First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam

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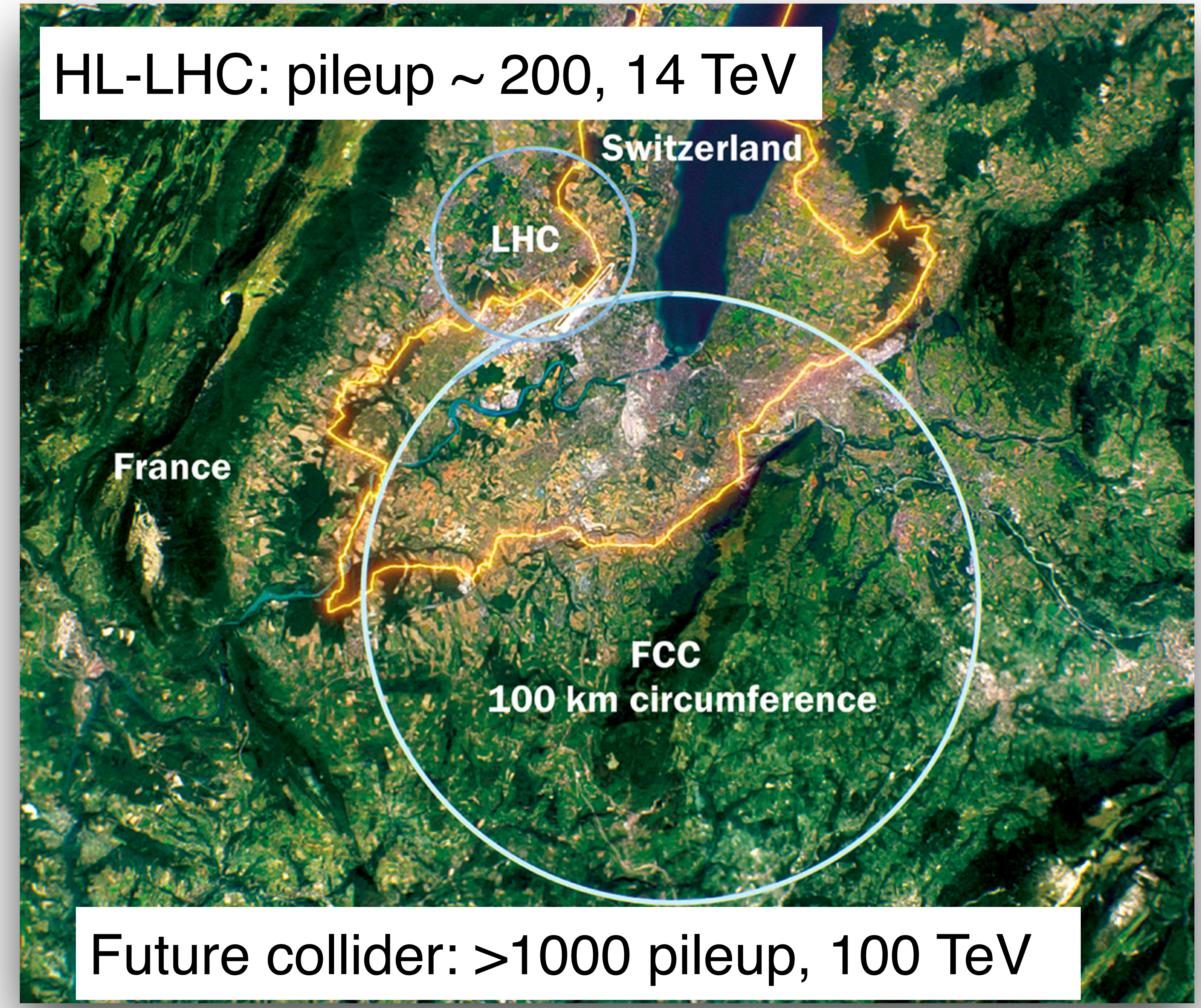
Future trackers need timing

- 4D-trackers will play a key role at 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

- HL-LHC timing detectors are a major step towards 4D trackers
  - LGADs with 1.3x1.3 mm^2 pixels
  - Resolutions of ~375 µm and 30 ps

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 25x50 μm^2 pixels
	Resolutions of 5 µm and <10 ps
Tracking for $\mu^+\mu^-$	Granularity: 25x25 μm^2 pixels
	Resolutions of 5 µm and <30 ps
Tracking for 100 TeV pp	Radiation tolerant up to $8x10^{17}$ n/cm^2
	Resolutions of 5 µm and <10 ps

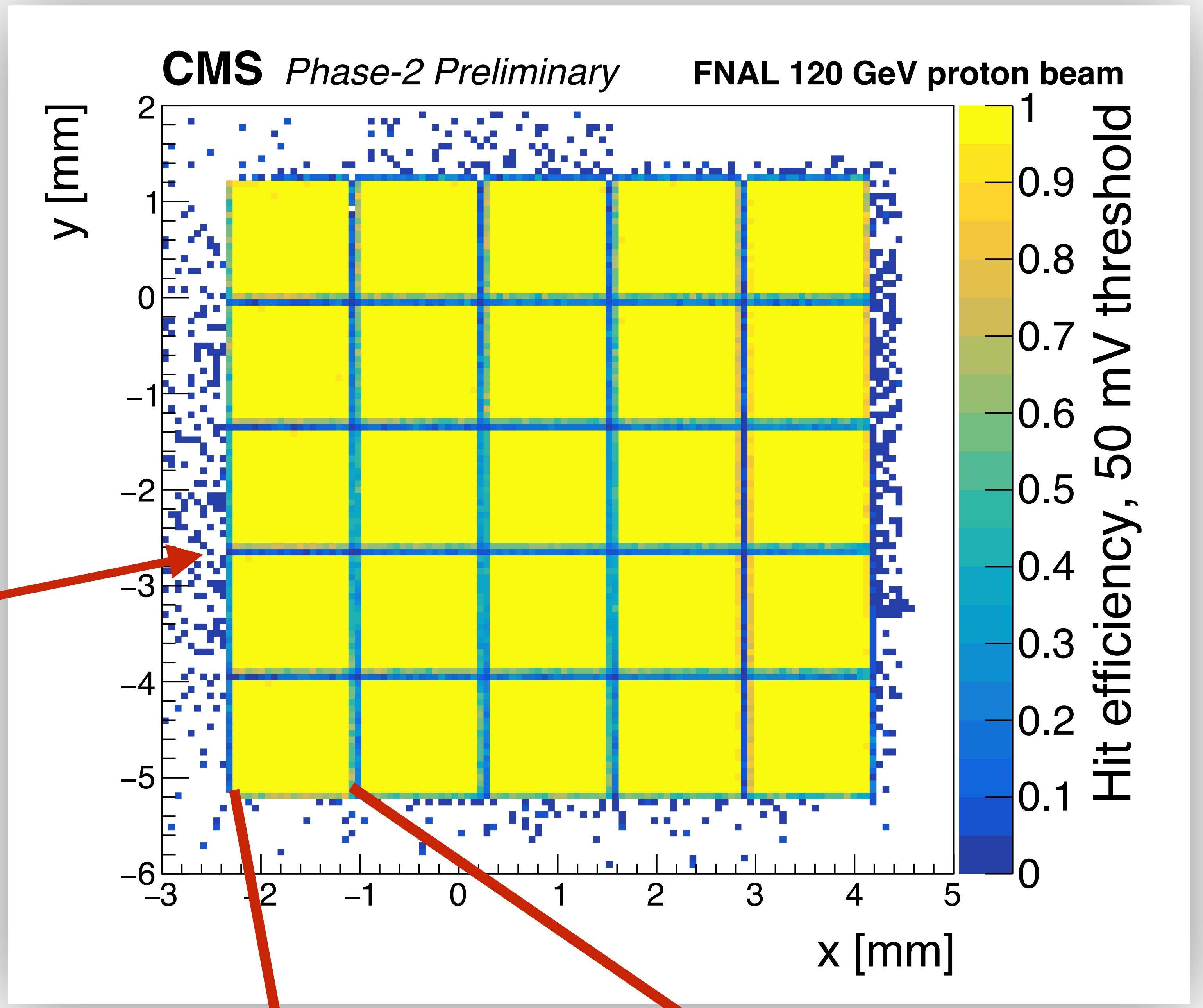
Technical requirements for future trackers:
from DOE's HEP BRN and Snowmass 4D tracker whitepaper



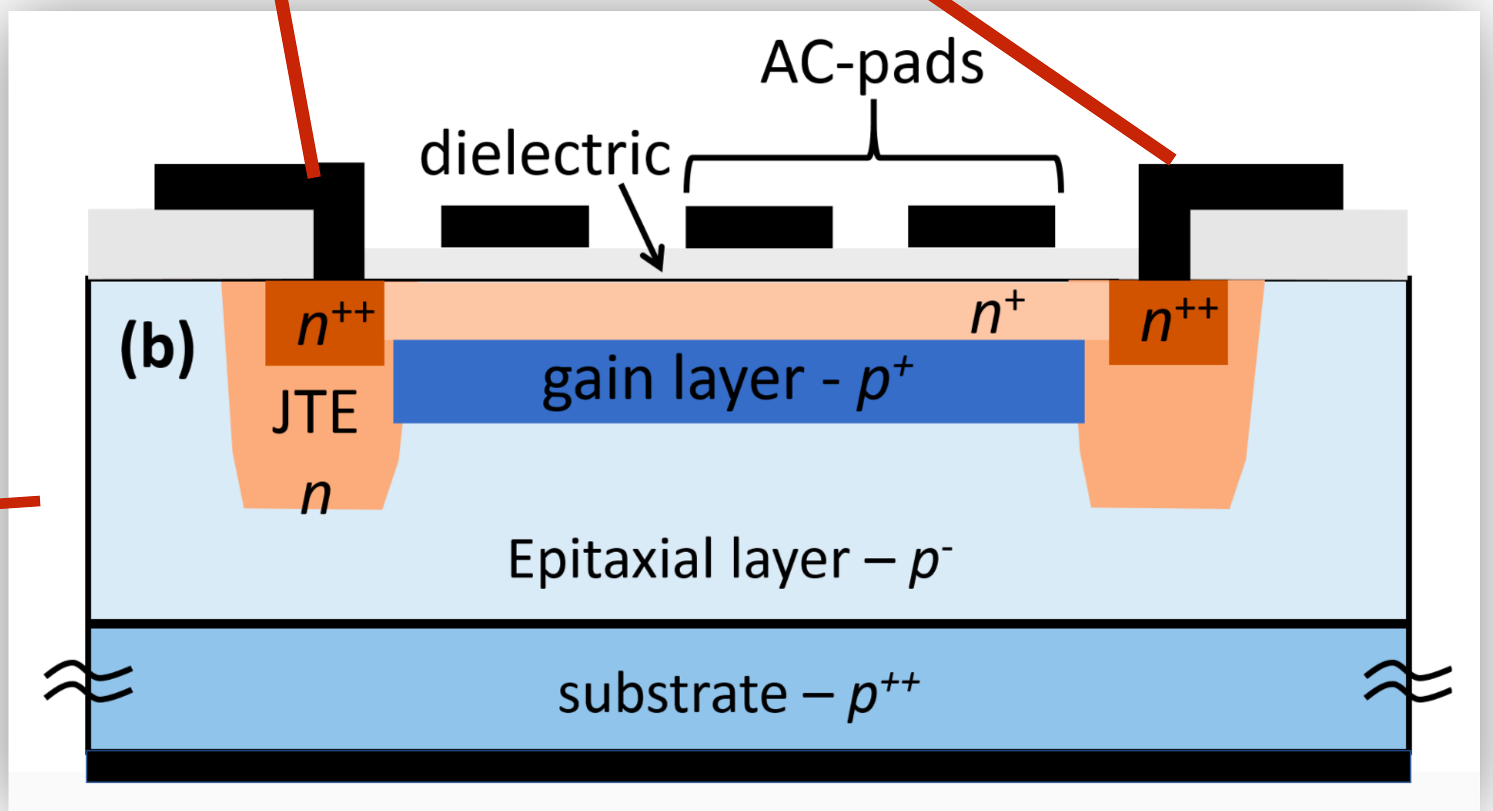
AC-coupled LGADs

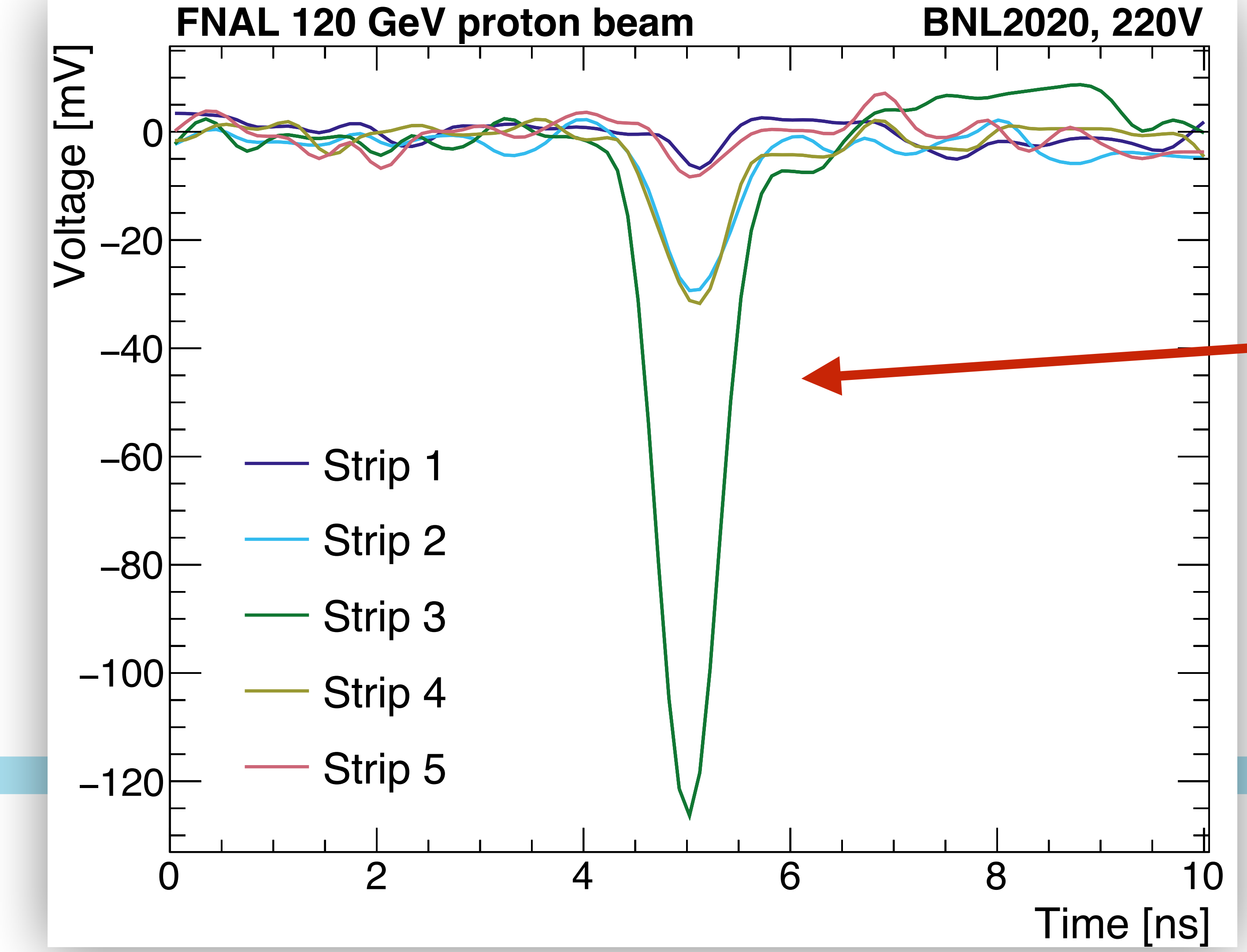
- Decreasing LGAD channel size from millimeter to the micron scale produces sensors with poor fill factor
  - Gain layer termination requires ~50 µm interchannel gap size
- AC-LGADs solve this issue
  - 100% fill factor, and fast timing information at a per-pixel level
  - Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge
    - Simultaneously improve position resolution via signal sharing
- Signal sharing allows for improved position resolution
  - Interpolating between channels

