Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Silicon precision timing detectors

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Seminar at Università degli Studi di Milano-Bicocca
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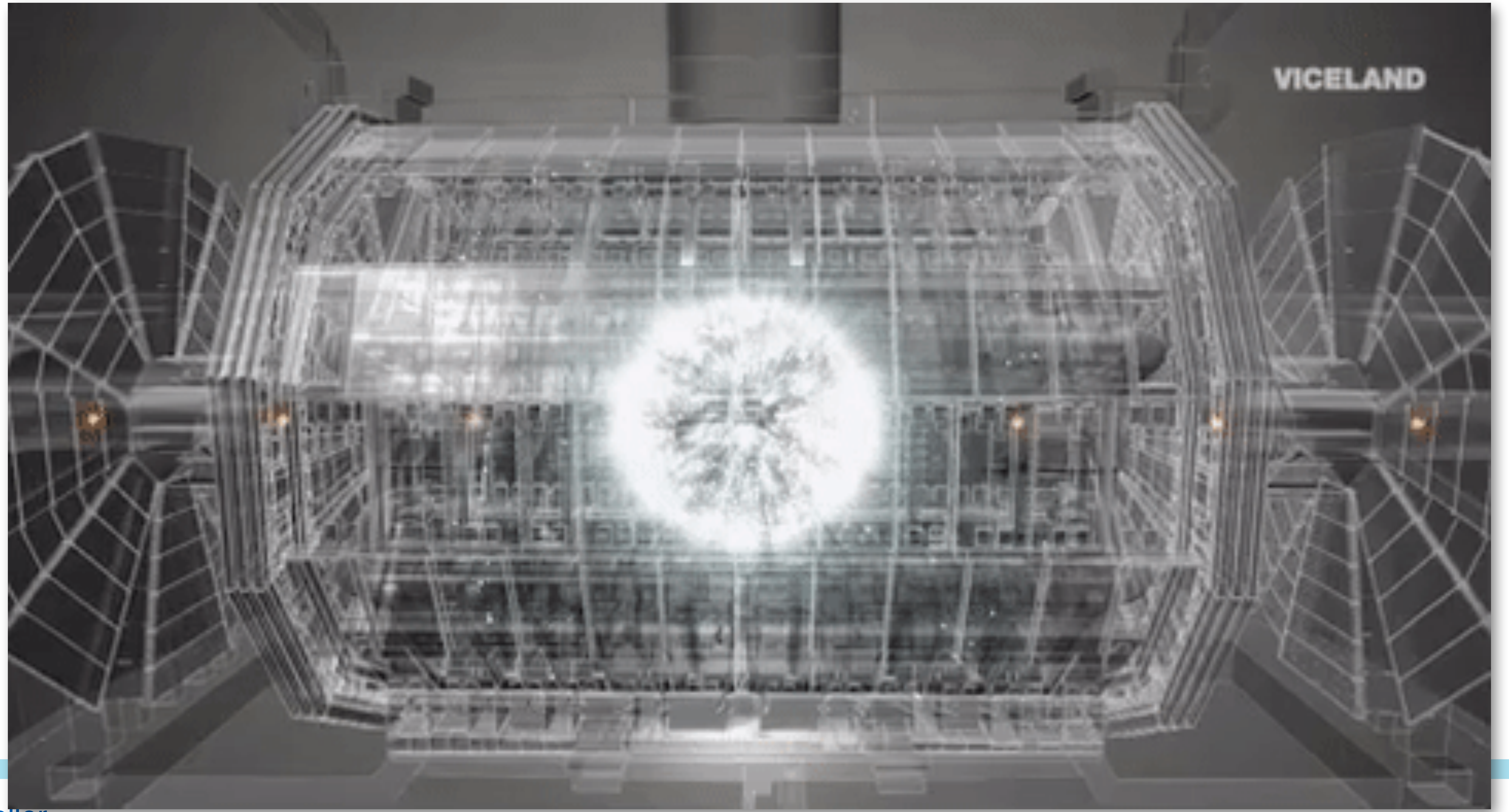
Precision timing: why do we need it?

- LHC proton bunches cross every 25 ns, lasting 0.5 ns each crossing.
- Detector readout repeats at 25 ns (40 MHz)—very fast!
  - But… mostly blind to time structure within each bunch crossing.

Collision structure at an LHC detector



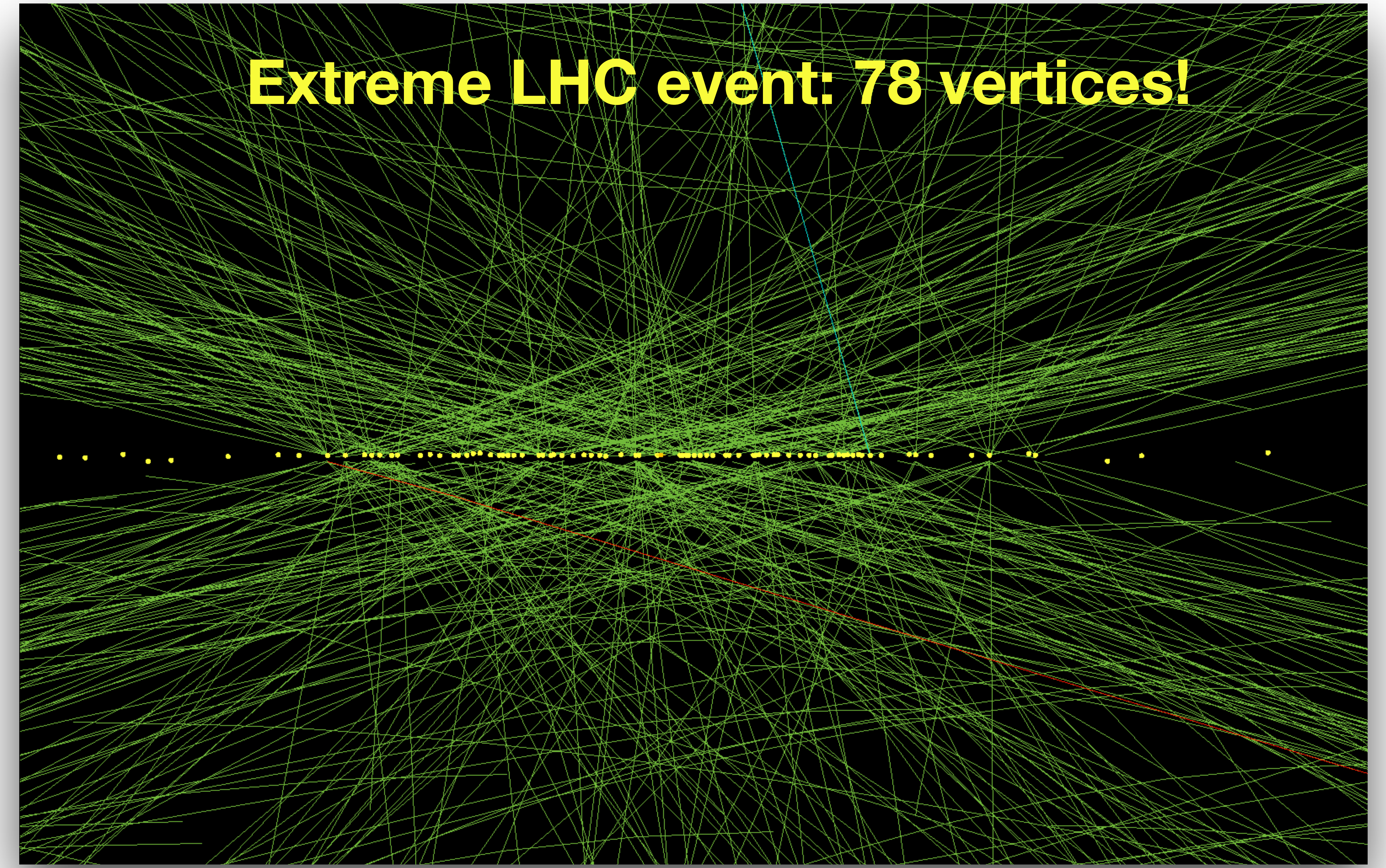
(N.B. real collisions aren't spherically symmetric!)

Precision timing: why do we need it?

- Each bunch crossing: tons of simultaneous pileup interactions!

Typical mean # of PU interactions:

- **LHC: 20-50**
- **High-Lumi LHC: 200**
- **Future hadron collider: 1000 (!)**

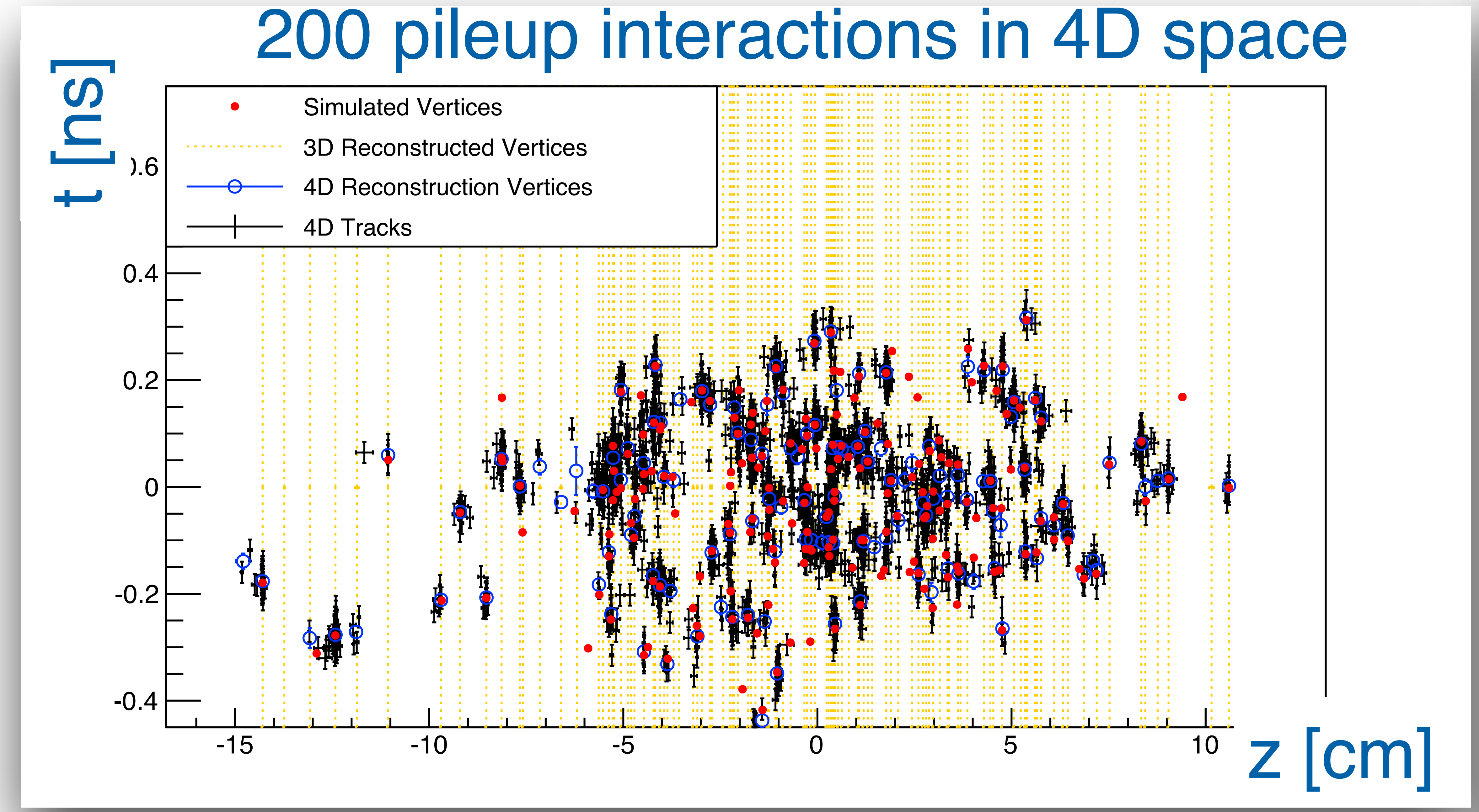


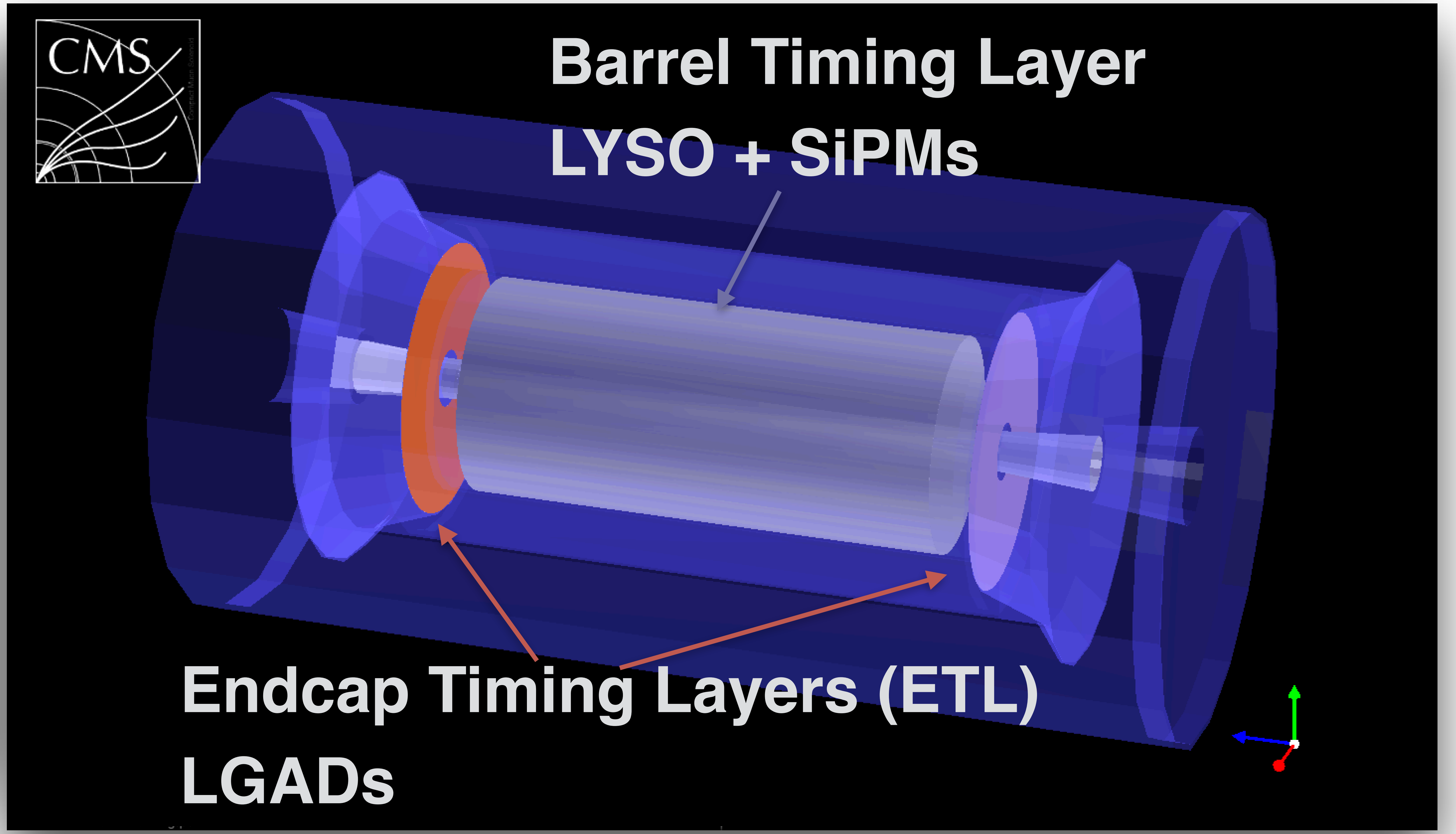
- High Lumi LHC: events too dense / complex to reconstruct accurately

- **Precision timing can provide simplification!**

Precision timing for CMS in HL-LHC era

- Separate spatially overlapping vertices with intra-bunch time information

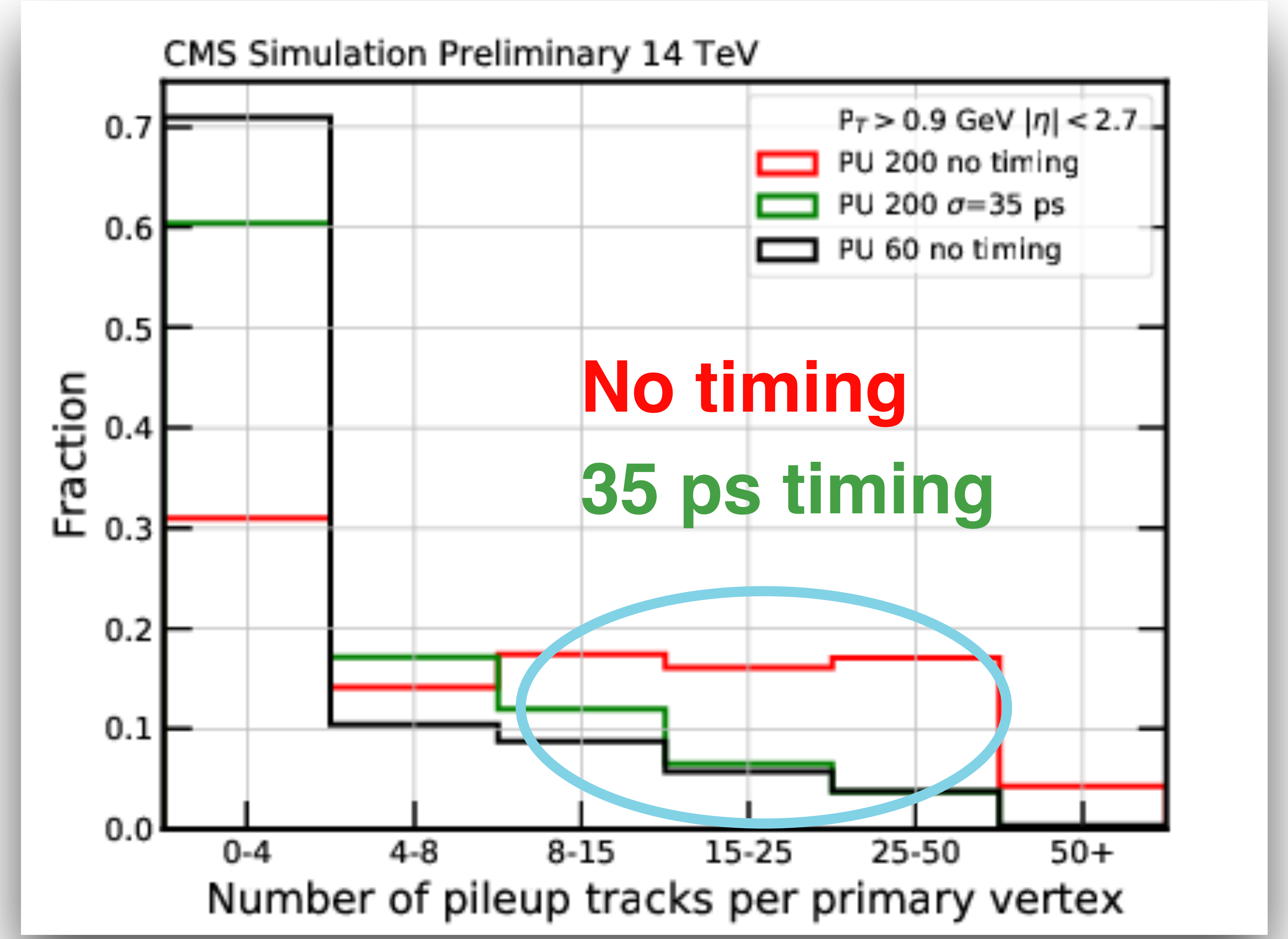


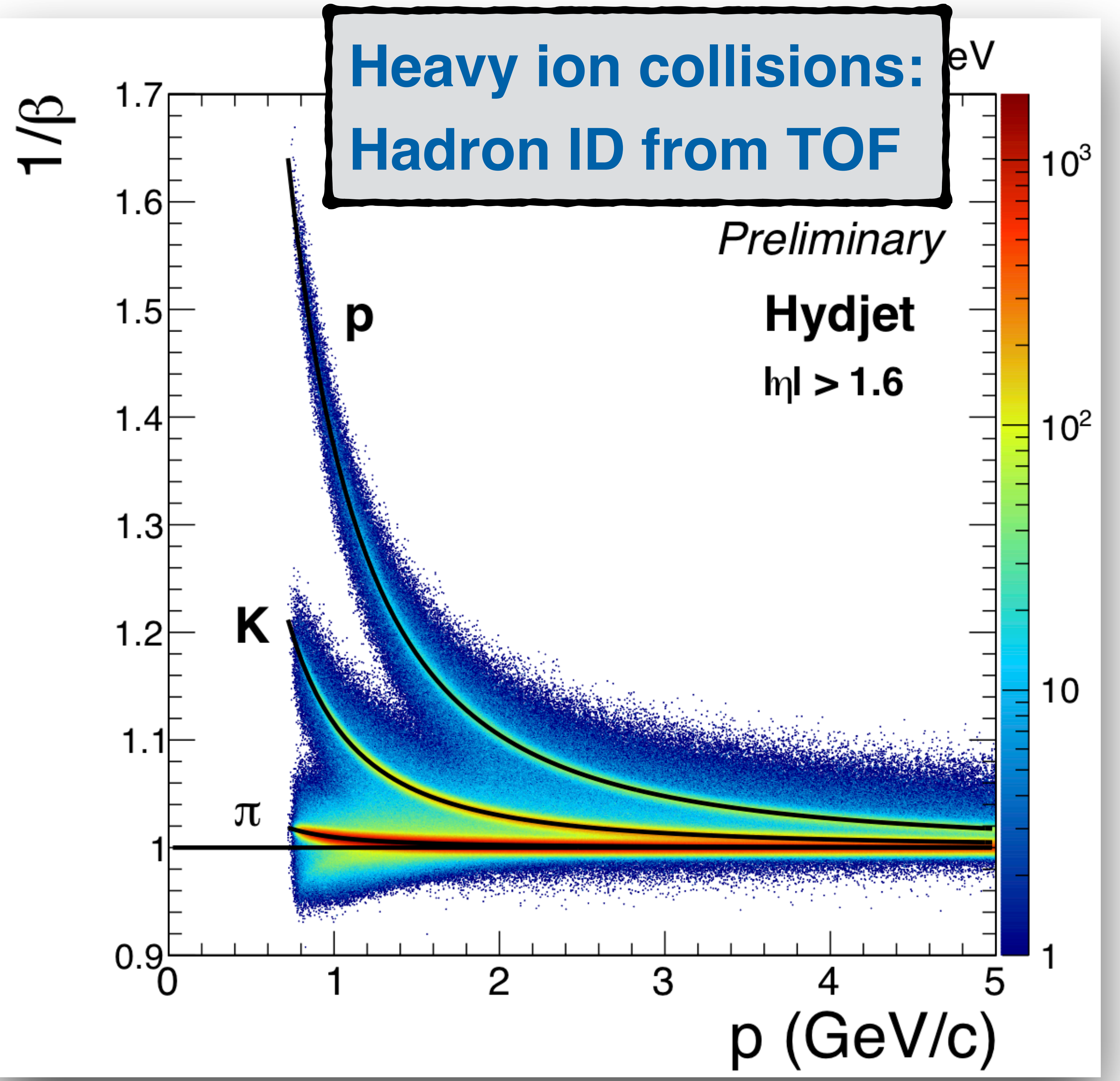


- MIP Timing Detector (MTD): timestamp every track with 30-60 ps resolution
  - Install in advance of HL-LHC.

Impact of timing on CMS performance

- Reduce effective pileup to current levels: maintain core physics performance
- Time of Flight identification for soft hadrons
- New discovery capability for exotic long-lived & slow moving particles





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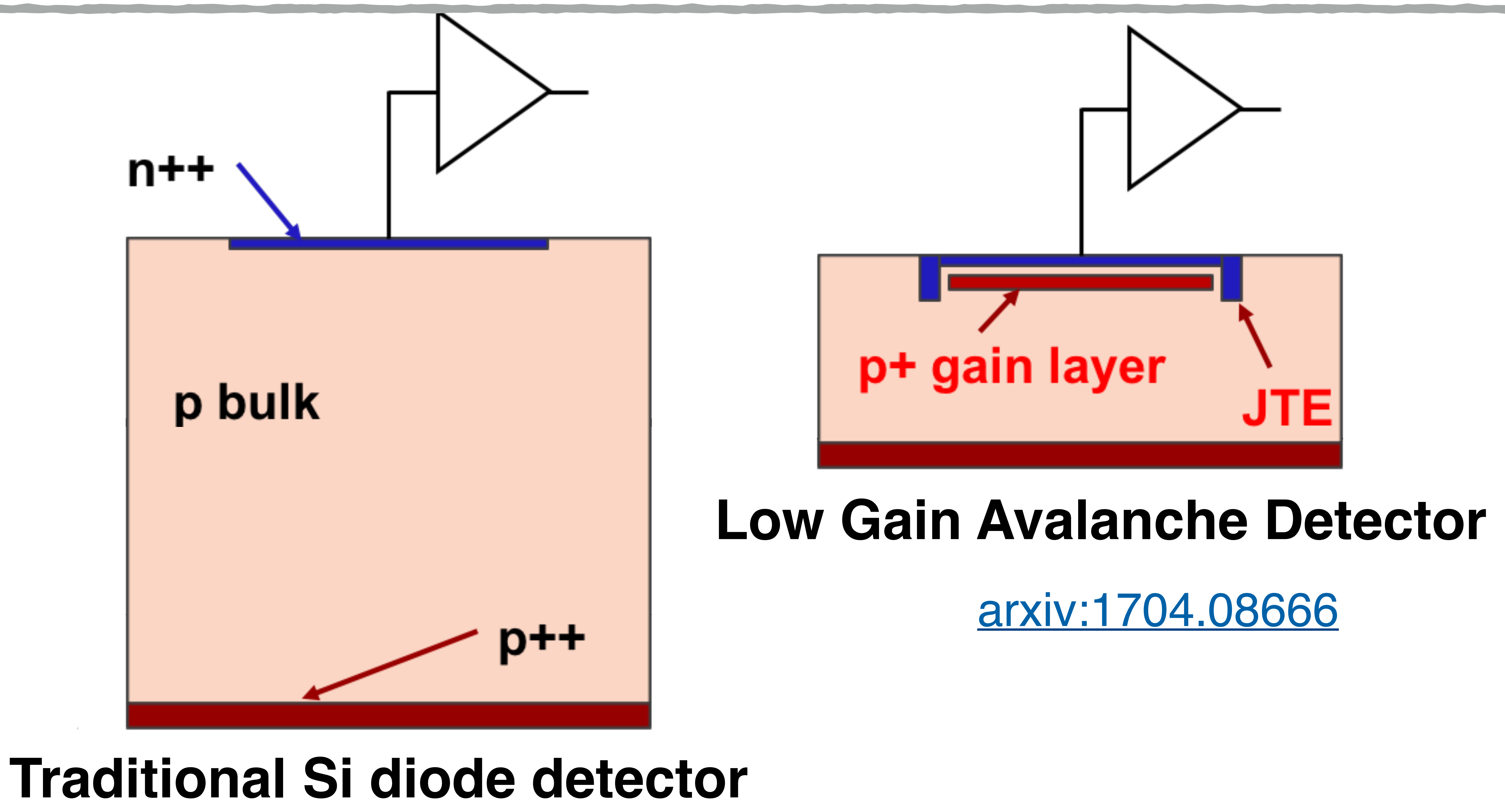
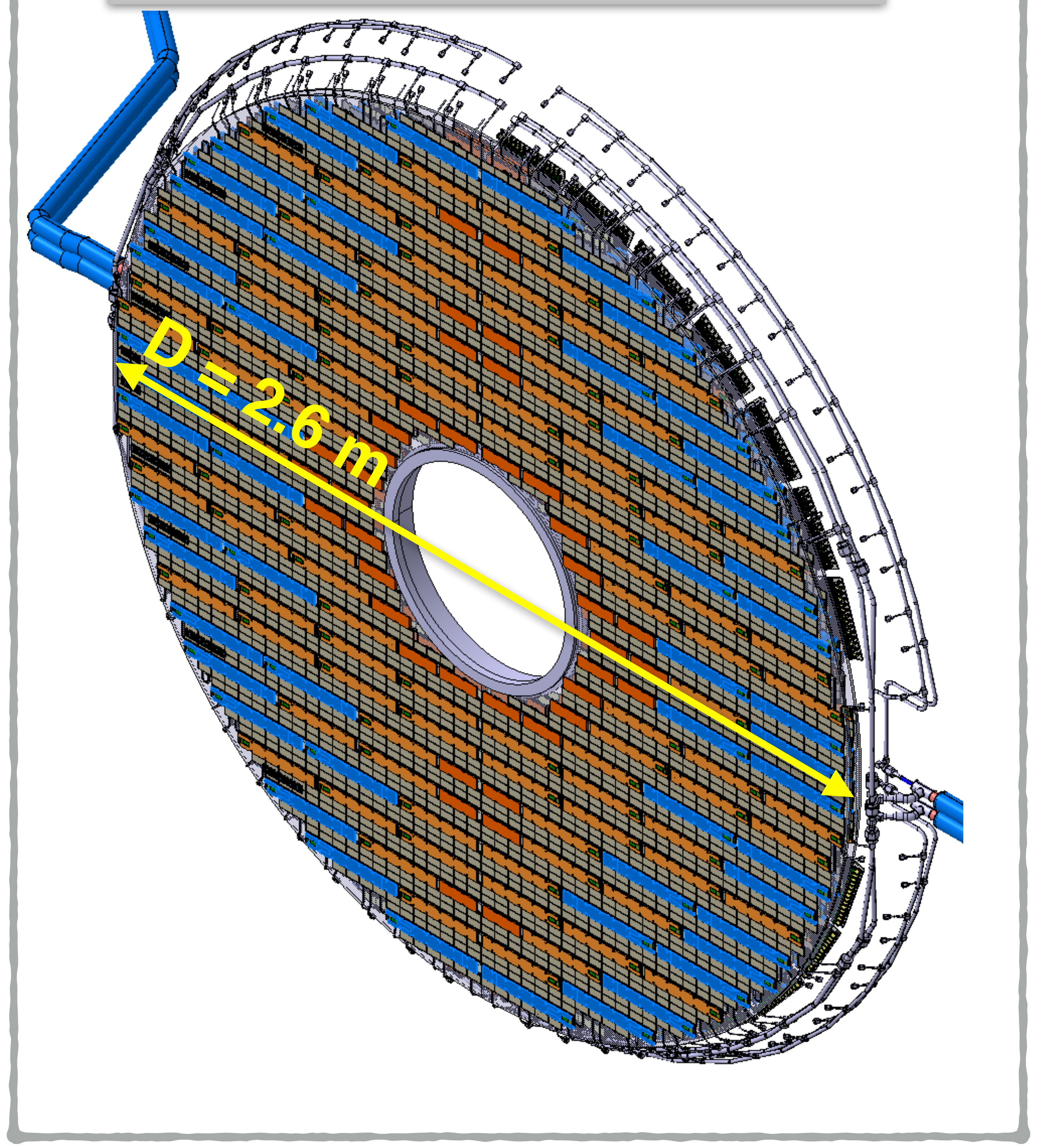
LGAD sensors

- Endcap region near beamline: high radiation tolerance required
- Silicon sensors optimized for timing: Low Gain Avalanche Detectors (**LGADs**)
  - Thin depletion region (50 micron): fast & uniform signals
  - Internal gain: boost signal-to-noise (x10-30)



arxiv:1704.08666

Endcap timing layer



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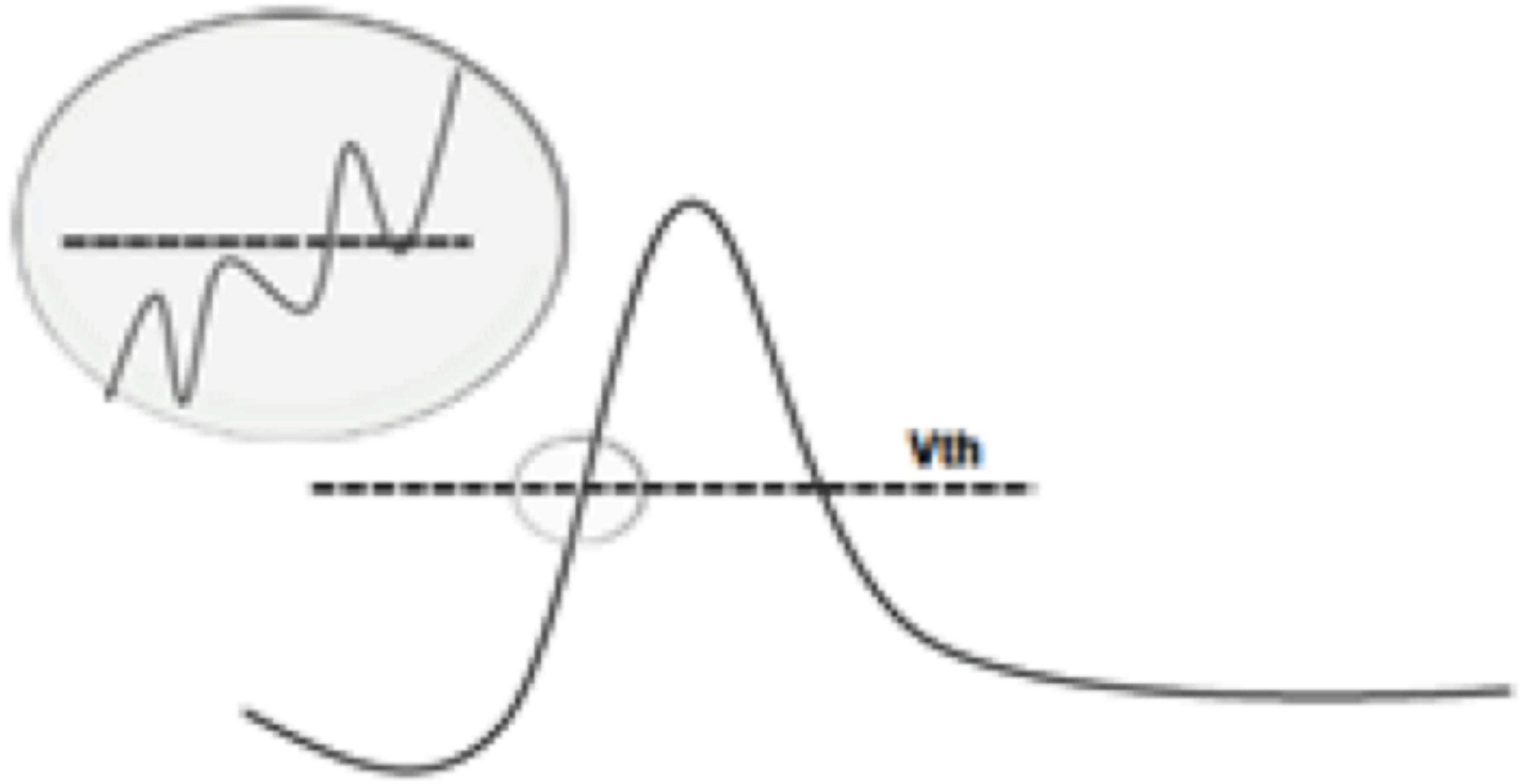
Ingredients to time resolution in silicon sensors

- Measuring time of arrival: look for signal to cross threshold.

- Main contributions to resolution:
  - Jitter — the impact of noise

$$\sigma_{\text{jitter}} = \frac{t_{\text{rise}}}{S/N} = \frac{N}{dV/dt}$$



Maximize signal: add internal gain

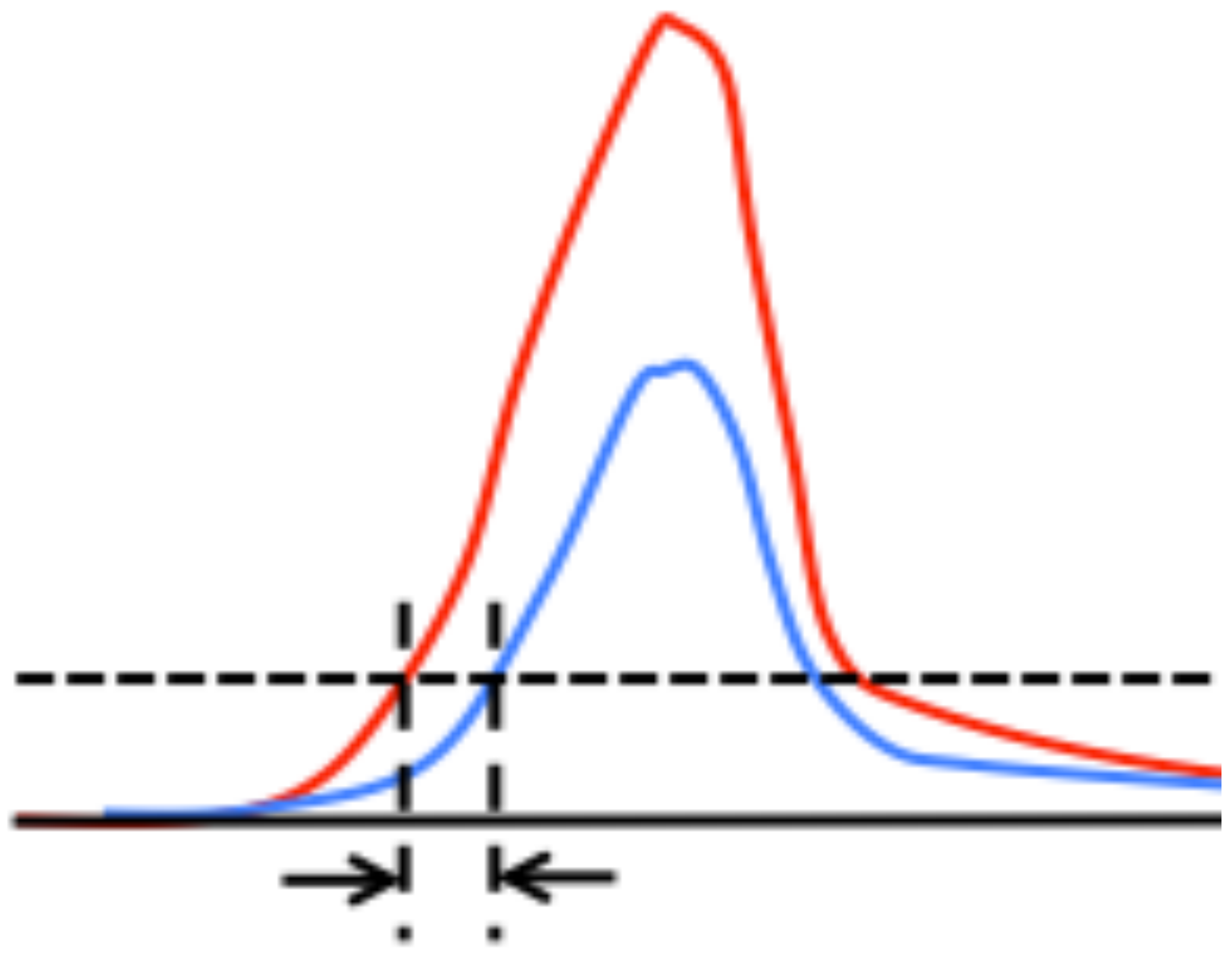
Minimize risetime: THIN sensors (50 µm)

Ingredients to time resolution in silicon sensors

- Measuring time of arrival: look for signal to cross threshold.

- Main contributions to resolution:
  - Jitter — the impact of noise
  - Signal variations — fluctuations in deposited charge
    - "Time walk": variation in TOTAL charge (Q)

Time walk on threshold crossing:



Easily corrected with measurement of total.

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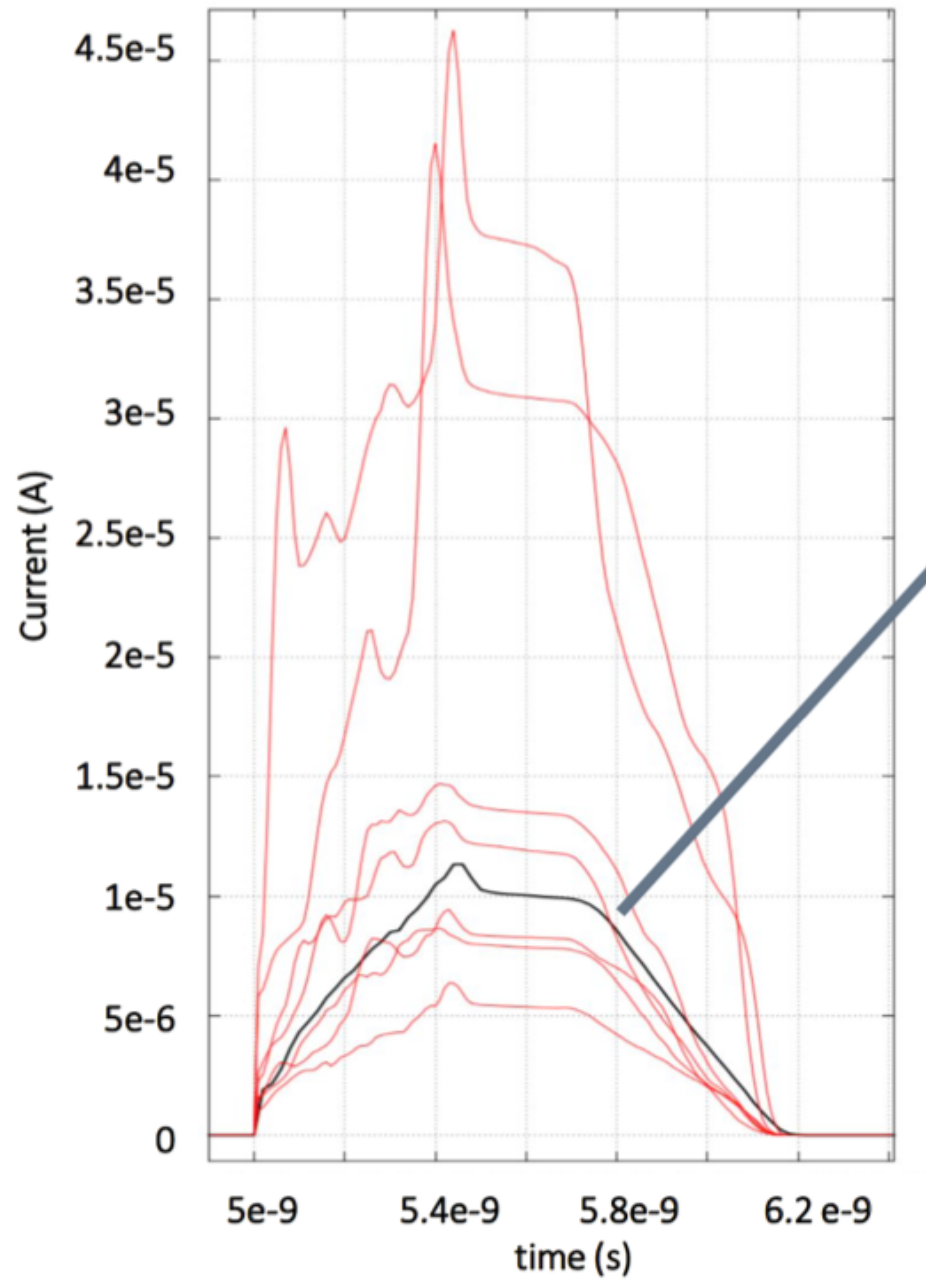
Ingredients to time resolution in silicon sensors

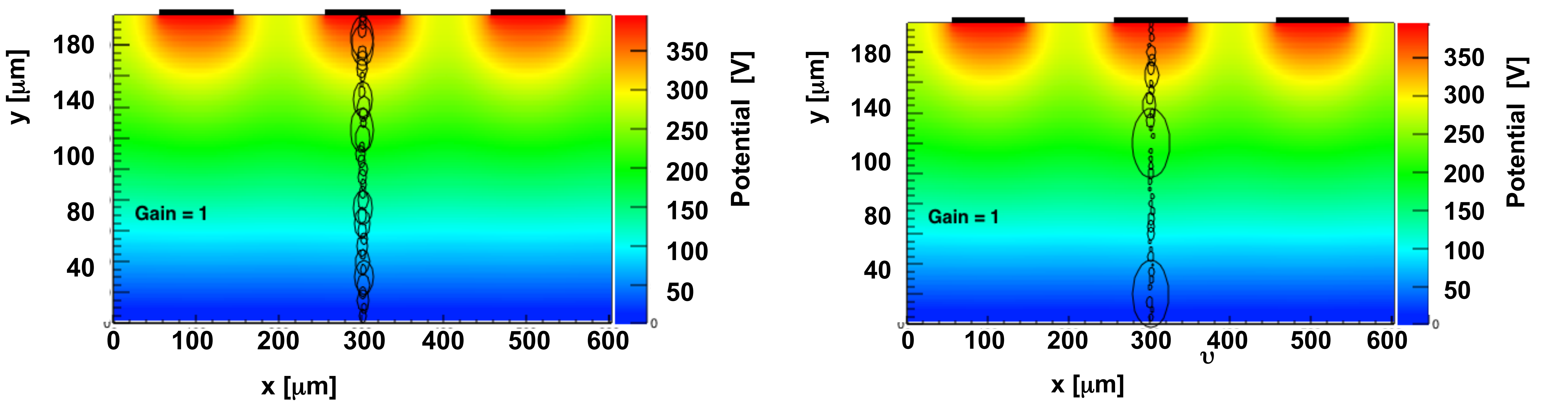
- Measuring time of arrival: look for signal to cross threshold.

