The Heavy Photon Search Experiment Software Environment

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for the HPS Collaboration

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Dark Matter

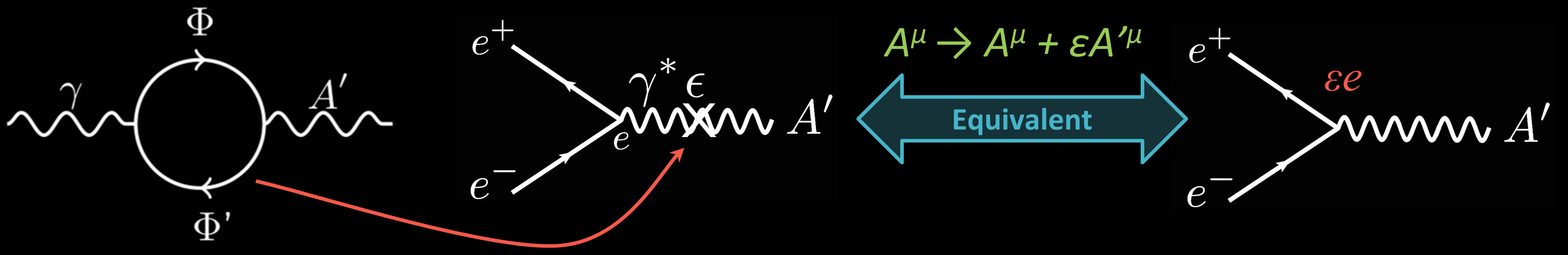
There is strong evidence for the existence of Dark Matter but its nature continues to elude us.
The HPS experiment searches for a so-called Heavy Photon (aka dark photon, A’) which is one well-motivated portal for DM and SM interactions.

- B. Holdom, *Two U(1)’s and ε 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’***

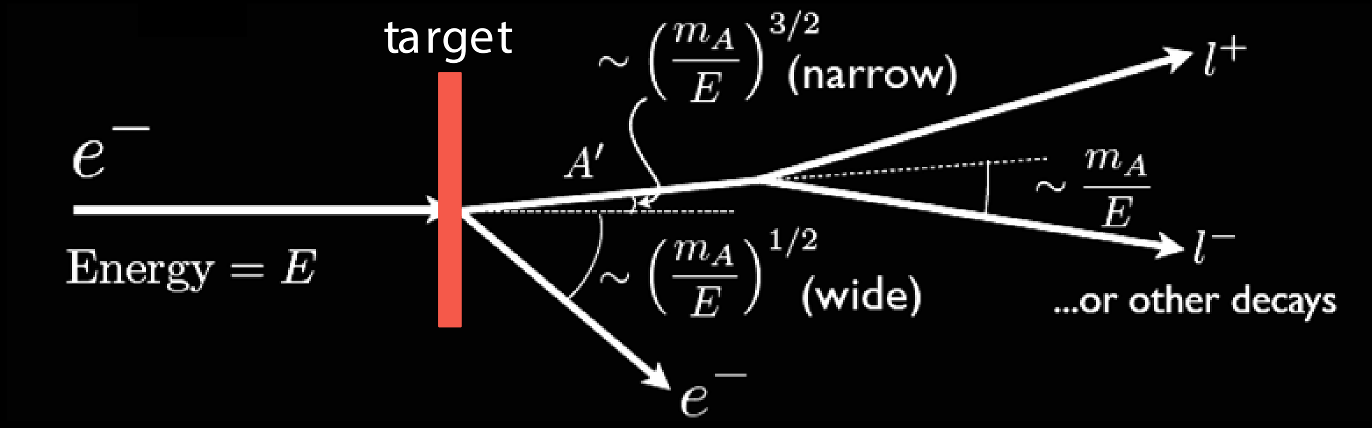
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

Kinetic mixing between SM photon and the dark photon → 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^-



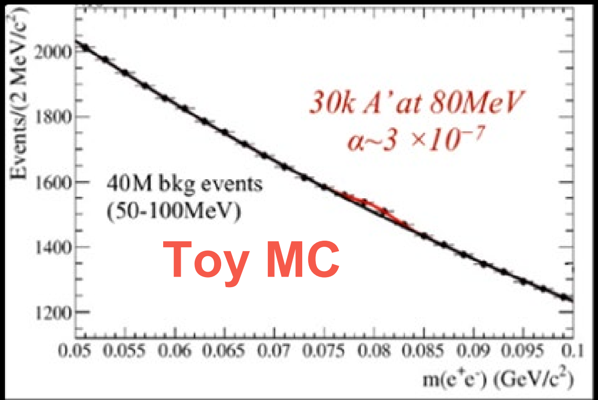
Kinematics are very different from bremsstrahlung

- Production is sharply peaked at x ≈ 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

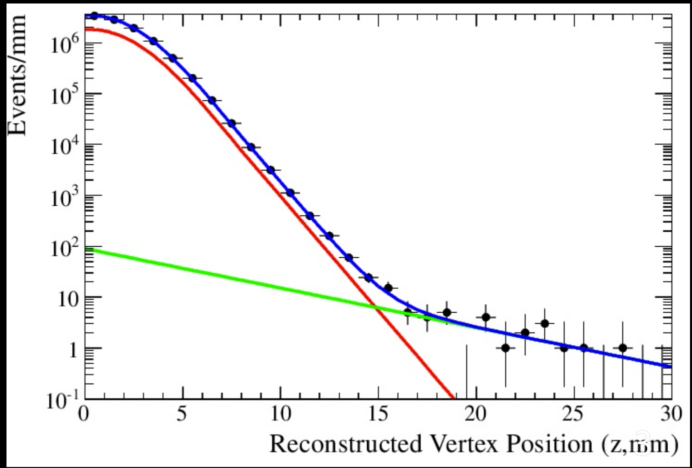
Resonance Search (Bump Hunt)

