Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Development of precision tracking detectors at Fermilab

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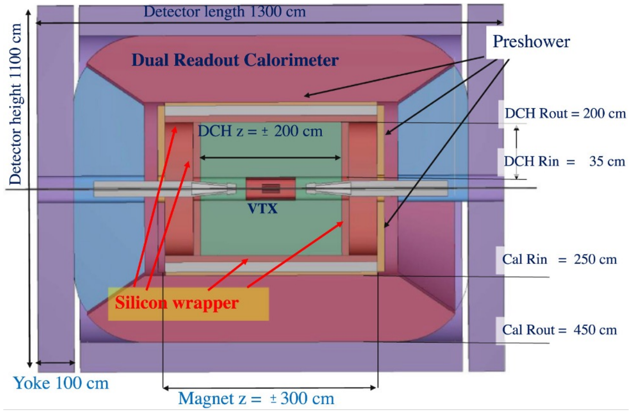
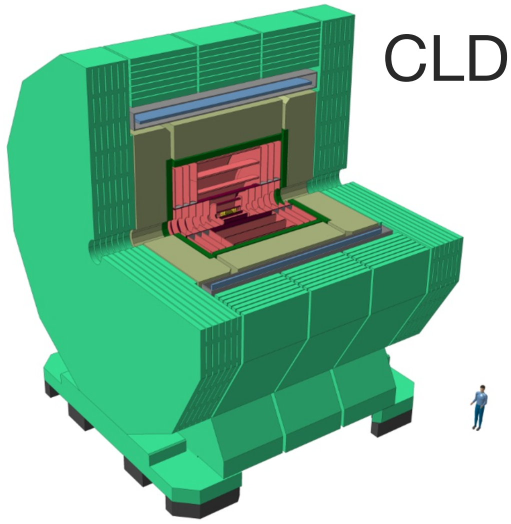
Requirements

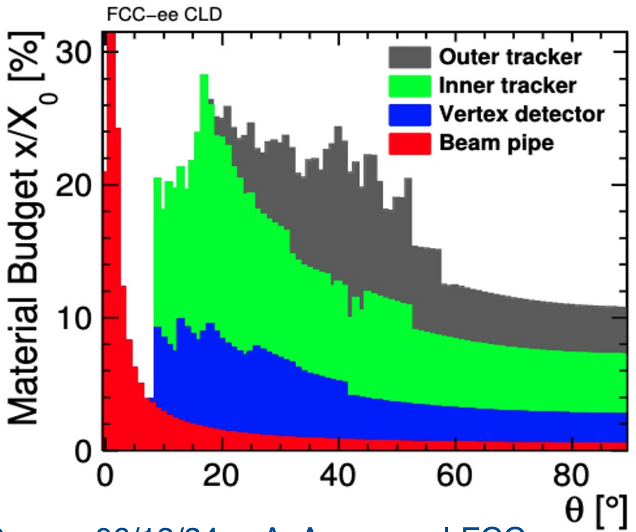
- Physics goals
  - Identify b/c quarks and tau leptons from **Higgs**
  - Perform a precise measurements of the **Z boson**
- Require a **5 μm** spatial resolution, angular resolution of **0.1 mrad**
- Very low mass budget
  - First detector layer material budget of 0.2% X_0
  - Total tracking material budget <30% X_0
- Particle ID with time-of-flight

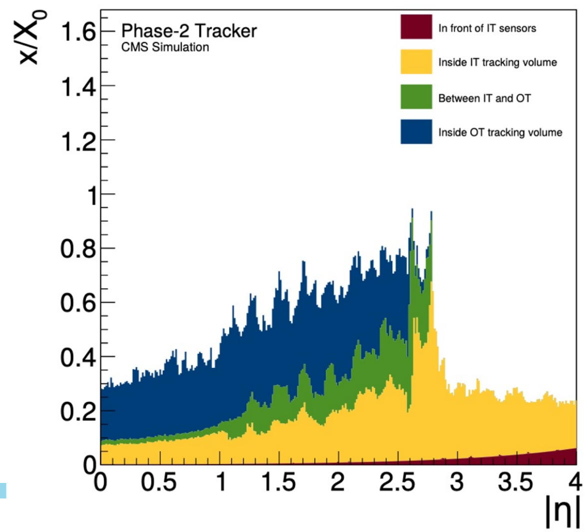
IDEA



CLD







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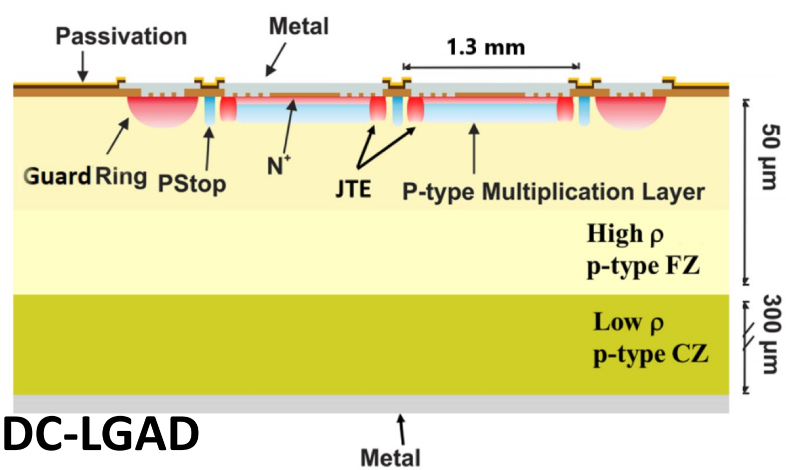
Activities in Fermilab

- Many active directions of R&D ongoing, some highlights:
  - Development of Low-Gain Avalanche Diode sensors and electronics
  - Monolithic Active Pixel Sensors
  - 3D-integrated sensors
  - AI-enabled pixelated sensors

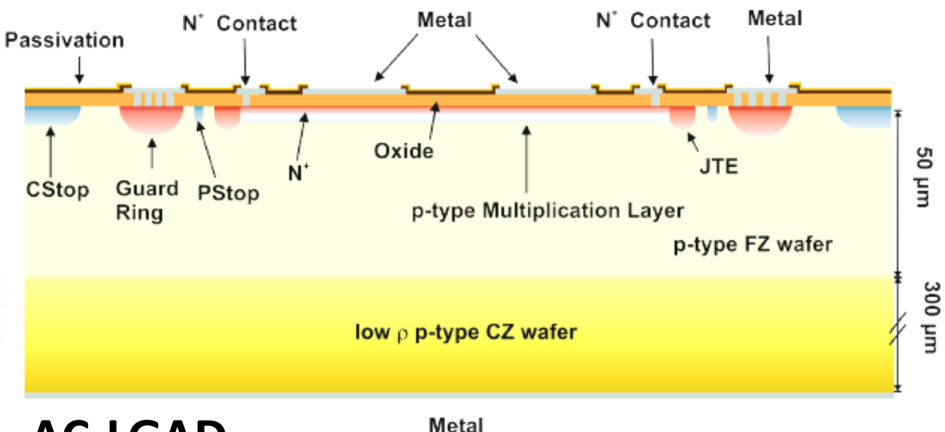
AC-coupled LGADs

- **Improve 4D-trackers to achieve 100% fill factor, and high position resolution**
- Active R&D at different manufacturers (FBK, BNL, HPK, etc)
  – 100% fill factor, and fast timing information at a per-pixel level
  – Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric
  – Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge.