Hit efficiency across surface of CMS 5x5 FBK LGAD



~50 µm gap size





arXiv:1906.11542

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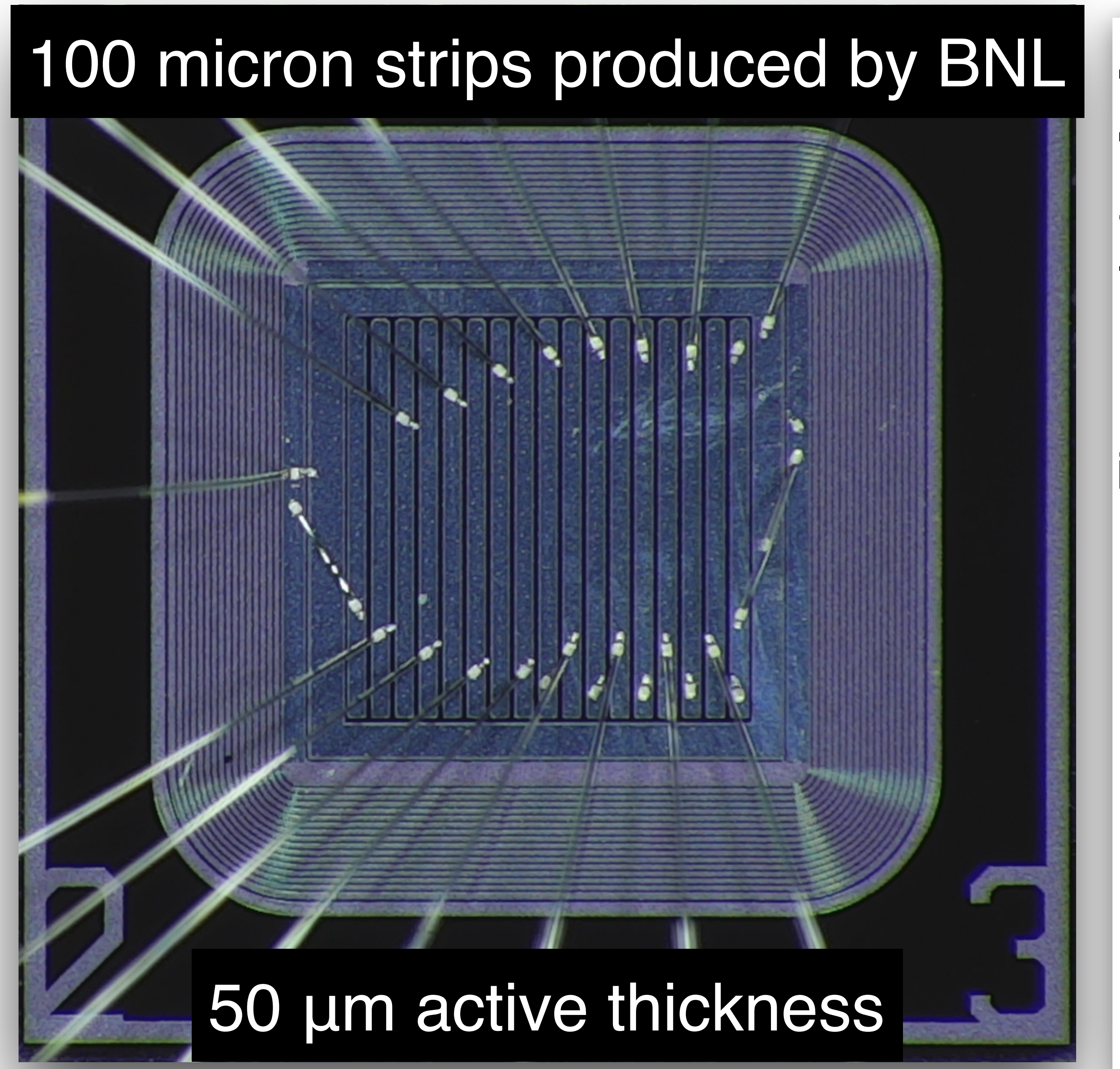
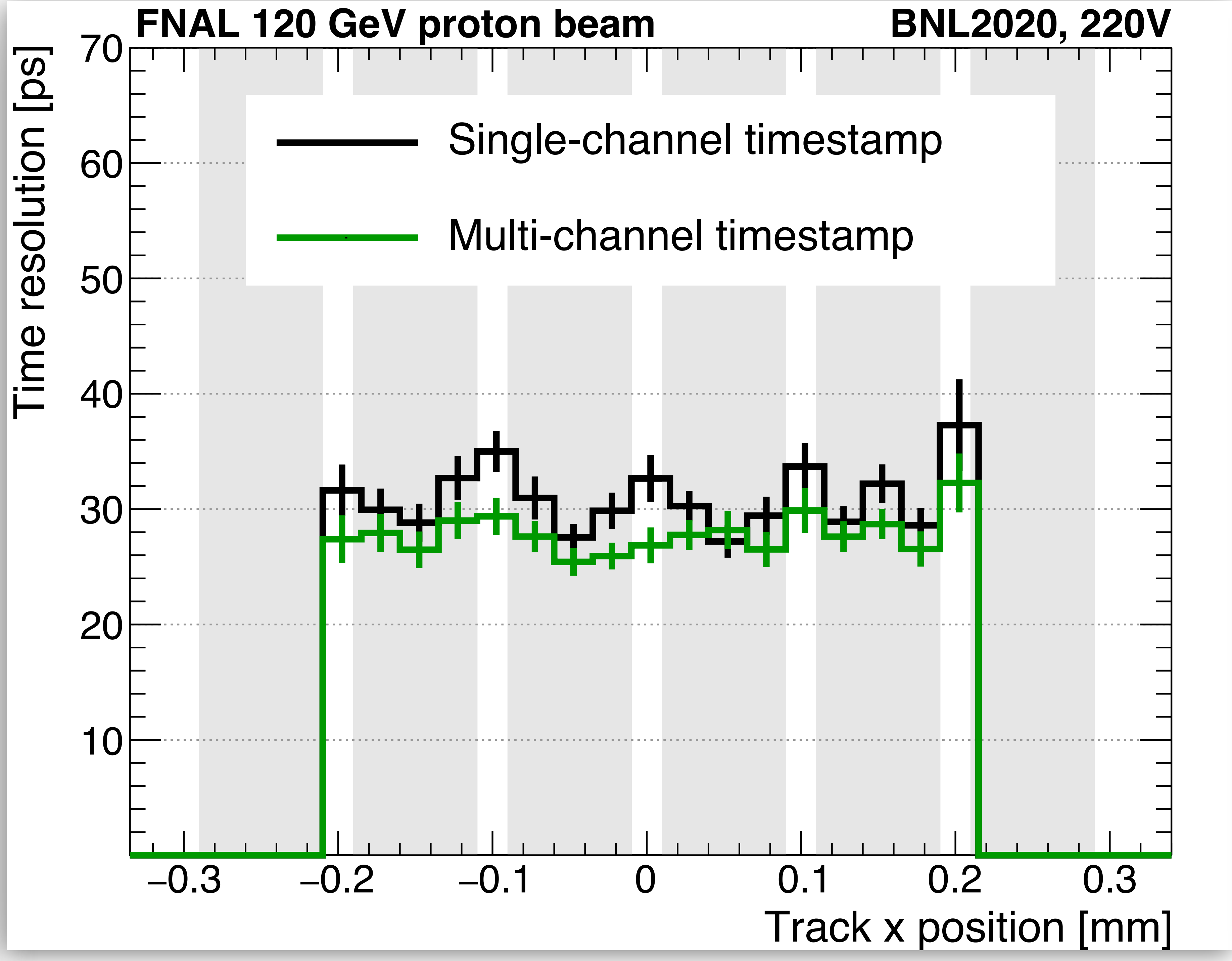
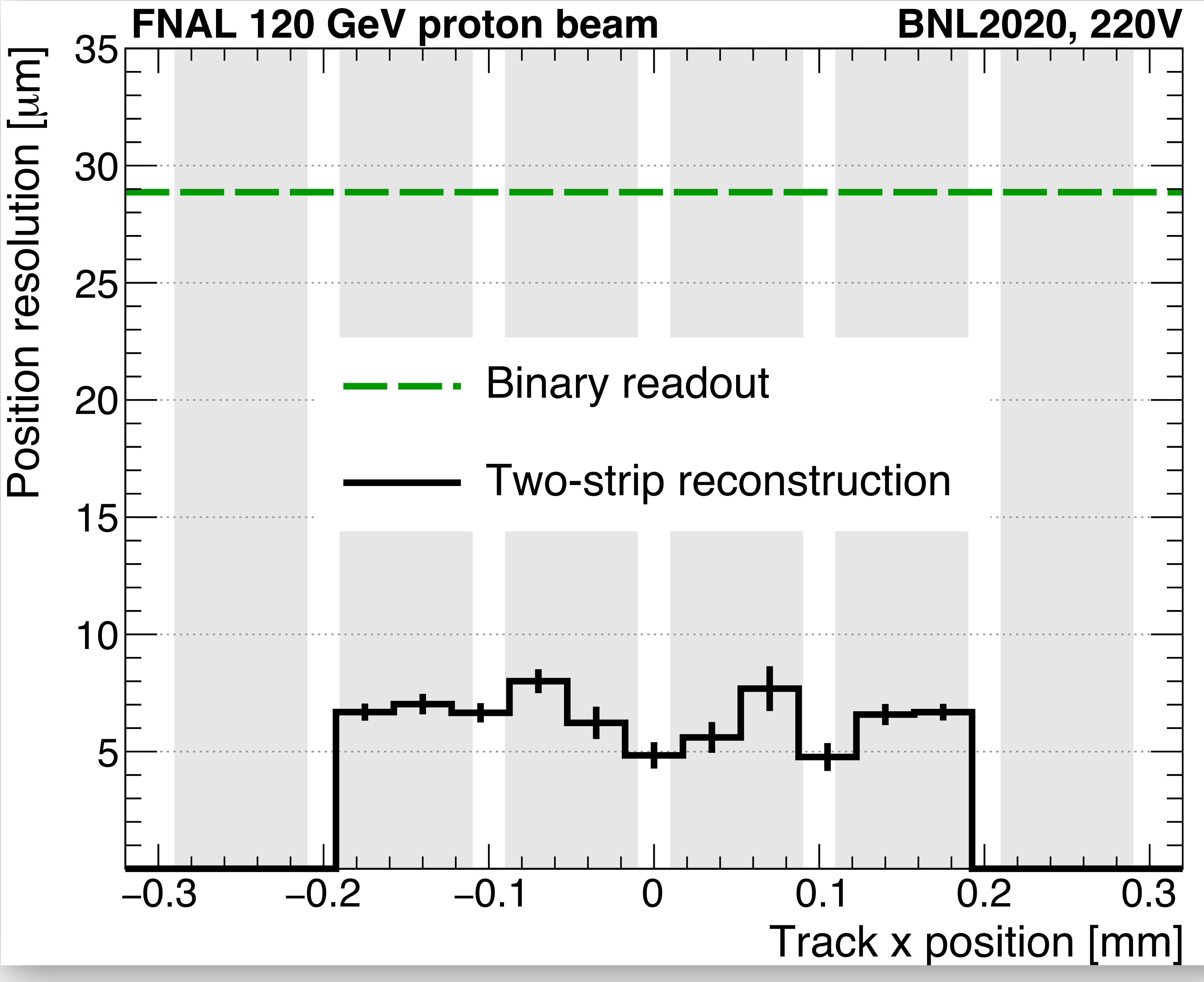
High resolution AC-LGAD strips

- Excellent performance from several BNL 100 to 200 µm strip prototypes
  - Well-tuned signal sharing → uniform 2-strip efficiency





