Test beam measurements of BNL and HPK AC-LGADs

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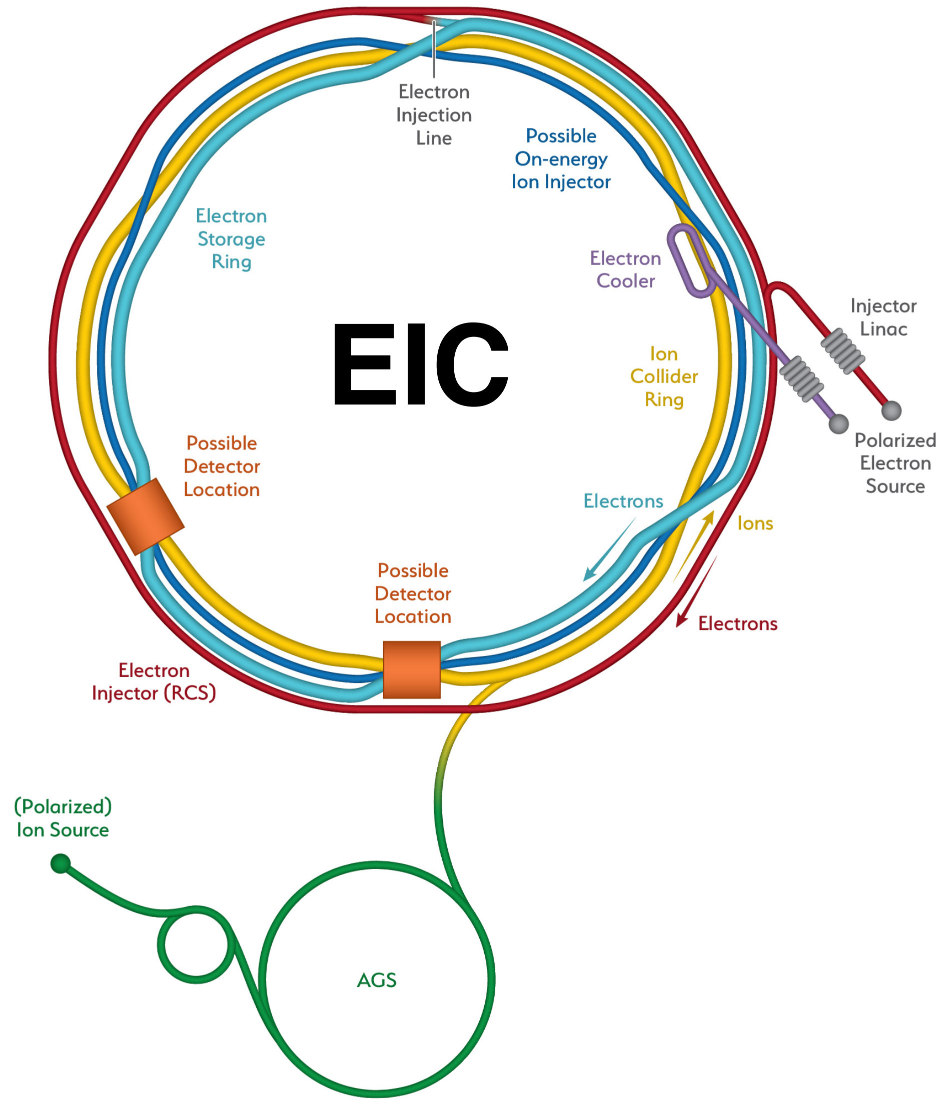
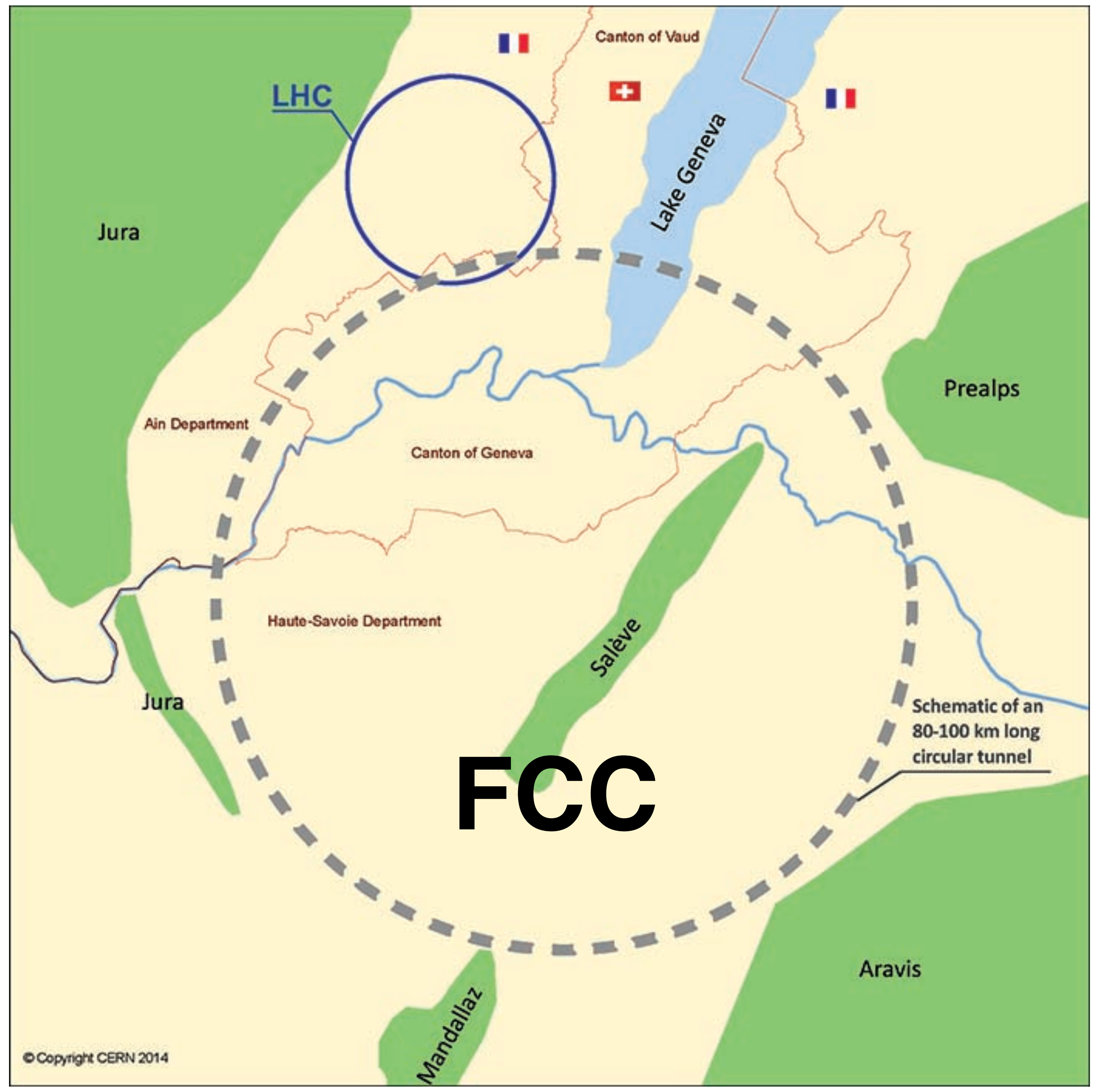
Future trackers will be 4D!

- 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

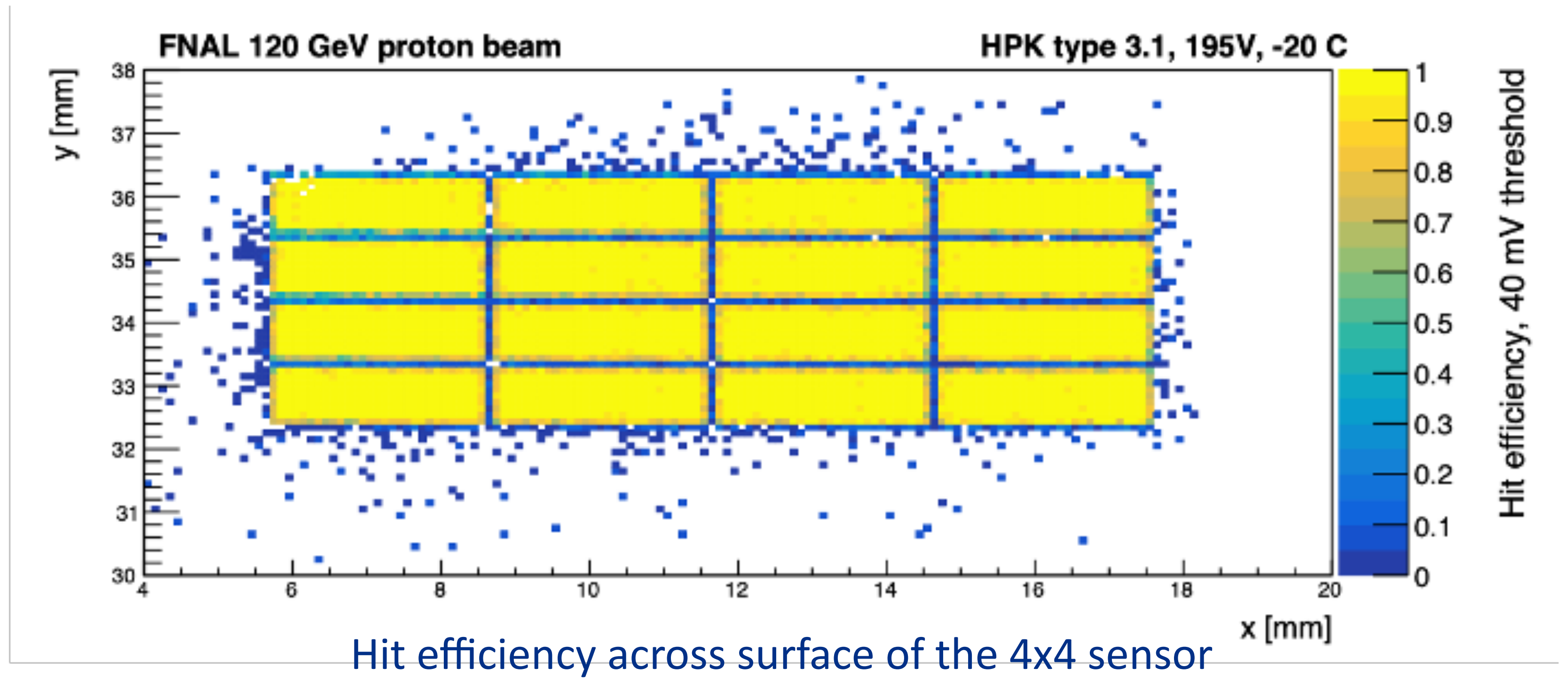
Technical requirements for future trackers: from DOE's HEP BRN





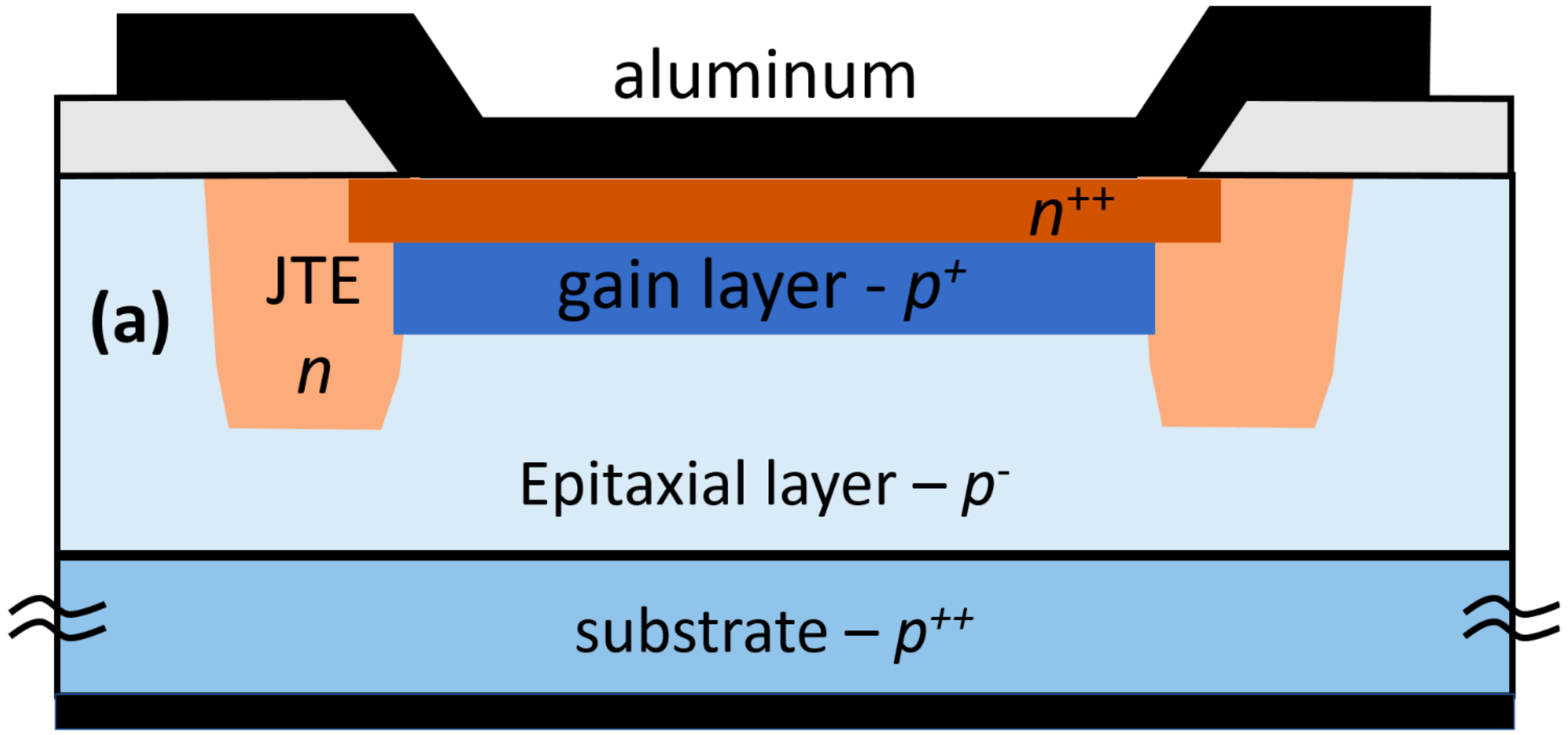
AC-coupled LGADs

- DC-LGADs have an issue with their fill factor when you make pixels small enough for a realistic tracker

