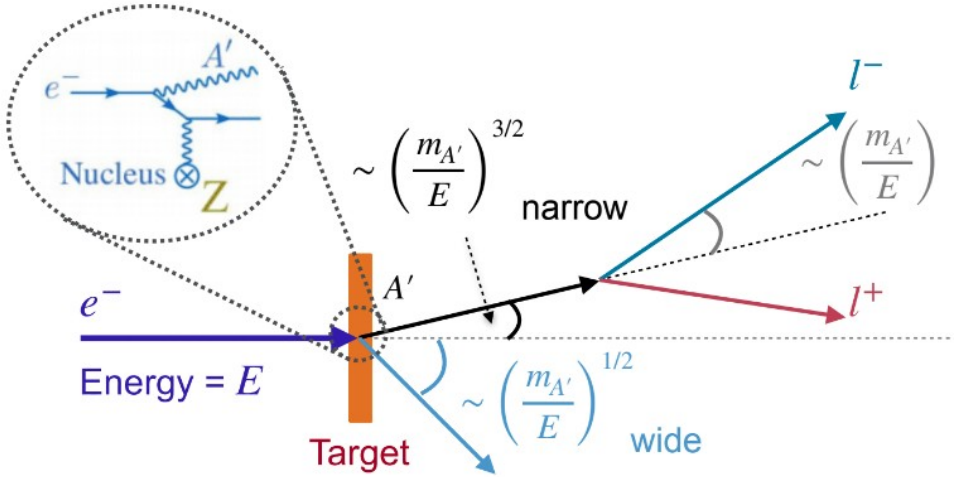
Search for Dark Matter – Dark Photons

- A' production via **fixed target dark bremm**, sharply peaked at $E_{A'} = E_{beam}$
- Electron beam provided by **Jefferson Lab CEBAF**
- $A' \rightarrow e^+e^-$ narrow opening angle $m_{A'}/E_{beam}$
- Short, but finite lifetime motivates **displaced vertex search** O(mm)
- Small production cross-section + large prompt QED background
- Requires sensitive, forward acceptance detector **0.5 mm from beam**

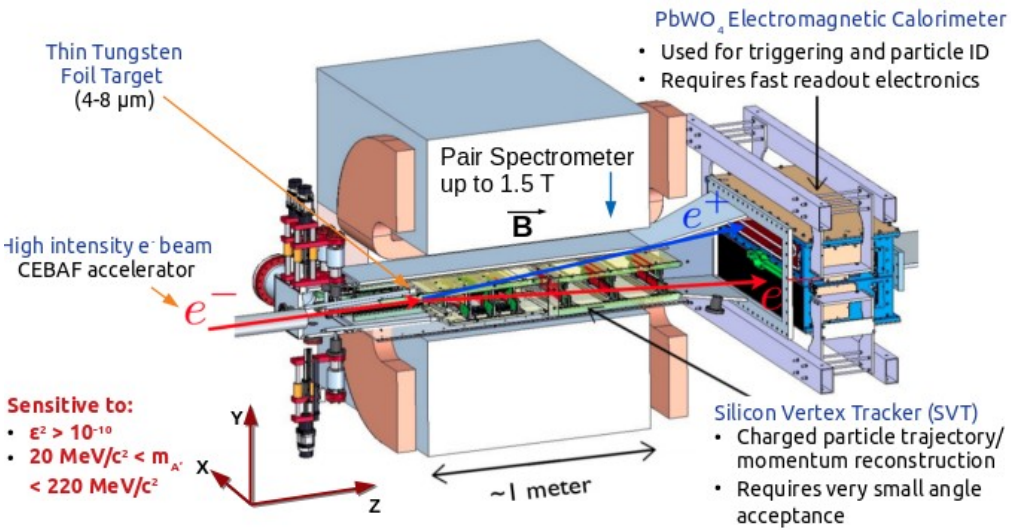
Lifetime

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

"Dark Bremm"

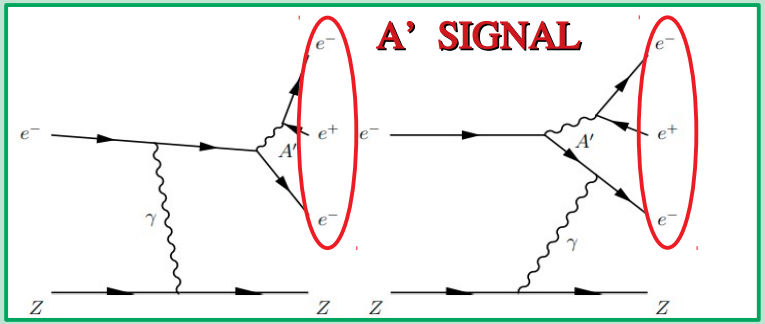


HPS Apparatus



A' Signal and Backgrounds

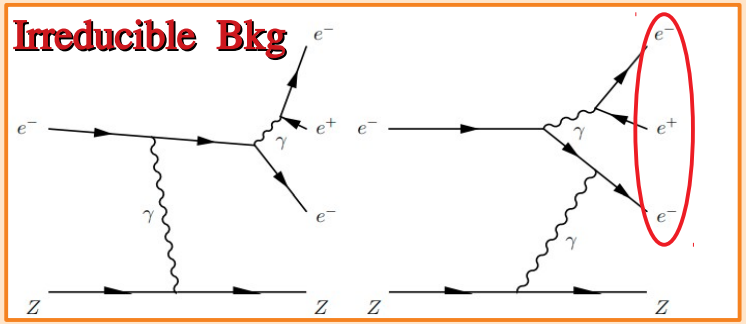
Heavy Photons



Only distinguishable through mass resonance or displaced vertex

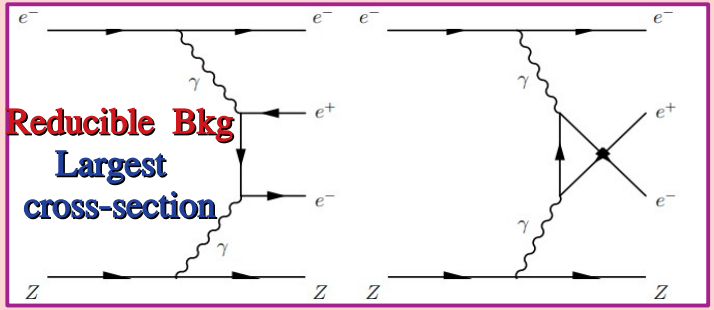
Radiative Tridents used to calculate expected A' production rate in MC

Radiative Tridents

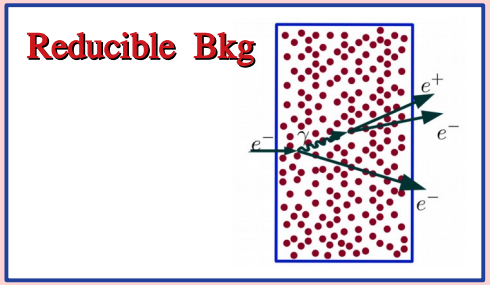


Backgrounds reducible through kinematic cuts

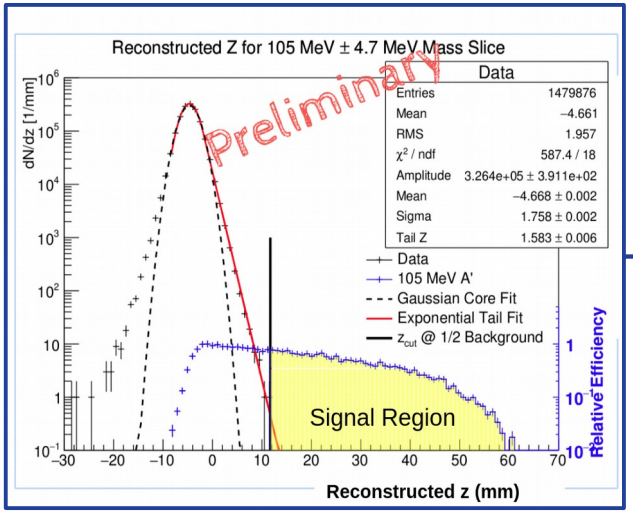
Bethe-Heitler Tridents



Wide-Angle Bremsstrahlung

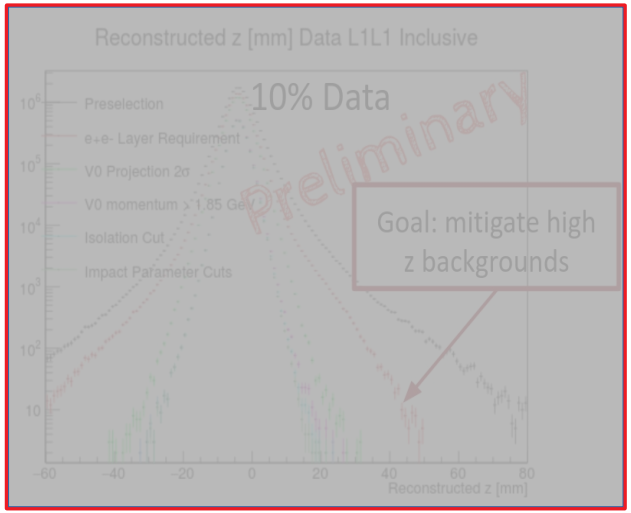


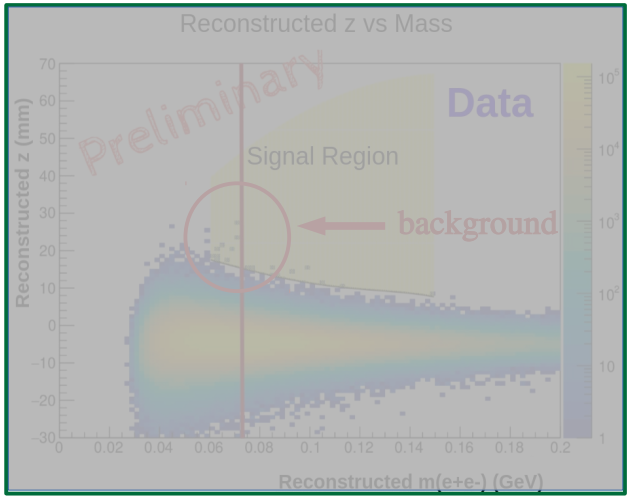
2016 Preliminary Displaced Vertex Search Results