Diagram credit: CNM



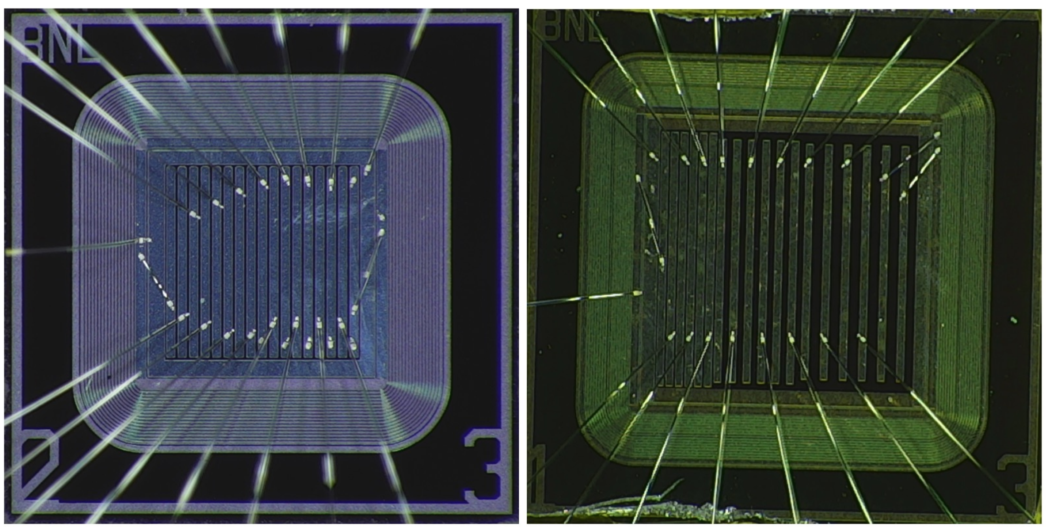
DC-LGAD



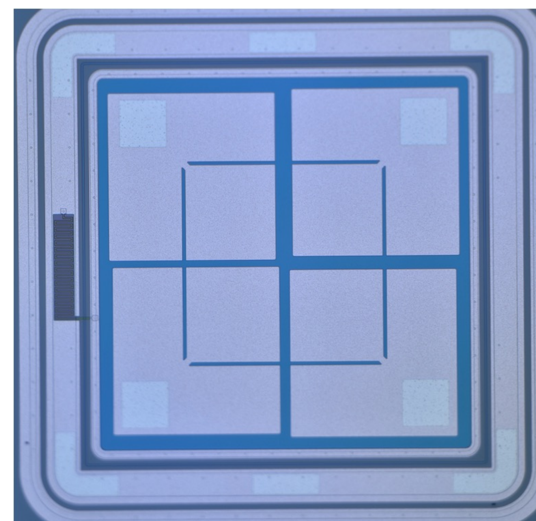
AC-LGAD

AC-LGAD sensors prototypes

- An active and highly successful consortium within US-Japan
  - 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
  - Optimize the geometry of readout, and sensor design for performance



BNL strip AC-LGAD

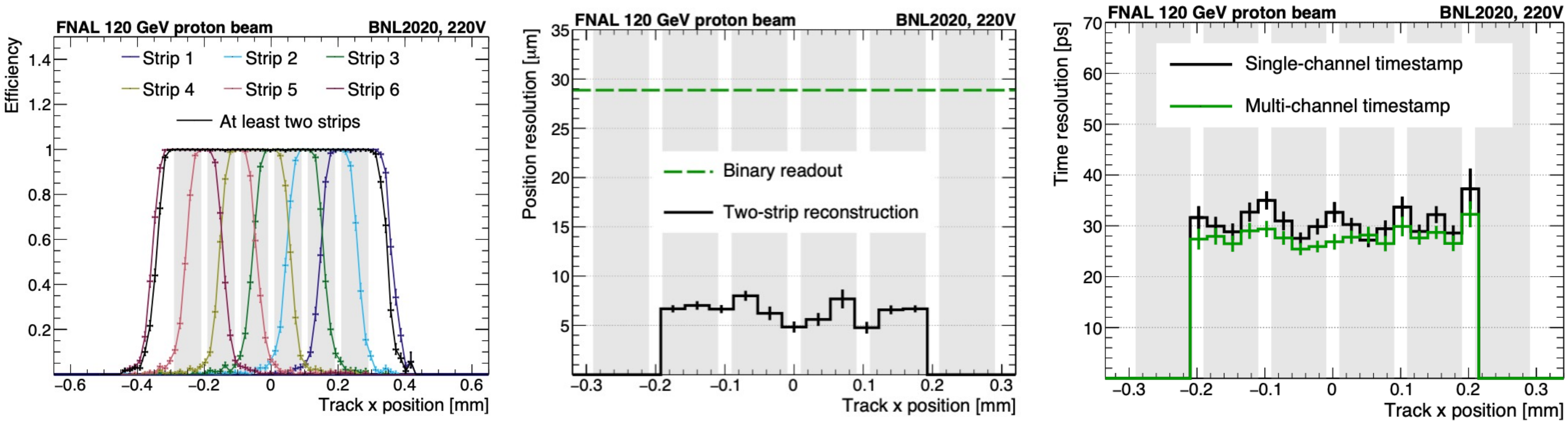


HPK pads AC-LGAD

Strip-sensor AC-LGADs (short sensors)