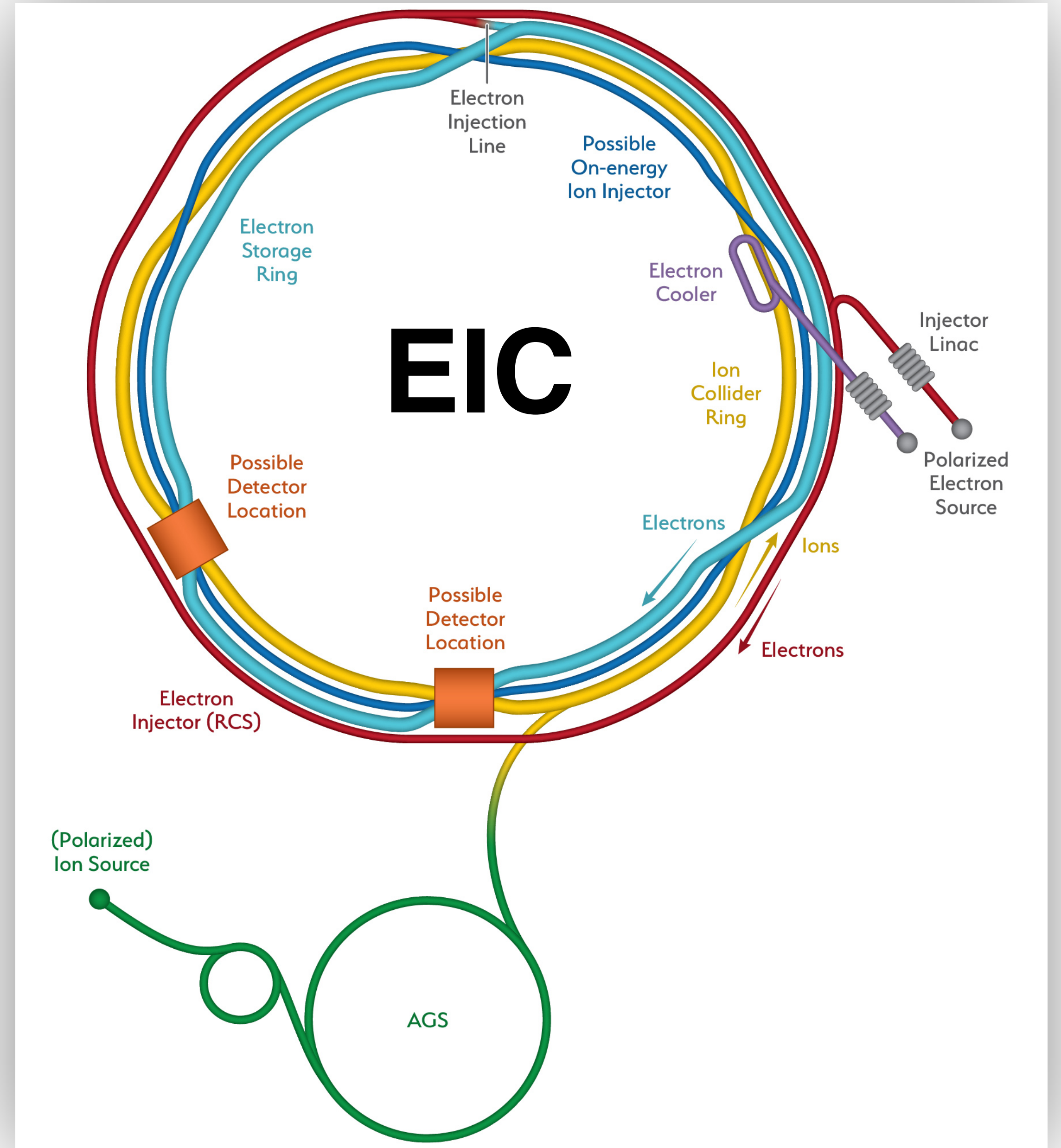


2022 JINST 17 P05001

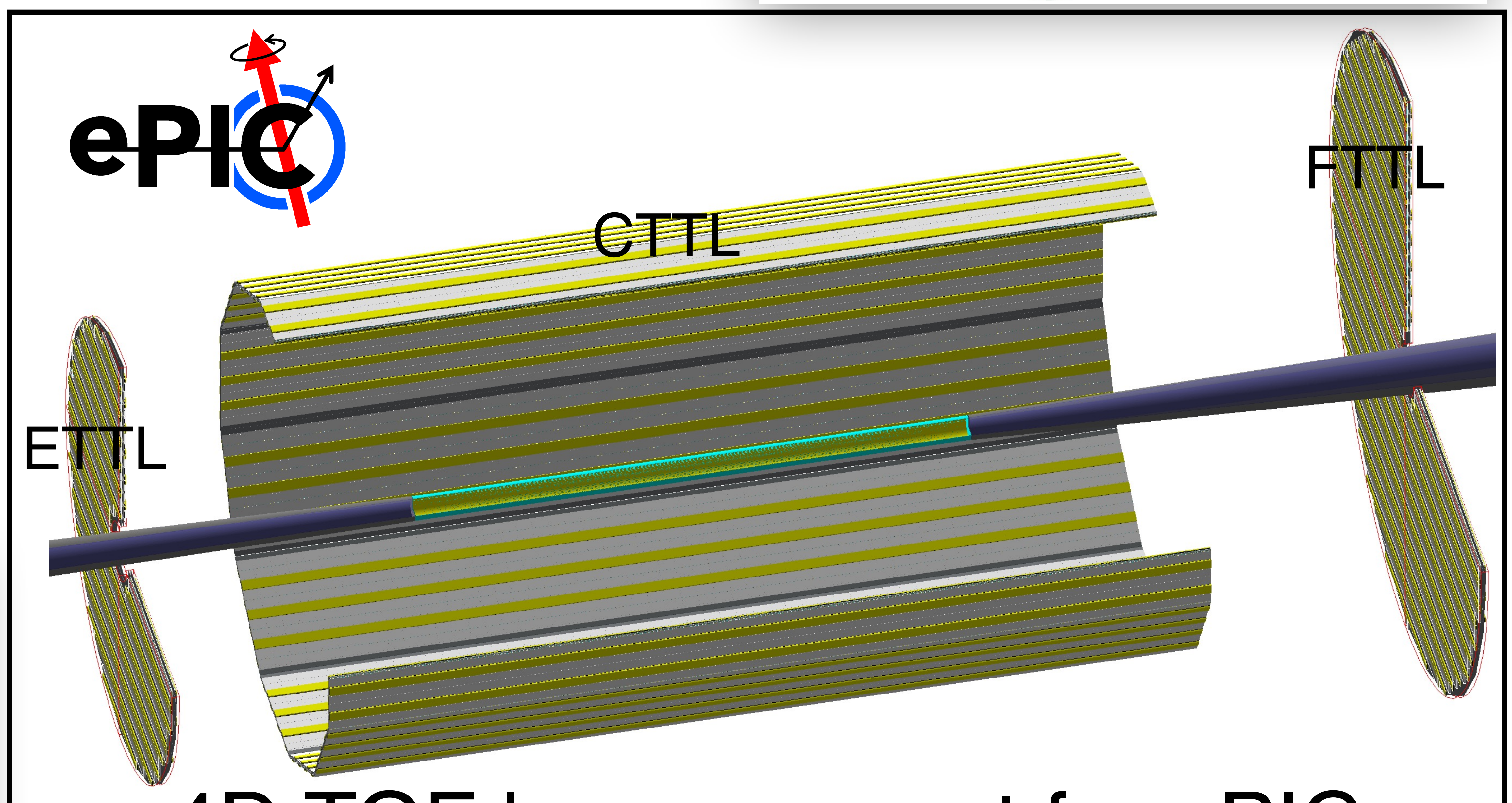
- Promising 4D sensors: 26-30 ps timing and 5-10 µm resolution
- Where do we go from here?

Large-area AC-LGAD strips

- Alternate direction: maintain performance with much sparser readout
  - High precision (time & space) with coarser readout & few channels
- Promising approach at the Electron Ion Collider for the ePIC detector's TOF layer
  - Particle ID via time of flight
- Considering centimeter length sensors with 500 µm pitch
  - Various 4D tracker needs



	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	$500/\sqrt{12}$ μm	0.01 X_0
Roman Pots	0.14	30 ps	$500/\sqrt{12}$ μm	no strict req.
Off-Momentum Detectors	0.08	30 ps	$500/\sqrt{12}$ μm	no strict req.



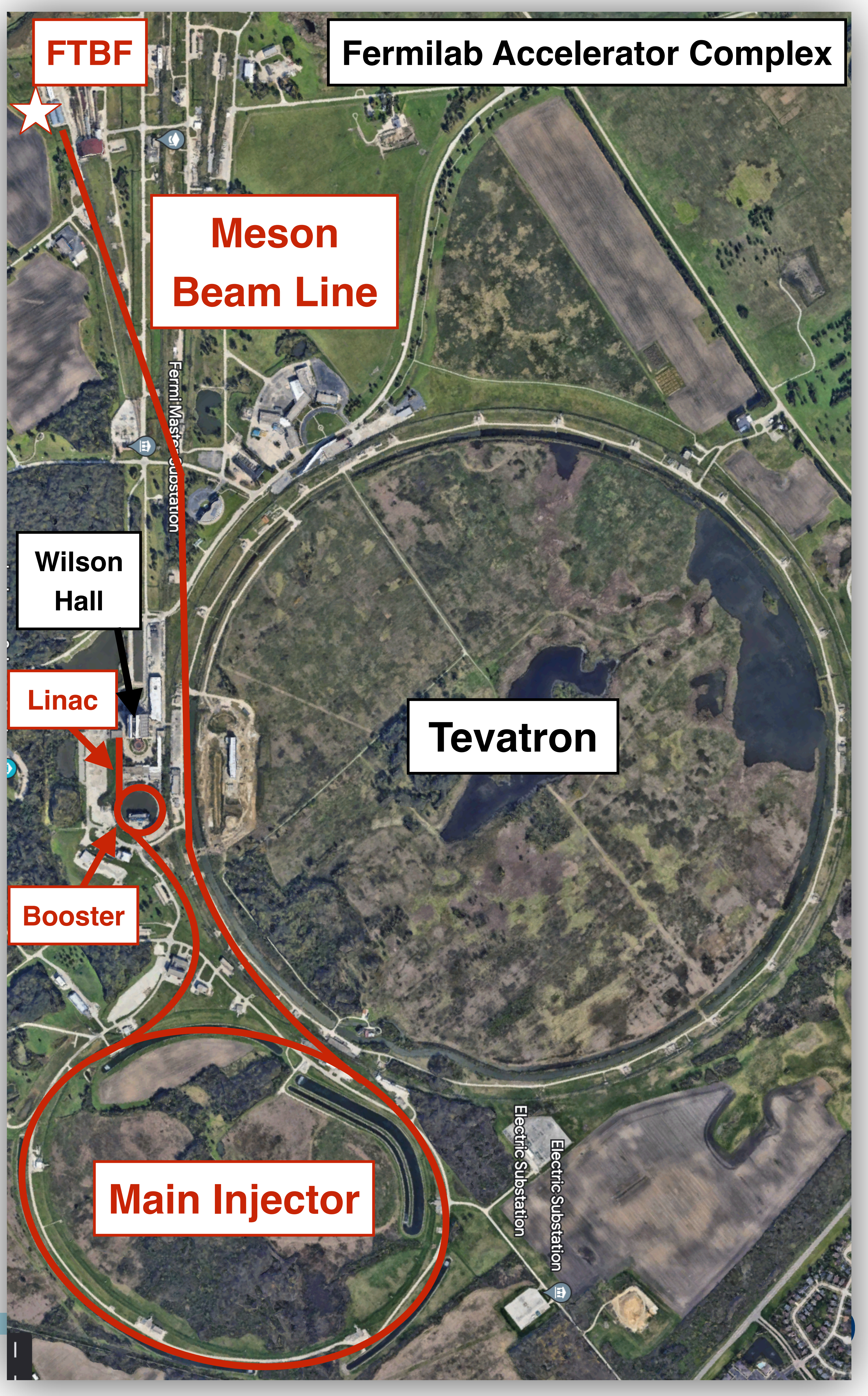
4D TOF layer concept for ePIC

Testing large-area AC-LGAD sensors

- **All measurements conducted at Fermilab Test Beam Facility (FTBF)**
  - Results based on two separate test beam campaigns
  - Used 120 GeV proton beam from main injector

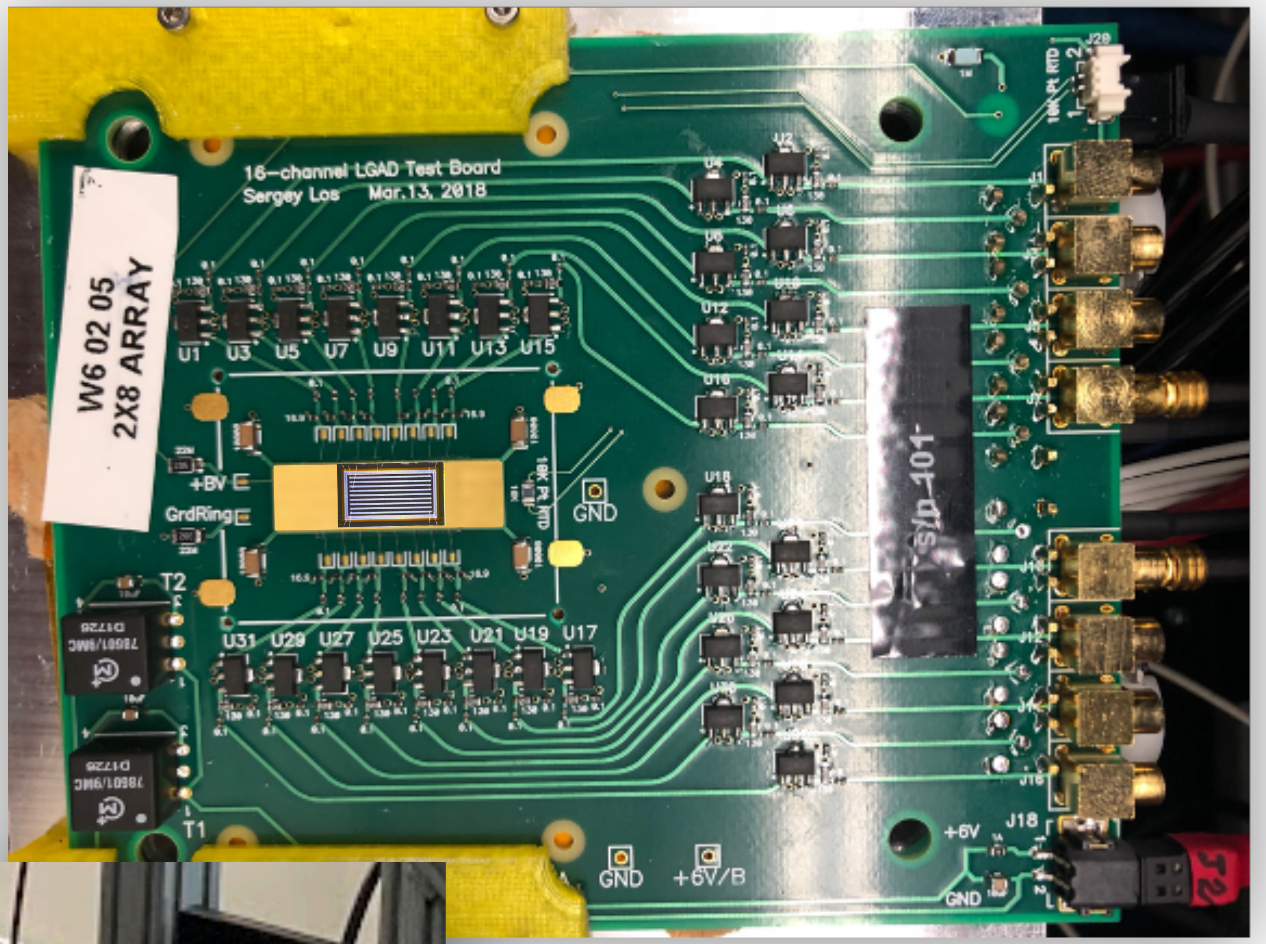
- **First beam test in March 2022** focusing on first batch of long strip BNL sensors
  - Paper detailing 2022 beam test results (arxiv.2211.09698)

- **Second beam test concluded in January 2023** on second batch of long strip BNL sensors and HPK pixels with thickness variation

