Fermilab

Aug 8, 2025

BlueSky R&D

Cristián Peña

FERMI NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by
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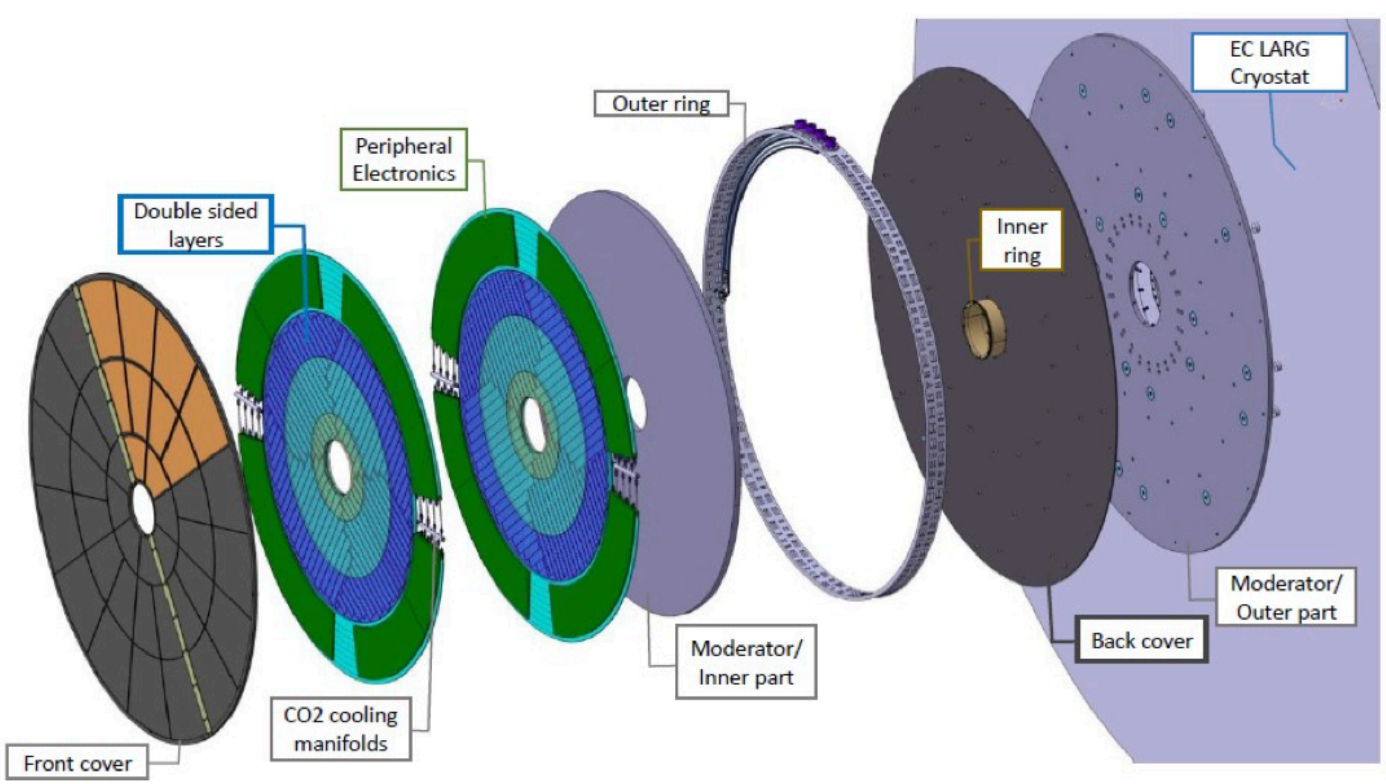
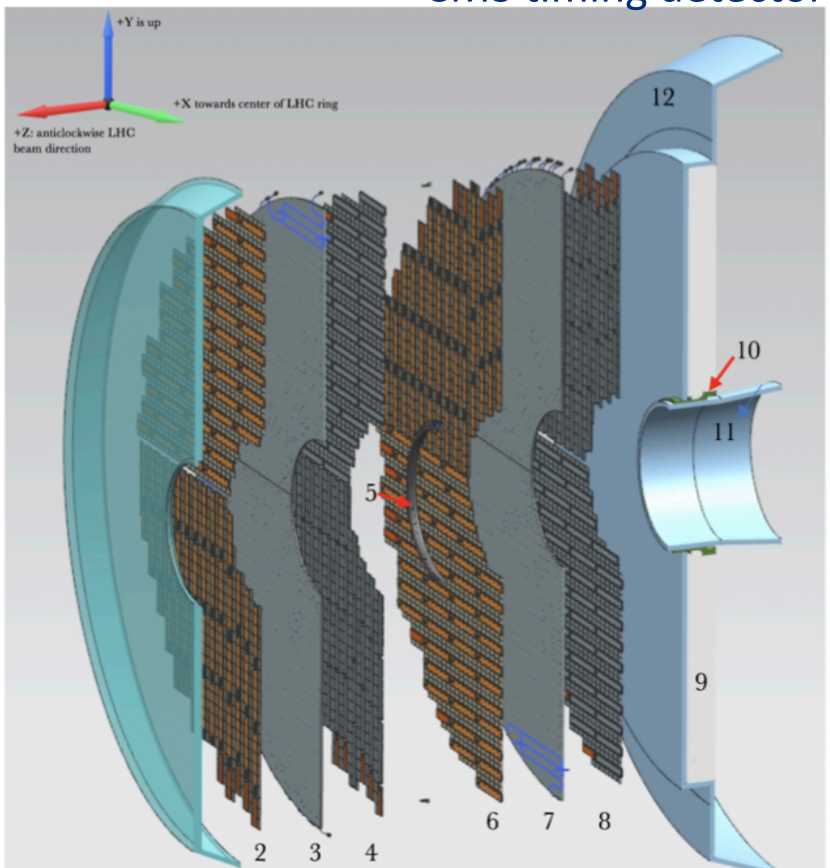
Next Generation Particle Detectors

- Collider experiments 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 **time domain information**
  - 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 experiment

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

Next Generation Particle Detectors

- Collider experiments measure very well
  - Position, charge and energy of particles
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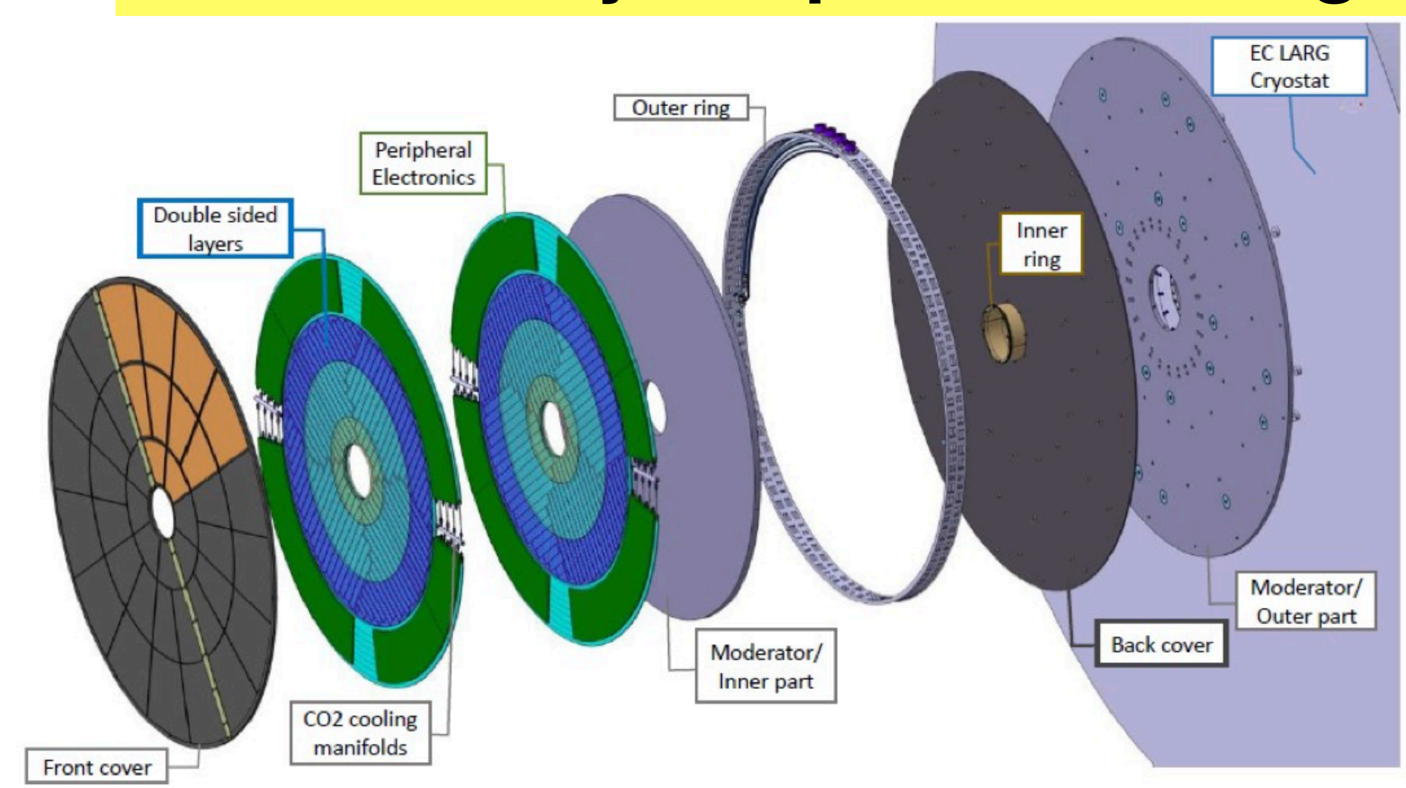
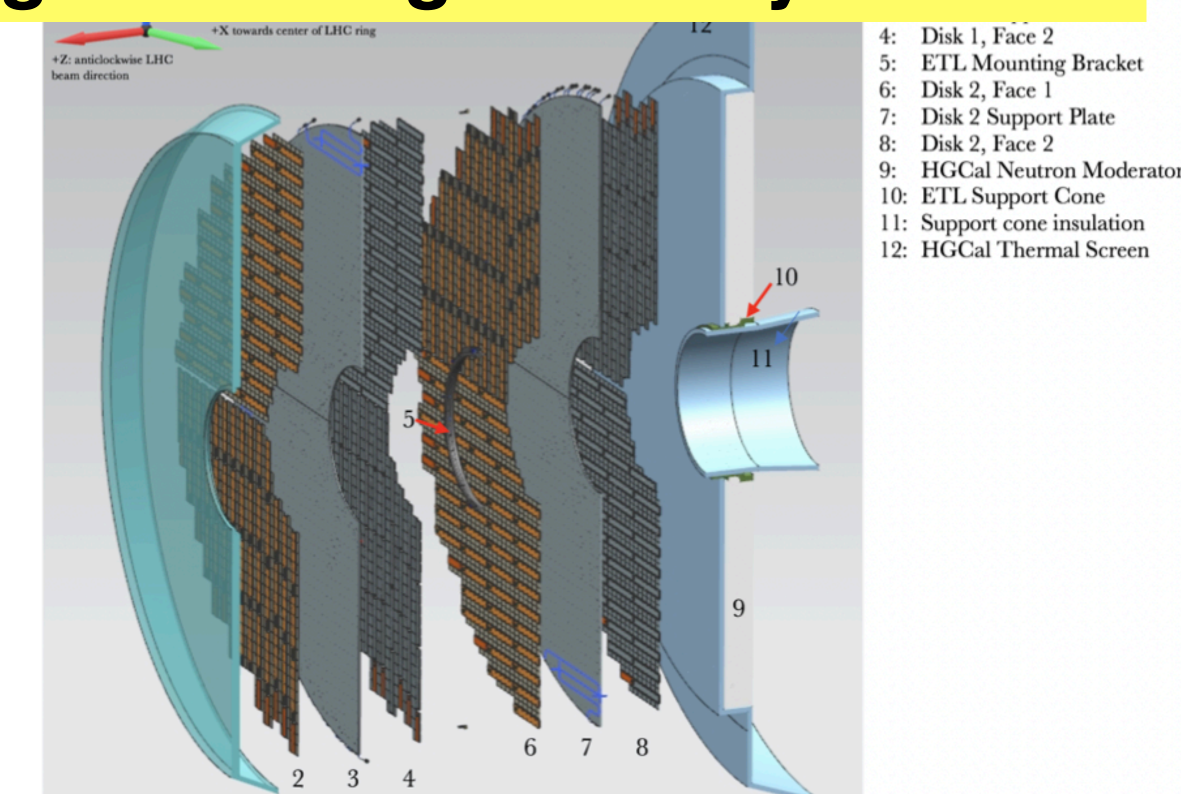
BlueSky R&D on Sensors, ASICs, front-end electronics and early adoption of emerging technologies is key

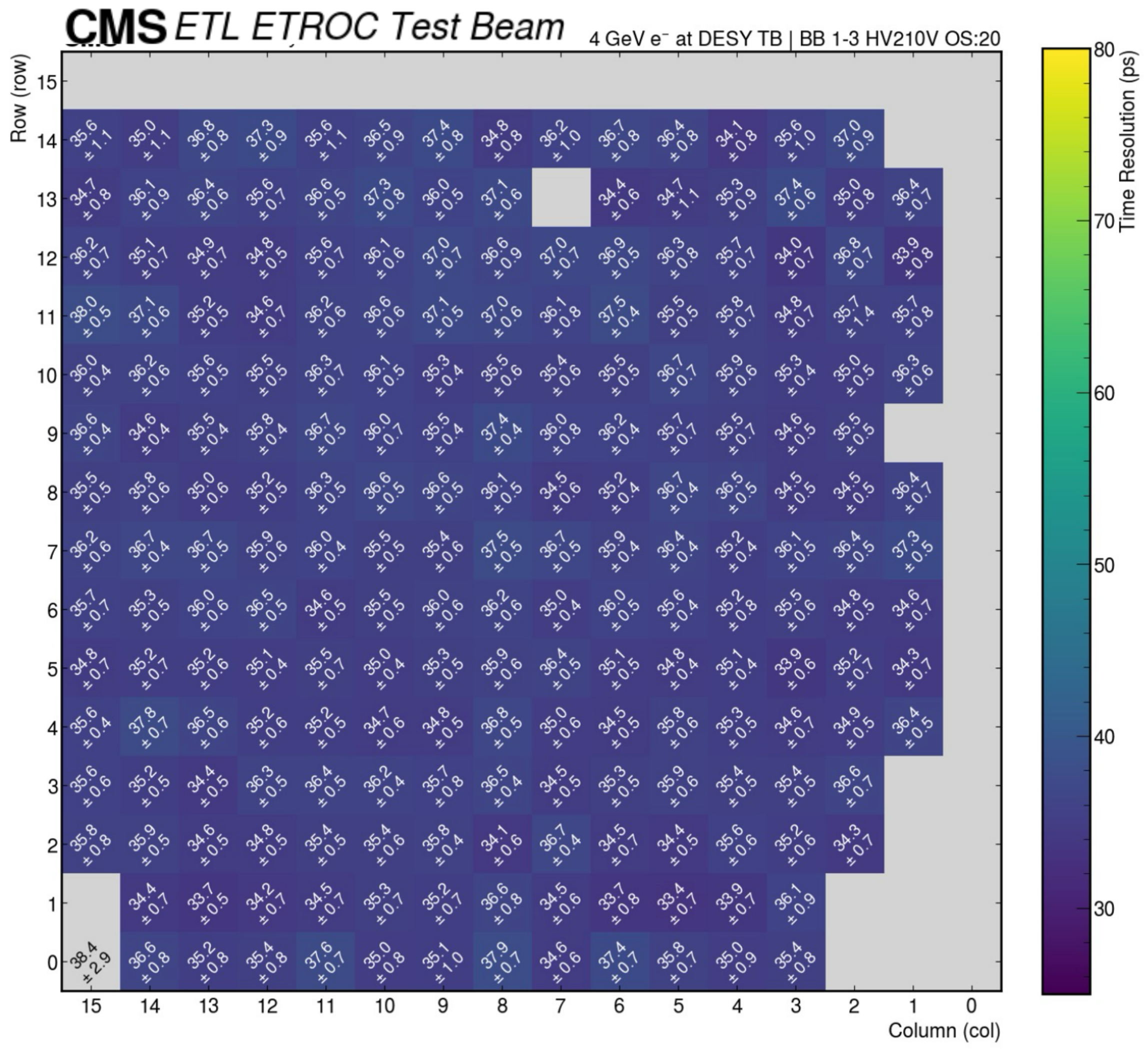


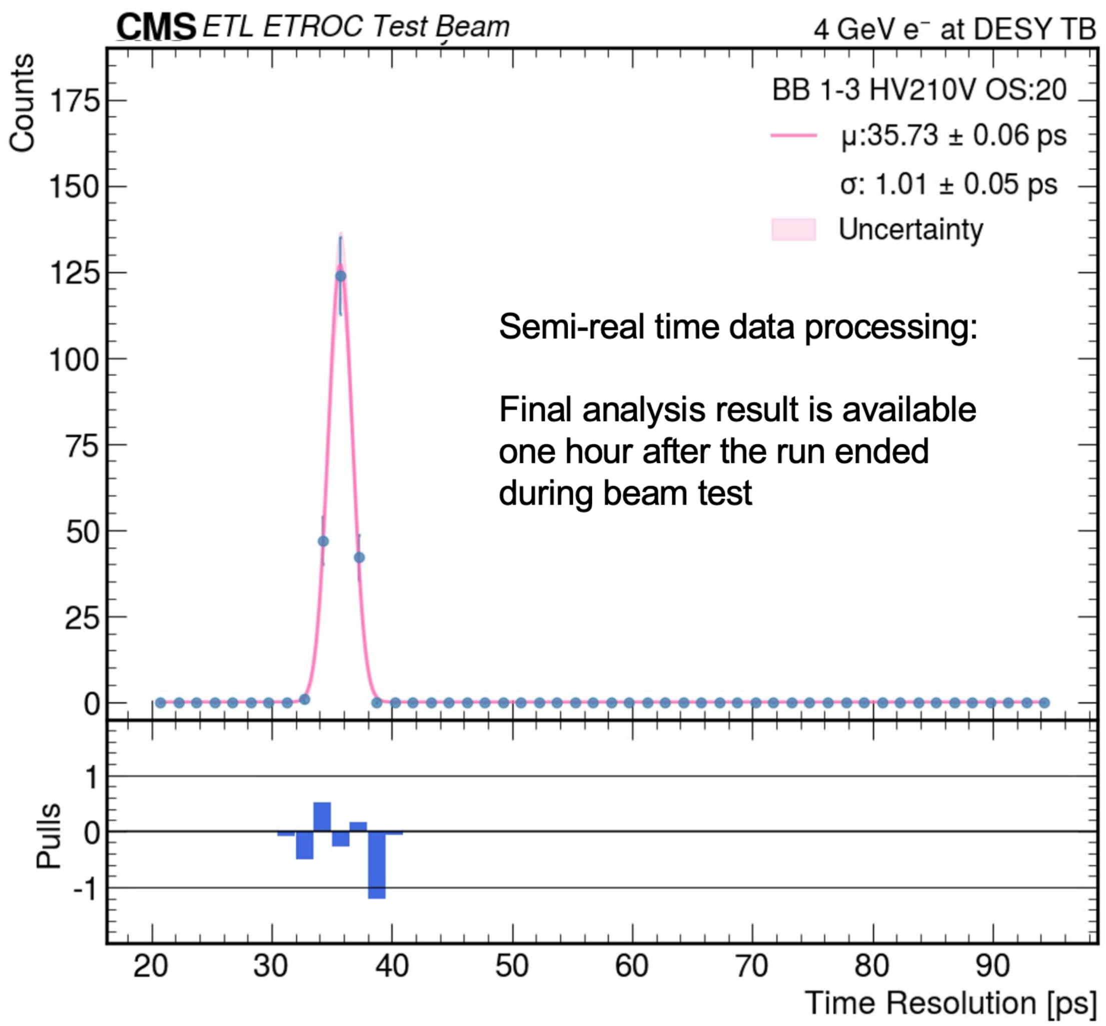


Current LGAD Sensor Performance in System

- 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

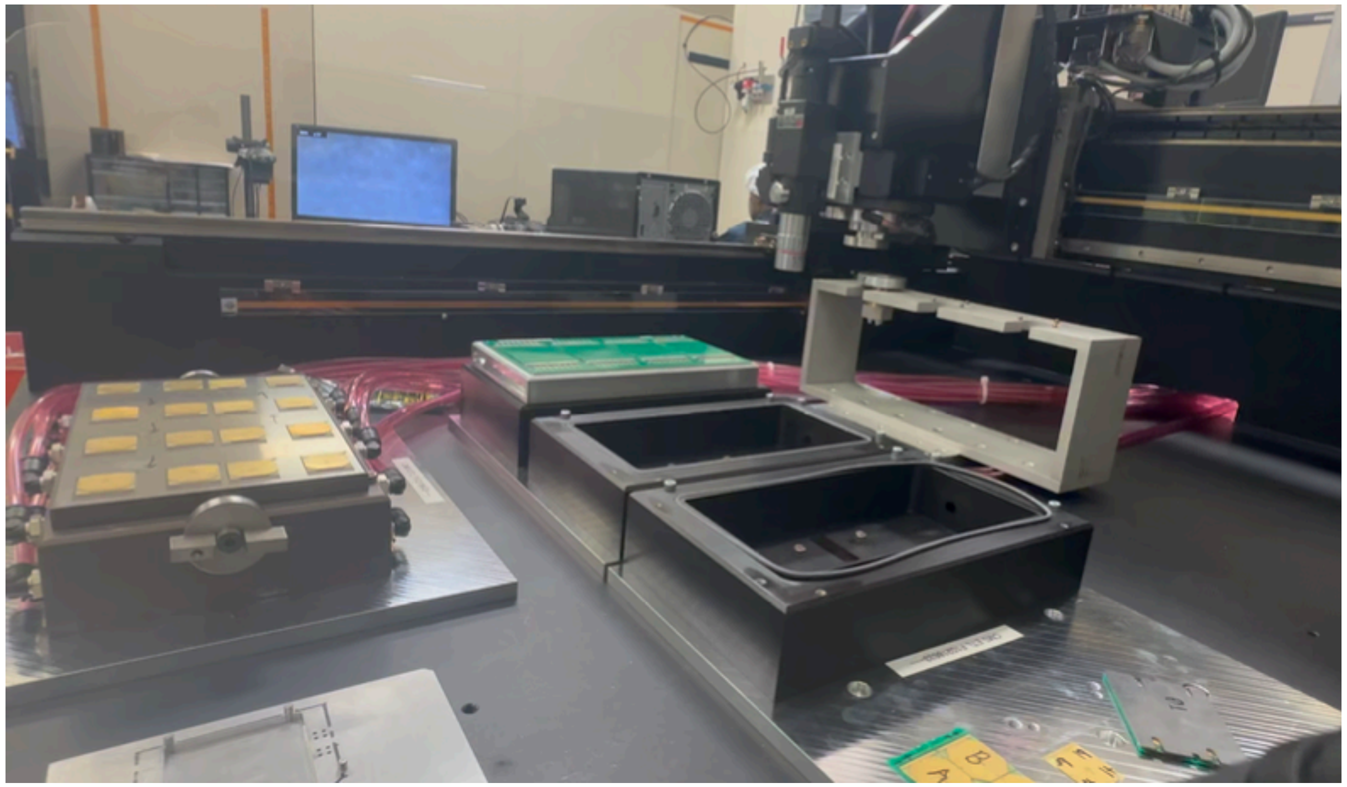


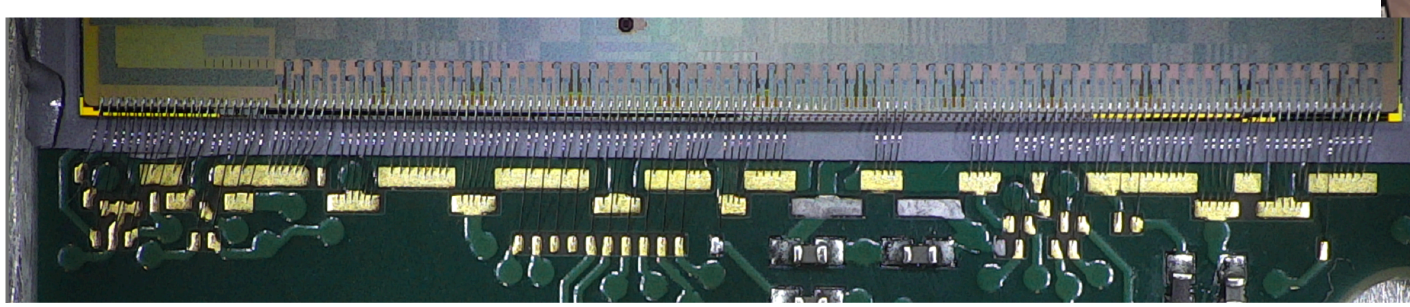


First large area precision timing detectors

See Detectors and Instrumentation R&D parallel
A. Apresyan, J. Ott, M. Safdari* (PT)

Timing Detectors Today



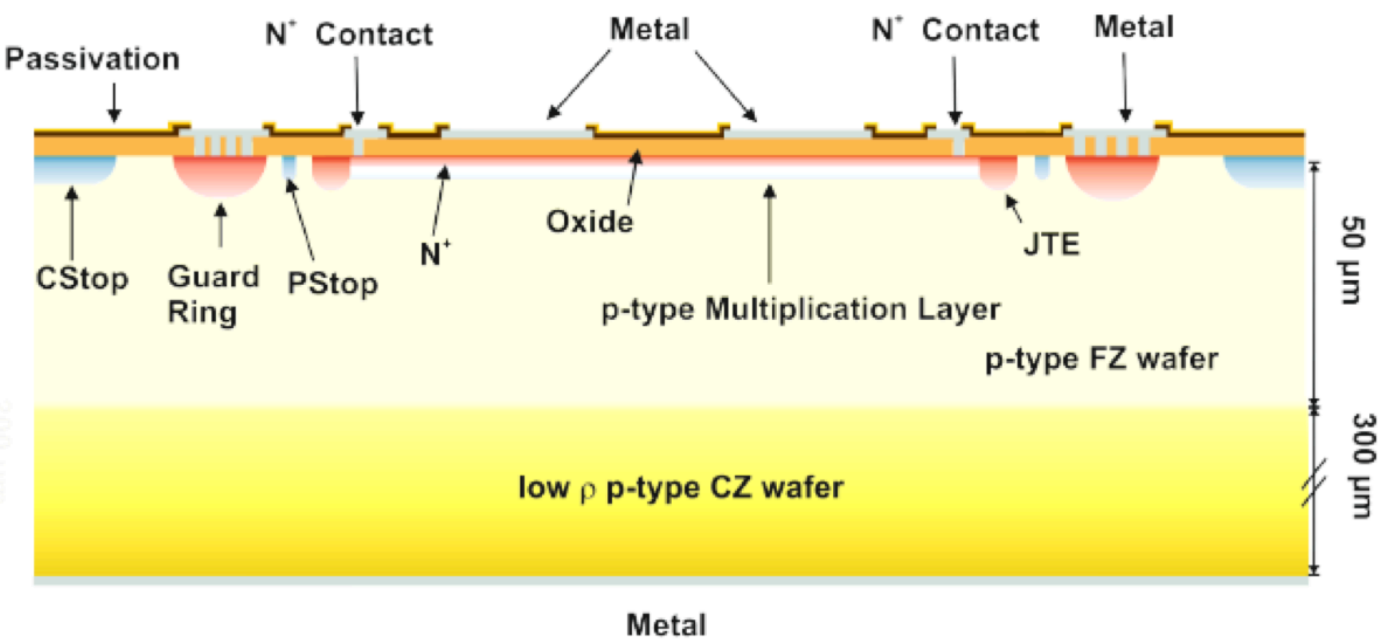


- Located at Lab D at SiDet in Fermilab
  - Configured to produce 12 modules per batch

