Development and testing of AC-LGAD sensors for future 4D-trackers

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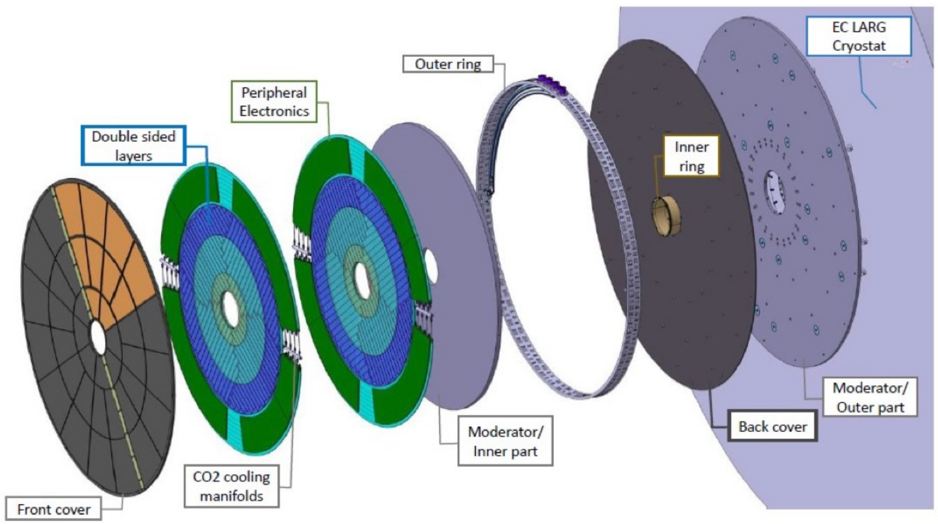
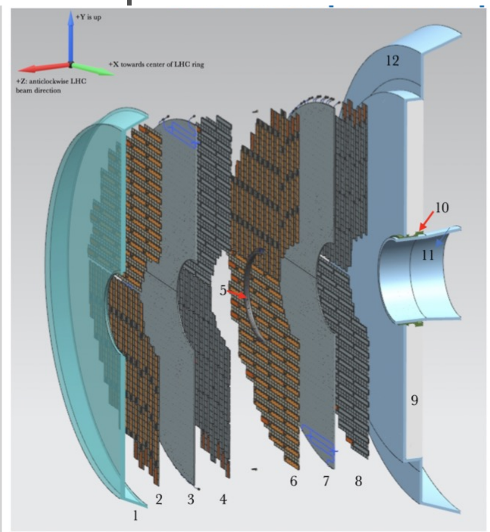
4D trackers: present and future

- CMS and ATLAS are building first-generation of 4D-detectors
  - Next generation detectors will be more sophisticated and evolve towards high granularity everywhere
  - Reduce backgrounds, track reconstruction, triggering at L1, PID and LLPs
- Active R&D on technologies to achieve the required performance for the future experiments
  - Sensors, ASIC, front-end electronics developments



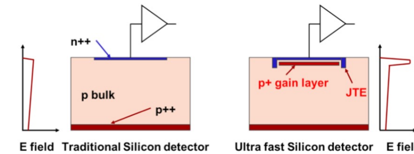
ATLAS timing detector



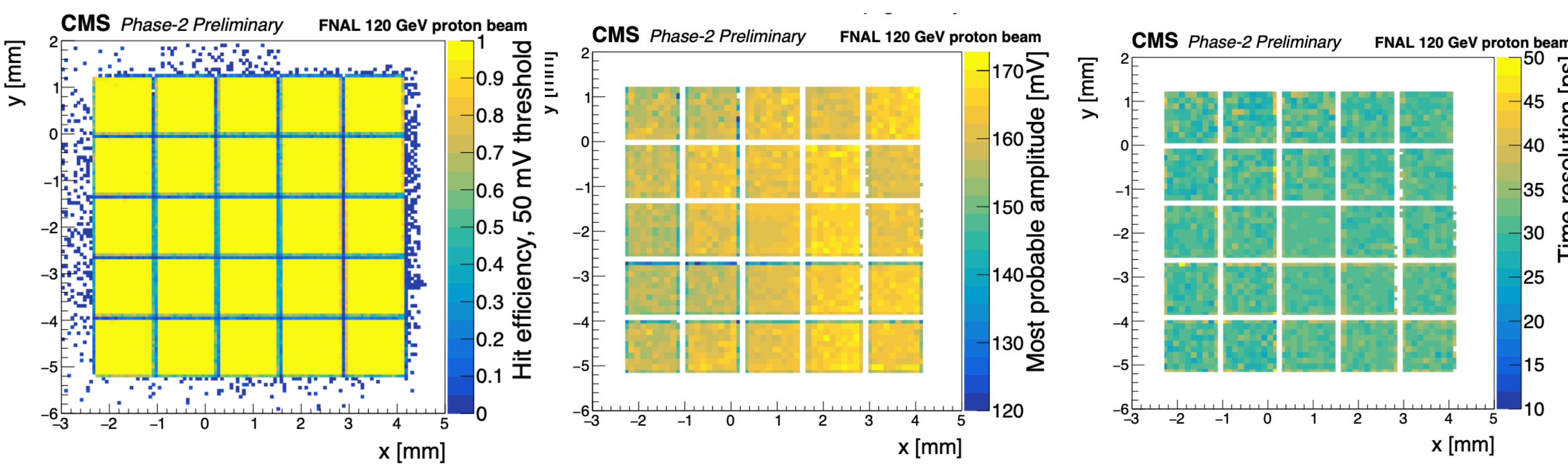
CMS timing detector

Advanced detector R&D for future experiments

- A key breakthrough is the recent development of trackers with the addition of timing information: full 4-vectors (x, y, z, t)
  - Low-Gain Avalanche Detectors (LGAD)
  - Silicon detectors with internal gain



