

# The Heavy Photon Search Experiment Software Environment

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for the [HPS Collaboration](#)

CHEP 2019 November 5, 2019

# Dark Matter

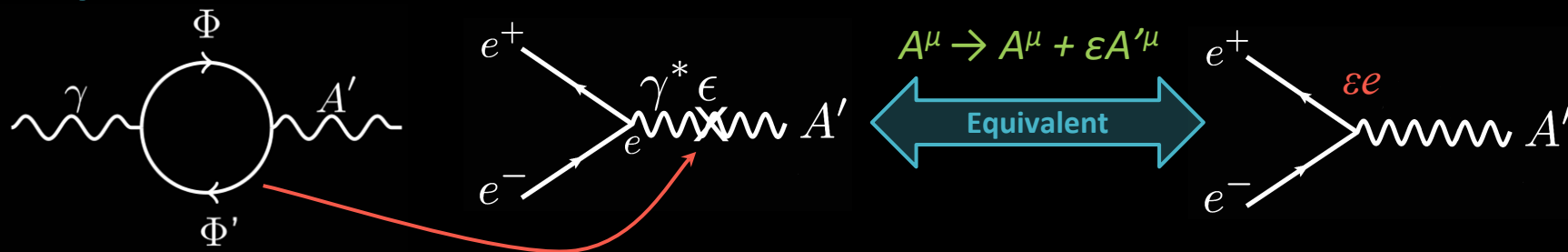
There is strong evidence for the existence of Dark Matter but its nature continues to elude us. The HPS experiment searches for a so-called Heavy Photon (aka dark photon,  $A'$ ) which is one well-motivated portal for DM and SM interactions.

- ☸ B. Holdom, *Two U(1)'s and  $\epsilon$  charge shifts*, Phys. Lett. B166 (1986) 196
- ☸ J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, *New fixed-target experiments to search for dark gauge forces*, Phys. Rev. D80 (2009) 075018, arXiv:0906.058
- ☸ Consider the case where DM interacts via a vector mediator

Search for this dark/heavy photon,  $A'$

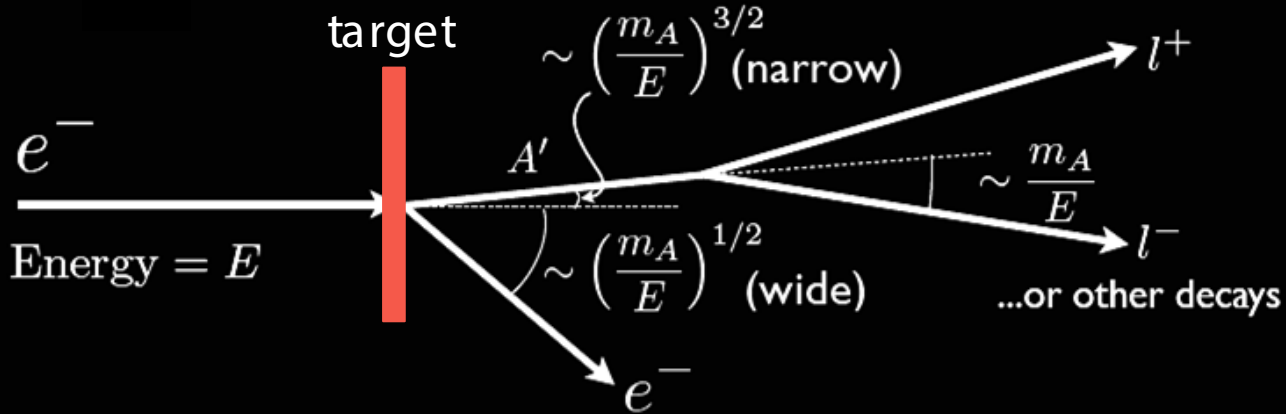
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \boxed{\frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^{\mu} A'_{\mu}$$

Kinetic mixing between SM photon and the dark photon  $\rightarrow$  induces weak coupling to electric charge



# Fixed Target Kinematics

If dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets subsequently decaying to  $l^+l^-$



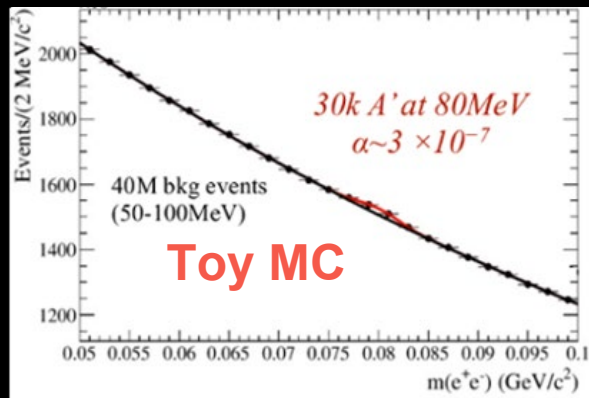
Kinematics are very different from bremsstrahlung

- Production is sharply peaked at  $x \approx 1$   
 $A'$  takes most of the beam energy
- $A'$  decay products opening angle,  $m_{A'}/E_{beam}$

The HPS experiment was designed to make use of such a production mechanism to search for a heavy photon using two methods