JINST 17 (2022) P05001

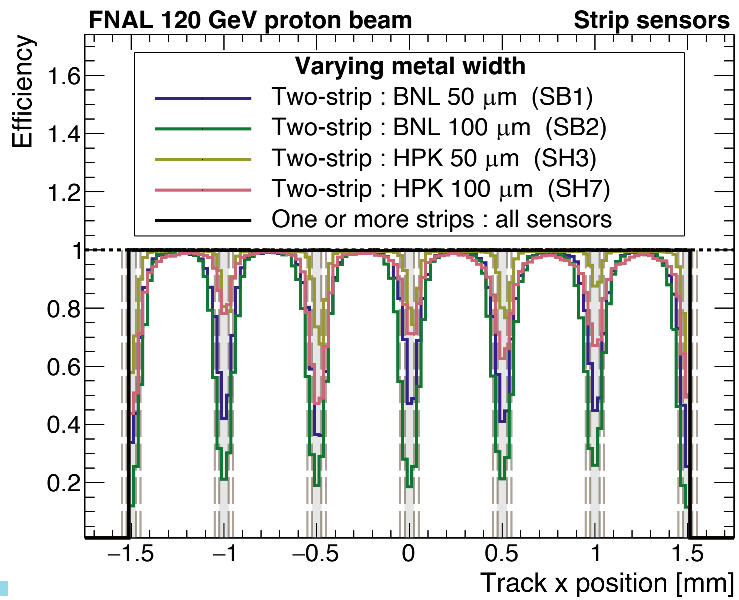
- Excellent performance from several strip prototypes
  - 100% particle detection efficiency across sensor surface
  - Signal shared between neighbors: measure position based on signal ratio
  - Well-tuned signal sharing → uniform 5-10 µm resolution

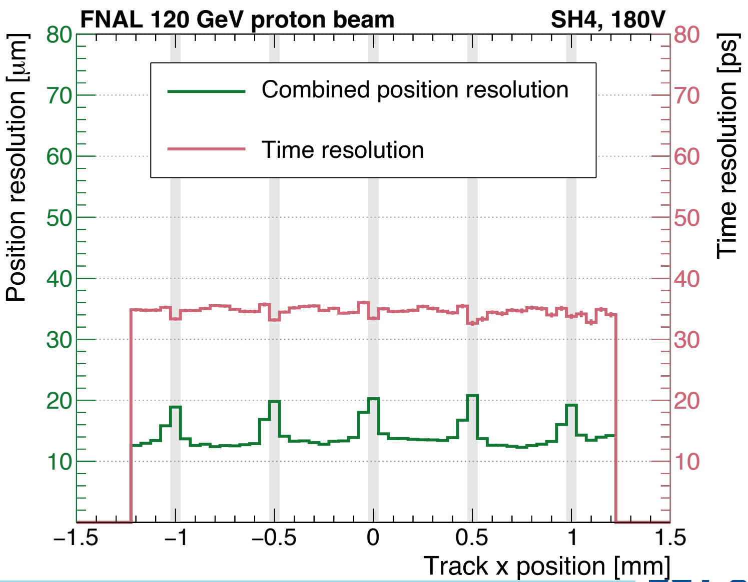


- **First demonstration of simultaneous ~5 µm, ~30 ps resolutions in a test beam: technology for 4D-trackers!**

Long AC-LGAD strip sensors performance

- Position reconstruction with ratio of amplitudes
  - Sensor provides 100% efficiency
  - Achieve 15-20 µm resolution in 10 mm strips with 500 µm pitch
- Excellent time
  - Combining 2 channels & correcting for position-dependent delays
  - Achieve 30-35 ps for 10 mm strips

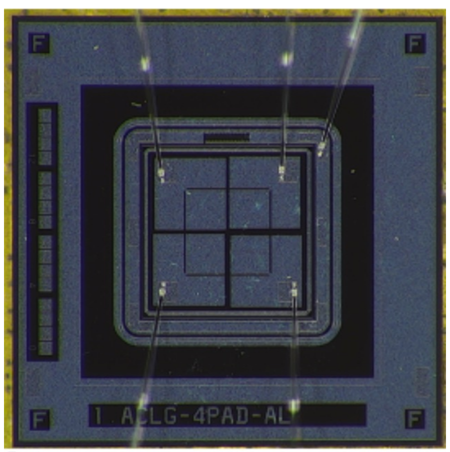




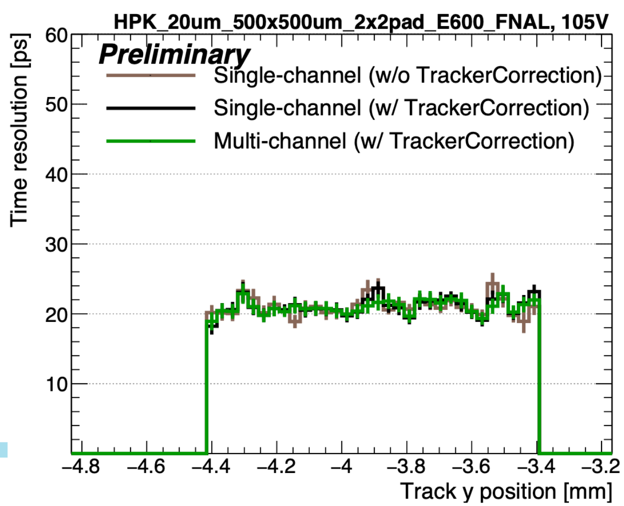
C. Madrid in TREDI 2023

Towards better time resolution

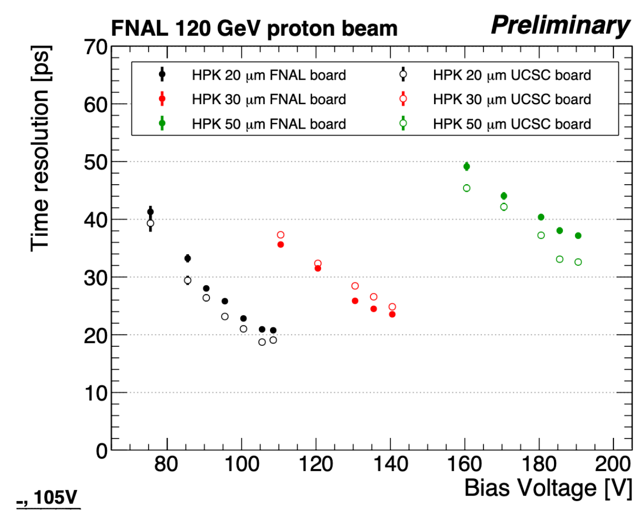
- How do you get better time resolution?
  - Thinner sensors to decrease Landau contribution
- AC-LGAD from HPK with 20, 30, 50 µm thickness
  - Almost fully metallized, optimized for timing performance
- Uniform time resolution across full sensor area
  - 25 ps for 30 µm thick sensor, 20 ps for 20 µm thick sensor



