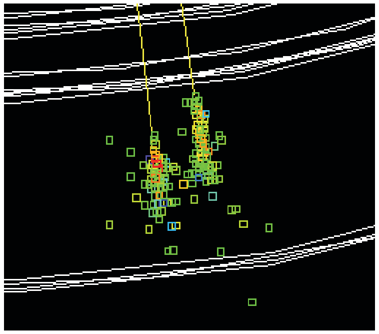
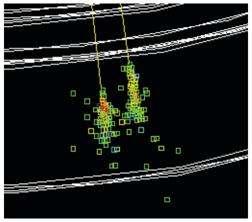


Prototype Silicon-tungsten ECal with Integrated Electronics: First Look with Test Beam

M. Breidenbach, D. Freytag, N. Graf, G. Haller, R. Herbst,
J. Jaros, T. Johnson, D. Khaghani, D. Onoprienko,
B. Reese, J. Russell, C. Sund
SLAC National Accelerator Center

J. Brau, R. Frey, C. Gallagher, D. Strom,
W. McCann, D. Mead (grad students),
K. Travis (undergraduate)
U. Oregon

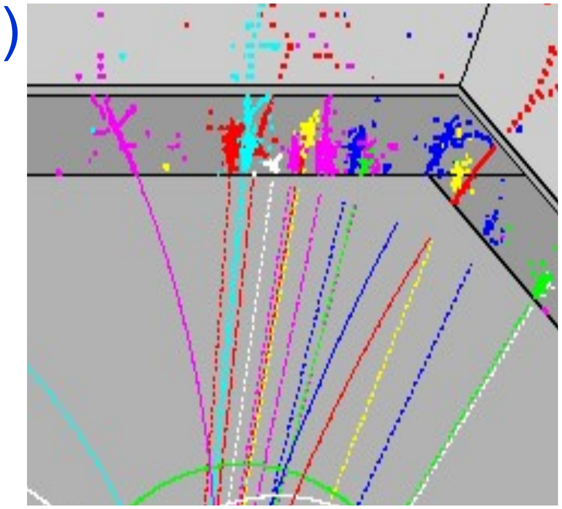
B. Holbrook, C. Neher, M. Tripathi, grad students
UC Davis

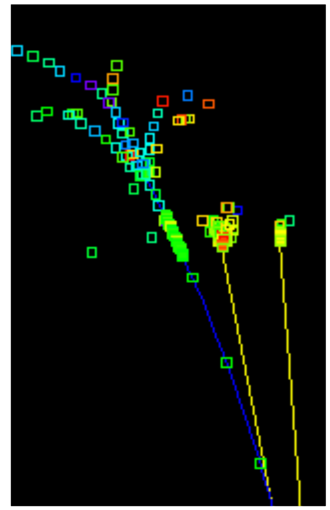


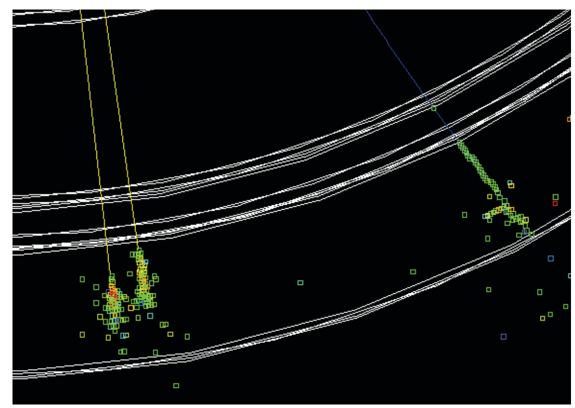
SiD "Imaging ECal": Motivated by LC Physics

Guiding principles: Measure all final states and measure with precision

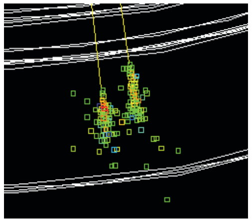
- Multi-jet final states (t-chan, missing E, combinatorics)
  - π° measurement should not limit jet resolution
  - id and measure h° and $h^{\pm}$ showers
  - track charged particles
- Tau id and analysis
  - Unique window on BSM
- Photons
  - Energy resolution, e.g. $h \rightarrow \gamma\gamma$
  - Vertexing of photons ($\sigma_b \sim 1$ cm), e.g. for GMSB
- Electron id
- Bhabhas and Bhabha acollinearity
- Hermiticity







⇒ Imaging (E)Calorimetry can do all this ("particle flow")

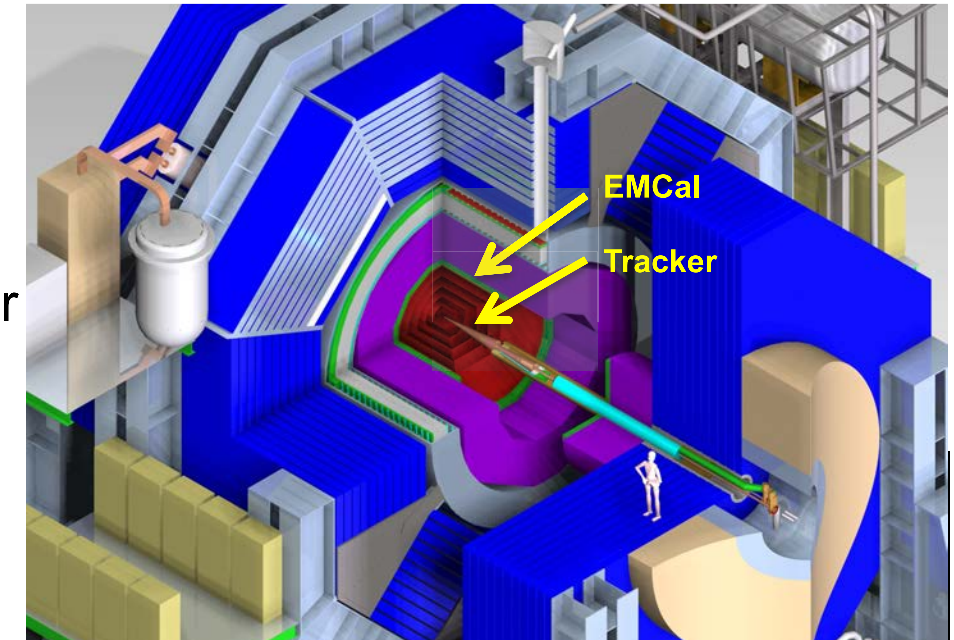


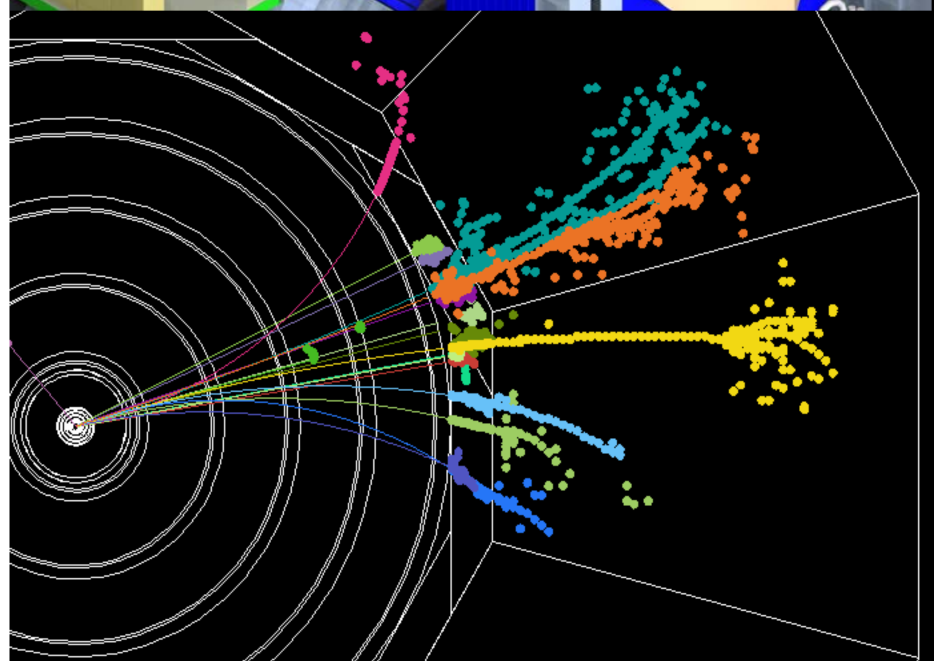
Particle Flow Calorimetry

SiD is designed for Particle Flow Calorimetry

Promises superb jet energy resolution

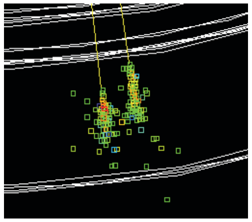
- Tracker measures charged momentum
- Calorimeters measure neutral energy after excluding energy from charged tracks
- <u>Fine segmentation required!</u>
- Current invariant mass resolution <4%
  Z's to light quarks at ILC500.





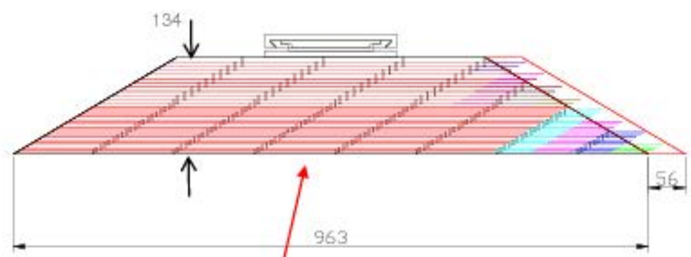
EMCal is critical element

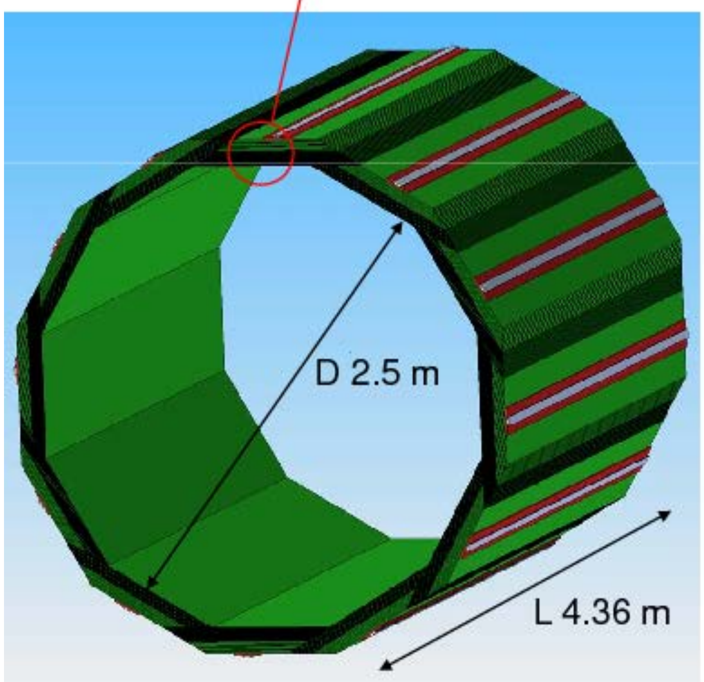
SiD has been developing a silicon-tungsten calorimeter to achieve the highly granular Ecal requirements of the PFA concept

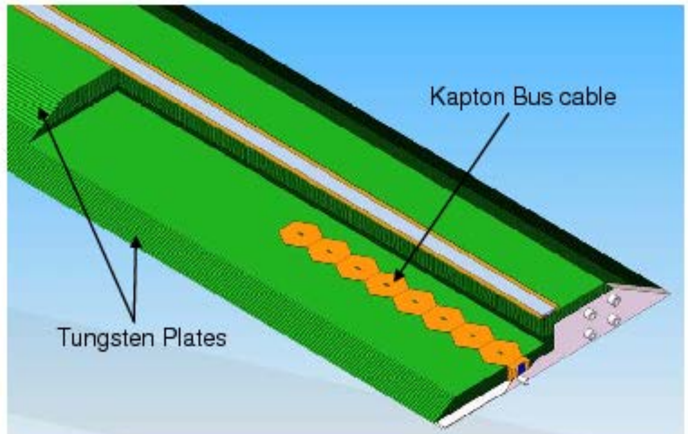


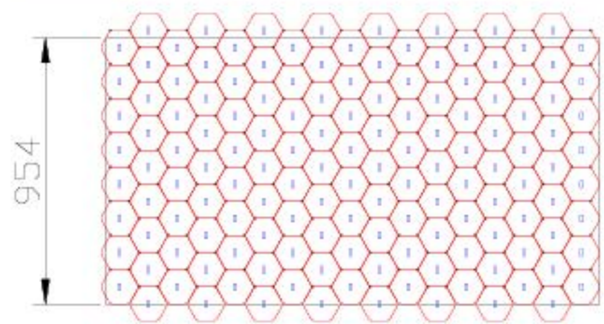
The SiD ECal Baseline

An imaging calorimeter: 30 layers tungsten interleaved with 30 layers pixellated silicon

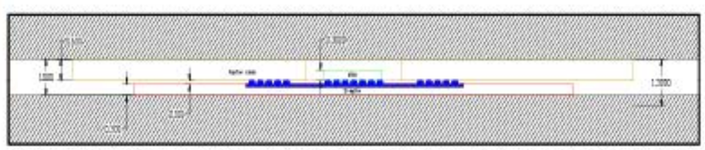








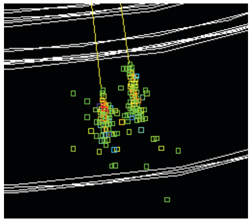
Hexagon sensors arrangement



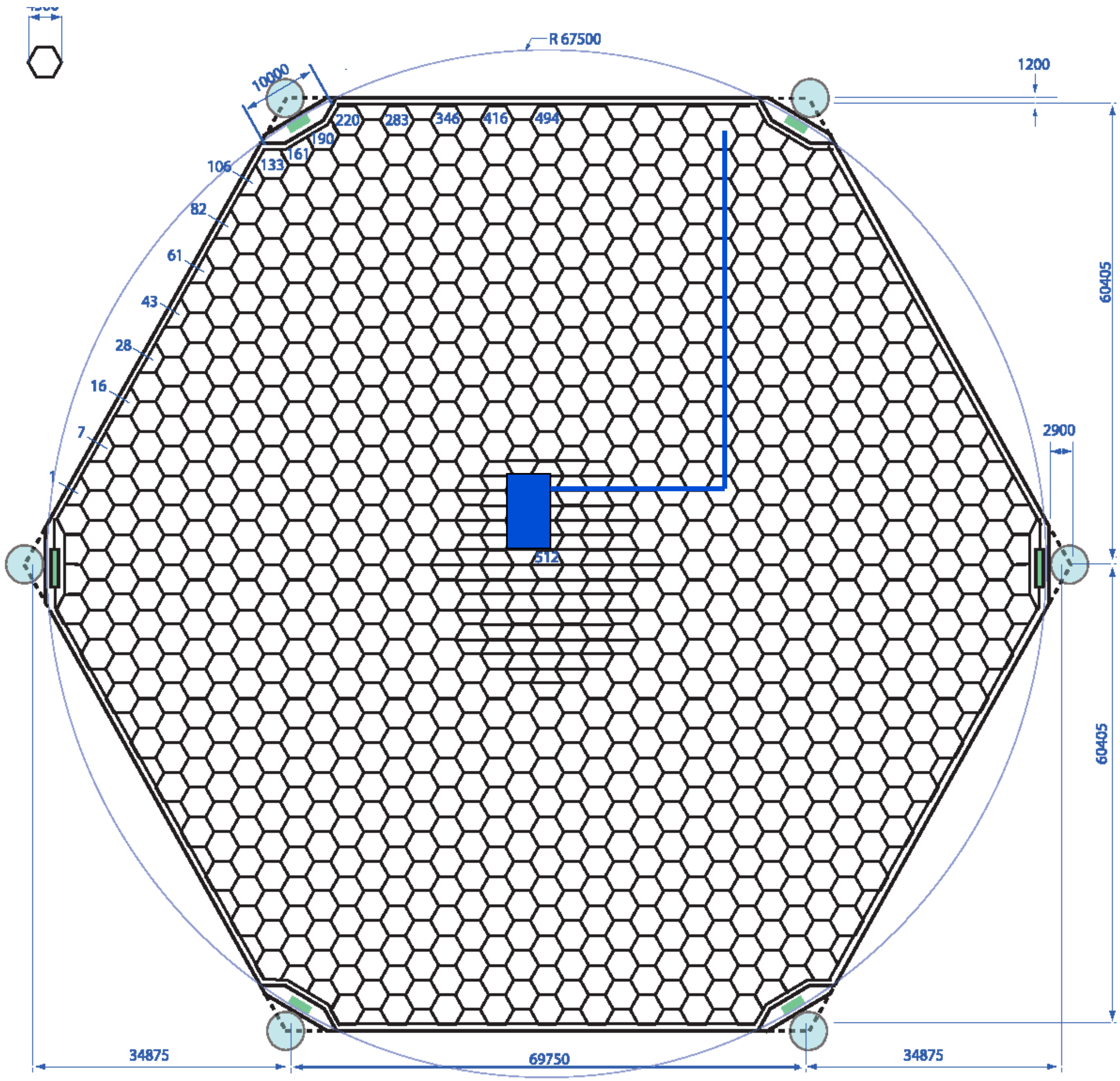
detector module between tungsten plates

<u>Baseline configuration:</u>

- transverse: 13 mm^2 pixels
- longitudinal: (20 x 5/7 X_0) + (10 x 10/7 X_0) $\Rightarrow$ 17%/sqrt(E)
- 1 mm readout gaps $\Rightarrow$ 13 mm effective Moliere radius