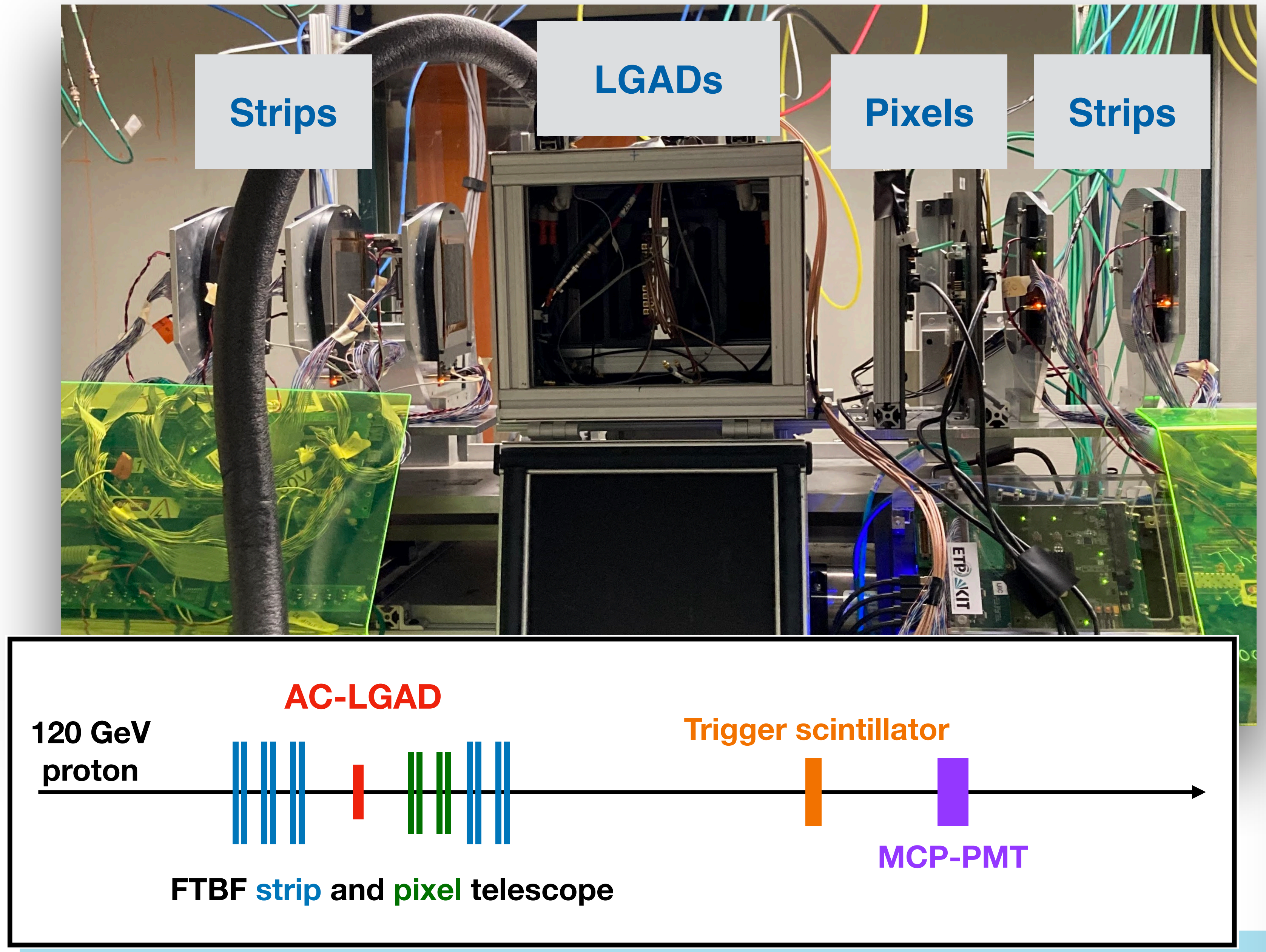


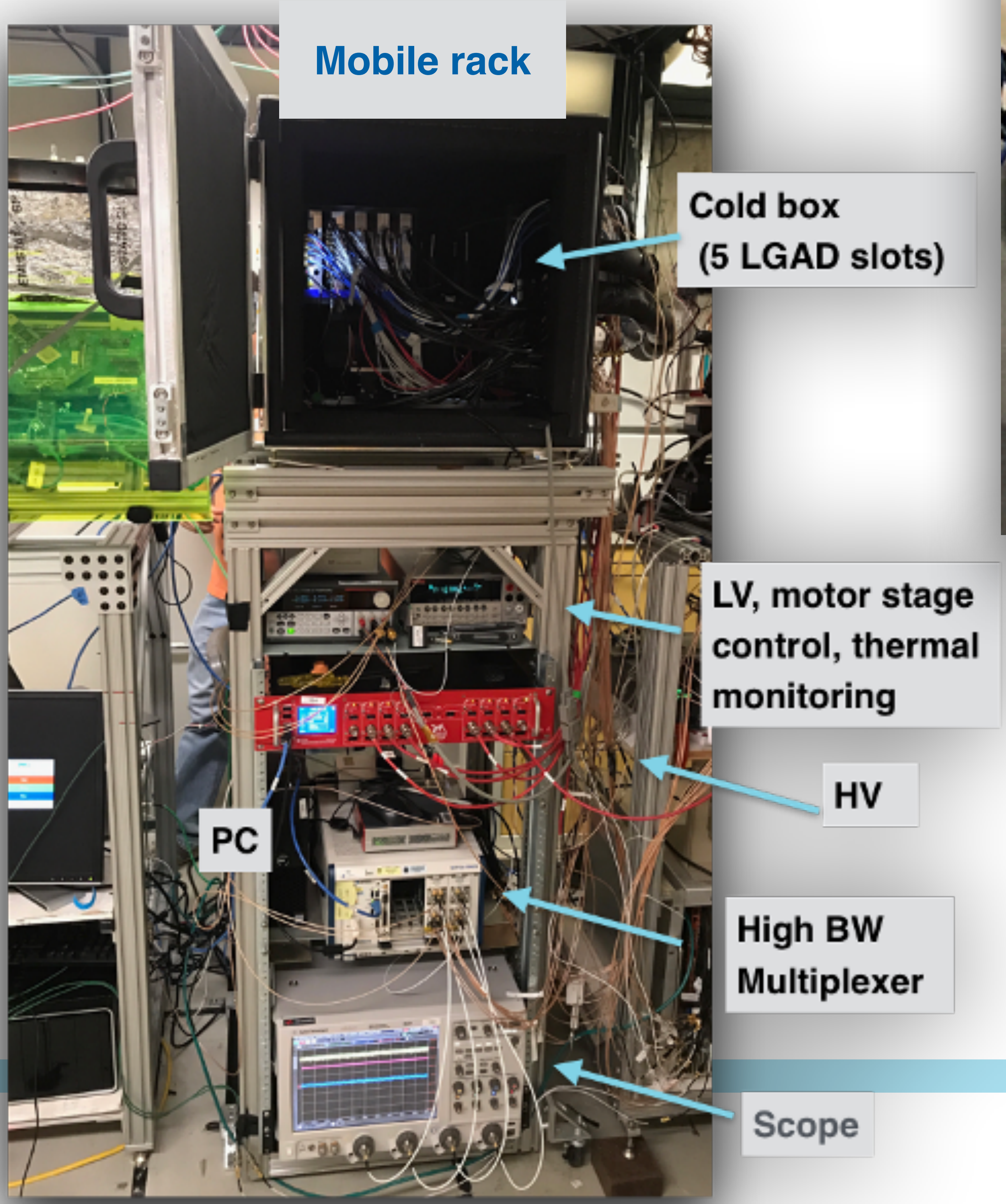
Fermilab 4D-trackers test beam infrastructure

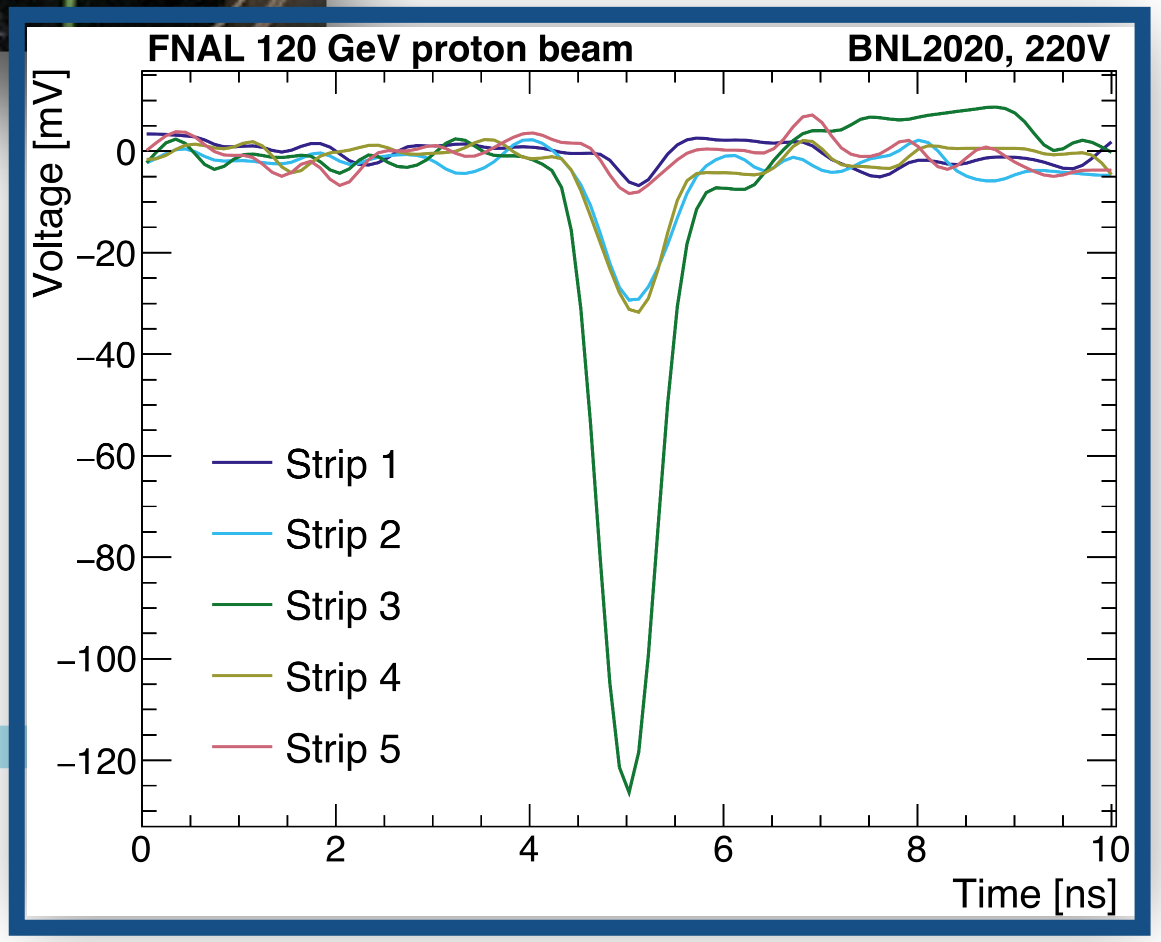
- Permanent setup in FNAL test beam facility (FTBF)
  - Movable: slide in and out of beamline as needed, parasitic use of beam
  - Environmental controls: sensor temperature (-25 C to 20 C), and humidity, monitoring
  - **Time reference with ~ 10 ps resolution (MCP)**
  - DAQ: high bandwidth, high ADC resolution **8-channel scope**
  - Record 20k events during 4 s spill,
  - **Tracker with ~5 µm resolution**
- Developed **readout boards** for the characterization of LGADs
  - Without complex ASIC and DAQ