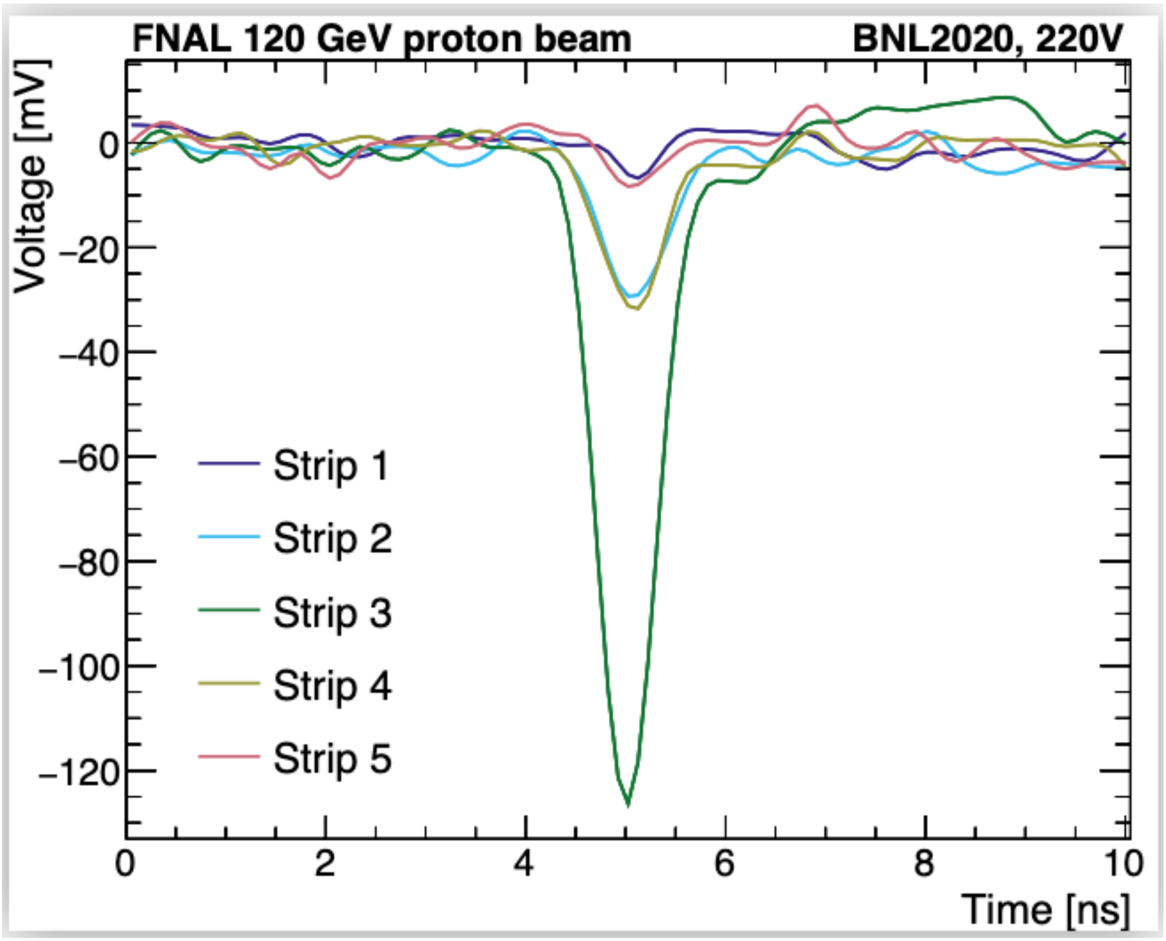
Large scale production imminent

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



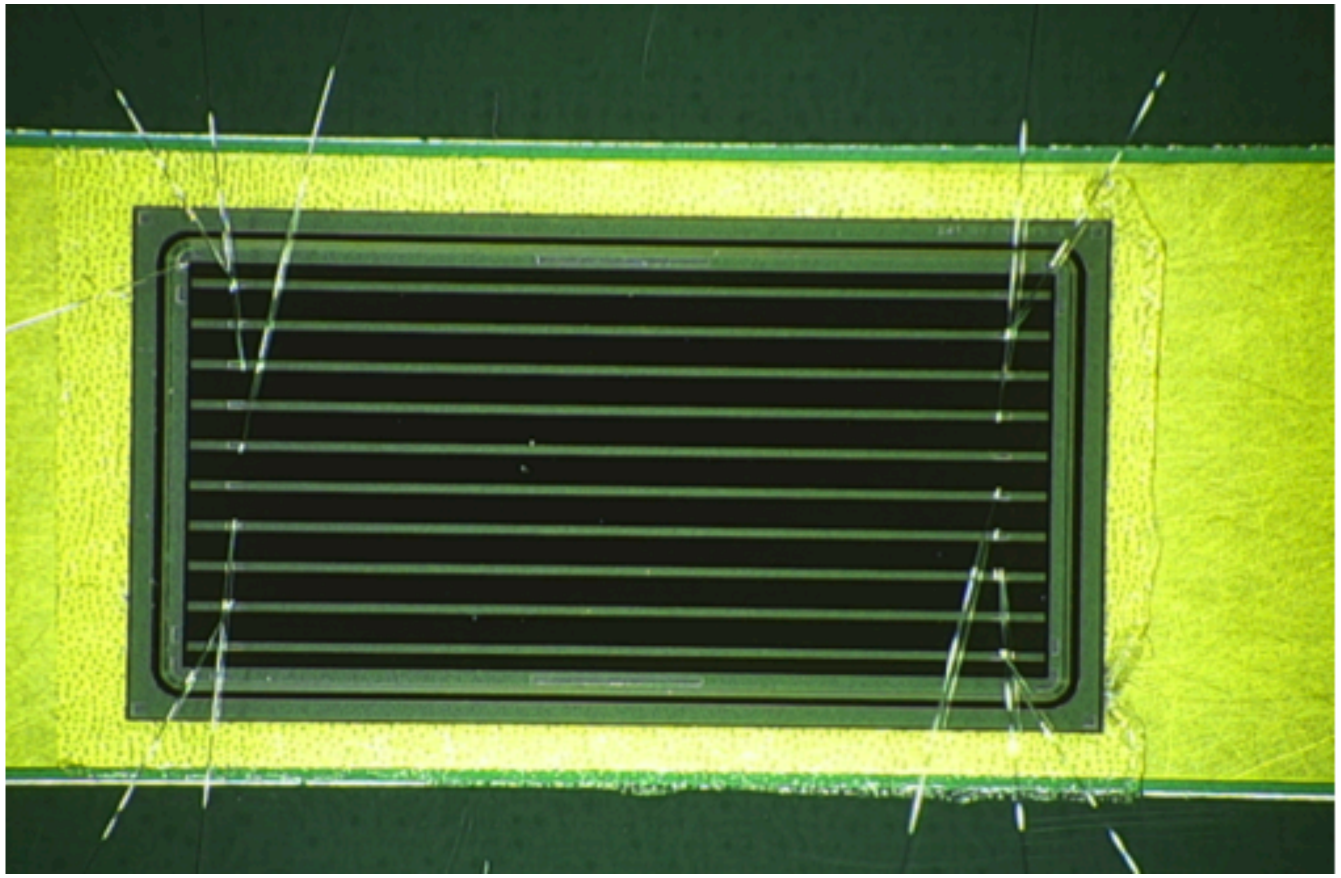
More details in A. Apresyan's talk

Signal sharing allows for improved position resolution

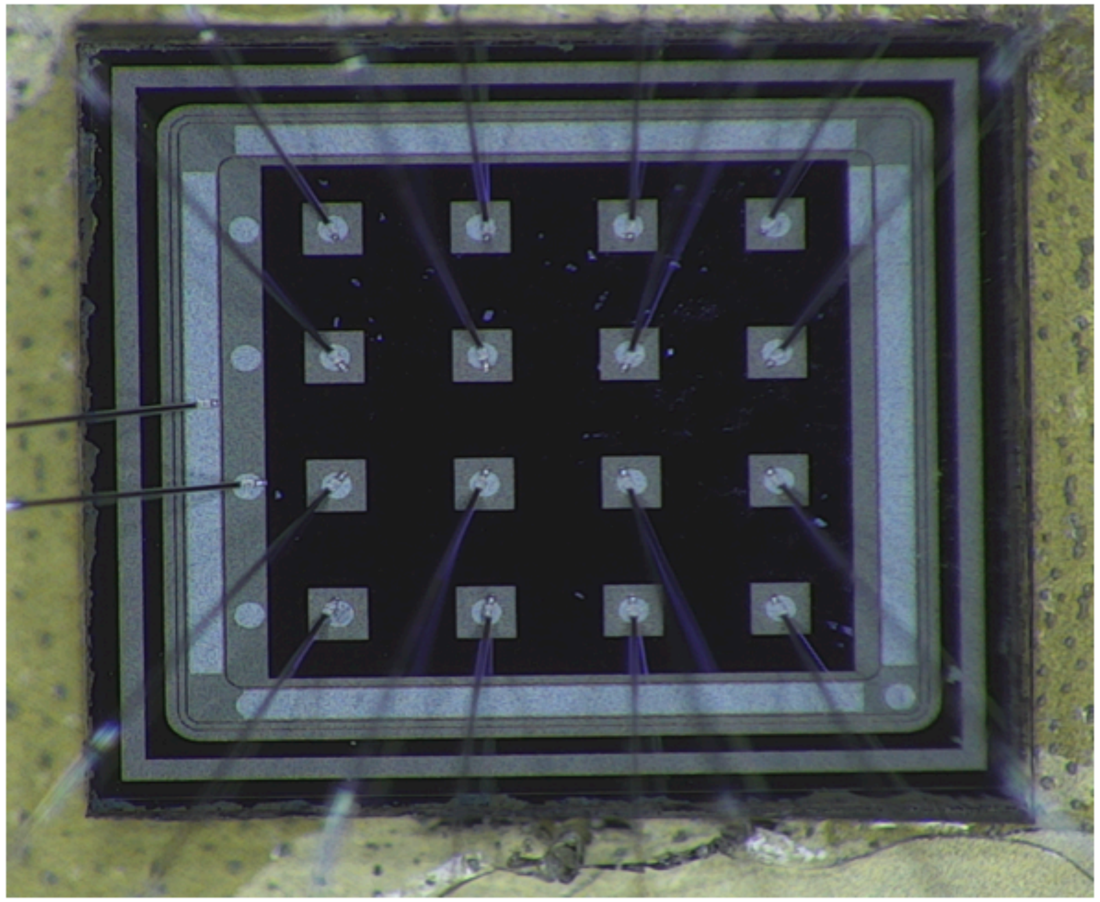
Sensor R&D and Optimization

- 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

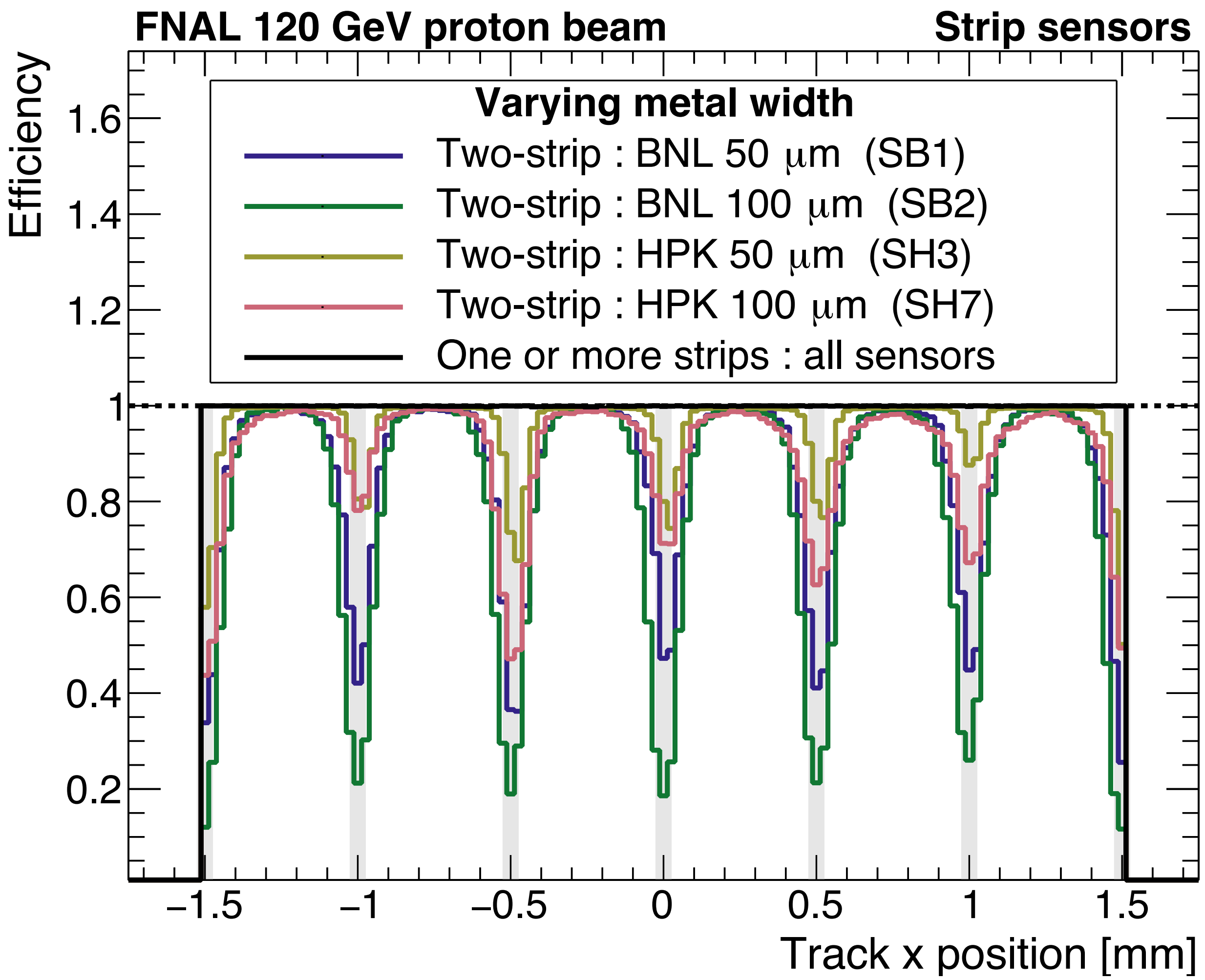


Photographs of the BNL AC-LGAD pixel devices tested in this campaign

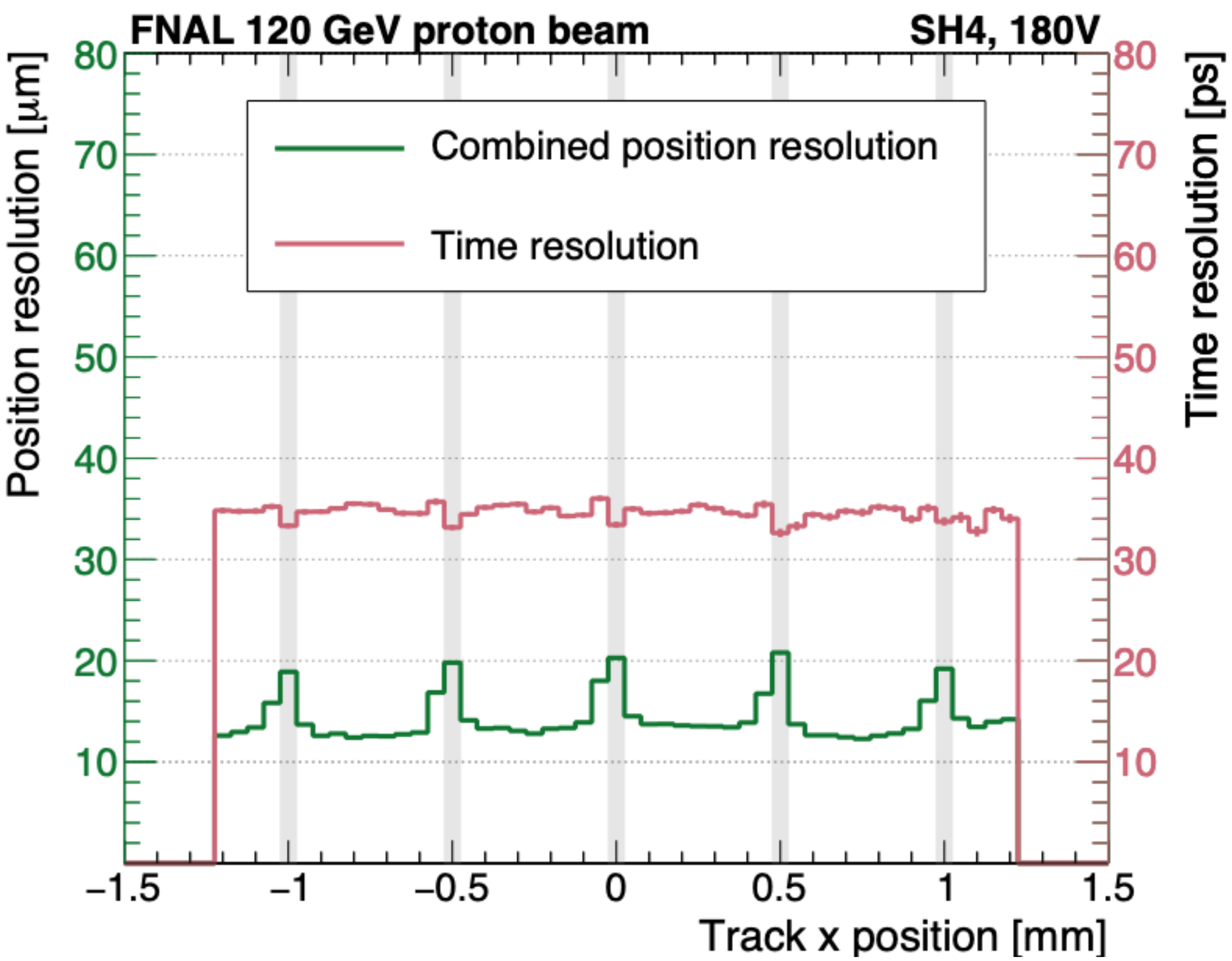
AC-LGAD Sensor Performance

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

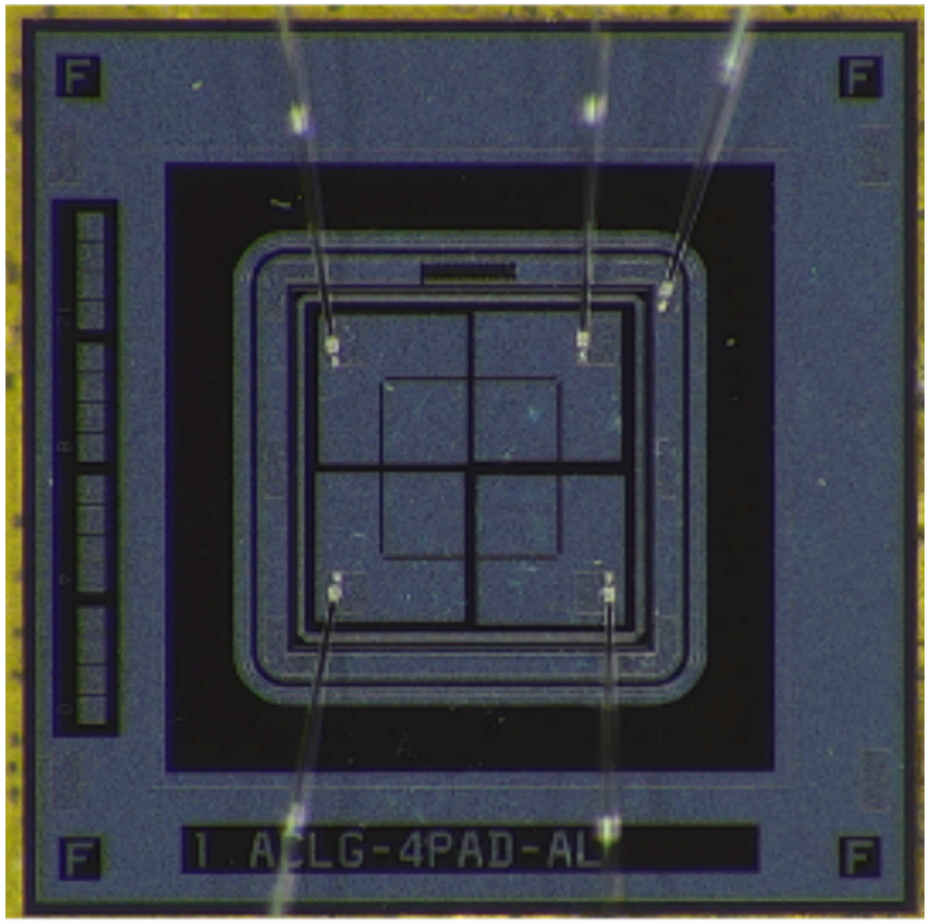


Position and **Time** resolutions across surface

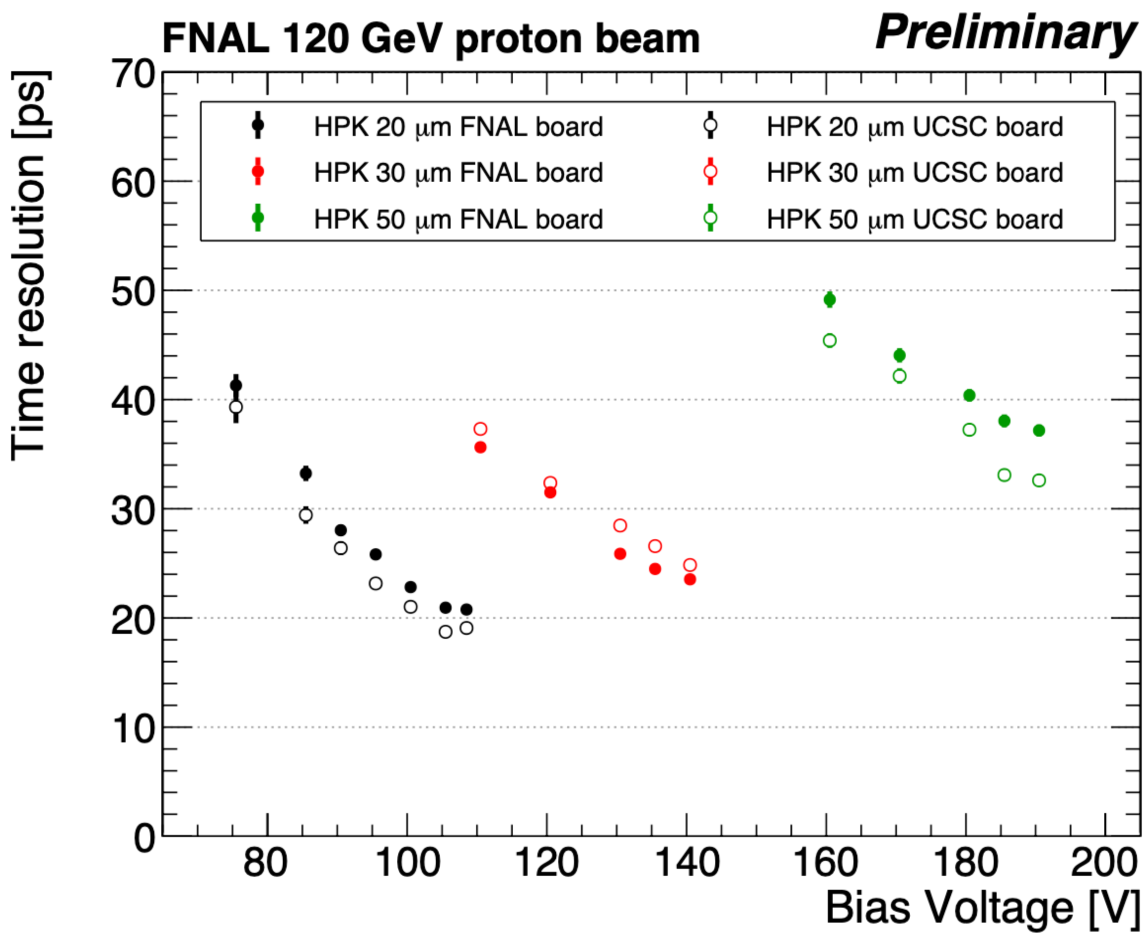
Towards Better Time Resolution

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



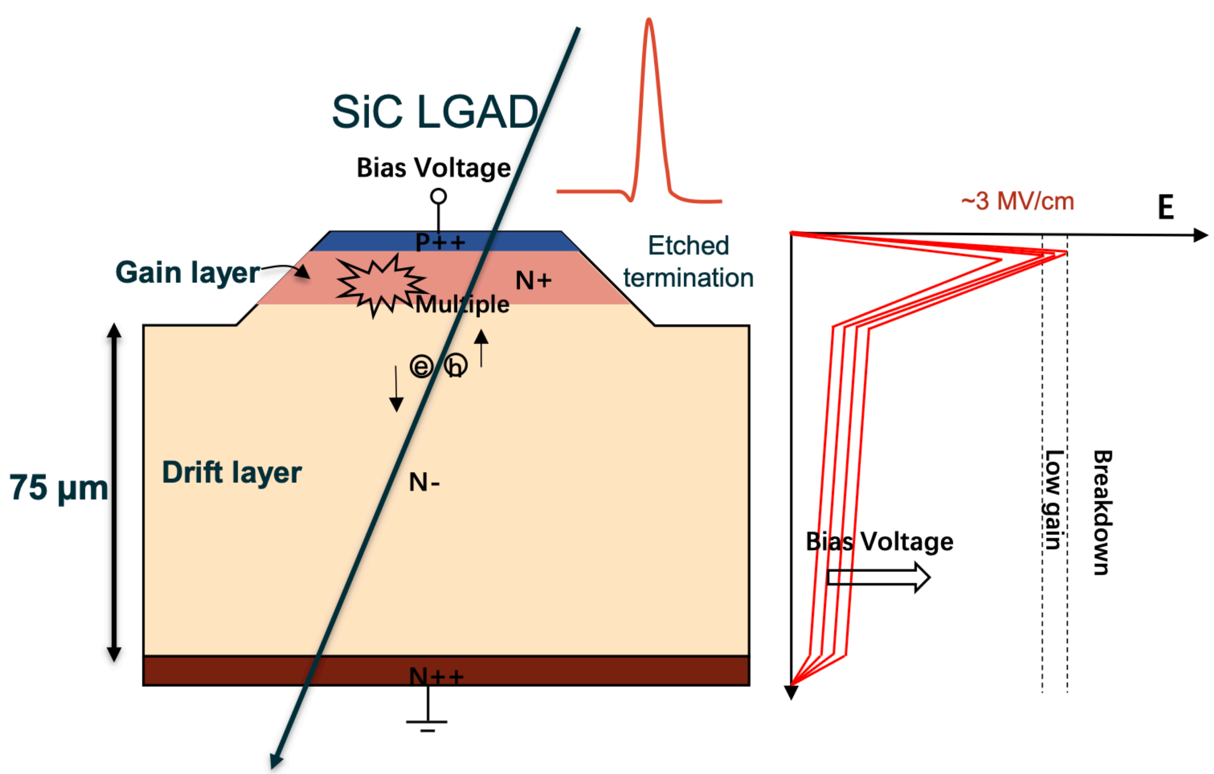
Time resolution for **20**, **30** and **50** µm-thick sensors

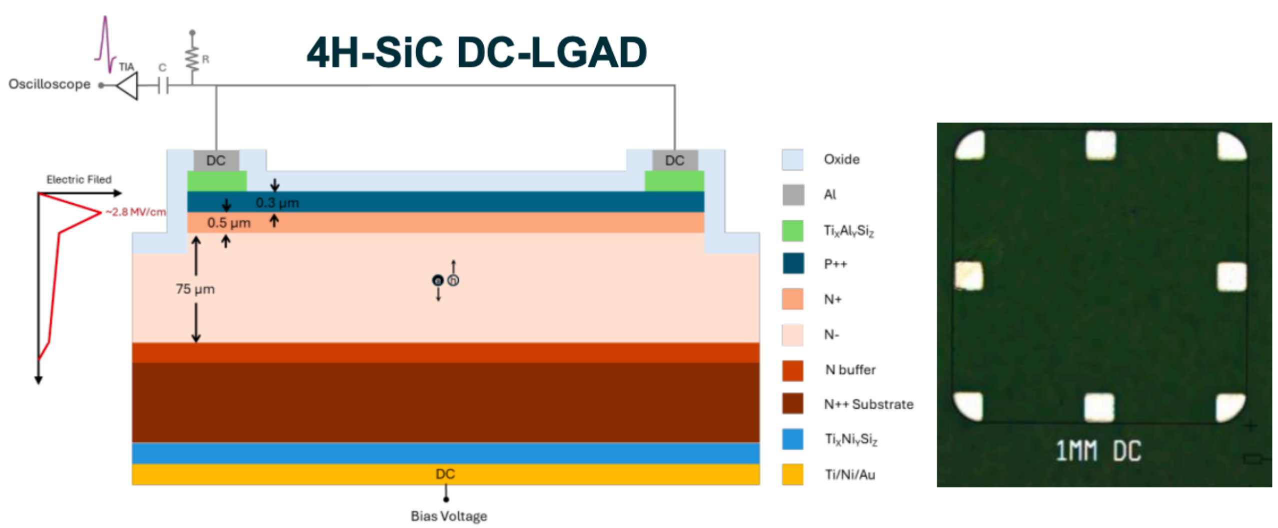
Silicon Carbide LGADs

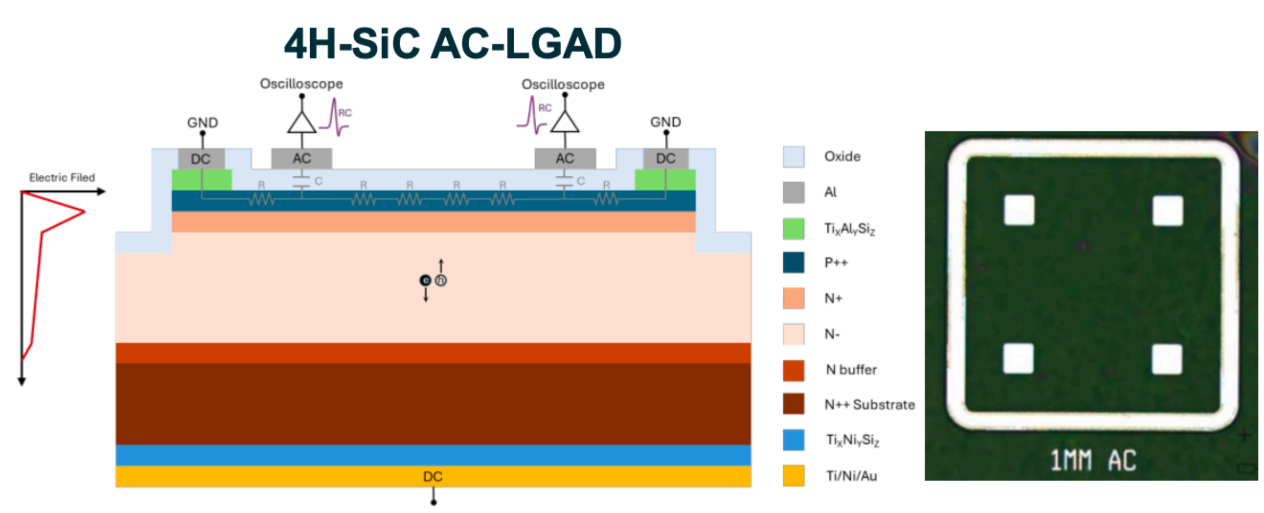
TaoYang @ CPAD2024

- 4H-SiC has potential applications in radiation detection, especially fast time detection and high temperature
- Fabrication and testing of DC and AC-LGADs is ongoing

More fabrication details on:
B.Sekely et al., “Progress Towards 4H-SiC Low Gain Avalanche Detectors (LGADs),” in Book of Abstracts from the ICSCRM 2024, pp.694-223695, Sept 2024. doi:10.4028/b-f6NMEP.224





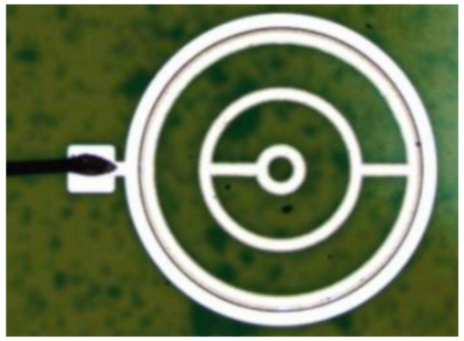


Silicon Carbide LGADs

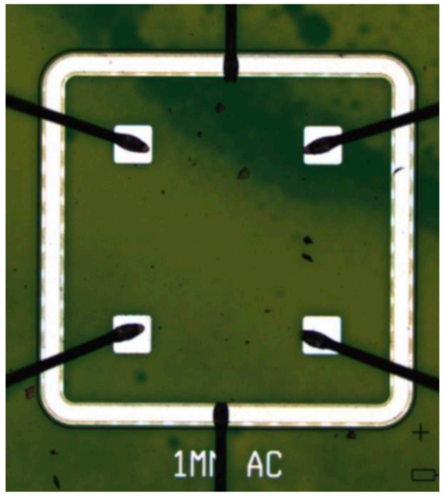
TaoYang @ CPAD2024

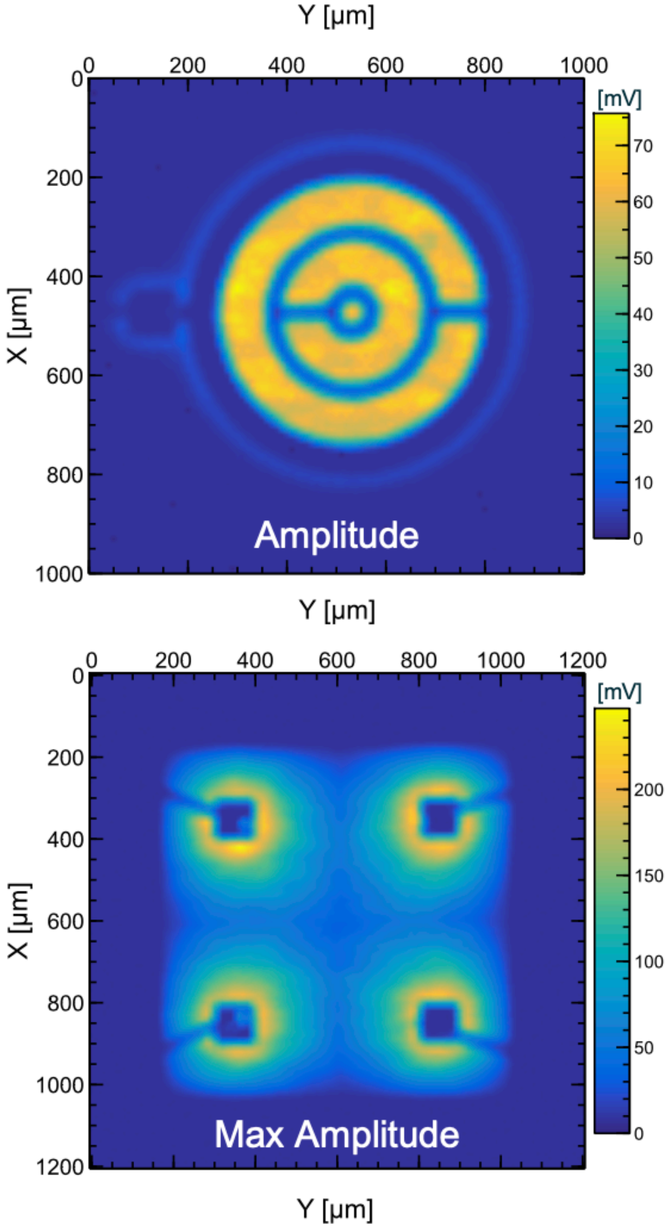
- Developed a UV-TCT to characterize SiC LGADs

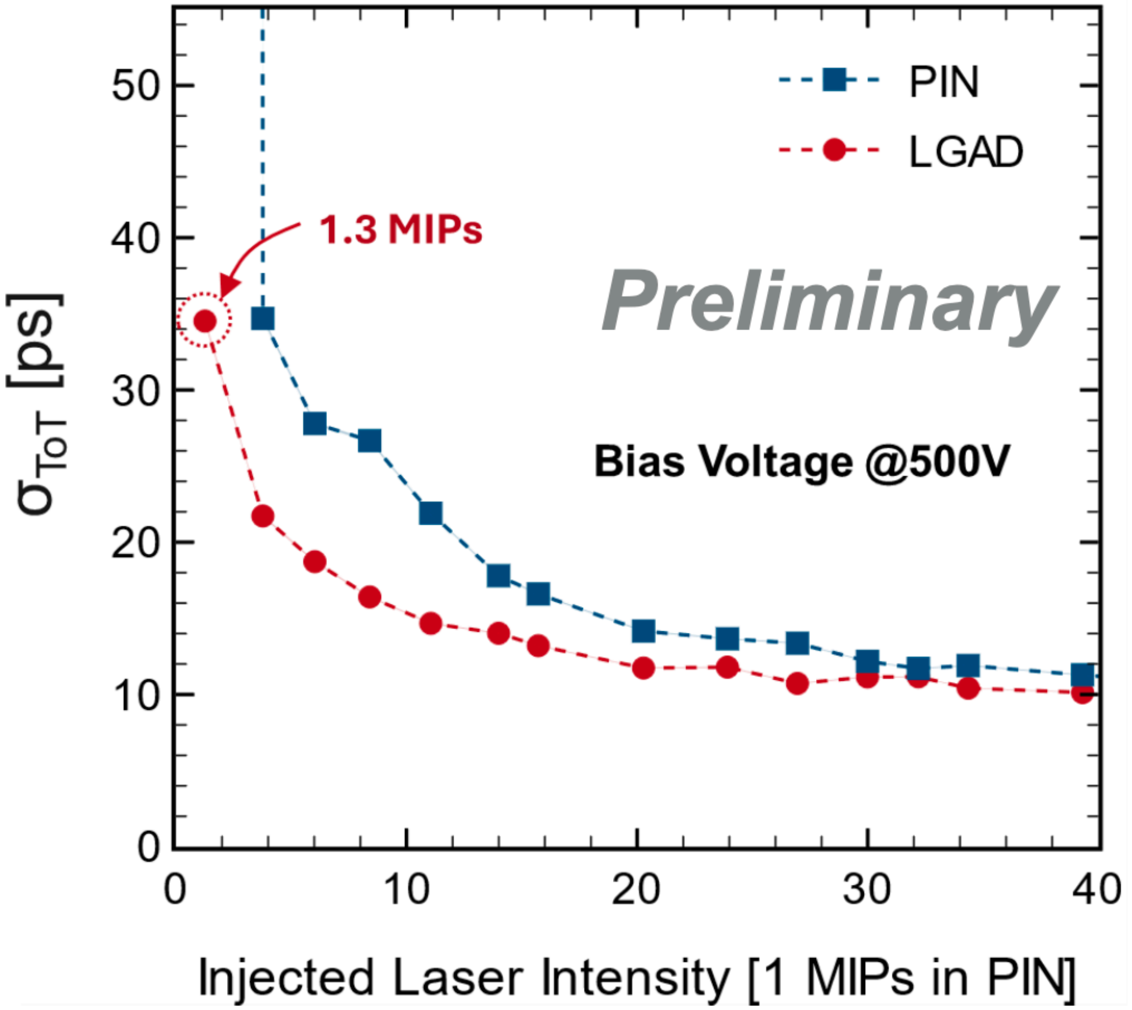
600 μm SiC DC-LGAD



1mm SiC Pixel AC-LGAD







Time resolution to MIP like signals ~35 ps

Silicon Carbide LGADs

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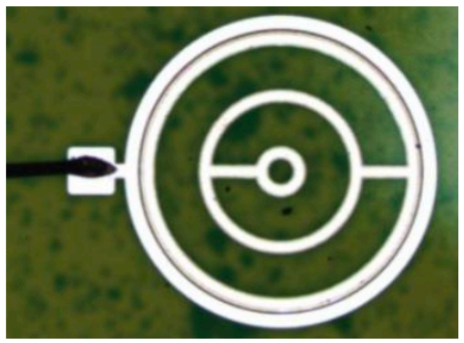
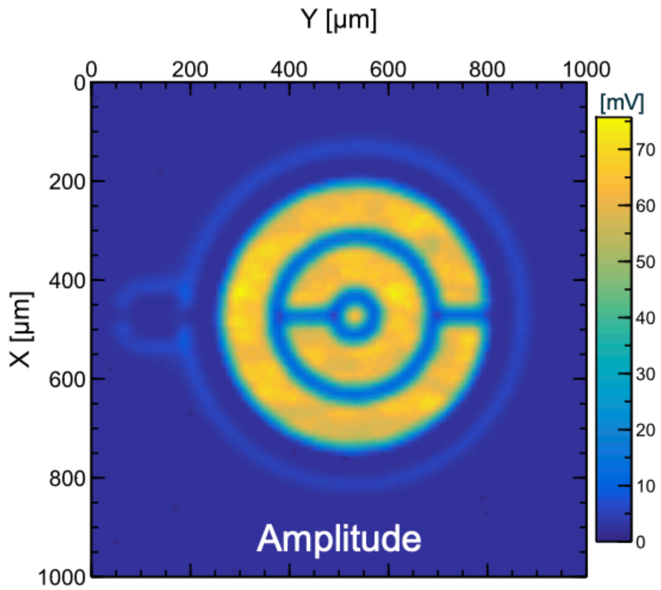
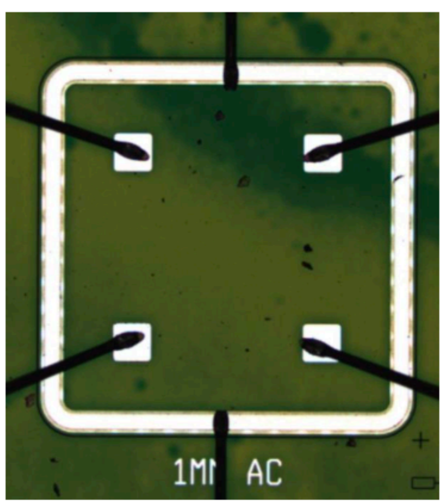
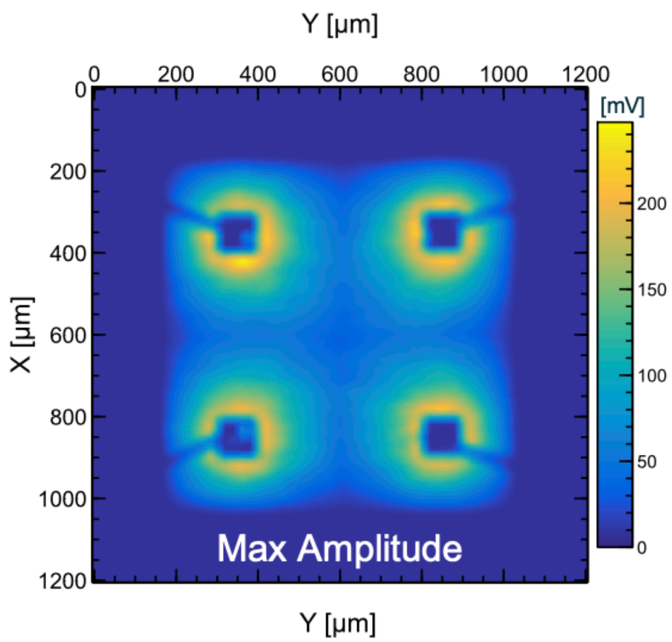
600 µm SiC DC-LGAD

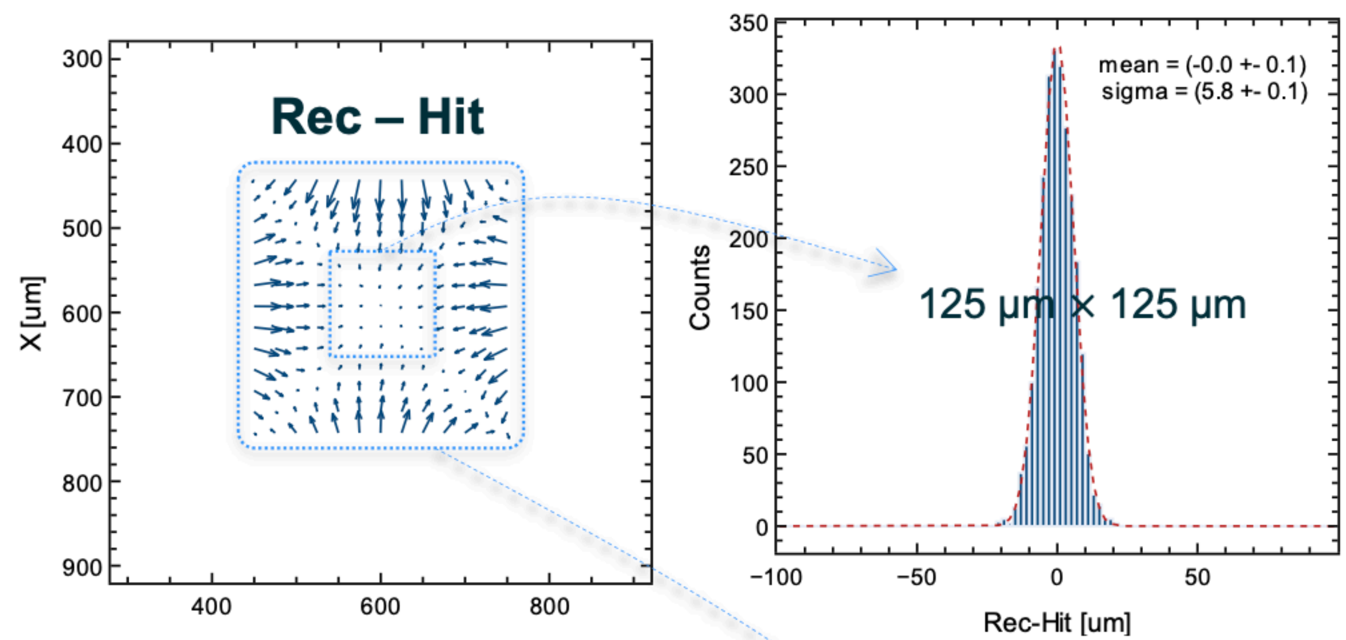




1mm SiC Pixel AC-LGAD





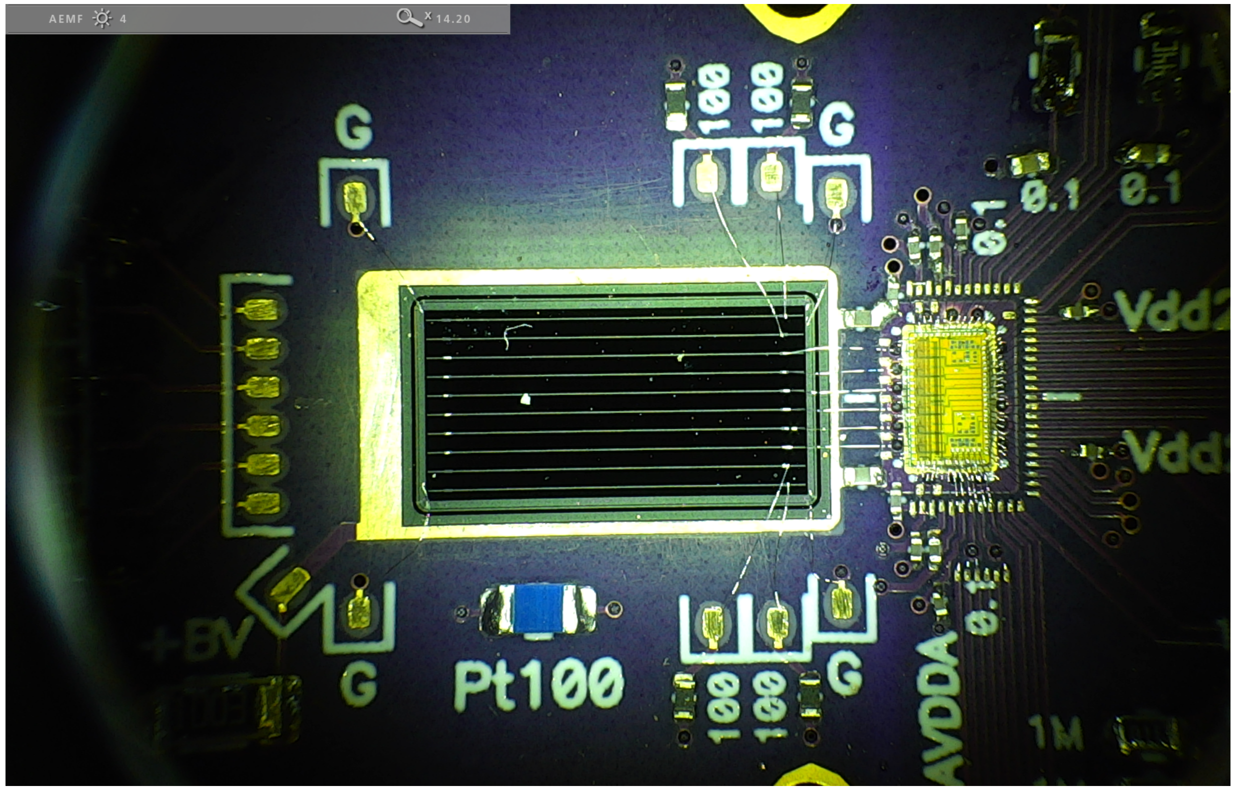


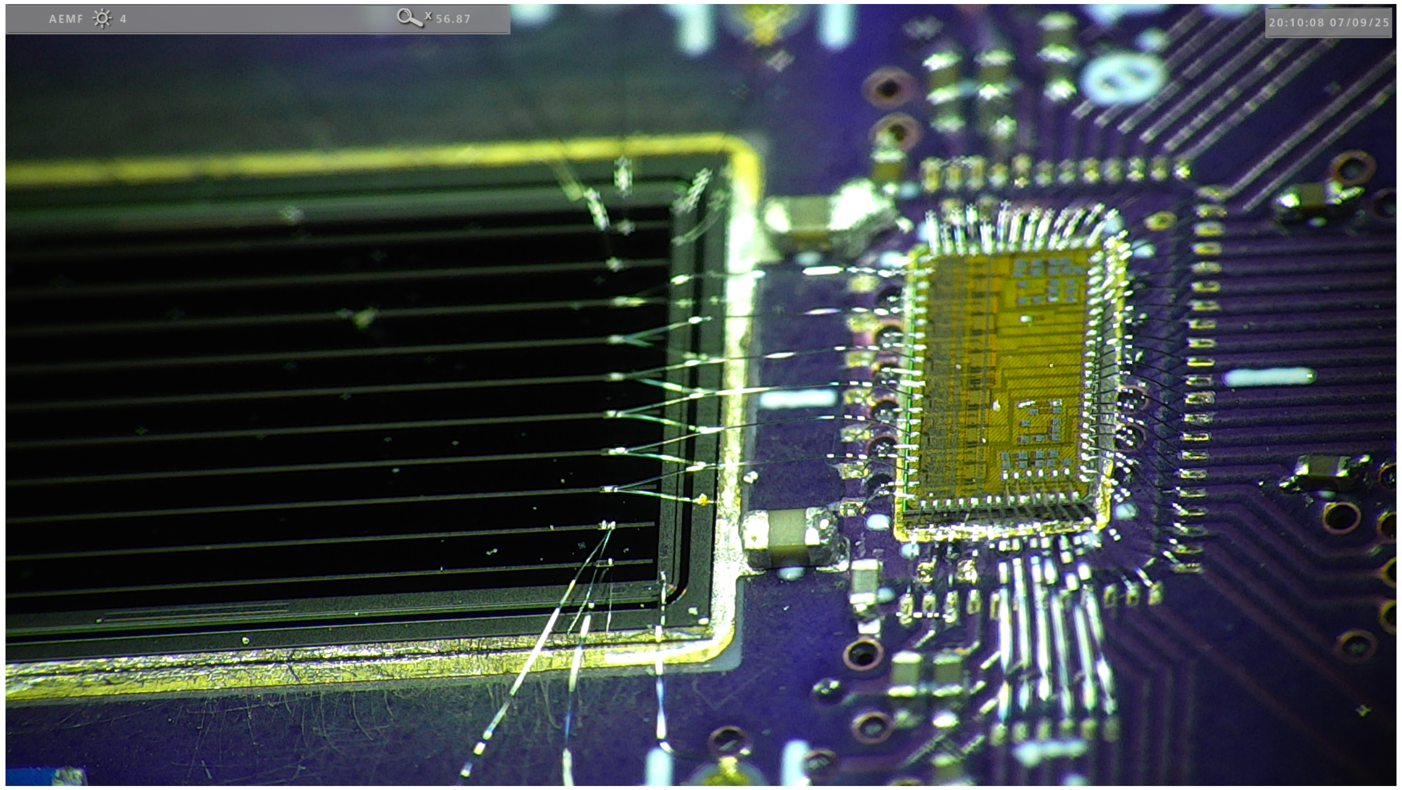
AC-LGAD position resolution is 5.8 µm

Next Generation Readout Chips

- Constant fraction discriminator (CFD) chip to remove time-walk effect
  - Several successful iteration fabricated and benchmarked
  - Latest iteration improves performance for AC-LGADs