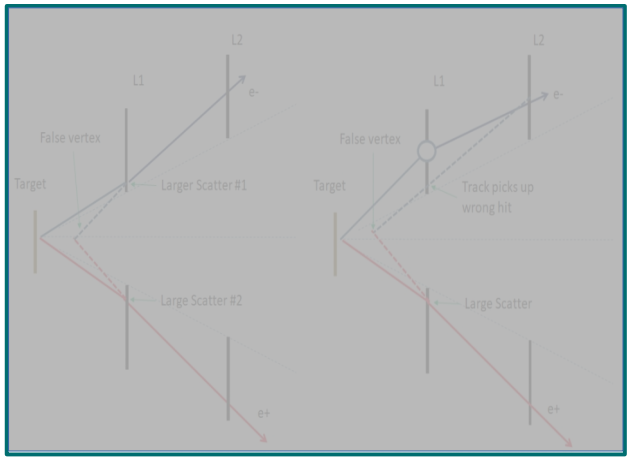


A' signal is displaced decay vertex in z

Signal region = Vtx_z w/< 0.5 bkg events







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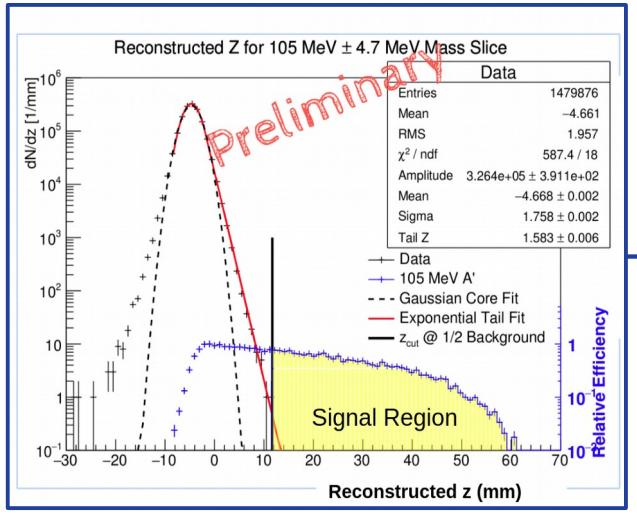

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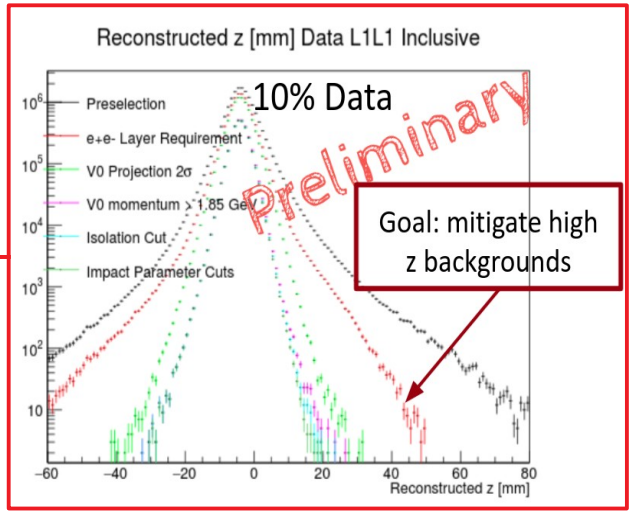
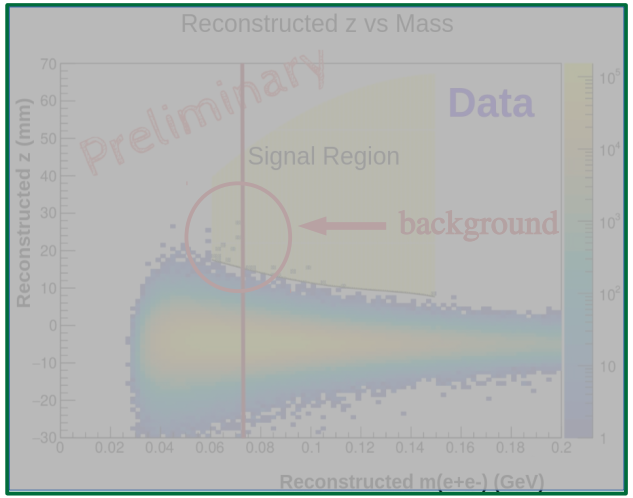
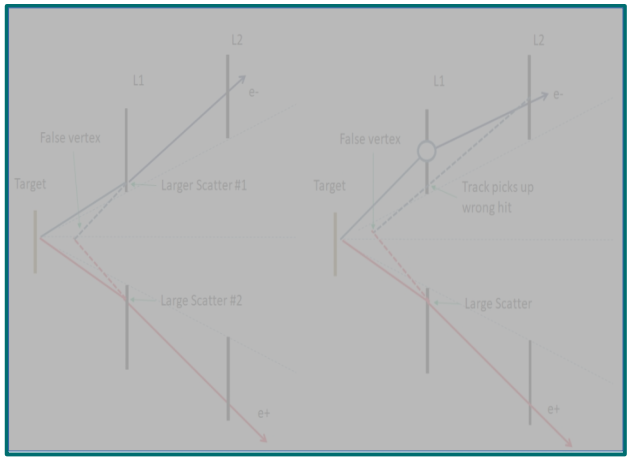
Z vertex distribution shows large background from tridents in signal region

Background reduced through series of cuts







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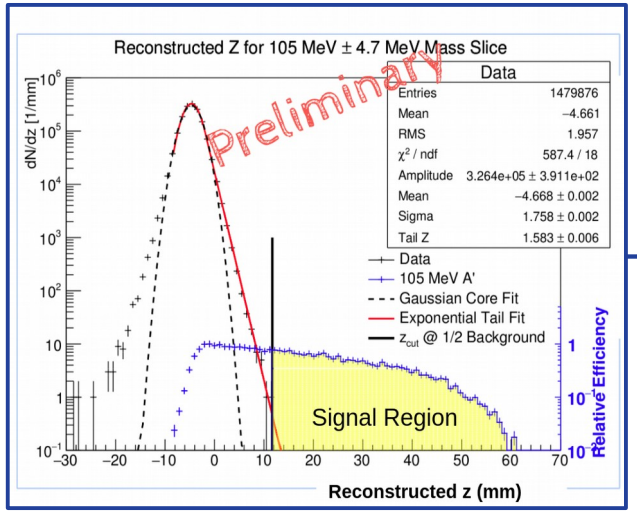

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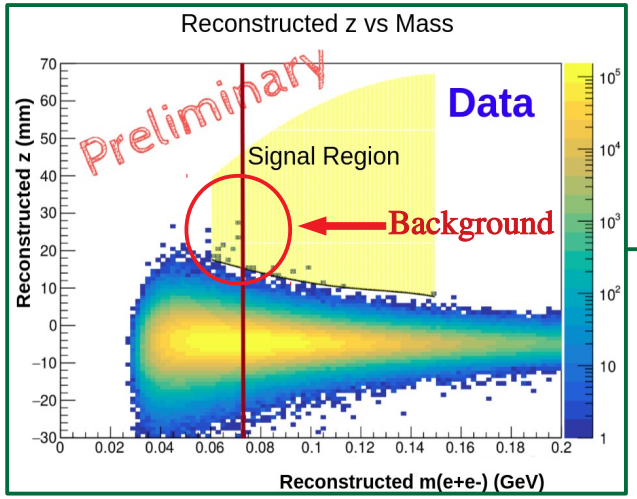

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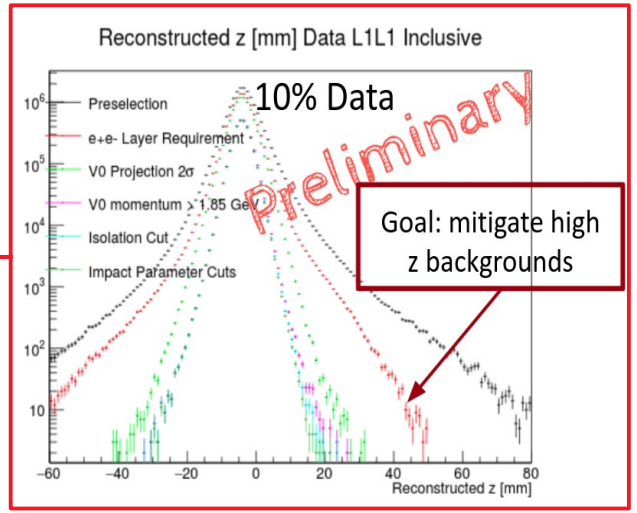

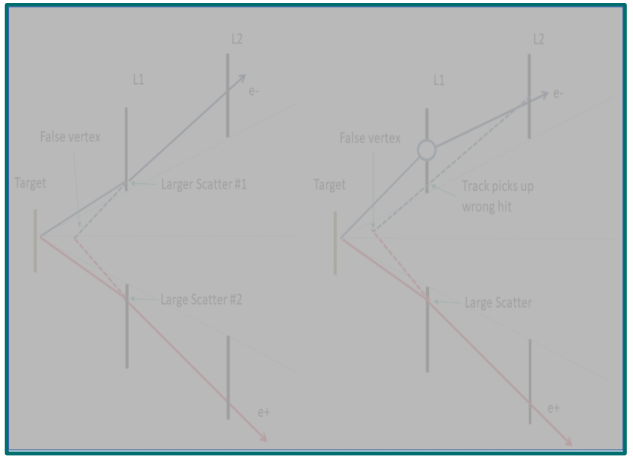

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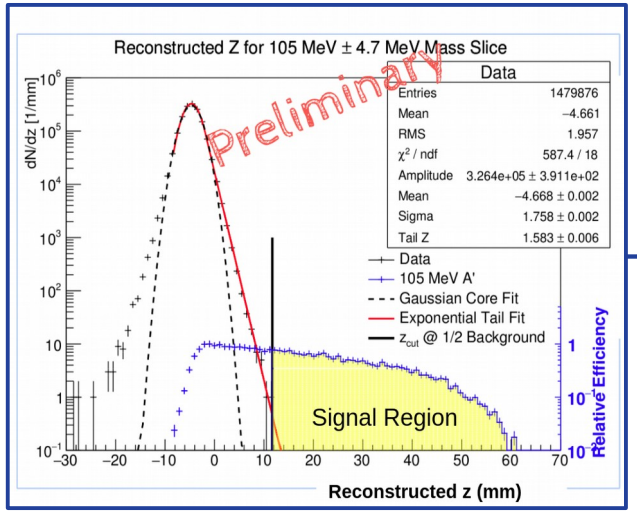

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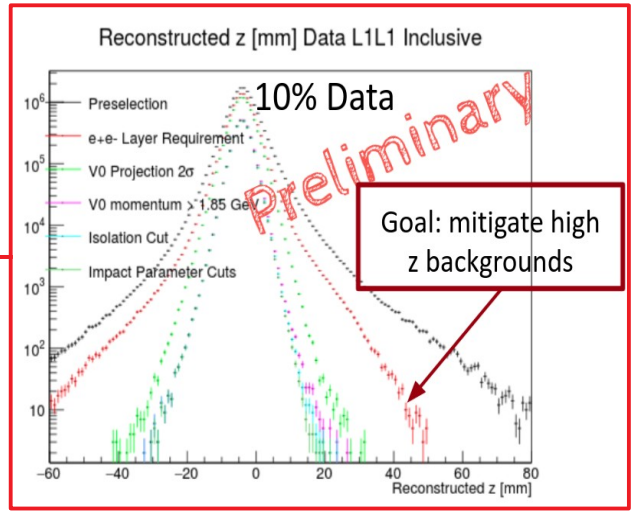