Variations in LGAD pulses (Sim.)



- Main contributions to resolution:
  - Jitter — the impact of noise
  - Signal variations — fluctuations in deposited charge
    - "Time walk": variation in TOTAL charge (Q)
    - "Landau": variations in profile (Q vs depth)

Ionization variations



Minimize Landau → go thin

Sensor time resolution

correct to < 5 ps

$$\sigma_t^2 = \sigma_{\text{timewalk}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{jitter}}^2$$

Depends on thickness:
30 ps for 50 µm

Depends on gain, thickness, noise:
~ 10 ps

Full detector resolution

Sensor — Electronics

$$\sigma_t^2 = \sigma_{\mathrm{Landau}}^2 + \sigma_{\mathrm{jitter}}^2 + \sigma_{\mathrm{TDC}}^2 + \sigma_{\mathrm{clock}}^2$$

30 ps — 10 ps — 10 ps — 10 ps

Full ETL system: possible to achieve ~35 ps resolution per hit!

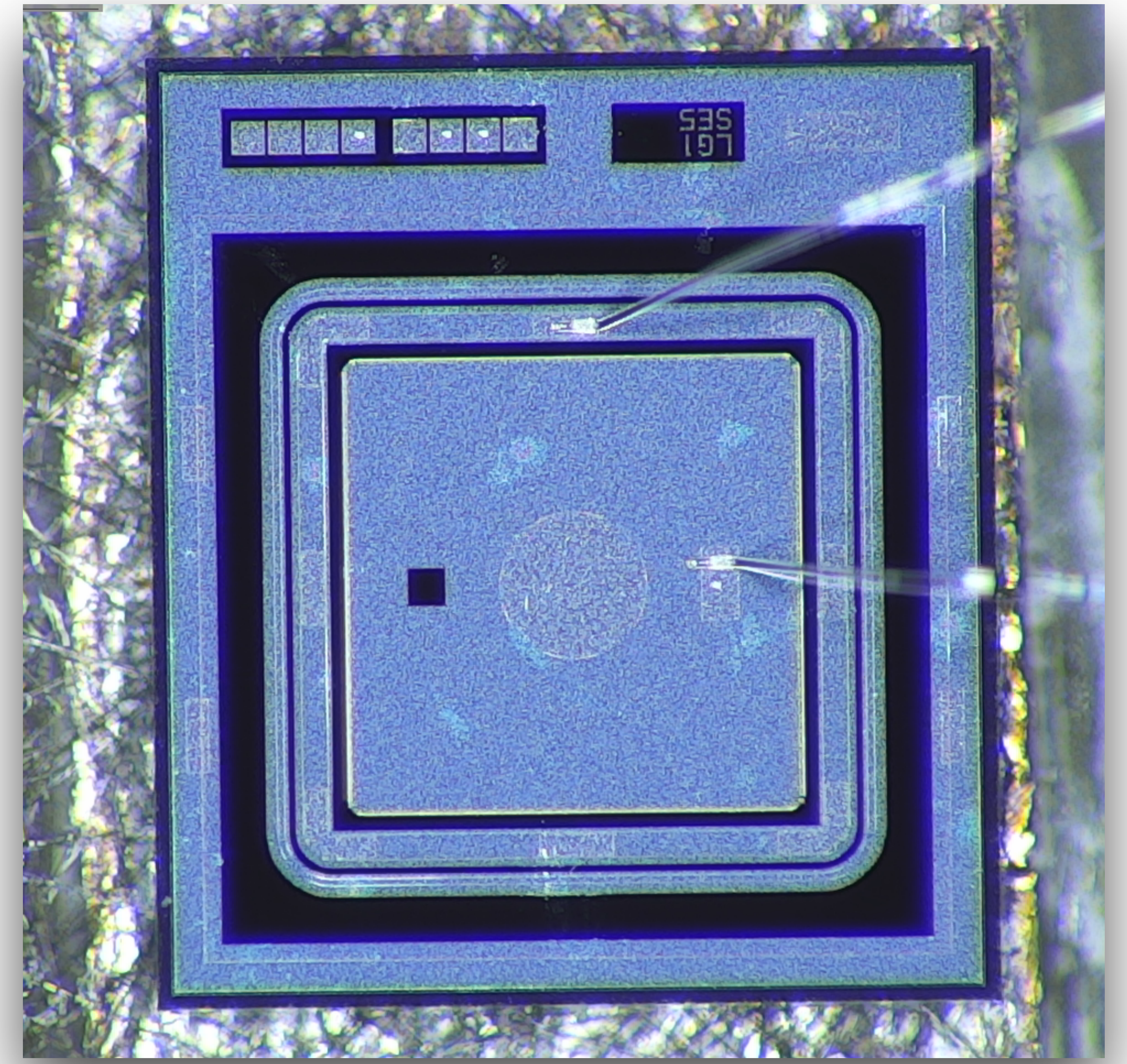
Good references:

Cartiglia, Hadrozinski, Seiden: arxiv:1704.08666

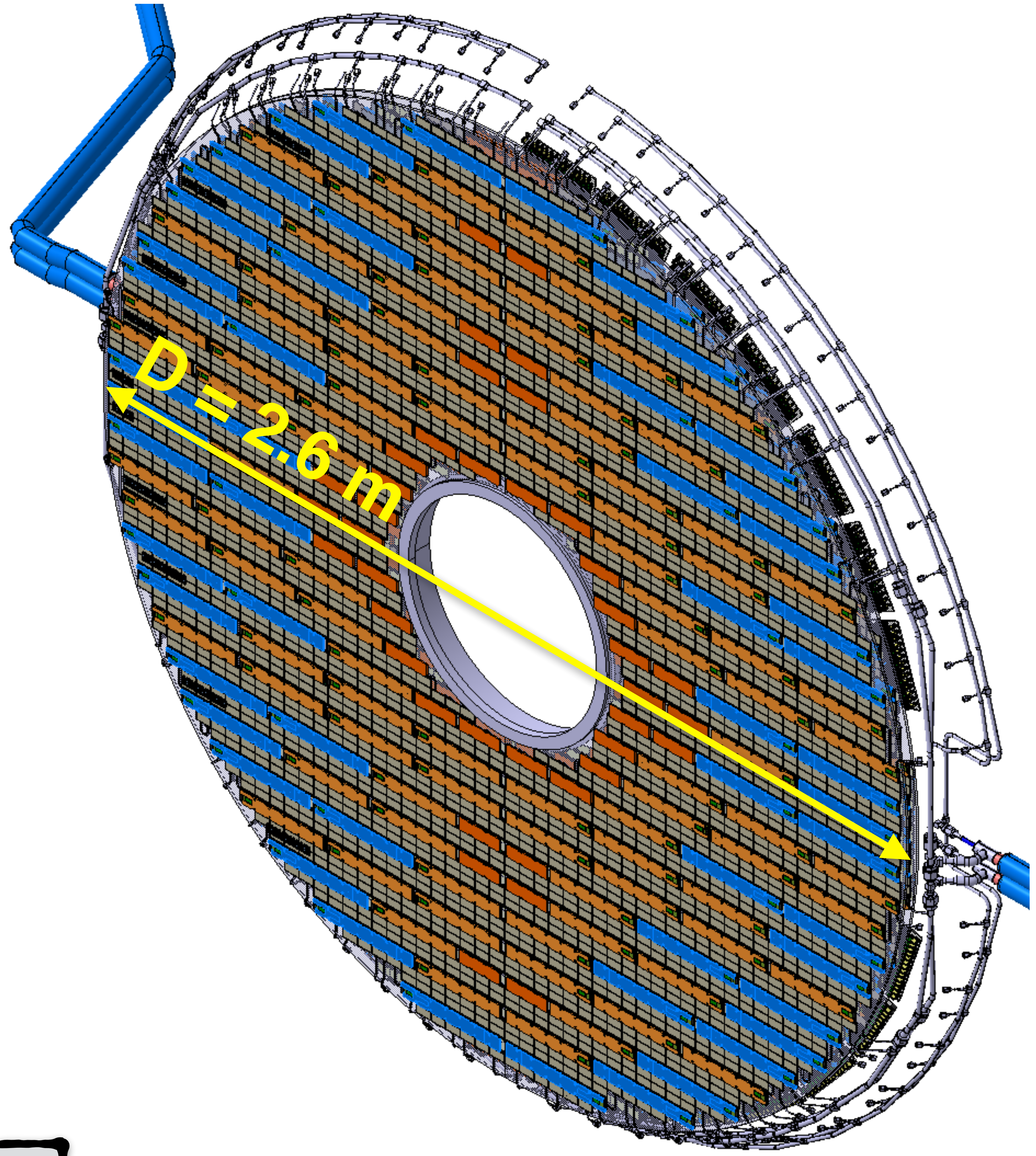
W. Riegler and G. Aglieri Rinella 2017 JINST 12 P11017

LGADs for ETL

HPK LGAD prototype, 1.3 mm pad



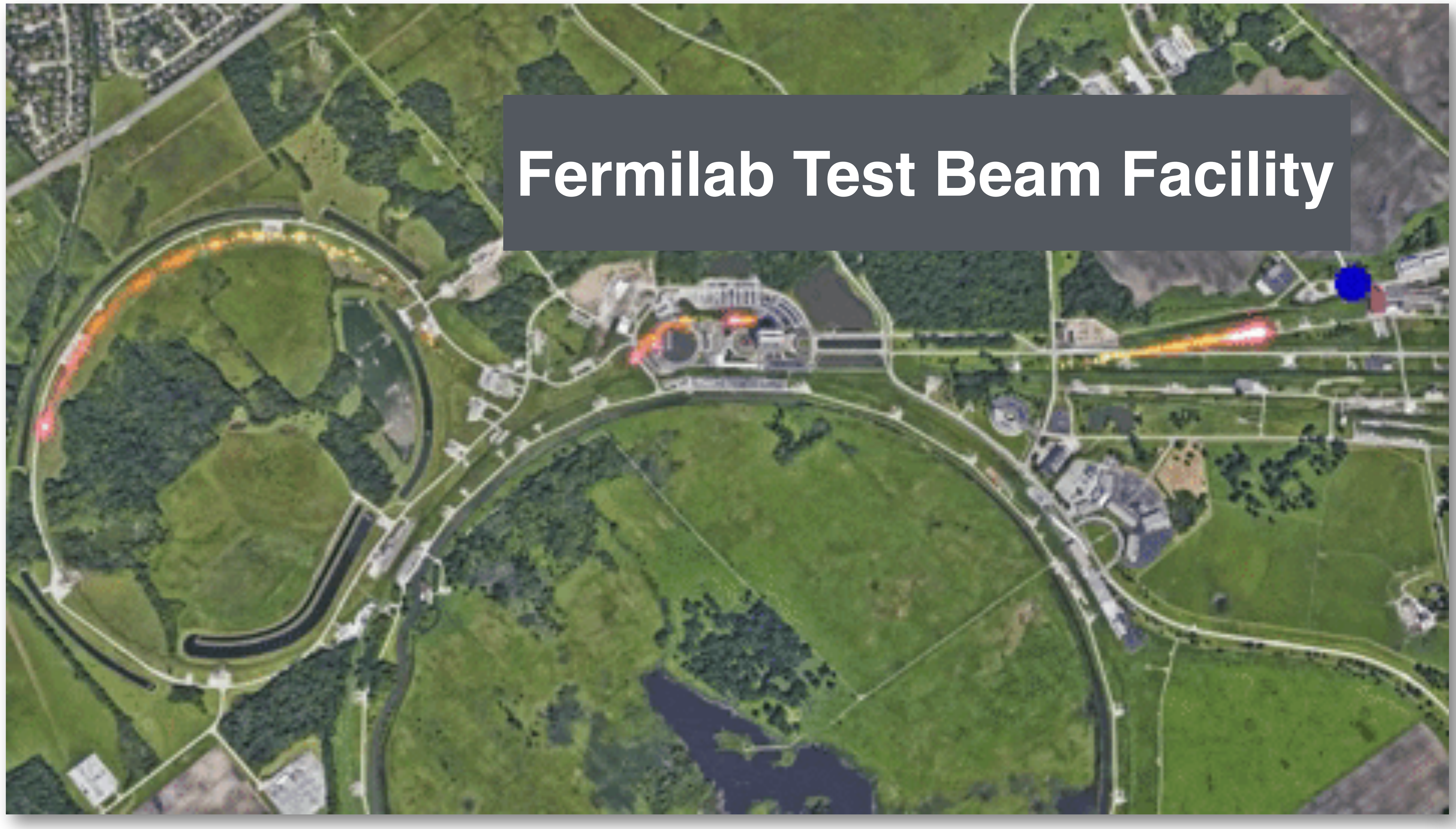
Endcap timing layer, 2.6 m

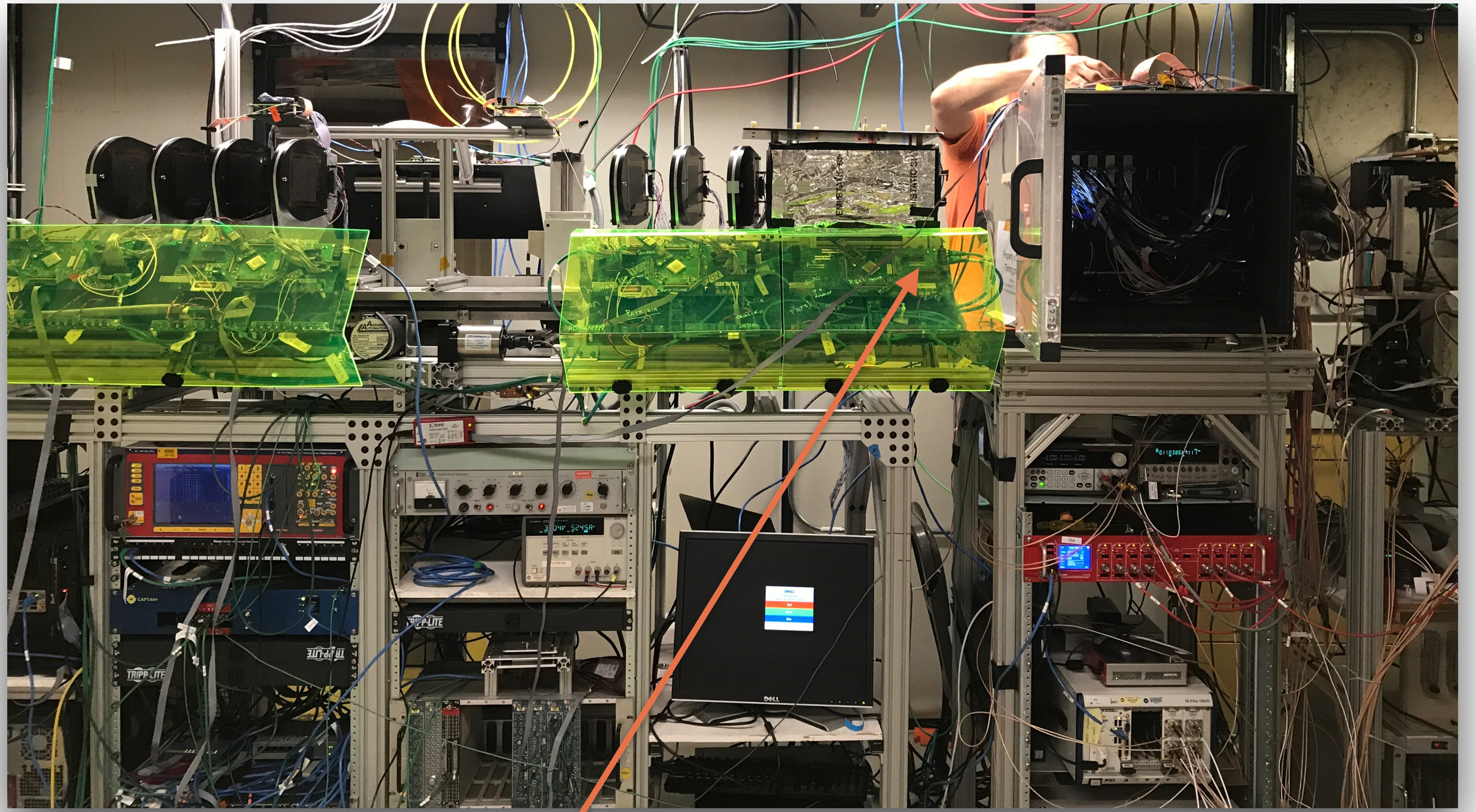


What does it take to scale from 1 mm² to 14 m² ?

How do we study LGADs?

- Best playground for collider detector: test beam





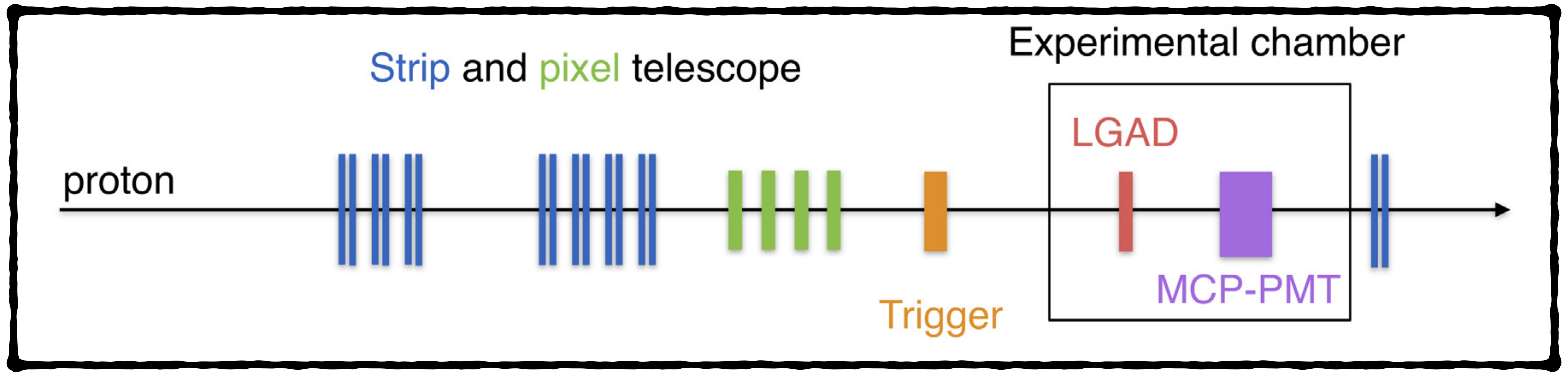
Telescope by L. Uplegger et al. (UniMi alum)

- 120 GeV proton beam as proxy for particles in CMS
- Key LGAD questions: uniformity in large sensors; radiation hardness (up to 1.5×10^{15} neq /cm^2)

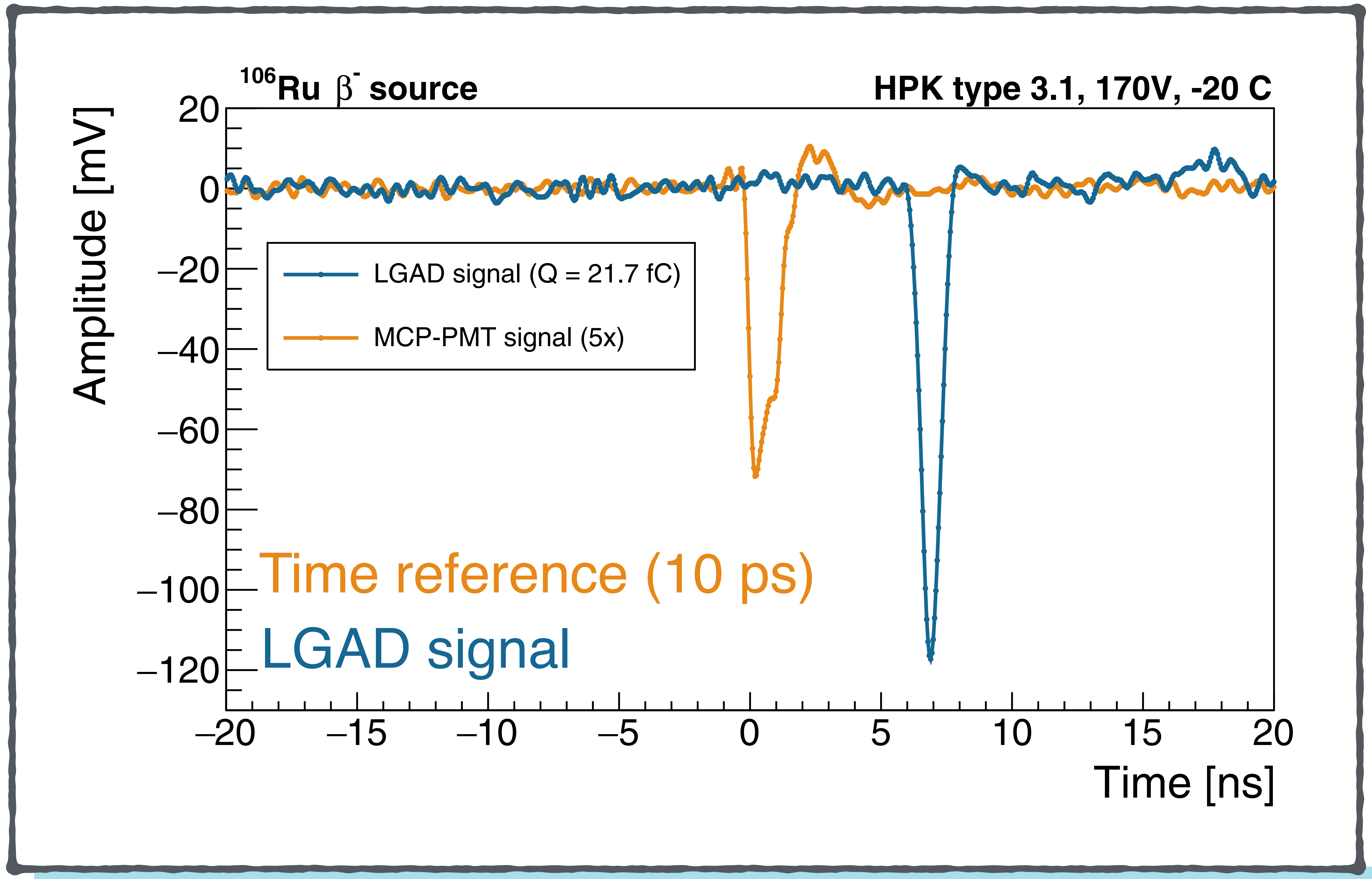
Test beam characterization facility

- For each proton, measure:
  - Arrival time, with fast MCP-PMT
  - Impact position, with tracking telescope

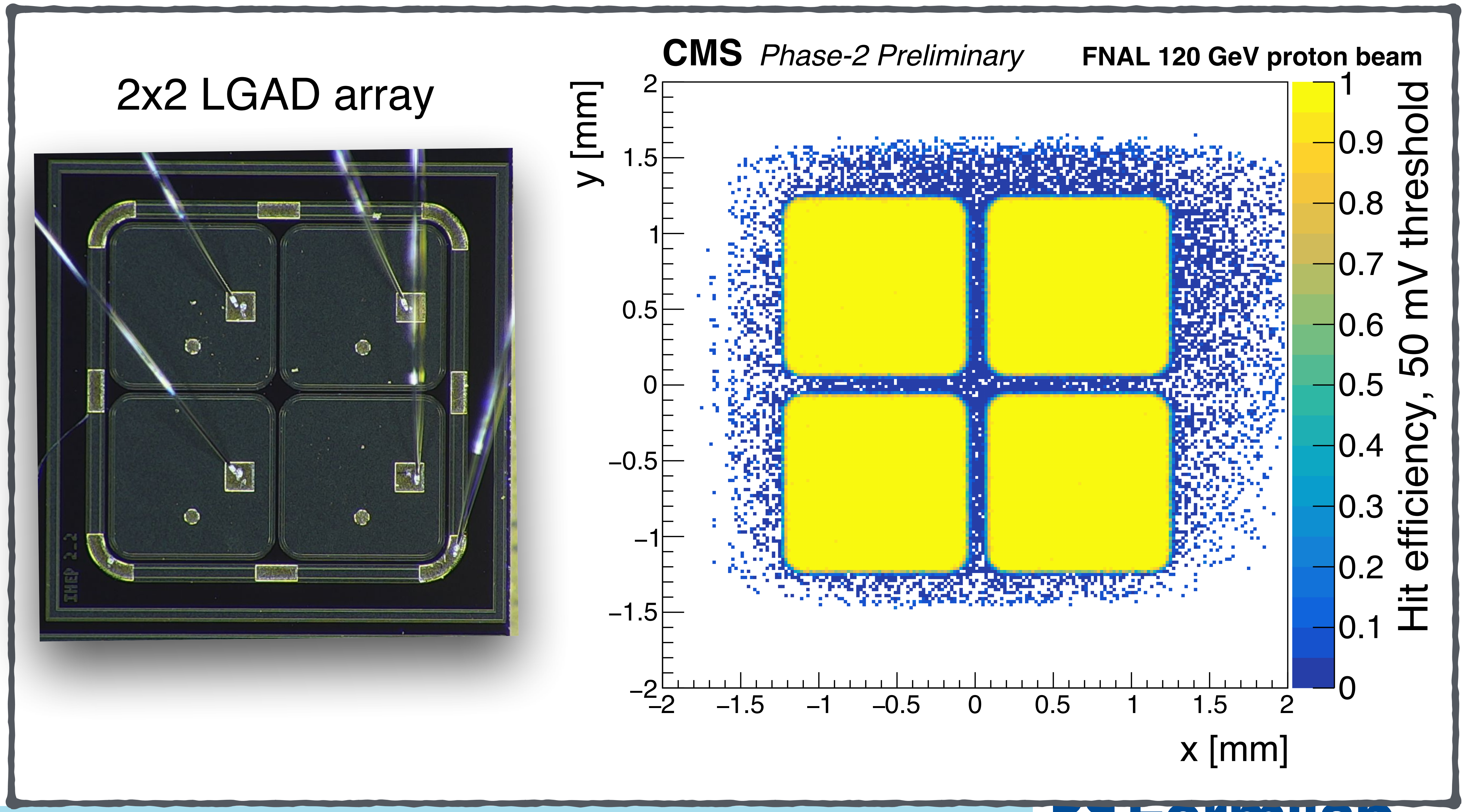
Beamline instruments



Record waveforms with oscilloscope / digitizer



Measure proton trajectory with tracker



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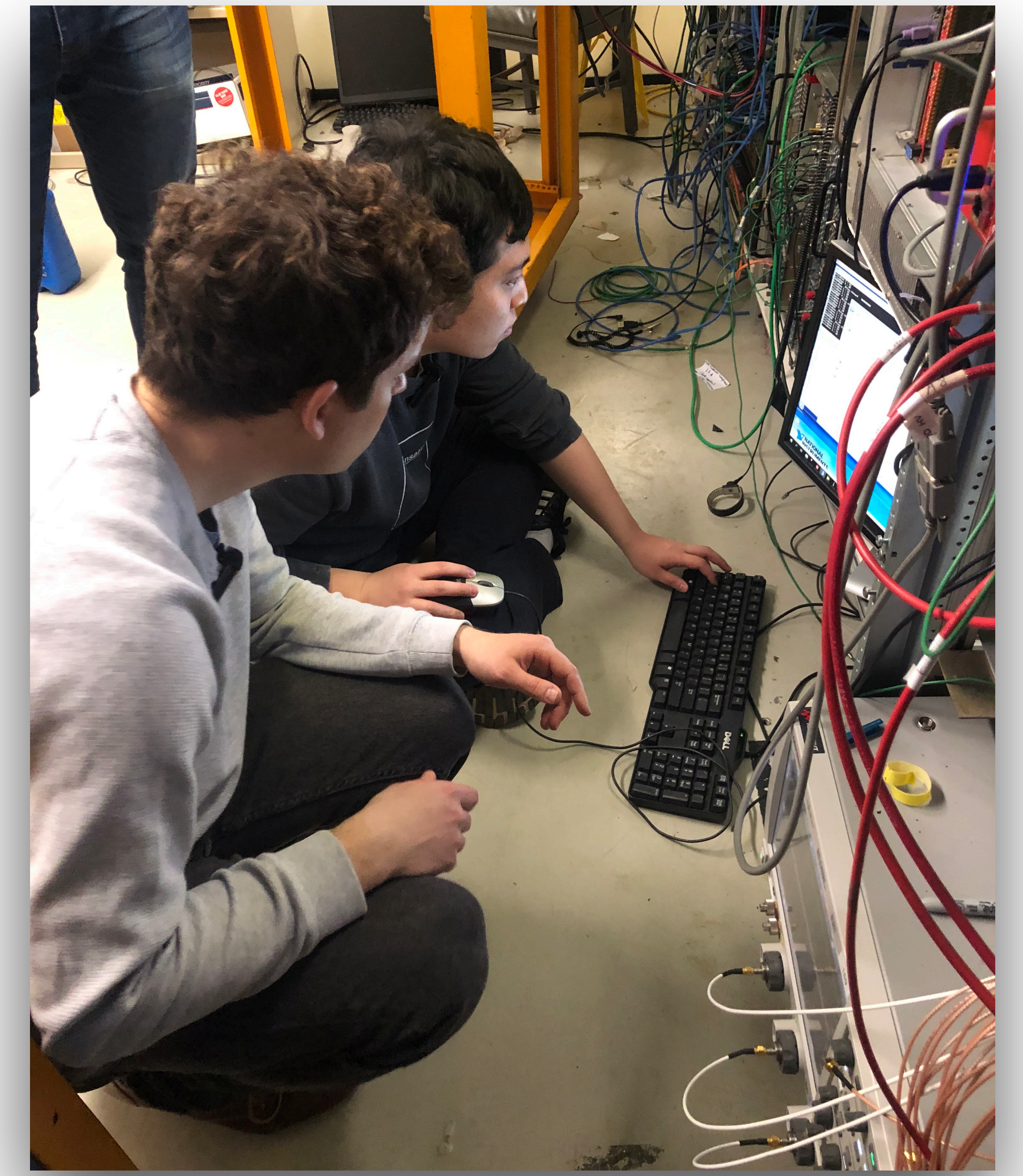
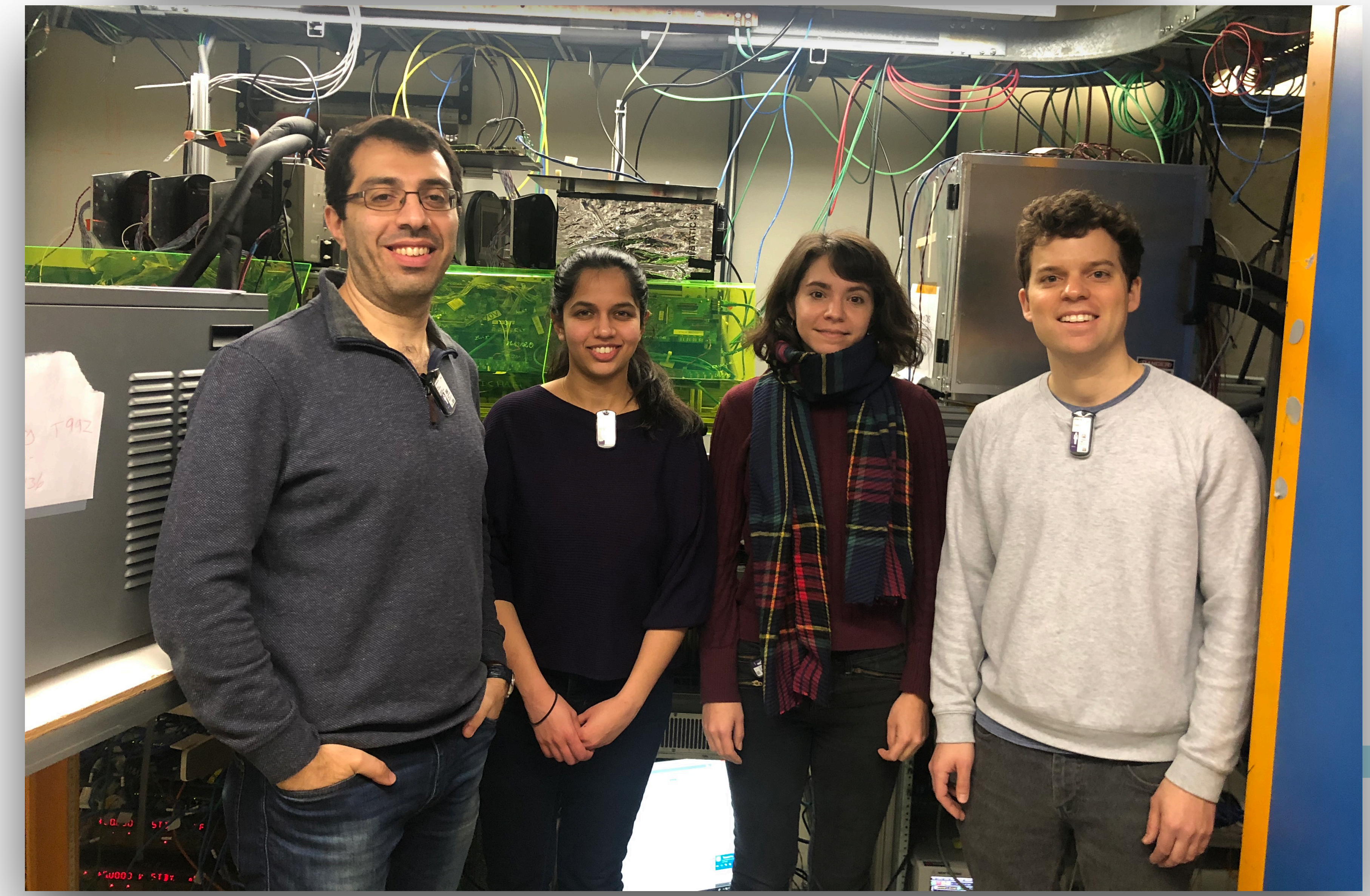
The team at work!

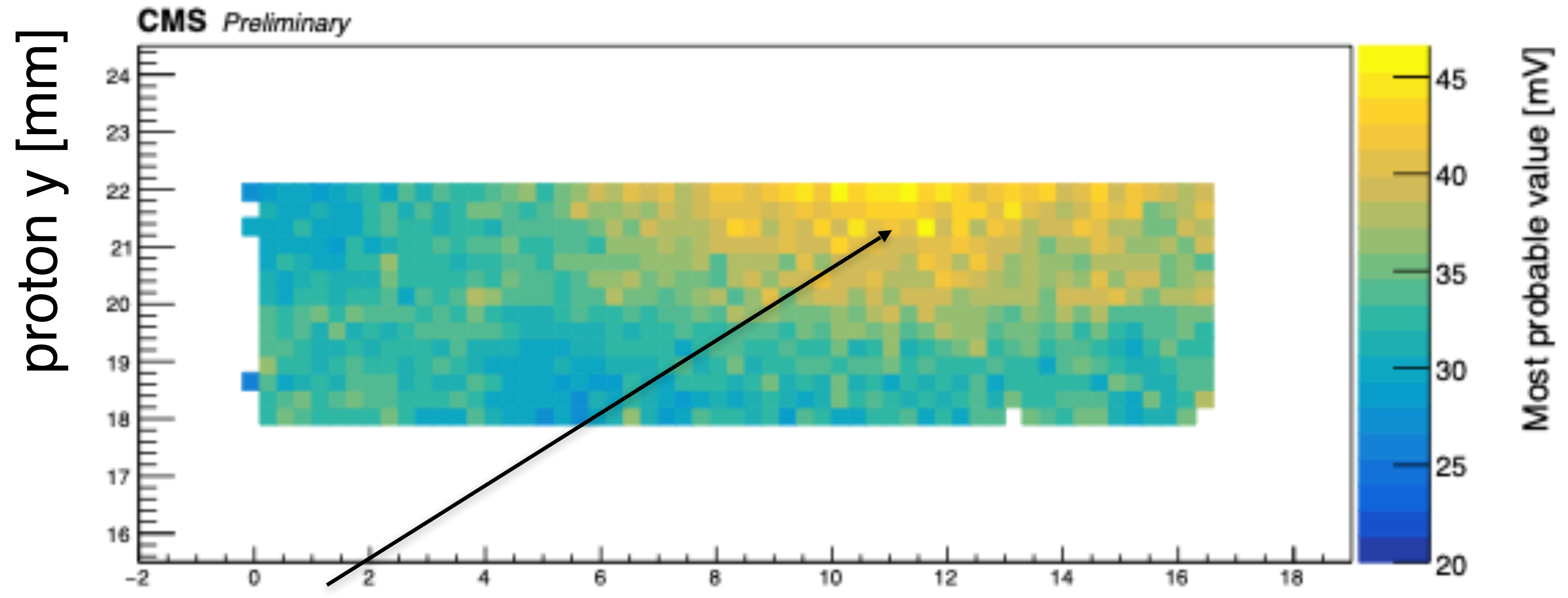




Key questions for LGADs

- Uniformity—
  - Large areas of detector (≥ 4x4 cm²) constrained to same bias voltage
  - If gain implant is not uniform—can't operate successfully.
- Early on, noticed sensors with rather severe gradients:

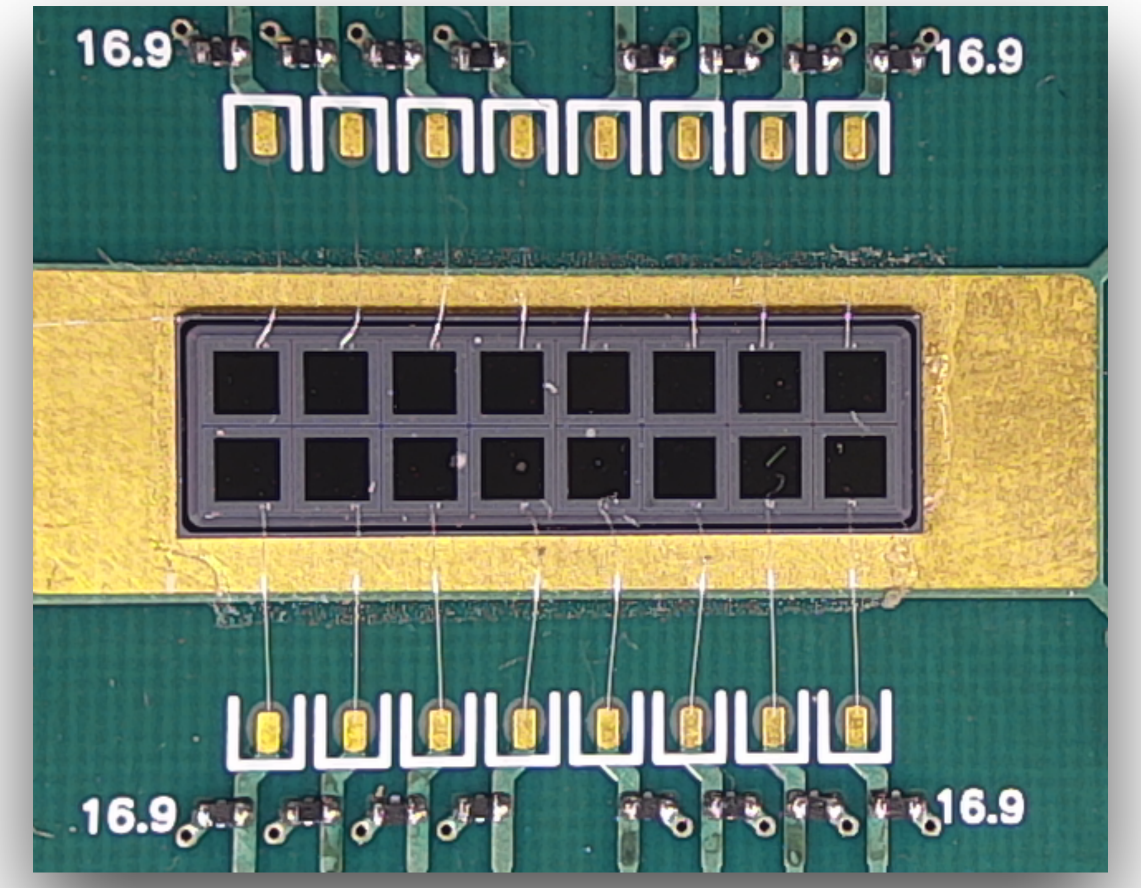
Map of signal amplitude (2019)



Hot spot: 50% higher gain

proton x [mm]

FBK array, 2x2 mm² pads



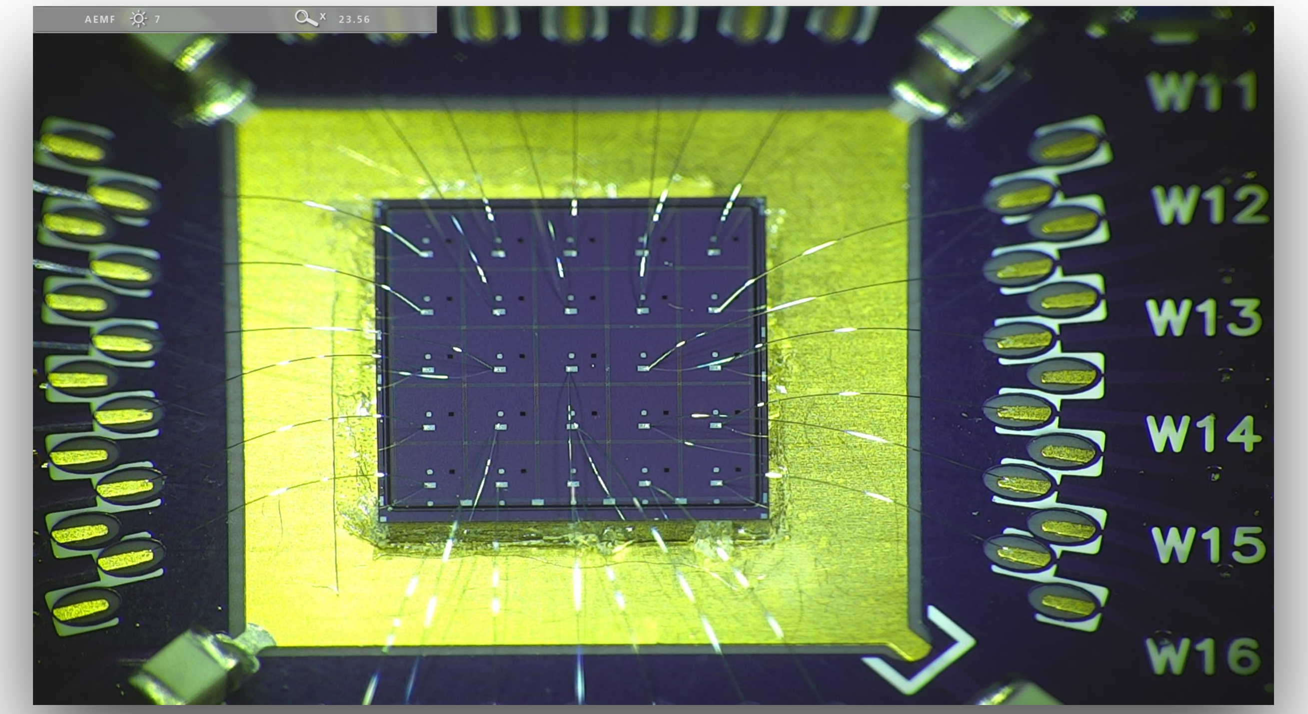
- Critical need to improve gain uniformity!

