AC-LGAD strip sensor measurements with 120 GeV protons

Karri Folan DiPetrillo

36th RD50 Workshop

4 June 2020

with Artur Apresyan, Wei Chen, Gabriele D'Amen, Gabriele Giacomini,
Ryan Heller, Hakseong Lee, Sergey Los, Chang-Seong Moon, Alessandro Tricoli

Fermilab

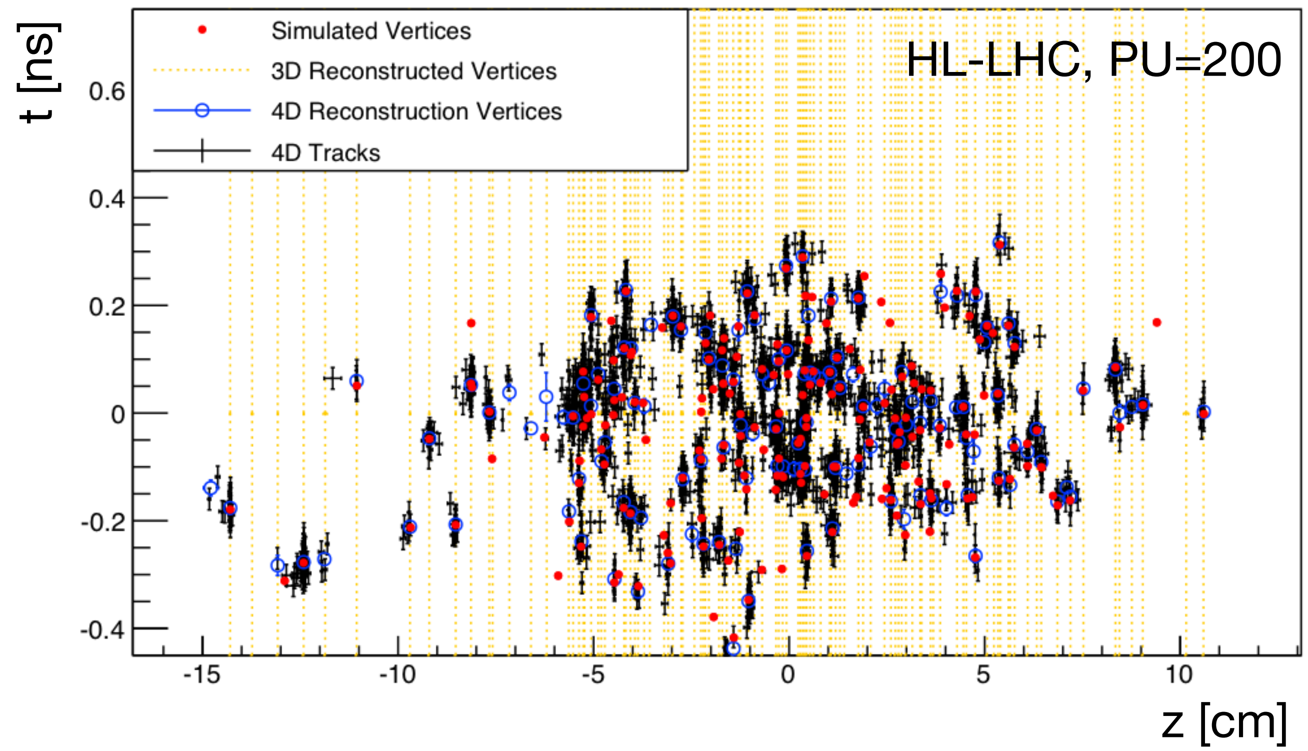
BROOKHAVEN NATIONAL LABORATORY

KNU KYUNGPOOK NATIONAL UNIVERSITY

Motivation for 4D Trackers

Future colliders present tremendous challenges for trackers

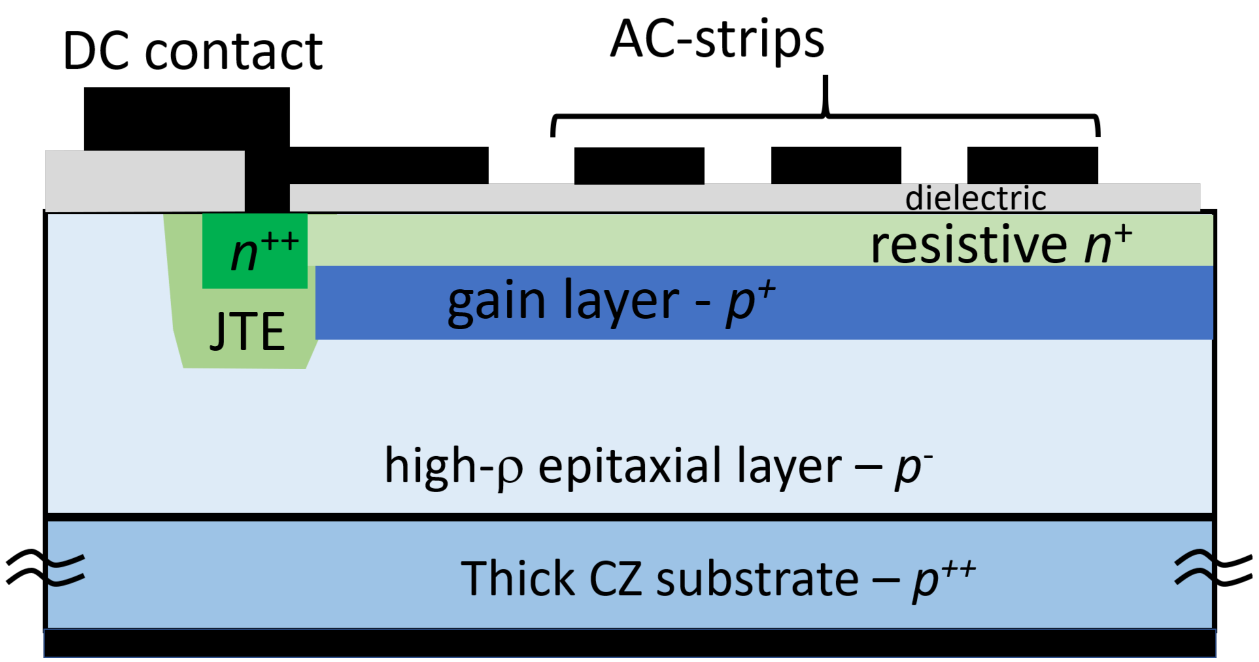
- Eg: at FCC-hh we expect 1000 pile-up interactions per bunch crossing
  - LHC: PU ~ 50
  - HL-LHC: PU ~ 200
- Future trackers need O(10 ps) and O(10 μm) resolution per-hit
  - simplify pattern recognition
  - correctly associate tracks to pile-up vertices
- Need a sensor with both precise time resolution and fine segmentation!



At HL-LHC already need ~50 ps time resolution per track to resolve pile-up vertices