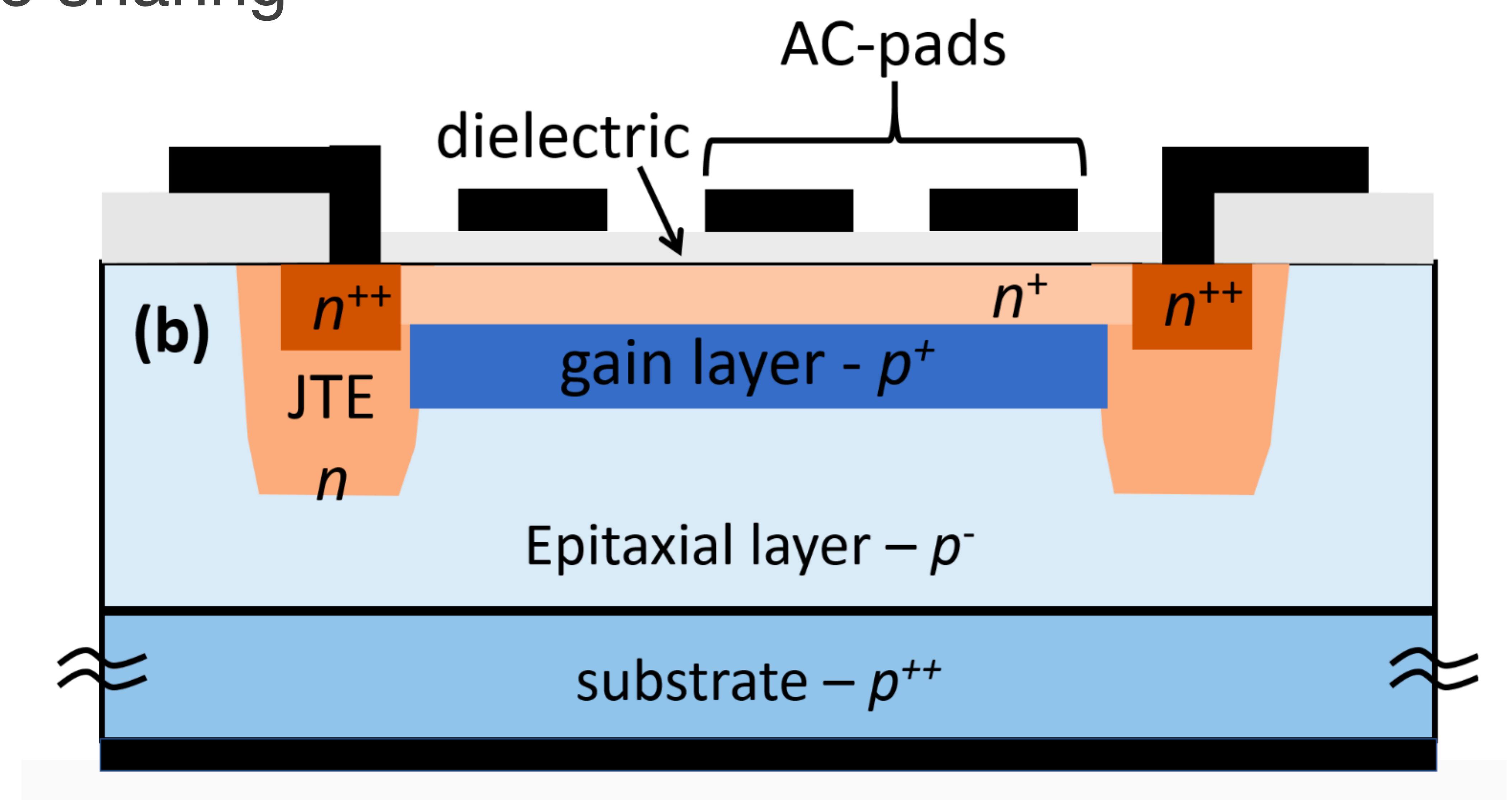


Hit efficiency across surface of the 4x4 sensor

- 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



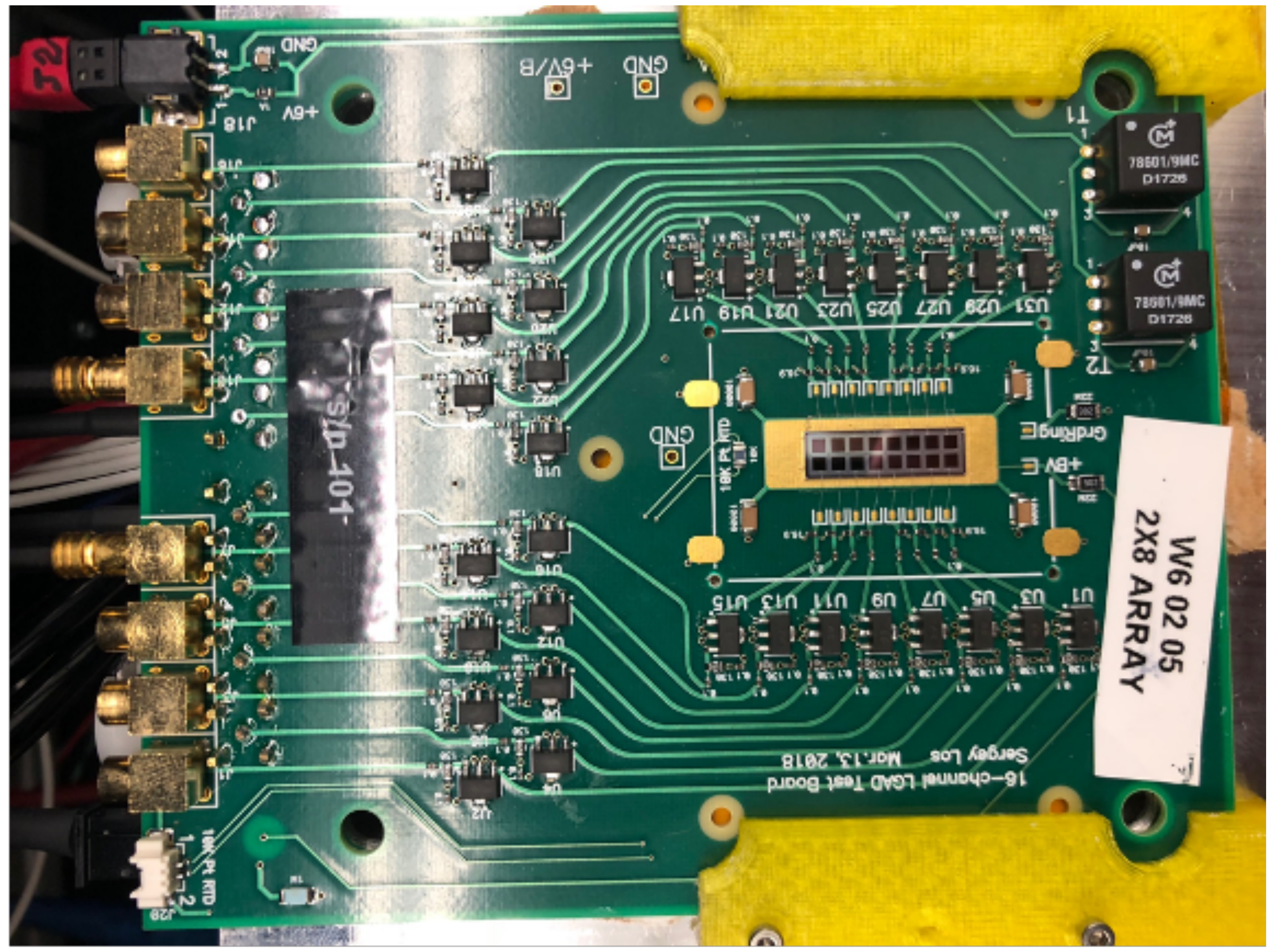
AC-LGAD

arXiv:1906.11542

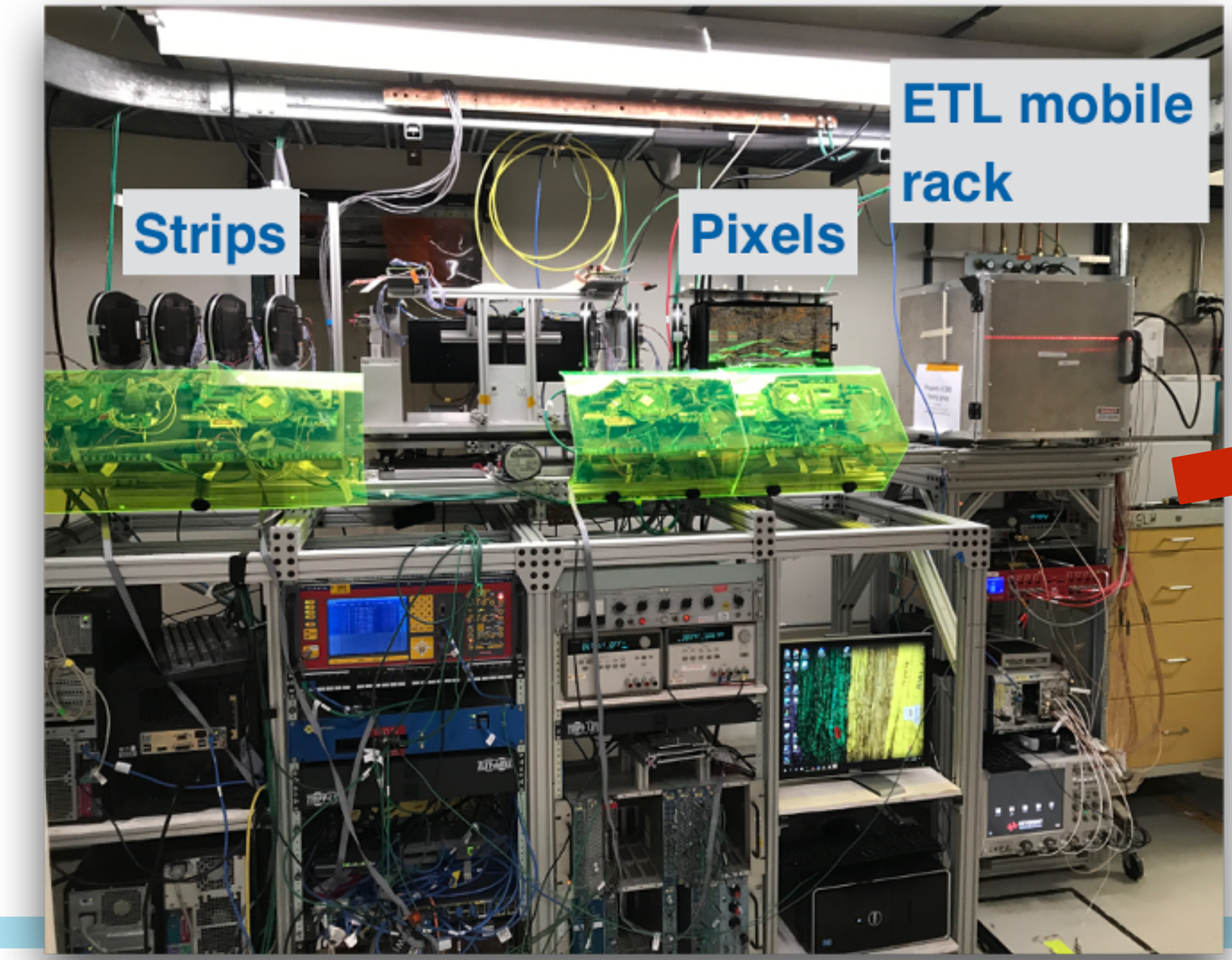
Fermilab

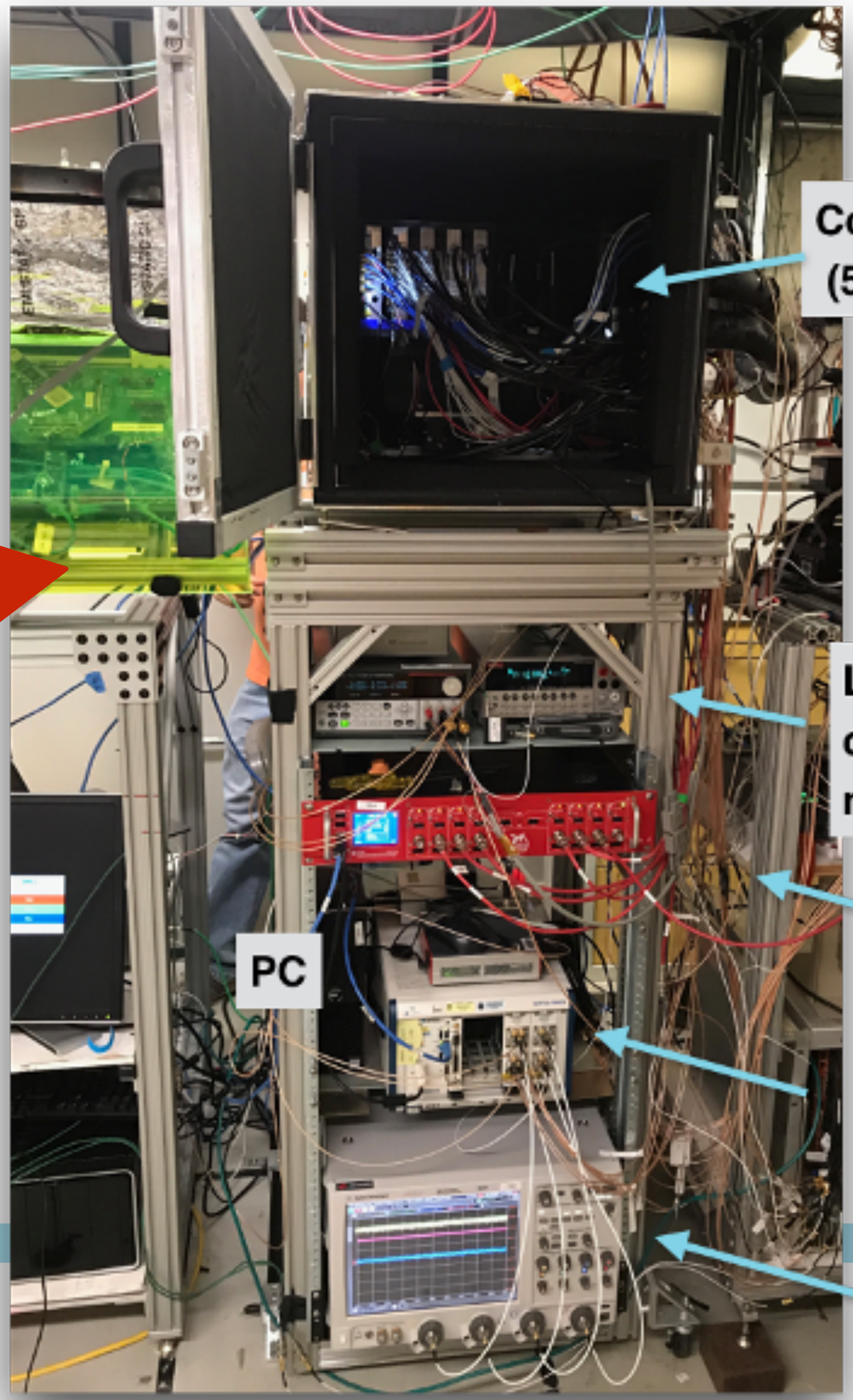
Fermilab 4D-trackers test beam infrastructure