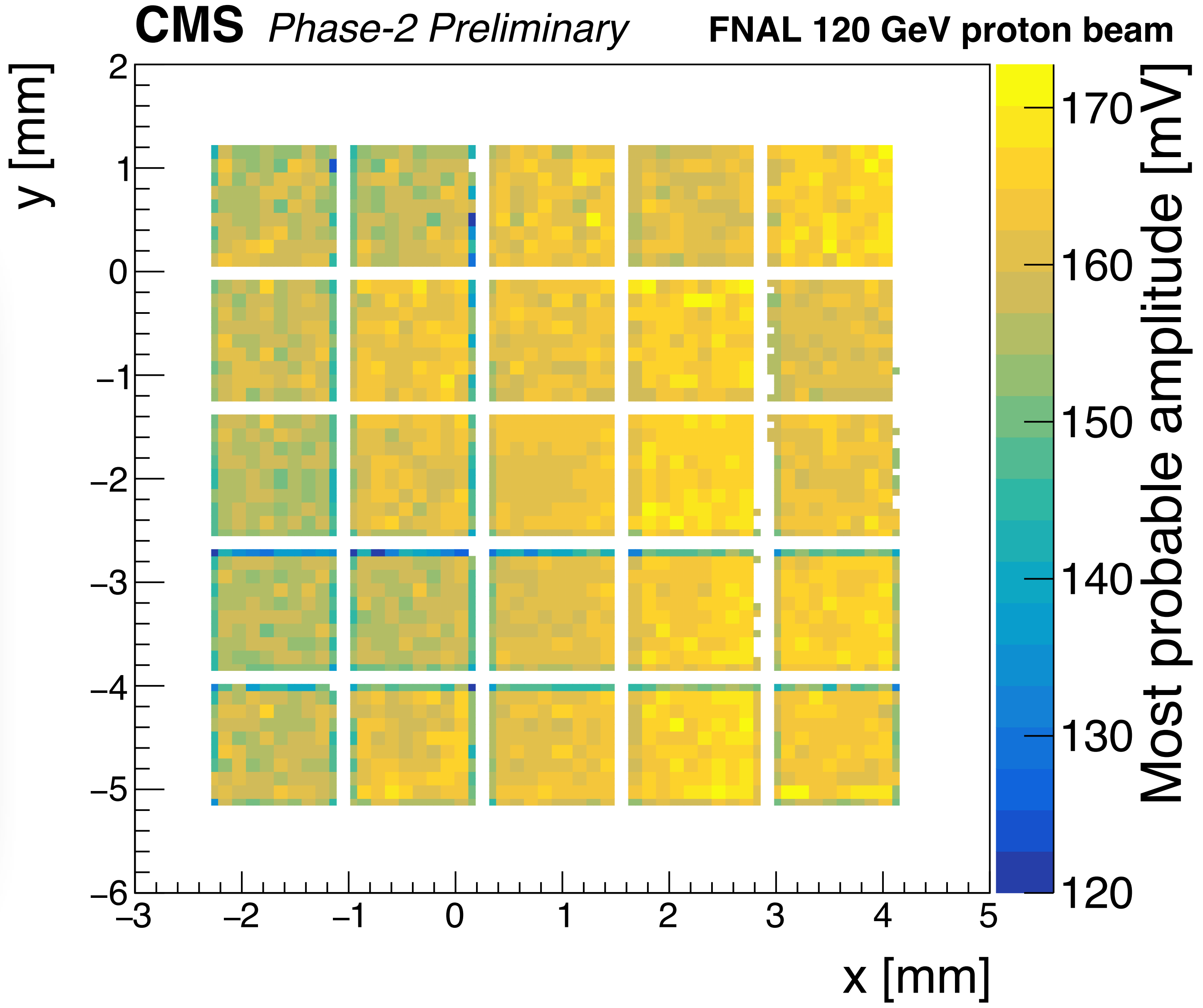
Demonstrating uniformity

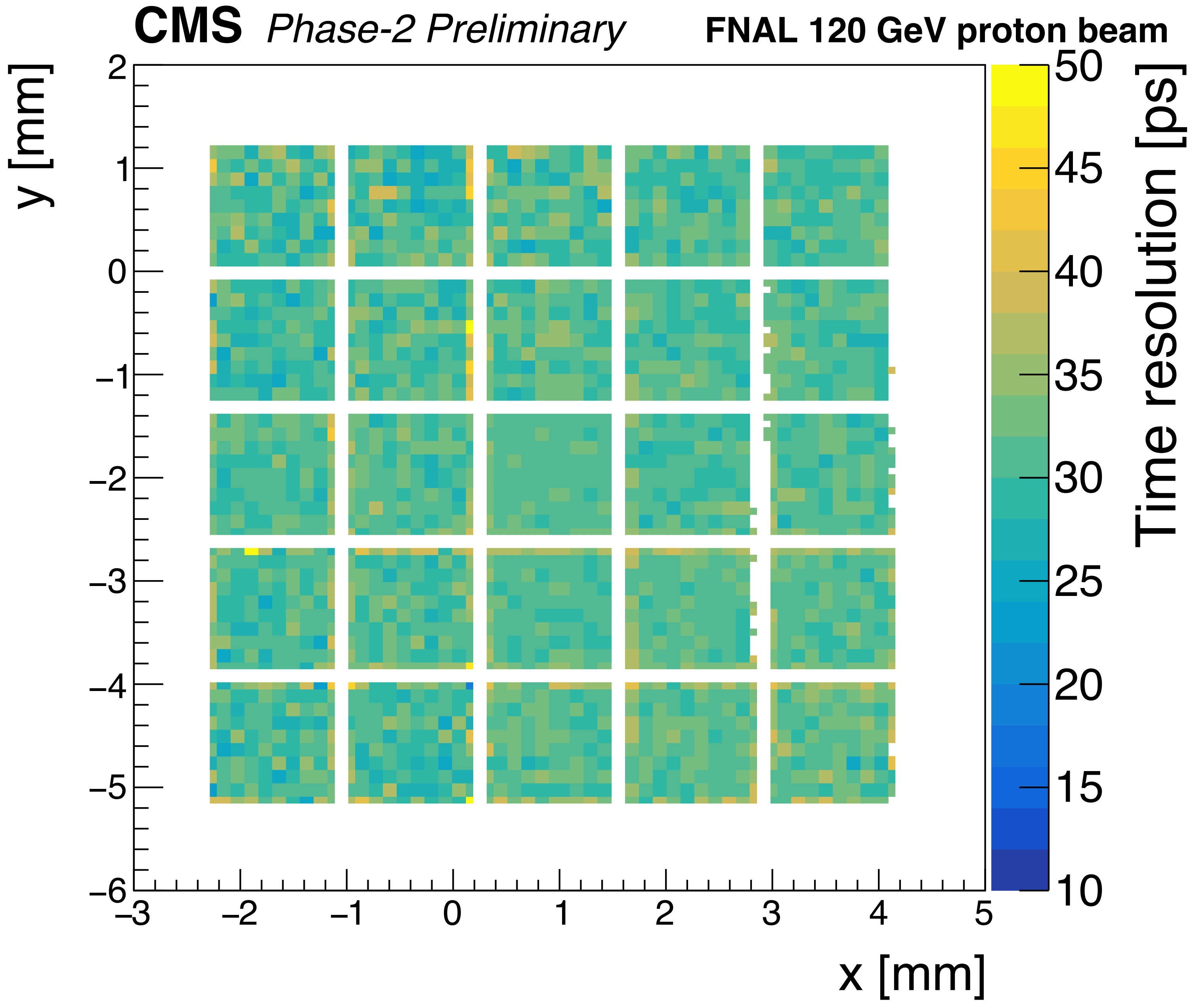
- Over time, iterated with foundries to improve uniformity
- In parallel, developed strategy to verify uniformity with simple probe tests

Latest sensor production: good uniformity

5x5 FBK LGAD array on 26-ch board (2022)







(Improved tracking—now resolve interpad gaps)

Demonstrating uniformity

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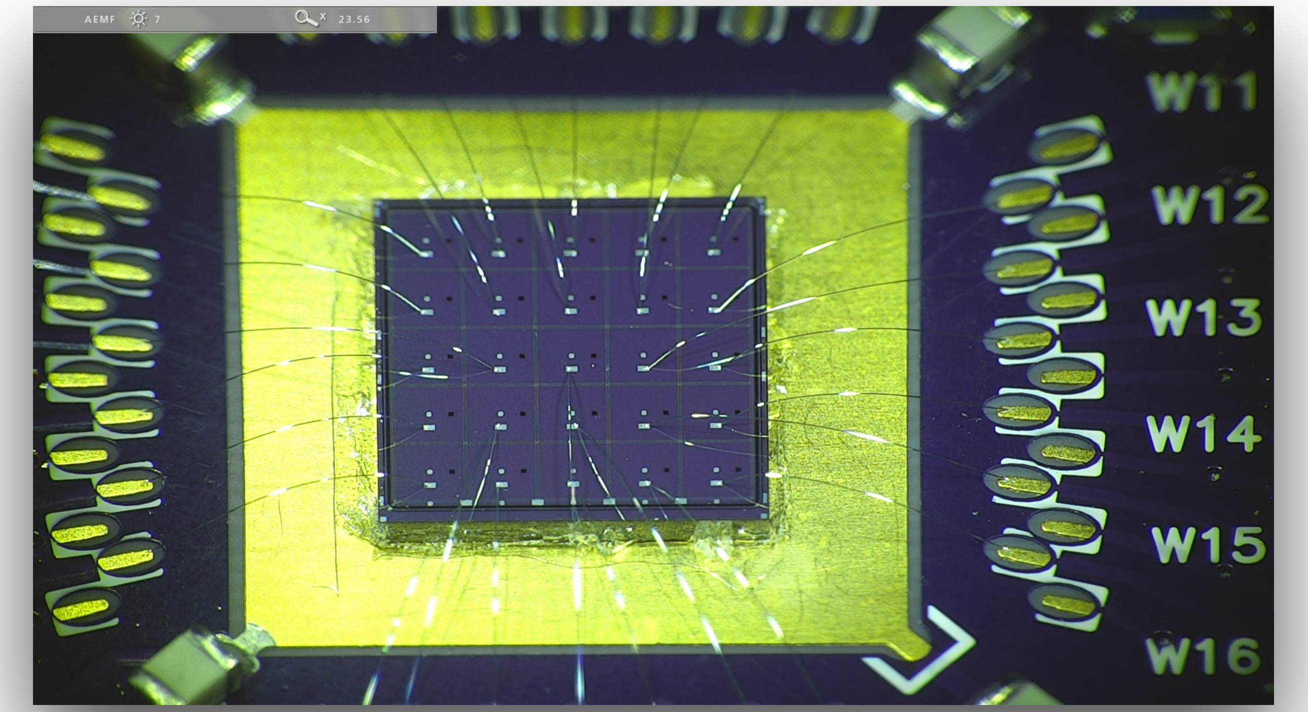
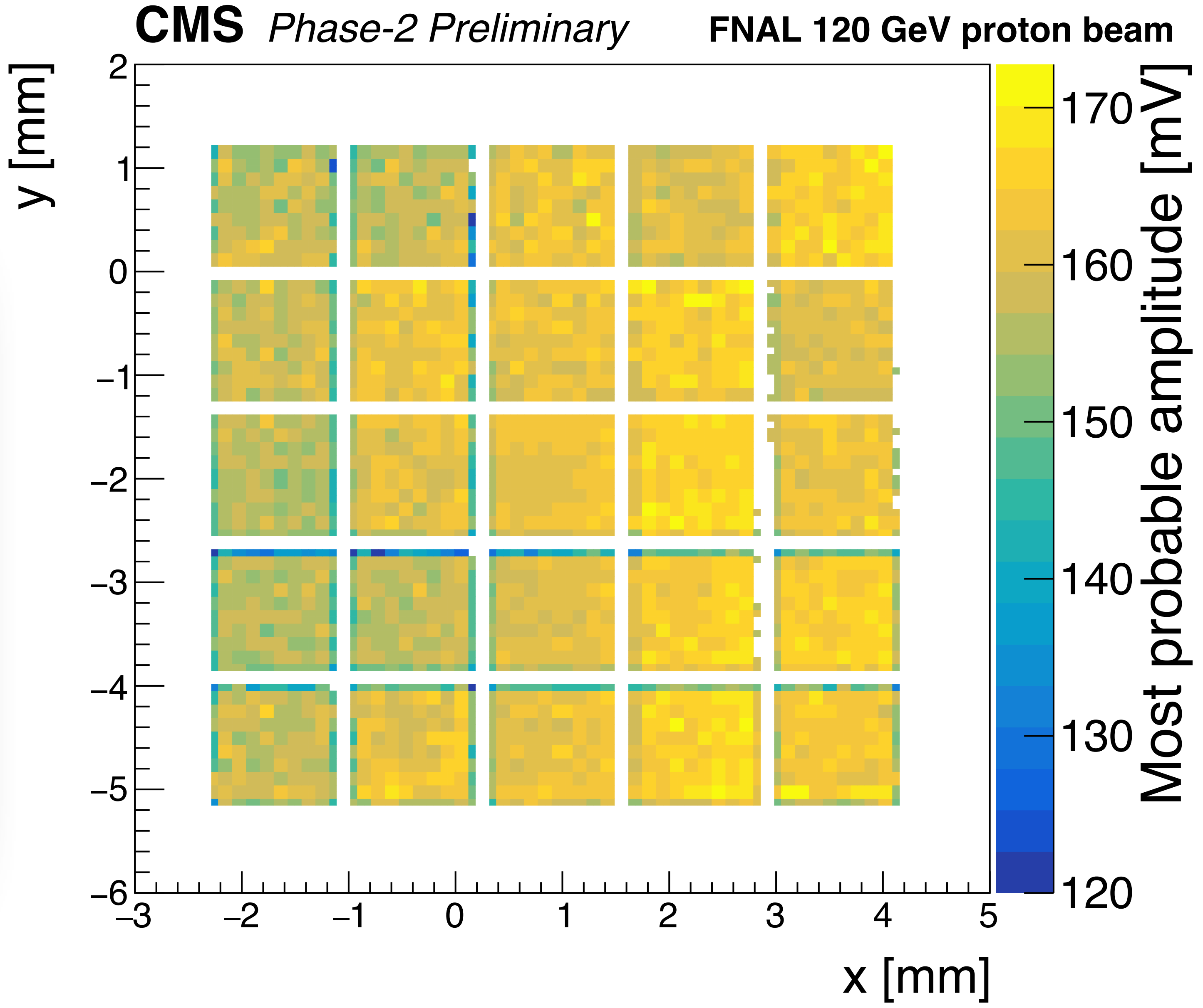
Latest sensor production: good uniformity

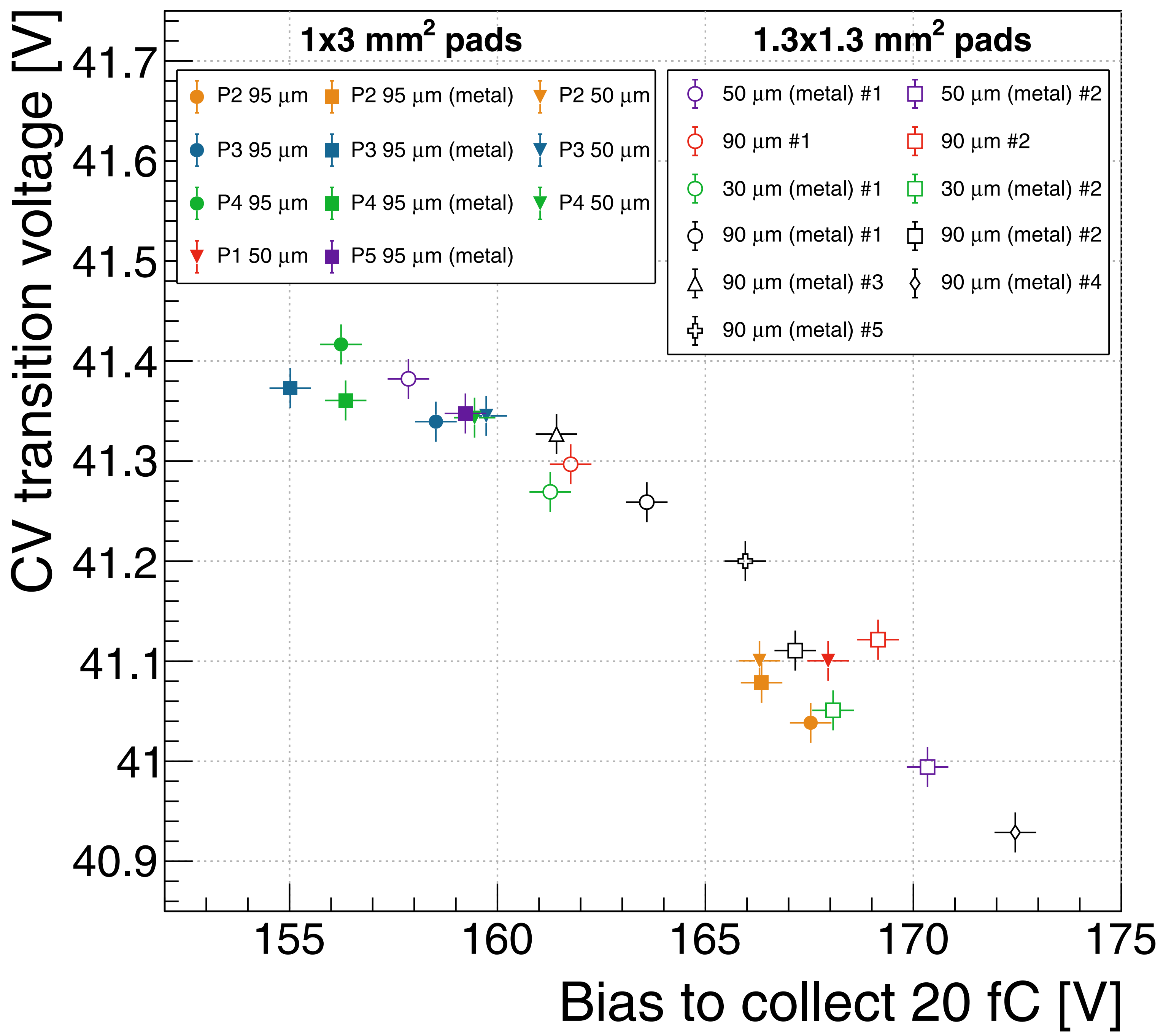
5x5 FBK LGAD array on 26-ch board (2022)





Correlate probe measurements (passive) with gain (active)

22 sensors

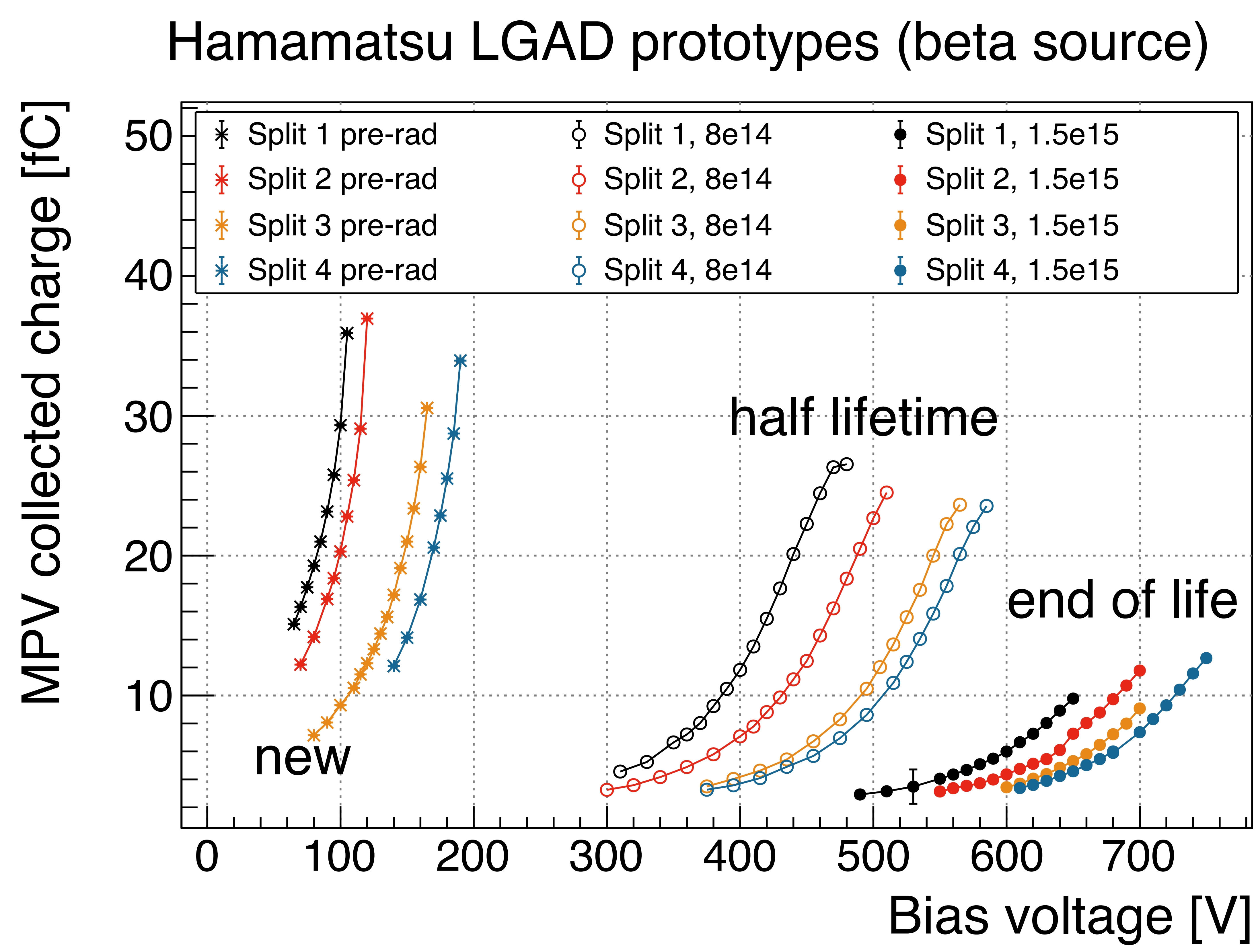


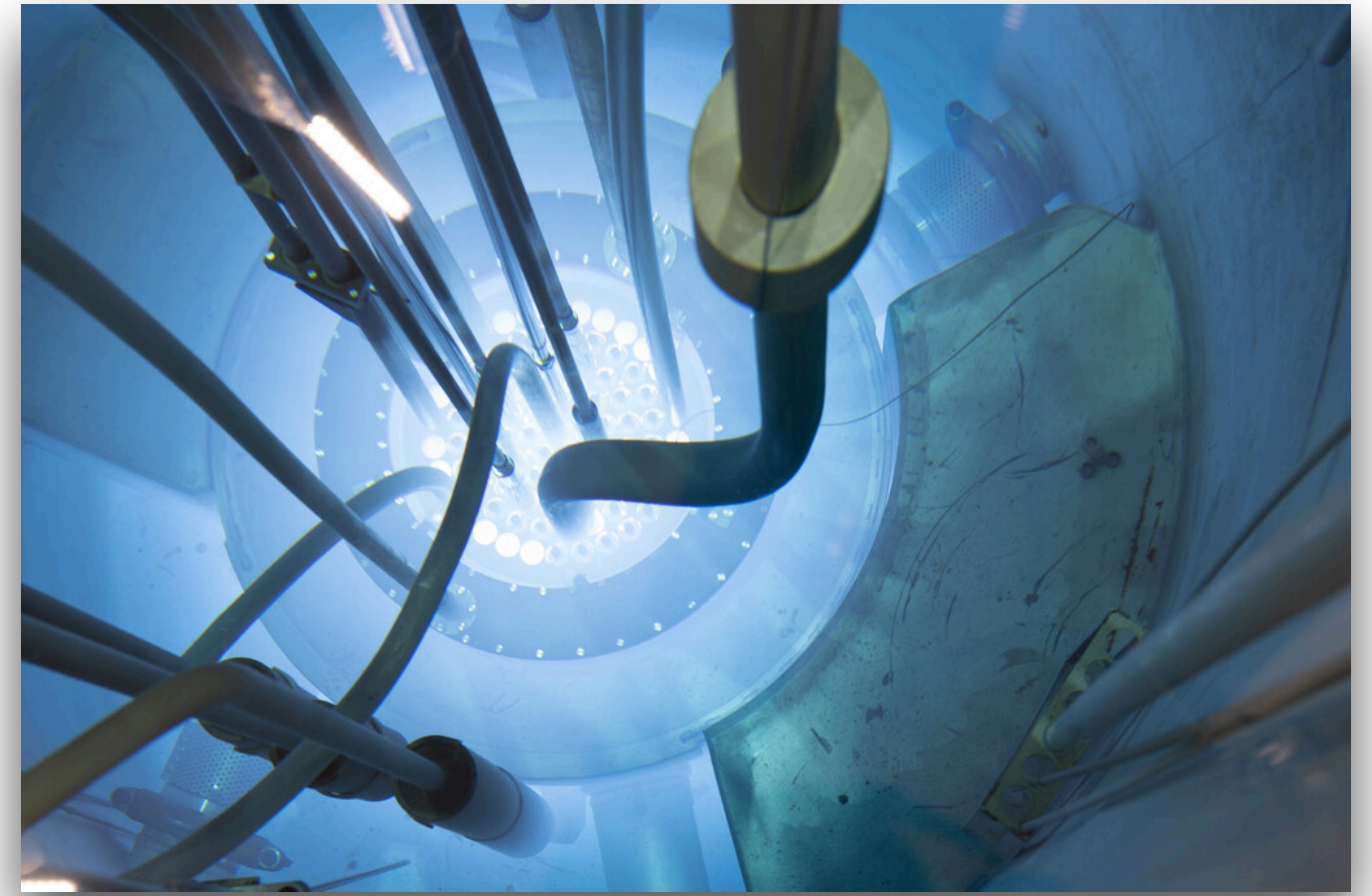
Nucl. Inst. Meth. A 1018 (2021) 165828

- Uniformity issue resolved, and procedure established for production QA/QC.

LGAD radiation hardness

- Gain implant de-activates with irradiation at LHC
- Emulate by exposure at nuclear reactor (up to 1.5 x 10^{15} neq / cm^2)





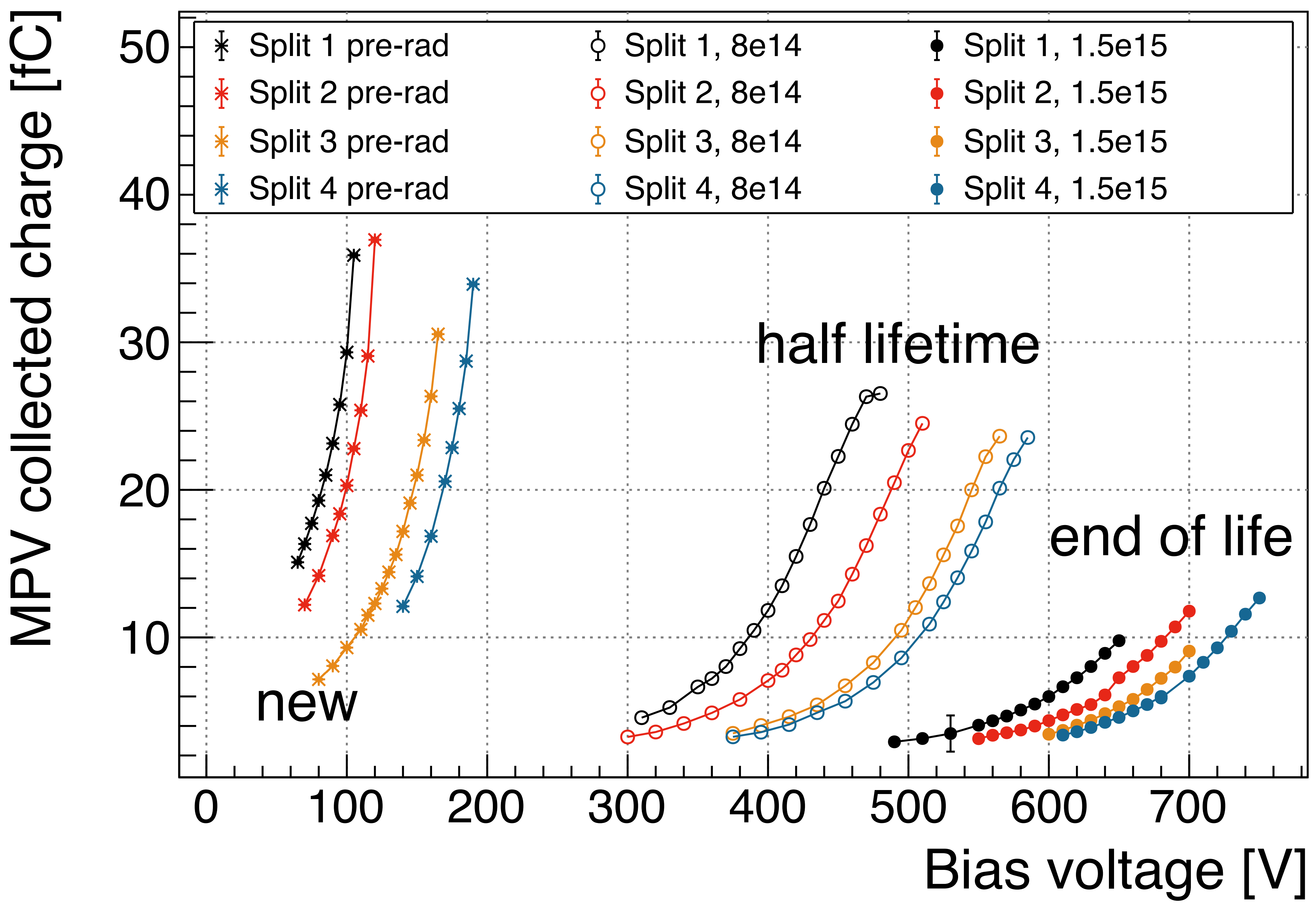
TRIGA reactor at JSI, Ljubljana, Slovenia

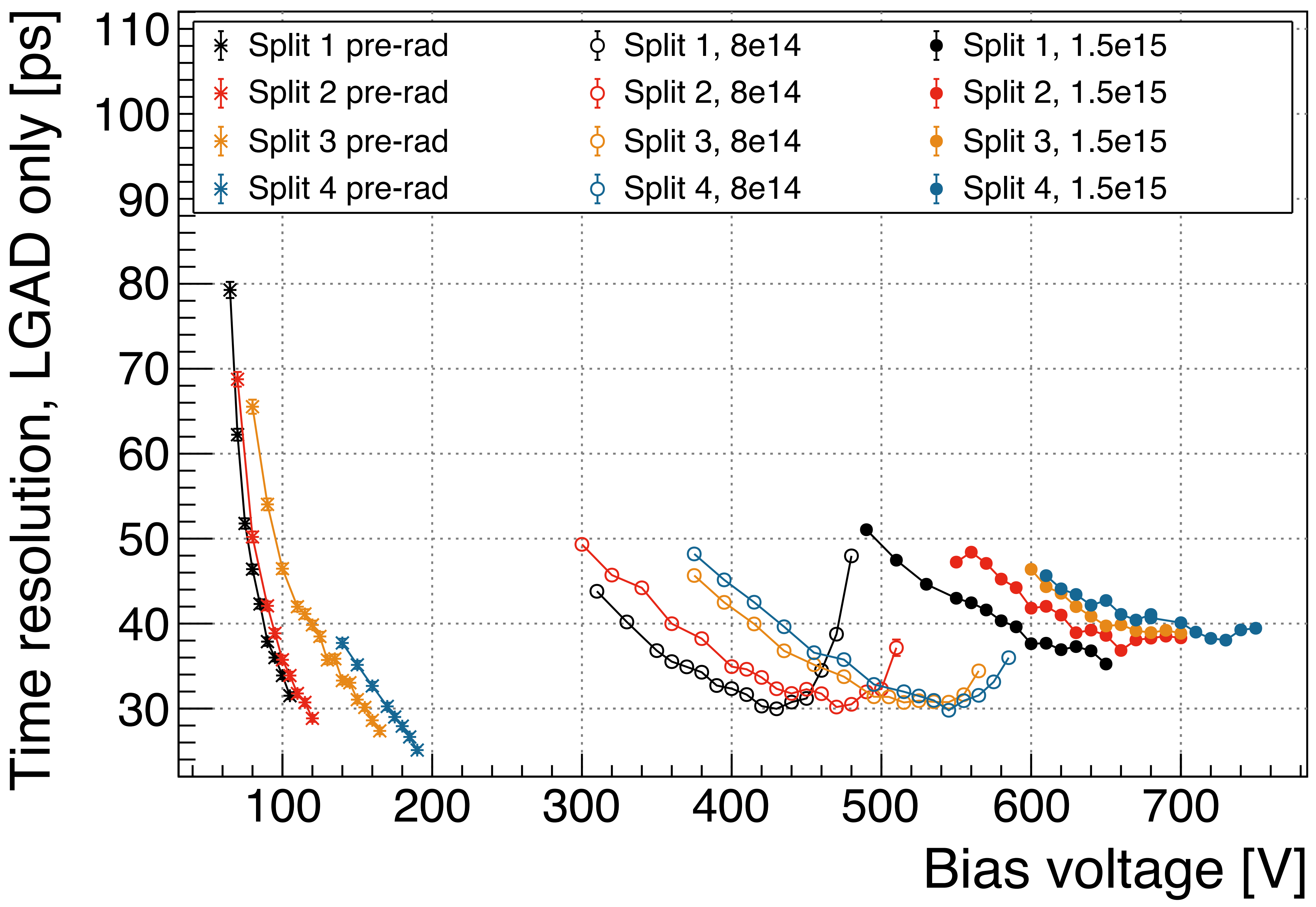
- Compensate by increasing bias.

LGAD radiation hardness

- Gain implant de-activates with irradiation at LHC
- Emulate by exposure at nuclear reactor (up to 1.5 x 10^{15} neq / cm^2)

Hamamatsu LGAD prototypes (beta source)





- Compensate by increasing bias.

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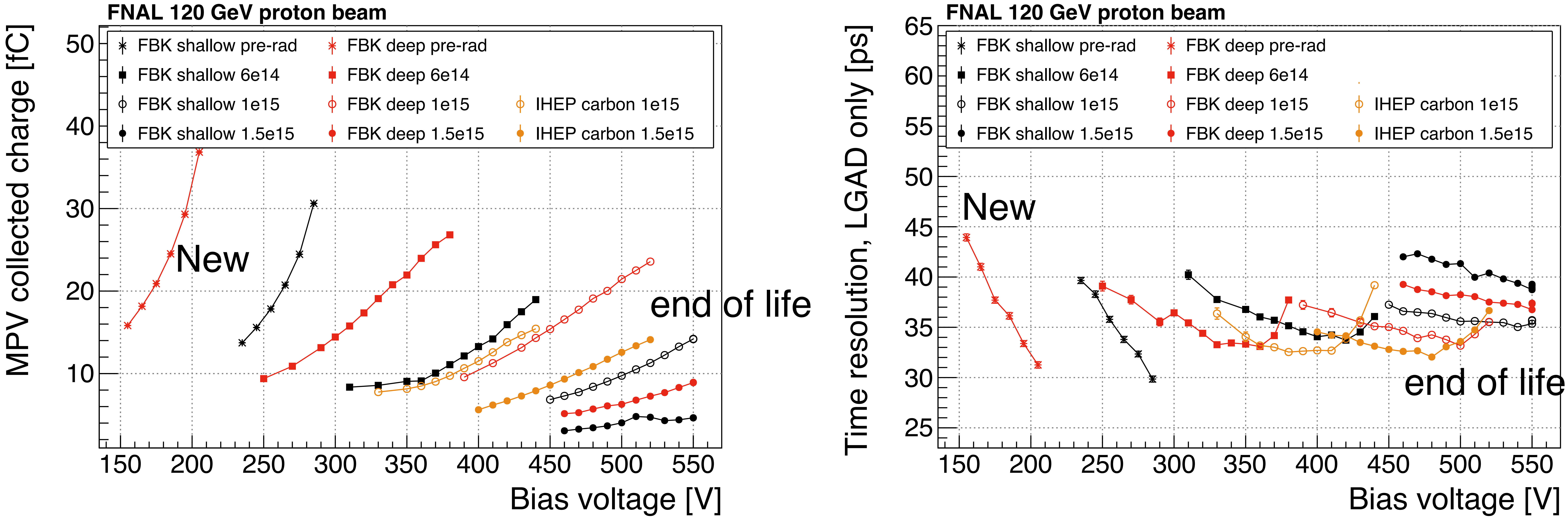
LGAD radiation hardness

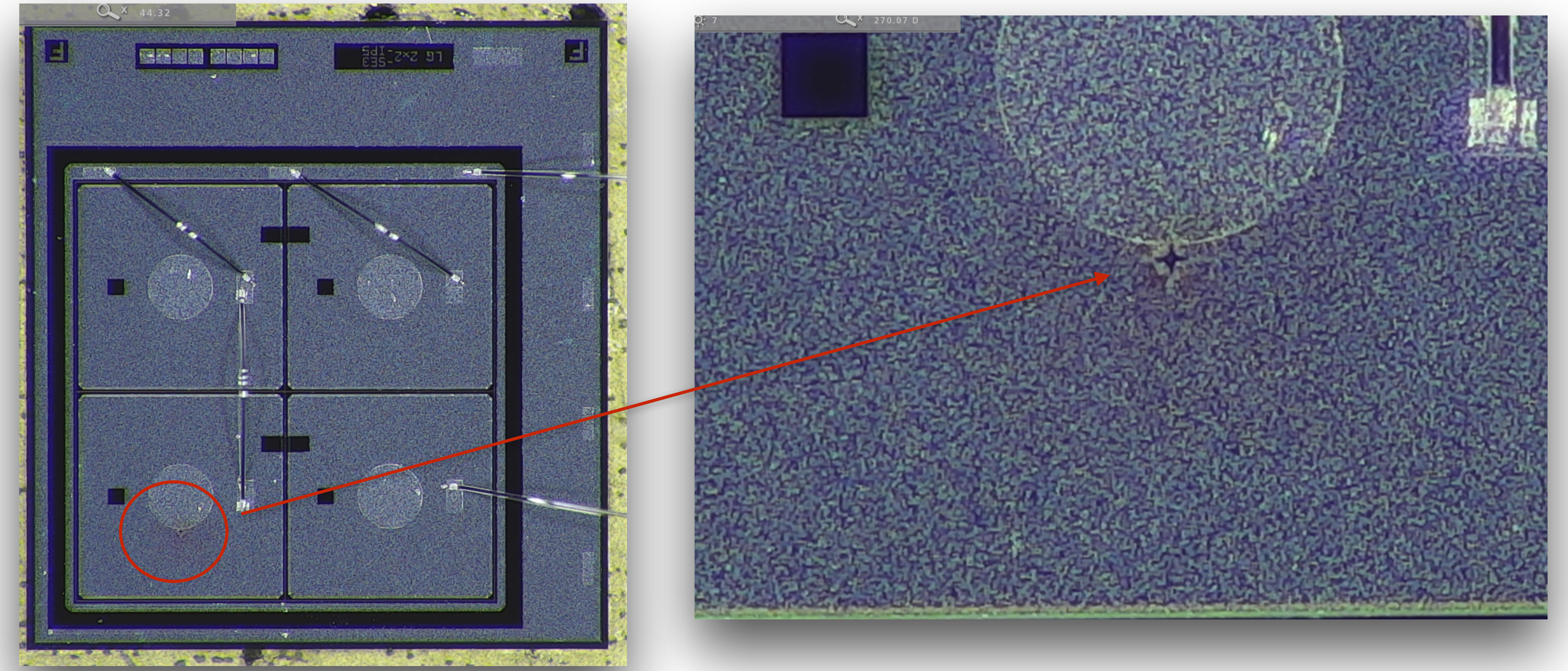
- Market survey underway—studying prototypes from several vendors.
- Co-implantation of carbon yields significantly improved radiation hardness
  - FBK and IHEP-IME



- Best designs keep 30—40 ps resolution at end of life, with bias < 550 V

LGAD mortality

- Anecdotally, noticed death of highly irradiated LGADs at test beams, at very high field.
  - Historically, not clear if caused by environmental/mishandling issue, or intrinsic sensor failure.



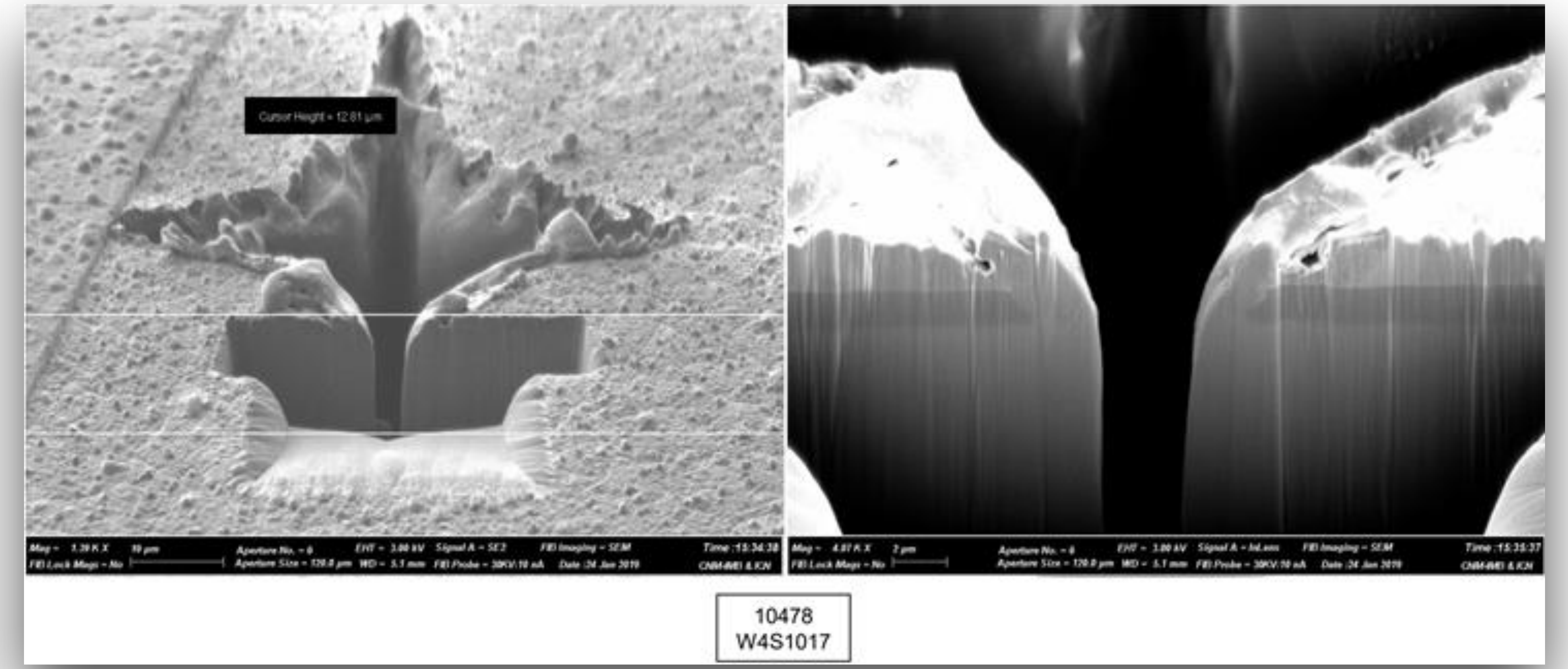


Photo credit: CNM, Barcelona

- Several test beam campaigns dedicated to study of LGAD mortality
  - Controlled death (30 sensors) → **understand death mechanism**
  - Survival demonstration (20 sensors) → **prove safe mitigation**

Controlled death studies with test beam

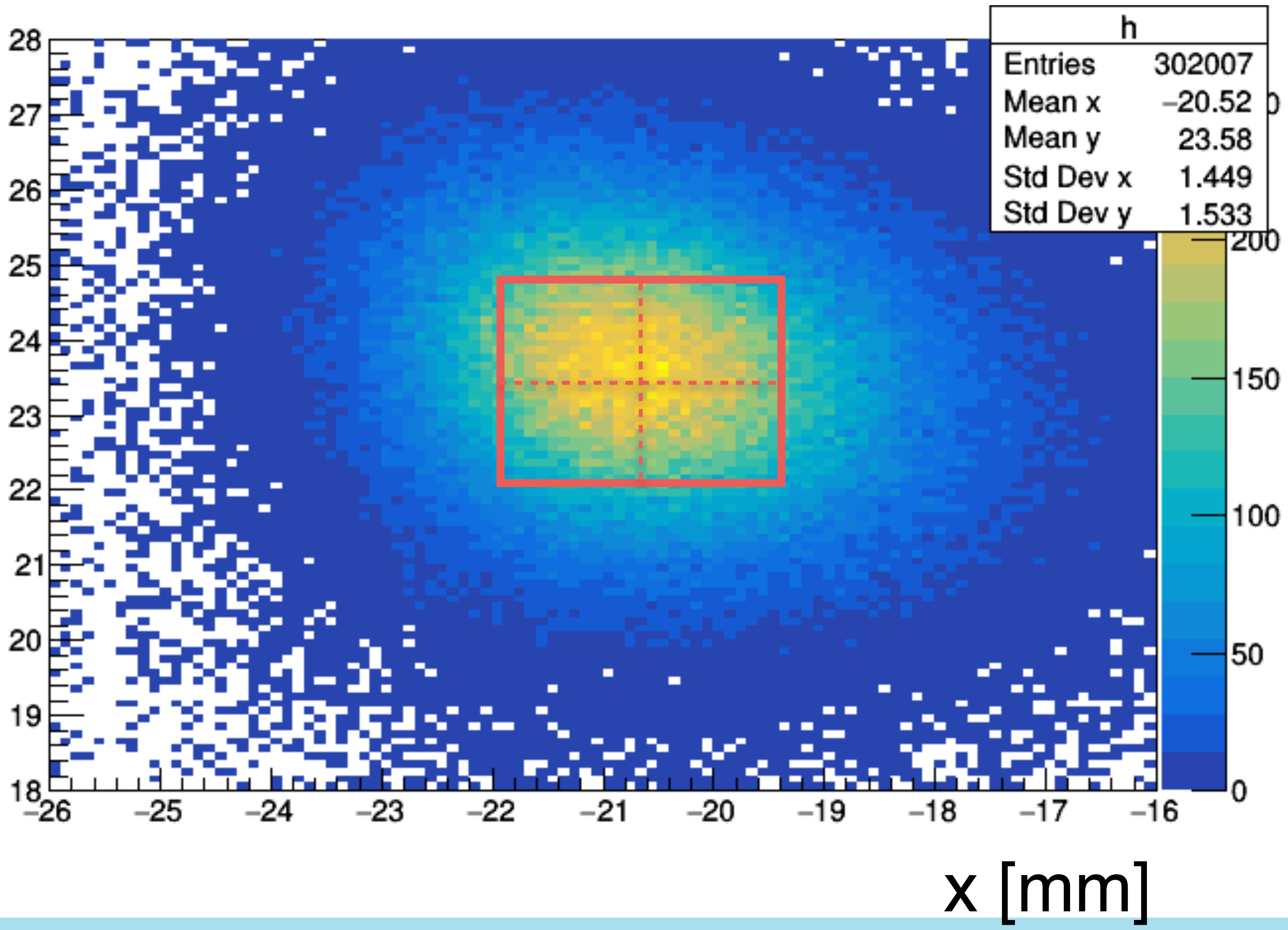
- Measure beam profile with tracker.
- Align each sensor with beam based on single-ch readout.
- Carefully increase bias voltage
  - ~3k protons on sensor per minute. Raise bias 25V after 100-200k protons.