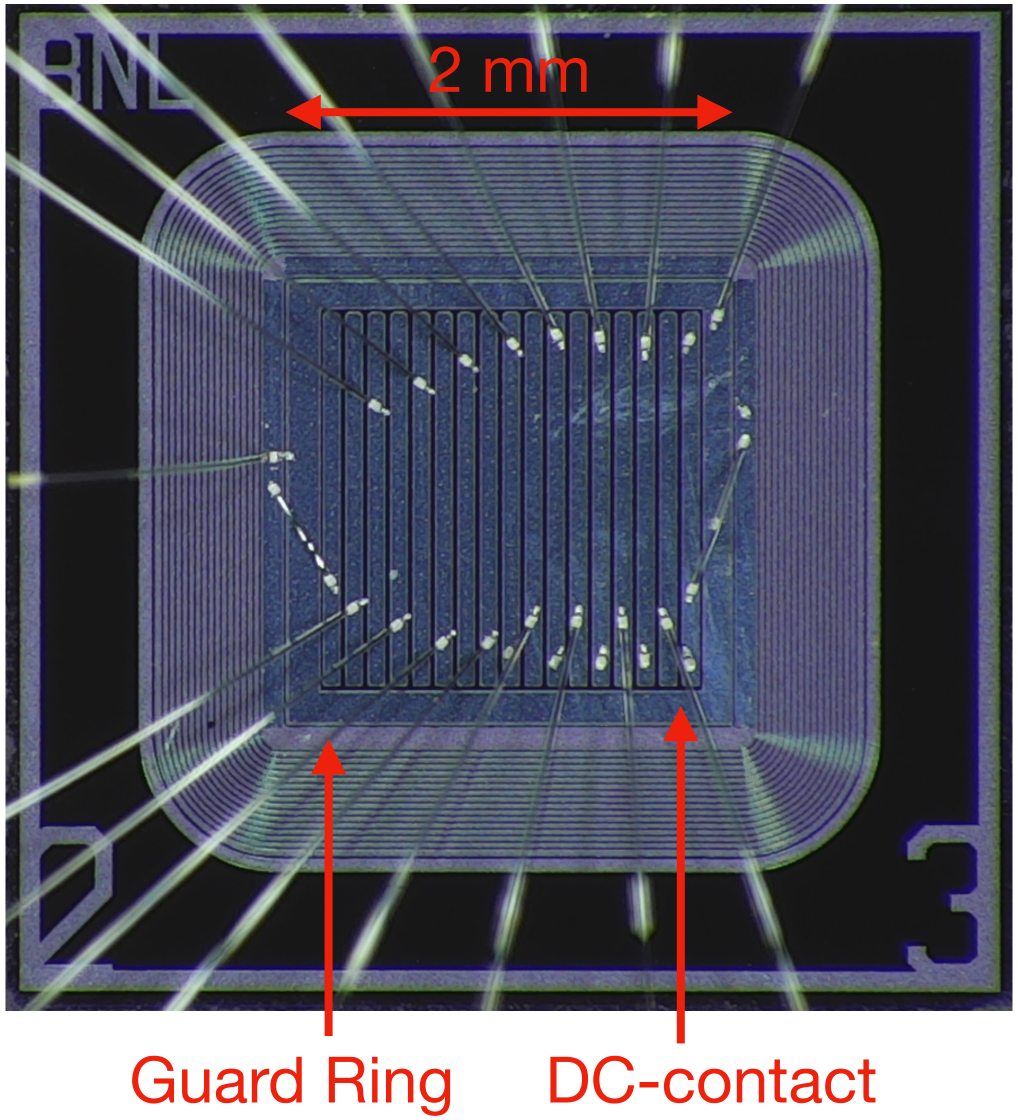
Why AC-LGADs

- Low Gain Avalanche Detectors (LGADs) achieve 30 ps time resolution
  - ATLAS and CMS plan to use 1.3 x 1.3 mm^2 pads at HL-LHC
  - cannot easily shrink pitch: 50-80 μm inactive region between pads
- AC-coupled LGADs solve the fill factor problem
  - uninterrupted gain layer, read out with AC-coupled electrodes
  - → smaller pitch and signal sharing between pads
  - can easily achieve O(10 μm) and 30 ps time resolution with same sensor



The AC-LGAD sensor

- Fabricated at BNL
  - 50 µm thick p- substrate
  - Depletion voltage -150 V
  - Breakdown -225 V at 22C
  - Bias Voltage -210 V
- 17 Strips
  - 100 µm pitch
  - 80 µm width
- DC contact surrounds pads
  - behaves as a standard LGAD when directly traversed by a proton
  - used to measure gain
- Readout with Fermilab 16-channel board
  - 15 strips (additional stage of amplification)
  - DC pad

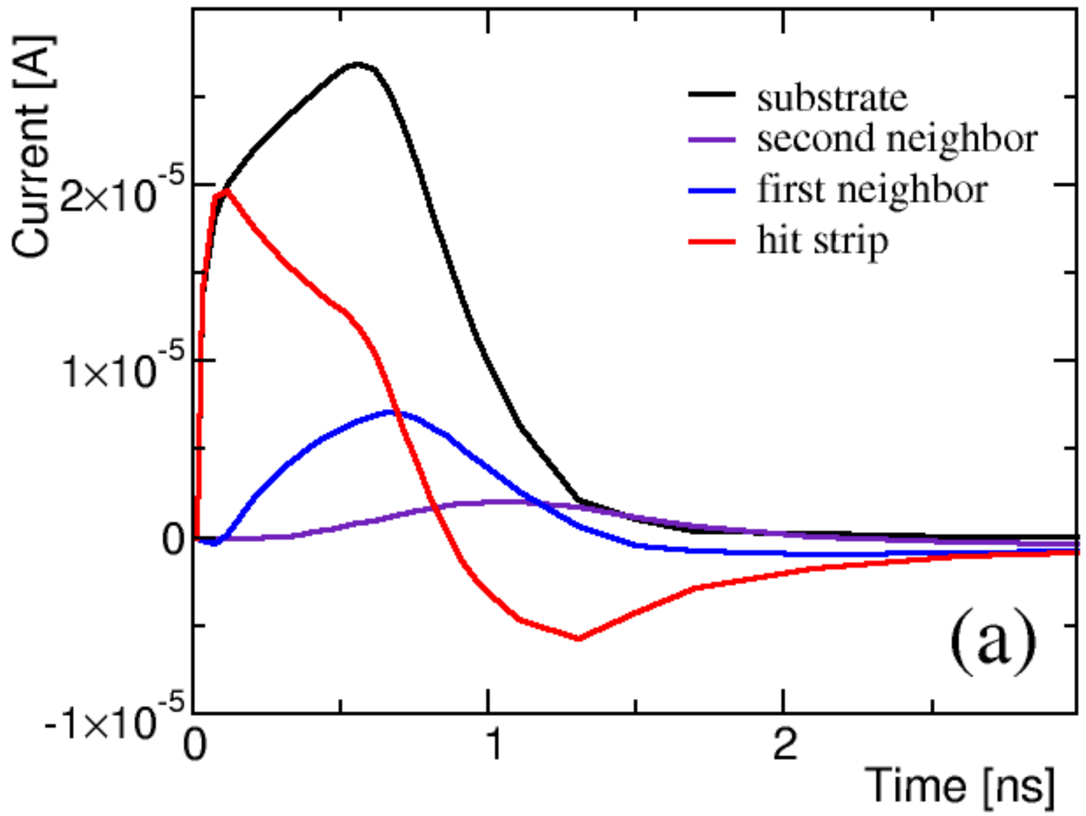


strips: 0-17

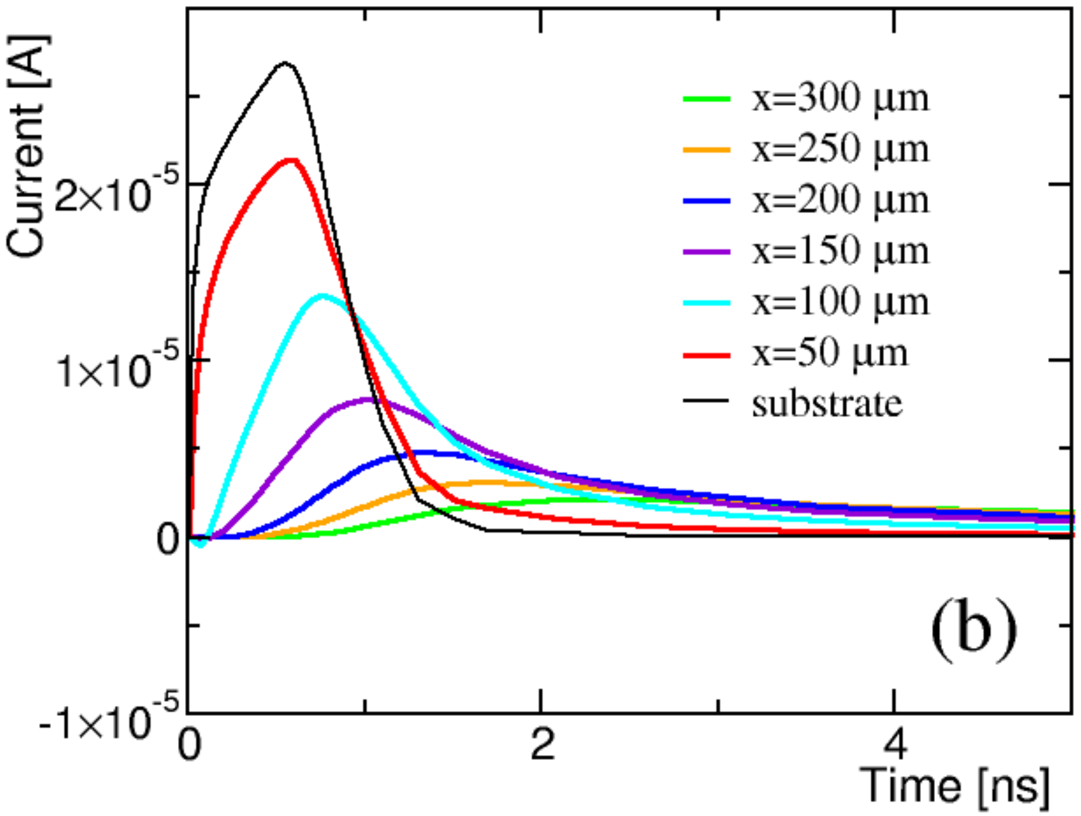
Simulation

- AC-LGAD simulations with a similar geometry
  - 100 μm pitch, 80 μm width, similar doping/gain, but shorter strip length
  - simulations performed with SILVACO

