Fermilab

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Intelligent ASICs for HEP

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U.S. DEPARTMENT of ENERGY
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AI/ML on the front-end

- Detectors at next-gen experiments can benefit from real-time machine learning in readout
  - Edge intelligence: feature extraction, classification, data compression
  - Efficiency: lower computational power/storage needs for transmission
- Implementations are being developed in FPGAs, ASICs

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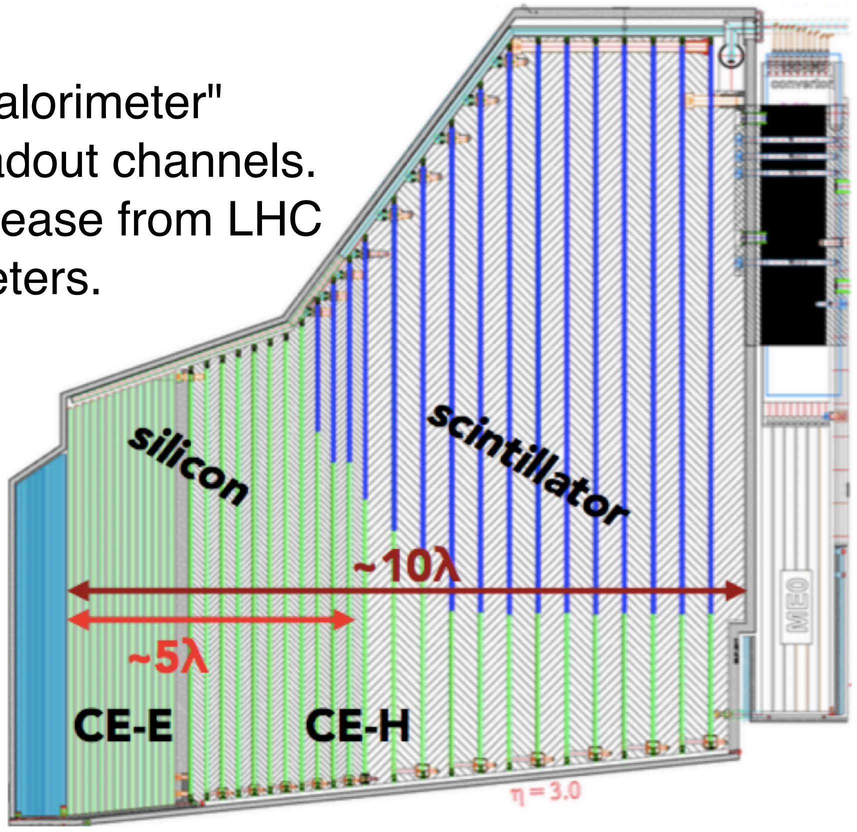
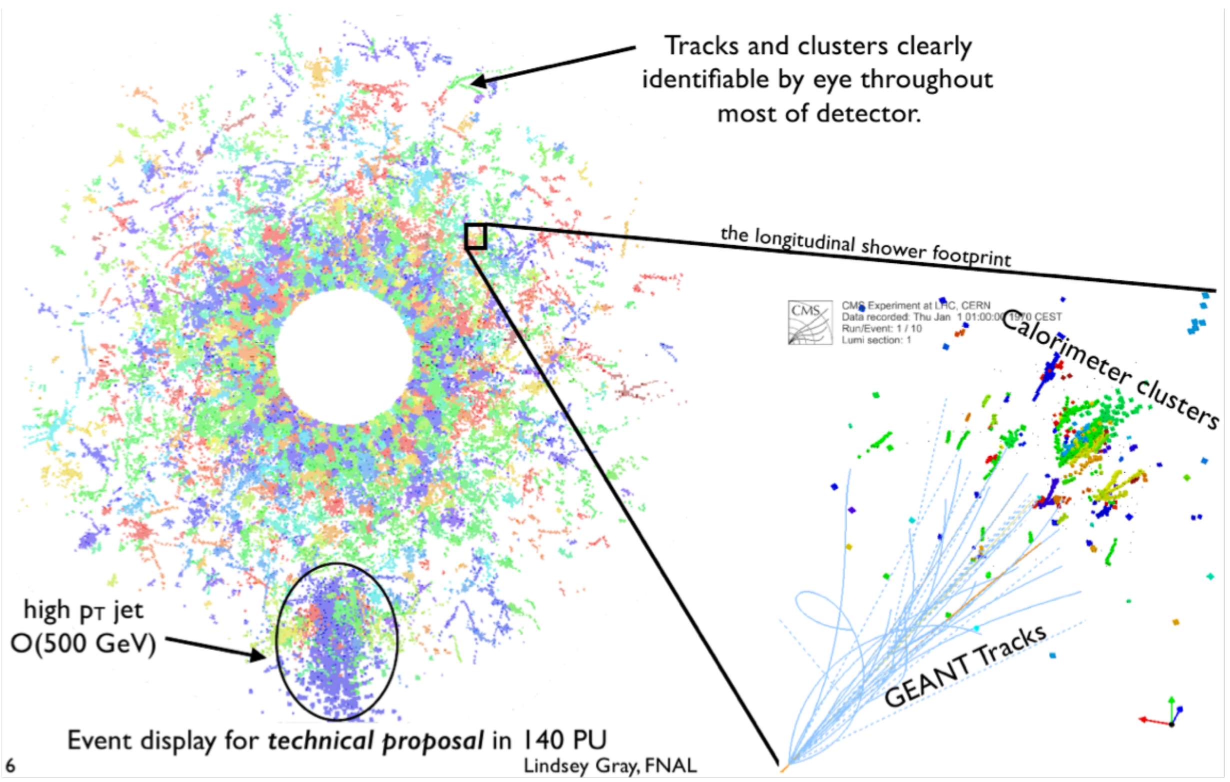
AI/ML on Calorimeters

- Data challenges at future colliders:
  - Data volume, complexity, power consumption, latency, and radiation tolerance
  - **Move more data processing to on-detector electronics**
- ECON-T ASIC : selects/compresses trigger data for transmission off-detector
  - Can we do **on-detector data compression with machine learning**?
- Neural Network (NN) autoencoder in ASIC for on-detector data compression
  - Low power consumption, latency and rad tolerance ➔ well suited to ASIC
  - Complexity: design must be re-configurable ➔ challenging for ASIC

"Imaging calorimeter"

- ~6M readout channels.
- 60× increase from LHC calorimeters.

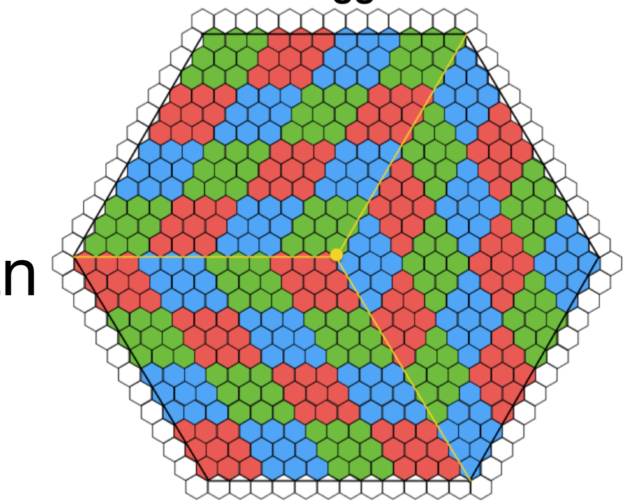




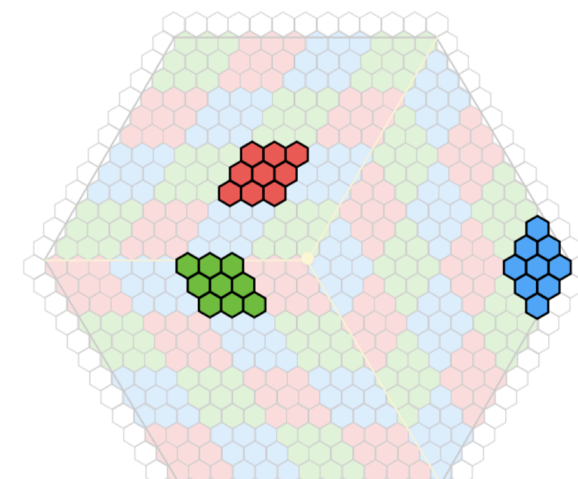
AI/ML on Calorimeters

- Reconfigurable NN for data compression
  - First use of machine learning on radhard ASIC for HEP
- Weights of the AutoEncoder algorithm are reprogrammable: can retrain the NN to suit future needs
- Design performed such as to optimize:
  - ASIC Metrics: **power, size, latency, number of registers**
  - Physics Metrics: energy resolution, trigger rates
- Chip testing in progress:
  - Autoencoder testing completed for full functionality and radiation-tolerance: works very well!
  - Physics performance of NN (with non-optimized training) comparable to threshold algo, optimization in progress

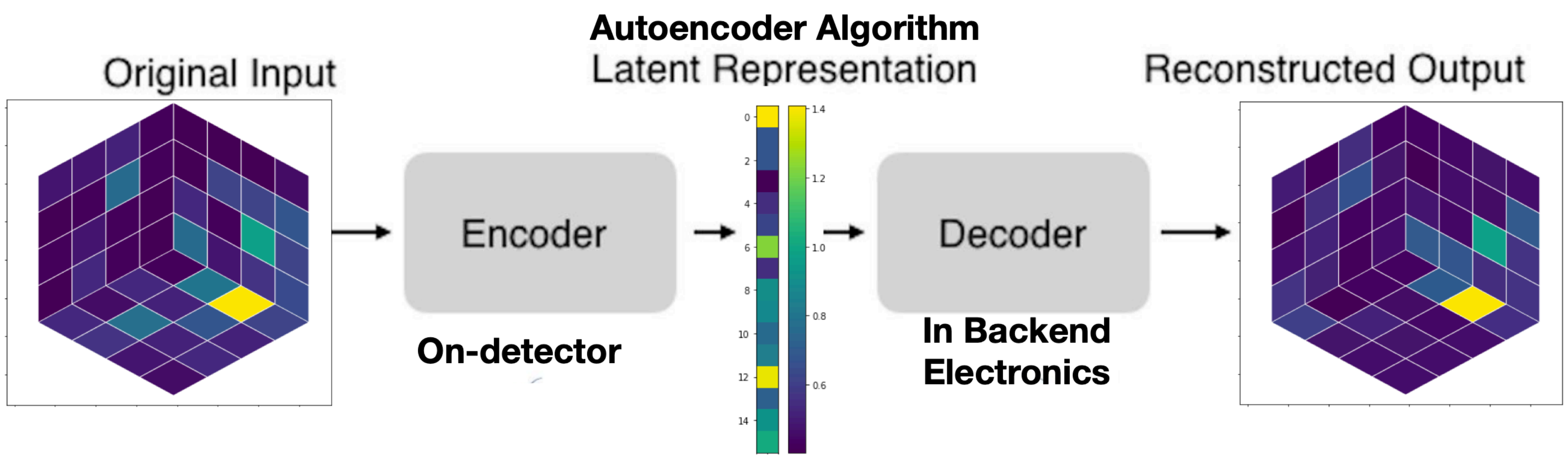
432 silicon sensor cells grouped into 48 trigger cells

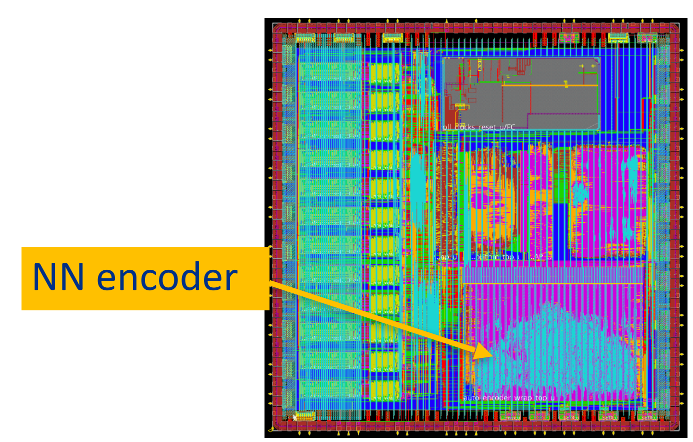


Selection of trigger cells above threshold



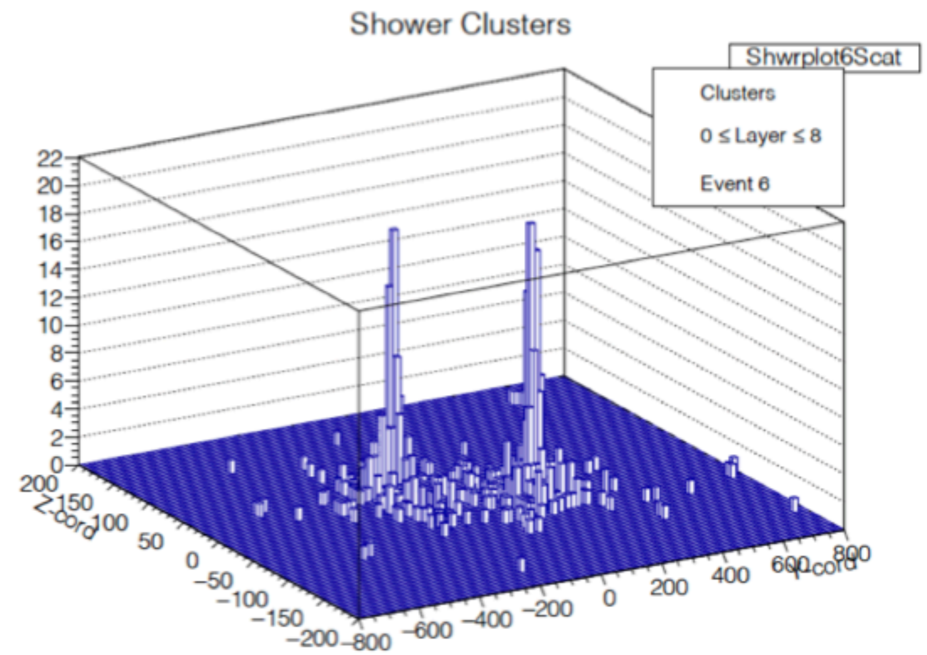
For ~80% of the detector, we have sufficient bandwidth to read out only 3 TC per BX. With the NN, can readout all 48 TC with lossy compression.



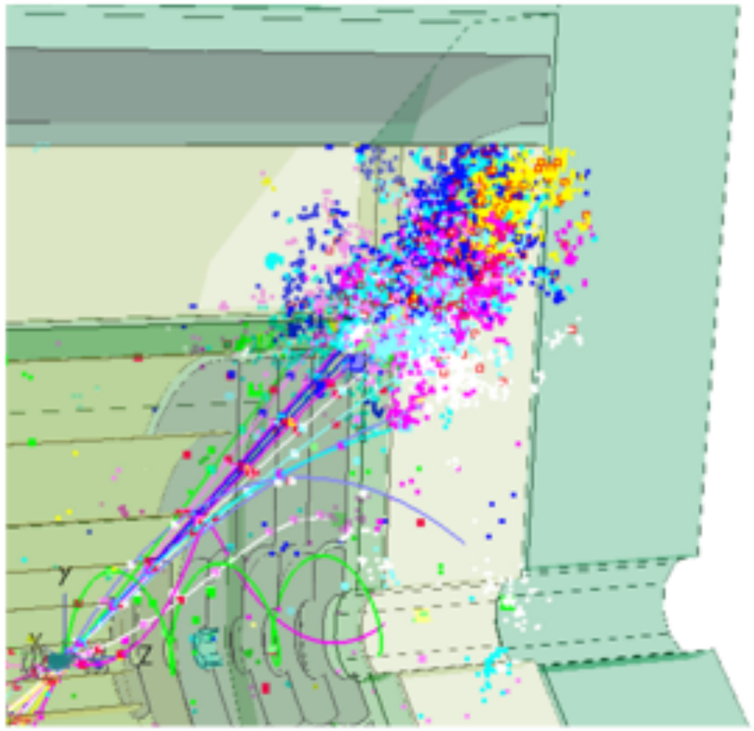


AI/ML on Calorimeters

- SiD detector configuration with 25x100 μm² pixel in the calorimeter at ILC
  - Changing analog to binary digital has no energy resolution degradation
- Synergies with developments of MAPS for tracking in Higgs Factories
  - MAPS applied to the ECal exceeds the physics performance as specified in the ILC TDR
  - Future planned studies include the reconstruction of showers and π0 within jets, and their impact on jet energy resolution
- Lots of available data available per shower
  - Possibilities for large gain in performance, new capabilities (anomaly detection), and data reduction using AI/ML on chip



GEANT4 simulations of Transverse distribution of two 10 GeV showers separated by one cm

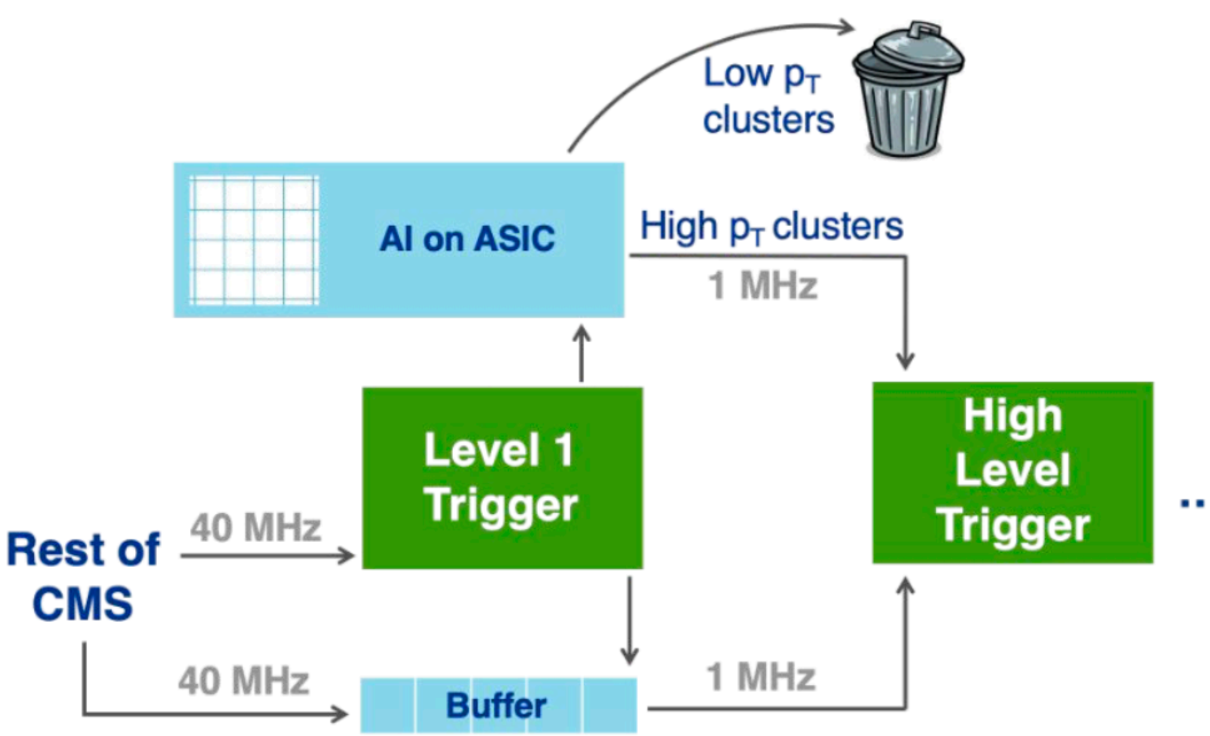


Eur. Phys. J. Plus (2021) 136:1066

AI on Chip: Smart Pixels

- AI embedded on a chip to:
  - Filter data at the source for data reduction
- Data reduction through
  - Filtering through removing low pT clusters
  - Featurization through converting raw data to physics information
- Customizable (reprogrammable weights) neural networks implemented directly in the front-end