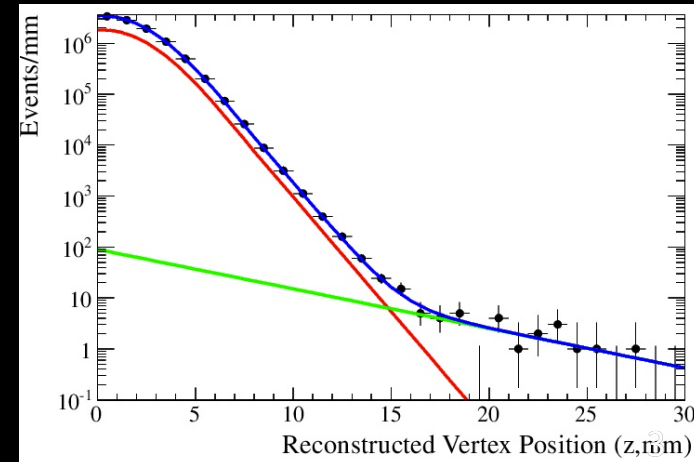
## Resonance Search (Bump Hunt)

Look for an excess above the large QED background. Large signal required so limited to large coupling.



## Displaced Vertex + Bump Hunt

Long lived  $A'$  will have a displaced vertex. Will help cut down prompt backgrounds but limited to small coupling.



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# Detector Design / Response Simulation

Short time between concept and end of Jlab 6-GeV era demanded quick turnaround for detector design.

Needed high-rate, high-precision (and, of course, low cost) detector. HPS adopted the use of [slic](#) as its detector response simulation package.

Executable program developed for Linear Collider simulations.

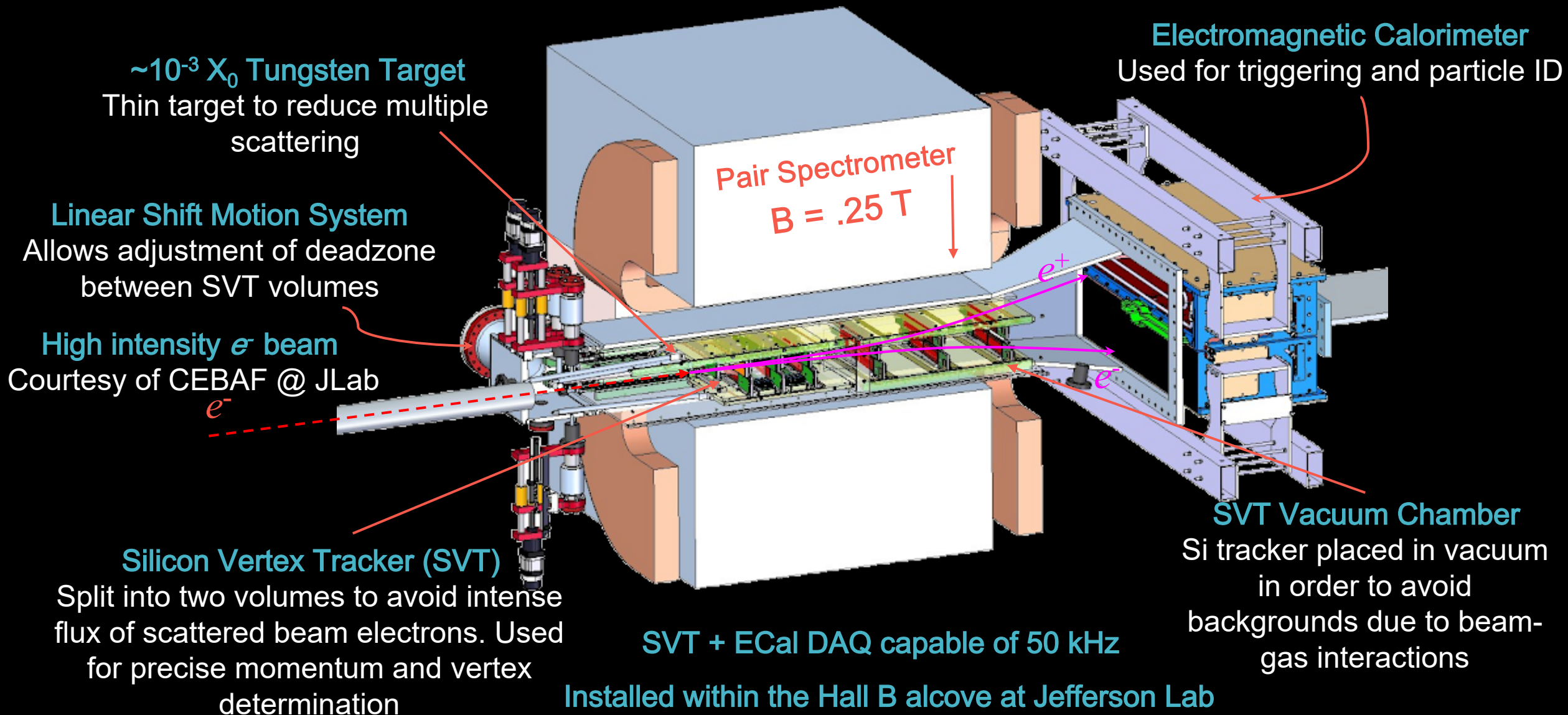
Full detectors (geometry, sensitive detectors, magnetic fields, ...) defined at runtime via input xml file.

Compact detector description feeds both simulation and reconstruction from a common source.

[lcdd](#) extension of GDML ([DOI: 10.1016/j.nima.2015.03.081](https://doi.org/10.1016/j.nima.2015.03.081))

Event data model and persistency employ [LCIO](#).