- 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



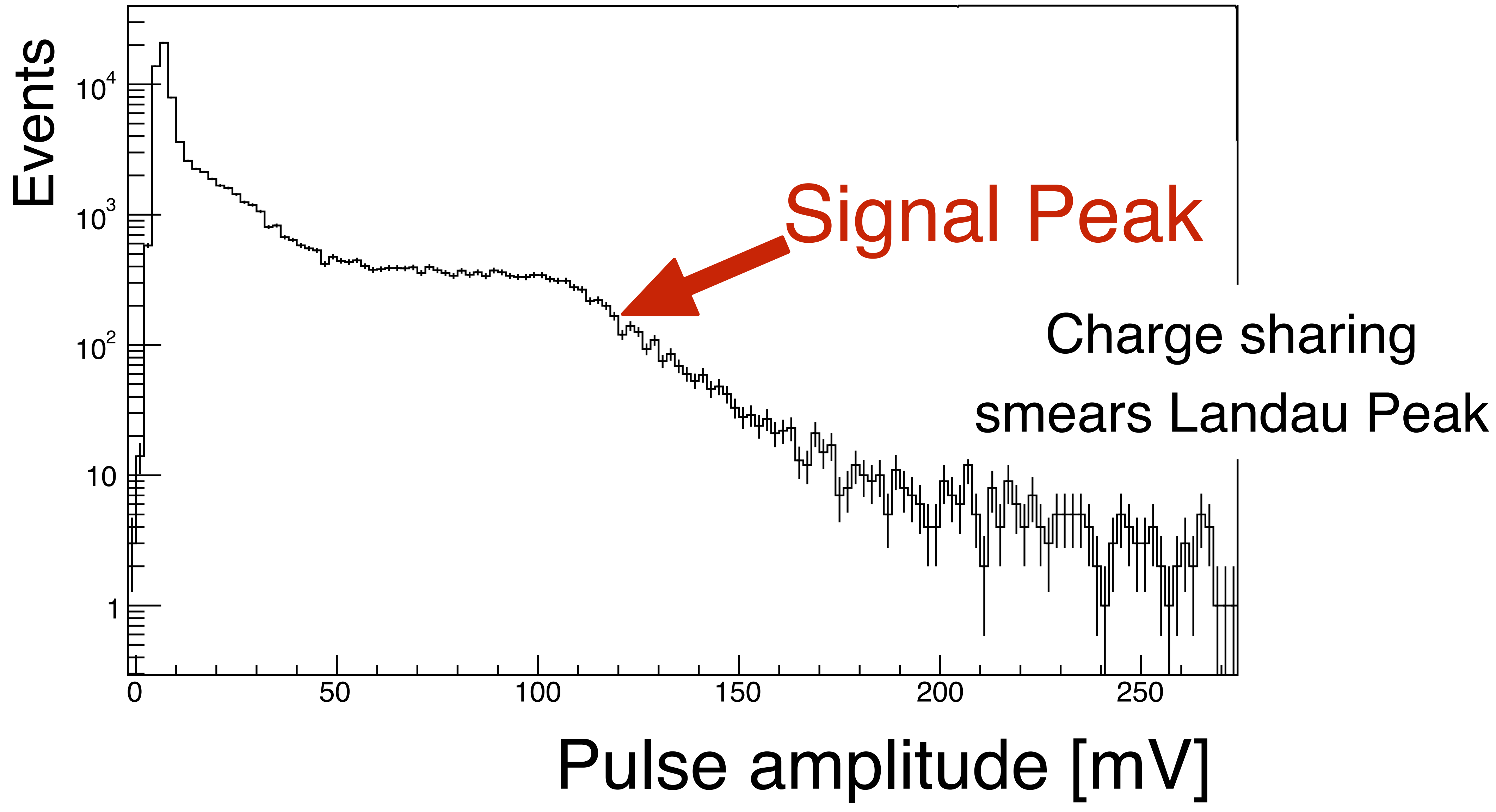
16-ch sensor LGAD on Fermilab readout board





Test beam results: BNL 2020 strips

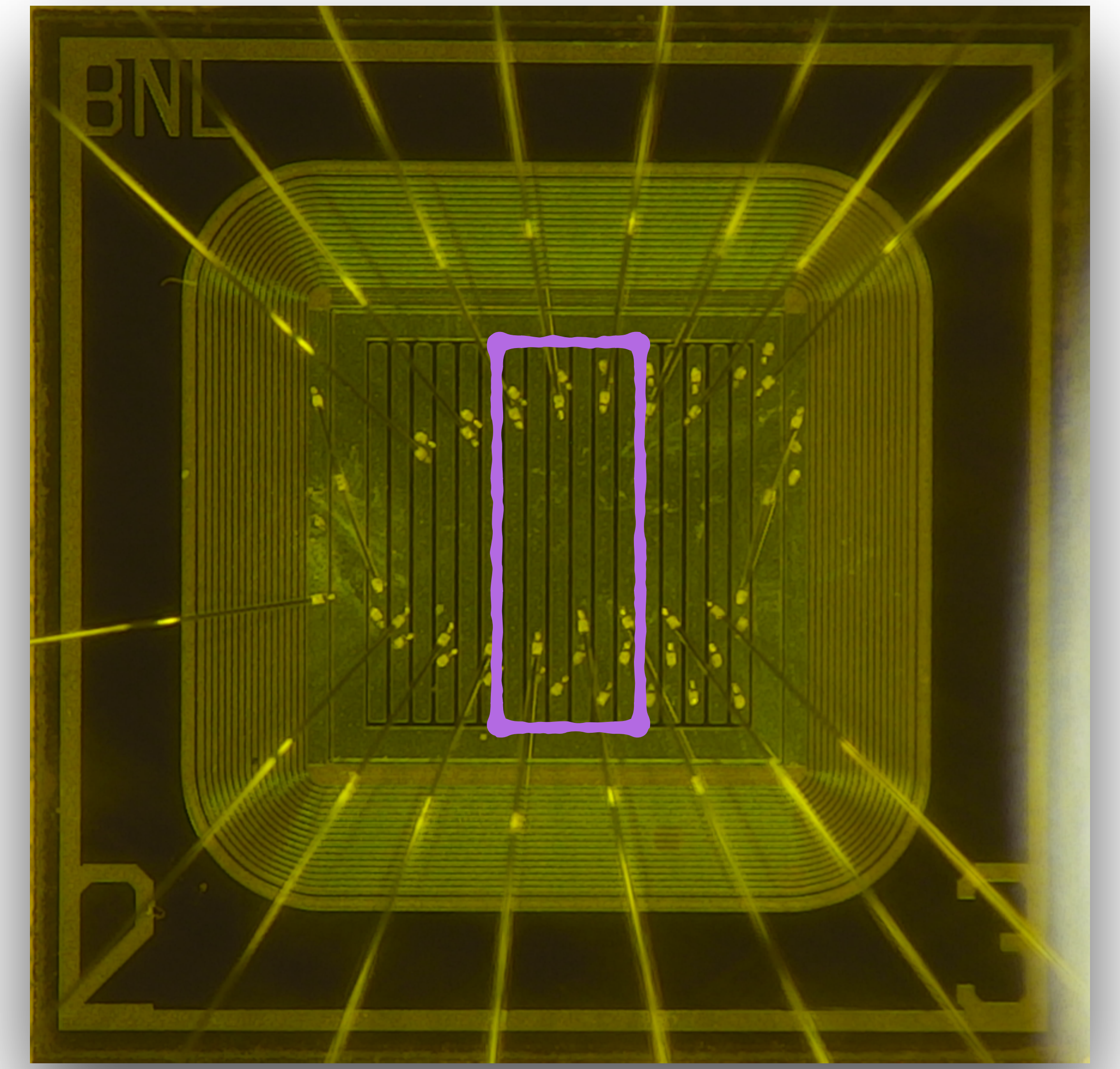
- Test beam results for a sensor produced by BNL in 2020
  - 120 GeV proton beam
- Read out 6 interior strips + DC ring + MCP timing reference
- Selected events with proton in inner 4 readout strips to see performance