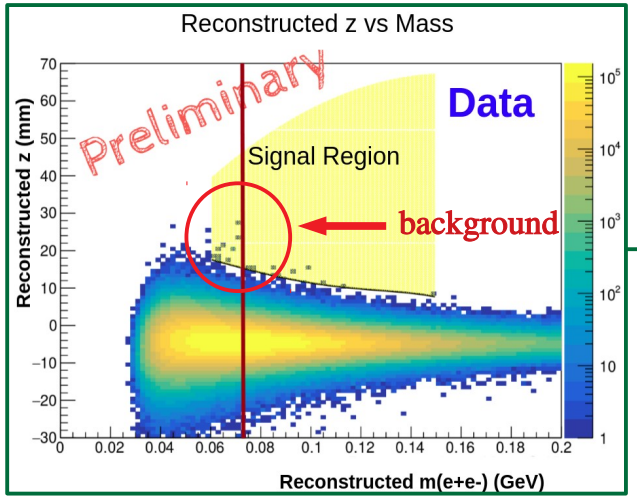

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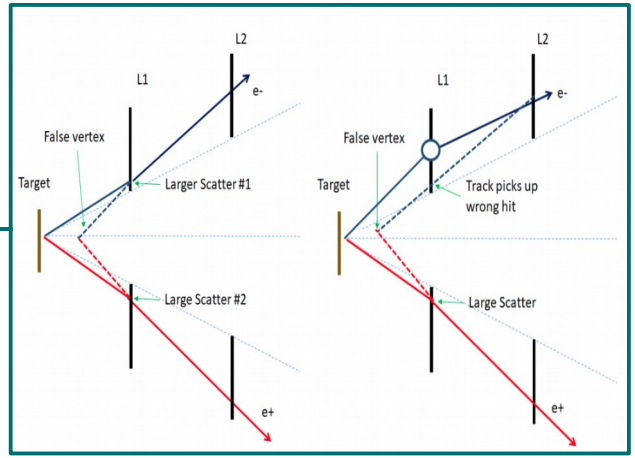
Background in signal region likely attributed to mis-tracking

Large scattering and hit mis-association cause false displaced vertex at high z



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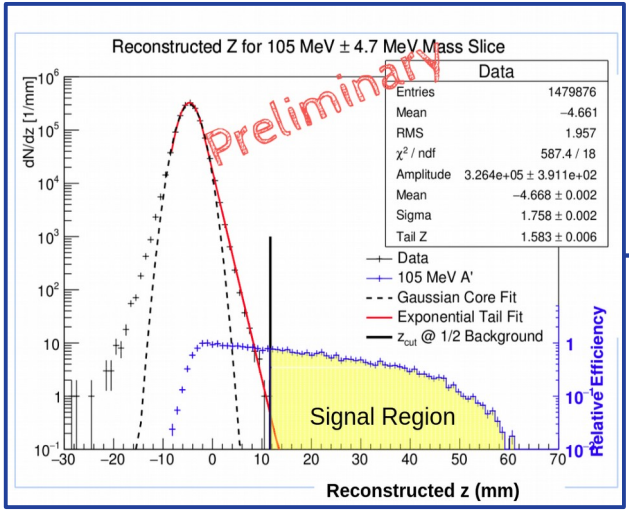

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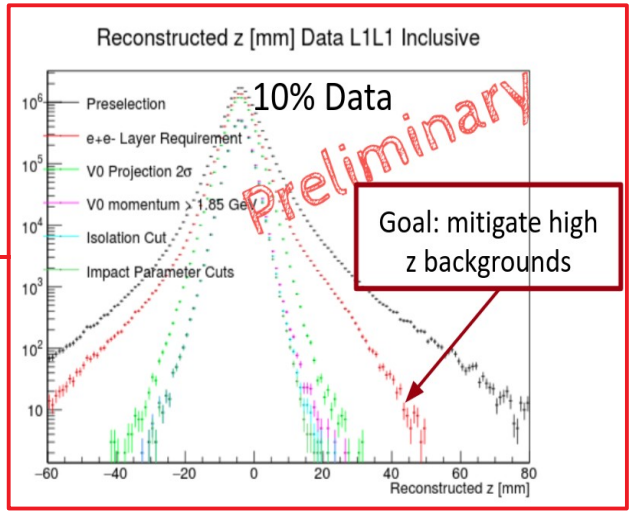

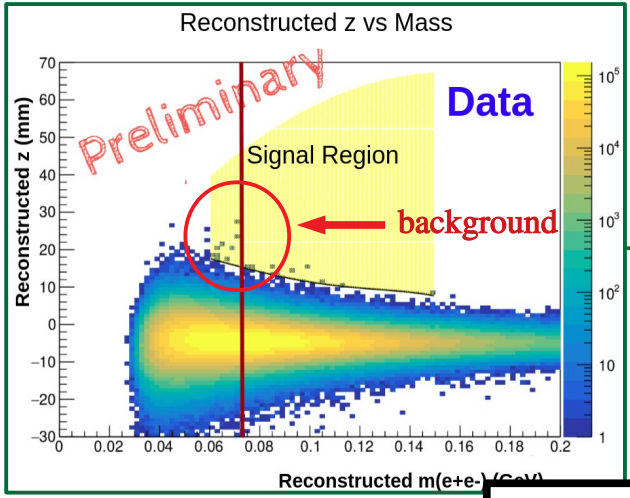

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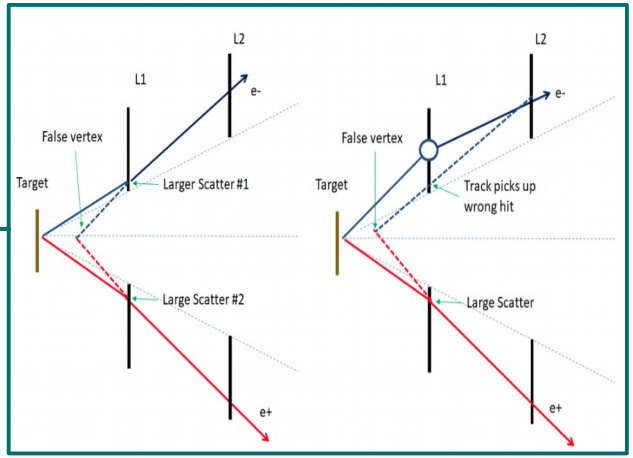
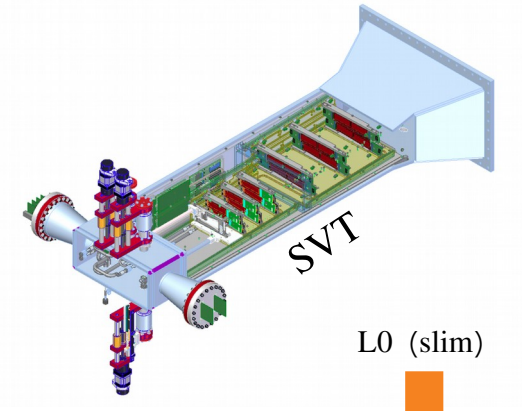
Motivates improving tracking detector and pattern recognition for 2019 Data Run

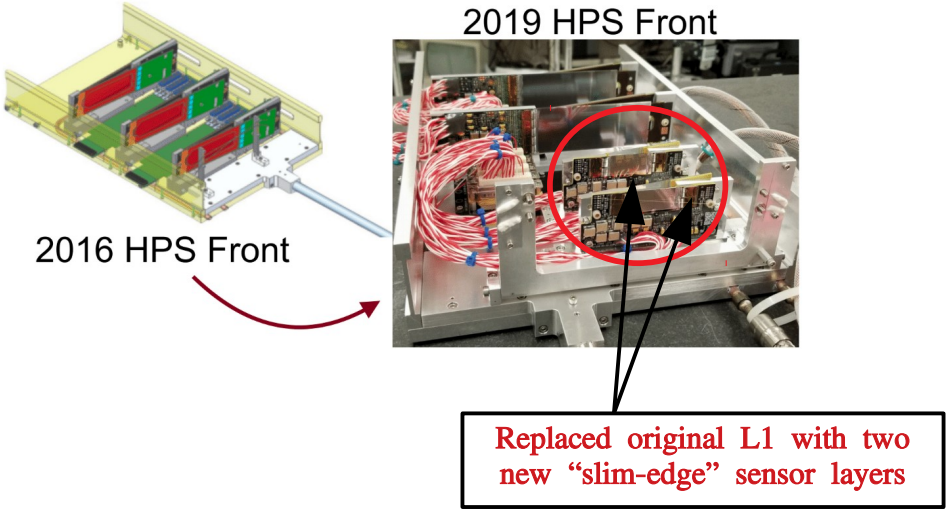


See Matt Solt's talk on July 13 at 16:45 for more 2016 details

HPS 2019 Detector Upgrade

- **2019 upgraded Silicon Vertex Tracker** to improve acceptance and z vertex resolution
- N Tracking Layers increased from 6→7

