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Characterization of ARCADIA sensors, and status of developments at Fermilab

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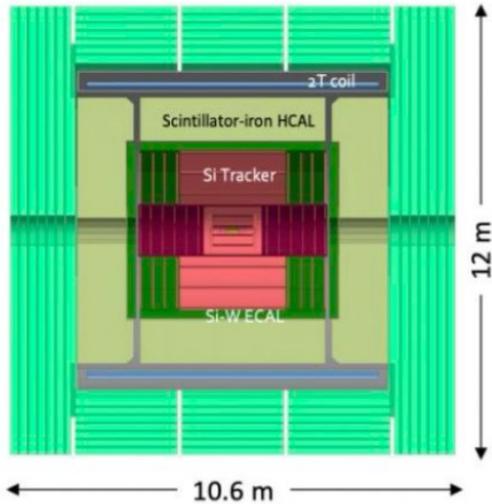


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Detector concepts

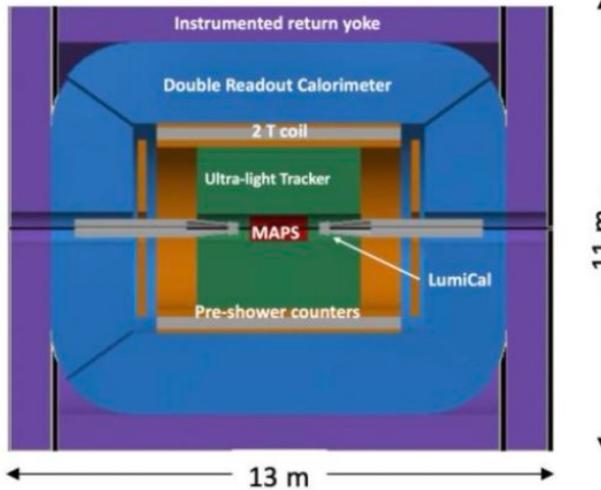
CLD



- Well established design
 - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
 - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
 - σ_p/p , σ_E/E
 - PID ($\mathcal{O}(10\text{ ps})$ timing and/or RICH)?

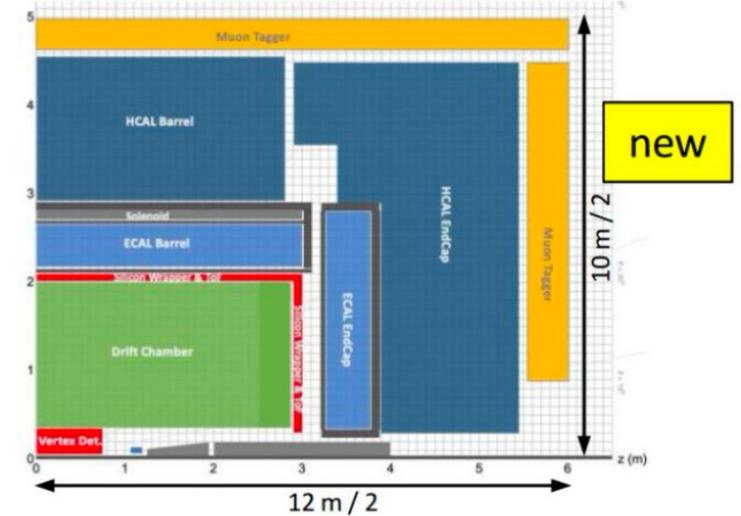


IDEA



- A bit less established design
 - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
 - Possibly augmented by crystal ECAL
- Muon system
- Very active community
 - Prototype designs, test beam campaigns, ...