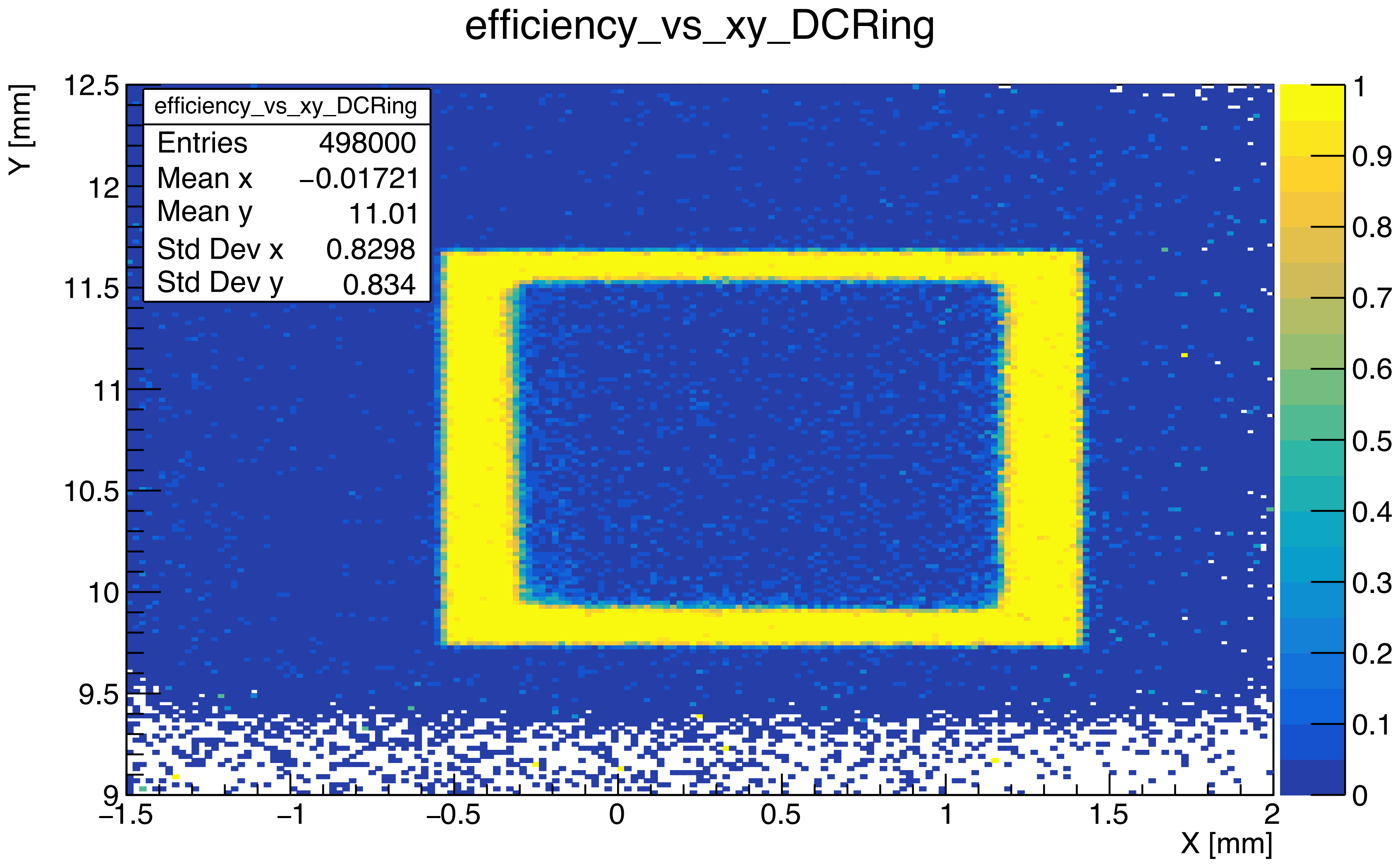
Signal Peak

Charge sharing smears Landau Peak

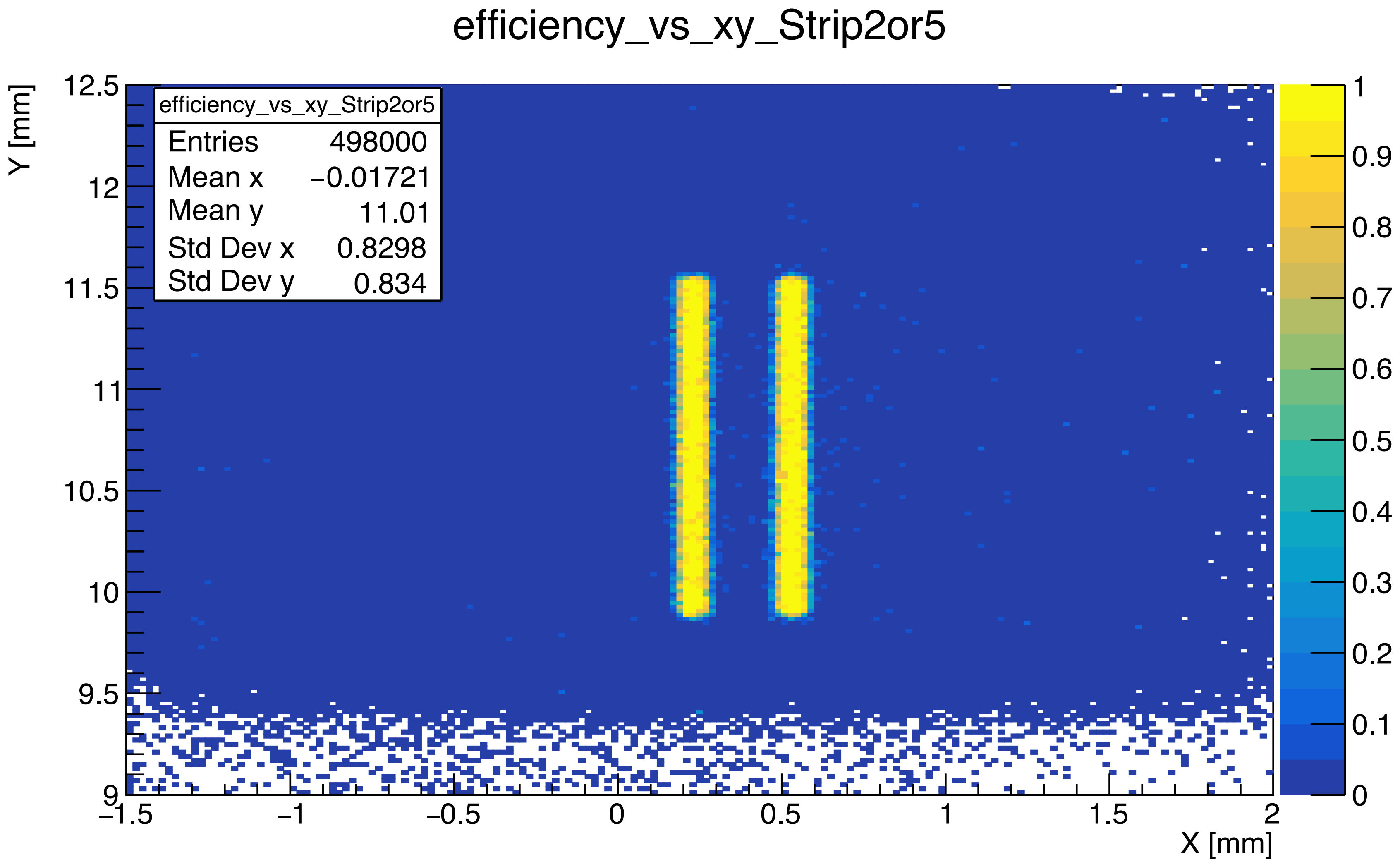
100 micron pitch, 20 micron gaps



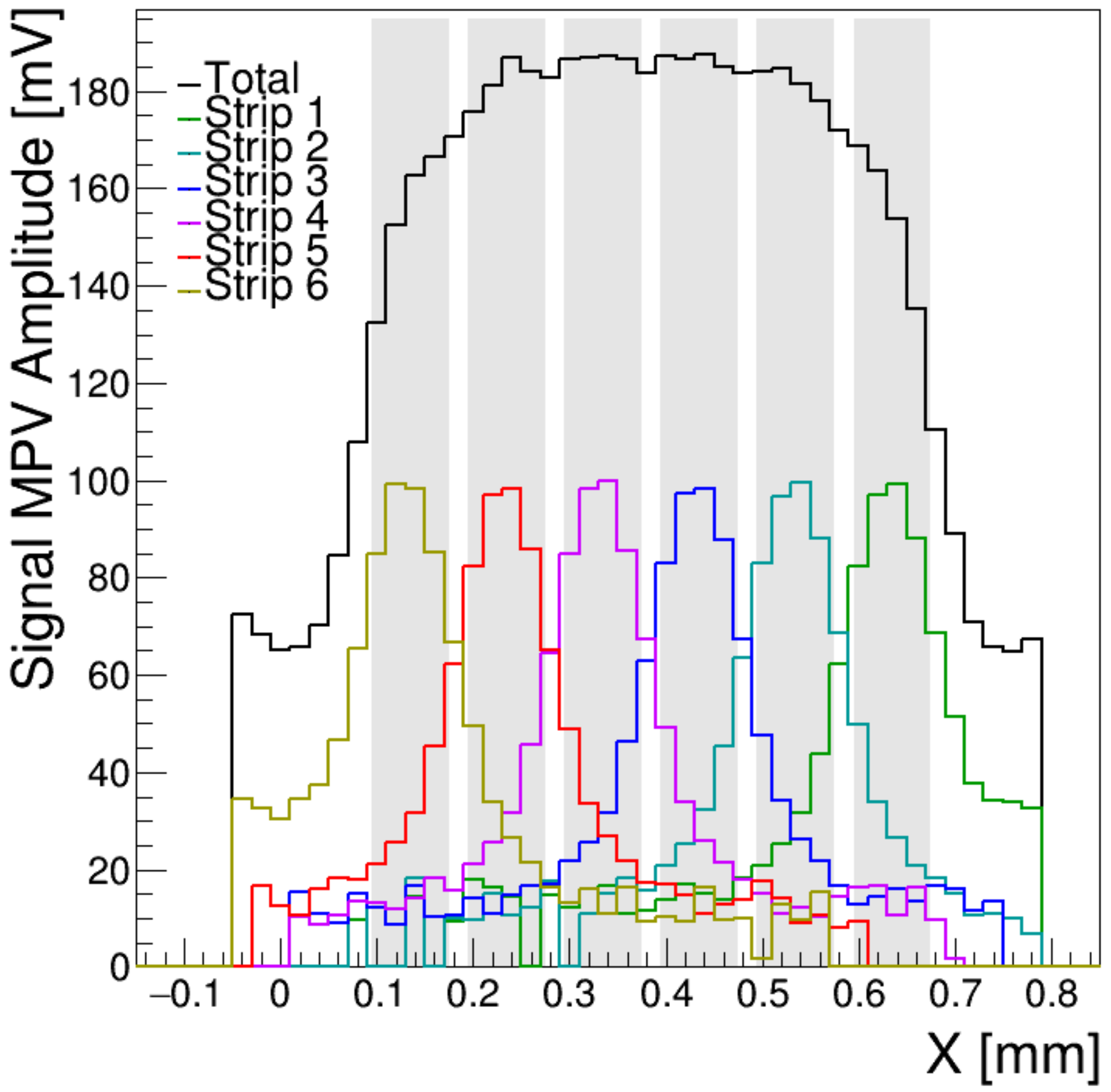
Efficiency, DC pad

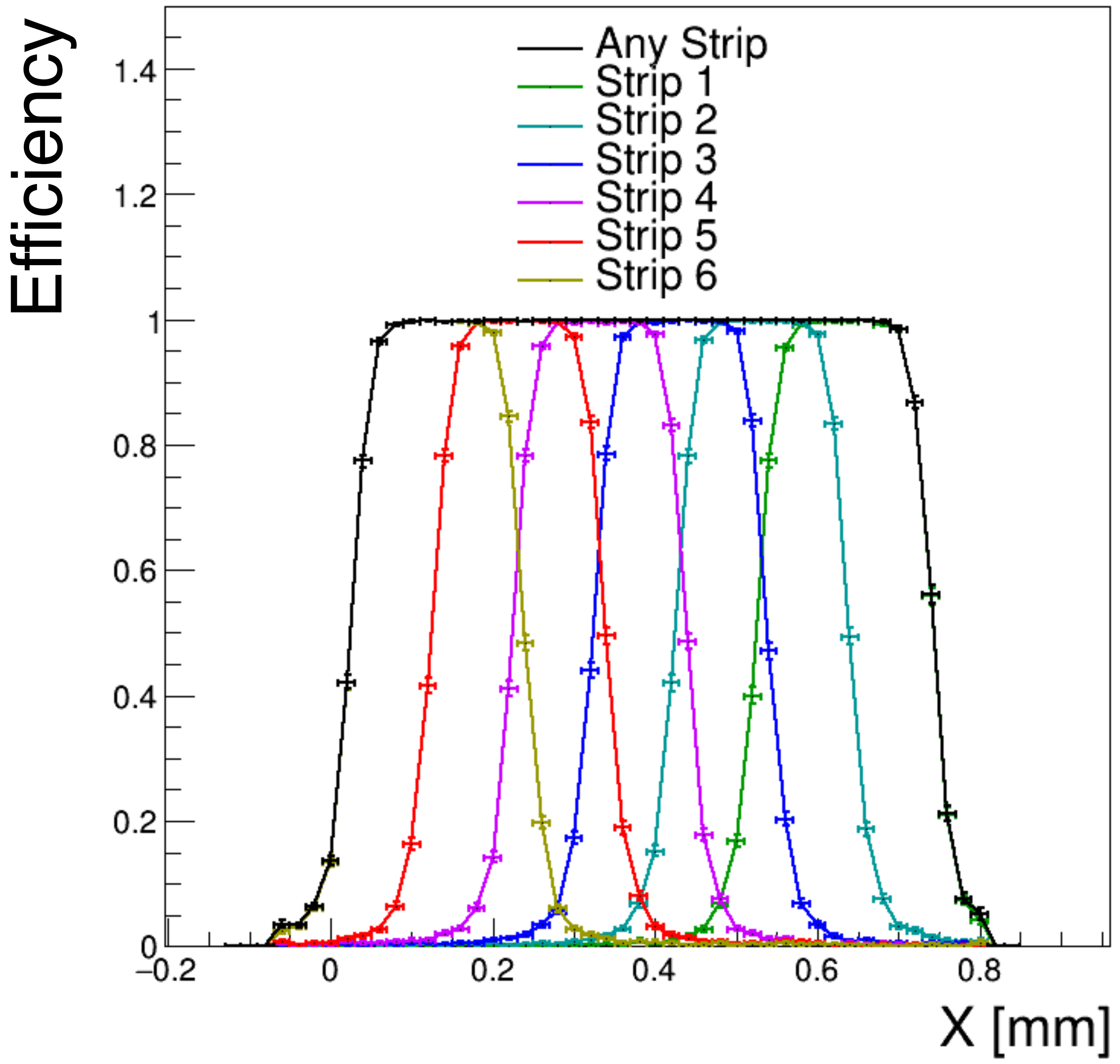


Efficiency, 2nd or 5th strip

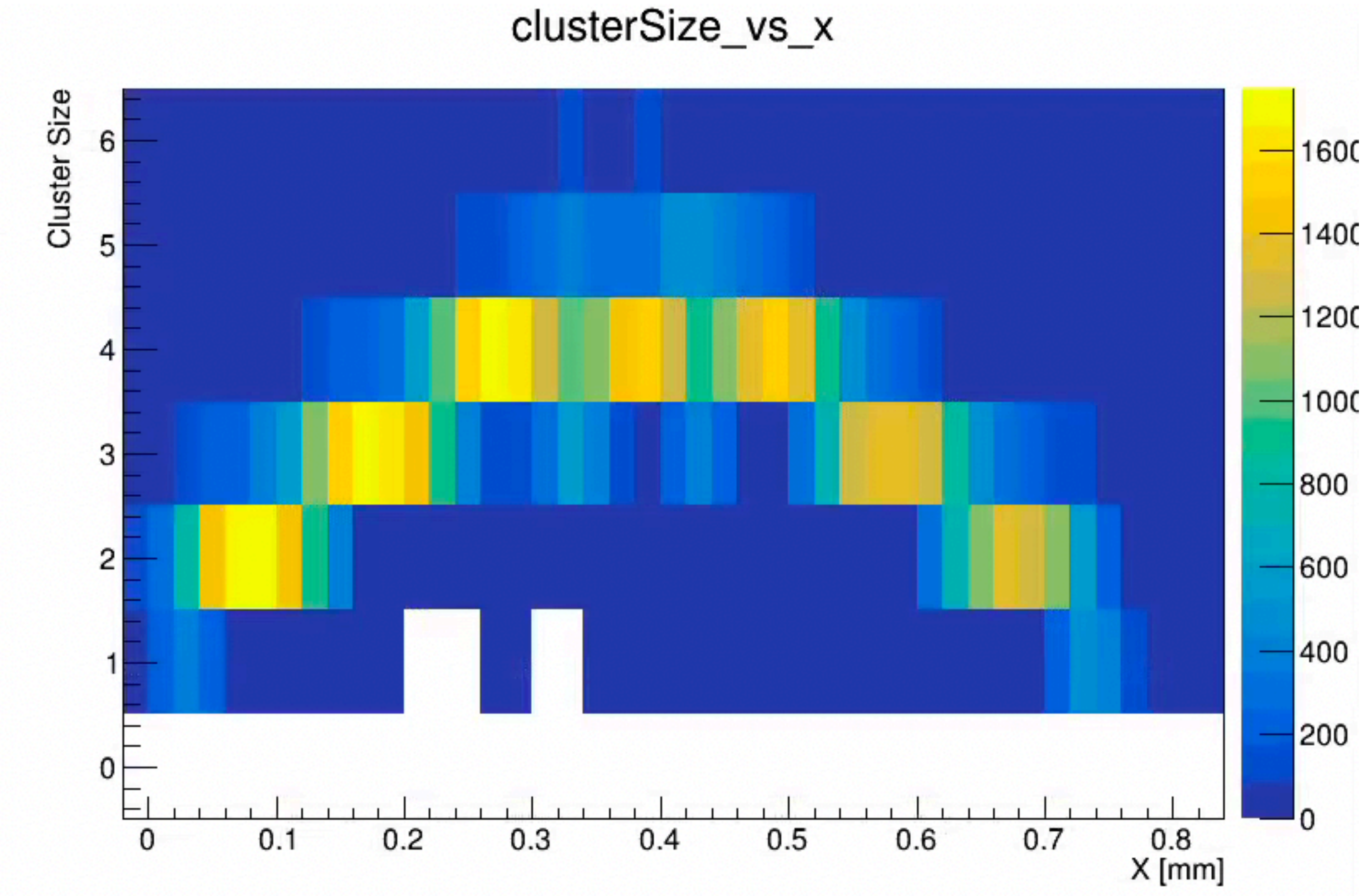


Charge sharing: BNL 2020





30 mV Threshold



30mV threshold on primary strip, 10mV signal on secondary strips

- 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 thresholds where the cluster size peaks for hits in the middle strips at around 4 strips

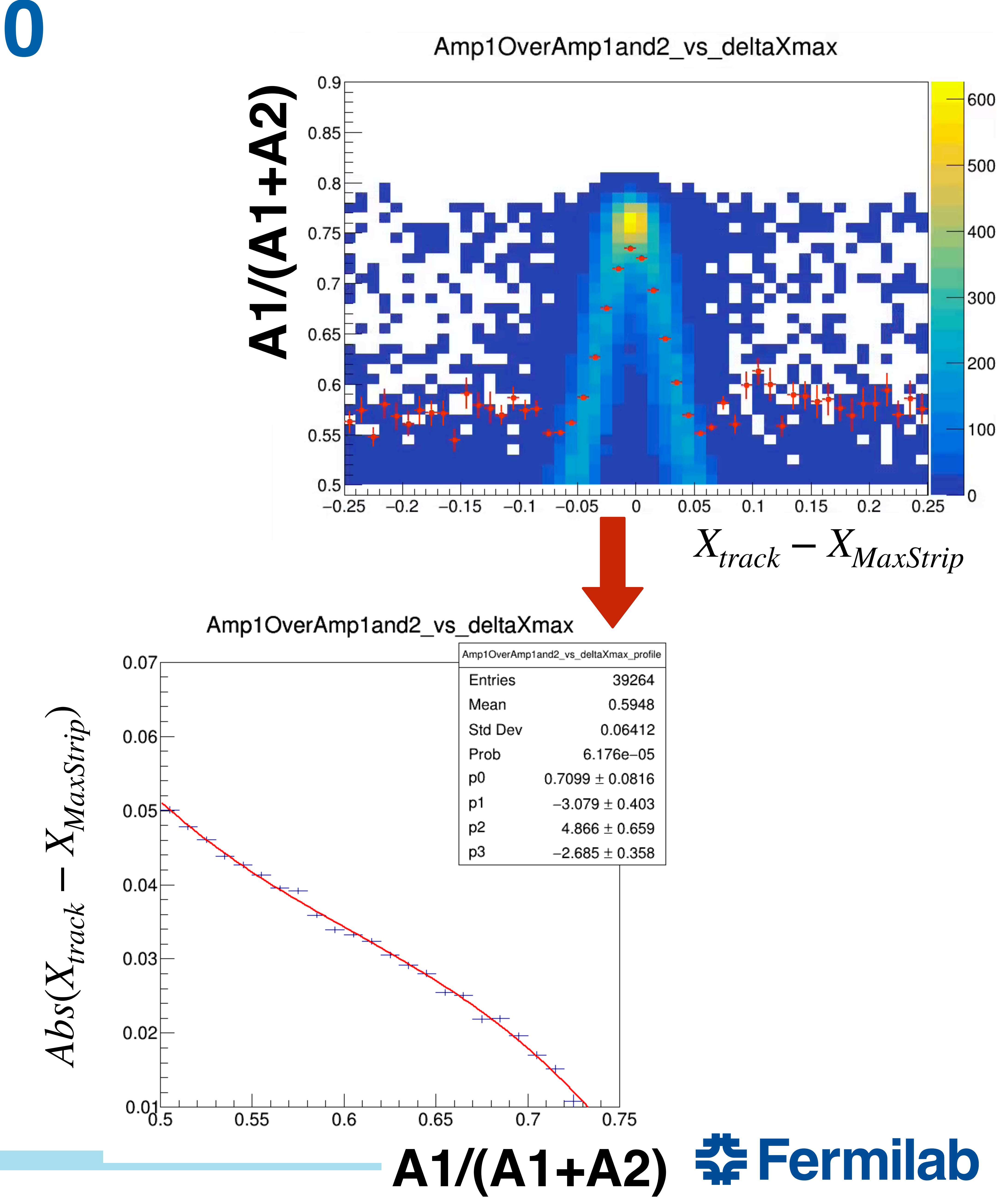
Position Reconstruction: BNL 2020

- 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

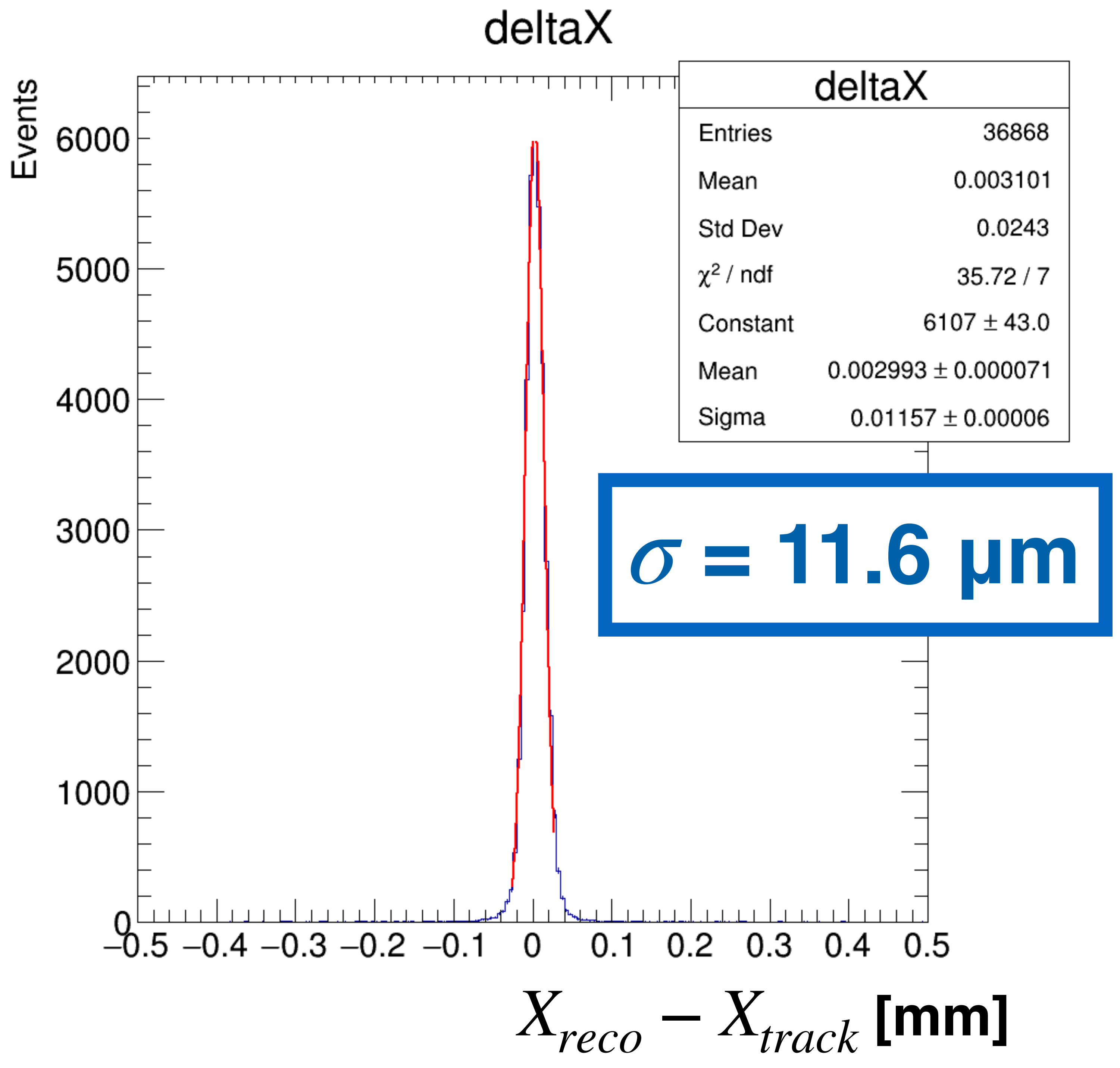
- Make Profile plot and fit to 3rd degree polynomial
  - Function mapping relative amplitude to distance from max strip location

