Test Beam Measurements of BNL and HPK AC-LGADs

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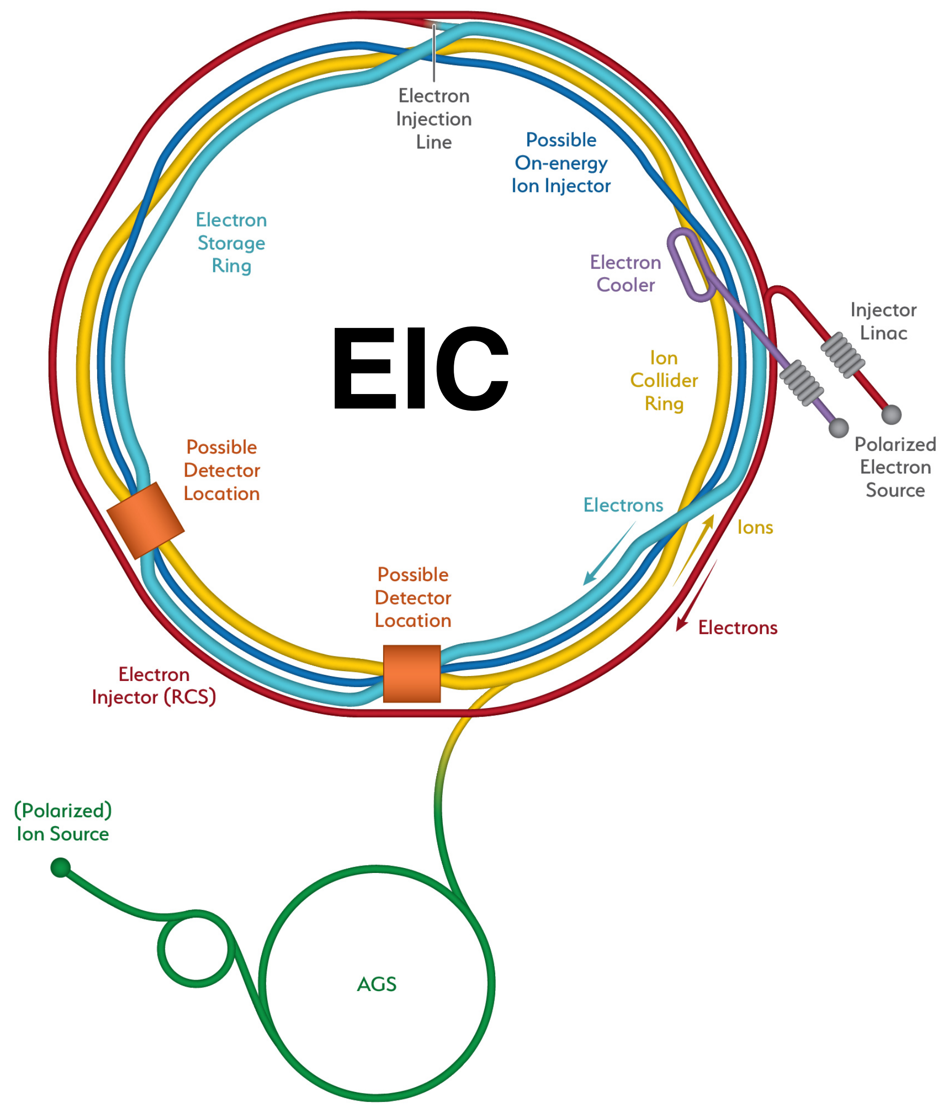
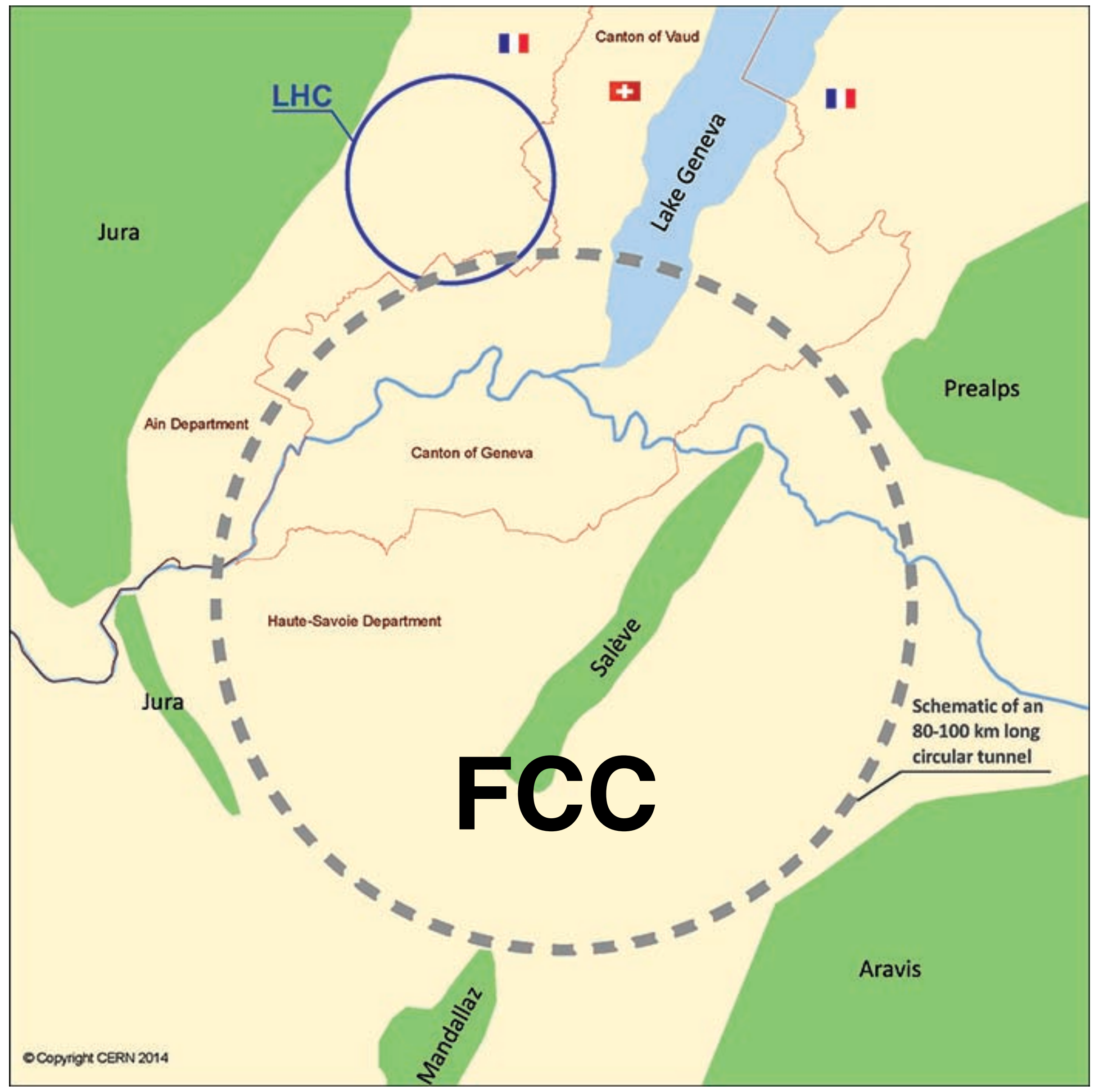
Future trackers will be 4D!

- The 4D-trackers will play a key role at the future machines
  - Reduce backgrounds, track reconstruction, triggering will need precision timing information in addition to precision position
  - Enhanced capabilities: PID and LLP reconstruction
  - All of these pose unique challenges, and opportunities to detector and electronics design, and event reconstruction

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 25x50 μm^2 pixels
	5 μm single hit resolution
	Per track resolution of 10 ps
Tracking for 100 TeV pp	Generally the same as e^+e^-
	Radiation toleran up to 8×10^{17} n/cm^2
	Per track resolution of 5 ps

Technical requirements for future trackers:
from DOE's HEP BRN





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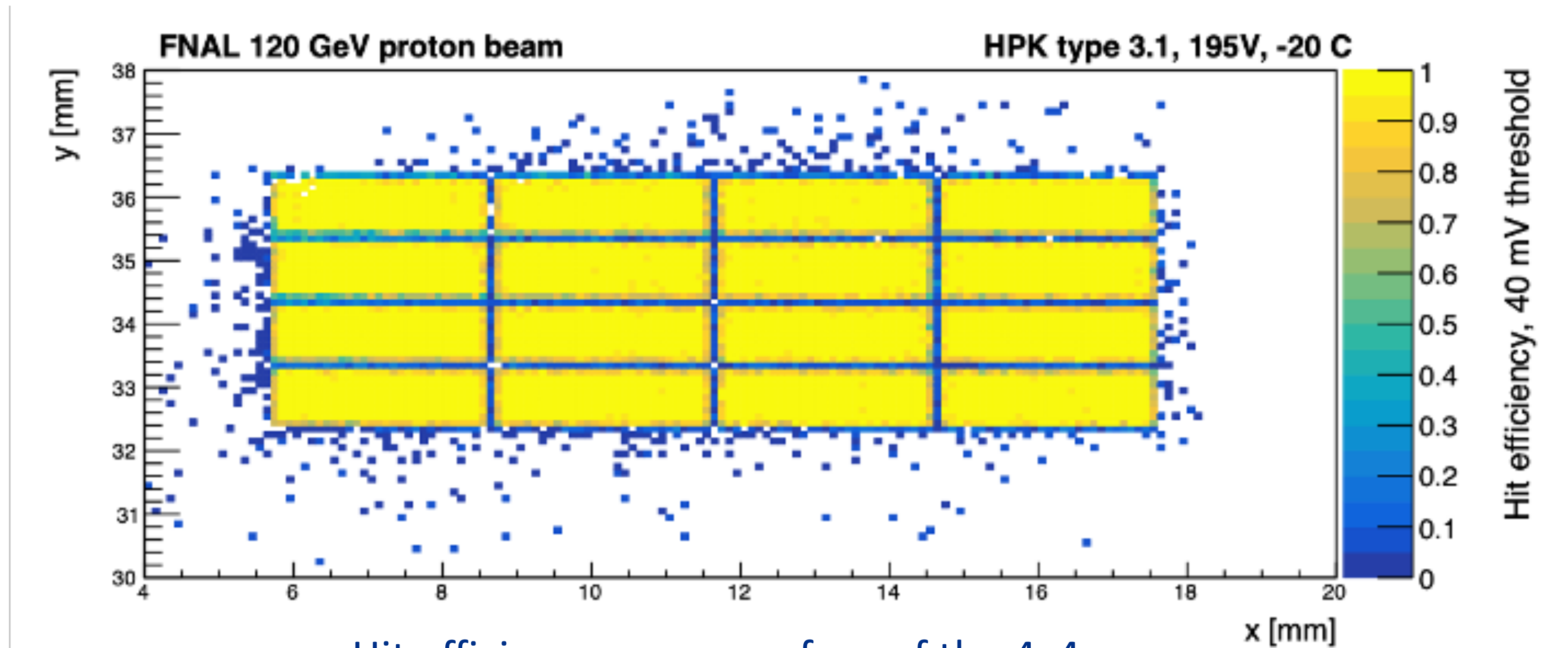
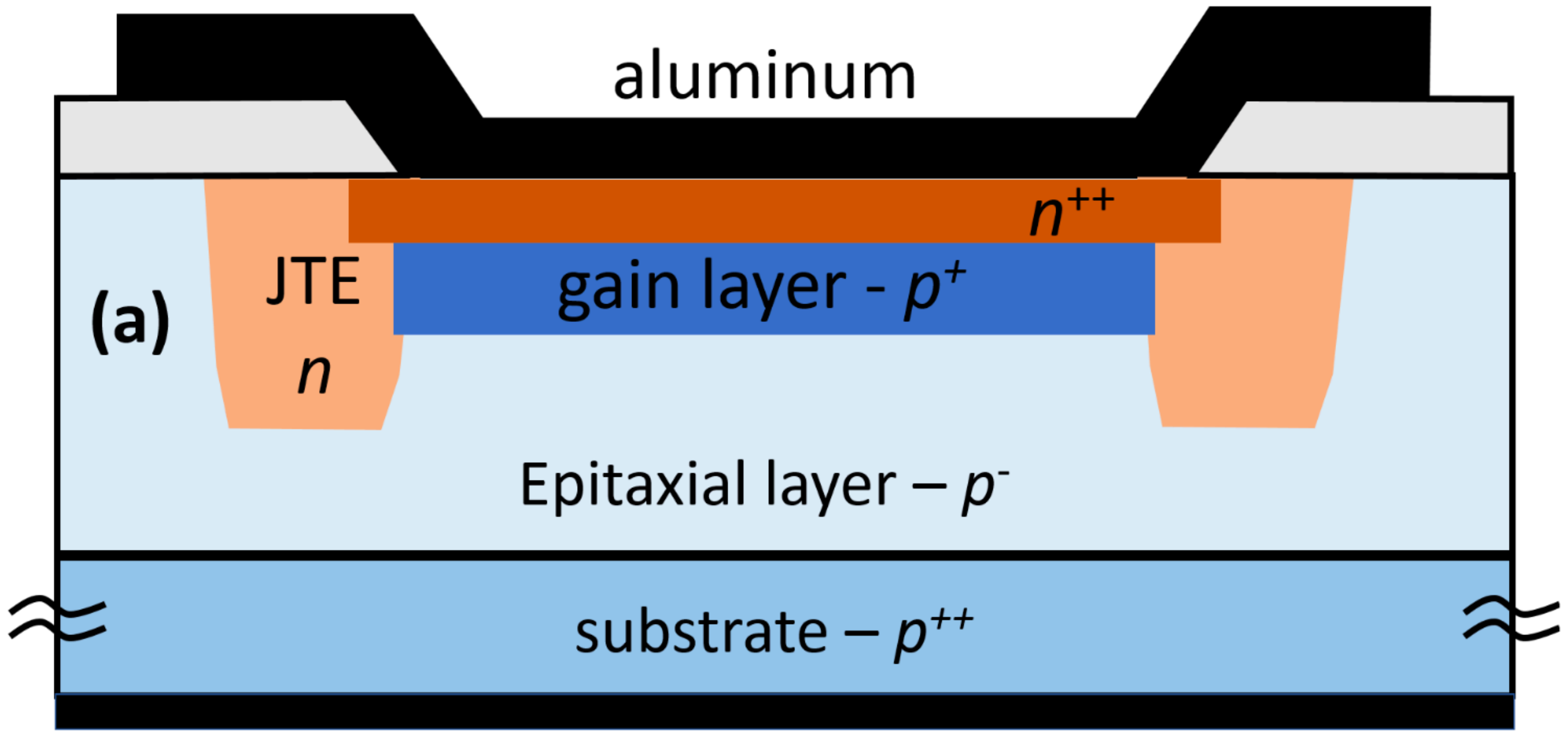
AC-coupled LGADs

- DC-LGADs are a promising sensor for timing detectors
  - Although, they have an issue with their fill factor when pixels are small enough for a realistic tracker

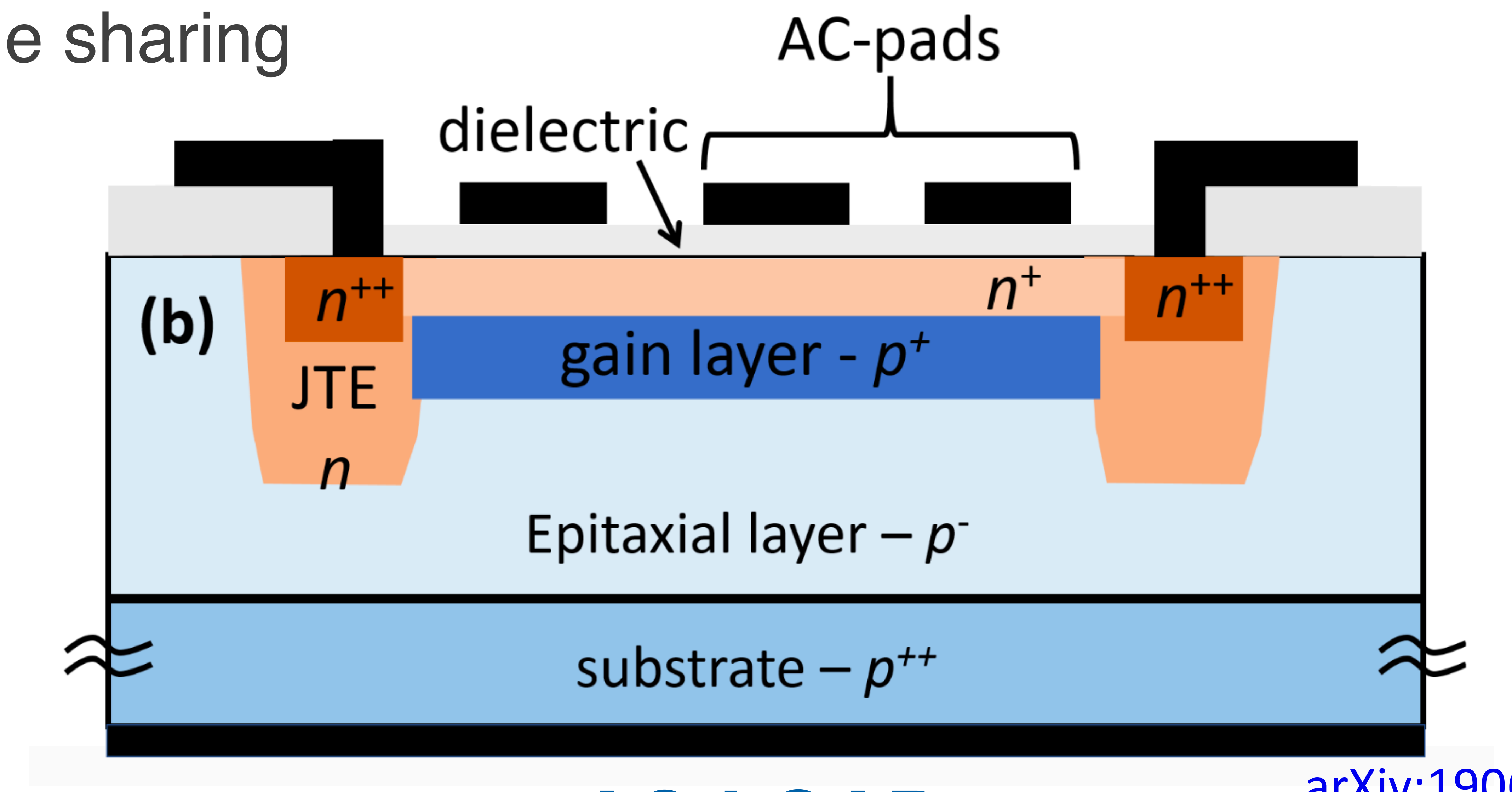


Hit efficiency across surface of the 4x4 sensor

- AC-LGADs can solve this issue
  - 100% fill factor, and fast timing information at a per-pixel level
  - Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge.
    - Simultaneously improve position resolution via charge sharing