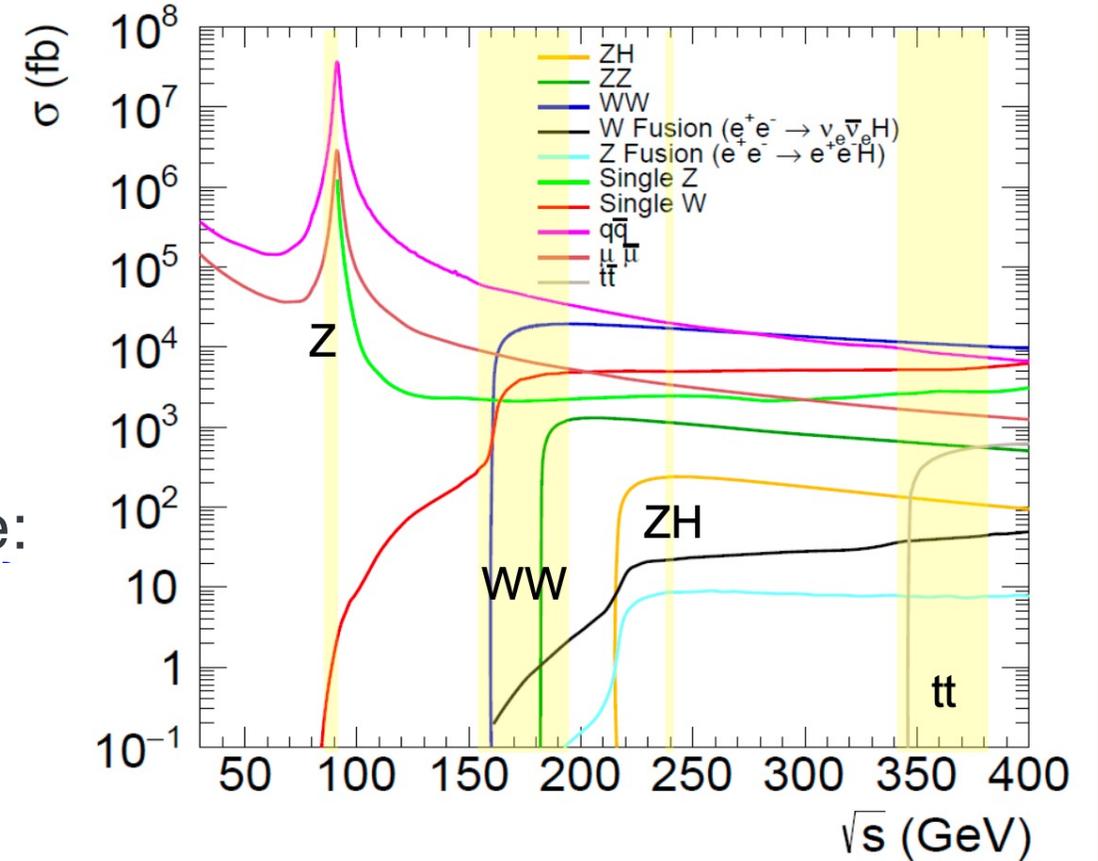
Noble Liquid ECAL based



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
 - Pb/W+LAR (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAR, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
 - Readout electrodes, feed-throughs, electronics, light cryostat, ...
 - Software & performance studies

✚ Requirements for tracking detectors

- A huge challenge is the environment in the collider, need to cover a wide dynamic range
 - Operate within $\sqrt{s} = 90 - 365$ GeV range
 - Be able to efficiently and with high precision reconstruct events in $L = 10^{34} - 10^{36}$ cm²/s regimes
- Most challenging is the operation at the Z pole:
 - Large collision rates ~ 33 MHz
 - Fast detector response / triggerless design, high occupancy in the inner layers
 - Absolute luminosity measurement at Z pole



✦ Requirements for tracking detectors

- A key requirement is unprecedented control of systematic errors

Initial state	Physics goal	Detector	Requirement
e^+e^-	hZZ sub-%	Tracker	$\sigma_{p_T}/p_T=0.2\%$ for $p_T < 100$ GeV $\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/\text{GeV}$ for $p_T > 100$ GeV
	$hb\bar{b}/hc\bar{c}$	Calorimeter	4% particle flow jet resolution EM cells $0.5 \times 0.5 \text{ cm}^2$, HAD cells $1 \times 1 \text{ cm}^2$ EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$ shower timing resolution 10 ps
Tracker		$\sigma_{r\phi} = 5 \oplus 15(p \sin \theta^{\frac{3}{2}})^{-1} \mu\text{m}$ $5 \mu\text{m}$ single hit resolution	

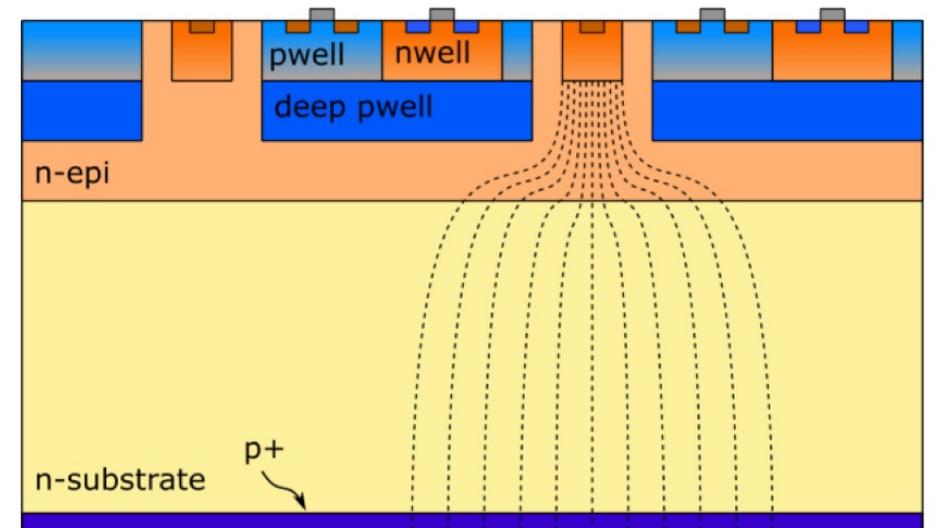
Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

- Requirements mostly driven by Higgs and Z-pole running specific benchmarks
- Technological advances can open **new opportunities** and **additional physics benchmarks**

ARCADIA MAPS with LF110

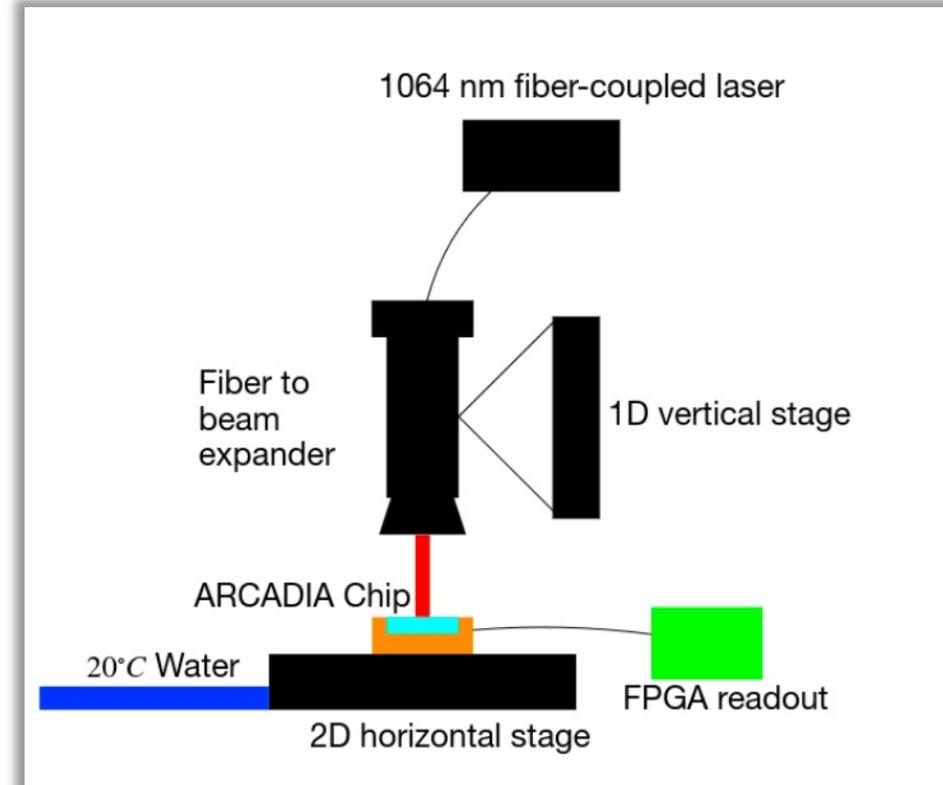
M. Rolo, VERTEX2023, <https://agenda.infn.it/event/35597/contributions/211639/>
L. Pancheri et al, 2019 JINST 14 C06016, DOI: 10.1088/1748-0221/14/06/C06016