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

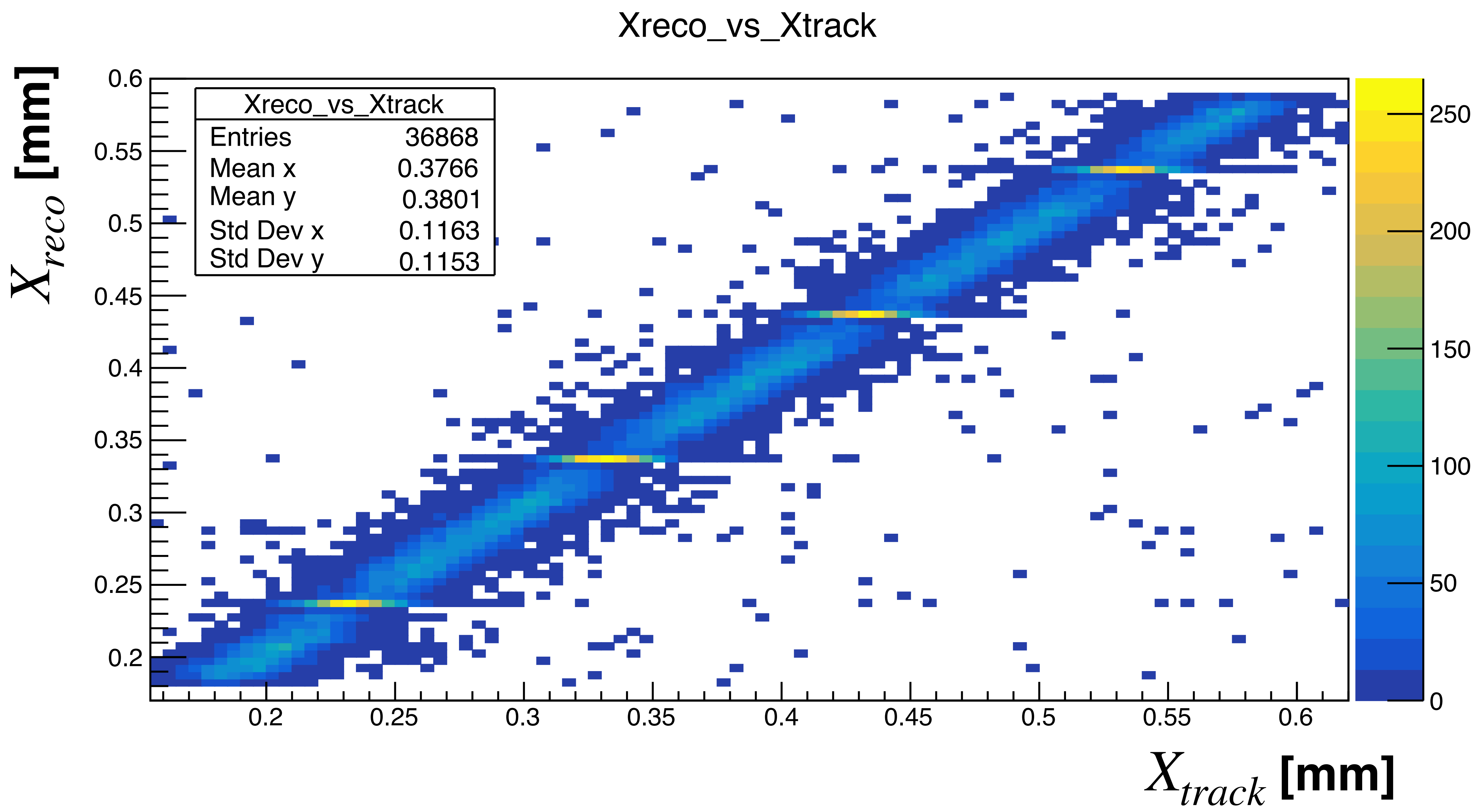


Amp1OverAmp1and2_vs_deltaXmax_profile	
Entries	39264
Mean	0.5948
Std Dev	0.06412
Prob	6.176e−05
p0	0.7099 ± 0.0816
p1	−3.079 ± 0.403
p2	4.866 ± 0.659
p3	−2.685 ± 0.358

Position Reconstruction: BNL 2020

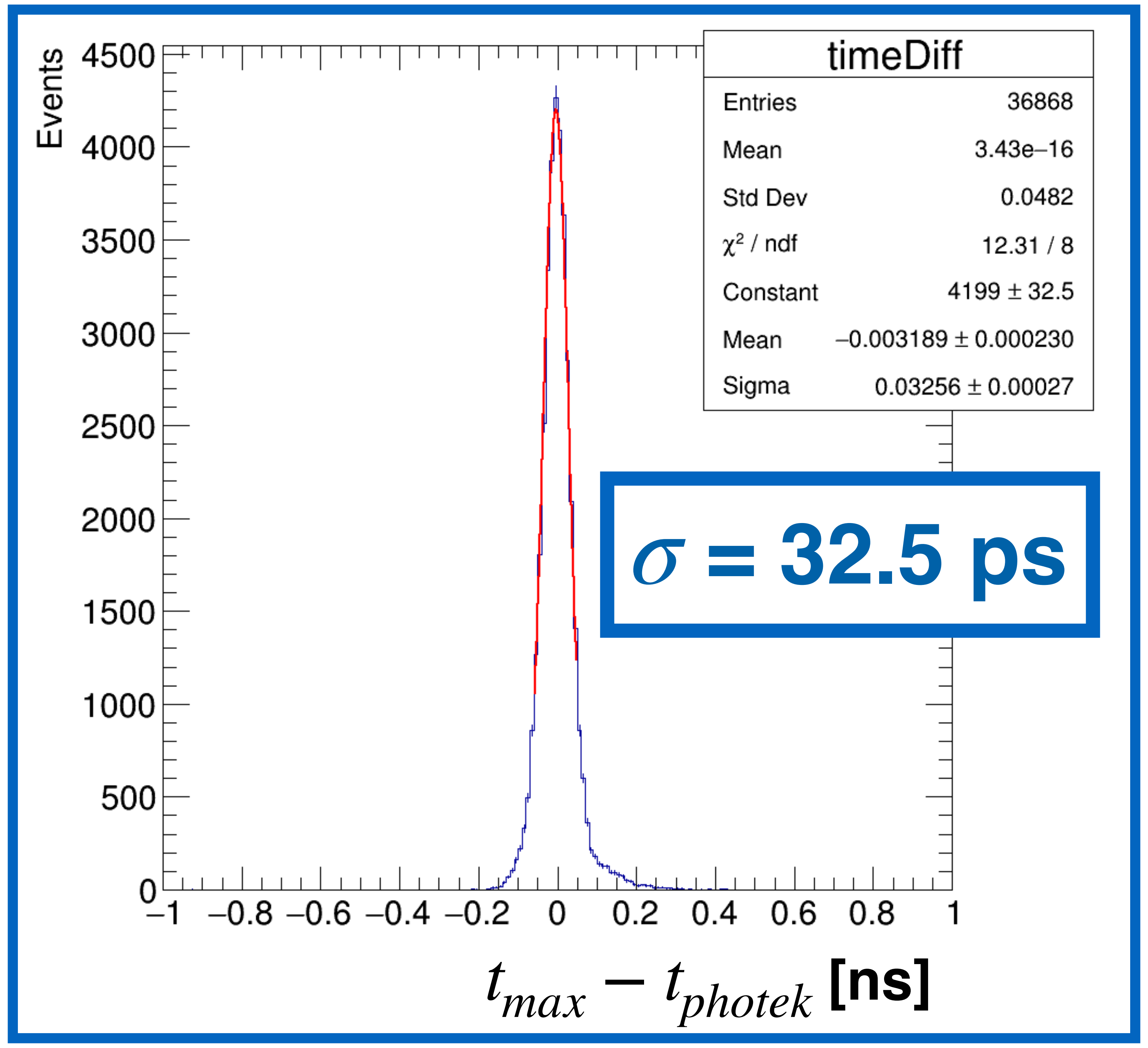


σ = 11.6 μm

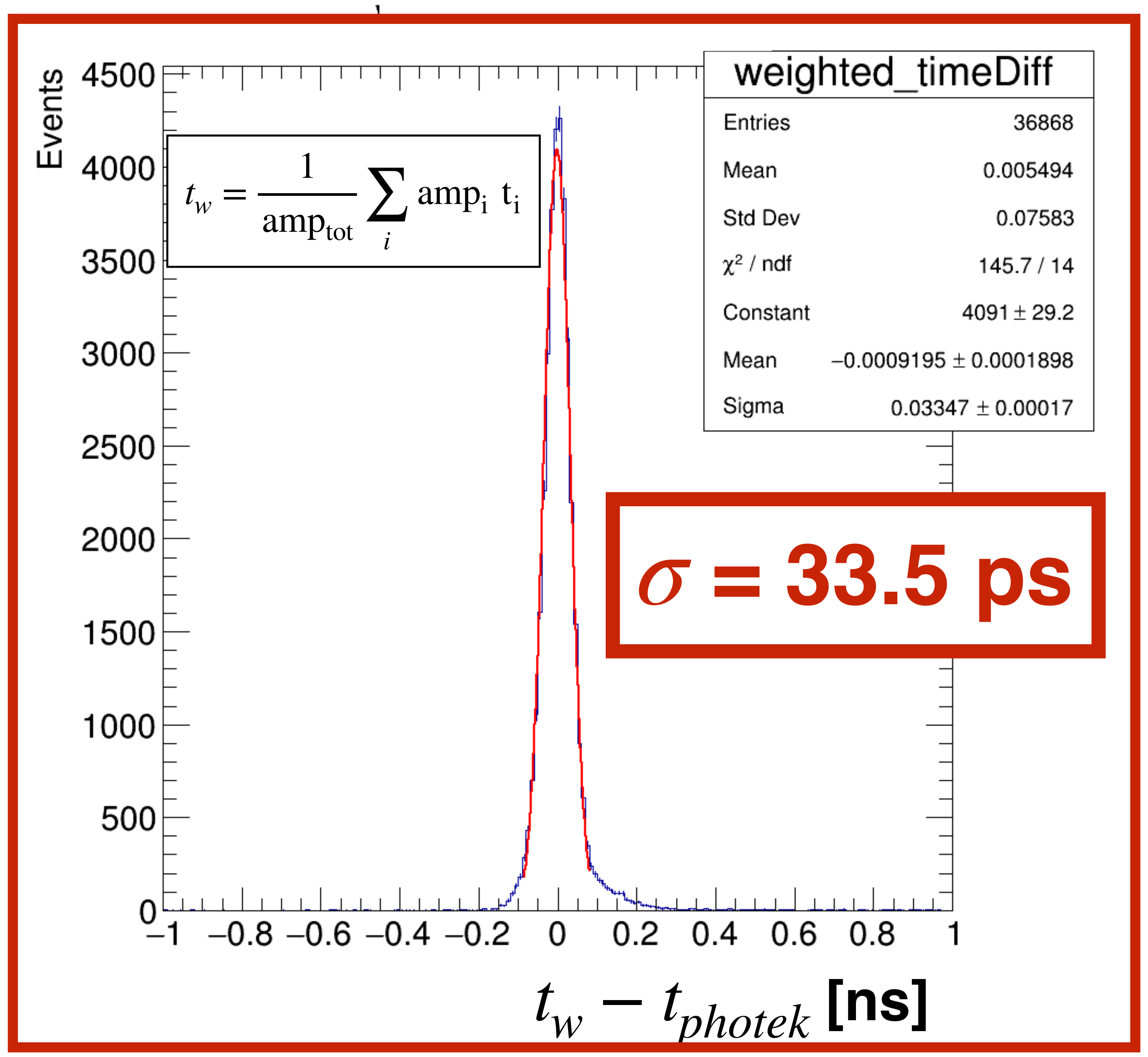


- Observed a position resolution of ~5 μm after removing reference tracker uncertainty (~10 μm)
- Discontinuities are observed where the relative fraction is large or when we get direct hits to the strip
  - Can explore other reconstruction methods
  - Preliminary results have shown a neural network can give the same results without the discontinuities