Current-sharing between adjacent strips

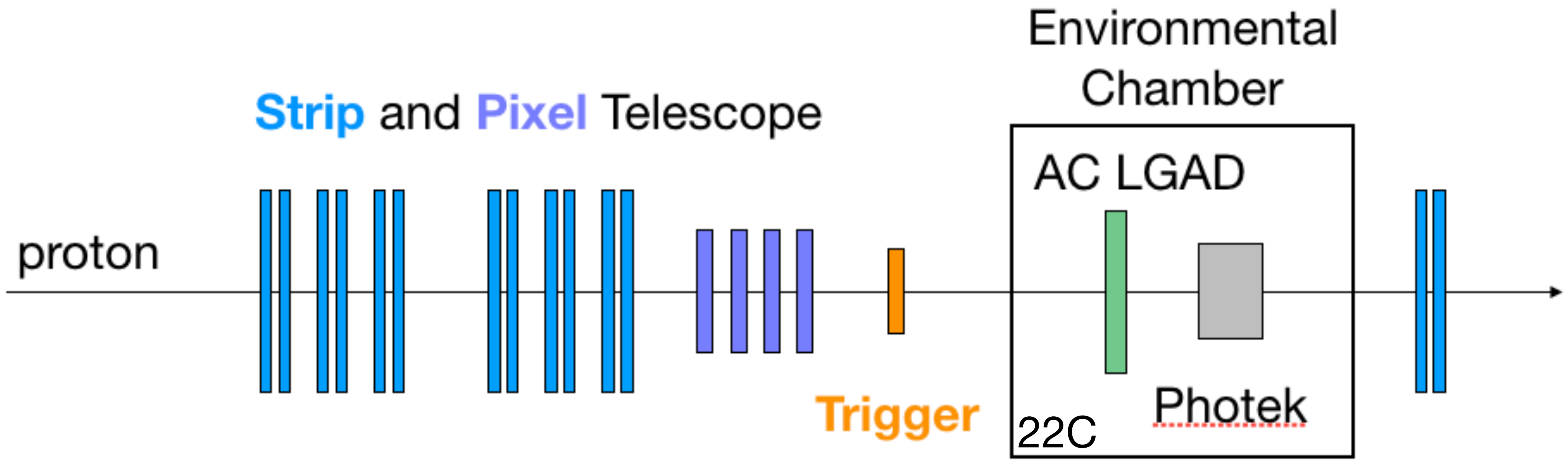


DC-contact signals for different proton positions

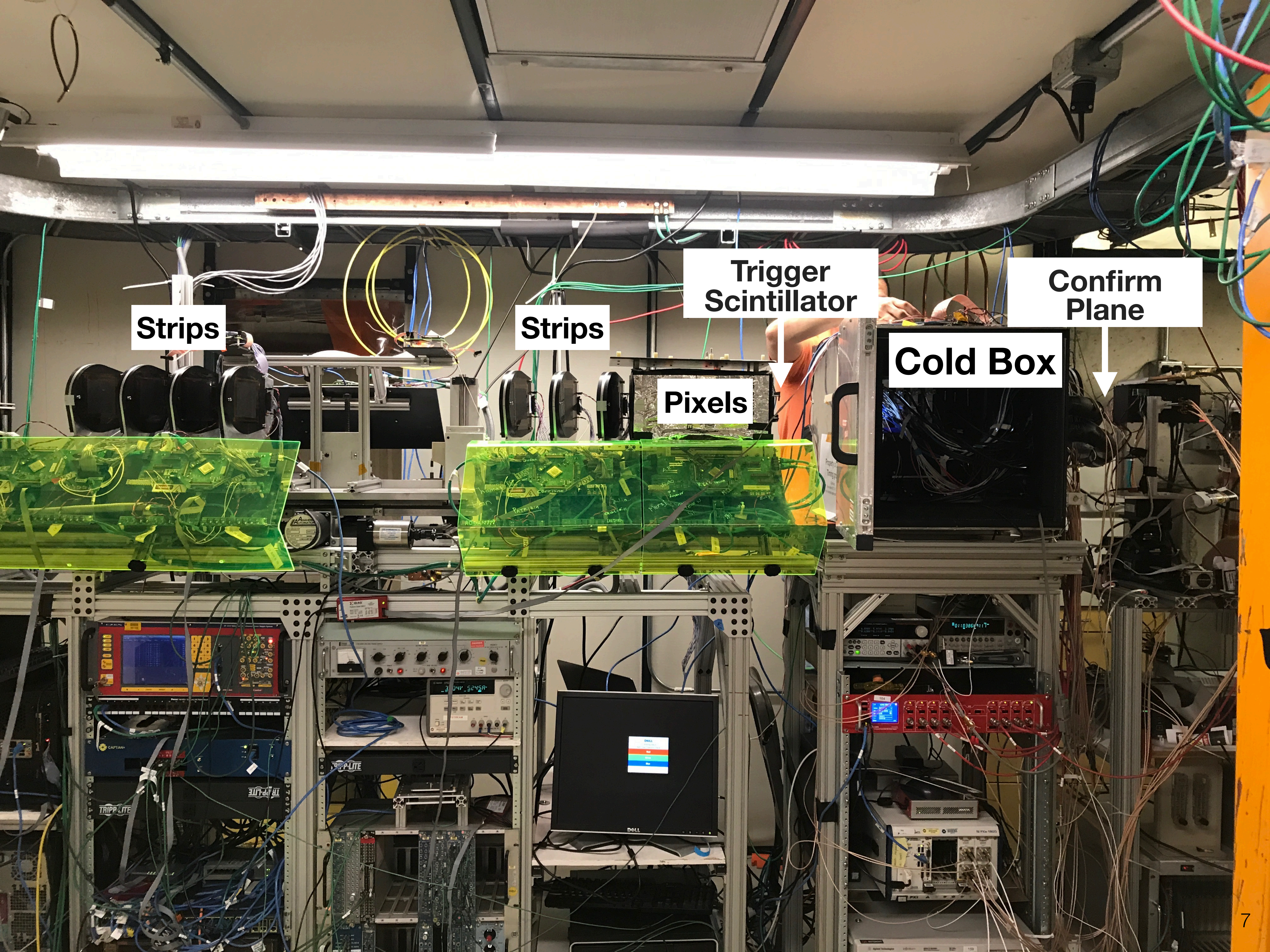


Fermilab Test Beam setup

- Main injector provides 120 GeV protons
  - Beam width: few mm to few cm
  - ~100k protons per 4 seconds spill, every minute