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



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)

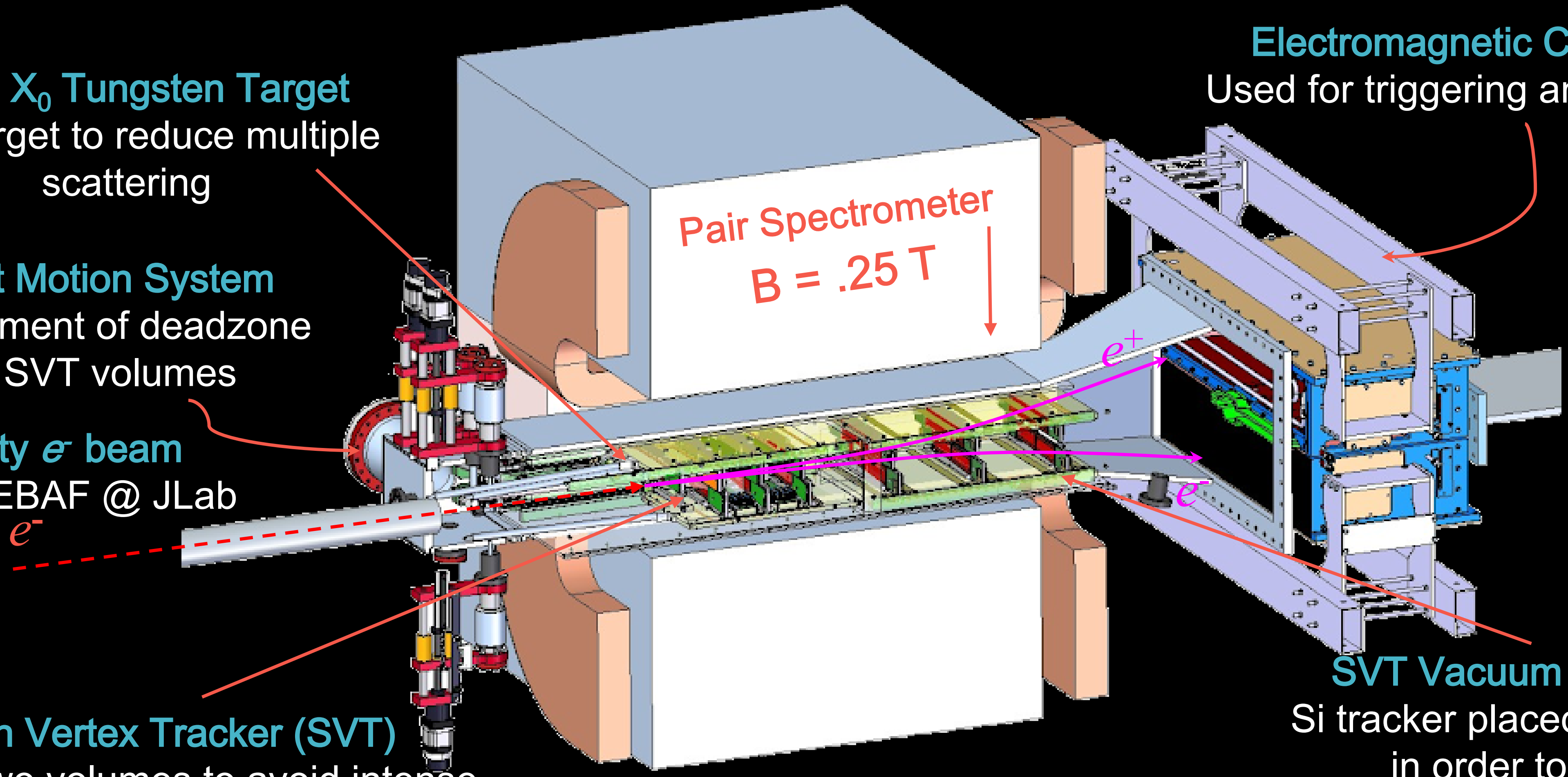
Event data model and persistency employ LCIO.

The HPS Apparatus

~10^{-3} X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

High intensity e^- beam
Courtesy of CEBAF @ JLab



Electromagnetic Calorimeter
Used for triggering and particle ID

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Used for precise momentum and vertex determination

SVT Vacuum Chamber
Si tracker placed in vacuum in order to avoid backgrounds due to beam-gas interactions