Time Reconstruction: BNL 2020



σ = 32.5 ps

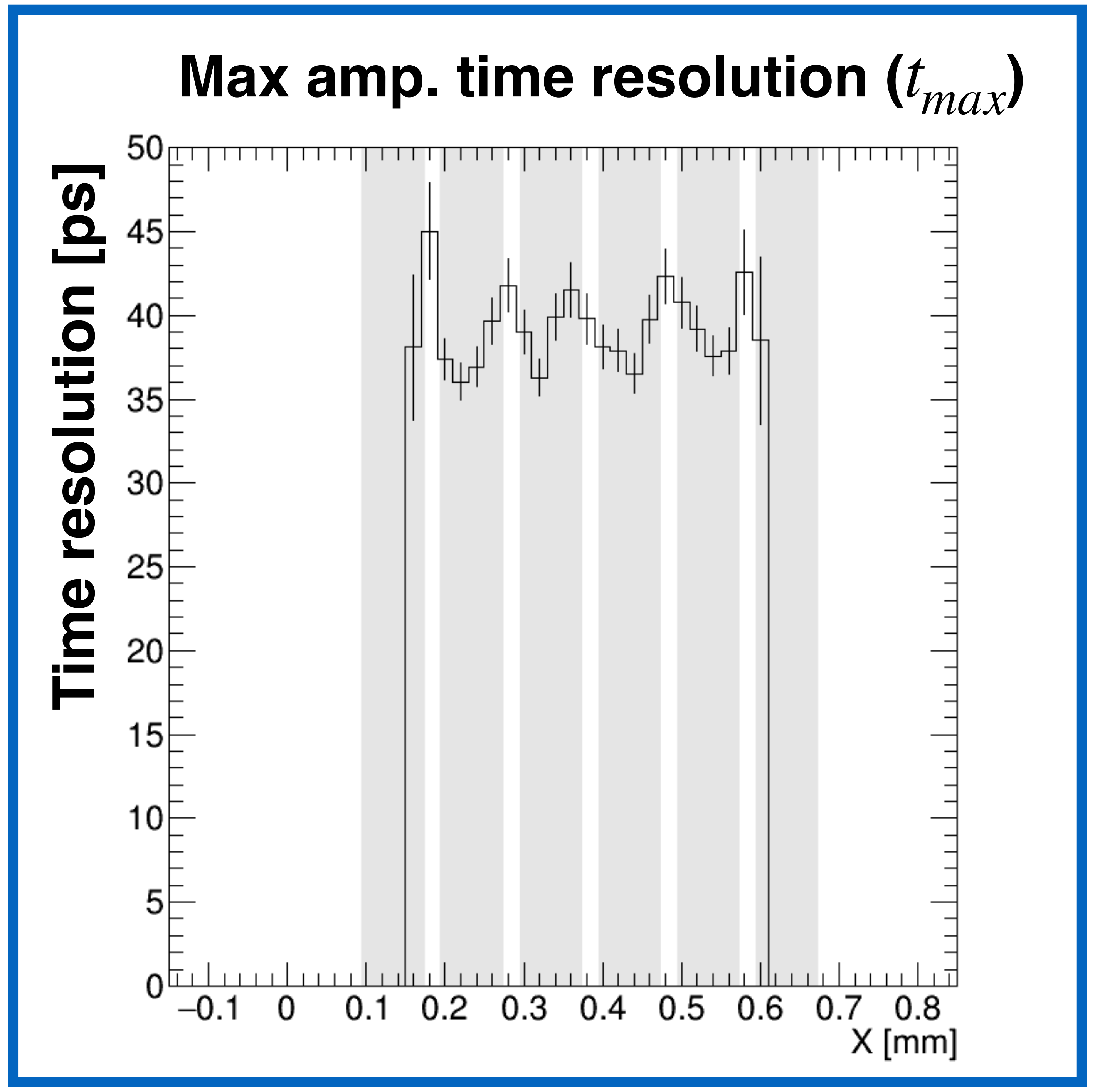


σ = 33.5 ps

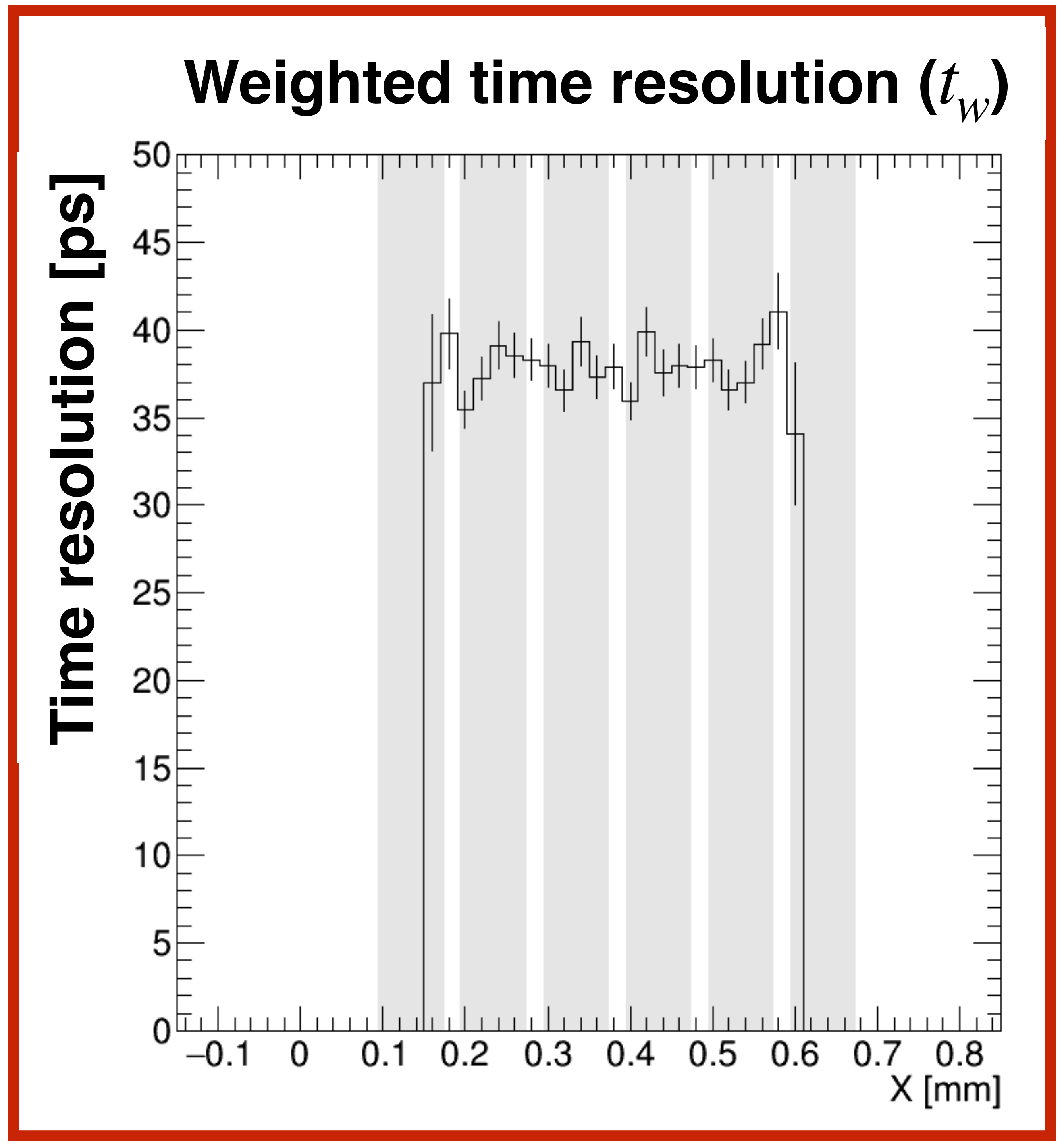
- With the success of charge sharing for position reconstruction we looked at different ways of reconstructing the time of the proton hit
- We see that across the surface of the sensor the time resolution is ~30 ps regardless of if we use time from max amplitude strip (t_{max}) or the amplitude weighted average time (t_w)

- What about the gaps between the strips?

Timing Resolution vs x: BNL 2020



Max amp. time resolution (t_{max})



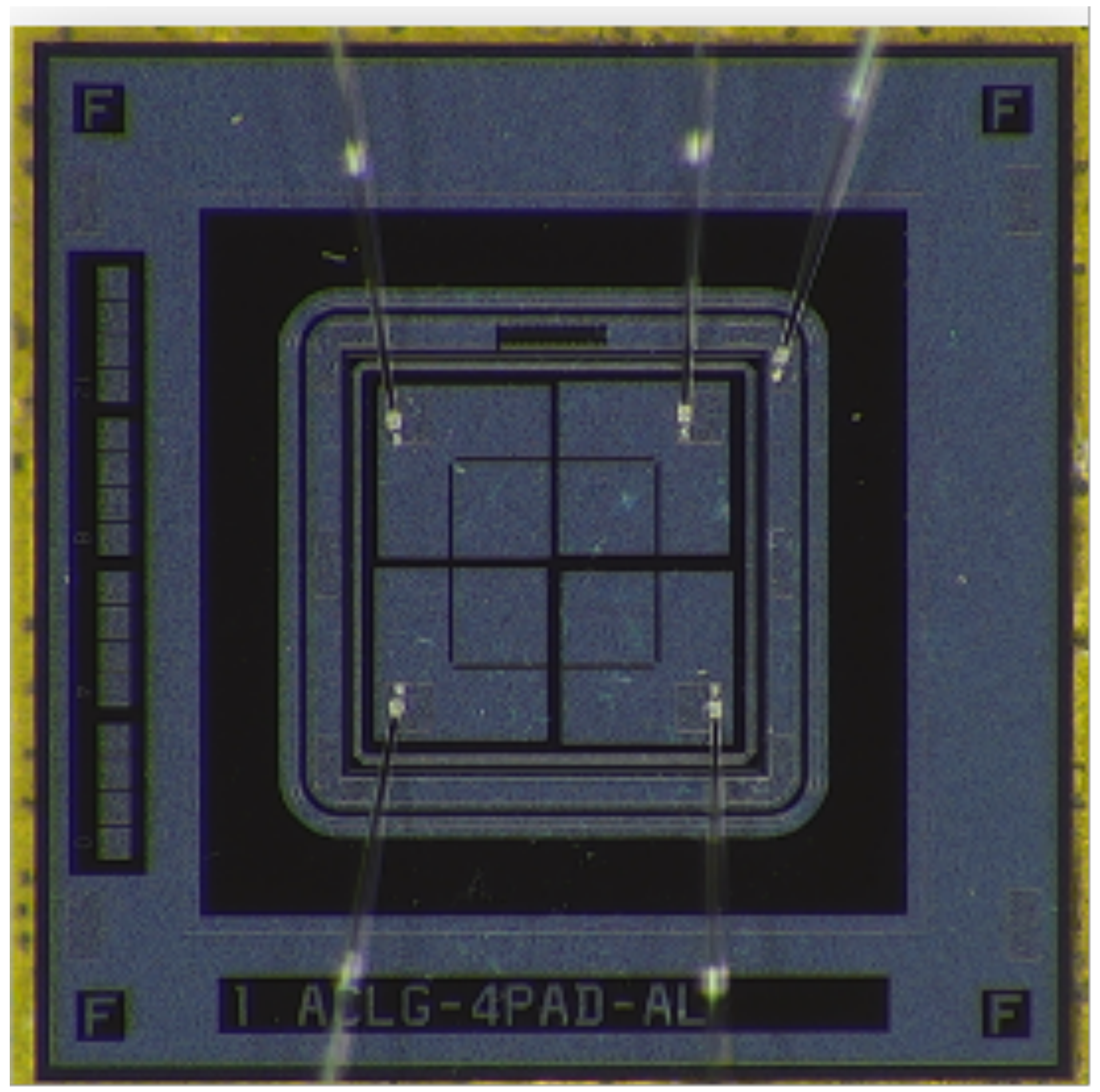
Weighted time resolution (t_w)

$$t_w = \frac{1}{\mathrm{amp_{tot}}} \sum_i \mathrm{amp_i}\ \mathrm{t_i}$$

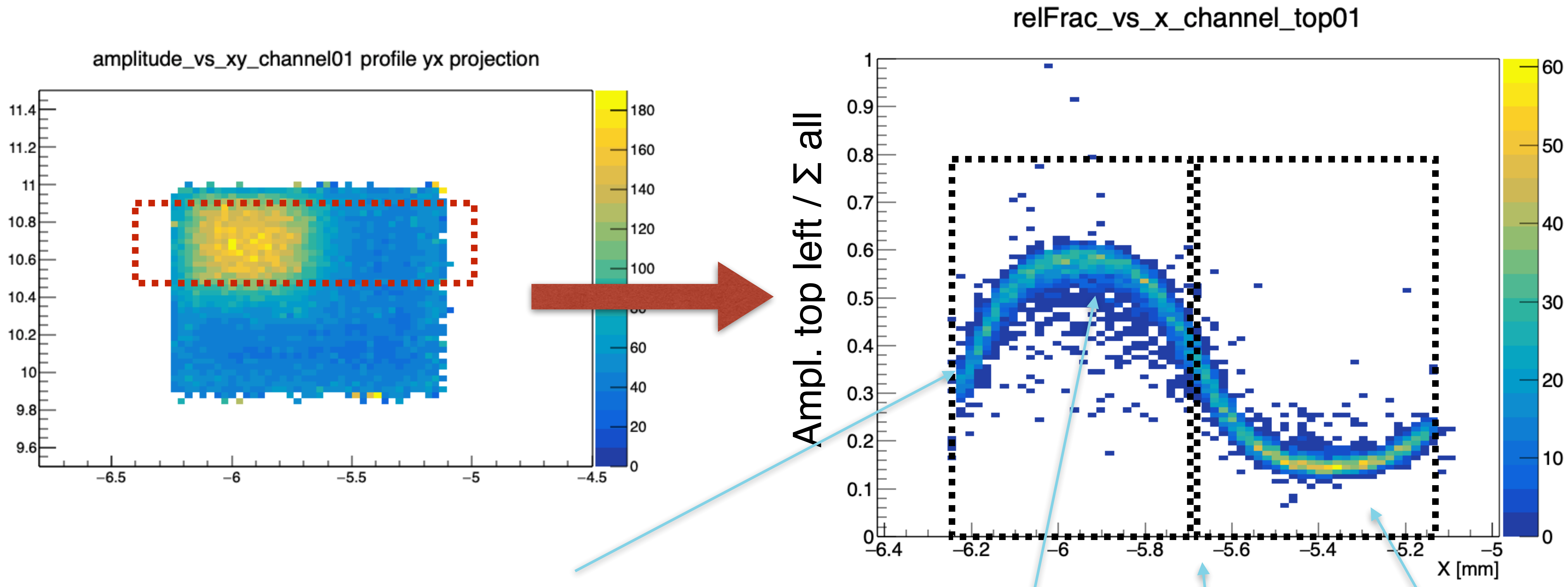
- We observe that the resolution from the time from the max amplitude strip can increase when we have hits to the gaps
- Using the amplitude weighted average time we can recover some of the performance loss in the timing reconstruction in the gaps
- Using charge sharing can have strips with a larger pitch to help limit the number of channels that need to be readout