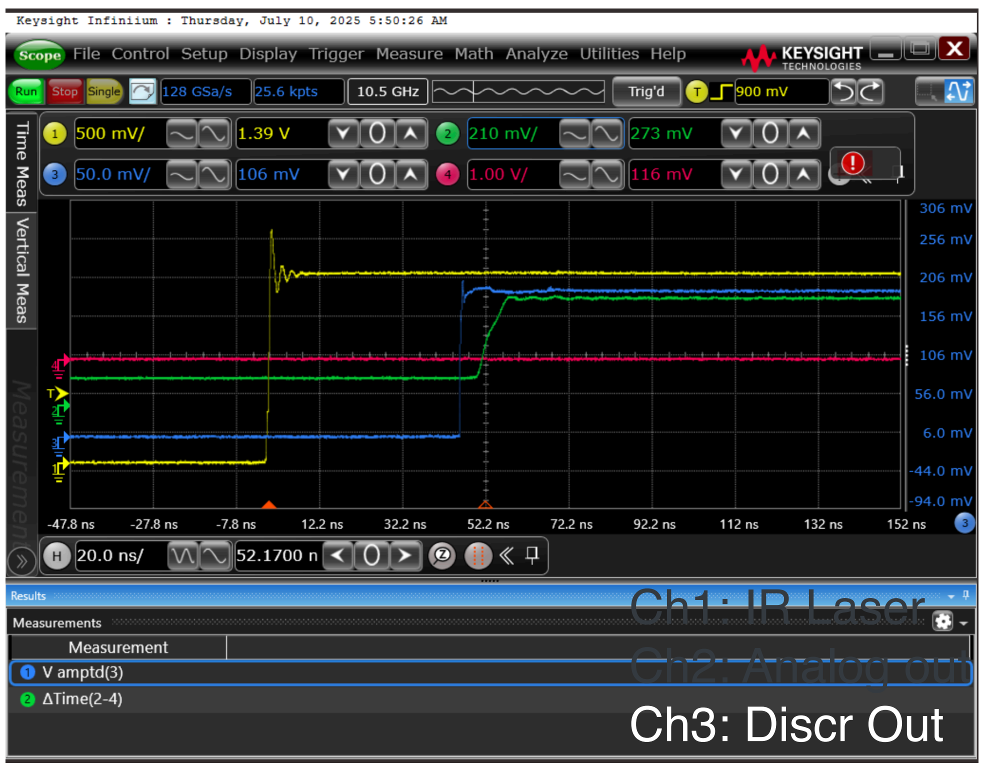
Low-power chip and new architecture towards scalable large area timing detectors

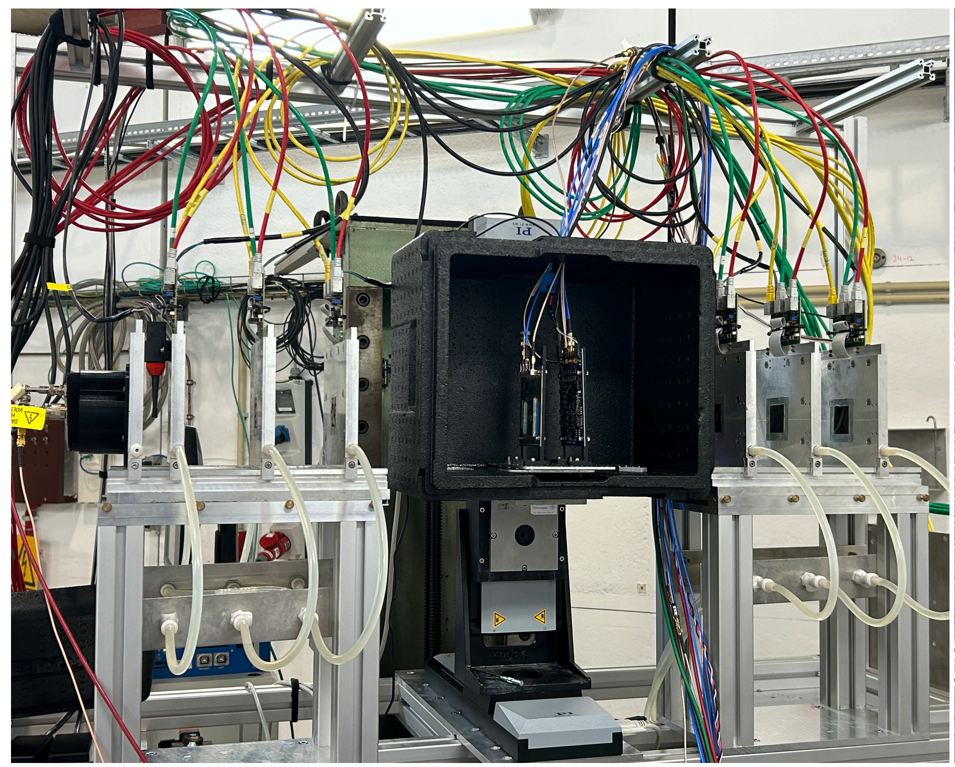


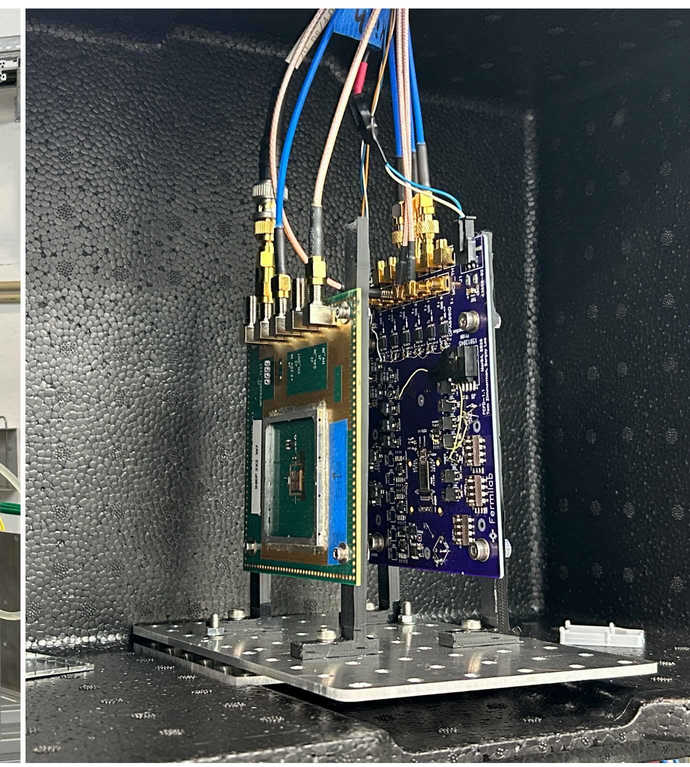


Next Generation Readout Chips

- Assembly, setup and characterization advancing at fast pace





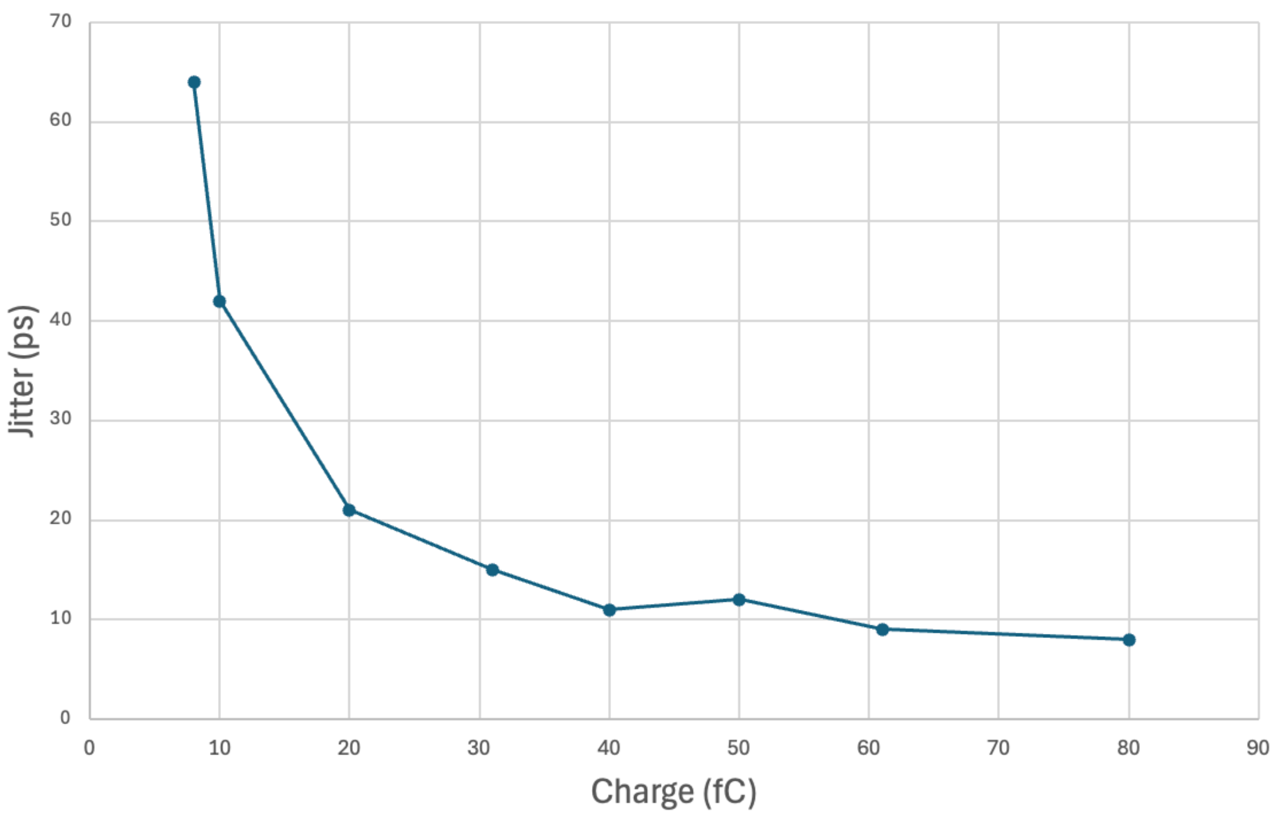


Since June, FCFDv1.1 already tested with charge injection, laser and 5 GeV electrons

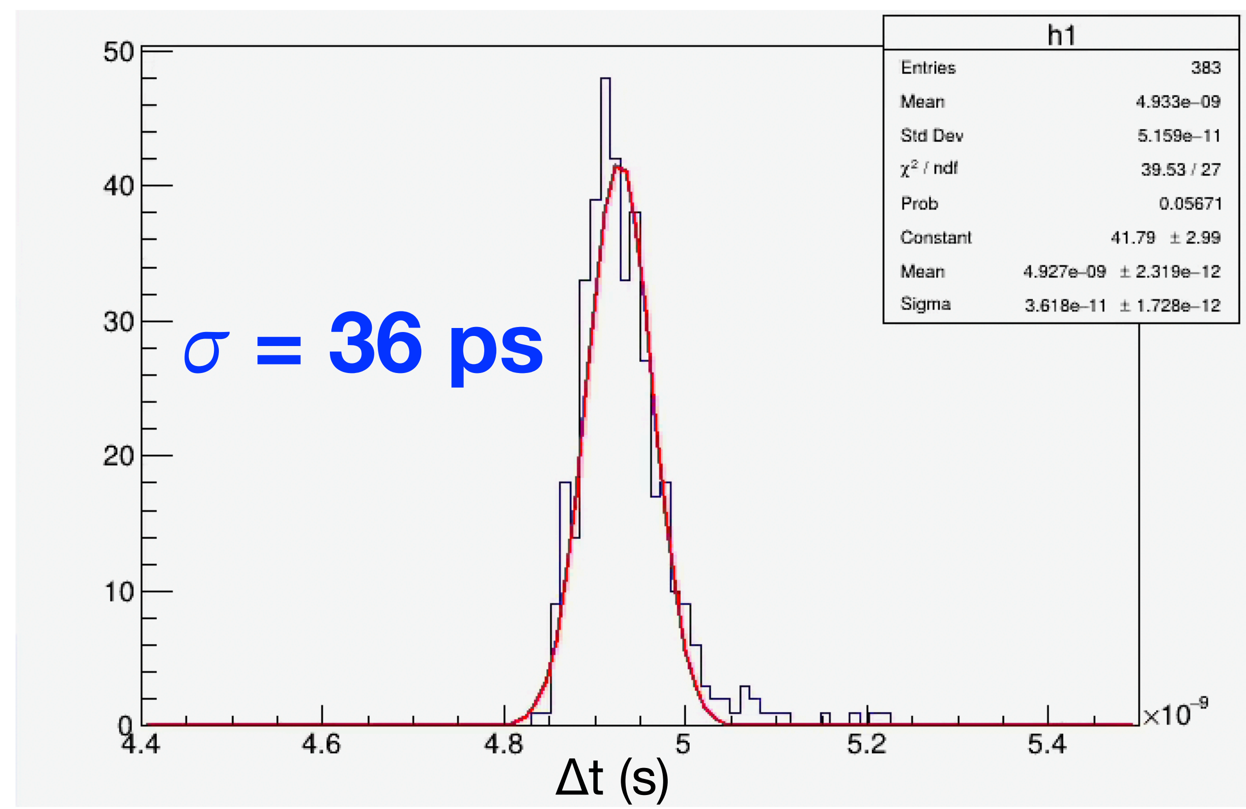
Next Generation Readout Chips

Preliminary results

Charge injection



5 GeV electrons

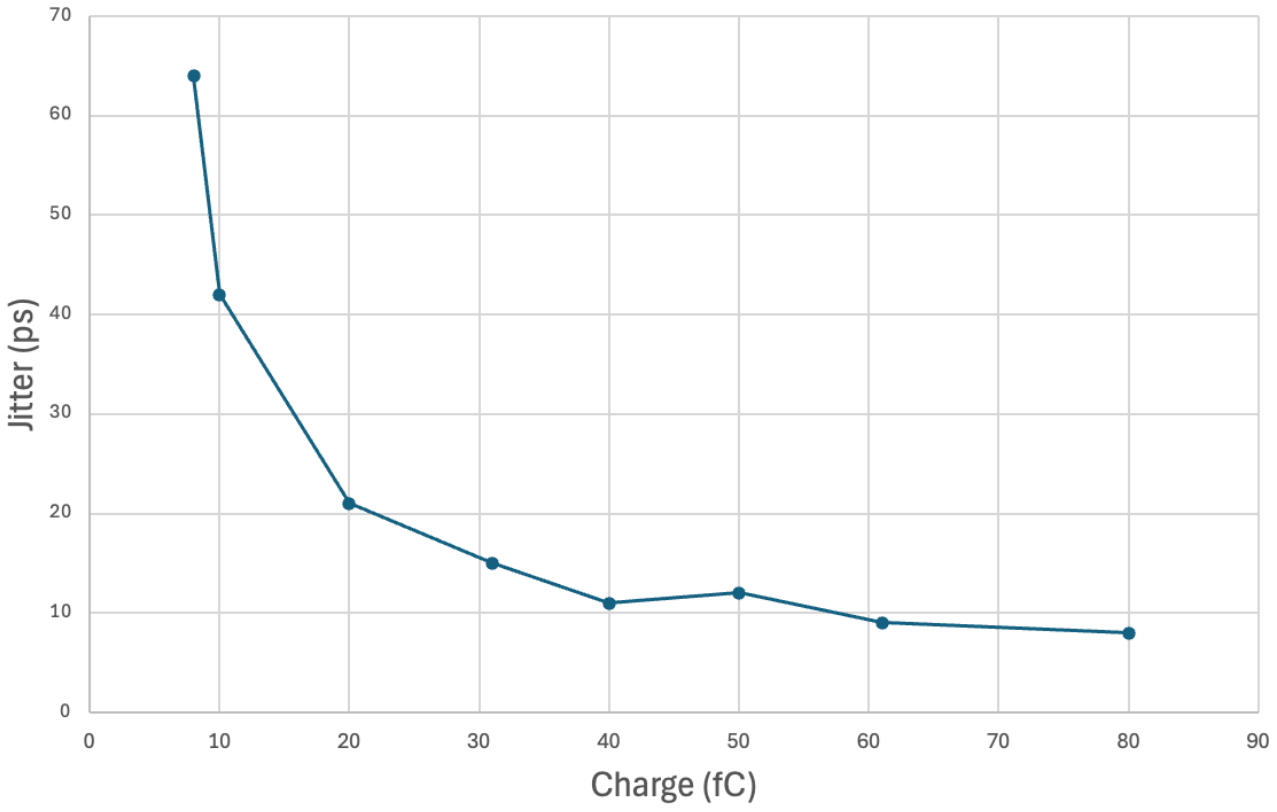


Charge injection according to spec and simulation

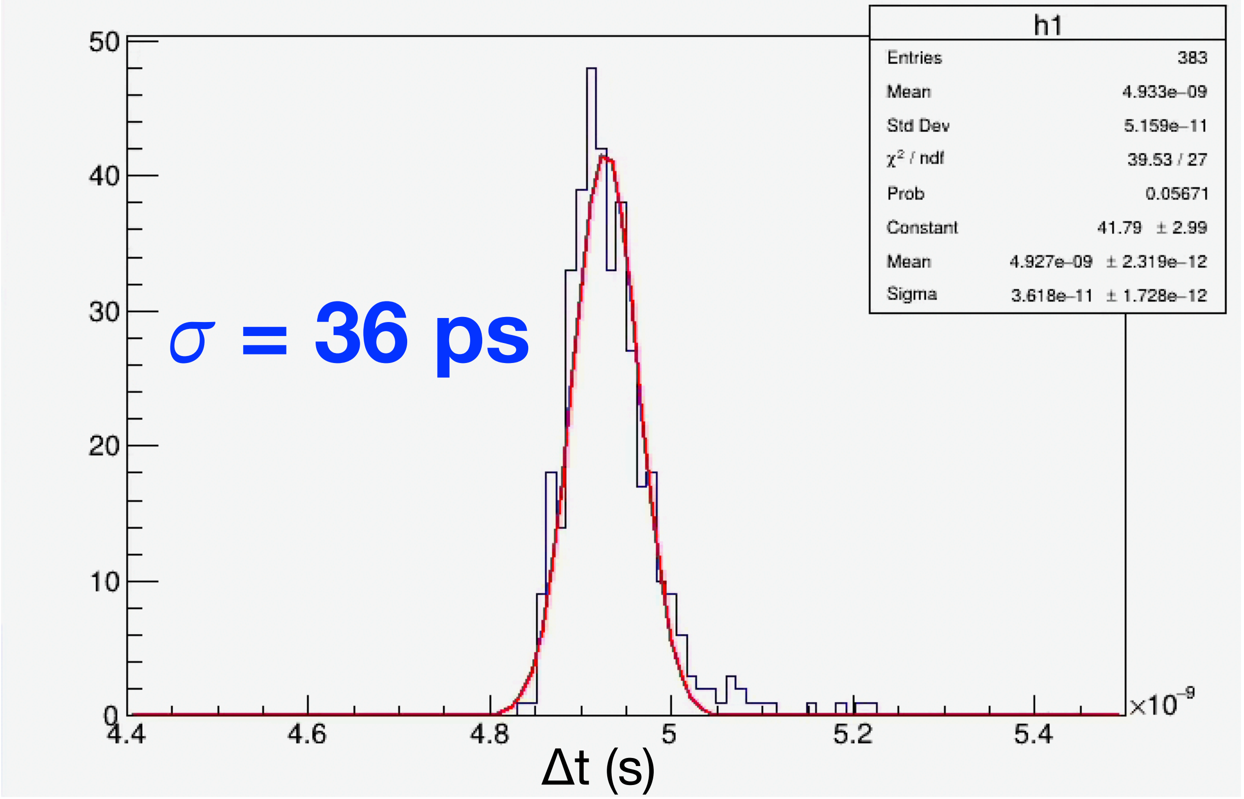
Next Generation Readout Chips

Preliminary results

Charge injection



5 GeV electrons



Excellent results: 36 ps time resolution for 5 GeV electrons

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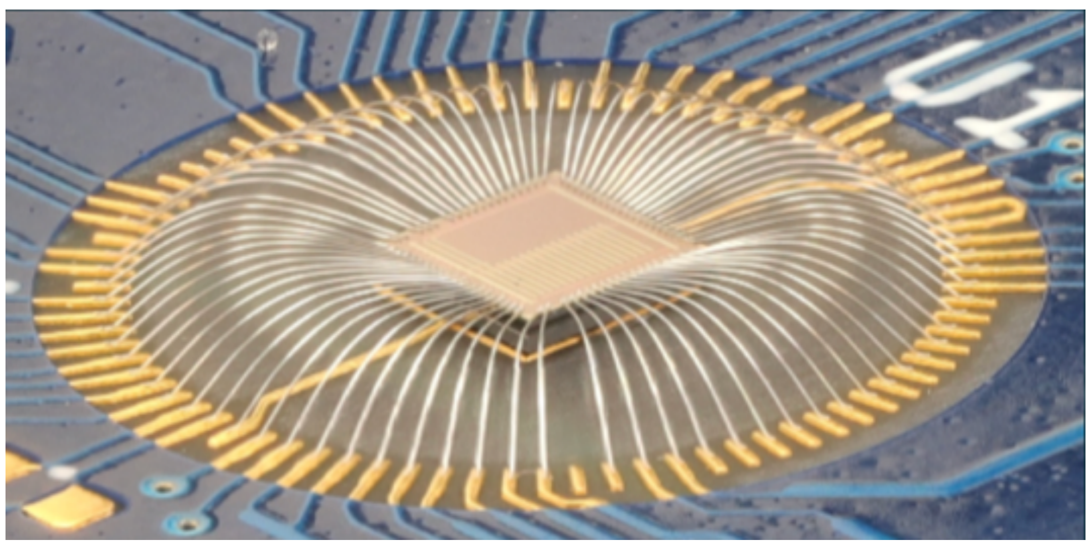
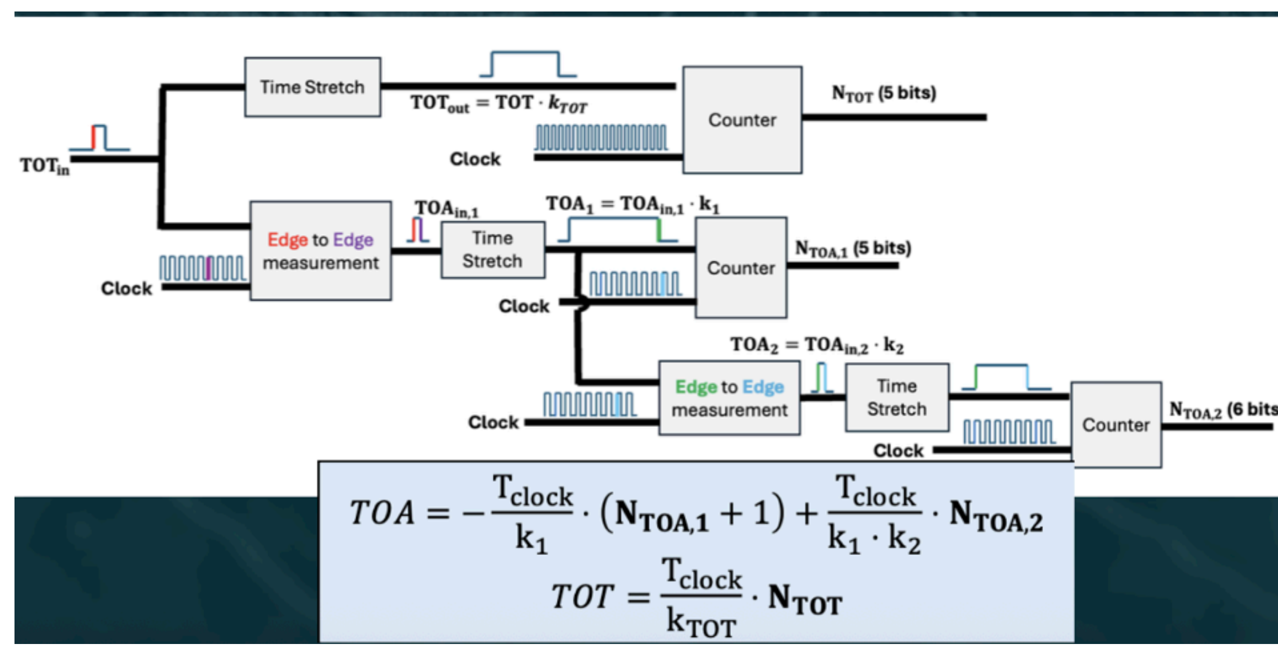
Readout Chip for Pixel Detectors

Input from T. Heim (LBL)

Progress towards readout chips for 4D pixels in 28 nm CMOS

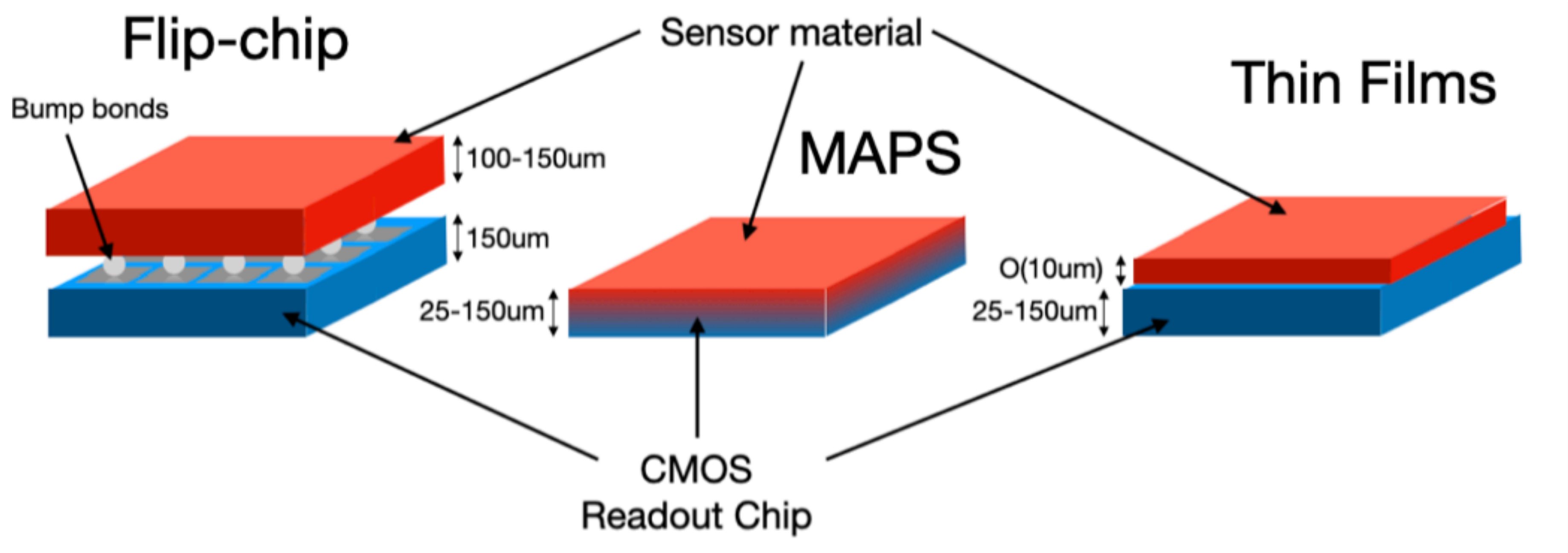




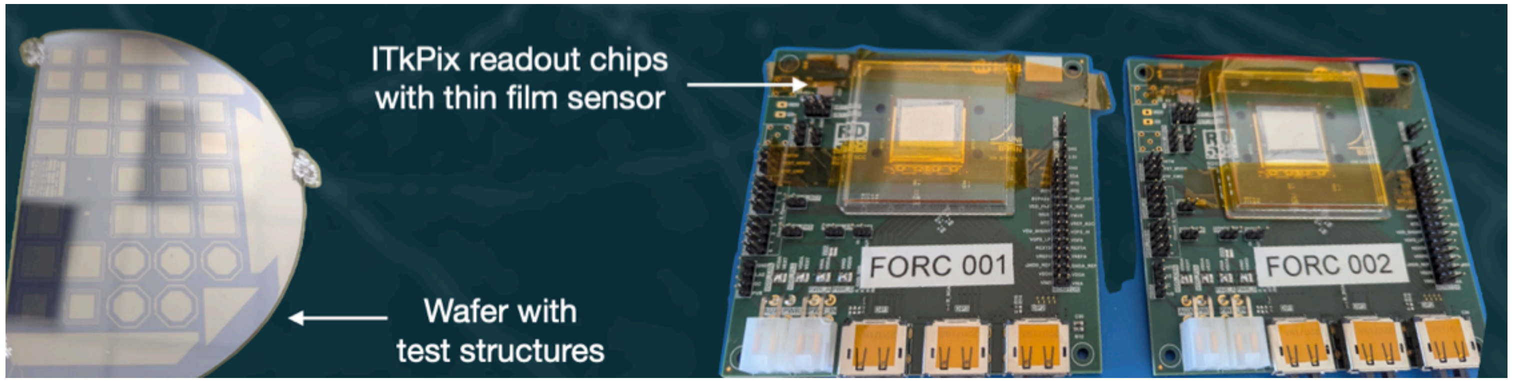
Targeting high time precision analog front-end and low TDC; in high radiation environment

FORC: Film on Readout Chip

Input from T. Heim (LBL)



Improve bump bonding limitations by using thin film deposition

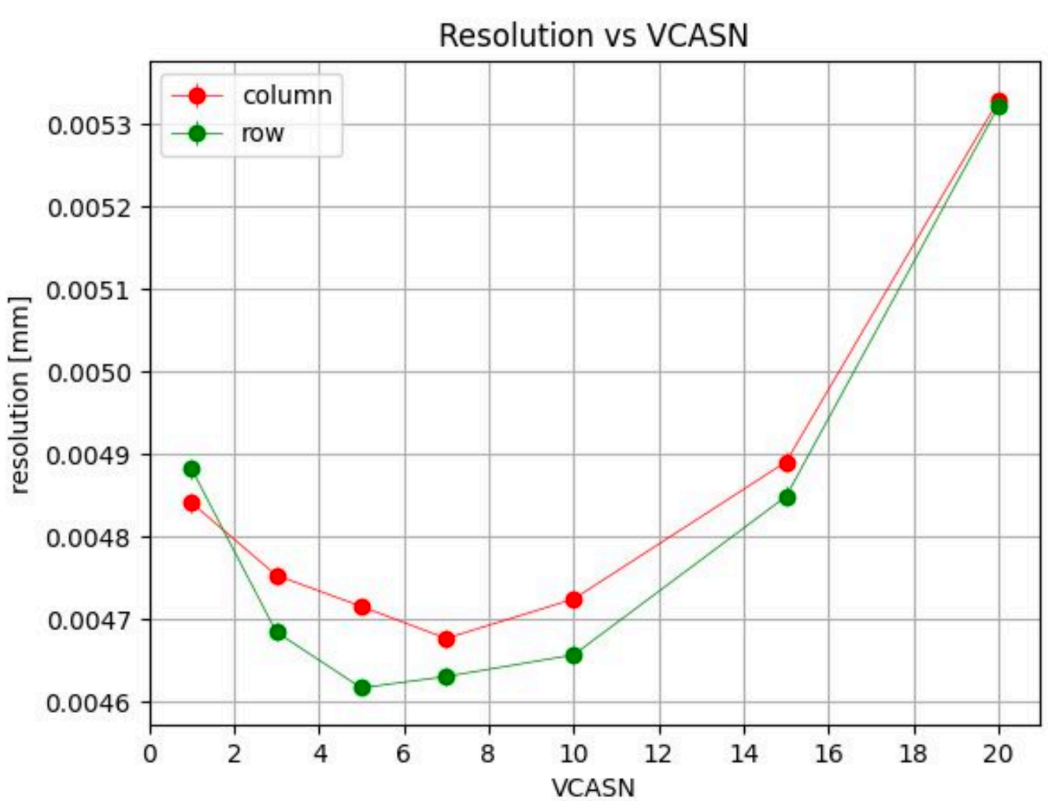


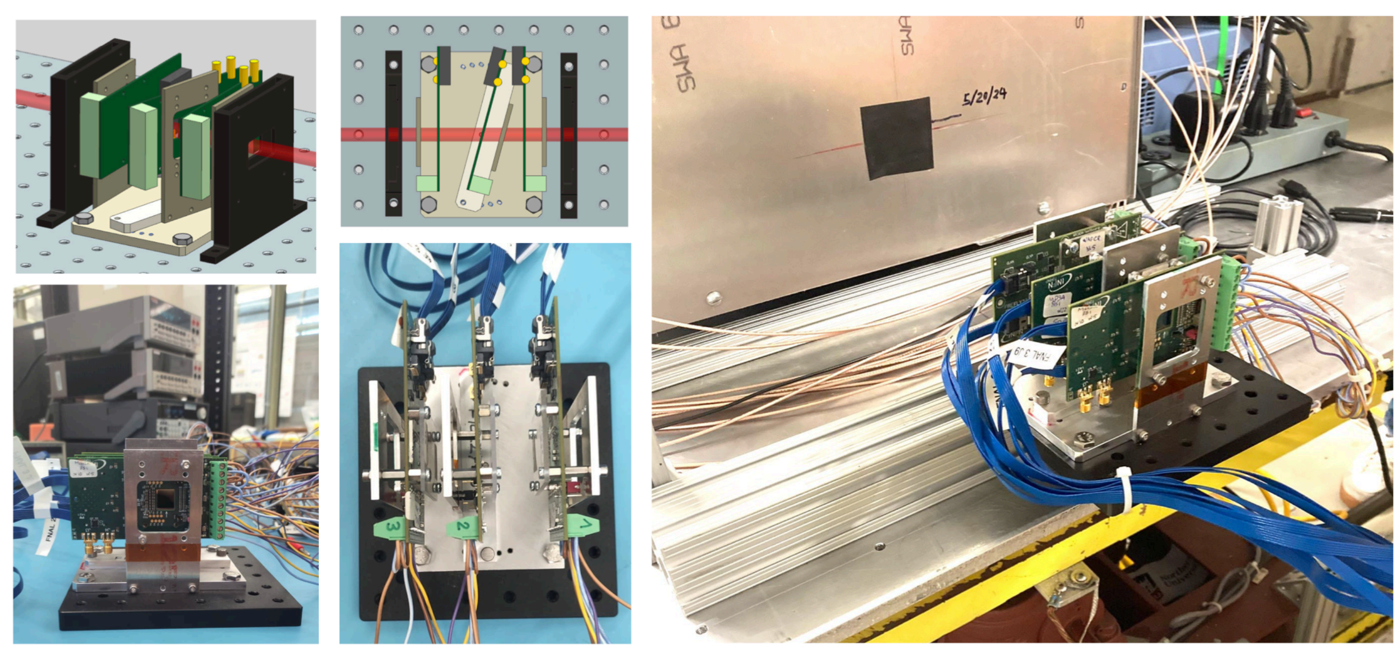
Allows readout chip and sensor to be optimized in independent technologies

MAPS

More details in A. Apresyan's talk

- Test beam at FNAL (120 GeV protons) in Summer 2024
- CMS 110 nm technology. 25 um pixel pitch, active area 1.28x1.28 cm^2
- Excellent performance demonstrated in test-beam
  - Position resolution around 5 µm
  - Efficiency near 100%
- Detailed measurements are now continuing with laser