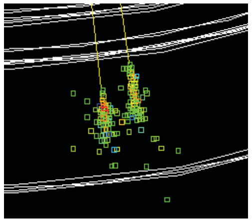


Si sensors



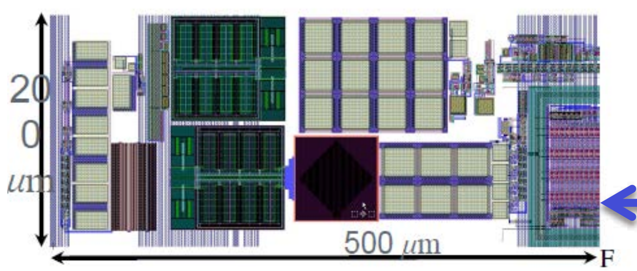
- 6 inch wafers
- 1024 13 mm^2 pixels
- KPiX readout is bump-bonded directly to sensor

KPiX ASIC and sample trace

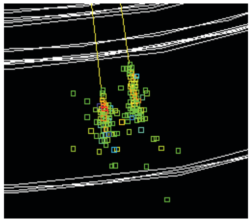


KPiX – System on a Chip

- KPiX is a 1024 channel ASIC to bump bond to Si detectors, optimized for the ILC (1 ms trains, 5 Hz rate):
  - Low noise dual range charge amplifier w/ 17 bit dynamic range.
  - Power modulation w/ average power <20 μW/channel (ILC mode).
  - Up to 4 measurements during ILC train; each measurement is amplitude and bunch number.
  - Digitization and readout during the inter-train period.
  - Internal calibration system
  - Noise Floor: 0.15 fC (1000 e^-)
  - Peak signal (Auto-ranging) 10 pC
  - Trigger Threshold Selectable (0.1 – 10 fC)

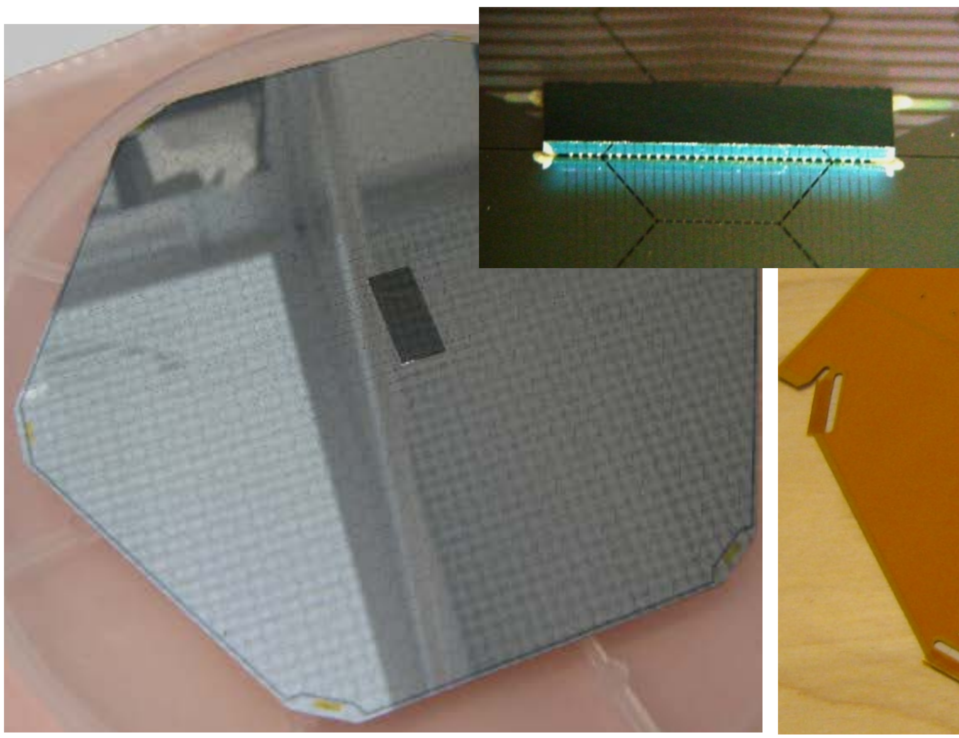


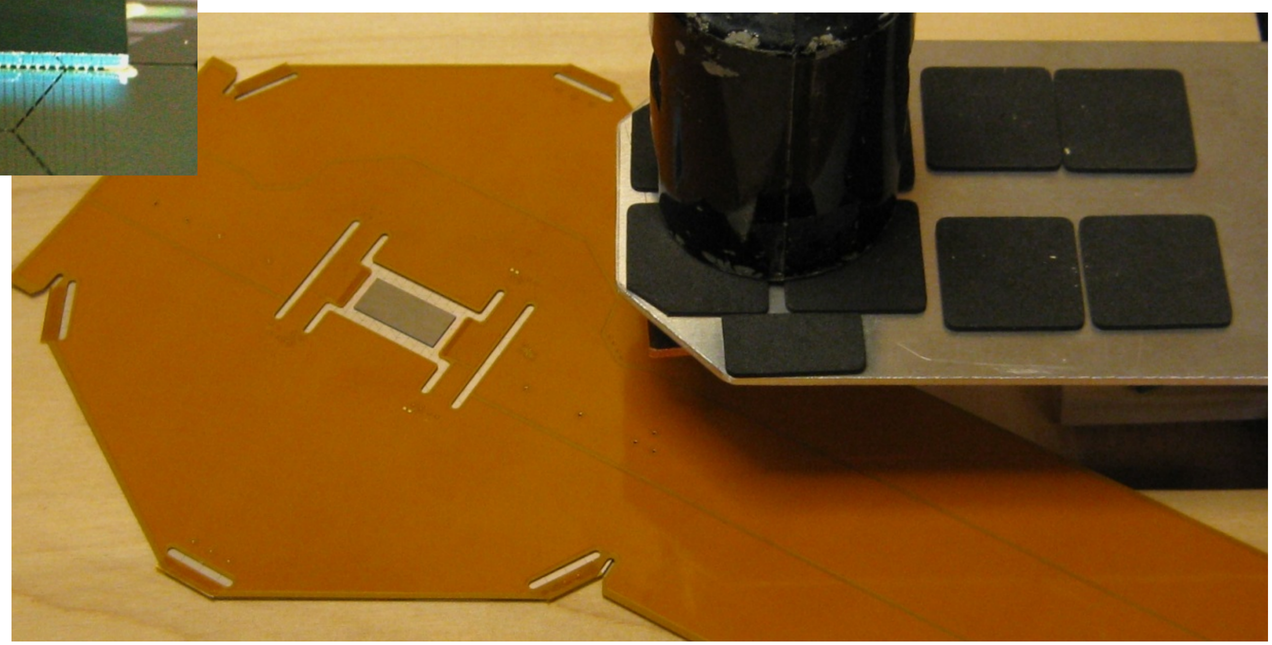
One pixel, 200 x 500 μmeters

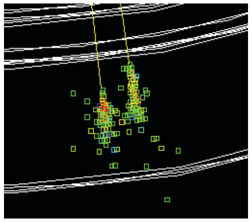


The R&D program

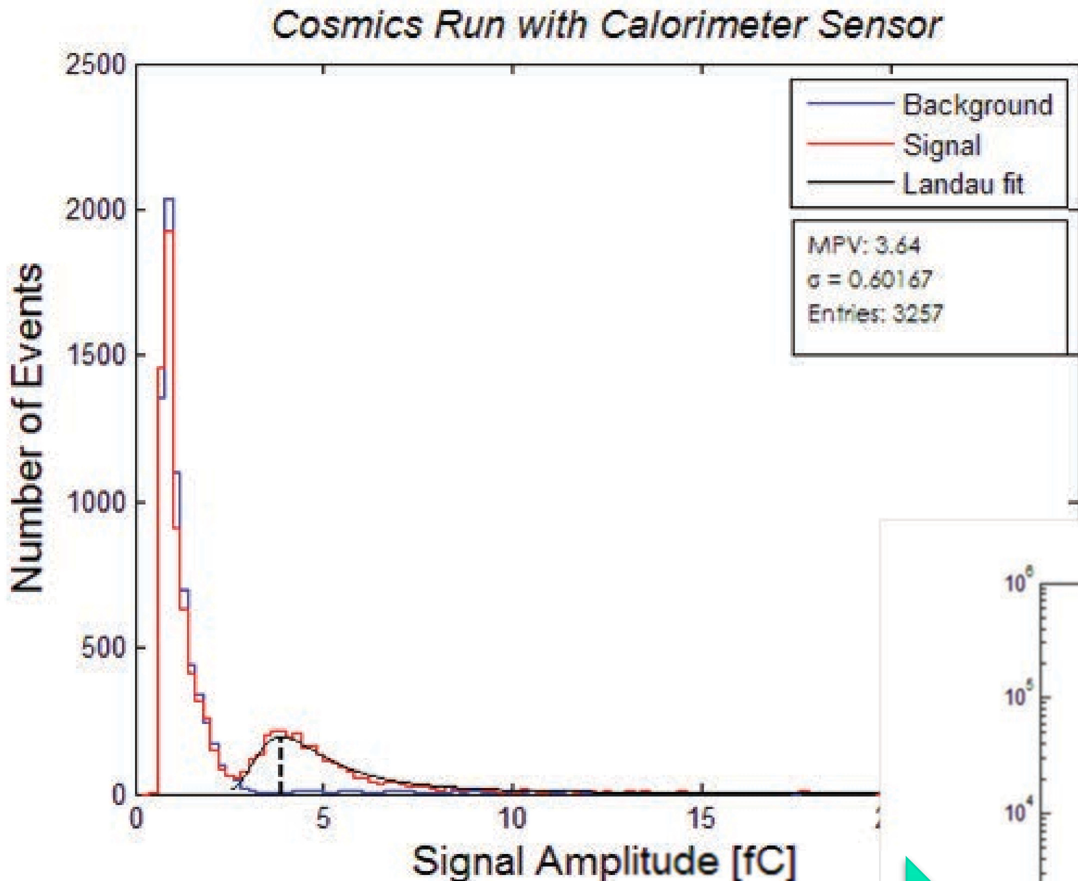
- Physics: A highly-segmented (13 mm^2) *imaging* ECal with small Moliere radius (~13 mm) which can image MIPs to 500 GeV EM showers without melting
- The key element: a highly integrated electronic readout
  - ~1024 pixel sensors readout and digitized by single chip (KPiX) with power pulsing which is bump-bonded to the sensor, read out on flex
- The R&D provides the required baseline ECal components (except large-scale mechanics) – now nearly completed