DC-LGAD



AC-LGAD

arXiv:1906.11542

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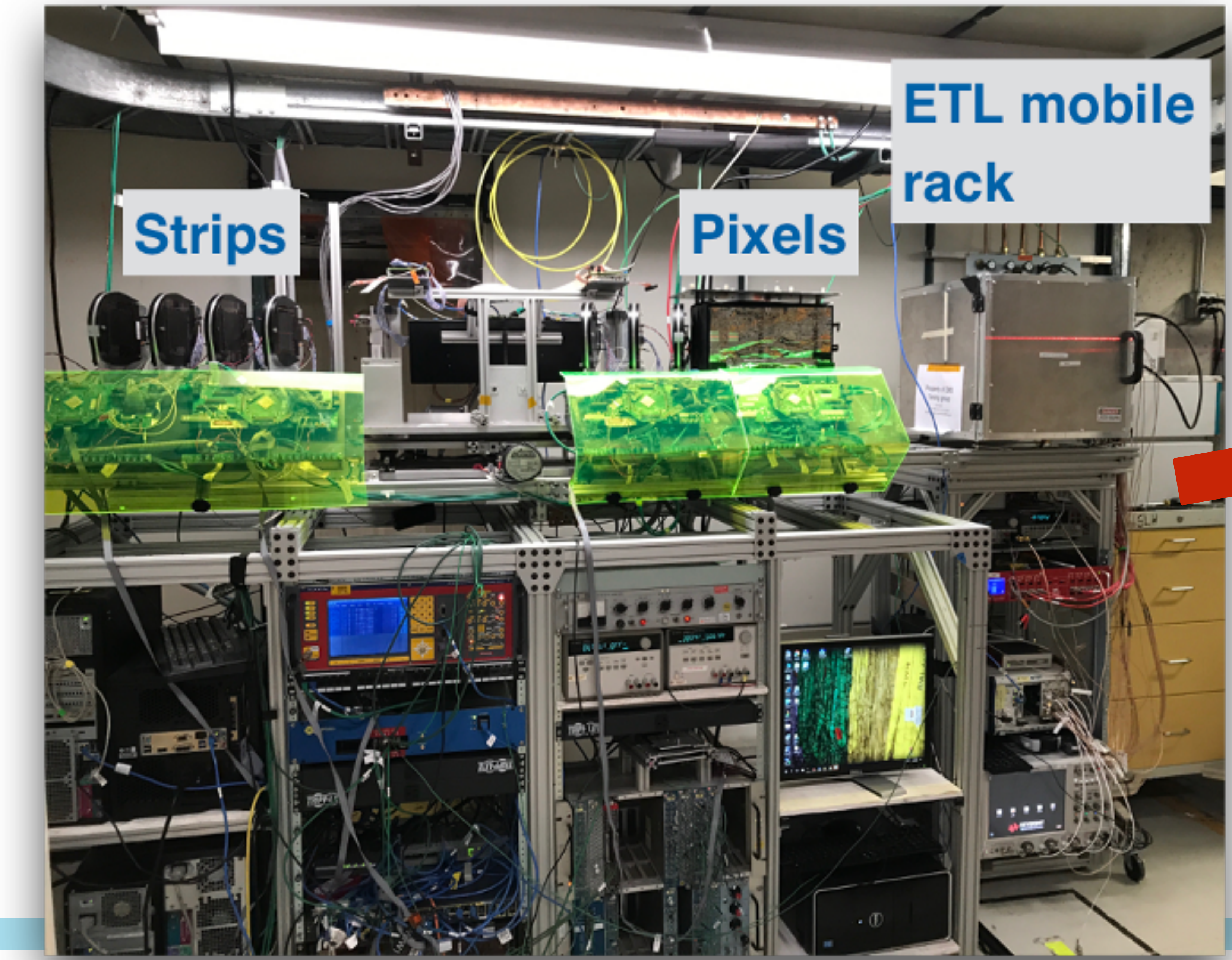
Development Directions

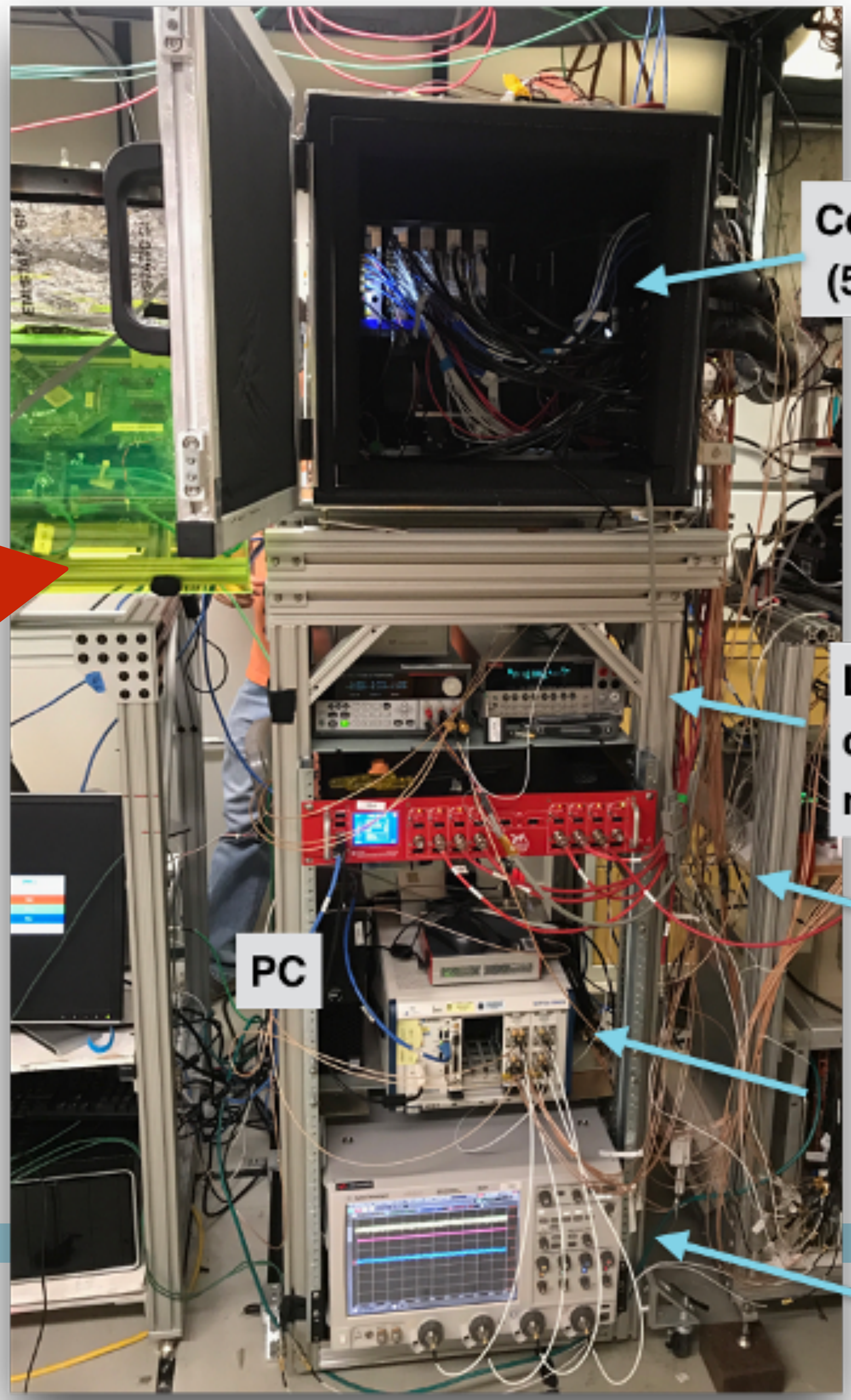
- **International collaboration** to develop AC-LGADs for 4D trackers
  - Supported by U.S.-Japan Cooperative Research in High Energy Physics

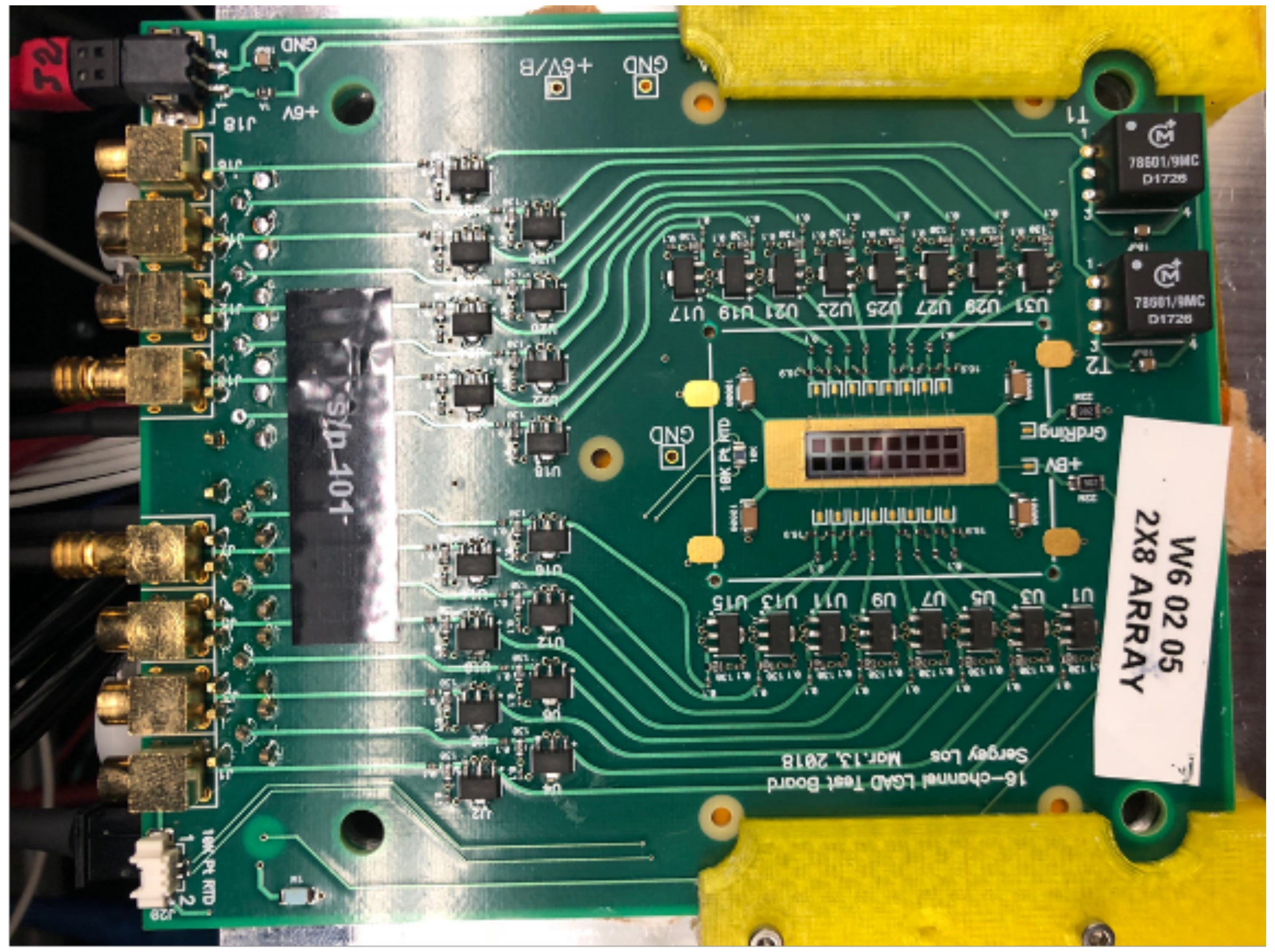
- US-Japan collaborative consortium
  - A. Apresyan, K. Di Petrillo, R. Heller, R. Lipton, S. Los, C. Madrid, C. Pena, S. Xie, T. Zimmerman (**FNAL**)
  - G. D'Amen, W. Chen, G. Giacomini, E. Rossi, A. Tricoli (**BNL**)
  - K. Nakamura, K. Hara, T. Ueda, S. Kita (**KEK, U. Of Tsukuba**)
  - S. Mazza H. Sadrozinski, B. Schumm, A. Siden (**UCSC**)

Fermilab 4D-trackers test beam infrastructure

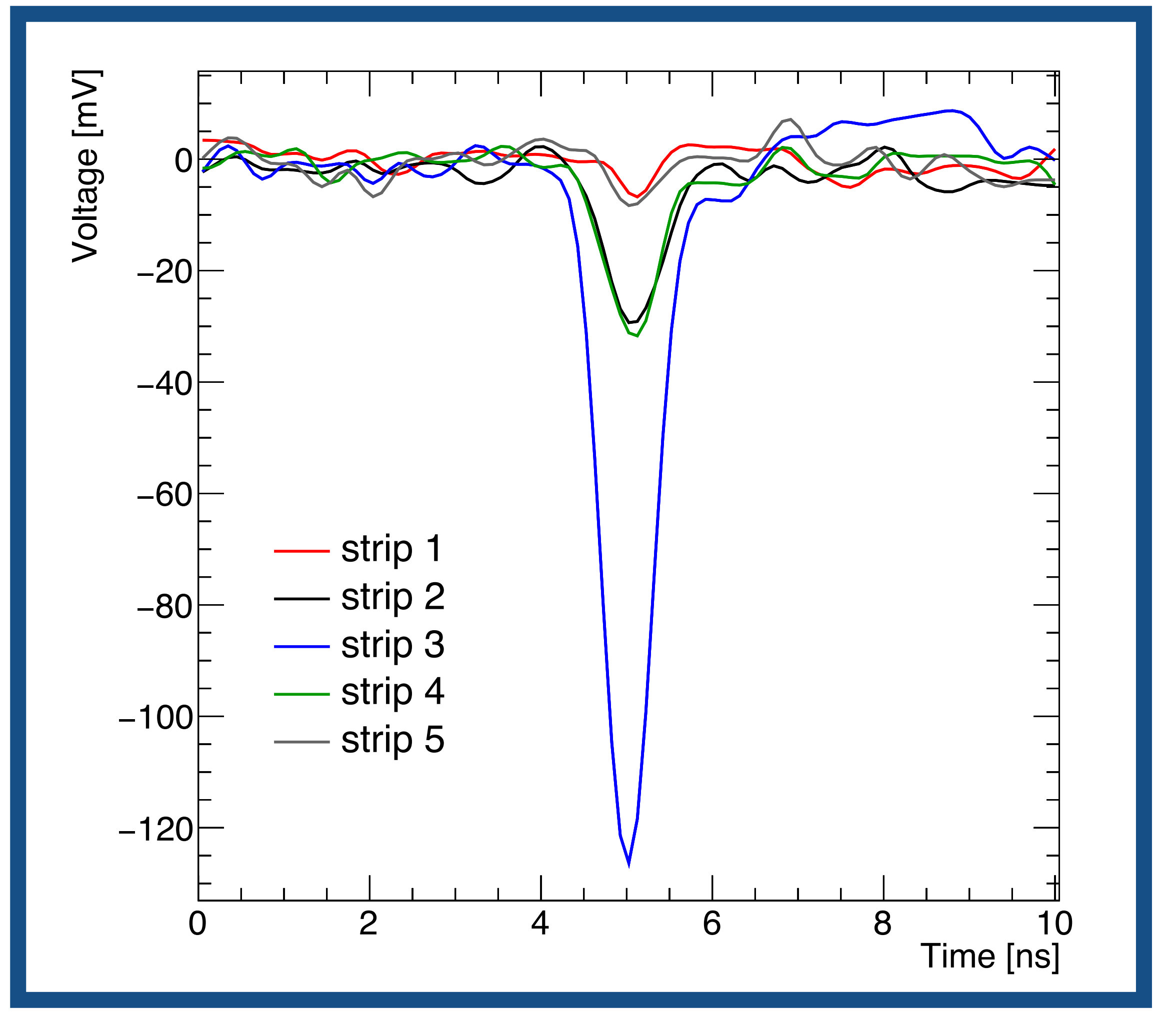
- Permanent setup in FNAL test beam facility (FTBF)
  - Movable: slide in and out of beamline as needed, parasitic use of beam
  - Environmental controls: sensor temperature (-25 C to 20 C), and humidity, monitoring
  - Remote control (stages, HV, LV), logging & reconstruction; σT ~ 10 ps time reference (MCP)
  - Cold operation of up to 10 prototypes at the same time
  - DAQ: high bandwidth, high ADC resolution scope 4- or 8-channel scope
  - Record 100k events per minute, tracker with ~10 µm resolution
- Developed readout boards for the characterization of LGADs
  - Without complicated ASIC and DAQ







