4D trackers for future collider experiments

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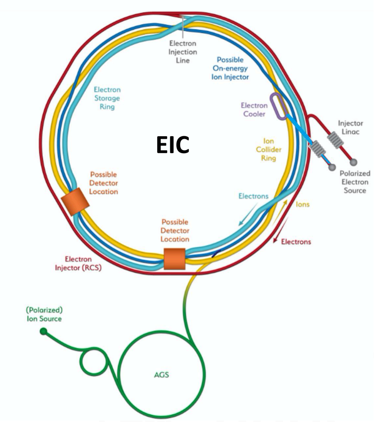
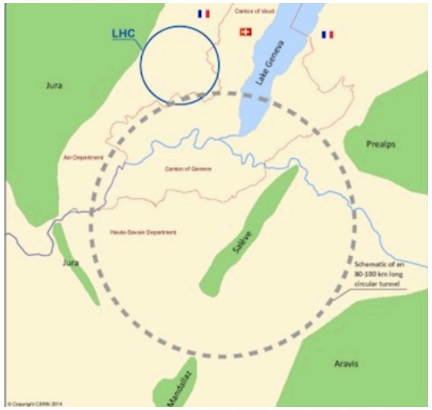
Future trackers will be 4D!

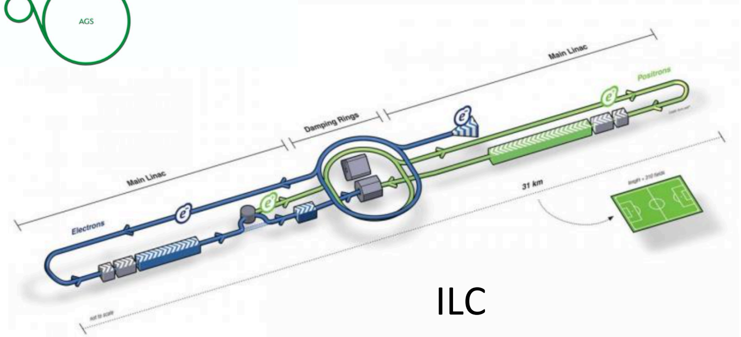
- The 4D-trackers will play a key role at the future machines
  - Reduce backgrounds, track reconstruction, triggering all will need precision timing information, in addition to the precision position
  - Enhanced capabilities: PID and LLP reconstruction
  - All of these pose unique challenges, and opportunities to detector and electronics design, and event reconstruction

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 25x50 μm² pixels
	5 μm single hit resolution
	Per track resolution of 10 ps
Tracking for 100 TeV pp	Generally the same as e^+e^-
	Radiation toleran up to 8×10^{17} n/cm²
	Per track resolution of 5 ps

Technical requirements for future trackers: from [DOE's HEP BRN]