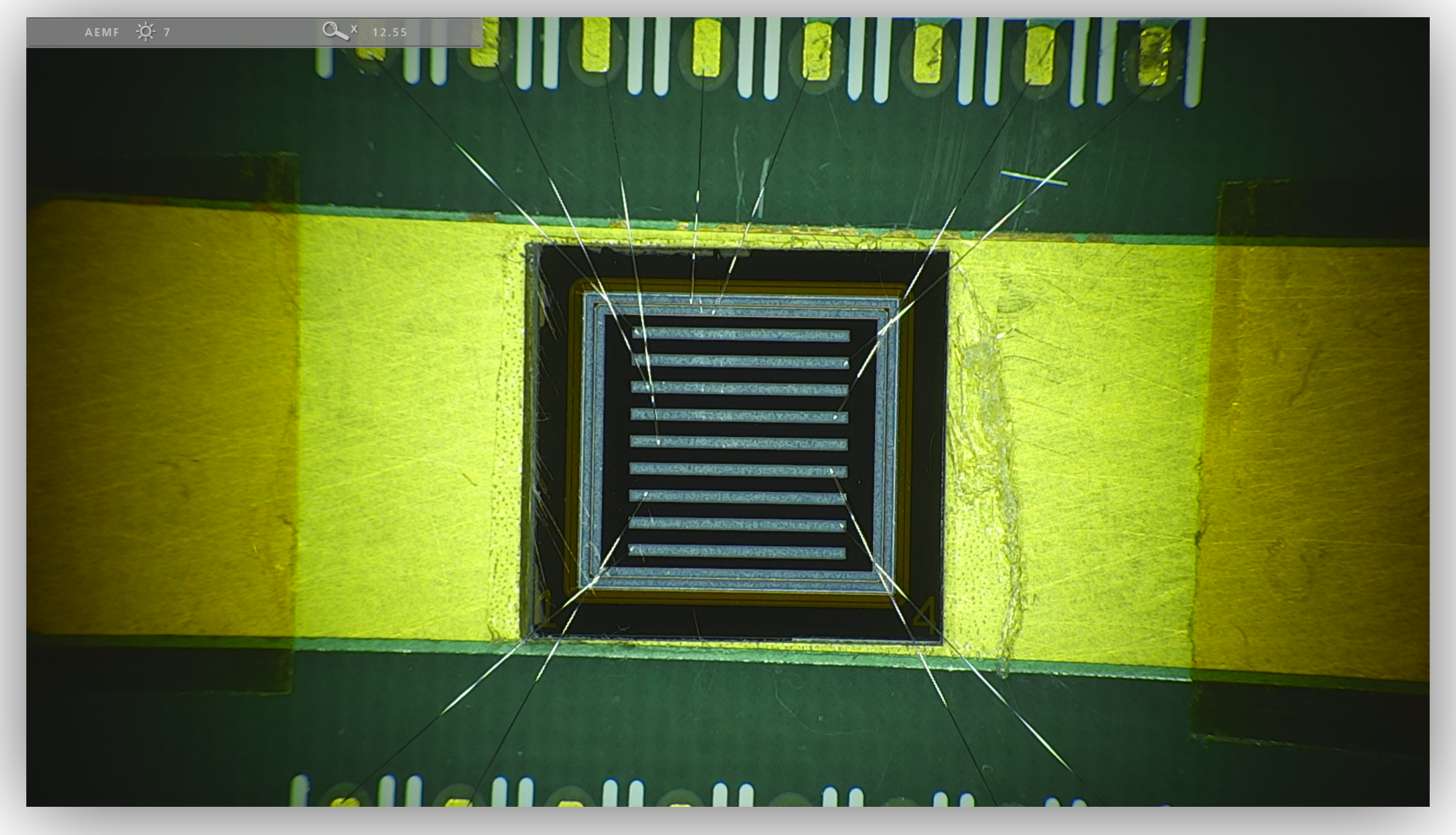
8-channel oscilloscope, 2 GHz, 10 GSa/s



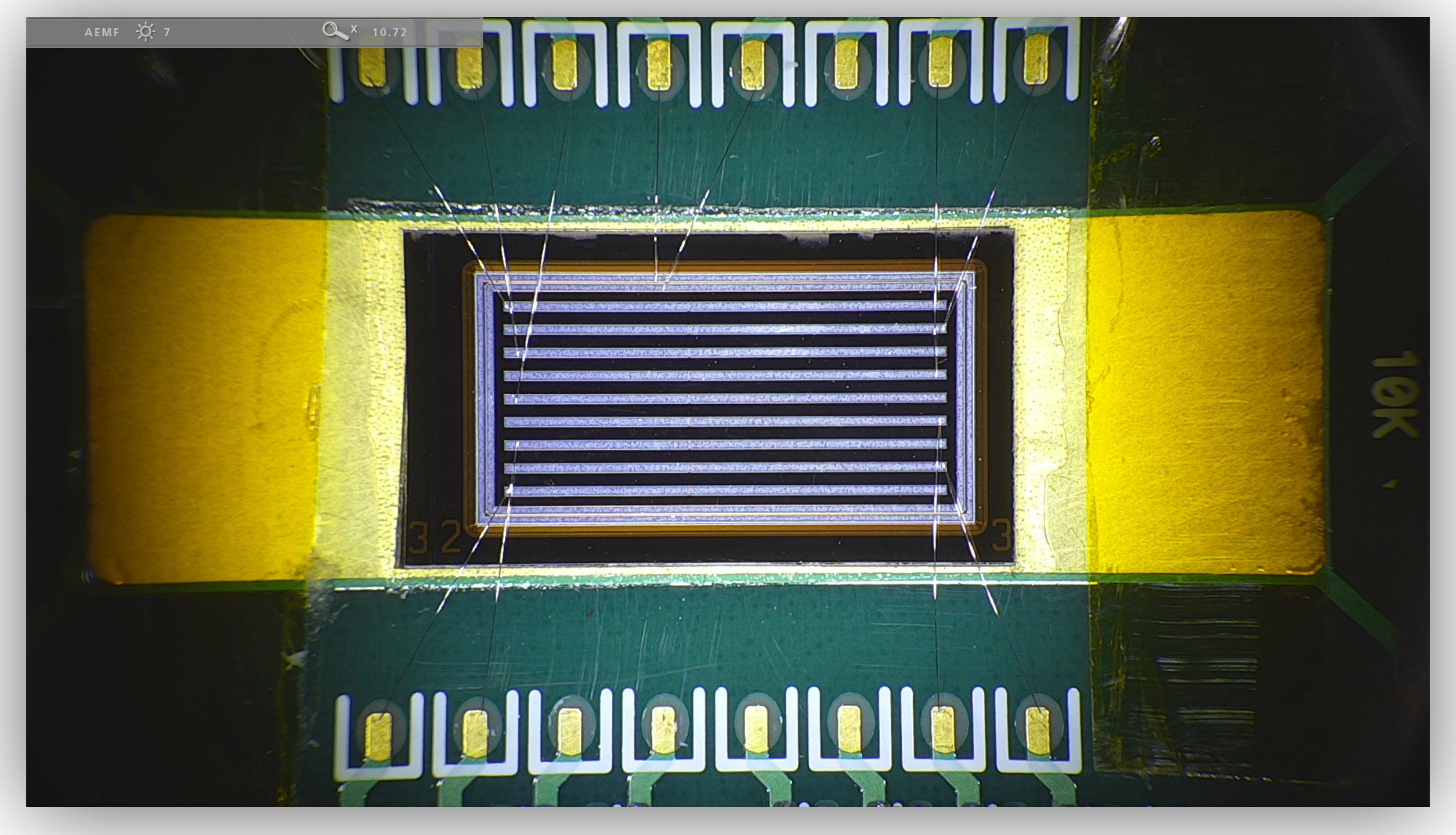




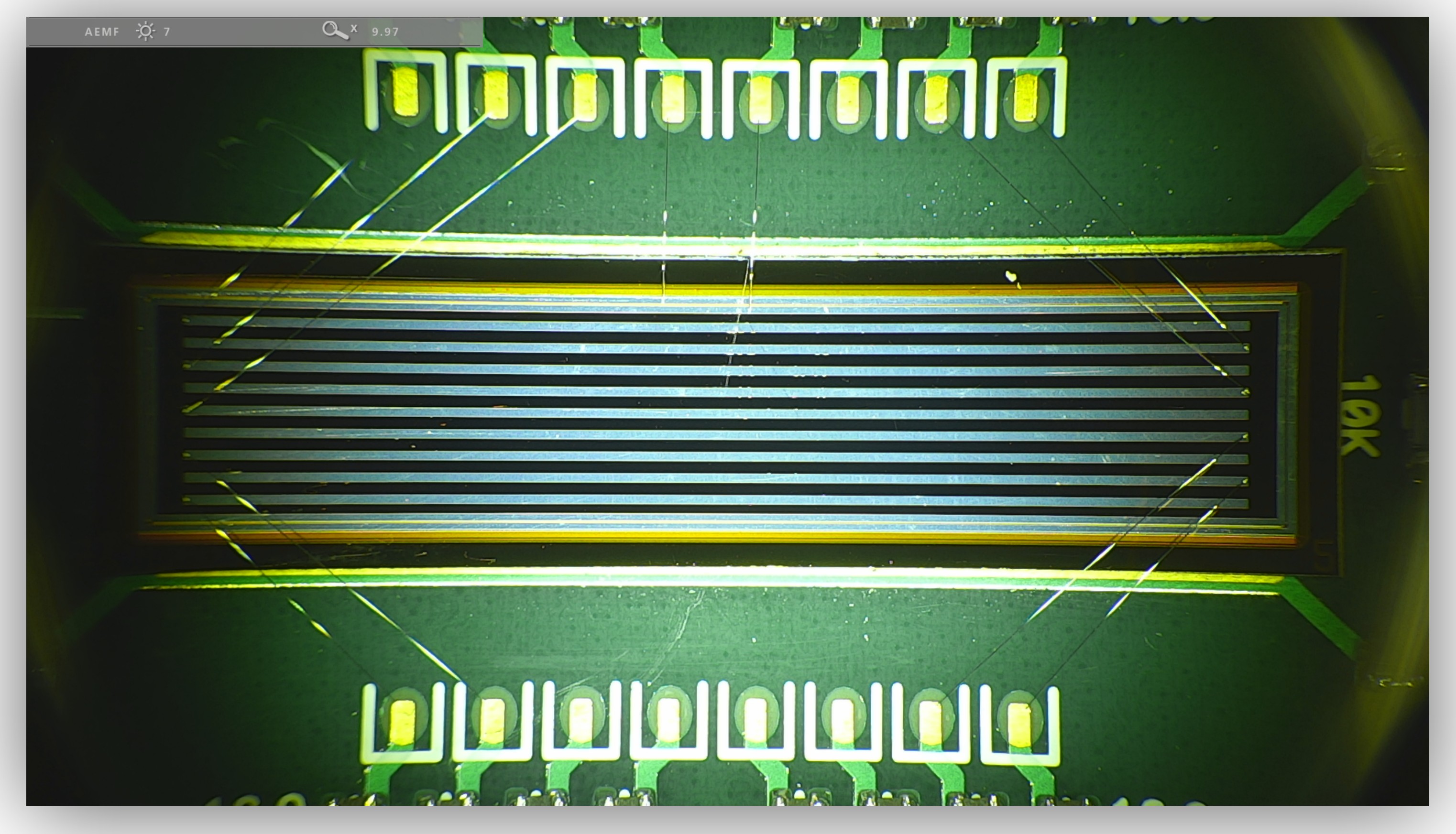
Long Strips Survey



BNL 500 µm x 5 mm



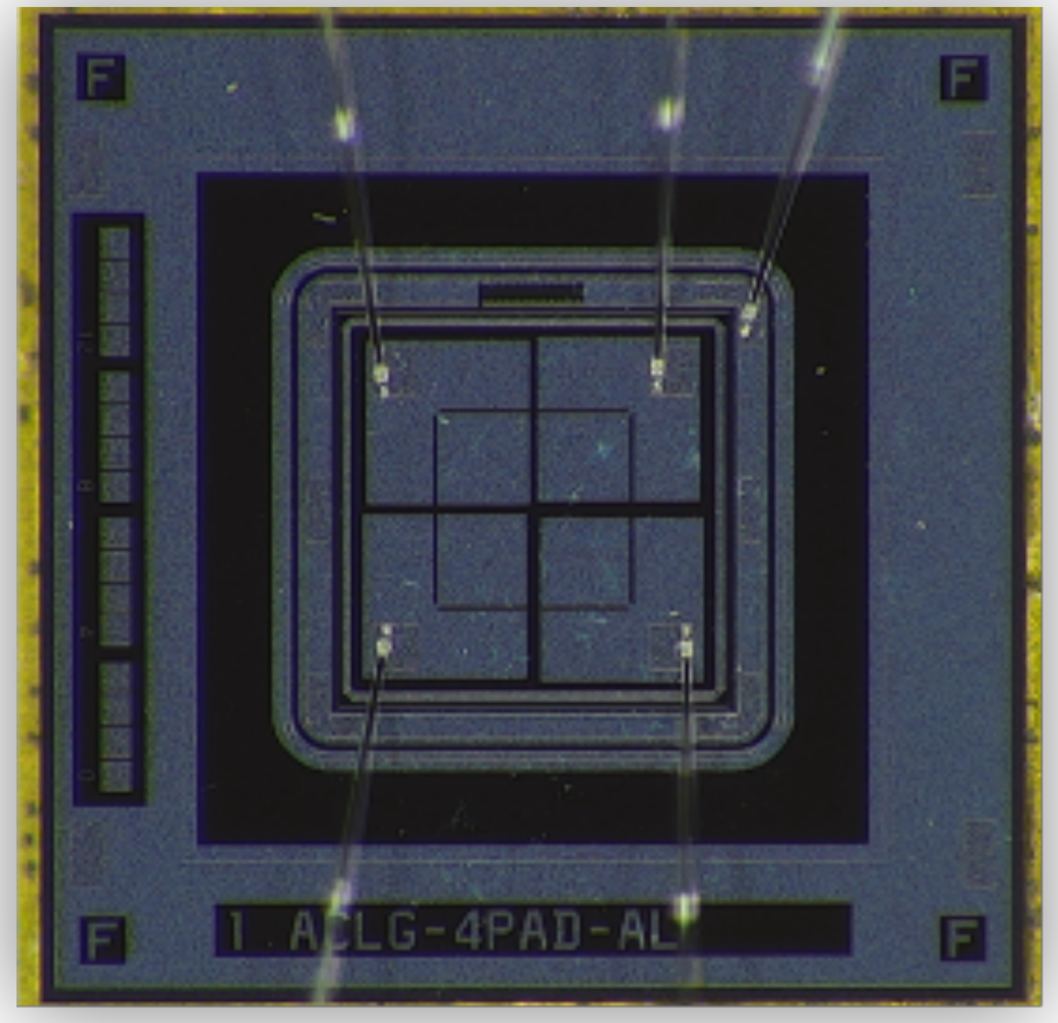
BNL 500 µm x 10 mm



BNL 500 µm x 25 mm

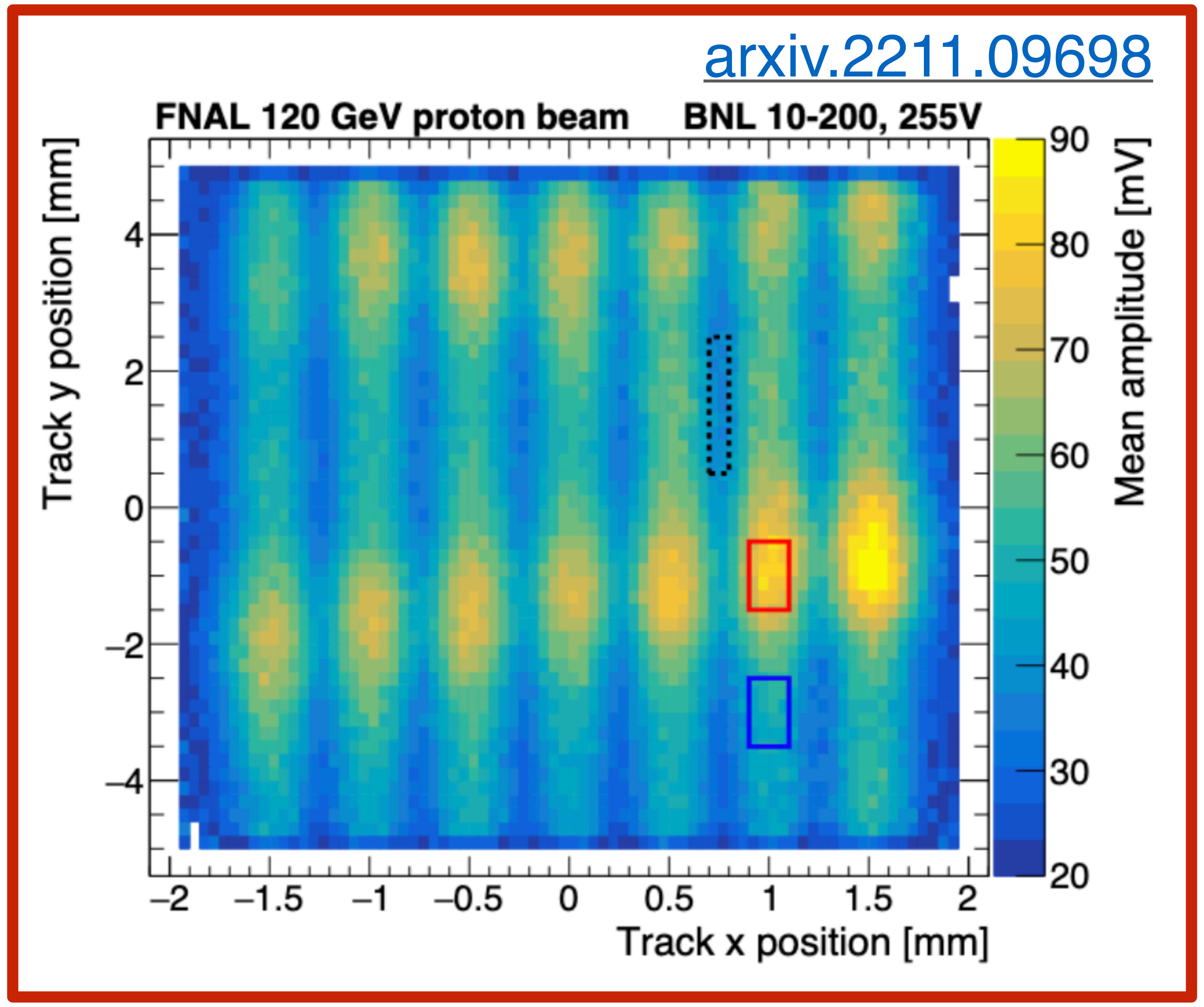
- Survey conducted on ~30 sensors
  - **Strips** with 500 µm pitch and **5**, **10**, and **25** mm long channels
  - **Pixels** with 500x500 µm² channel size