- Sensor
 - n-type high resistivity active region (up to 500 μm)
 - backside p+ implantation: depletion from back to top
- Scalable readout architecture with ultra-low power capability $O(10 \text{ mW}/\text{cm}^2)$
- Full chip demonstrator MD3
 - Pixel array 512x512 pixels, pitch 25 μm
 - Data-driven binary readout
 - Power consumption $< 30 \text{ mW}/\text{cm}^2$ (down to $10 \text{ mW}/\text{cm}^2$ in low-rate mode)



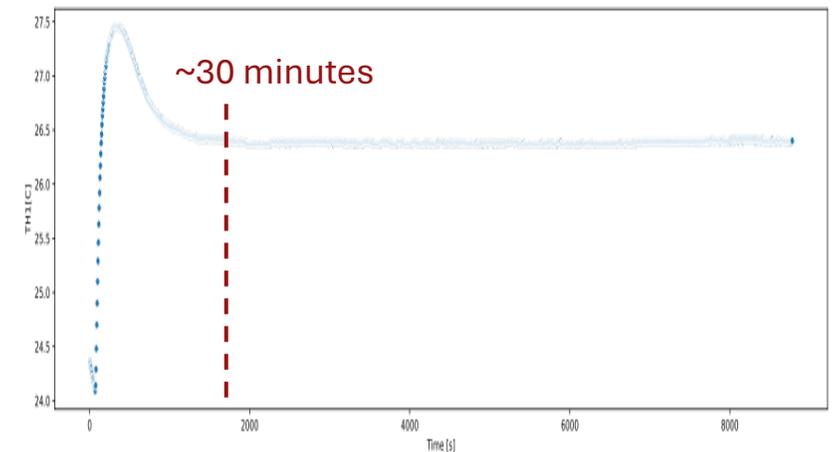
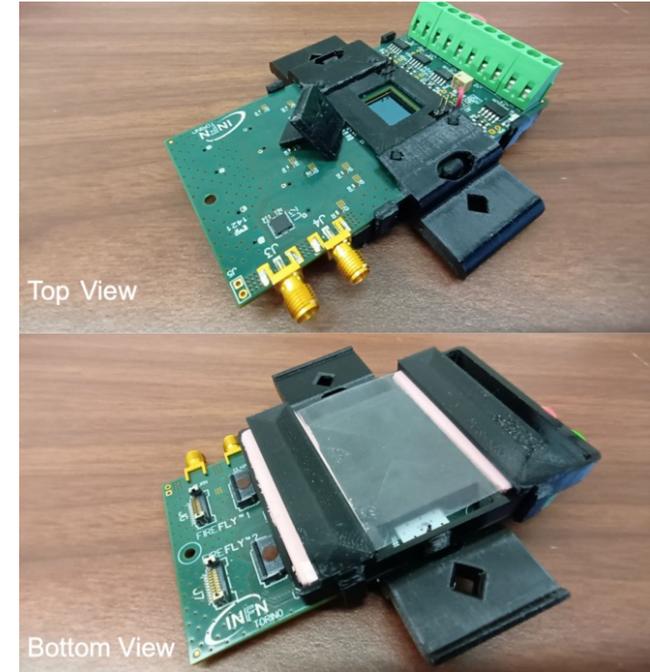
Measurements in the lab in HEERC

- New lab for silicon detector studies for future colliders
- Two stations for laser and beta-source studies:
 - Flexible setups for a variety of studies: scope or FPGA readout



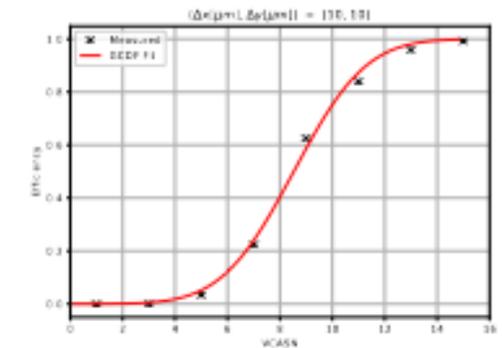
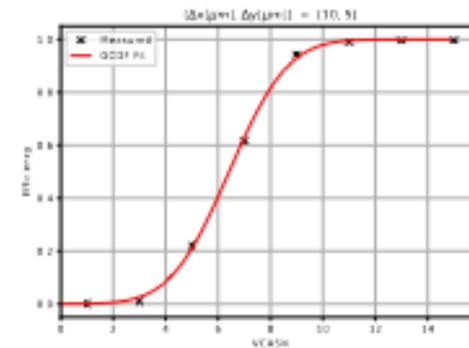
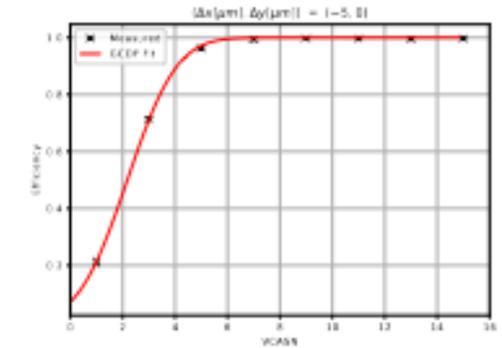
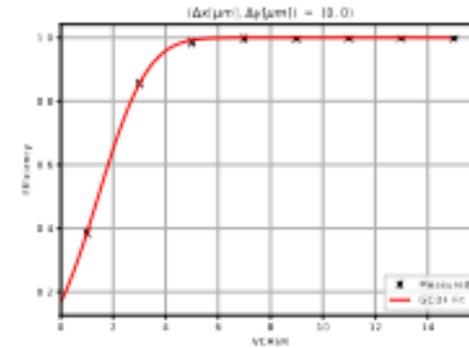
Measurements in the lab