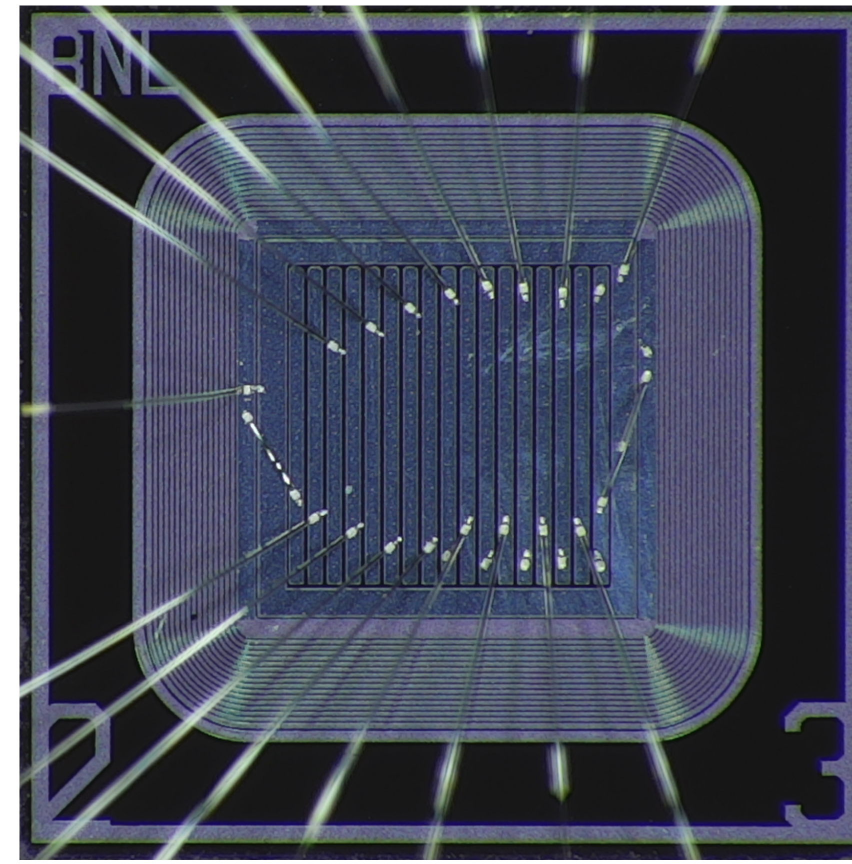


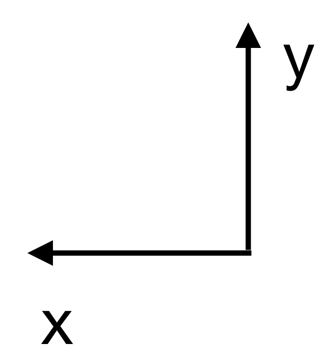
- Independent scintillator provides trigger
- Telescope provides proton track position
- Photek MCP serves as time reference (10 ps resolution)
- Oscilloscope saves waveforms from Photek and three channels
- Study Δt(AC-LGAD,Photek)


Strips
Strips
Trigger
Scintillator
Confirm
Plane
Cold Box
Pixels

Analysis strategy

- Basic requirements
  - Well measured proton track
  - Photek signal
  - proton x and y consistent with sensor
- Can only study 3 strips + Photek at a time with oscilloscope
  - three adjacent strips
  - or stitch separate events together
- Hit amplitude thresholds
  - strips: 110 mV
  - DC contact: 11 mV
- Clusters formed from adjacent strips with hits

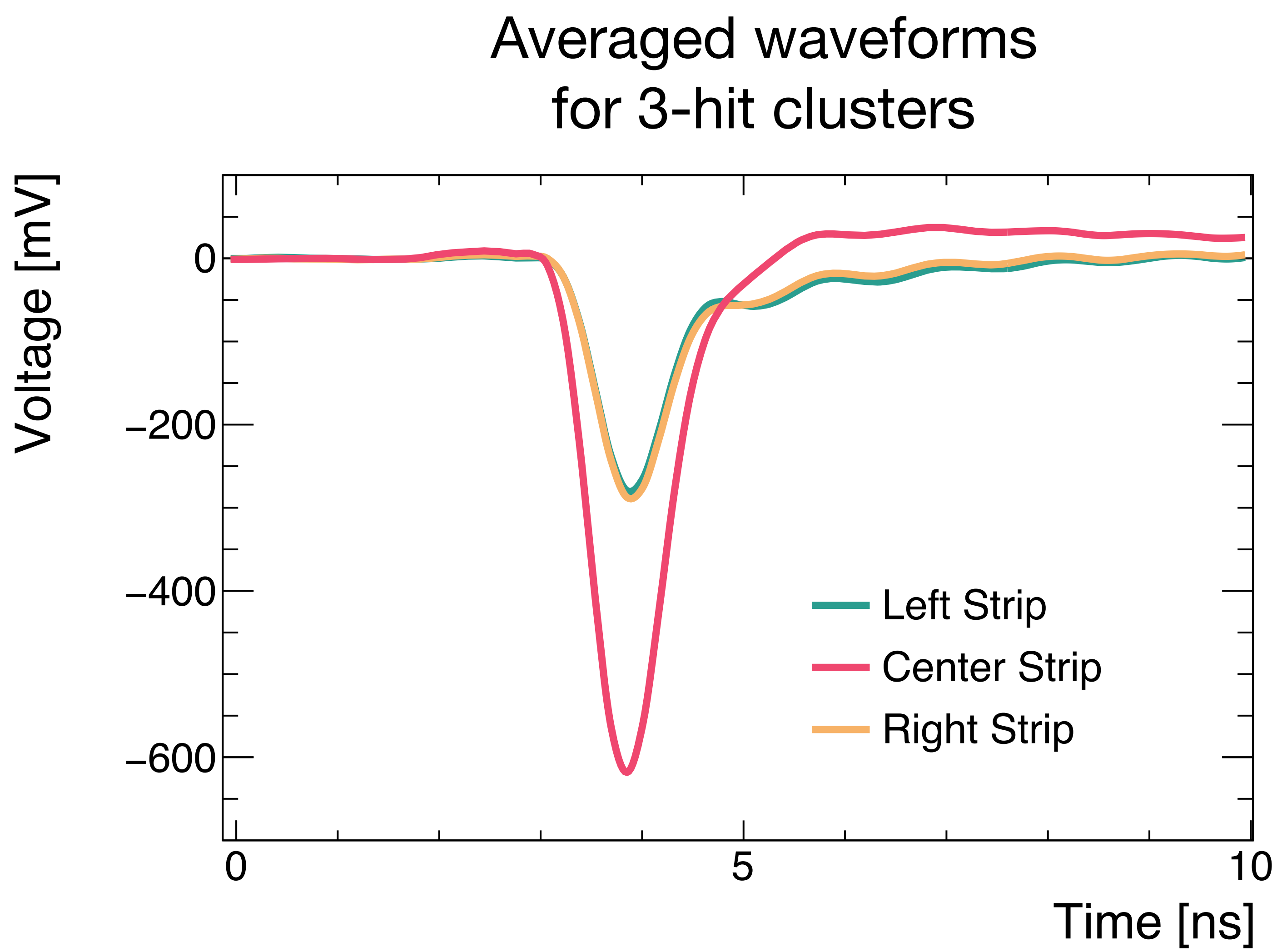




*following slides include amplifier gain

Signal Properties

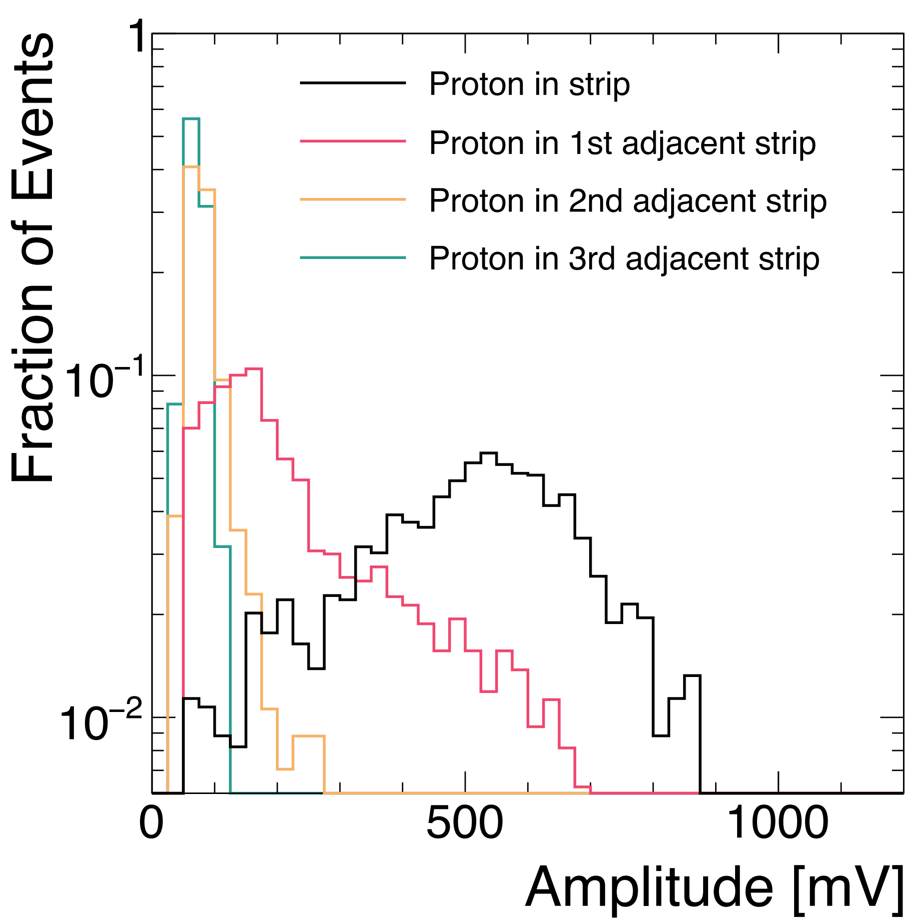
- Center strip
  - initial negative pulse
  - 1 ns FWHM
  - followed by overshoot
  - S/N~27
- Adjacent strips
  - lower amplitude signals
  - longer tails