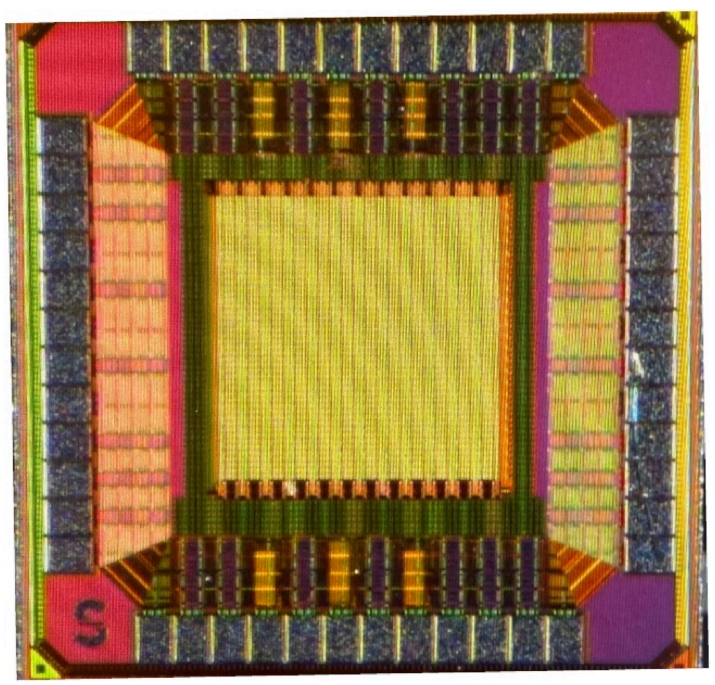




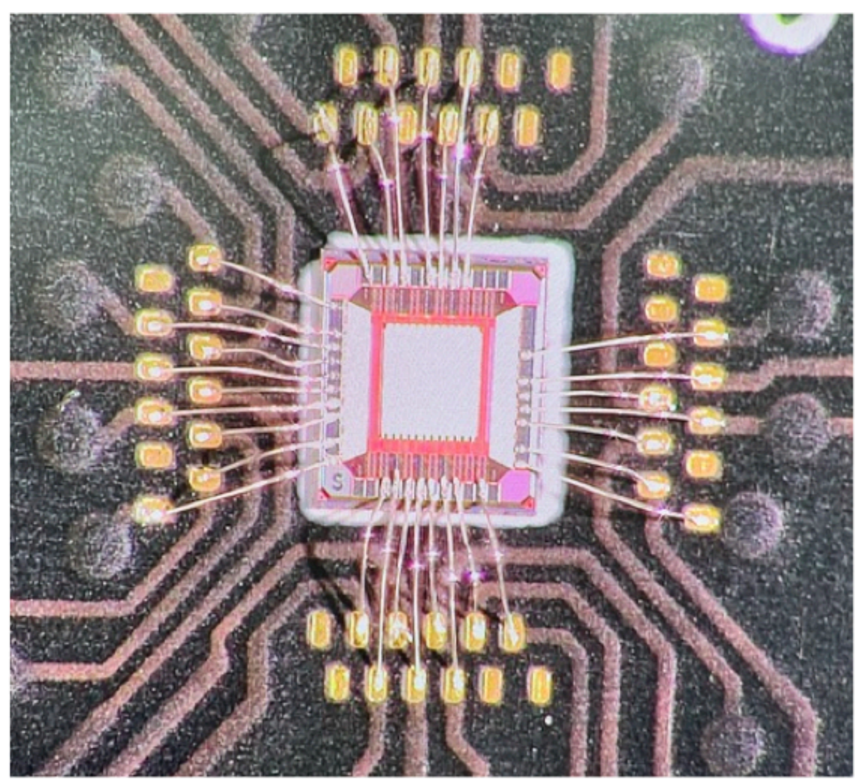
SLAC MAPS efforts

More details in A. Apresyan's talk

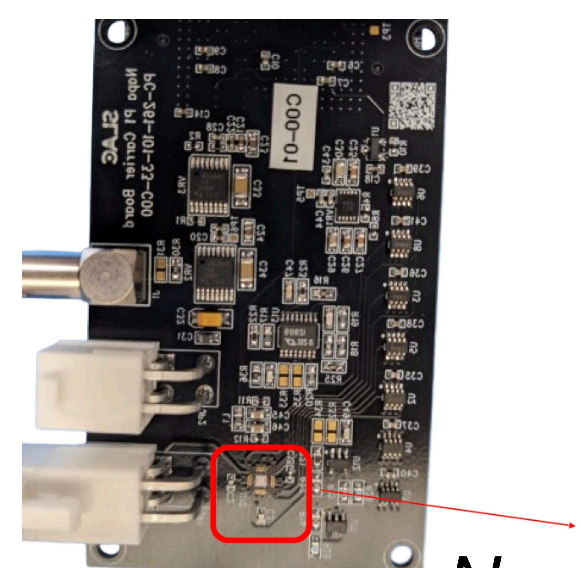
- Novel TowerJazz-Panasonic (TPSCO) 65 nm CMOS imaging process
  - Available through CERN WP1.2 collaboration
- First prototype preliminary results encouraging: Threshold and RMS decrease with BV. More testing ongoing
- Design of NAPA-p2 has started to tackle large sensor challenges



Picture of NAPA-p1 prototype from WP1.2 shared submission



Napa-p1

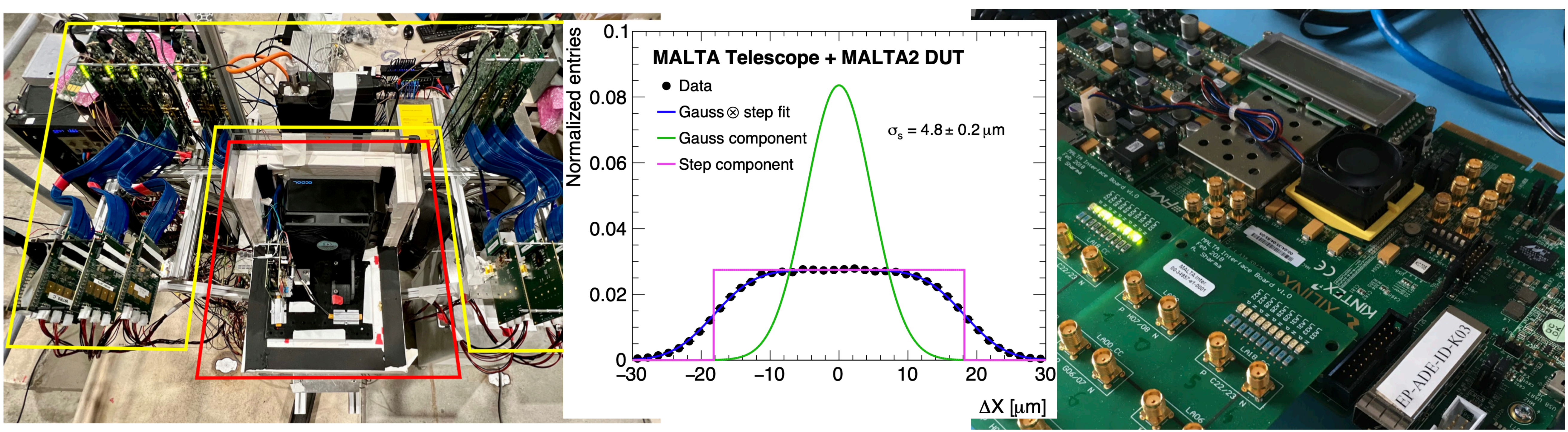


Napa-p1

DMAPS Results: MALTA Telescope

More details in A. Apresyan's talk

- MALTA: DMAPS in Tower 180 nm CMOS
- Telescoped developed for beam tests at SPS CERN
  - 6 MALTA planes. Each sensor is 512x512 pixels, each of 36.4 um. Plane efficiency above 94%
- Track position resolution: 4.7um. Track timing resolution: 2.1 ns

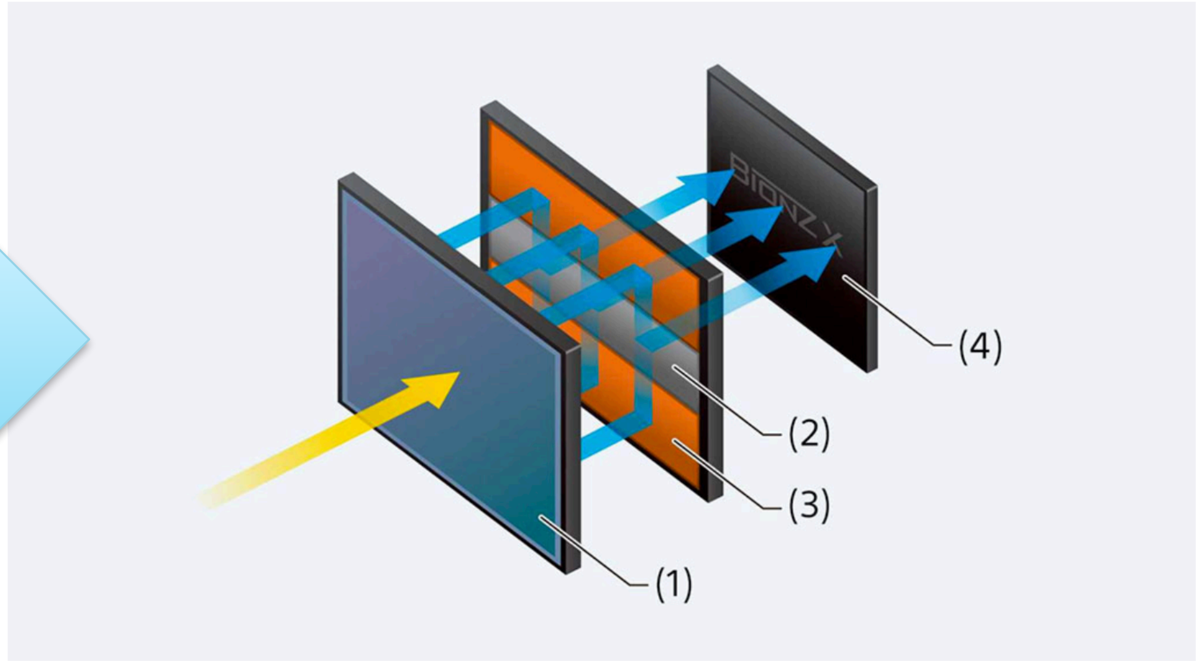


https://arxiv.org/pdf/2304.01104

3D-Integrated Sensors

- 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)

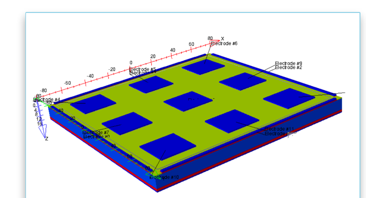


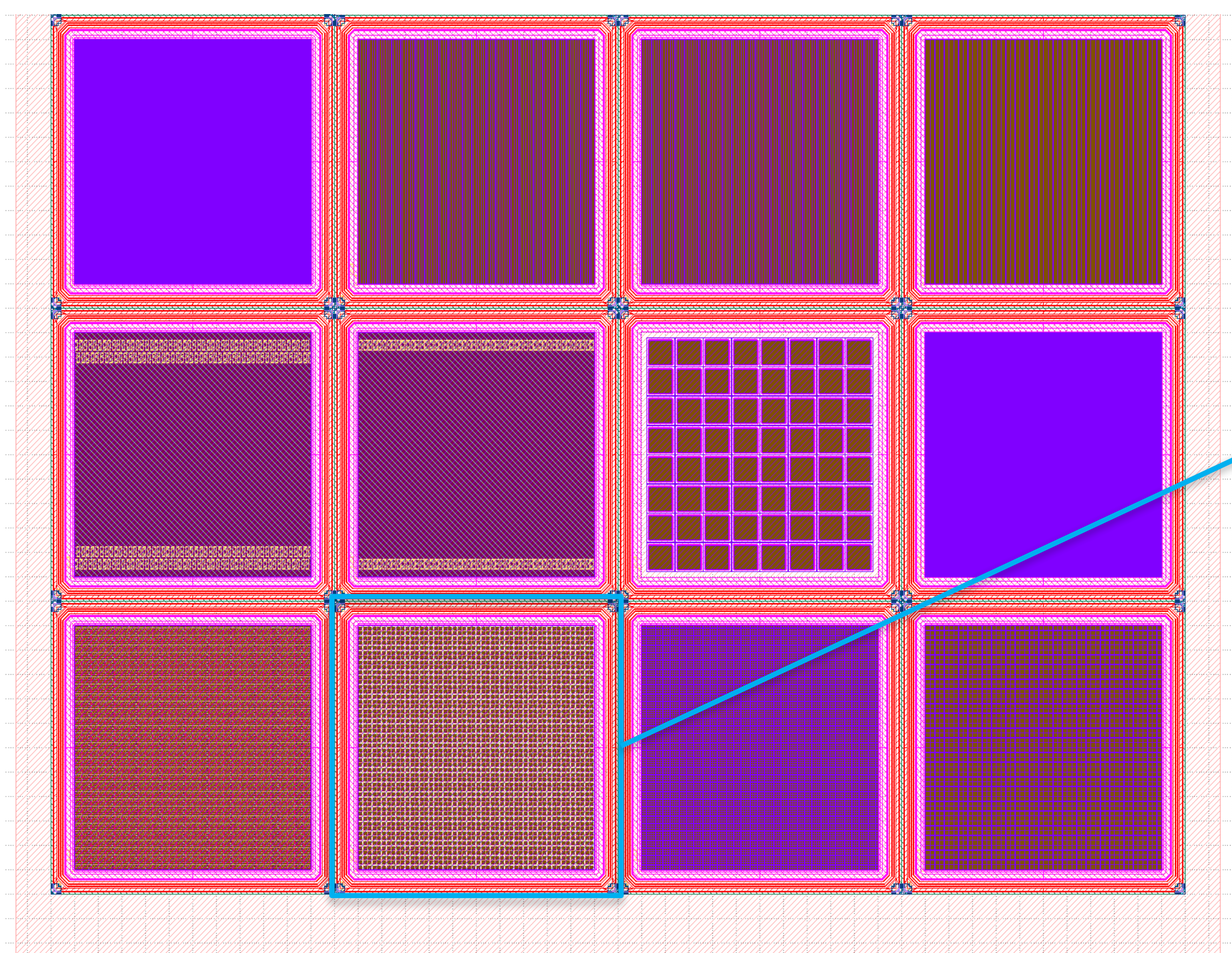
1) Pixel area – 2) Integral memory – 3) Hi-speed signal processing circuit – 4) Image processing engine

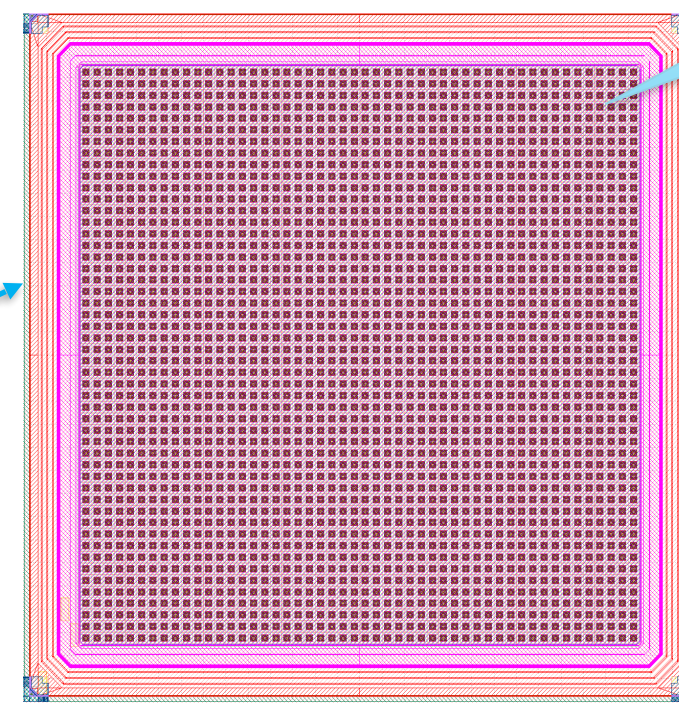
3D-Integrated Sensors

- In partnership with Tower Semiconductor
  - Full wafer run on 12”, 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

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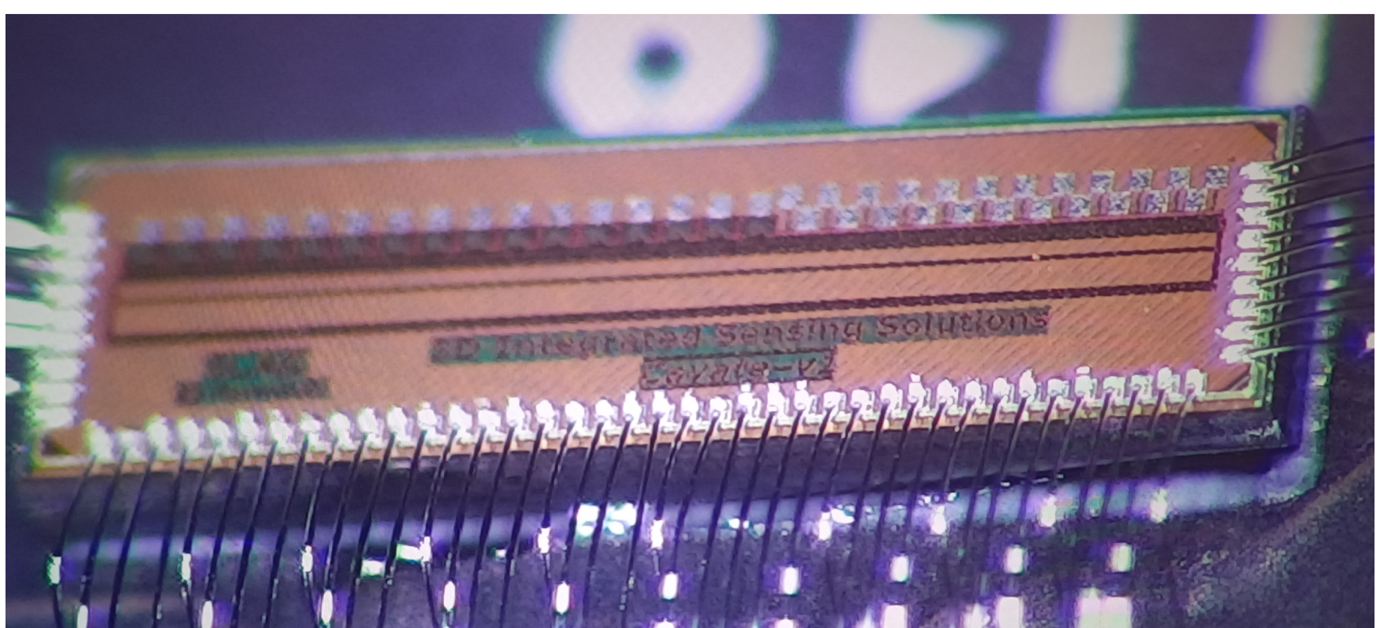
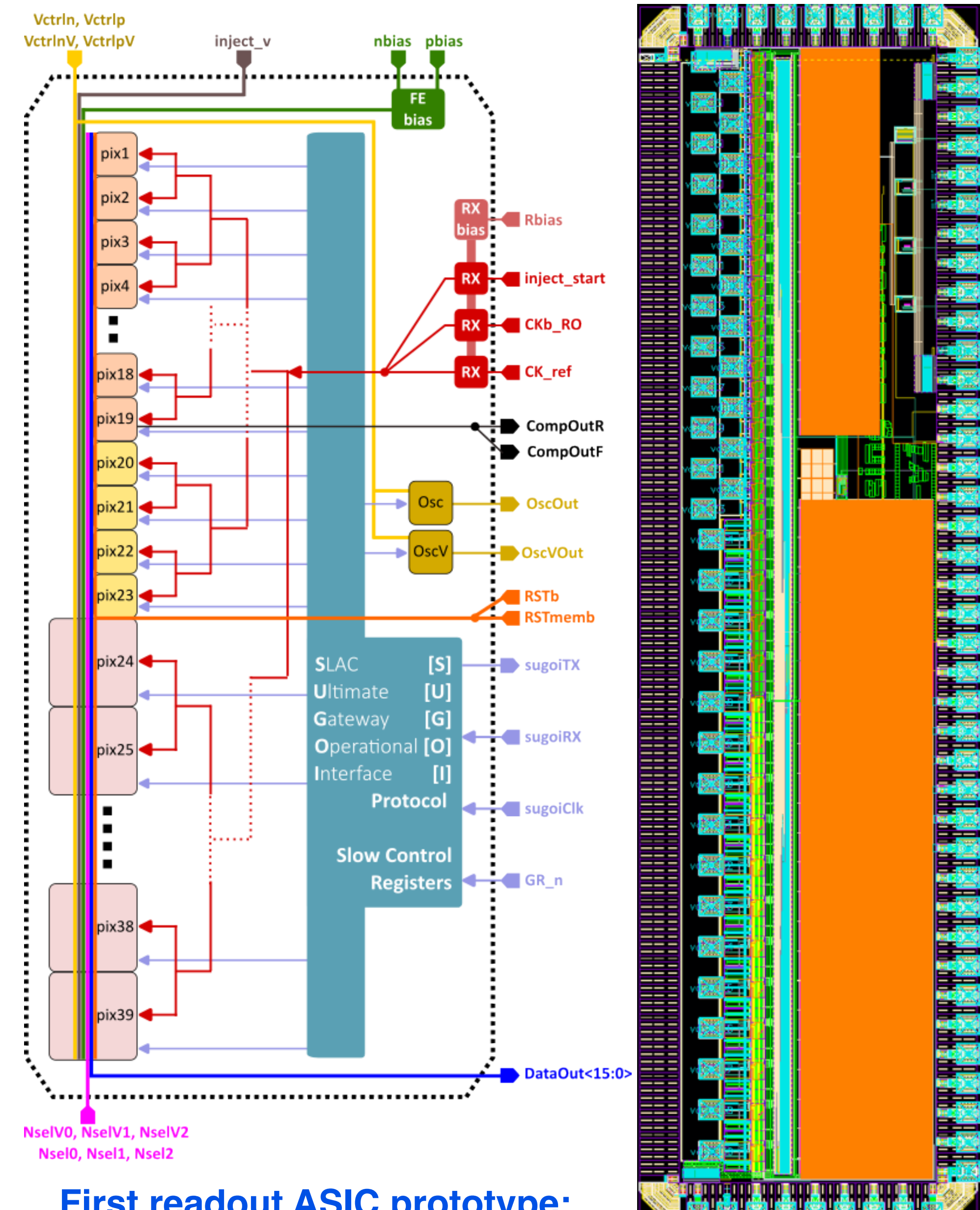
3D-Integrated Sensors

- 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 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

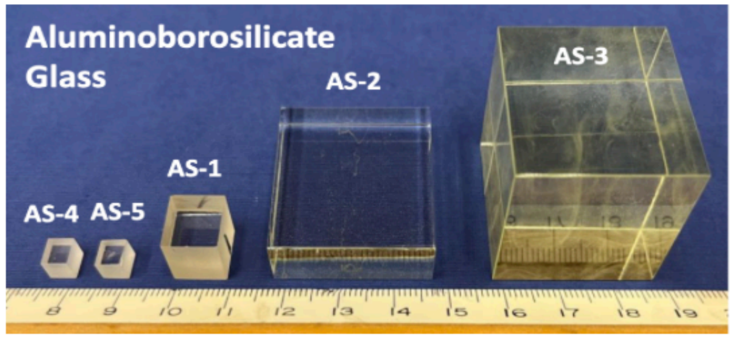


First readout ASIC prototype: block schematic and layout

Calorimetry Blue Sky: Inorganic Scintillators

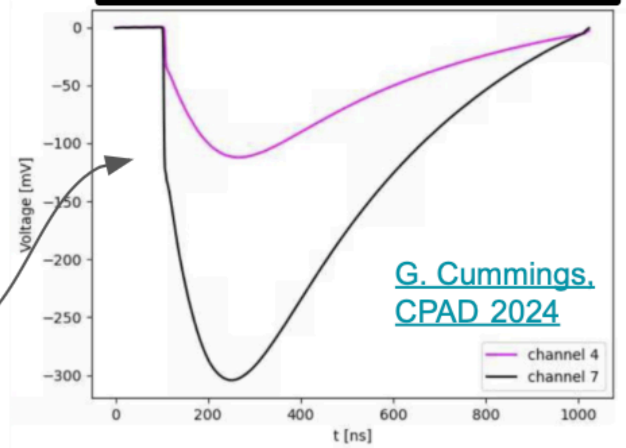
Input from G. Cummings (FNAL)

- Scintillating Glass development
  - Cheaper than crystals
  - Customizable
  - Challenge
    - Density
    - Uniformity + Quality
    - Radiation tolerance?
  - Goals:
    - Homogenous HCAL
    - Cheaper homogenous calorimeters in general
- Novel Implementations
  - GRANiTA
    - Crystal grains bathed in high-Z liquid
  - Dual Readout in crystals
    - Precision EM resolution not yet achieved w/ Cherenkov and Scintillation separation



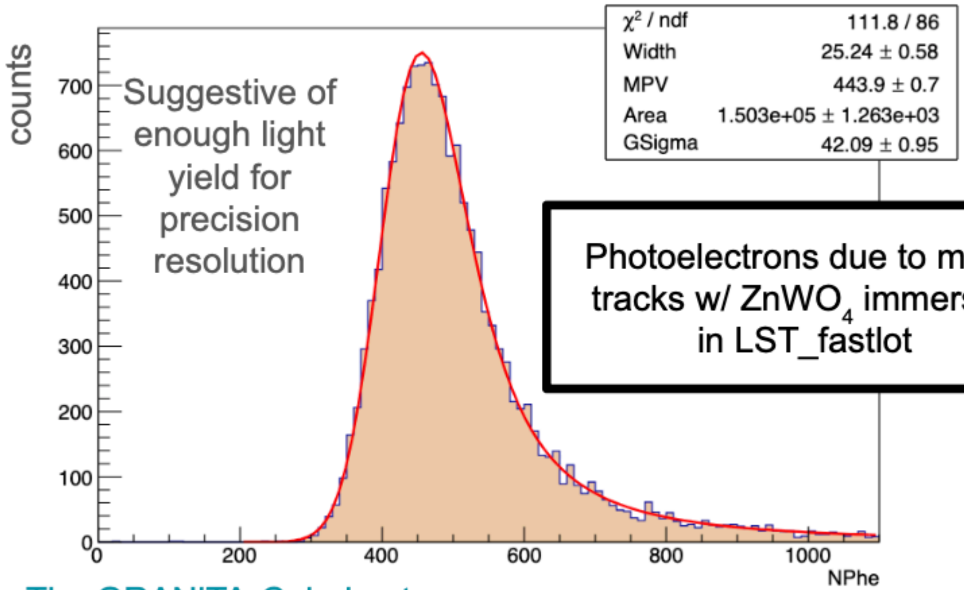
R. Zhu CPAD 2023

Pulse in ABS Glass due to 2 GeV Electron Beam



You can see the Cherenkov edge!

G. Cummings, CPAD 2024



Suggestive of enough light yield for precision resolution

Photoelectrons due to muon tracks w/ $ZnWO_4$ immersed in LST_fastlot

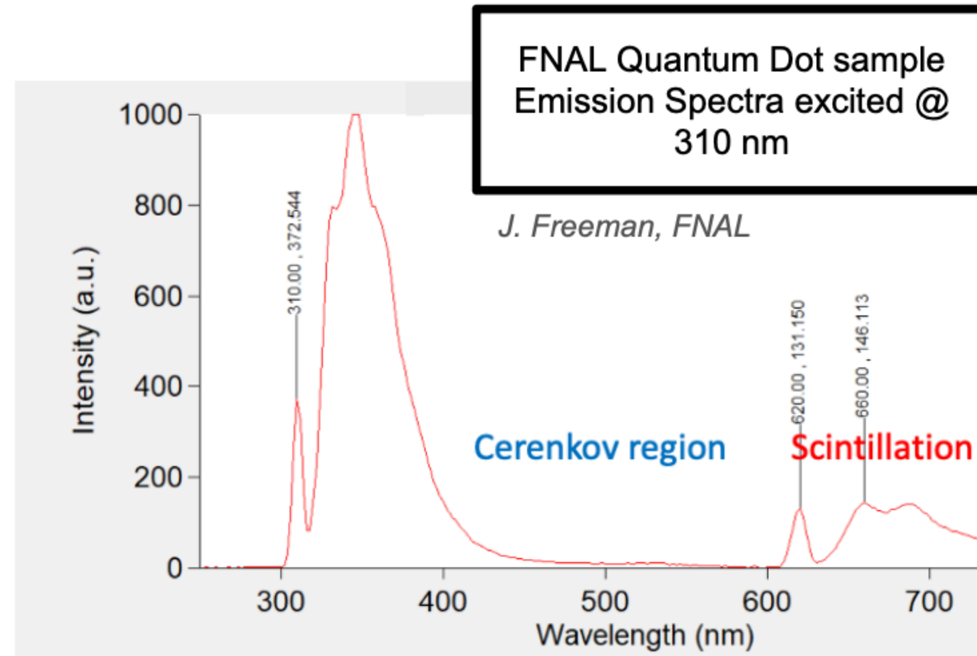
The GRANiTA Calorimeter

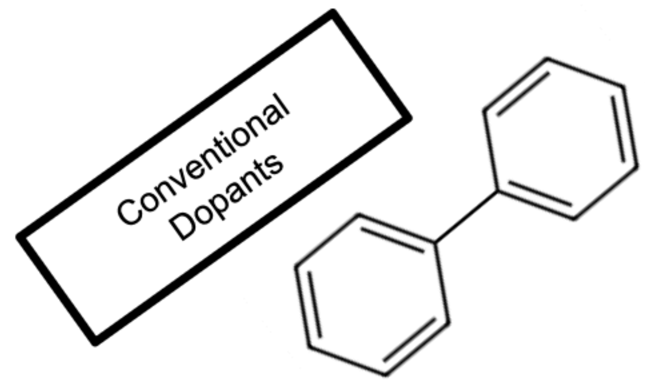
R&D towards cost-effective homogenous calorimeters

Calorimetry Blue Sky: Organic Scintillators

Input from G. Cummings (FNAL)

- Goal: Dual Readout in plastics
  - Separation of Cherenkov and Scintillation Light
- Challenge: Spectra overlap
  - Scintillation Blue (and a lot of it)
  - Cherenkov Green (and little of it)
- Two Methods
  - Quantum Dot Doping
    - Red-shift scintillation spectrum
    - Delay scintillation spectrum for pulse shape discrimination
  - Conventional Dopants w/ delayed time structure
    - Push scintillation more into UV
    - Delay the emission, and separate by time

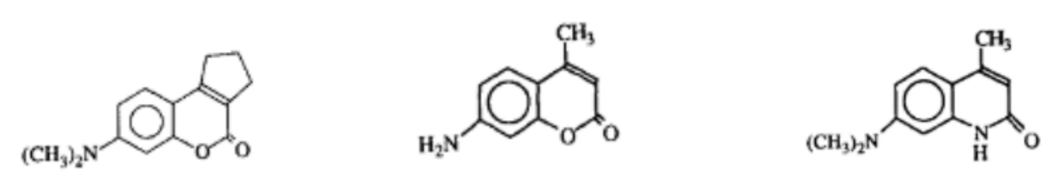




Biphenyl → 16 ns decay, 290 - 390 nm

NEEDS UV SIPM

... IF NO UV SIPM, SECONDARY DOPANT NEEDED

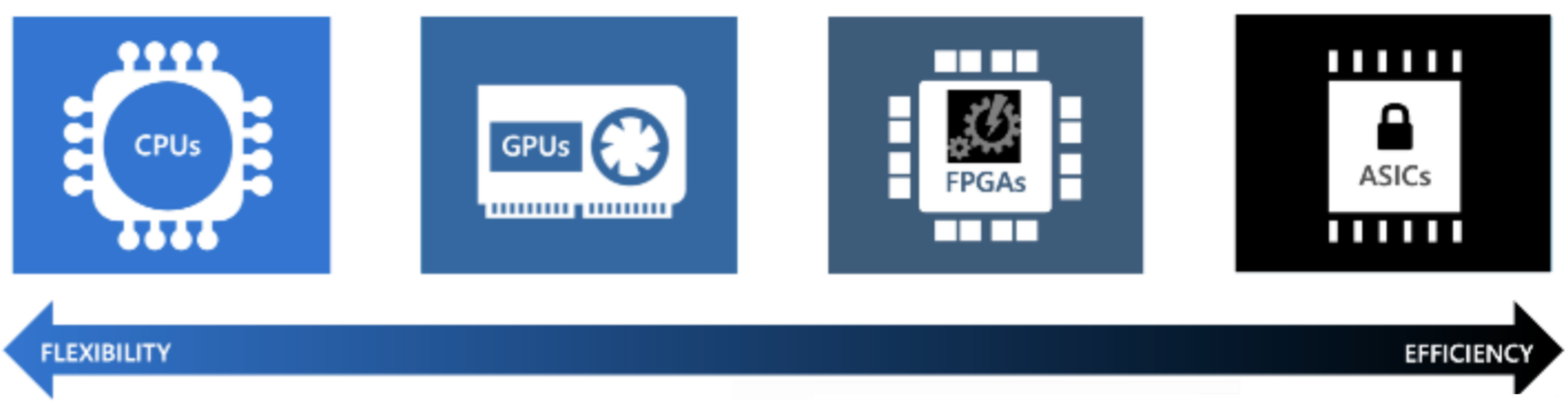


R&D towards dual readout calorimetry with plastics scintillators and emerging technologies (QDots)

FERMI NATIONAL ACCELERATOR LABORATORY

AI/ML on the front-end

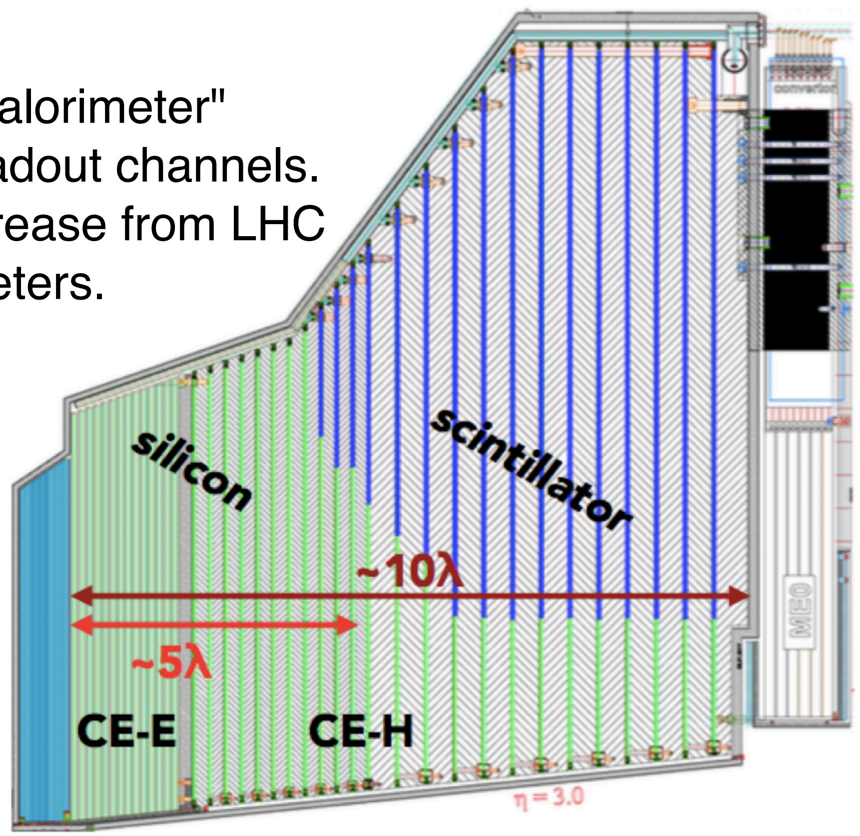
- Detectors at next-gen experiments can benefit from real-time machine learning in readout
  - Edge intelligence: feature extraction, classification, data compression
  - Efficiency: lower computational power/storage needs for transmission
- Implementations are being developed in FPGAs, ASICs

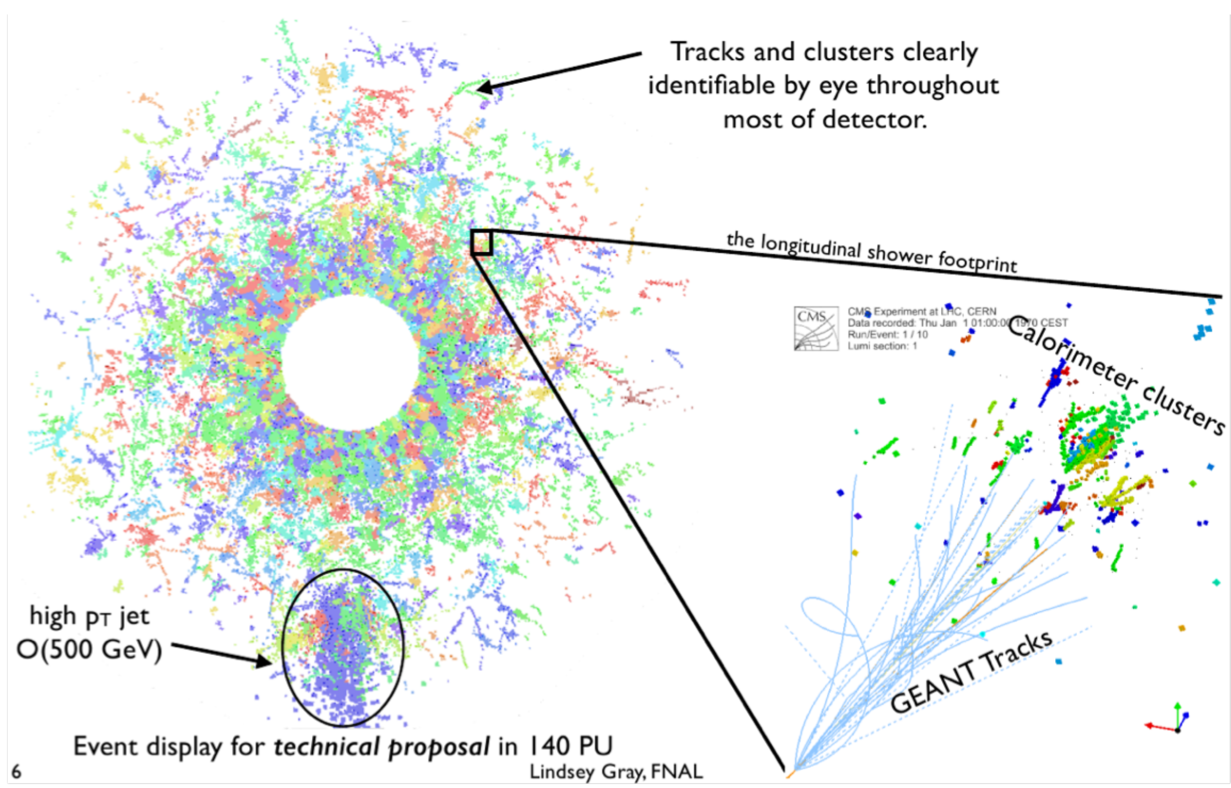


AI/ML on Calorimeters

- 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

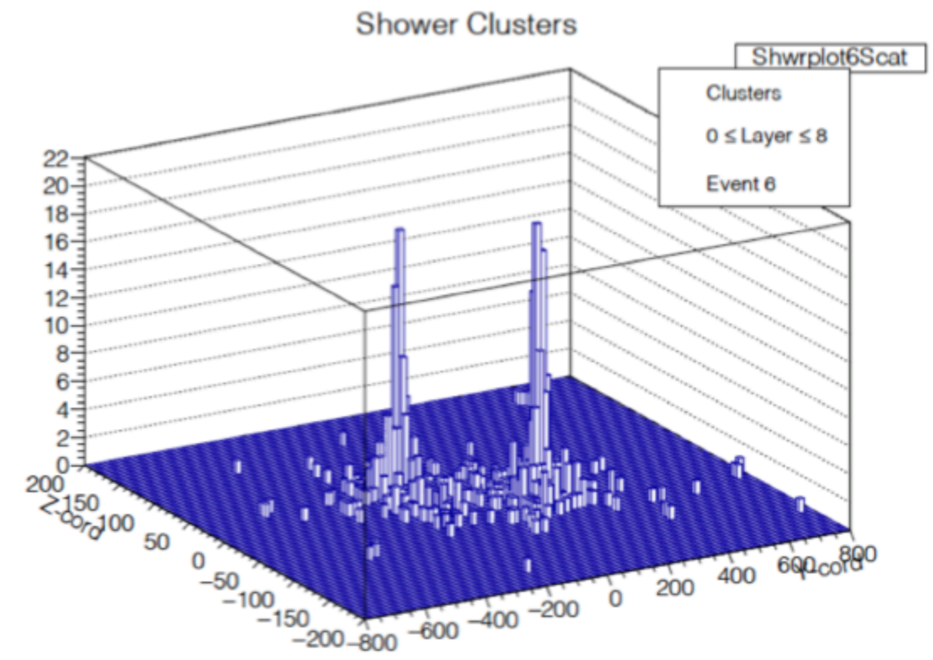
"Imaging calorimeter"
- ~6M readout channels.
- 60× increase from LHC calorimeters.