- Laser calibration:
 - Tune the intensity to reproduce a MIP signal
 - Use beta-source and cosmic muons for calibration
 - Achieve beam-spot around 10 μm FWHM
 - Edge scanning and dedicated CCD camera
 - Calibrate the laser power to monitor for output power changes : fiber split for monitoring
- Automatized control of motion stages to perform μm scans
 - Calibrate stage movement to account for rotations when moving in 2D directions
 - Temperature control: measurements performed at room temperature



Measurements in the lab

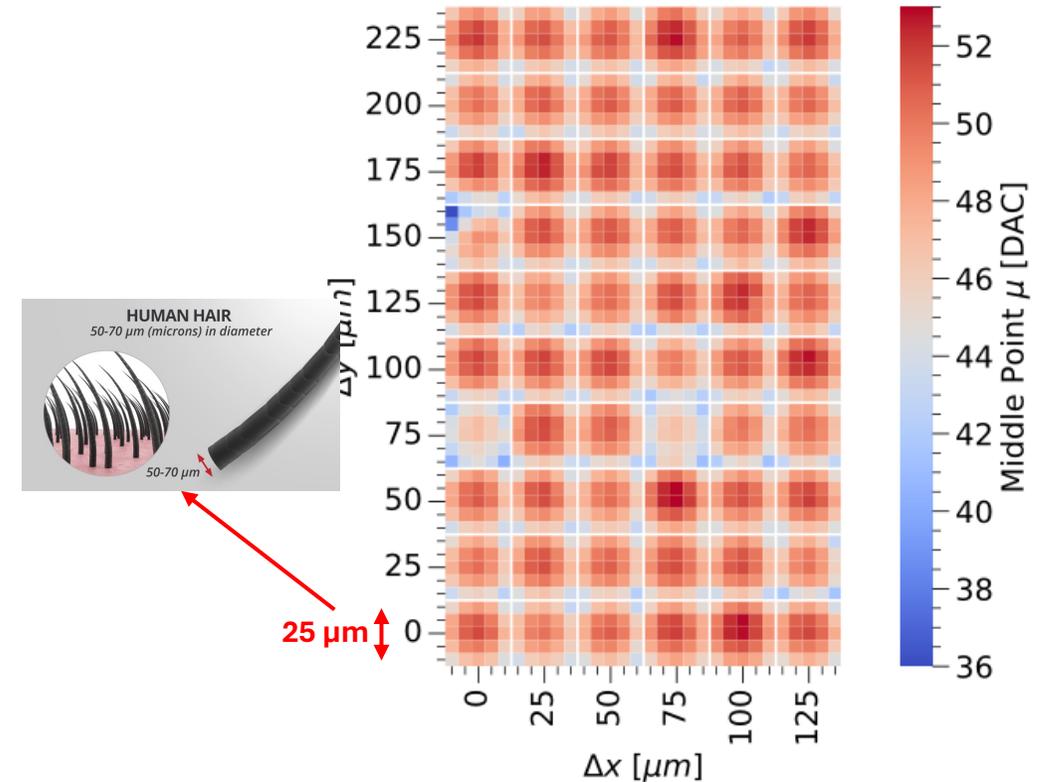
- An area of 6×10 pixels used to characterize cluster efficiency
 - Step size of $5 \mu\text{m}$ is used across the scanning area
 - Total 25 scans per pixel.
 - Vary VCASN from 1 to 11, with steps of 2 to measure the efficiency.



Results of S-curve fits on scan points within pixel (0,0)