16-ch sensor LGAD on Fermilab readout board



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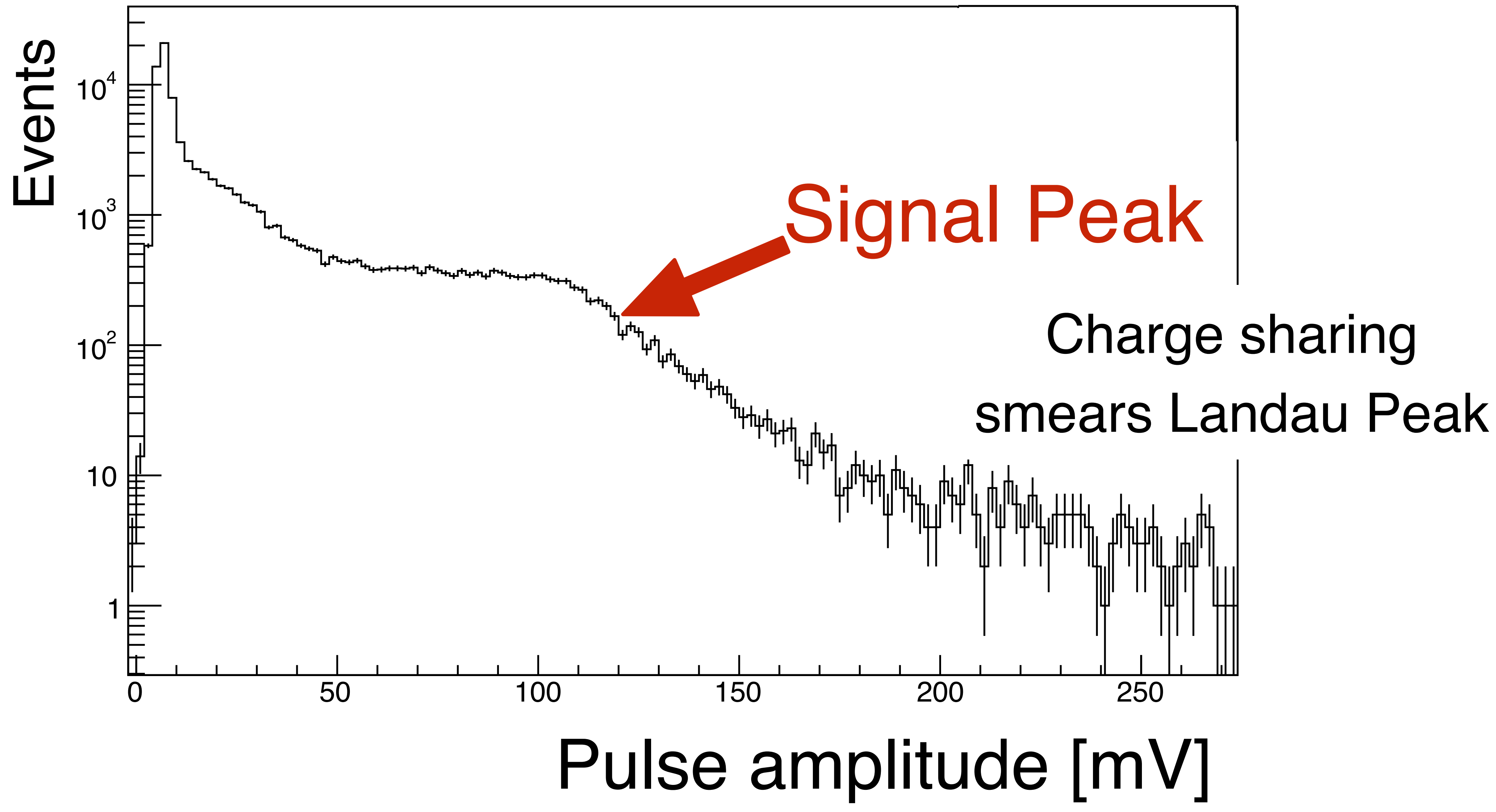
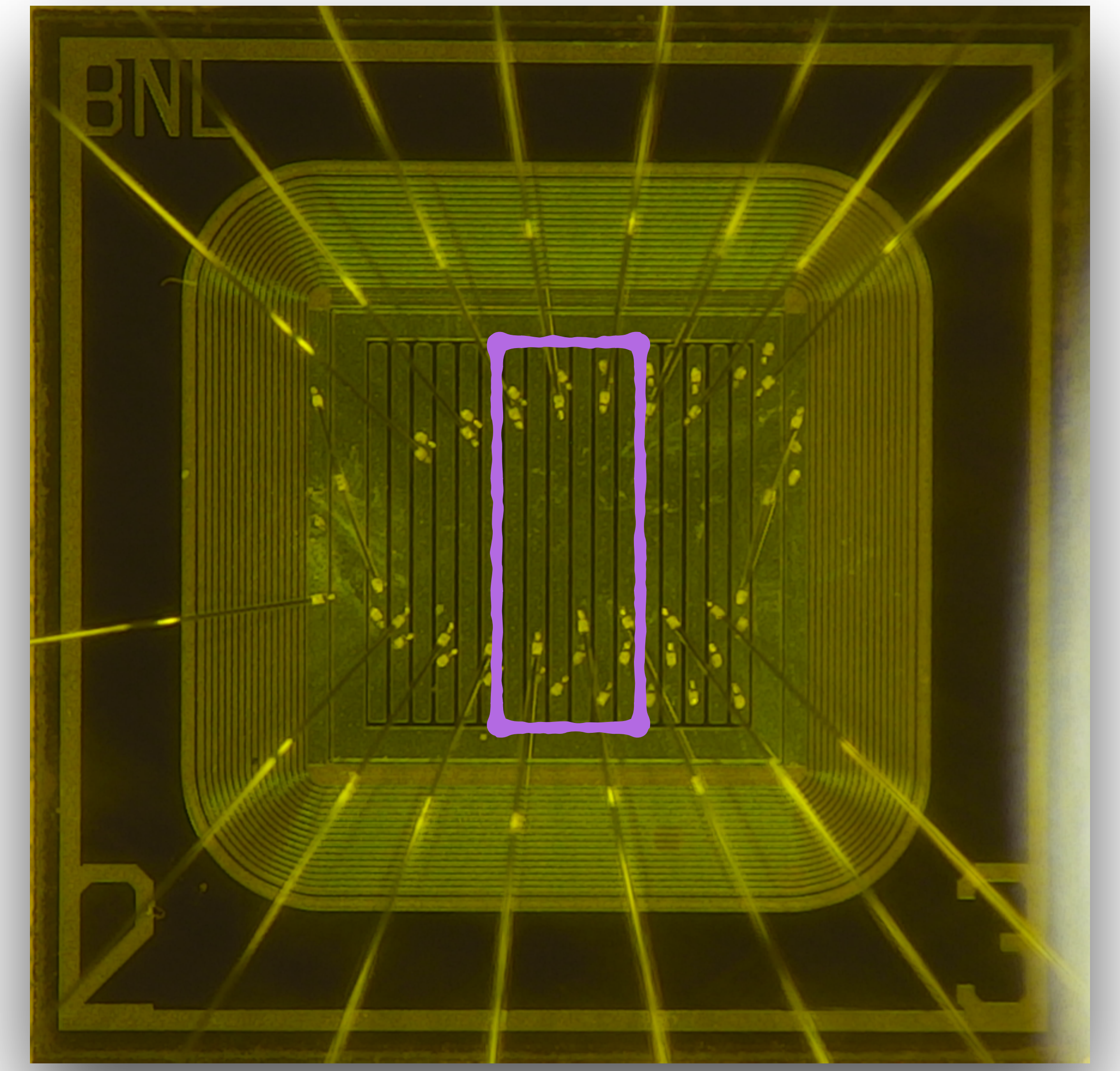
Test beam results: BNL 2020 strips

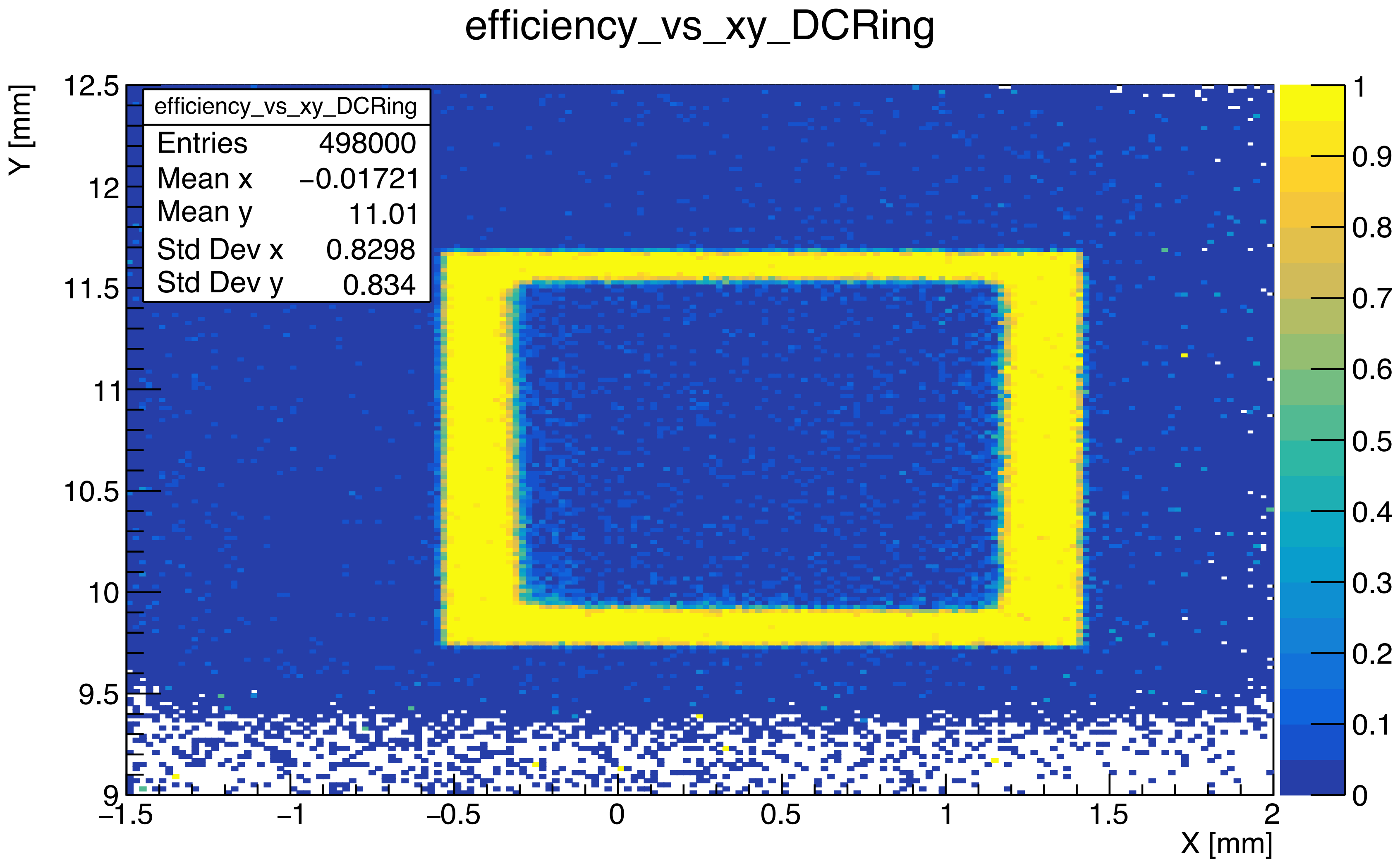
- Test beam results for a sensor produced by BNL in 2020
  - 120 GeV proton beam
- Read out 6 interior strips + DC ring + MCP timing reference
- Selected events with proton in inner 4 readout strips to see performance



