Survey of AC-LGADs for future 4D trackers with a proton beam

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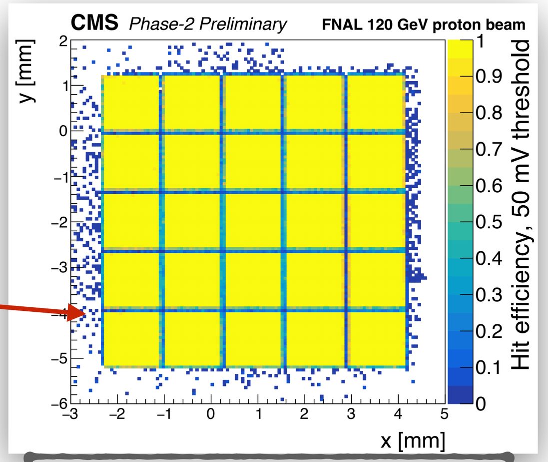
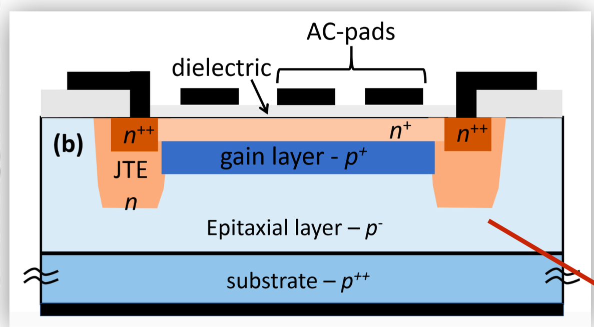
What are AC-LGADs?

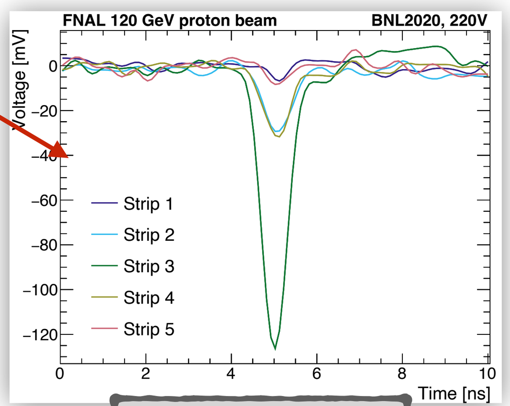
- LGADs: Low Gain Avalanche Detectors
  - Si device with internal gain (10-20): Large signals and low noise
  - Thin (<50 micron depletion region): Uniform field, fast rise-time
- Decreasing LGAD channel size produces sensors with poor fill factor
  - Gain layer termination requires ~50 µm gap size
  - AC-coupled LGADs solves fill factor issue



Hit efficiency of a CMS 5x5 LGAD



- AC-LGADs introduce an n+ layer and does not terminate the gain layer for each channel



Single hit waveform

- Electrons move from n+ to the edge
  - Signal is AC-coupled to metal electrodes from n+
- Introduces signal sharing between channels
  - Interpolating between channels allows for enhanced hit reco.

Why do we need 4D tracking?

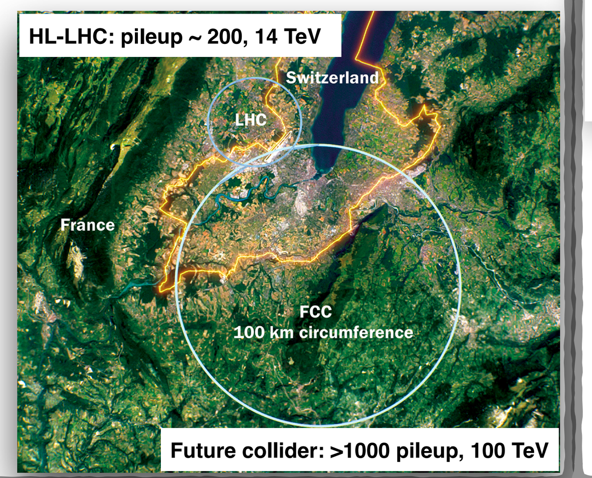
Future machines

- 4D-trackers improve the physics reach of future detectors
  - Reduces beam induced backgrounds
  - Used for track reconstruction and triggering
  - Enhanced capabilities: PID and LLP reconstruction
- Many proposed future machines will need 4D trackers