Measurements in the lab

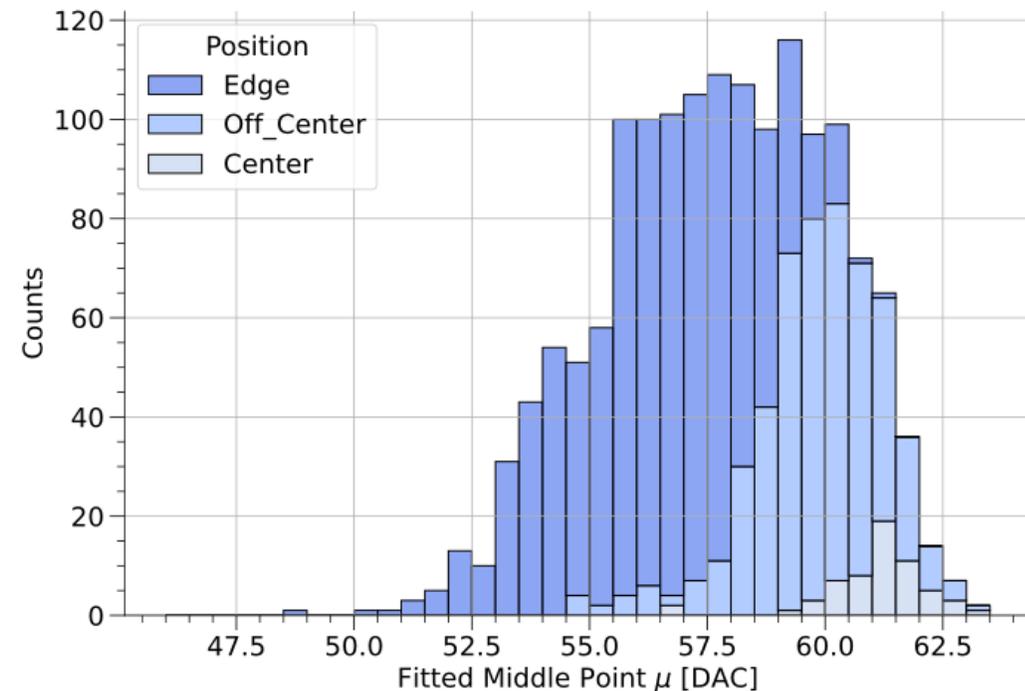
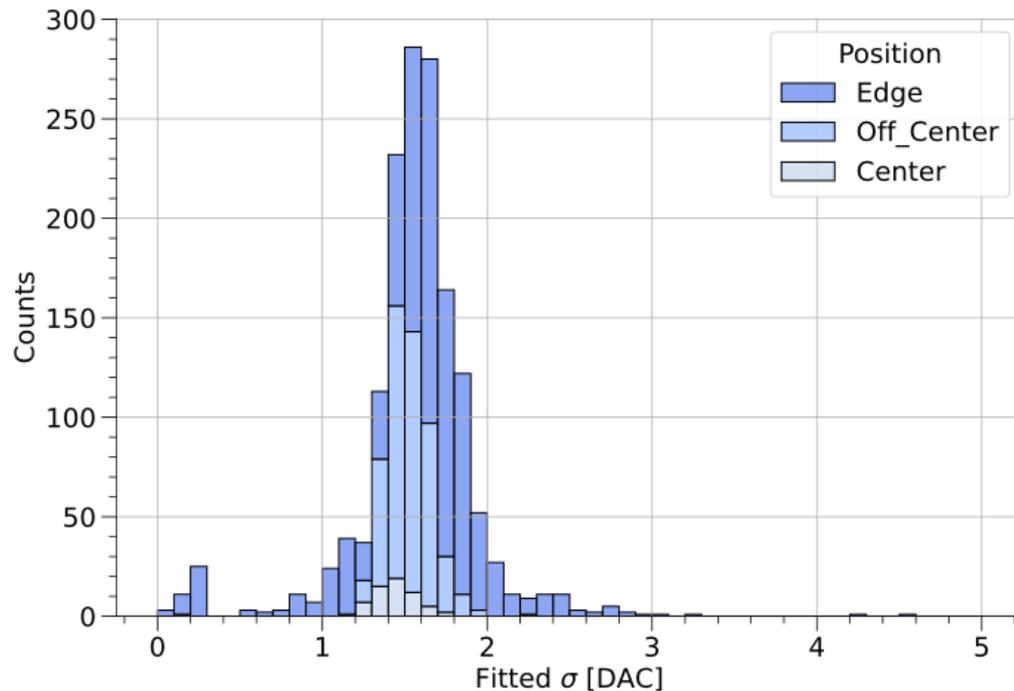
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- Due to charge sharing, the value of μ is lower at pixel edges and higher at the center

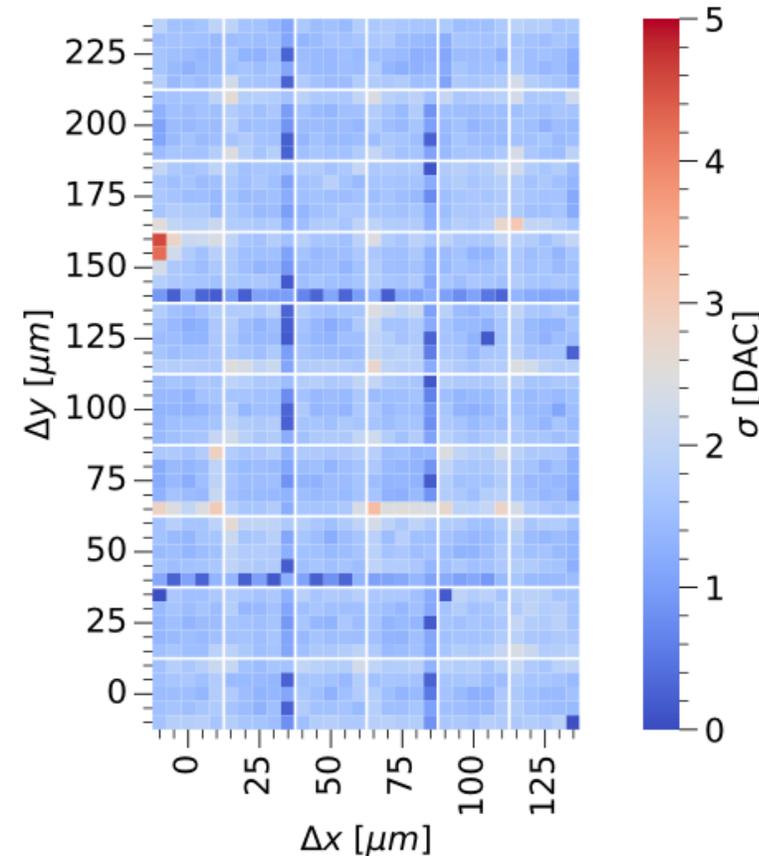
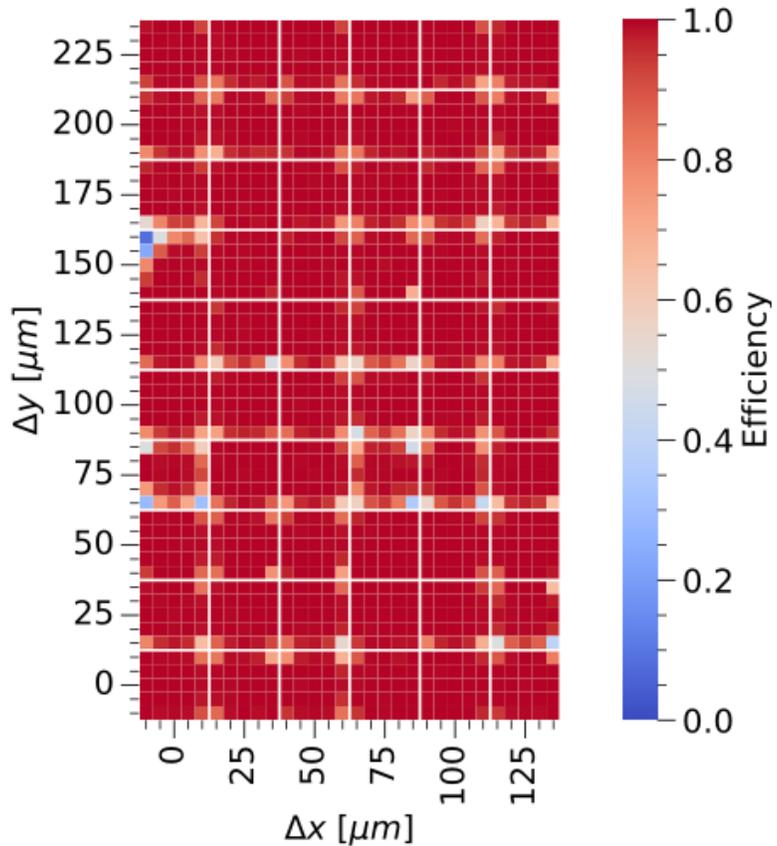
Measurements in the lab