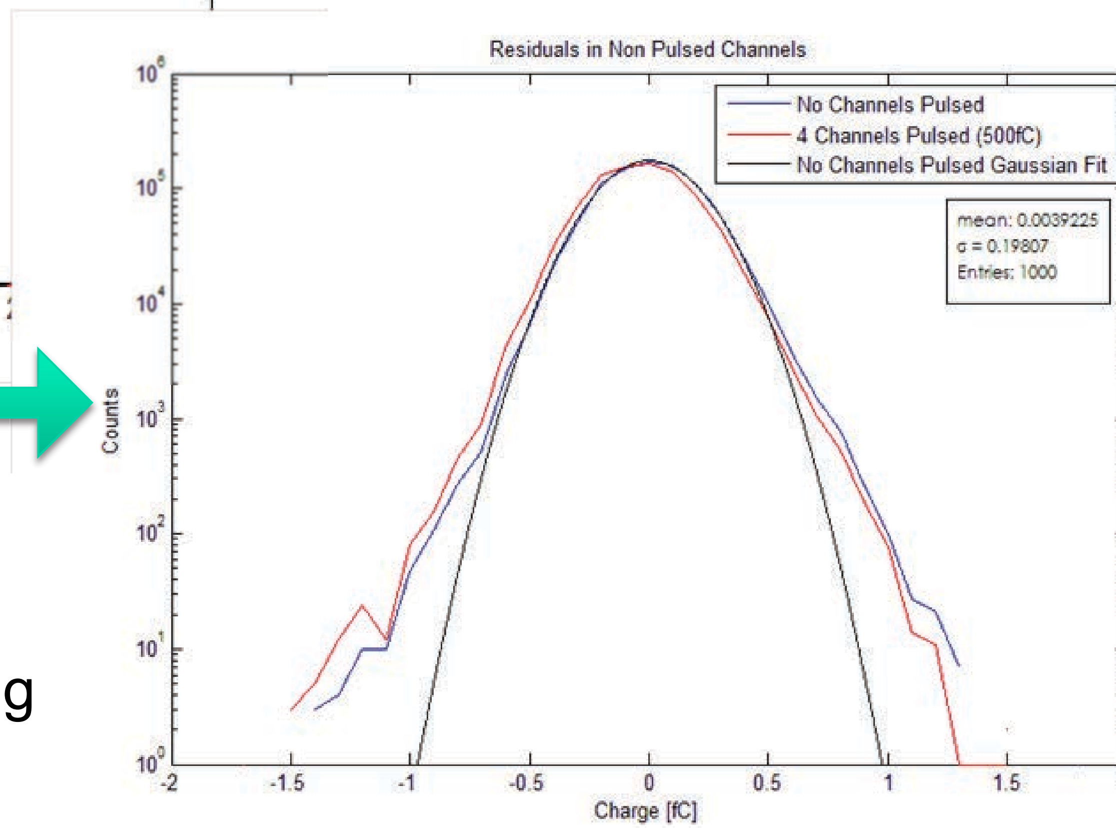




Basic performance is very good



Cosmic MIPs



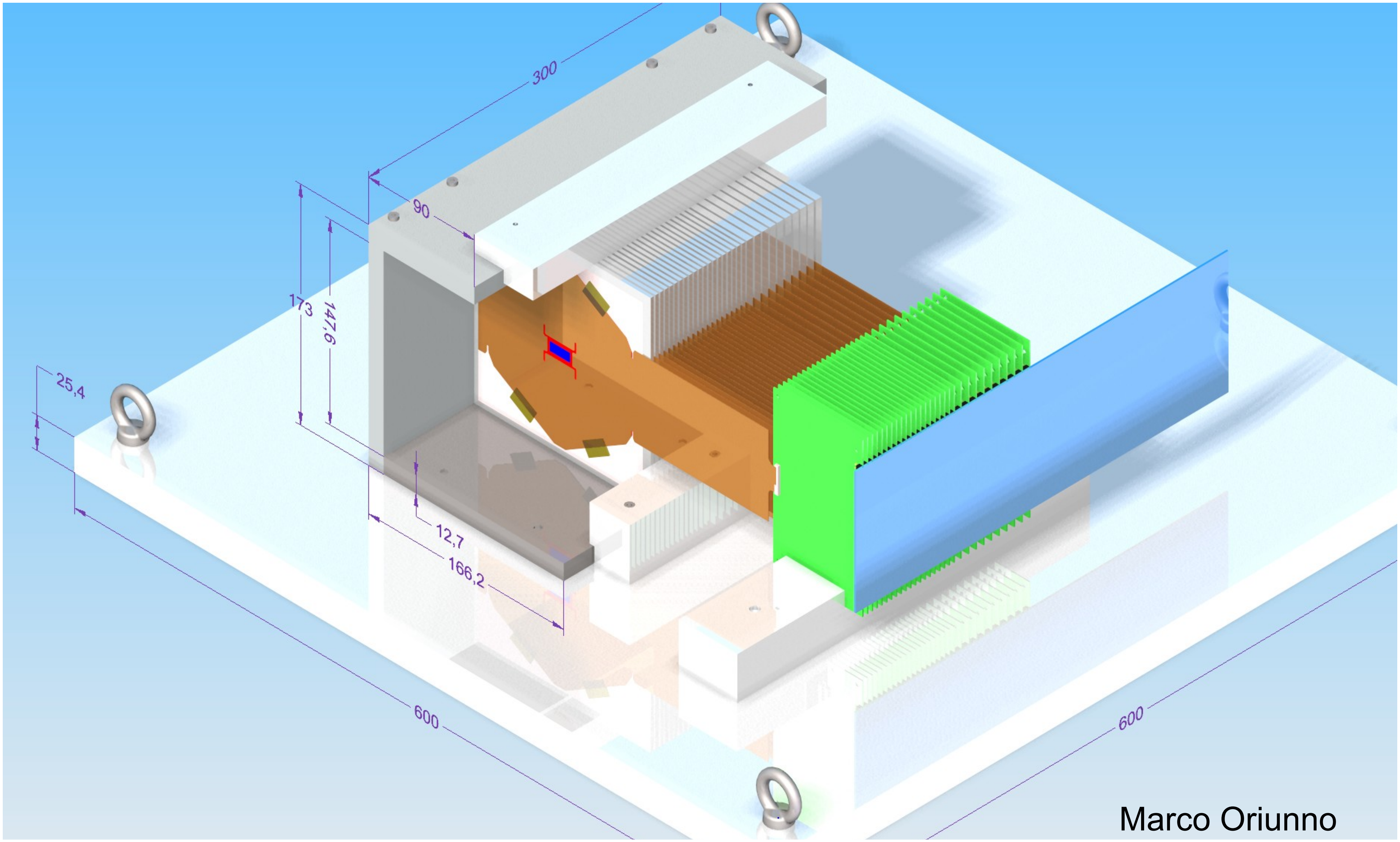
<u>Cross talk study:</u>

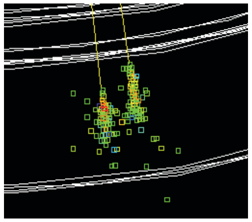
Red: 4 pixels pulsed at 500 fC, all other channels shown.

Blue: no pixels pulsed.

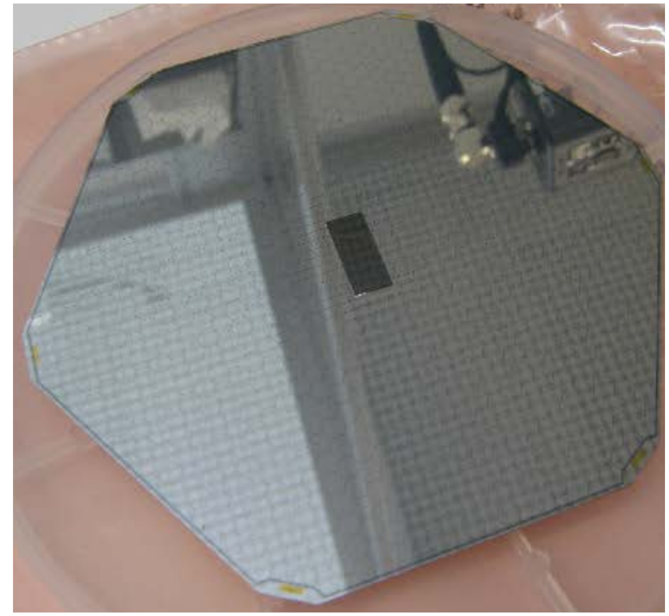
Good isolation – but only testing feedthrough from 4 pixels

R&D goal: Test beam module – 30 layers with same long. profile as SiD

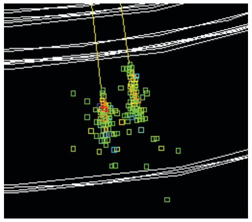




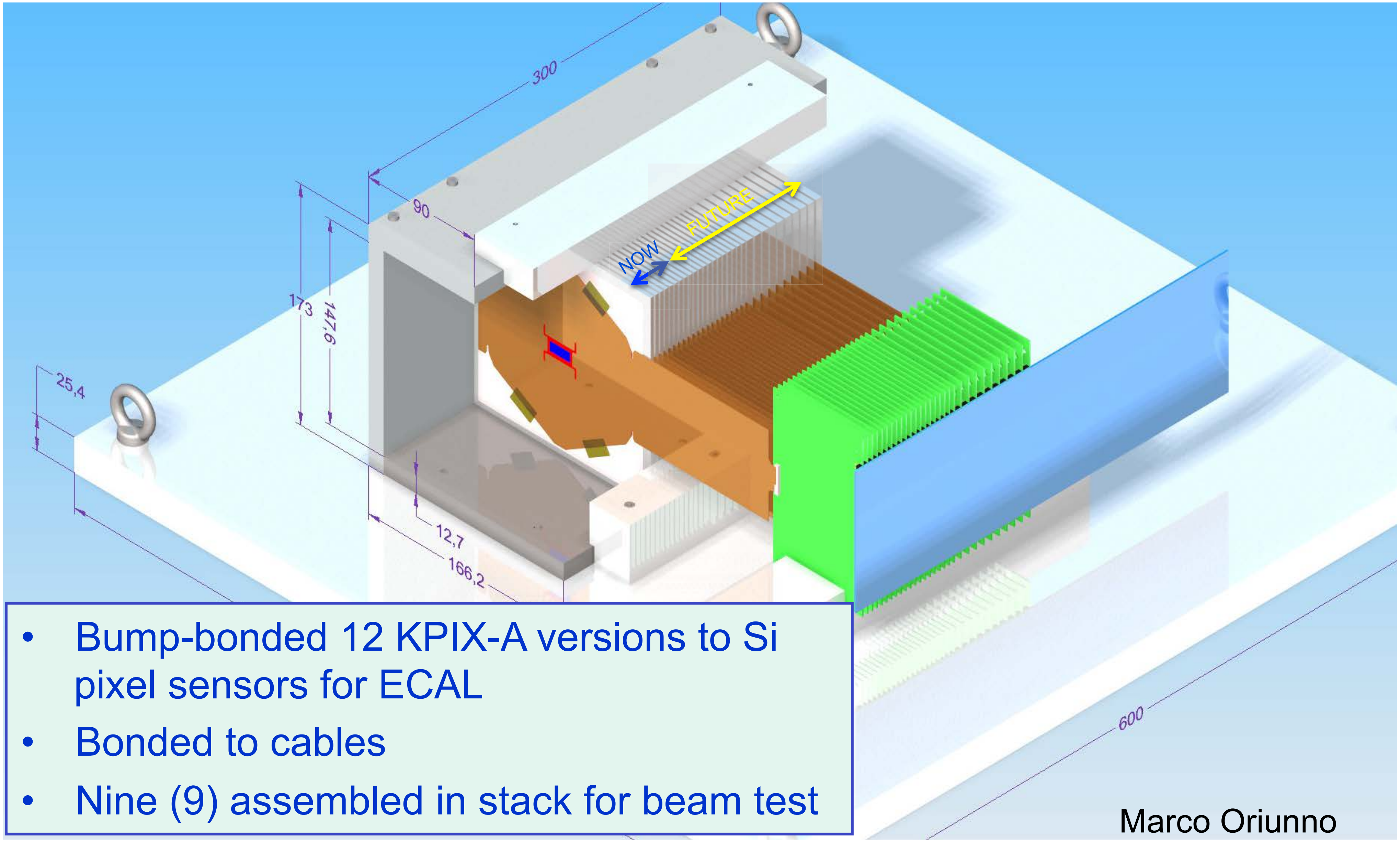
Interconnects update



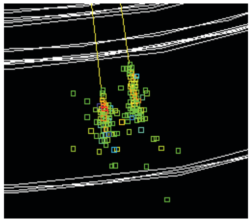
- The Hamamatsu sensors have Al bonding pads → Al oxide
- The KPiX chips (v-A) come from TSMC with eutectic Sn-Pb solder bumps
- Enlisted IZM to prepare the sensors (Ar ion etch + electro-plating of Ni-Au) and complete the bump bonding.
- Successful for ~90%, but 10% of pixels have shorts or opens
  - Mostly shorts
  - “Shorts” are connected to another pixel (crosstalk)
- Inspection found that these were associated with visually identified defects ➔ Leading hypothesis is that IZM processing (ion wash) led to ESD or ESD-like damage
- The first batch of these sensors used in test beam prototype.



Initial test beam module for T-511 only 9 Si + 8 W layers (~ 6 X_0)

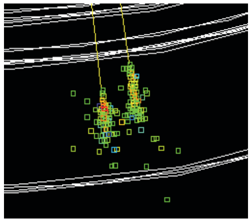


- Bump-bonded 12 KPIX-A versions to Si pixel sensors for ECAL
- Bonded to cables
- Nine (9) assembled in stack for beam test

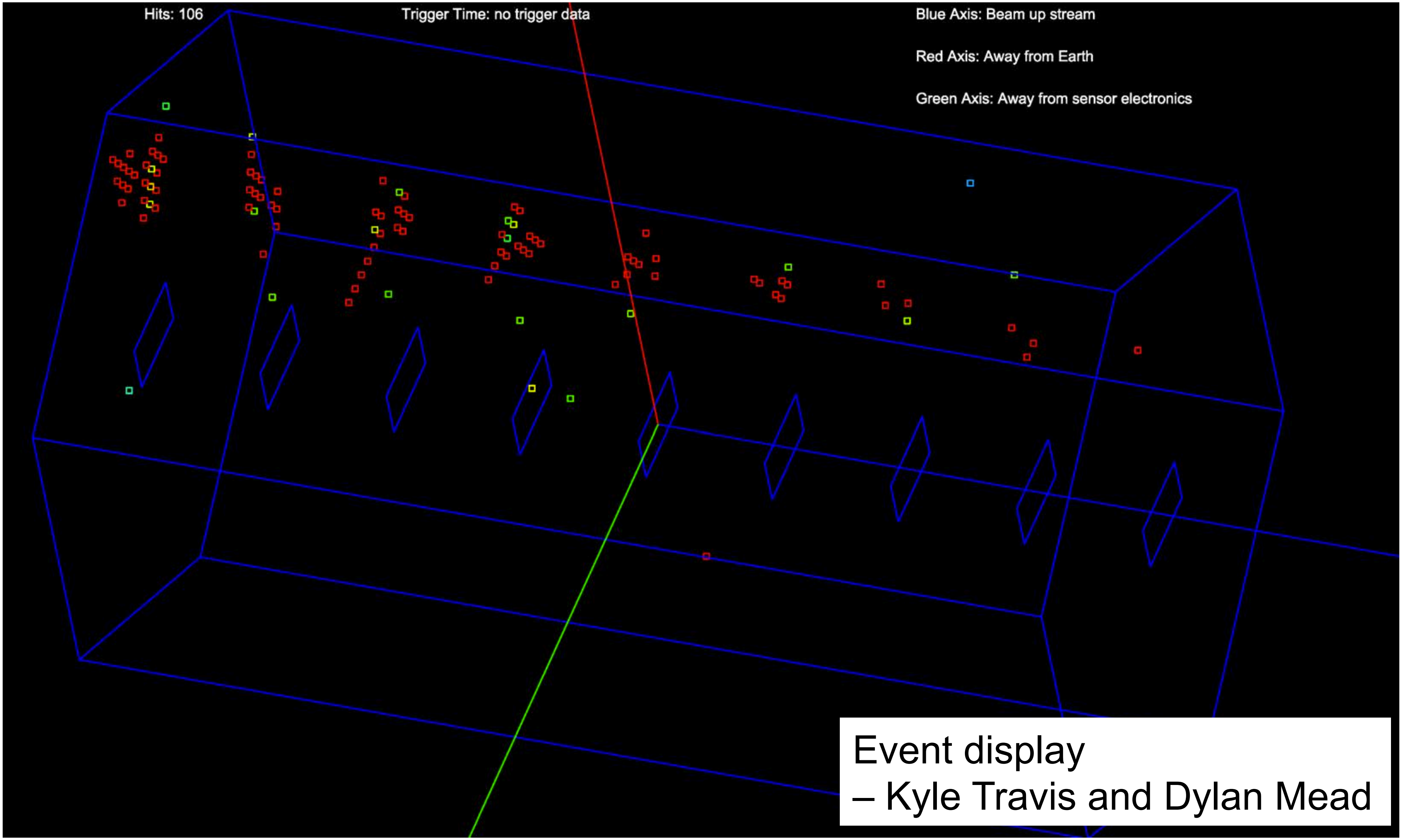


Beam Test (T-511) Overview

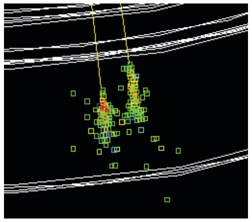
- SLAC End Station A
- 4 half-days of good running, July 26-29
- 12.1 GeV electrons, ~ 0.5 to ~ 5 /pulse
- well-defined beam, movable x-y platform, upstream instrumentation: one plastic scintillator
- remote control and monitoring at CLA
- online analysis using JAS (thanks to Dima Onoprienko, Tony Johnson)
- excellent support from SLAC (thanks to Carsten Hast, Christine Clarke)
- recorded lots of data
  - In general noise, linearity, etc good
  - However, some performance issues revealed by test