Machine	Technical requirement
Tracking for e^+e^-	Granularity: 25x50 µm² pixels
	Resolutions of 5 µm and <10 ps
Tracking for $\mu^+\mu^-$	Granularity: 25x25 µm² pixels
	Resolutions of 5 µm and <30 ps
Tracking for 100 TeV pp	Radiation tolerant up to 8x10¹⁷ n/cm²
	Resolutions of 5 µm and <10 ps

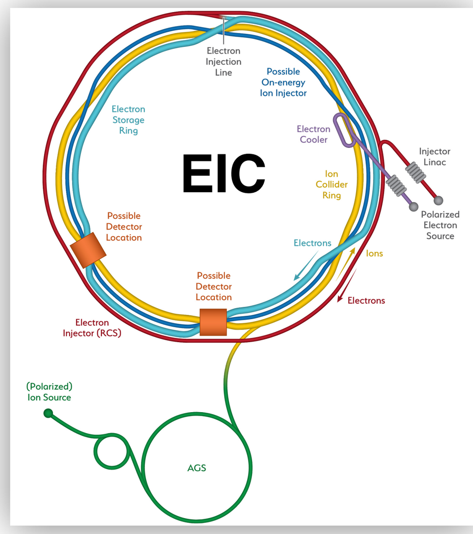
Spatial and time resolution needs for future HEP machines

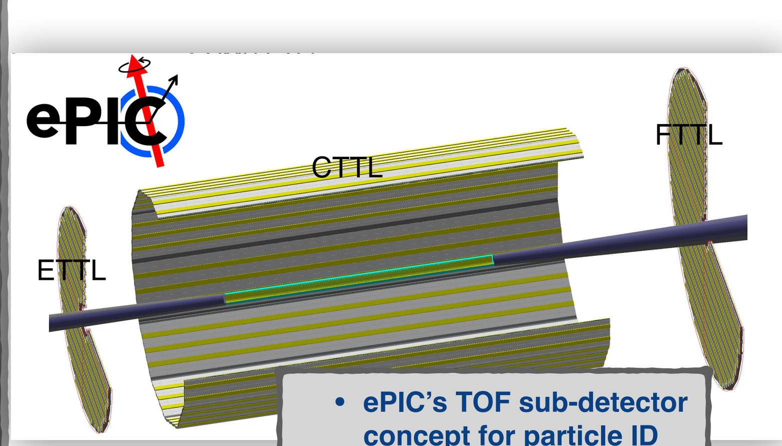
- HL-LHC timing detectors are a major step towards 4D trackers
  - 1.3x1.3 mm² pixels
  - ~375 µm and 30 ps res.
  - Mitigate ~200 pileup impact
- FCC-hh needs are beyond what is possible today
  - Pushing 4D tracking R&D



Electron Ion Collider

- EIC is a future machine hosted at Brookhaven National Laboratory
  - Will study the nature of the strong force
  - For example, precise measurements of proton PDFs and quark-gluon plasma
- The ePIC detector is currently in the R&D phase
  - Needs precise particle tracking
  - Particle ID using time-of-flight (TOF) information is critical for the physics needs