- Excellent readout performance and response to laser scans
 - Lower charge threshold, and higher noise further away from the pixel center.
 - This behavior is largely due due to charge sharing between pixels



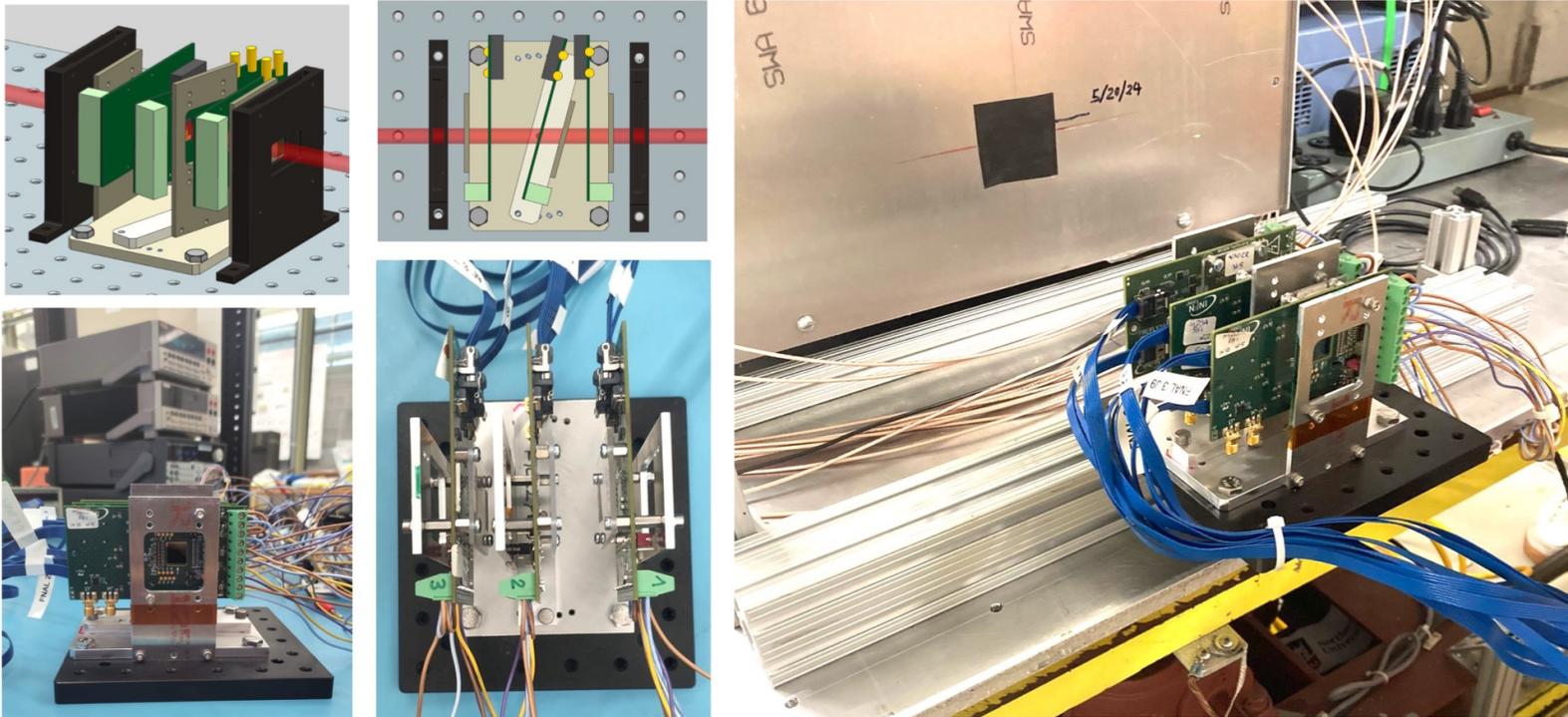
Measurements in the lab

- Excellent uniformity of detection efficiency across the pixel area
- Noise is mostly uniform across detector surface