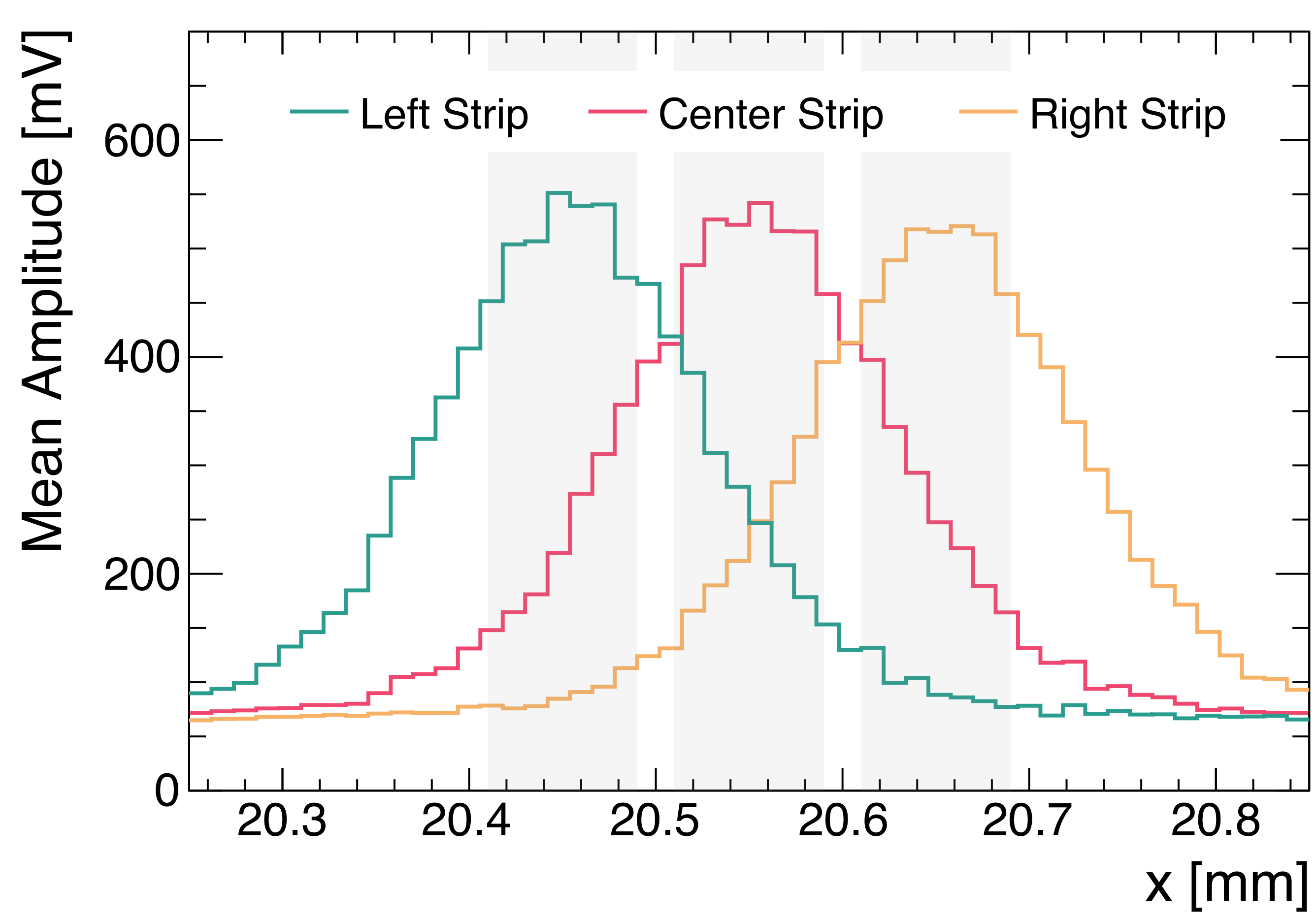
Signal sharing between strips

- Confirms predictions from simulation
  - strip amplitude decreases with distance to proton
  - adjacent strip sees lower amplitude signal, usually above threshold
  - 2nd adjacent rarely sees signal above threshold (few percent)