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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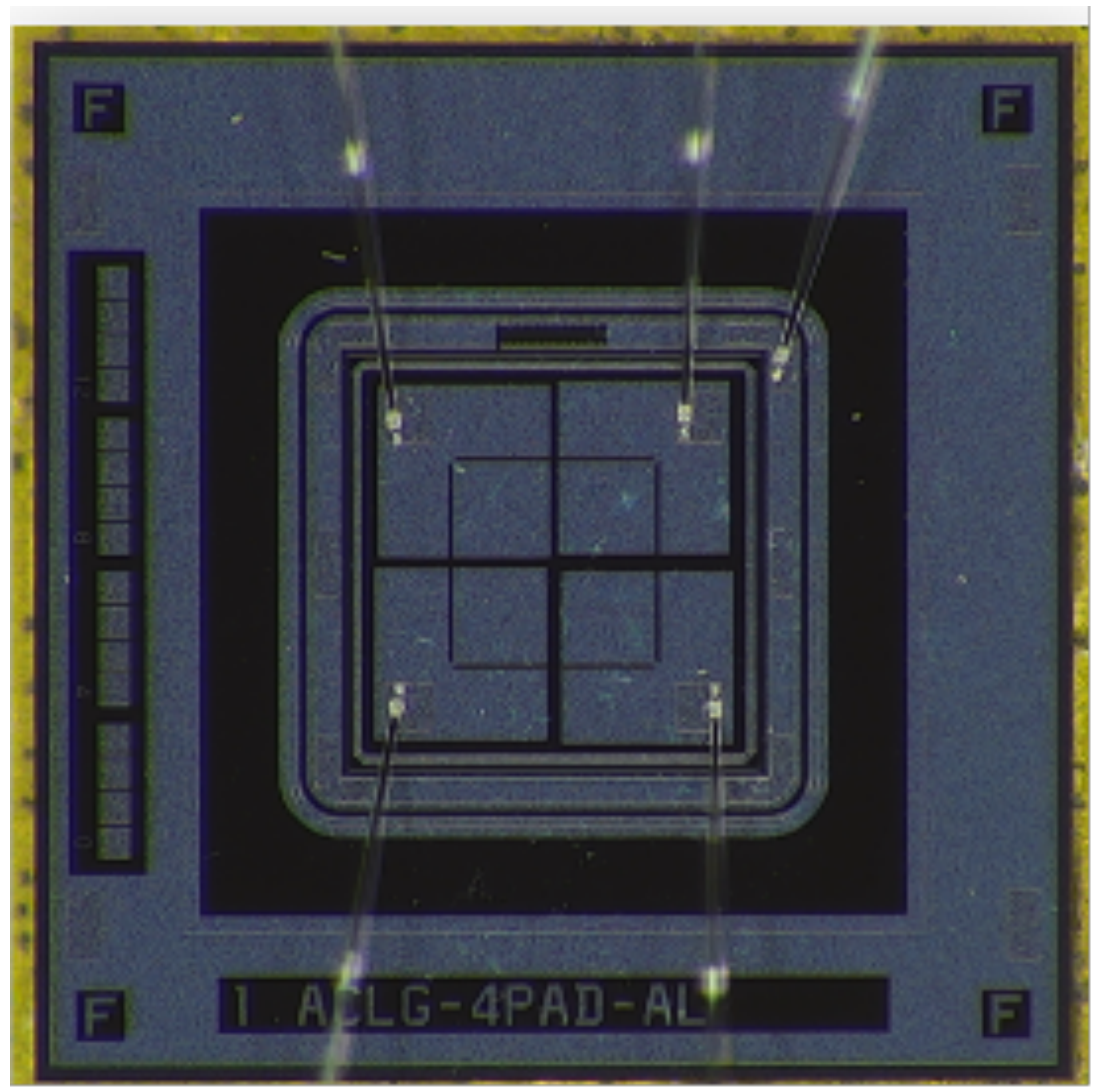
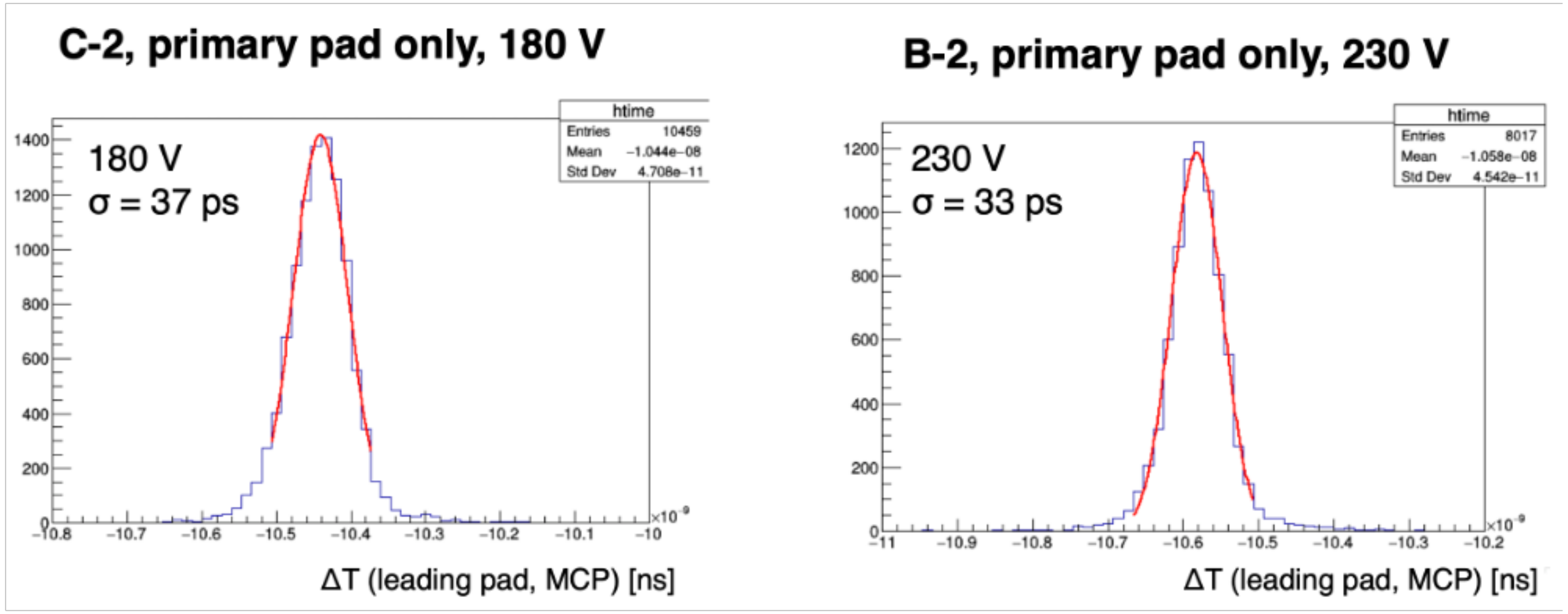


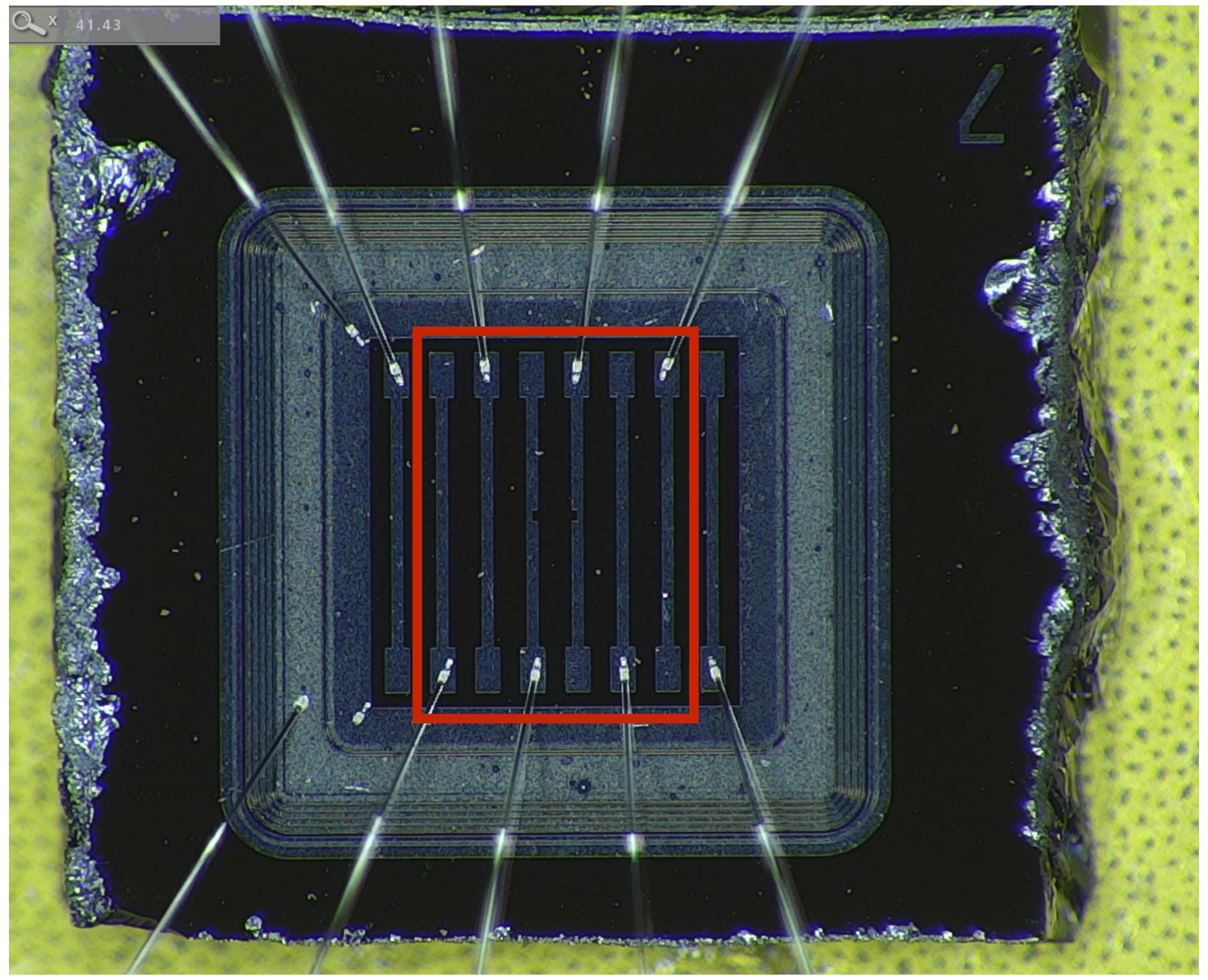
HPK 2x2, 500 µm pad size


C-2, primary pad only, 180 V

B-2, primary pad only, 230 V

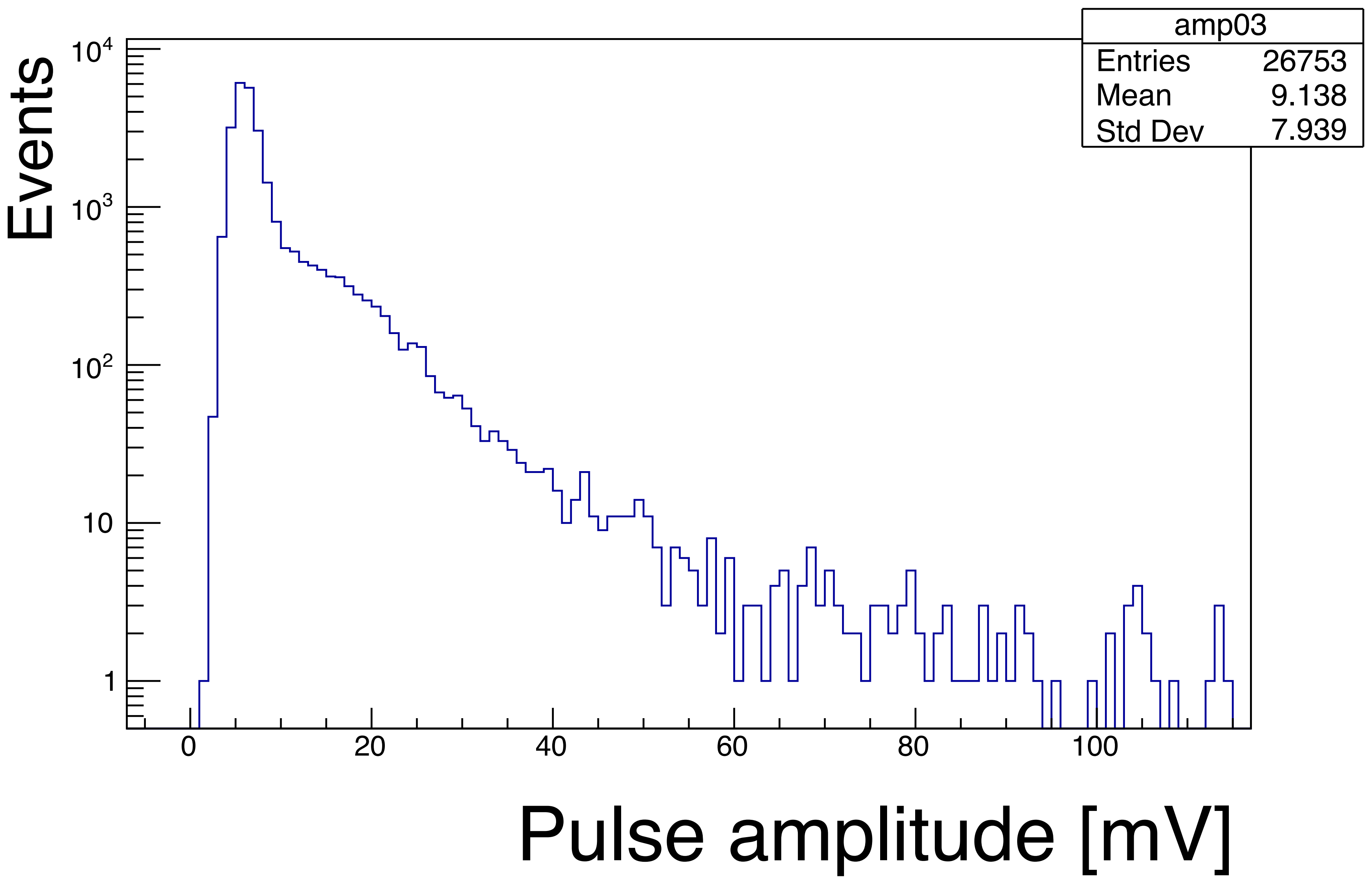
Buried Layer LGADs

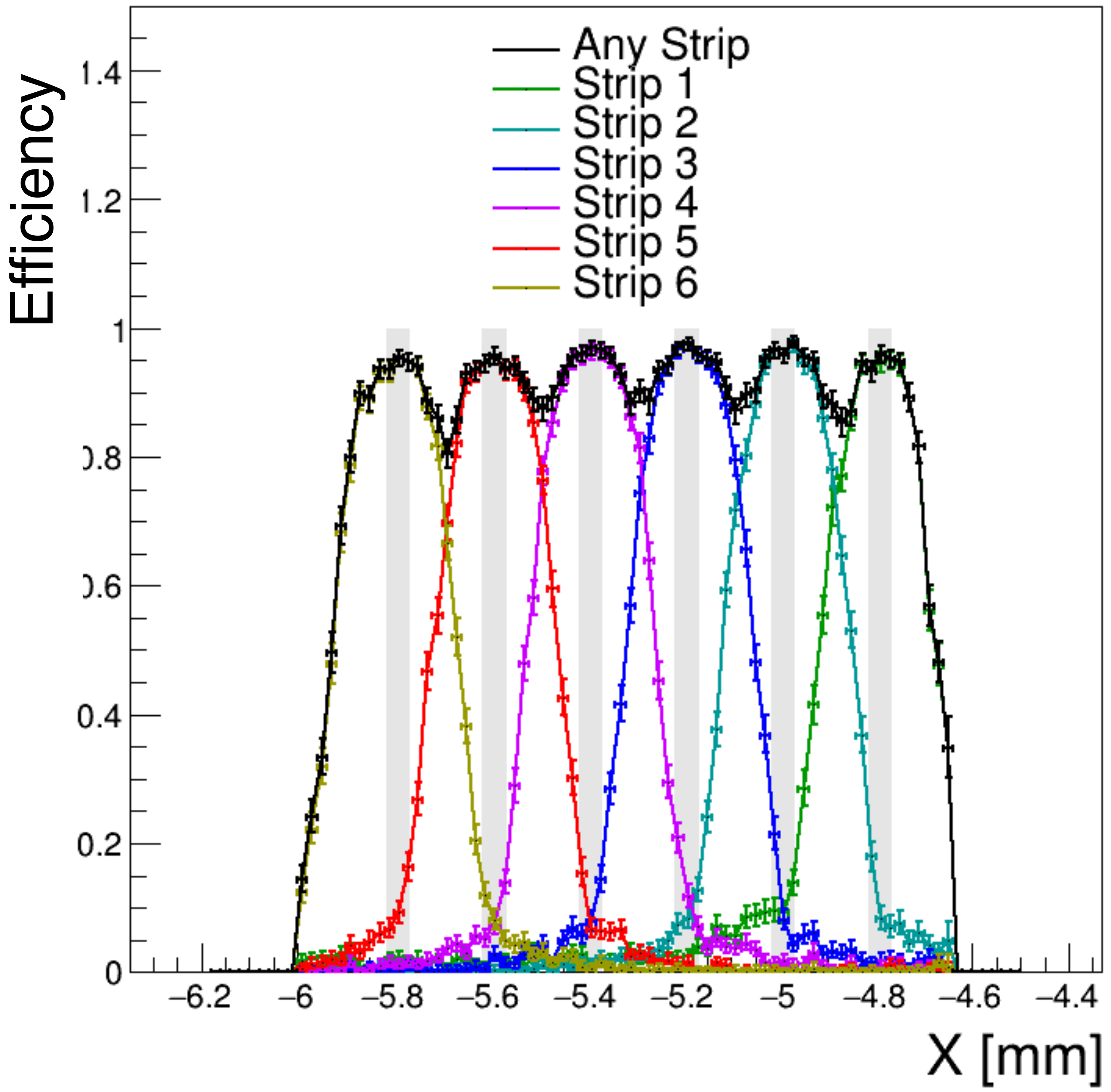
- Similarly to the AC-LGADs another variation on the design of the CMS/ATLAS style LGADs is the buried layer LGADs
- By utilizing different sensor production techniques we can have a gain layer that is larger and deeper into the sensor
  - Leading to better radiation tolerance and overall gain in the sensor
- We have recently produced and tested the first of these type of sensors
  - Sensor had a stacking fault during assembly that prevents us from reaching large gain
- More information on simulation and production was show recently by **Ron Lipton**