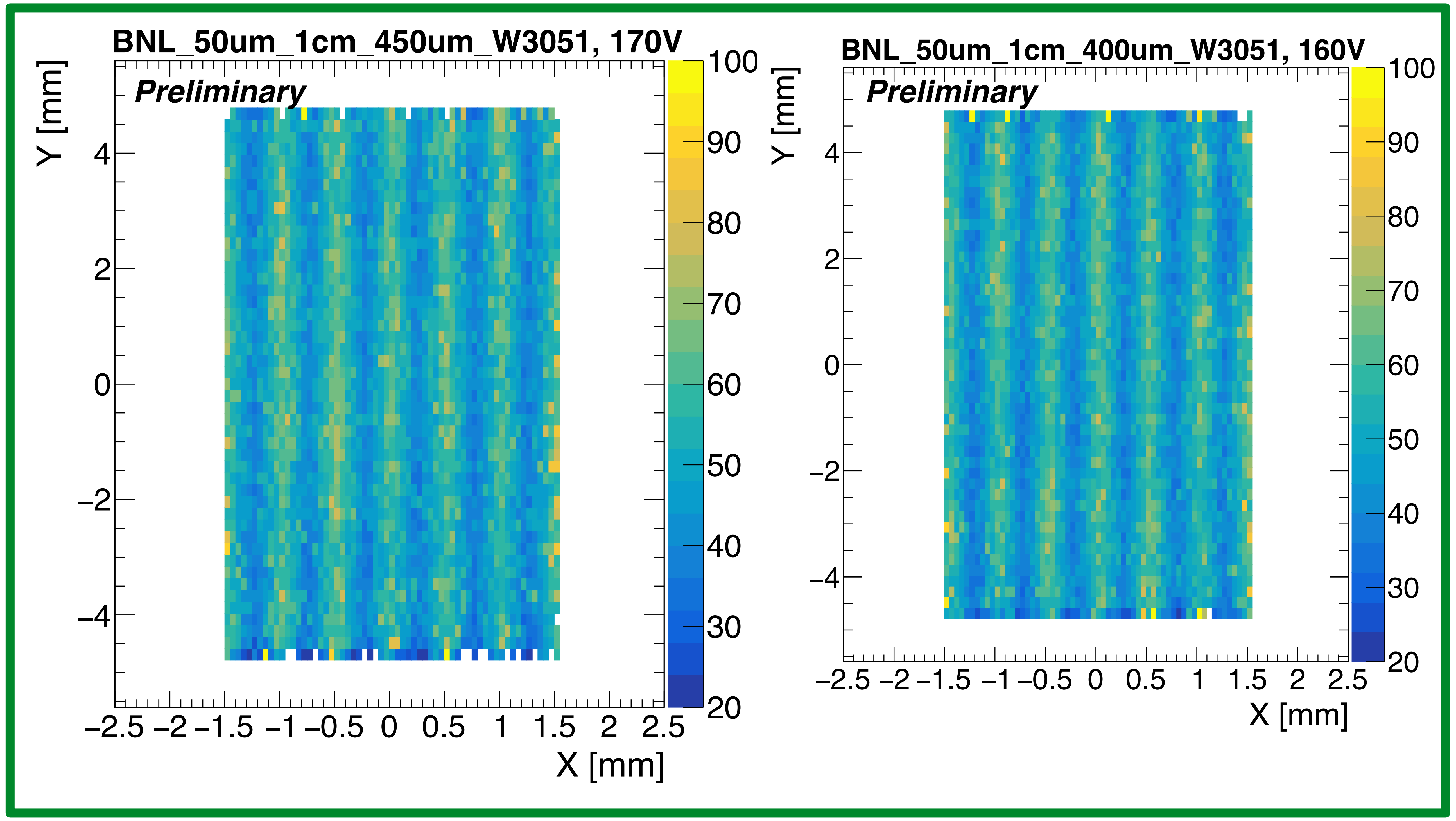
- Focused on geometry optimization and tradeoffs with larger channels



HPK 500 x 500 µm²

Checking gain uniformity



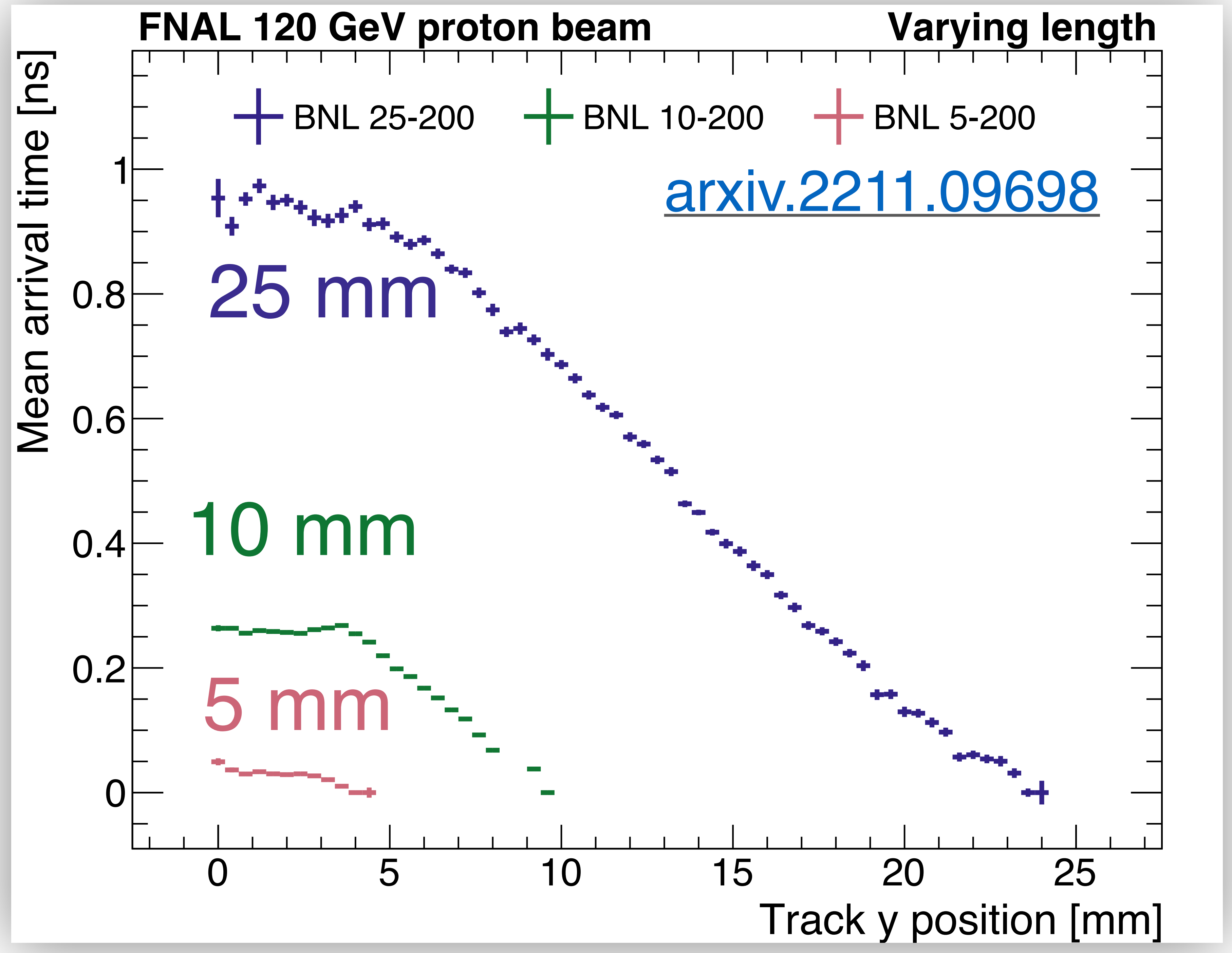


- **Initial sensors** had localized gain featured
  - BNL adapted their gain implantation procedure
- Greatly improved gain uniformity with **second batch**

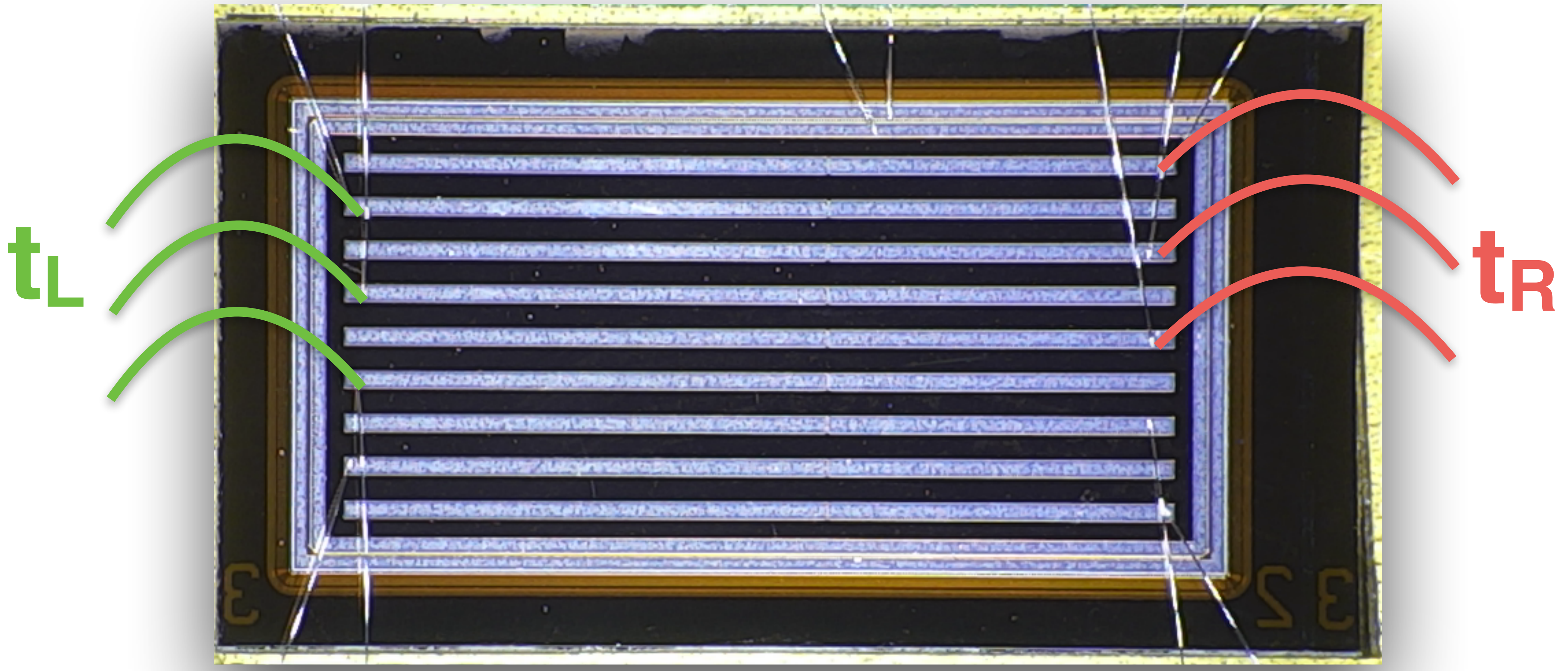
Propagation delays across surface

- Large electrodes → distant signals arrival with delays O(100 ps)

O(100 ps) delays



Correct with alternating dual-end readout



Δt_{L-R} → reconstruct longitudinal position with mm precision

- Easily correct for position dependent delays:
  - Trivial within collider tracking system
  - OR, with dual-end readout: self-correcting!

4D tracking performance: BNL 1cm strips

arxiv.2211.09698

- Sensor provides 100% efficiency but only ~80% at least two strip efficiency
- Measure mostly uniform 20 µm position resolution
- Quantified different time resolutions based on how the time delayed is accounted
  - Using track information to account for the delay can achieve ~40 ps time resolution