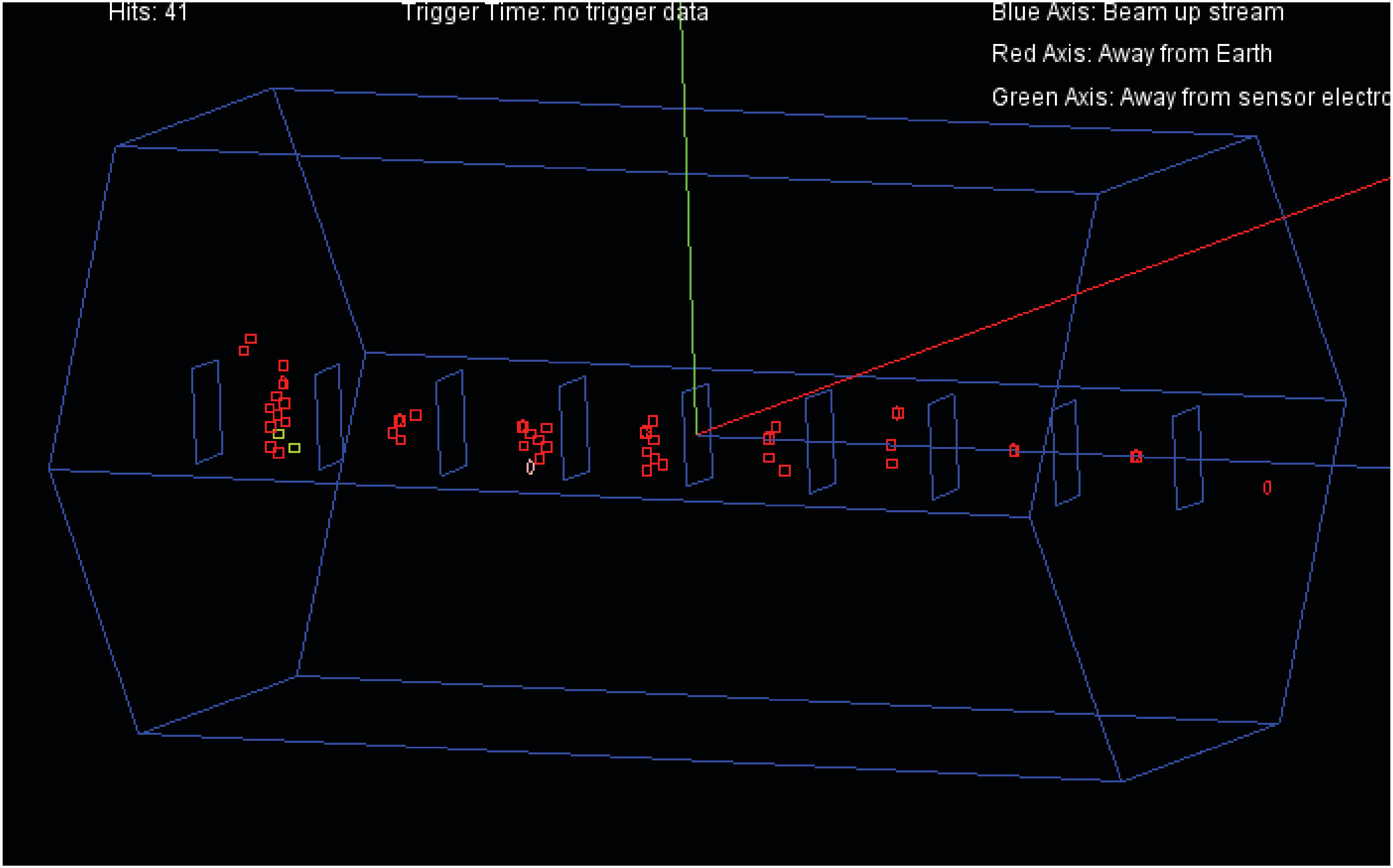
single-electron showers



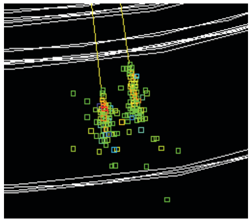
Event display
– Kyle Travis and Dylan Mead