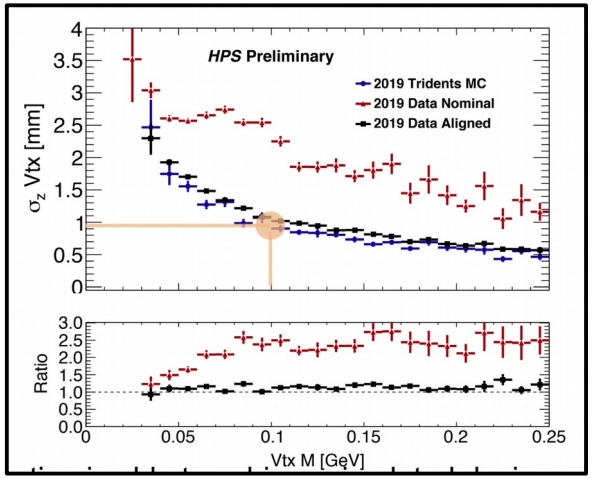


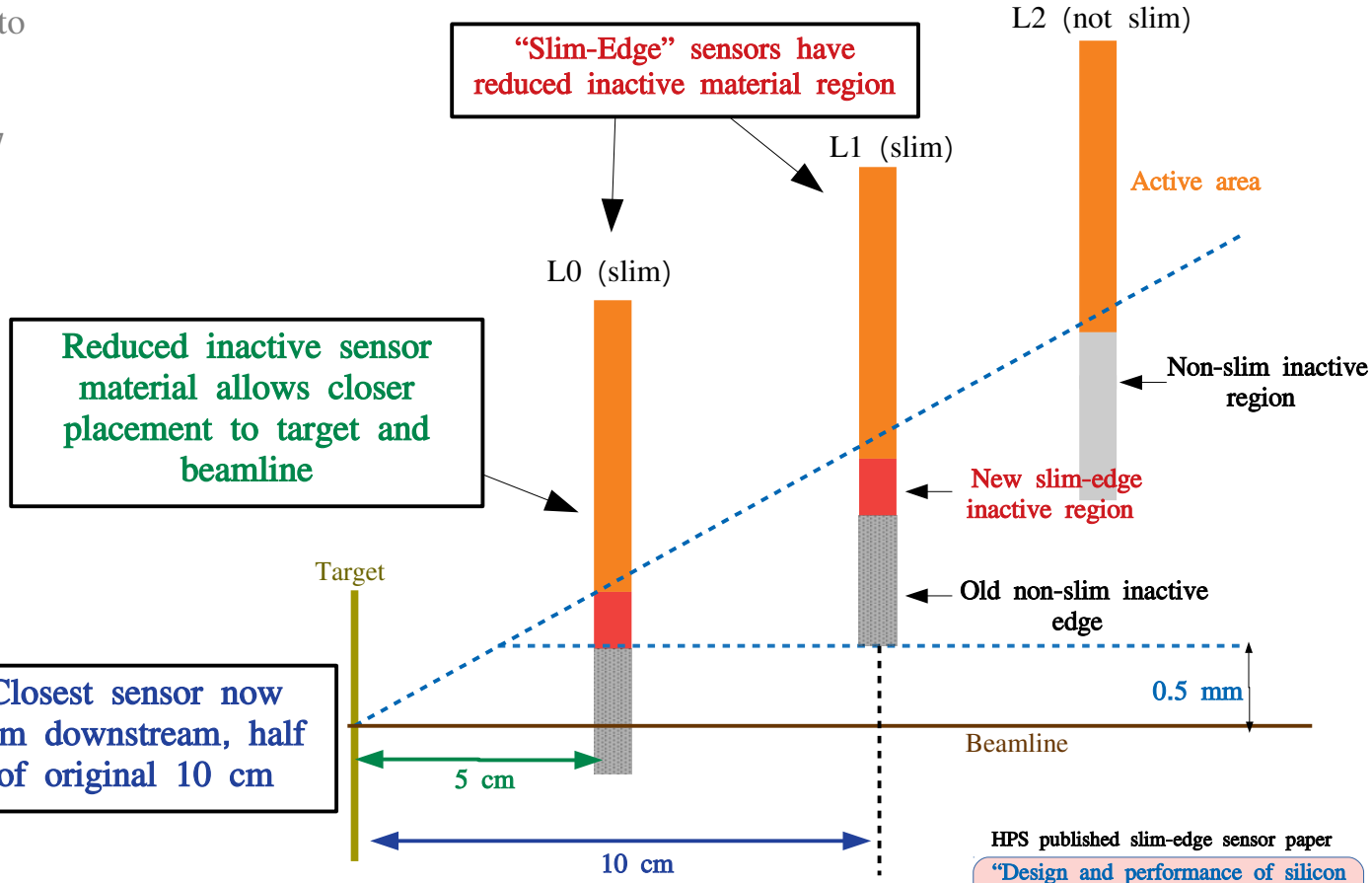


HPS published slim-edge sensor paper
"Design and performance of silicon strip sensors with slim edges for HPS experiment" V. Fadeyev et al.

HPS 2019 Detector Upgrade

- 2019 upgraded Silicon Vertex Tracker to improve acceptance and z vertex resolution
- N Tracking Layers increased from 6→7
- New slim-edge **L0 placed closer to Target** and beamline than possible in 2016
- MC and prelim data show **z vertex resolution improved by factor ~2**





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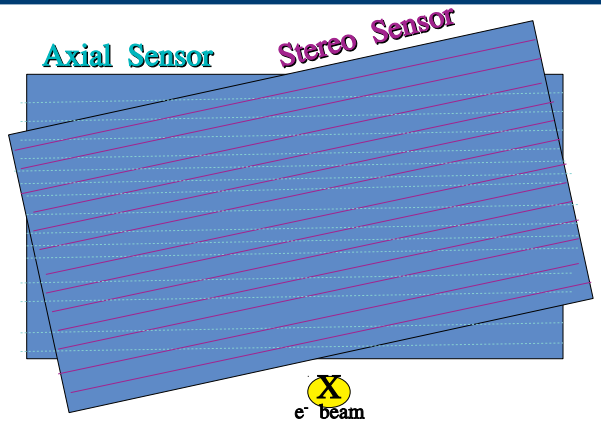
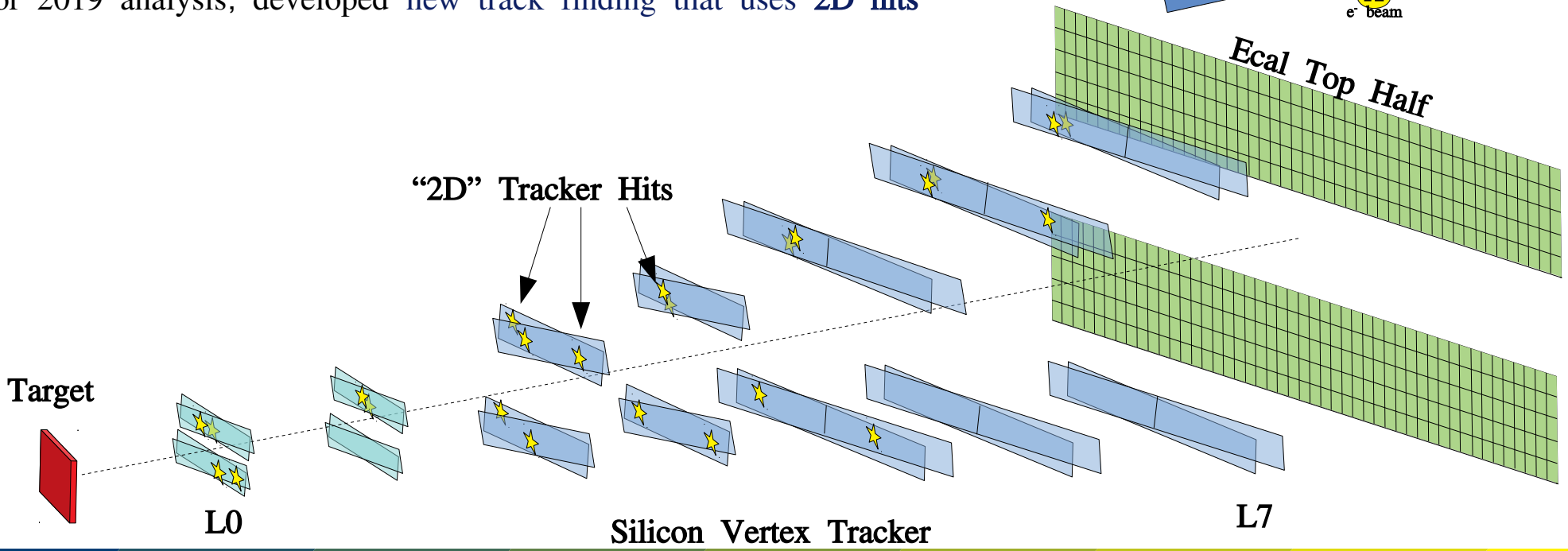
2019 Tracking Upgrade

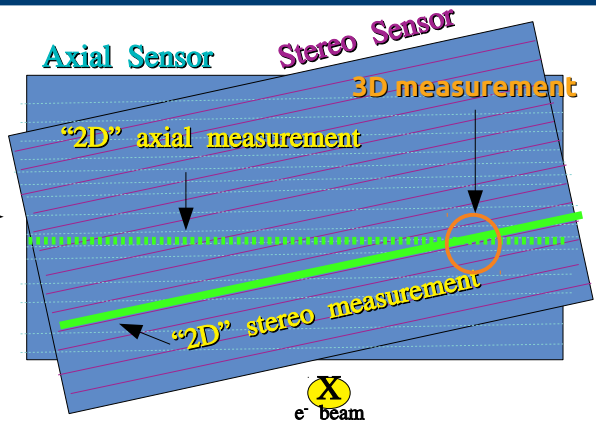
- **2019 also upgraded tracking software**
- Pre-2019 (Legacy) Track finding algorithm only uses **3D hits** (clustered 2D hits)
  - Inefficient when hardware fails…as happened in 2019
- For 2019 analysis, developed new track finding that uses **2D hits**

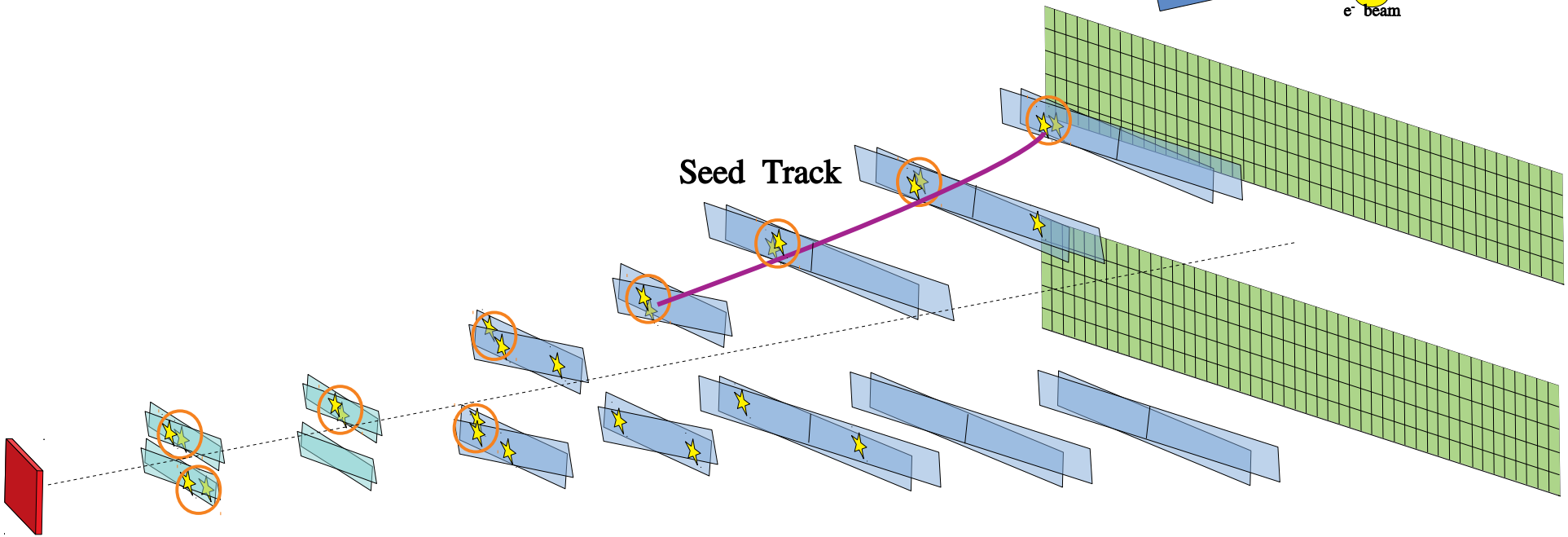




2019 Tracking Upgrade

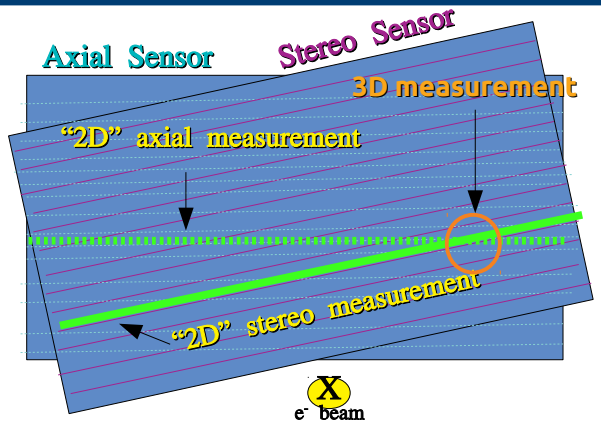
- Axial and stereo sensor silicon strips intersect
- 2D strip hits are clustered at intersection to form **3D hit**
- Legacy track finding uses **3D hits** to form seed tracks via global chi2 fit