HPK 2x2, 500x500 µm² pixel size



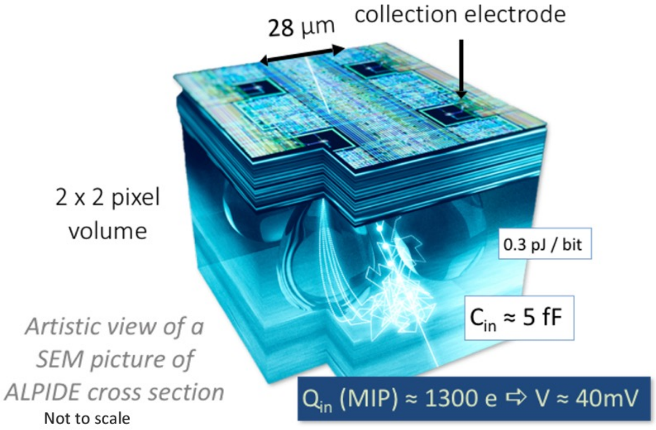
20 ps across full sensor surface



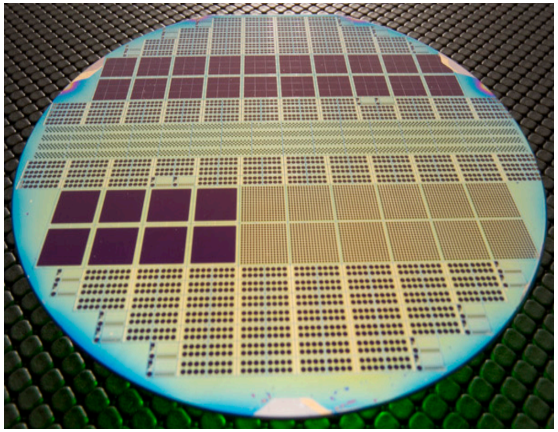
Time resolution for **20**, **30** and **50** µm-thick sensors

MAPS design efforts with Skywater

- **GOALS**
  - US manufactured sensor capability for HEP experiments
  - Optimize the process towards HEP sensors
  - Co-design sensor and readout electronics
  - Broad adoption of development in community



- **HOW?**
  - Partner with Skywater Technologies
  - Consortium of UC, UIC, UF, Purdue, Cornell, for device simulation and testing
  - Engineering run with various designs
  - Testing of sensors at Fermilab and partners



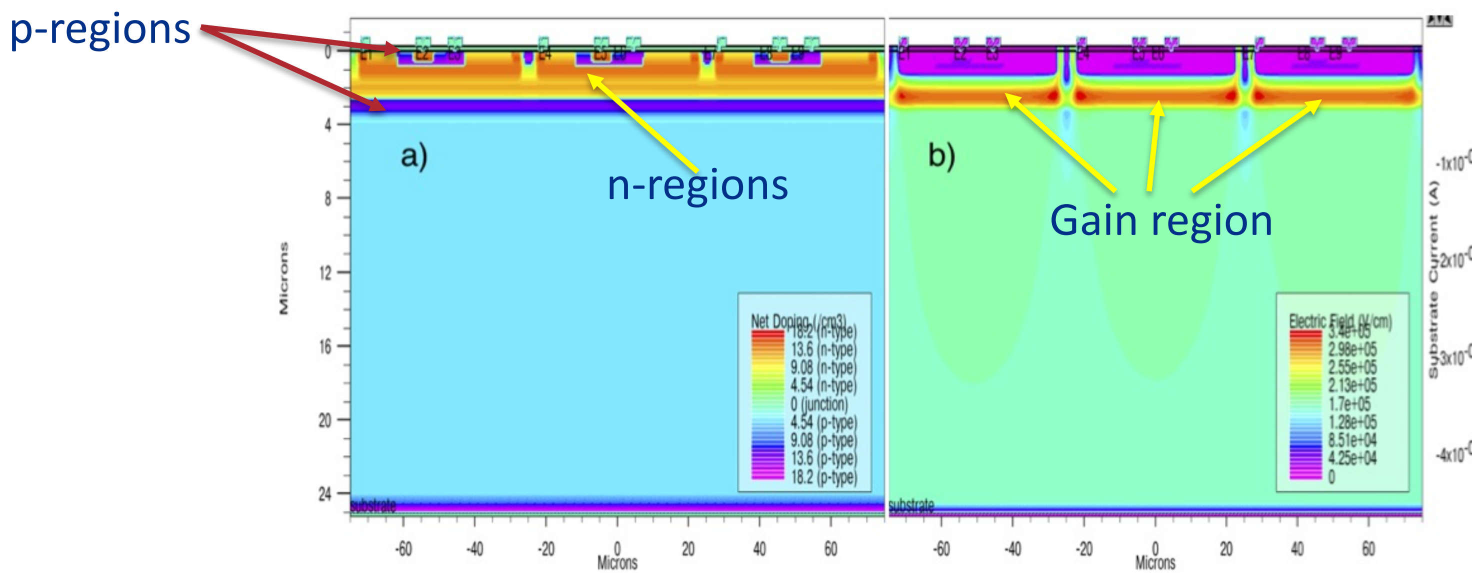
Commercial Partner

- Most **advanced process** among HEP MAPS
  - Fabricated on SkyWater's **90 nm** process
  - Demonstrate domestic production for future HEP experiments

- We will work with SkyWater to modify their standard epitaxial silicon layer
  - Adapt and optimize SkyWater process to develop particle detectors
  - Use thicker, higher-resistivity epitaxy with deep-well implants on a standard CMOS substrate
  - The standard CMOS process flow can then be used to fabricate IC resulting in a monolithic sensor with integrated signal processing

Simulations

- TCAD simulations were used to establish the feasibility of the proposed work, and we started discussions with SkyWater.
  - The initial TCAD studies for SkyWater CMOS are based on our previous work to establish designs for 8" sensor wafer production

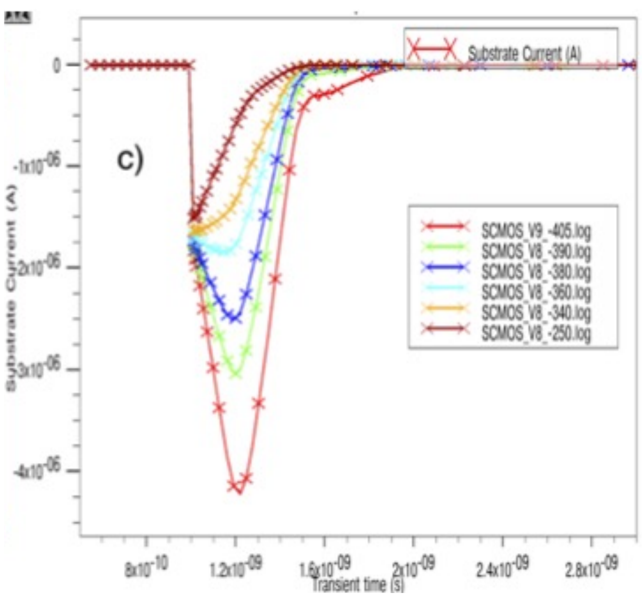


Net doping density of the structure

Electric field profile

Simulations

- Depleted CMOS sensor operation can be limited by the fields in the region of the deep wells causing breakdown or affecting transistor operation.
  - While the SkyWater 90 nm process is not an explicit HV design, it is likely compatible with the fields in fully depleted sensors
  - Can mitigate the fields near the wells with deep n-implant