SVT + ECal DAQ capable of 50 kHz

Installed within the Hall B alcove at Jefferson Lab

HPS Engineering Runs

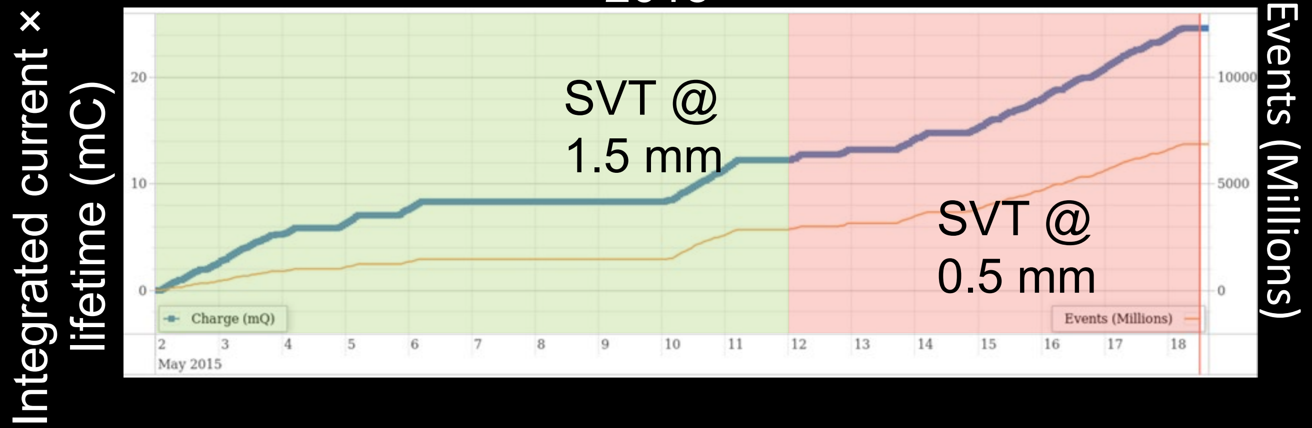
Two successful JLab engineering runs

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

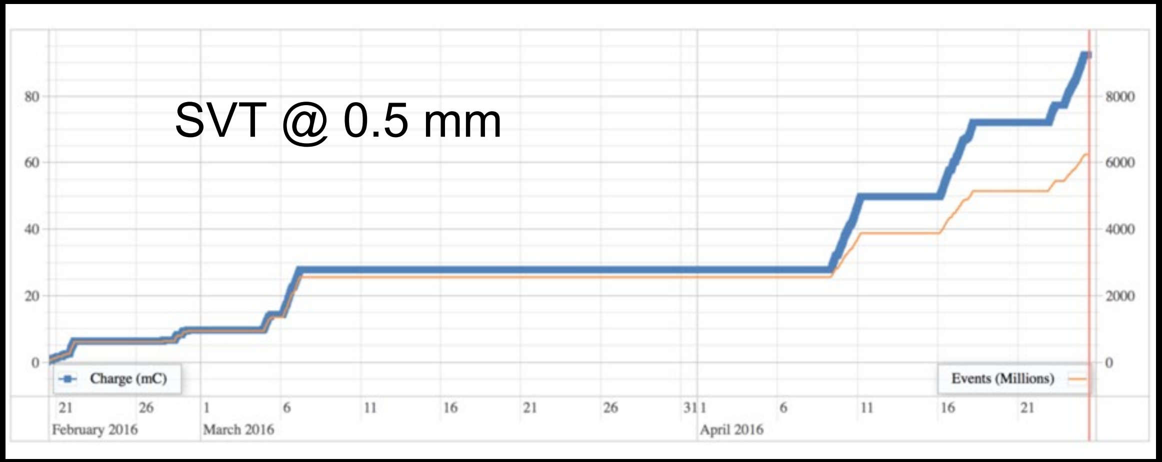
Goal: Understand the performance of the detector and take physics data.

- 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

2015



2016

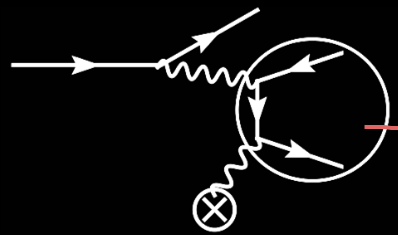


Backgrounds

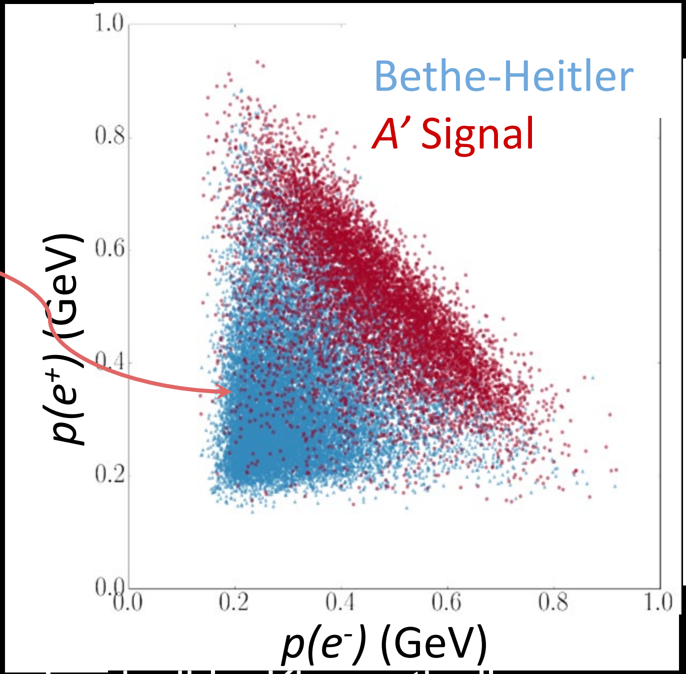
The search for an *A'* involves looking for a narrow resonance in the e^+e^- invariant mass spectrum on top of a large, continuous background composed of several components