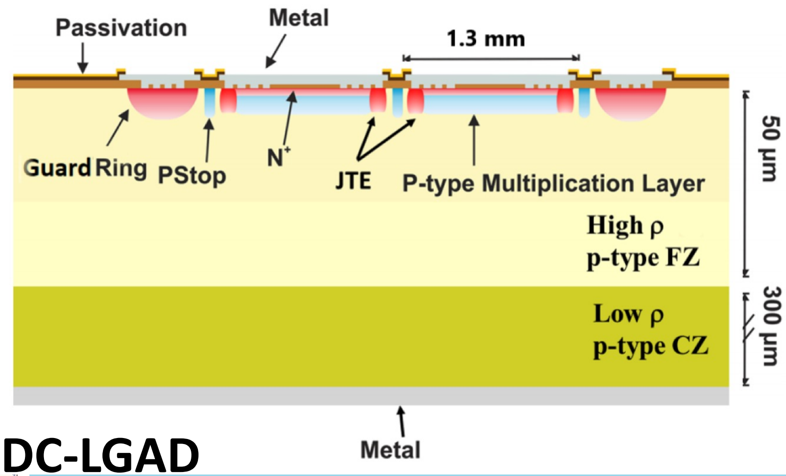
- Sensors developed for CMS and ATLAS show high degree of uniformity, excellent time resolution, rad hard up to **~3x10^{15} n/cm^{2}**
  - However, no-gain gaps between pixels: due to presence of JTE



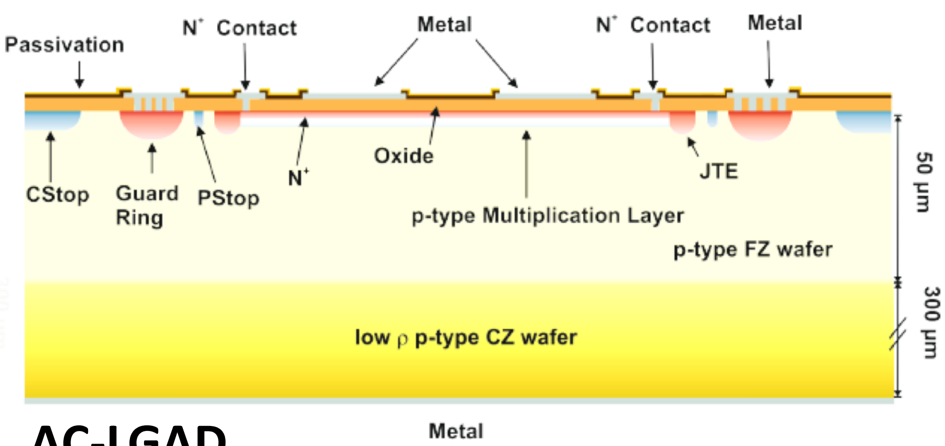
AC-coupled LGADs

- **Improve 4D-trackers to achieve 100% fill factor, and high position resolution**
- Active R&D at different manufacturers (FBK, BNL, HPK, etc)
  - 100% fill factor, and fast timing information at a per-pixel level
  - Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric
  - Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge.

Diagram credit: CNM



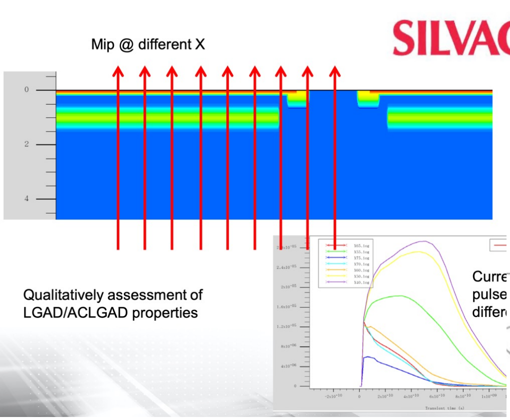
DC-LGAD



AC-LGAD

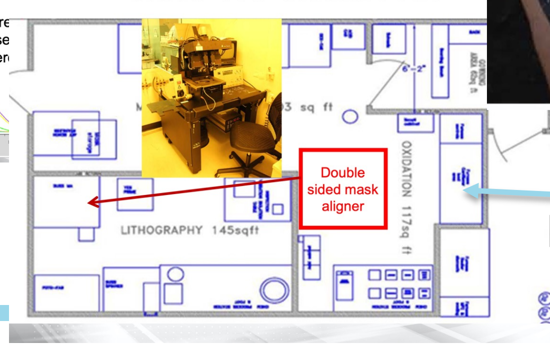
Collaborative development

- Next gen detector R&D requires a lot of infrastructure, expertise, and development cycles
  - Develop dedicated **readout boards and testing infrastructure** for characterization of sensor prototypes,
  - Design, manufacture and test **sensor prototypes**
  - Design, manufacture and test **full systems** integrating sensors and readout electronics