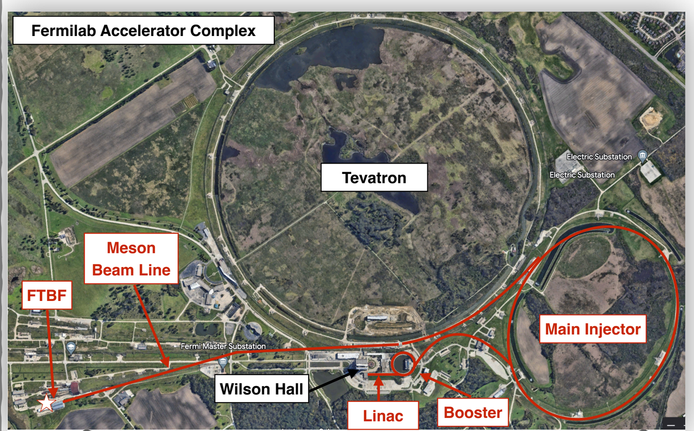
ePIC's TOF sub-detector concept for particle ID

- AC-LGADs are a good candidate for many ePIC of sub-detectors
- Exploiting signal sharing allows for larger channel size

	Area (m^2)	Time resolution	Spatial resolution	Material budget
Barrel Timing Tracking Layer	11	30 ps	30 μm in $r \cdot \phi$	0.01 X_0
Endcap Timing Tracking Layers	1.2+2.2	25 ps	30 μm in x and y	0.08 X_0
B0 Tracker	0.07	30 ps	$500/\sqrt{12}\ \mu m$	0.01 X_0
Roman Pots	0.14	30 ps	$500/\sqrt{12}\ \mu m$	no strict req.
Off-Momentum Detectors	0.08	30 ps	$500/\sqrt{12}\ \mu m$	no strict req.

Spatial and time resolution needs for a given ePIC sub-detector

Setup at the Fermilab Test Beam Facility



Fermilab Accelerator Complex

- A survey of AC-LGADs has been performed [1-2]
- All measurements are conducted at Fermilab Test Beam Facility (FTBF)
  - Main Injector provides 120 GeV protons
- Good position and time reference are critical
  - FTBF telescope: track position ($\sigma \sim 5\ \mu m$)
  - MCP-PMT: time reference ($\sigma \sim 10$ ps)
- FTBF has been critical in establishing LGAD technology, design optimization, and makes way for future 4D detectors

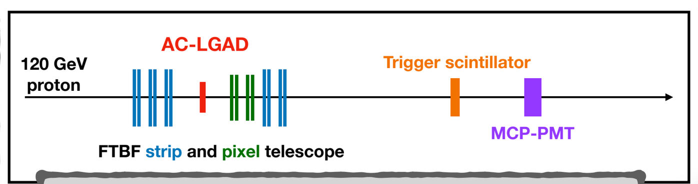
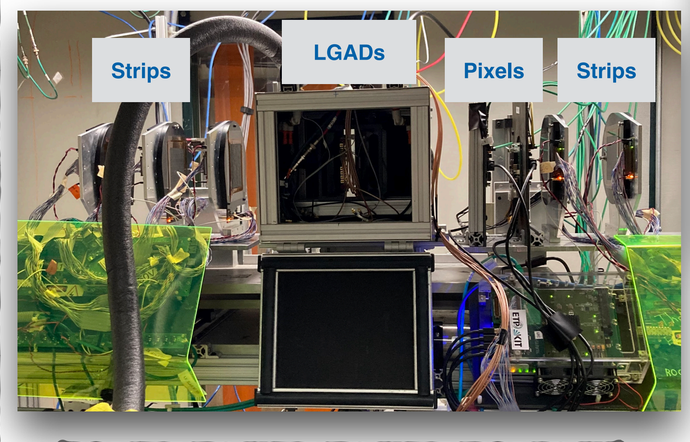
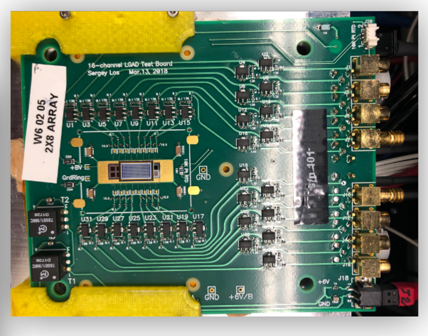