# The HPS Apparatus



# HPS Engineering Runs

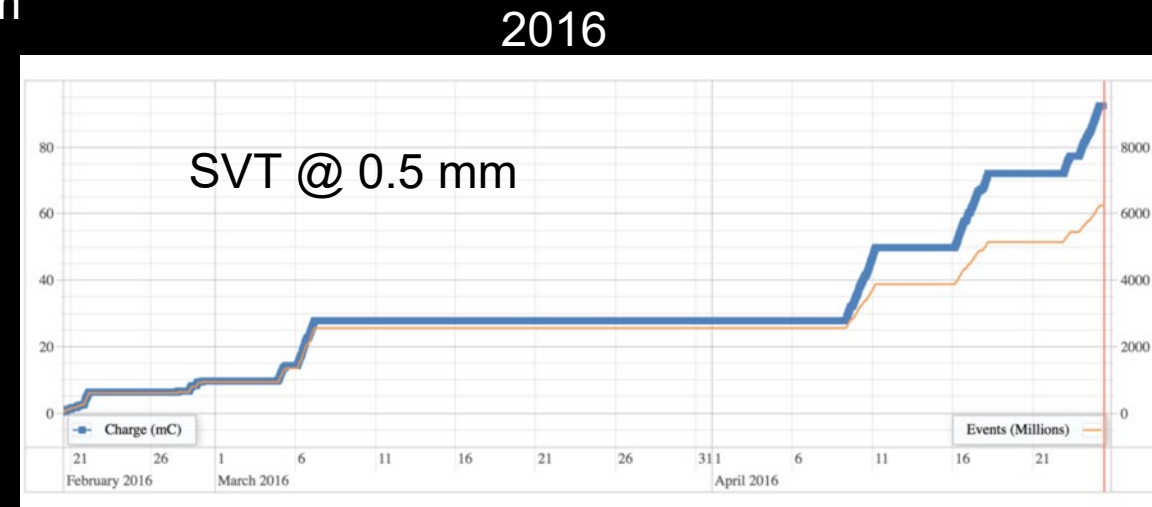
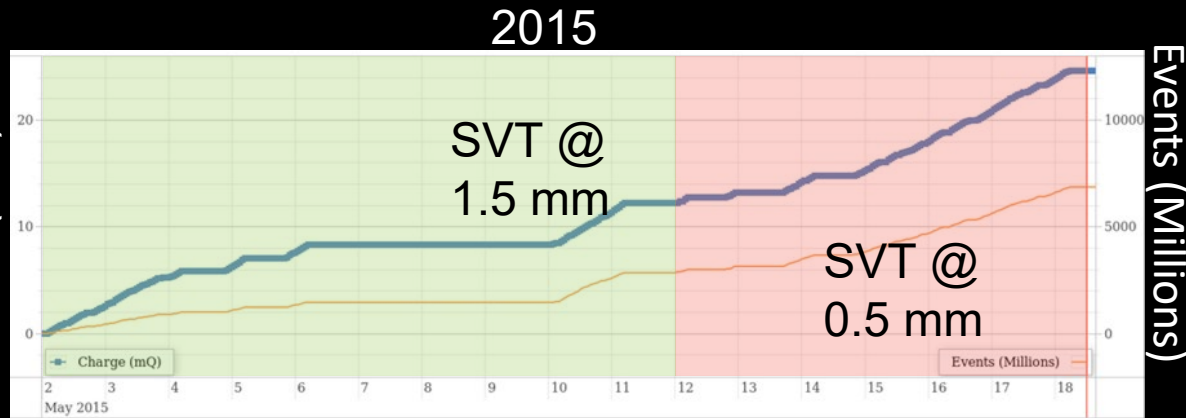
Two successful JLab engineering runs

- ☢ **Spring 2015:** 50 nA, 1.056 GeV electron beam (night and weekend running)
- ☢ **Spring 2016:** 200 nA, 2.3 GeV electron beam (weekend running)

**Goal:** Understand the performance of the detector and take physics data.

- ☢ For the 2015 run, data was taken with the Silicon Vertex Tracker (SVT) in two configurations: inactive edge at 1.5 mm and 0.5 mm from the beam plane
- ☢ **2015:** 10 mC with the SVT at 1.5 mm and 10 mC (**1.7 PAC days**) at 0.5 mm
- ☢ **2016:** 92.5 mC (**5.4 PAC days**) with the SVT at 0.5 mm

Integrated current x  
lifetime (mC)