See L. Gray's talk later today



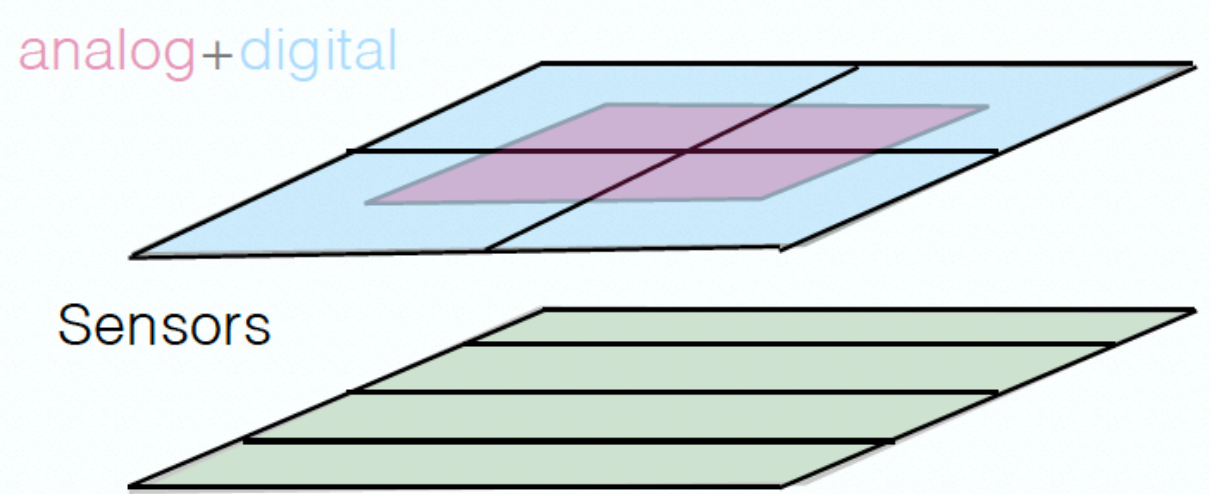
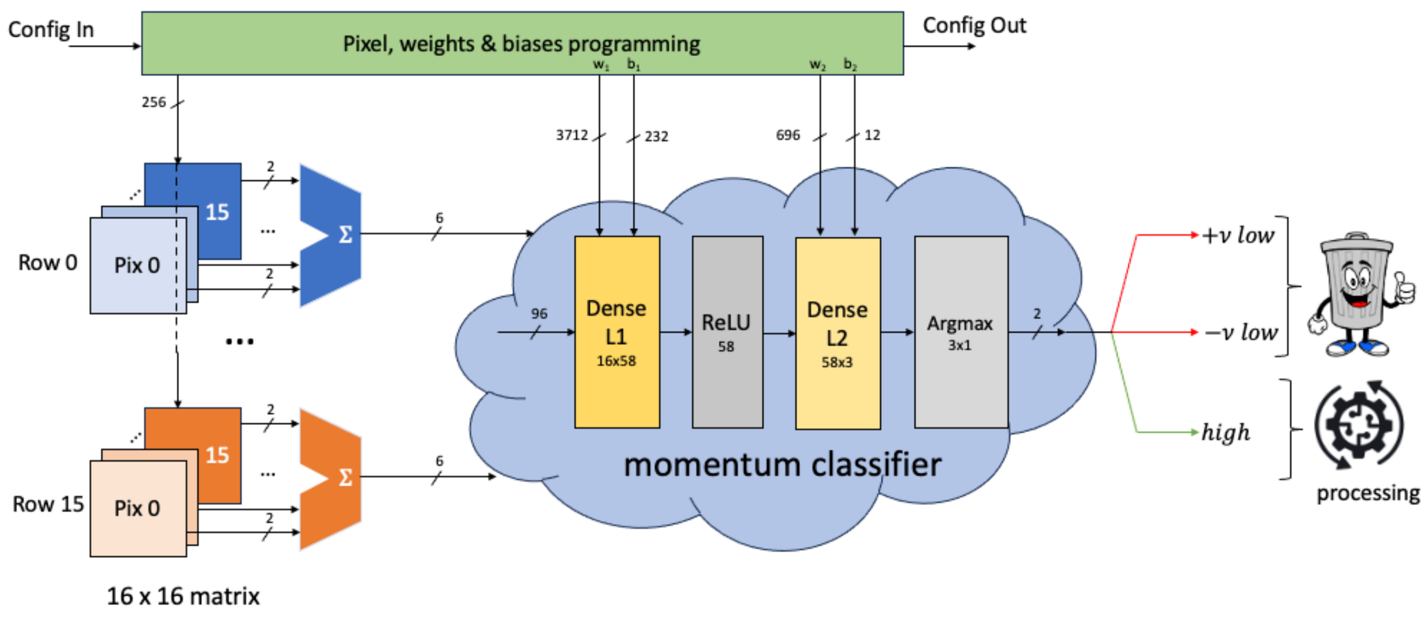
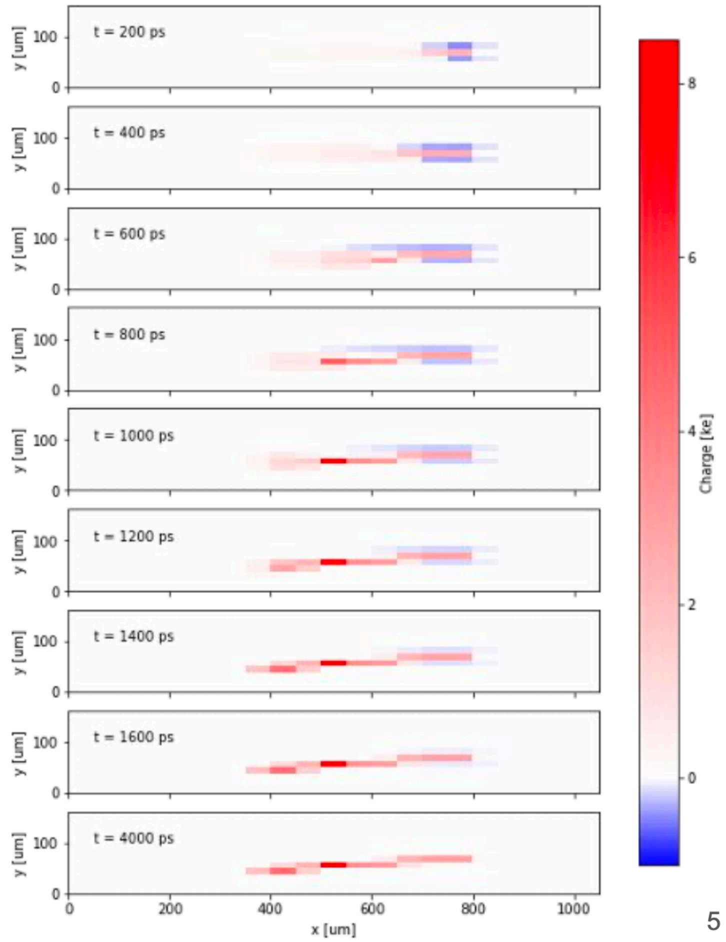
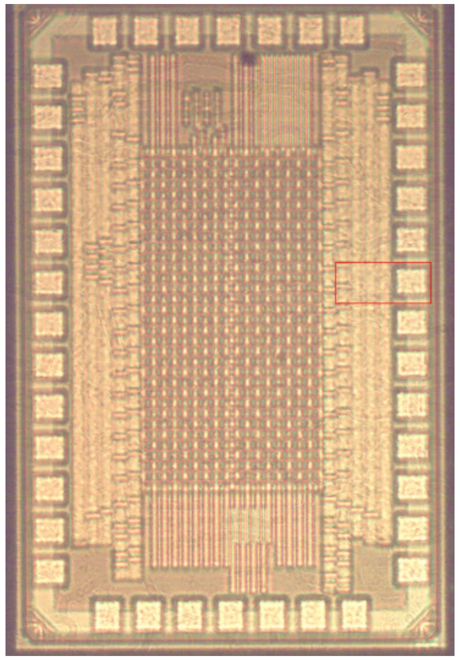


Diagram of pixel sensors + readout chip

AI/ML Implementation



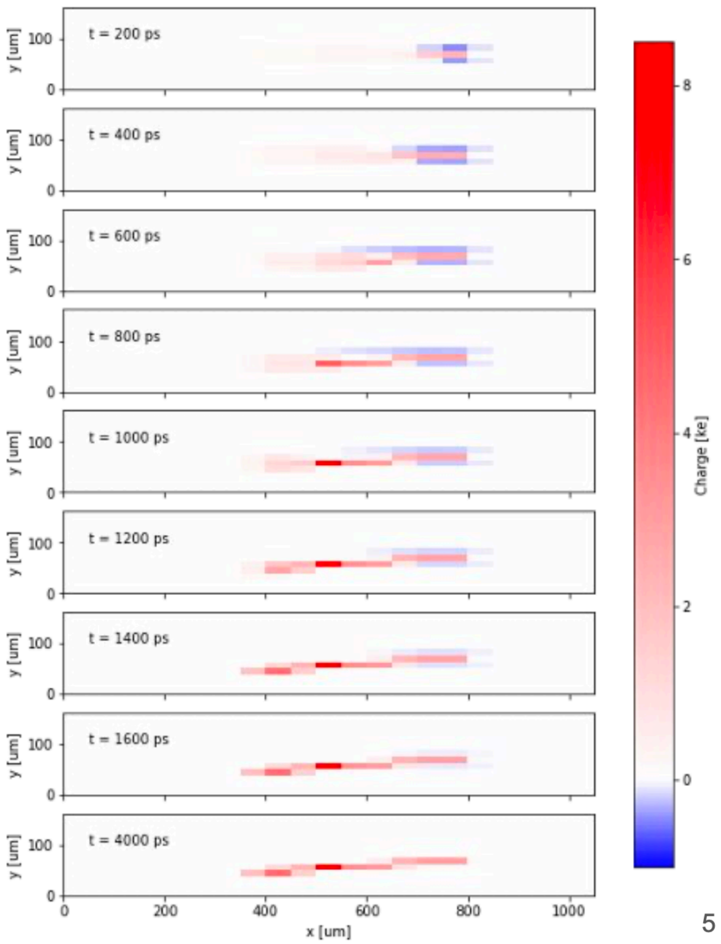


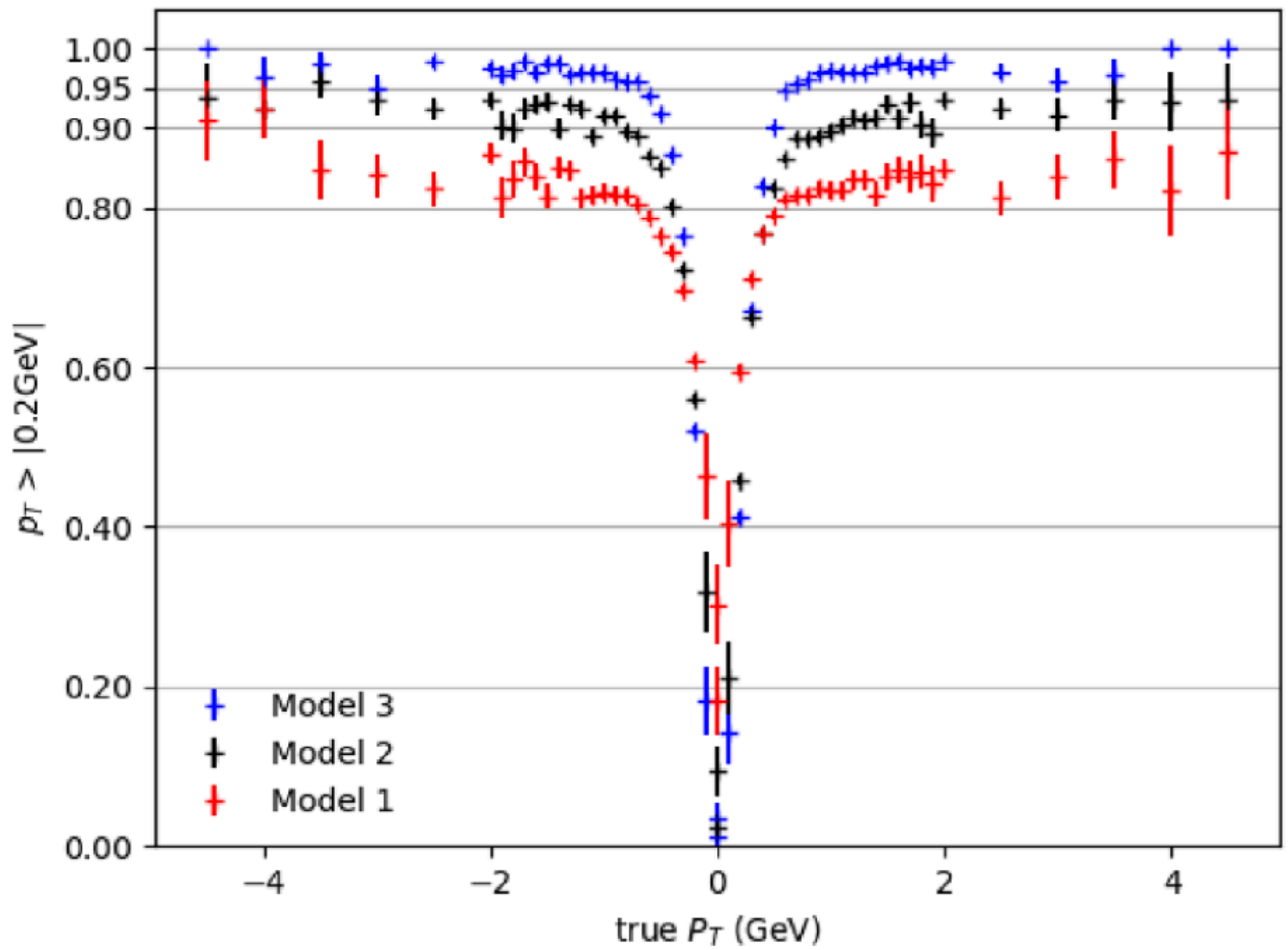


- Use AI/ML due to complicated pulse shapes, and drift & induced currents
  - y-profile is sensitive particle's p_T, x-profile uncorrelated with p_T
- Co-Design development with analog frontend pixels connected to a fully combinatorial digital classifier
  - Combinatorial design reduces dynamic power
  - Digital power estimated to be 300 µW for 256 pixels: ~1 µW/pixel
- Total power density (AFE + digital) < 1 W/cm^2

AI/ML Implementation

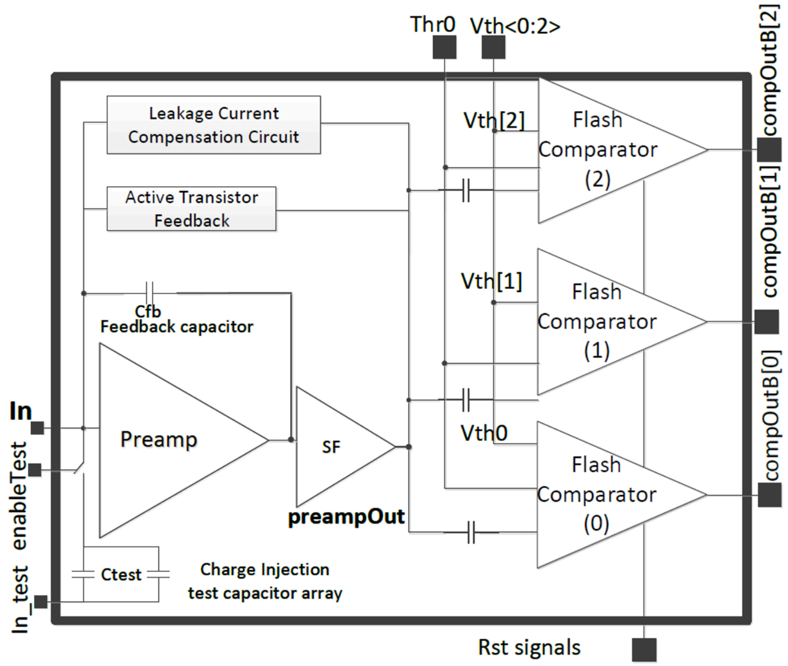
arXiv:2310.02474

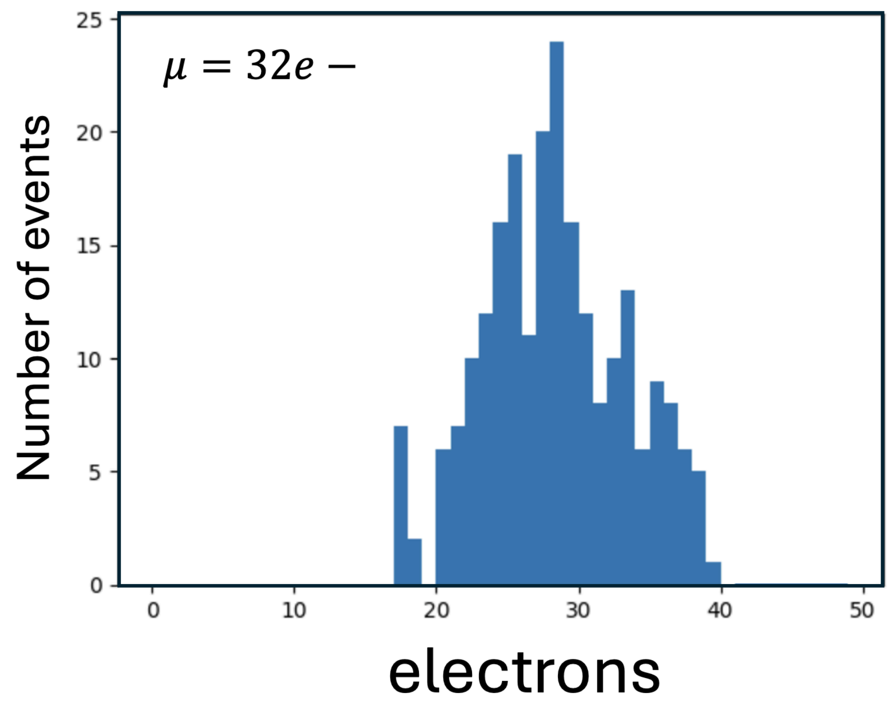


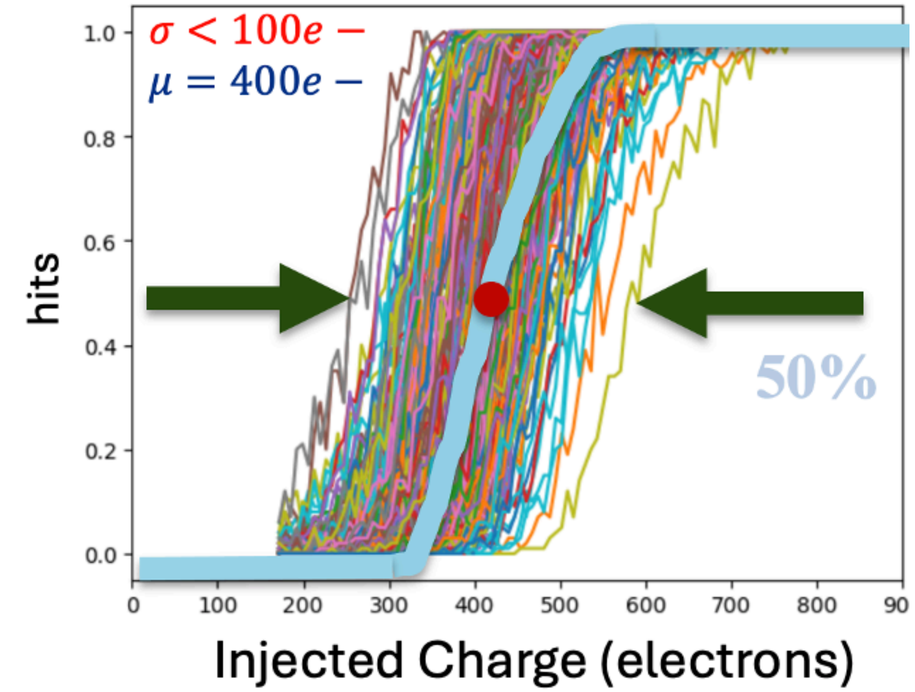


Classifier signal acceptance ~93%
Data reduction is ~57-75%

Analog Frontend Prototype





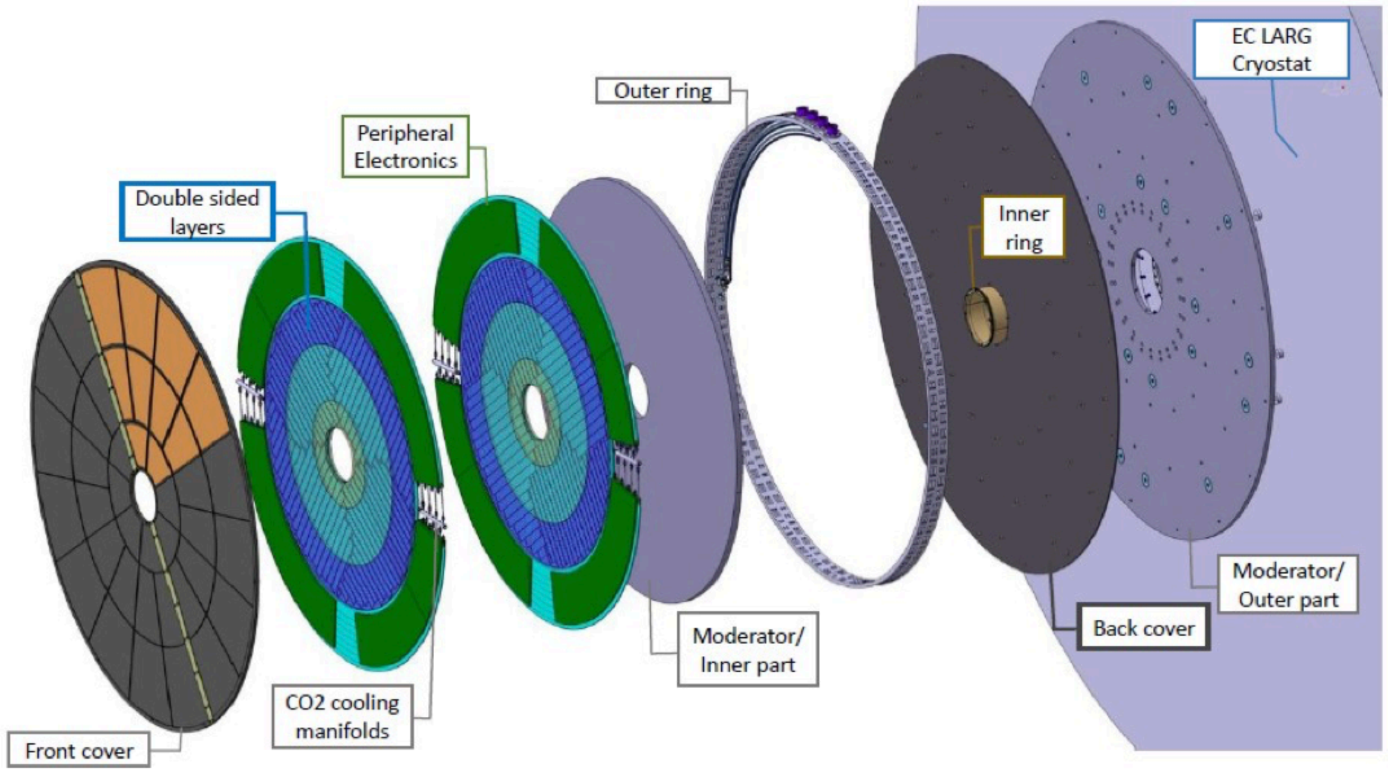


- The AFE prototype designed in TSMC 28 nm
  - ROIC pixel size is 25 μm^2
  - Low power performance : ~5 µW/pixel
- Preamplifier dynamic range 64 aC – 2.1 fC
  - Equivalent noise charge (ENC) 31e^- with 400e^- threshold (no sensor cap)
  - Total charge dispersion < 100e^- across entire matrix with 400e^- threshold (no sensor cap)

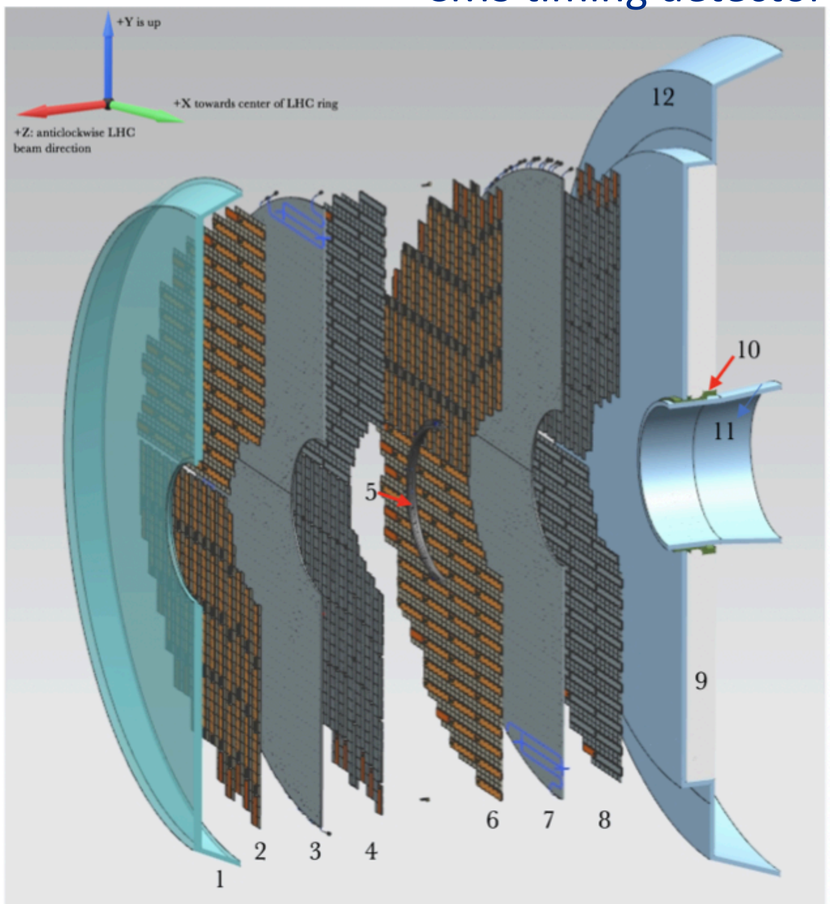
Precision Timing Detectors

- Traditionally in collider experiments we measure very well
  - Position, charge and energy of particles
- CMS and ATLAS are building first-generation of 4D-detectors
  - Next-gen detectors will have high granularity also in **time domain**
  - At the tracker, calorimeter, muon detectors, and L1 trigger
- Future detectors moving towards full **5D Particle Flow**
  - Active R&D to achieve required performance for future experiments
  - Sensors, ASIC, front-end electronics developments