Diagram of the setup along beam line



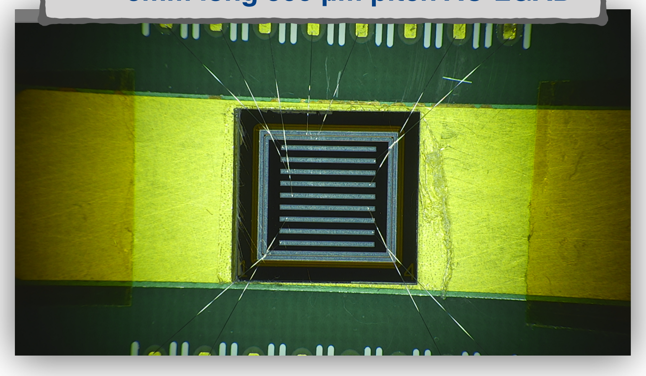
Dark box within FTBF telescope



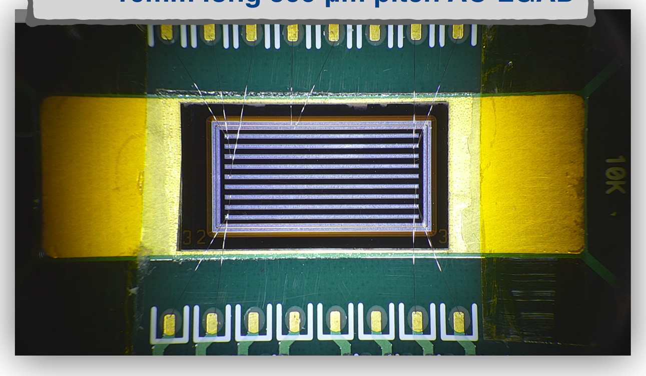
- Sensors are mounted onto Fermilab 16-channel board
- Signals can be readout directly with an oscilloscope

- Readout utilizes Lecroy scope for detailed waveform processing
- Process ~100k events per 4 second spill