Physics Backgrounds

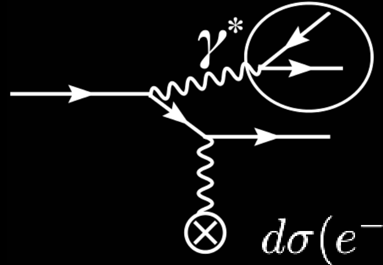
Bethe-Heitler



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



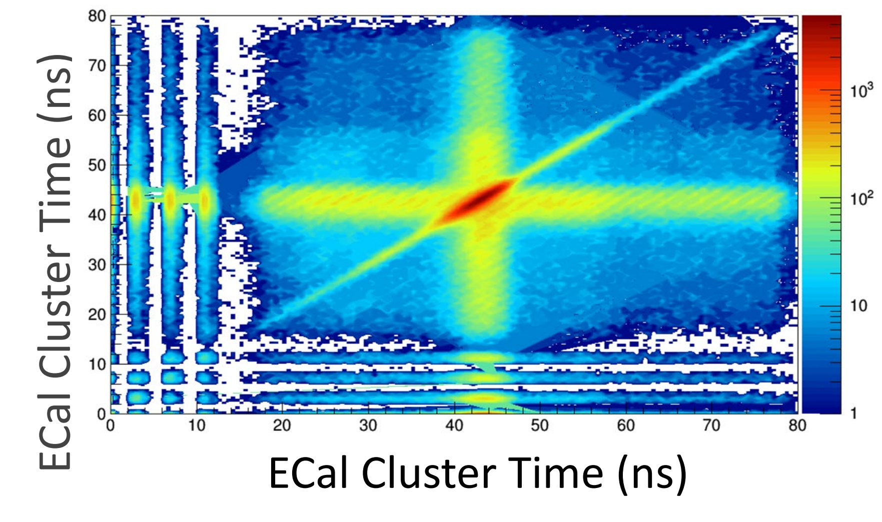
Radiative



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

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

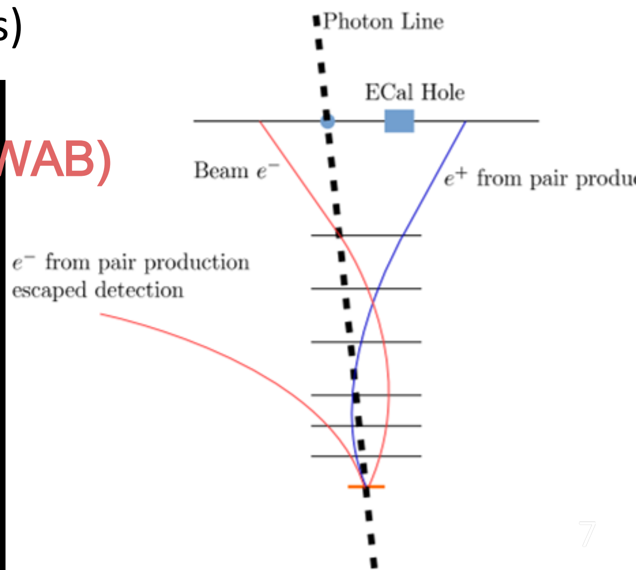
Accidentals



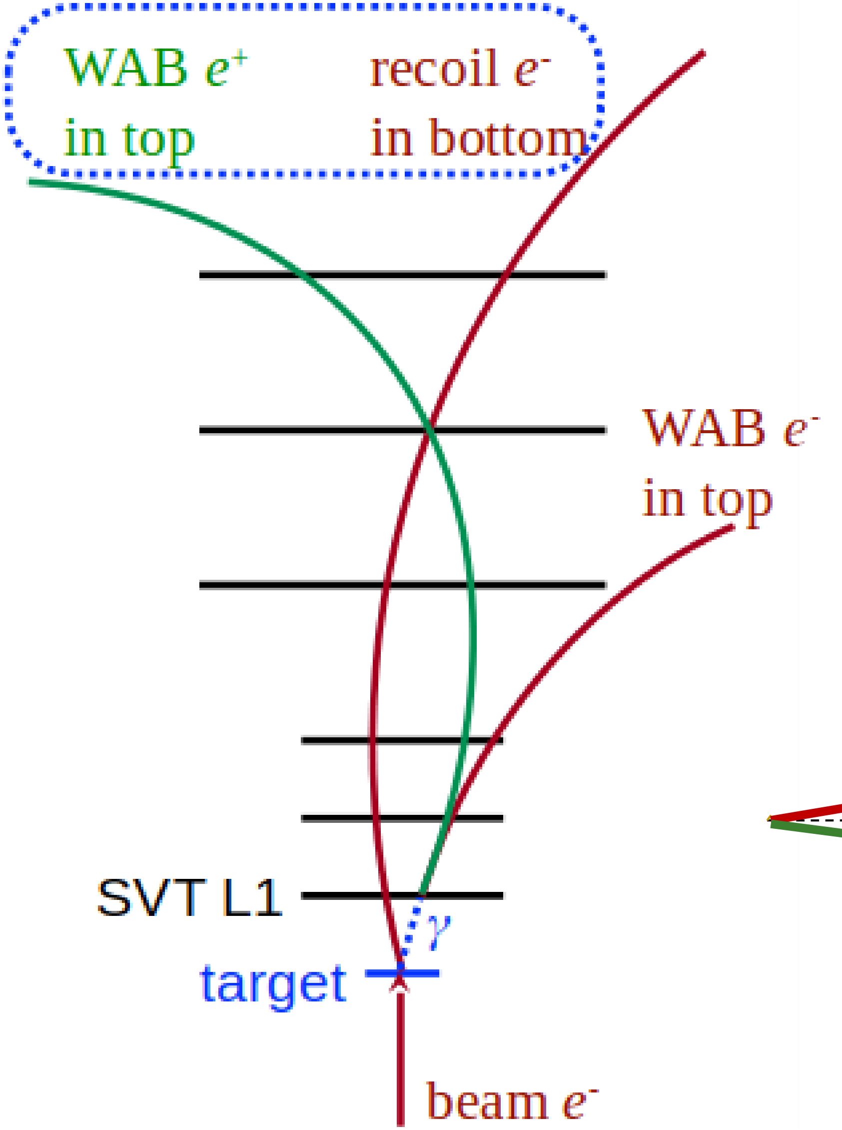
True e+e- pairs will have time-coincident clusters in the calorimeter. Can be suppressed using time cuts and cuts used to remove scattered beam electrons.