ATLAS timing detector



CMS timing detector

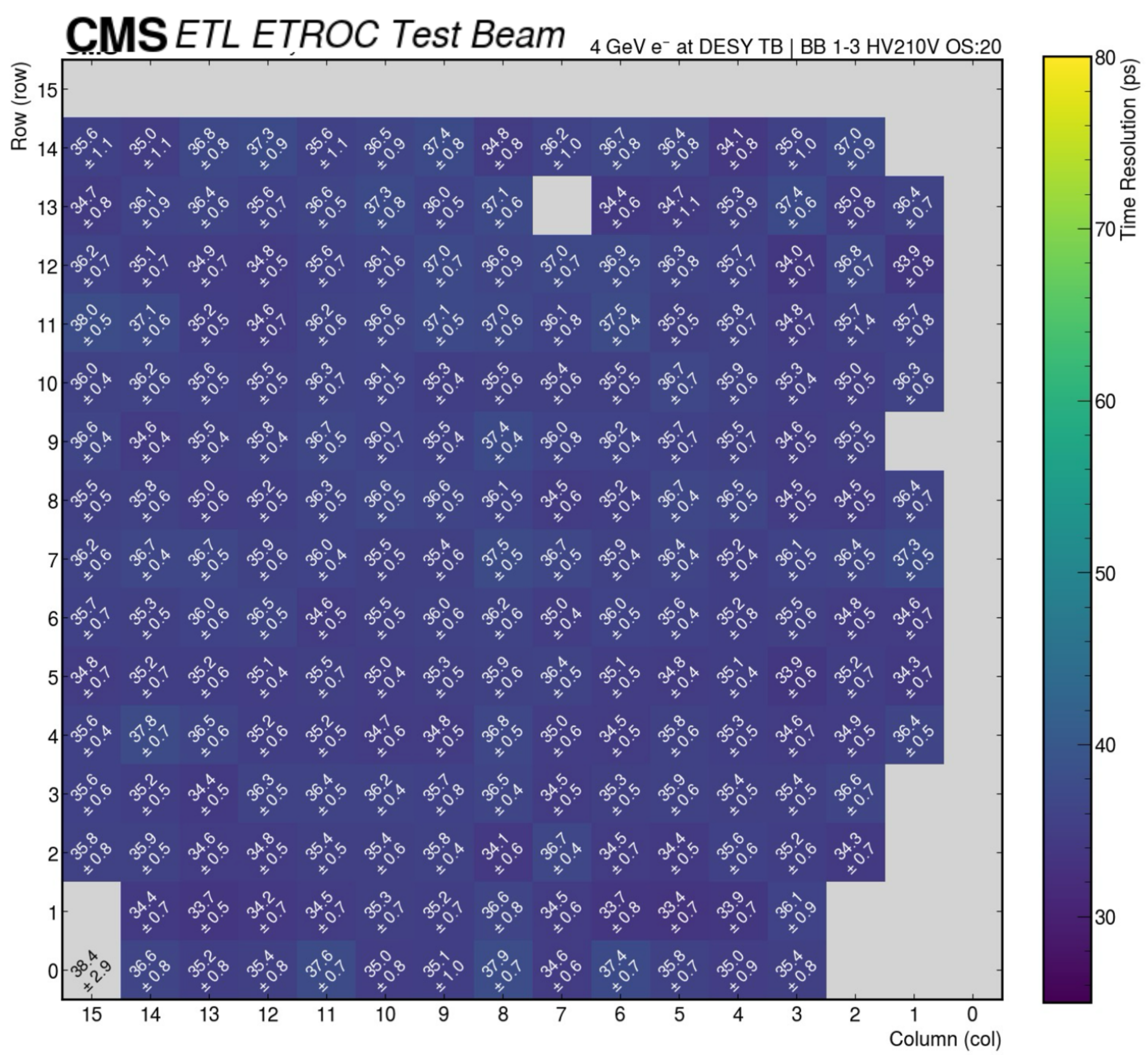


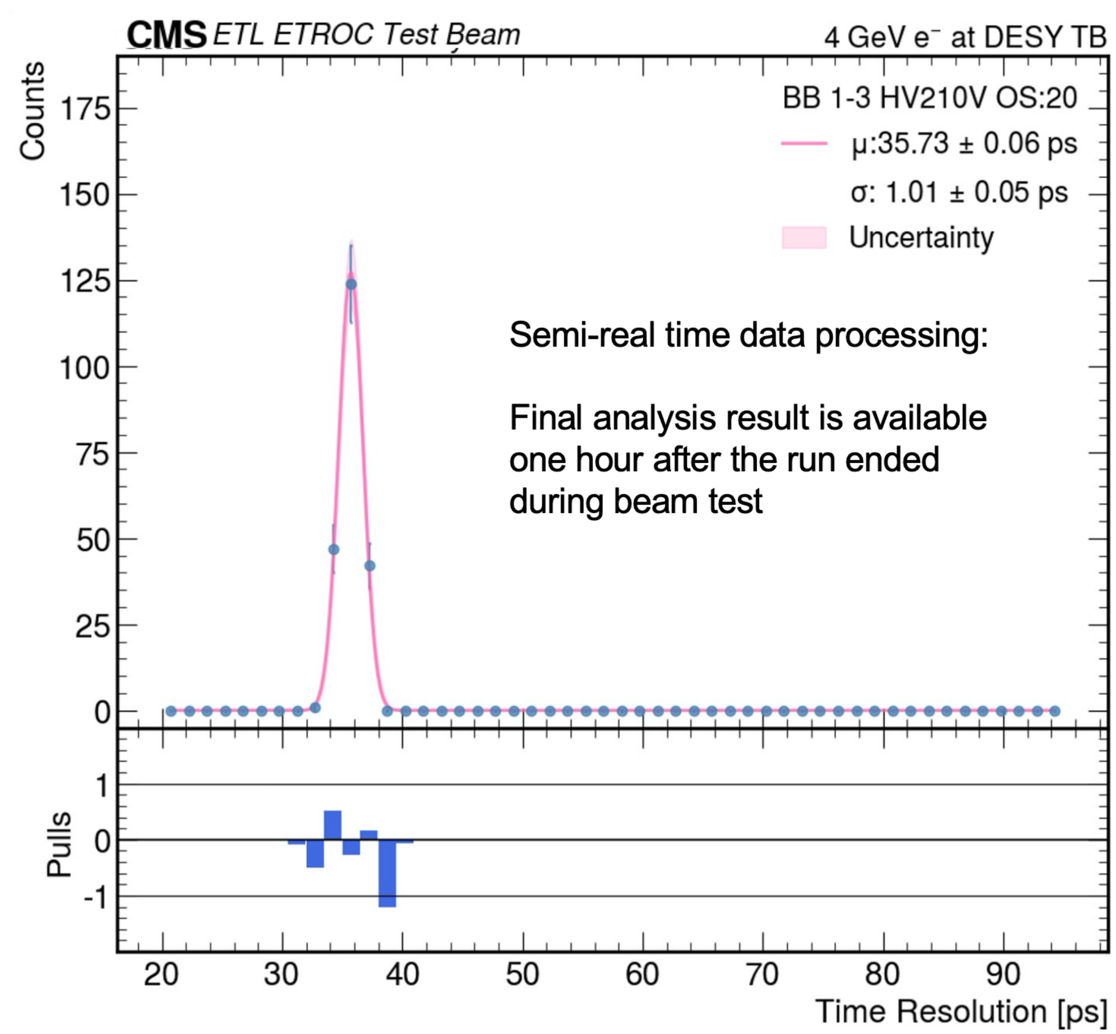
1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

LGAD Sensor Performance in System

- Developments for the LHC applications are now frozen
  - Current activities focused to scale up the production with high yields and QA/QC
- Excellent performance achieved for CMS/ATLAS applications

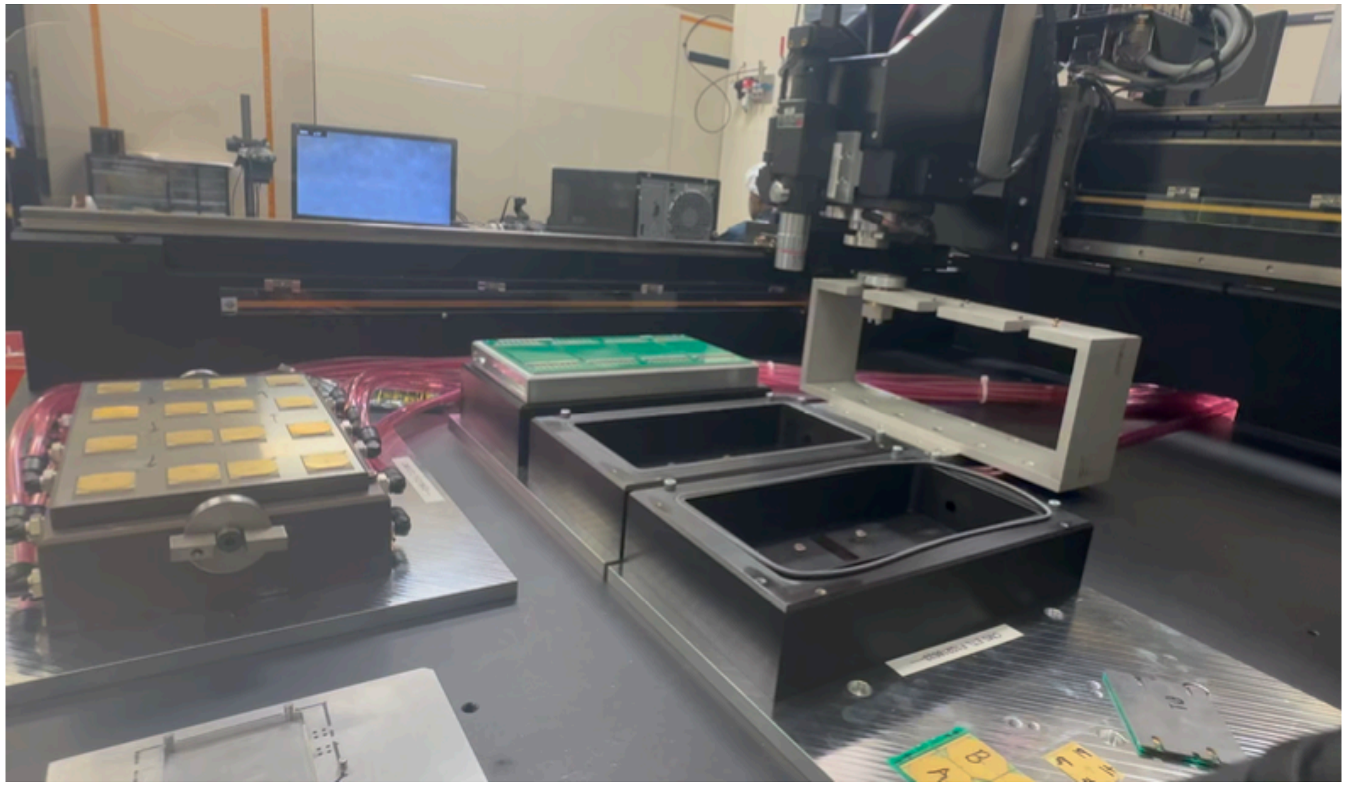
From T. Liu
@ TWEPP24

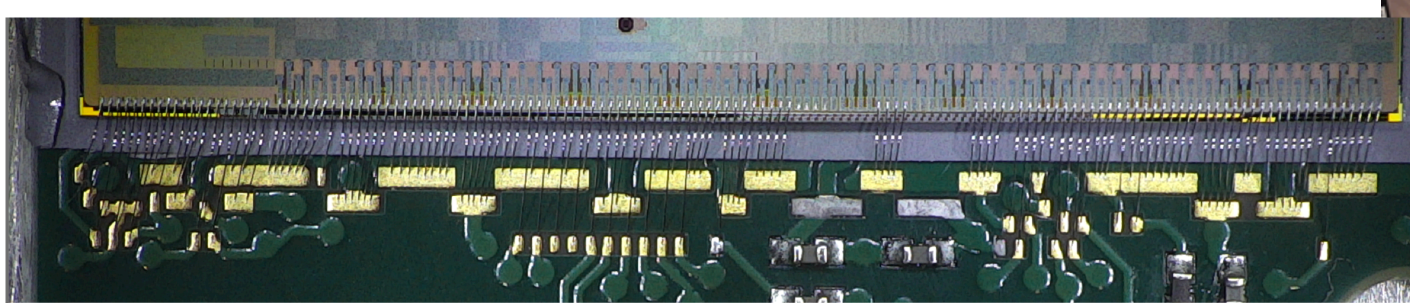




Uniform performance over the surface of the sensor

Timing Detectors Today



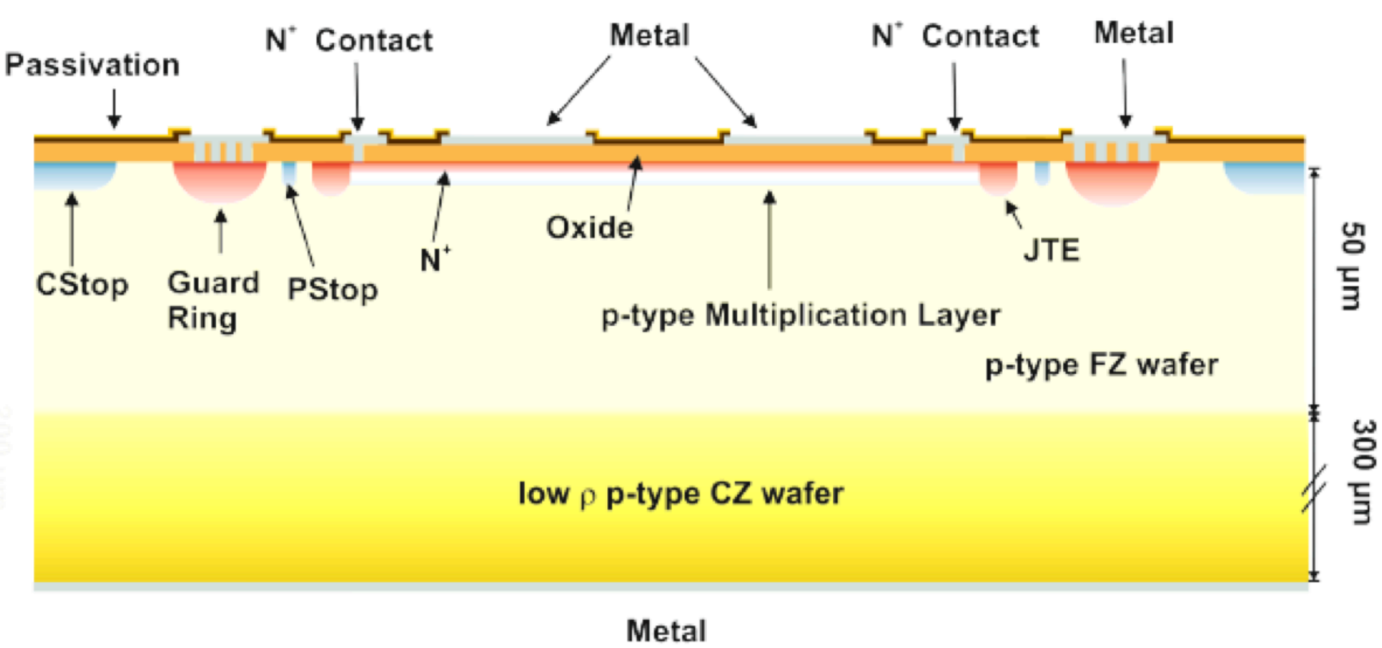


- Located at Lab D at SiDet in Fermilab
  - Configured to produce 12 modules per batch

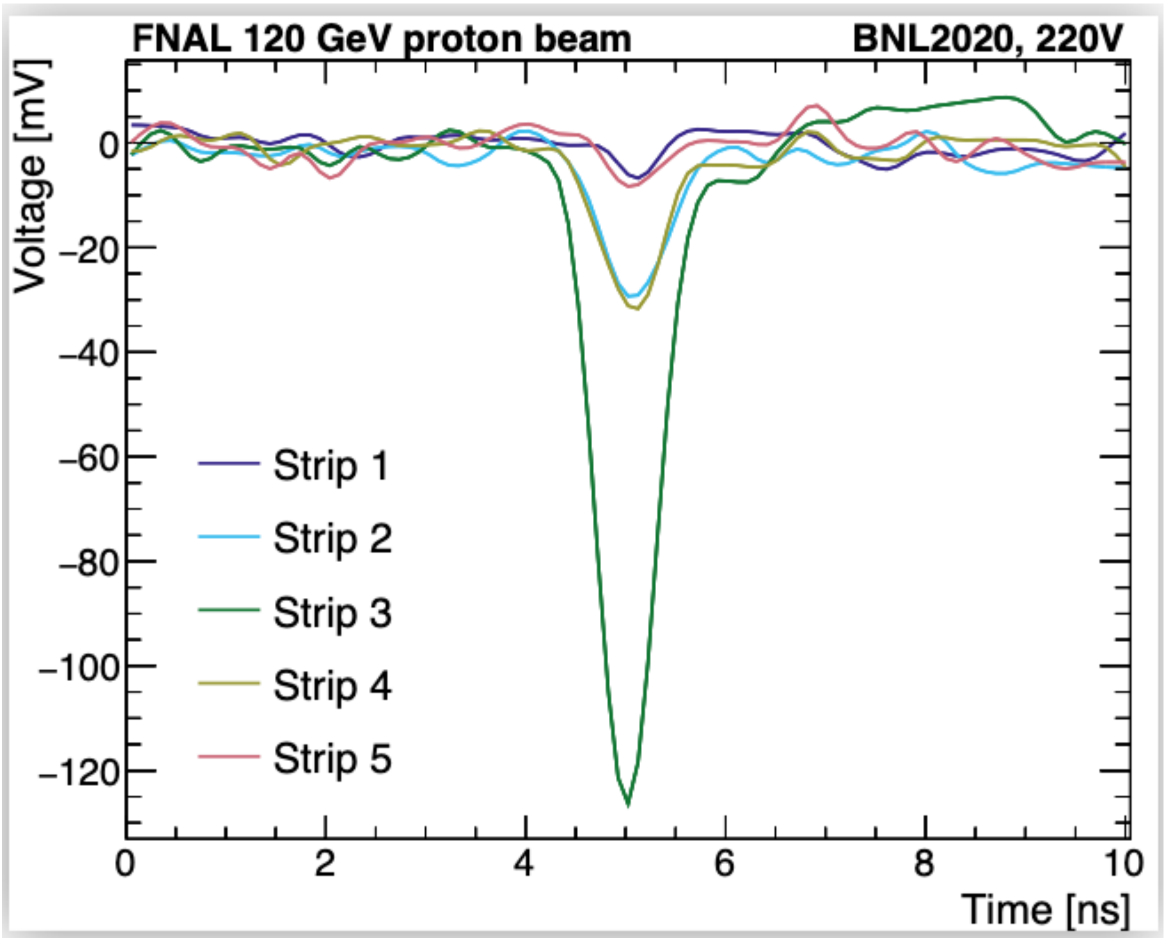
Entering production stage in early 2026

AC-Coupled LGADS (AC-LGADs)

- **Improve 4D-trackers to achieve 100% fill factor, and high position resolution**
- An evolution of DC-LGADs
  - Excellent time resolution achieved across full sensor surface
  - Charge sharing enables excellent position resolution without fine pixelation