- Substrate current pulses for bias voltages from 250 (brown) to 405 (red) volts showing the onset of gain.
- Rise time of the top electrodes will be determined by the details of the CMOS well capacitance

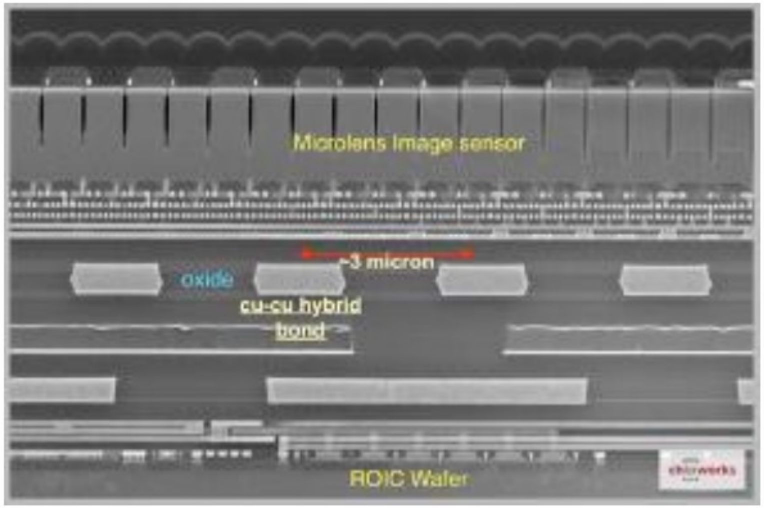
Project Deliverables

- Design and manufacture sensors using SkyWater's 90 nm CMOS process
- Create a HEP specific MPW run
  - Reticle divided into dies of varying designs: ½ wafer with only sensors and ½ wafer with sensors & readout circuits
  - Perform detailed characterization of MAPS, LGAD, and SPAD detectors, and quantify their performance for HEP

- Enable US-teams to lead the design and fabrication of tracking detector(s) for a future Higgs factory
  - B**road participation of university groups** in cutting edge instrumentation

3D-integrated sensors project

- Development of low-power, highly granular detectors in ($\vec{x}$, *t*)
  - Required to achieve breakthroughs across HEP, NP, BES, and FES
  - Adoption of 3D-integration has been cost-prohibitive in academia
- Supported by DOE “Accelerated Innovation in Emerging Technologies”
  - Joint development effort of SLAC and FNAL teams
  - Partner with industry leaders to implement new technologies
  - Design goal is to achieve position resolution ~5 µm, timing ~ 5-10 ps



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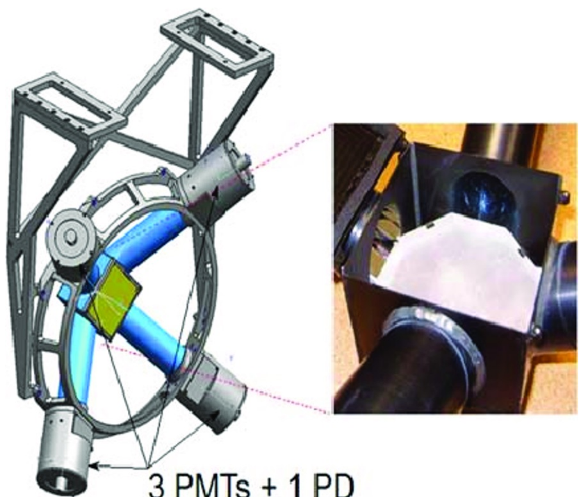
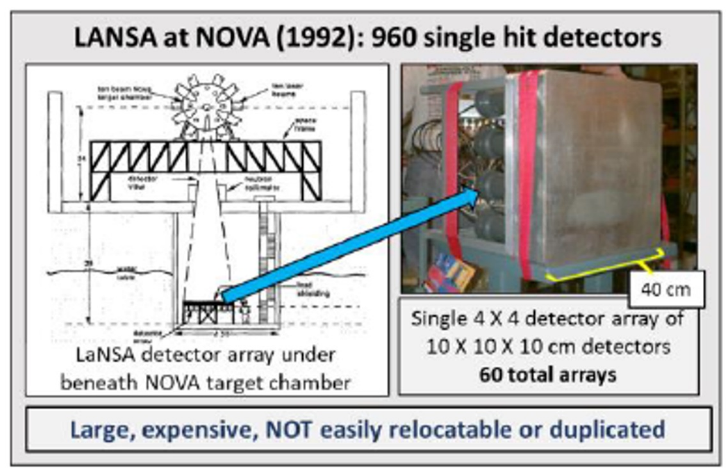
Synergies with other areas

- **Designs for BES applications**
  - The principal difference of applications is a requirement to also measure the deposited energy for soft X-ray imaging
- **Designs for FES applications**
  - Inertial Confinement Fusion (ICF) experiments measure peak plasma burn durations below 100 ps: need to sample with precision ~10 ps
  - X-ray imaging requires full 2D image samples over this burn history