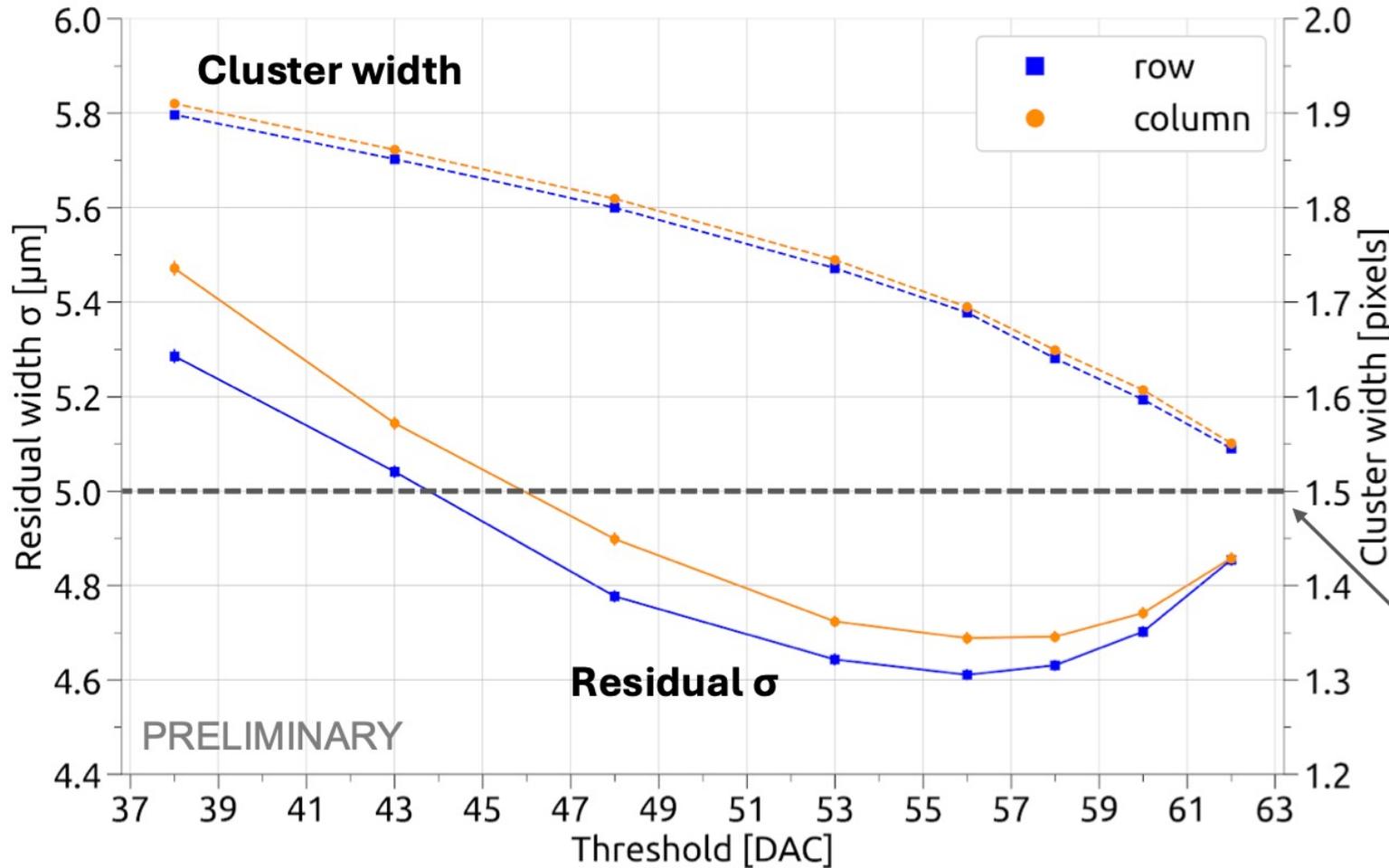
Measurements in beams

- Test beam at FNAL (120 GeV protons) in Summer 2024
 - Mini-telescope with 3 ARCADIA-MD3 sensors
 - Threshold, sensor HV and incidence angle parametrization: study of cluster size, collection efficiency, spatial resolution