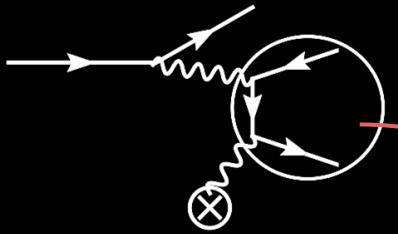




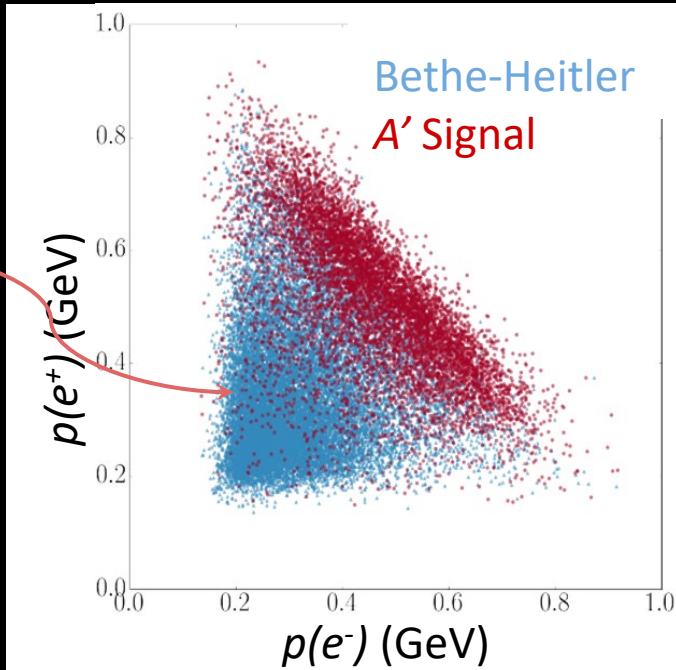
# Backgrounds

The search for an  $A'$  involves looking for a narrow resonance in the  $e^+e^-$  invariant mass spectrum on top of a large, continuous background composed of several components

## Physics Backgrounds Bethe-Heitler

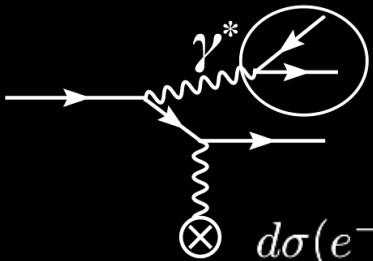


Dominant, but most lies below the  $A'$  signal region.



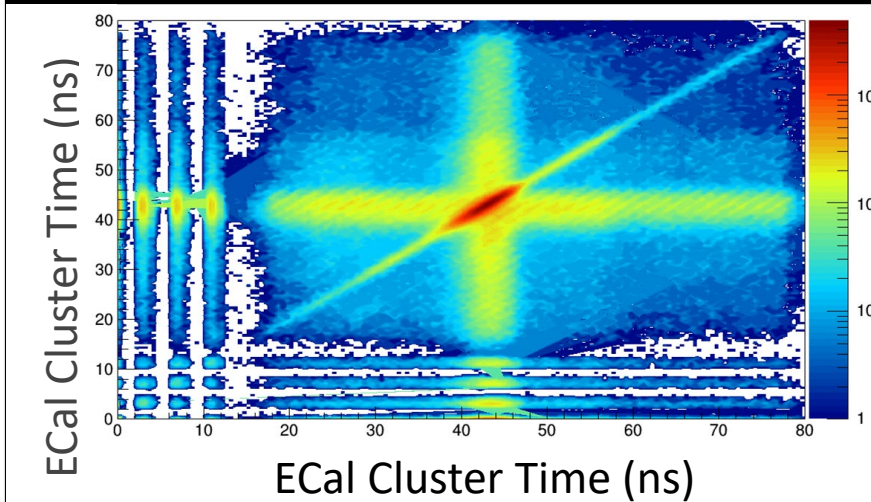
Irreducible. Kinematically identical to  $A'$  but can be used to understand expected  $A'$  rates.

## Radiative



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

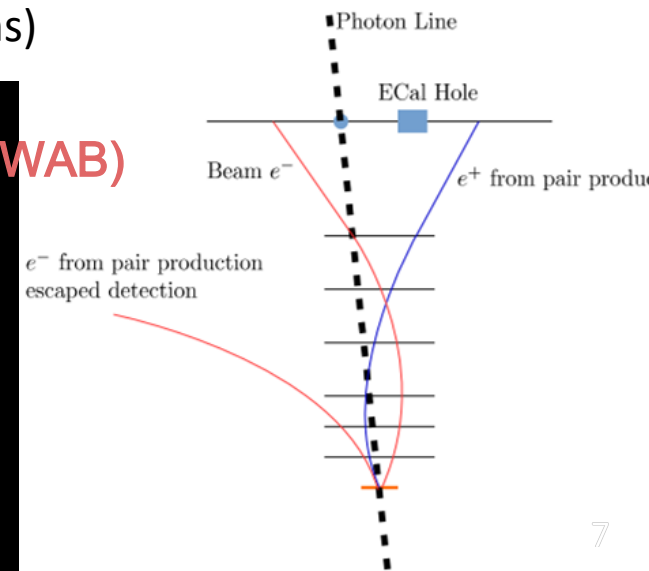
## Accidentals



True  $e^+e^-$  pairs will have time-coincident clusters in the calorimeter. Can be suppressed using time cuts and cuts used to remove scattered beam electrons.

## Wide Angle Bremsstrahlung (WAB)

Conversions of photons produced in the target and first few layers of the SVT can mimic a trident  $e^+e^-$  pair