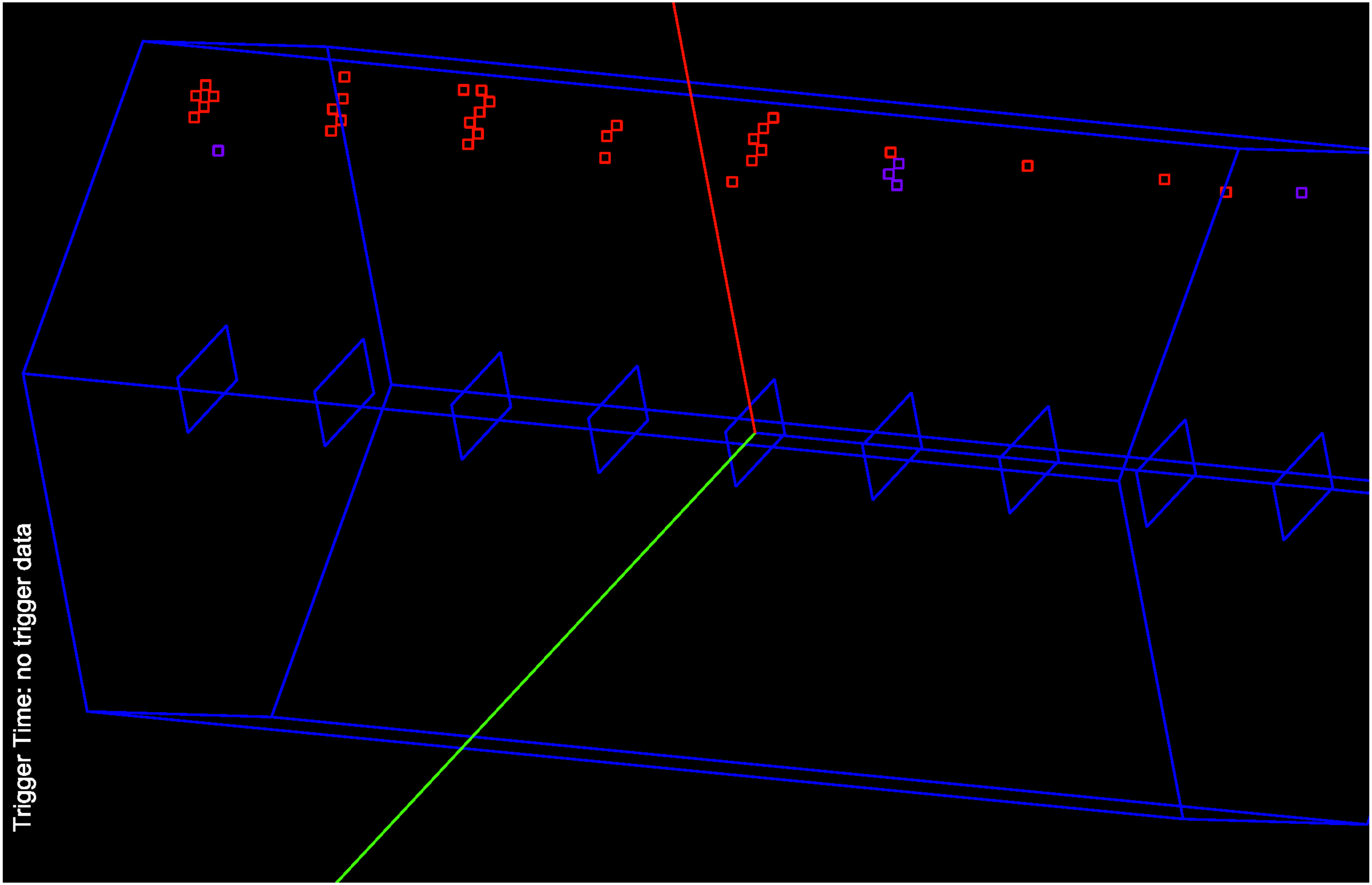


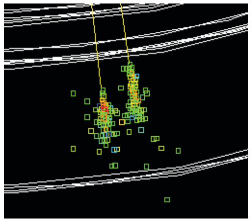
another one-electron event



another one-electron event

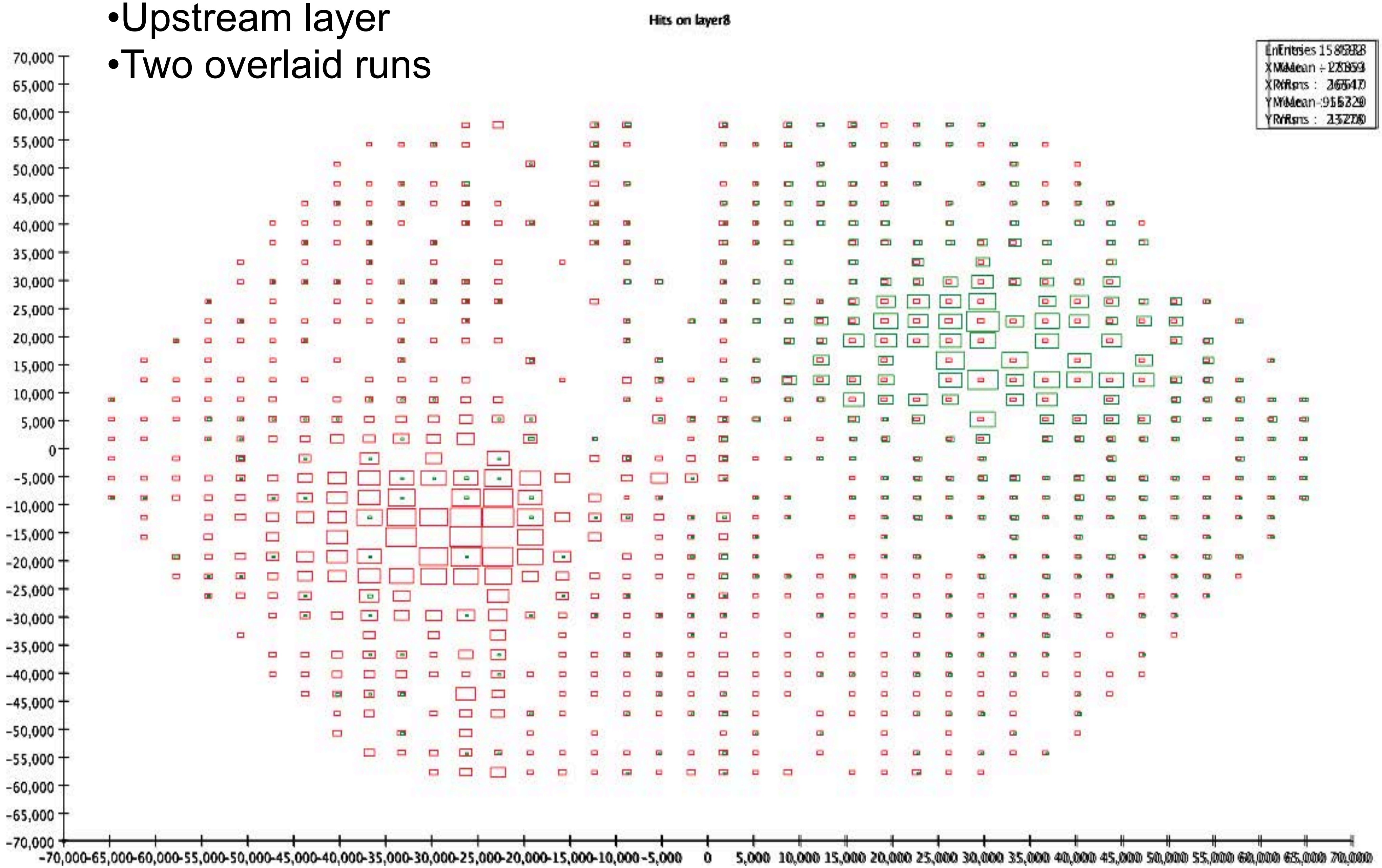


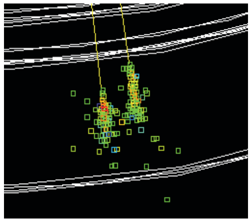




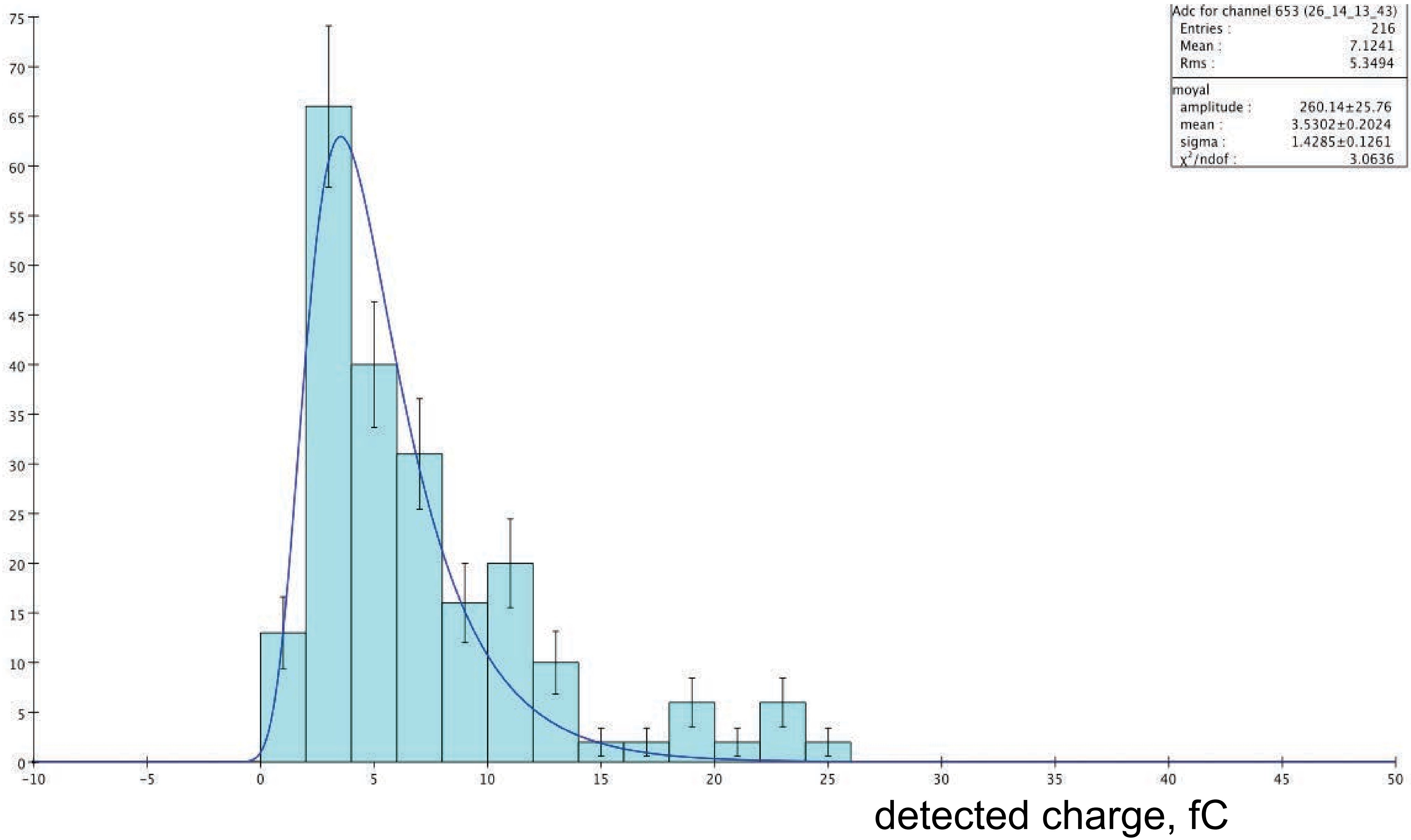
beam size

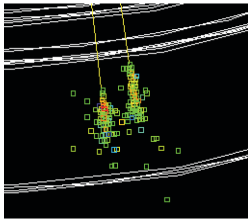
- Upstream layer
- Two overlaid runs



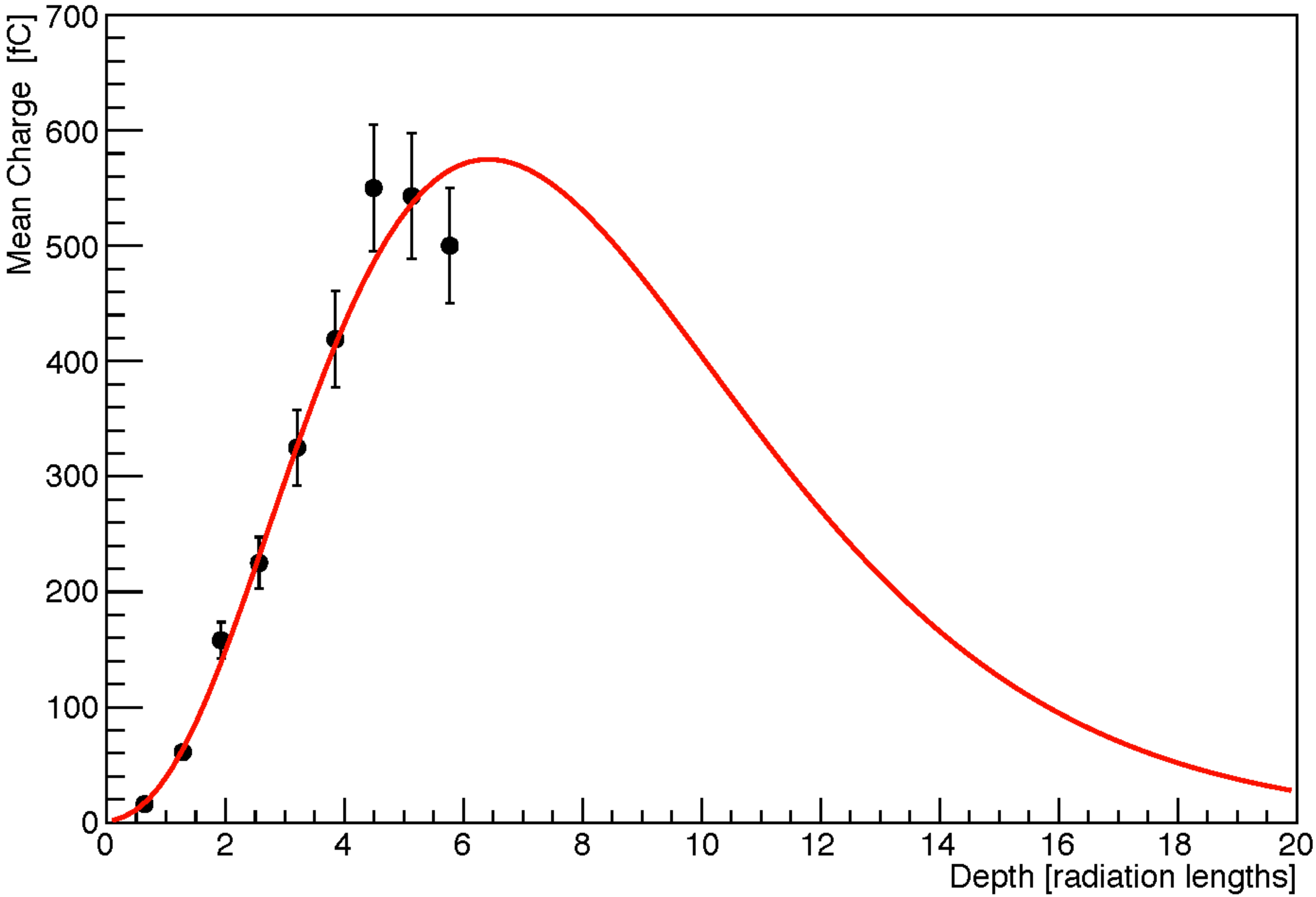


Upstream layer - MIPs

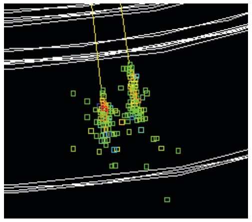


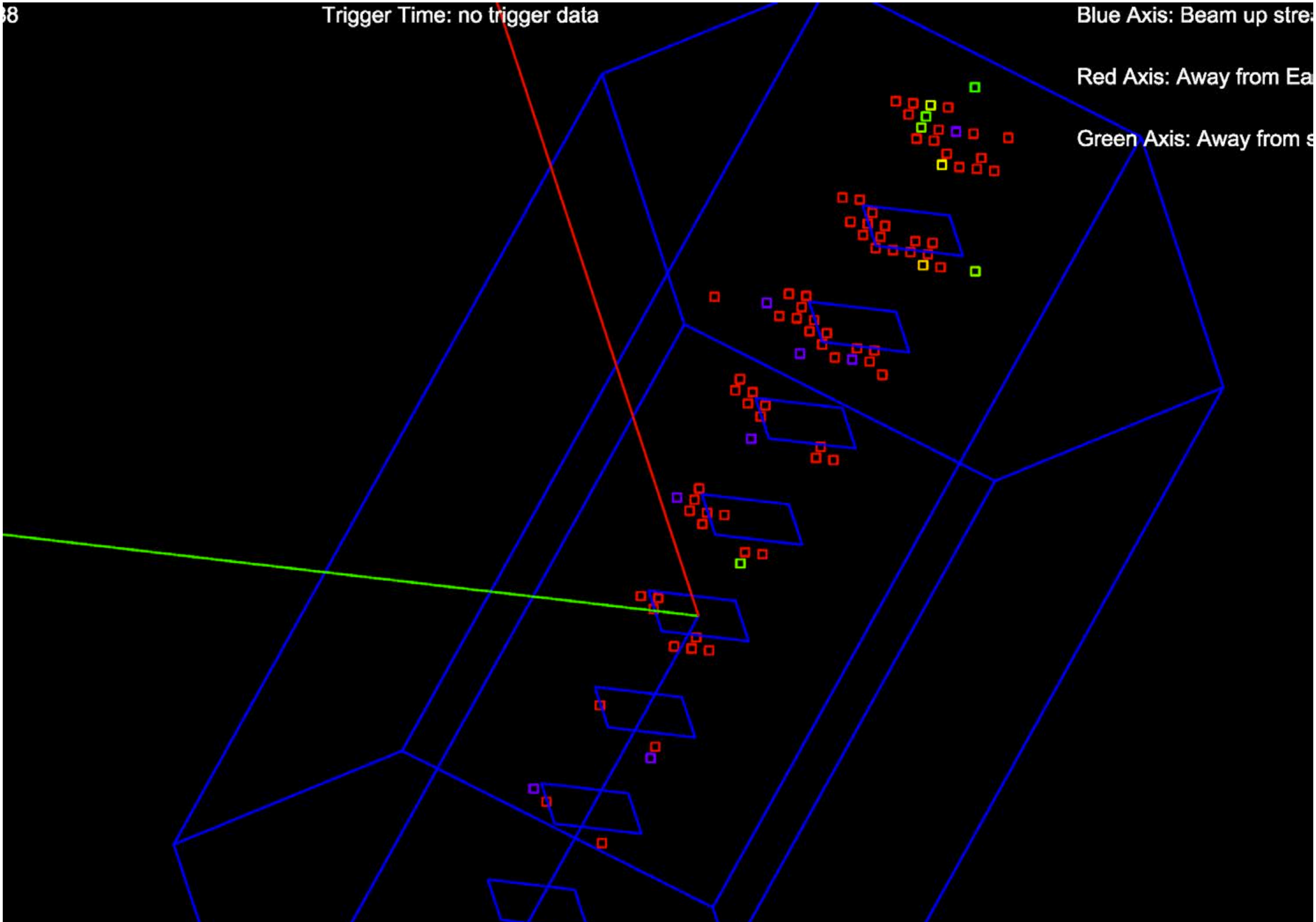


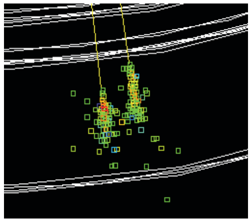
profile in depth



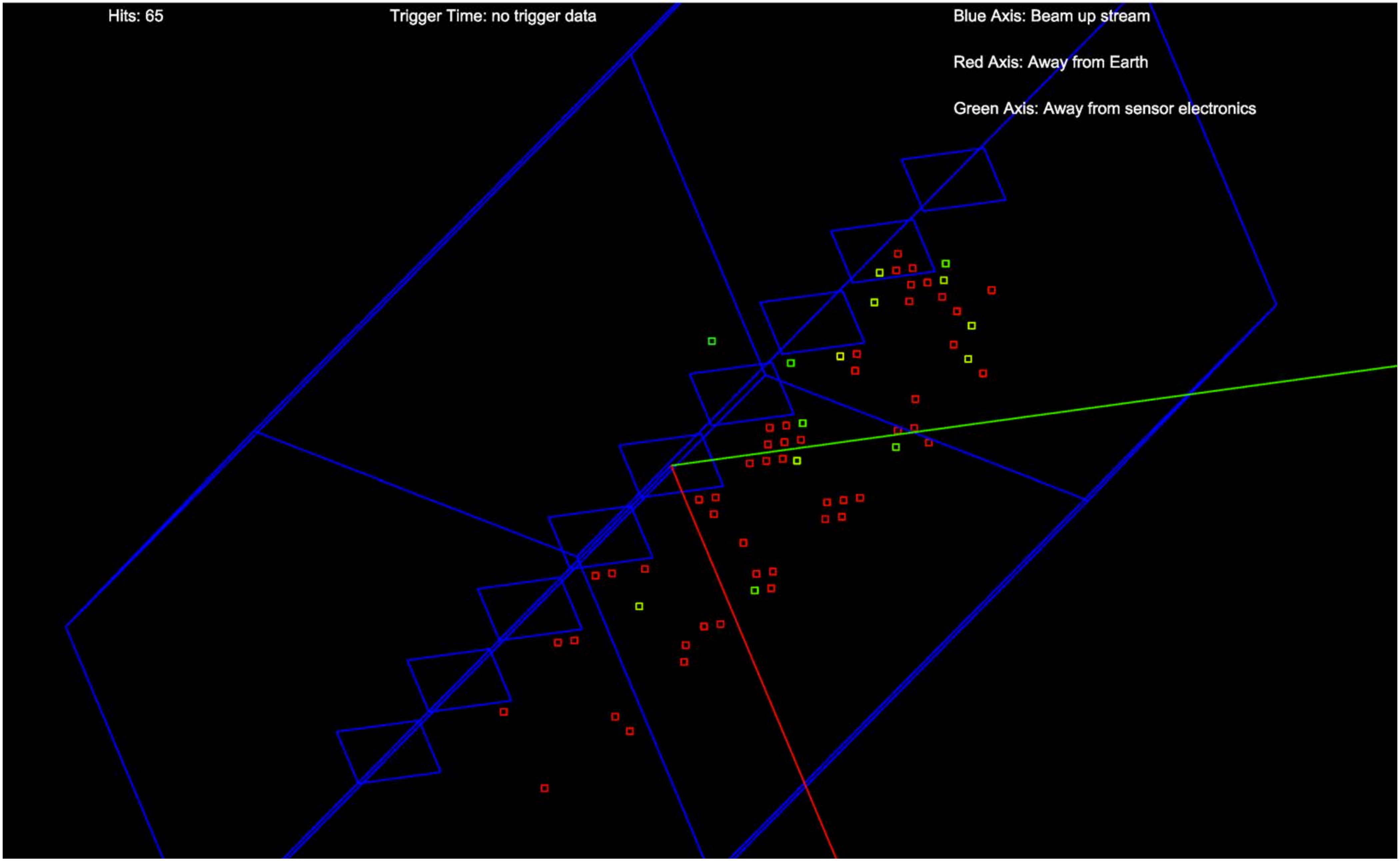
2 electrons



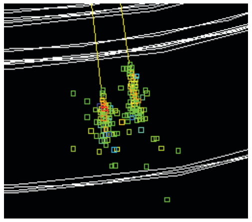

Trigger Time: no trigger data
Blue Axis: Beam up stre
Red Axis: Away from Ea
Green Axis: Away from s



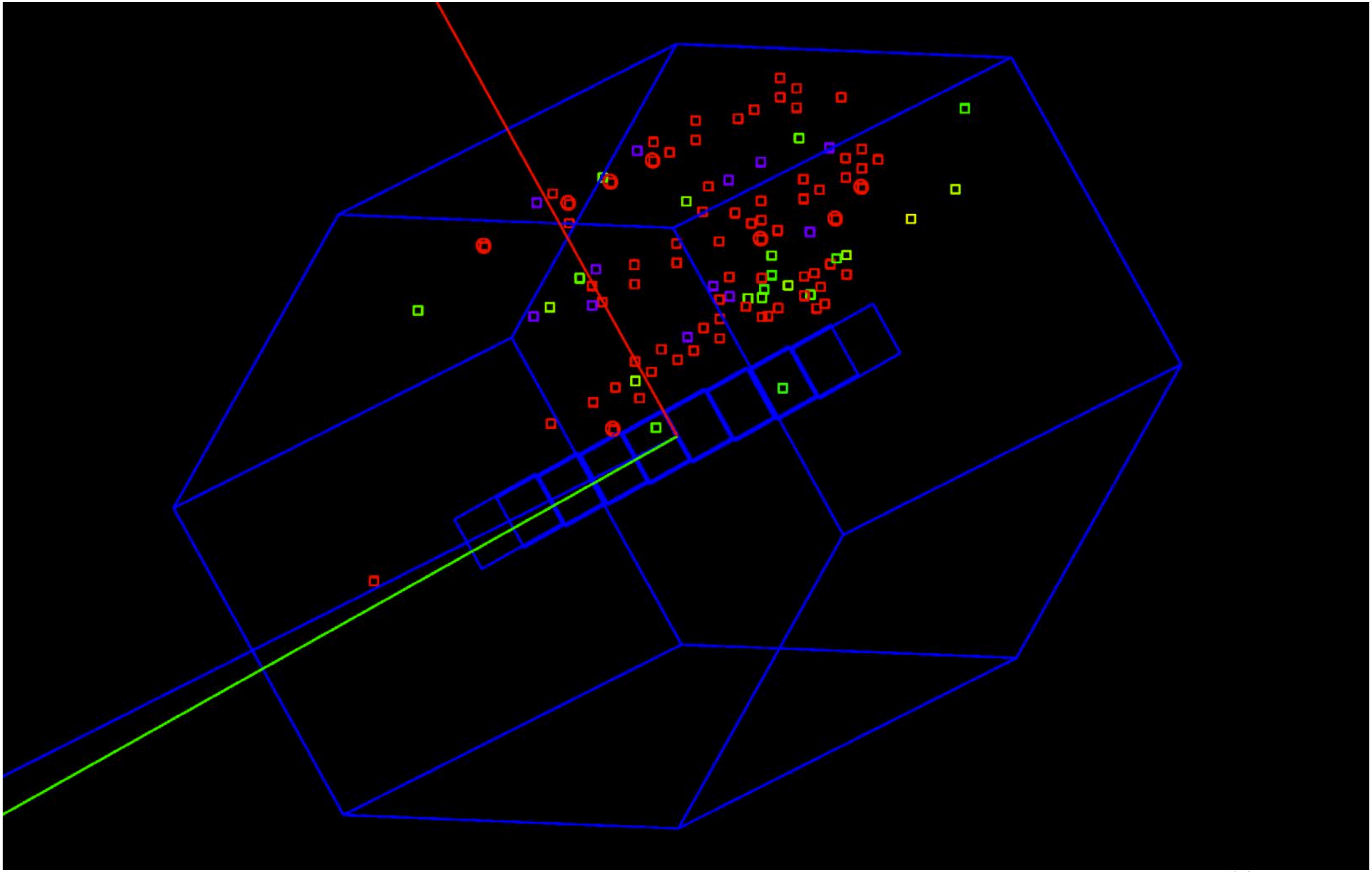
2 electrons

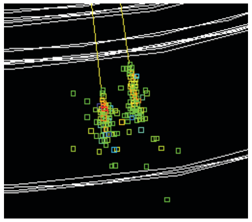


Hits: 65
Trigger Time: no trigger data
Blue Axis: Beam up stream
Red Axis: Away from Earth
Green Axis: Away from sensor electronics