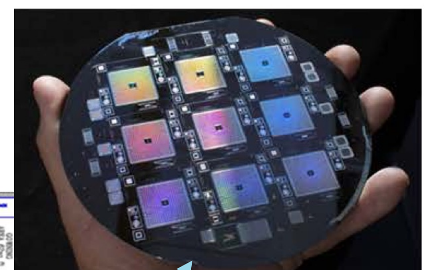


Design

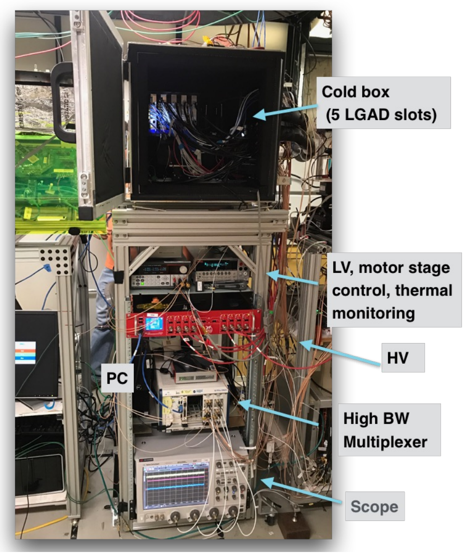
Class 100 Cleanroom



Finish Processed Wafer



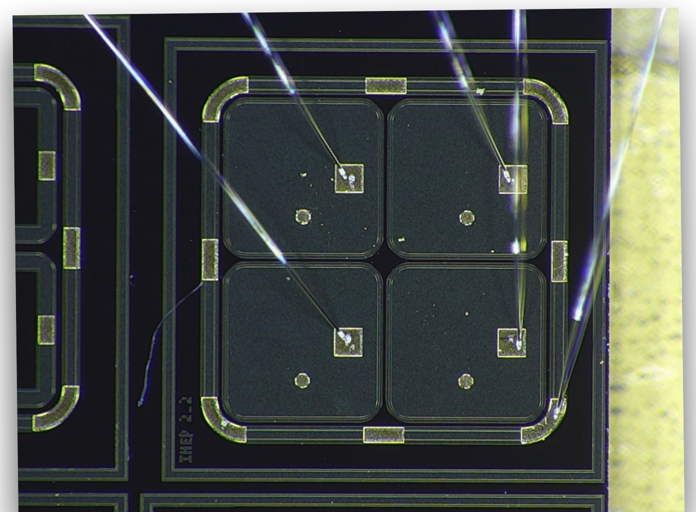
Fabrication



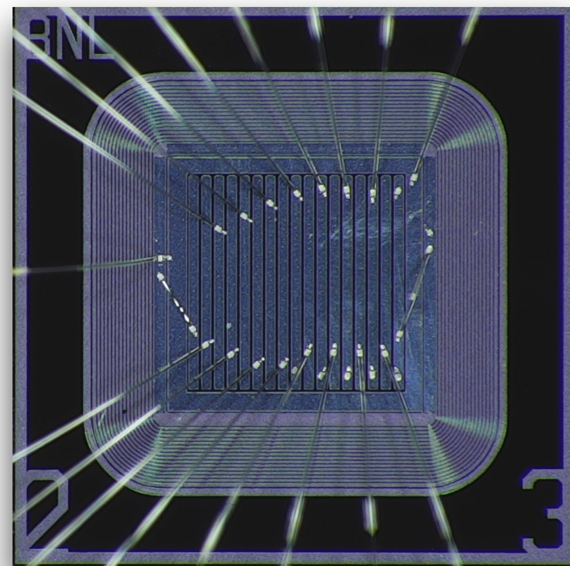
Testing in beams

AC-coupled LGADs

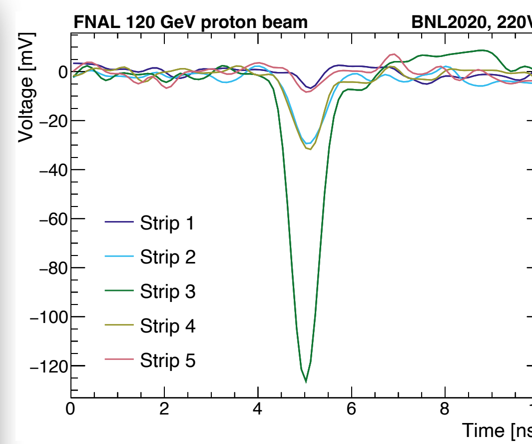
- AC-coupled electrodes w/ continuous gain region to achieve segmentation: "AC-LGADs”
  – Signal shared between neighbors: measure position based on signal ratio



2x2 IHEP-IME DC-LGAD sensor

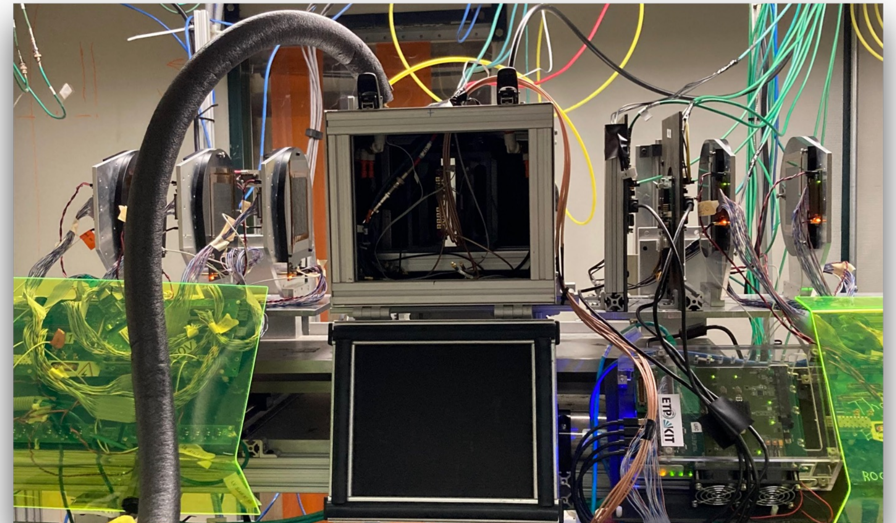


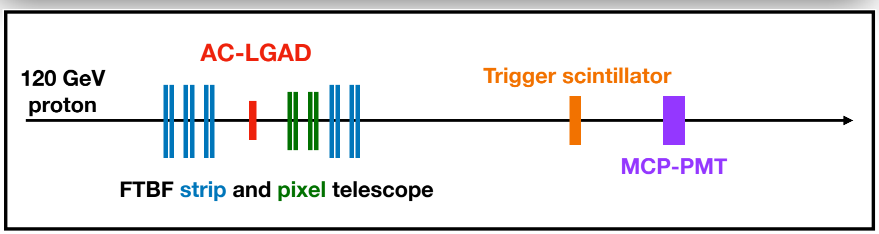
BNL AC-LGAD, 100 micron strips, no dead space



Interpolate to find impact parameter with fine precision

FNAL test beam setup for AC-LGADs





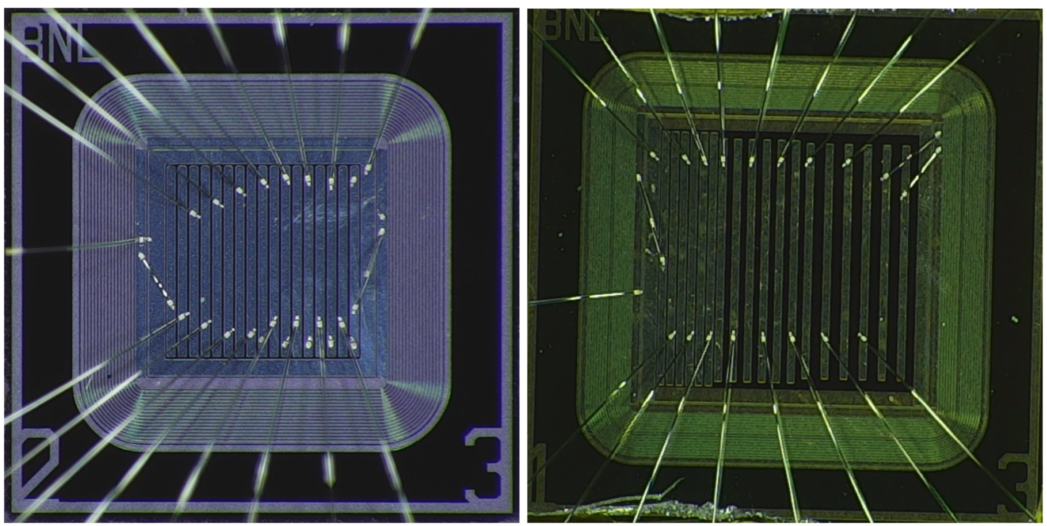
- Critical for AC-LGAD characterization:
  - Fine resolution tracker reference
  - Read many channels!