Most sensors in 2x2 geometry

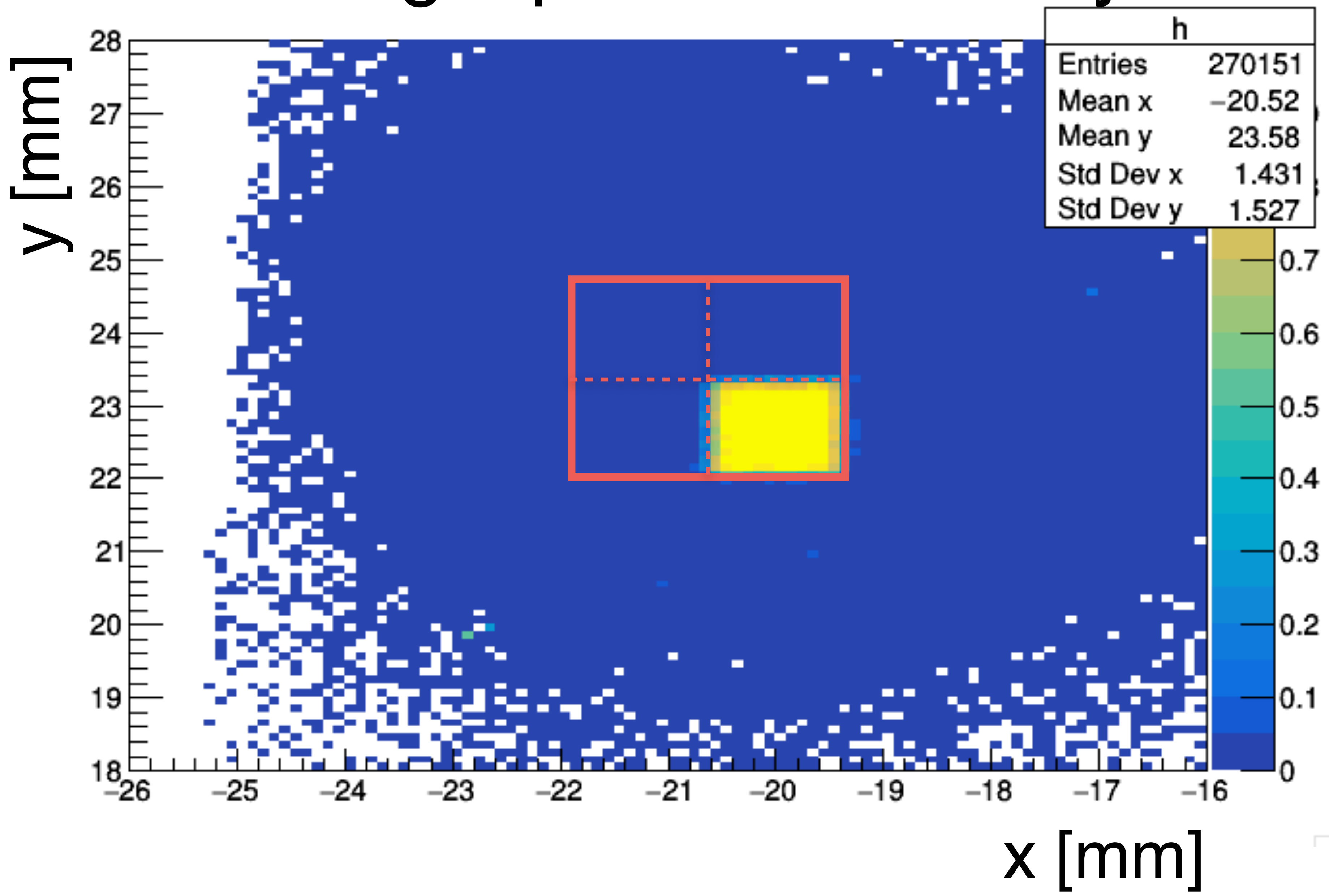
Most from Hamamatsu

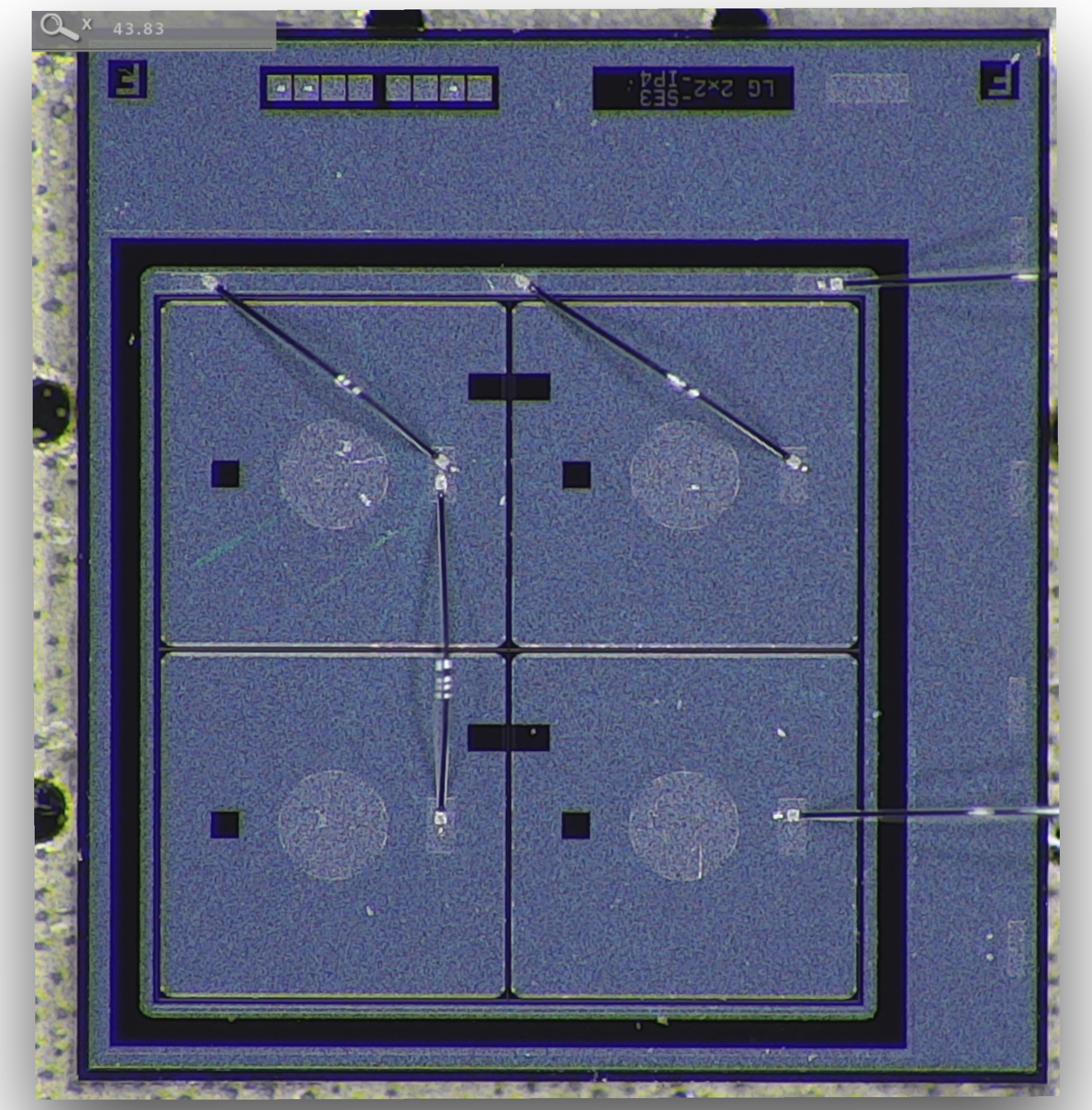
pre-irradiated 8e14-2.5e15 neq

Beam profile



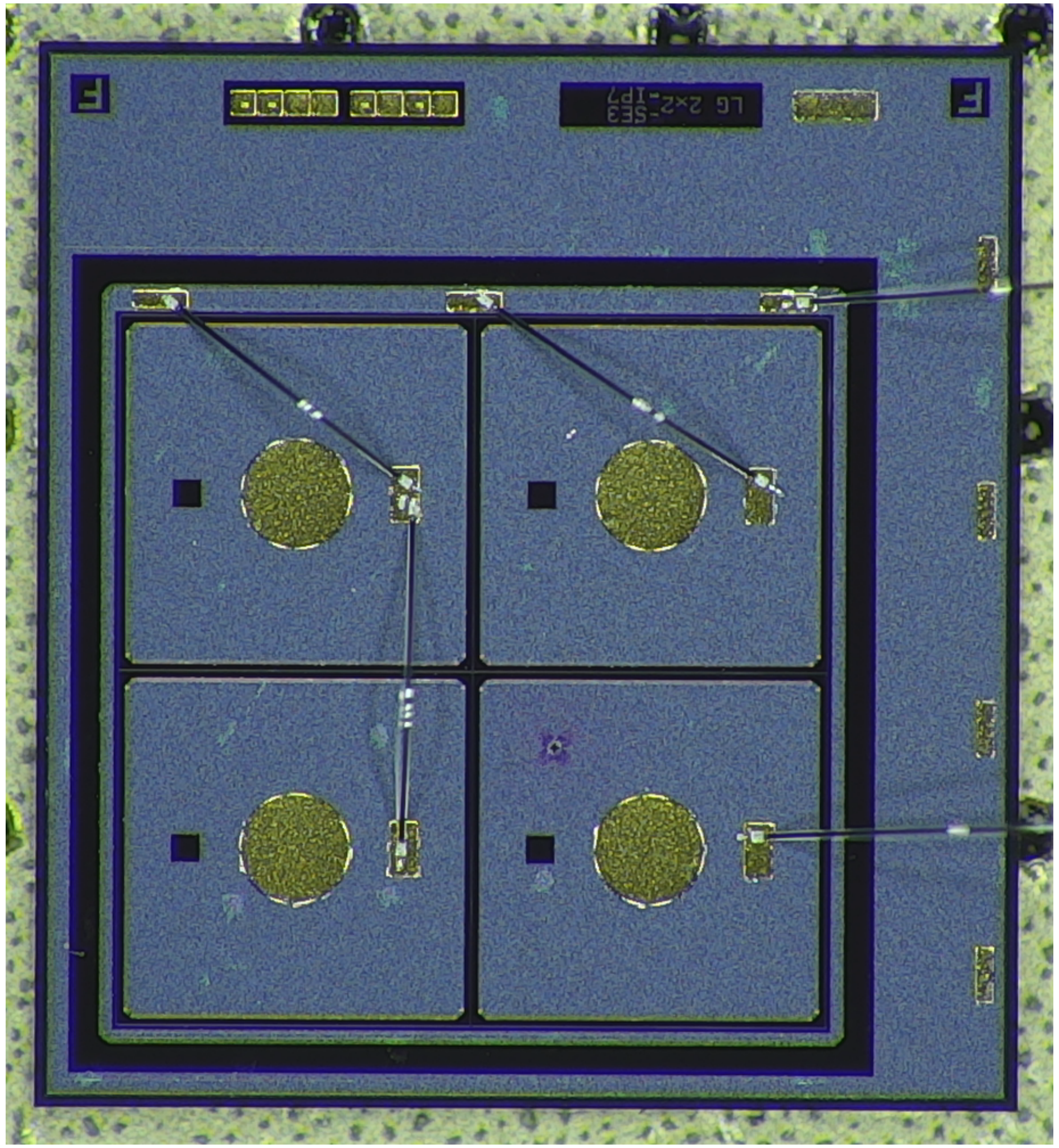
Single pad hit efficiency



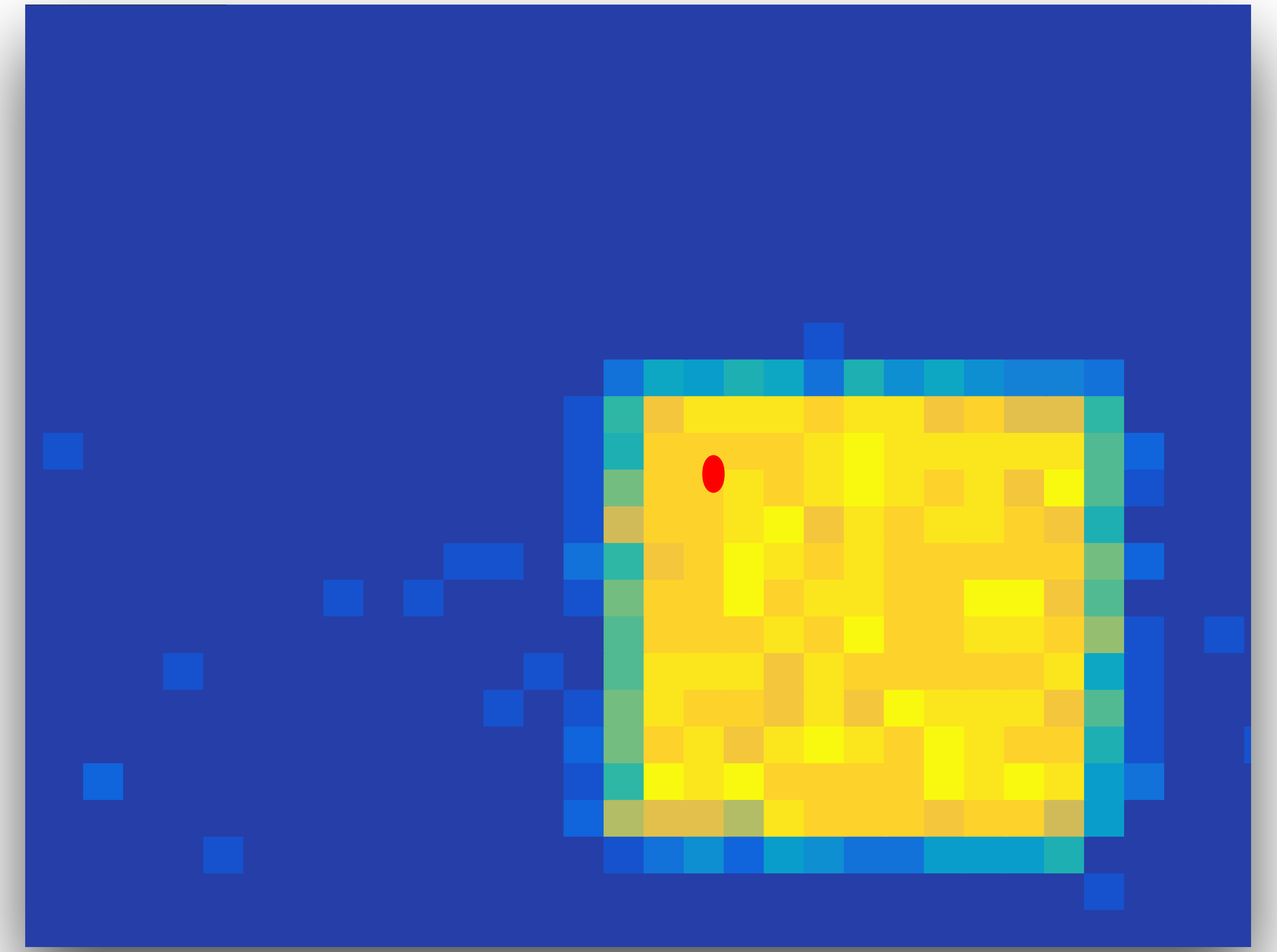


Example burnout event

Hamamatsu 1.5e15 neq/cm^2



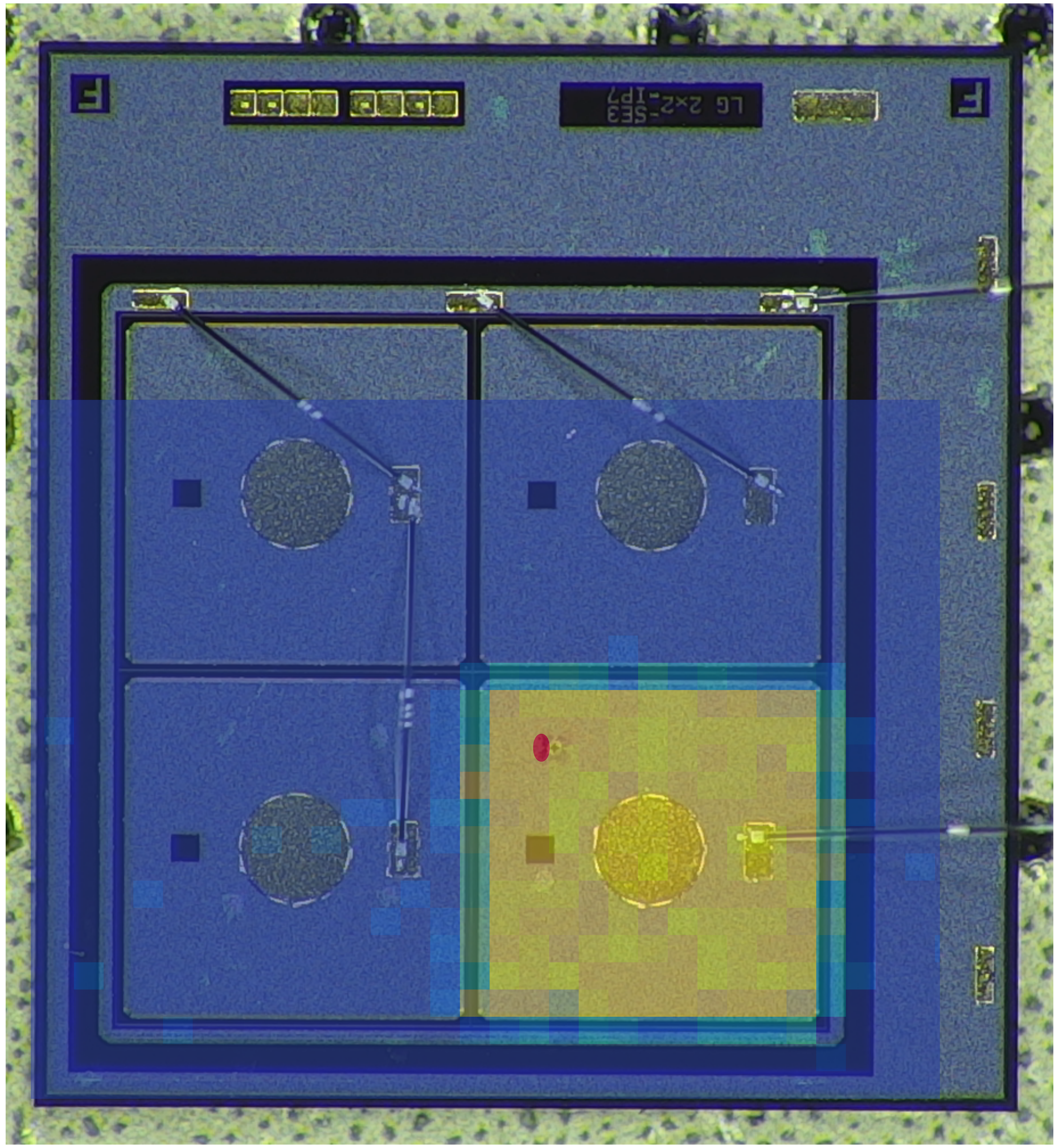
- When death occurs, first observe short on bias supply
- Then, find LGAD waveform indicating moment of death
- Compare track position in fatal event with crater location.



Efficiency map, lower right pad.

Example burnout event

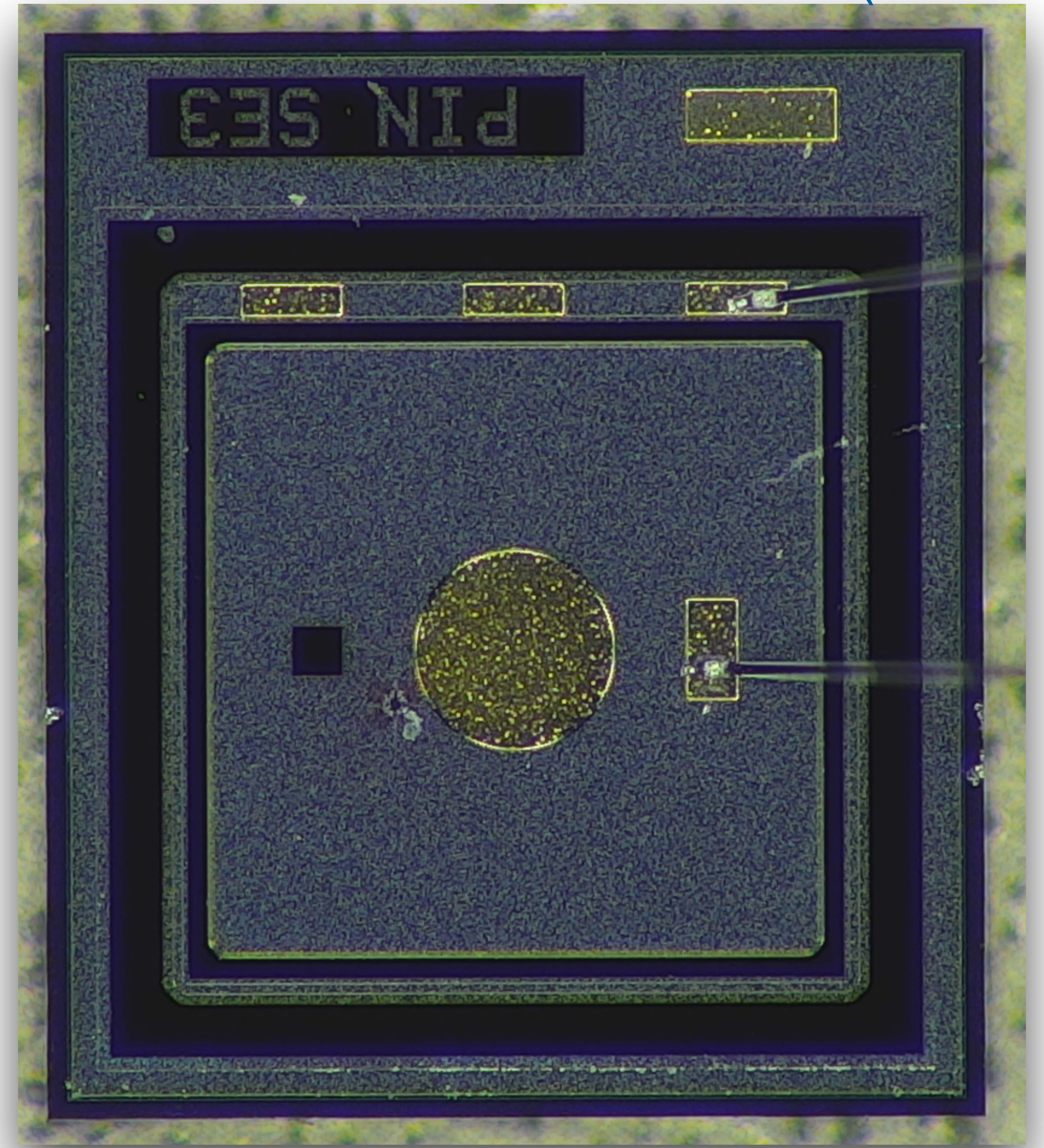
Hamamatsu 1.5e15 neq/cm²

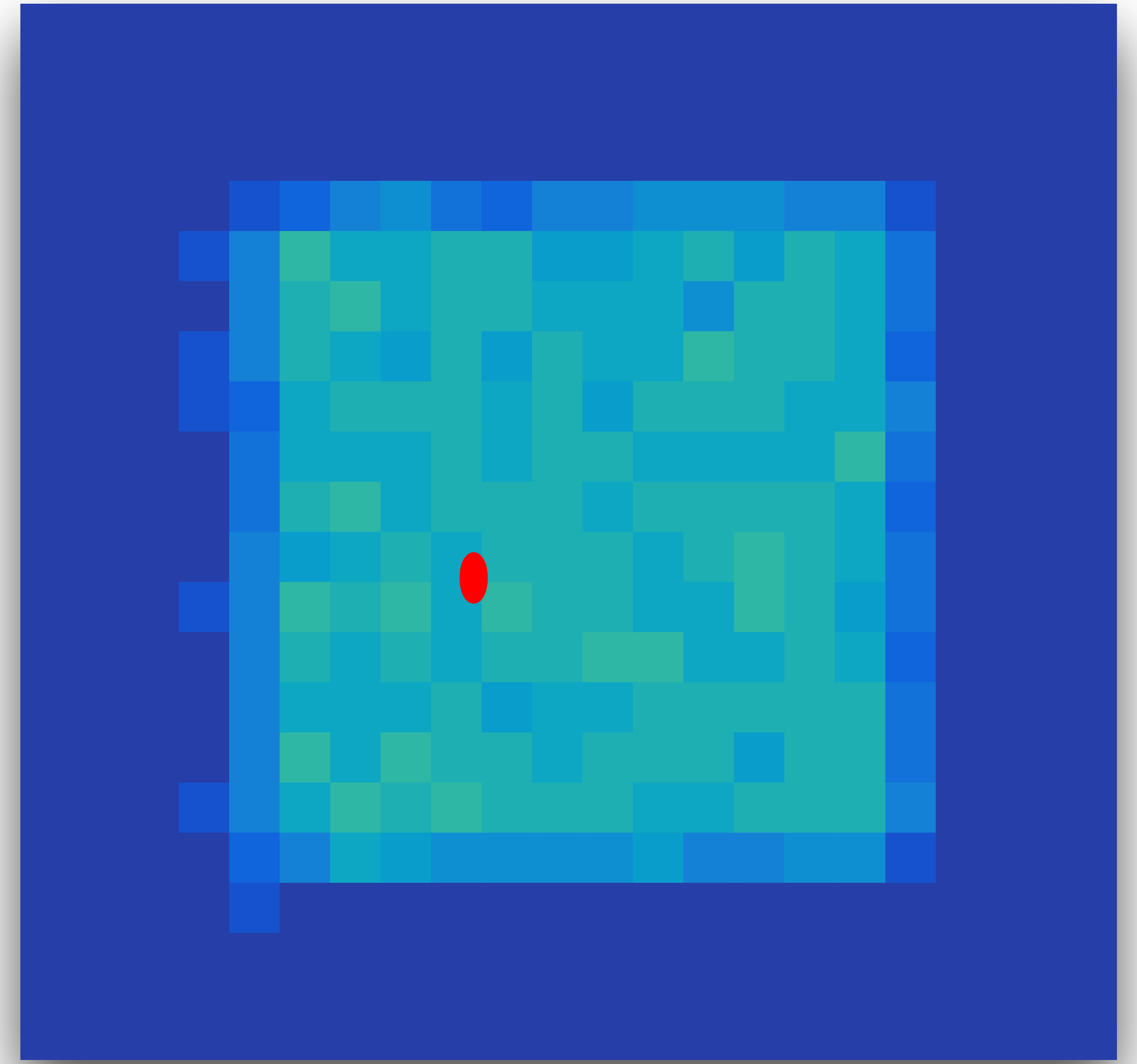


Burnout is decisively caused by proton!

Burnout in PIN diode—no gain.

Gamma-irradiated HPK PIN diode (50 micron)





Even diodes die the same way→ gain is not needed.

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Conclusions from initial burnout studies

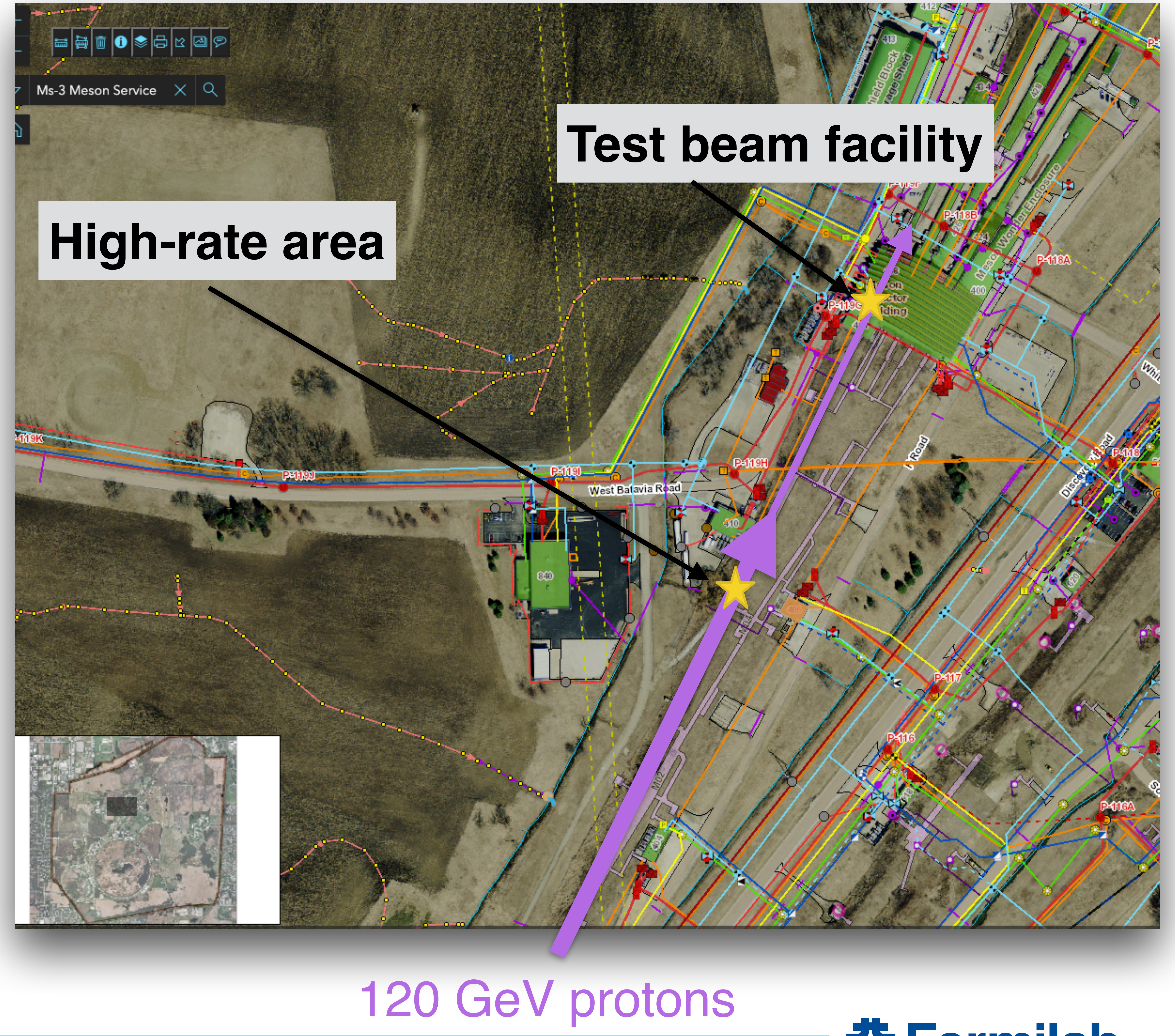
- All 50 micron sensors susceptible to death at bias ≥ 600 V
  - Gain, fluence not relevant for death mechanism.
  - Susceptibility depends on voltage & thickness ONLY

- Suspected mechanism, “Single Event Burnout” (SEB)
  - Rare, extremely high ionization events with energy deposit > 50-100 MeV
  - Excess charge produces narrow conductive path across diode at extreme field: burnout due to high current density.

- Hint towards mitigation strategy: safe below ~ 11–12 V / micron.

Survival demonstration

- Initial survival demonstration: ~10^9 protons, no deaths.
- But, CMS flux is $10^{12\text{-}13}$ charged particles / year / sensor...
  - No guarantee of safety!
- For realistic flux, need to use ultra high-rate facility upstream.
  - 10^9 protons on target per minute, rather than 10^5



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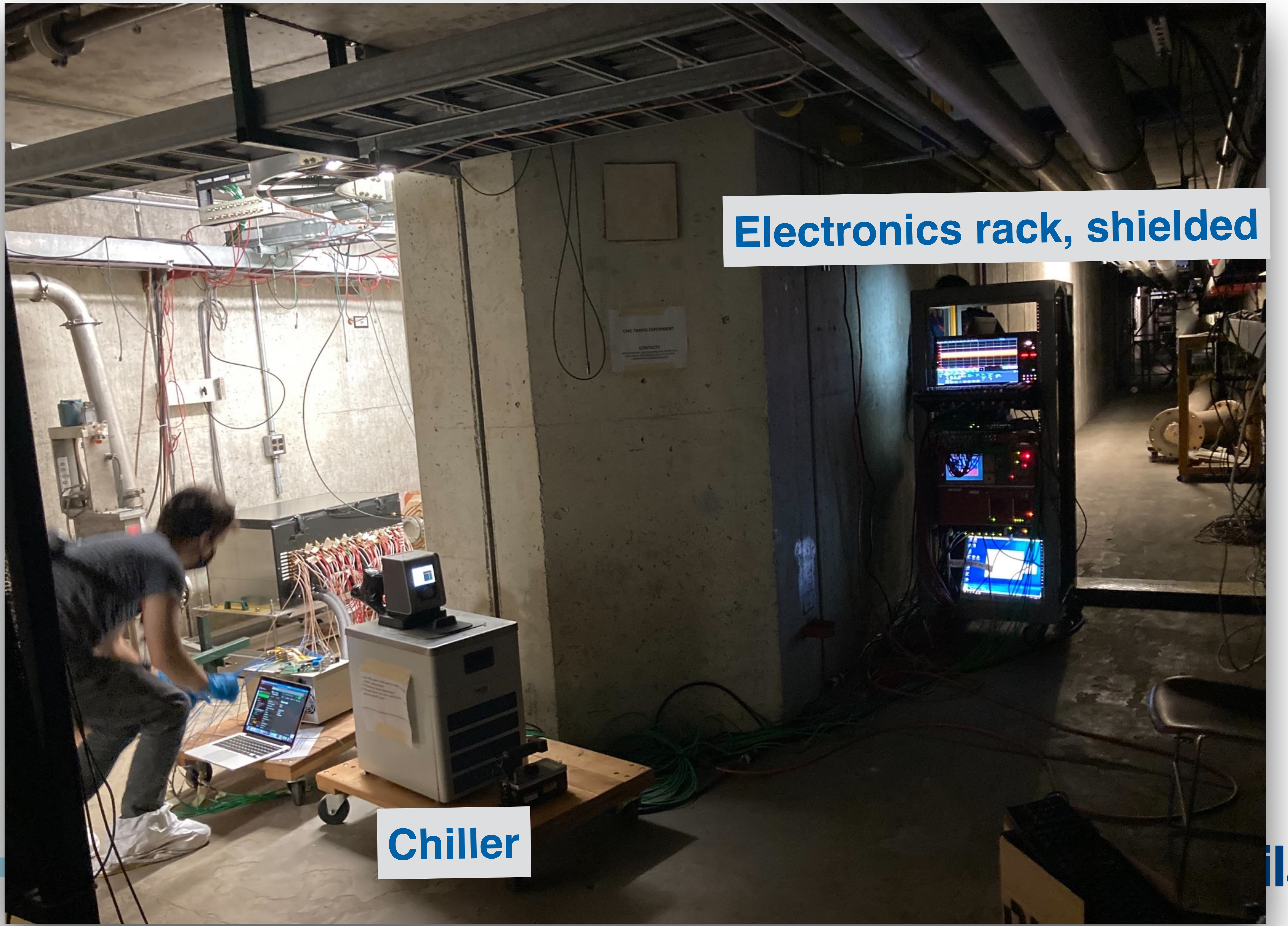
New setup at high-rate area

- Built entirely new setup to support 20 LGADs in high-rate beam
- Hazardous environment..
  - High radiation, frequent SEUs, oxygen deficiency hazard, many barriers to entry



Measuring beam intensity

- No tracker or beam monitor: use LGADs themselves to measure delivered intensity!
- Within 10 millisecond acquisition, count signals in 8 channels.

Single protons in 19 ns buckets

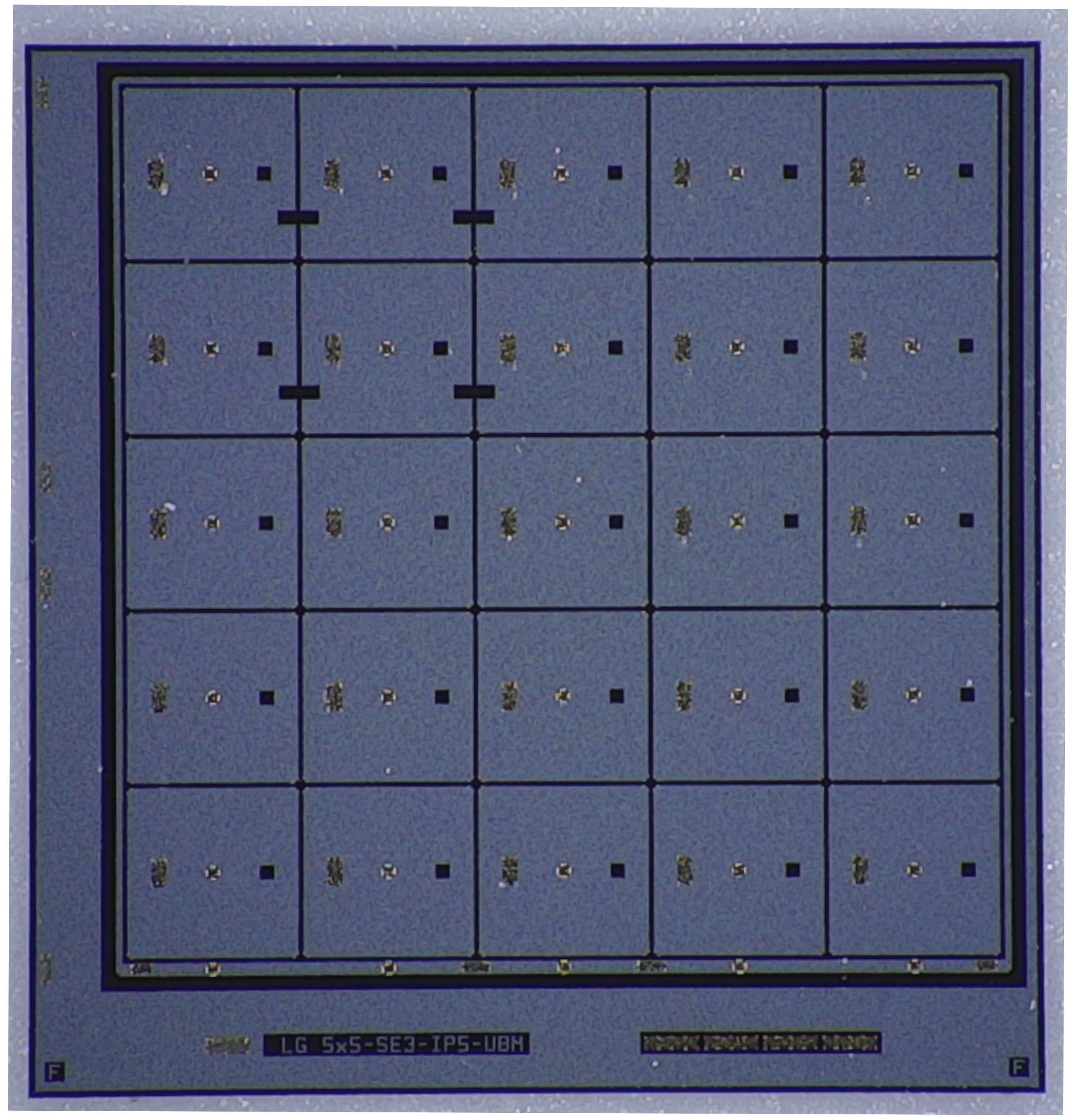
1.6 µs “batches”, repeated every 11.2 µs

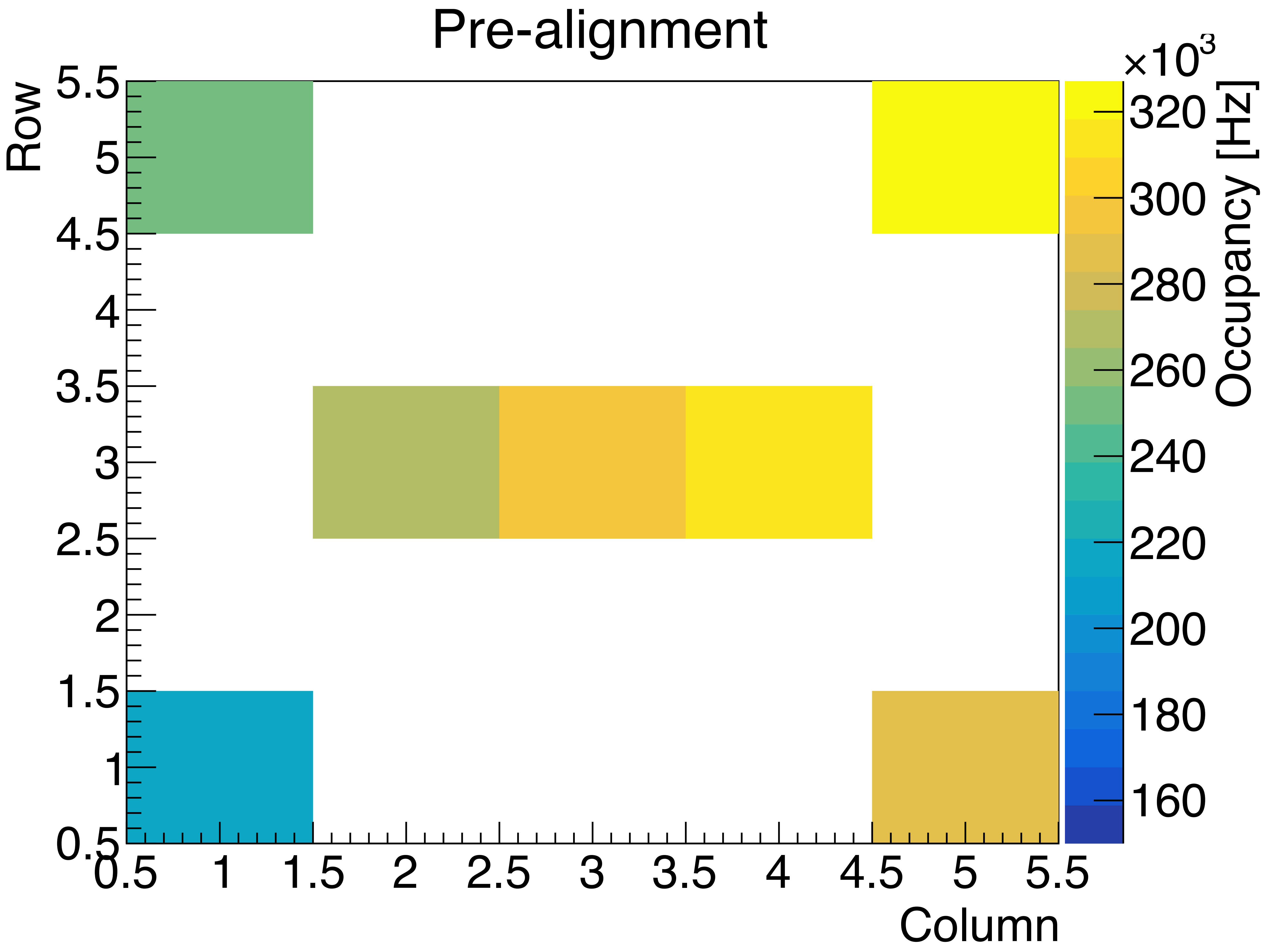
Intensity variation on ms scale

- Study occupancy across 5x5 sensor: enable alignment to beam.
- Final occupancy: **200M protons / sensor / minute**
  - x2000 larger flux per sensor than max achieved in regular test beam (slightly less than expectation)