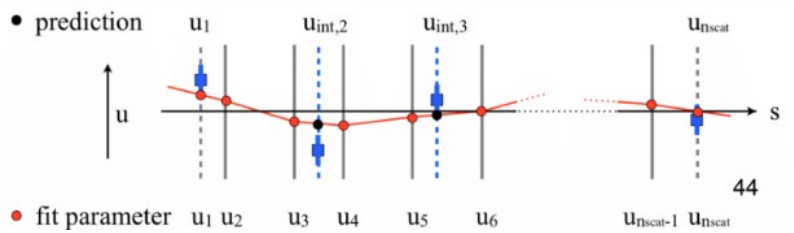




2019 Tracking Upgrade

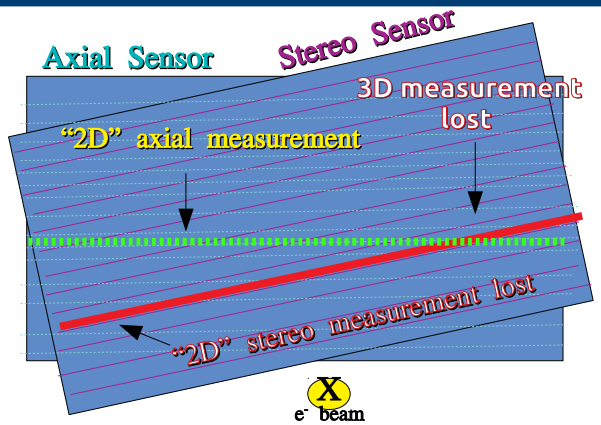
- Axial and stereo sensor silicon strips intersect
- 2D strip hits are clustered at intersection to form **3D hit**
- Legacy track finding uses **3D hits** to form seed tracks via global chi2 fit
- Seed tracks extended to find full track candidates
- Track candidates refit with General Broken Lines
  - Treats multiple scattering



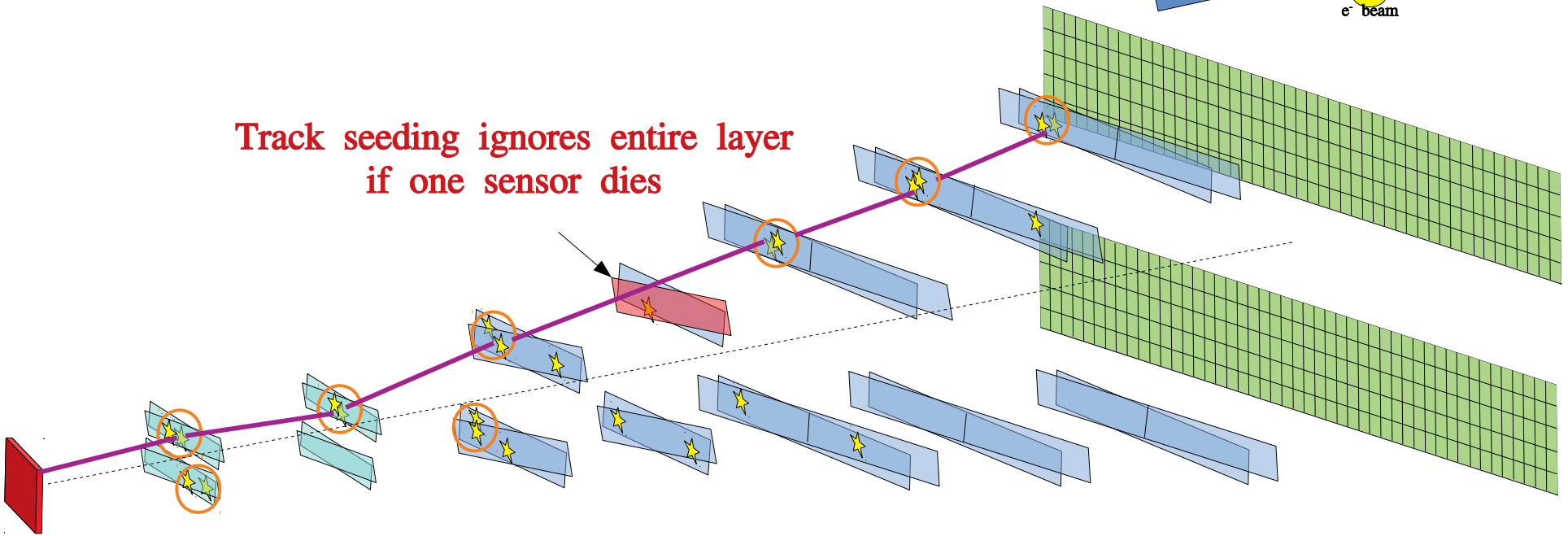


2019 Tracking Upgrade

- If one sensor in pair **fails**, **lose 3D hit reconstruction** on layer
- Legacy track reconstruction then loses that layer
- **Recover hits from dead layers** with new pattern recognition that uses **2D hits**

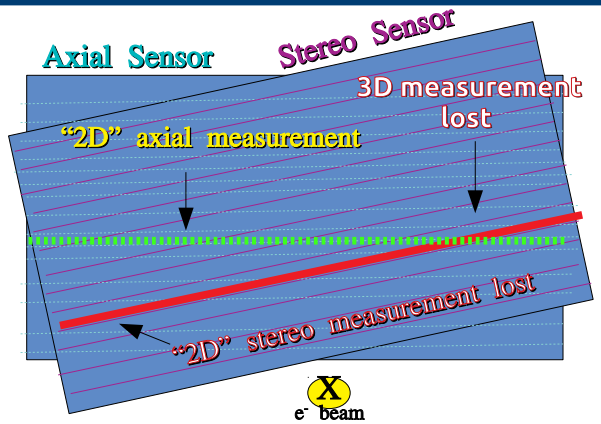


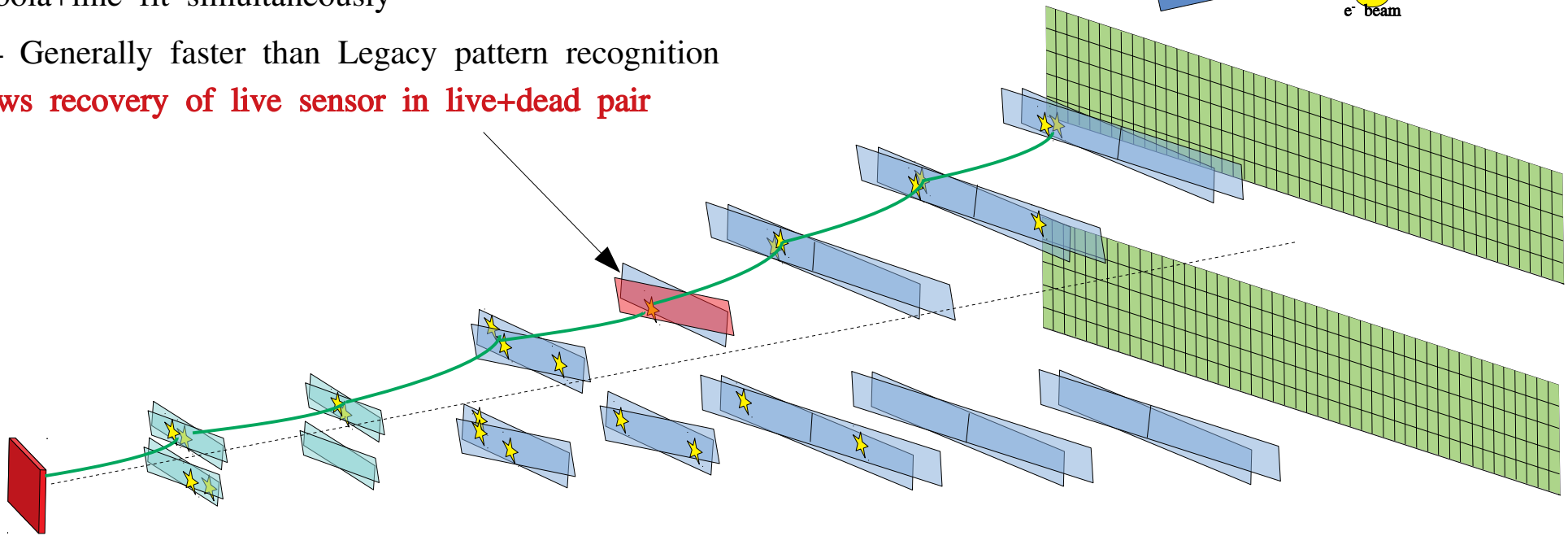
Track seeding ignores entire layer if one sensor dies



2019 Tracking Upgrade

- HPS replaced Legacy tracking with combinatorial pattern recognition that uses **Kalman Fitting**
  - treats multiple scattering and non-uniform field
- Tracks seeded with **5 2D hits** (3 axial+2 stereo) for parabola+line fit simultaneously
  - Generally faster than Legacy pattern recognition
- **Allows recovery of live sensor in live+dead pair**