8-channel oscilloscope, 2 GHz, 10 GSa/s
Large memory: take 20k events during 4 s spill

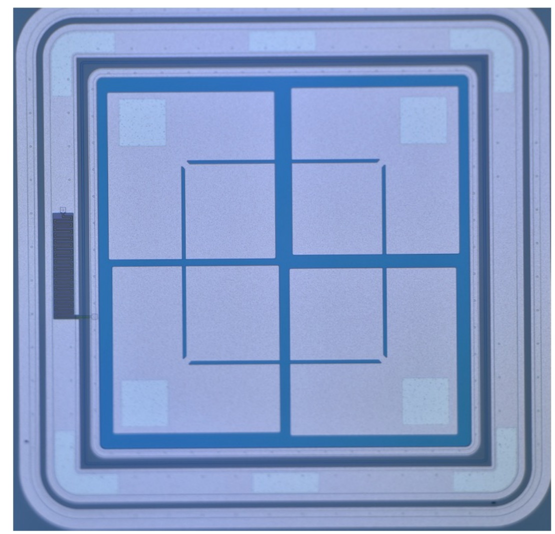
- Tracking telescope resolution: ~ 5 μm
  - 4x CMS RD53a pixels (25x100 μm) + 10x strips (60 μm)
  - MCP time ref resolution: 10 ps

AC-LGAD measurements in beams

- Several rounds manufactured over the last few years
  - Excellent performance in the beam showing high efficiency
  - First measurements in the beam summary in: JINST 15 P09038 (2020)
- Extensive characterization and design studies
  - Optimize the geometry of readout, and sensor design for performance



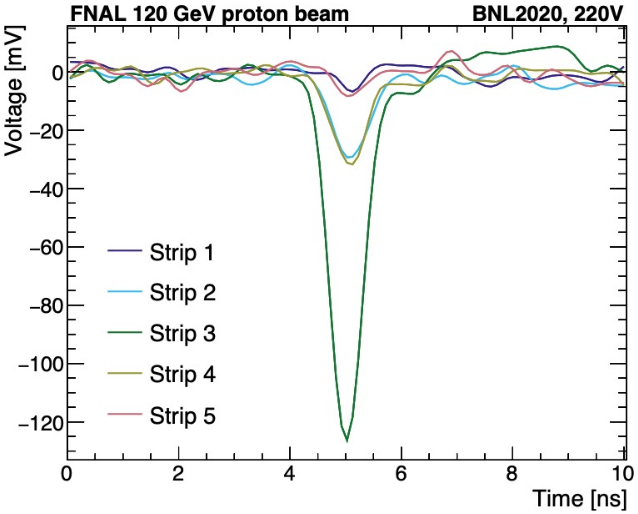
BNL strip AC-LGAD



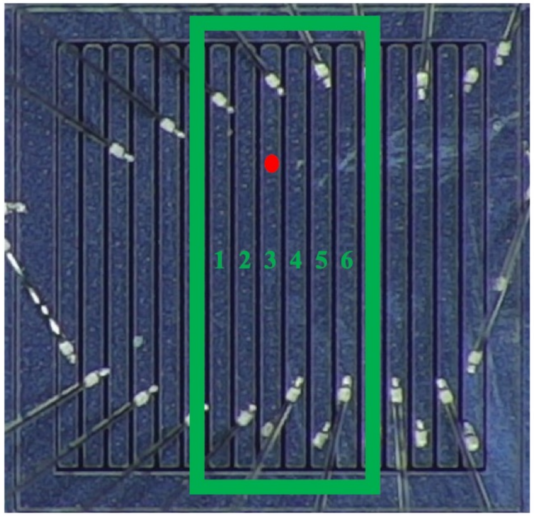
HPK pads AC-LGAD

Signal properties

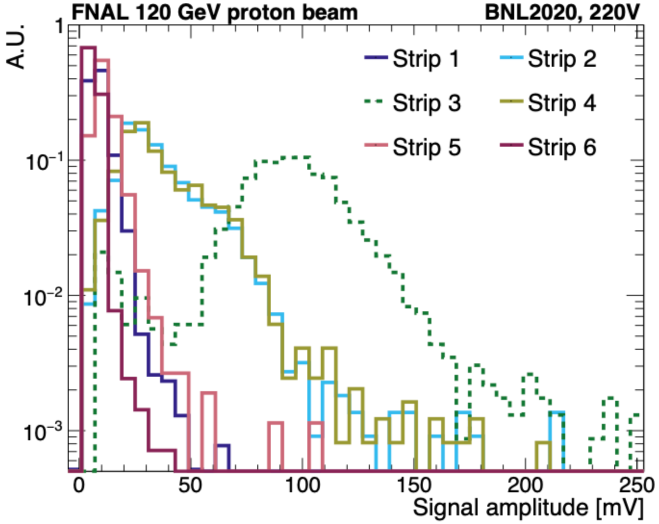
- Waveforms of analog signals recorded by the oscilloscope
  - Analyze waveforms to measure the amplitude and ToA
- Large primary signal from the channel closest to the hit
  - Signals with amplitudes well above noise for secondary channels
  - Signals decrease for strips that are increasingly further away from the primary strip.