AC-LGAD

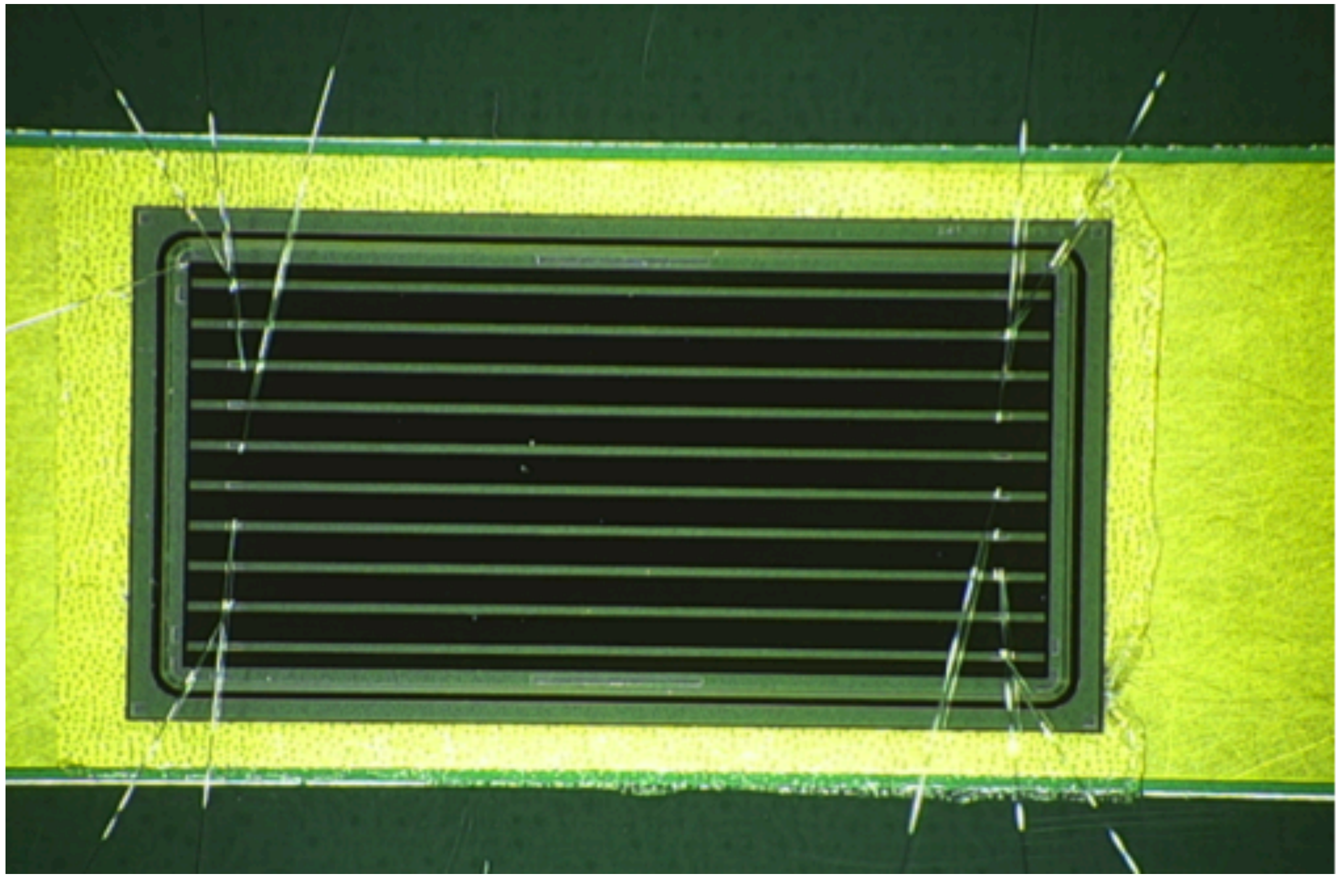


Signal sharing allows for improved position resolution

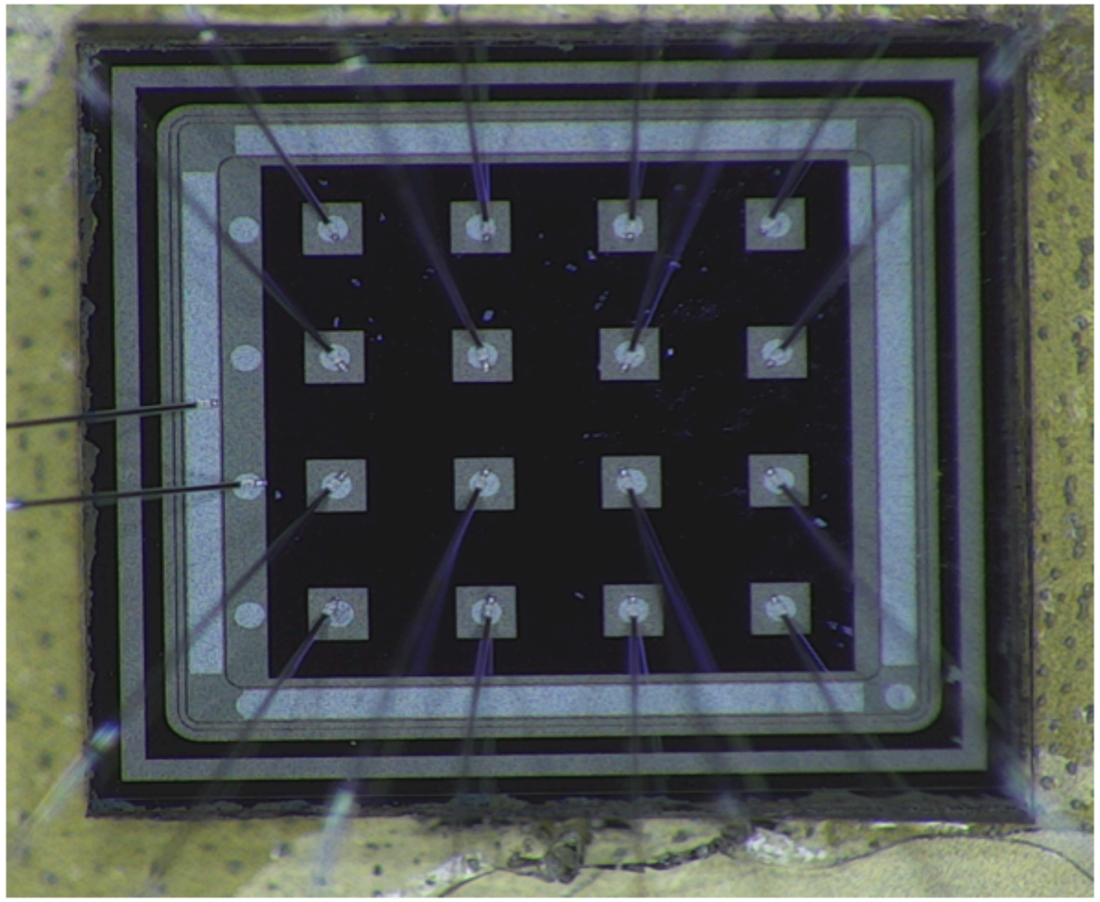
Sensor R&D and Optimization

- Several rounds manufactured over the last few years
  - R&D from developments for HL-LHC, synergies between HEP and NP
  - Optimize position resolution, timing resolution, fill-factor, …
- Extensive characterization and design studies

JINST 17 (2022) P05001



Photographs of some of the HPK AC-LGAD strip devices tested in this campaign

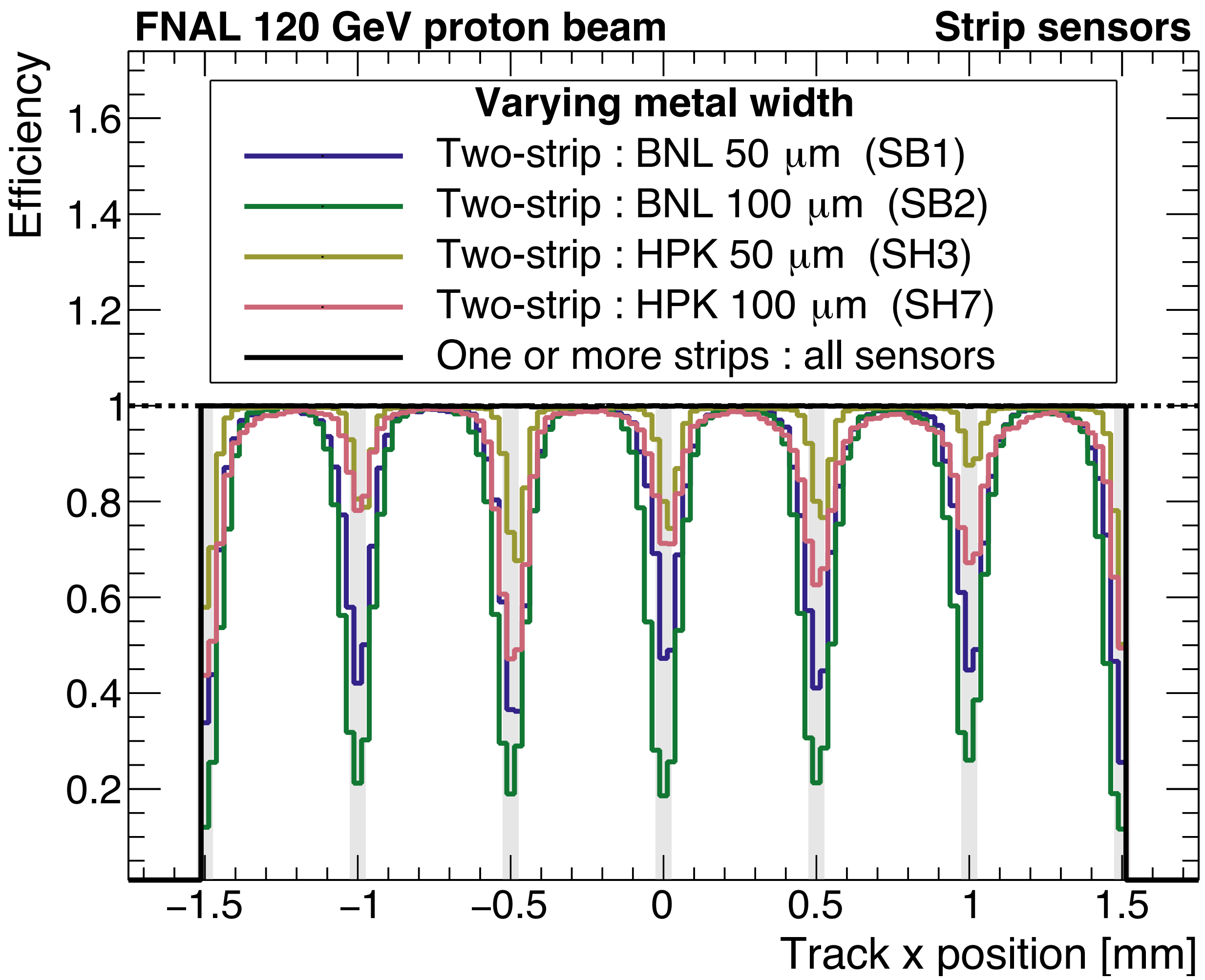


Photographs of the BNL AC-LGAD pixel devices tested in this campaign

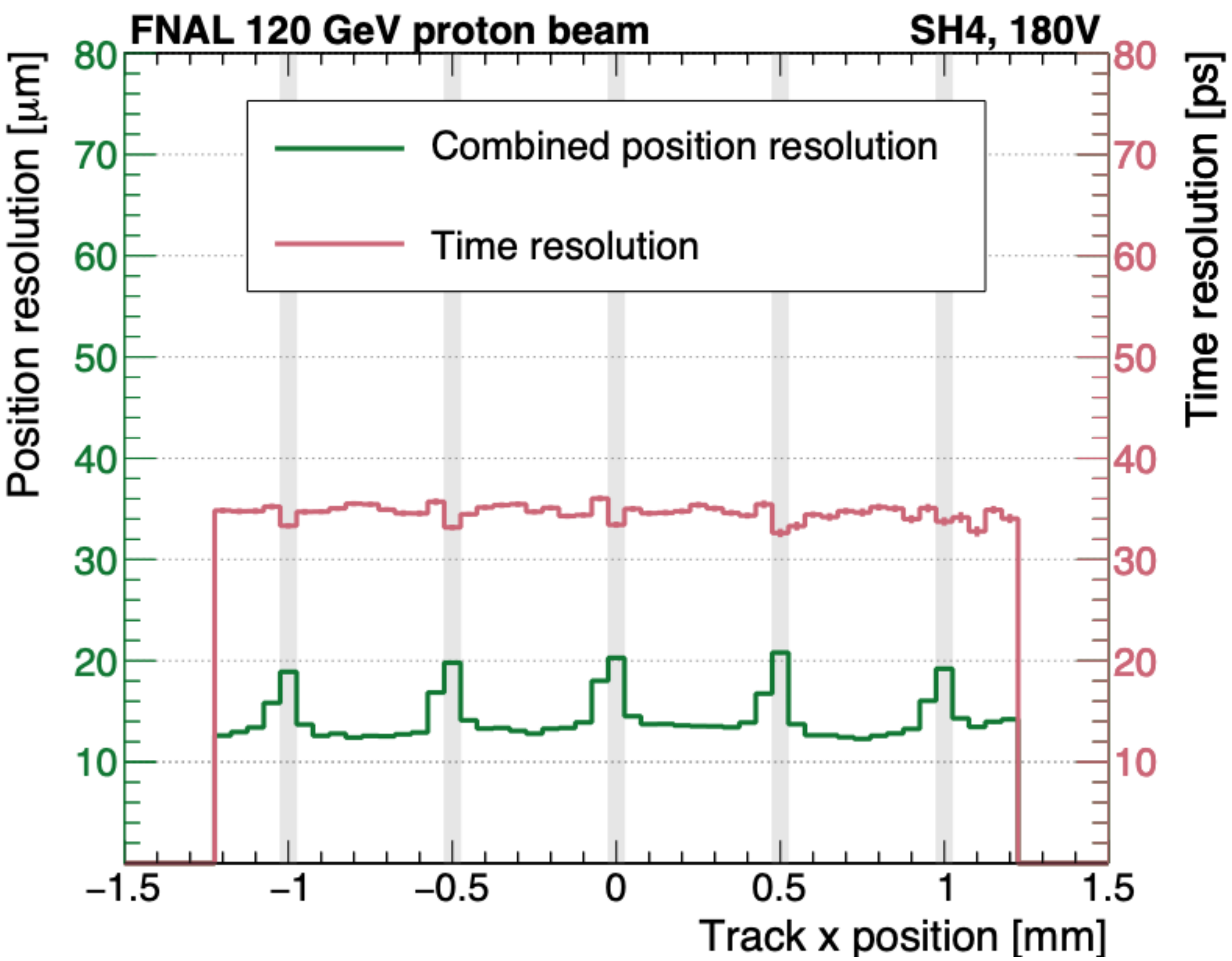
AC-LGAD Sensor Performance

JINST 18 (2023) P06013

- Position reconstruction
  - **Achieve 15-20 μm** resolution in 10mm strips, 500 μm pitch
- Excellent time resolution
  - **Achieve 30-35 ps** for 10 mm strips



Detection efficiency across surface

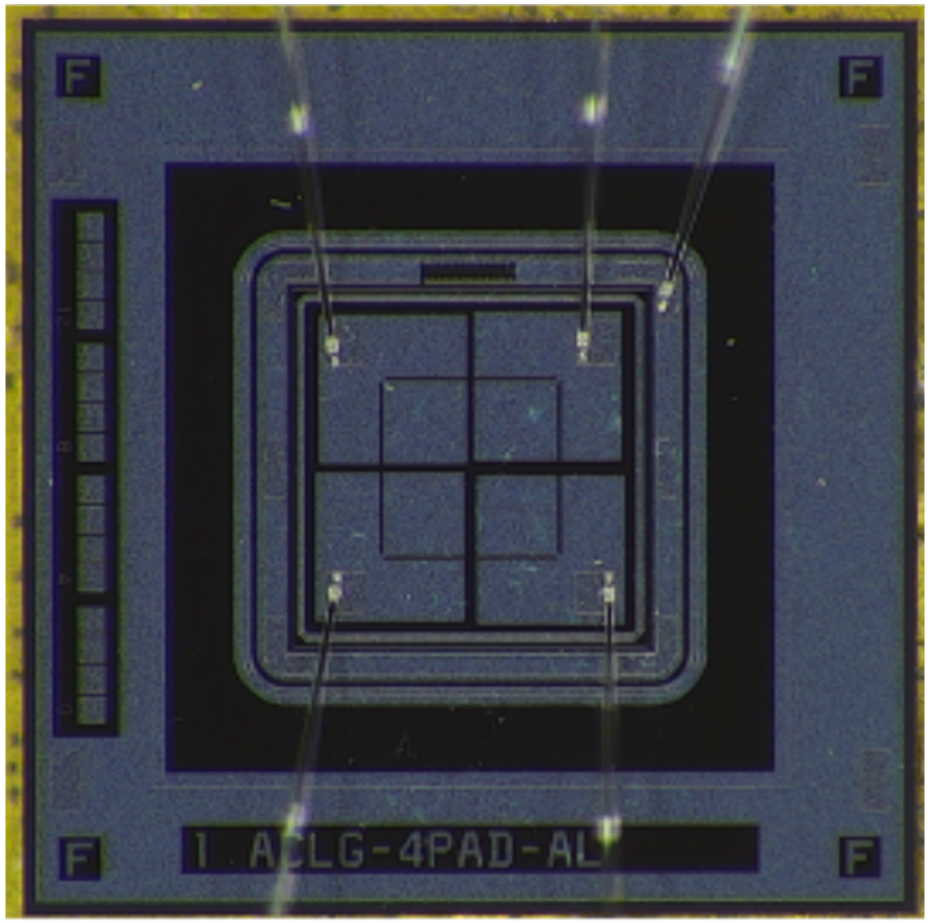


Position and **Time** resolutions across surface

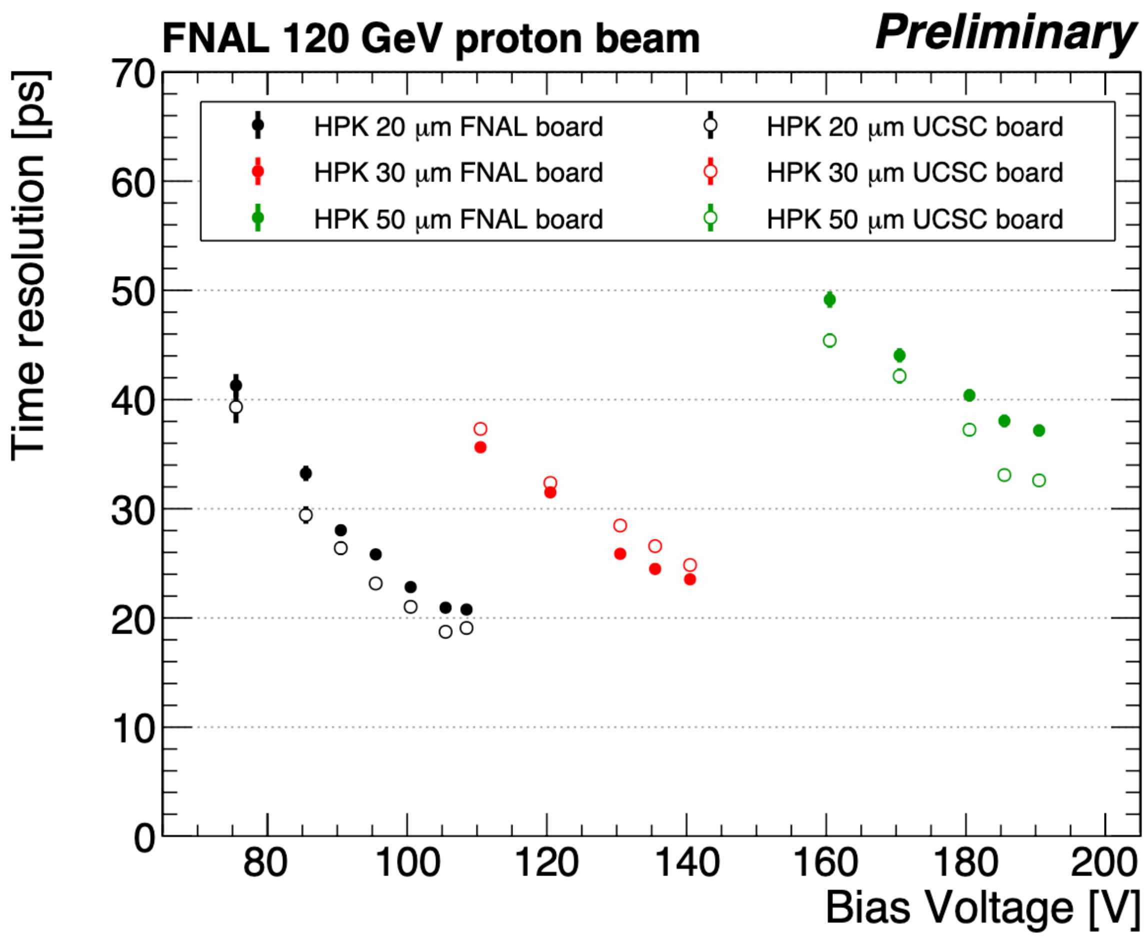
Towards Better Time Resolution

NIM A (2025) 170224

- Thinner sensors improve time resolution by decreasing Landau contribution
  - AC-LGAD from HPK with 20, 30, 50 µm thickness
  - Almost fully metallized, optimized for timing performance
- Uniform time resolution across full sensor area
  - 25 ps for 30 µm thick sensor, **20 ps for 20 µm thick sensor**



HPK 2x2, 500x500 µm² pixel size

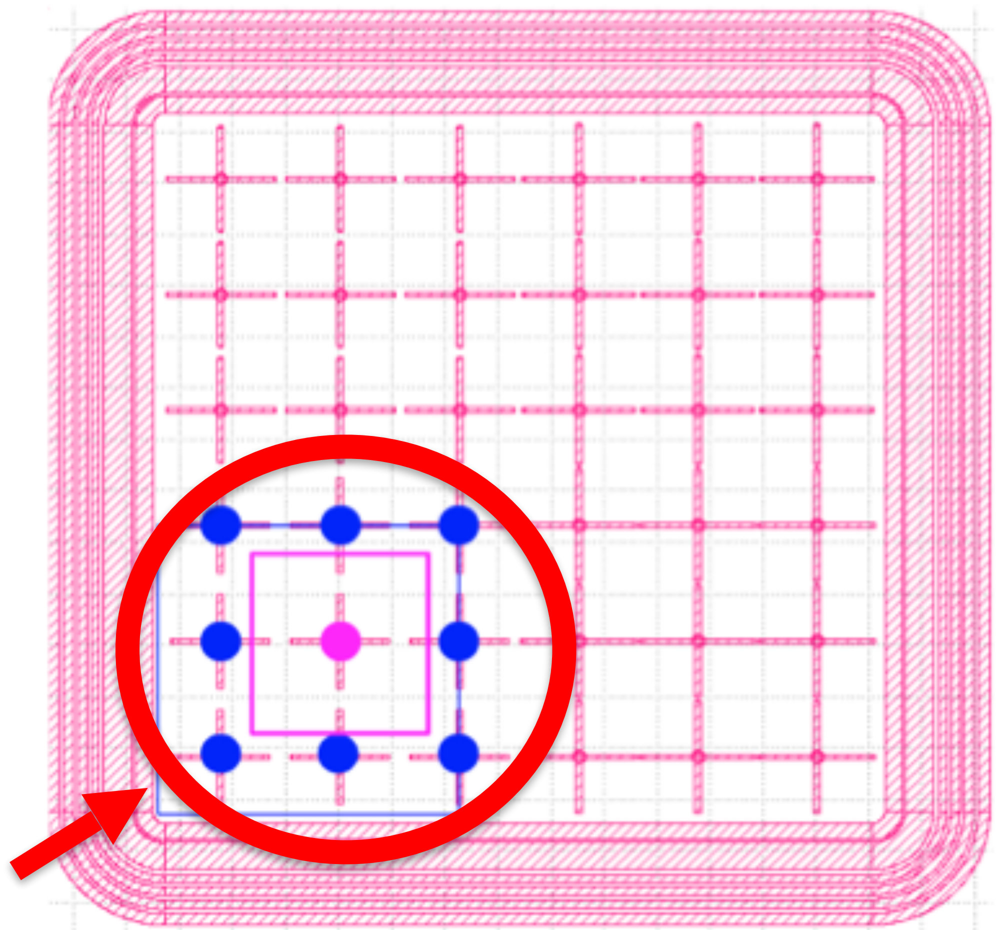


Time resolution for **20**, **30** and **50** µm-thick sensors

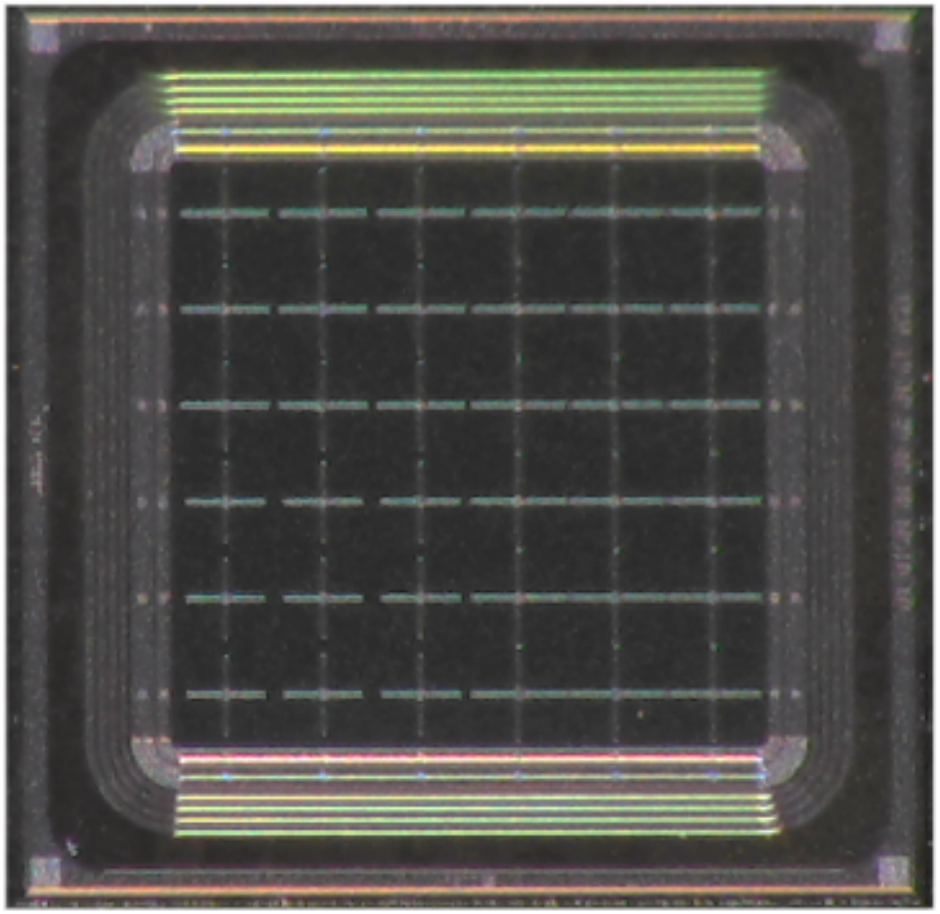
Towards AI/ML for AC-LGADs

- AC-LGAD sensors have a complex signal signature due to charge sharing
- Position reconstruction is based on the extraction of the signals read out by each electrode
  - Used to infer the x–y coordinates of the particle hit position