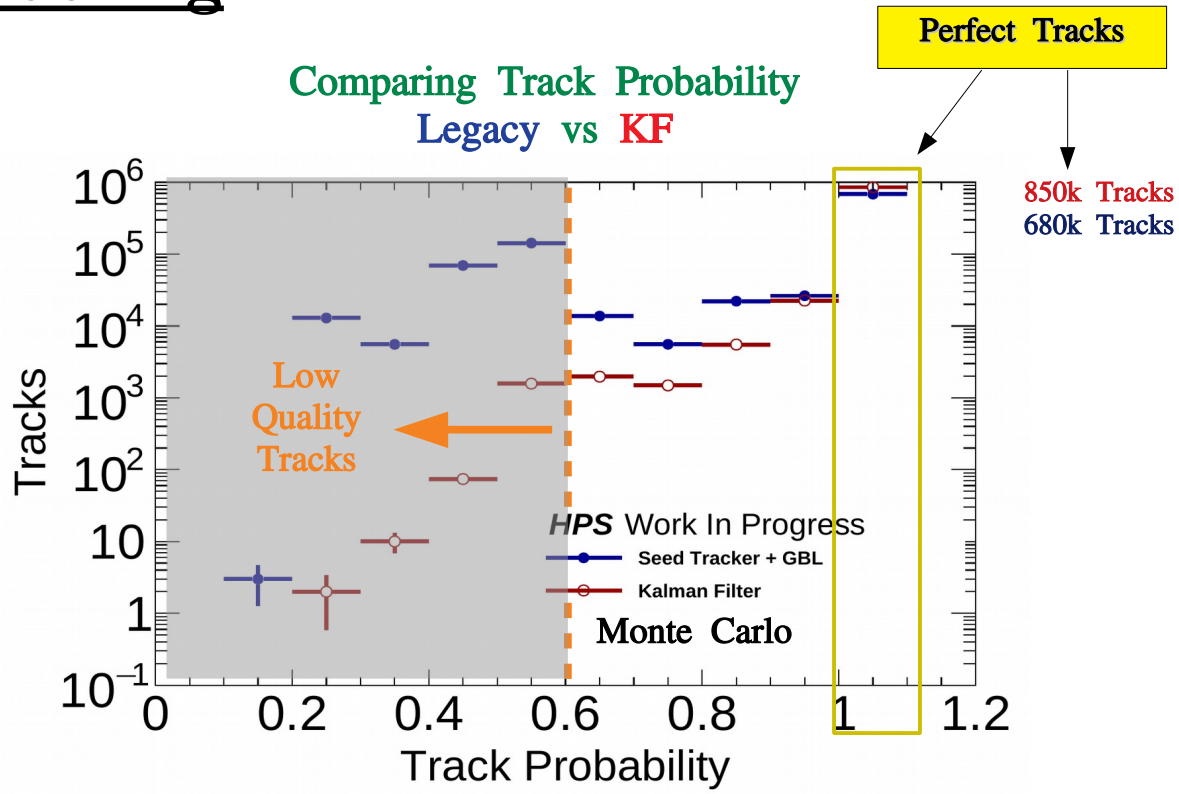


Kalman Filter vs Legacy Tracking

- MC Simulation Truth Studies compare New (Kalman Filter) to Legacy (Seed Tracker + GBL) tracking
- "Track Probability" indicates quality of hits on MC reconstructed track
- TrackP = 1 tracks have perfect hit content

- KF tracking shows large expected improvement in selecting hits on tracks | (25% more Perfect Tracks)

Improved hit selection expected to reduce mis-tracking background in signal region



Track Probability = (N_{truth_hits} / $N_{hits\_on\_track}$)

N_{truth_hits} = N hits from generated particle

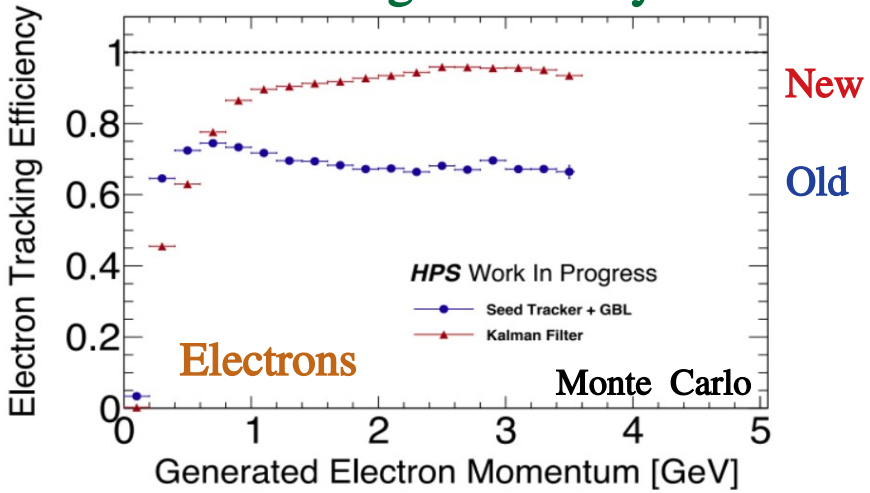
Kalman Filter vs Legacy Tracking

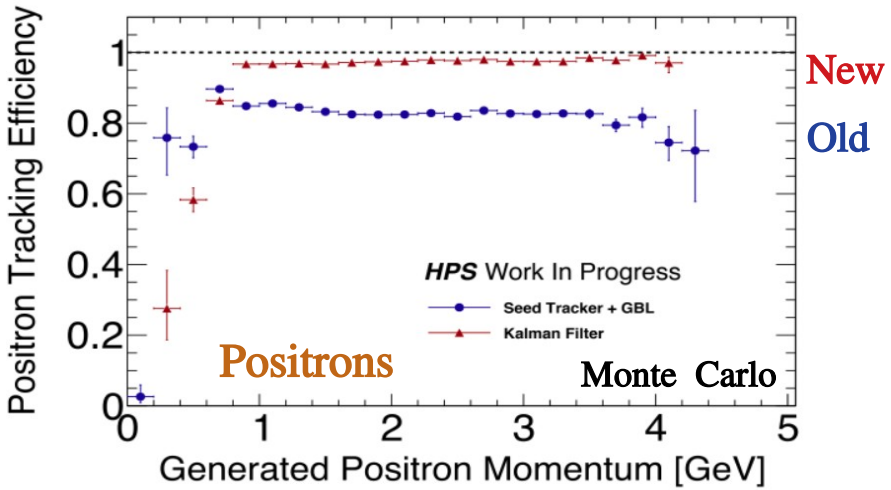
- How many "reconstructable" tracks found? (Tracking Efficiency)
- Restricted to "high-quality" Tracks (TrackP >= 0.8)
- KF Efficiency: >85% (>95%) for $e^-(e^+)$
- Legacy Effiency: 70-75% (~85%) for $e^-(e^+)$
- New tracking shows improved tracking efficiency beyond ~1 GeV

Tracking Efficiency

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

Tracking Efficiency



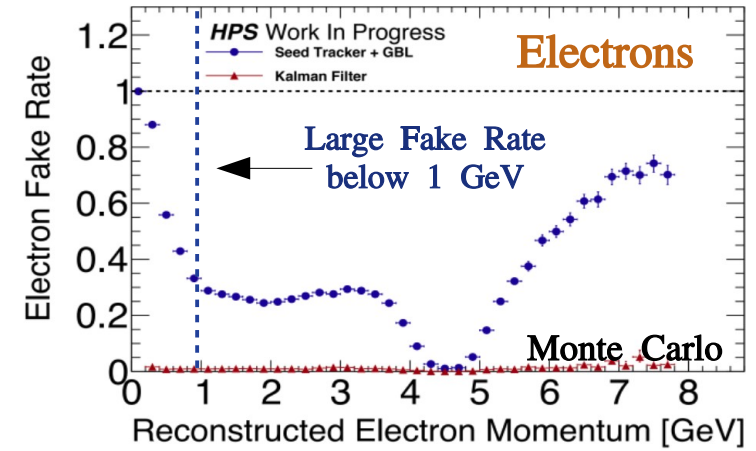


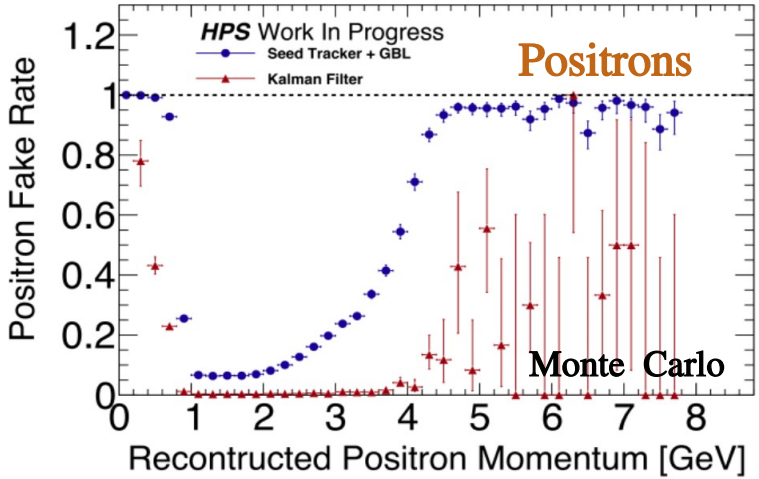
Kalman Filter vs Legacy Tracking

- How many reconstructed tracks are fakes?
  - Tracks w/TrackP < 0.8
- **"Fake Rate" =** Binned ratio of N "fake" tracks to N reconstructed tracks
- Old Tracking shows large fake rate below 1 GeV
- New Tracking has very low fake rate across range

These MC studies suggest that new track reconstruction algorithm is more robust to mis-tracking

Tracking "Fake Rate"

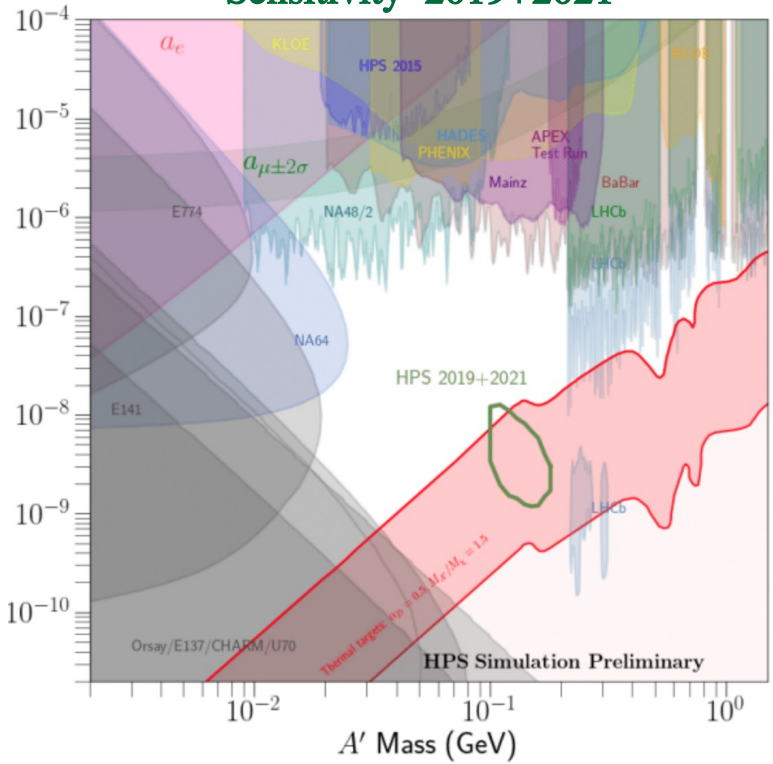




Conclusions

- HPS is designed to search for heavy photons, well motivated LDM-LDM and LDM-SM mediators
- 2016 Engineering Run analysis motivated detector and software upgrades for the **2019 Data analysis**
  - **Vertex z resolution improved by factor of 2**
  - **Expect cleaner tails due to improved vertex z resolution**
  - **Tracking upgrade expected to reduce mis-tracking background**
  - 2019 data calibration and processing (on-going)
- **Preparing for 2021 Data Run, 3.7 GeV @ 4 weeks**
- 2016 performance was close to A' sensitivity, and with the resulting upgrades the **2019 Data Run is expected to be sensitive to A' discovery!**

HPS A' Expected Sensitivity 2019+2021



Thank You!