Amplitude distributions for different proton positions

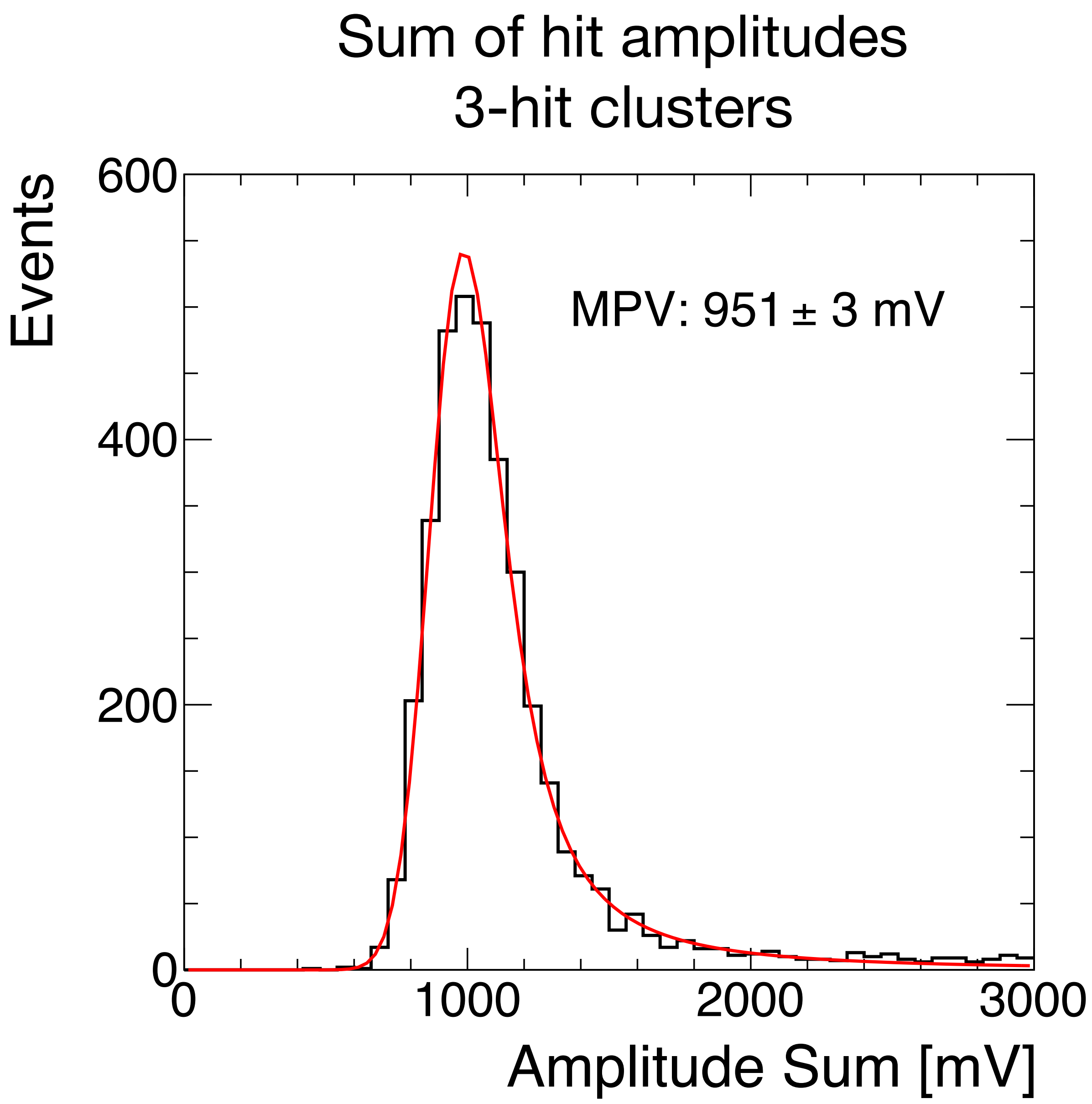


Mean amplitude versus perpendicular distance to proton



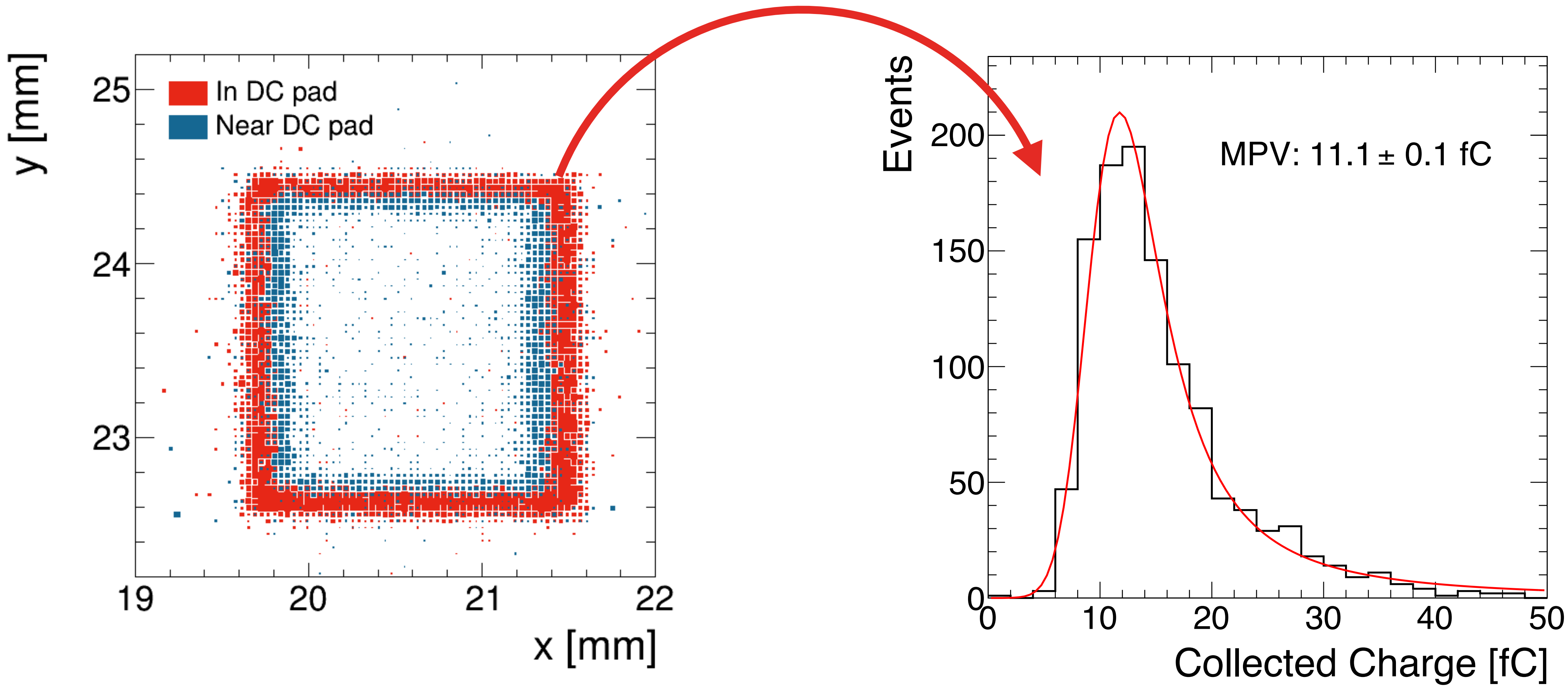
Estimating cluster size

- Since we can only read out 3 channels at once, we use amplitude distributions to estimate cluster size
  - ~70% of events have a 3 hit cluster
  - ~25% have 2 hits
  - few% will have a 4th or 5th hit
  - <1% of clusters have 1 hit or less
- Majority of signal contained within three strips
  - sum of amplitudes well described by landau convolved with a gaussian