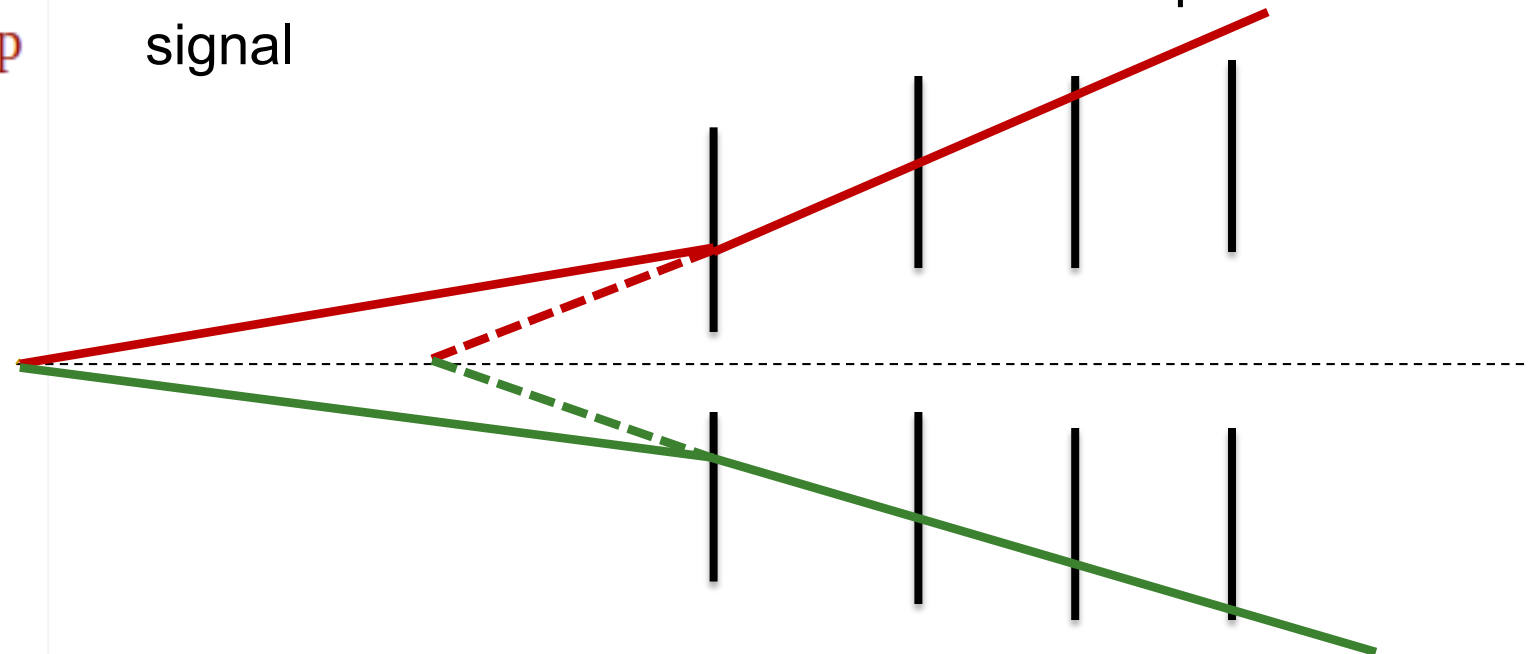
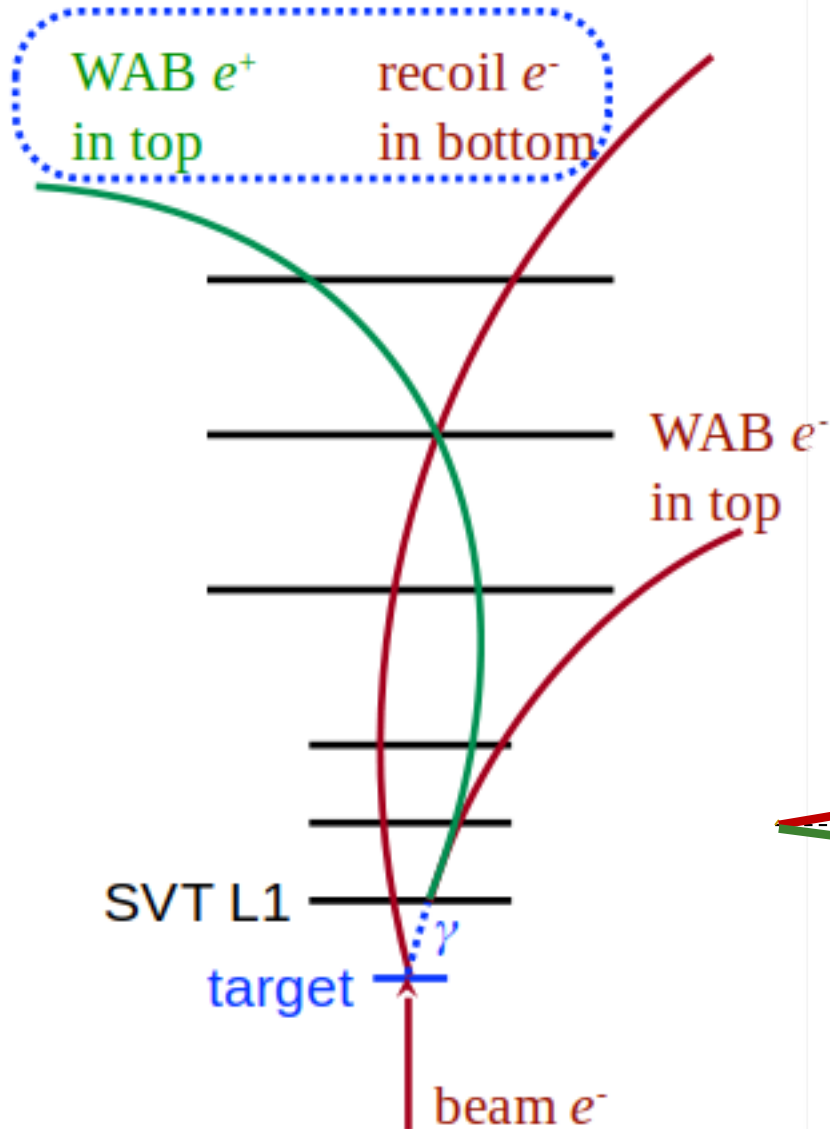


# Wide-Angle Bremsstrahlung & Large-Angle Scatters

During the analysis we realized that in the final state there is a significant contribution from the two step process: WAB  $\rightarrow$  conversion in SVT layers

WABs aren't in any of the standard generators or MC systems (GEANT4, EGS).