Backup

Expected Signal

- 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 $\epsilon_{vtx} = \frac{\phi_{A'}(\epsilon^2)}{\phi_{\gamma^*}}$ ("efficiency vertex") is ratio of combined detector acceptance and efficiency for A' and virtual photon decays into charged particles

Expected Signal (Radiative Fraction)

- Expected signal proportional to radiative trident production rate

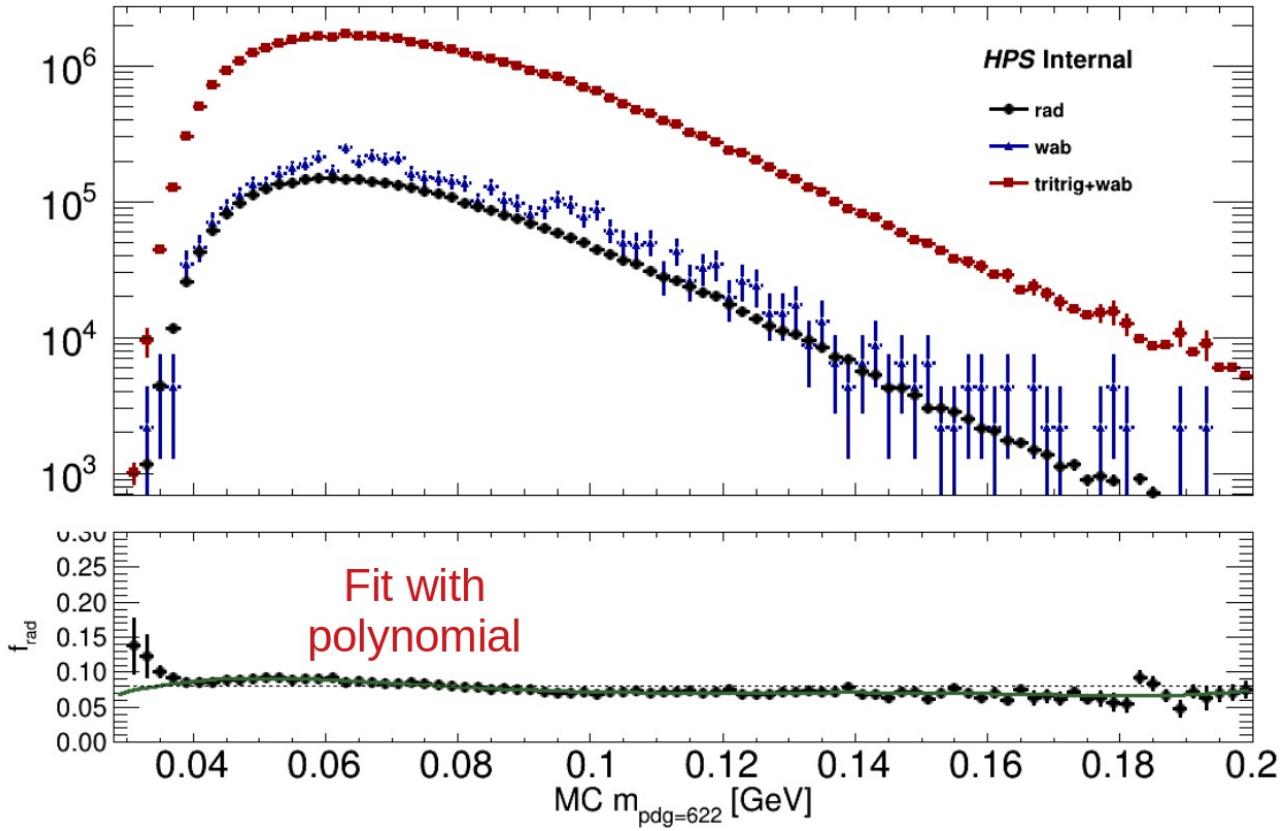
$$N_{A'} = \frac{3\pi m_{A'}\epsilon^2}{2N_{eff}\alpha}\epsilon_{vtx}\frac{dN_{\gamma^*}}{dm_{A'}}$$

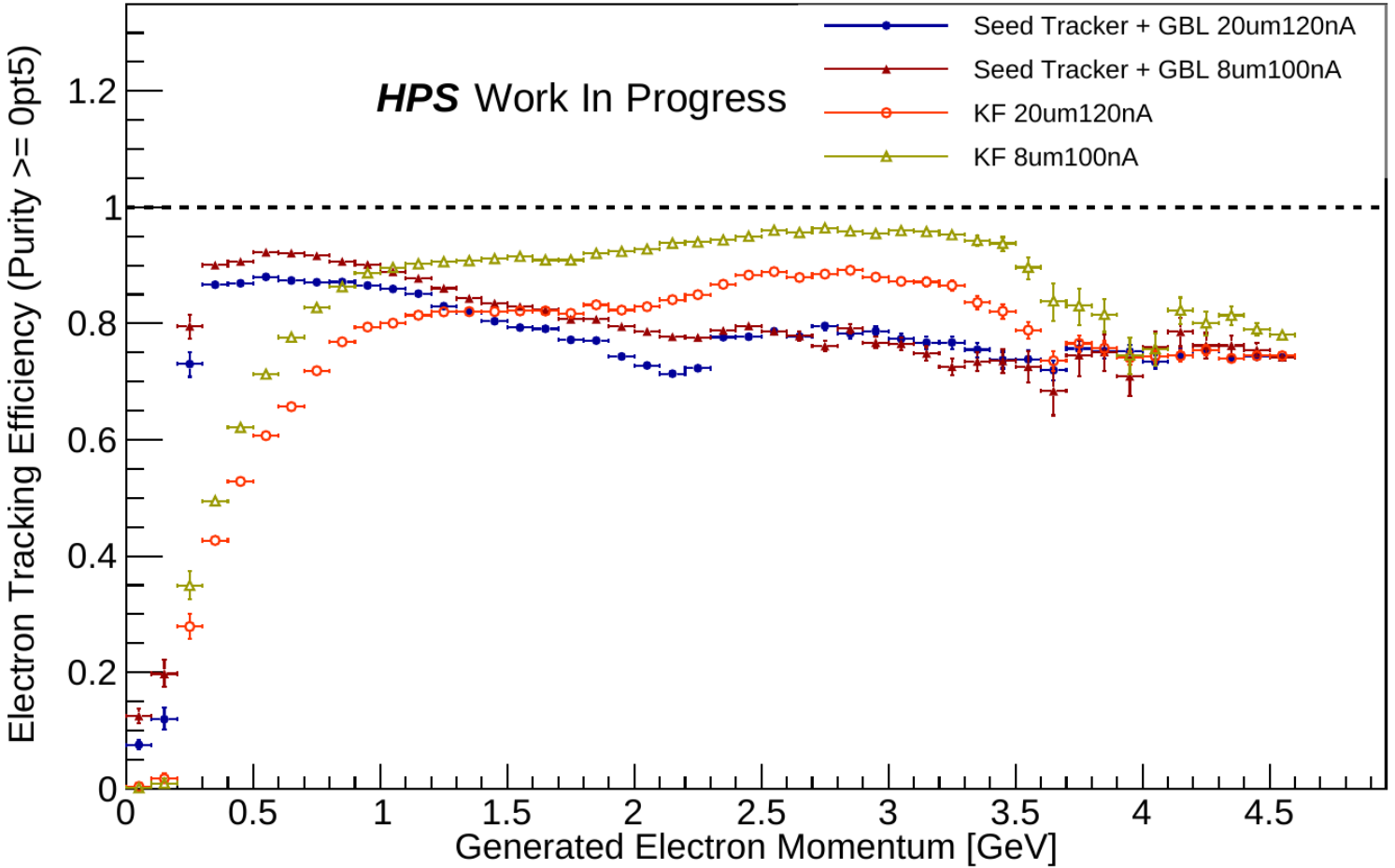
← Not measurable in data

- Relate Radiative Tridents to Background:
  - $\frac{dN_{\gamma^*}}{dm_{A'}} = f_{rad}\frac{dN_{bkg}}{dm_{reco}}$
  - where $f_{rad} = \frac{dN_{\gamma^*}}{dm_{A'}} / \frac{dN_{bkg}}{dm_{reco}}$ ("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

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

Expected Signal (Radiative Fraction)




HPS Work In Progress
Seed Tracker + GBL 20um120nA
Seed Tracker + GBL 8um100nA
KF 20um120nA
KF 8um100nA
Electron Tracking Efficiency (Purity >= 0pt5)
Generated Electron Momentum [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
0.5
1.5
2
2.5
3
3.5
4
4.5