JINST 19 (2024) C01028



These pixels
are read out



FBK sensor with 6×6 matrix
450 µm pitch pixels

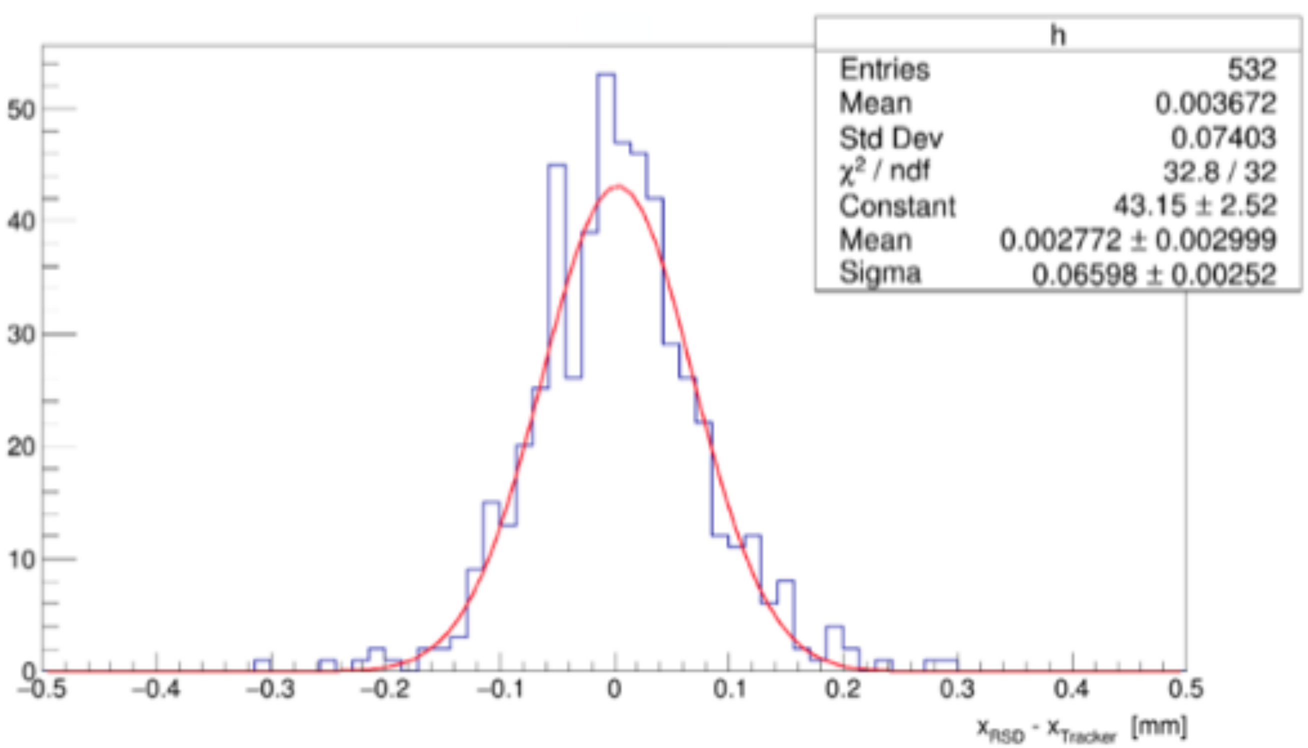
Towards AI/ML for AC-LGADs

- Improve position reconstruction using AI/ML tools
  - Trained using IR-laser dataset, tested on test-beam dataset
  - As a reference, compare to analytical reconstruction

$$x_{\text{RSD-centroid}} = \frac{\sum_{i=1}^{9} A_i \cdot x_i}{\sum_{i=1}^{9} A_i}$$

- **Measure position resolution 65 µm**
  - A standard binary read-out : ~130 µm resolution
  - Can achieve ~10-15 µm resolution by increasing sensor gain
- **Huge expected performance gain from ML on chip!**

JINST 19 (2024) C01028



Difference between predicted (x_{RSD}) and measured (x_{Tracker}) positions

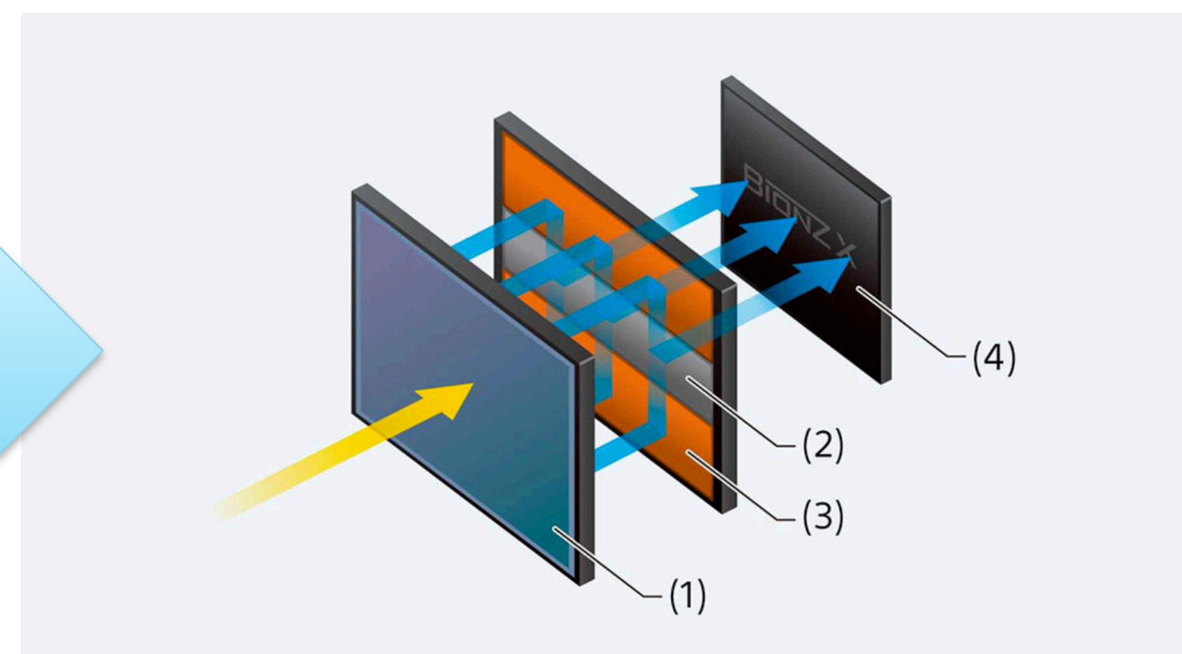
Position resolution as a function of the total amplitude of the 4 highest signals

3D-Integrated Sensors

Fermilab SLAC
Lawrence Livermore National Laboratory

- Low-power, highly granular detectors in (***x***, *t*)
  - Adoption of 3D-integration has been cost-prohibitive in academia
  - Will enable breakthroughs across HEP, NP, BES, and FES
- **Joint development effort of SLAC, FNAL and LLNL teams**
  - Partner with industry leaders to implement new technologies
  - **Design goal is to achieve position resolution ~5 µm, timing ~ 5-10 ps**

The Nikon Z 9's Stacked CMOS sensor reads out fast enough to eliminate the need for a mechanical shutter (Credit: pcmag.com)



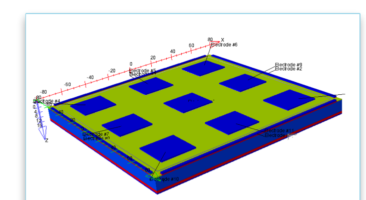
1) Pixel area – 2) Integral memory – 3) Hi-speed signal processing circuit – 4) Image processing engine

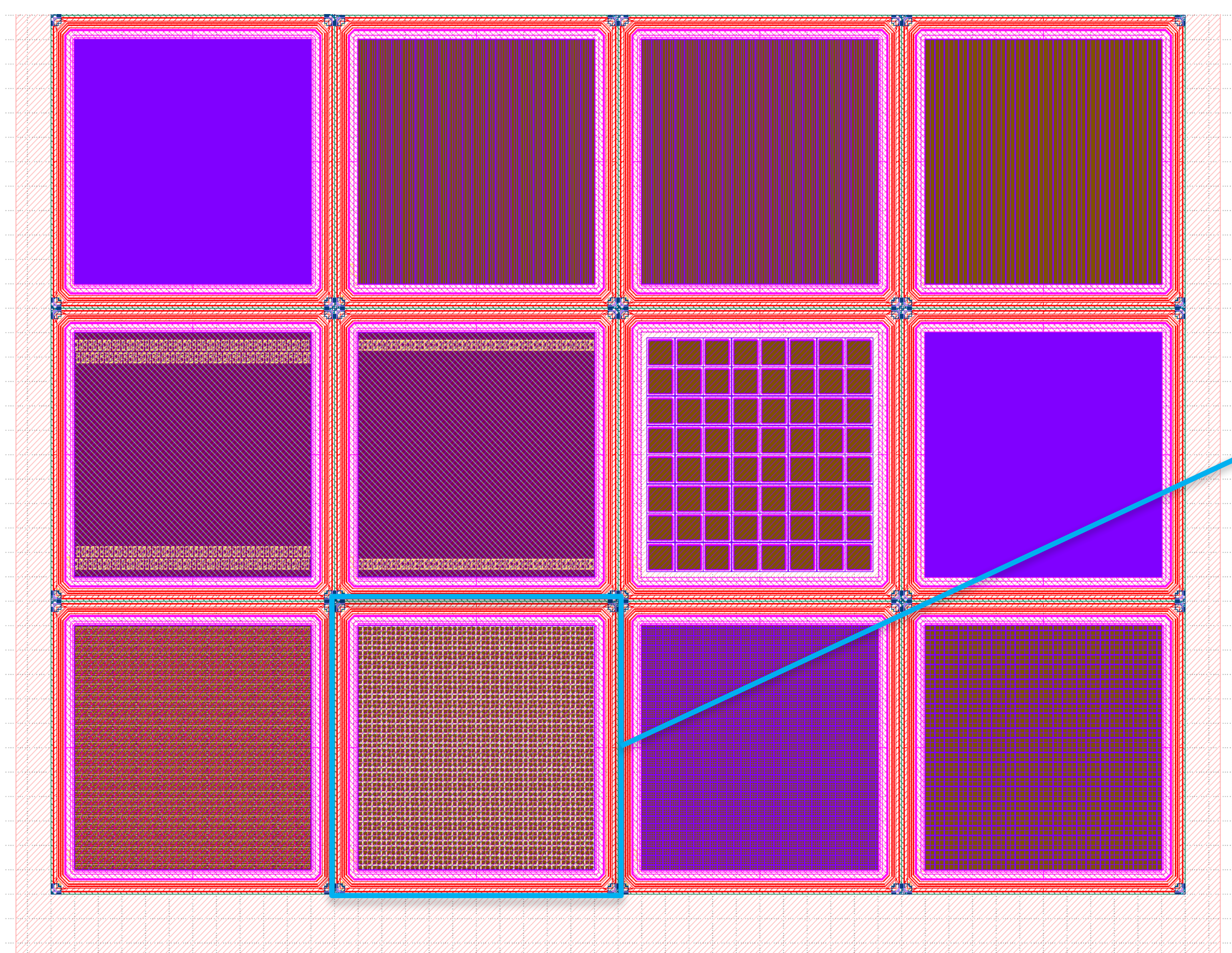
3D-Integrated Sensors

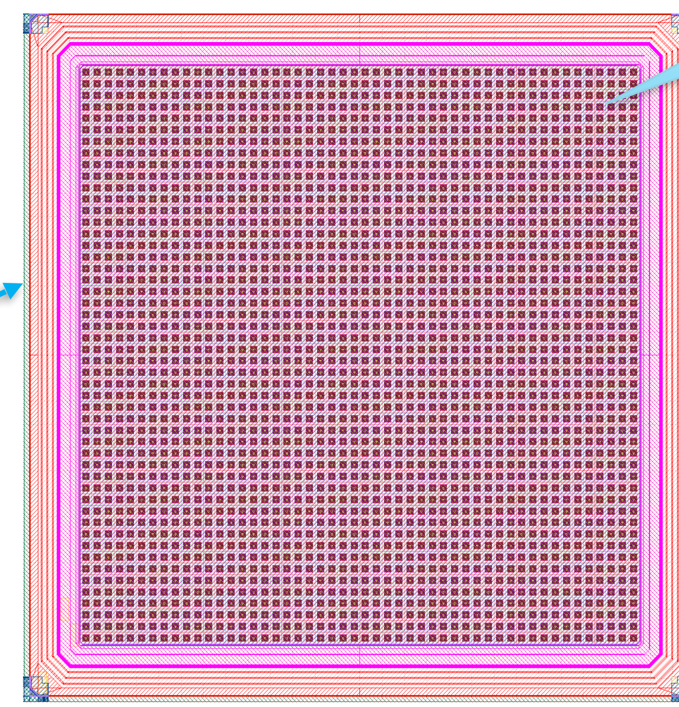
Fermilab SLAC
Lawrence Livermore National Laboratory

- In partnership with Tower Semiconductor
  - Full wafer run on 12” process, using their **65 nm** process
  - Layout Variations: pixels vs. strips
- Design submitted: expect back in 3-5 months

3D TCAD model of an AC LGAD.
The electrode pitch is 50 microns



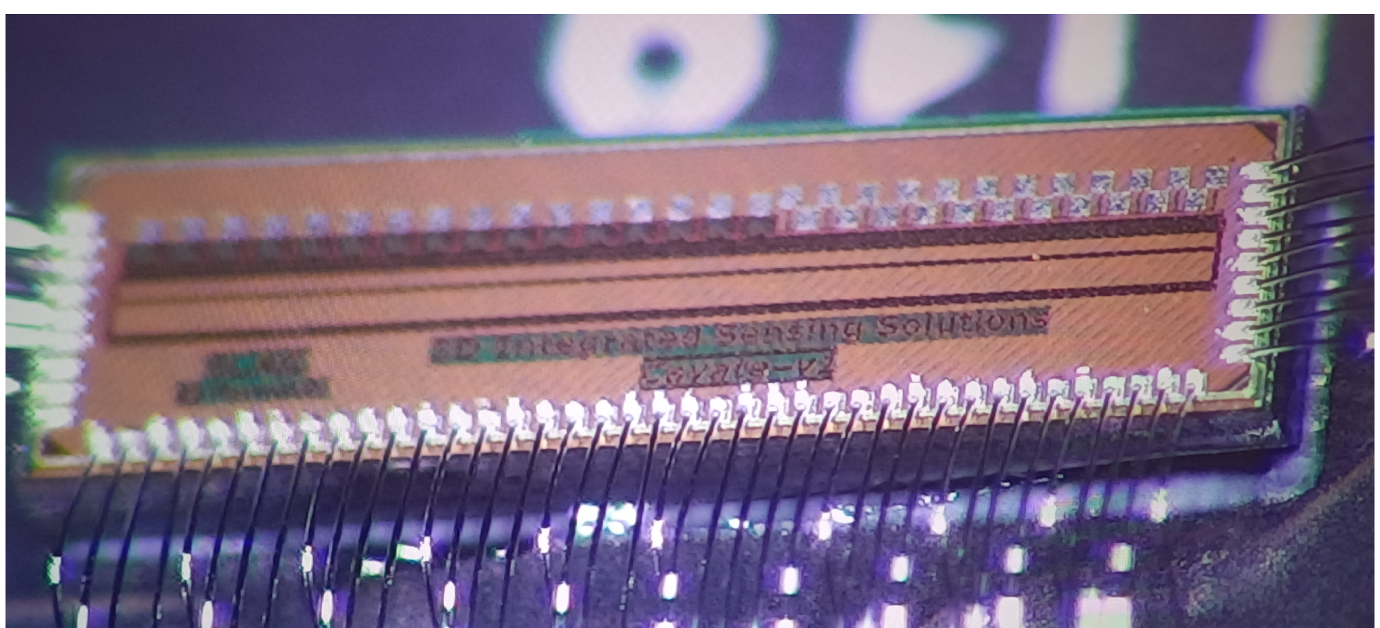




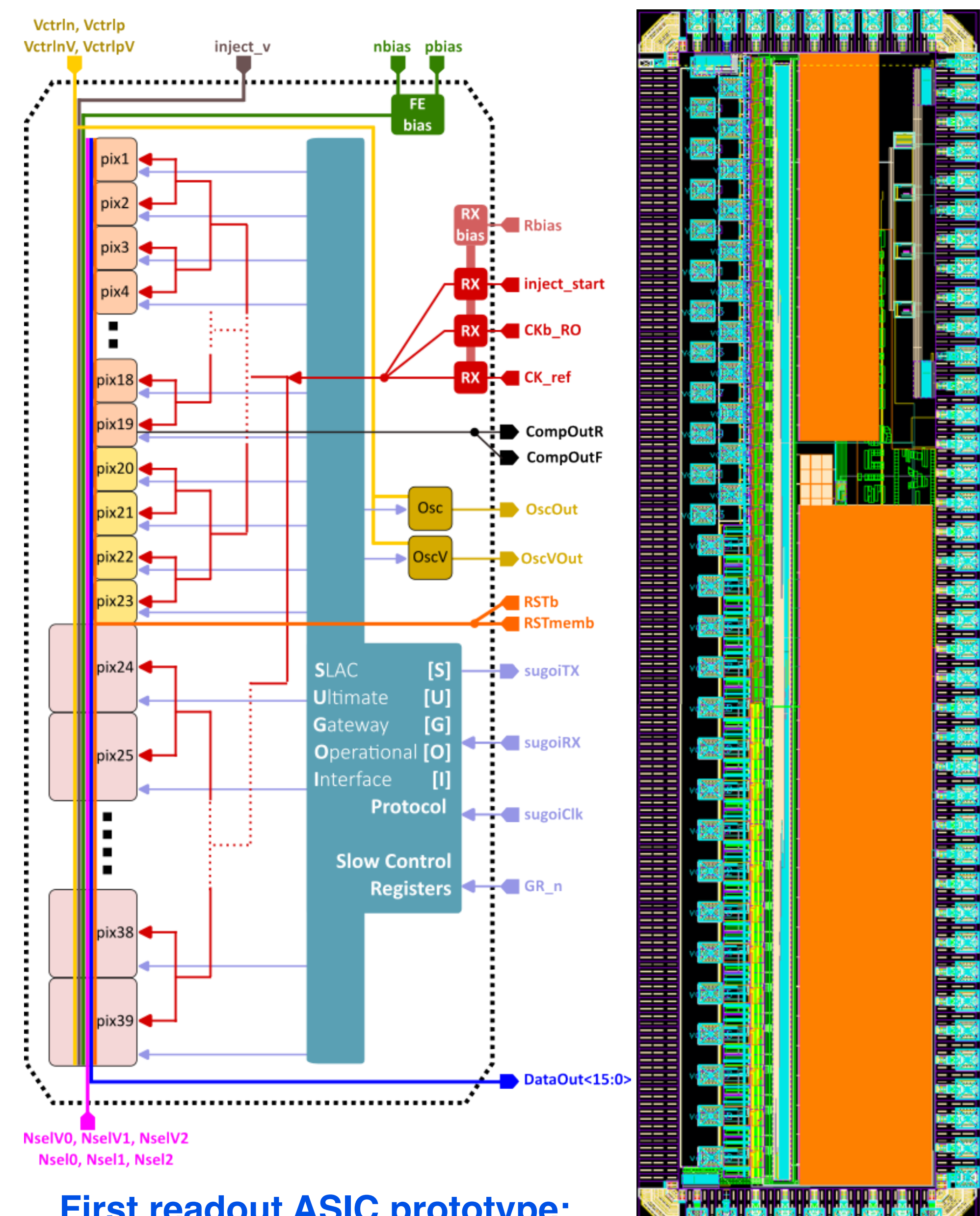
100x100 µm^2 array sensor

3D-Integrated Sensors

- The first 28nm readout ASIC prototype (1x3 mm^2) submitted to TSMC in August
  - Linear pixel array: two variants of 50μm and one variant of 100μm size pixels
  - Main goals are to test the main ingredients to implement in the full chip
- During 2025, we will tape-out another MPW run (5x6 mm^2)
  - Main priority is a 50x50 µm^2 pixels, but can be bump-bonded also to larger sensor pitch