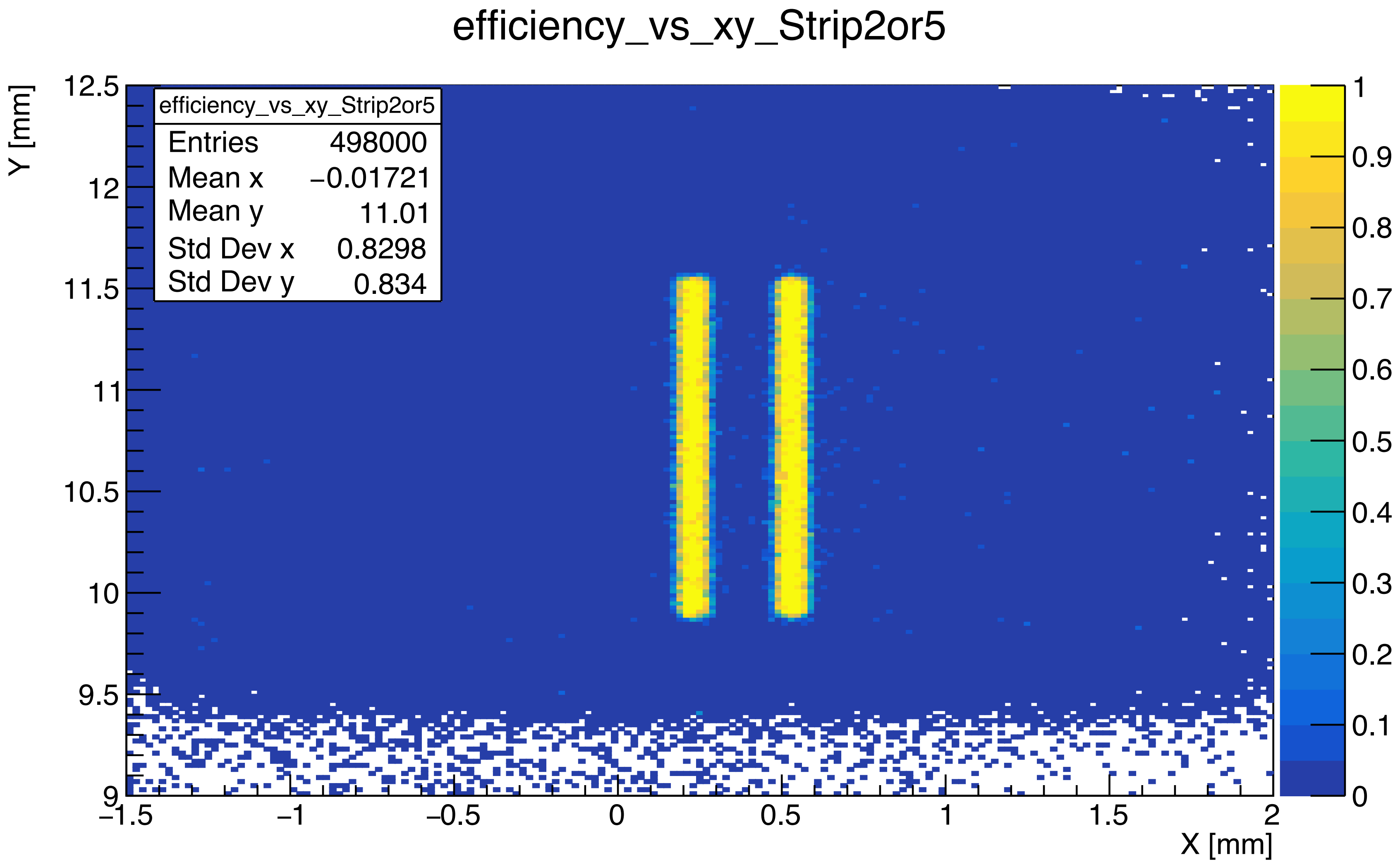
100 micron pitch, 20 micron gaps



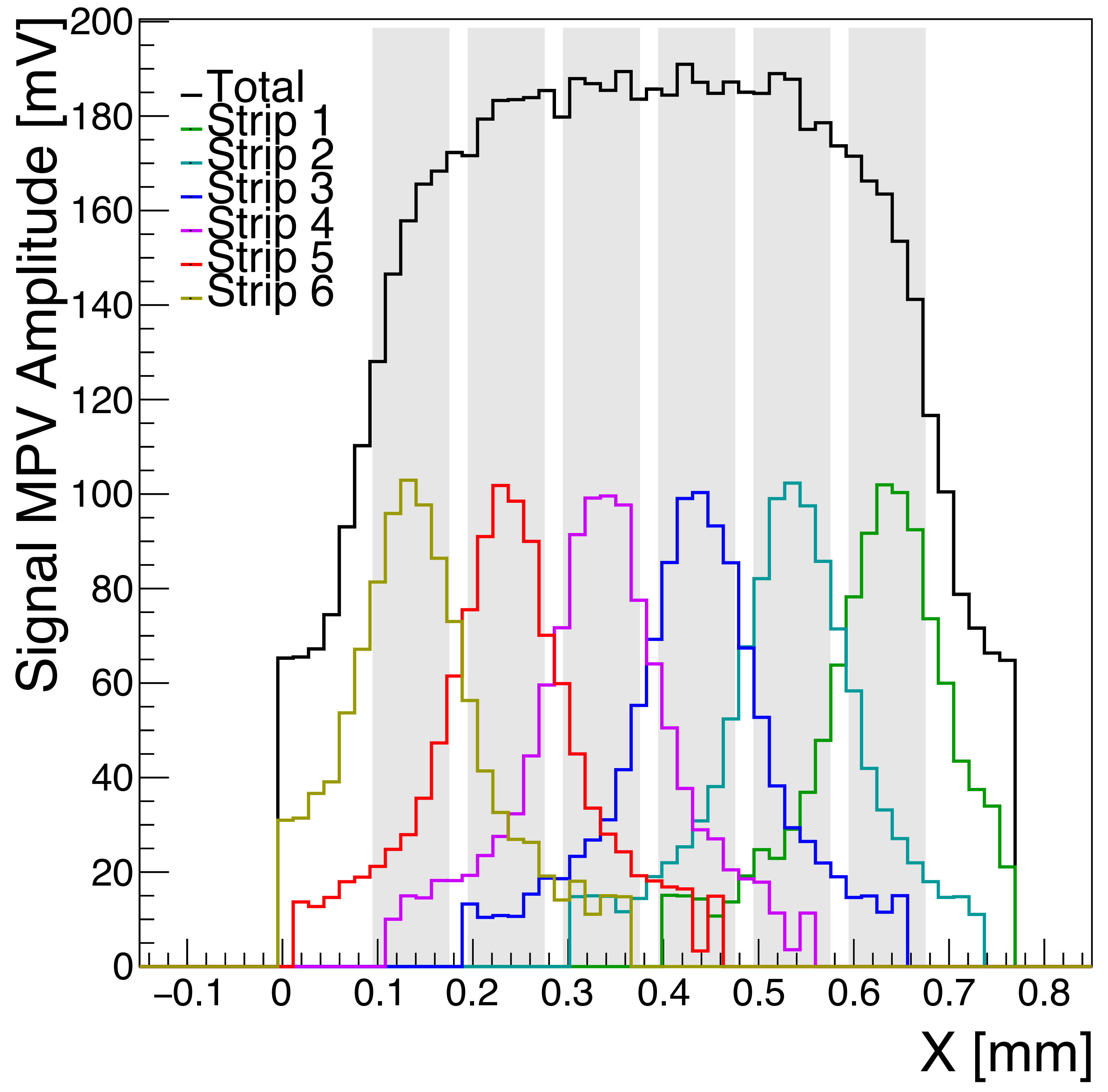
Efficiency, DC pad

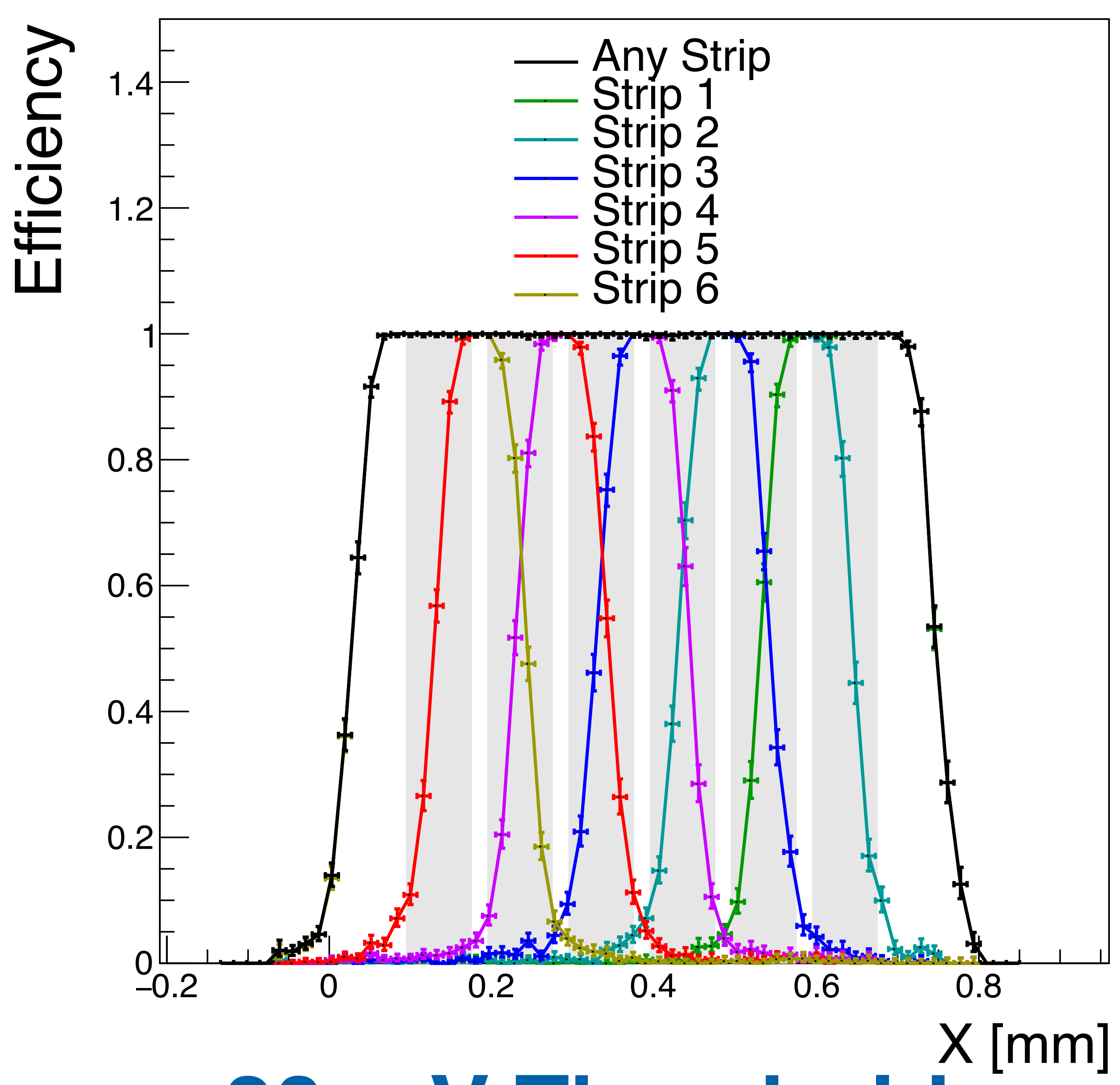


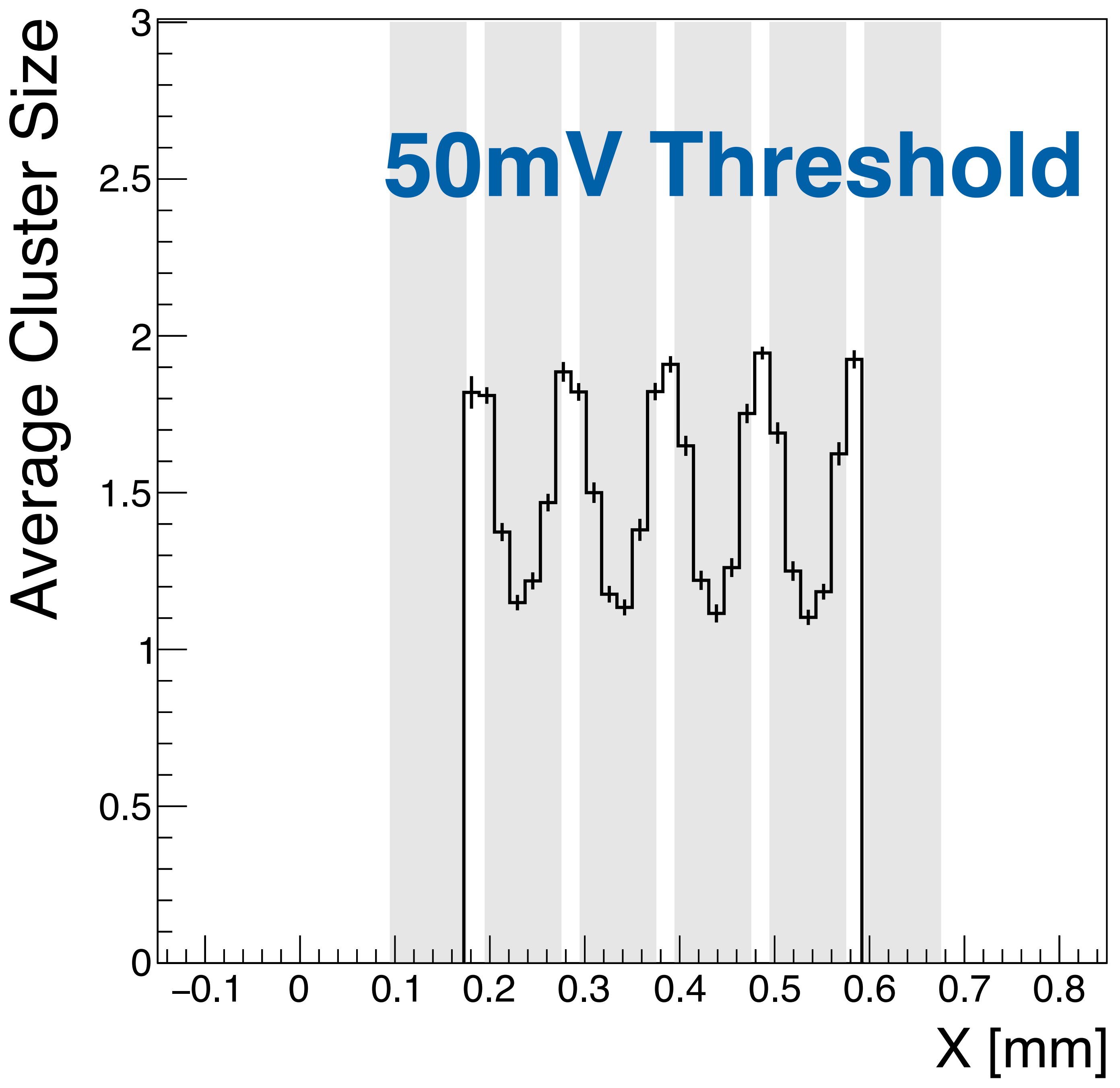
Efficiency, 2nd or 5th strip



Charge sharing: BNL 2020







30 mV Threshold

- We can see the effects of charge sharing between strips
- Amplitude peaks at around 100 mV per strips and effectively shares charge between almost all strips
- 100% efficiency across all strips
- Can define a cluster as number of strips above some threshold

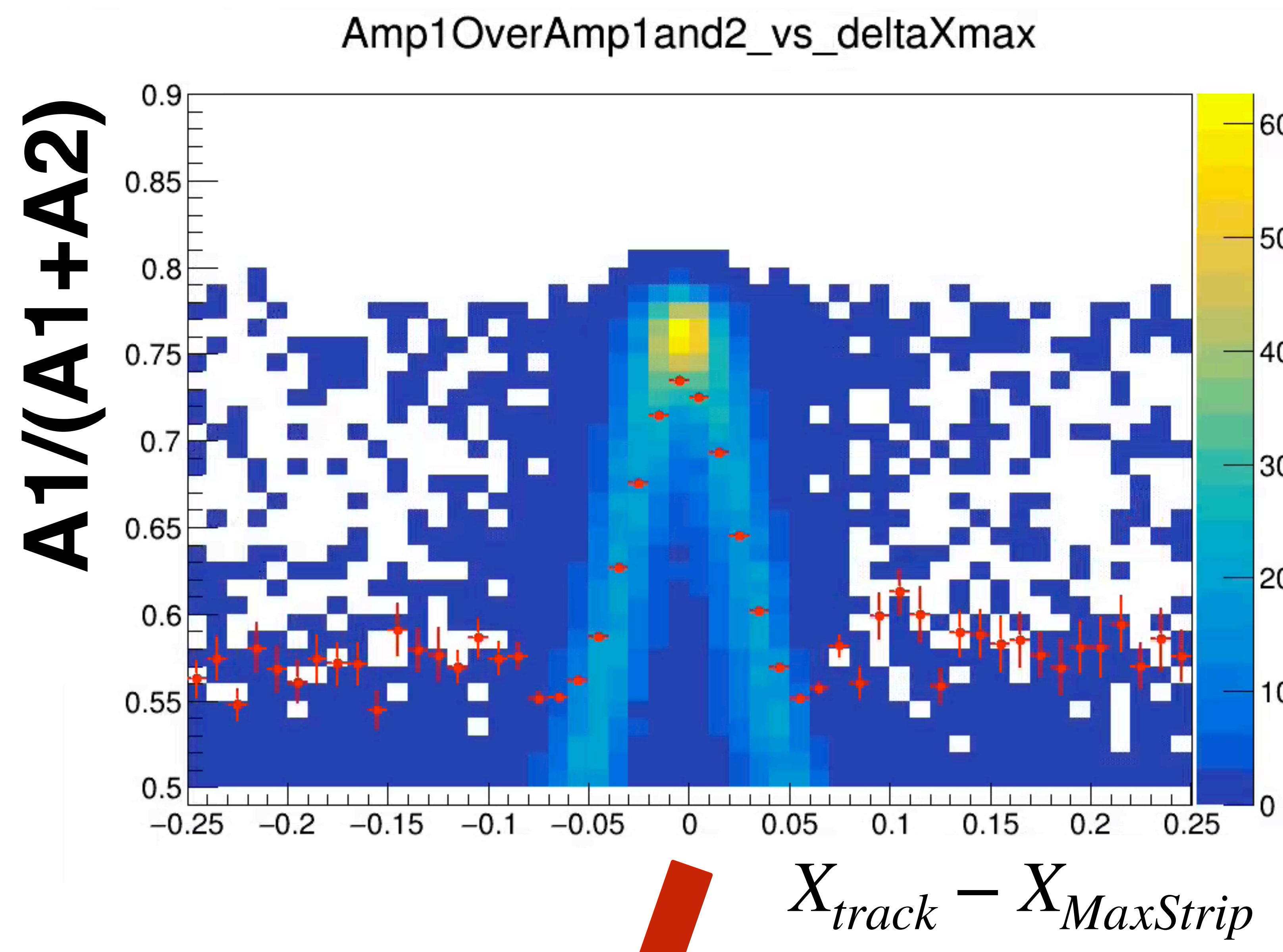
Position Reconstruction: BNL 2020

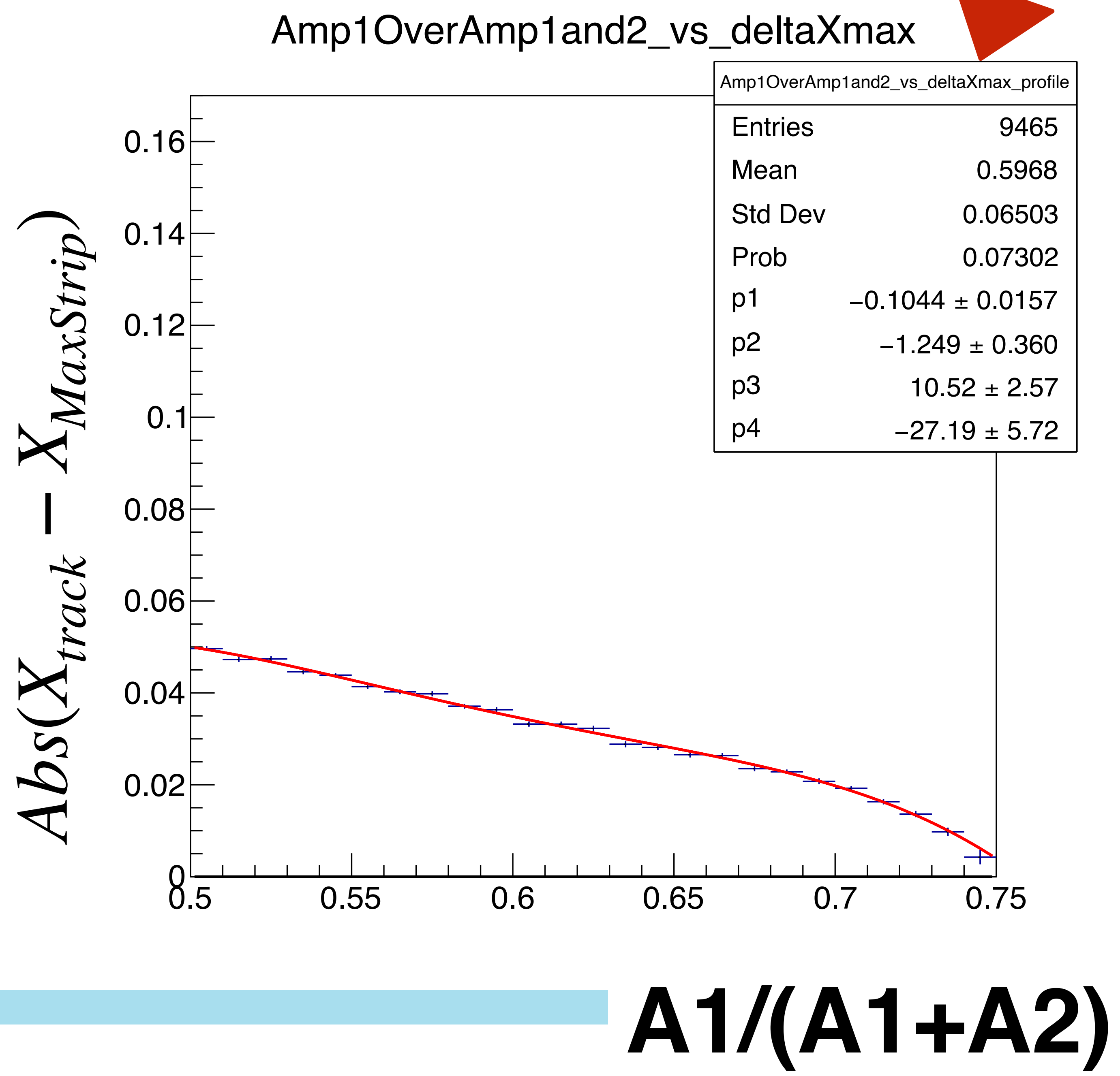
- Utilizing the charge sharing between strips we can accurately reconstruct the location of the proton hit using the primary strip and secondary strip relative amplitude
  - Minimal information required
  - Possibly better performance can be achieved with more complex reconstruction methods