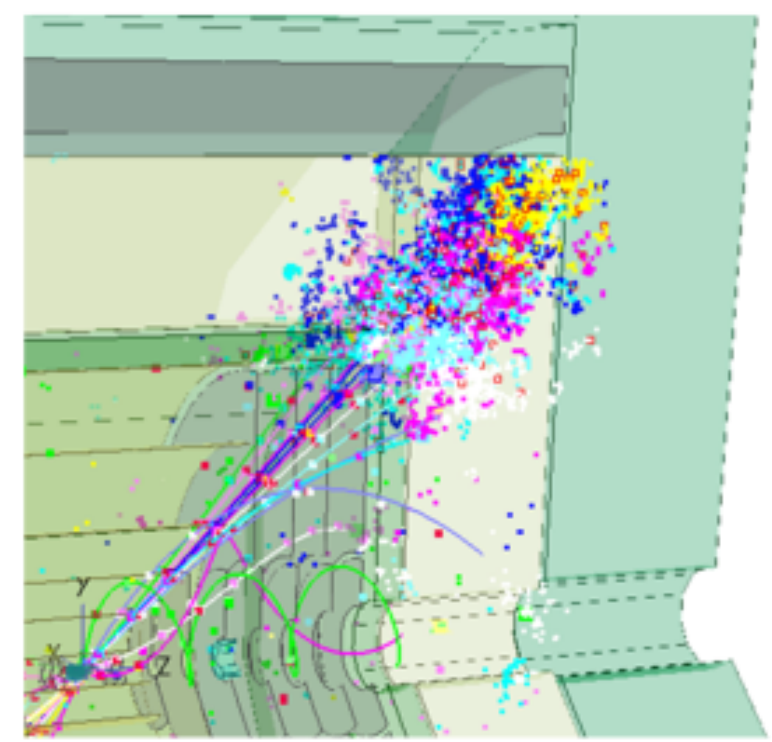


AI/ML on Calorimeters

- SiD detector configuration with 25x100 μm^2 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



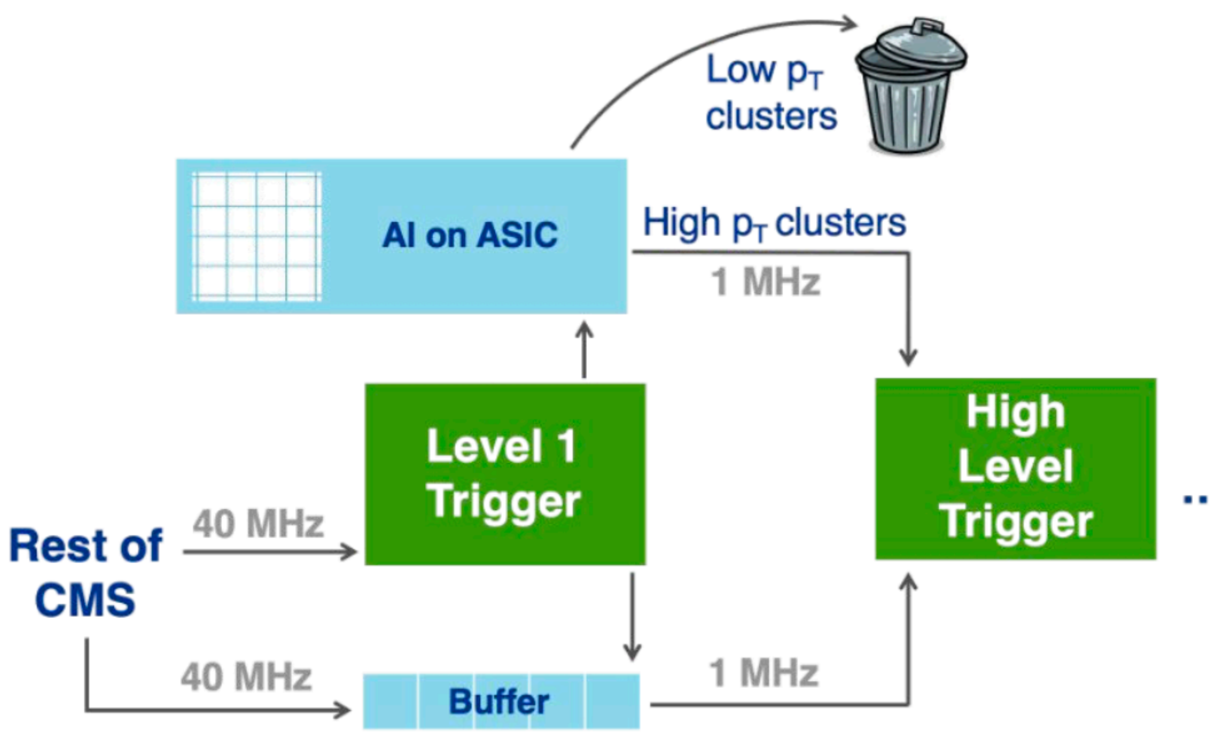
GEANT4 simulations of Transverse distribution of two 10 GeV showers separated by one cm



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) NN implemented directly in the front-end



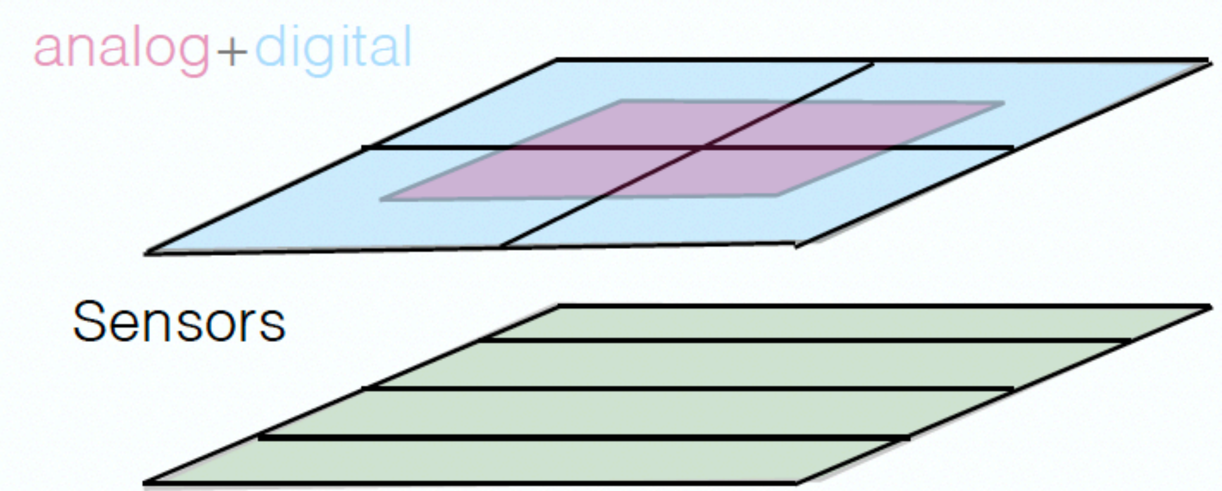
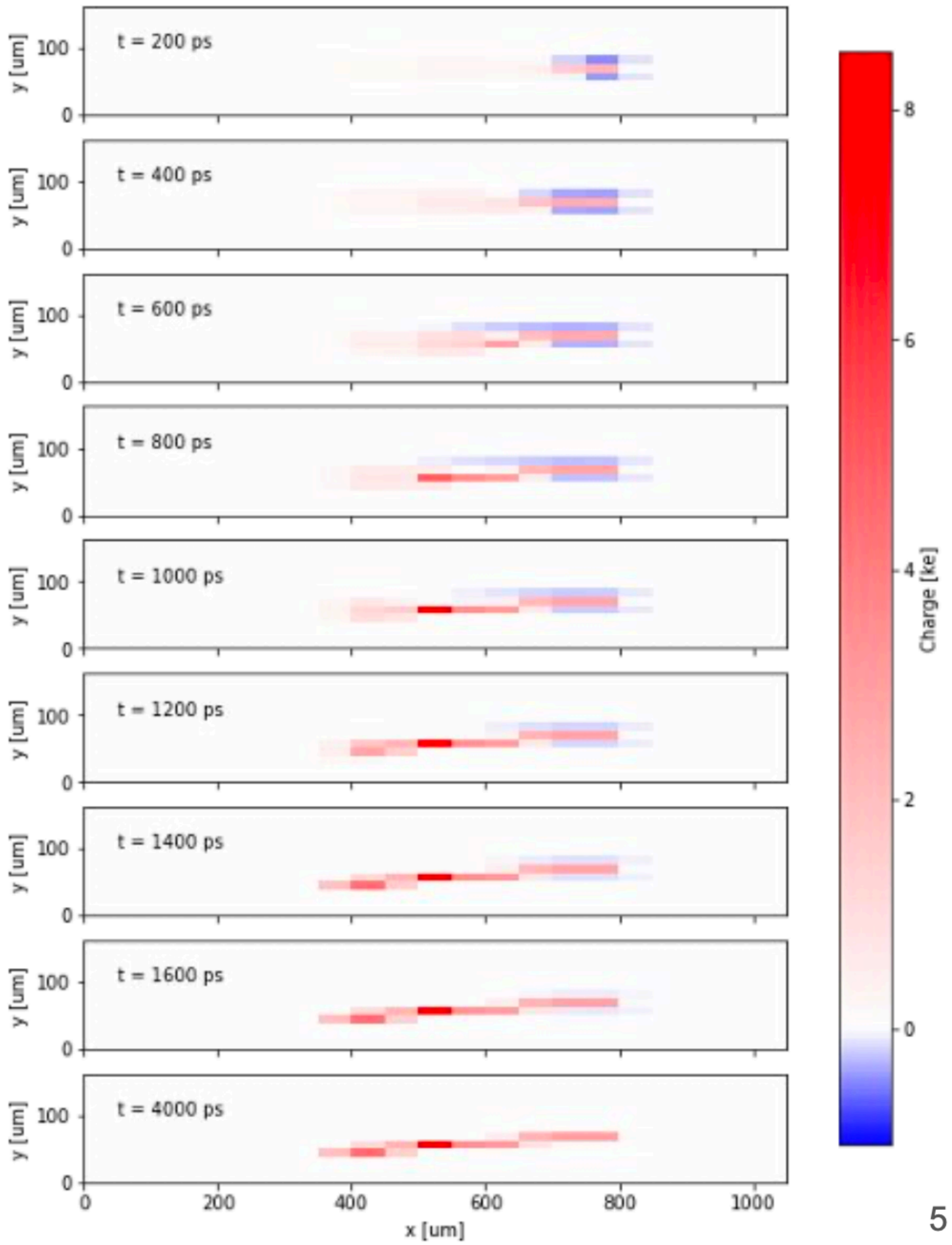
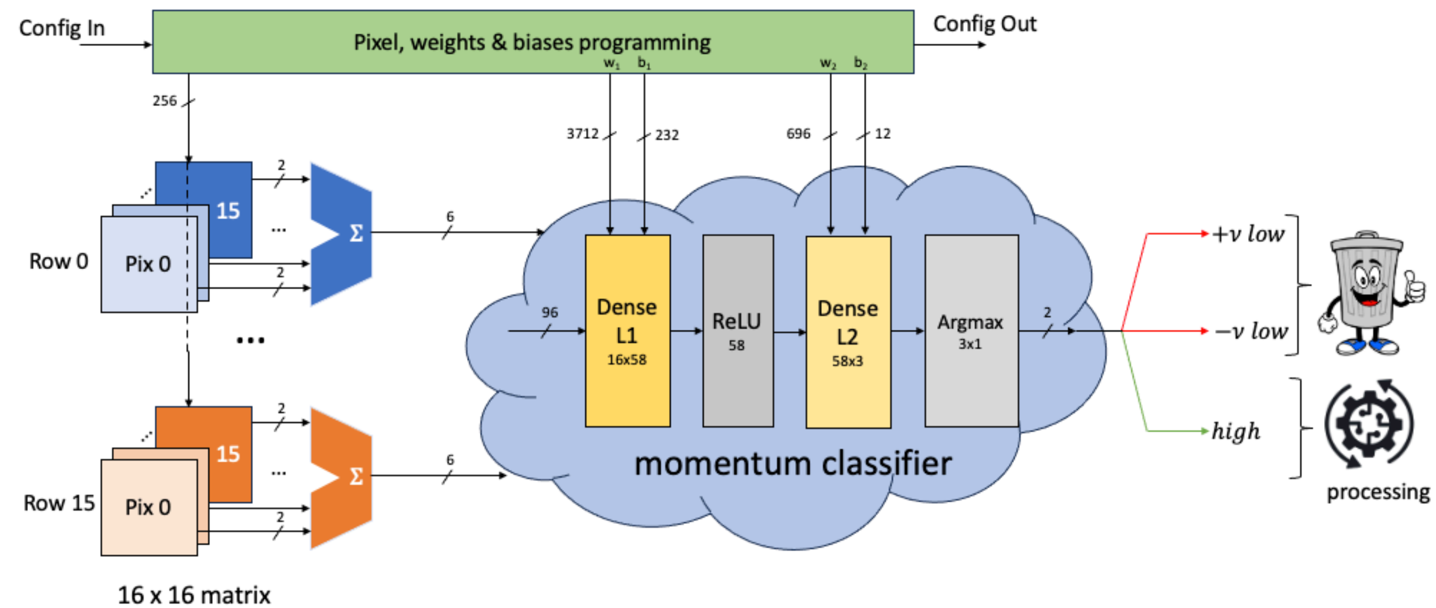
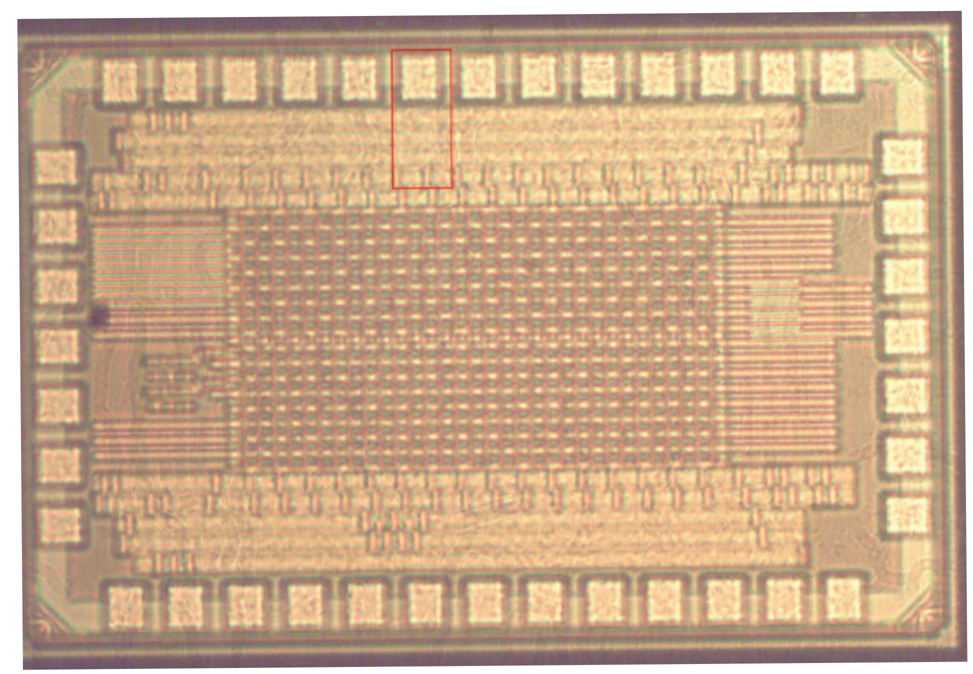


Diagram of pixel sensors + readout chip

AI/ML Implementation

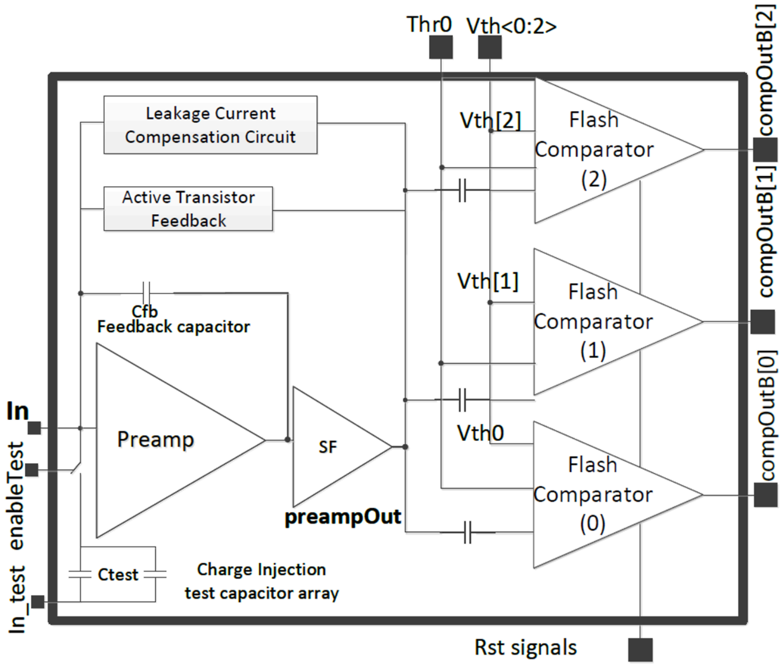


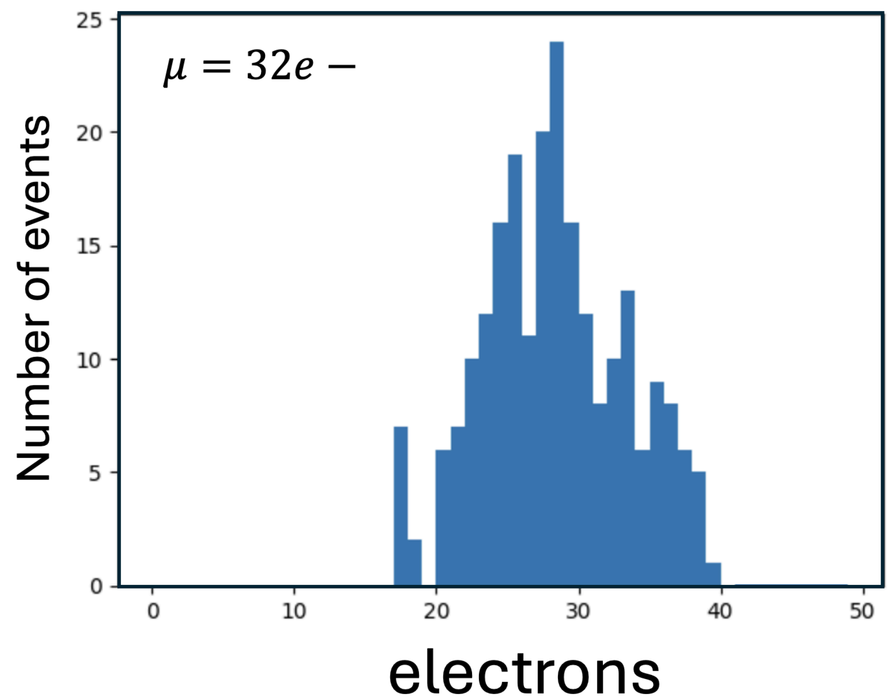


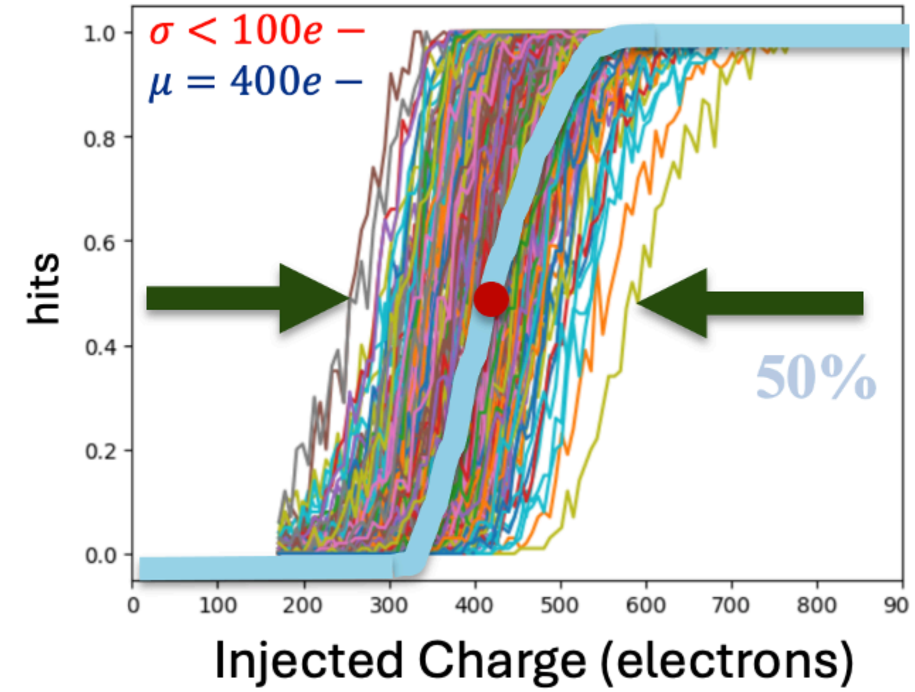


Smart data reduction at the edge using pulse shapes, and drift & induced currents

Analog Frontend Prototype







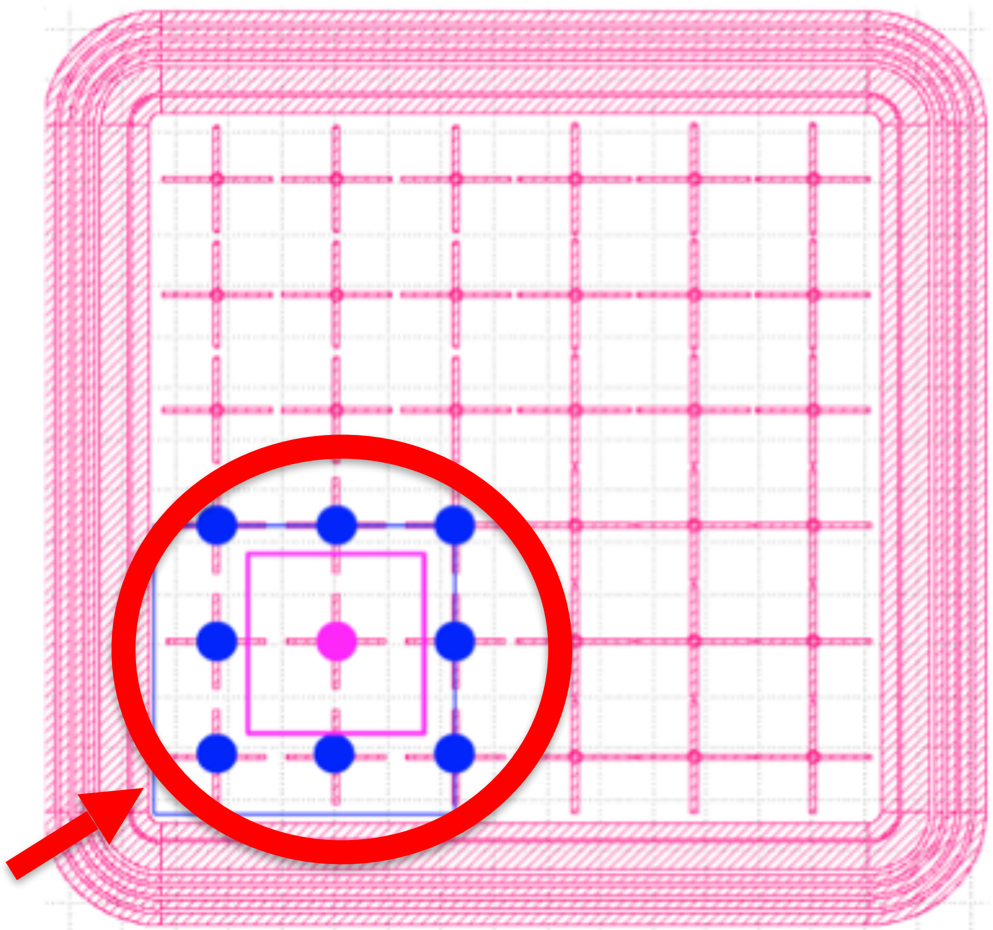
- The AFE prototype designed in TSMC 28 nm
  - ROIC pixel size is 25 μm^2
  - Low power performance : ~5 µW/pixel
- Preamplifier dynamic range 64 aC – 2.1 fC
  - Equivalent noise charge (ENC) 31e$^-$ with 400e$^-$ threshold (no sensor cap)
  - Total charge dispersion < 100e$^-$ across entire matrix with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

Lots of progress on actual chip implementation

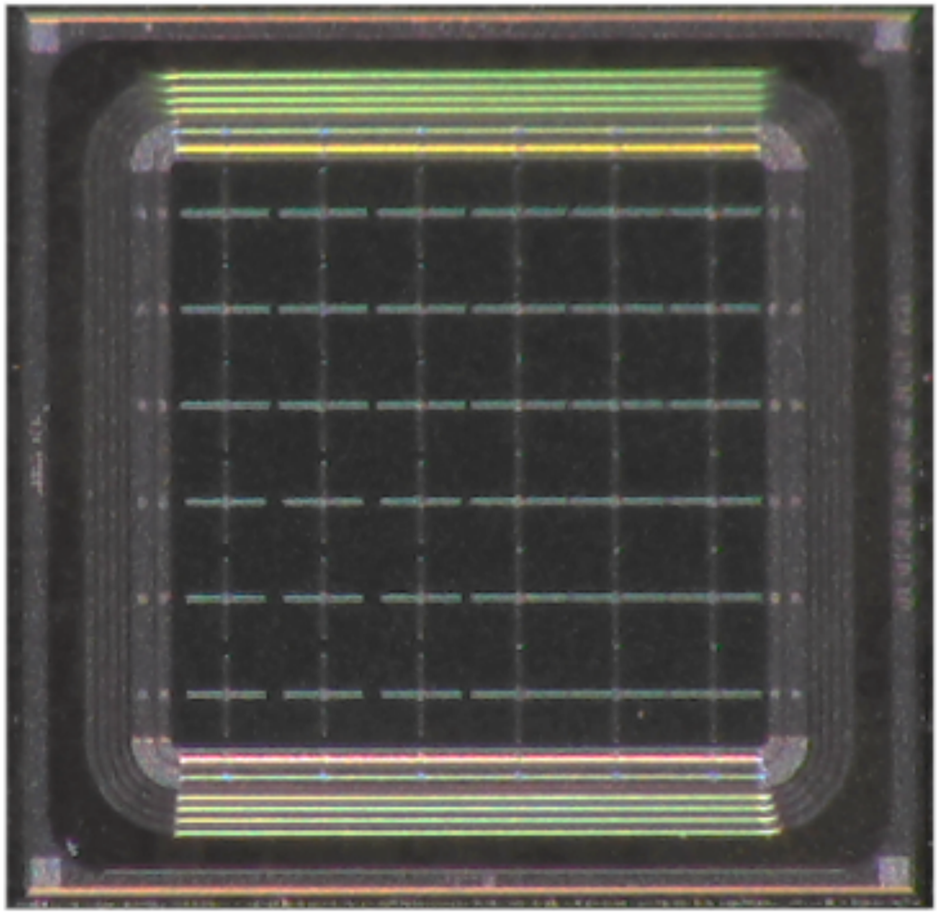
Towards AI/ML for AC-LGADs

- 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



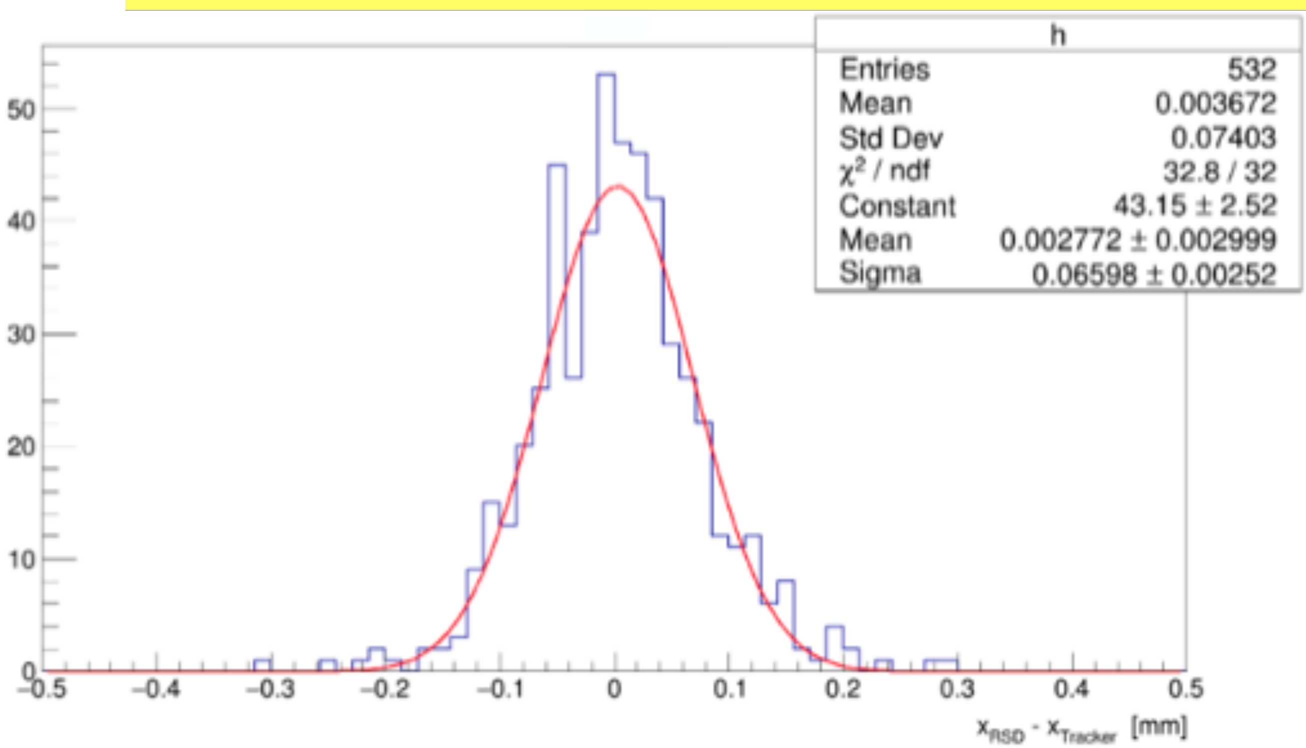
FBK sensor with 6×6 matrix
450 µm pitch pixels

Towards AI/ML for AC-LGADs

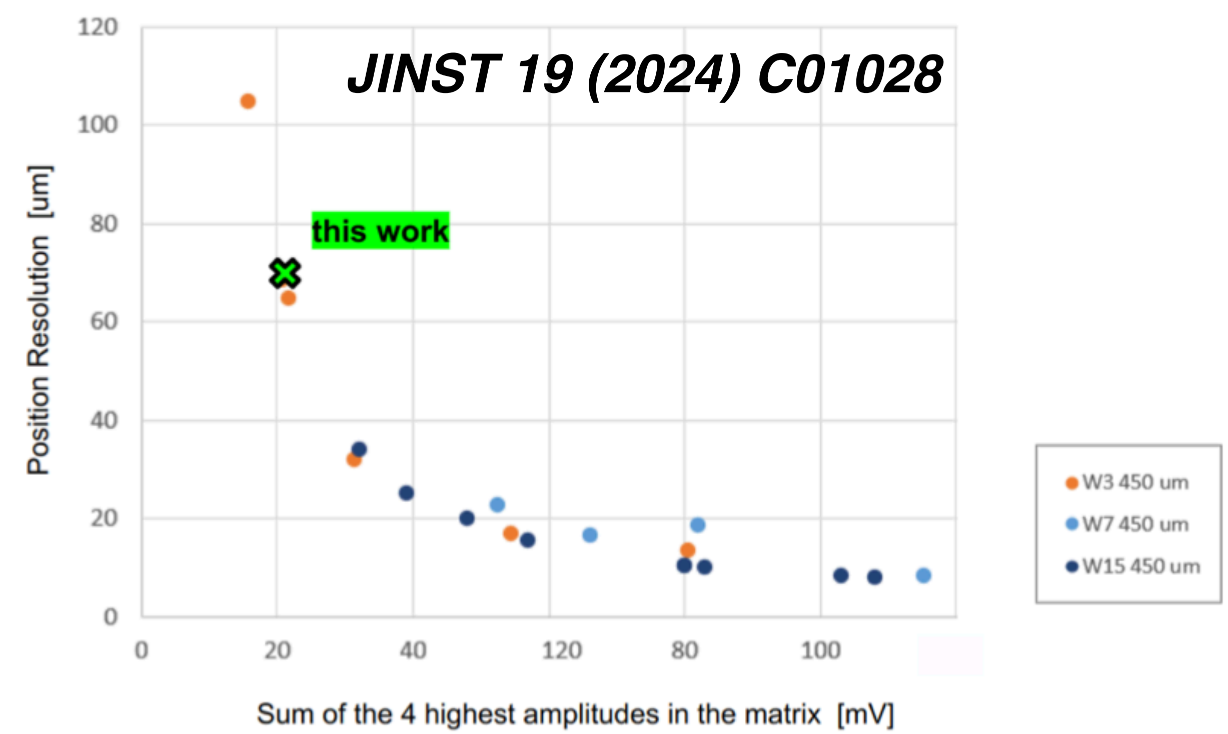
- Improve position reconstruction using AI/ML tools
  - Trained using IR-laser dataset, tested on test-beam dataset
  - As a reference, compare to analytical reconstruction
- **Measure position resolution 65 μm**
  - A standard binary read-out : ~130 μm resolution
  - Can achieve ~10-15 μm resolution by increasing sensor gain

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

Huge expected performance gain from ML on chip!