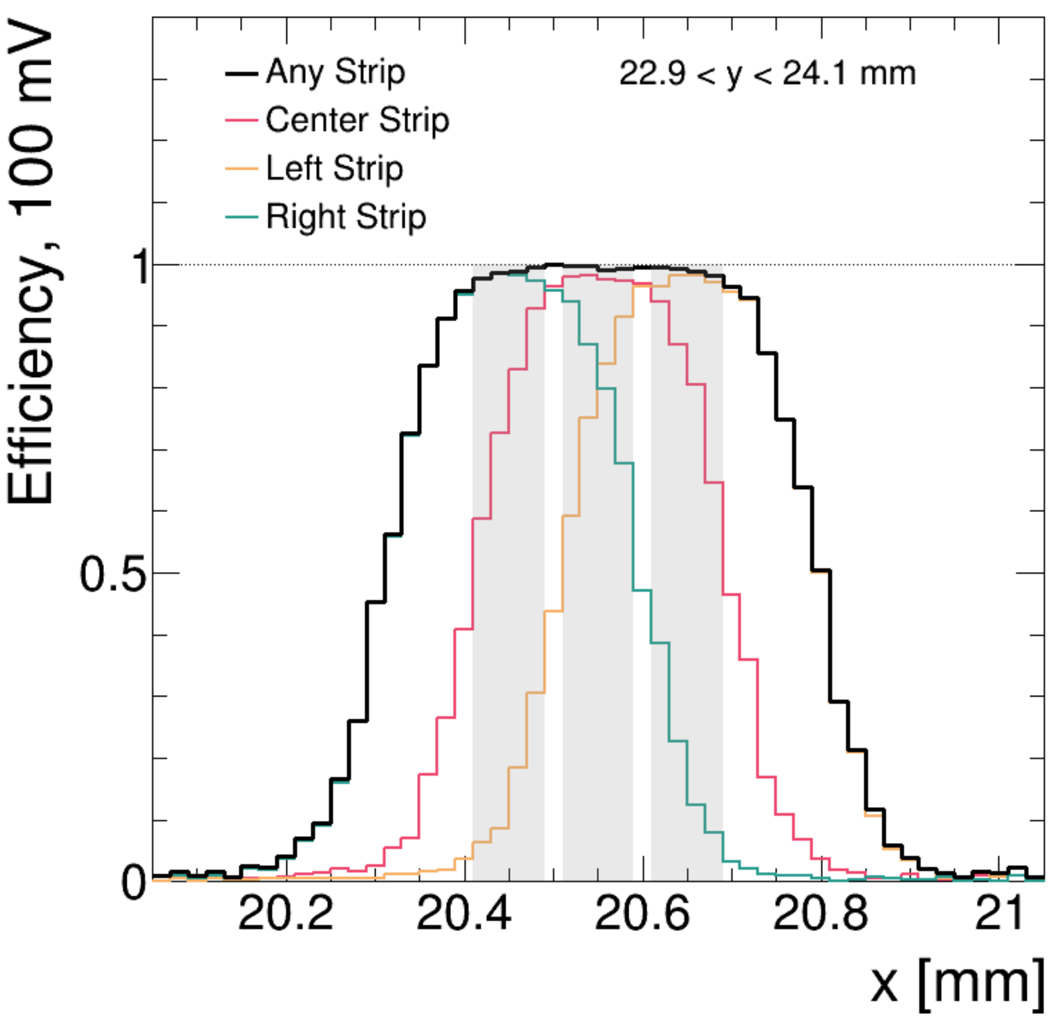
DC-contact

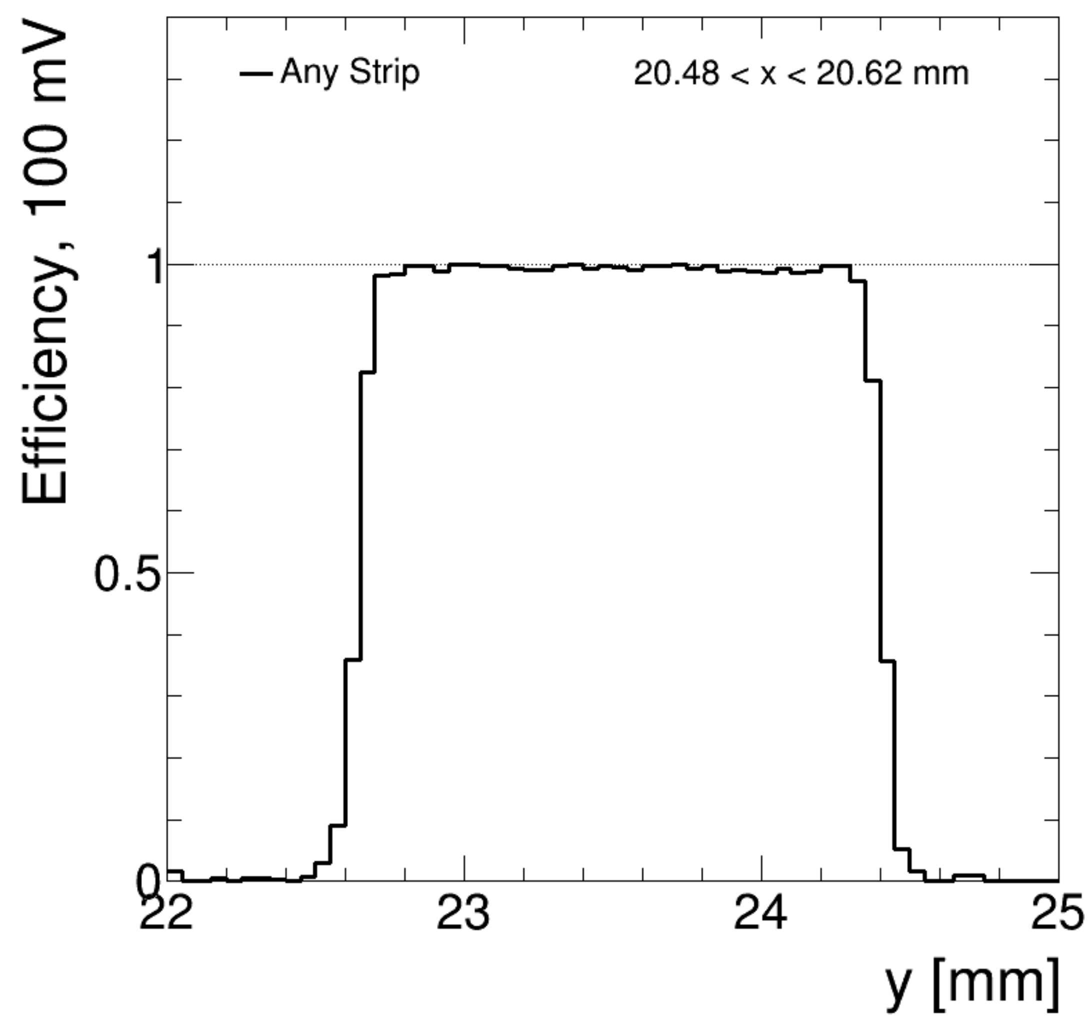
- DC-pad signal amplitude decreases with distance to incident proton
  - direct hits in DC pad (>30 mV), induced hits near DC pad (11-30 mV)
- DC-pad behaves like a standard LGAD when struck directly by proton
  - measure collected charge to be 11 fC, 30% systematic uncertainty
  - corresponds to gain of 17



Efficiency measurement

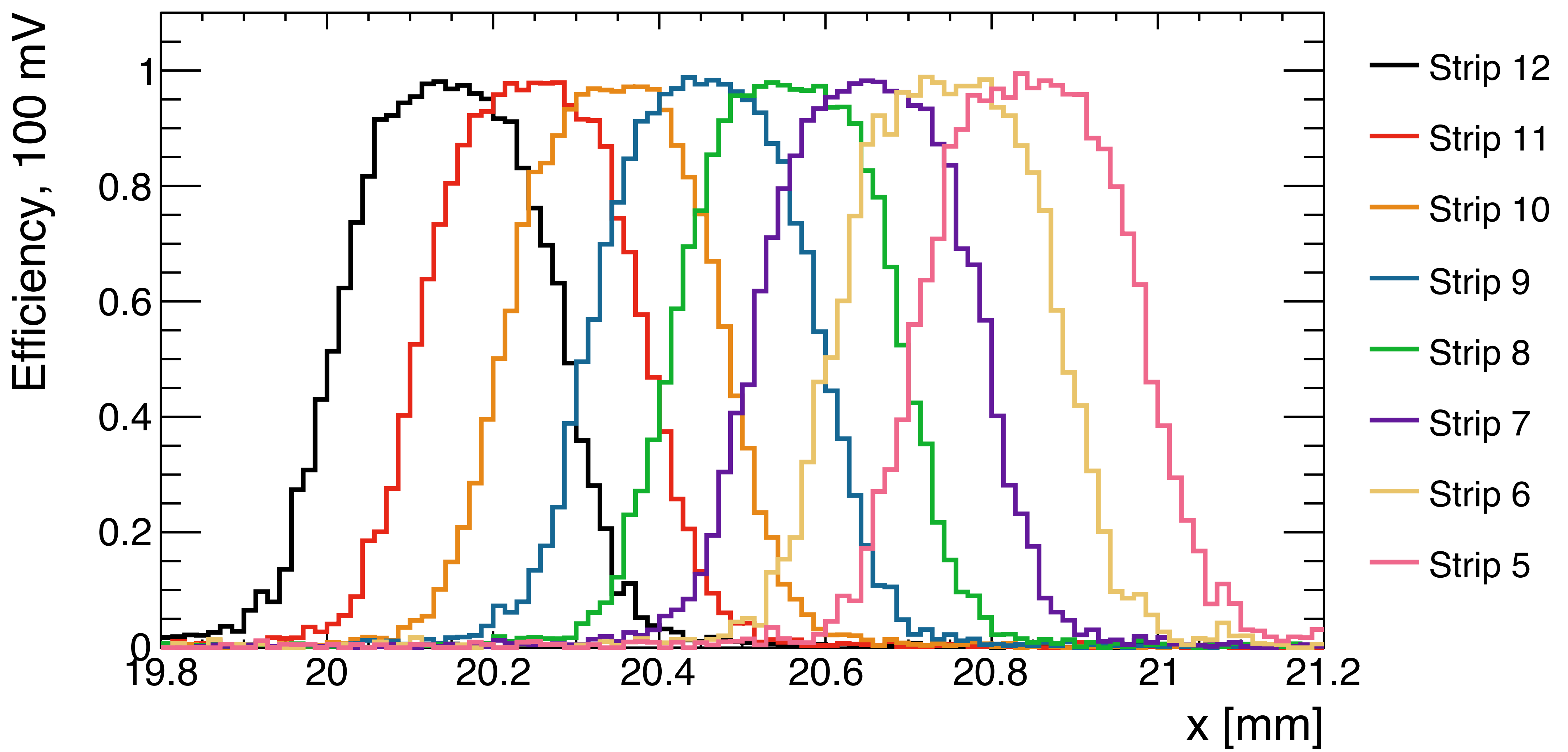
- Study the efficiency as a function of proton x and y position
  - efficiency definition: amplitude > 100 mV, t_{peak} ~ consistent with MIP
  - measure efficiency = 99.4 ± 0.1
  - observe no loss of efficiency between strips!





Efficiency measurement cont.