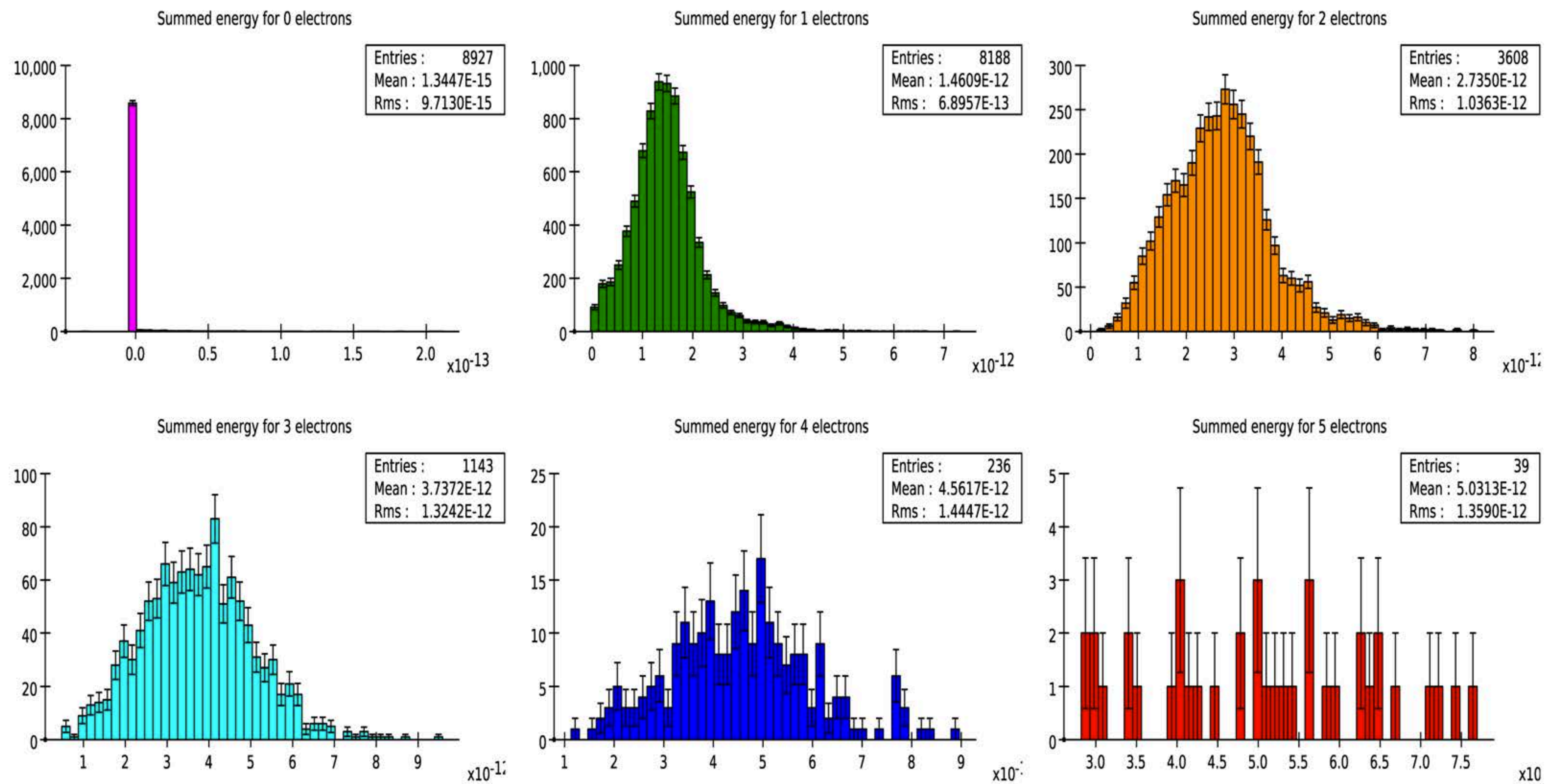


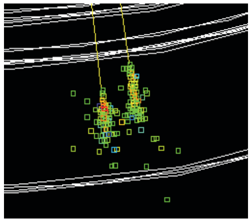
three electrons





pattern recognition to separate electrons -- 1st attempt





Circuit and pixel coupling

- 2 circuits – (1) ADC branch; (2) trigger branch
- Some triggers have been found with negative charge
  - In time OR out of time
  - Coupling between channels at detector
  - With 4 buffers, out of time can be discarded, but wastes buffers

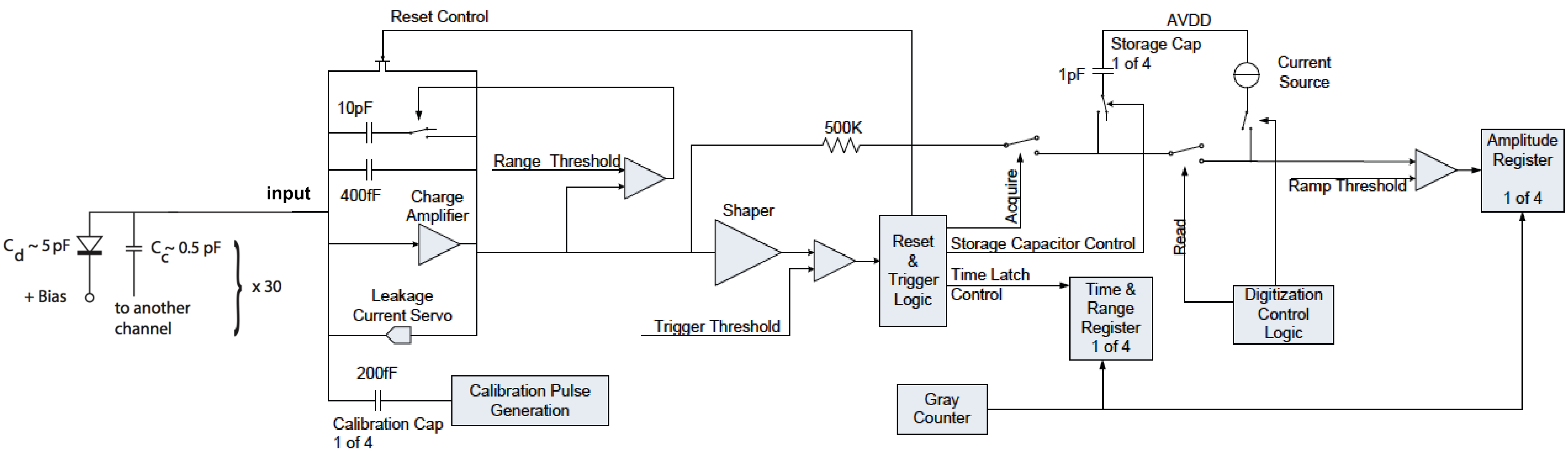
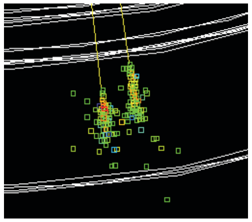
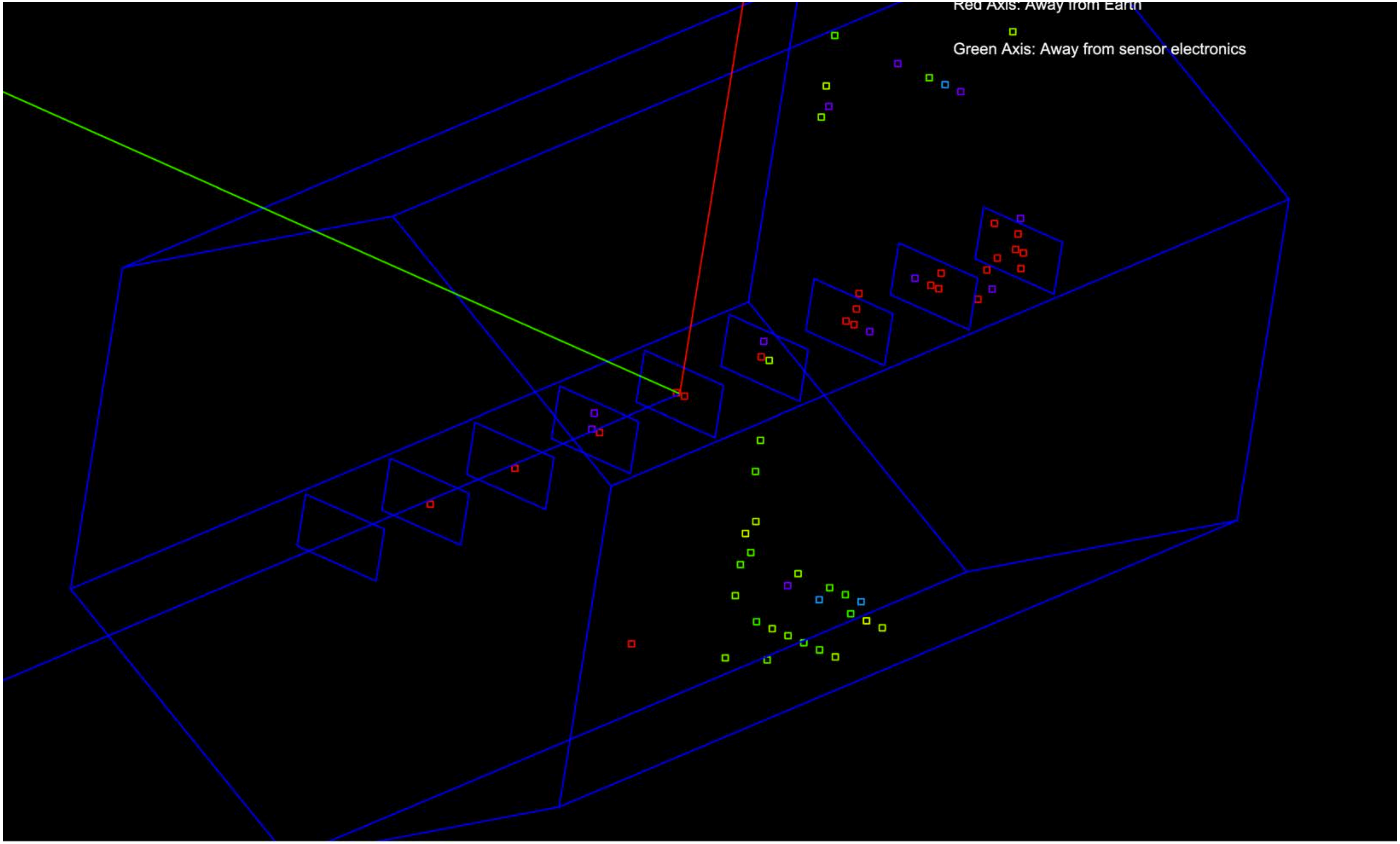
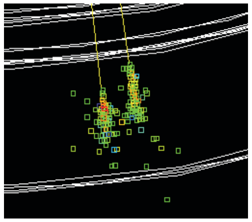


Fig. 4. Simplified block diagram of a single KPiX readout channel (out of 1024 channels).

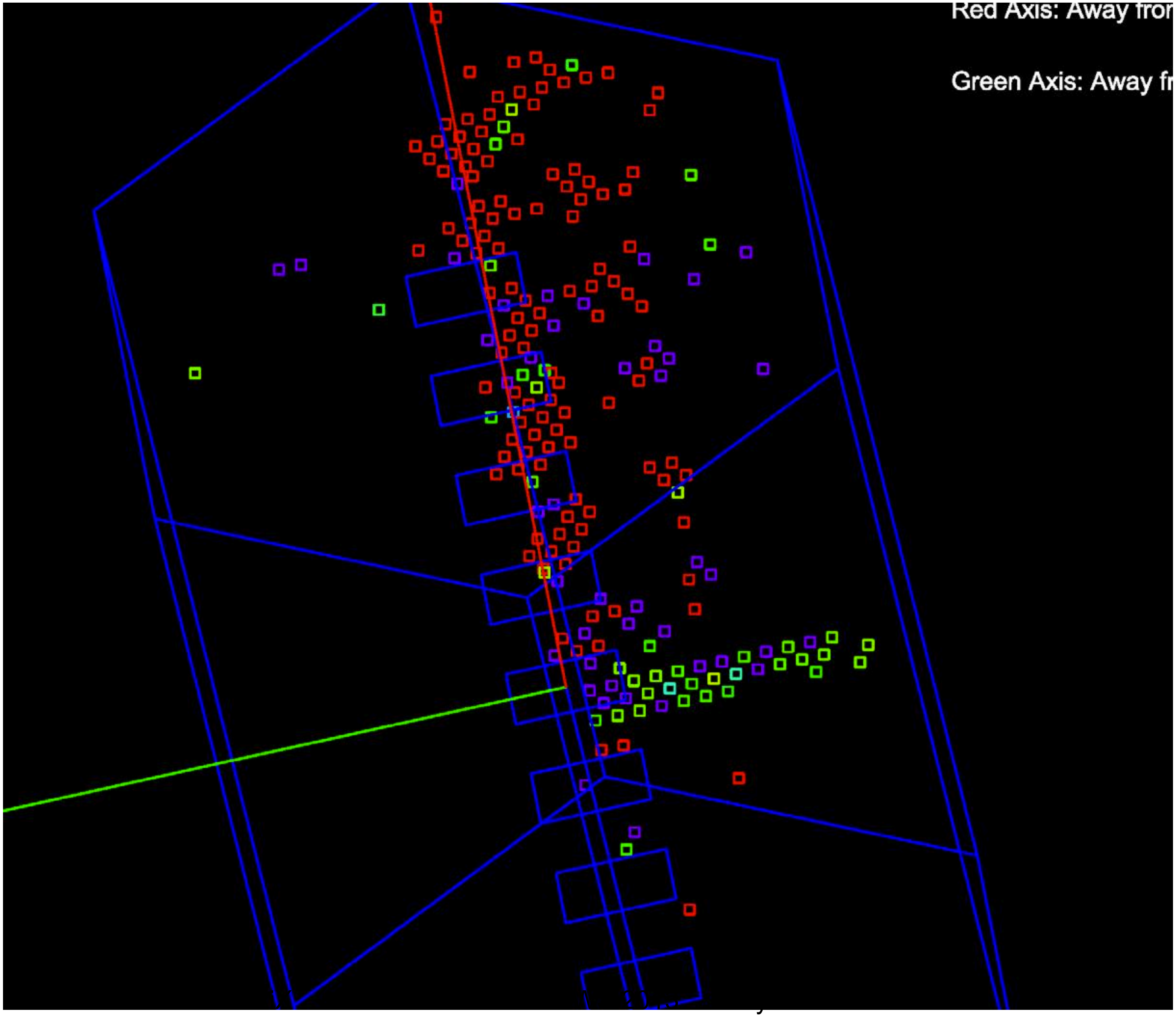


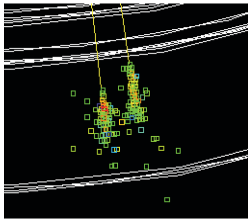
some events with non-physical negative-amplitude hits