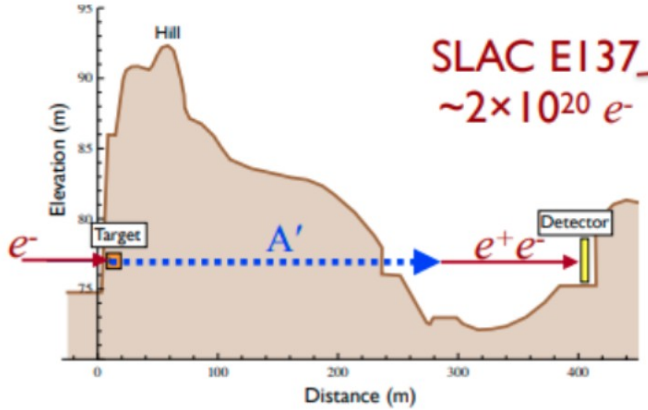
A' Parameter Space

"Bump hunts" for prompt A' decay to lepton pairs

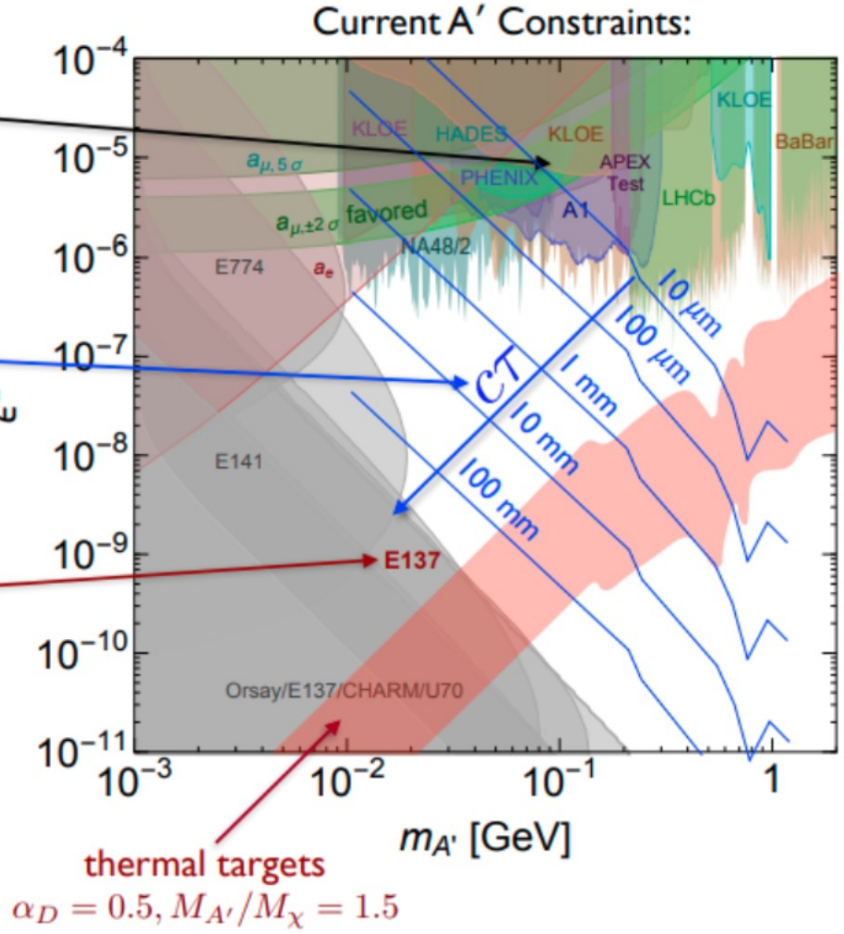
A' long lived at small coupling

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

Constrained by "beam dump experiments"



SLAC E137
~2×10²⁰ e^-

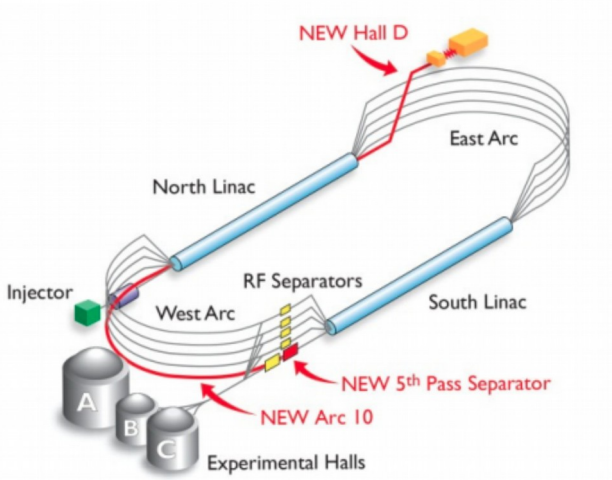


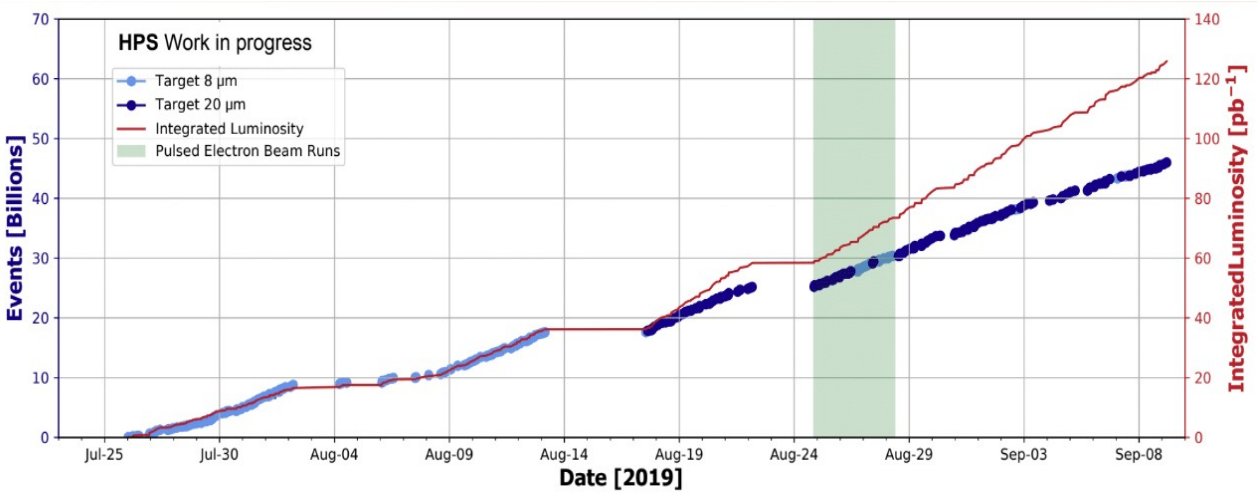
thermal targets
$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

2019 Physics Run

- JLab Continuous Electron Beam Accelerator Facility delivered continuous electron beam (2 ns bunches)
- Tight beamspot with small tails required to accommodate close SVT layers

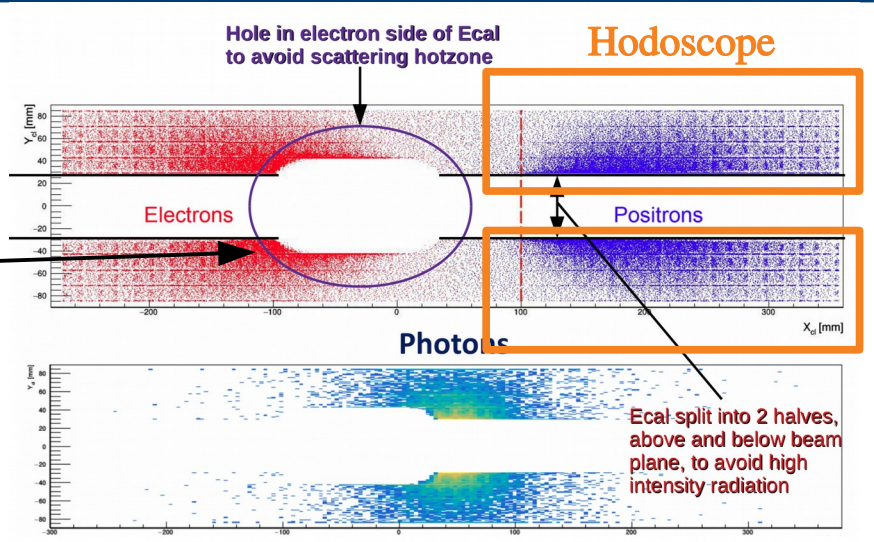
3.5 Weeks @ 4.4 GeV
~150 nA on 8um & 20um W
Integrated charge ~ 386 mC
Lumi = 122 pb^{-1}



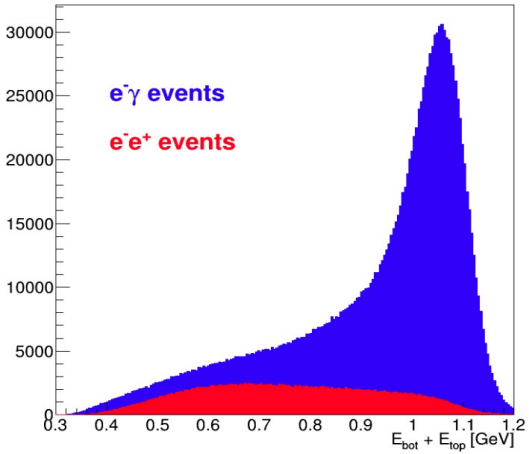


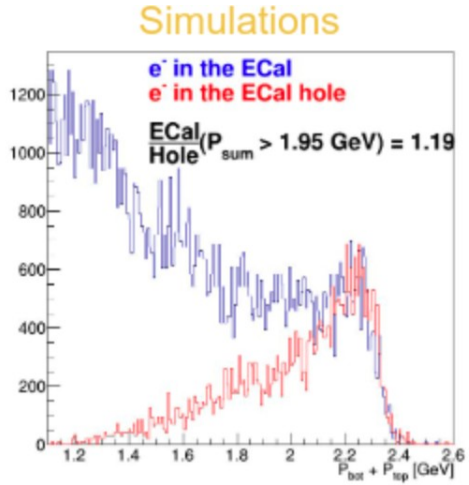
2019 Hodoscope Upgrade

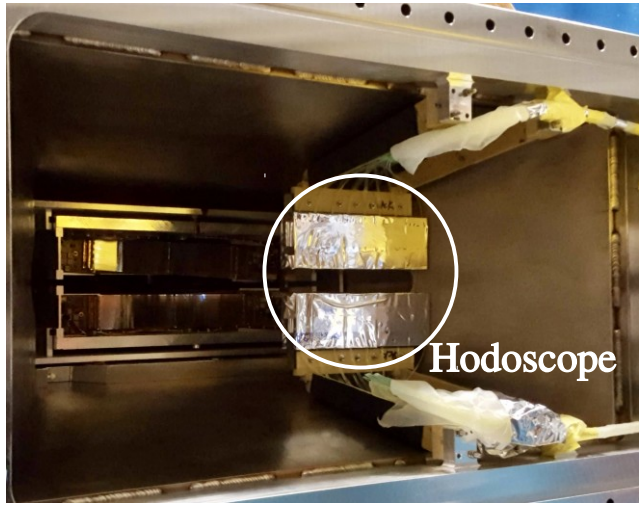
- Ecal triggers on (e^- e^+) pair in opposite halves of ECal
- 2016 found Trigger dominated by WAB events (e^- γ)
- 2016 data and simulation also shows large portion of electrons lost in Ecal hole at high P_{sum} (events lost)
- 2019 added Hodoscope over positron side of Ecal
- With Hodoscope, implement positron only trigger
- Reduces WAB triggers and recovers events with lost e^-



Triggered Events Sample







2019 Detector Diagram