Aligning to beam

- Study occupancy across sensor w/ 8-ch
- Follow gradient to align sensor

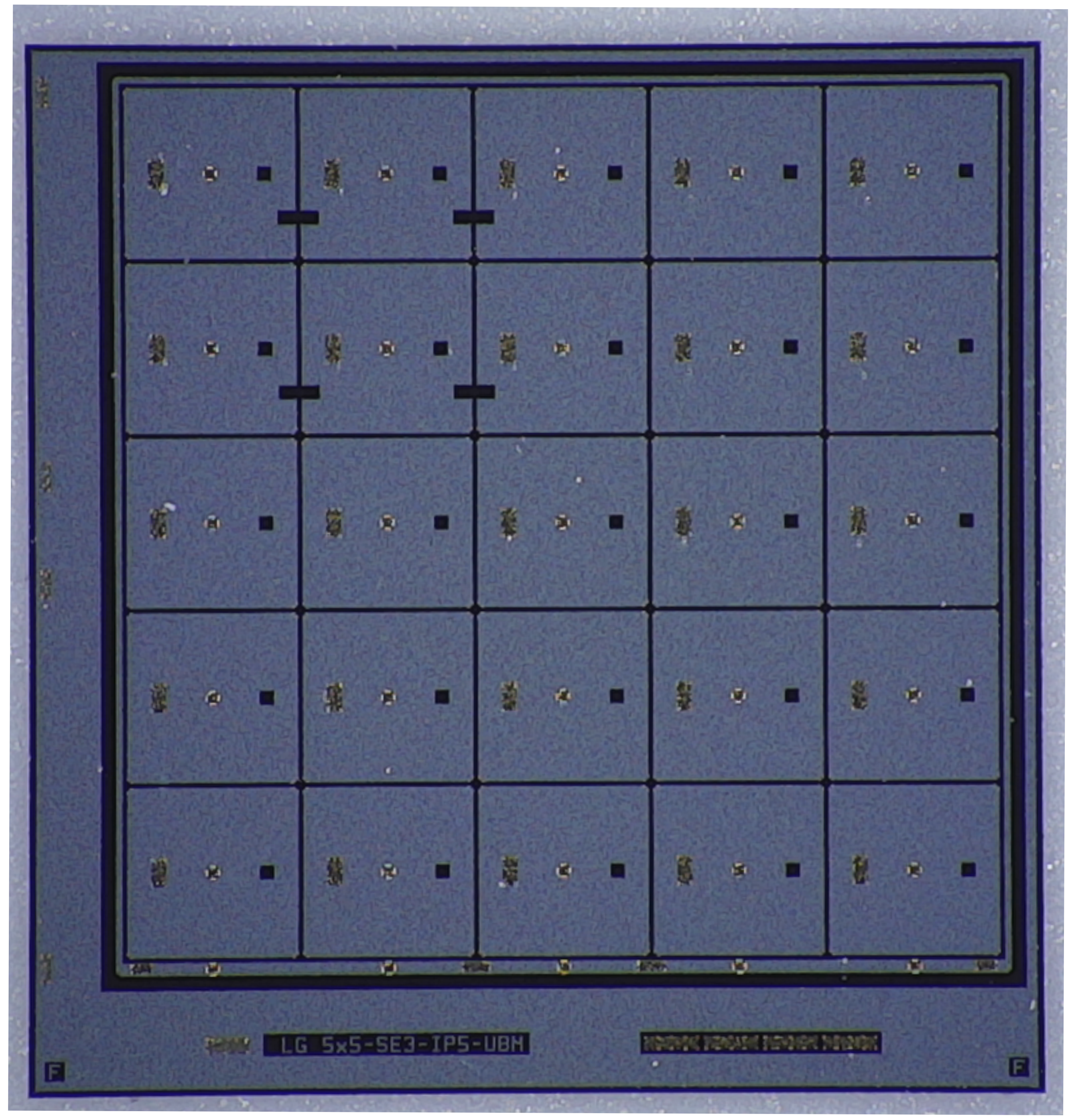


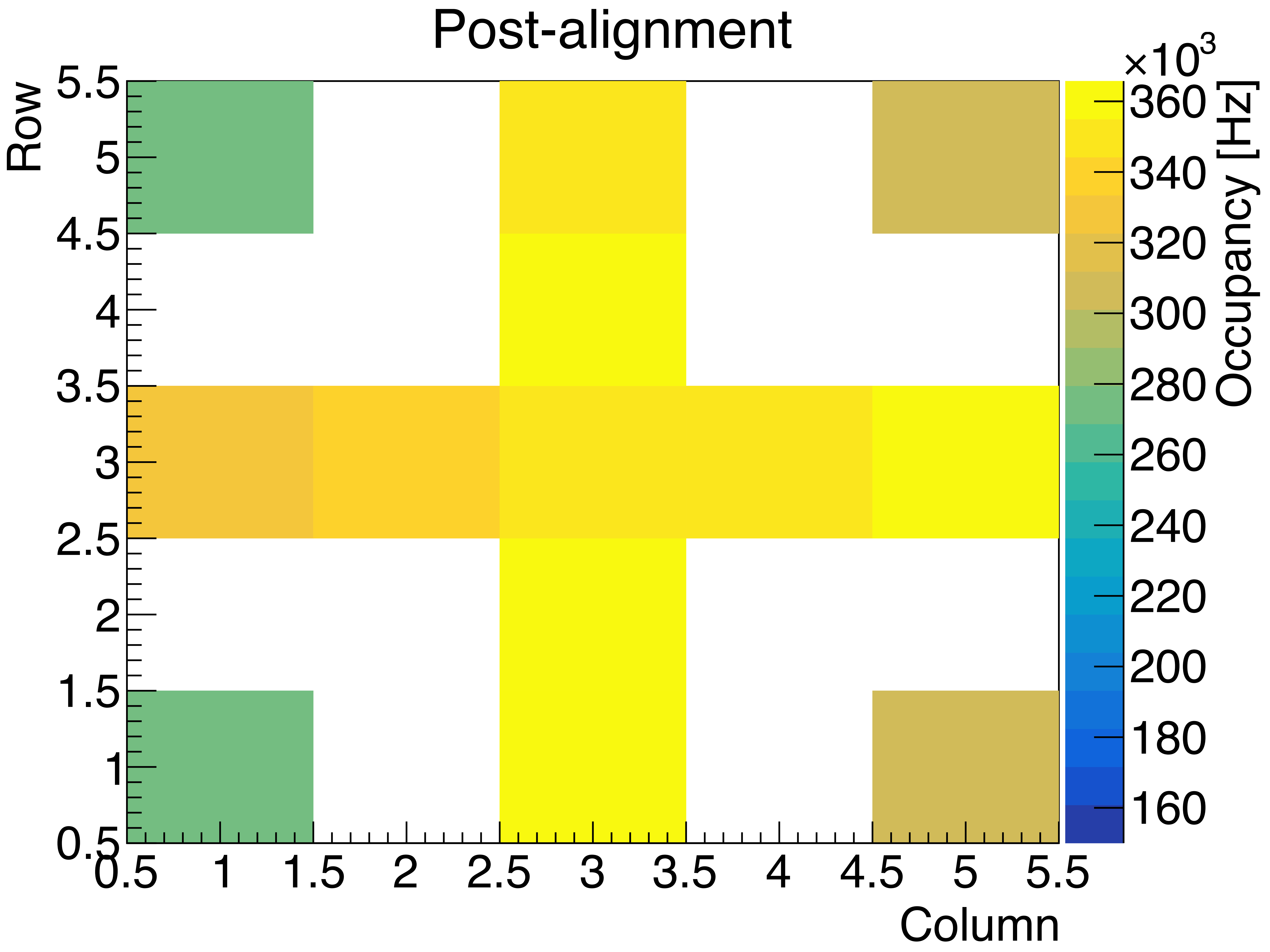


- With best alignment, occupancy in edge pads is 80-90% of center (wide beam)
- Final sensor occupancy: **200M protons / sensor / spill**
  - x2000 larger flux per sensor than max achieved in regular test beam (slightly less than expectation)

Aligning to beam

- Study occupancy across sensor w/ 8-ch
- Follow gradient to align sensor





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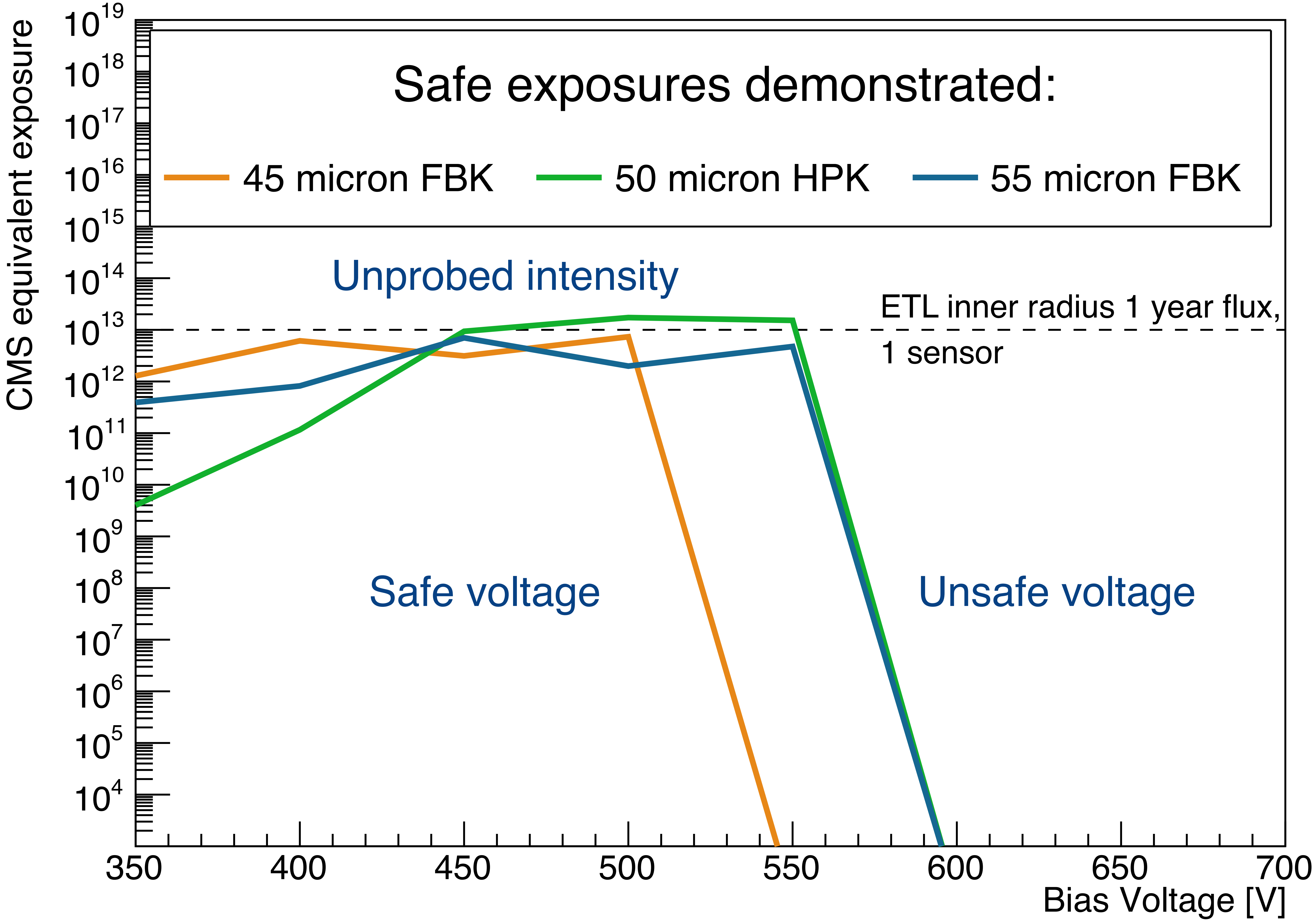
Exposure summary

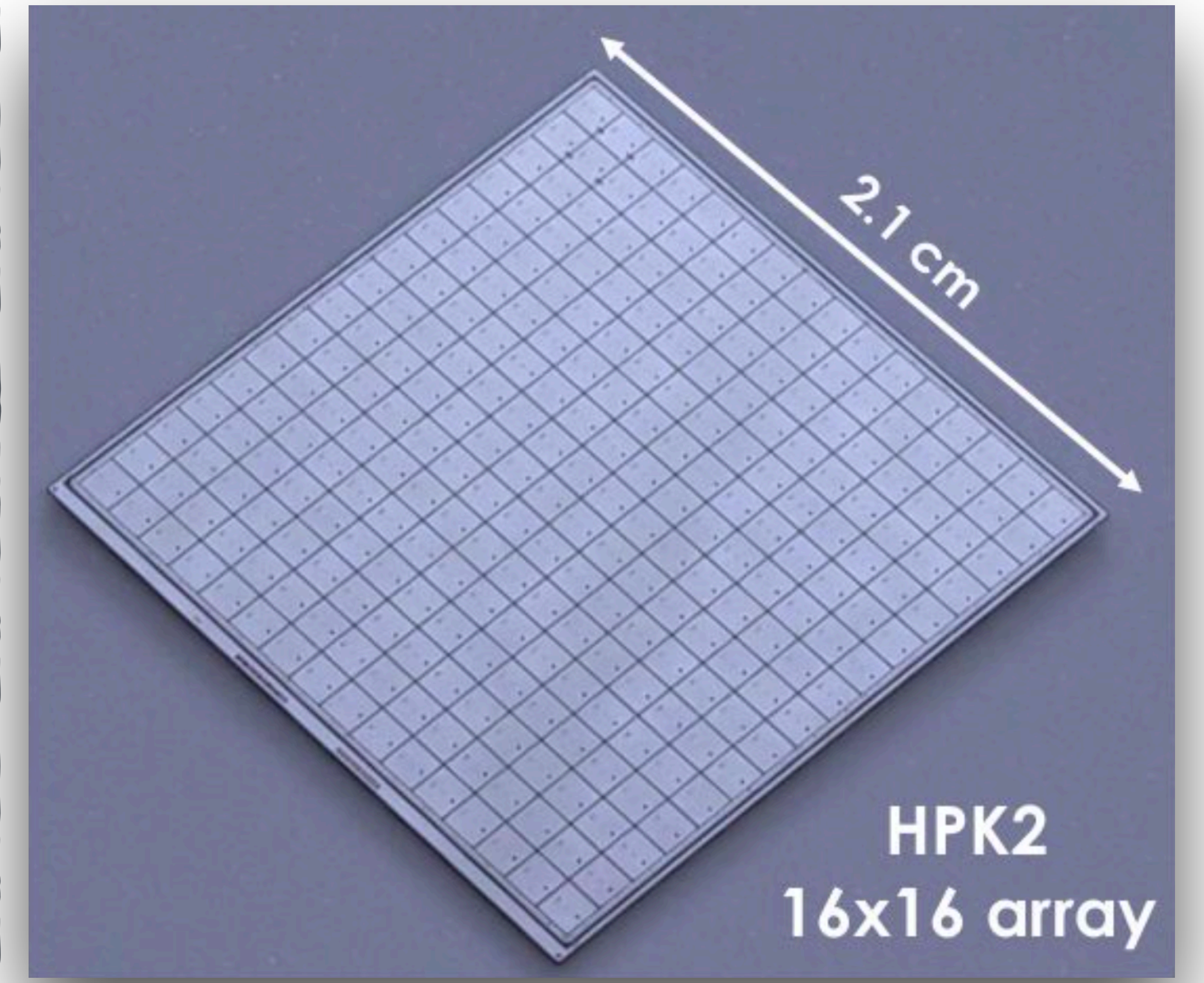


- Demonstrated safe operation with flux comparable to 1 year in CMS, with 3 proposed thicknesses / vendors!
- Best designed sensors operate happily at safe voltage through full life.
- No longer considered risk to the project!

Assembling a realistic detector

- Real detector: 16x16 sensors, bump-bonded to custom readout chip “ETROC”

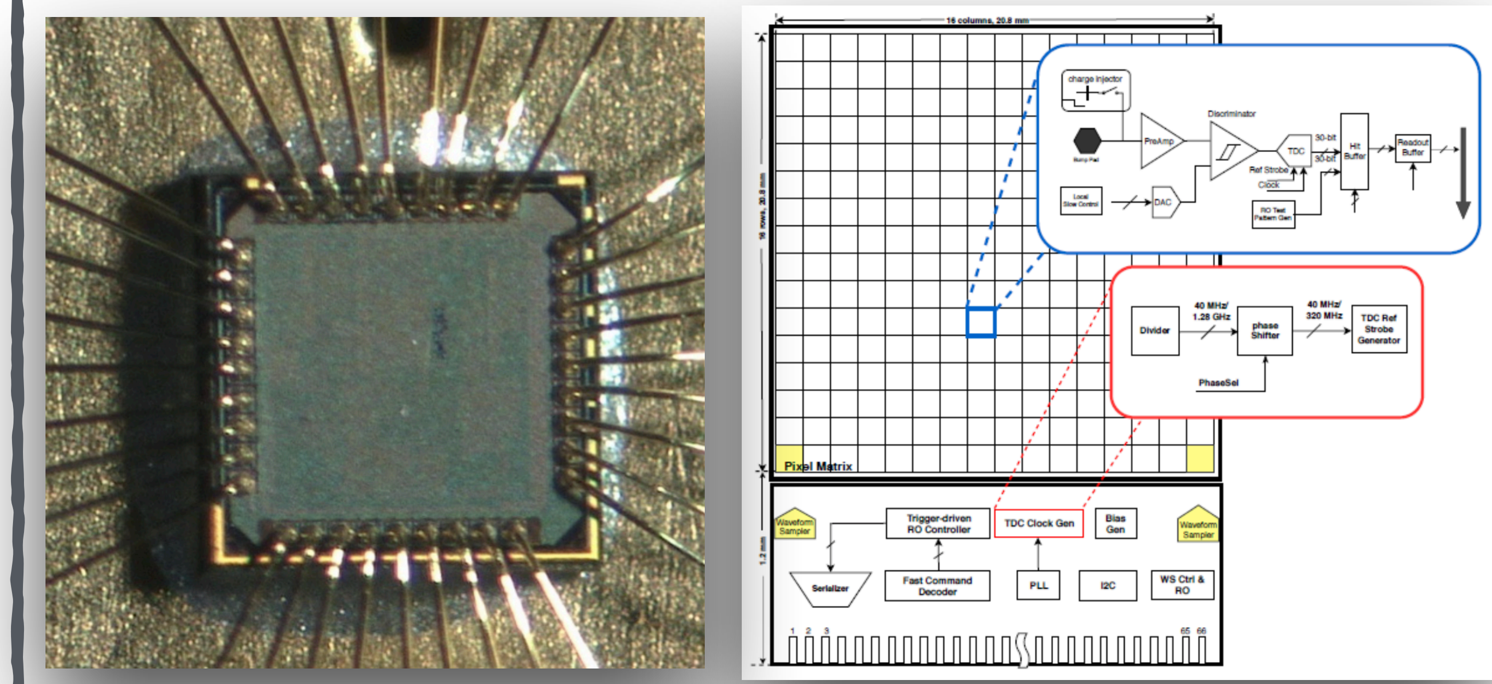
Full size sensor



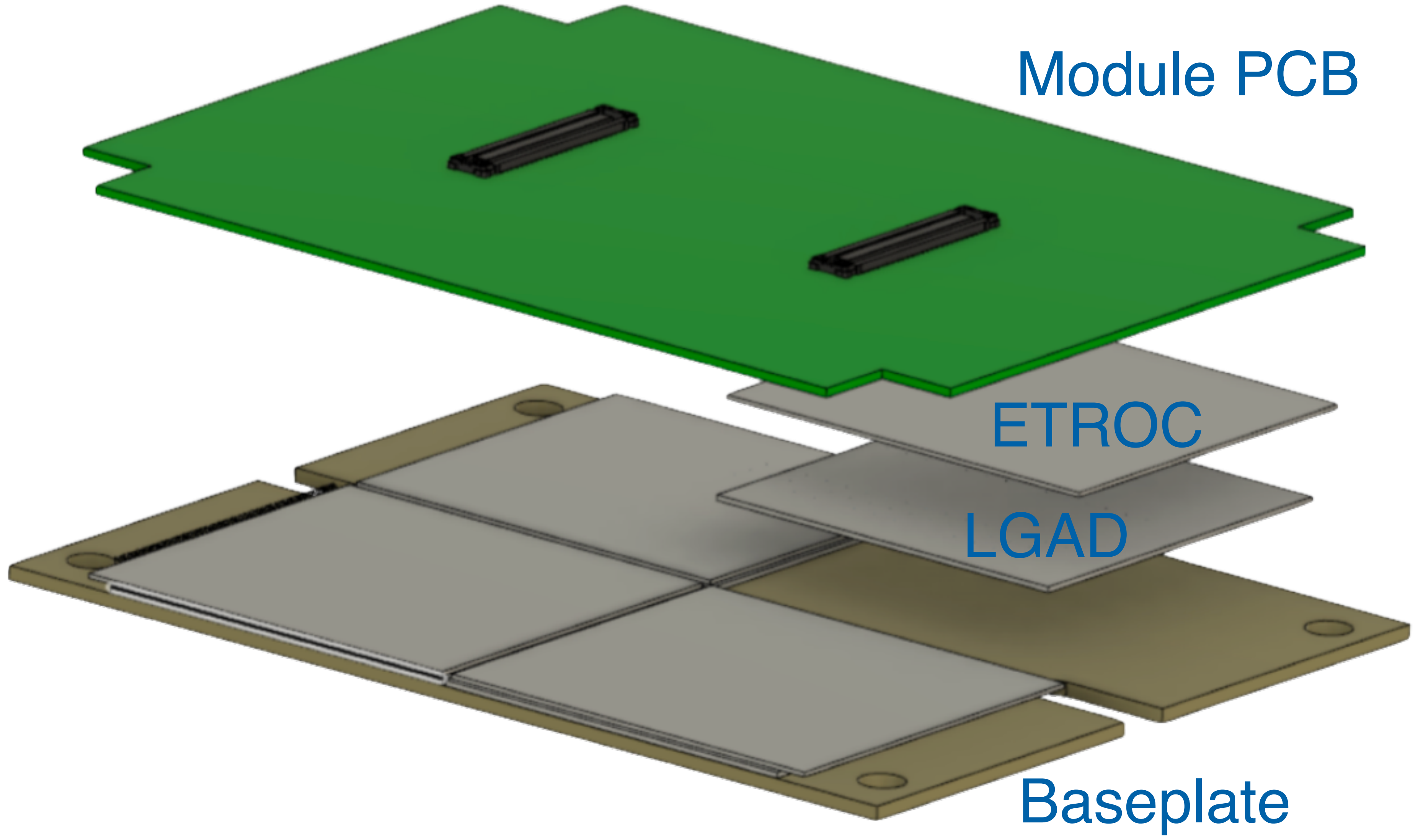
ETROC

(Endcap Timing ReadOut Chip)

early prototype | full design



Full module

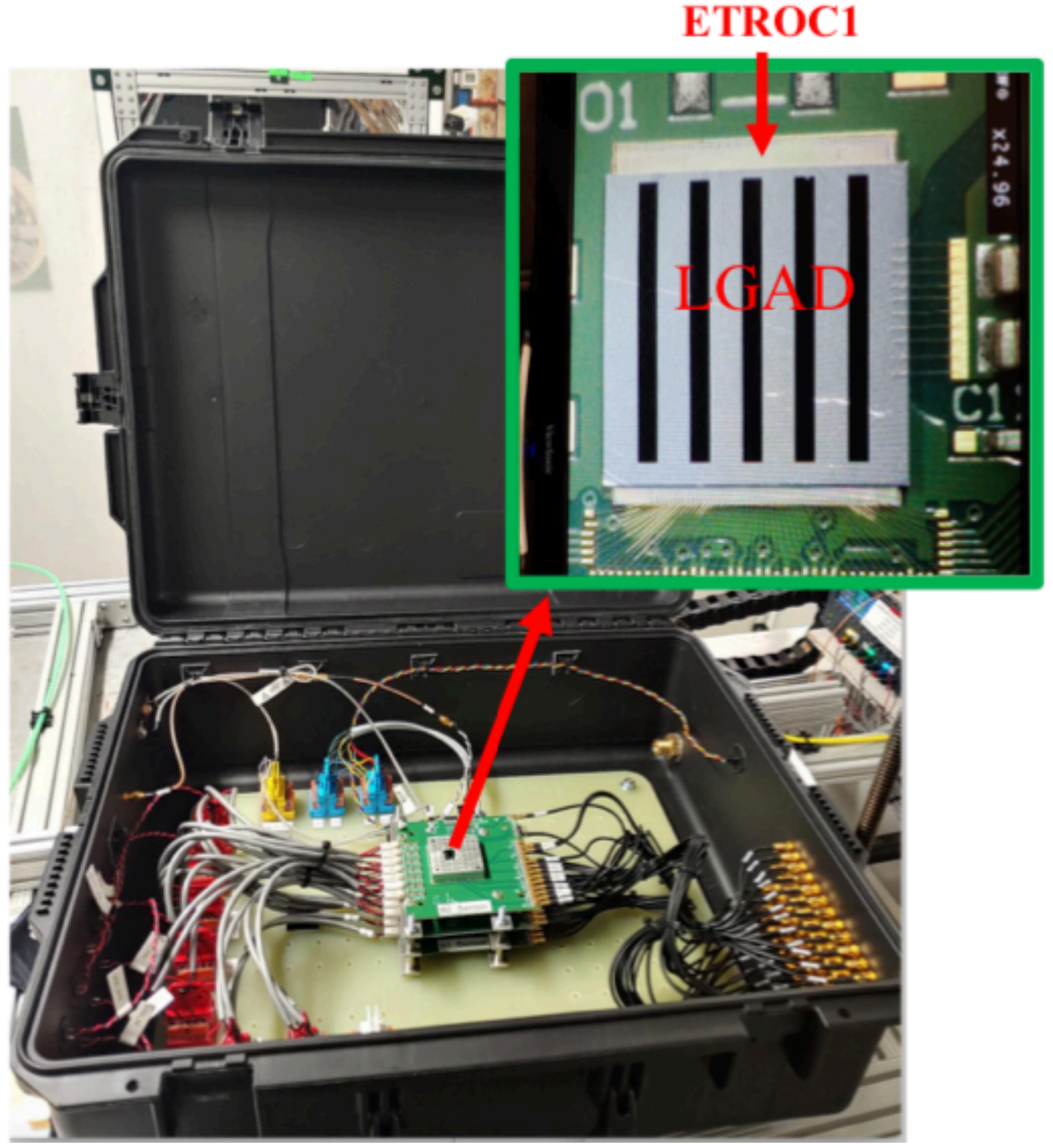


- Major focus on validation with realistic components and operation modes—
  - Performance with ETROC, ETL service hybrids, and DAQ system
  - Cooling & mechanical constraints with modules, services routing, mechanical structures

ETROC testing

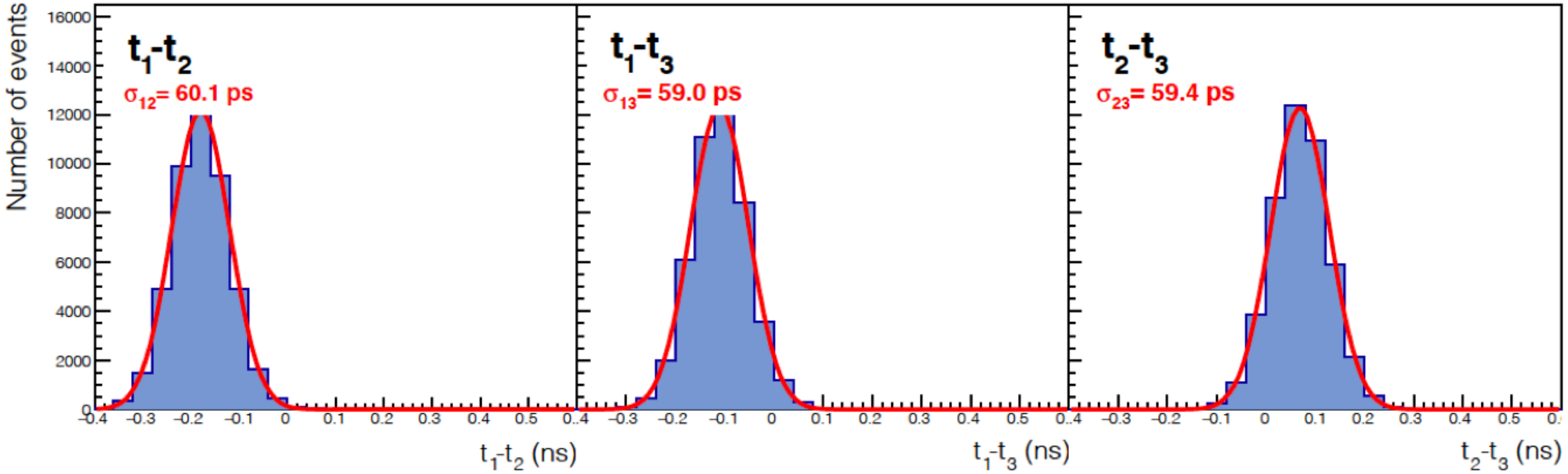
- ETROC chip: provide ToA and ToT for every hit.
- Early prototypes ETROC0 and ETROC1 studied extensively at beam test
- Achieve 42 ps resolution for LGAD + ETROC1 — within specifications!

3 detectors aligned in test beam



Study pairwise combinations to extract single-channel resolutions:

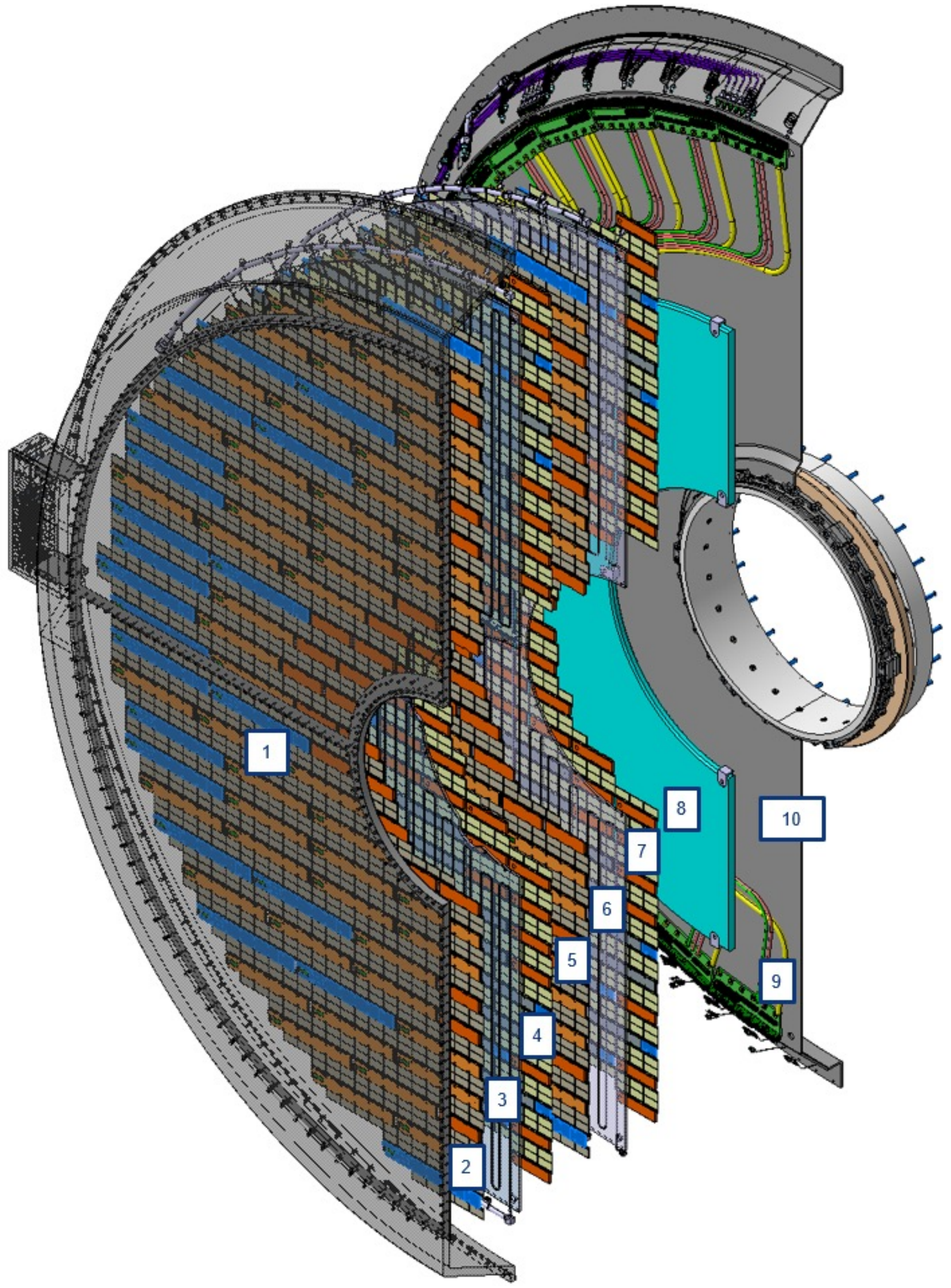
$\sigma_{1/2/3}$ = 42.0 / 42.7/ 41.3 ps

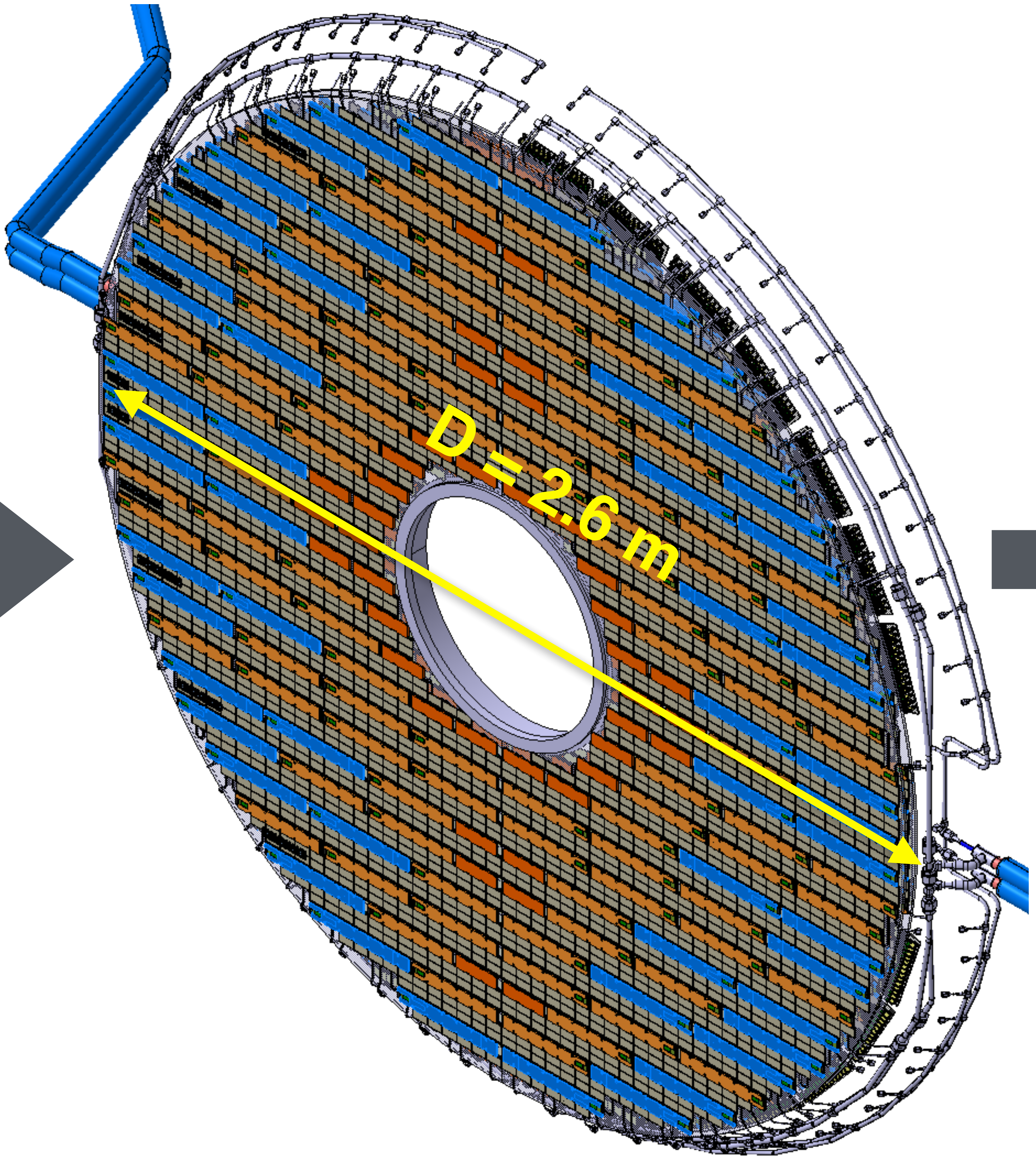


- Next generation ETROC2 submitted Oct. 2022!
  - 4x4 → 16x16 channels (full size)
  - CMS-compatible digital interface

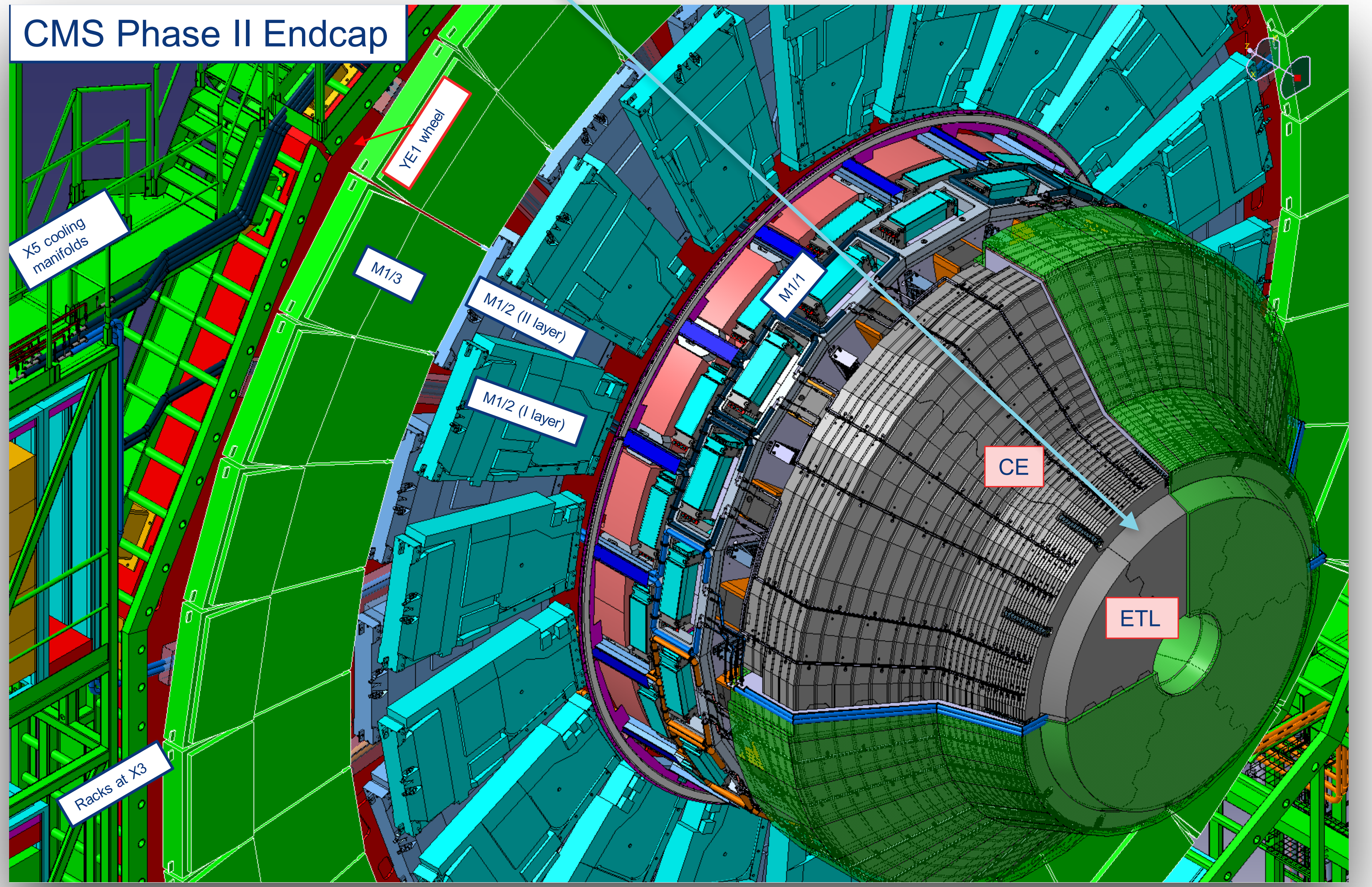
Endcap Timing Layer

- Attach modules to service hybrids; assemble into disks
- Two layers per endcap → about 1.6 hits per track.
  - 45-50 ps per hit → 30-35 ps per track





Position on CMS endcap



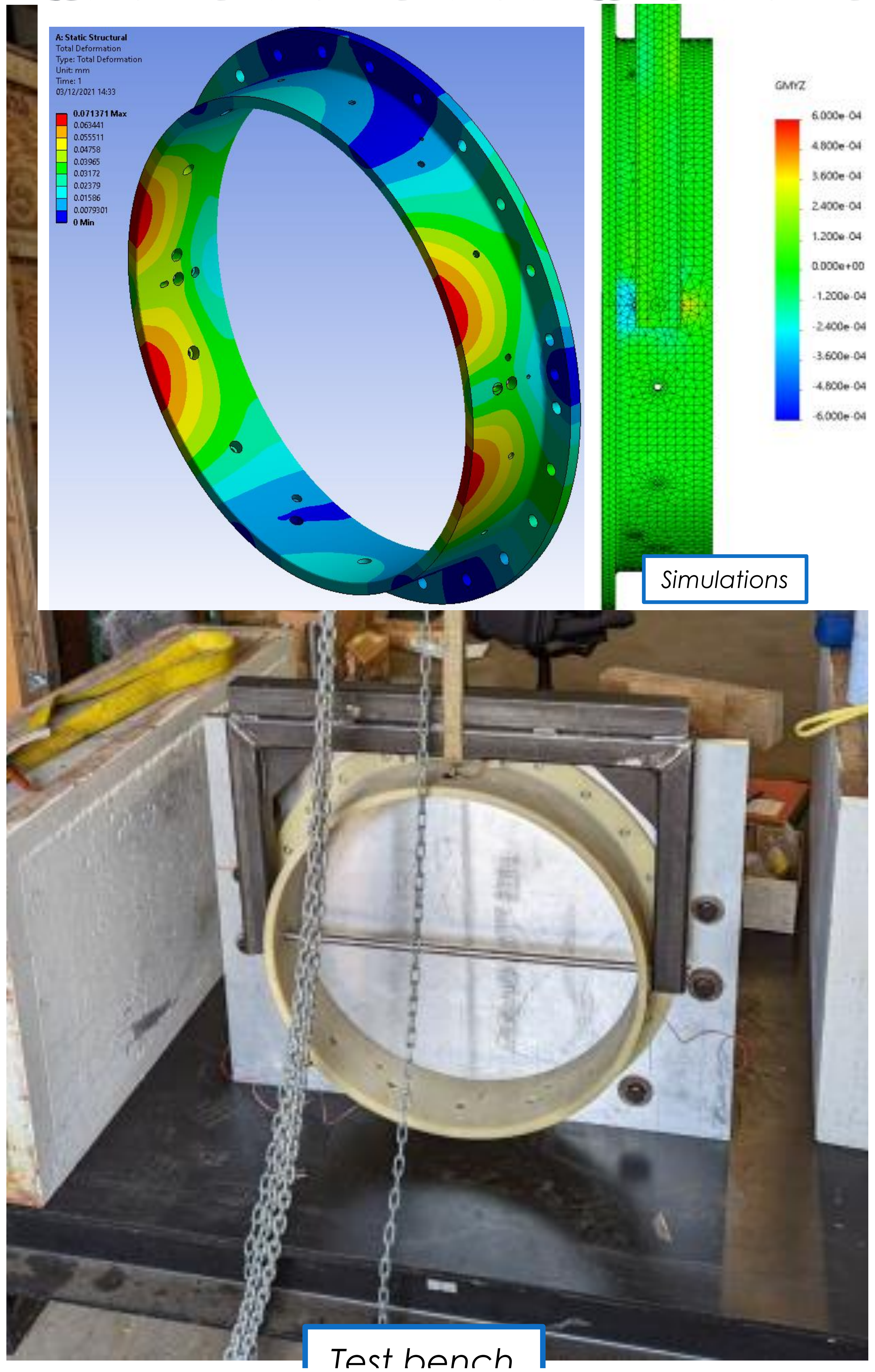
Each endcap:

- Total thickness ~ 10 cm
- 16k sensors, 4M channels
- 25-35 kW power consumption
- Operating temp: -25 C!