- Performed position reconstruction by comparing max amplitude (A1) to second highest amplitude (A2) strip as a function of external tracker X location

- Make Profile plot and fit to 3rd degree polynomial
  - Function mapping relative amplitude to distance from max strip location

- The reconstruction method does not depends strongly on location within the inner 4 readout strips or sensor bias voltage





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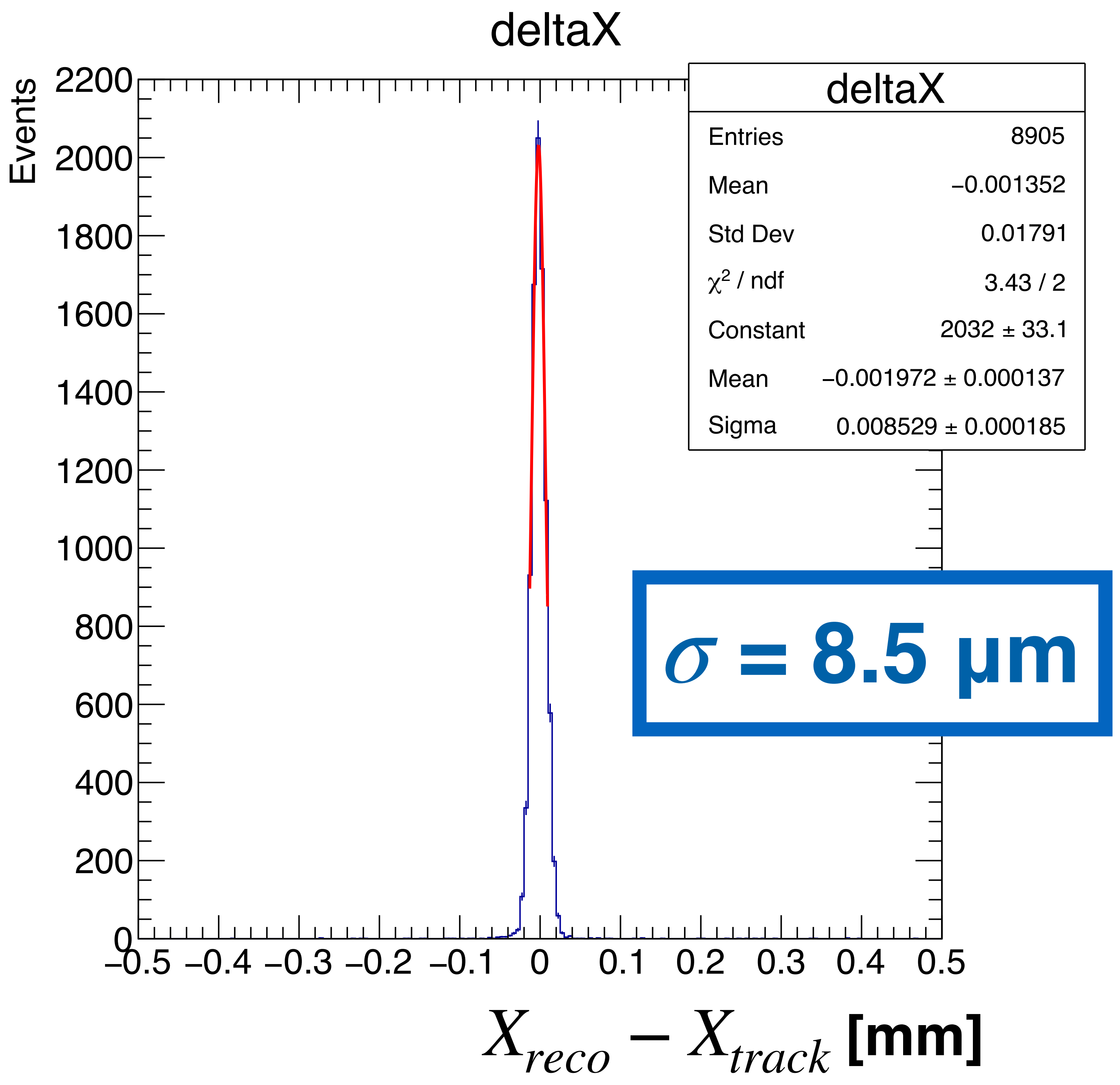
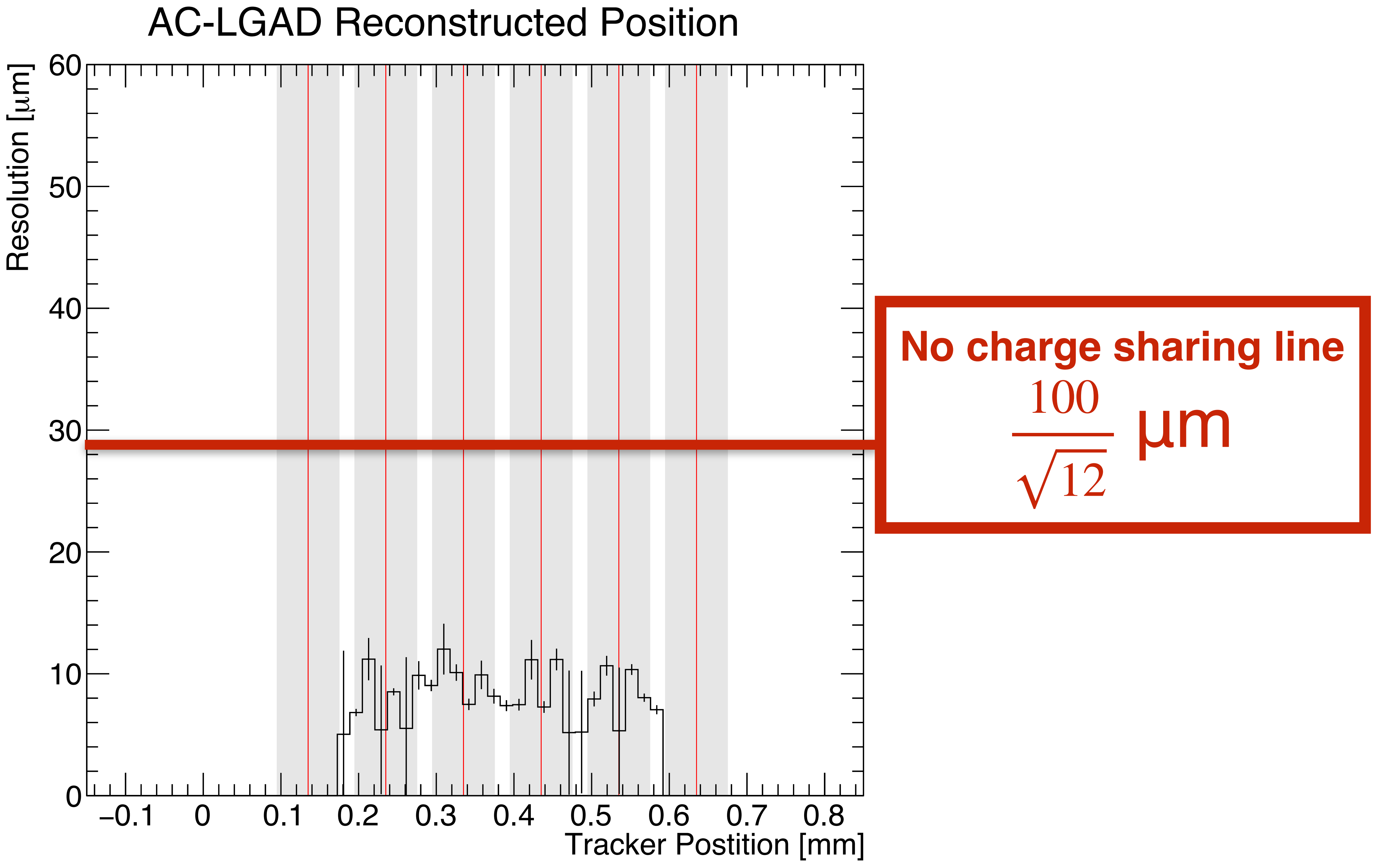
Position Reconstruction: BNL 2020





- Observed a position resolution of ~5 µm after removing reference tracker uncertainty (~7 µm)
- Discontinuities are observed where the relative fraction is large or when we get direct hits to the strip
  - Can explore other reconstruction methods
  - Preliminary results have shown a neural network can give the same results

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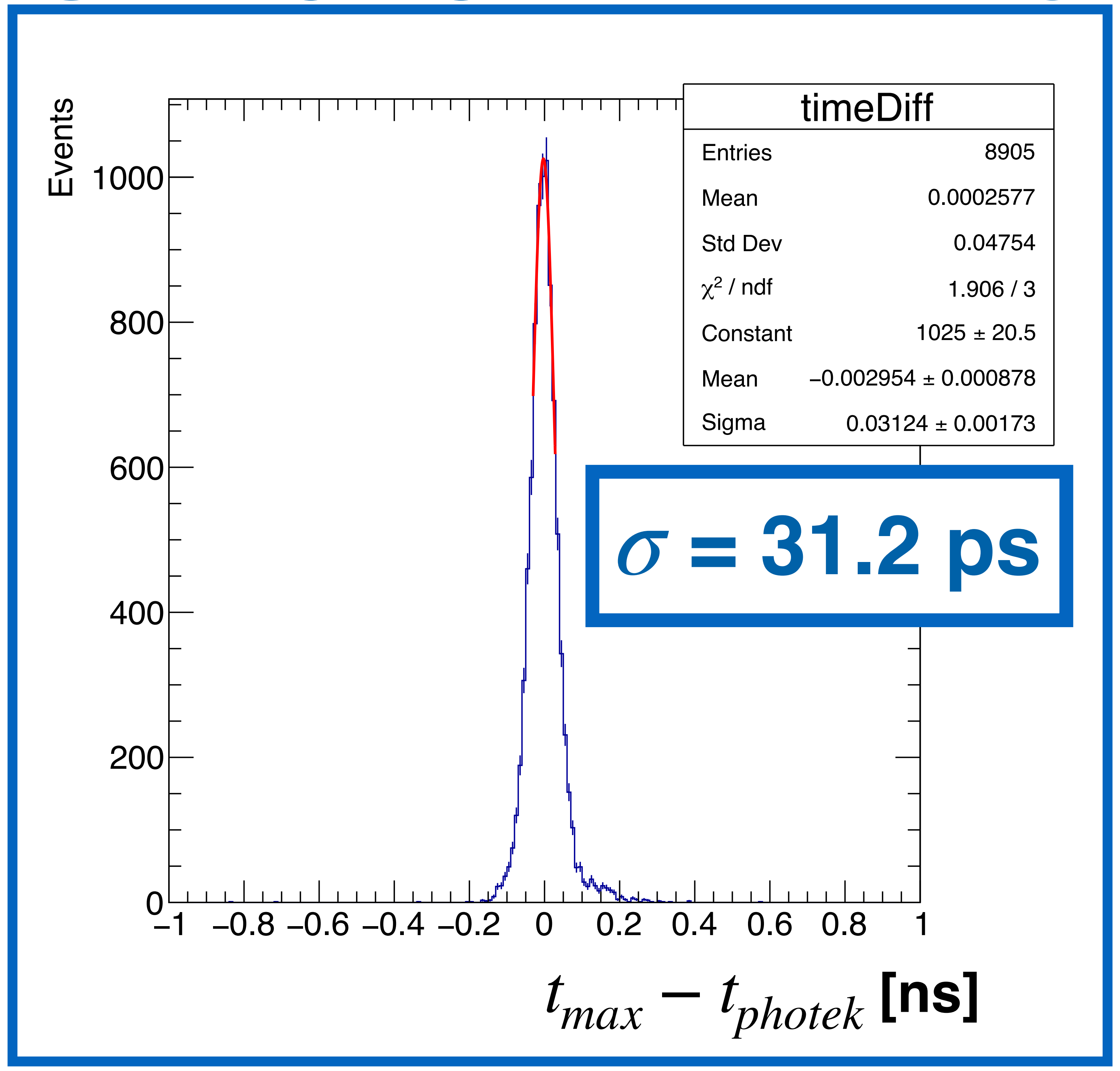
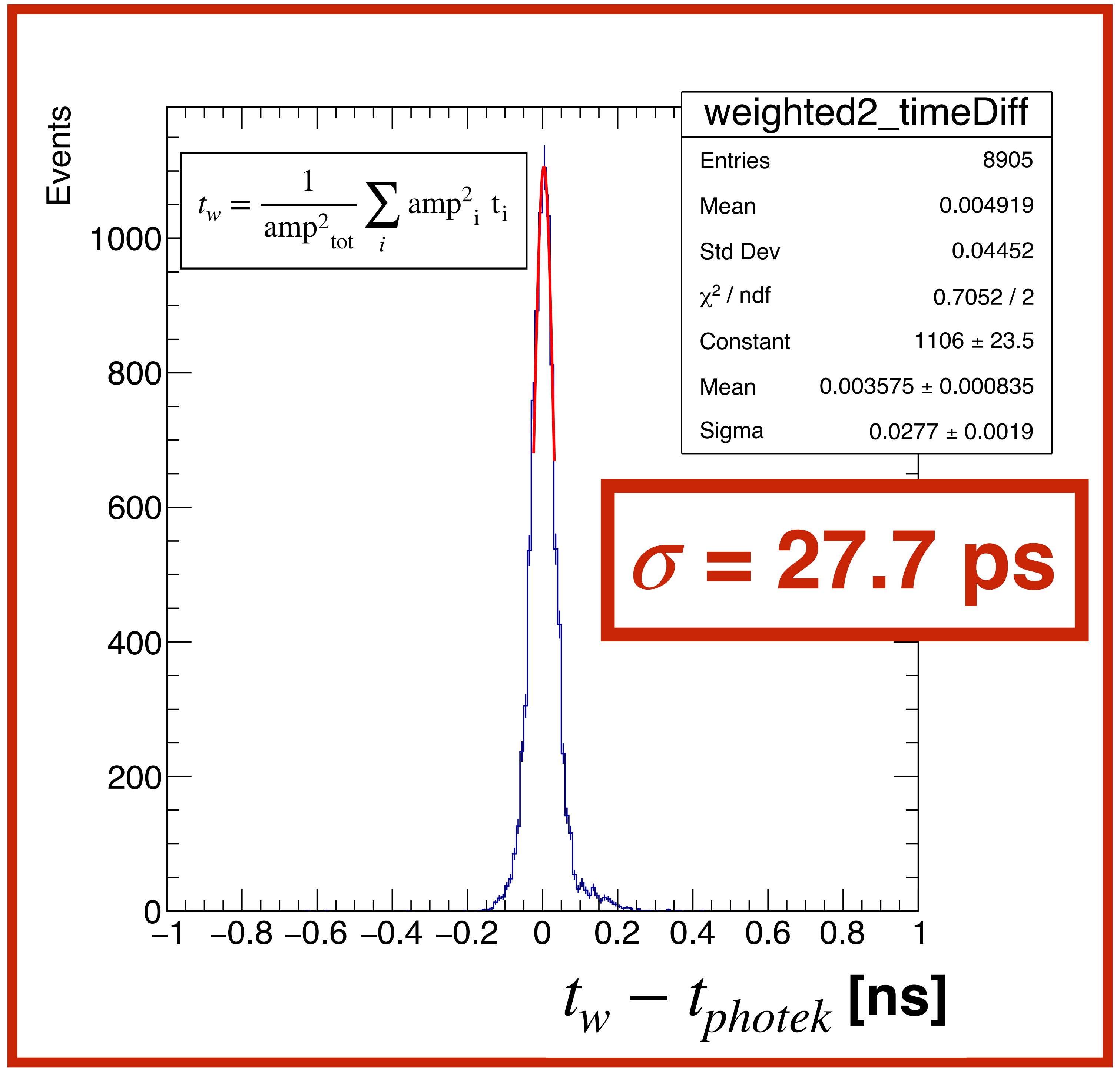
Time Reconstruction: BNL 2020





- With the success of charge sharing for position reconstruction we looked at different ways of reconstructing the time of the proton hit
- We see an improvement of the time resolution over using time from max amplitude strip (t_{max}) vs. the amplitude weighted average time (t_w)
  - Expect improvements to come from hits in the gaps between strips