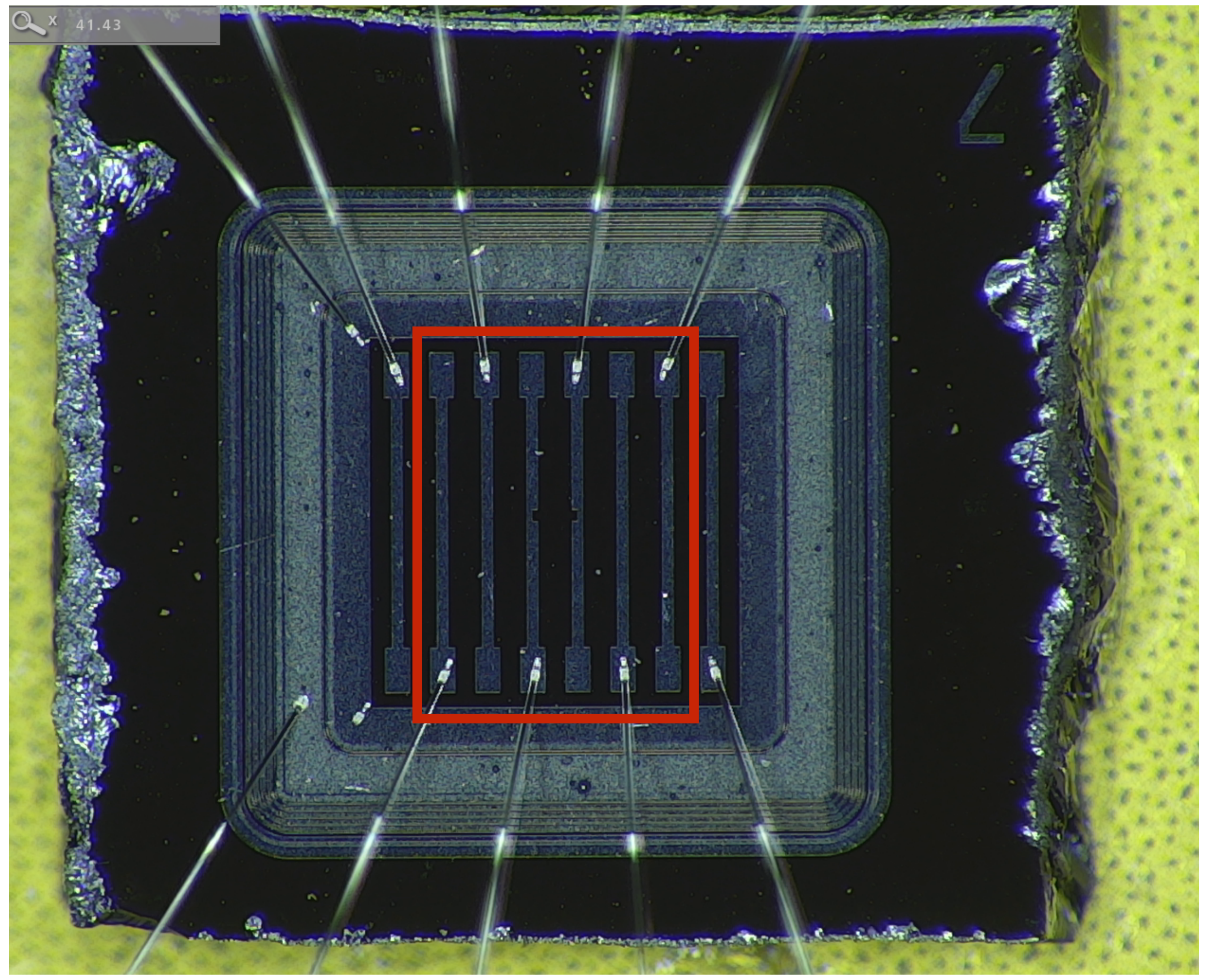
8-channel strips
200 micron pitch
50 micron metal
Bias: -350 V

Test beam results: Buried Layer LGADs





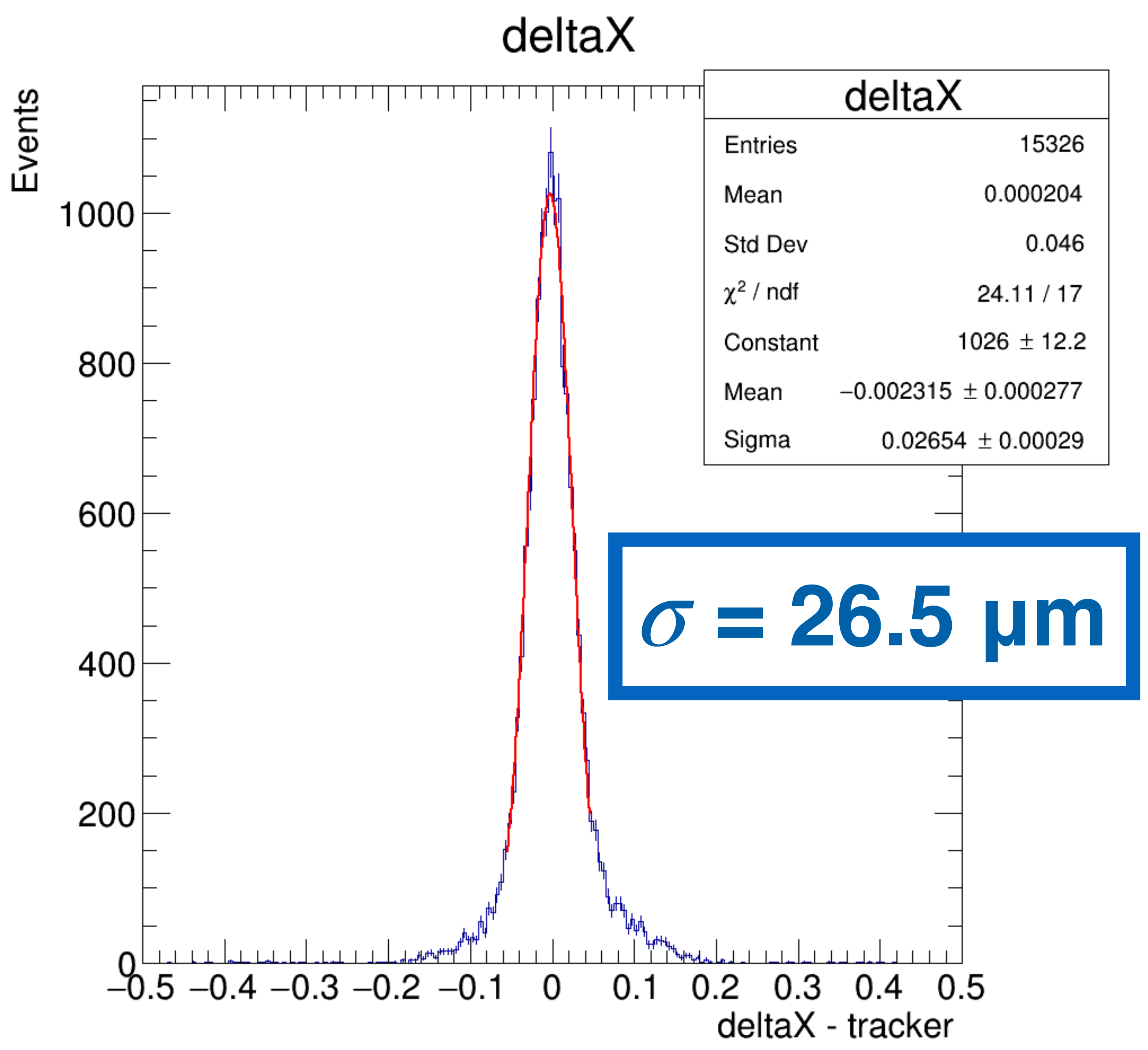
10 mV Threshold



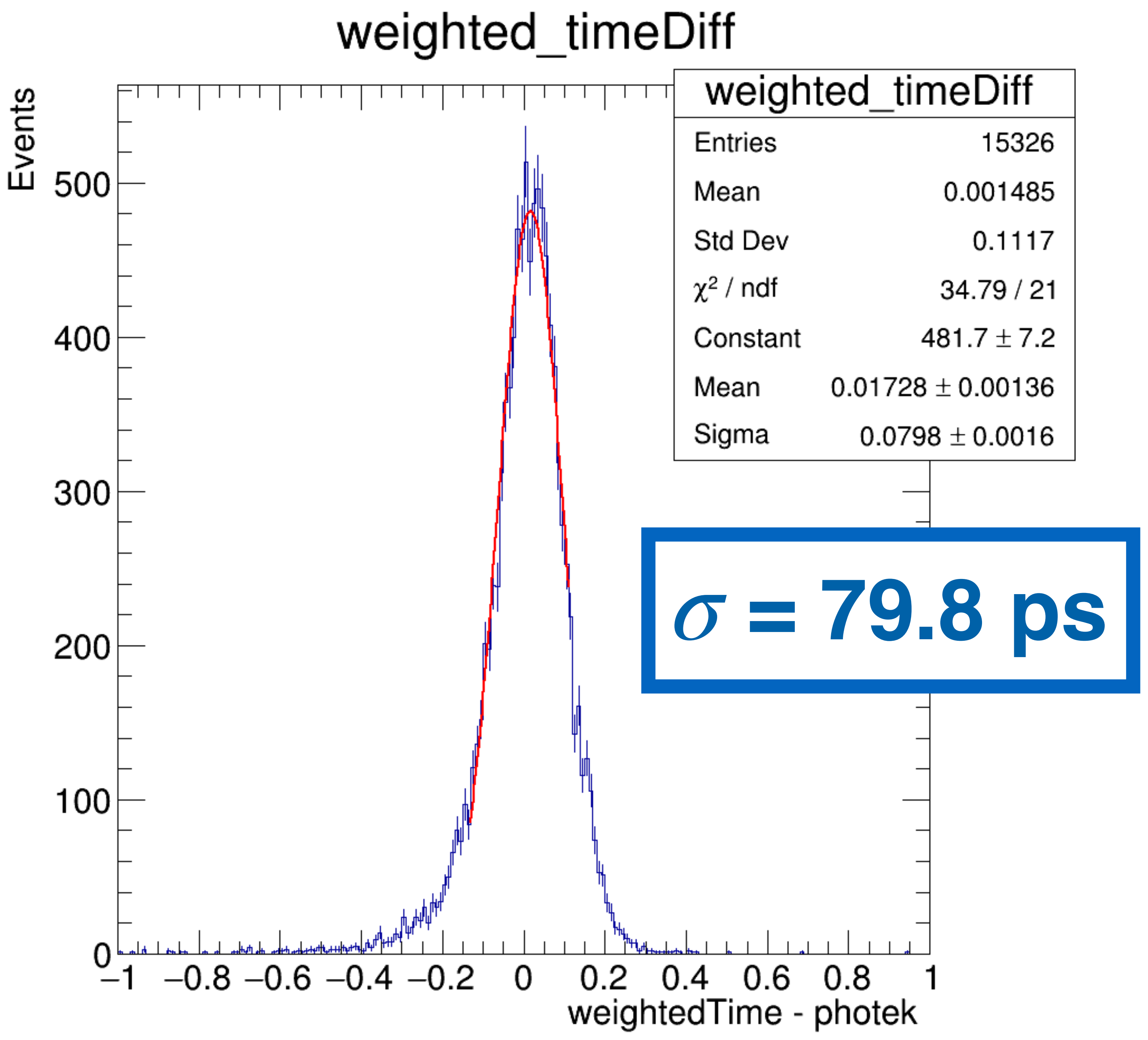
8-channel strips
200 micron pitch
50 micron metal
Bias: -350 V

- The observed signal amplitude is about 15 mV
- There is a loss of efficiency in the gaps between strips with a 10 mV threshold used
  - This is caused by the low overall gain in the sensor
- We do see favorable charge sharing between strips showing it is behaving similarly to the AC-LGADs

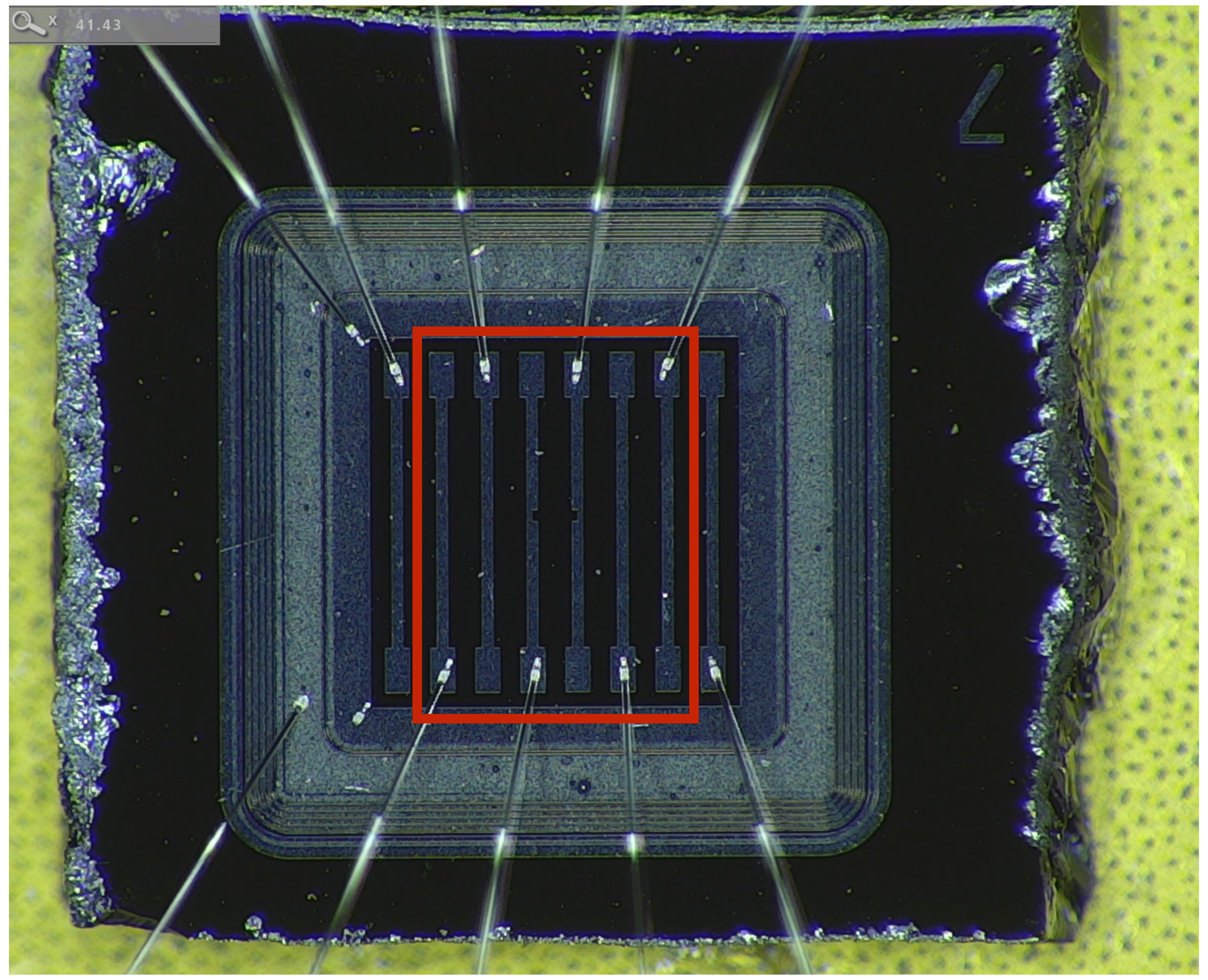
Test beam results: Buried Layer LGADs



σ = 26.5 μm



σ = 79.8 ps



8-channel strips
200 micron pitch
50 micron metal
Bias: -350 V

- Using the position and time reconstruction methods discussed before we can achieve a position and time resolution of ~24.5 μm and ~79 ps
- The sensor in general has low gain but shows promising position resolution

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 this test beam campaign delivered comparable performance

- First attempt at buried layer LGADs had issues with the gain layer manufacturing resulting in low overall gain but still delivered a ~25 μm position resolution and good timing resolution