Waveforms for an AC-LGAD strip sensor



Photograph of the six readout strips. Red dot shows the location of the proton

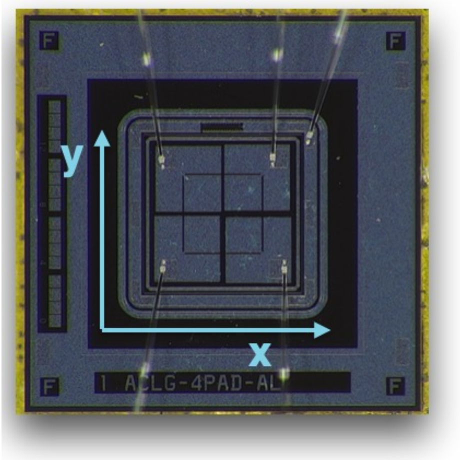


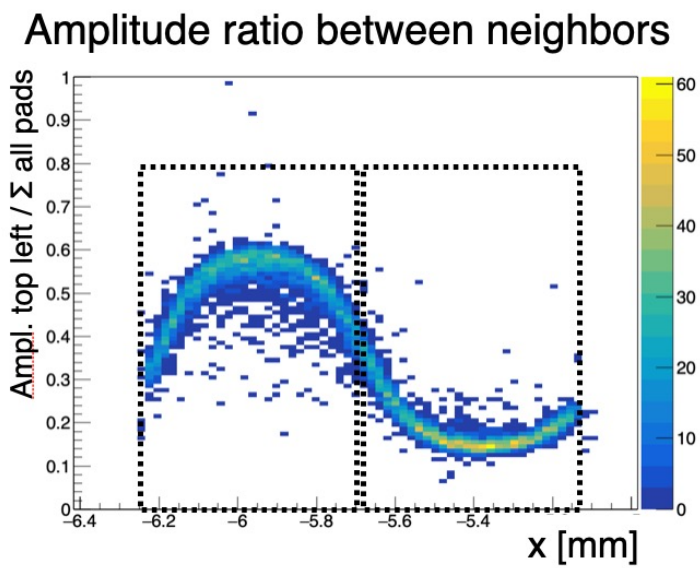
Amplitudes for all channels, the proton hits Strip 3

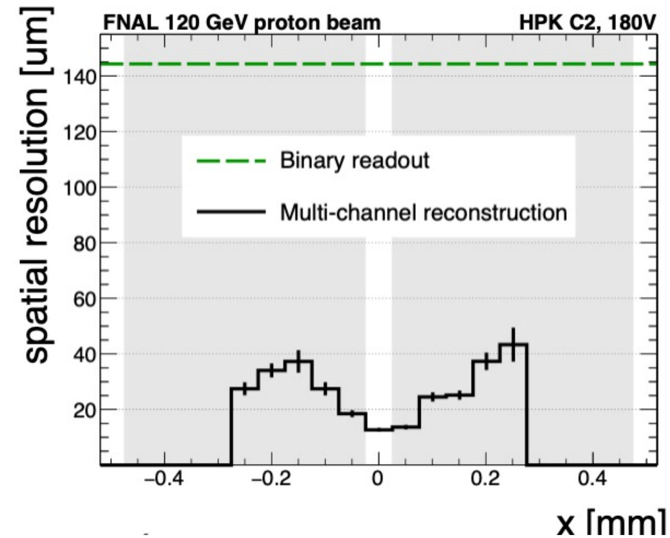
AC-LGAD results for 2020/2021 campaigns

- Signal shared between neighbors—interpolate position based on signal ratio

HPK AC 2x2 pads
500 micron pitch, 2021



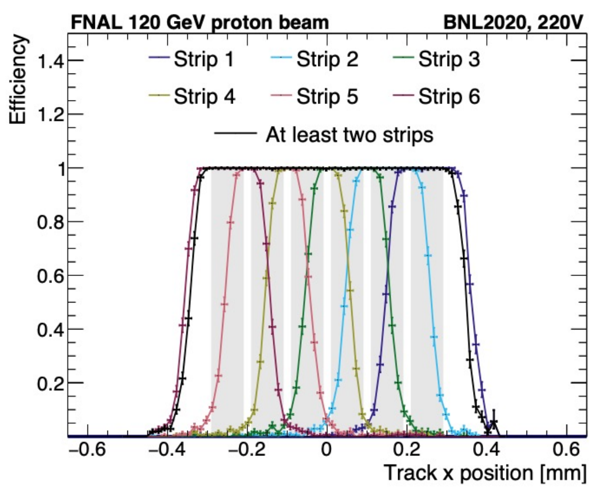


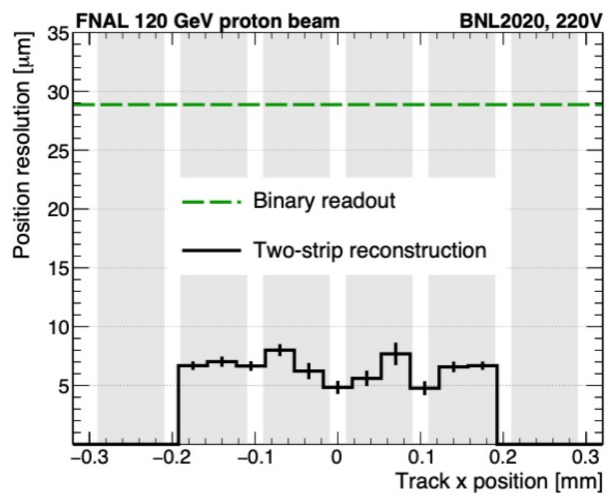


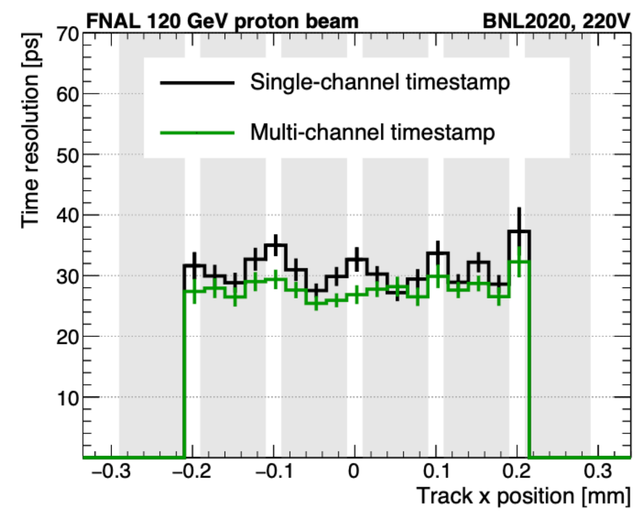
- Due to high gain, obtain resolution much finer than pitch / √12
  - In this case: 20-40 μm (and 30 picosecond time resolution!)
- Tuning of n+ resistivity and electrode geometry needed for optimal sharing...