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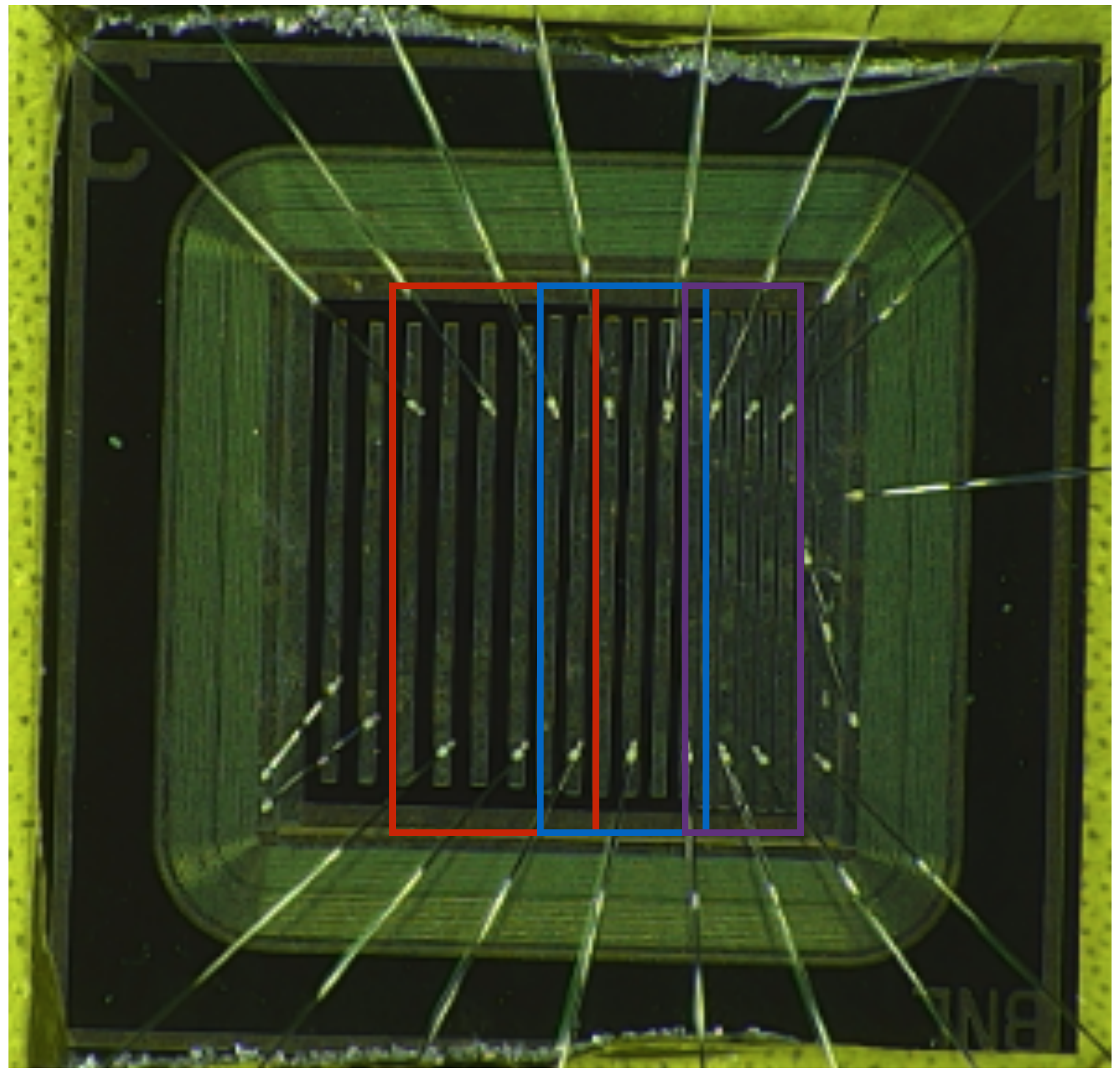
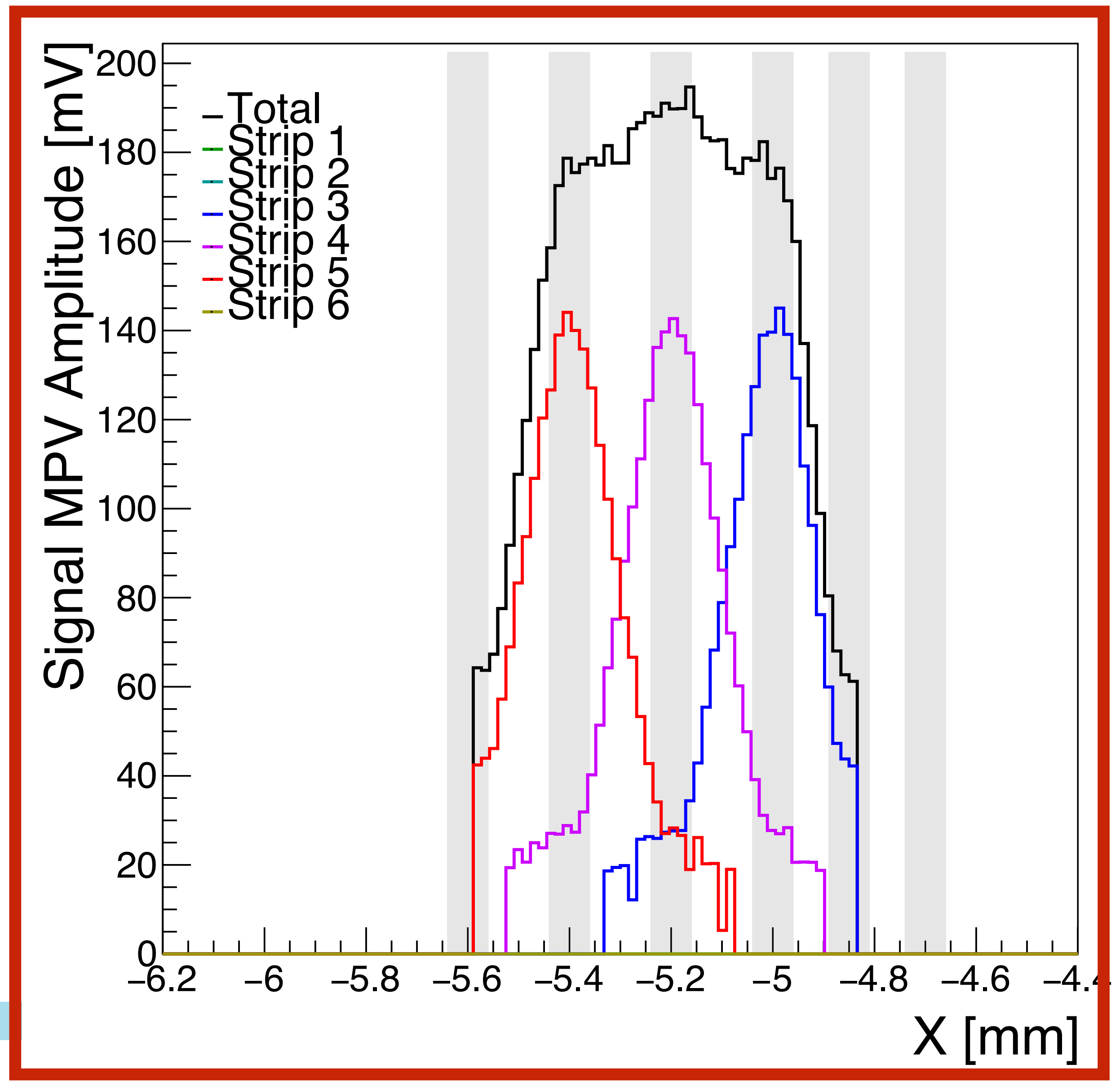
Test beam results: BNL 2021 strips

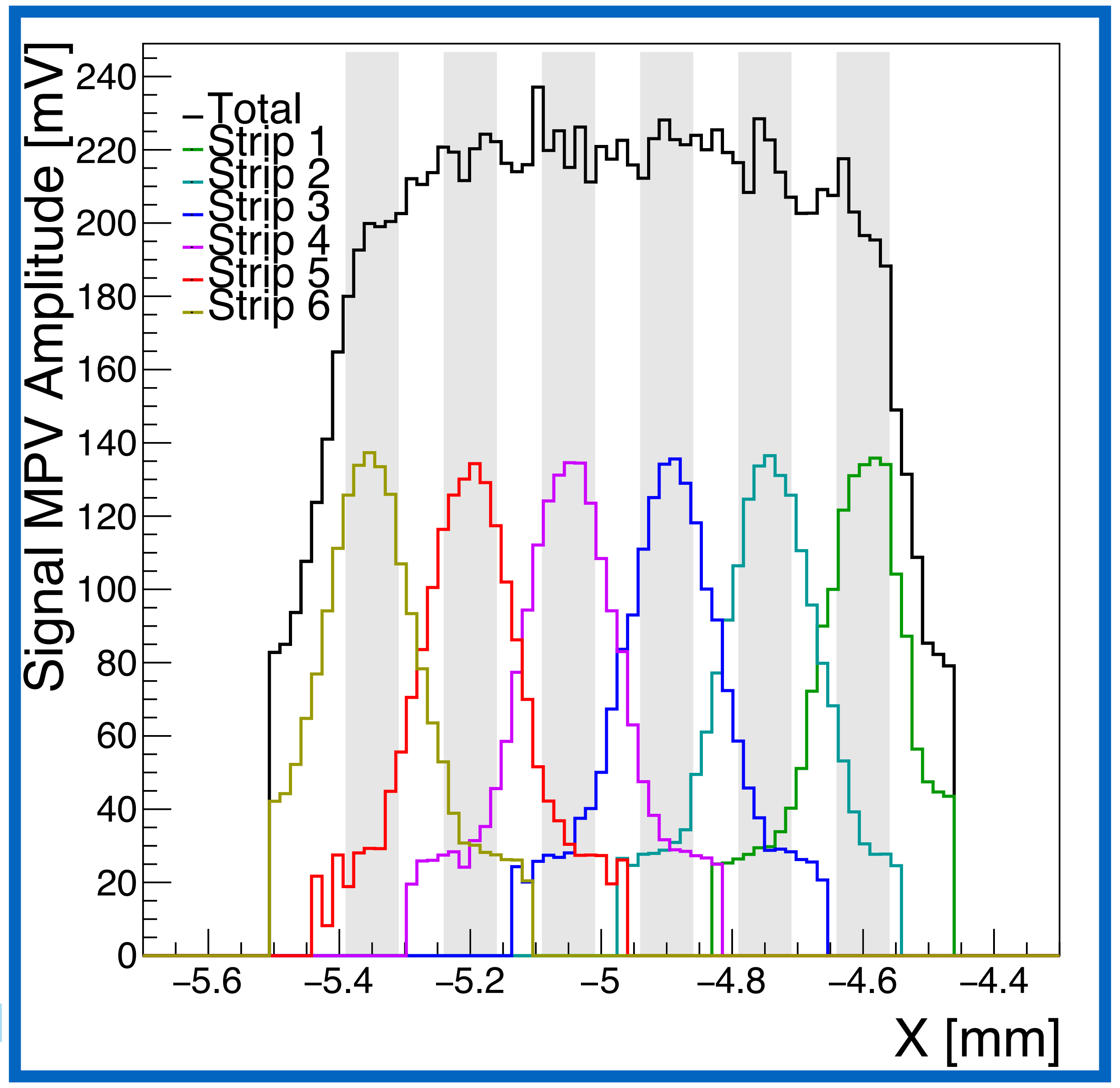
- Test beam results for another BNL sensor produced in 2021 with three pitch variations
- Similar charge sharing properties to BNL 2020 sensor discussed above
- Repeated position and time reconstruction analysis for each variation
  - Similar performance for each pitch variation

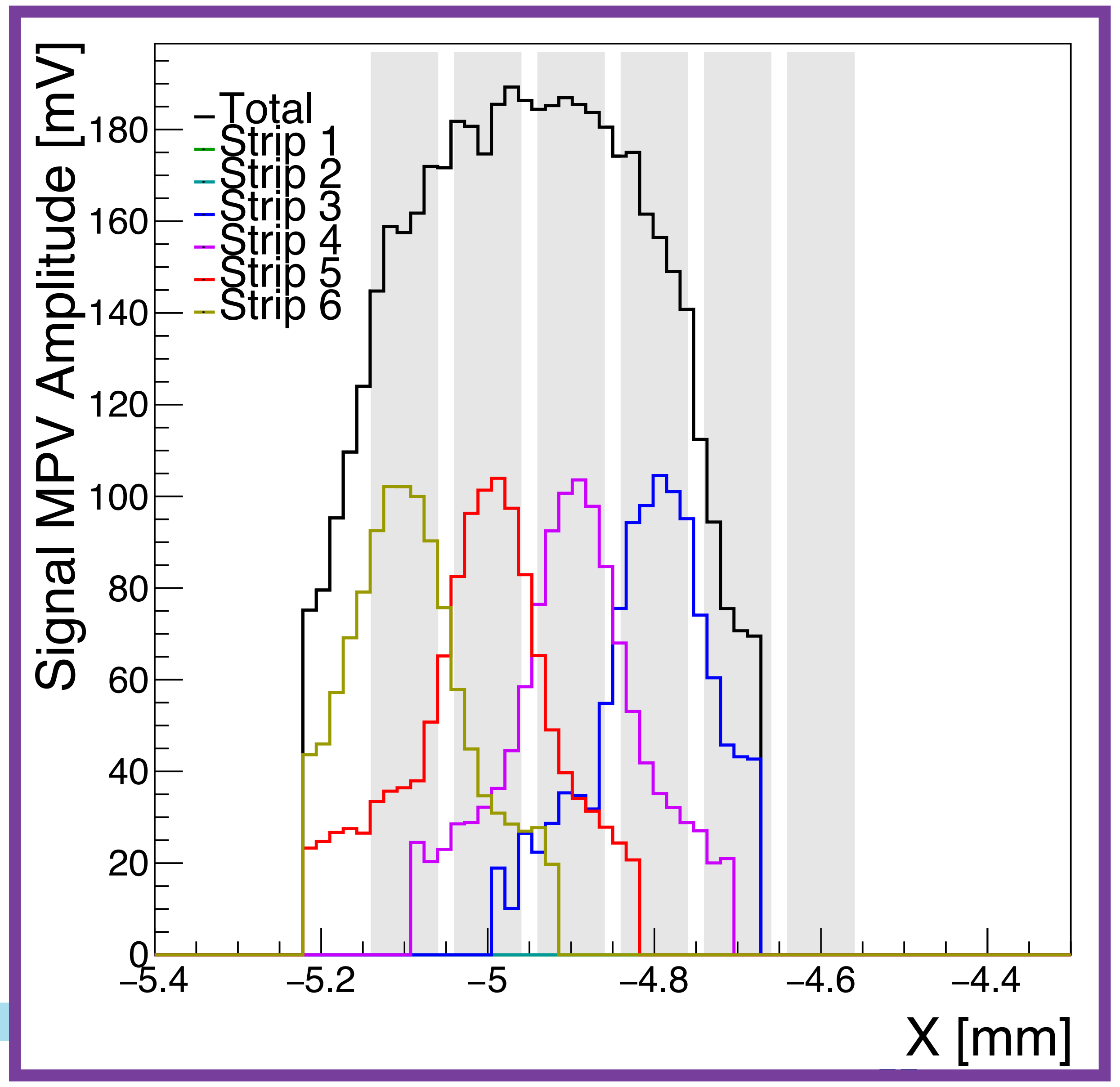
	Wide 200 um	Medium 150 um	Narrow 100 um
Time Resolution	34.8 ps	30.9 ps	38.3 ps
Position Resolution	8.4 um	10.5 um	6.4 um