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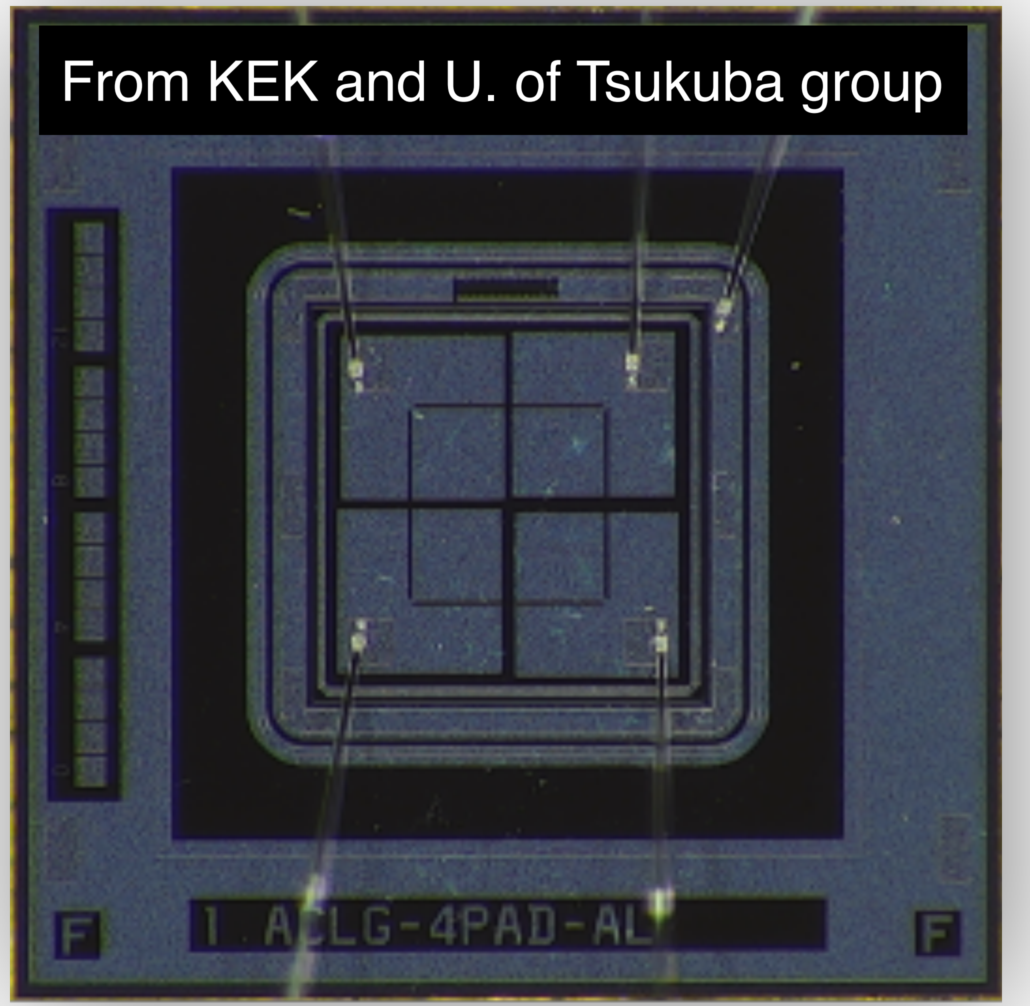
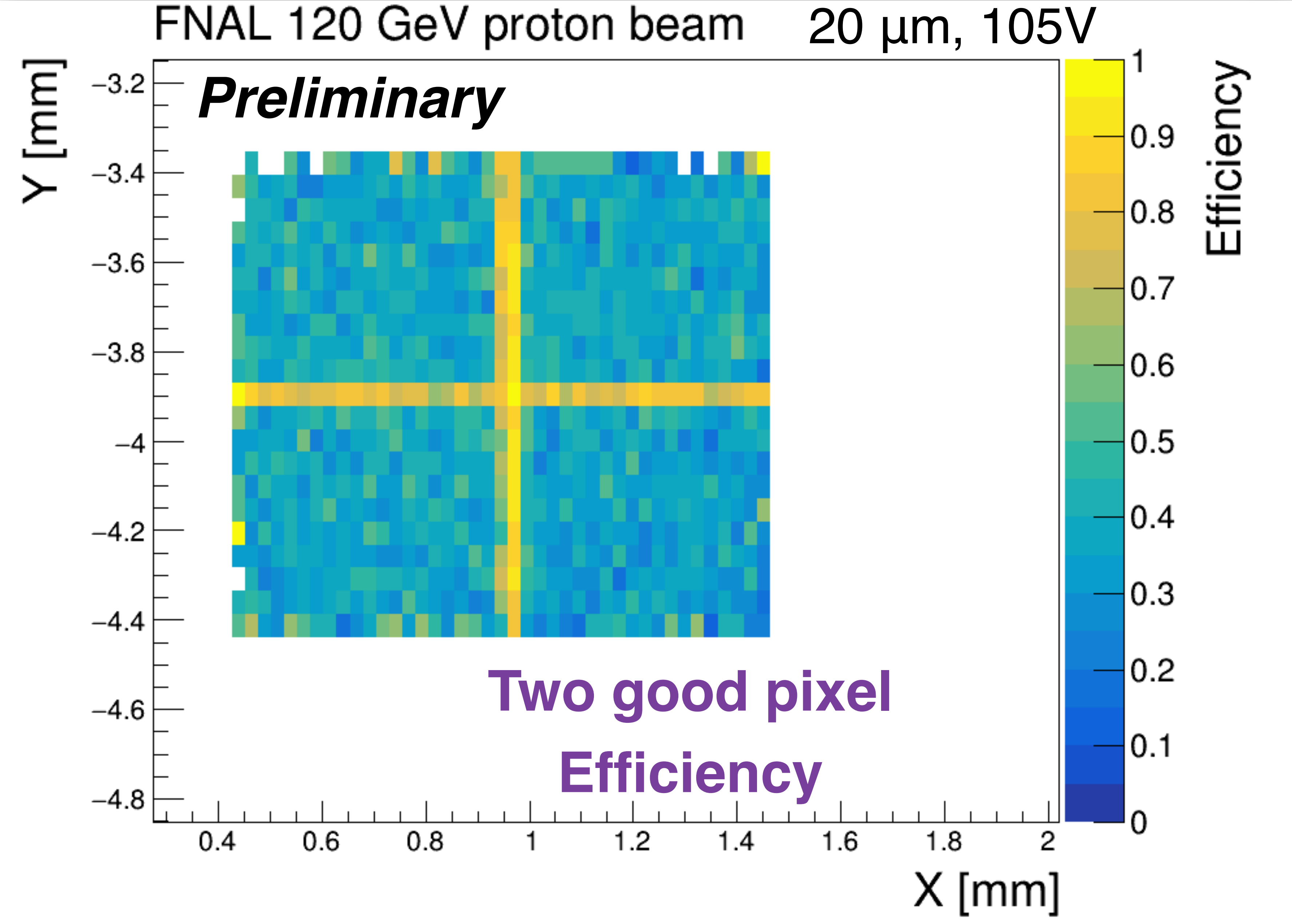
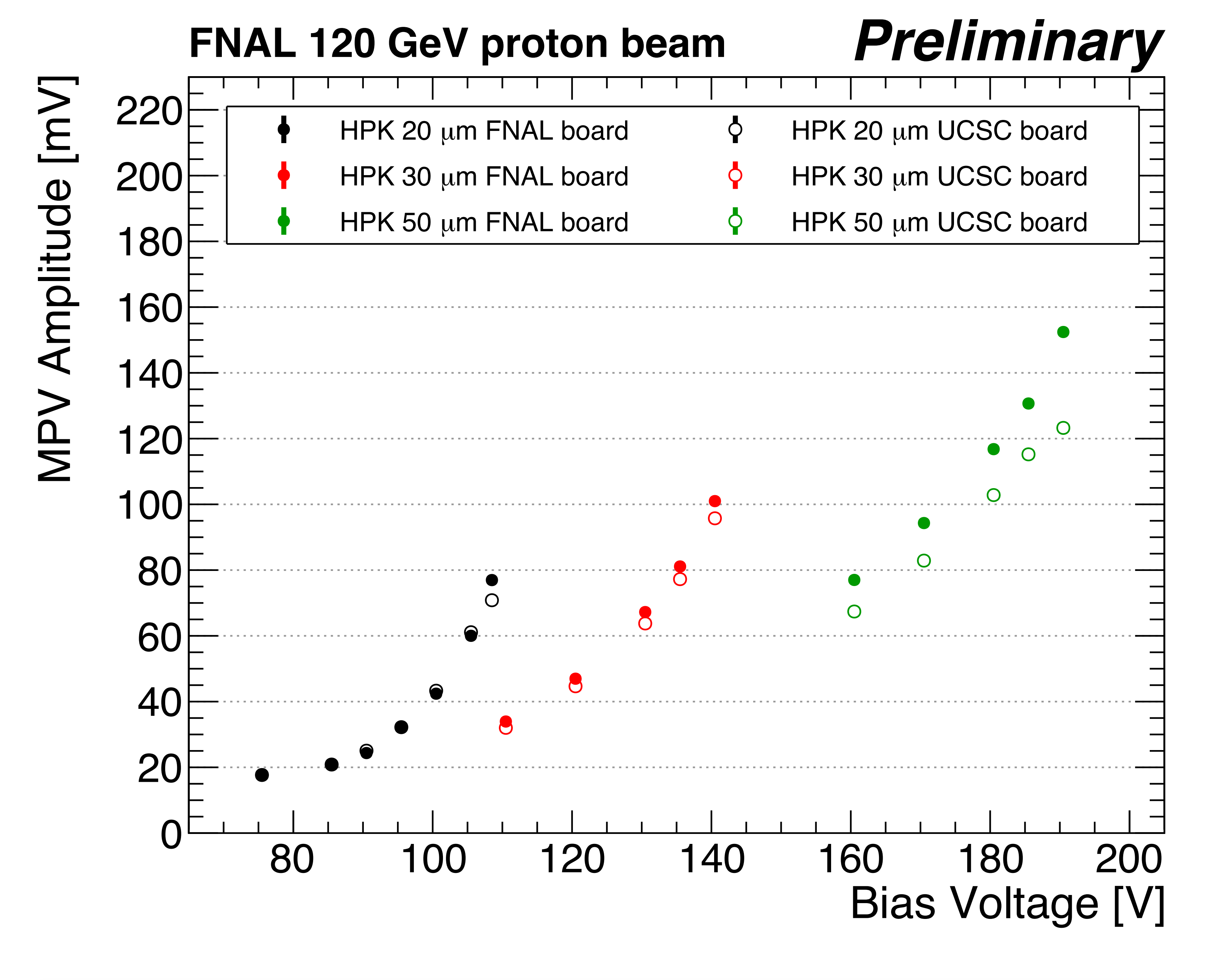
Sensor thickness variations

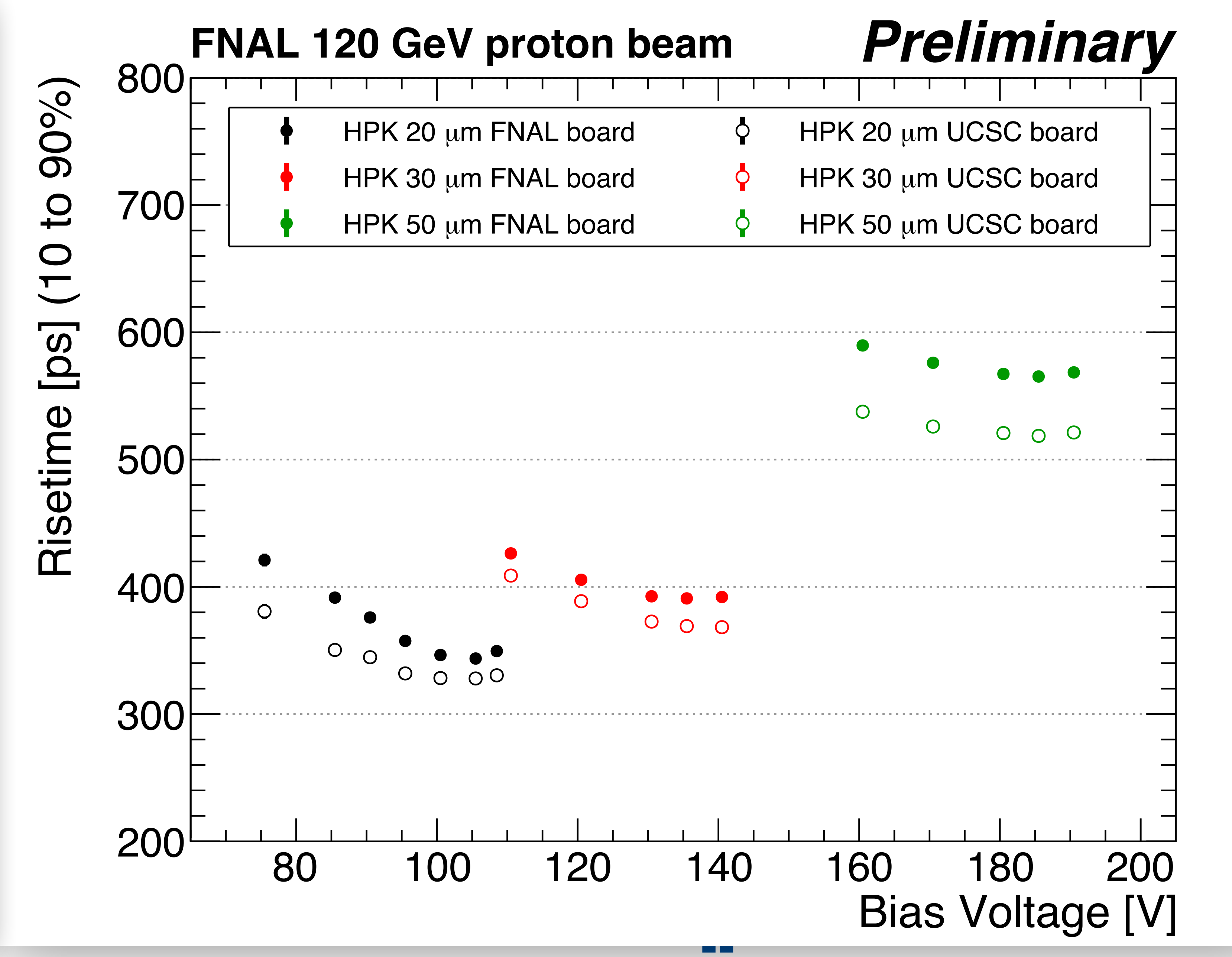
- **How do you get better time resolution?**
  - Thinner sensors to decrease Landau contribution
- **Results for HPK sensors that are 20, 30, and 50 µm thick**
  - Almost fully metallized
  - Optimized for timing performance
- Do not have 2 pixel efficiency outside of the small non-metallized gaps
  - Can not use signal sharing for position reconstruction
- Faster risetime