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



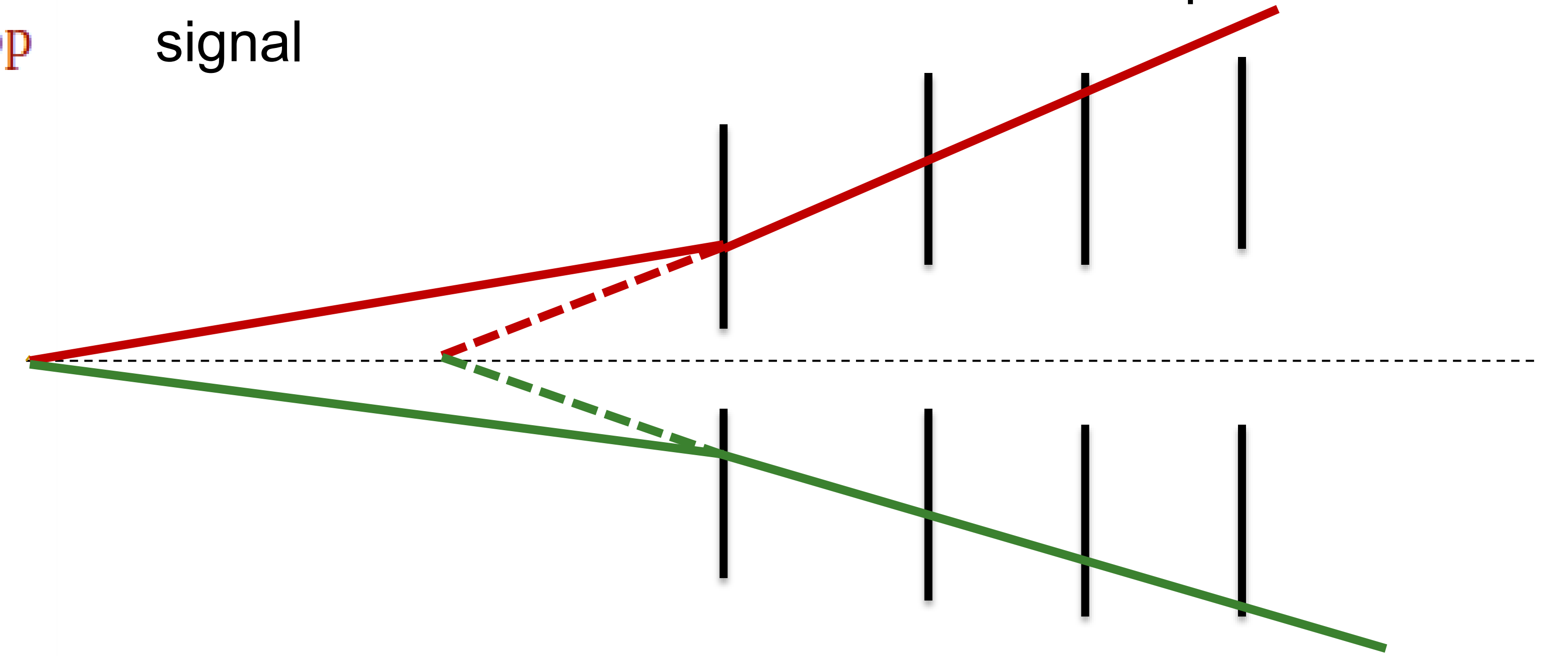
Wide-Angle Bremsstrahlung & Large-Angle Scatters



During the analysis we realized that in the final state there is a significant contribution from the two step process: WAB → 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



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.)

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

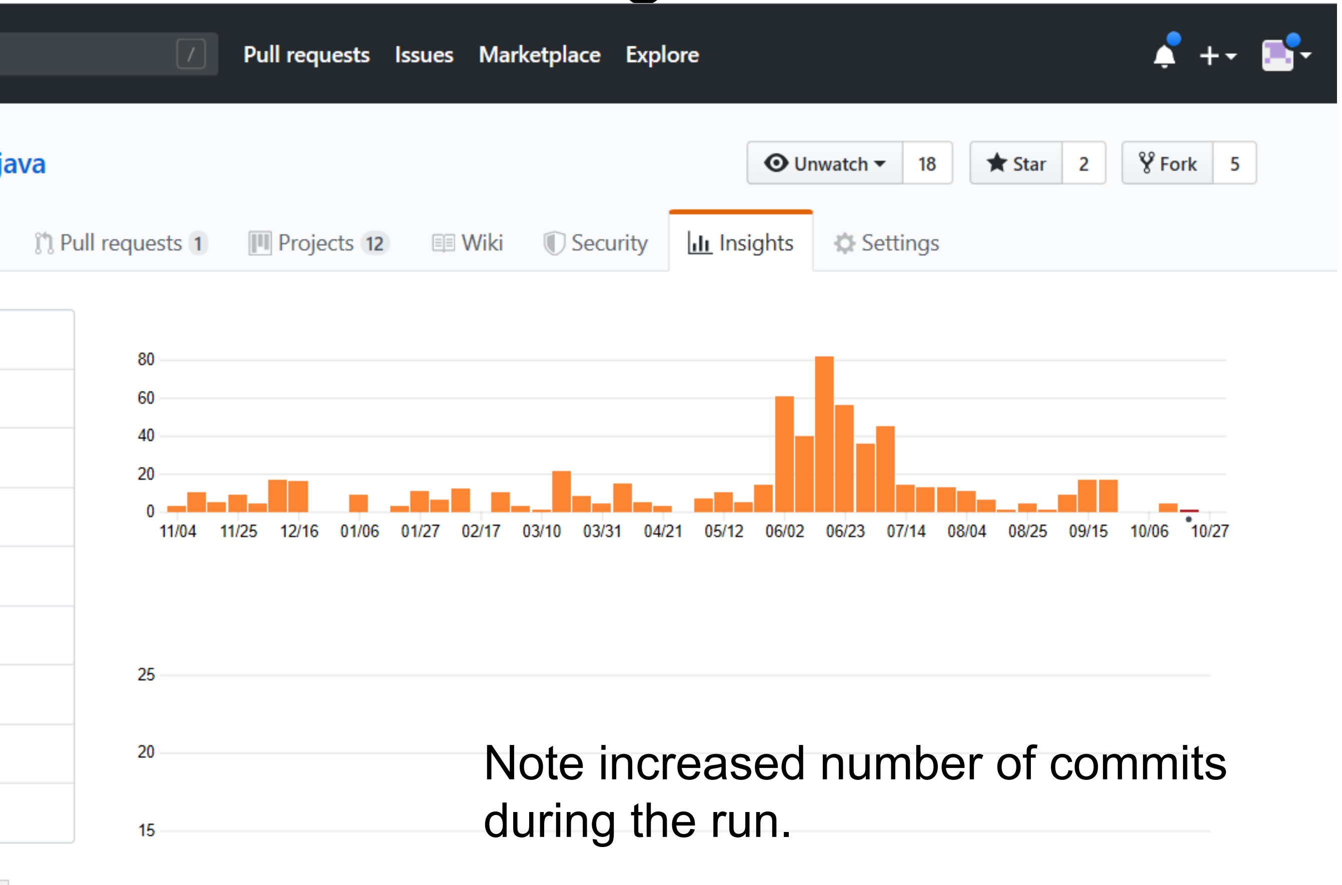
Unit tests are automatically run for individual classes and components, assertions in code ensure correct behavior.