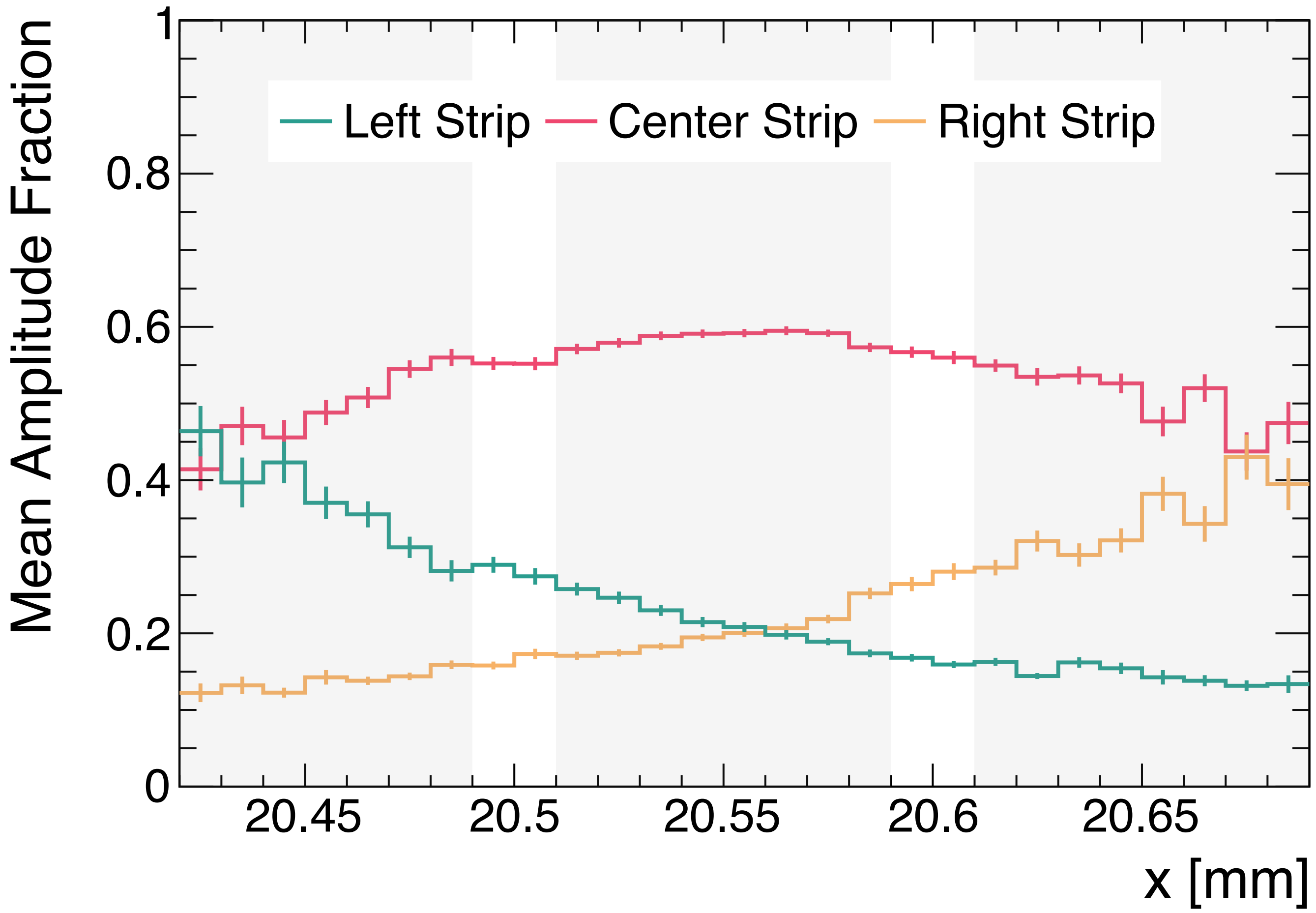
- Can also study efficiency of individual strips
  - consistent across the device
  - indicative of good uniformity!



Spatial Resolution

- AC-LGAD feature - signal sharing between strips can improve position measurement beyond (strip size)/$\sqrt{12}$
- Our measurement
  - $\sigma(x_{sensor} - x_{tracker})$
  - dominated by tracker resolution ~50 μm*
- Looking into ways to improve tracker resolution for future

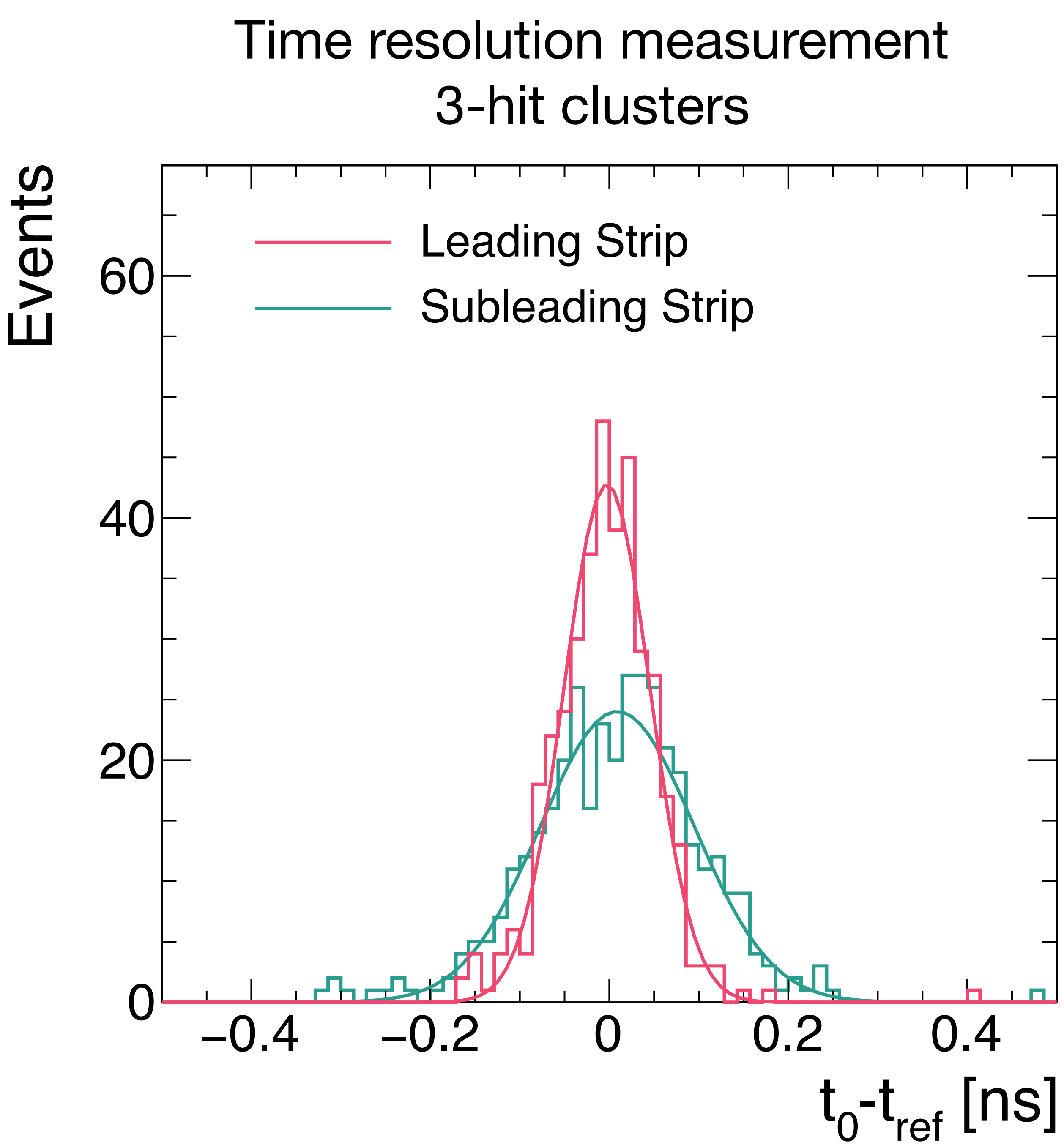
Mean amplitude fraction v. x within 3-hit clusters



*50 μm res due to extrapolation to DUT, not intrinsic to telescope

Time resolution

- Measurement:
  - time difference with respect to photek (t_0 - t_{ref})
  - t_0 and t_{ref} defined at 20% of pulse maximum amplitude
  - resolution: sigma of gaussian fit
- Within a 2 or 3 hit cluster
  - leading strip: 45-47 ps
  - subleading: 70-90 ps
  - no significant improvement from combining hits within clusters - at most few ps expected
- Future improvements
  - investigate lower noise electronics
  - systematic study of how gain/ geometry/charge sharing impacts time resolution



Conclusions

- AC-LGADs make excellent candidates for future 4D trackers
- We present numerical simulations & first measurements of an AC-LGAD strip sensor with 120 GeV pp-collisions
  - characterization of signal properties, including signal sharing
  - efficiency demonstrated to be >99%
  - steps towards spatial & time resolution measurements
- Read more in arXiv:2006.01999