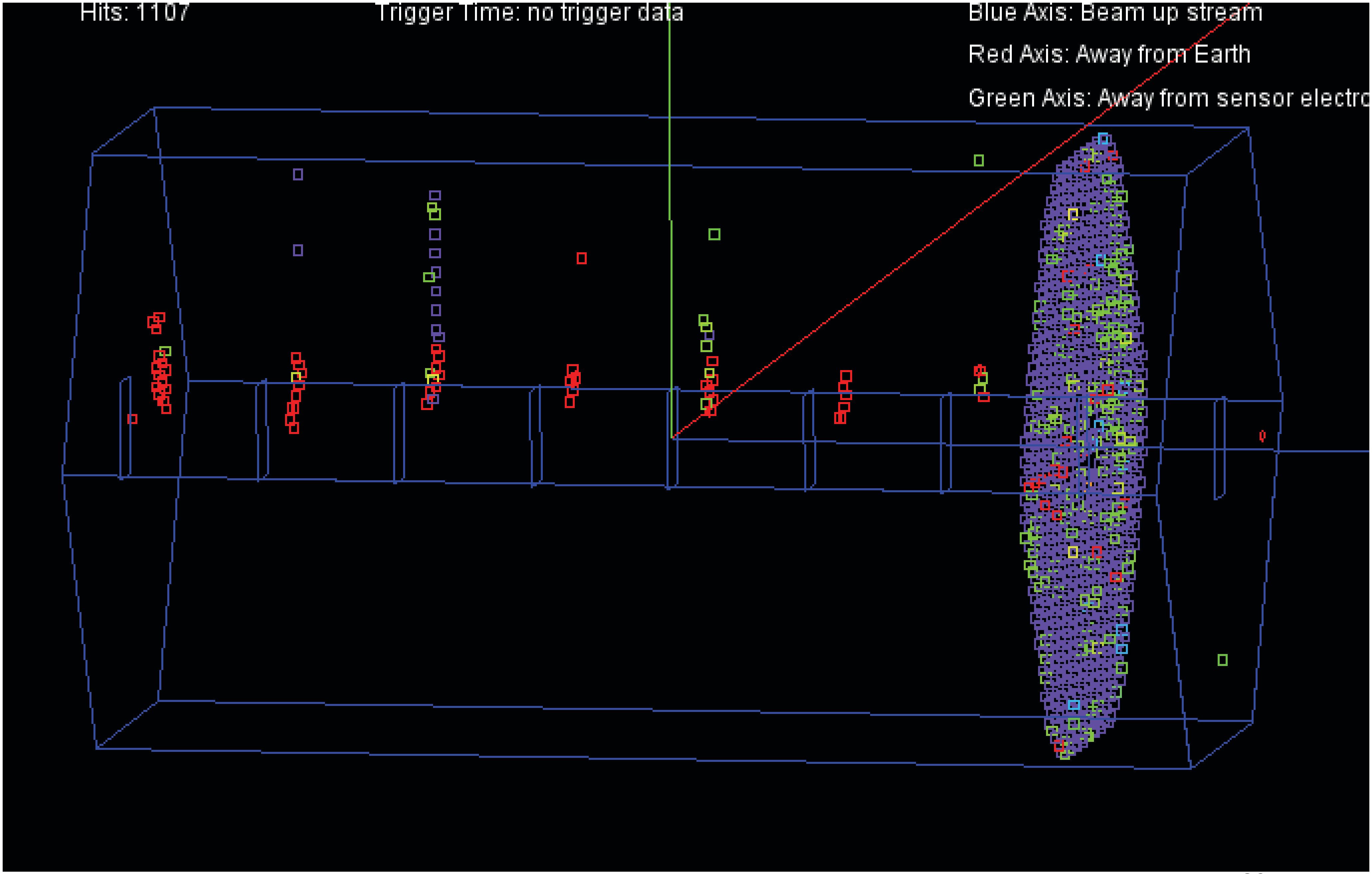


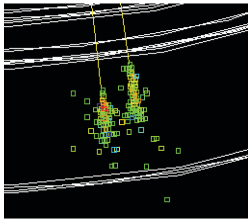
more non-physical hits



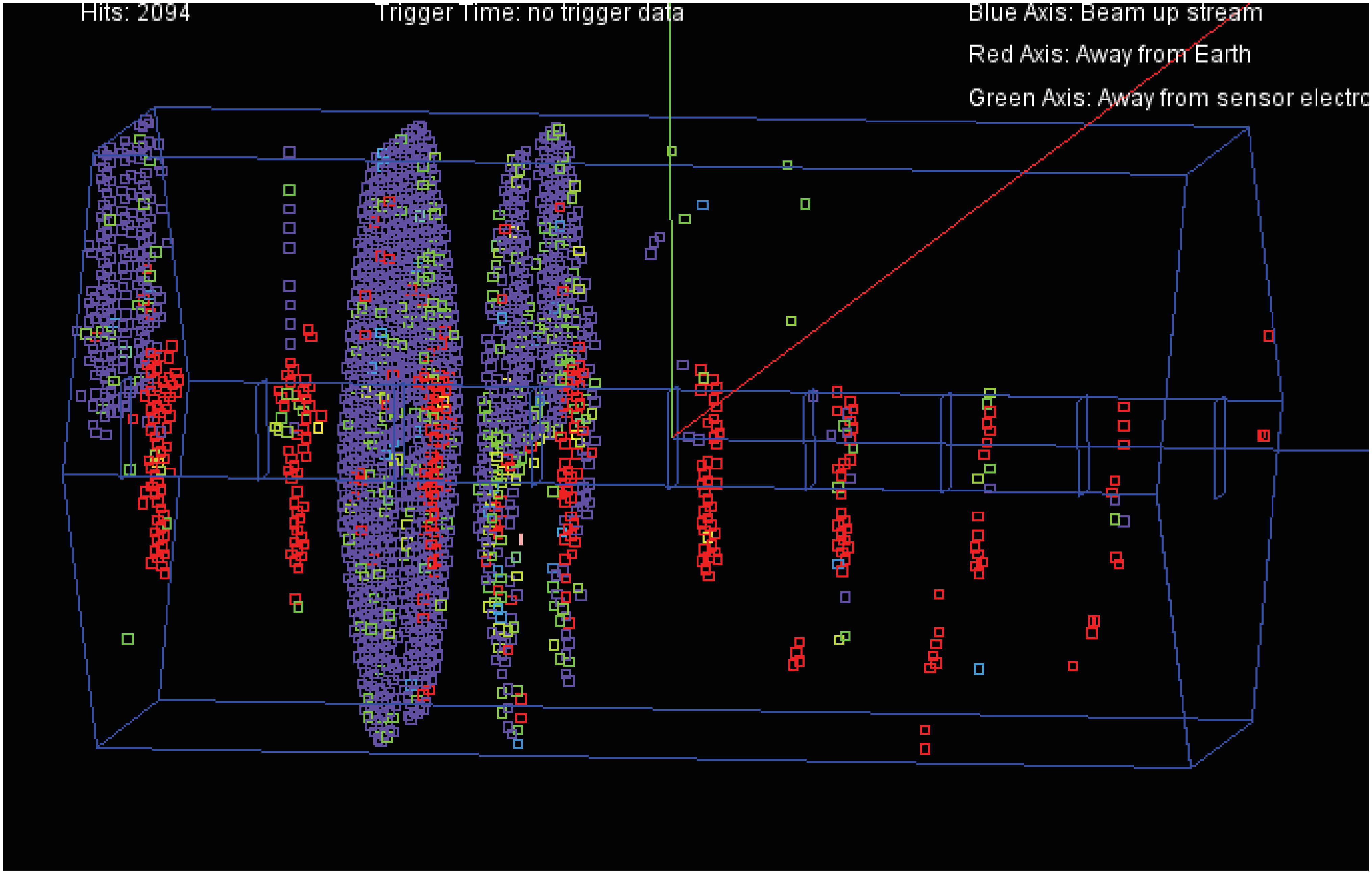


"monster events" with many negative amplitude and out of time hits



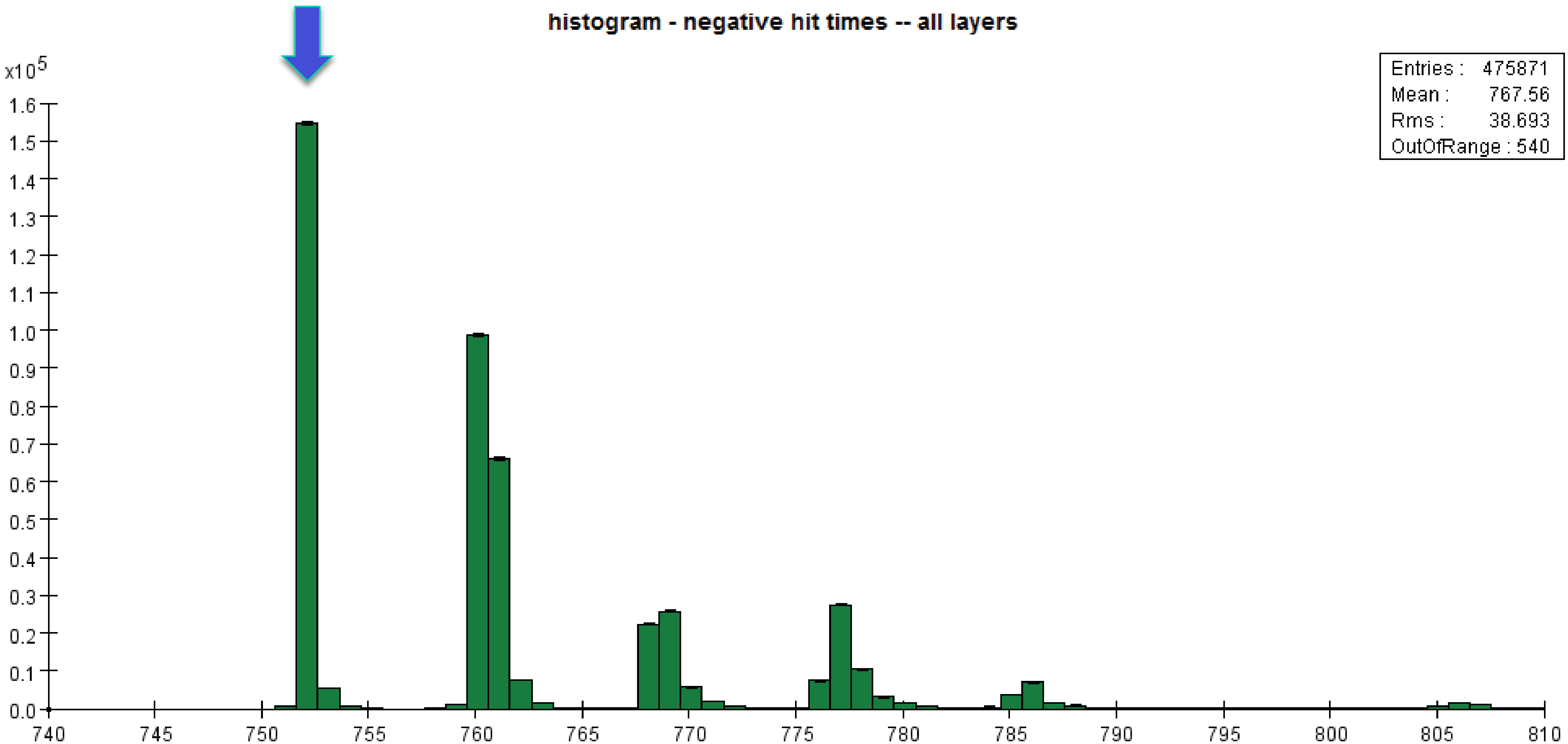


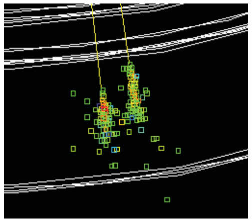
monster behavior increases with more hit pixels (multi-electrons)