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.

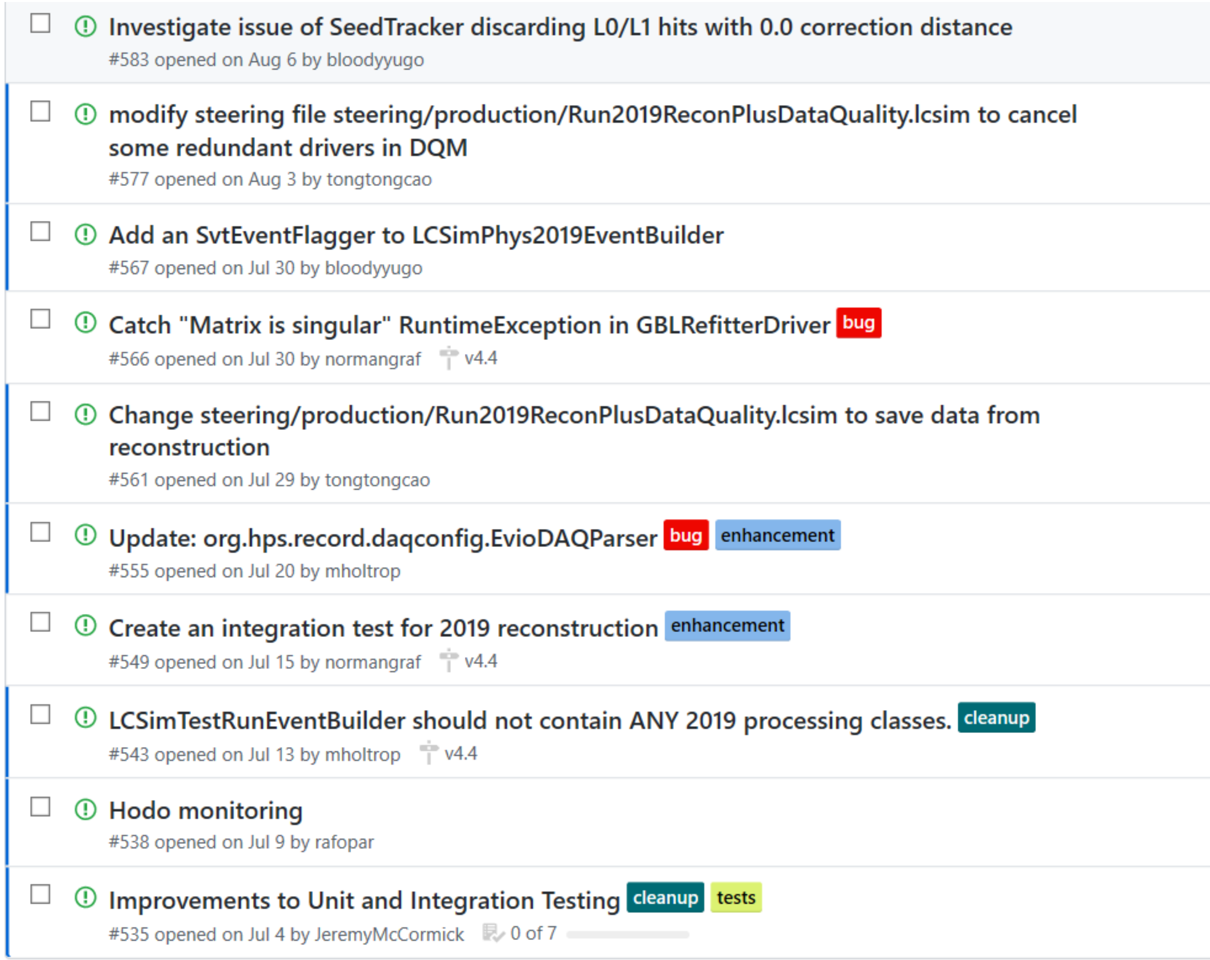
Executable jar files are deployed to nexus repository.

Code Management

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



Note increased number of commits during the run.