First readout ASIC prototype, TSMC 28 nm

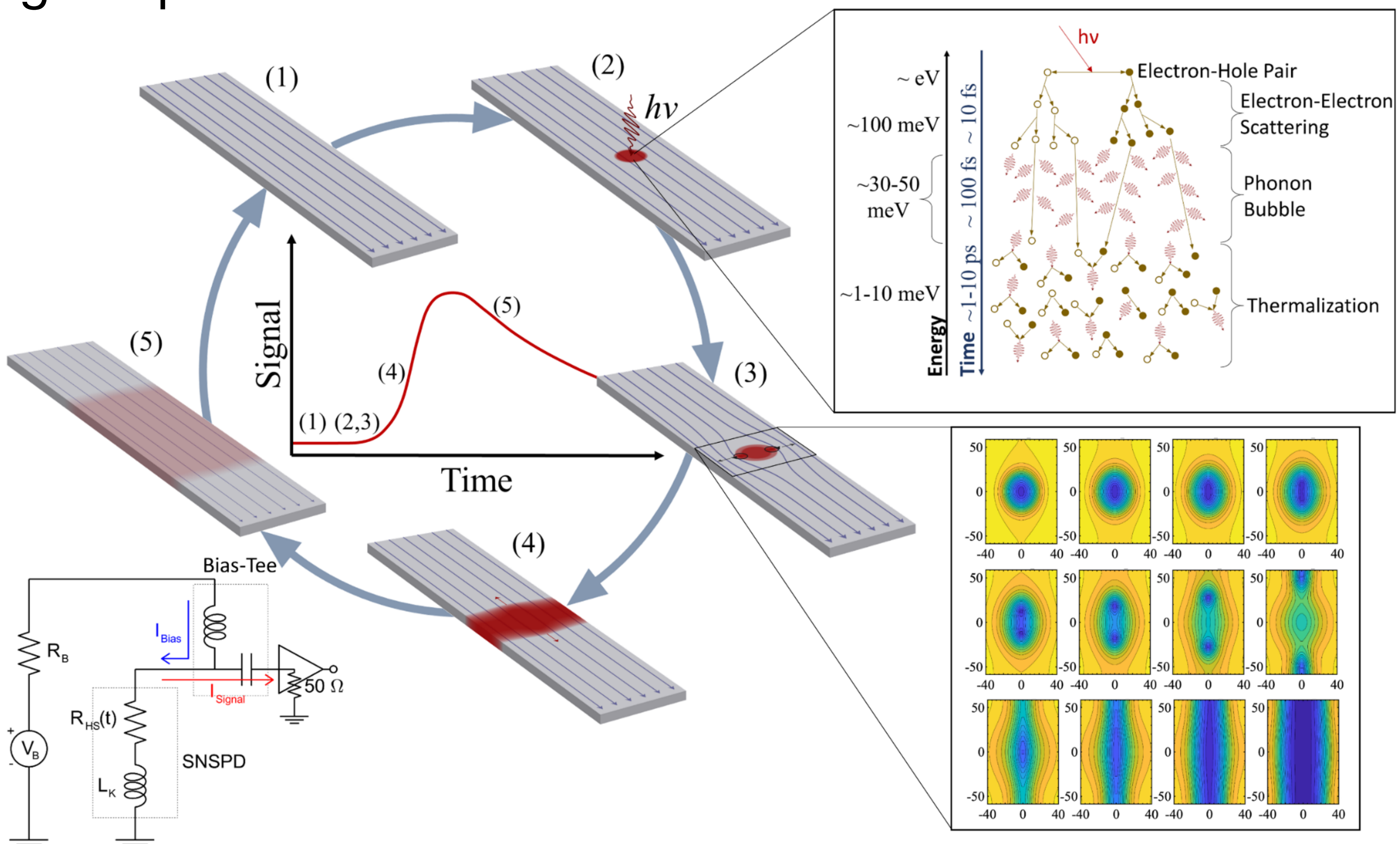


First readout ASIC prototype: block schematic and layout

The Next Frontier: Going Cold

Quantum Sensors: superconducting nanowire single photon detector

- Single photon (heat) triggers detector out of superconductor state
- Resistance quickly (ps) jumps to few kΩ → detector current into readout
- Highest performance single-photon detector, from UV to mid-infrared
- Operating temperature : 1-4 Kelvin



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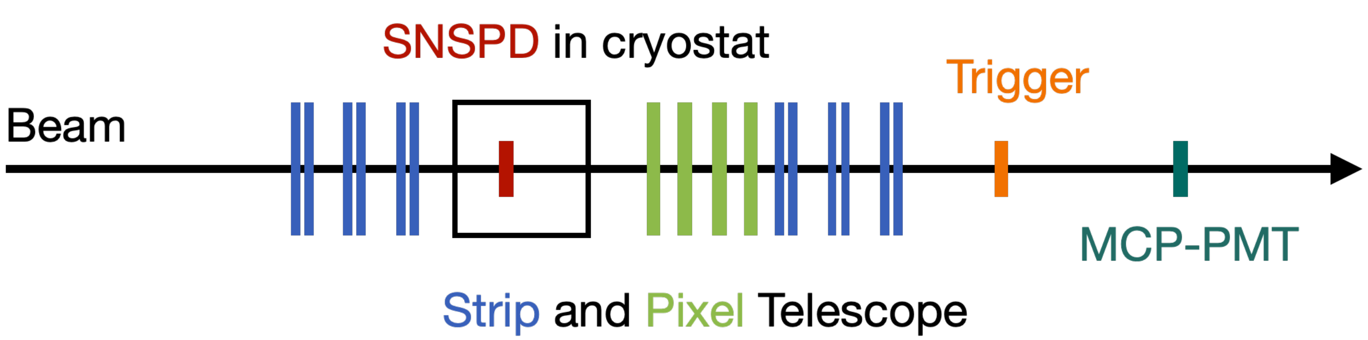
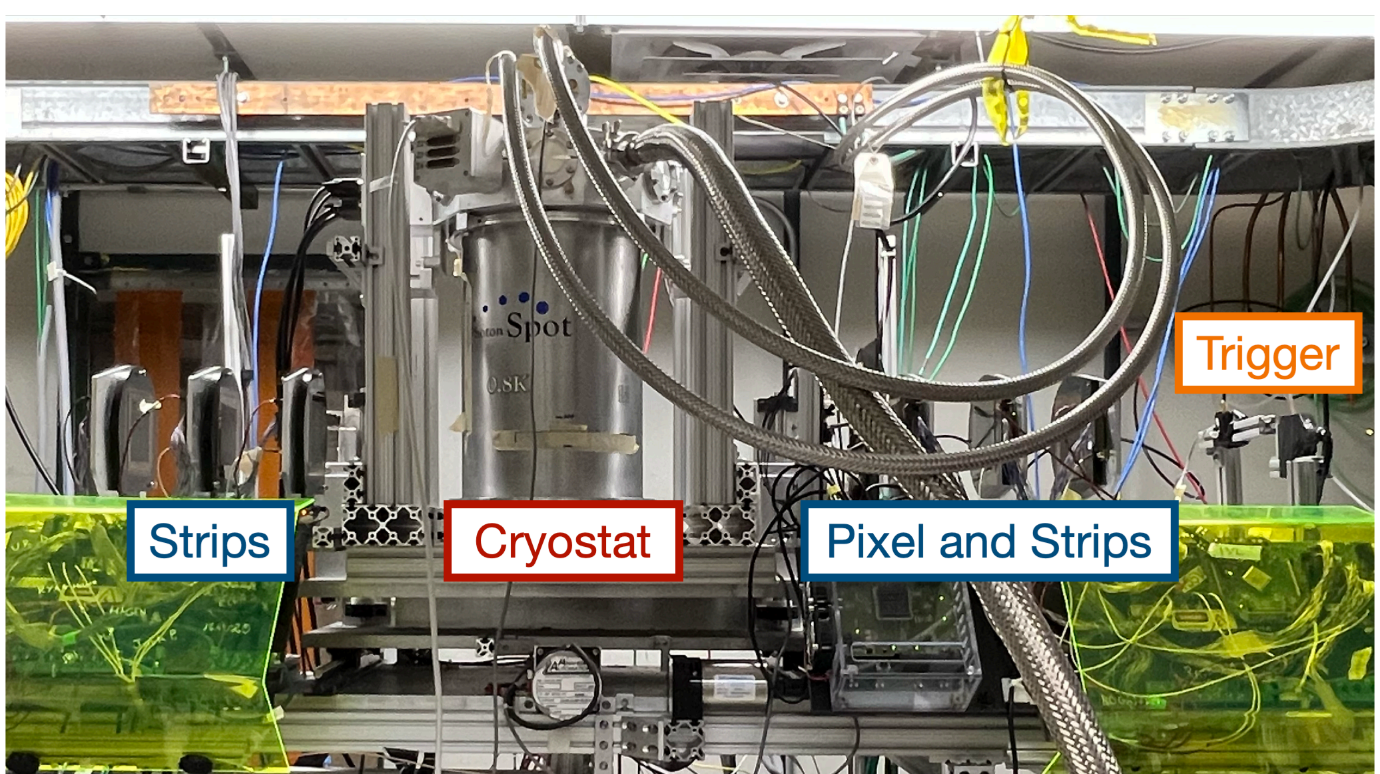
The Next Frontier: Going Cold

New thrust towards sub-eV charged particle tracking with picosecond level time resolution



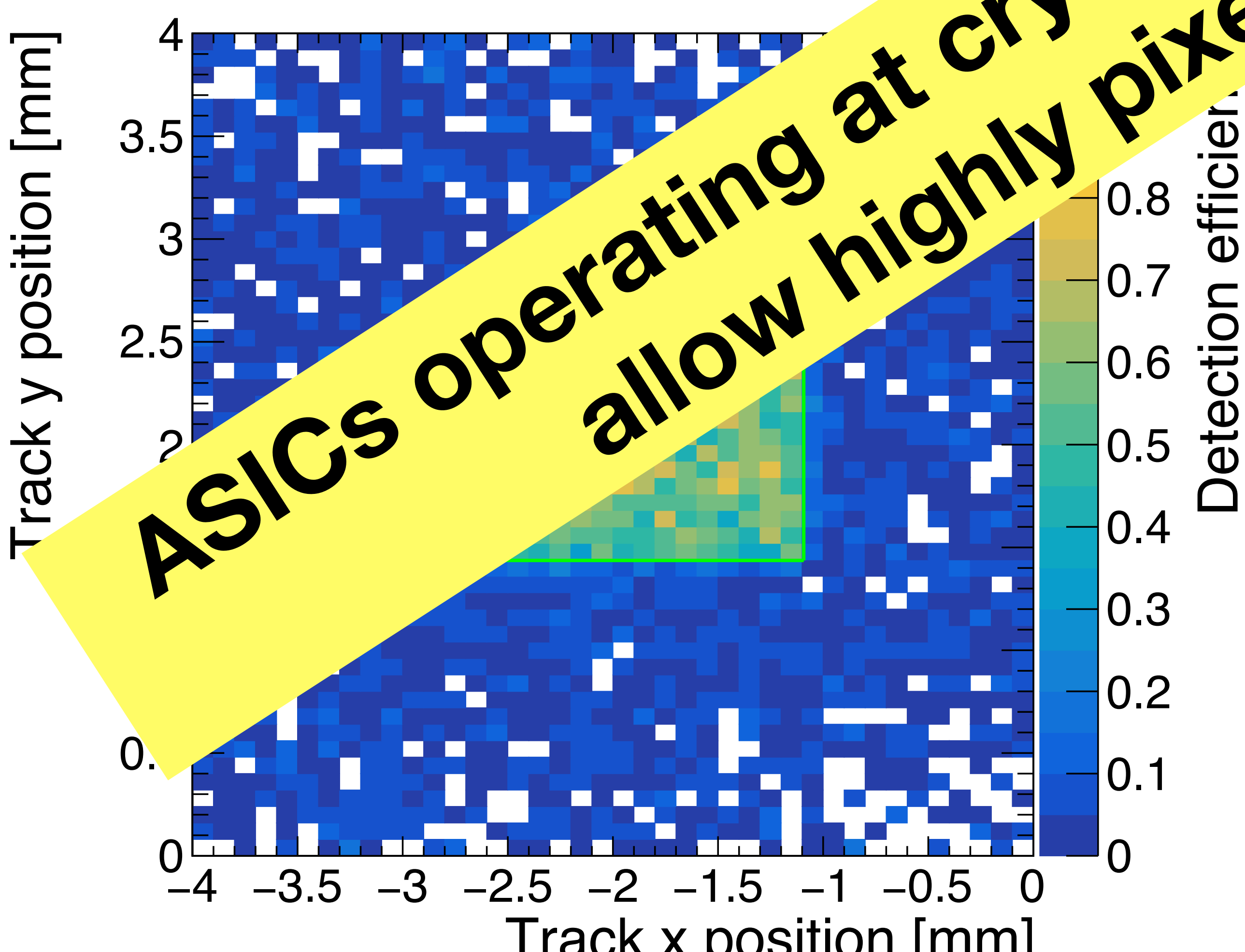


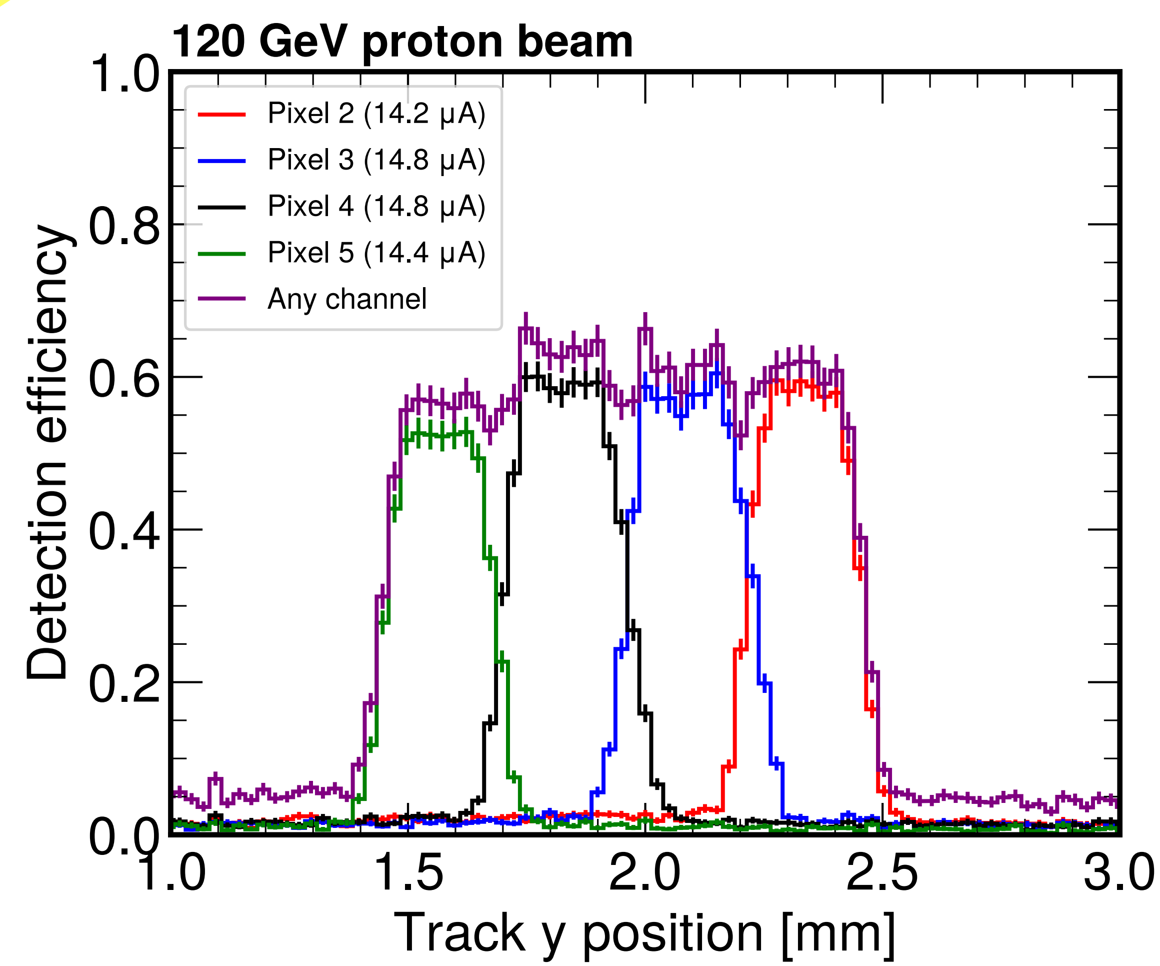
- New R&D program for SNSPD to detect high energy particle with the Fermilab Test Beam Facility
- **First test beam** to detect 120 GeV proton and 8 GeV electrons and pions with **large-area** (2×2 mm^2) **multi-pixel** (8-pixel) SNSPD

The Next Frontier: Going Cold

- Only 4 channels. Constrained by … needs
- Precise tracking telescope … allow to measure absolute efficiency and … uniformity

ASICs operating at cryogenic temperatures will allow highly pixelated sensor





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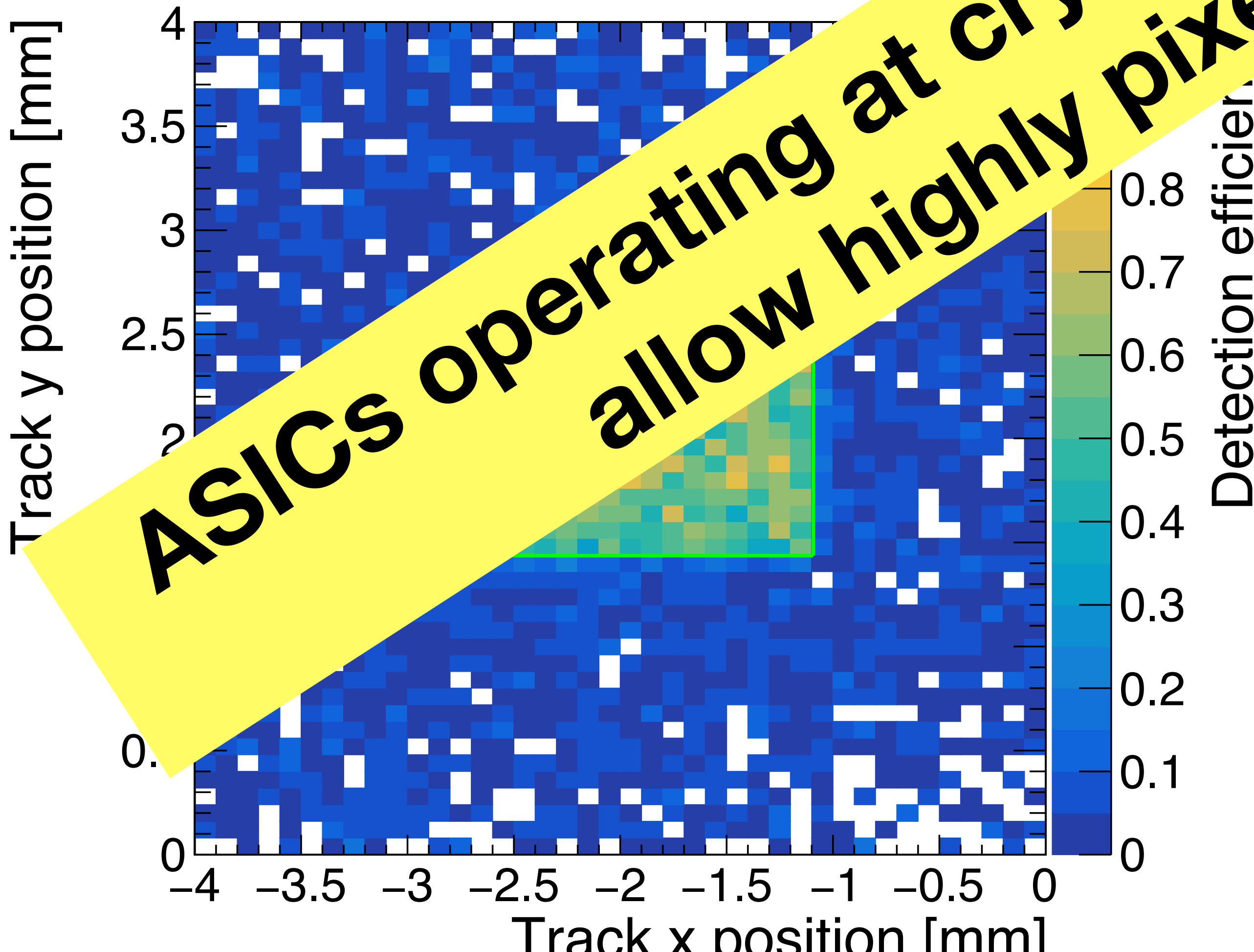
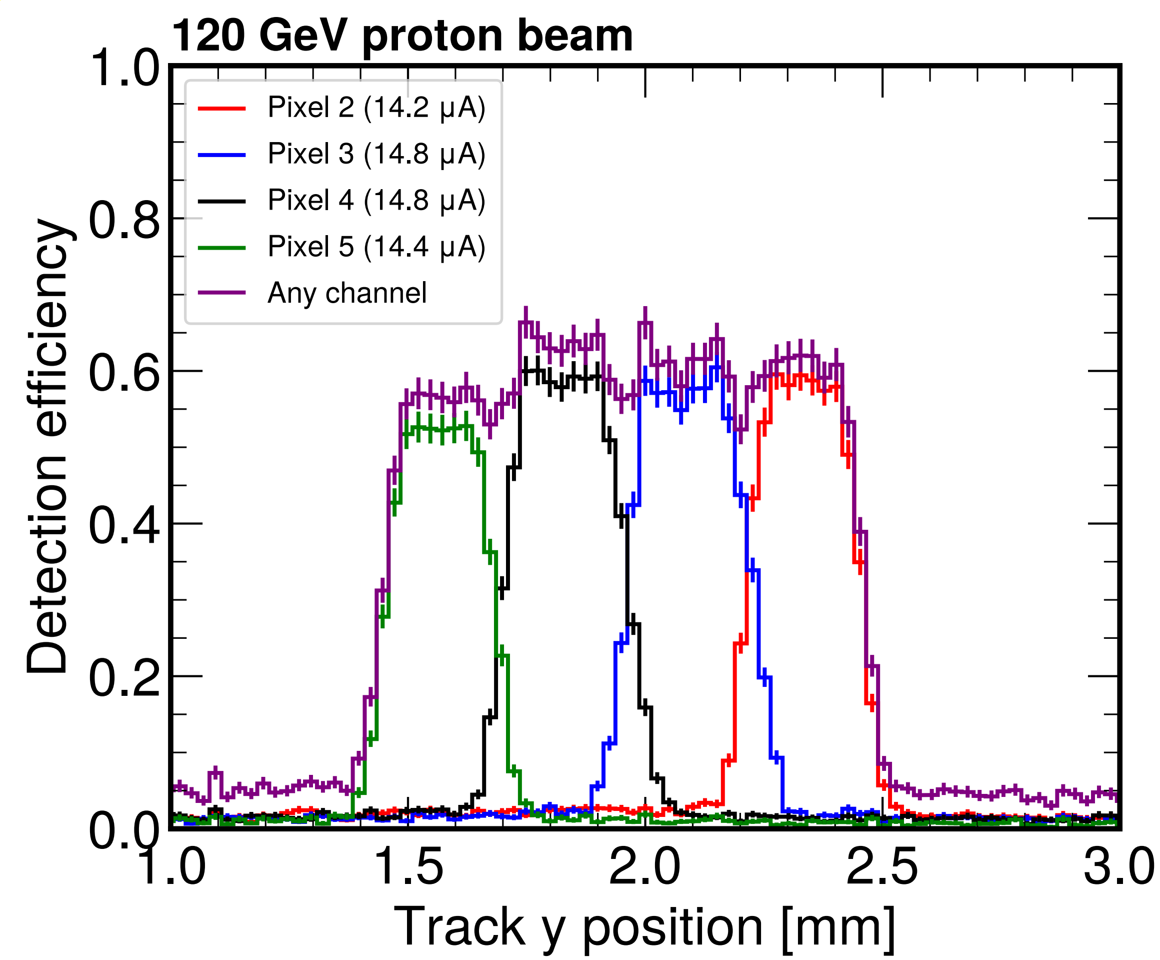
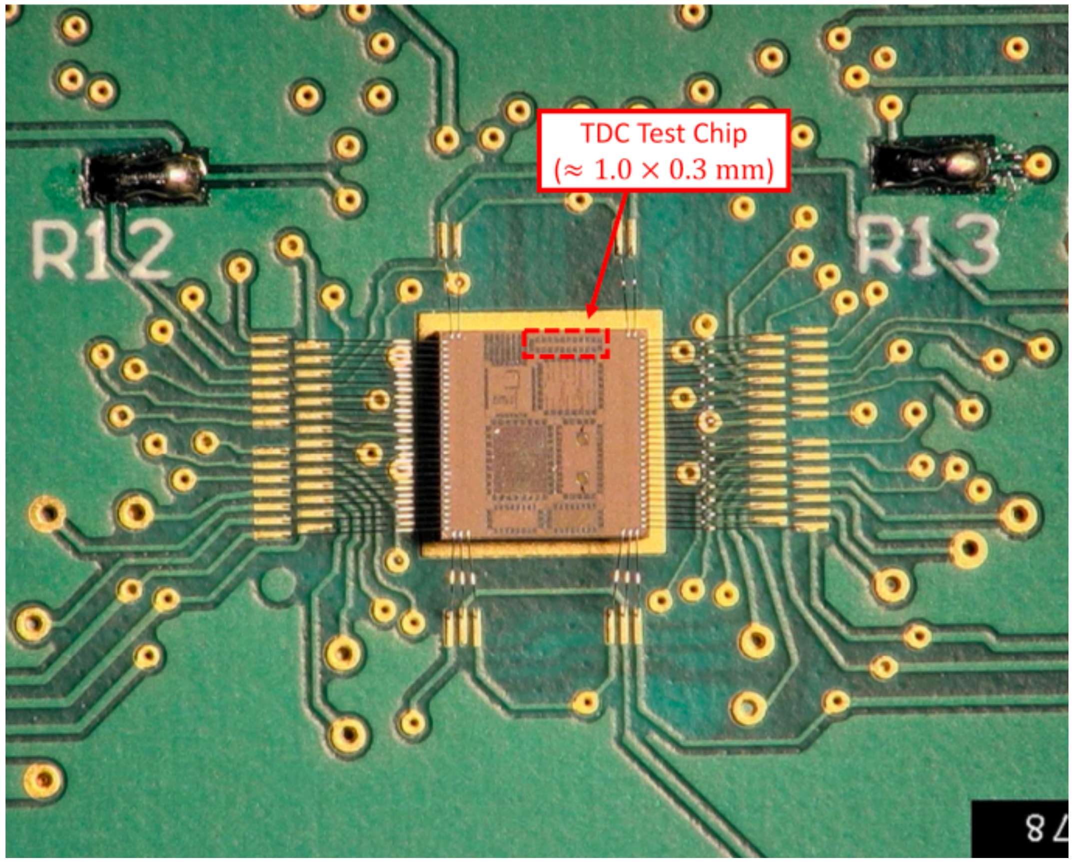