Large-angle scatters in the early layers can create fake downstream vertices which mimic the displaced vertex signal





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# Simulating Rare Backgrounds

Large-angle scatters in early layers of silicon can produce fake vertices which are displaced downstream from the target, mimicking our signal.

Difficult to simulate either the WAB conversion or such events using slic other than through brute-force large-statistics runs.

Working on a replacement simulation program which employs a plugin mechanism to interrupt the Geant4 processing when desired interactions happen (or not).

Plugins can also introduce processes which are not currently available within GEANT4 (e.g. trident production in the silicon by elastically scattered beam particles.)

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# Reconstruction and Analysis Software

Event reconstruction and analysis done using Java.

hps-java builds upon the lcsim.org reconstruction package used for Linear Collider physics and analysis.

Software built using maven: compile, test, deploy

Unit tests are automatically run for individual classes and components, assertions in code ensure correct behavior.

Integration tests run the full reconstruction over selected event samples. Analyses are run over output, histograms are compared against reference histograms. Changes flag differences in expected behavior.

Executable jar files are deployed to nexus repository.

# Code Management

git is used as our code repository as well as our issue tracker and release manager.

Navigation tabs: Pull requests (1), Projects (12), Wiki, Security, Insights, Settings.

Repository statistics: Unwatch (18), Star (2), Fork (5).



Note increased number of commits during the run.

- Investigate issue of SeedTracker discarding L0/L1 hits with 0.0 correction distance  
#583 opened on Aug 6 by bloodyyugo
- modify steering file steering/production/Run2019ReconPlusDataQuality.lcsim to cancel some redundant drivers in DQM  
#577 opened on Aug 3 by tongtongcao
- Add an SvtEventFlagger to LCSimPhys2019EventBuilder  
#567 opened on Jul 30 by bloodyyugo
- Catch "Matrix is singular" RuntimeException in GBLRefitterDriver **bug**  
#566 opened on Jul 30 by normangraf v4.4
- Change steering/production/Run2019ReconPlusDataQuality.lcsim to save data from reconstruction  
#561 opened on Jul 29 by tongtongcao
- Update: org.hps.record.daqconfig.EvioDAQParser **bug** **enhancement**  
#555 opened on Jul 20 by mholtrop
- Create an integration test for 2019 reconstruction **enhancement**  
#549 opened on Jul 15 by normangraf v4.4
- LCSimTestRunEventBuilder should not contain ANY 2019 processing classes. **cleanup**  
#543 opened on Jul 13 by mholtrop v4.4
- Hodo monitoring  
#538 opened on Jul 9 by rafopar
- Improvements to Unit and Integration Testing **cleanup** **tests**  
#535 opened on Jul 4 by JeremyMcCormick 0 of 7

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# Tracking

Currently using track-finding and initial fitting inherited from the ILC lcsim.org packages

Final refits use a java port of the General Broken Lines ([GBL](#))

Tracker alignment is conducted using [millepede](#)

Work underway to provide simultaneous pattern recognition/track fitting using a Kalman Filter approach.

# Event Display / Data Browser / Analysis Studio

## Java Analysis Studio JAS3

File Edit View Tuple Loop Window Help

run5772\_pass6\_V0CandidateSkim.slcio

Visibility Info Cuts

View

Types

- DetectorType
  - Barrel
  - ECalScoring
  - ECal
  - Tracker
  - Endcap
- EventType
  - BeamspotConstrainedMollerCandidates
  - BeamspotConstrainedMollerVertices
  - BeamspotConstrainedMollerVerticesTracks
  - BeamspotConstrainedV0Candidates
  - BeamspotConstrainedV0Vertices
  - BeamspotConstrainedV0VerticesTracks
  - EcalCalHits
  - EcalClusters
  - EcalClustersCorr
  - EcalReadoutHits
  - FinalStateParticles
  - GBLTracks
  - HelicalTrackHits
  - MatchedTracks
  - RotatedHelicalTrackHits
  - SVTRawTrackerHits
  - StripClusterer\_SITrackerHitStrip1D
  - TargetConstrainedMollerCandidates
  - TargetConstrainedMollerVertices
  - TargetConstrainedMollerVerticesTracks
  - TargetConstrainedV0Candidates
  - TargetConstrainedV0Vertices
  - TargetConstrainedV0VerticesTracks
  - UnconstrainedMollerCandidates
  - UnconstrainedMollerVertices
  - UnconstrainedMollerVerticesTracks

Instances

- Detector
- Event

Apply immediately Apply

Hide Types below level: 7

Hide Instances below level: 3

JAS3Tree x WIRED x

0 End of Header. Data follows in above format

----> ... done reading

Click to zoom in, Shift-Click to zoom out, Drag inward or outward to instant zoom.