Tracking

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

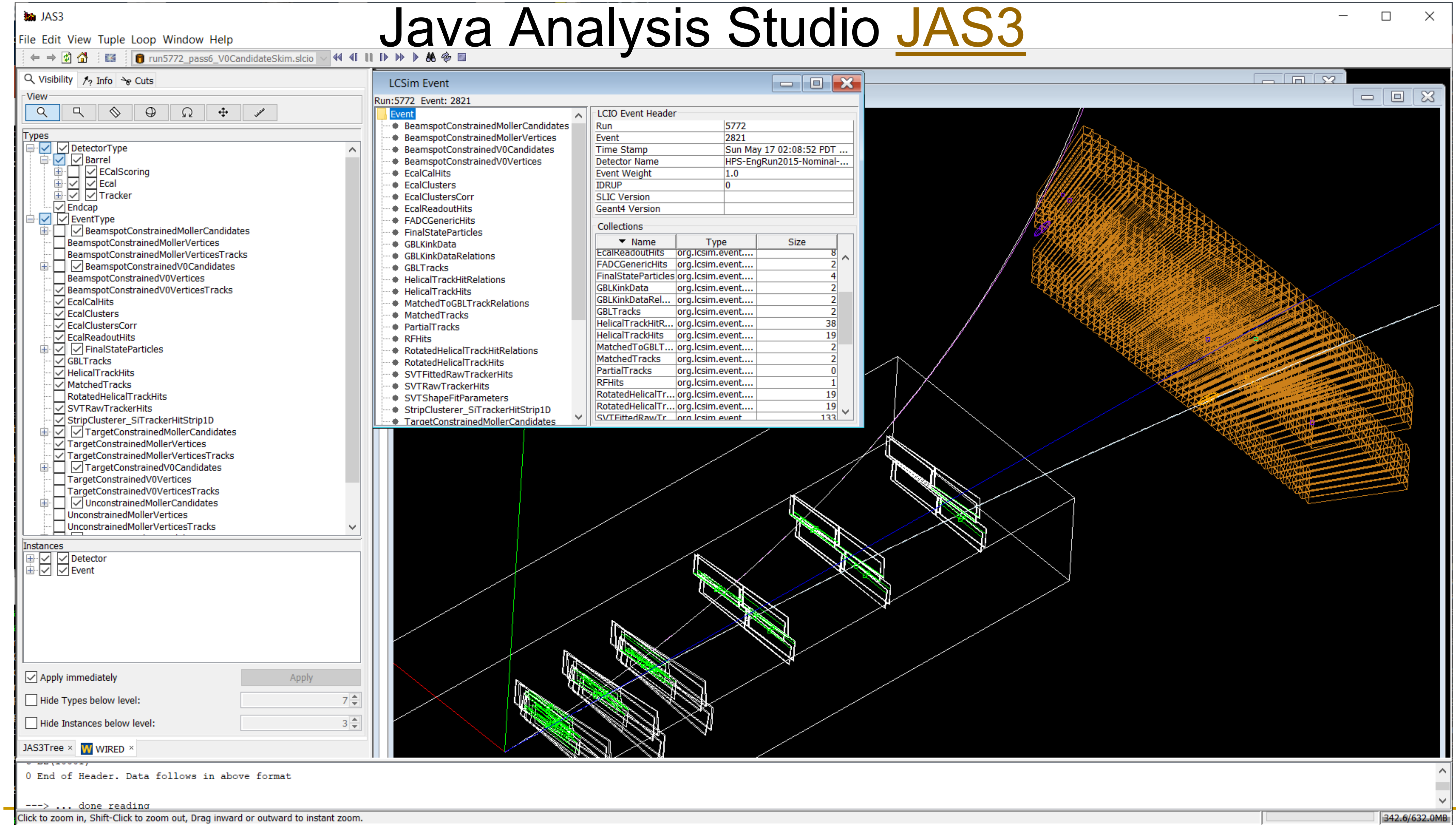
Final refits use a java port of the General Broken Lines (GBL)

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



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.

Documentation

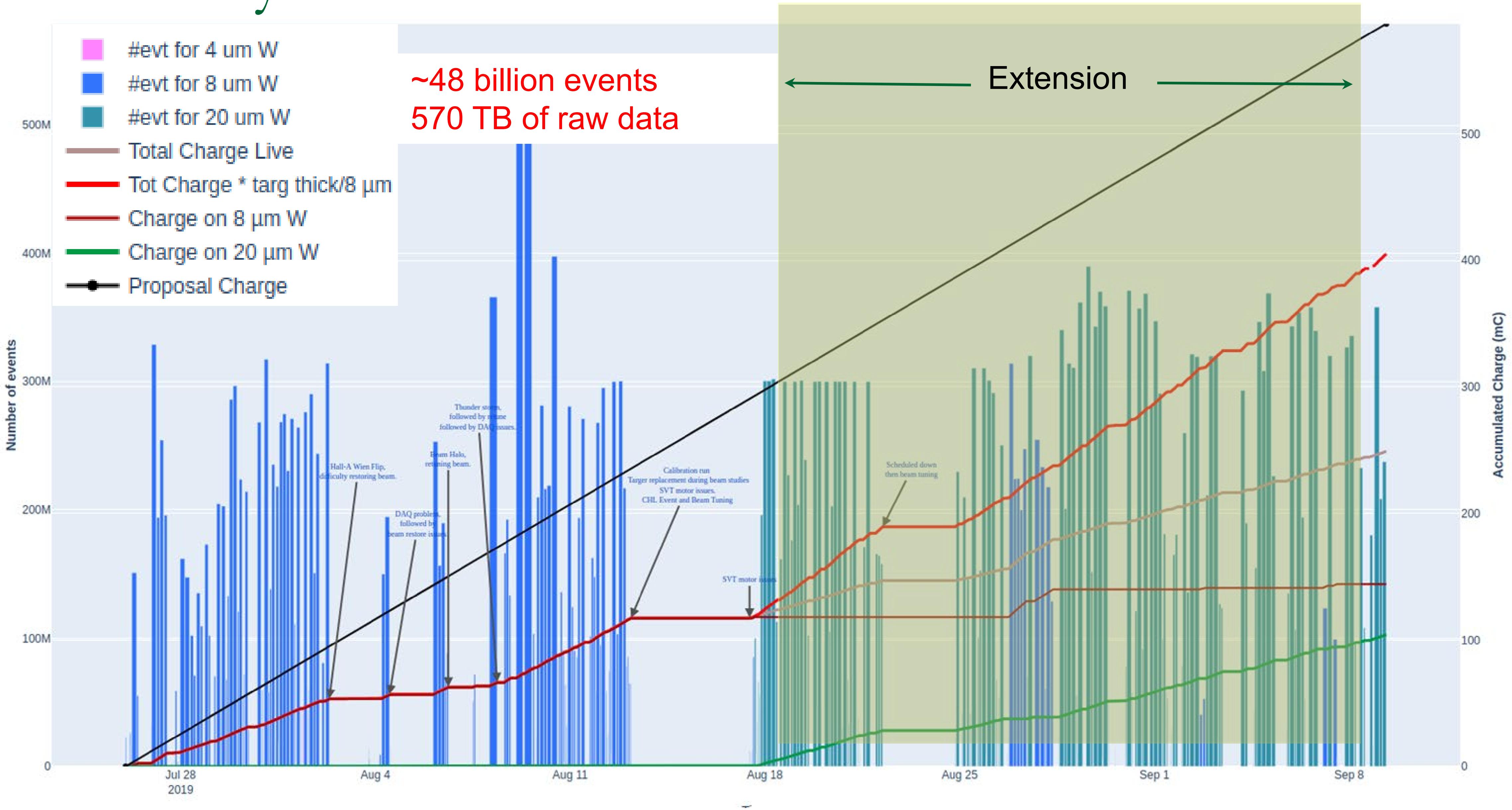
slack is used for rapid communication, quick turnaround