Fermilab

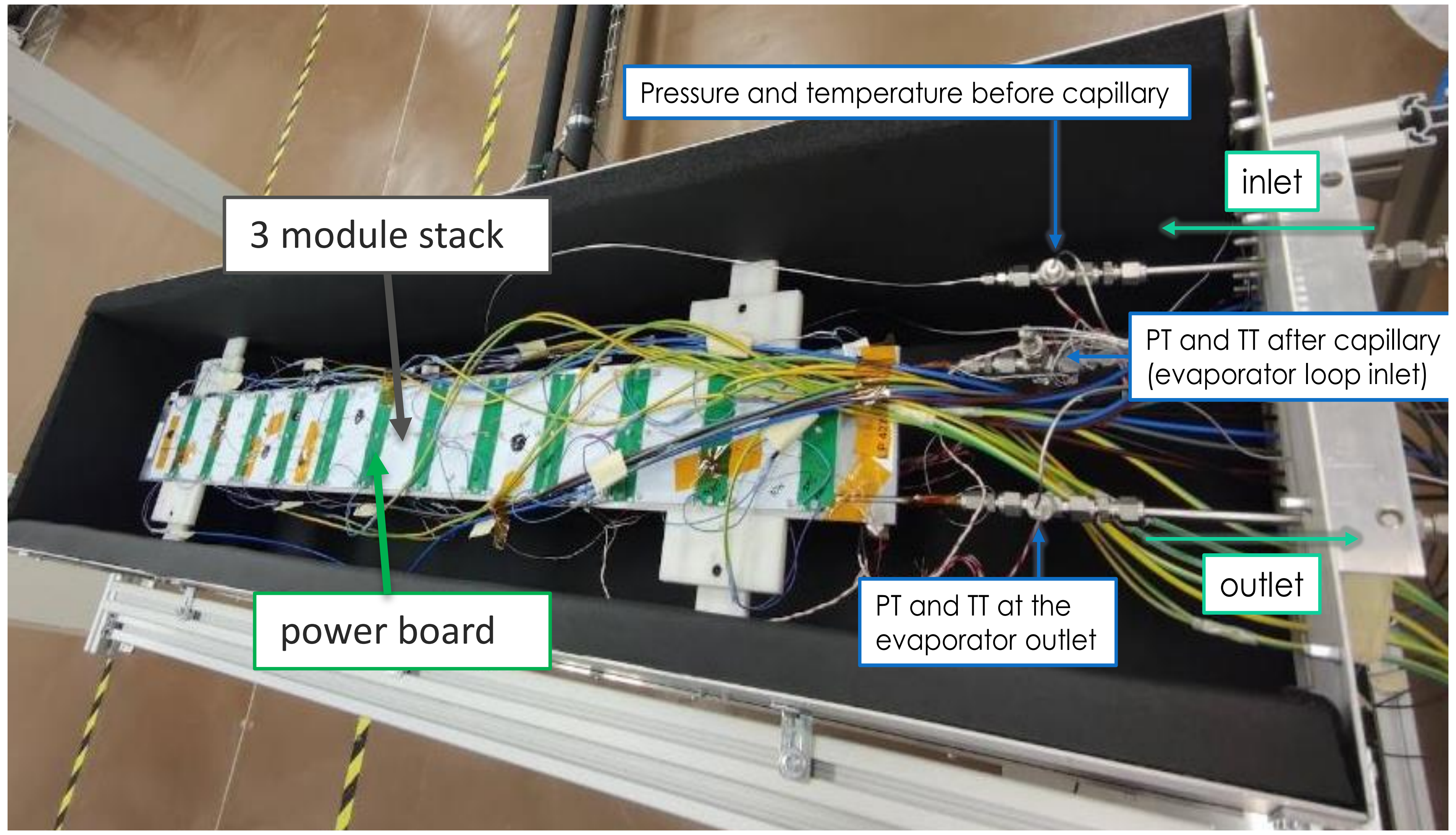
Mechanical prototyping

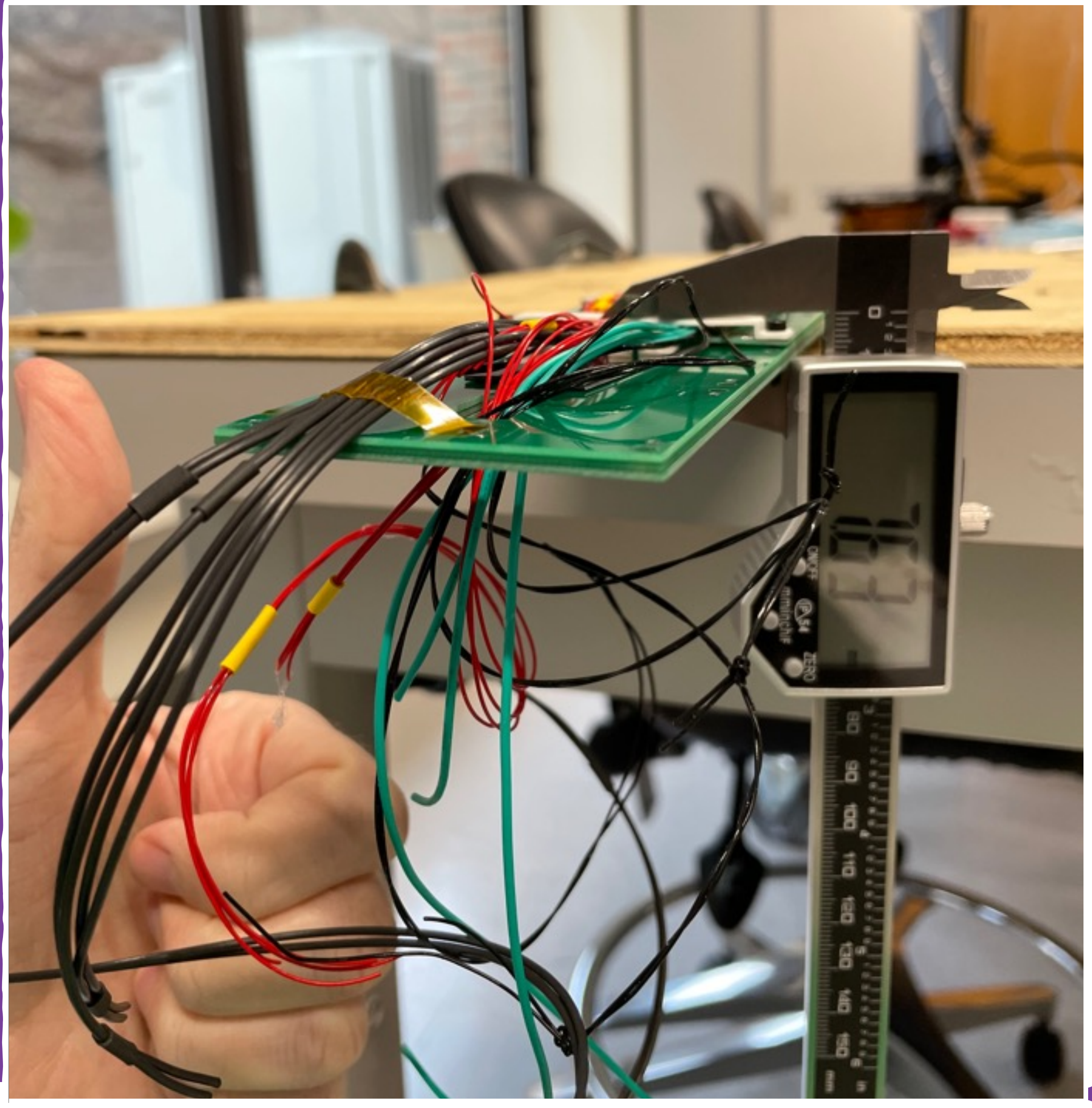
Strain testing of support tube



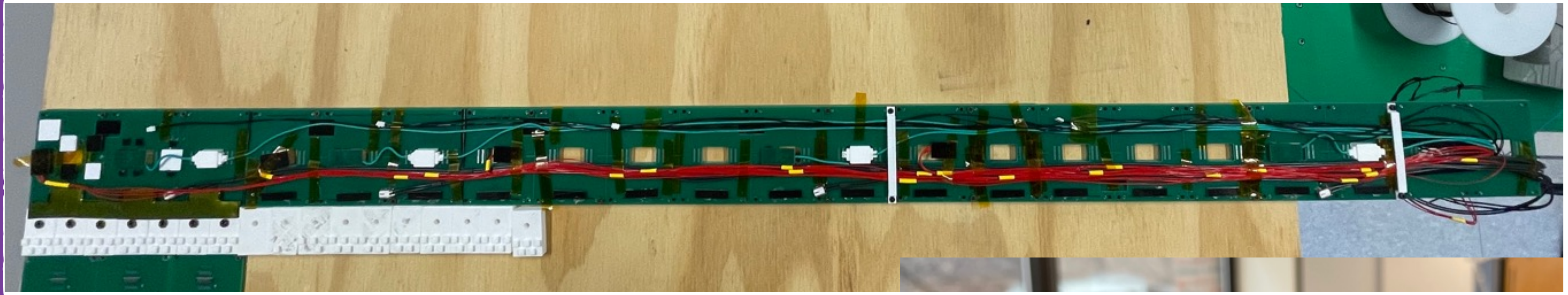
- Intensive activity to verify mechanical & thermal performance!

CO_2 cooling test w/ service hybrid



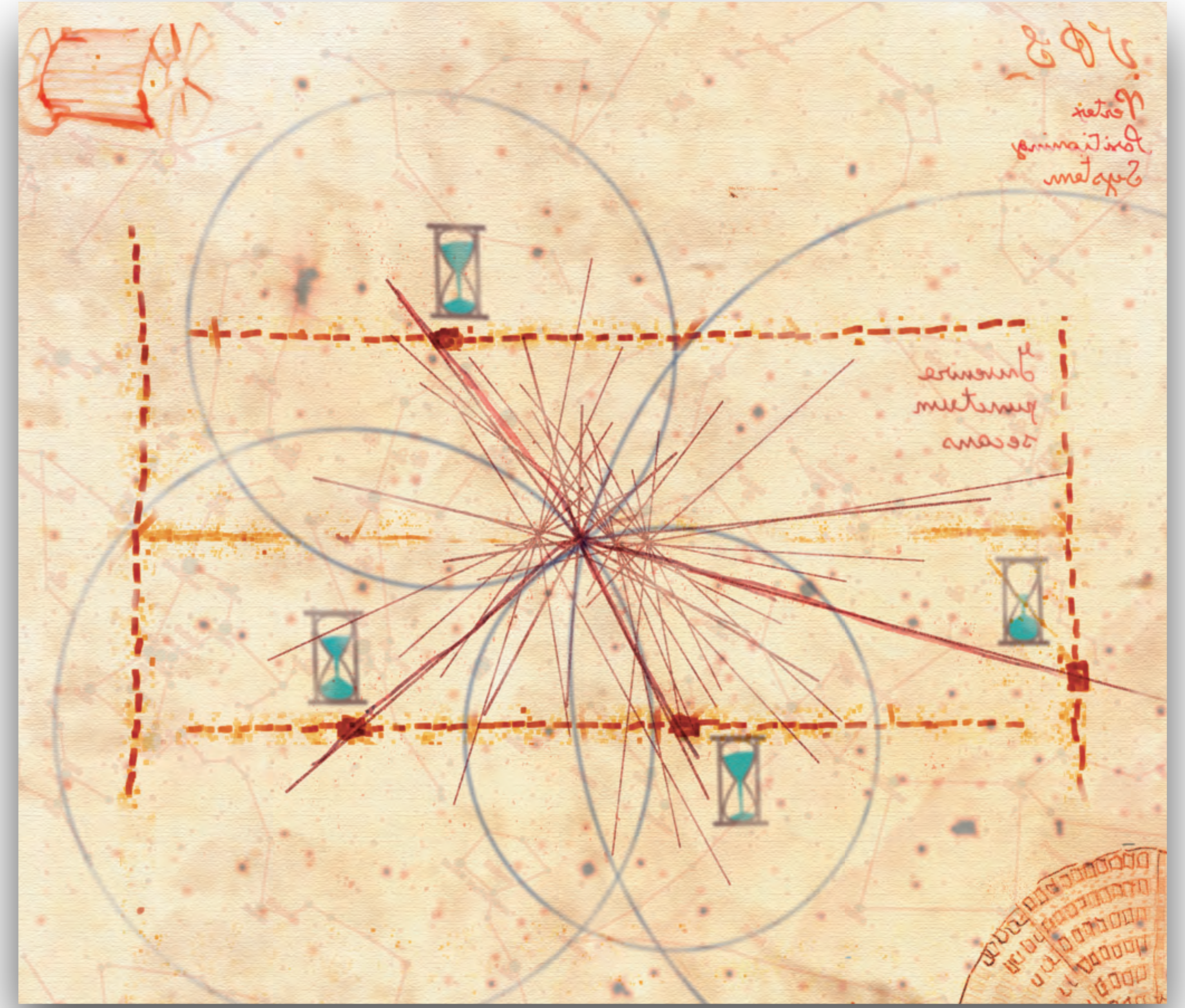


Service routing with full-length stave



CMS MTD

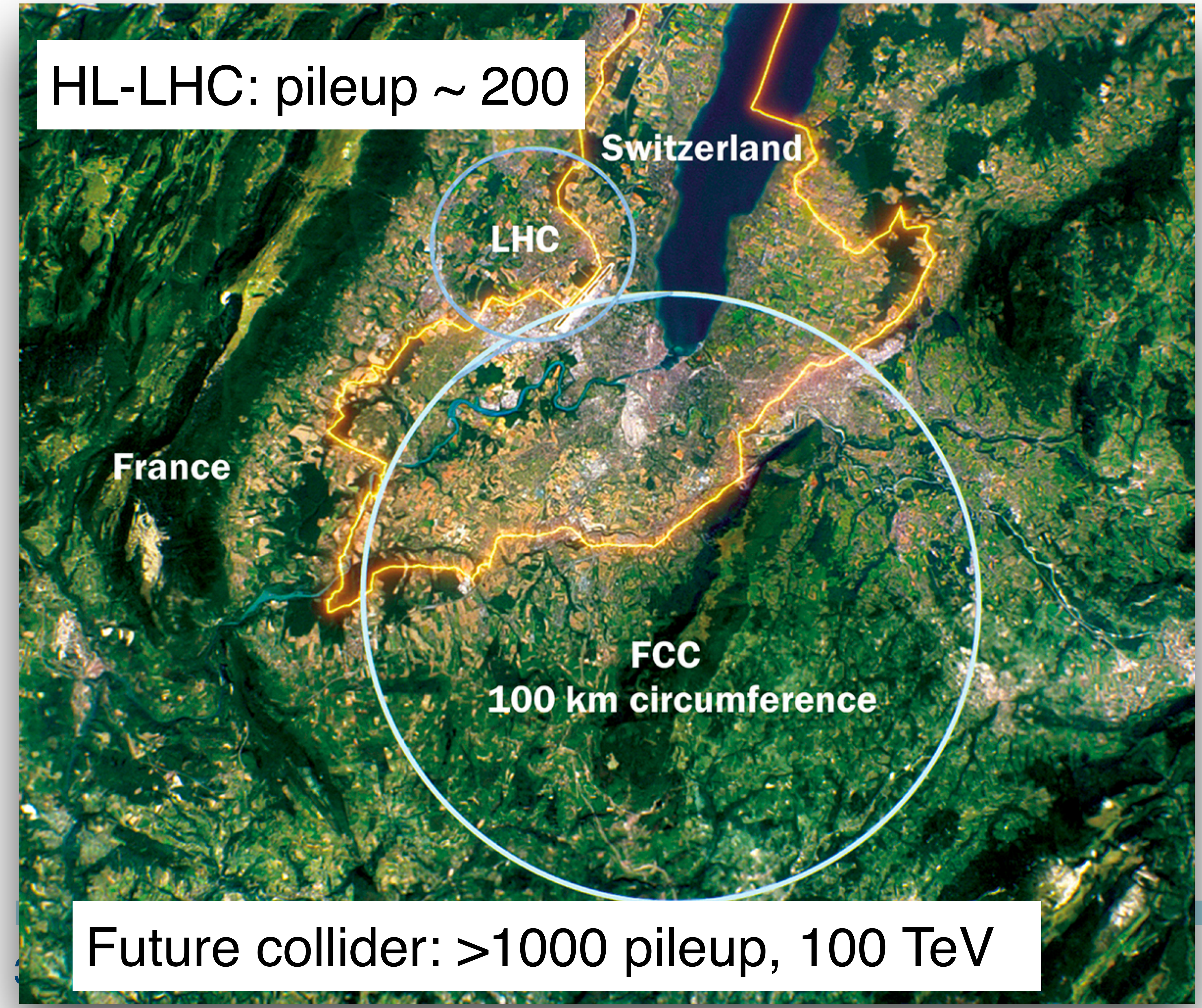
- CMS MTD on track to be first-of-its kind timing detector
- Established mature understanding of LGAD sensors
- Focus now within ETL on validation of full system, and transition towards procurements and production.



Where do we go next?

Timing for future colliders

- Future collider experiments: pileup only more severe
  - 1000s of simultaneous collisions: too dense for trackfinding
- Precision timing in each tracking layer vastly simplifies pattern recognition
- Major effort towards "4D tracking" (e.g. 10 ps & 10 micron)



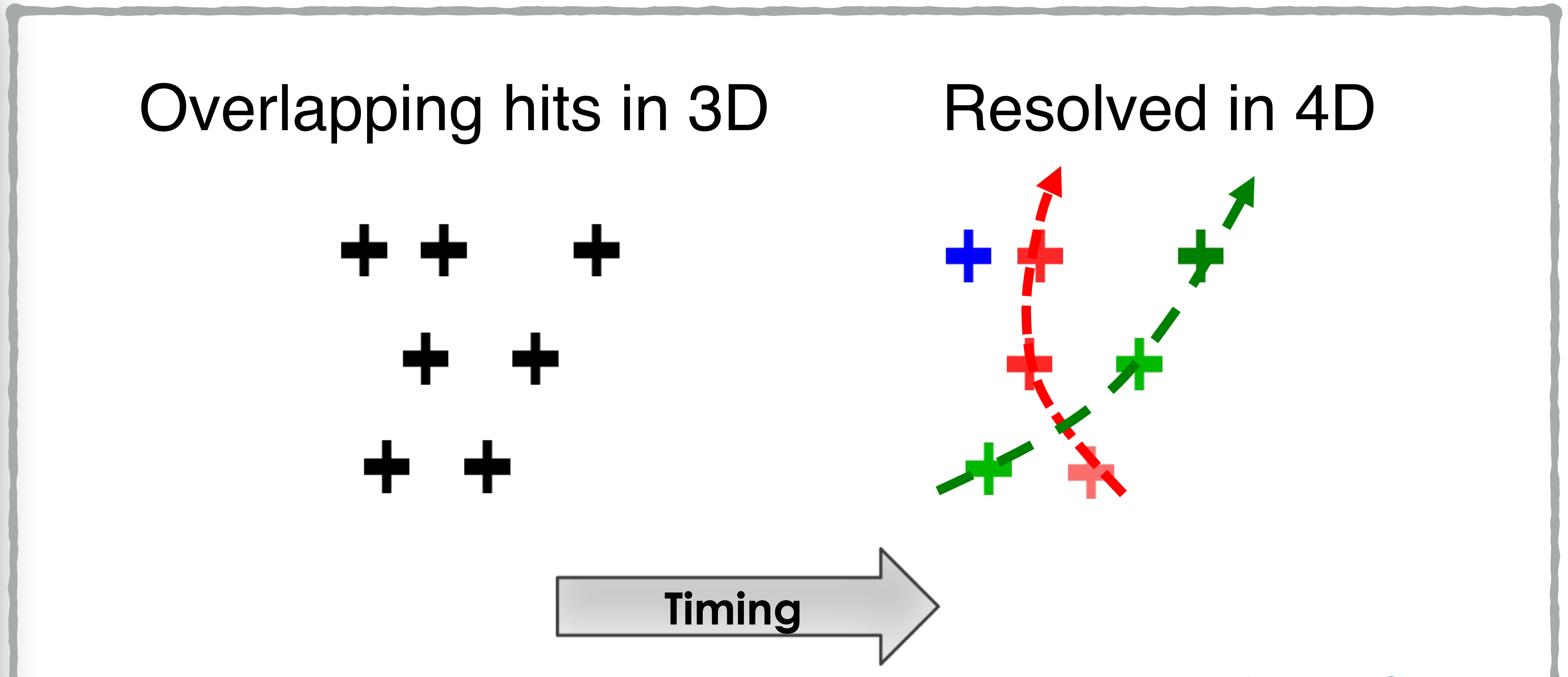


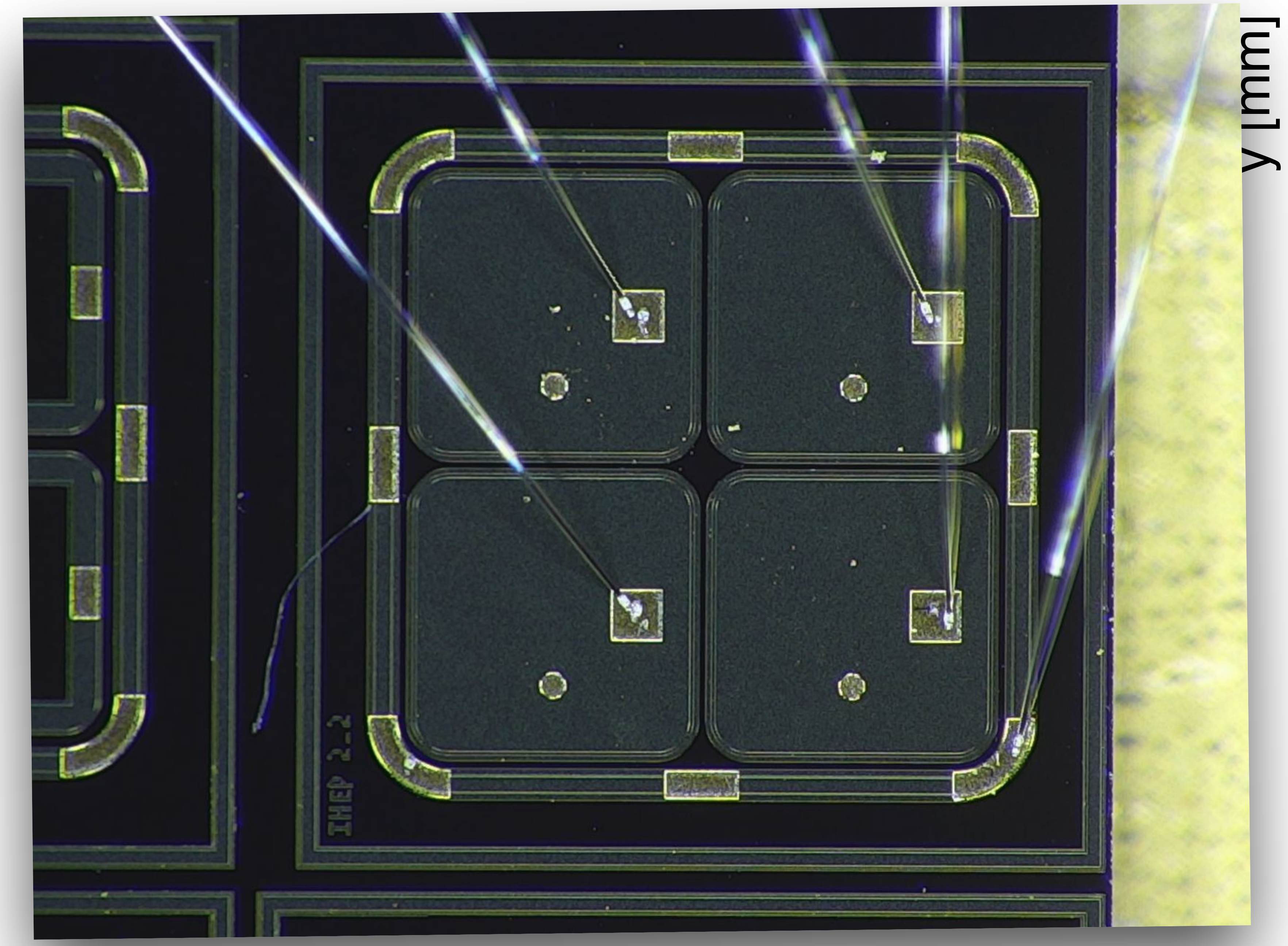
diagram from N. Cartiglia

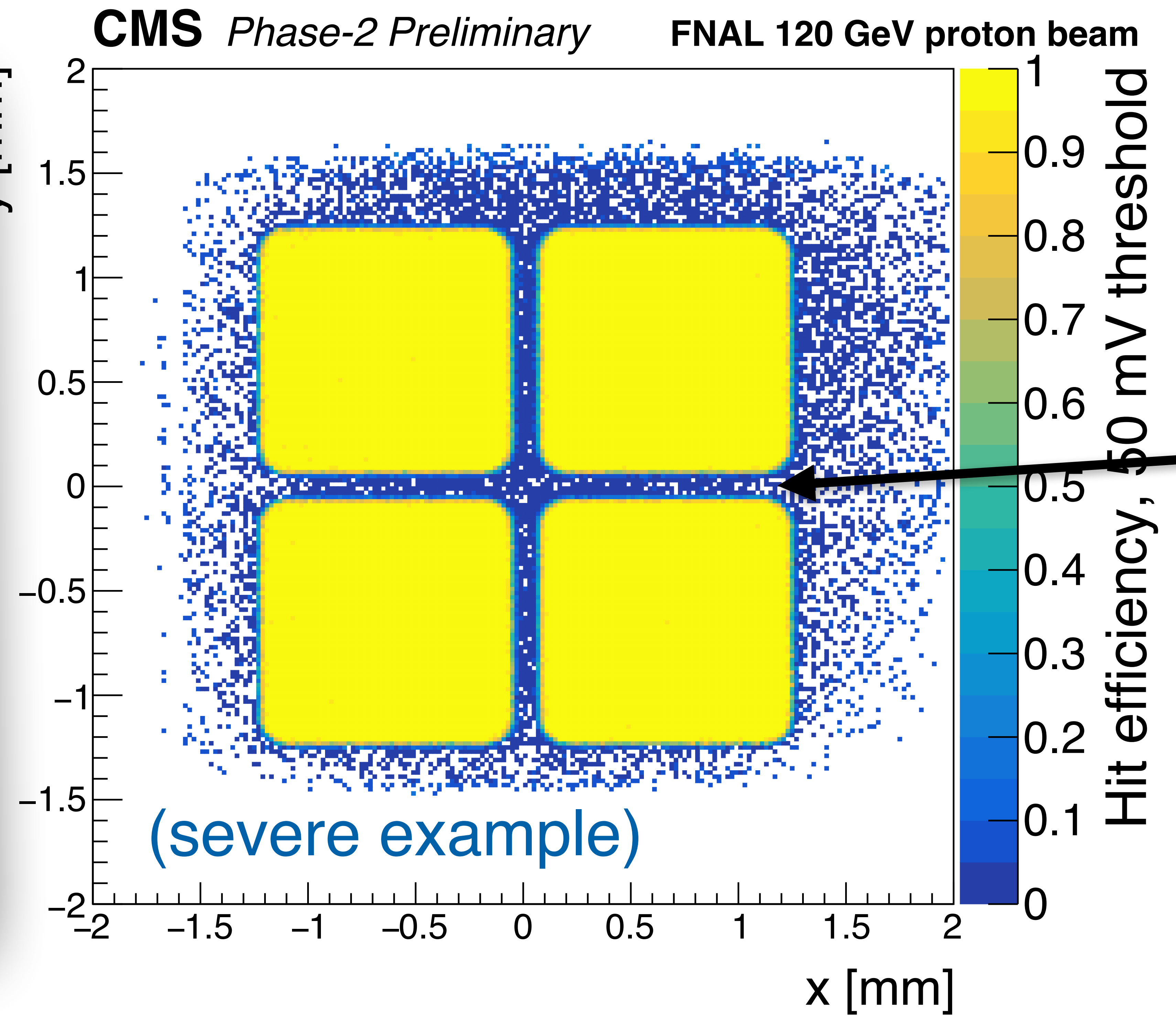
Snowmass 4D tracking whitepaper arXiv:2203.13900

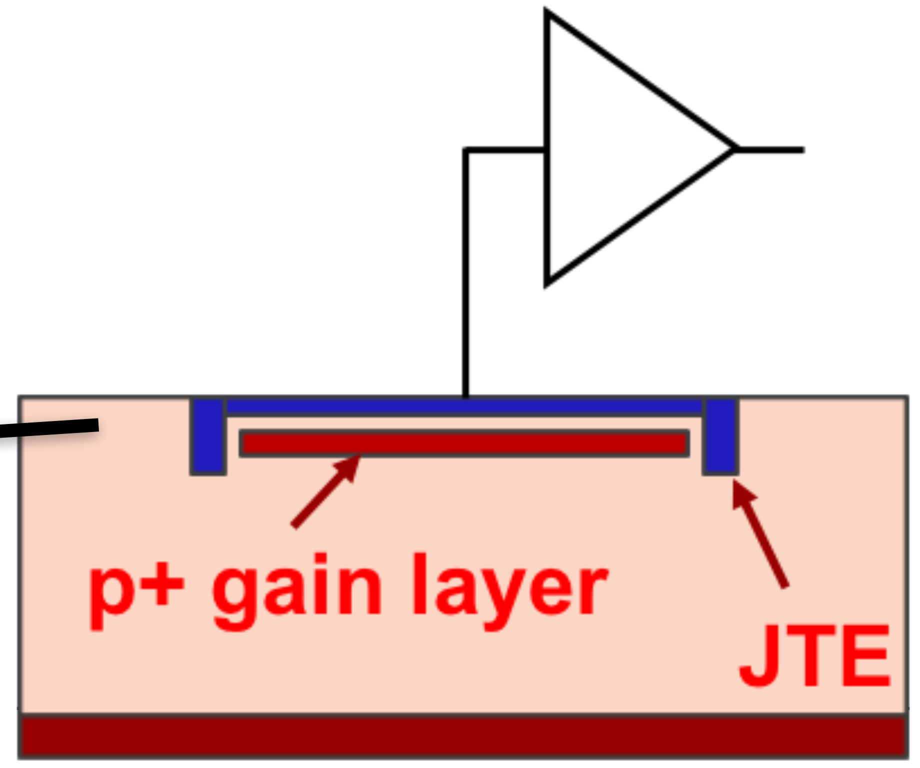
4D tracking with LGADs

- LGADs— not trivial to miniaturize from millimeter to micron scale
  - Gain layer termination requires ≥ 50 micron dead space between channels

2x2 IHEP-IME array







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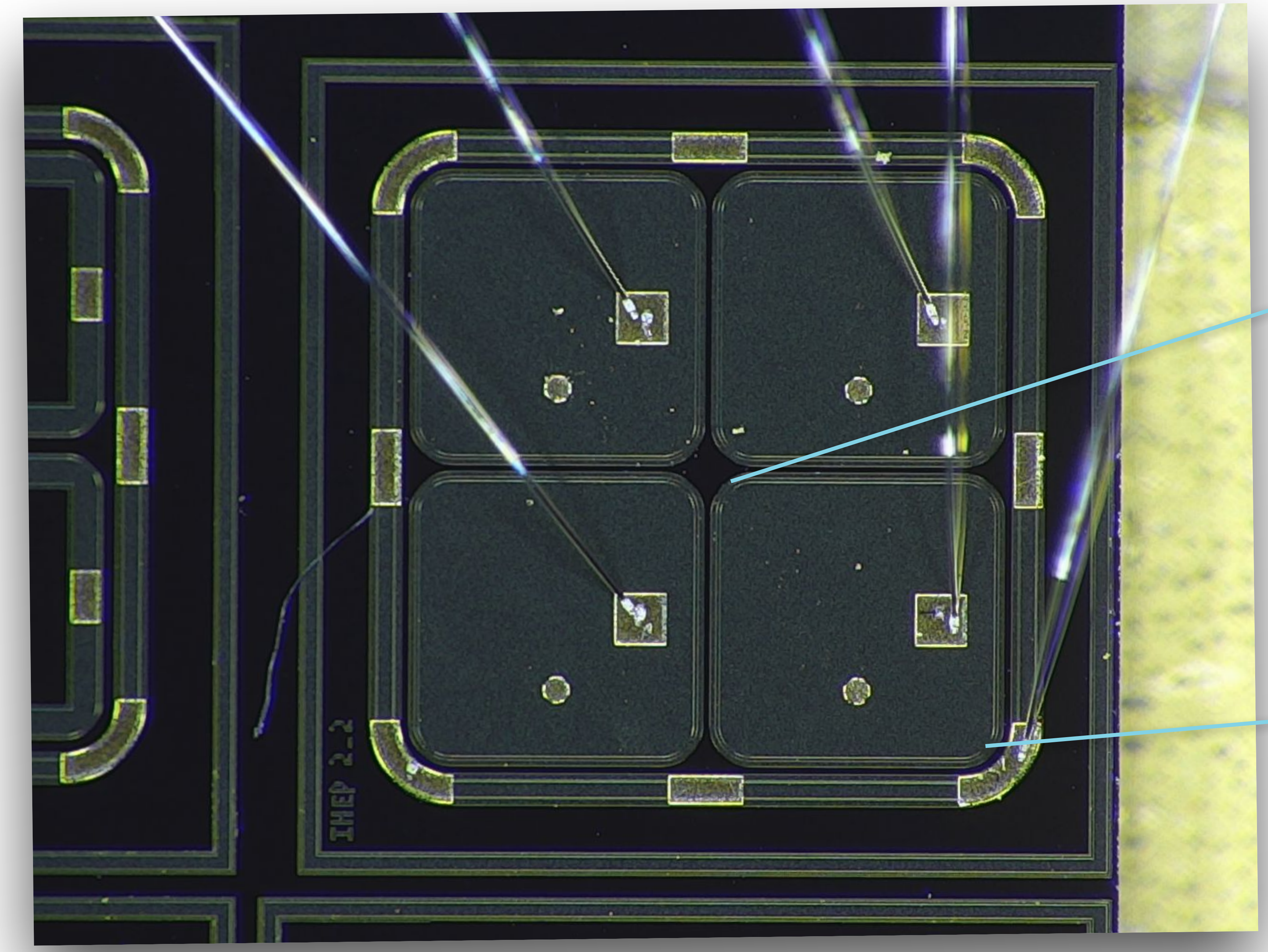

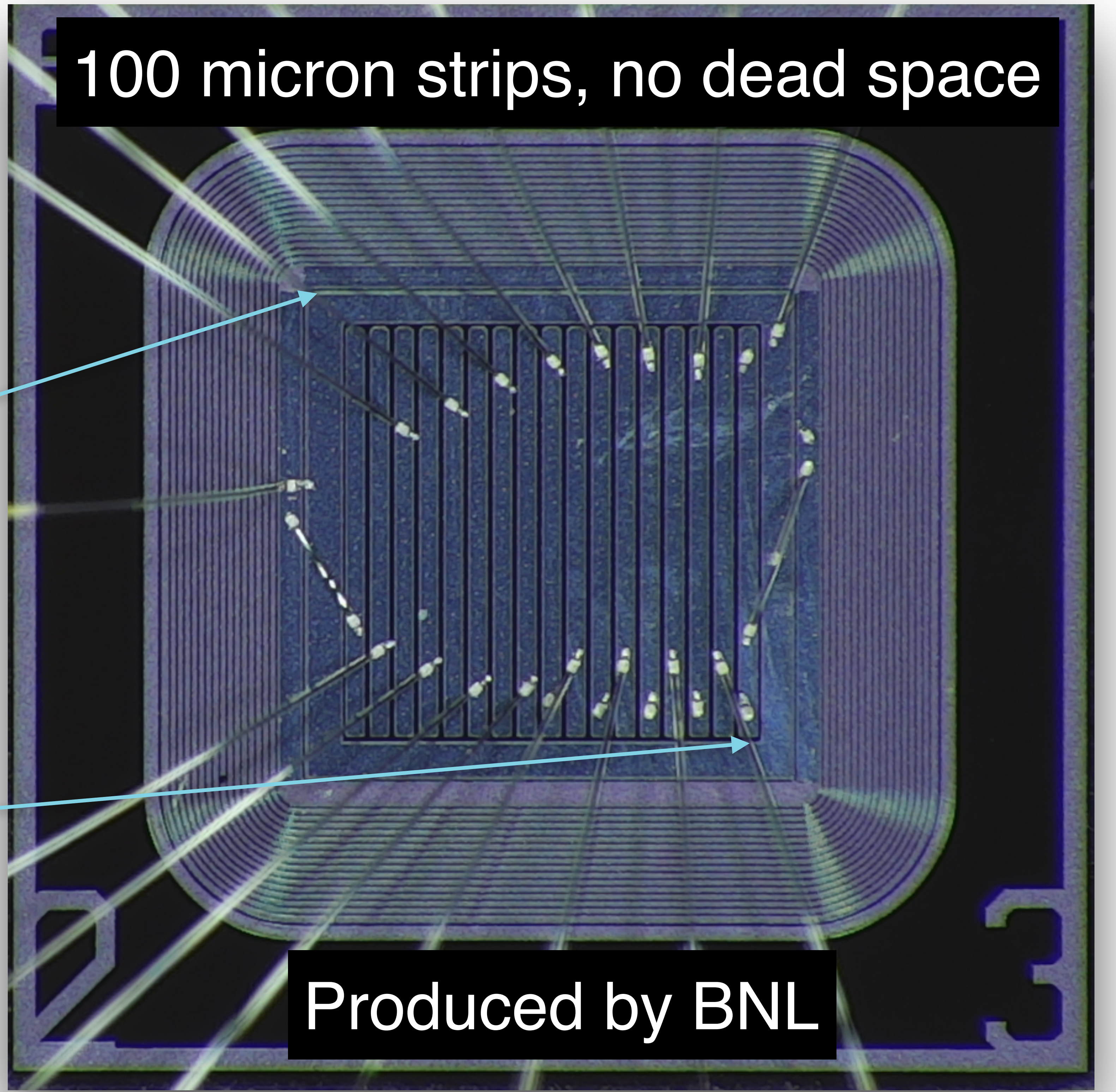

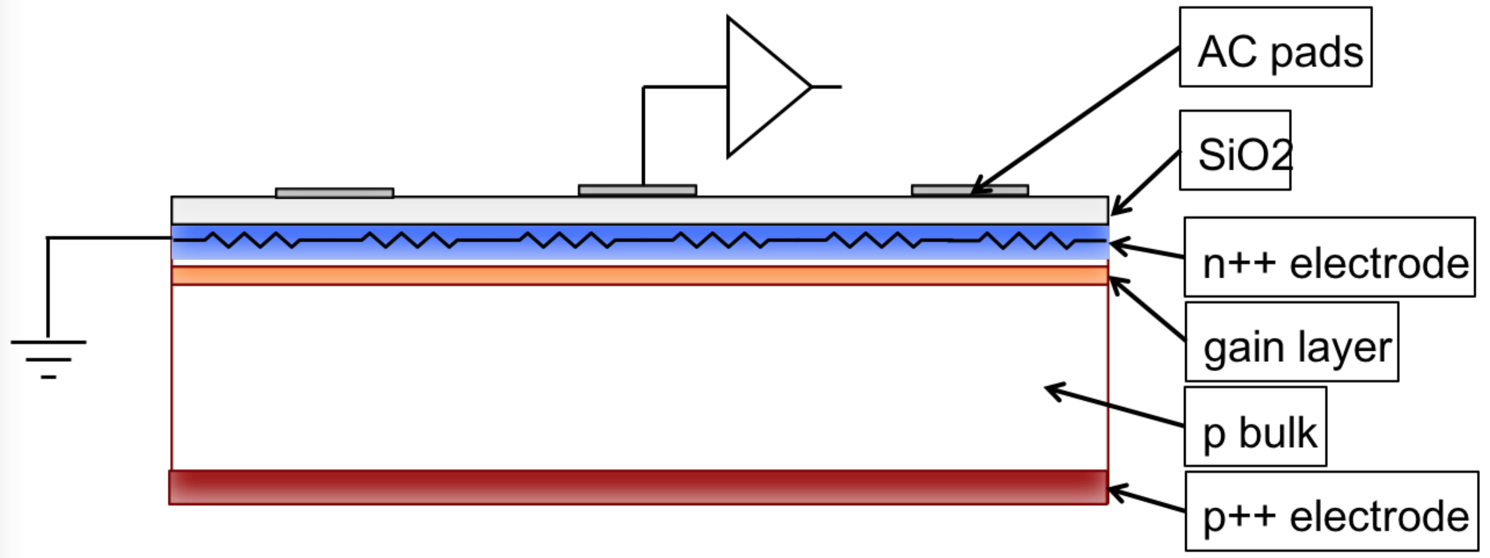

- Instead, add AC-coupled electrodes w/ continuous gain region to achieve segmentation: "AC-LGADs"
- Resistive n+ surface layer controls how signals spread across sensor.