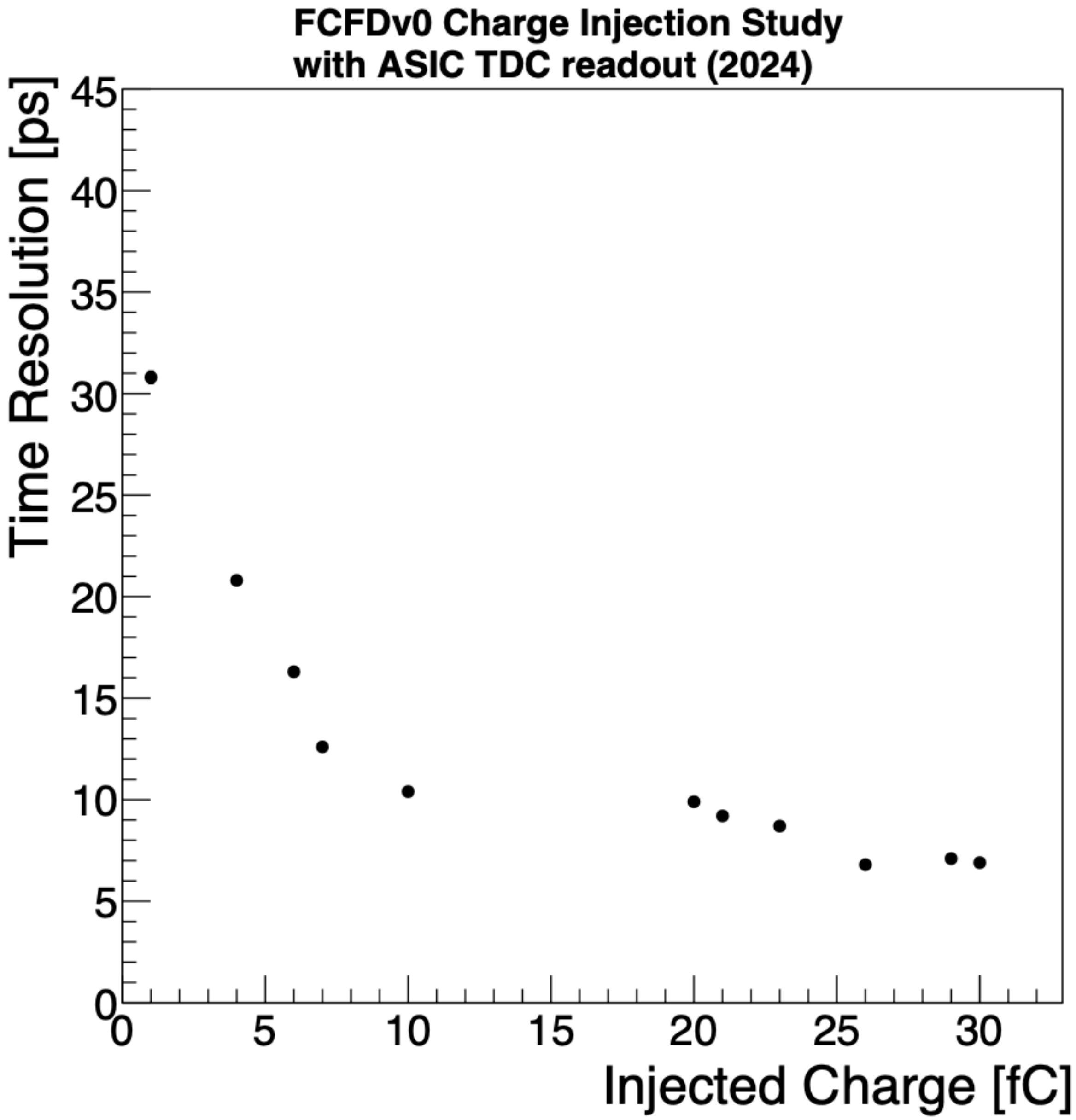


TDC at Cryogenic Temperatures

10.36227/techrxiv.173949128.88095436/v1

Achieve ~7 ps resolution for ~25 fC injected charge

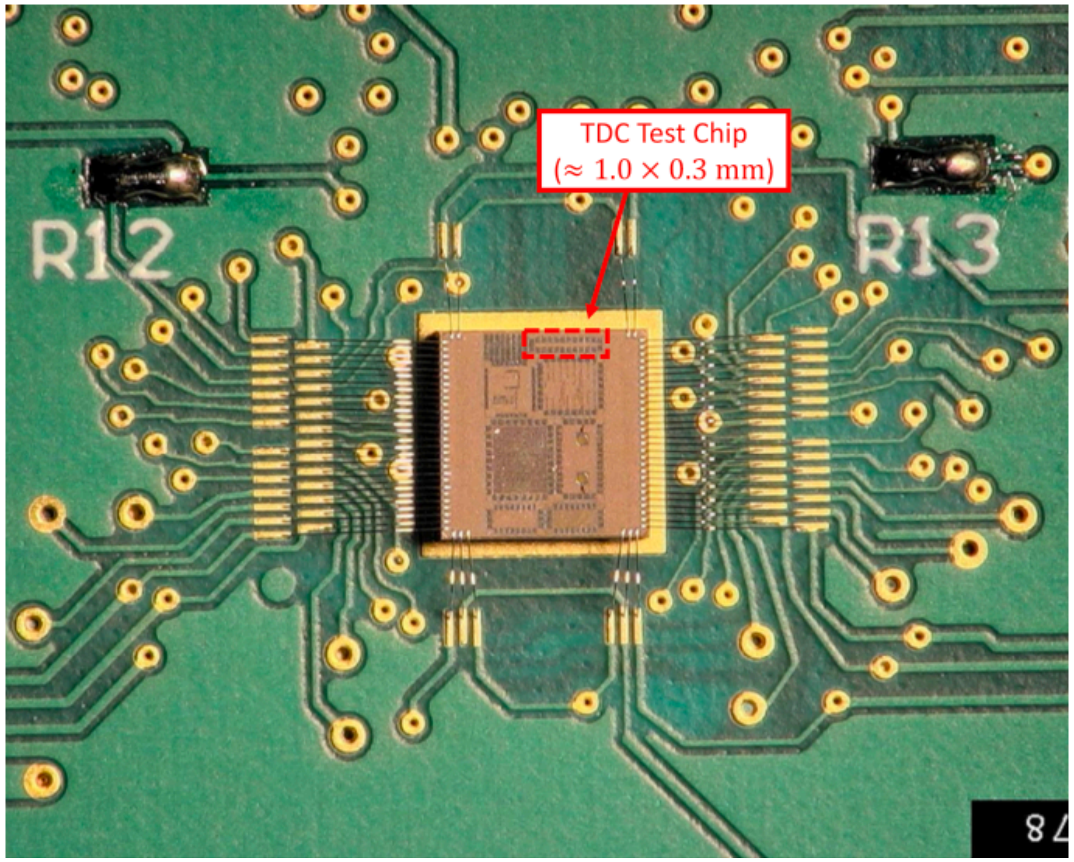


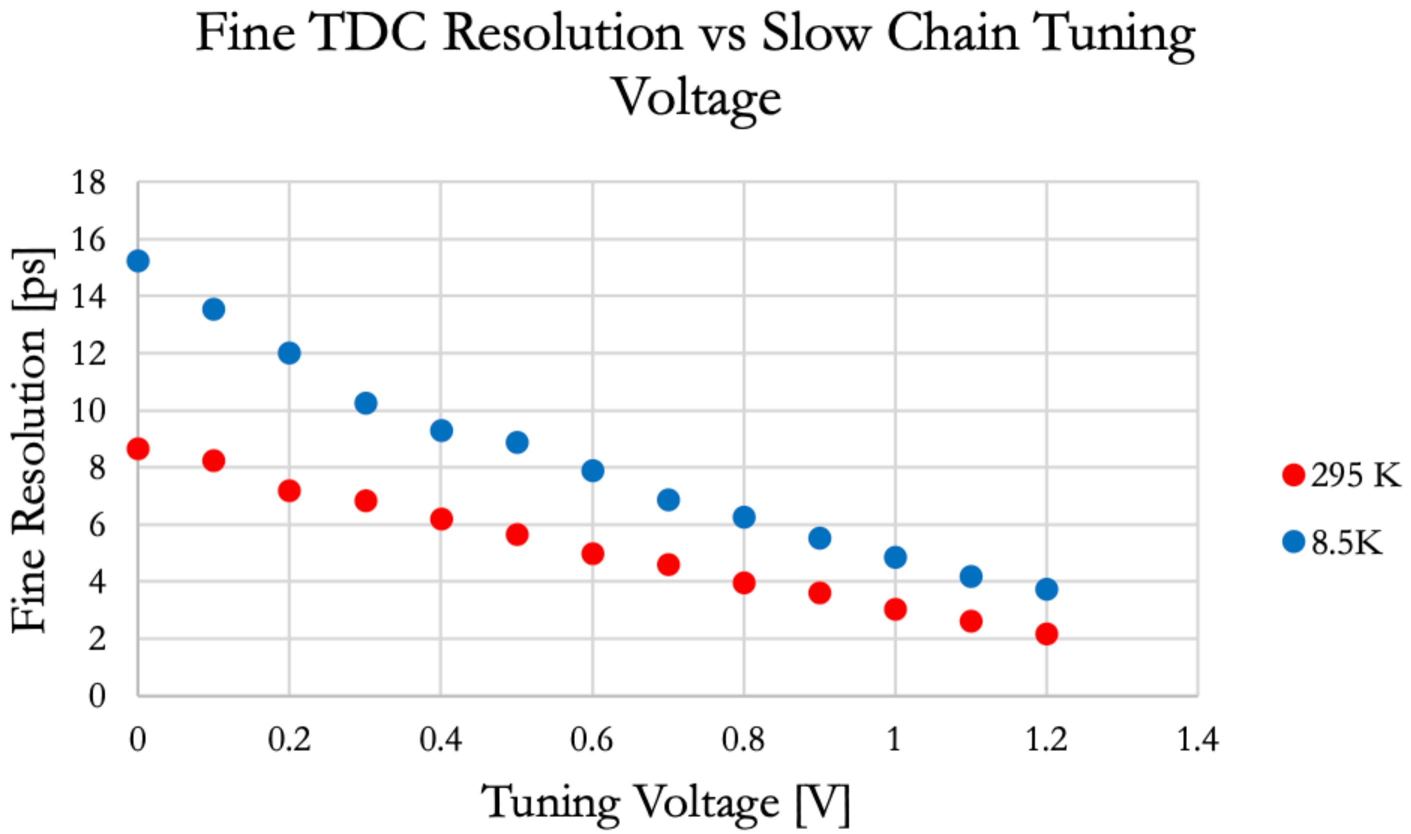


TDC at Cryogenic Temperatures

10.36227/techrxiv.173949128.88095436/v1

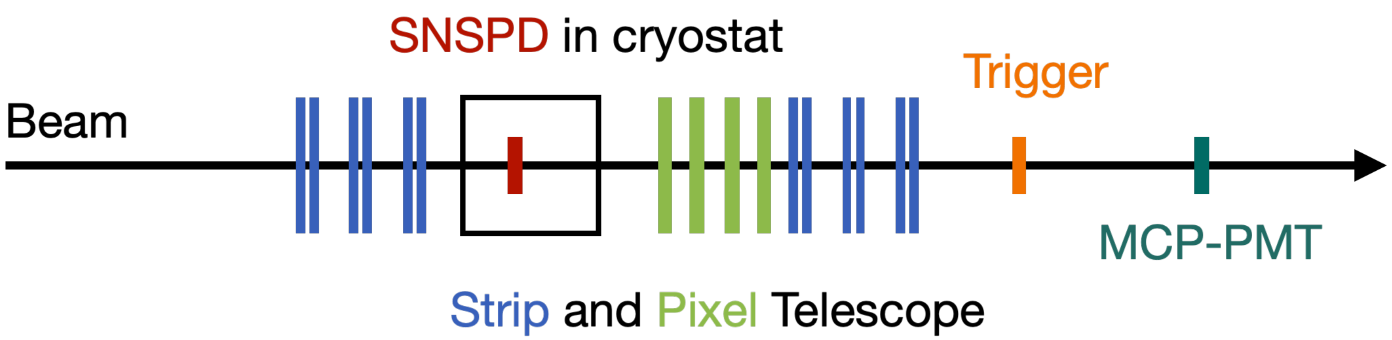
Excellent performance observed at cryo temperatures

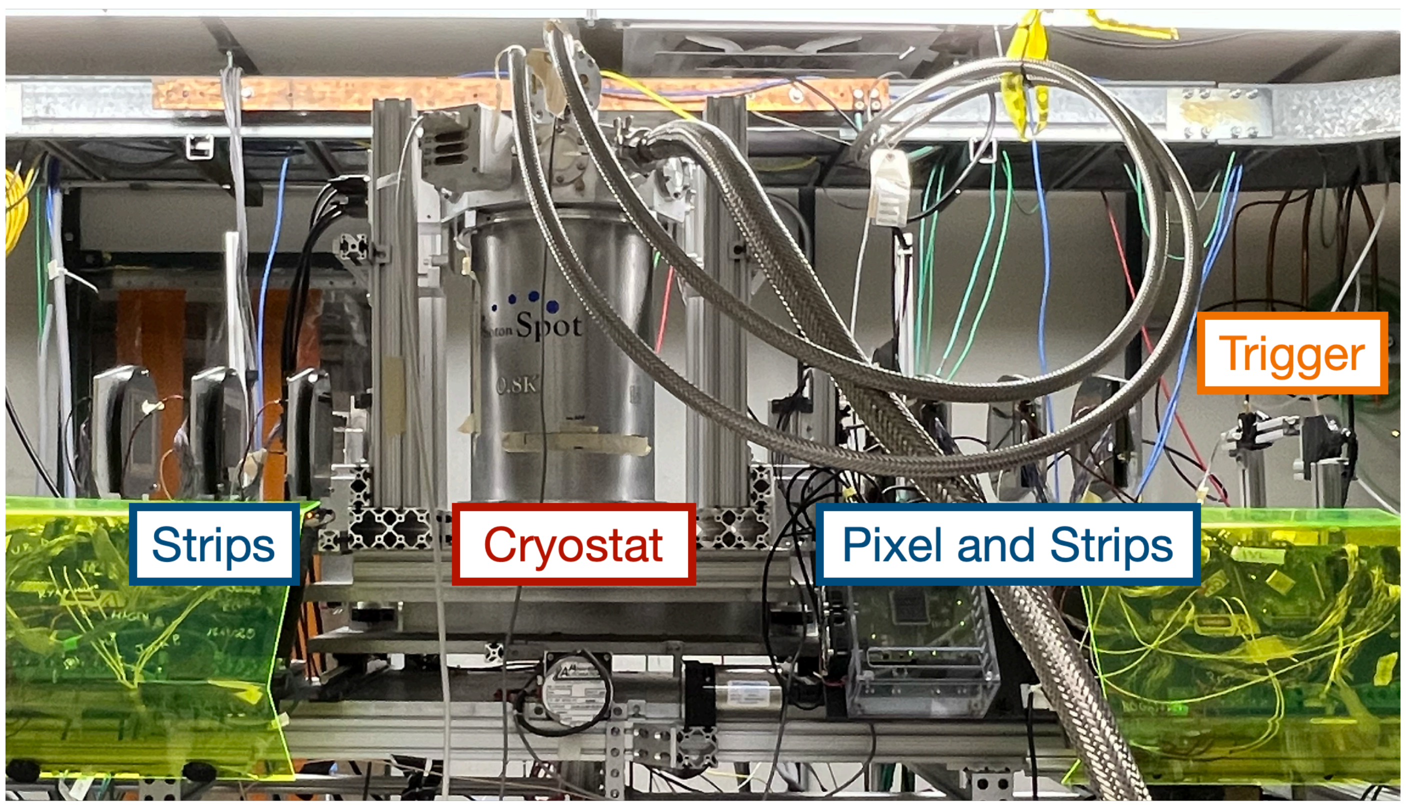




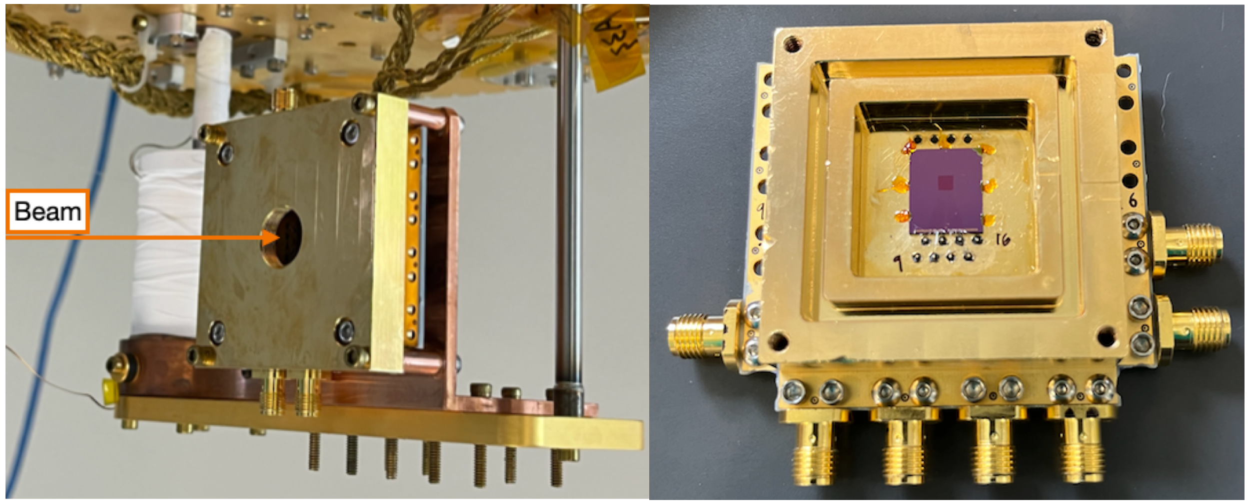
Thank You!