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

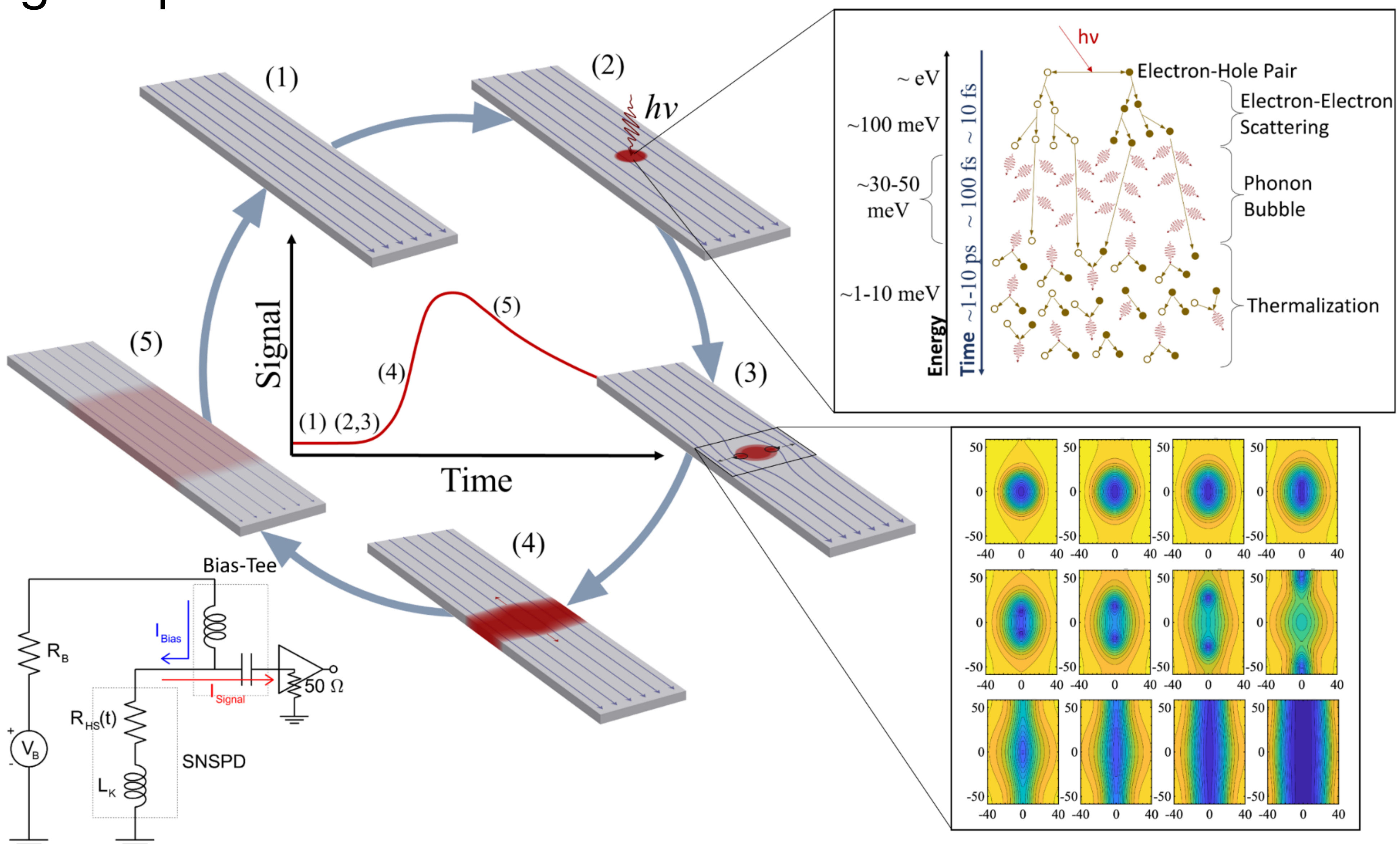


Position resolution as a function of the total amplitude of the 4 highest signals

The Next Frontier: Going Cold

Quantum Sensors: superconducting nanowire single photon detector

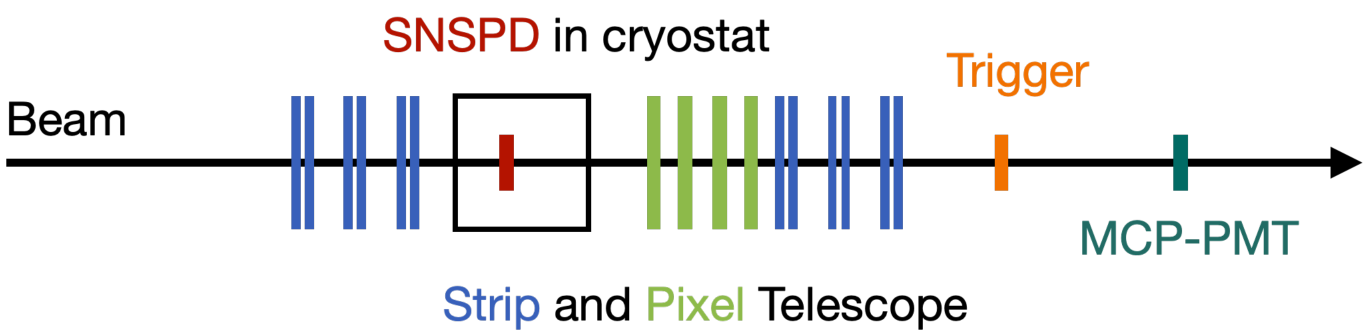
- Single photon (heat) triggers detector out of superconductor state
- Resistance quickly (ps) jumps to few kΩ → detector current into readout
- Highest performance single-photon detector, from UV to mid-infrared
- Operating temperature : 1-4 Kelvin

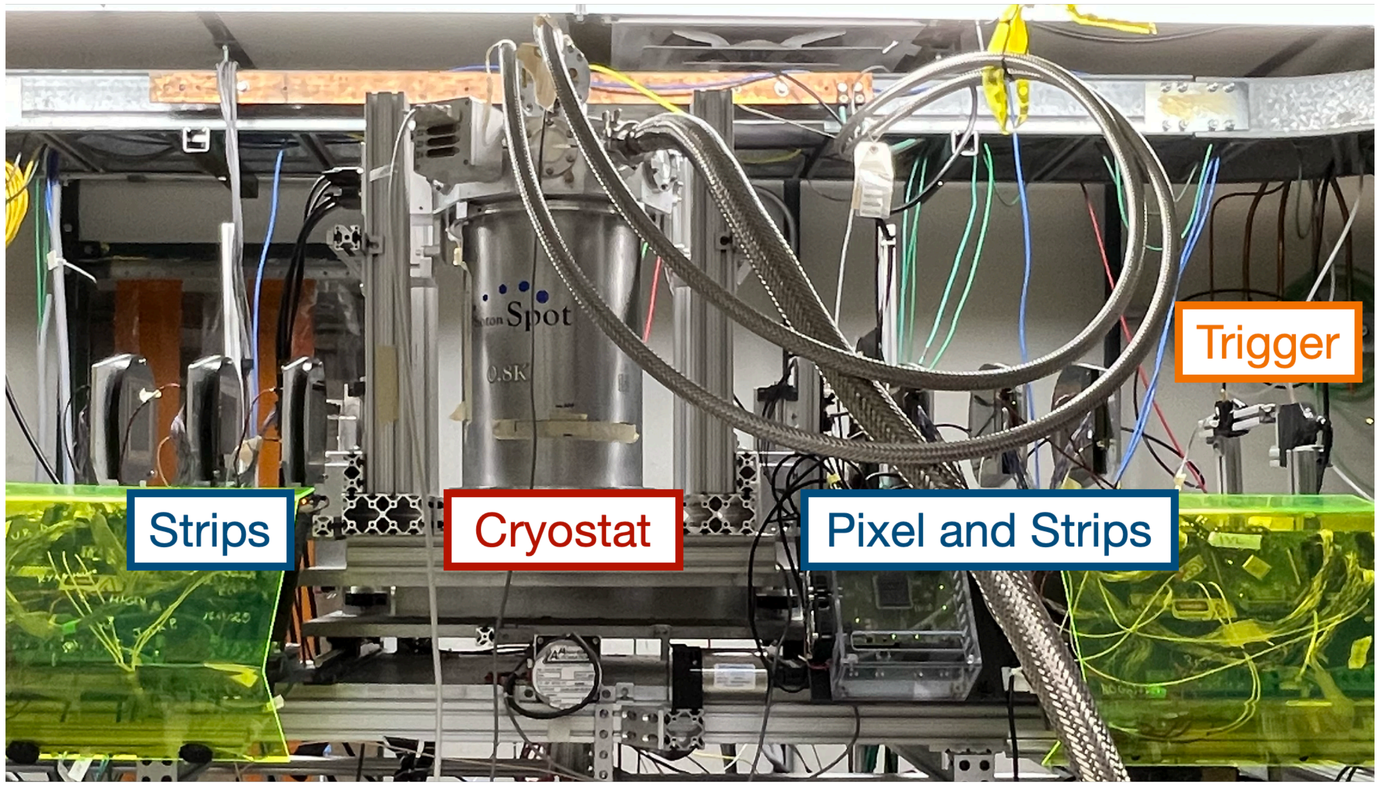


The Next Frontier: Going Cold

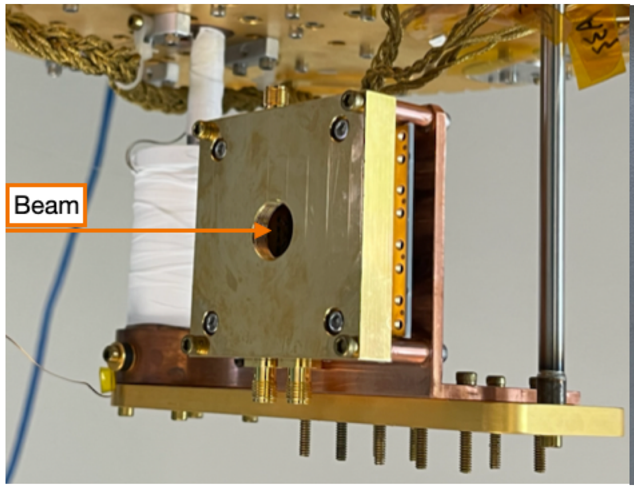
New thrust towards sub-eV charged particle tracking with picosecond level time resolution

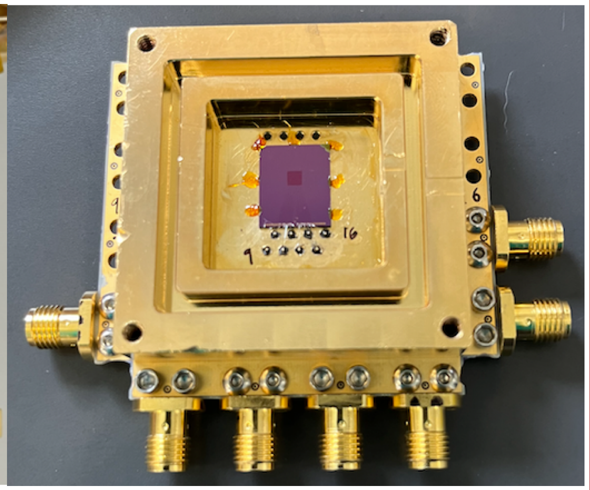
New: JINST 20 P03001



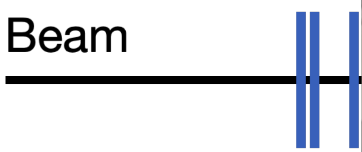


- New R&D program for SNSPD to detect high energy particle with the Fermilab Test Beam Facility
- **First test beam** to detect 120 GeV proton and 8 GeV electrons and pions with **large-area** (2×2 mm^2) **multi-pixel** (8-pixel) SNSPD



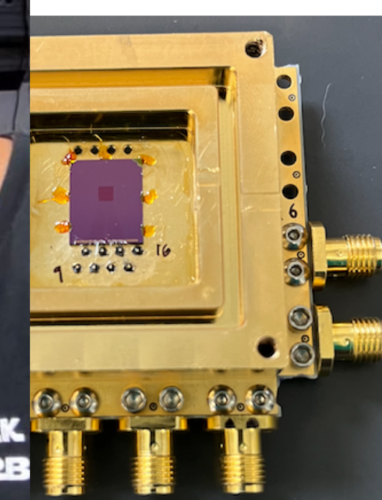


Superconducting Nanowire Single ~~Photon~~ Particle Detector (SNSPD)



PD to detect
e Fermilab

20 GeV
and pions
multi-pixel

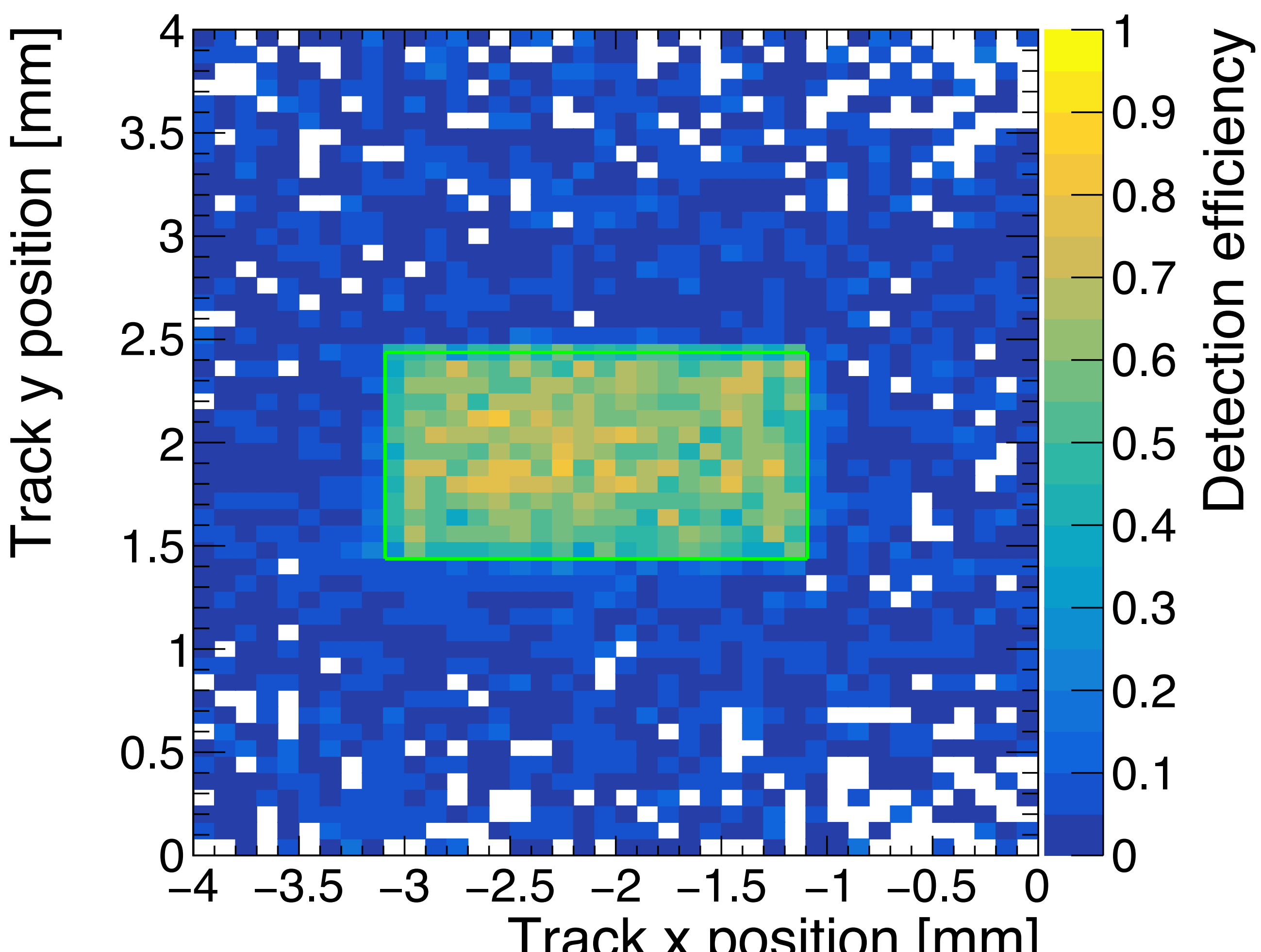


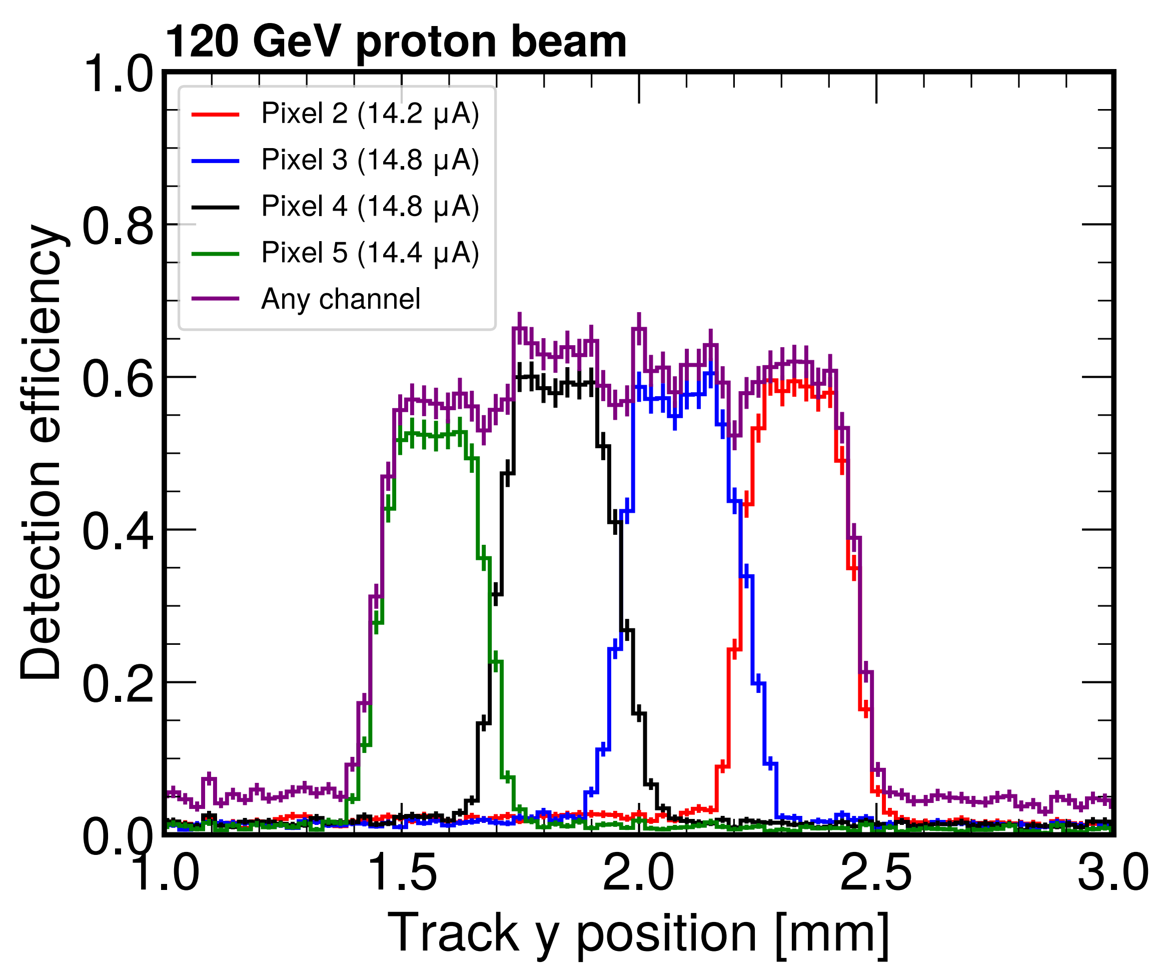
New thr
racking
with picosecond level time resolution

The Next Frontier: Going Cold

New: <u>JINST 20 P03001</u>

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



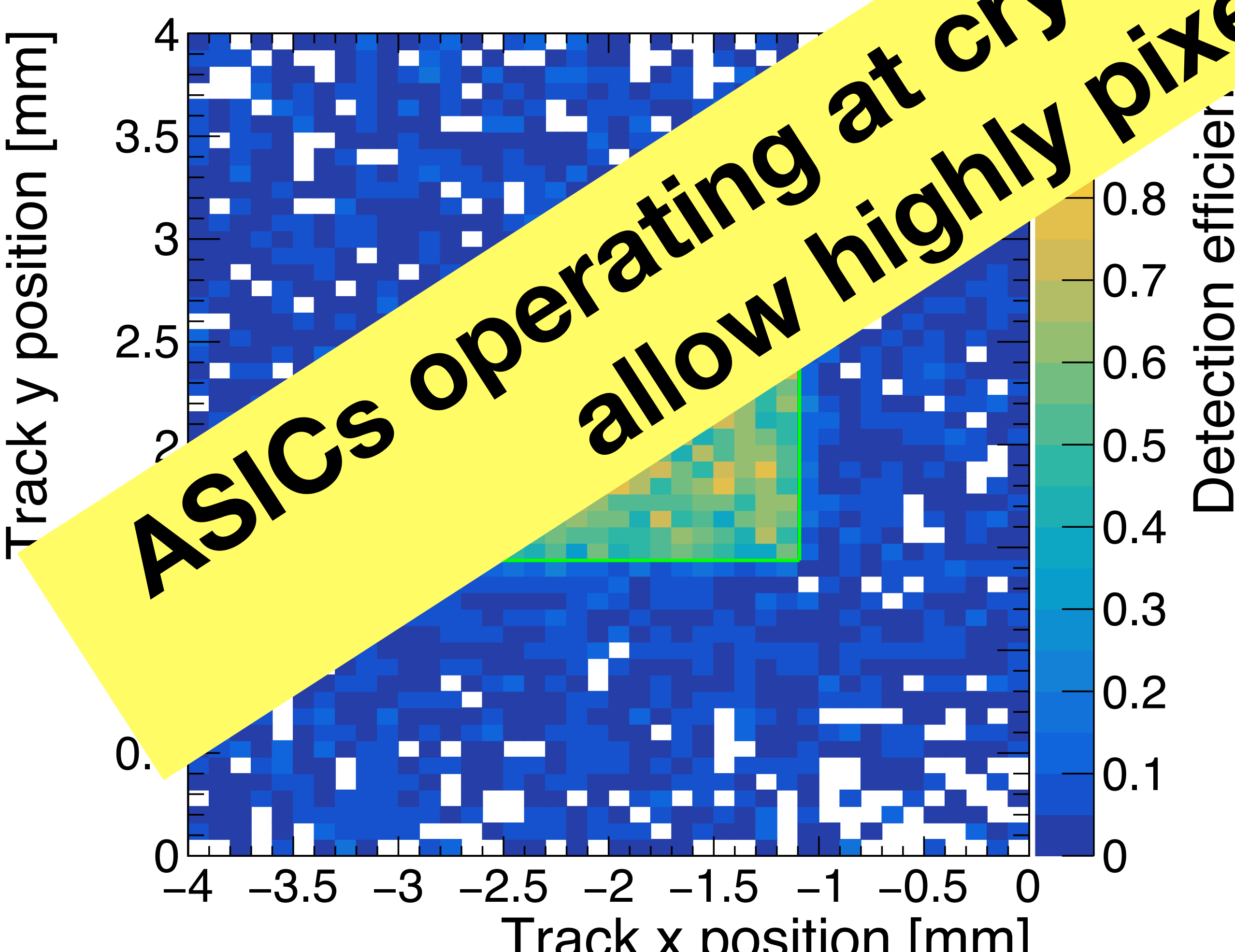


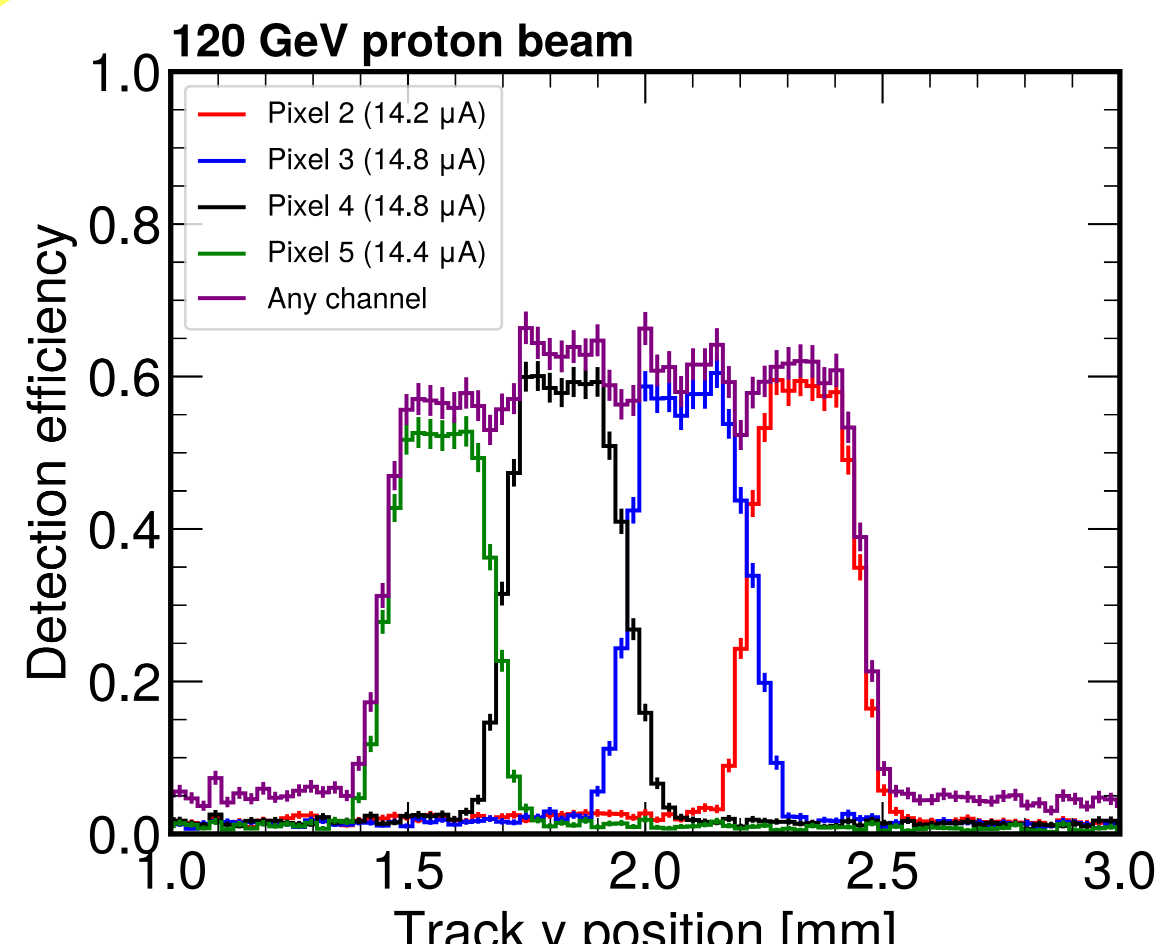
The Next Frontier: Going Cold

New: <u>JINST 20 P03001</u>

- 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



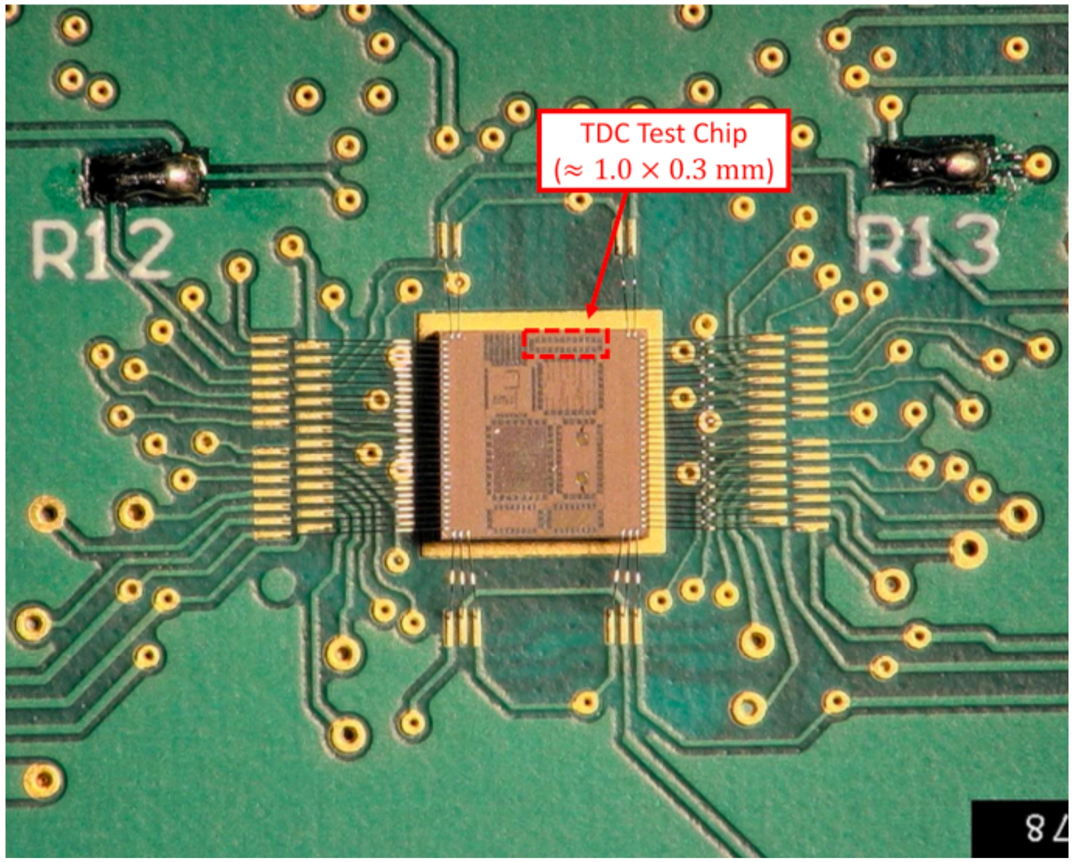


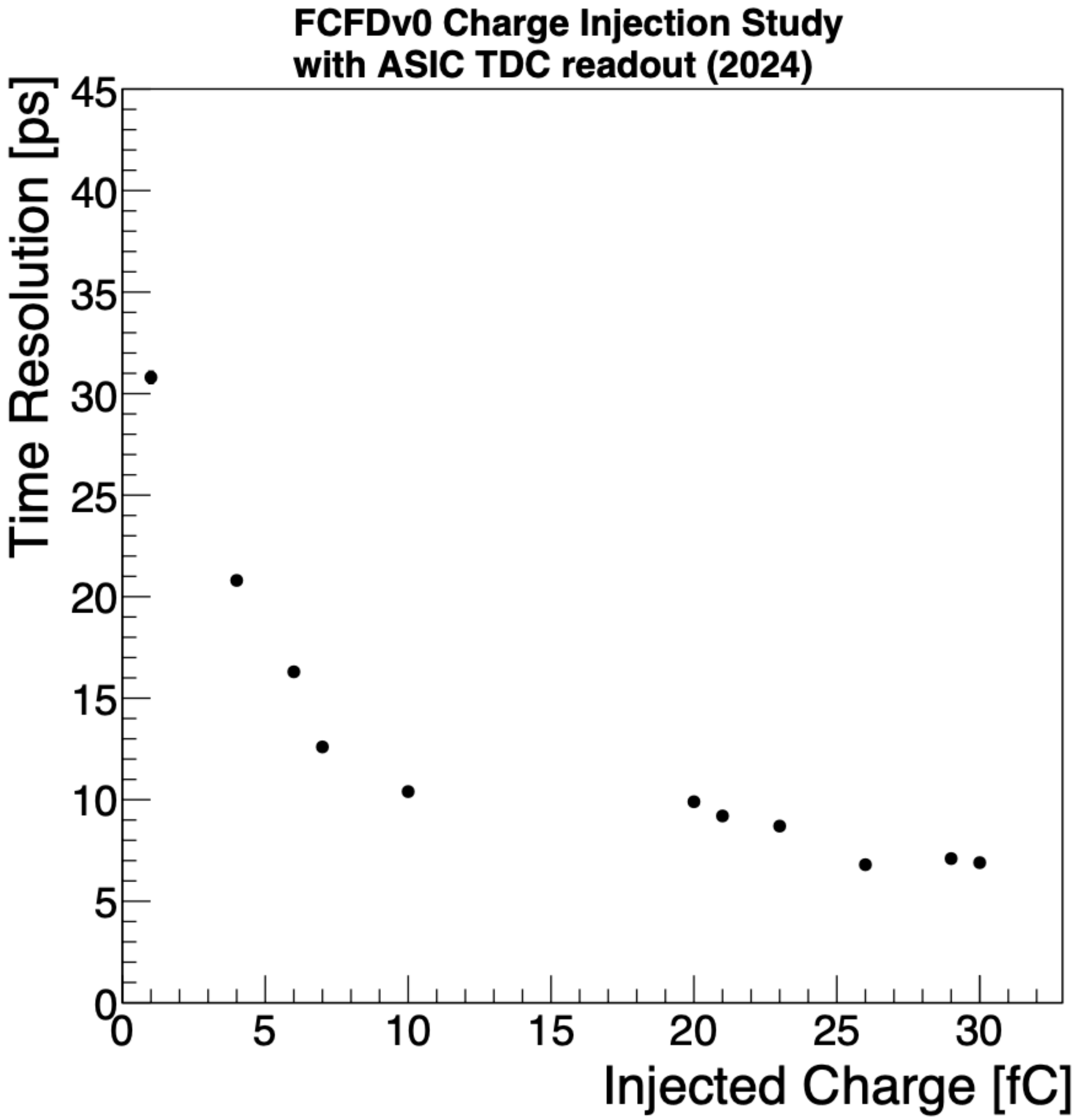
TDC at Cryogenic Temperatures

10.36227/techrxiv.173949128.88095436/v1

Achieve ~7 ps resolution for ~25 fC injected charge

22 nm CMOS Global Foundry



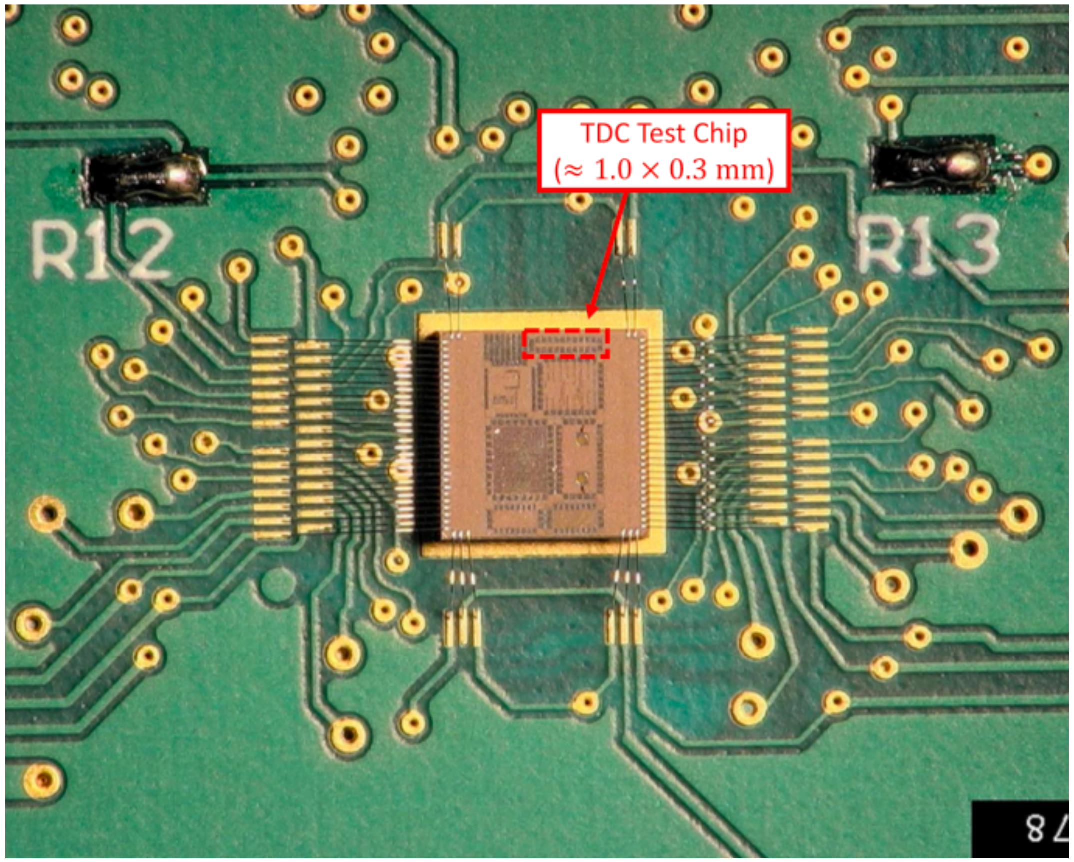


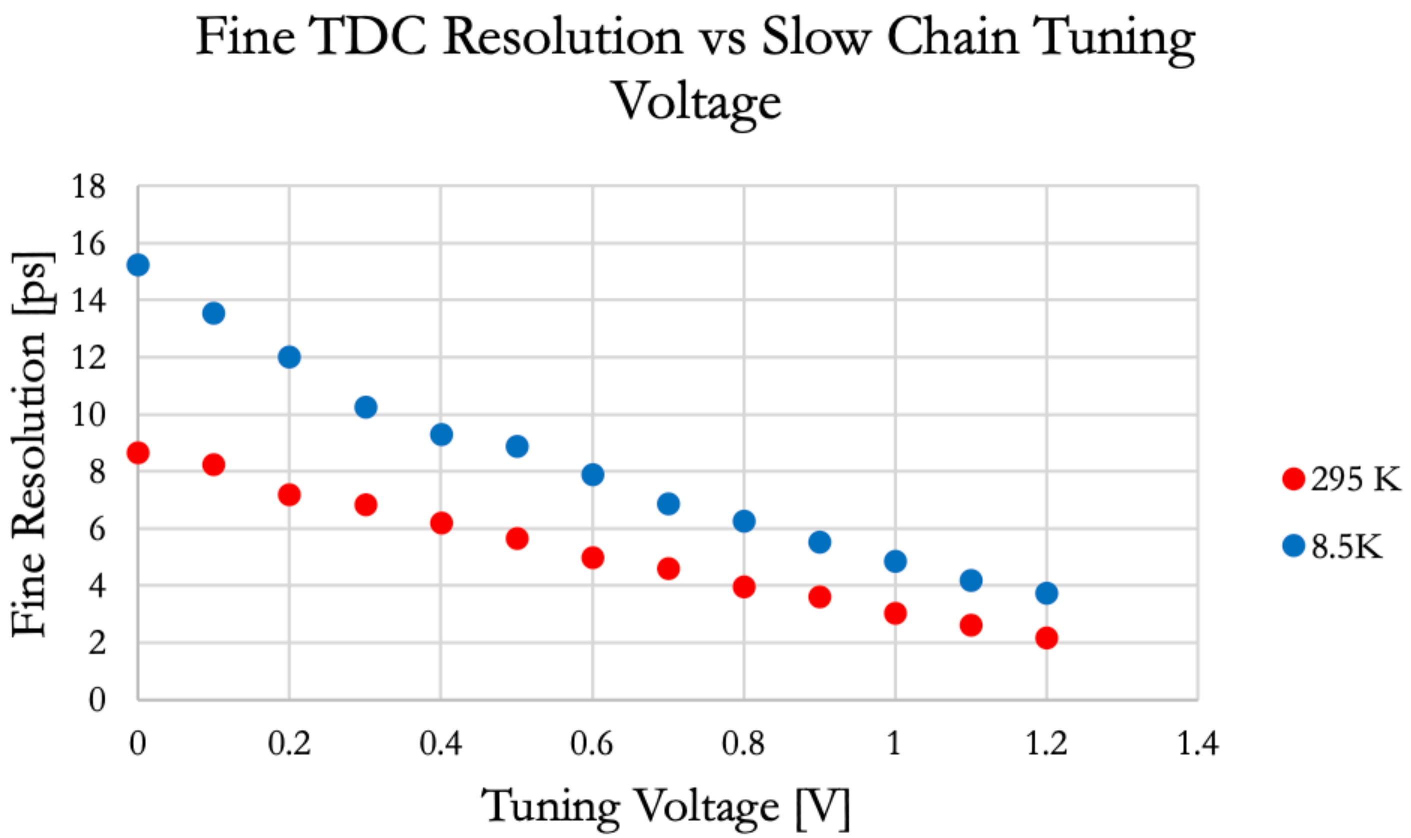
TDC at Cryogenic Temperatures

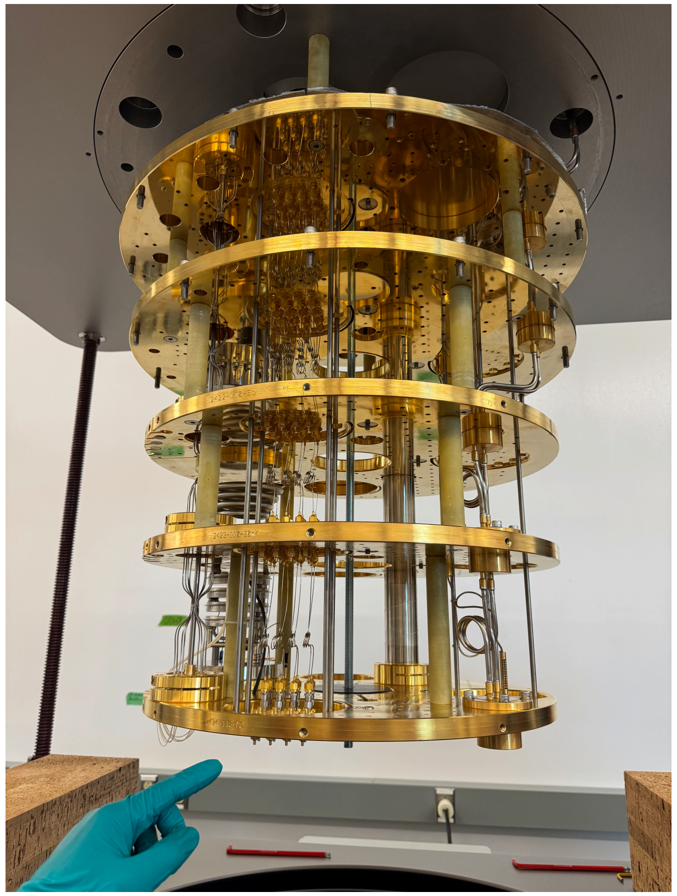
10.36227/techrxiv.173949128.88095436/v1

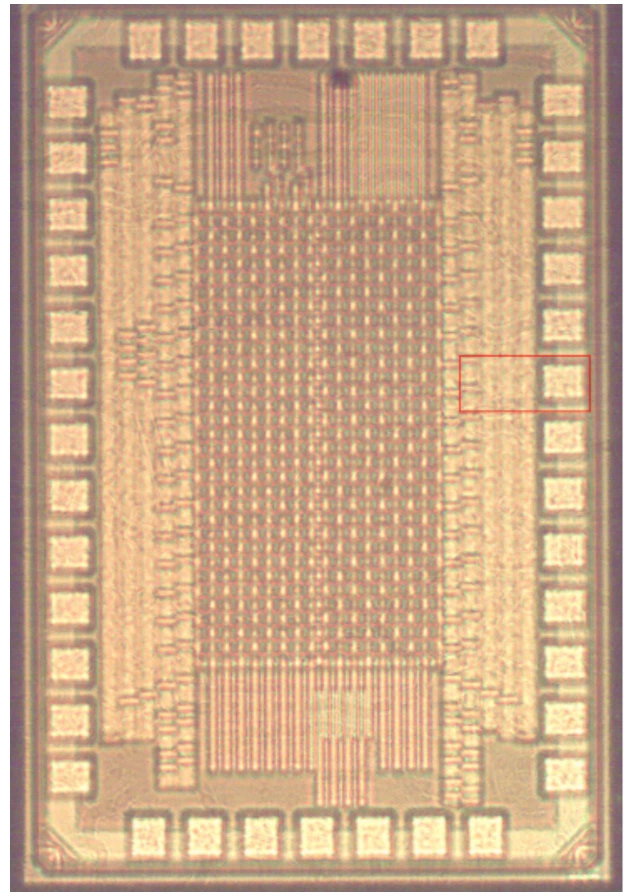
Excellent performance observed at cryo temperatures

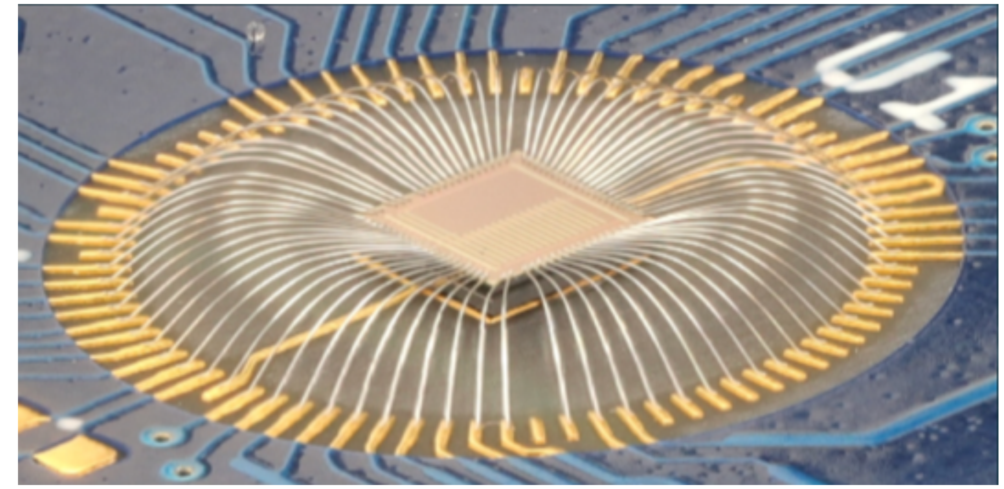
22 nm CMOS Global Foundry

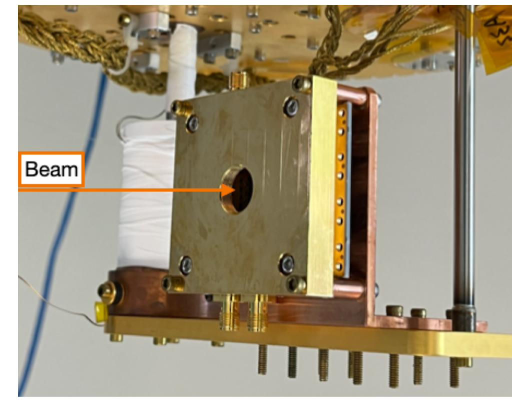


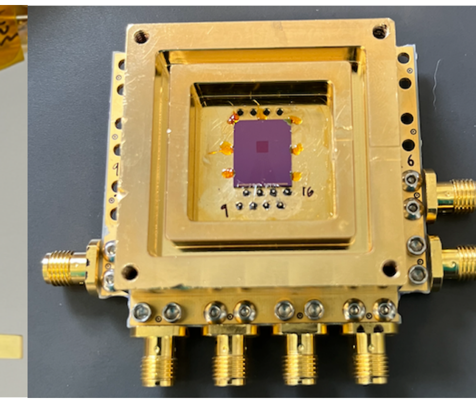












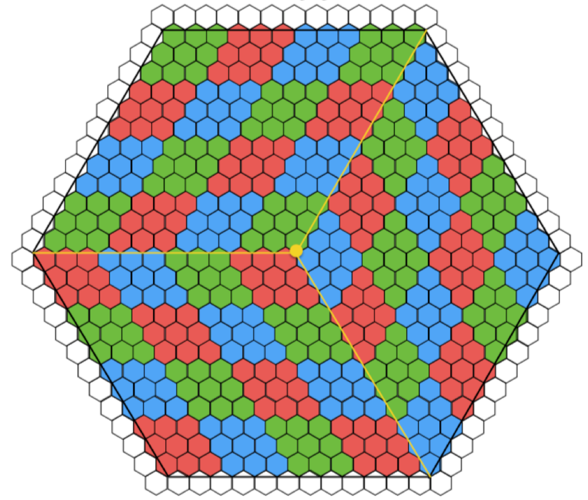
Advanced detector R&D calls for extraordinary talent & long term commitment

Thank You!