200 um, **150 um**, and **100 um** pitches

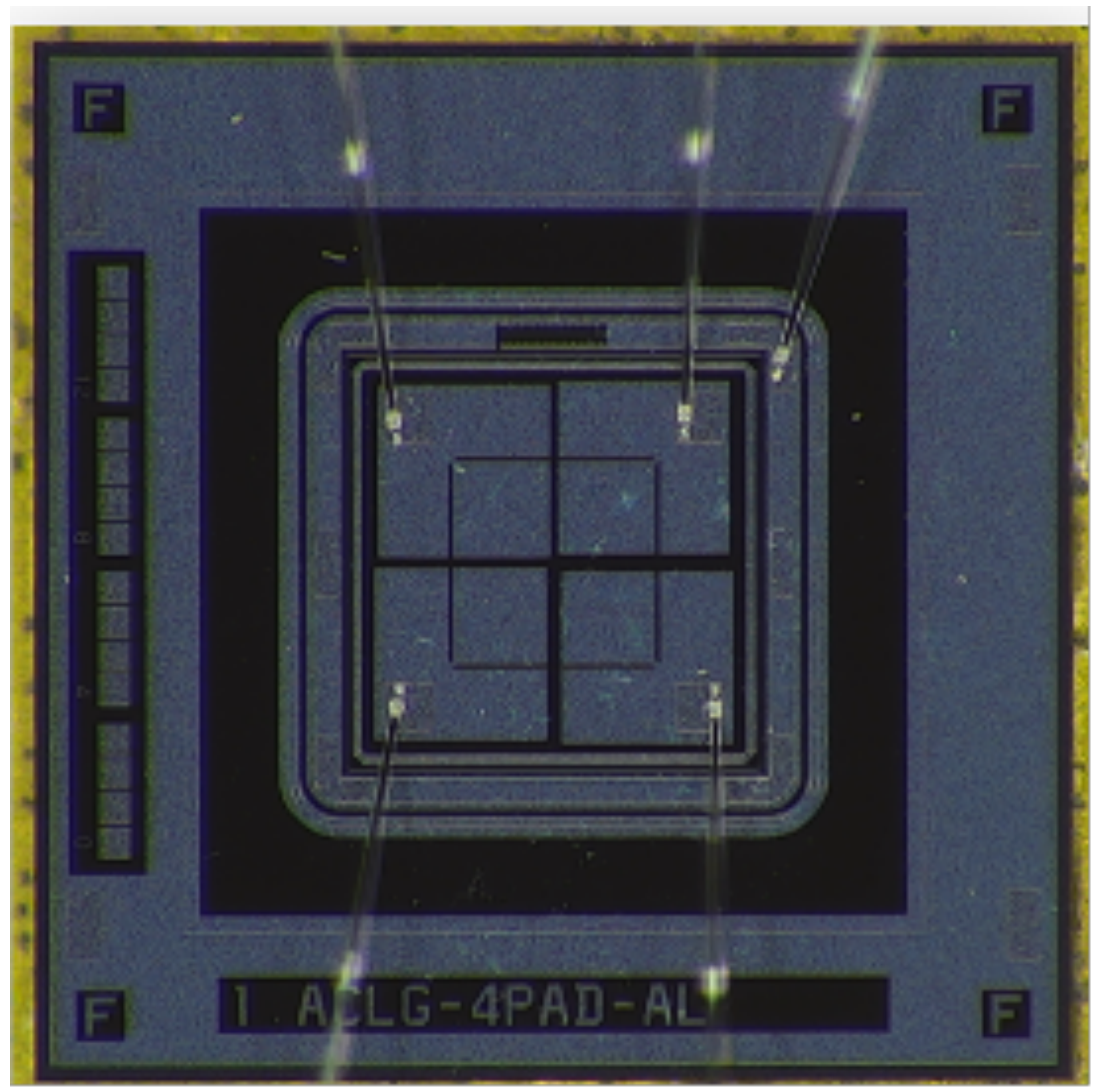




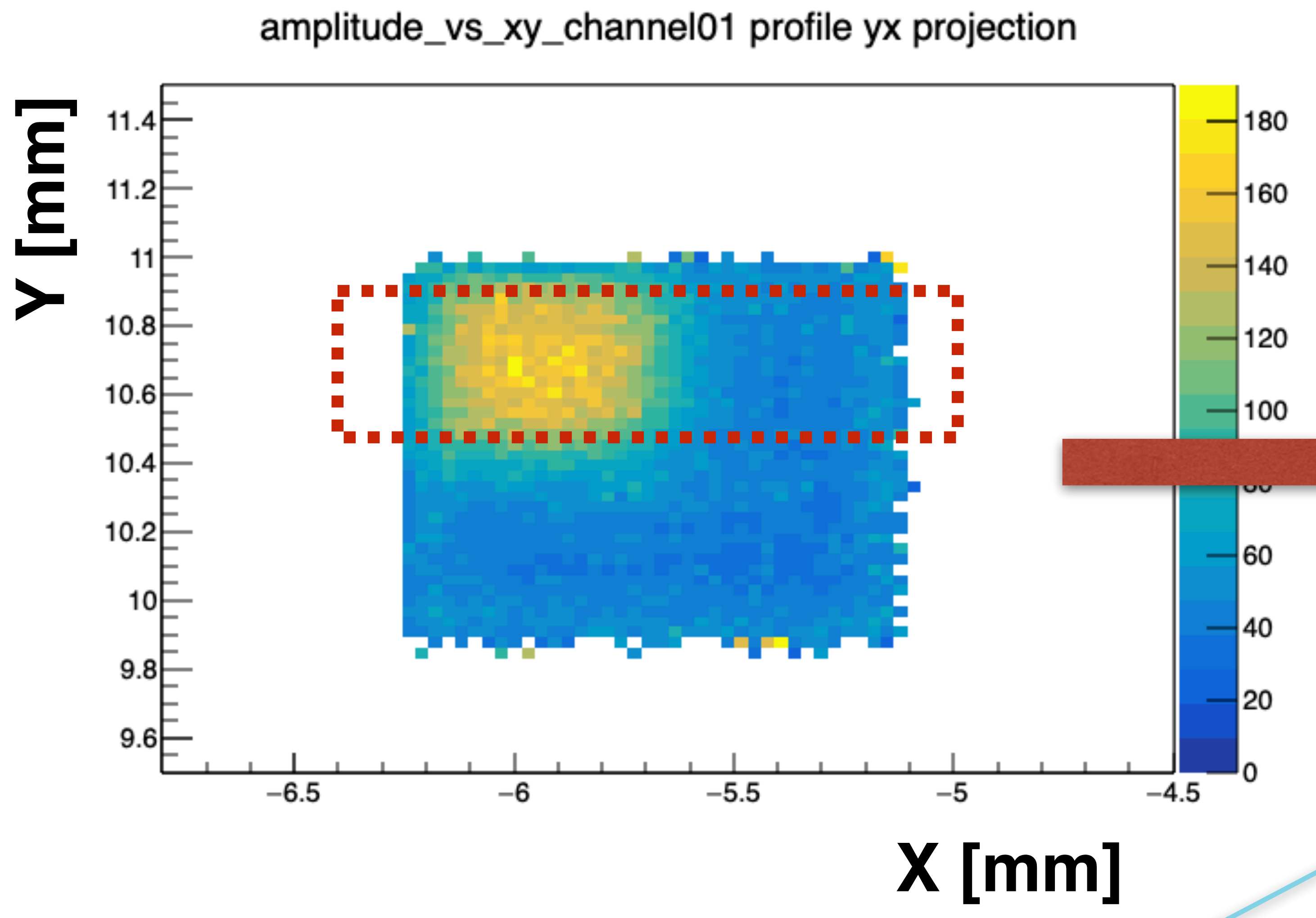


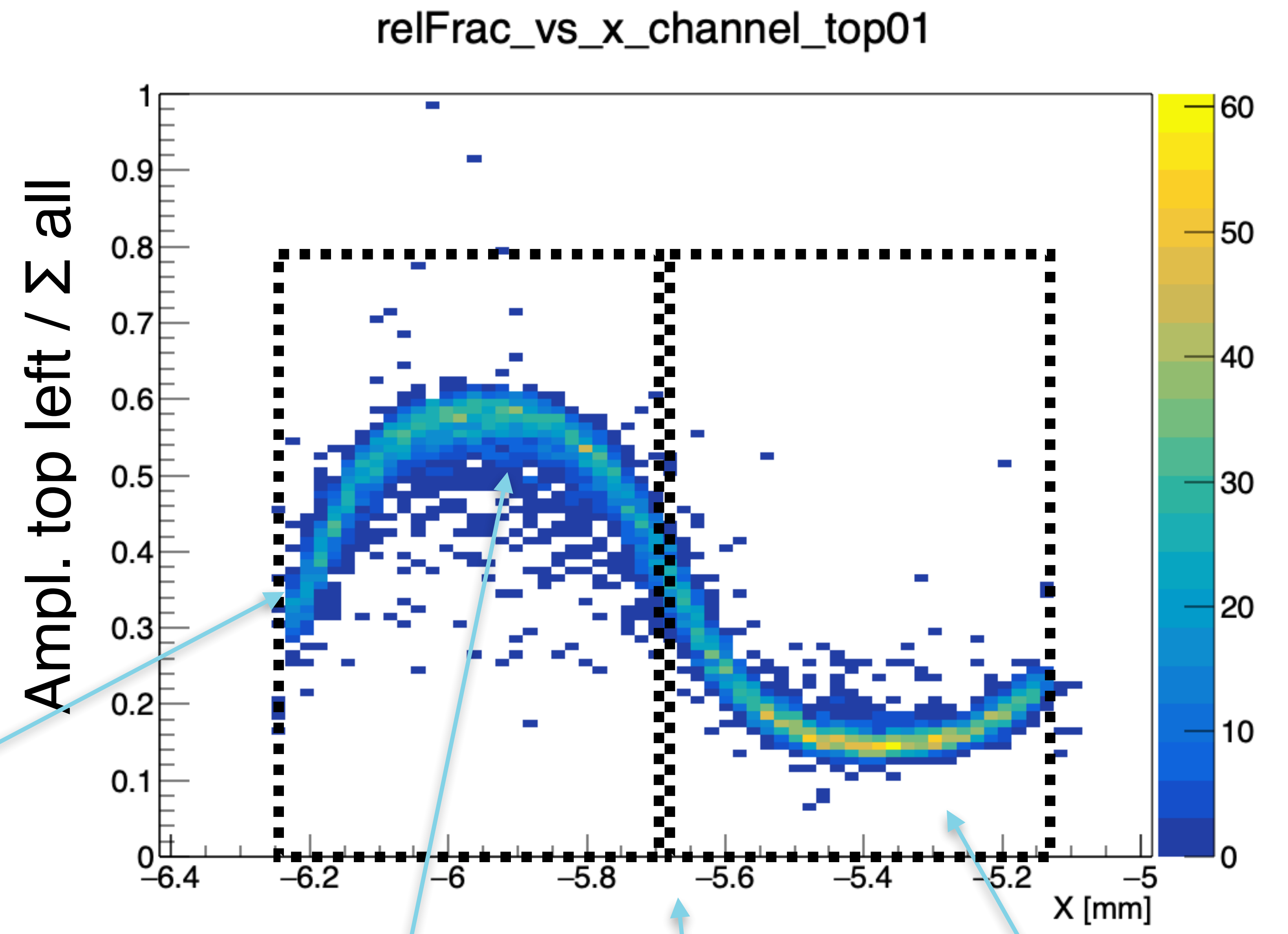
Test beam results: HPK Pads

- Similarly to the sensor produced by BNL we have sensors from KEK and U. of Tsukuba that are fabricated at HPK
- The overall performance we observe is very similar
- Here we have a 2x2 pad sensor with 500 µm size pads
- We can see the effects of charge sharing in 2 dimensions by looking at the efficiency for primary hits to the top left pad



HPK 2x2, 500 µm pad size





Decreased coupling near pad edge

Signal fraction flat at center

300 micron linear region!

Constant distant coupling.

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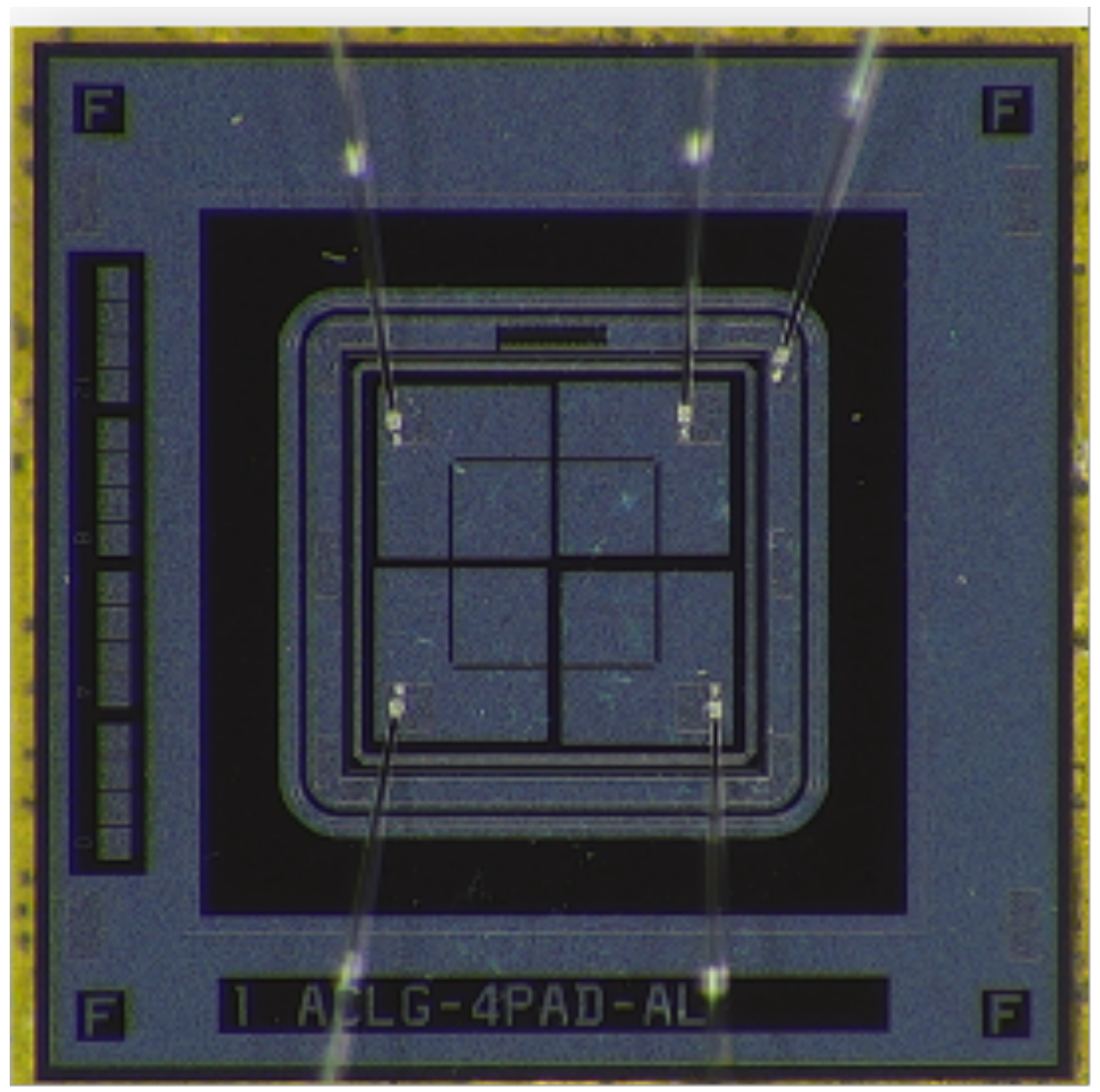

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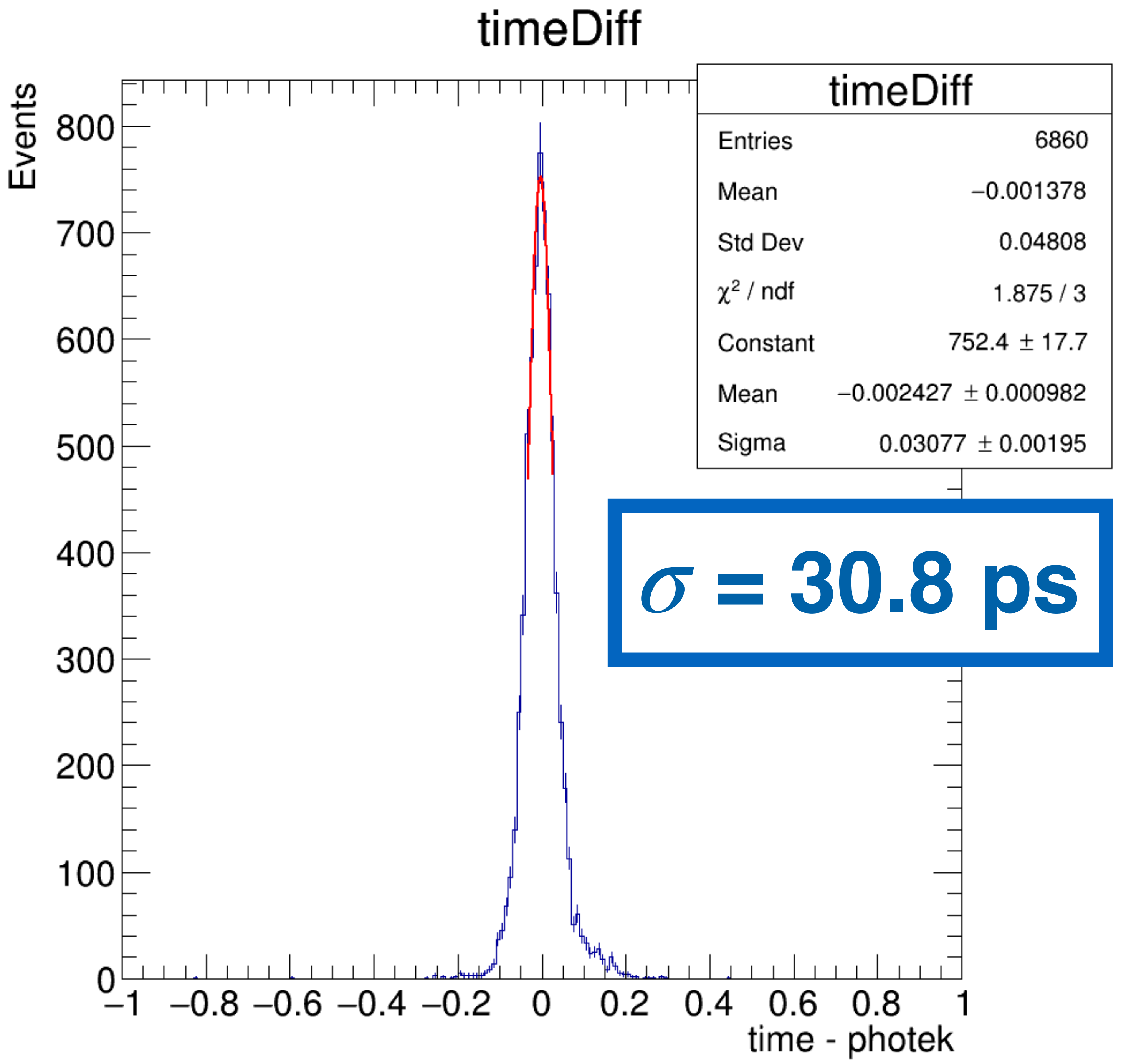