4D tracking with LGADs

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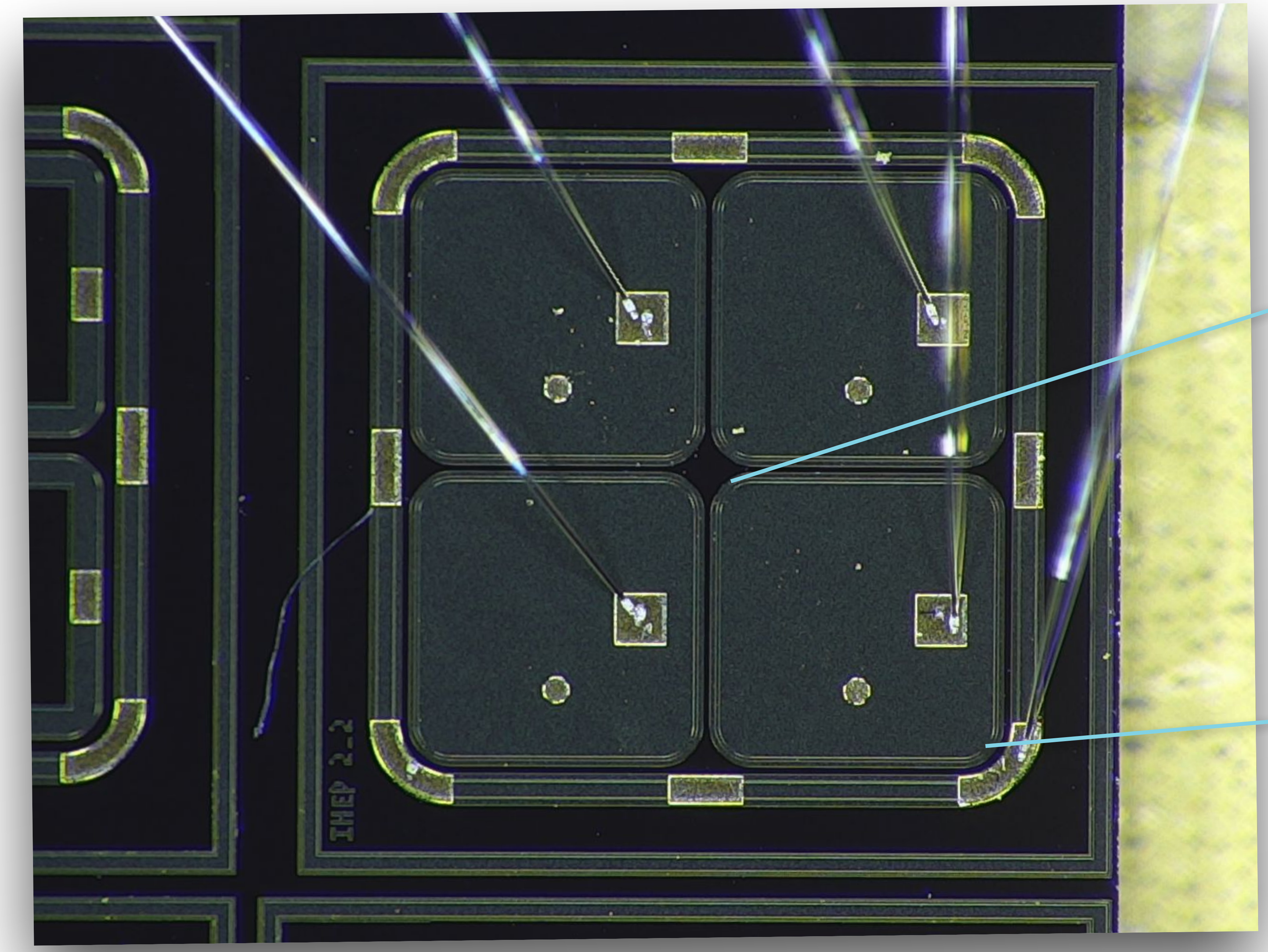
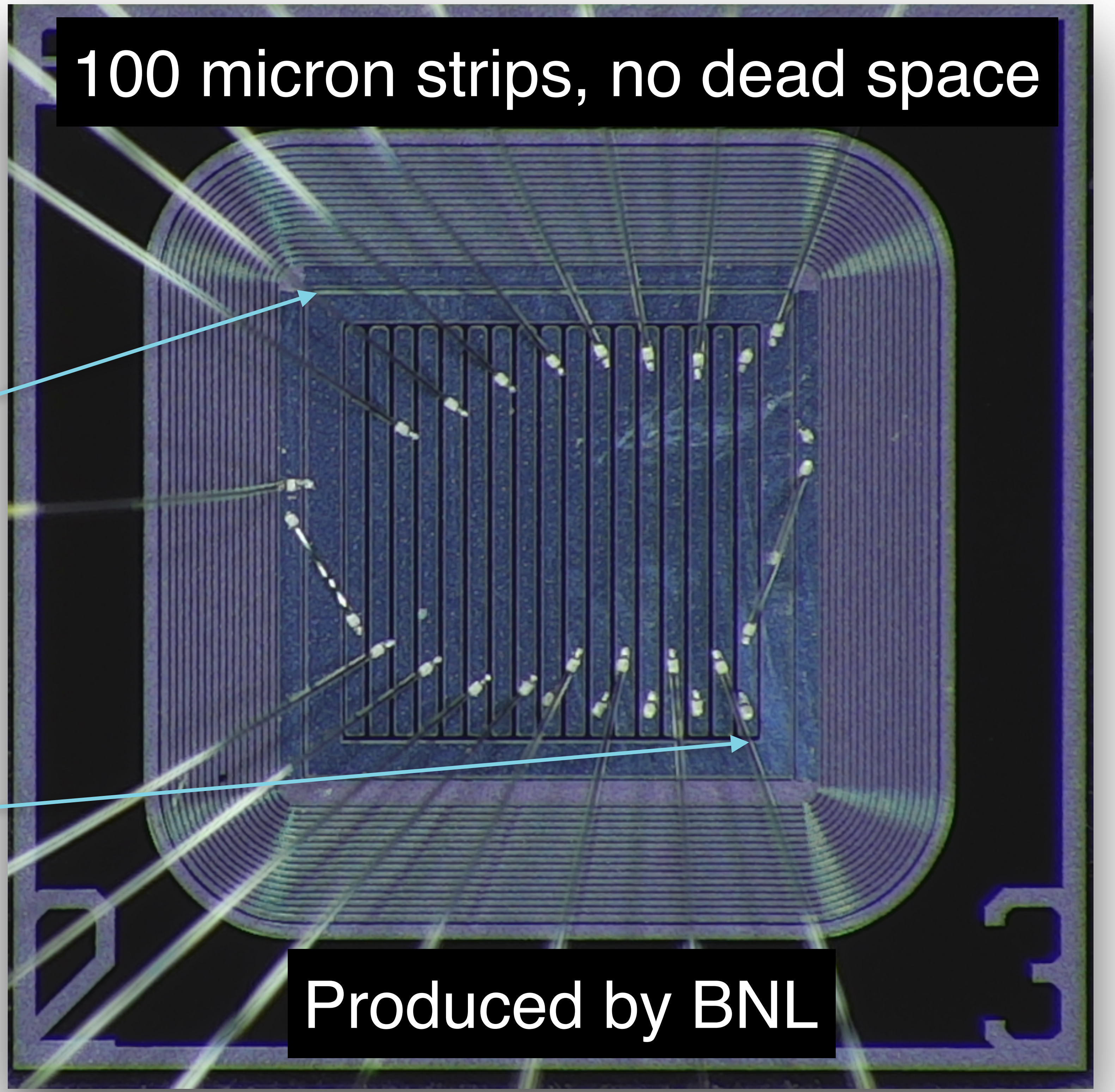
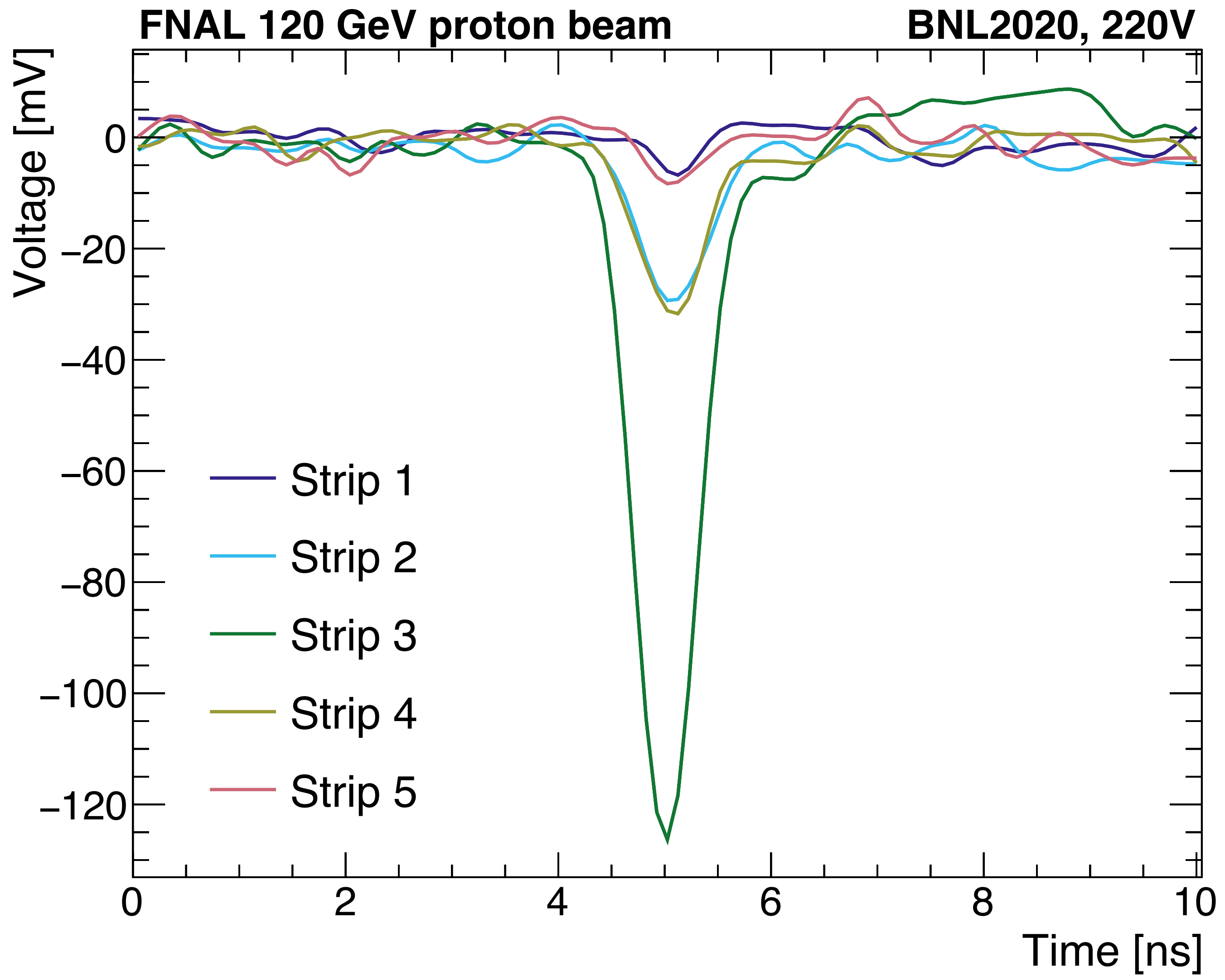


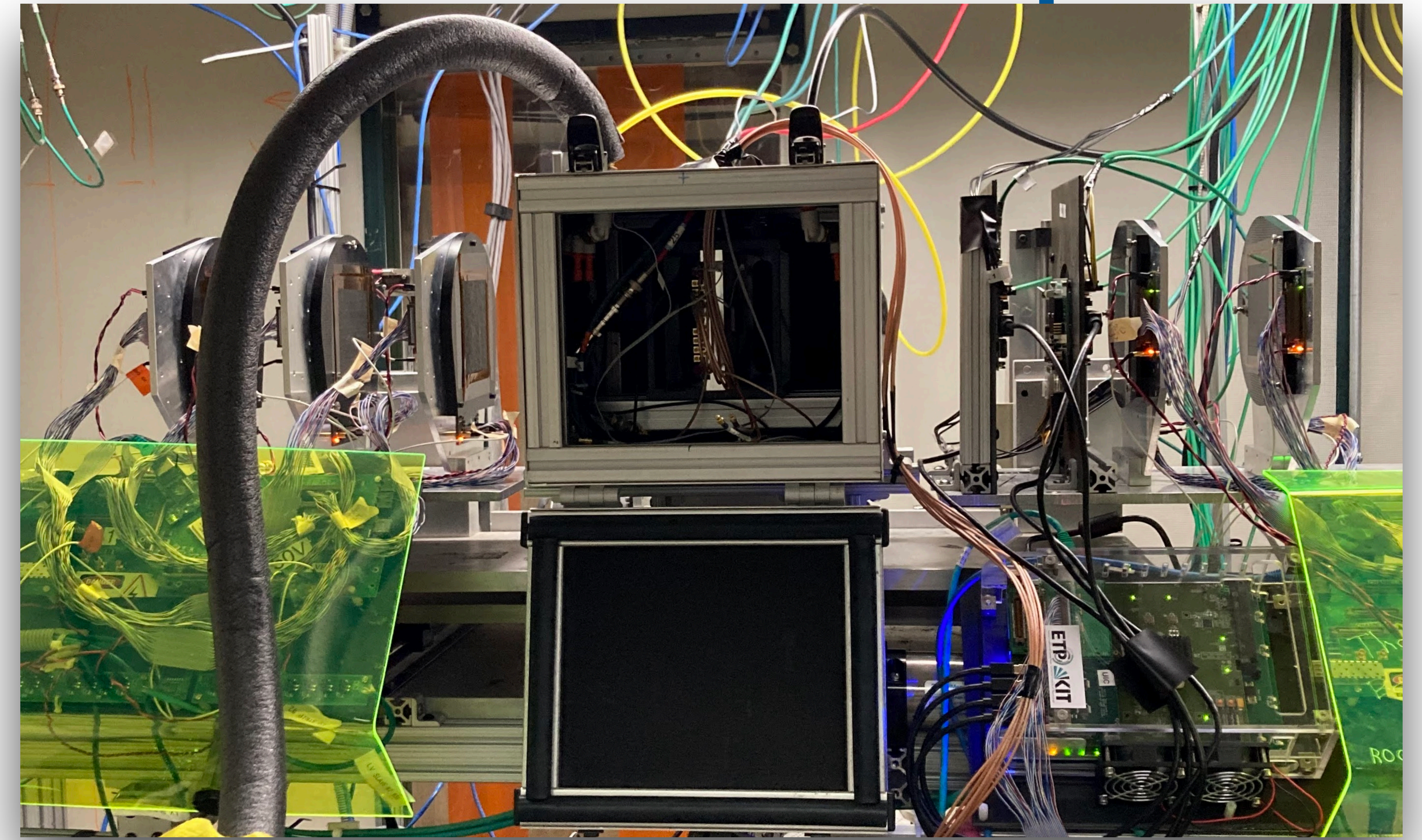


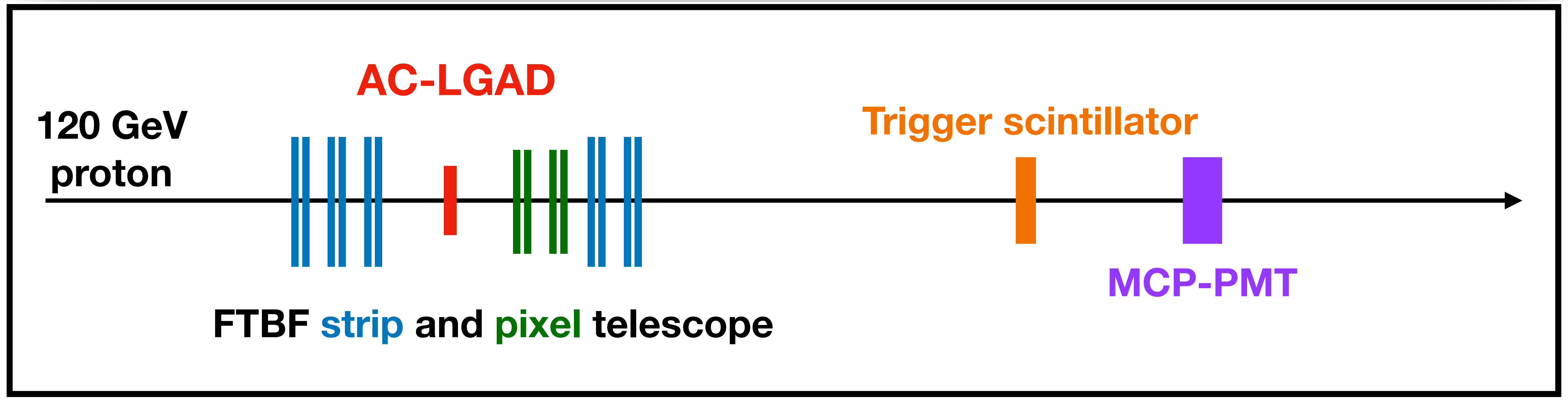
Interpolate to find impact parameter with fine precision



- Instead, add AC-coupled electrodes w/ continuous gain region to achieve segmentation: "AC-LGADs"
- Resistive n+ surface layer controls how signals spread across sensor.

FNAL test beam setup for AC-LGADs





- Tracking telescope resolution: ~ 5 microns
  - 4x CMS RD53a pixels (25 x 100 um) + 10x strips (60 microns)
- MCP time ref resolution: 10 ps

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

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

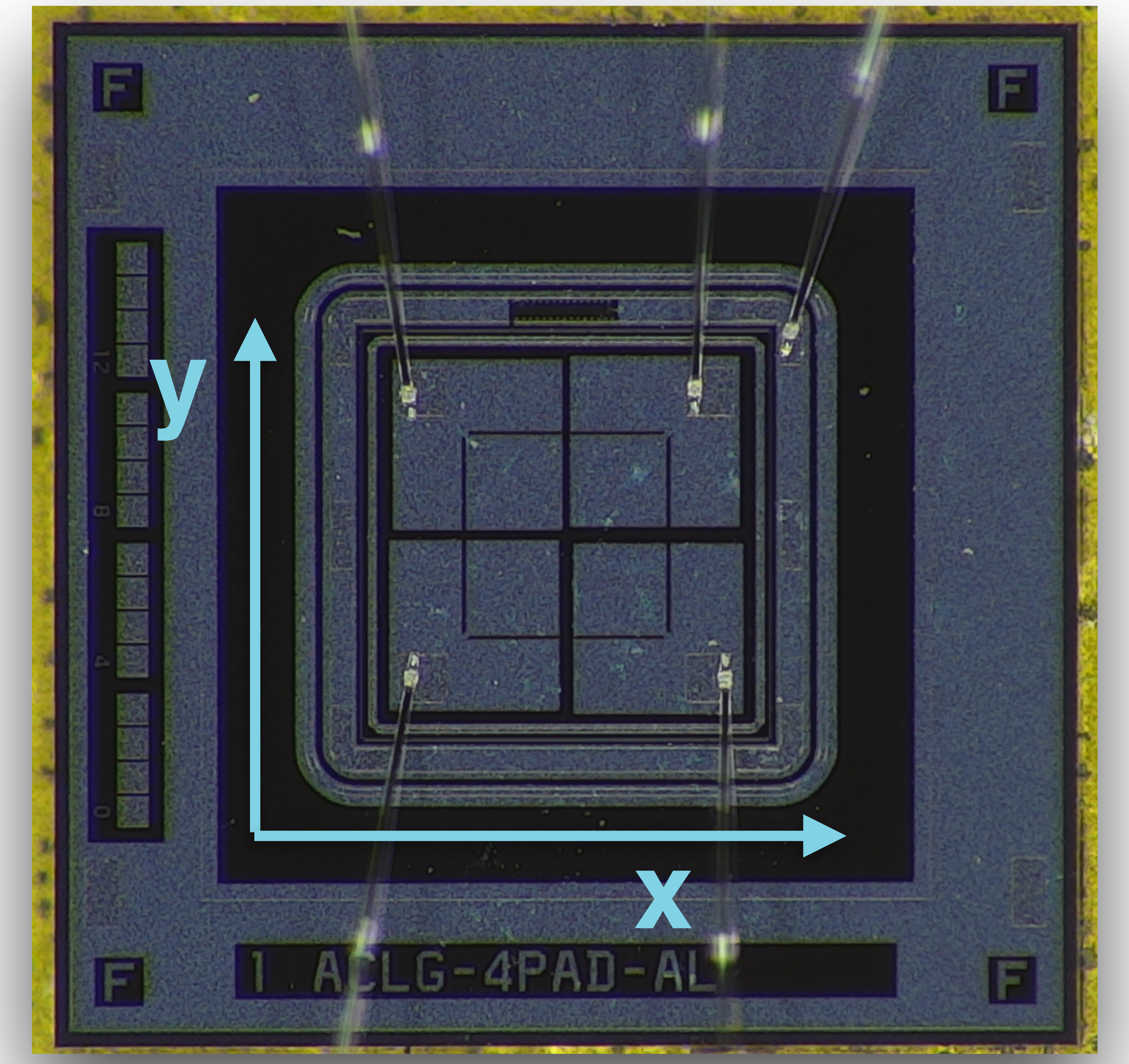
Large memory: take 20k events during 4 s spill

Example AC-LGAD operation

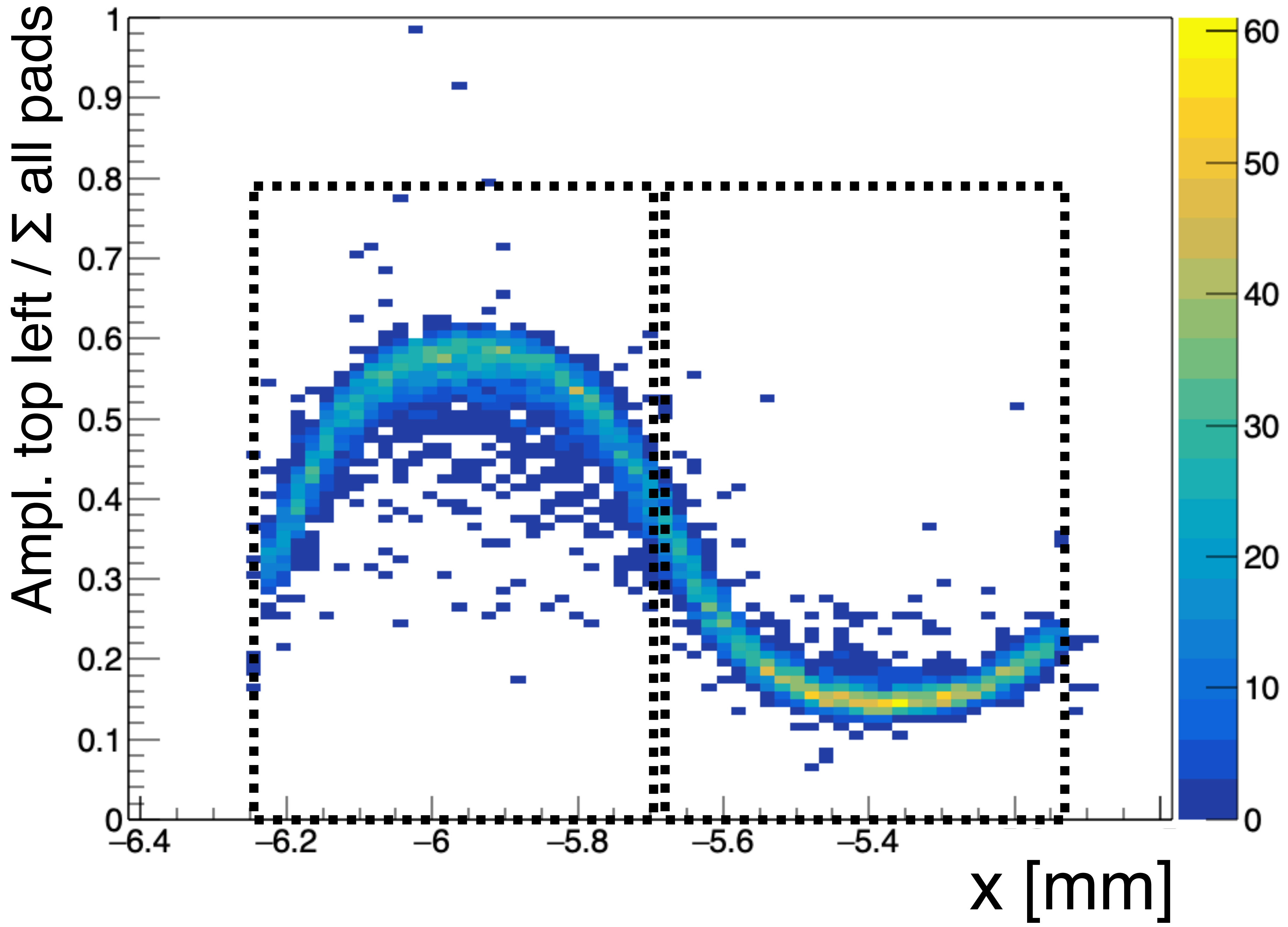
- Signal shared between neighbors—interpolate position based on signal ratio

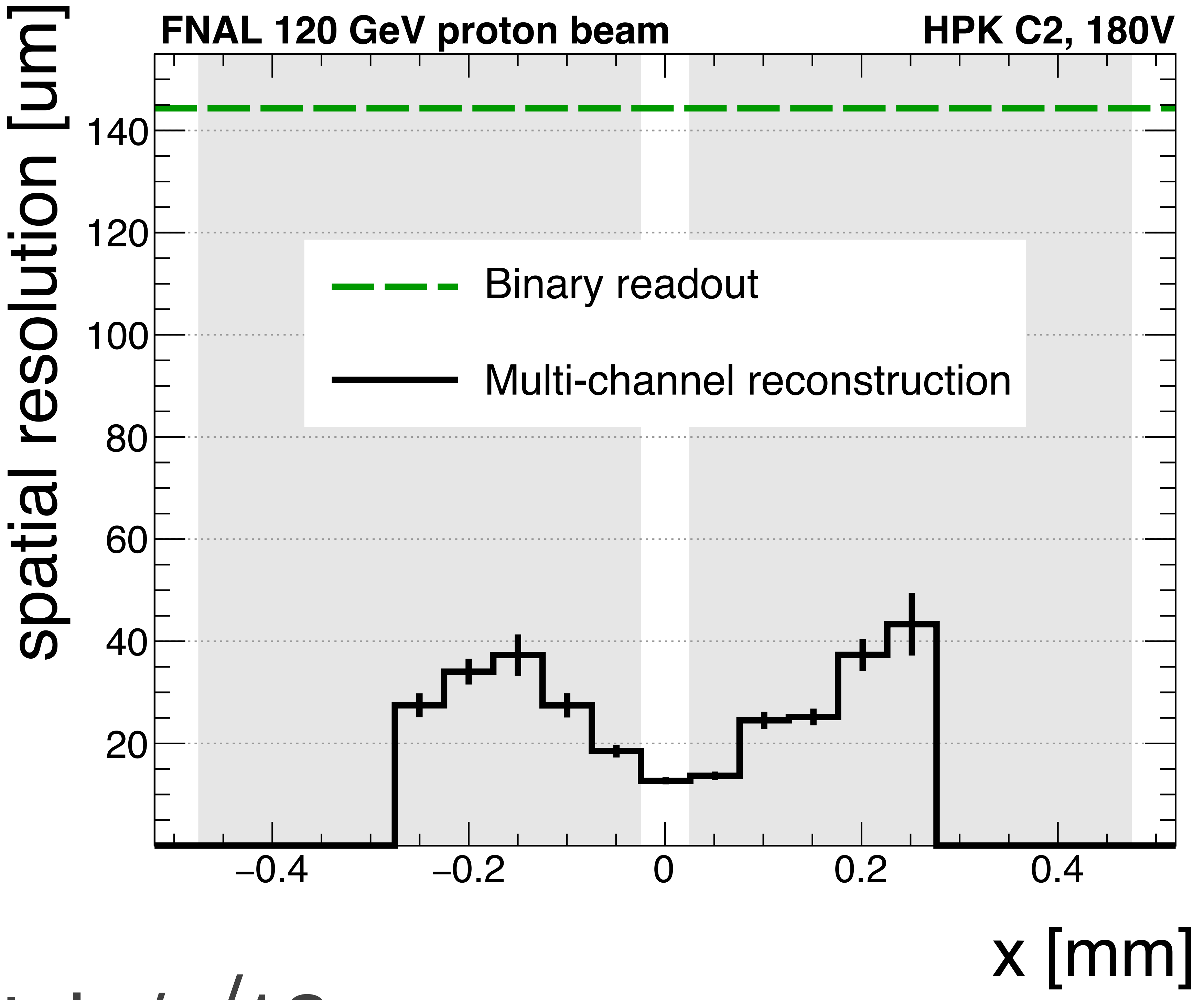
HPK AC 2x2 pads

500 micron pitch, 2021



Amplitude ratio between neighbors

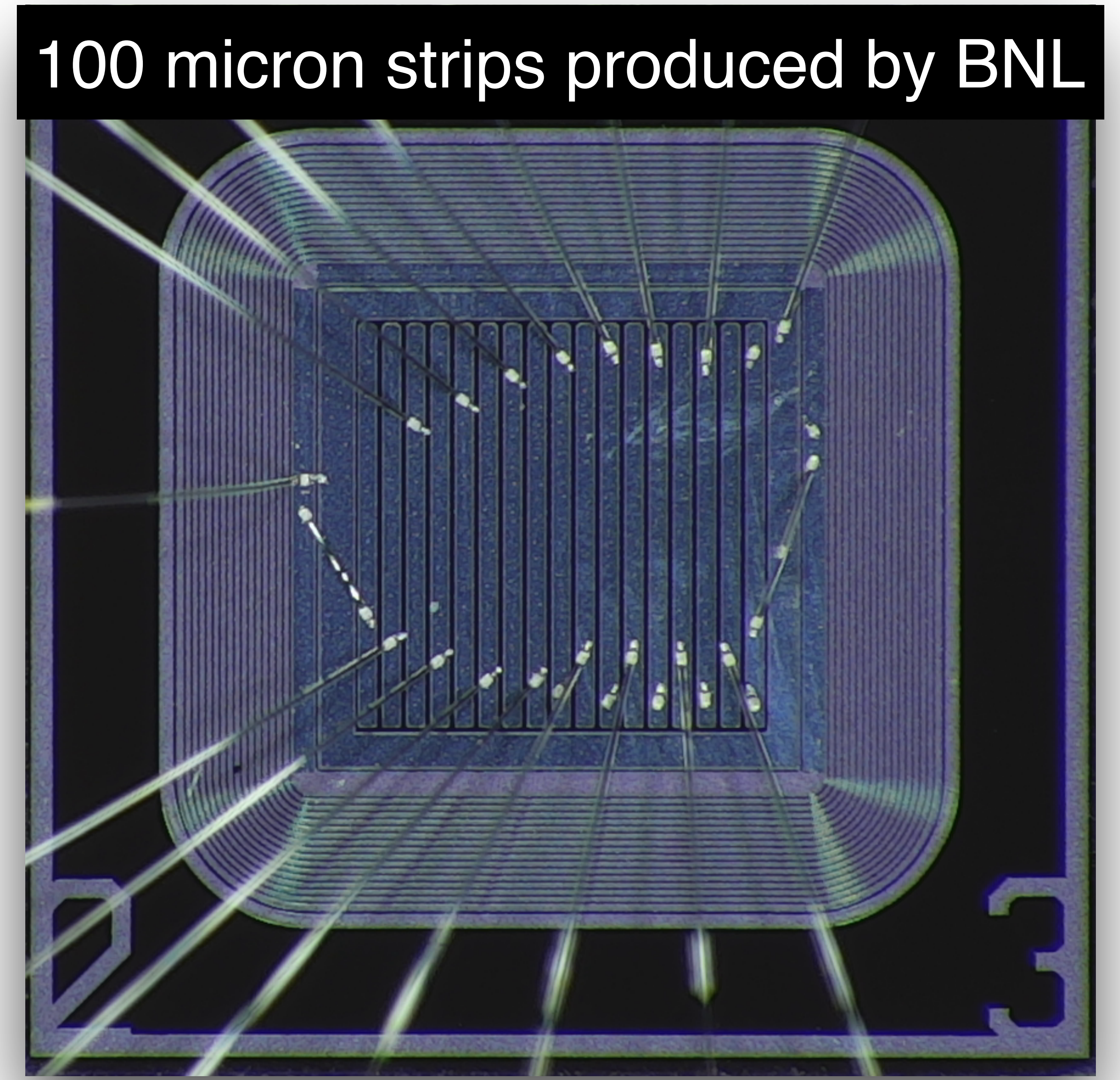


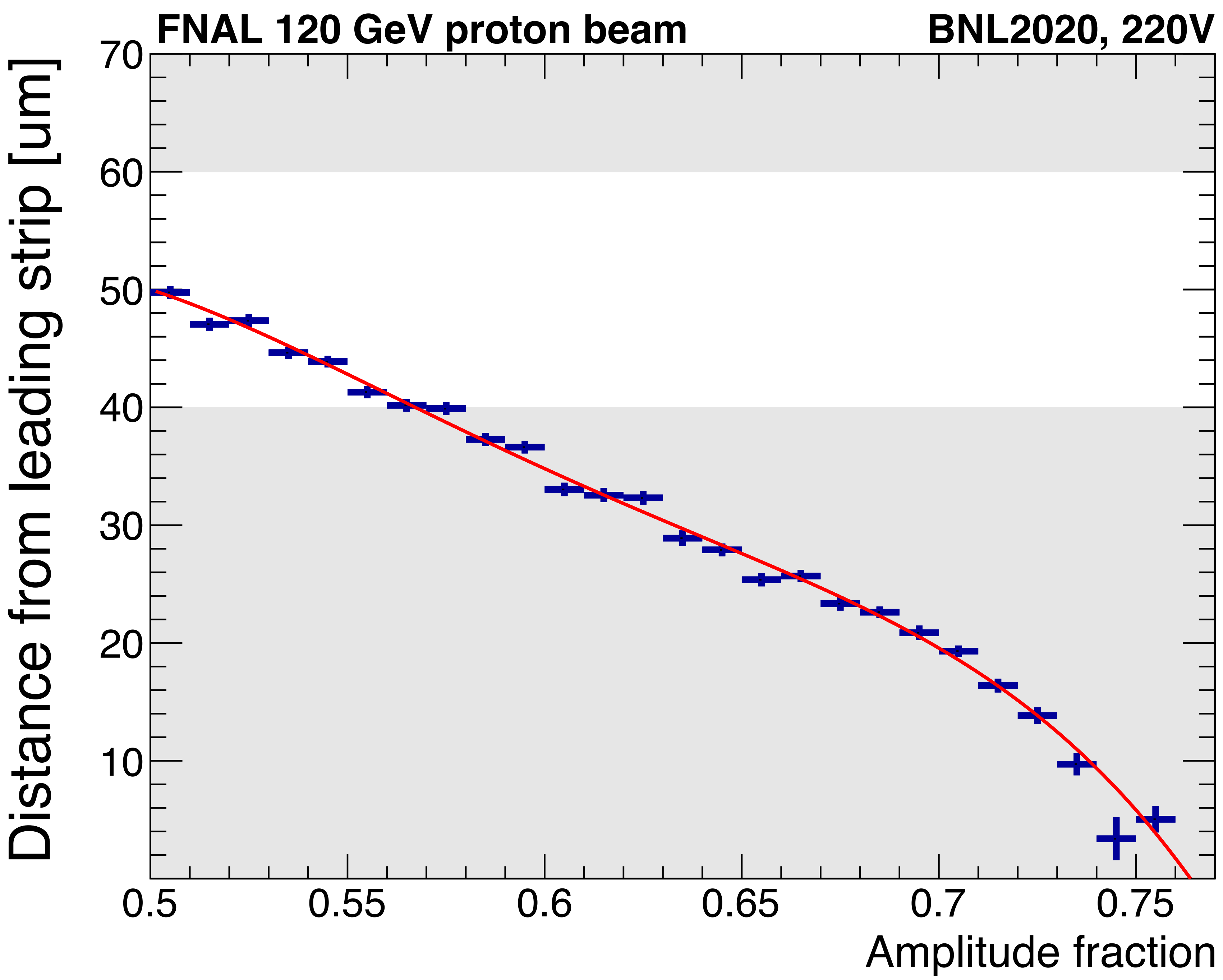


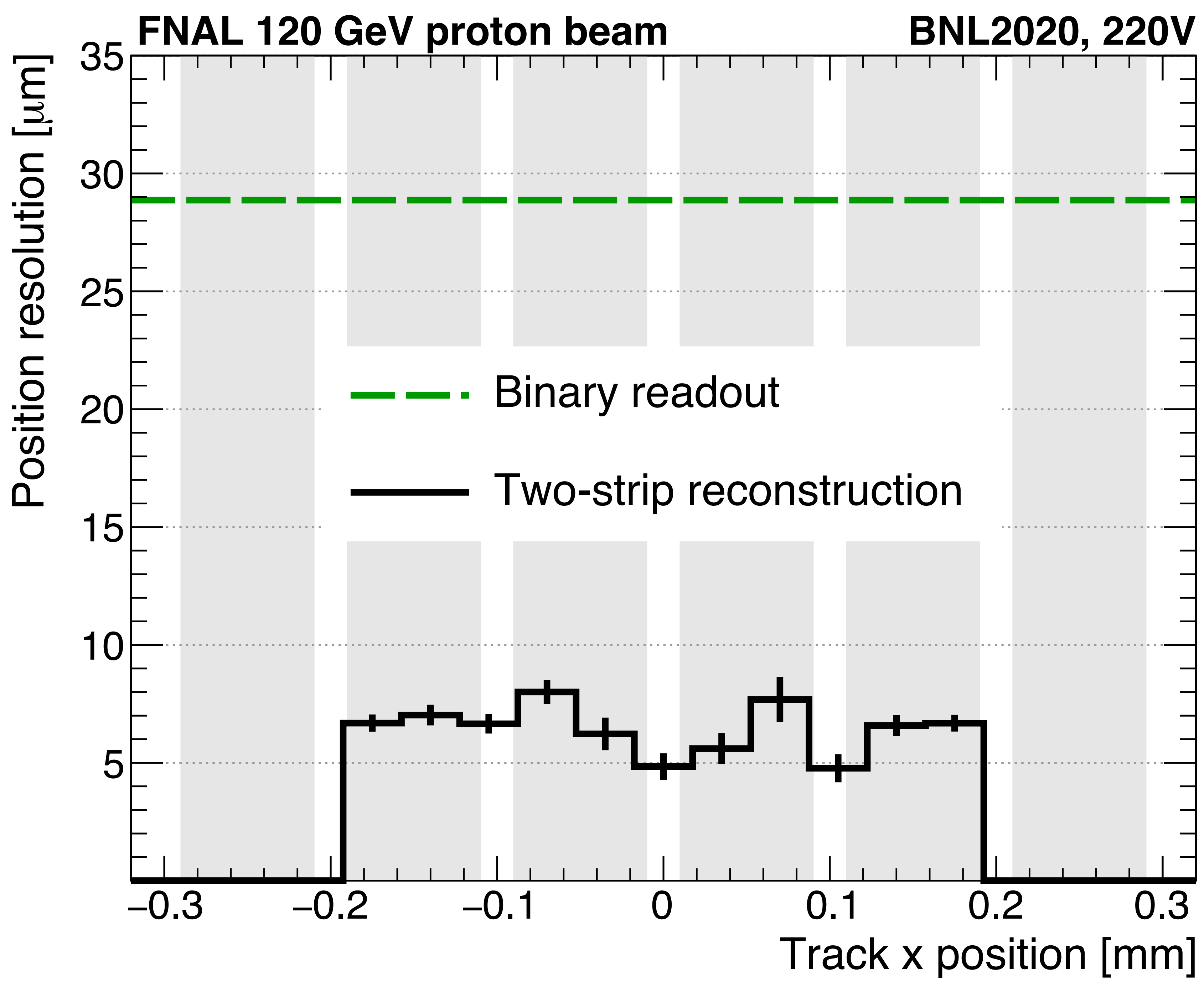
- Thanks to high gain, obtain resolution much finer than pitch / √12
  - In this case: 20-40 microns (and 30 picosecond time resolution!)
- Tuning of n+ resistivity and electrode geometry needed for optimal sharing...

High resolution AC-LGAD strips

- Good performance from several BNL 100 to 200 micron strip prototypes
  - Well-tuned signal sharing → uniform 2-strip efficiency → uniform 5-10 um resolution.







- Promising 4D sensors: 30 ps timing and spatial resolution ~ pitch / 30

2022 JINST 17 P05001

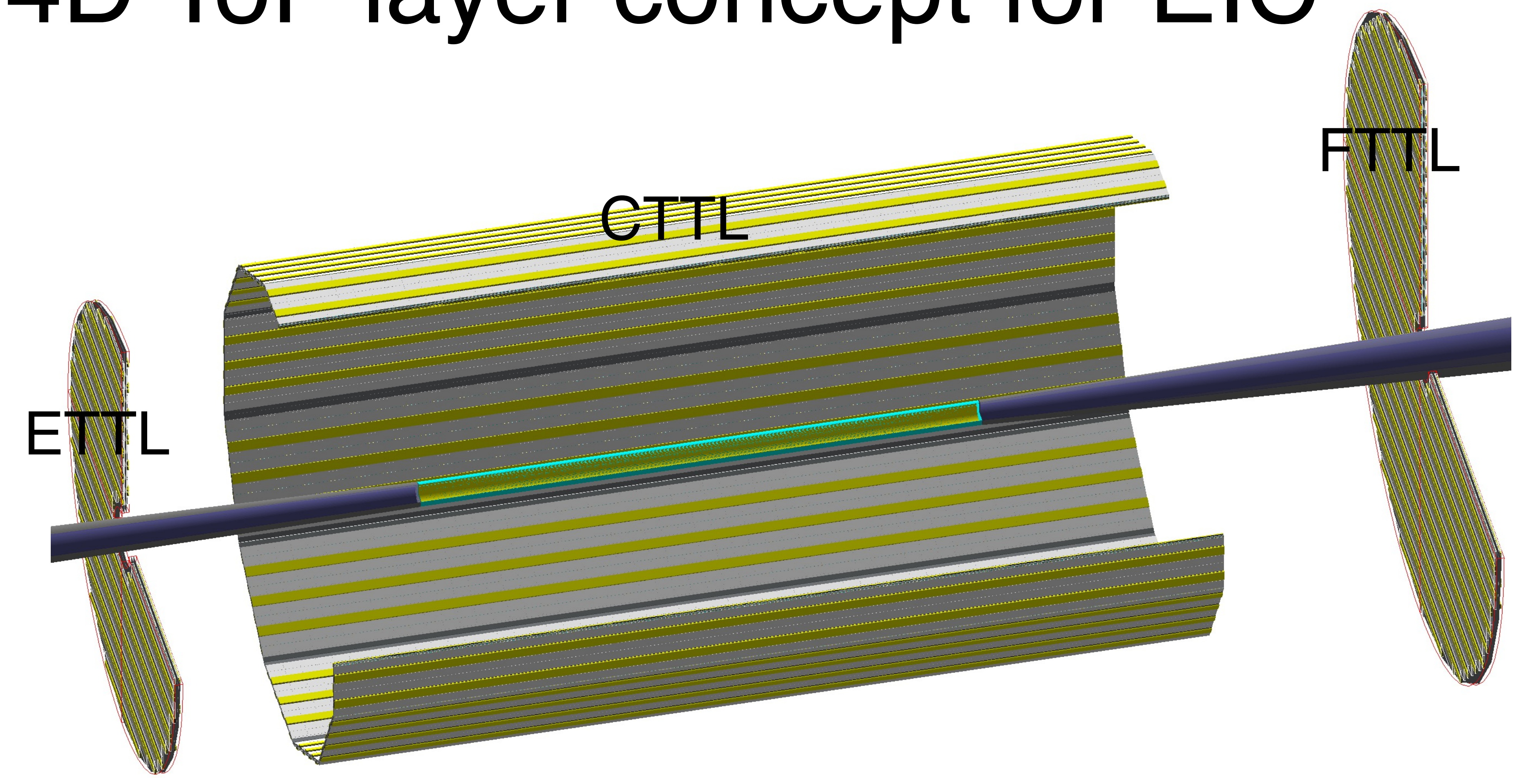
Large-area 4D detectors

- Alternate direction: maintain performance with much sparser readout
  ➡High precision (time & space) with coarser readout & few channels

Large-area 4D detectors

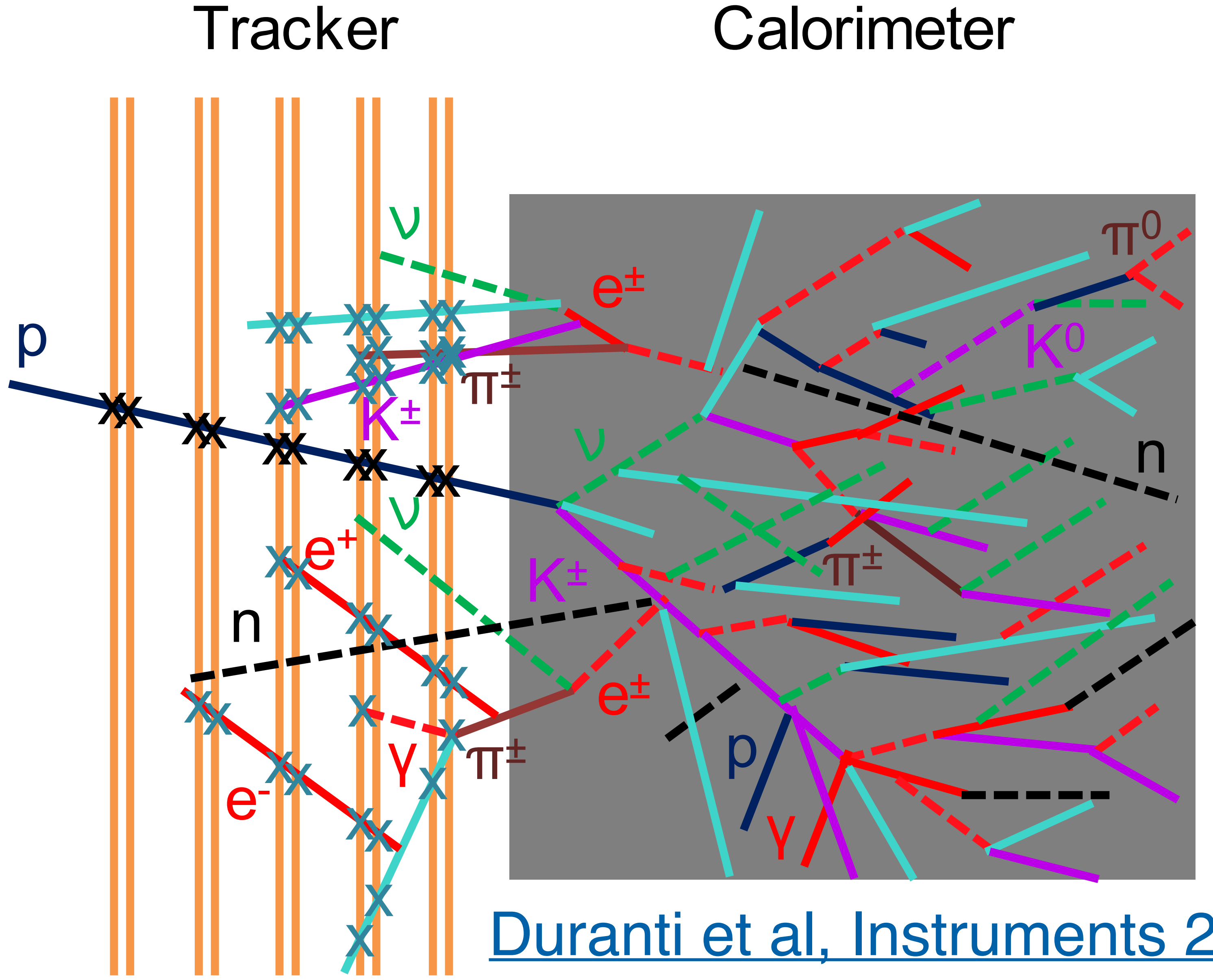
- Alternate direction: maintain performance with much sparser readout
  ➡High precision (time & space) with coarser readout & few channels
- Promising for
  - Electron Ion Collider timing layer: particle ID via time of flight.
  - Space-based— power constraints

4D ToF layer concept for EIC



Goal: 30 ps + 20 micron resolution w/ few channels

Space-based 4D tracking



Duranti et al, Instruments 2021, 5(2), 20

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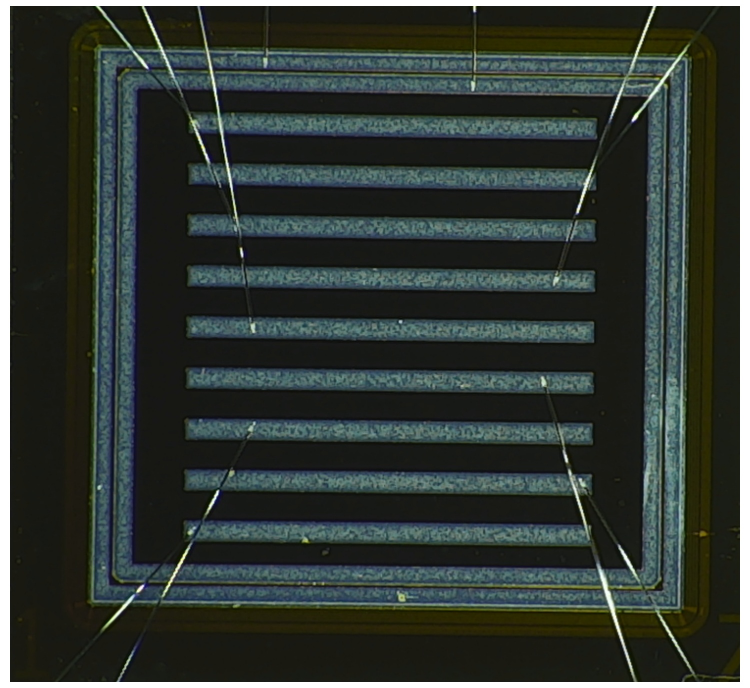
2022 large strips campaign

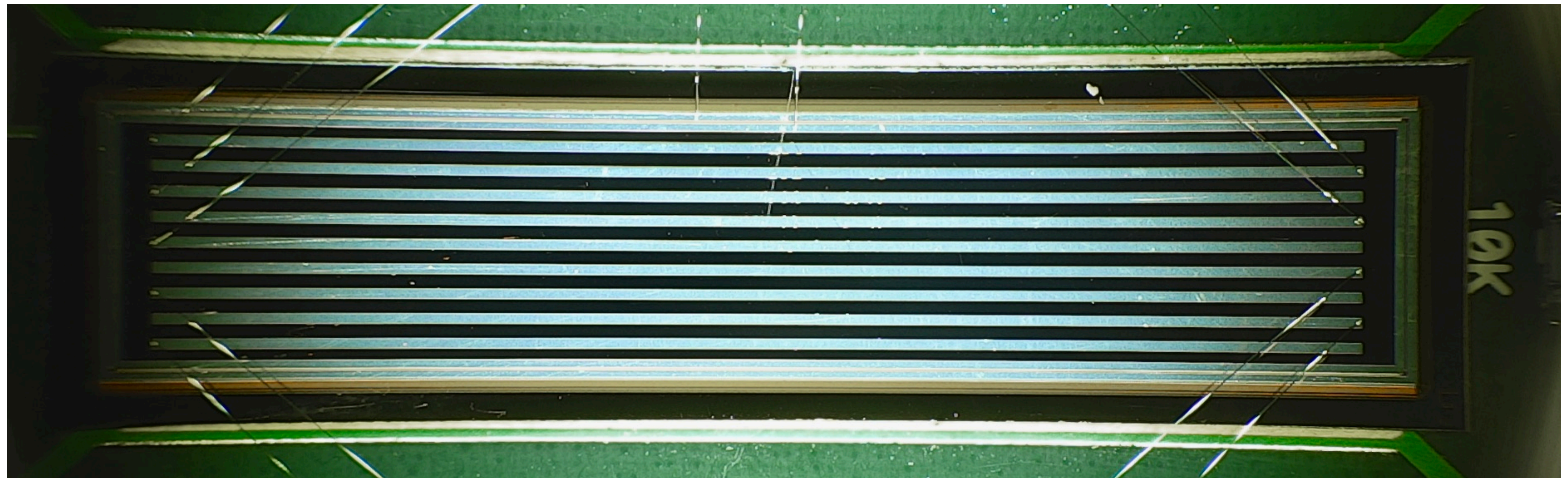
- For realistic application, need to demonstrate large area sensors.
- Extensive campaign to study 15 BNL AC-LGADs in test beam
  - Length 5-25 mm & pitch 500 um (10x longer and 5x coarser than previous sensors)
  - Focus on geometry optimization & tradeoffs with longer sensors.