Current nTOF uses 4-PMTs

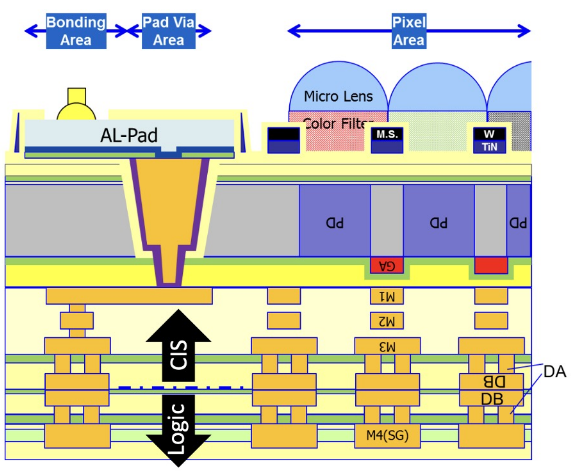




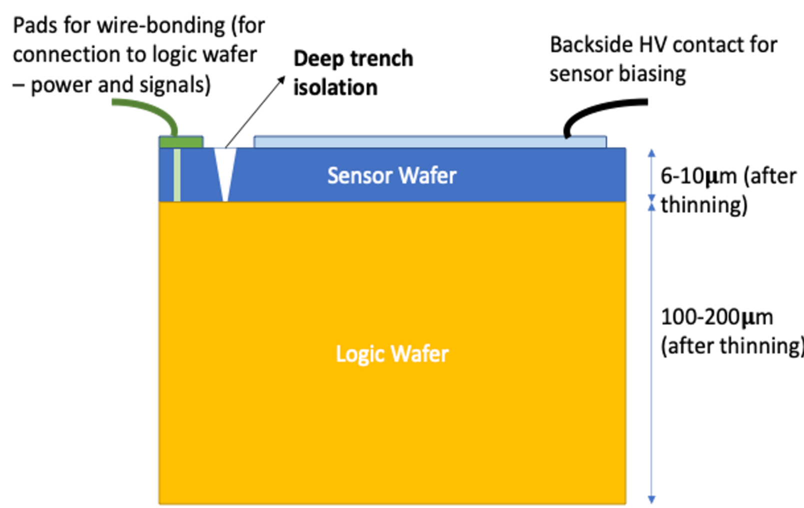
M. B. Nelson, M. D. Cable; LaNSA: A large neutron scintillator array for neutron spectroscopy at Nova. Rev. Sci. Instrum. 1 October 1992; 63 (10): 4874–4876. https://doi.org/10.1063/1.1143536

Development of sensors

- Produce sensors on 12” wafers with a commercial partner
  - Process is a 10 µm epi; 130-150 Ohm-cm resistivity
- Simulations to study the feasibility of both gain and timing performance using vendor’s parameters



Our DRM supports down to 2.5um pitch



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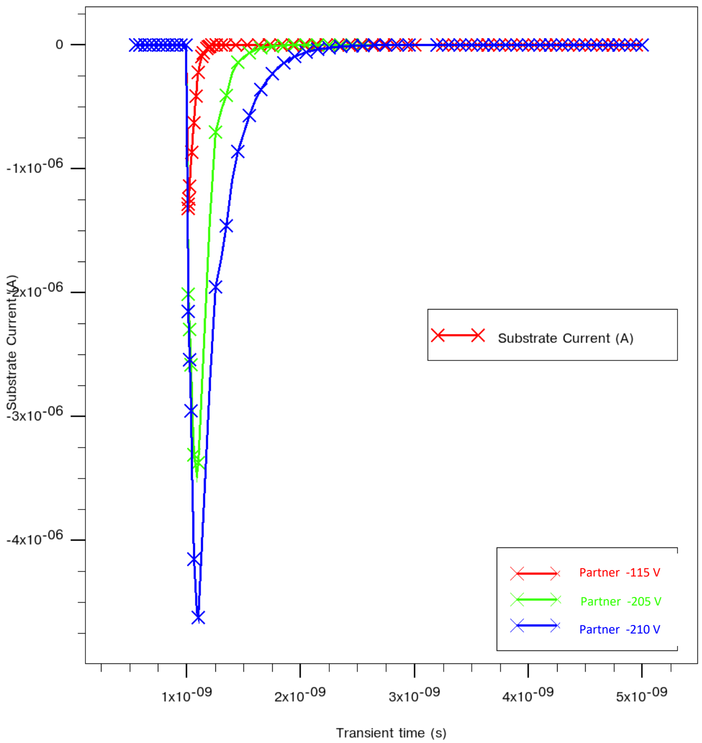
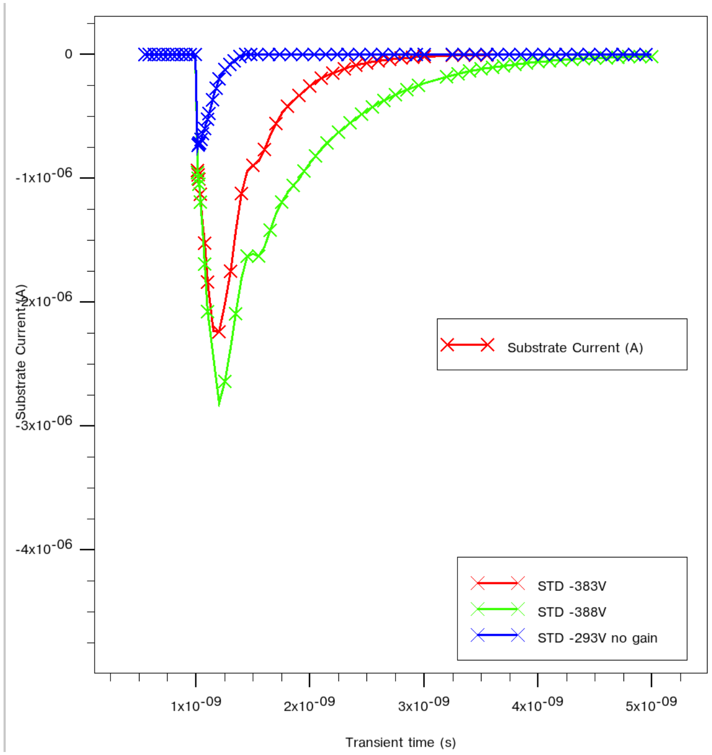
Pulse simulations





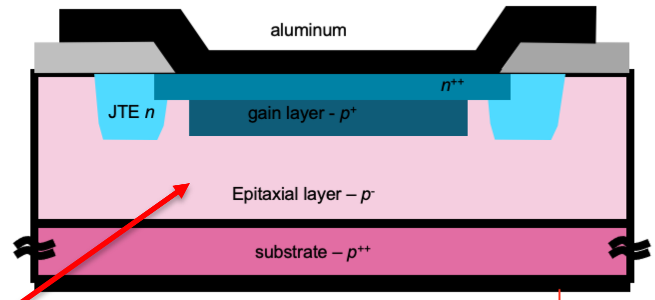
- Simulations of a “standard” LGAD and partner’s 65 nm process.
  - ”Standard” process - 20 µm thick high resistivity
  - “Partner” process - 10 µm thick, moderate resistivity
- Signals from “partner” process are narrower and faster rise time