Superconducting Nanowire Single ~~Photon~~ Particle Detector (SNSPD)





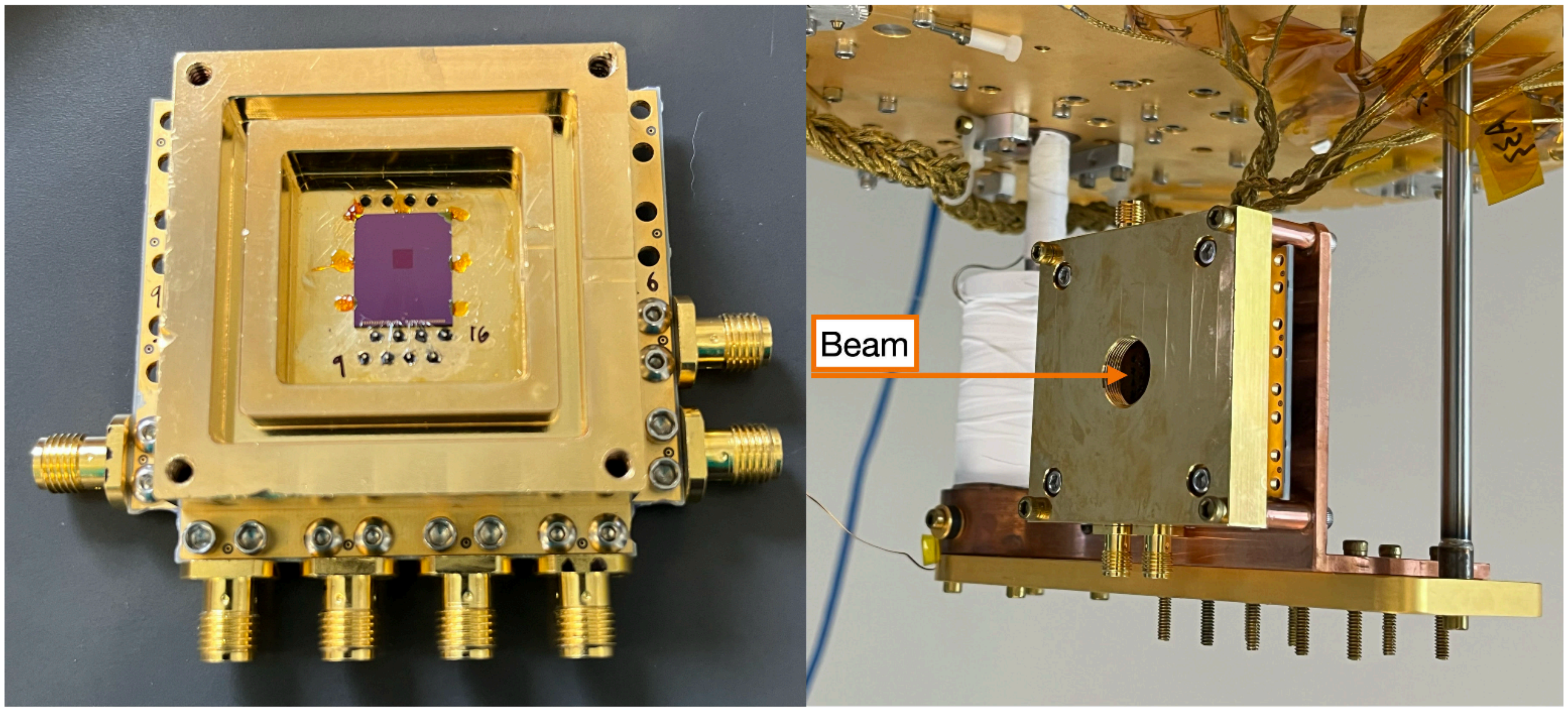
- New R&D program for SNSPD to detect high energy particle with the Fermilab Test Beam Facility
- **First test beam** to detect 120 GeV proton and 8 GeV electrons and pions with **large-area** (2×2 mm^2) **multi-pixel** (8-pixel) SNSPD

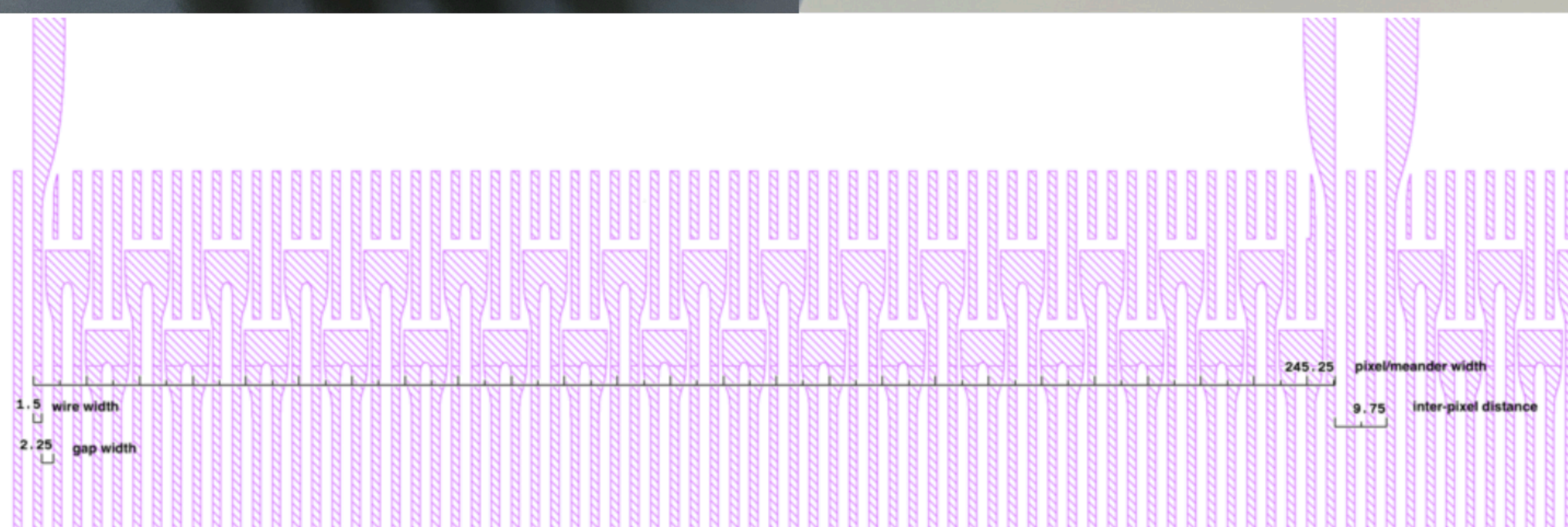


New thrust towards sub-eV charged particle tracking with picosecond level time resolution

SNSPD Under Testing

- WSi: 1.5µm, 40% fill factor, $T_c = 2.8$ K; pixel size is 0.25x2 mm^2



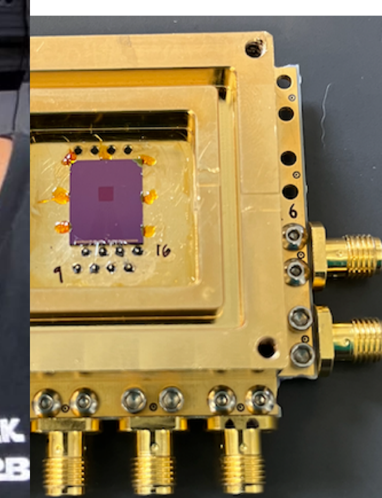


Superconducting Nanowire Single ~~Photon~~ Particle Detector (SNSPD)

Beam

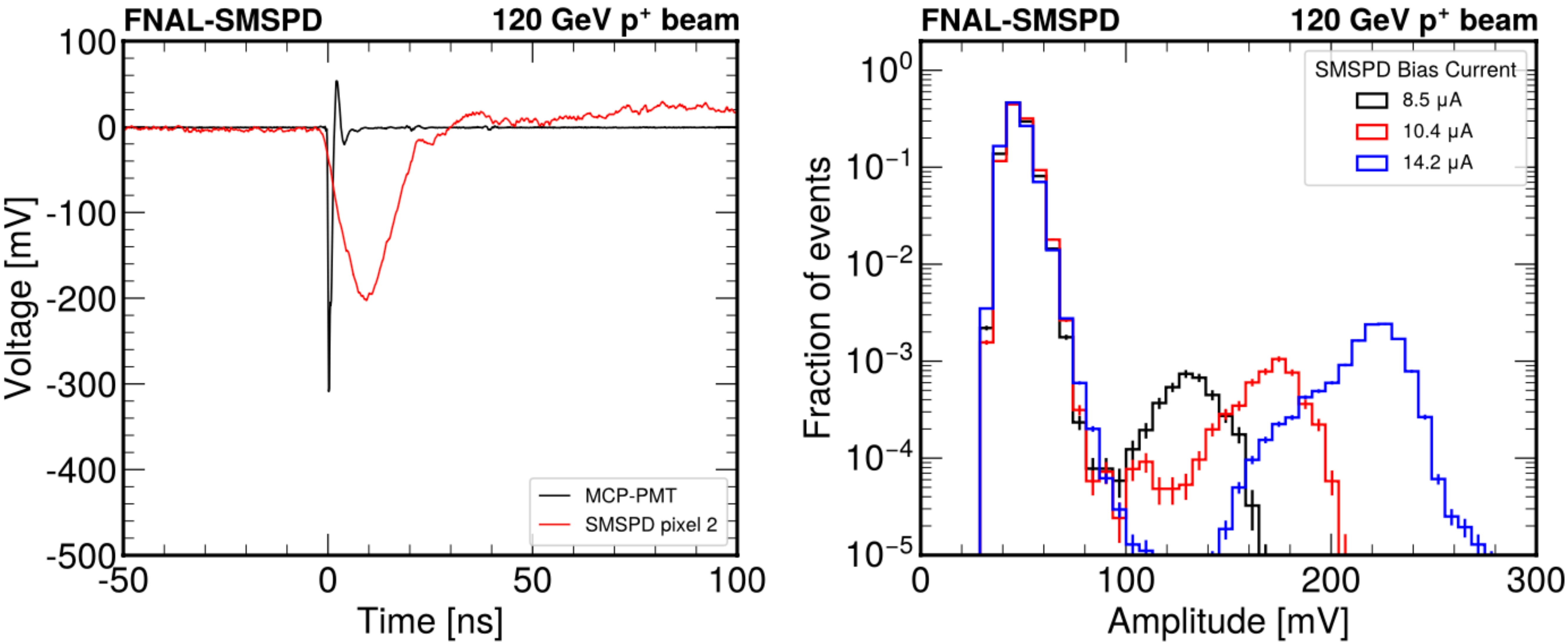
PD to detect
e Fermilab

20 GeV
and pions
) **multi-pixel**



New thr … **racking**
with picosecond level time resolution

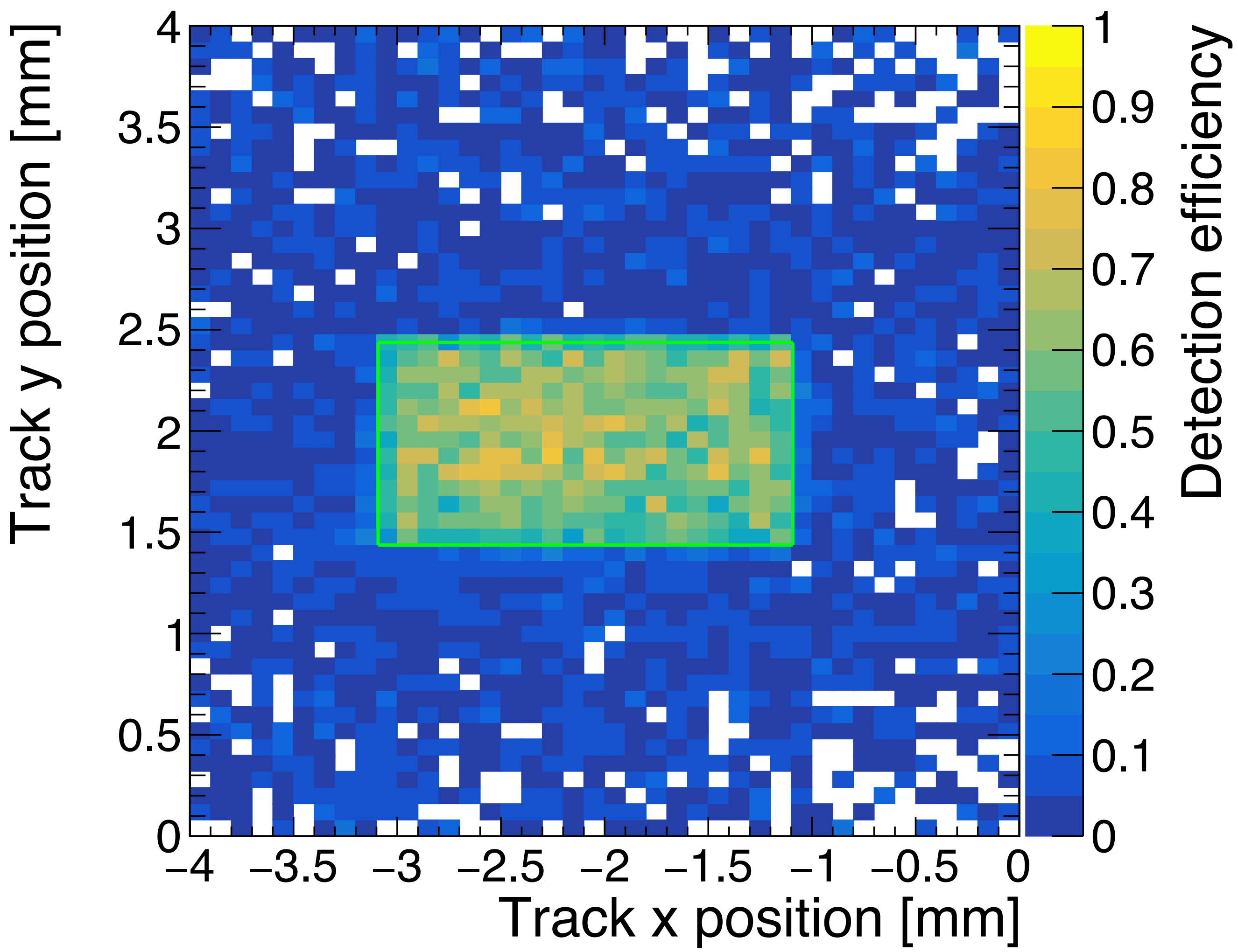
SNSPD Under Testing

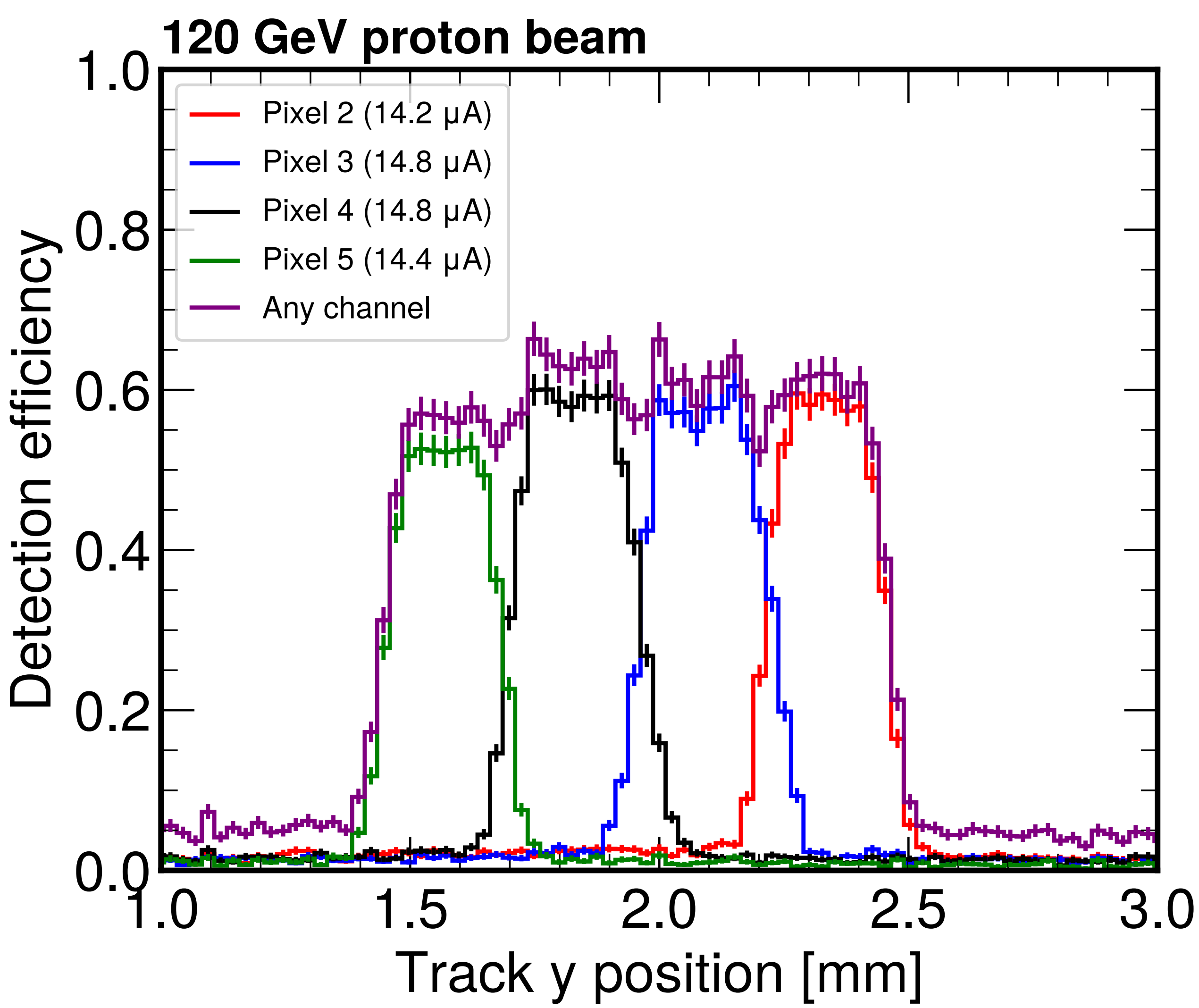


Clear coincidence with reference MCP-PMT and signal clearly above noise for all currents

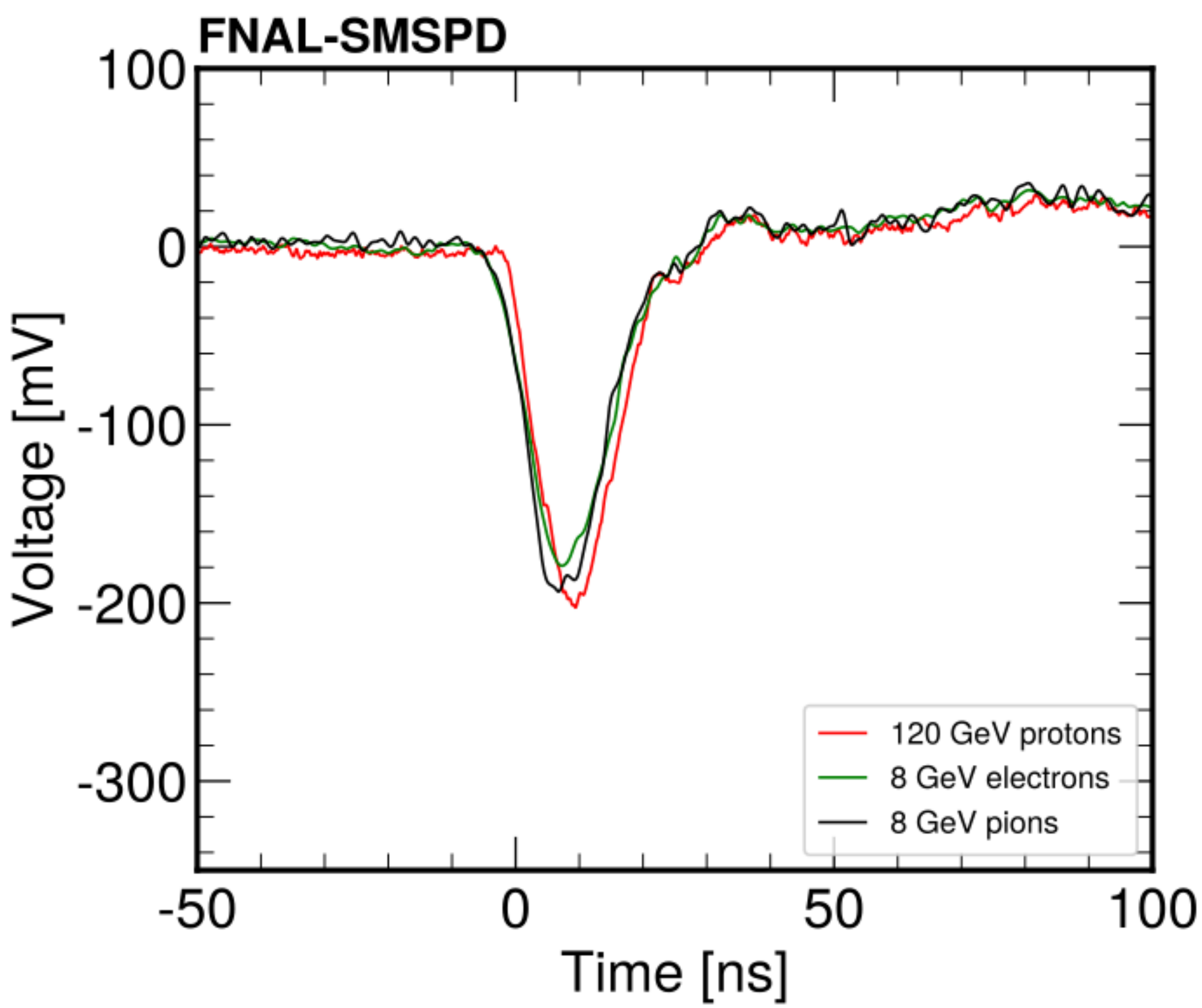
SNSPD Particle Detection Efficiency

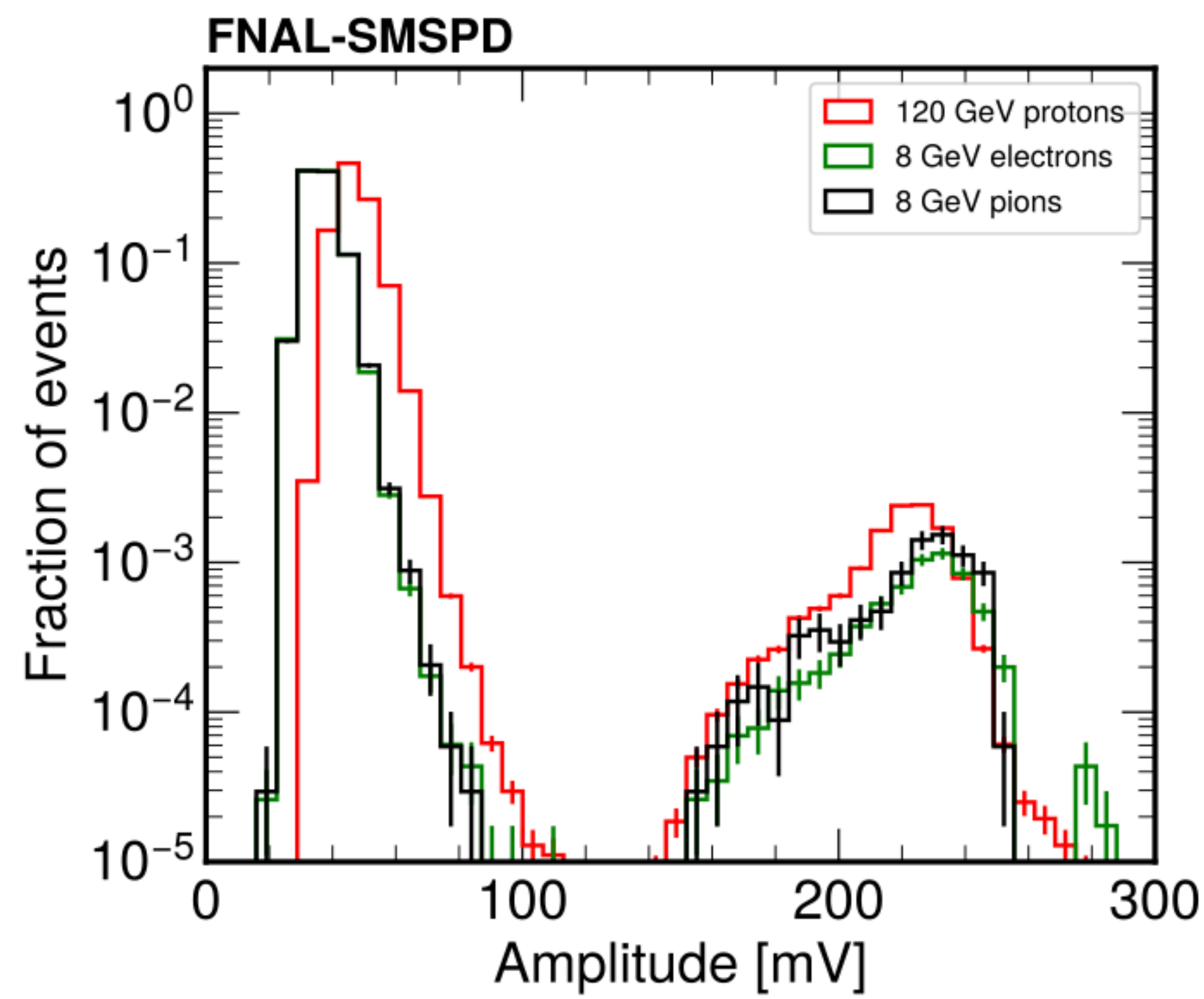
- Readout 4 channels
- Precise tracking telescope (30um spatial resolution) to measure absolute efficiency and response uniformity for the first time





SNSPD response for protons, electrons, and pions





Very similar behavior among the 3 particle types

SNSPD Time Resolution

- MCP-PMT (<10 ps time resolution) provides a precise reference time stamp to measure the time resolution of SNSPD of 1 ns for the first time
- Next step: optimize SNSPD to measure intrinsic nanowire time resolution. **Possibility to tackle the sub-ps and sub-micron 4D-tracking challenge!**