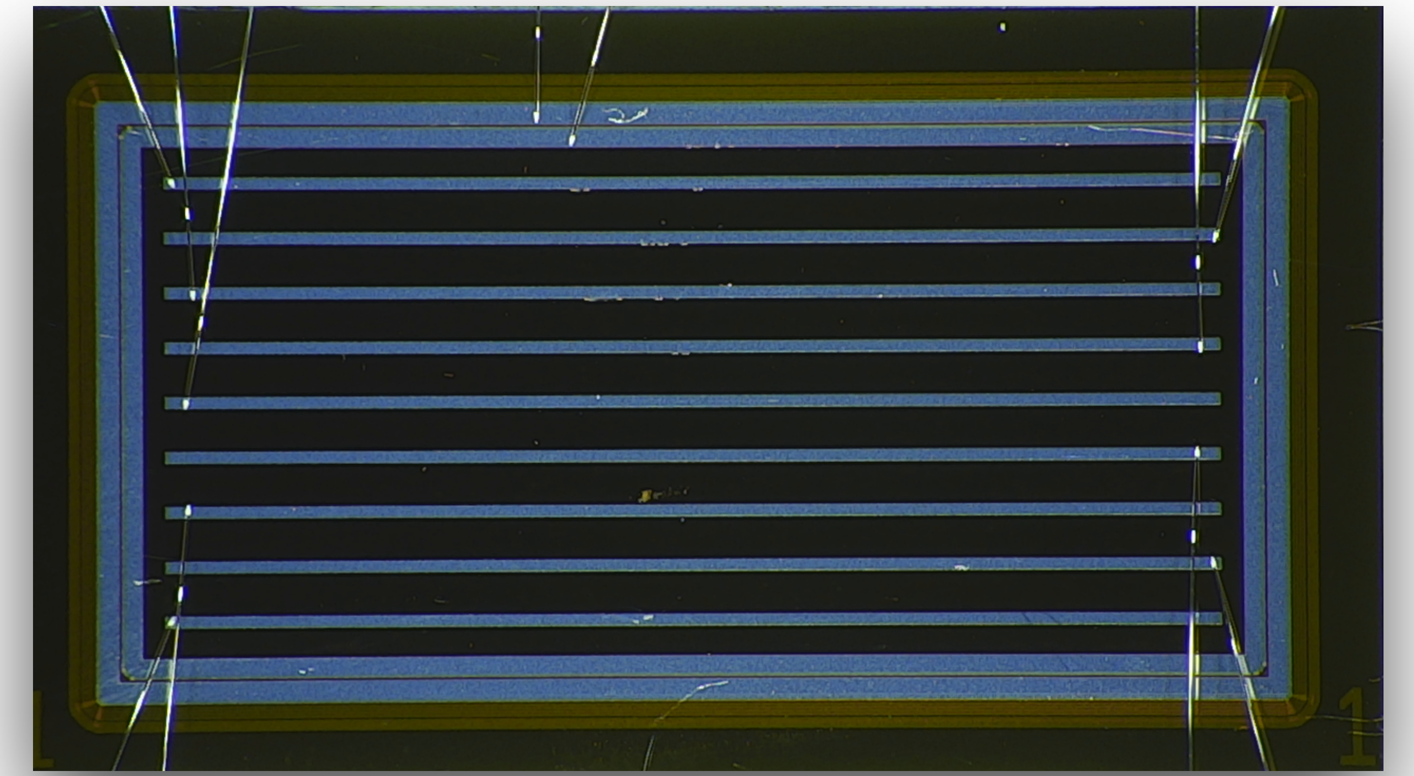
500 um pitch

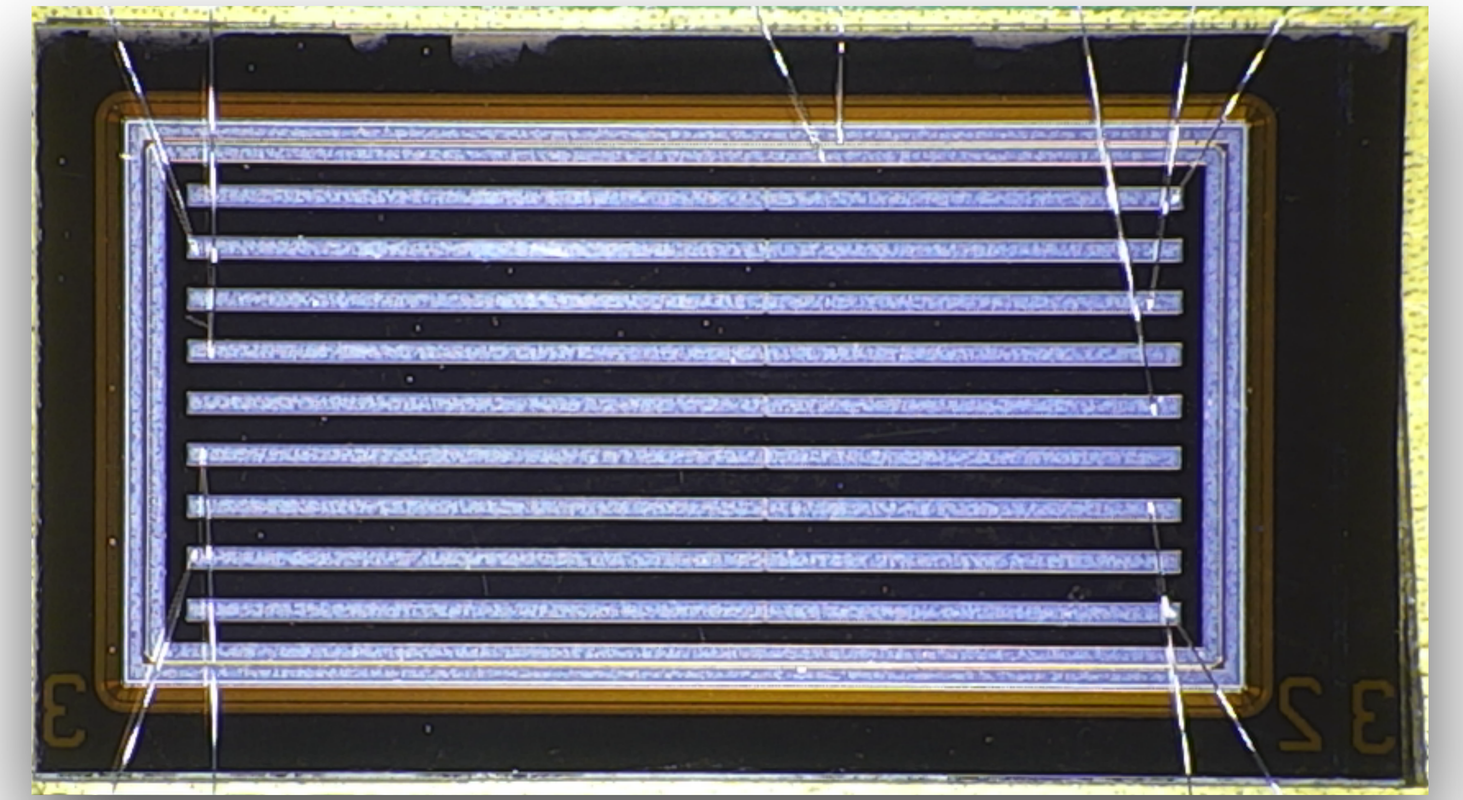
5, 10, 25 mm lengths

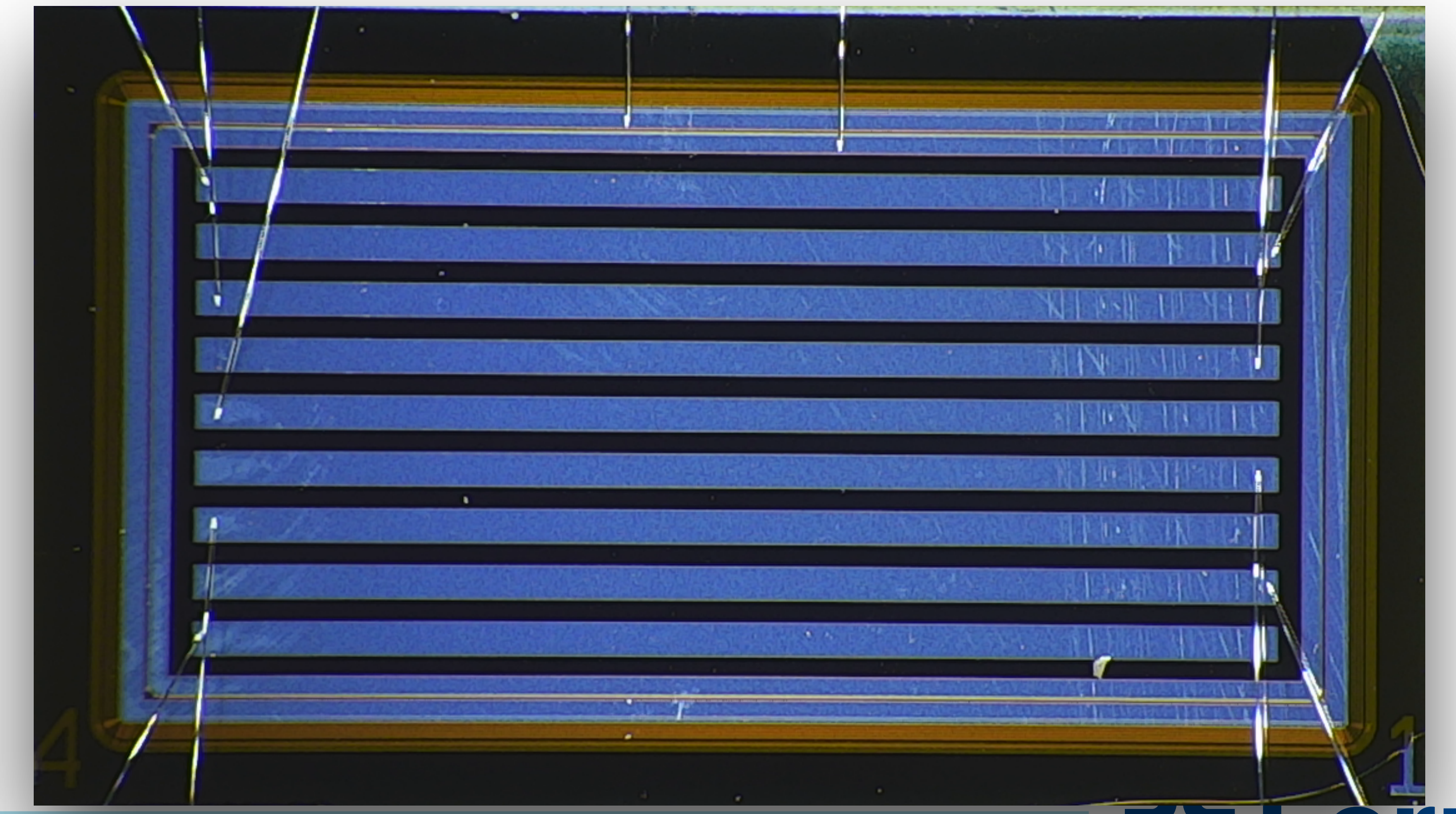
100, 200, 300 um metal widths







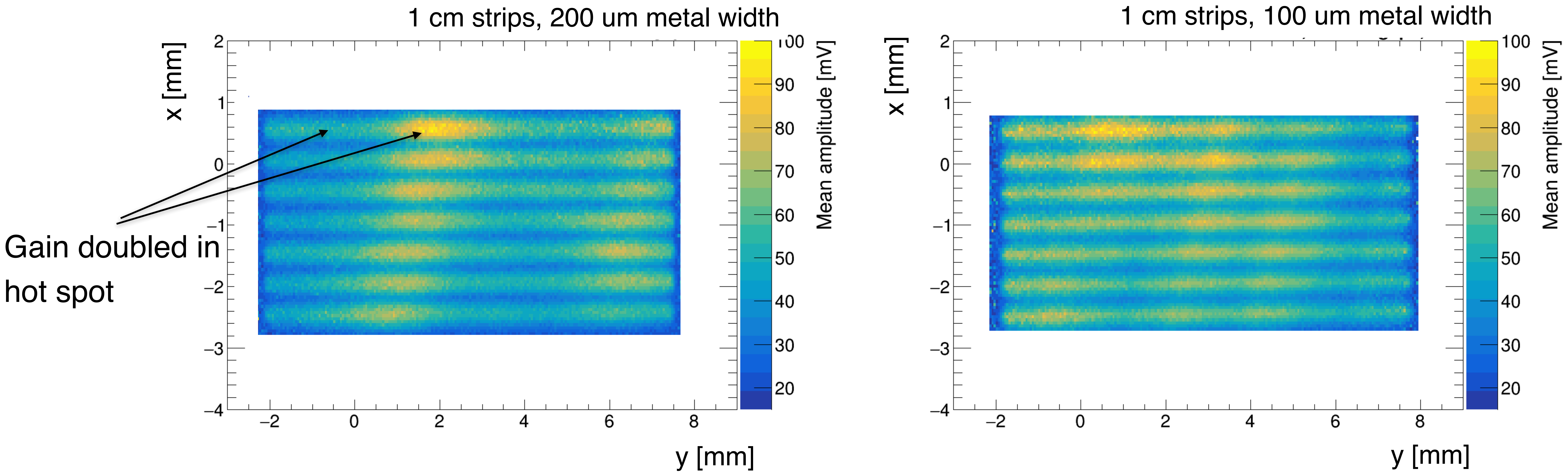




- Today: preview of results to appear on arXiv soon!

Gain uniformity

- 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 underbiased

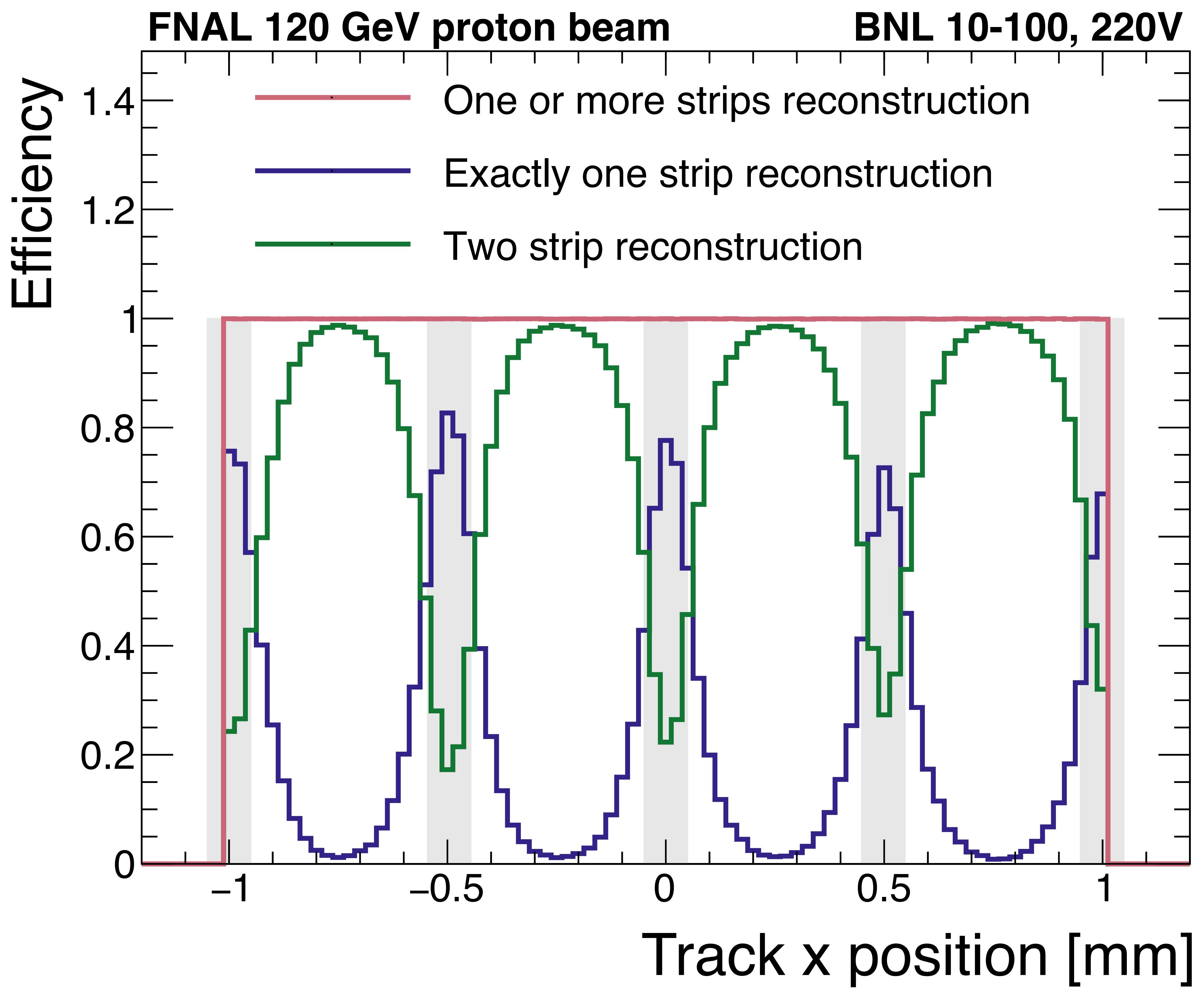


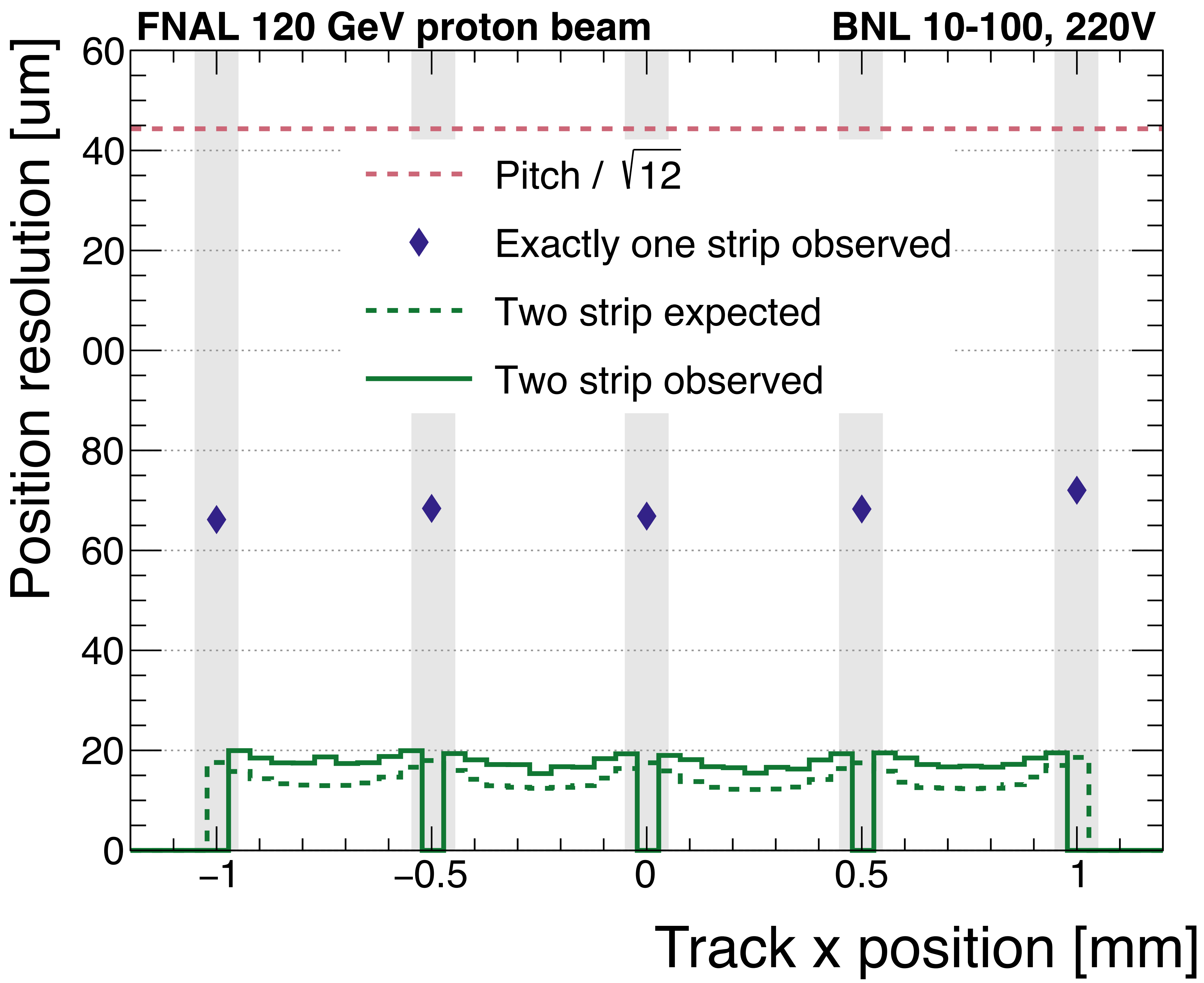
- Expect improved uniformity in next prototypes
  - Uniform 2x2 cm^2 LGADs for ATLAS/CMS already demonstrated
  - Still extract useful lessons despite non-uniformity!

Spatial resolution

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

Performance for 1 cm strips, 500 um pitch w/100 um metal

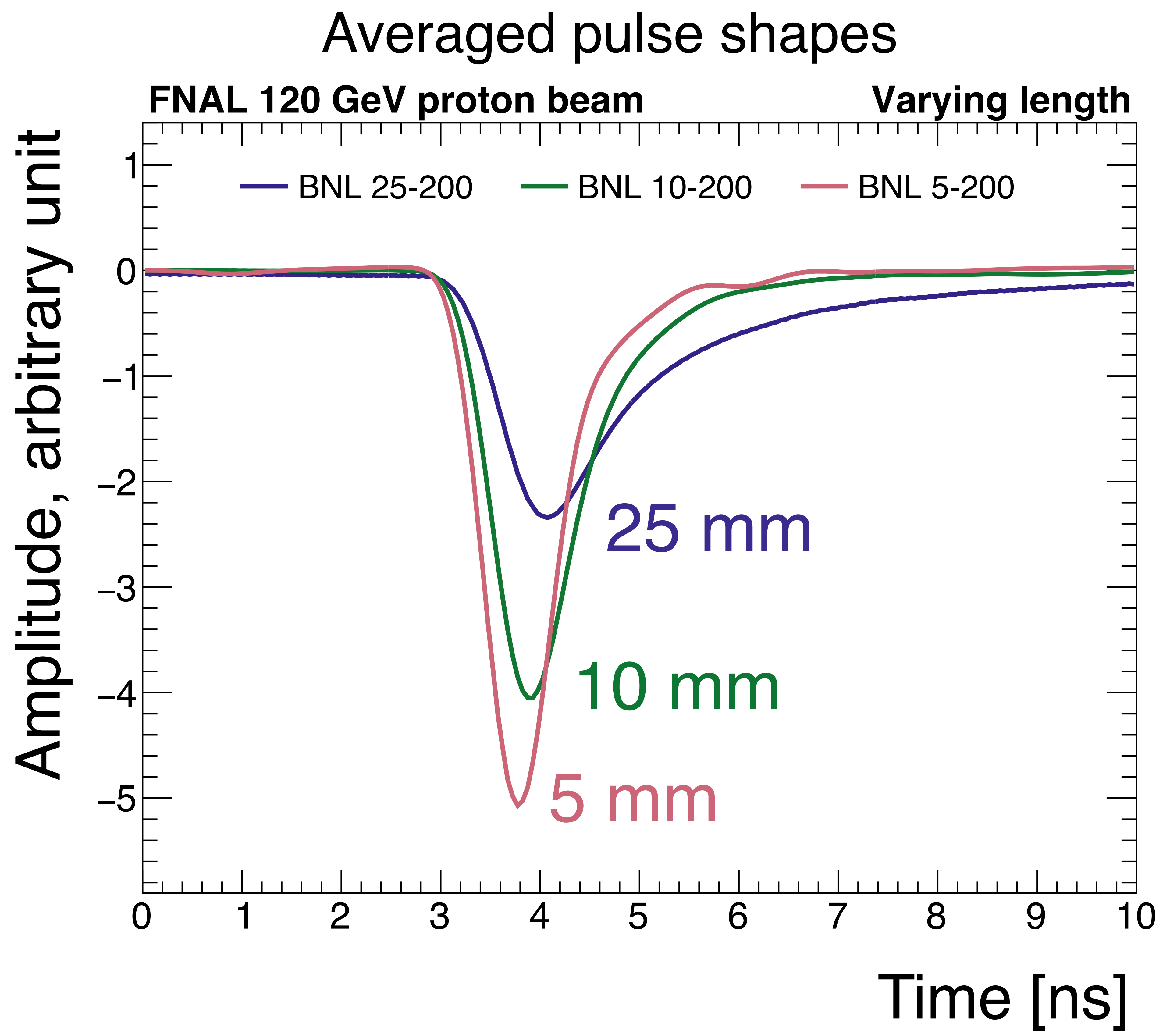


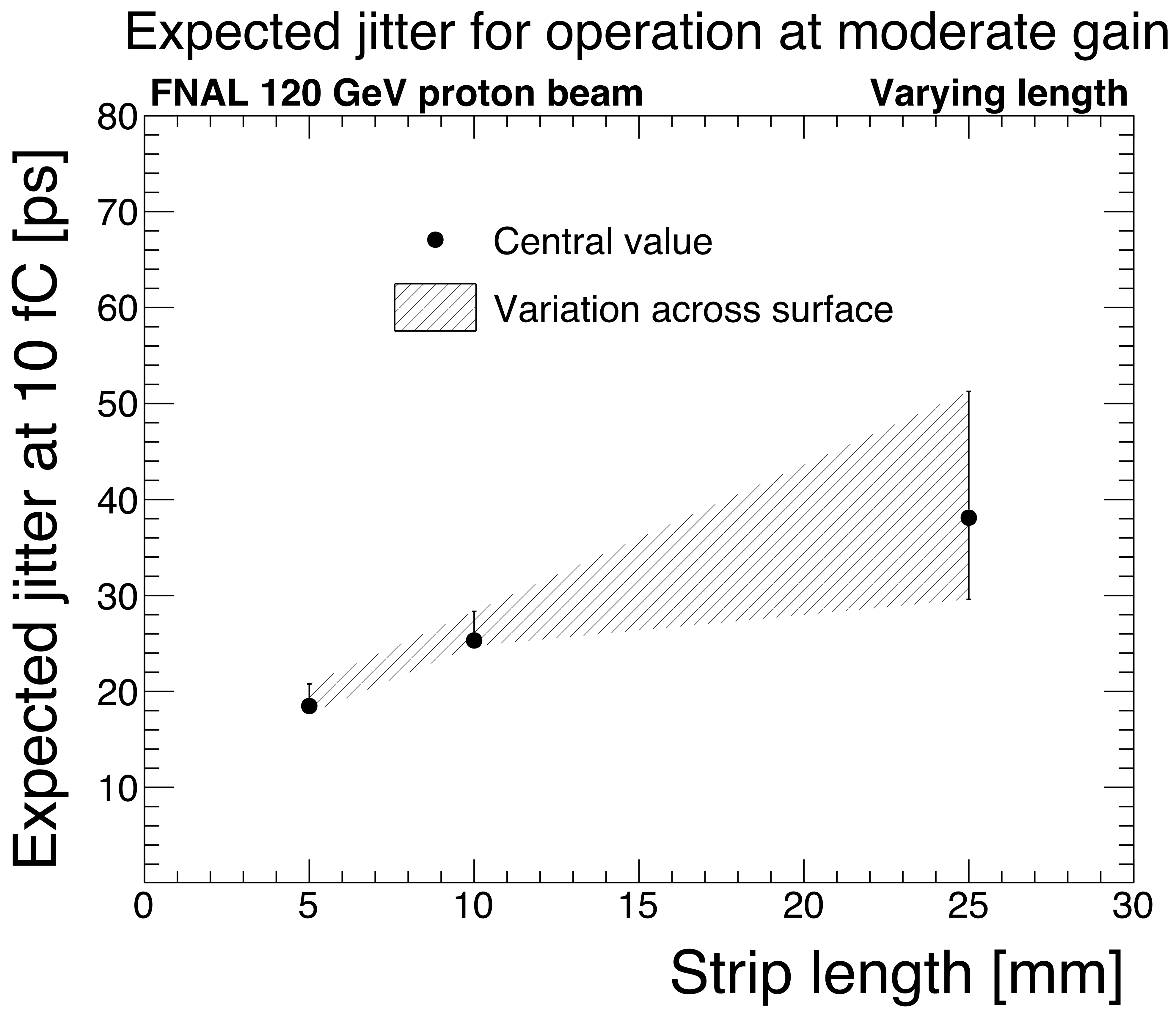


- Latest production optimized for full 2-hit coverage: 20 um resolution everywhere (pitch / 25!)

Pulse shapes for precision timing

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



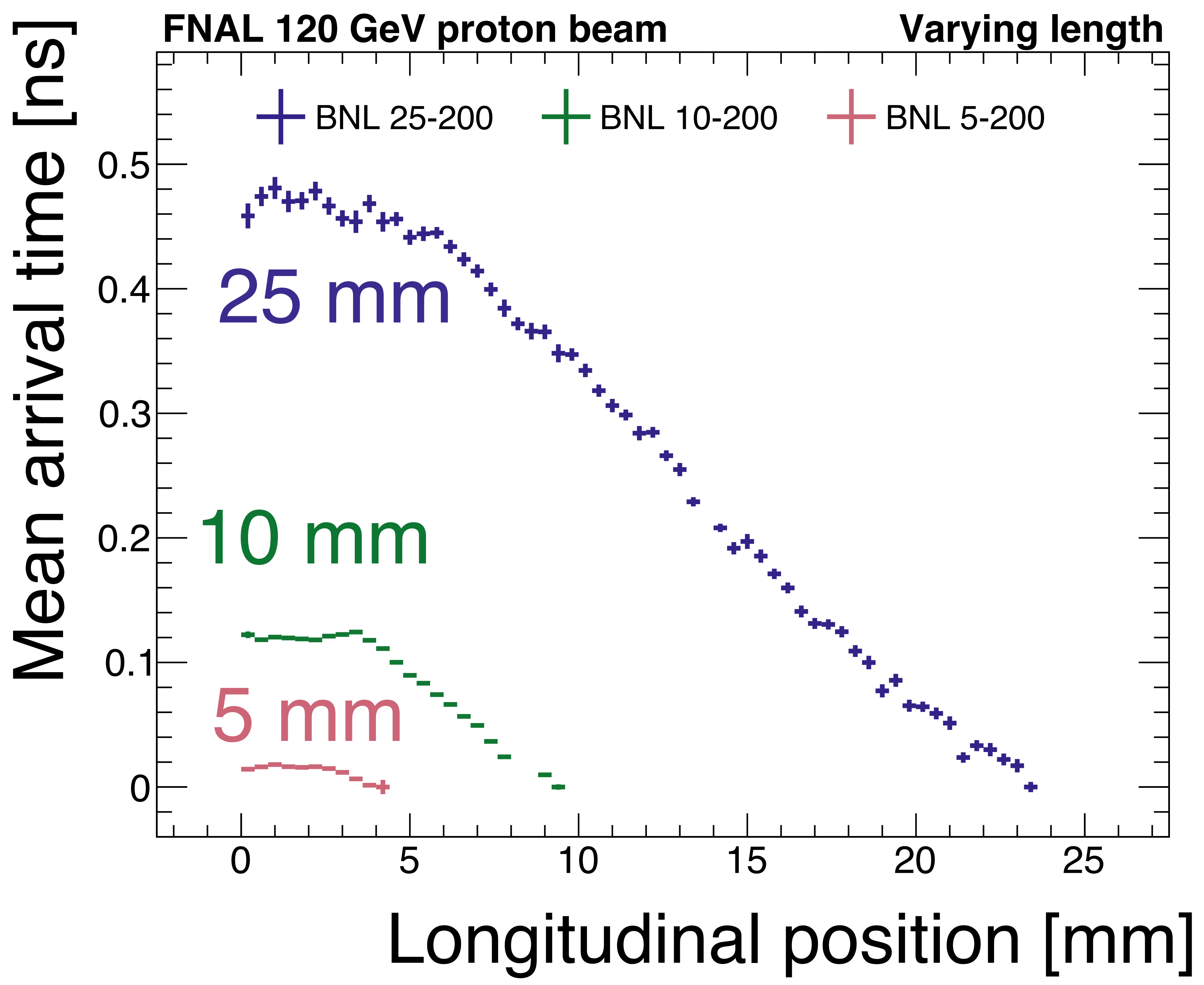


- 1 cm strips: already work well!
- > 2 cm: trying few ideas to improve in next beam test.

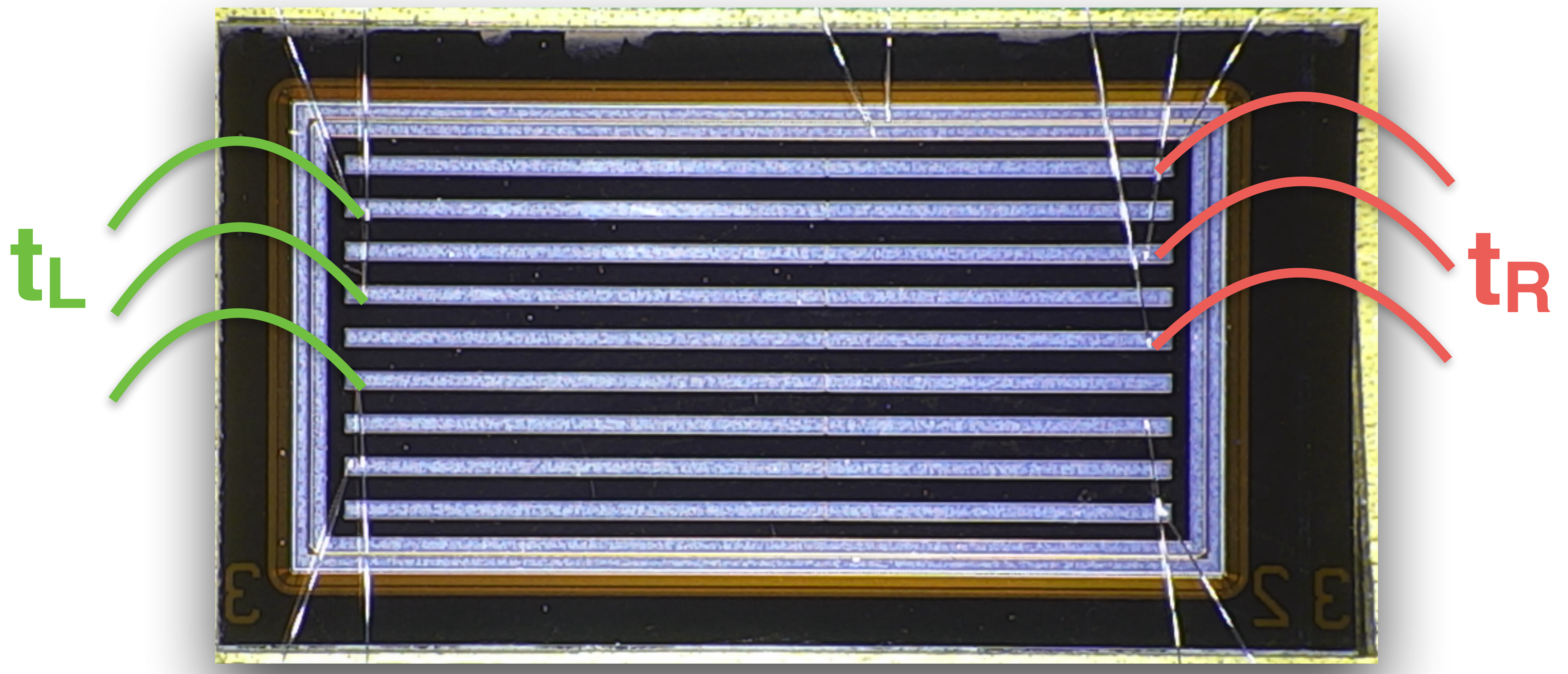
Propagation delays across surface

- 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!

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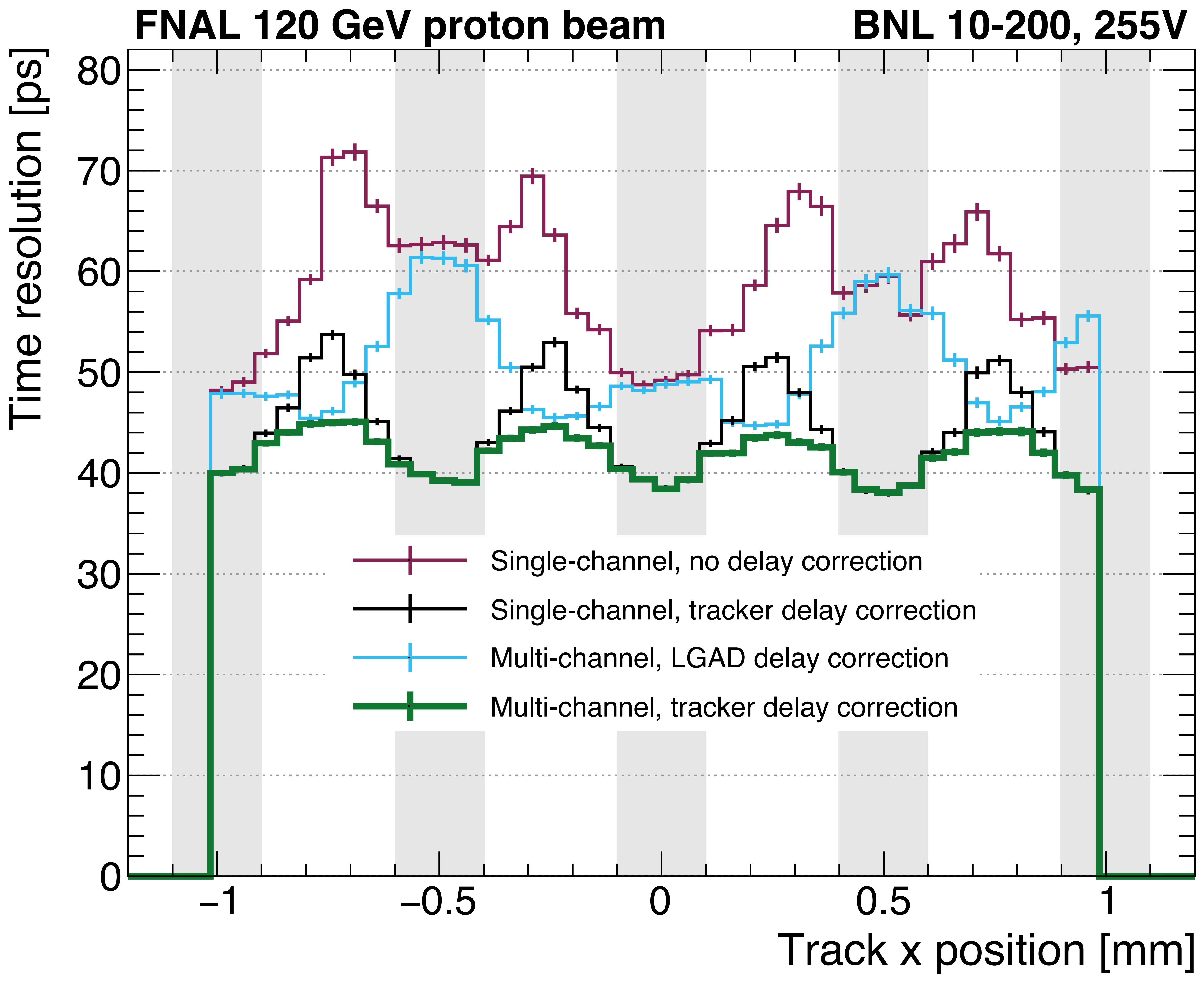
Time resolution

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



- Time resolution ~ 40 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.

	Name	Time resolution
		High gain
	Unit	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

Conclusions

- Timing capability will be essential in future colliders detectors
  - CMS MTD: first trailblazer
  - 4D trackers to follow in footsteps.

- AC-LGADs can provide excellent 4D performance—
  - 30 ps time resolution and spatial resolution ~20-30x smaller than pitch

- Large, coarse pitch sensors promising—
  - 20 microns & 30 picoseconds resolutions in best regions
  - Uniform gain & 2-strip efficiency expected in next prototypes

Thank you for your attention!