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 collected about half of the expected statistics.

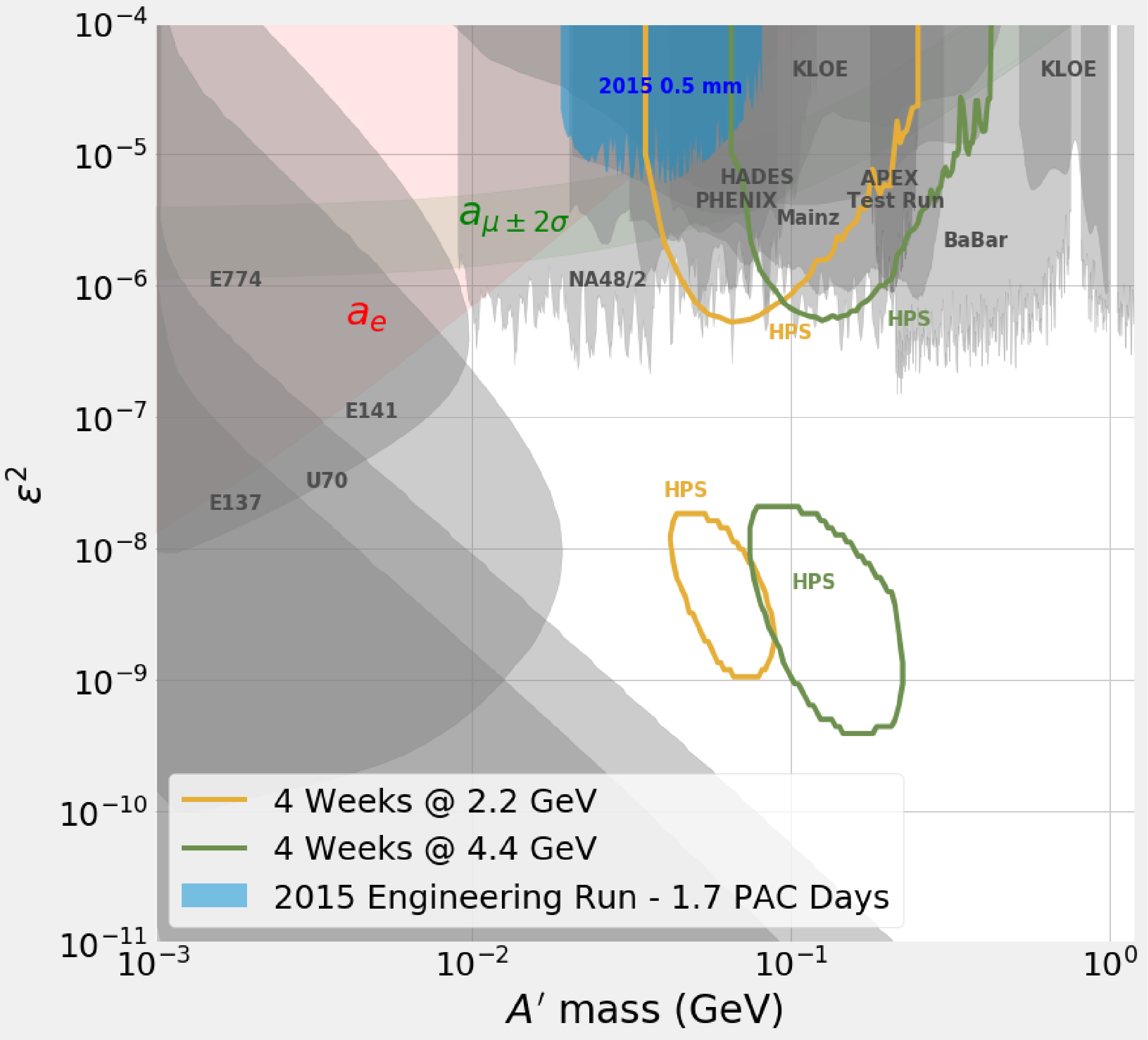
Data is now being calibrated.

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…



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.