Measurements in beams

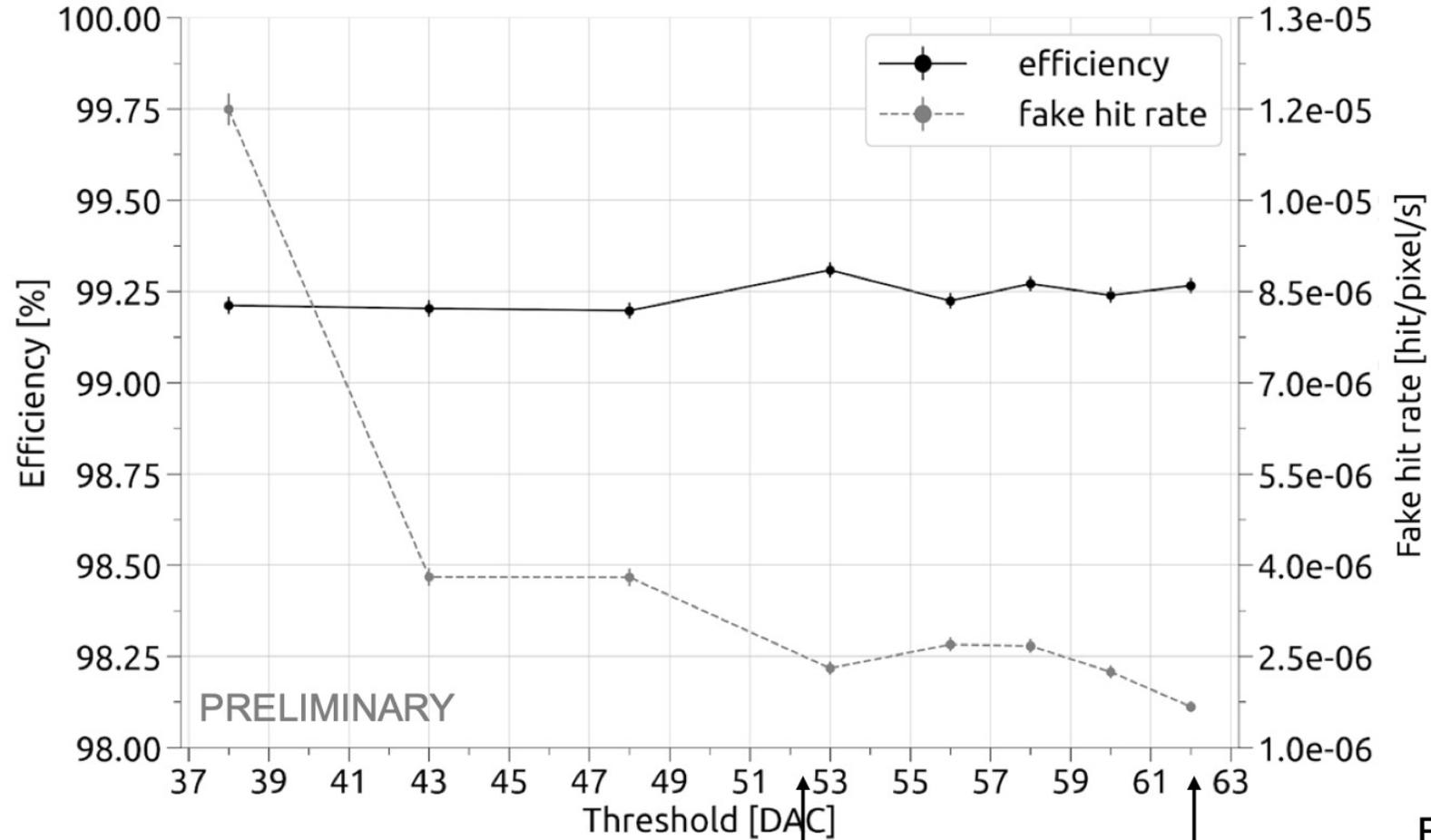


Cluster width always greater than 1.5 pixels

- Residual width always below the binary resolution (7.2 μm)



Measurements in beams



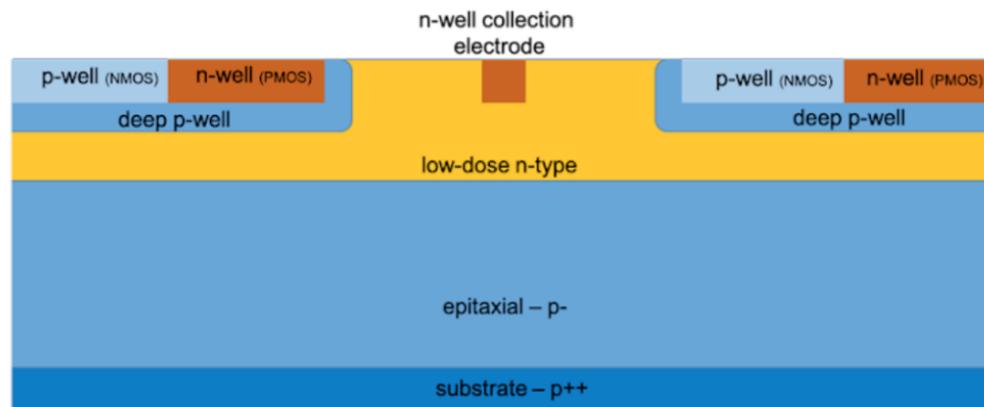
1200 e⁻

2200 e⁻

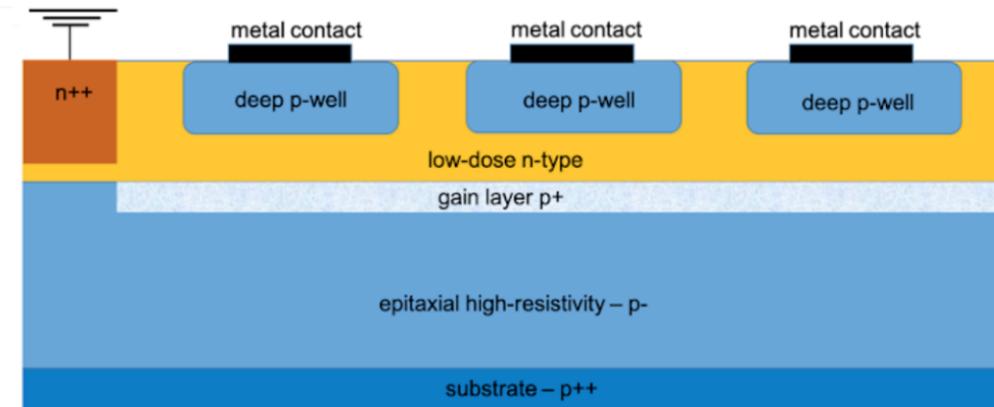
Fake hit rate measured during no-beam time
12 masked pixels on the DUT

Developments with SkyWater

- Develop MAPS sensors in a commercial process that will provide fast timing (10 ps) and precise spatial resolution (5 μm)
 - Target application 4D tracking detectors for future e^+e^- Higgs factories
 - Short on funding, but we continue exploring production with a domestic foundry
- Electronics for signal processing are placed in dedicated p- and n-wells contained within a deep p-type well
 - Intrinsic gain will allow MAPS detectors to perform precise time measurements in addition to spatial measurements



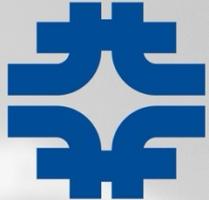
CMOS sensor



Monolithic AC-LGAD

Summary

- Excellent performance of ARCADIA demonstrated in particle beams
 - Spatial resolution of around 4.6 μm
 - Cluster width of about 1.6 pixels
 - Efficiency always above 99%
 - Uniform detection efficiency across pixel area
- Developments with a SkyWater are starting off, in SBIR collaboration with Caporus
 - Aiming to produce prototypes within the next year.



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