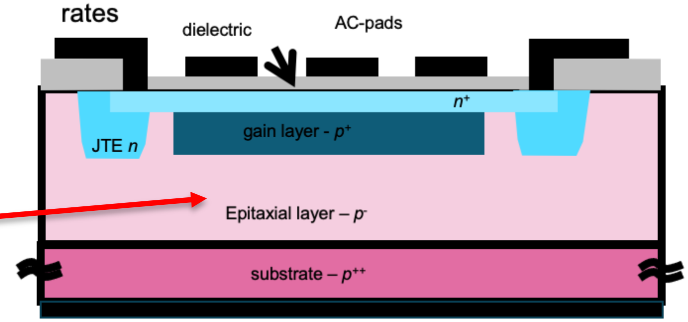
Additional processing

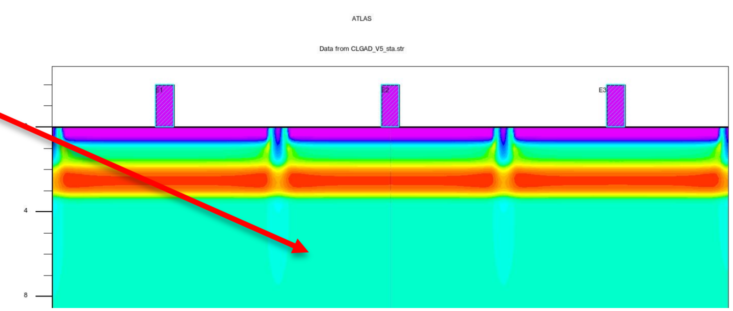
- The basic functionality of the device looks good with 10 µm epitaxy.

- Additional structures to be produced:
  - DC LGAD: ”standard” devices
  - AC LGAD: 100% fill factor, good position resolution
  - Deep junction LGAD: for higher radiation hardness

- Working closely with our partner on the design of sensors







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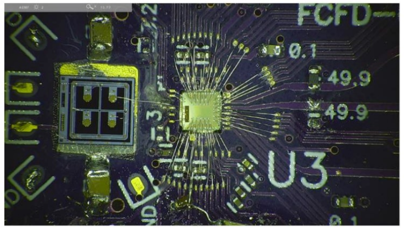
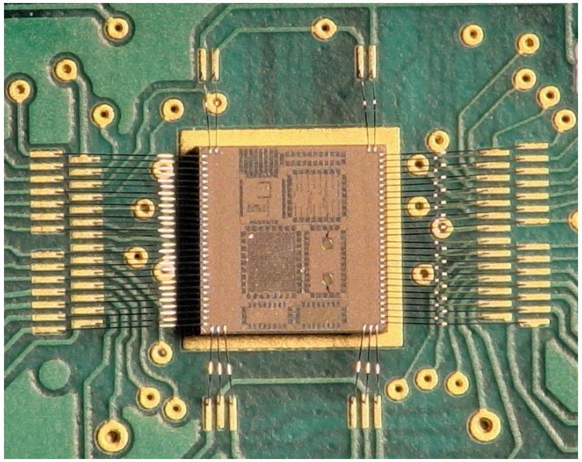
Development of ICs

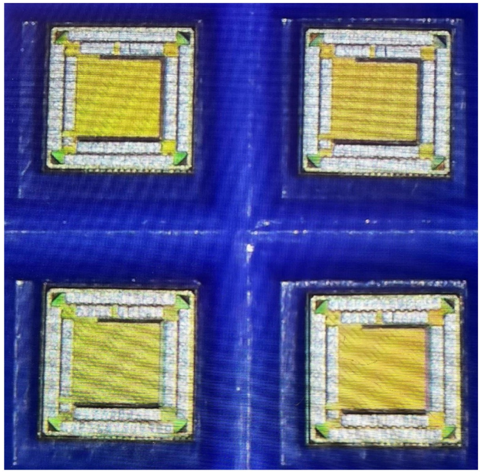
- During the 1st stage we are working to optimize and produce ASIC prototypes on MPW runs to identify the best solutions
  - **Technology**: the HEP community's choice for the future 28 nm
  - **Low Noise Amplifier**: tuned for capacitances of smaller pixels
  - **Discriminator:** Design simple and robust discriminator for low-power
  - **TDC**: dominant consumer for devices with many small pixels, need innovative solutions



FCFDv0 pre-amp + discriminatorFCFDv0

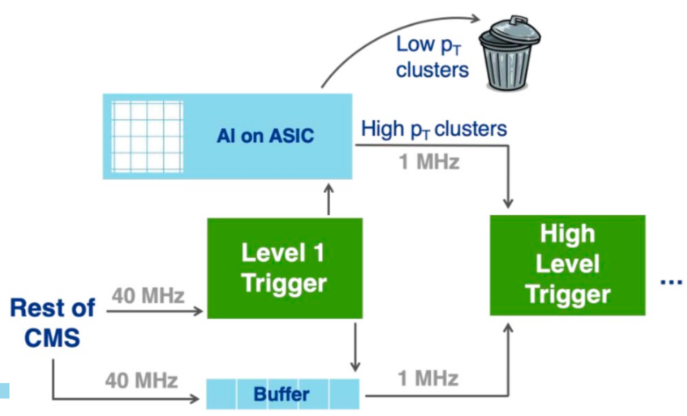

Multi-channel FCFCv1


FNAL TDC


SLAC TDC

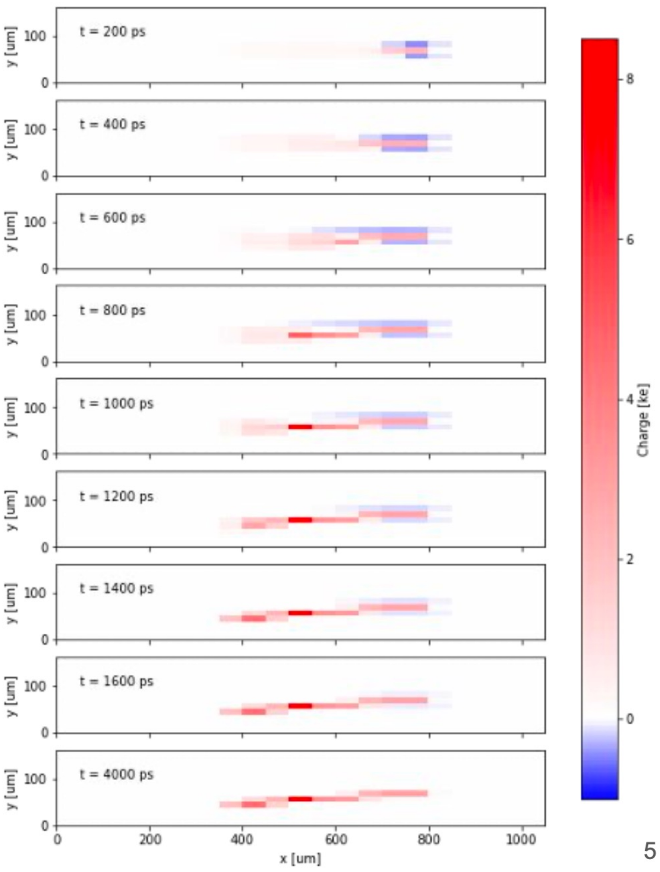
Smart Pixels project

- AI embedded on a chip to:
  - Filter data at the source to enable data reduction
  - Take advantage of pixel information to enable new physics measurements and searches
- Data reduction through
  - Filtering through removing low p_T clusters
  - Featurization through converting raw data to physics information
- Combination of approaches can reduce data rate enough to use pixel information at Level 1