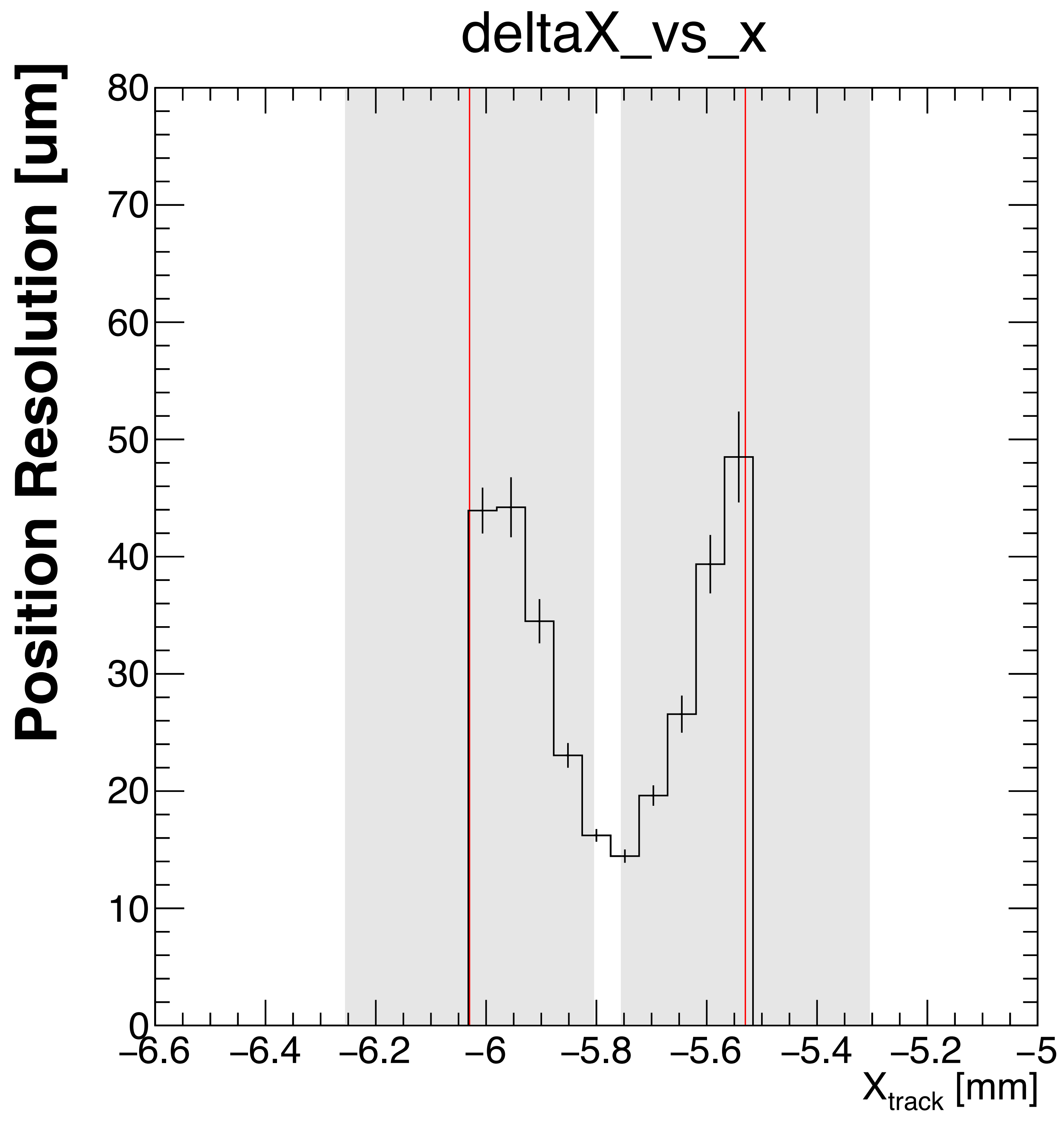

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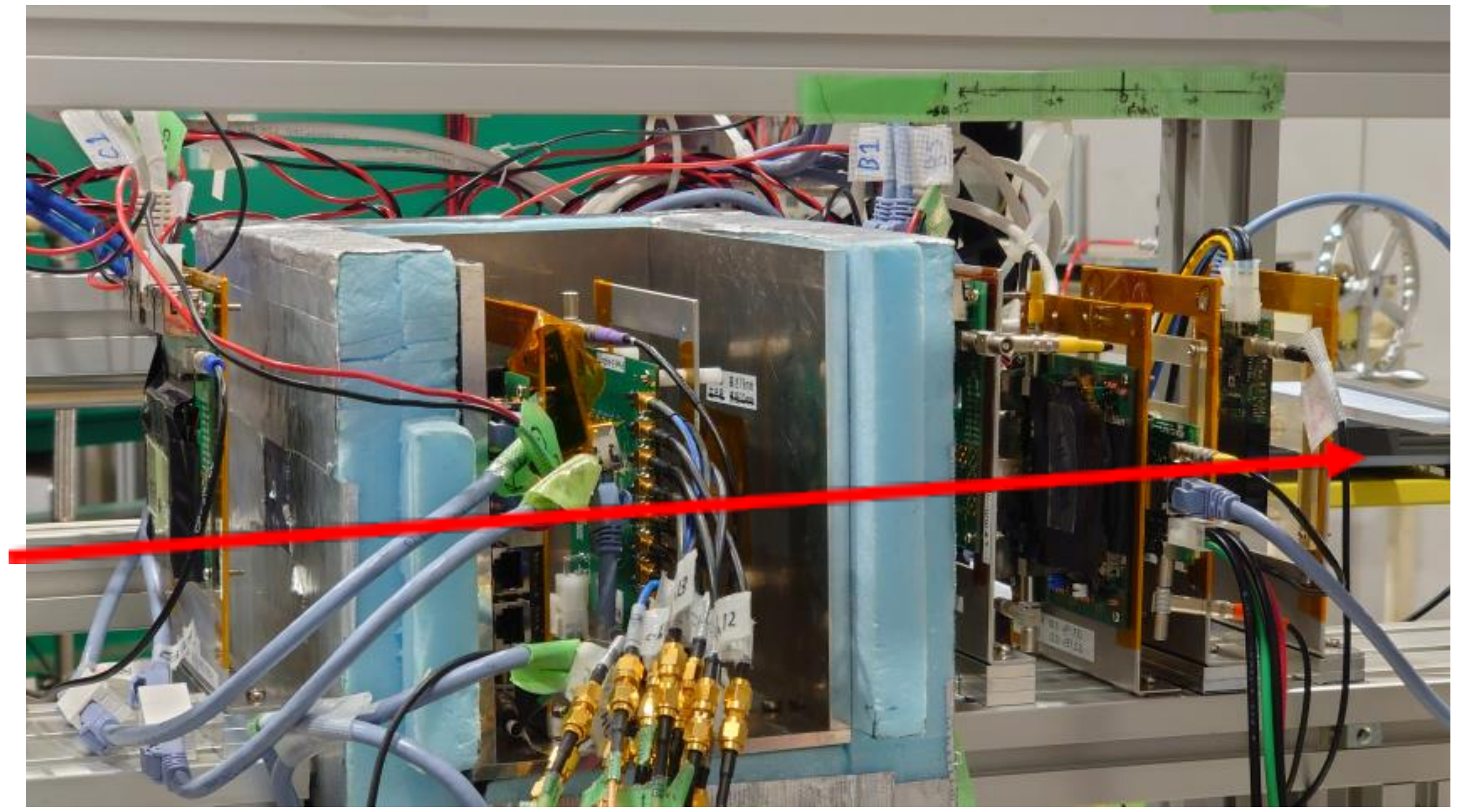
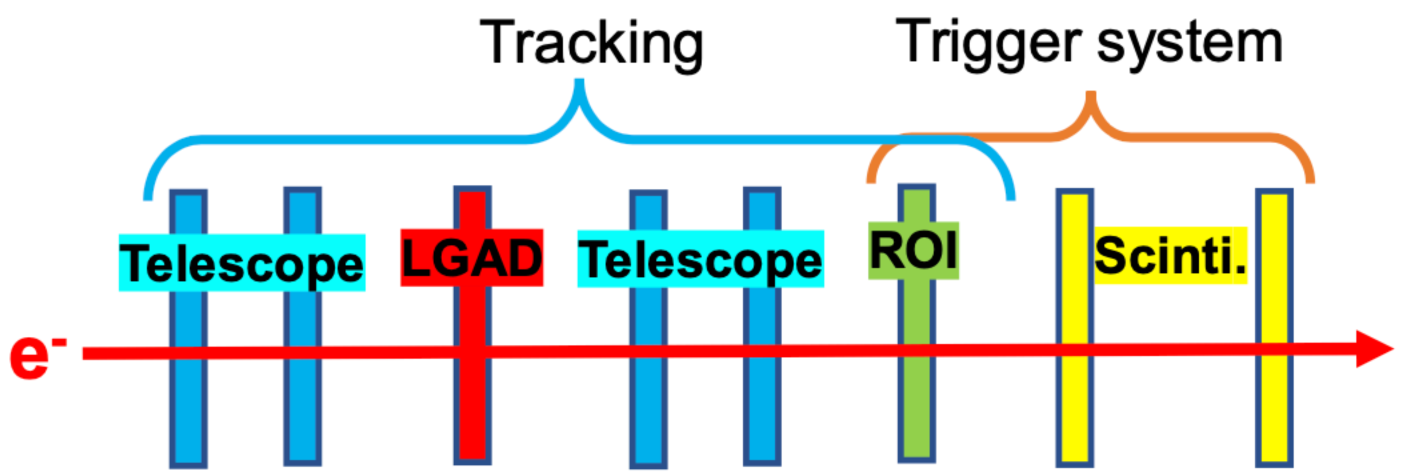
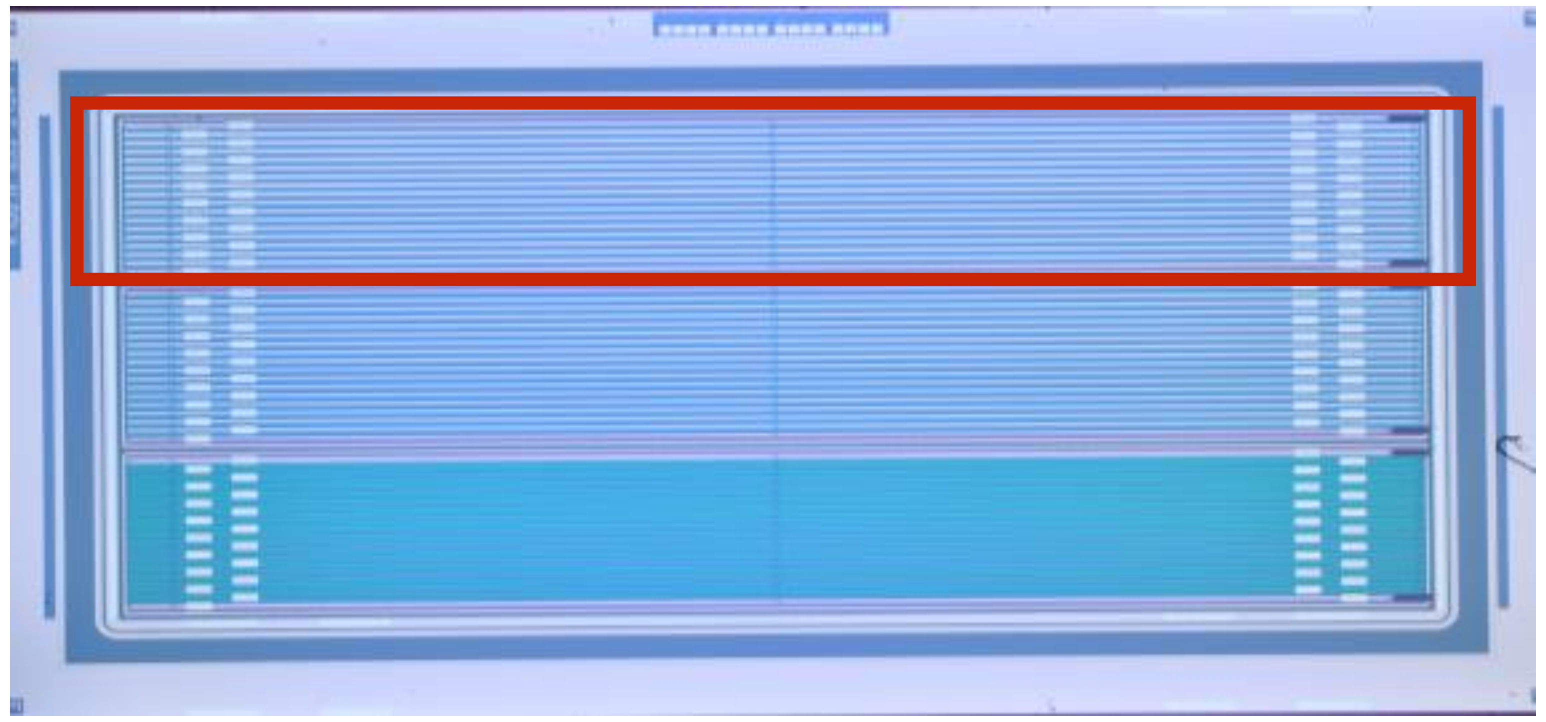
HPK Strips Measured at ELPH Test beam

800 MeV
e⁻ Beam



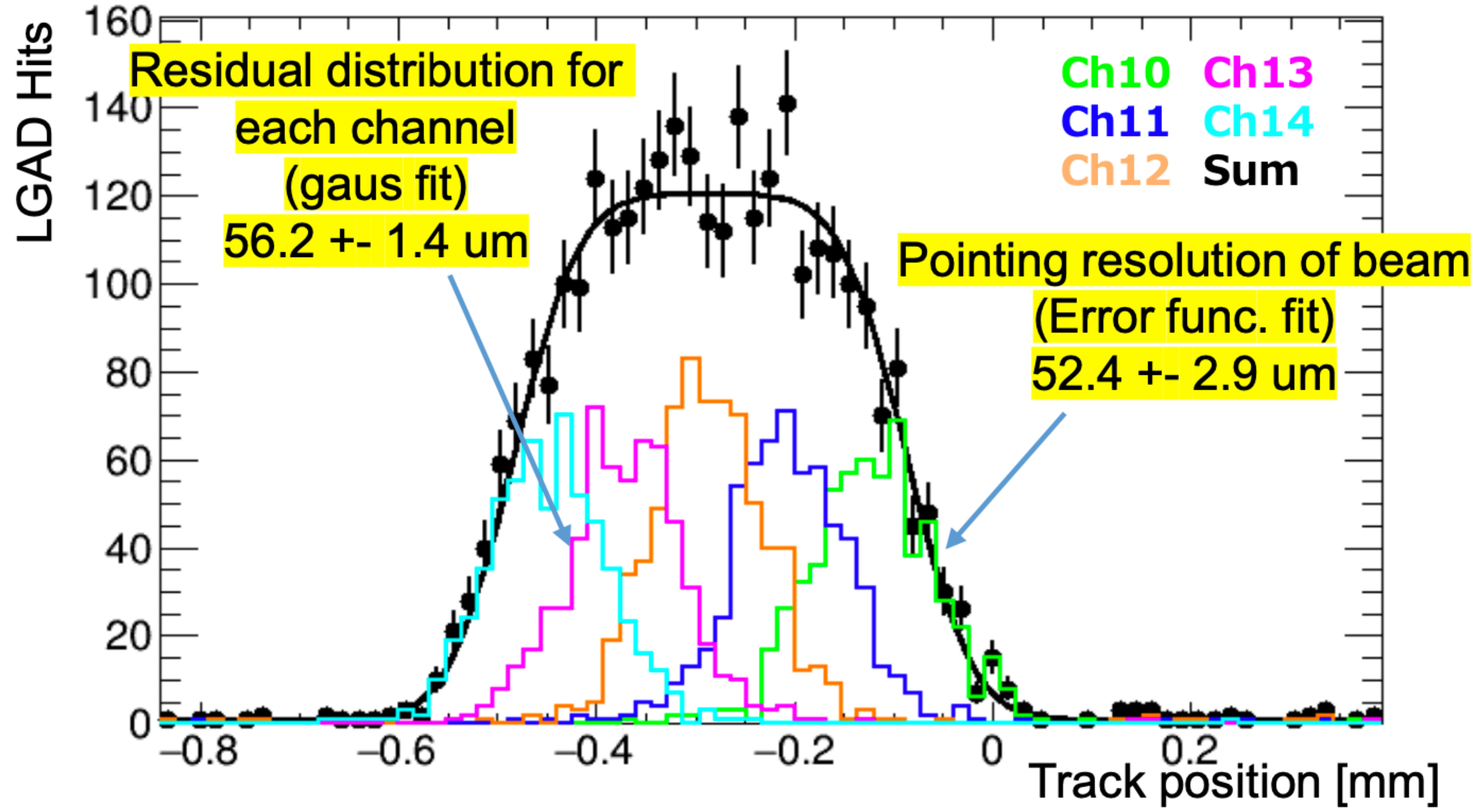


Event selection
- ✓ Good tracks
  - : have hits for all tel and ROI
  - : χ^2/NDF : < 18 (x,y)
- ✓ LGAD hit : > 14mV



Strip Sensor
40 um x 9880 um, 16 channel
80 um pitch

- Another HPK strip sensor was tested after the FNAL test beam at Tohoku University
- Uses a 800 MeV electron beam at a rate of ~200-400 Hz
- Collected ~600,000 events
- Results shown previously at *IEEE NPSS by S. Kita*
- Measured position resolution of **~20 um** without the use of charge sharing



Spatial resolution : 20.3+- 3.2um (tracking resolution subtracted)

Summary

- First demonstration of simultaneous ~5 um and ~30 ps resolutions in a test beam

- AC-LGADs offer the benefits of charge sharing that can be utilized for timing and position reconstruction compared to standard silicon detectors
  - Giving uniform time and position resolution across sensor

- Both BNL and HPK manufactured sensors tested during these test beam campaigns delivered comparable performance