342.6/632.0MB

Run	5772
Event	2821
Time Stamp	Sun May 17 02:08:52 PDT ...
Detector Name	HPS-EngRun2015-Nominal-...
Event Weight	1.0
IDRUP	0
SLIC Version	
Geant4 Version	

Name	Type	Size
EcalReadoutHits	org.lcsim.event...	8
FADCGenericHits	org.lcsim.event...	2
FinalStateParticles	org.lcsim.event...	4
GBLKinkData	org.lcsim.event...	2
GBLKinkDataRelations	org.lcsim.event...	2
GBLTracks	org.lcsim.event...	2
HelicalTrackHitRelations	org.lcsim.event...	2
HelicalTrackHits	org.lcsim.event...	38
MatchedToGBLTrackRelations	org.lcsim.event...	19
MatchedTracks	org.lcsim.event...	2
PartialTracks	org.lcsim.event...	0
RFHits	org.lcsim.event...	1
RotatedHelicalTrackHitRelations	org.lcsim.event...	1
RotatedHelicalTrackHits	org.lcsim.event...	19
SVTFittedRawTrackerHits	org.lcsim.event...	19
SVTRawTrackerHits	org.lcsim.event...	19
SVTShapeFitParameters	org.lcsim.event...	19
StripClusterer_SITrackerHitStrip1D	org.lcsim.event...	19
SVTFittedRawTr...	org.lcsim.event...	133

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# Heavy Photon Search Toolkit for Reconstruction

Support for root-based analyses is provided via tuples created from the reconstruction output and also via [HPSTR](#), an analysis framework which provides native root access to high-level reconstruction objects.

Raw Data (evio) → Reconstruction (LCIO) → DST (tuples, root)

Primarily aimed at final “physics” analyses which need access to the large library of fitting and analysis tools available in root.



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# Documentation

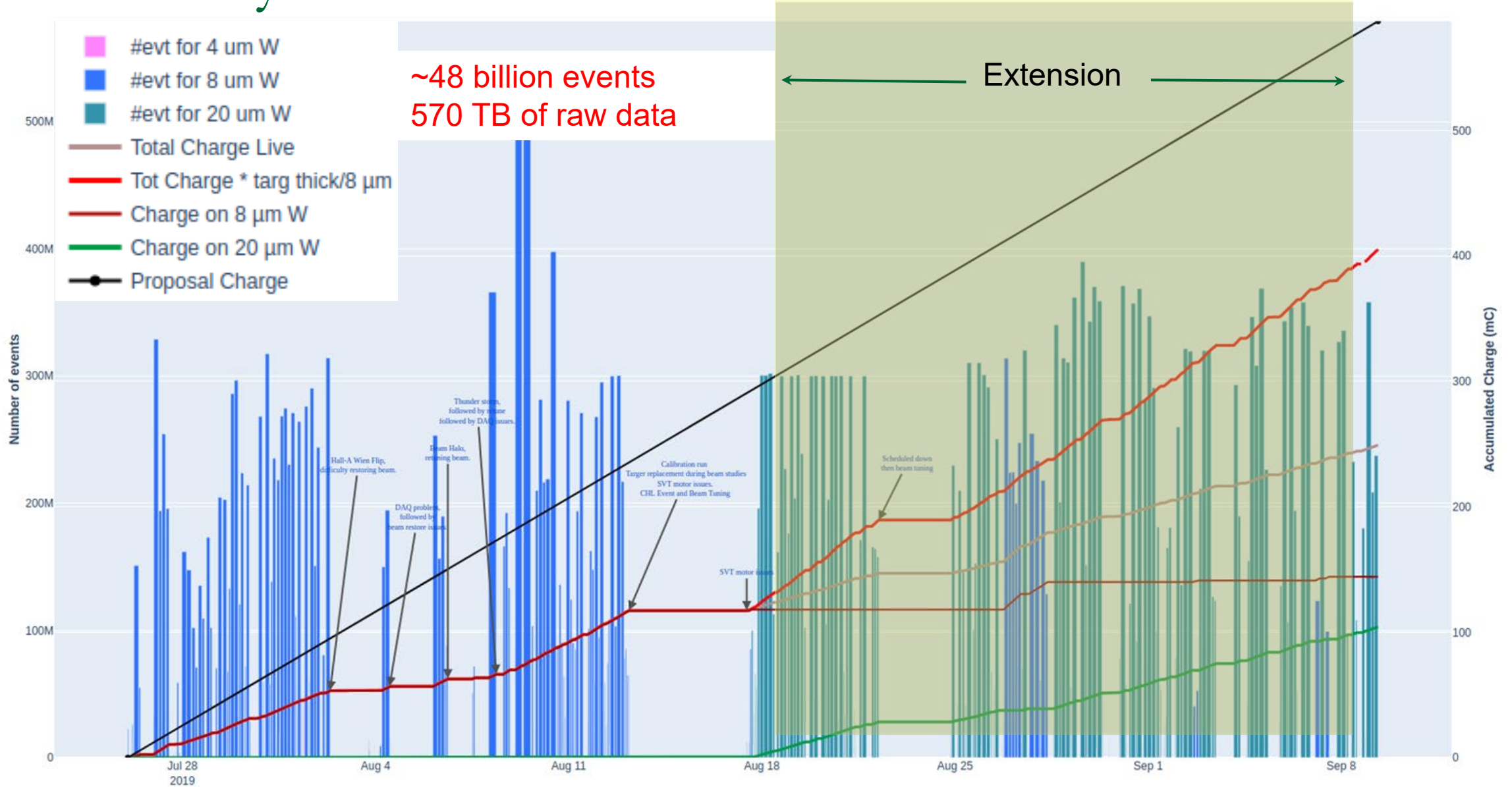
slack is used for rapid communication, quick turnaround

Confluence is used as our portal to documentation

indico is used for collaboration meetings, etc.