times of negative-amplitude hits

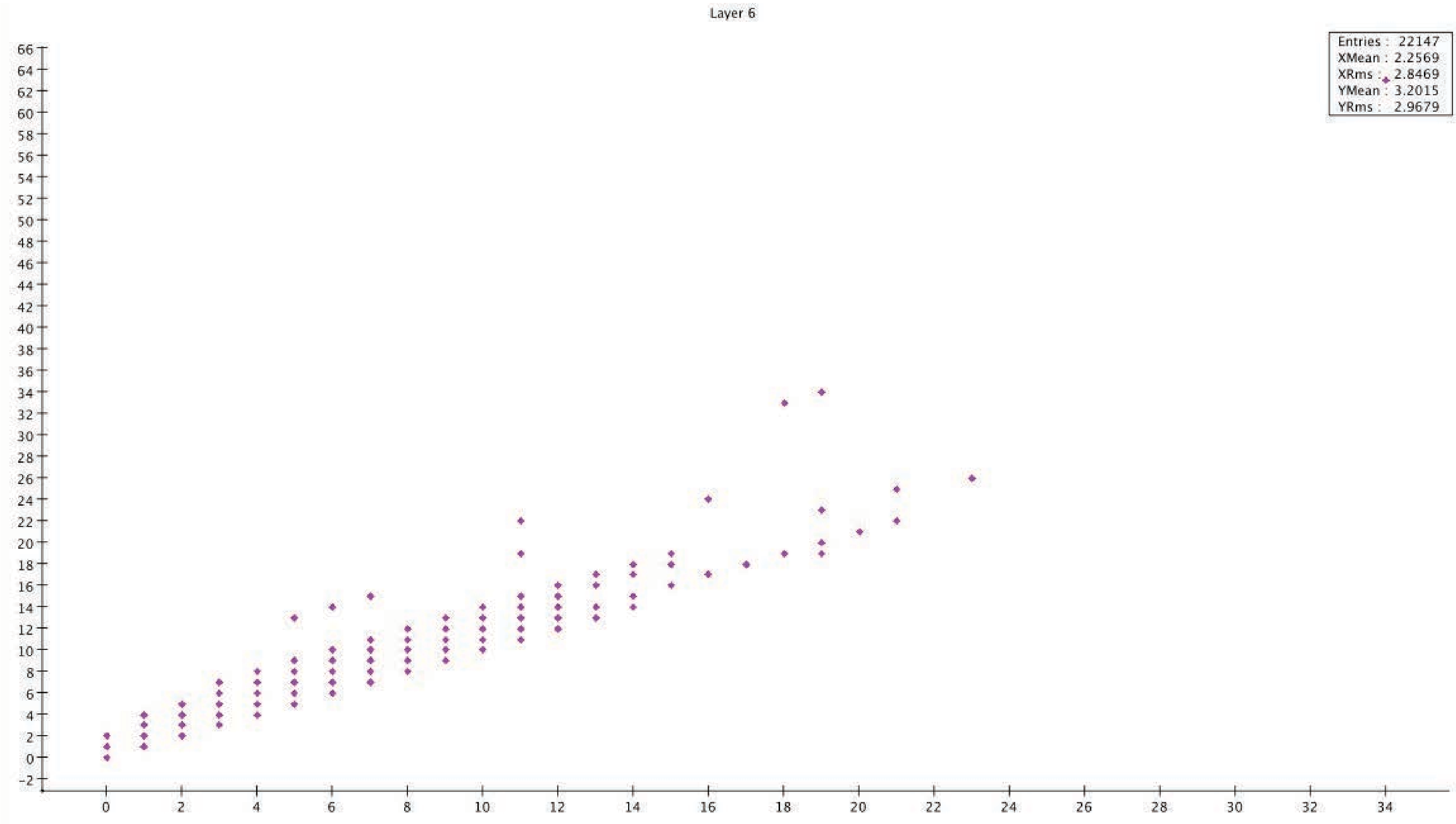
beam time

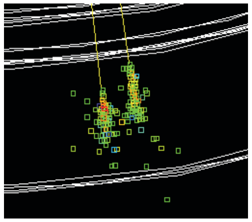




all hits vs in-time hits

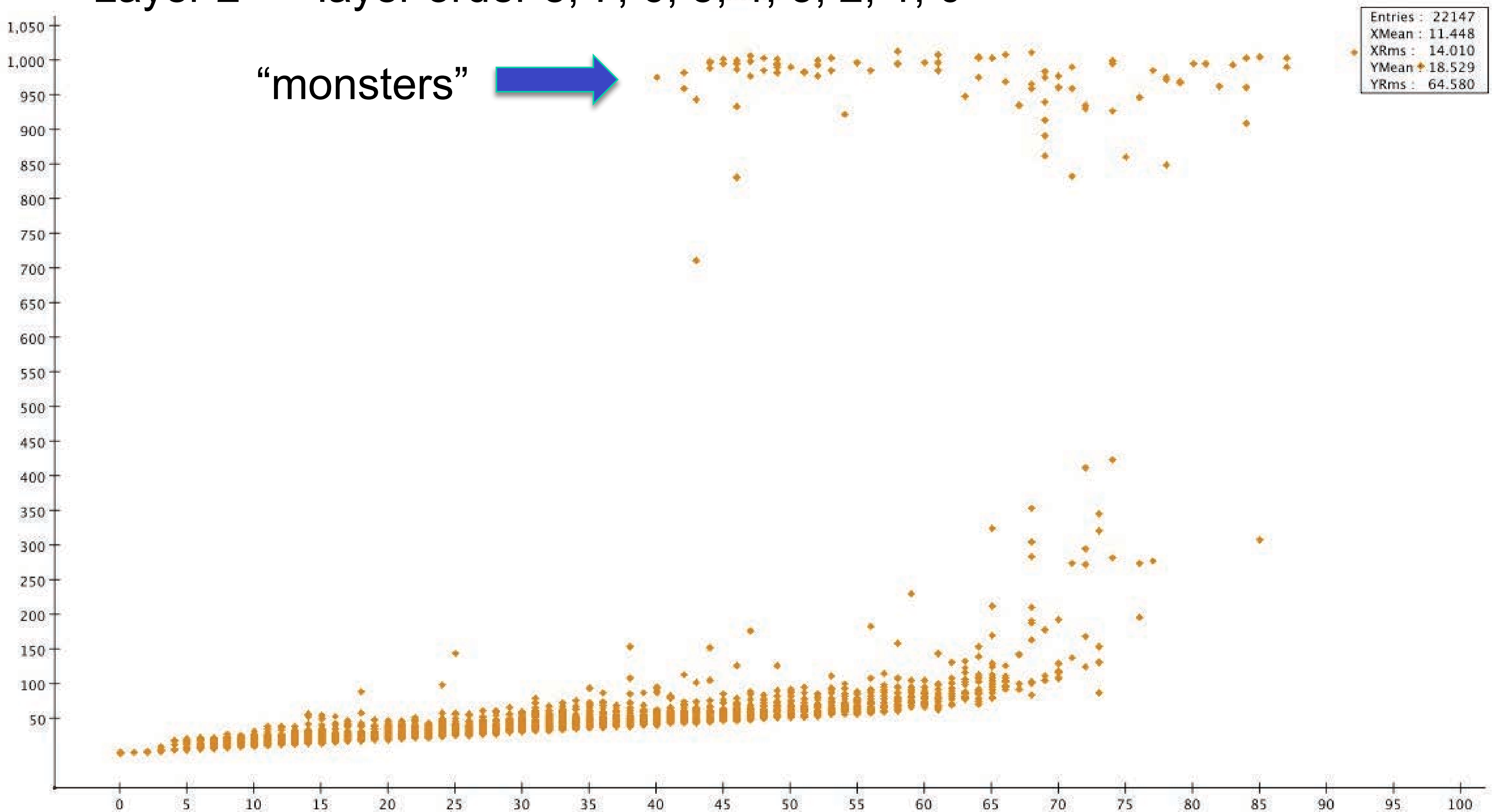
- Single electrons
- “Layer 6” – layer order 8, 7, 6, 5, 4, 3, 2, 1, 0

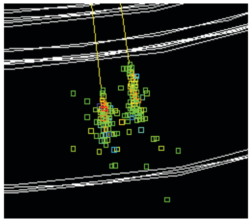




all hits vs in-time hits

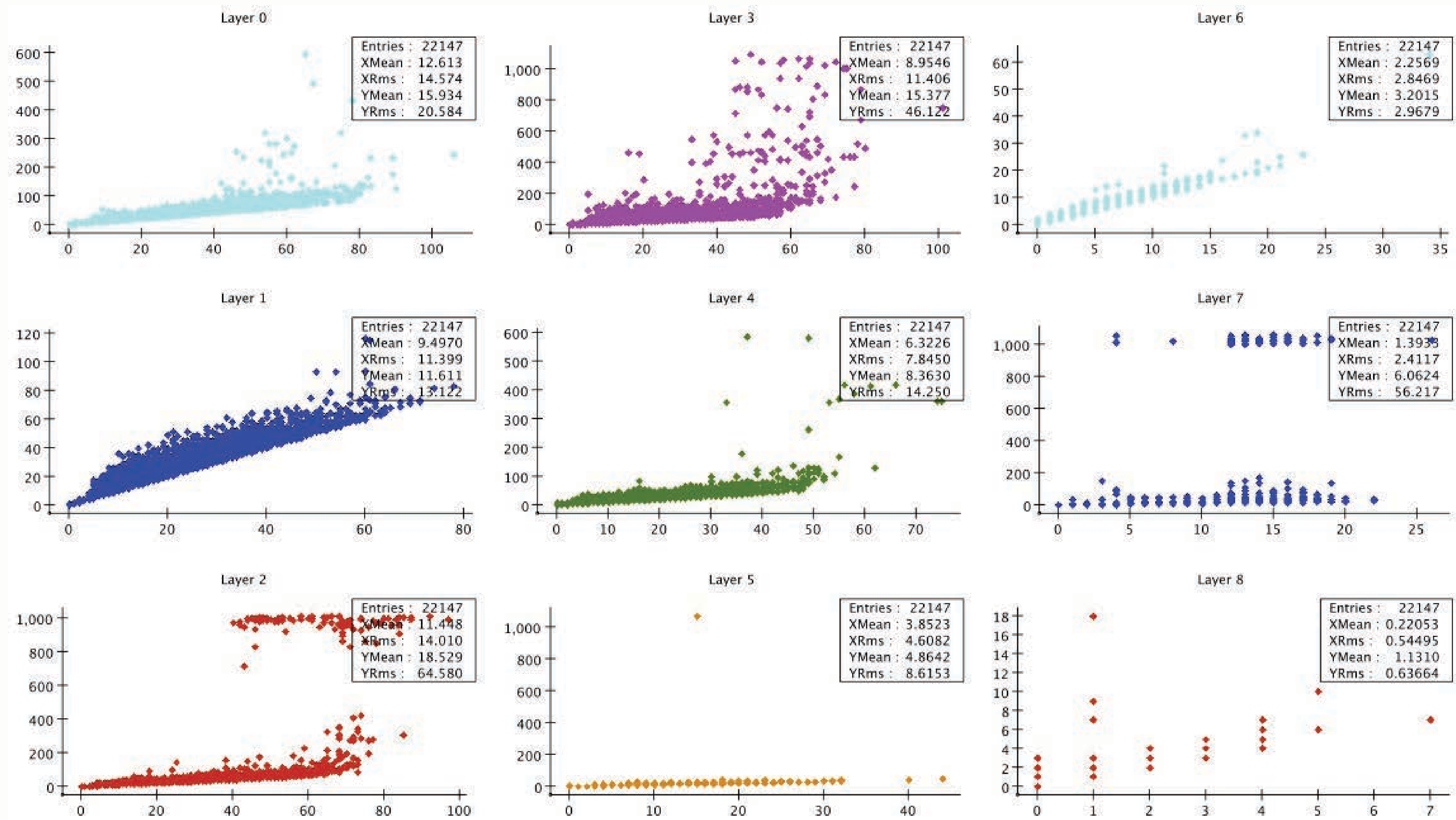
- Single electrons
- "Layer 2" – layer order 8, 7, 6, 5, 4, 3, 2, 1, 0

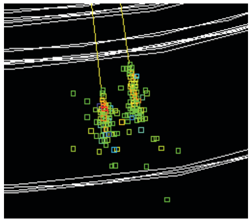




all layers – single electrons all hits vs in-time hits

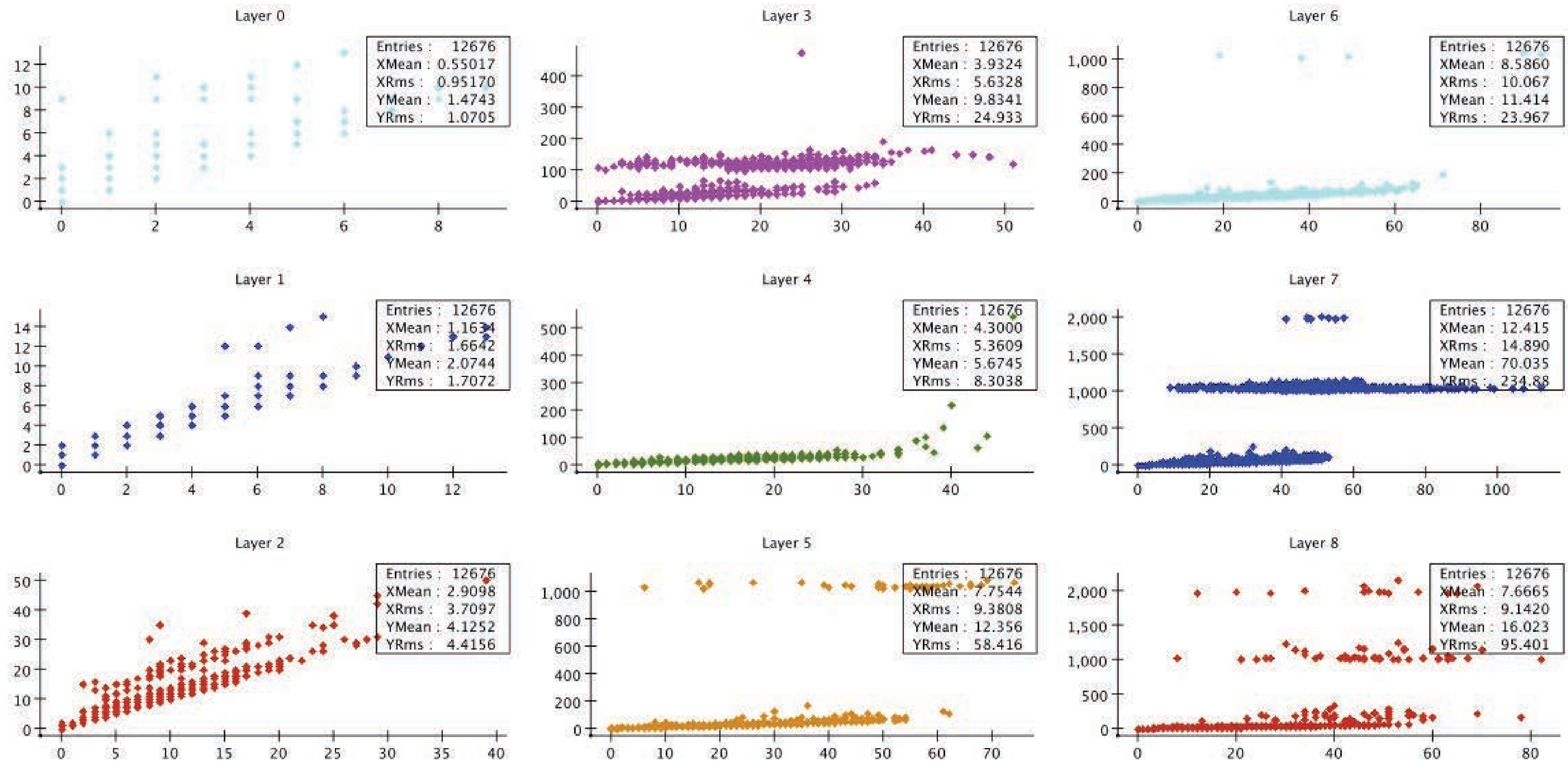
– layer order 8, 7, 6, 5, 4, 3, 2, 1, 0

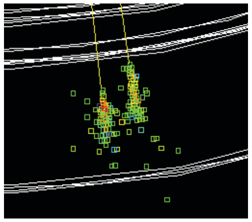




all hits vs in-time hits for 5-electron run

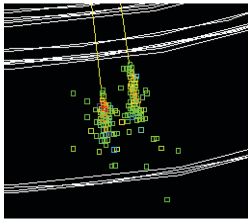
– layer order for this run: 0, 1, 2, 3, 4, 5, 6, 7, 8





KPiX performance issues to be addressed: Cross-talk

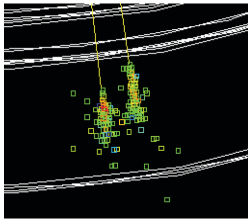
- There are two types of crosstalk to other channels
  - In-time (at the same time as the channel receiving the signal)
  - Out-of-time (at the time when the reset on the primary channel occurs)
- Especially an issue for large events when many channels are hit, leads to “monster” events where most channels on KPIX are triggered
- There may be two types of out-of-time cross talk depending on the amount of charge collected on the detector and the number of channels involved.



In-time crosstalk

- Cause: parasitic capacitances on sensor between pixels (several pF, mainly due to traces on top of pixels)
  - Charge-amplifier has finite response time so signal deposited at input takes time of order 100 ns to be removed by the amplifier -> voltage transient at input node -> coupling to other channels
    - Causes other channels to trigger, but measured charge in ADC branch is very small or negative (since it is transient)
- Discussions are ongoing whether this issue is acceptable for ILC running …

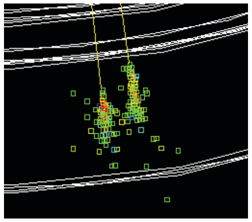
  but we plan to remove the crosstalk, nevertheless



In-time crosstalk

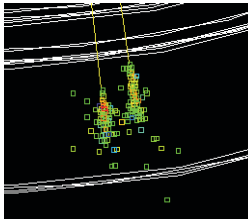
- Solutions
  - Reduce parasitic capacitances on sensor
    - Would require additional shielding metal layer, only where input traces cross other pixels
      - Being investigated, but might be difficult
  - Use knowledge of when signal arrives, make trigger sensitive only for a short duration in ~500 ns bunch crossing period
    - Would eliminate above crosstalk. Simulations show that one can gate shaper and comparator in a way to ignore transient signal.
    - Requires circuit modification in pixel and new submission
  - Increasing current in charge amplifier decreases crosstalk by reducing response time, but not a solution, trade-off with power dissipation

- There seems also to be crosstalk internal to KPIX when many pixels, e.g. most of a column, is triggered
  - Being investigate, might be due to trace coupling to trigger threshold voltage
    - Was already modified in KIPX-C (in-hand) but not measured yet



Out-of-time crosstalk

- Crosstalk that is apparently due to the switching (i.e. charge amplifier reset) in the KPIX
  - Again due to the parasitic input capacitances to other pixels, charge deposited at input of pixel being reset causes other pixels to trigger
  - At reset time, so usec's after driven channel receives charge at input
  - For events when there is signal charge in many channel (large events), can lead to "Monster" events, channels getting parasitically triggered and in turn trigger other channels when they are reset
    - "Monster" events appear to be related to internal KPIX structures
- Solutions
  - Reducing sensor coupling (see last slide)
  - Use knowledge when reset occurs to gate when channels are sensitive (-> from simulations)
    - Requires circuit change and resubmission



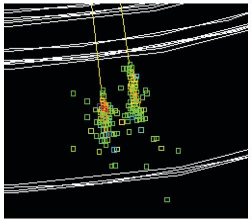
More change requests: Calibration

- Normally baseline in a channel is obtained in a calibration run by lowering threshold until channels trigger without any input signal (just noise)
  - Can’t be done in current KPIX, threshold does not extend low enough
  - Also makes it hard to quantify threshold noise

- Request
  - Modify threshold DAC to be able to self-trigger on noise. At same time increase resolution of DAC to improve ability to measure efficiency of trigger

- Current calibration mode used to obtain gains and baseline:
  - Charge is injected one channel at a time using internal calibration capacitors.
  - All channels are triggered simultaneously using a “forced” trigger
    - Using the “self-trigger” mode is not a good option due to the crosstalk issue
  - But forcing all channels simultaneously seems to result in different baseline when extrapolating to 0 input signal
    - Large events where multiple channels are triggered simultaneously may suffer similar baseline shift

- Request
  - Add masking in each pixel so “forced” trigger can be applied to single (or arbitrary pattern) of pixels.
  - Modify calibration DAC, already addressed above



Summary

- Successful test beam run with partially outfitted prototype

- Uncovered some unexpected behavior
- Unphysical negative-amplitude hits – current hypotheses:
  - Small number of in-time hits: cross-talk in sensor and baseline shift of KPiX virtual ground
  - Many out of time hits for some layers when many hit pixels: associated with KPiX resets? cascading?

- Other questions about thresholds and A/D range

- In general good results, works as intended but
  - Several KPiX modifications needed to address performance issues discovered during test-beam
  - All modifications are doable with additional ASIC fabrication run