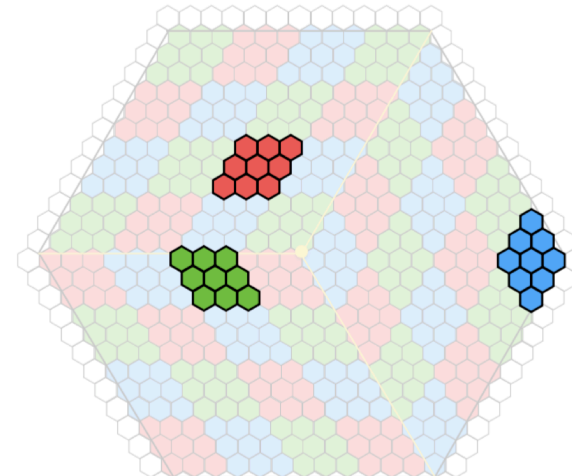
AI/ML on Calorimeters

- 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

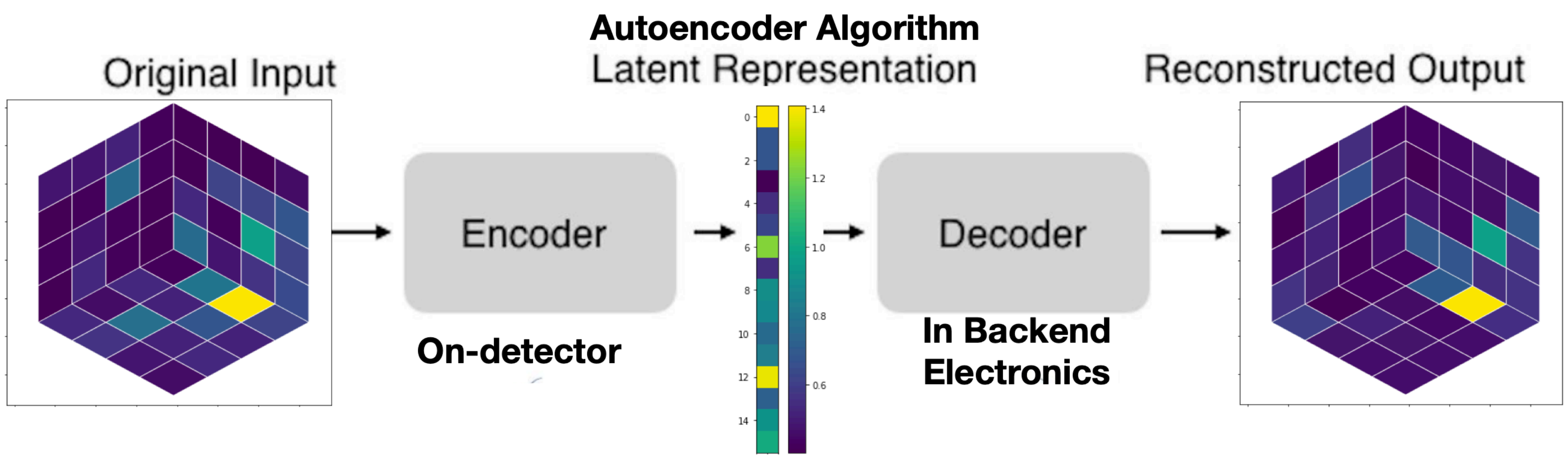
432 silicon sensor cells grouped into 48 trigger cells

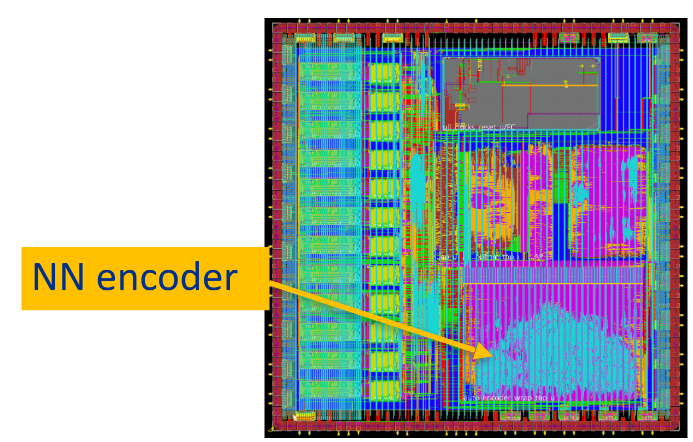


Selection of trigger cells above threshold

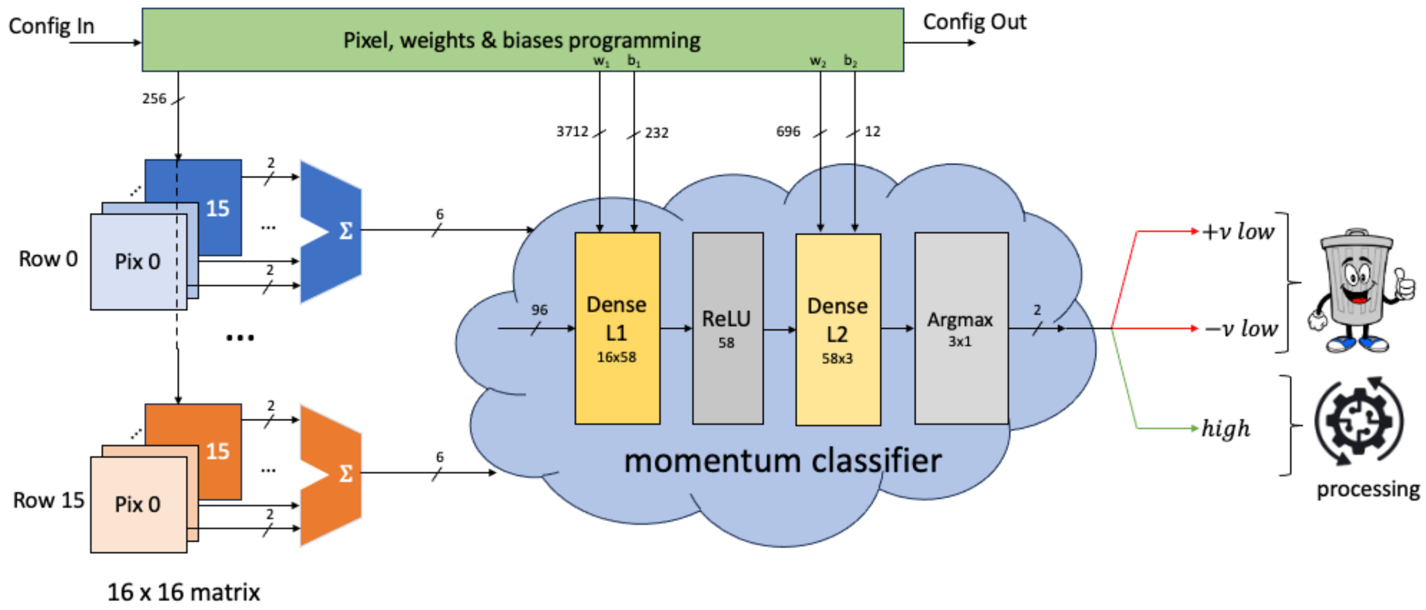


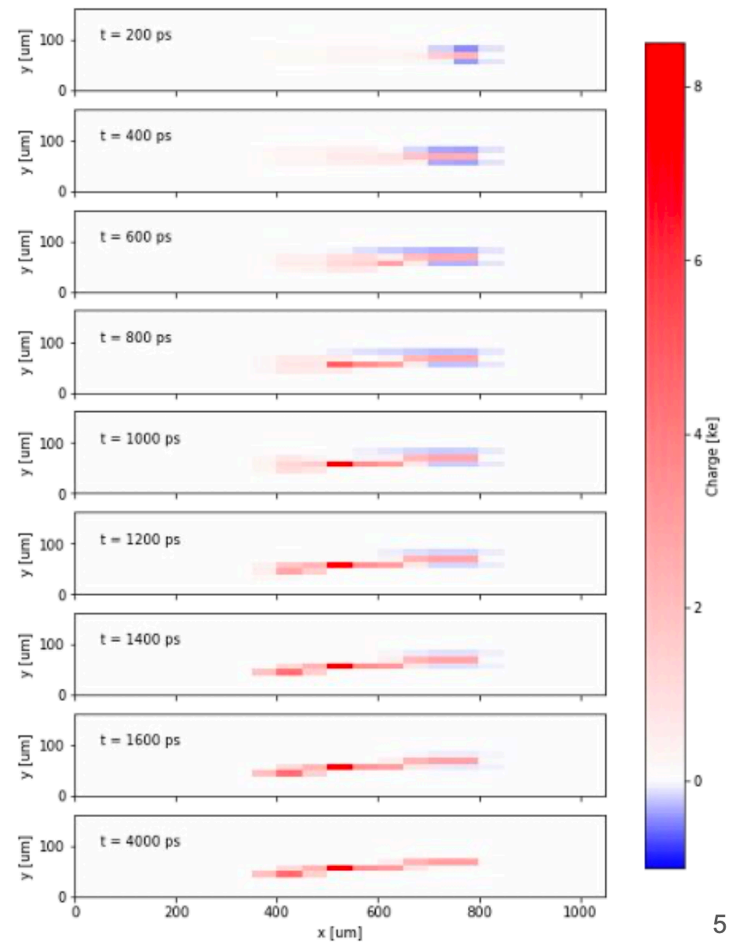
For ~80% of the detector, we have sufficient bandwidth to read out only 3 TC per BX. With the NN, can readout all 48 TC with lossy compression.

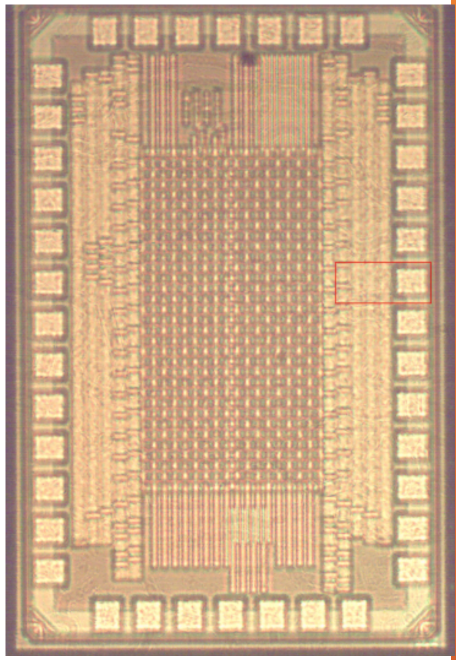




AI/ML Implementation



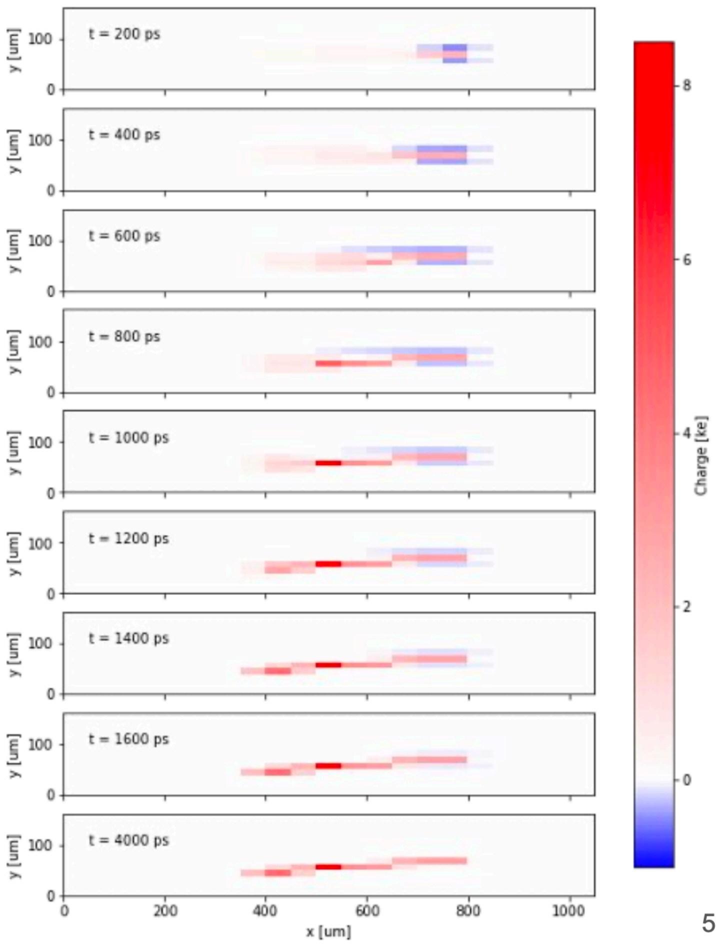


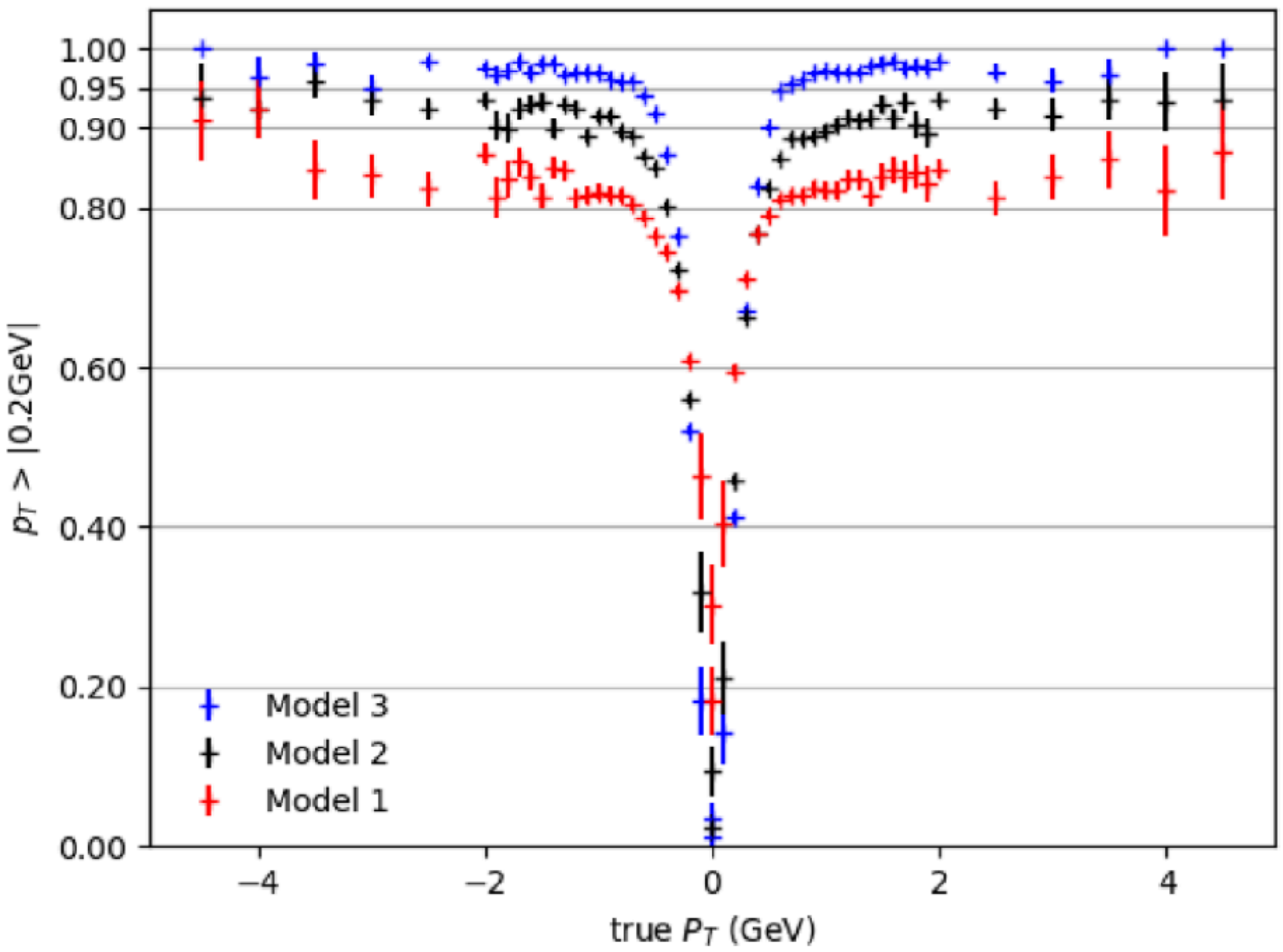


- Use AI/ML due to complicated pulse shapes, and drift & induced currents
  - y-profile is sensitive particle's p_T, x-profile uncorrelated with p_T
- Co-Design development with analog frontend pixels connected to a fully combinatorial digital classifier
  - Combinatorial design reduces dynamic power
  - 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

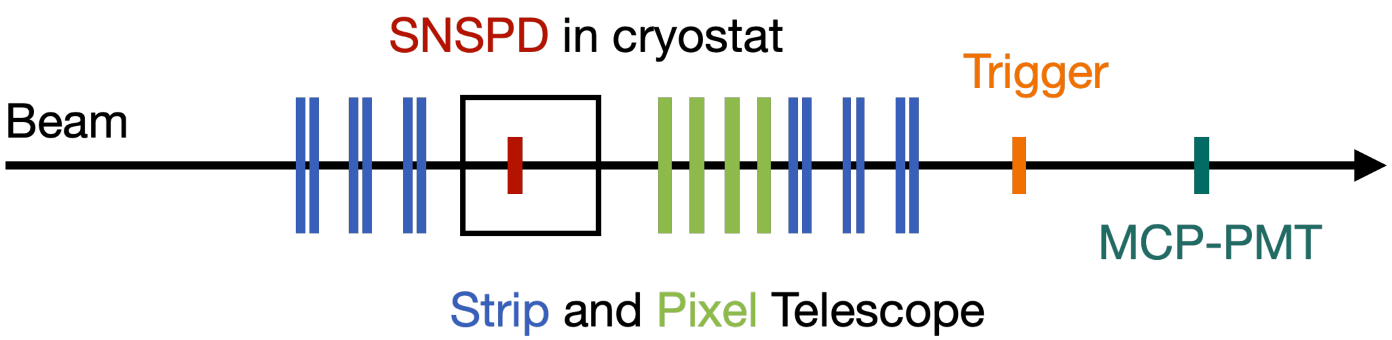
arXiv:2310.02474

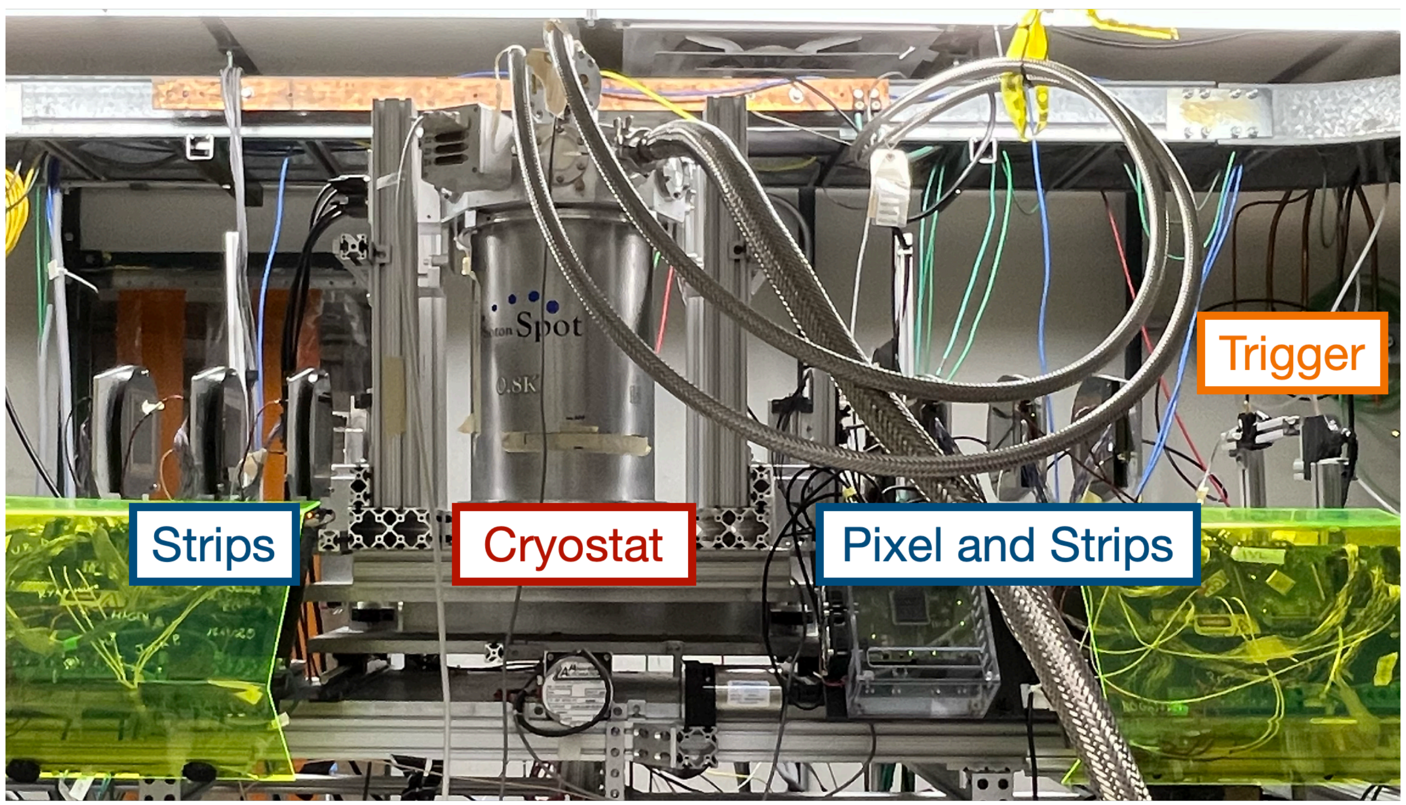




Classifier signal acceptance ~93%
Data reduction is ~57-75%

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





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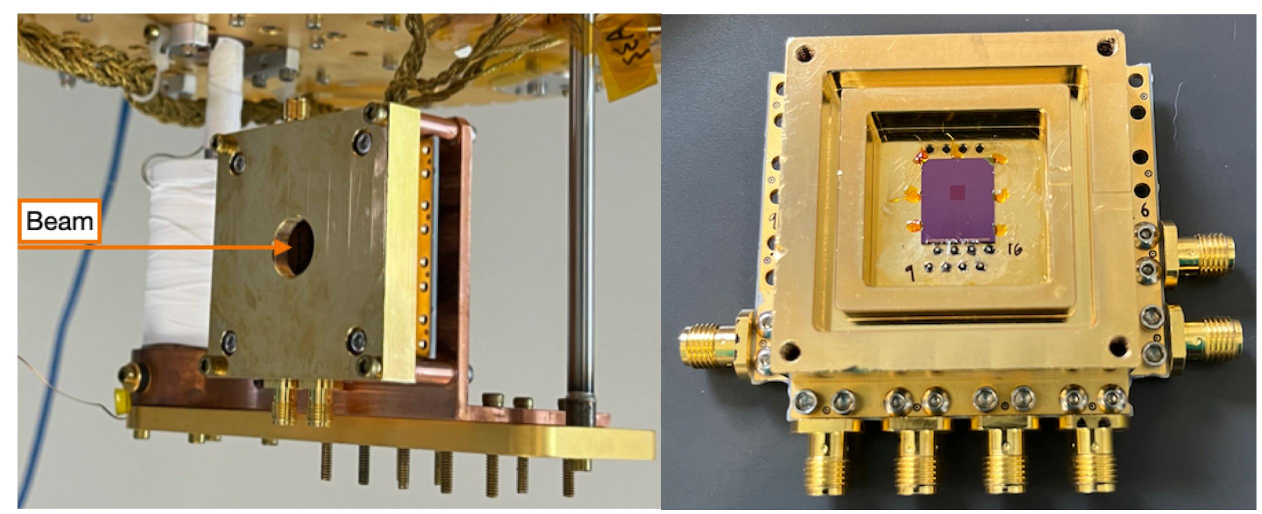
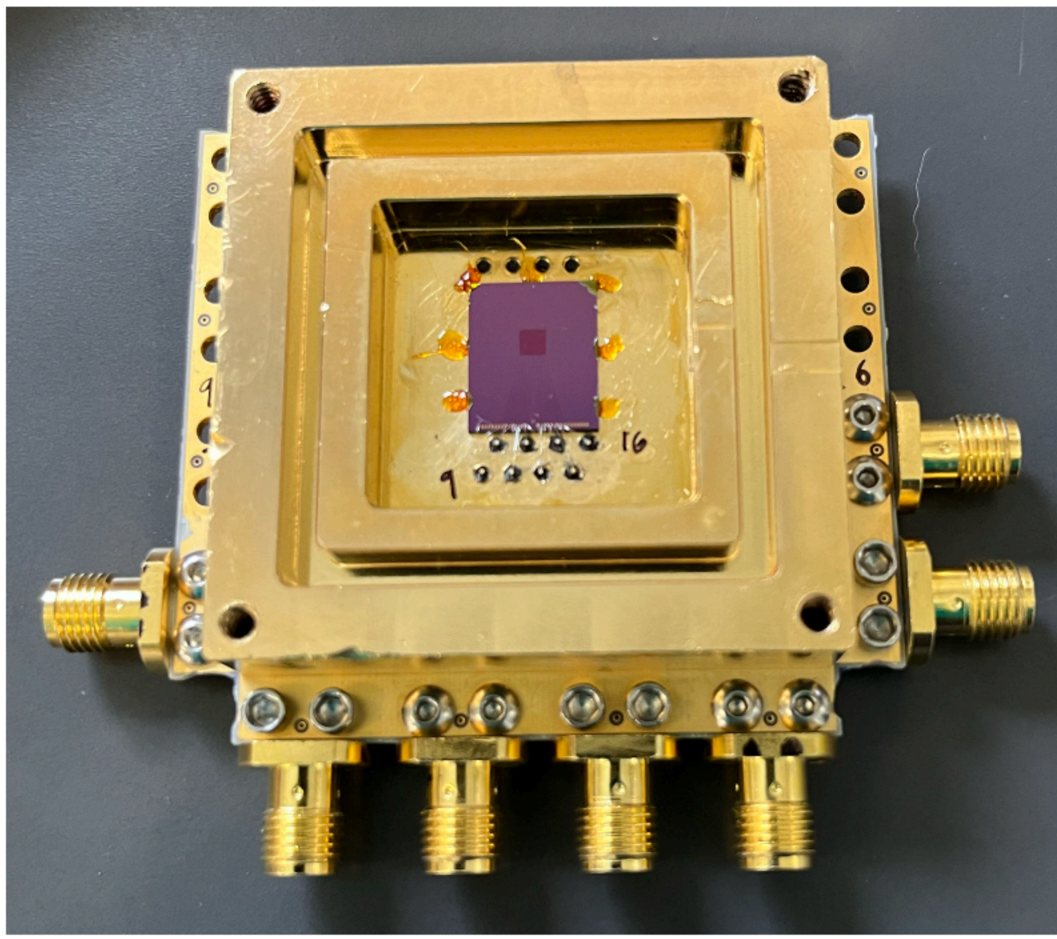
- **First test beam** to detect 120 GeV proton and 8 GeV electrons and pions with **large-area** (2×2 mm^2) **multi-pixel** (8-pixel) SNSPD

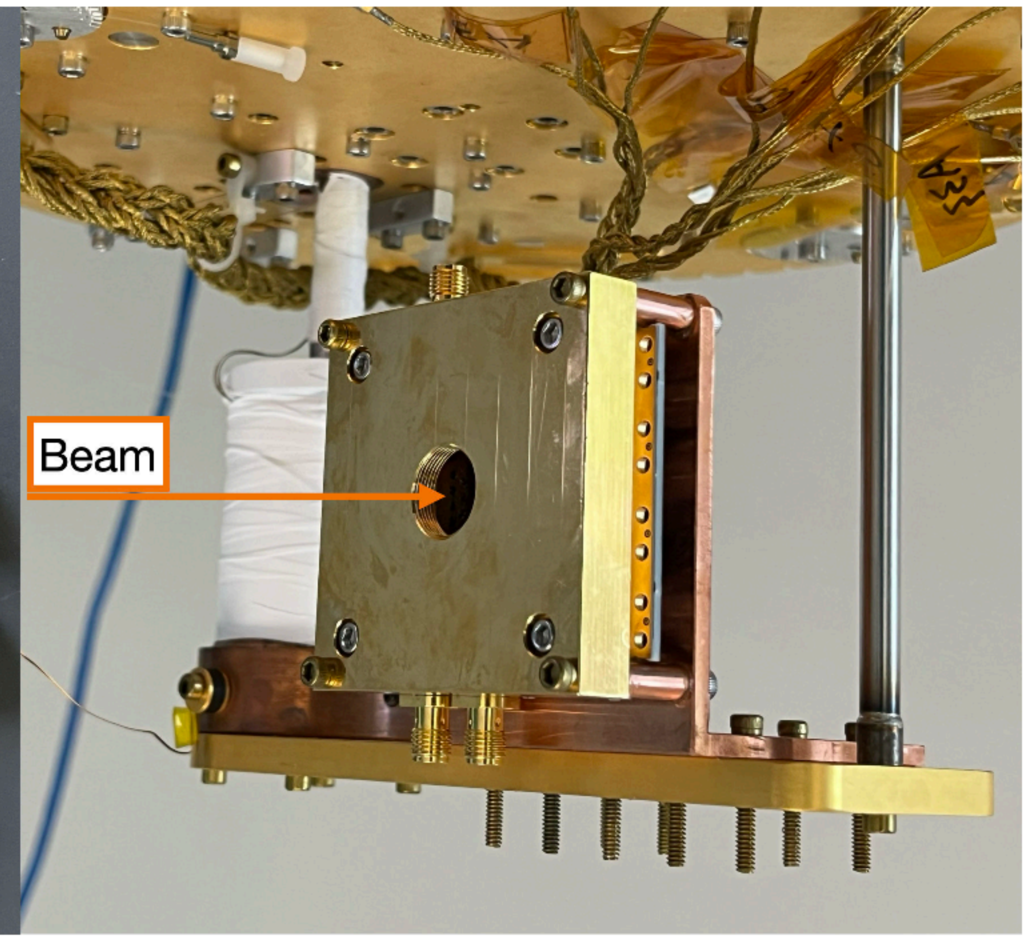


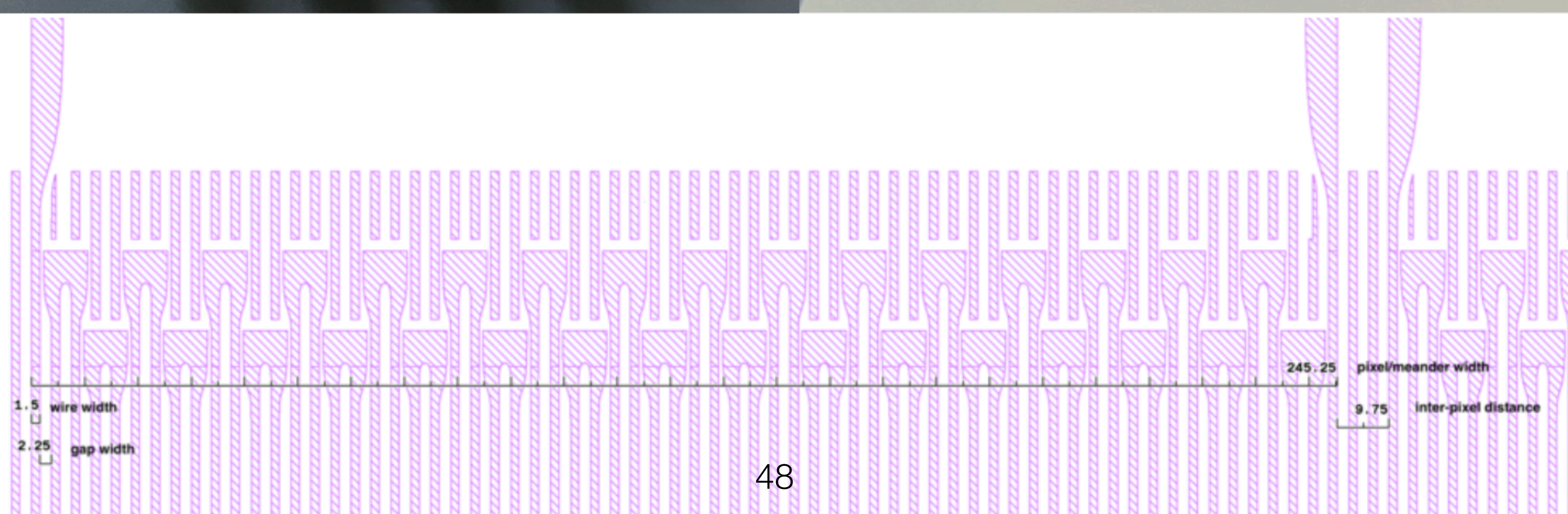
New thrust towards sub-eV charged particle tracking with picosecond level time resolution

SNSPD Under Testing

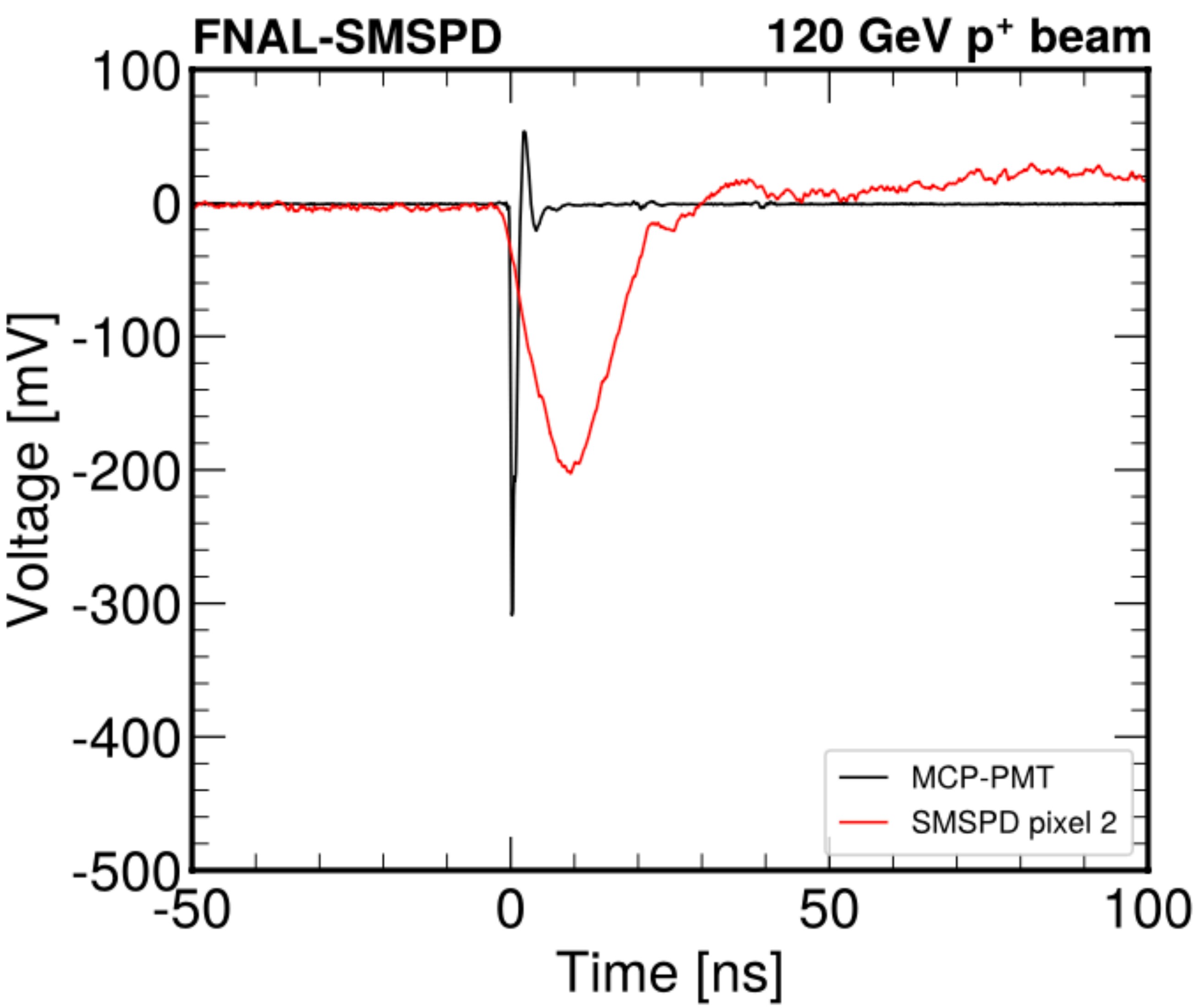
- WSi: 1.5μm, 40% fill factor, T_c = 2.8 K; pixel size is 0.25x2 mm^2