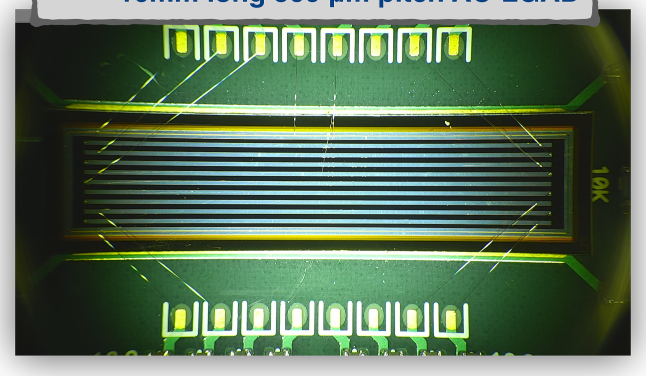
Large area strips



5mm long 500 µm pitch AC-LGAD

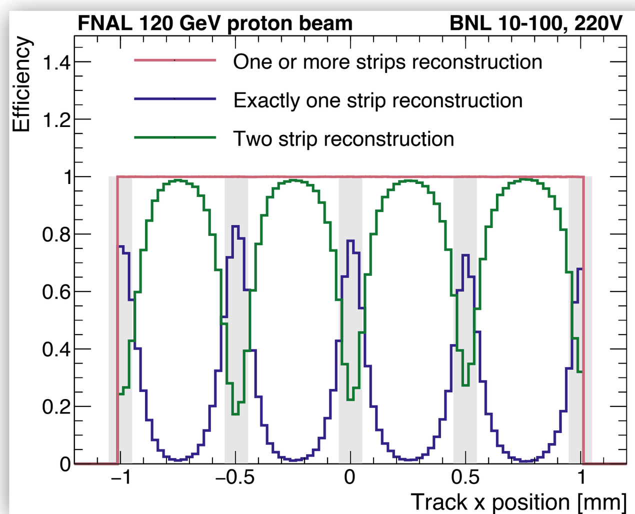


10mm long 500 µm pitch AC-LGAD

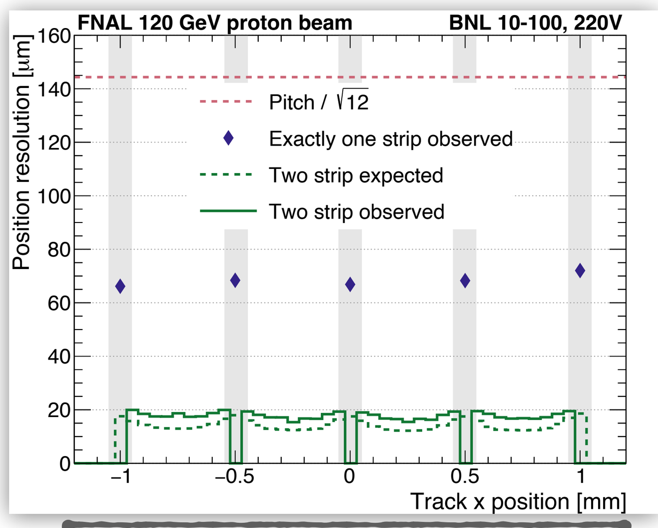


10mm long 500 µm pitch AC-LGAD

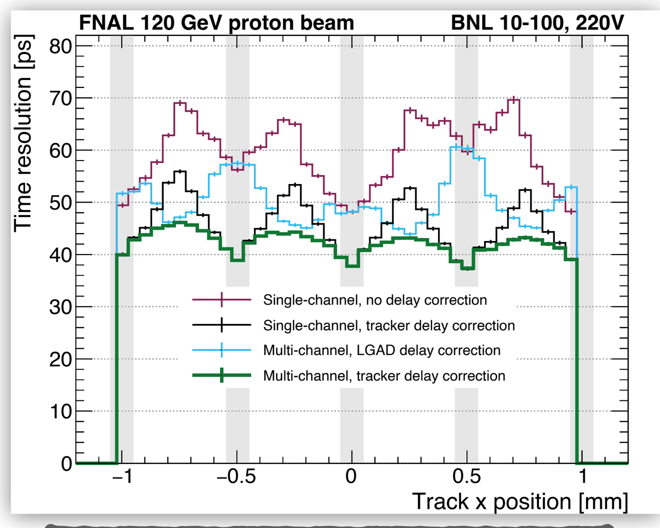
- Large pitch (500 µm) strip AC-LGADs targeting the ePIC TOF detector [1]
  - Exploiting signal sharing allows for position reco. resolution equivalent to sensors with ~10x the channel count
  - Measures performance of various strip lengths: 5mm, 10mm, and 25mm lengths
- The resolutions obtained with several prototypes are presented, reaching simultaneous 18 µm and 32 ps resolutions
- With only slight modifications, these sensors would be ideal candidates for a 4D timing layer at the EIC