Simulation

- Simulated charge deposition from pions
- Assume a futuristic pixel detector
  - 21x13 array of pixels
  - 50x12.5 μm pitch, 100 μm thickness
  - Located at radius of 30 mm
  - 3.8 T magnetic field
  - Time steps of 200 picoseconds
- Use ML due to complicated pulse shapes, and drift & induced currents
  - y-profile is sensitive particle's p_T
  - x-profile uncorrelated with p_T



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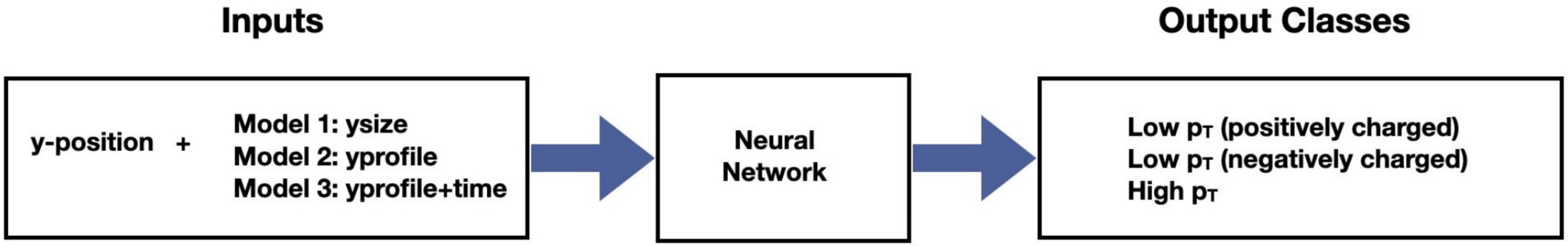
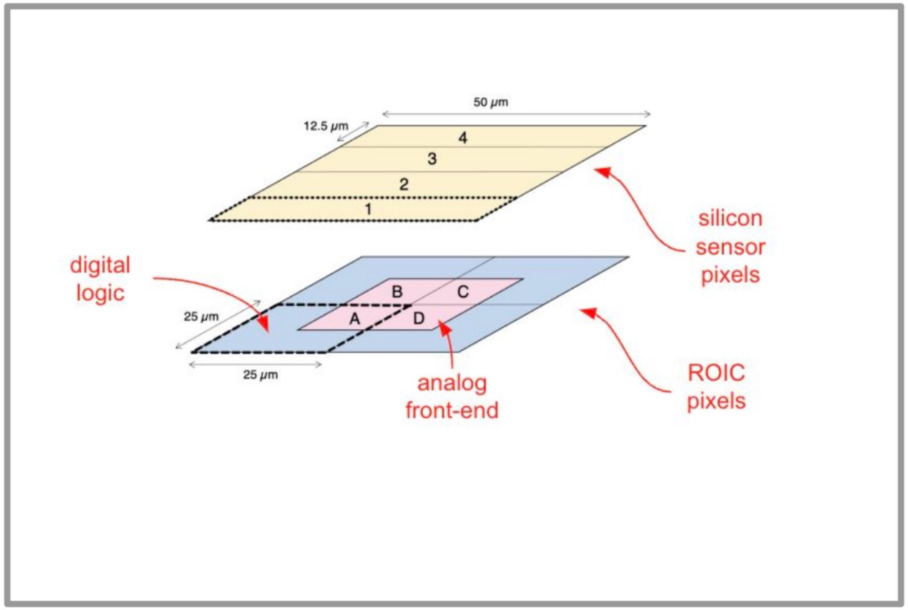
Classification

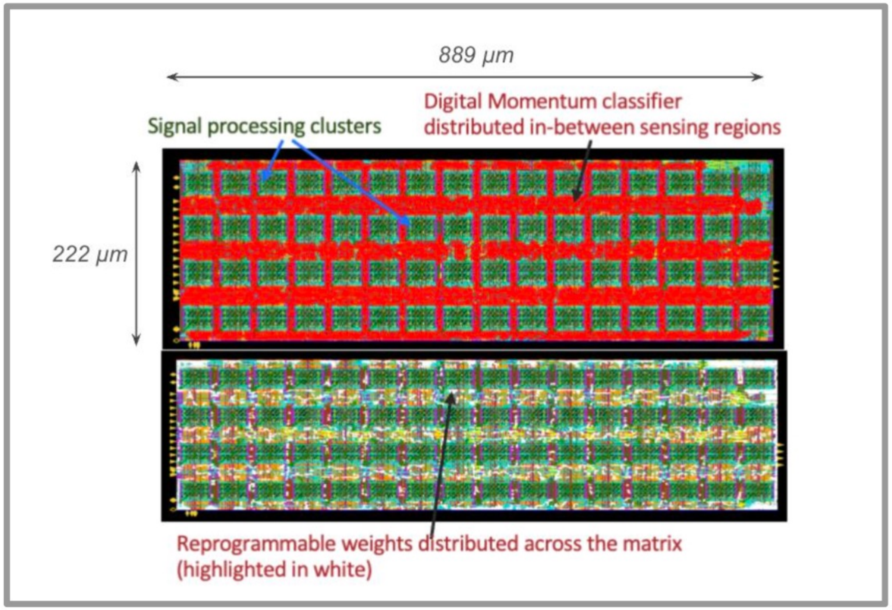
- Classification goals
  - Keep as many high p_T clusters as possible for physics
  - Decrease data bandwidth

- Region specific implementation
  - 13 locally customizable (reprogrammable weights) neural networks implemented directly in the front-end
  - Reconfigurable weights so we can adapt to changing detector conditions



ROIC implementation





- 4 analog frontends, surrounded by a digital region
- Simulation: 13 x 21; Chip: 16 x 16

- Design expected to operate at < 300 µW
- Area < 0.2mm^2

- The second chip has been submitted for tape out and received this spring, testing in progress

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Summary

- Many exciting R&D areas that promise to enable and enrich the physics potential of the FCC-ee experiments
  - New, disruptive technologies are emerging

- Collaborative efforts are a key for the progress in many challenging directions
  - Many examples of successful collaborations presented