OverLeaf is used for technical notes, analysis notes, other more “formal” documentation. Very nice collaborative online LaTeX editor with versioned backups

# 2019 Physics Run



# Prospects

The bump-hunt analysis of the 2015 data was published: Phys. Rev. D 98, 091101(R).

The displaced-vertex analysis of the 2016 data is ongoing.

Despite issues during the 2019 run, HPS managed to collect about half of the expected statistics.

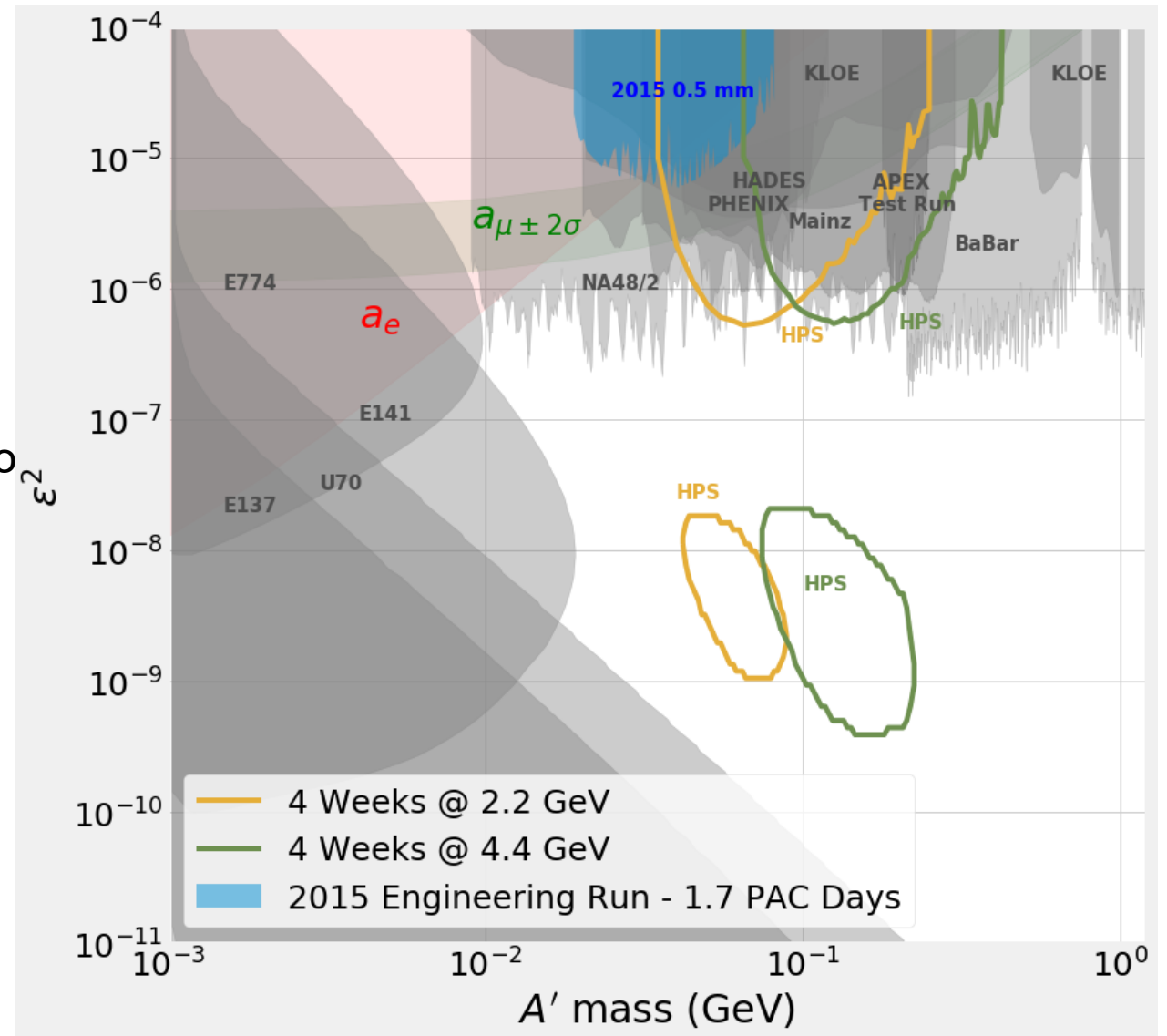
Data is now being calibrated.

Alignment of the detector is in progress.

Monte Carlo simulations will start soon.

Reach plot based on 4 weeks of running at 4.4GeV

Stay tuned...



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# Summary

Software developed for Linear Collider detector simulations and physics analysis has been successfully adopted and used by a much smaller fixed-target experiment.

Many of the benefits of developing collaborative, “generic” software (e.g. LCIO, slic, lcsim) have been realized.

Java-based reconstruction is working well for HPS (build once, run anywhere really works)

Standard software development tools (git, maven, nexus) and procedures (automatic builds, unit and integration tests) make code development and deployment much easier.

Modern documentation and communication software (slack, confluence, etc.) integrate well.

Using existing, proven and available collaborative tools allows us to concentrate on the physics, not computer science.