Hit efficiency as a function of track x position

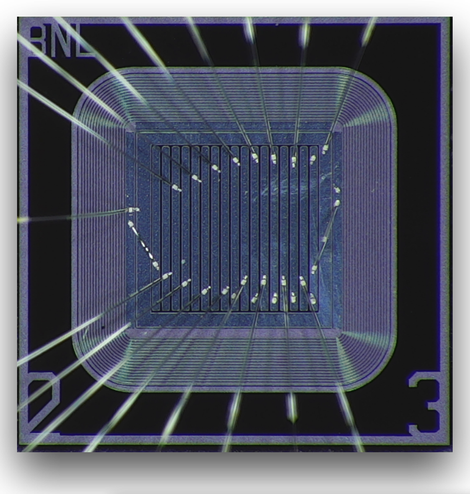


Position resolution as a function of track x position

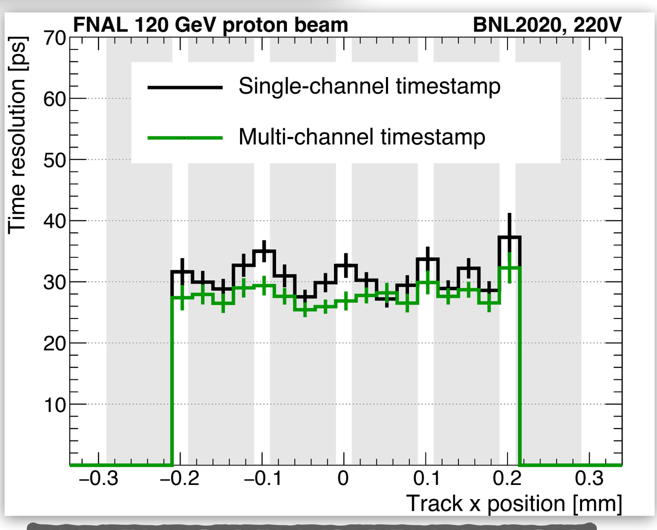


Timing resolution as a function of track x position

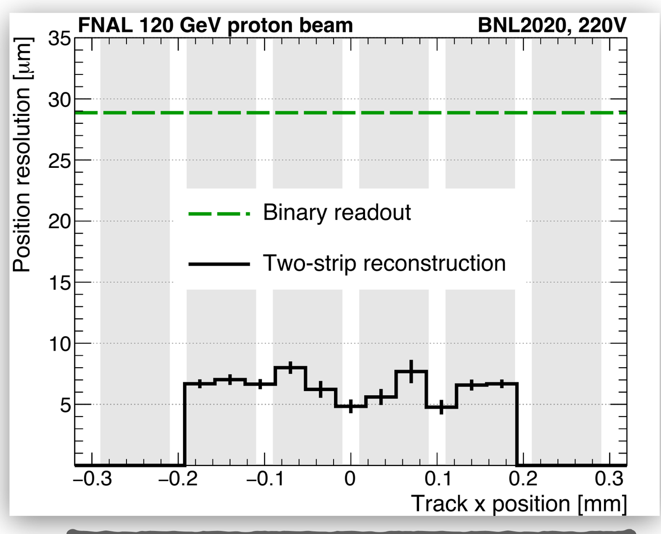
High resolution strips



- AC-LGAD strips with relatively narrow pitch (100 µm) have been measured [2]
  - Again, utilizing signal sharing allows us to achieve great position resolution
- We present a world's first demonstration of silicon sensors in a test beam that simultaneously achieve better than 6-10 µm position and 30 ps time resolution
- This device is promising for future 4D tracker
  - Moving forward we will explore longer strips (~1 cm)



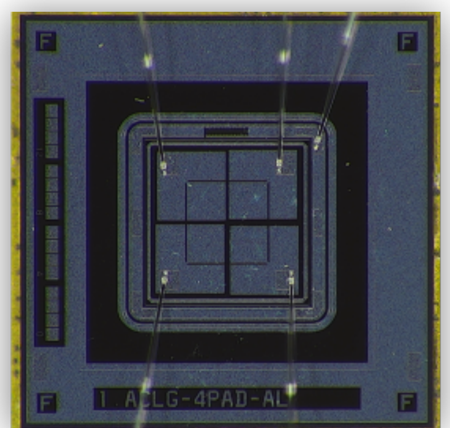
Timing resolution as a function of track x position



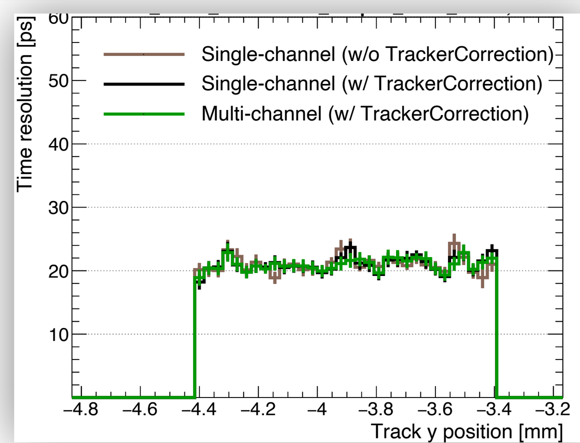
Position resolution as a function of track x position