AC-LGAD results for 2020/2021 campaigns

- Excellent performance from several BNL 100, 200-µm strip prototypes
  - Well-tuned signal sharing → uniform 5-10 µm resolution
  - 100% particle detection efficiency across sensor surface





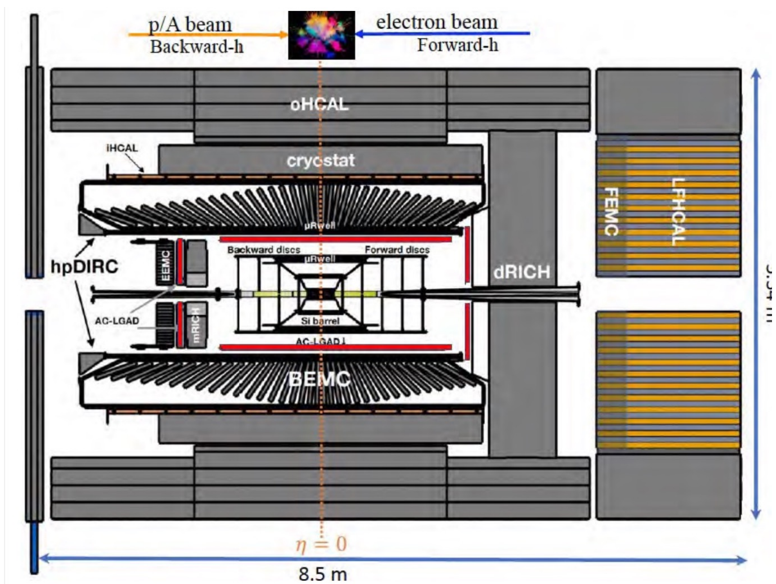


- **First demonstration of simultaneous ~5 µm, ~30 ps resolutions in a test beam: technology for 4D-trackers!**

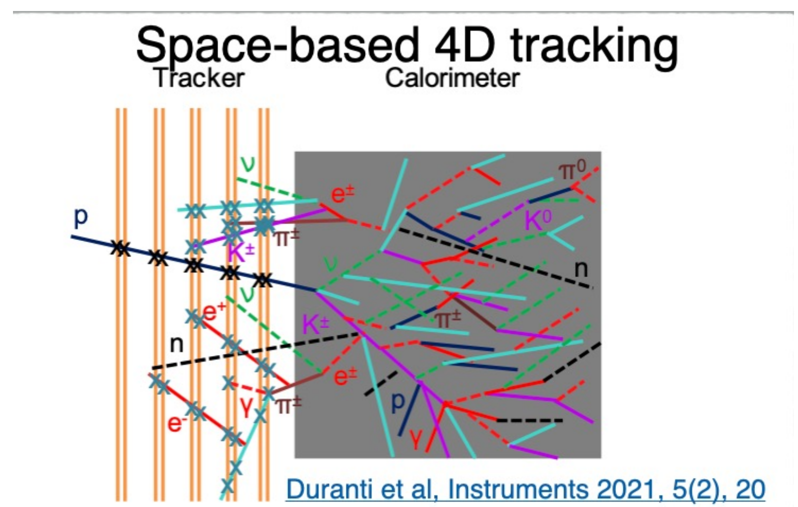
Fermilab

Studies of long AC-LGAD strip sensors

- First studies of large AC-LGAD sensors
  - Technology demonstrator for 4D-tracking and detectors for EIC
  - Multiple sensors, geometries and designs studied in March 2022
- Multi-institutional effort: students, postdocs from US and abroad
  - Key insights for larger sensors
  - Metal vs. pitch size is important for position reconstruction



EIC experiments: TOF PID and tracking



Space-based sensors: power constraints require minimizing number of channels

Large strips campaign

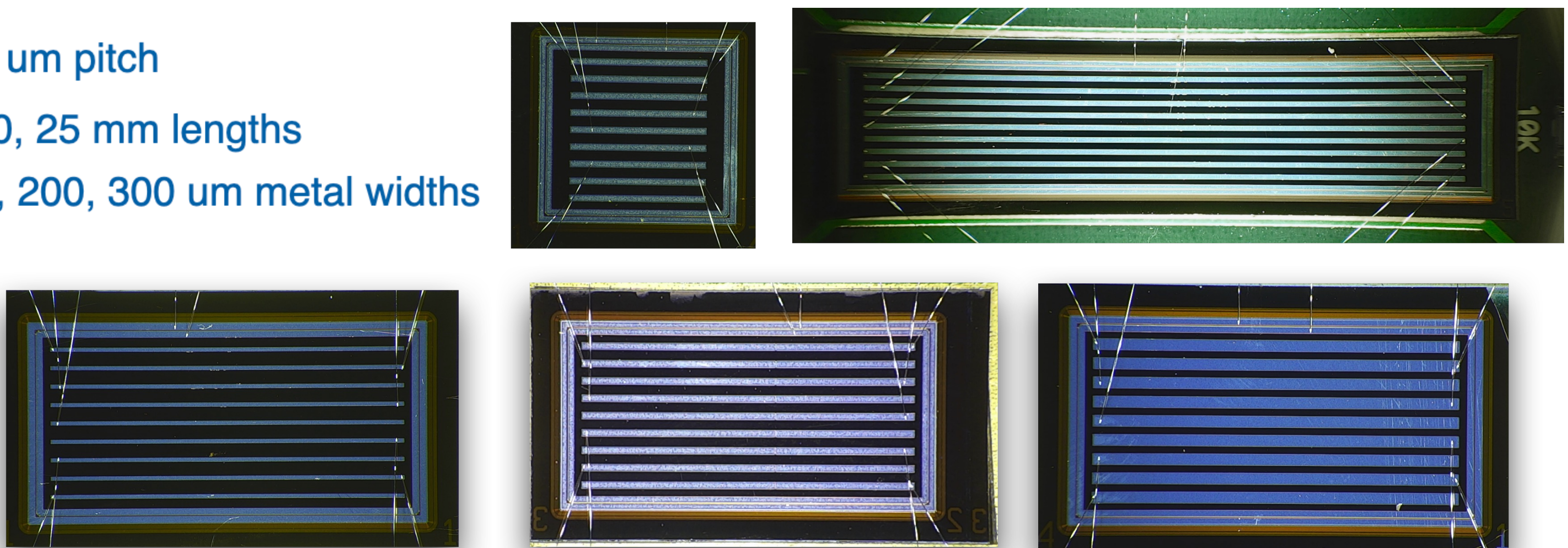
Submitted to JINST
arXiv 2211.09698

- For EiC application, need to demonstrate large area sensors.
  - Extensive campaign to study 15 BNL AC-LGADs in test beam
  - Length 5-25 mm, and pitch 500 µm (10x longer and 5x coarser than previous sensors)
  - Focus on geometry optimization and tradeoffs with longer sensors