HPK 2x2, 500x500 µm² pixel size

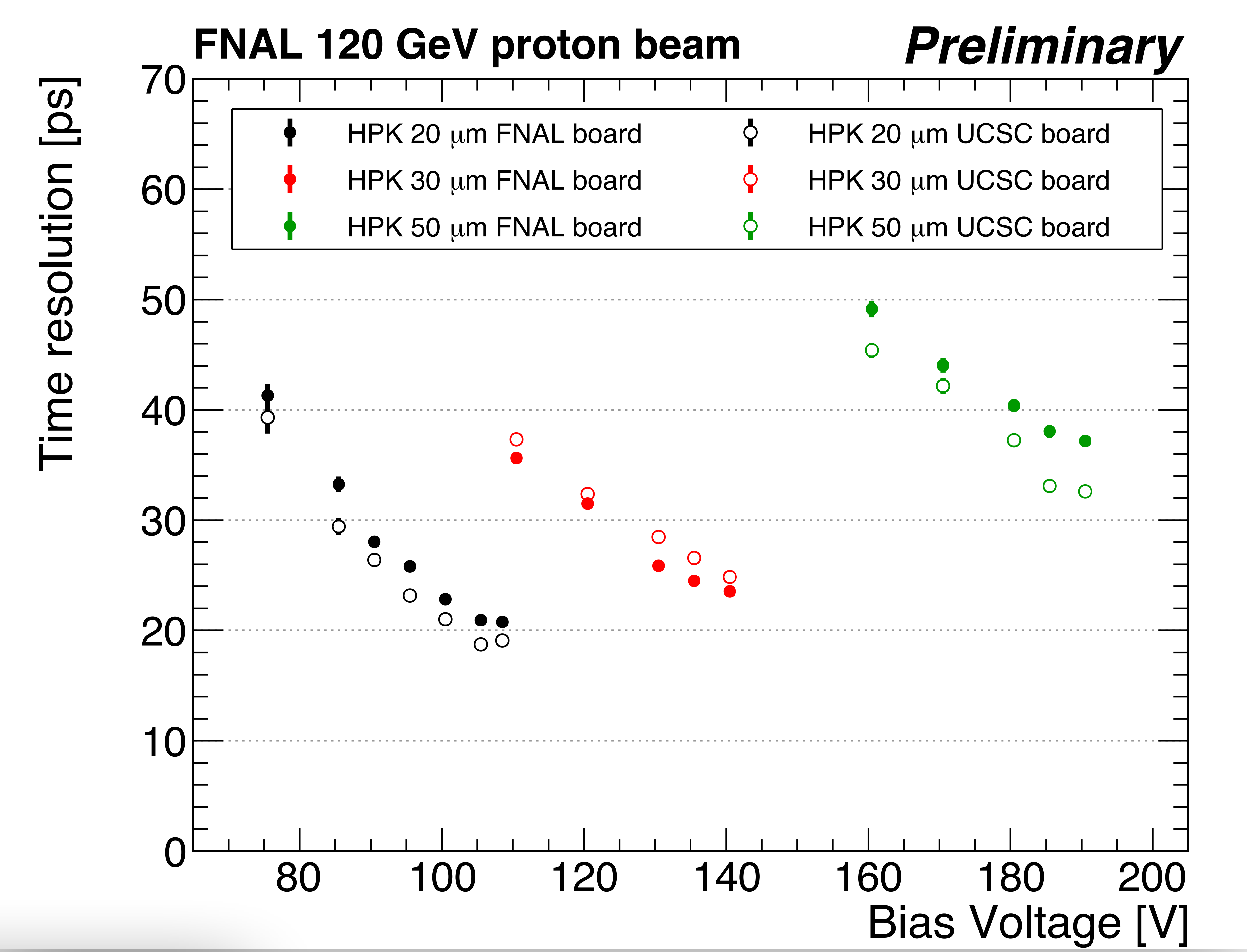


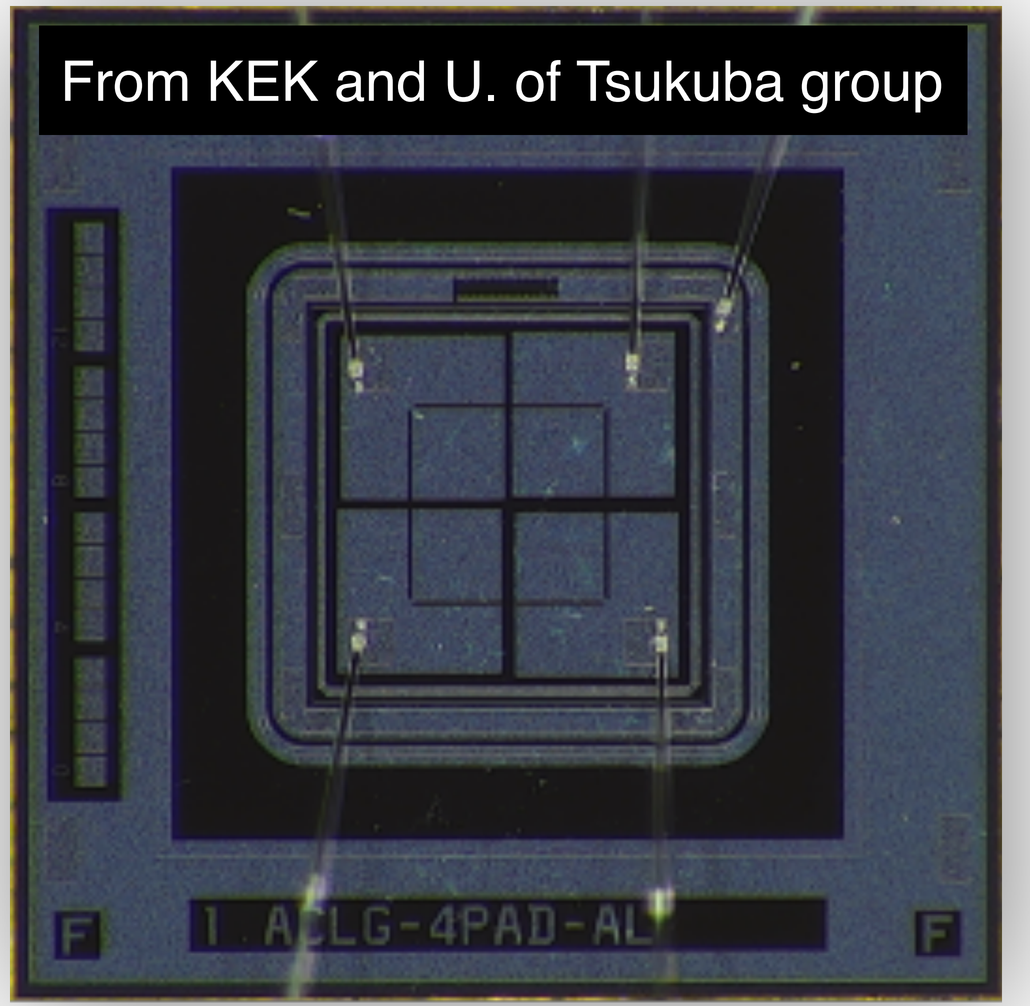




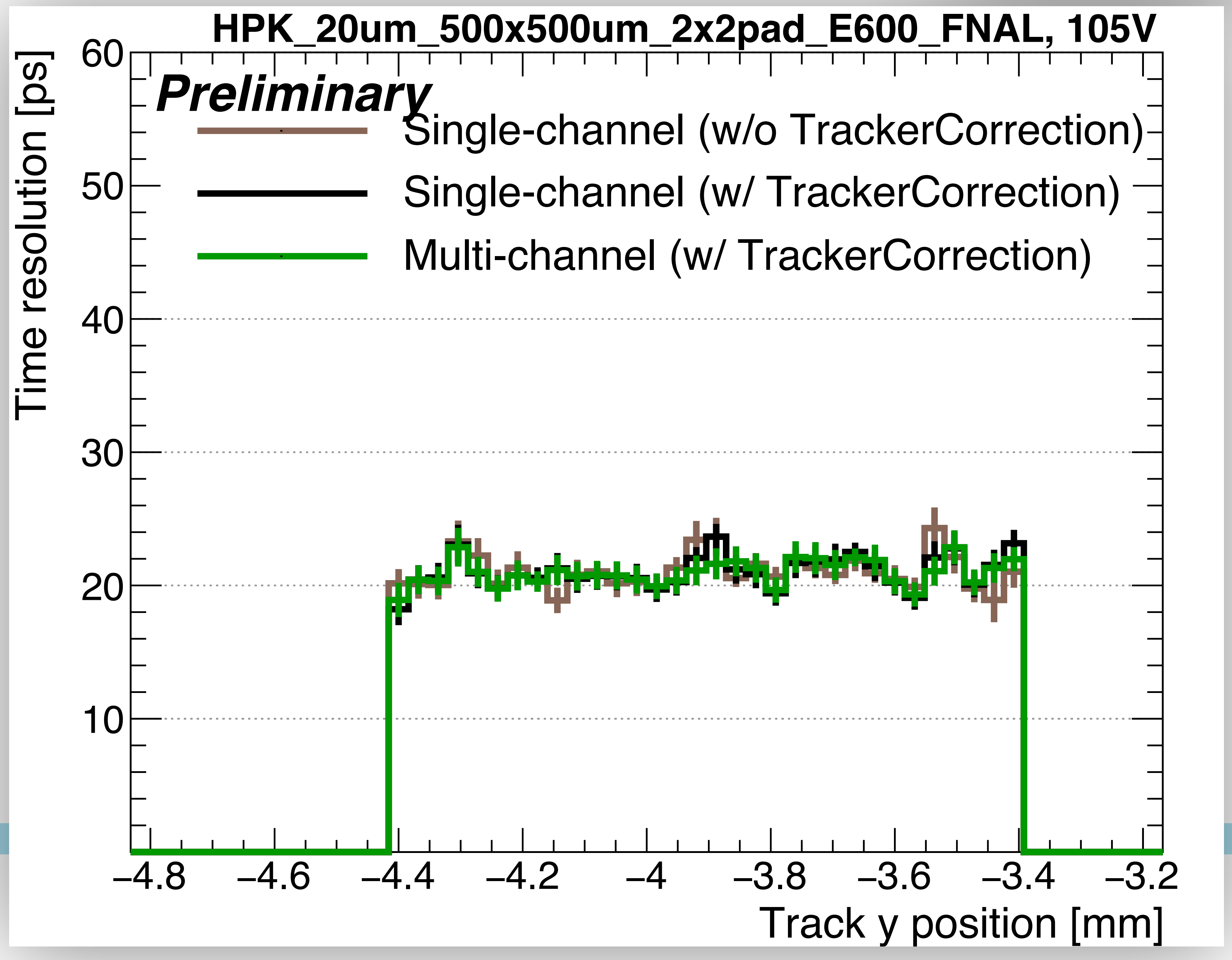
Sensor thickness variations

- Enough signal sharing to cover gap fully
- Great timing performance
- **Observe uniform time resolution across full sensor area**





HPK 2x2, 500x500 µm² pixel size



- **~25 ps for 30 µm thick sensor**
- **~20 ps for 20 µm thick sensor**

Summary

- AC-LGADs provide excellent 4D performance, with timing resolution comparable to LGADs
  - 100% fill factor
  - spatial resolution ~20-30x smaller than pitch

- Large, coarse pitch sensors show promising performance, obtaining resolutions of 20 microns & 40 picoseconds simultaneously in best regions
  - Targeting EIC's ePIC detector and close to meeting design goals

- HPK 20 and 30 µm thick sensors reach below 25 ps time resolution
  - Uniform and excellent time resolution

Backup

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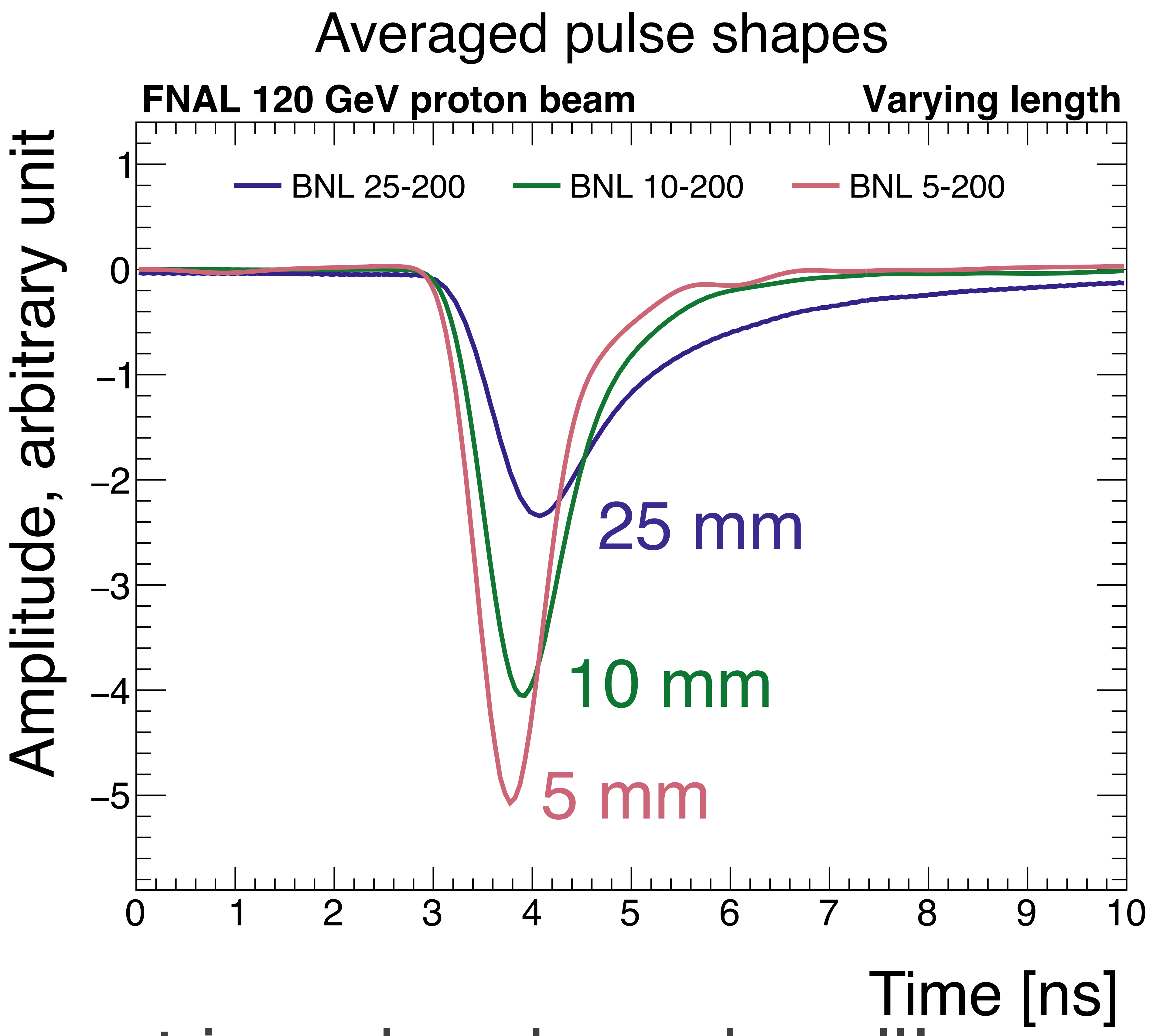
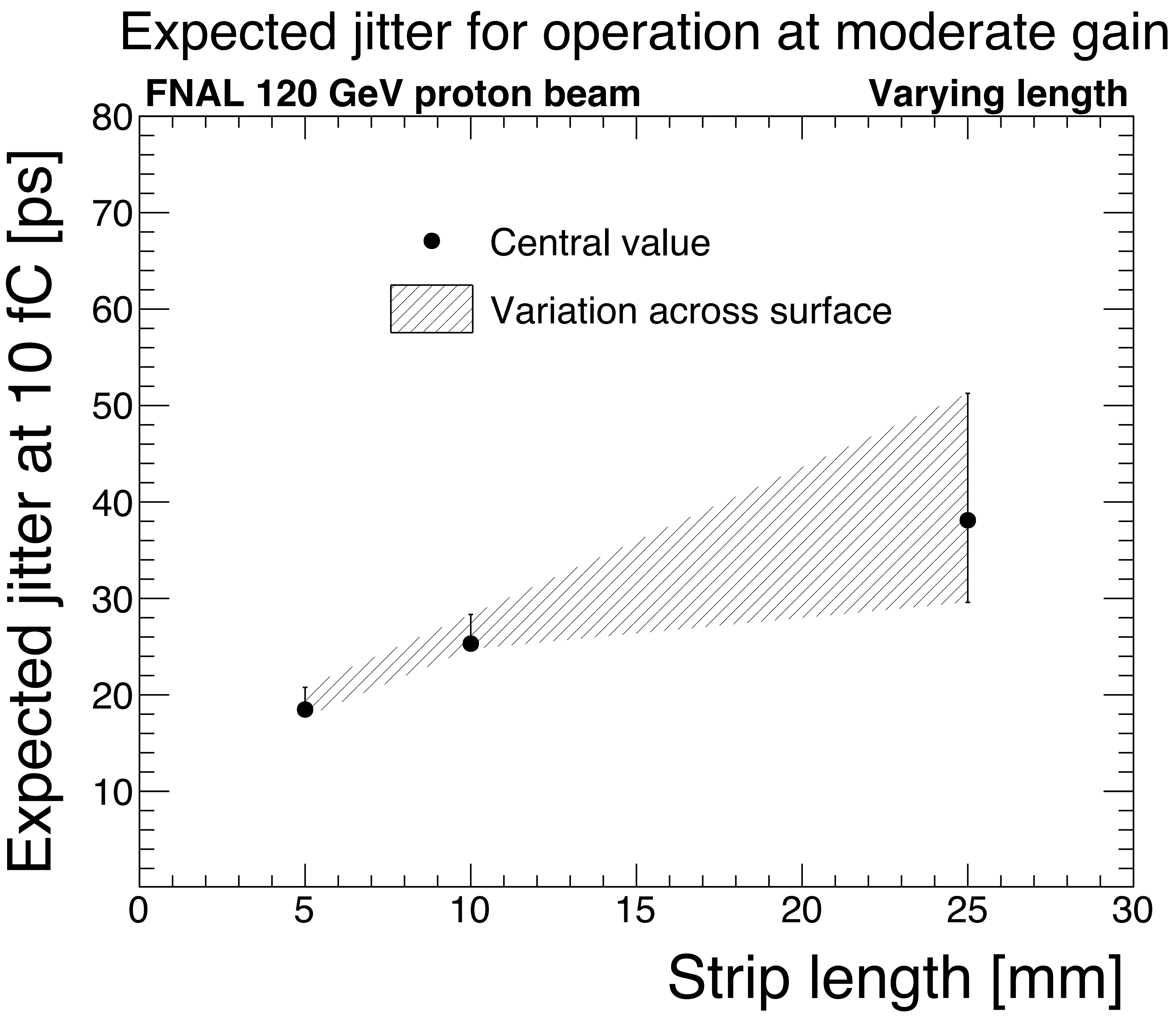
Pulse shapes

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





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