Thin pixels

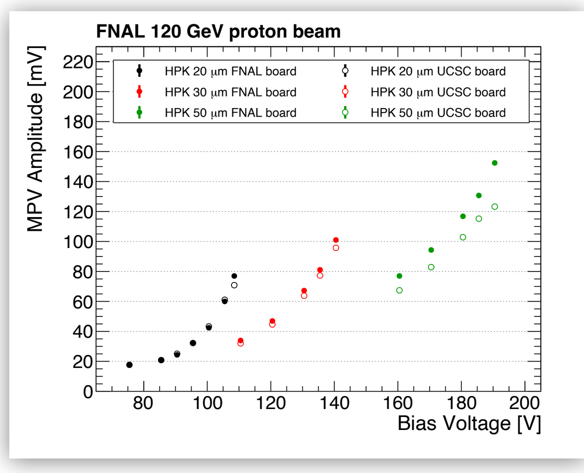
- The time resolutions for LGADs has been well established to be ~30 ps for 50 µm thick sensors
  - The thickness of the sensor is the limiting factor for the time resolution
  - Limiting the Landu fluctuations of the Si and charge particle is the next step
- AC-LGADs with active thickness of 20, 30, and 50 µm have been measured
- The time resolution now reaches a uniform ~ 20 ps for these devices



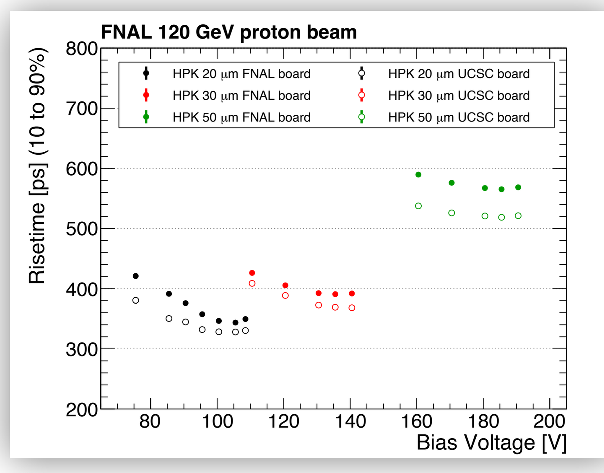
500x500 µm² AC-LGAD



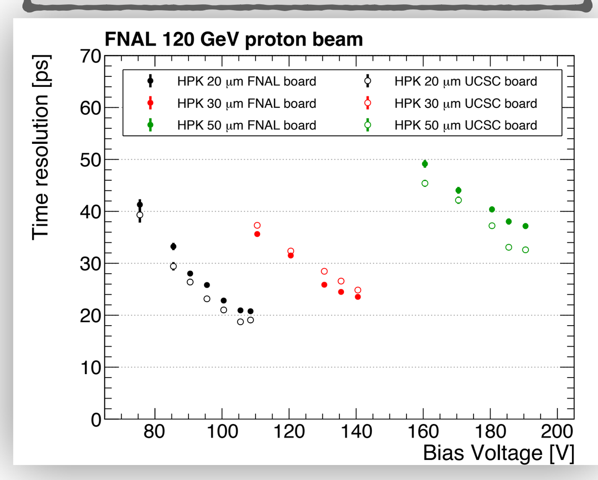
Time resolution as a function of track y position



Signal amplitude vs. Bias Voltage



Risetime vs. Bias Voltage



Time resolution vs. Bias Voltage

Conclusions

- A survey of many AC-LGADs scanning channel size and active thickness has been presented
- Look forward to future 4D trackers, AC-LGADs are a prime candidate for EIC's ePIC detectors and show promise for tracking at future HEP colliders

Acknowledgement and references

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[1] C. Madrid, et al., First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam (2022). arXiv:2211.09698
[2] R. Heller, C. Madrid, et al., Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam, JINST 17 (05) (2022) P05001. arXiv:2201.07772, doi:10.1088/1748-0221/17/05/p05001

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