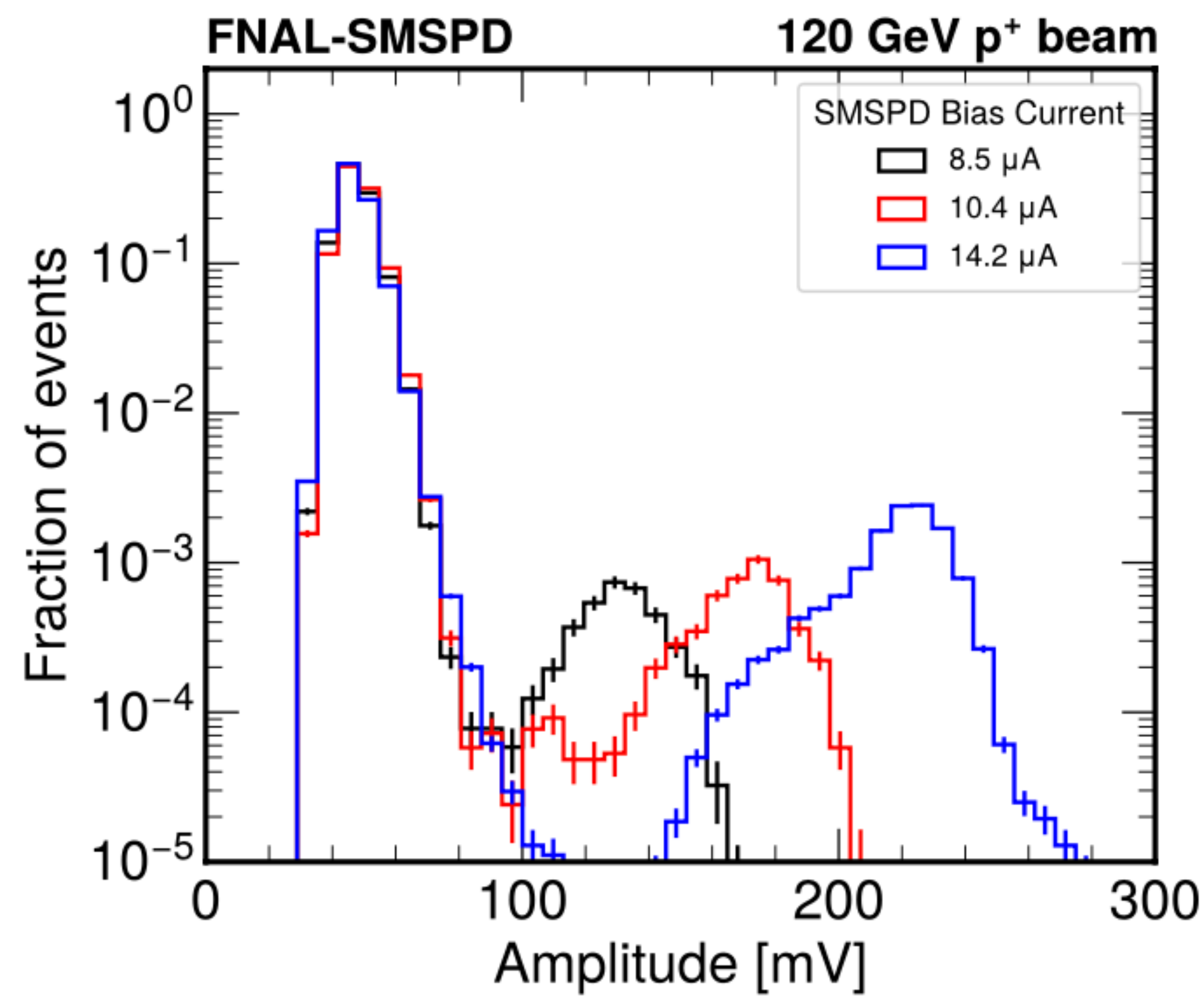






SNSPD Under Testing

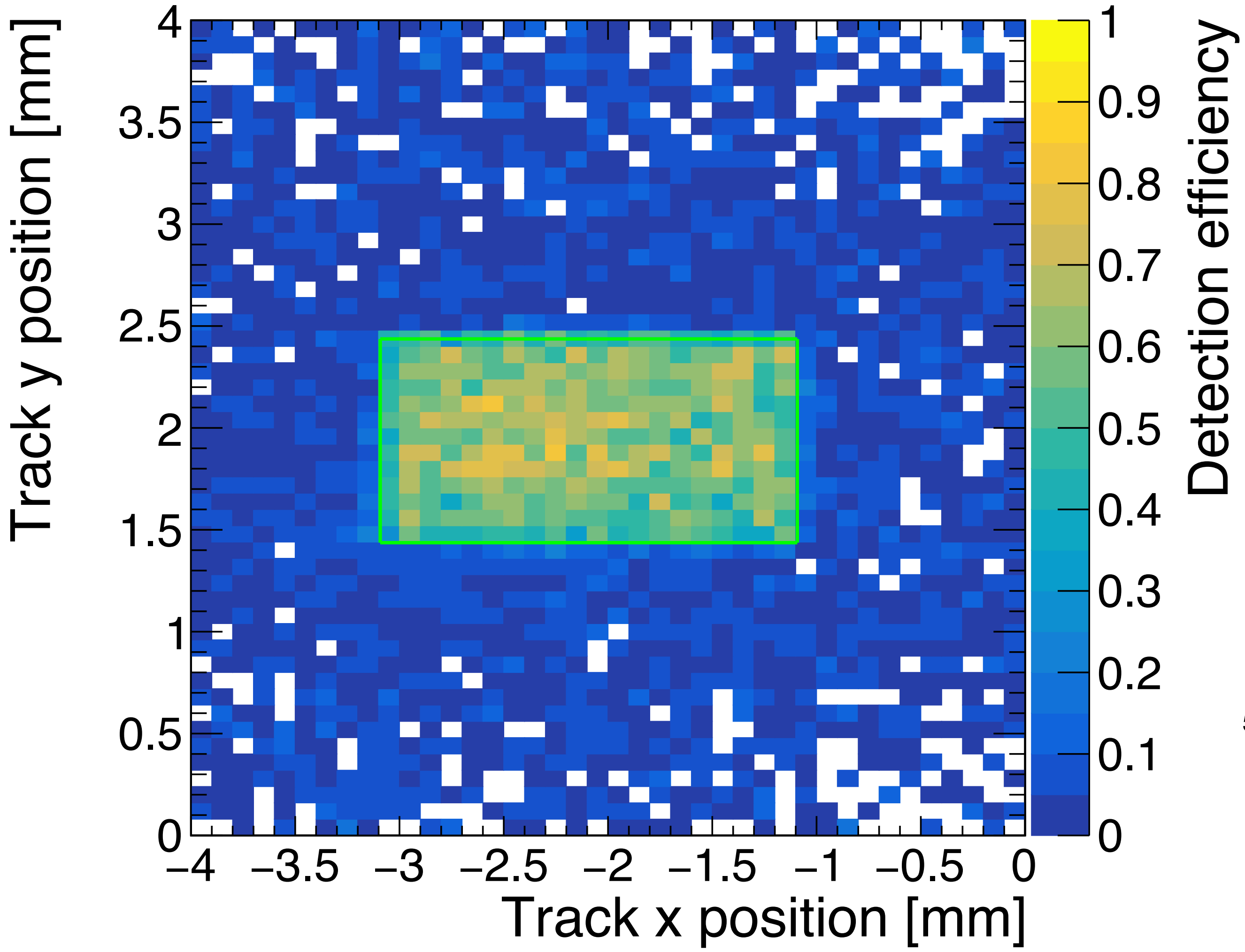


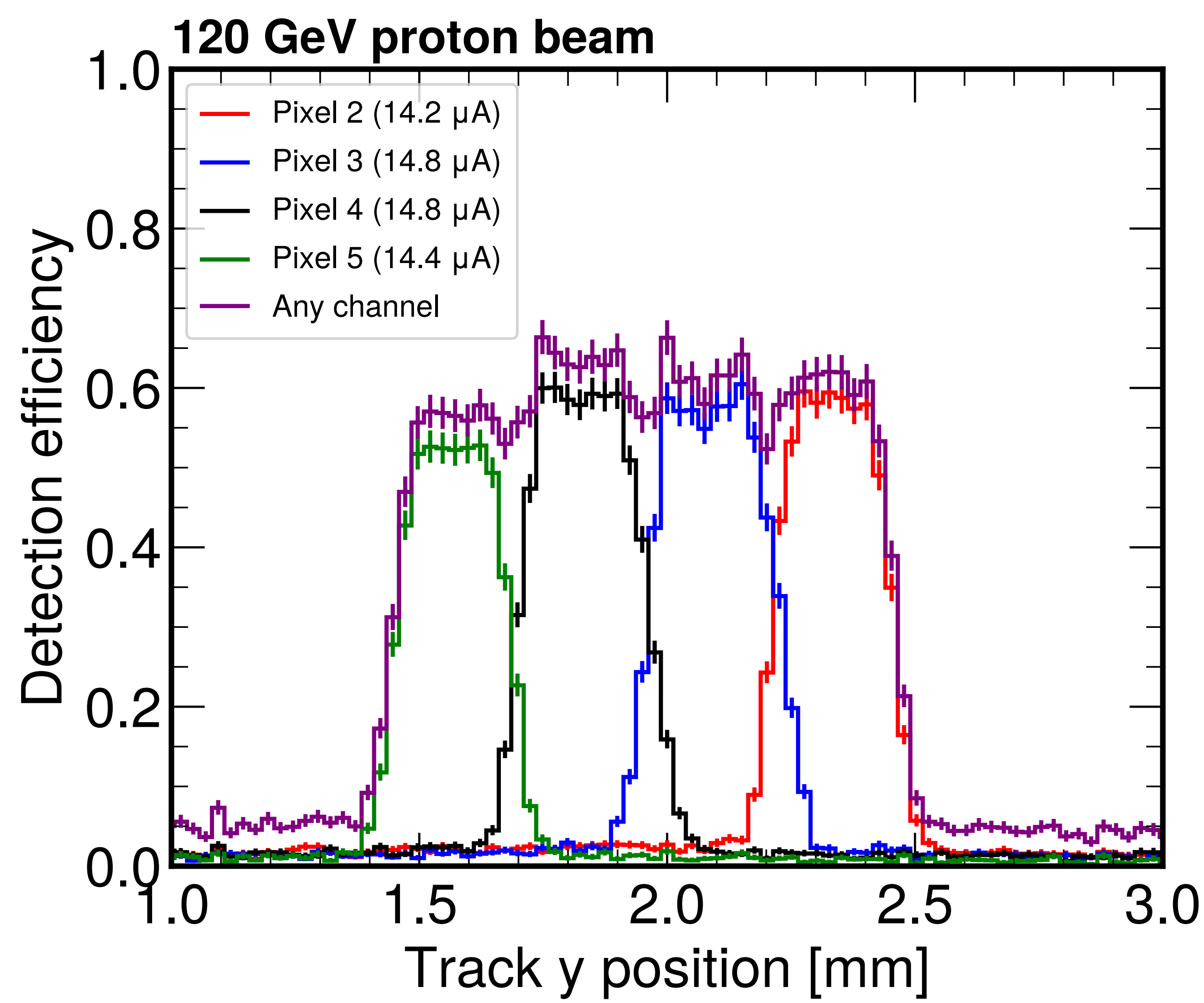


Clear coincidence with reference MCP-PMT and signal clearly above noise for all currents

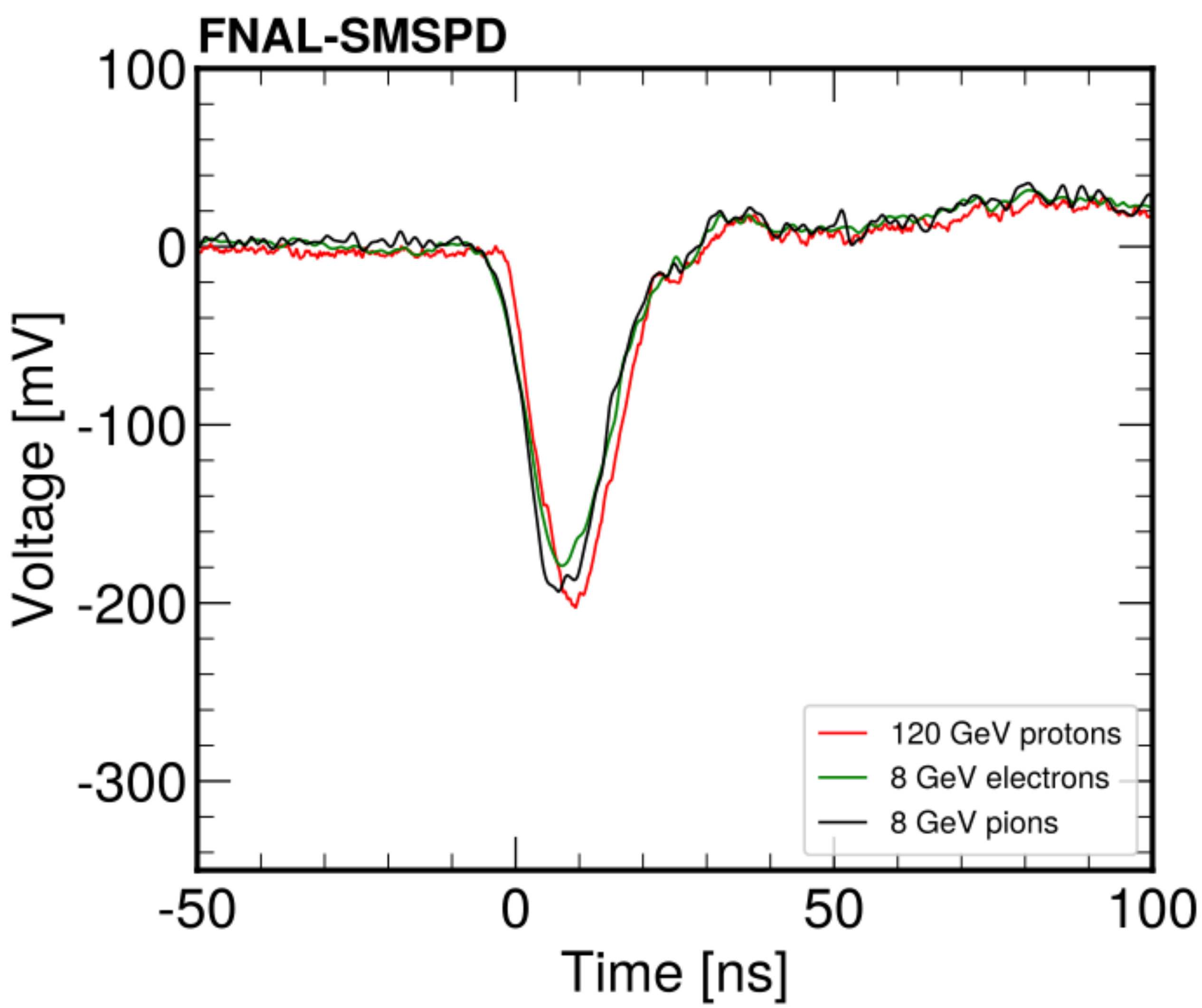
SNSPD Particle Detection Efficiency

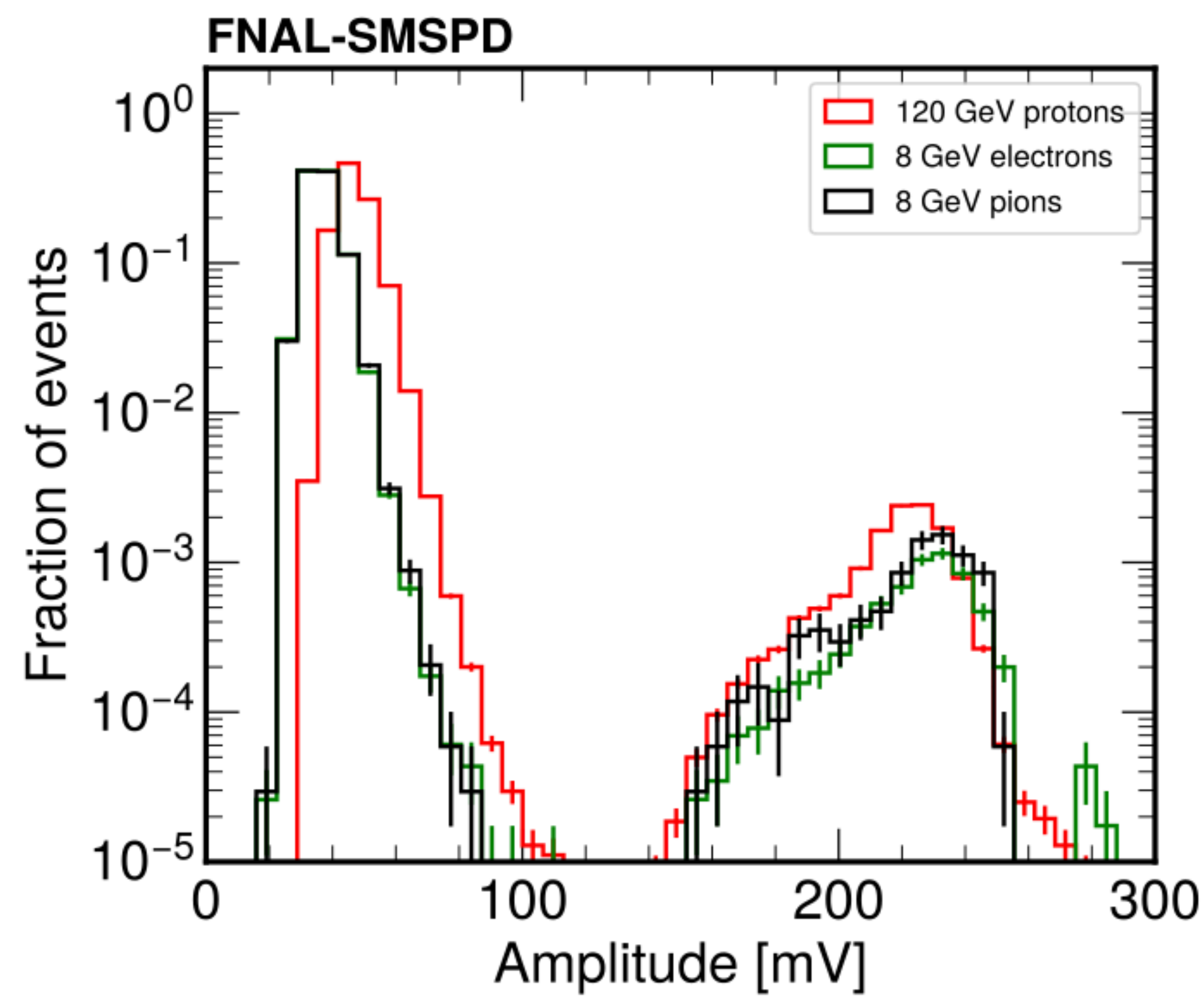
- Readout 4 channels
- Precise tracking telescope (30um spatial resolution) to measure absolute efficiency and response uniformity for the first time





SNSPD response for protons, electrons, and pions

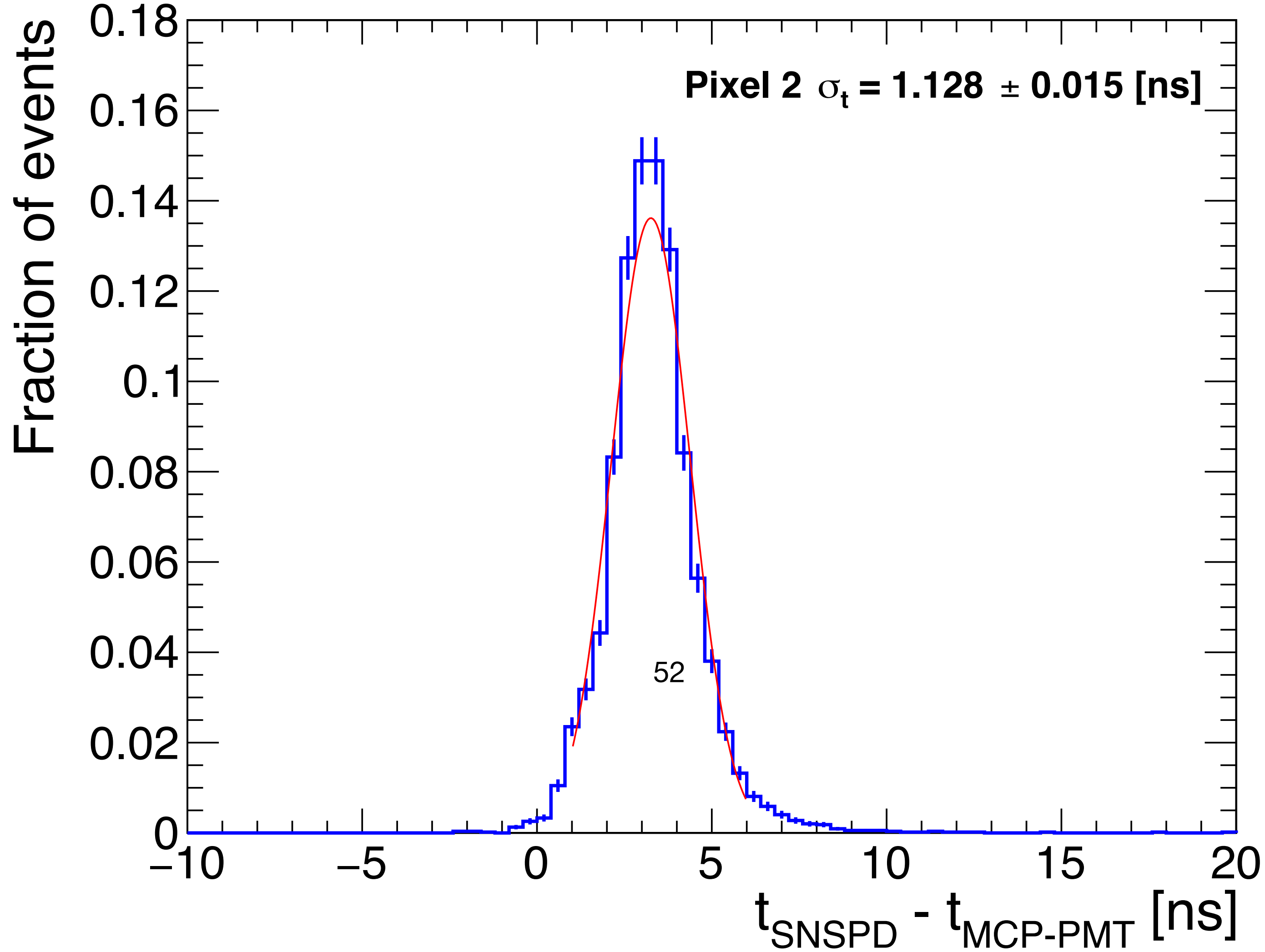




Very similar behavior among the 3 particle types

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!**



CMS Timing Detector

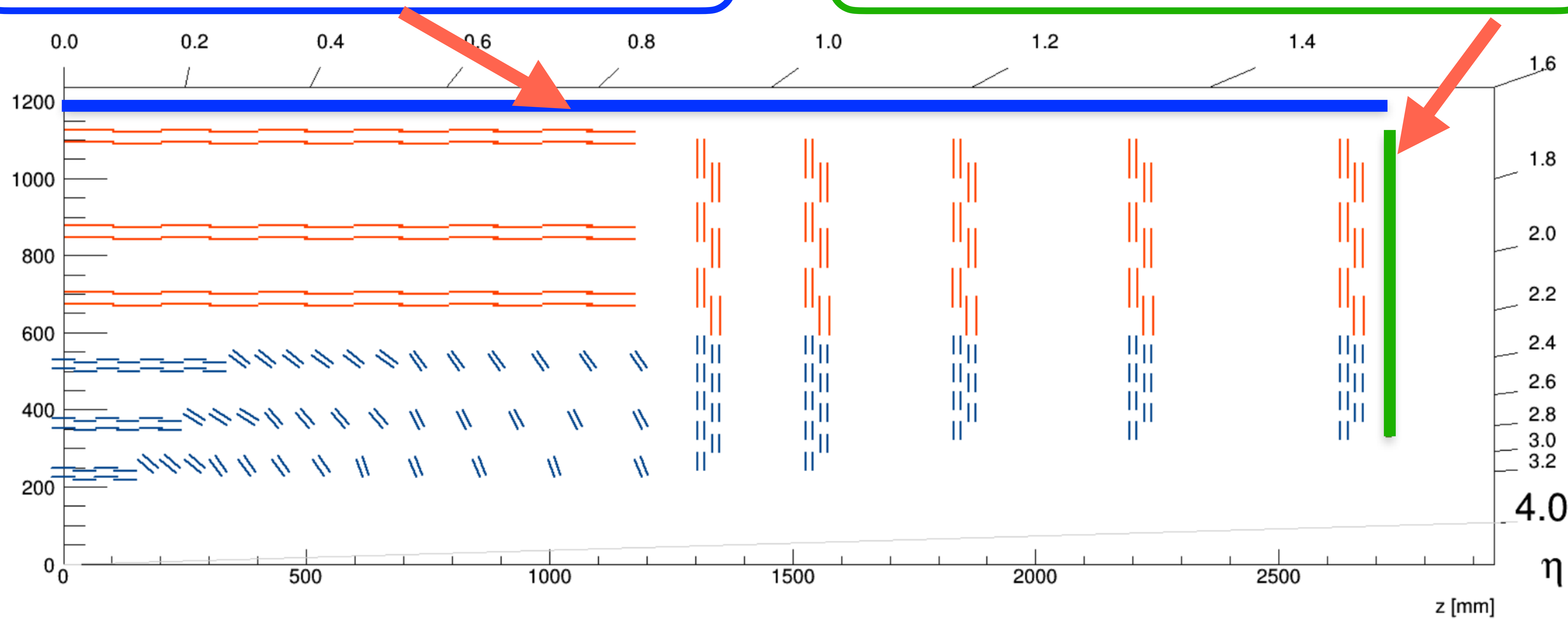
- **Caltech CMS** group the leader of this project since 2012 (with FNAL)
- Sustained effort and progress in precision timing R&D

Barrel Timing Layer:

Scintillating crystal + SiPM

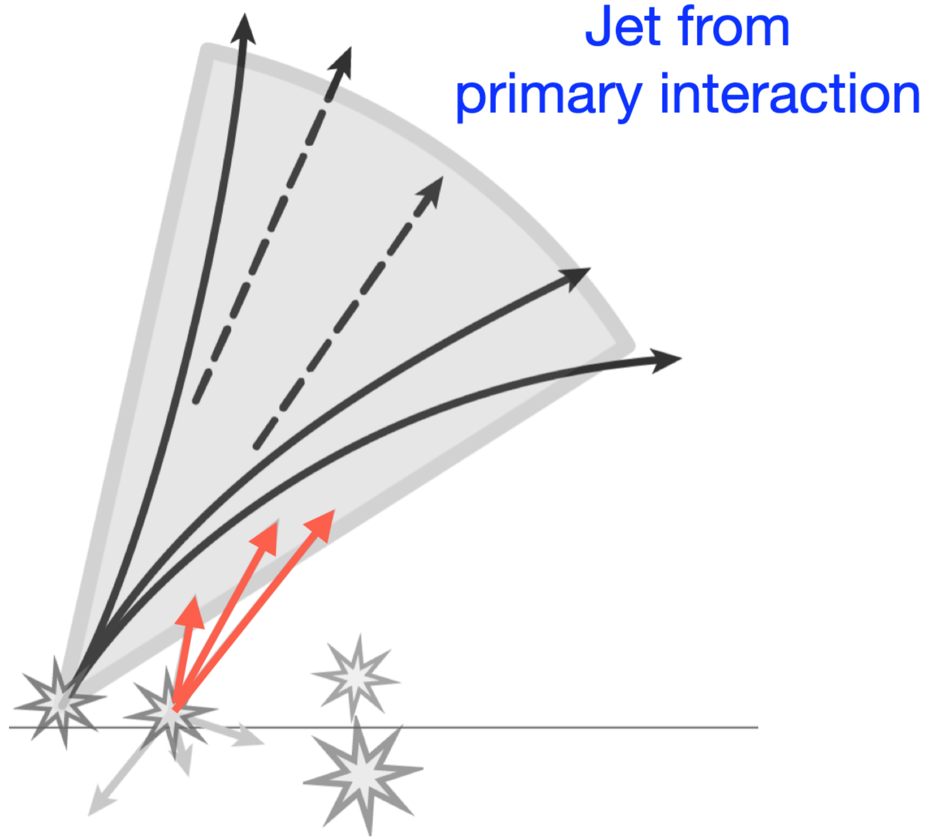
Endcap Timing Layer:

Silicon Sensor with Gain

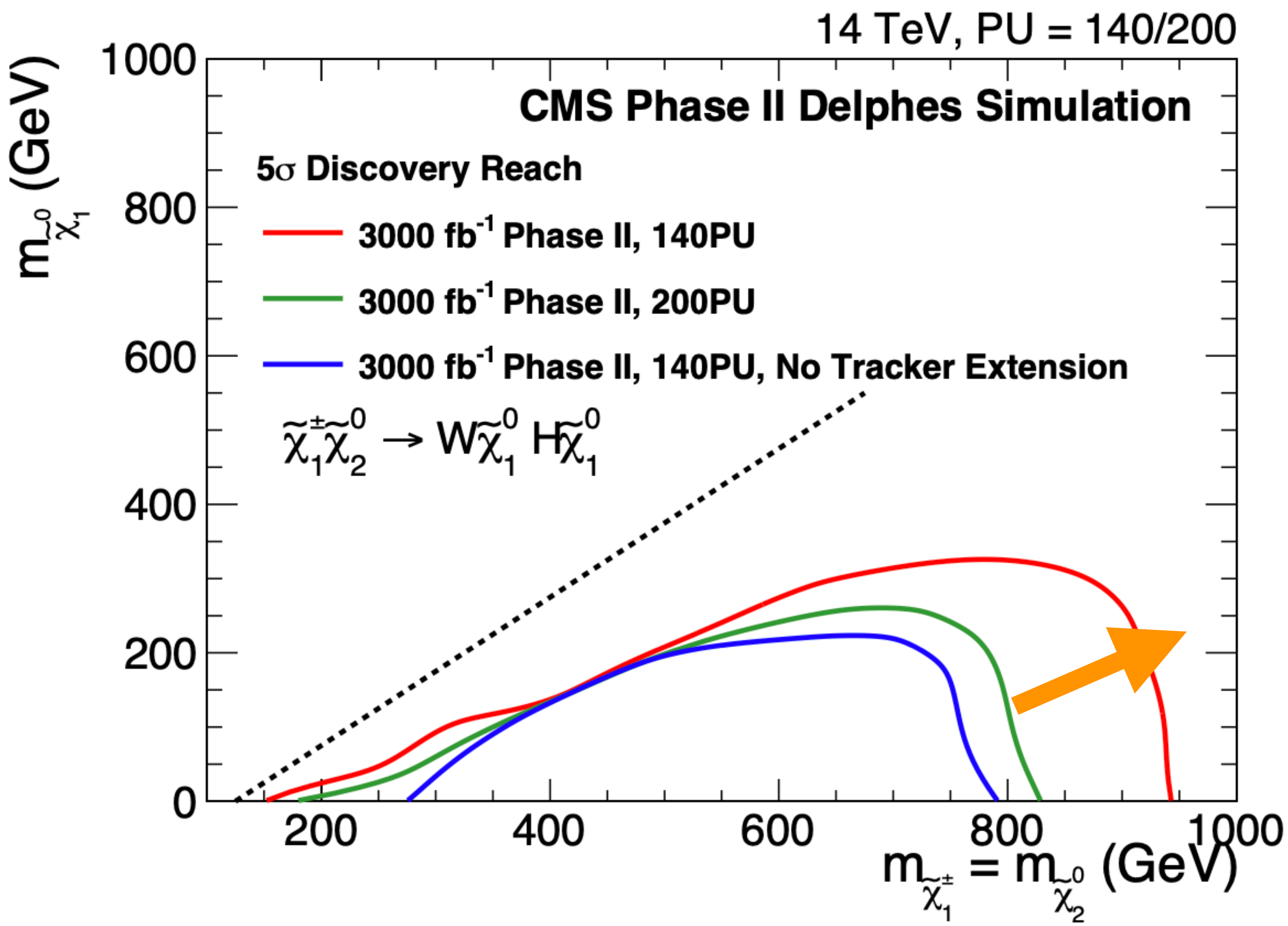


Enhanced Physics Reach

Pileup degrades <u>missing energy resolution</u>



For SUSY searches: timing significantly reduces background

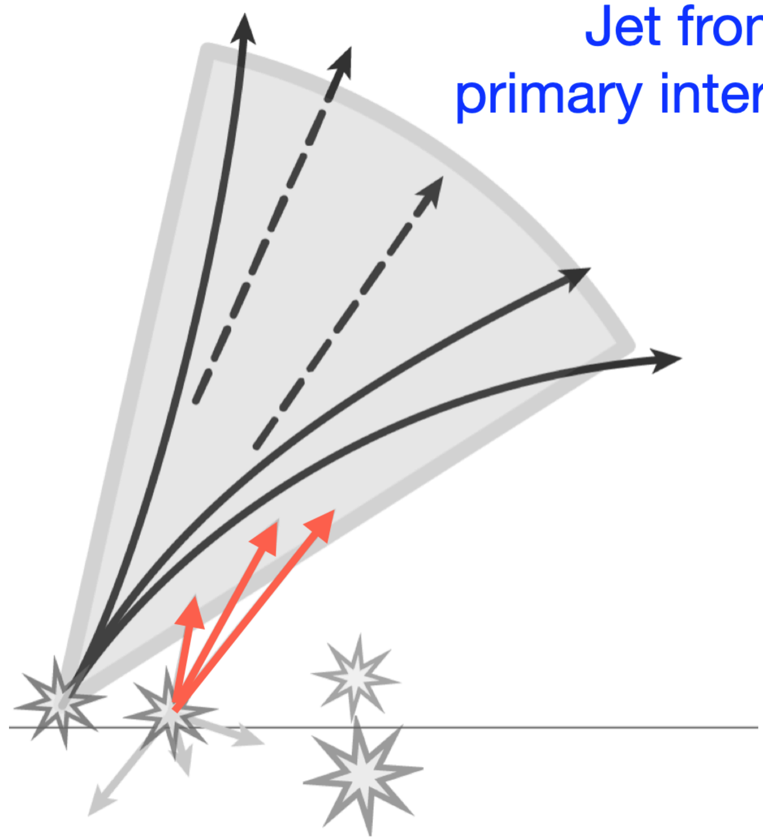


Precision Timing

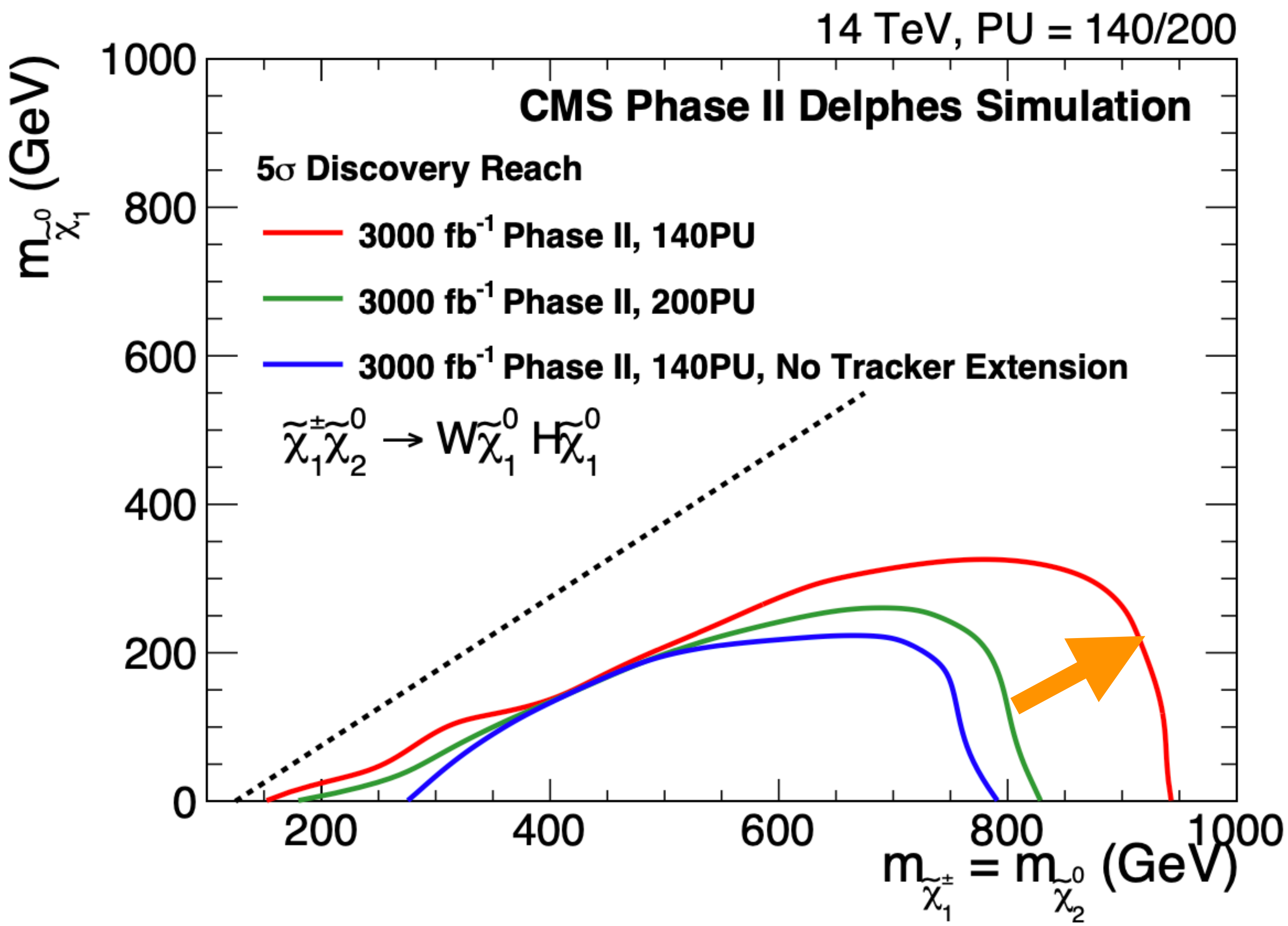
Increase EWK-SUSY mass discovery reach by ~150 GeV

Enhanced Physics Reach

Pileup degrades missing energy resolution



For SUSY searches: timing significantly reduces background



Precision Timing

Accessing 3x smaller production rates!