500 um pitch

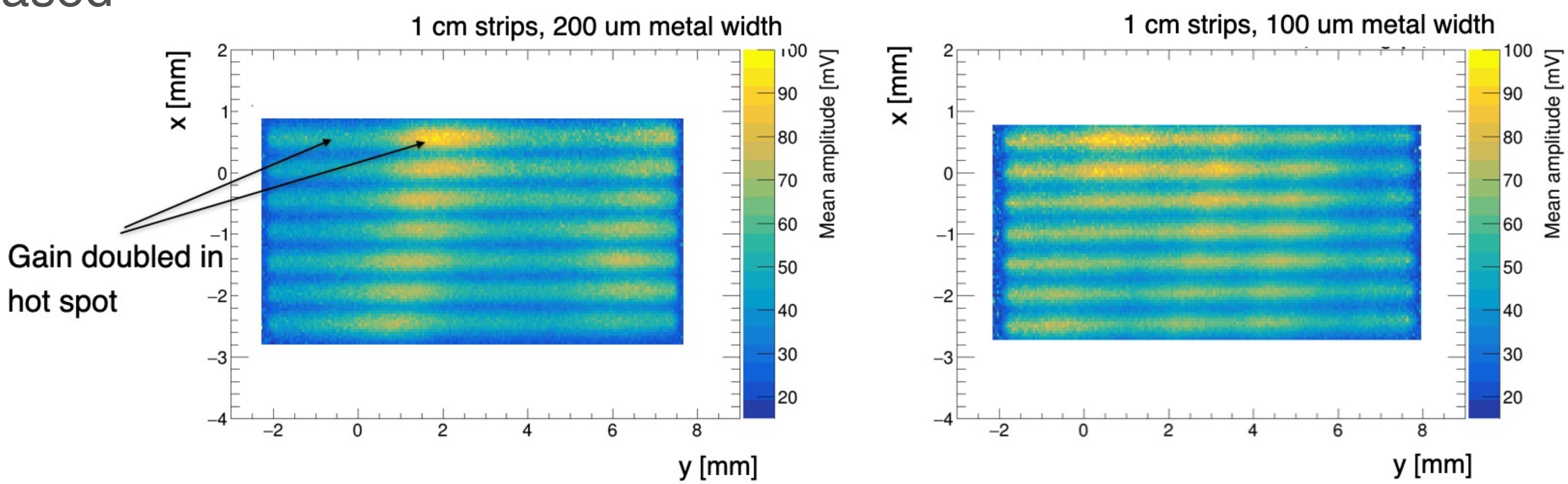
5, 10, 25 mm lengths

100, 200, 300 um metal widths



Gain uniformity over large surfaces

- New challenge with large area: sensitivity to non-uniformity in gain layer
  - Stripe patterns of high gain observed in most sensors of this production
  - High gain regions limit operating voltage → other regions remain under-biased

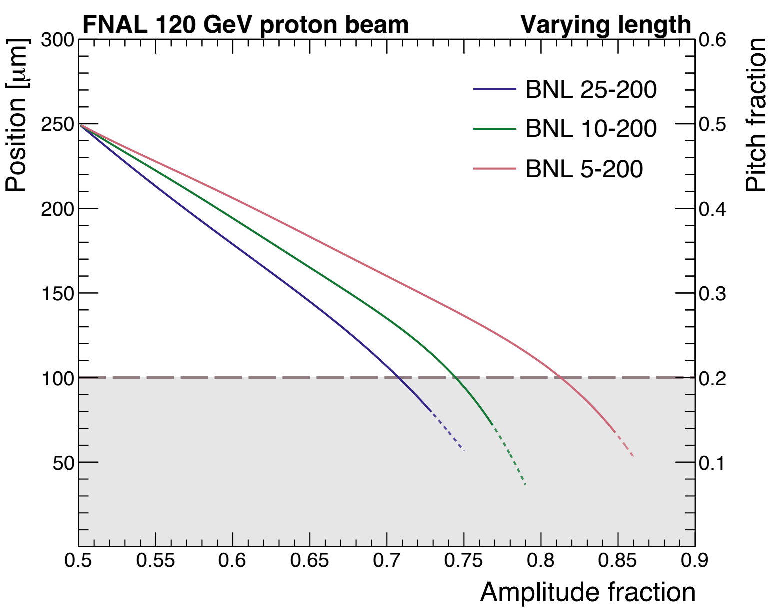


- Expect improved uniformity in next prototypes
  - Uniform 2x2 cm^2 LGADs for ATLAS/CMS have been demonstrated
  - Still extract useful lessons despite non-uniformity!

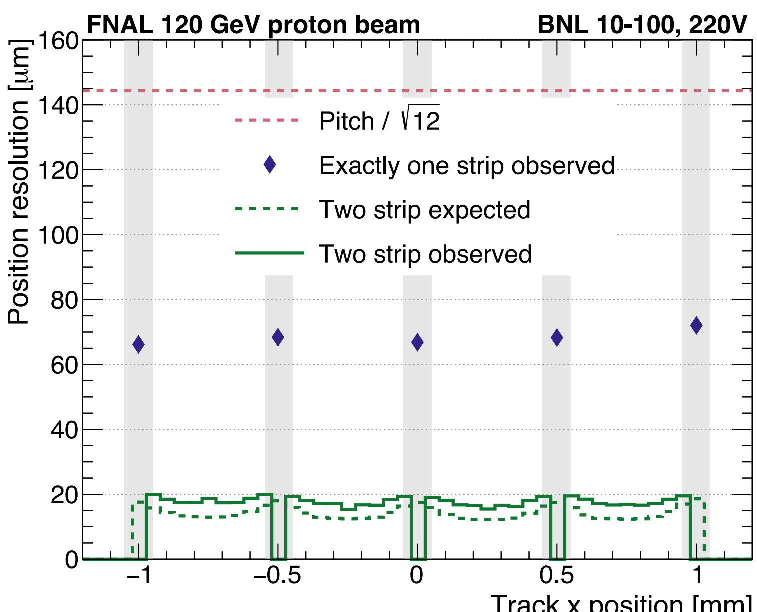
Spatial resolution

- Position reconstruction w/ ratio of amplitudes: robust against non-uniformity.
  - Achieve 15-20 µm resolution for 2-strip events in all 5-10 mm strips
  - Slight degradation from 1-strip events from within metal, or low gain regions

Amplitude ratios for various lengths



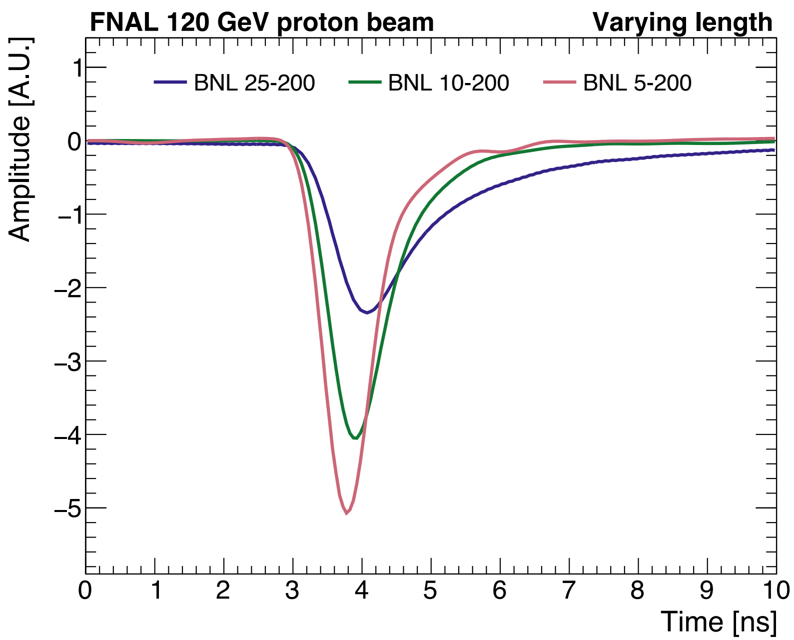
Performance for 1 cm strips, 100 um metal



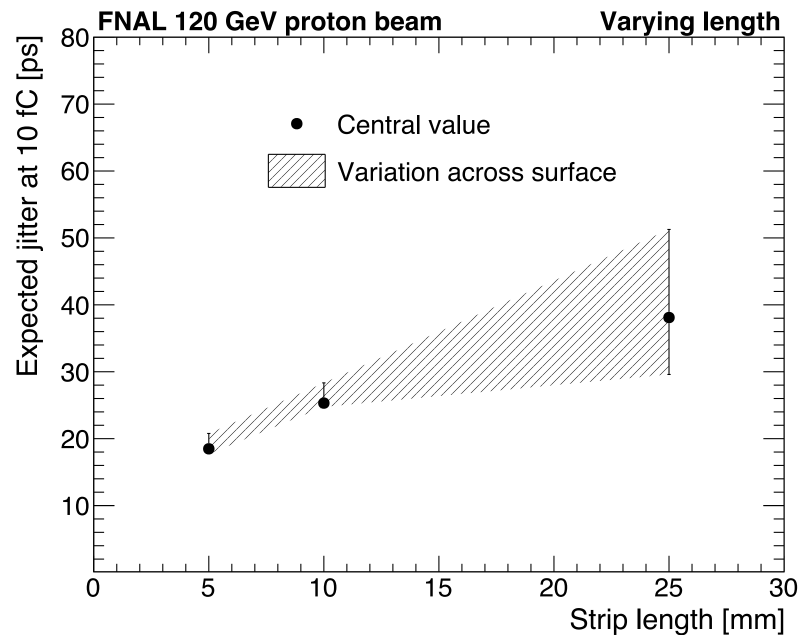
Pulse shapes for precision timing

- Longer strips associated with slower rising edge
  - Likely due to extra capacitance, and transmission line reflection effects

Averaged pulse shapes



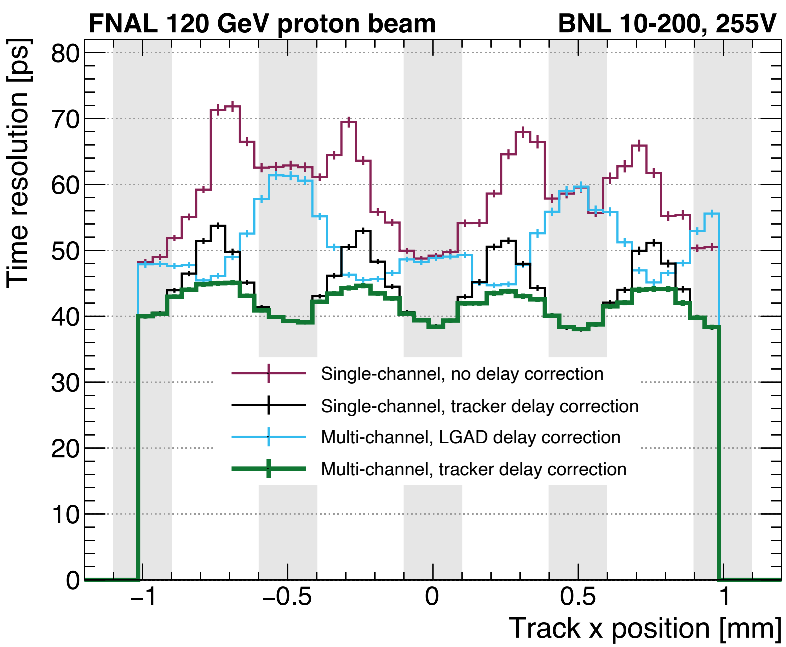
Expected jitter for operation at moderate gain



- 1 cm strips: already work well!
  - > 2 cm: trying few ideas to improve in next beam test.

Time resolution

- Time resolution 40-45 ps for 1 cm strips
  - Combining 2 channels & correcting for position-dependent delays
  - Decent performance even neglecting delays: 50-60 ps.
  - High gain regions— achieve 30-35 ps for 5 to 10 mm strips.
  - Representative of uniform, high gain sensor.



1 cm strips, 200 um metal width, 500 um pitch

	Name	Time resolution
	Unit	High gain ps
5 mm	BNL 5–200	30 ± 1
10 mm	BNL 10–100	35 ± 1
	BNL 10–200	32 ± 1
	BNL 10–300	36 ± 1
25 mm	BNL 25–200	51 ± 1

Summary

- Excellent convergence of expertise and facilities, and strong collaborative effort on development of next-gen sensors

- AC-LGADs provide excellent 4D performance
  - Timing resolution comparable to LGADs, and 100% fill factor
  - Spatial resolution ~20-30x smaller than pitch

- With few modifications, sensors for EIC timing layer are within reach!
  - Improved gain implant uniformity
  - Improved two-strip efficiency, w/ reduced metal width or increased n++ concentration.
  - Mitigation for length effects for > 2 cm sensors.
  - All implemented in latest prototypes to be tested soon