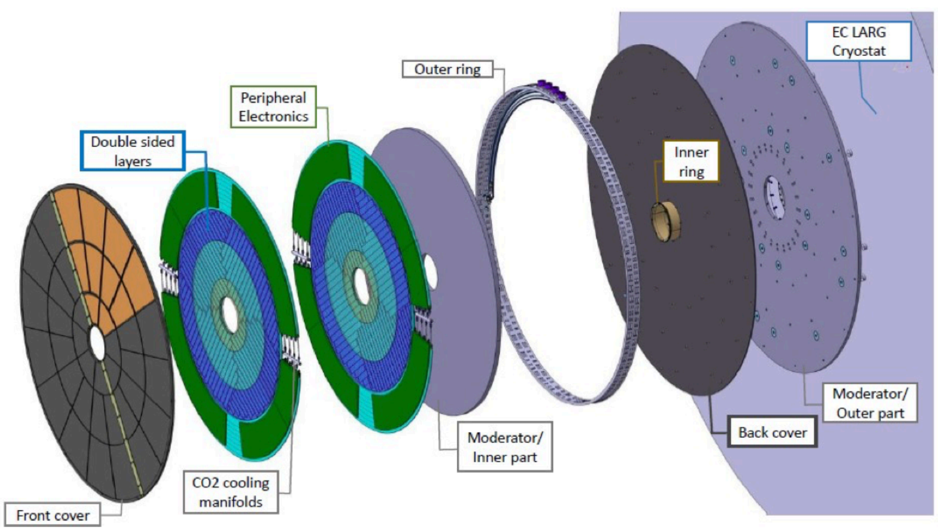




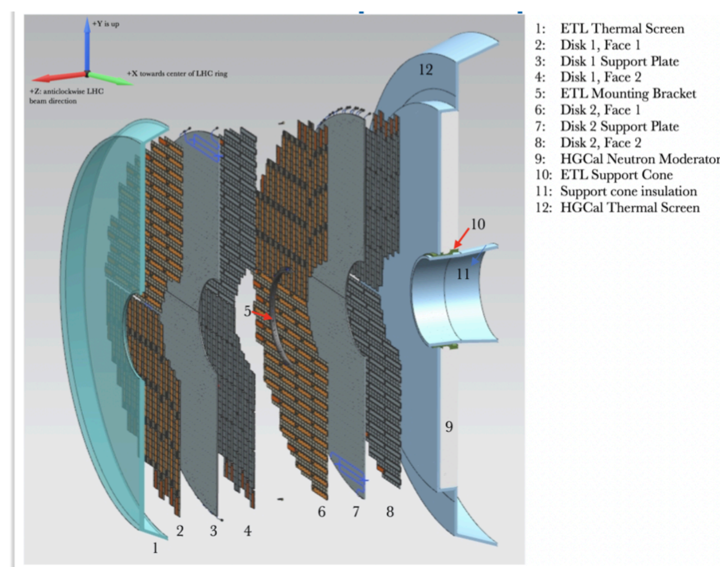
ILC

4D trackers: present and future

- CMS and ATLAS are building Gen-1 4D-tracking detectors
  - Single or two hits per charged particle, and large pixels
  - Next generation detectors will be more sophisticated and replace tracker
- Active R&D on technologies to achieve the required detector performance
  - Sensors, ASIC, front-end electronics developments



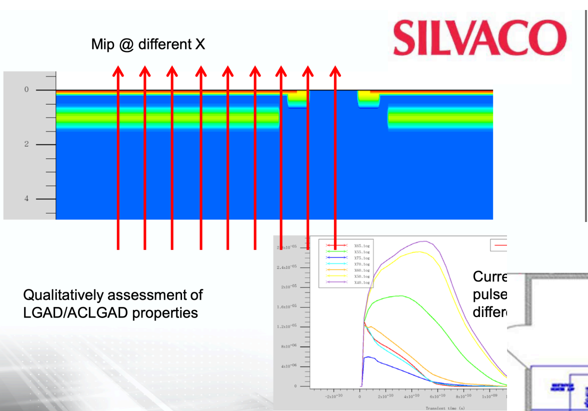
ATLAS timing detector



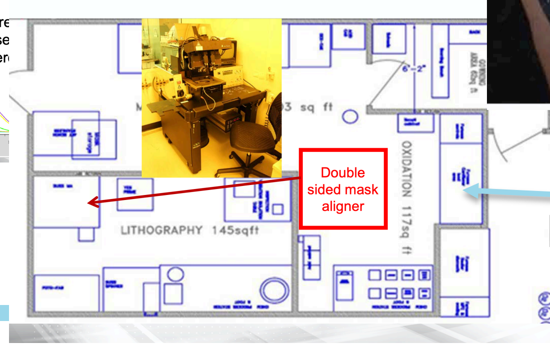
CMS timing detector

Development directions

- Next gen detector R&D requires a lot of infrastructure, expertise, and development cycles
  - Our group has developed dedicated **readout boards and testing infrastructure** for characterization of sensor prototypes,
  - Design, manufacture and test **sensor prototypes**
  - Design, manufacture and test **full systems** integrating sensors and readout electronics

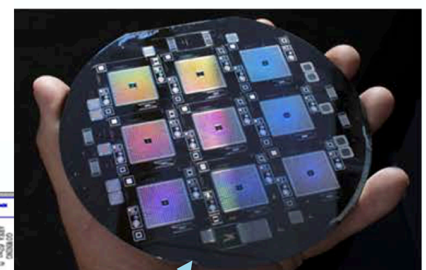


Design

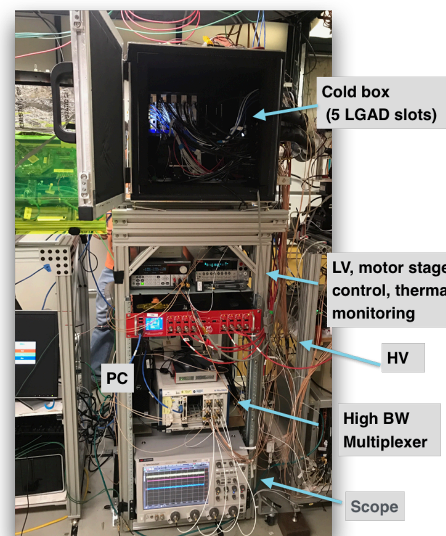


Class 100 Cleanroom

Finish Processed Wafer



Fabrication

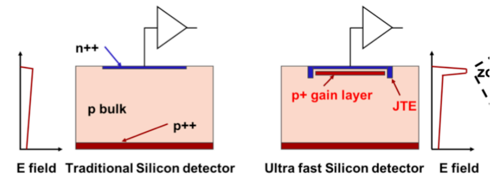


Testing in beams

Development directions

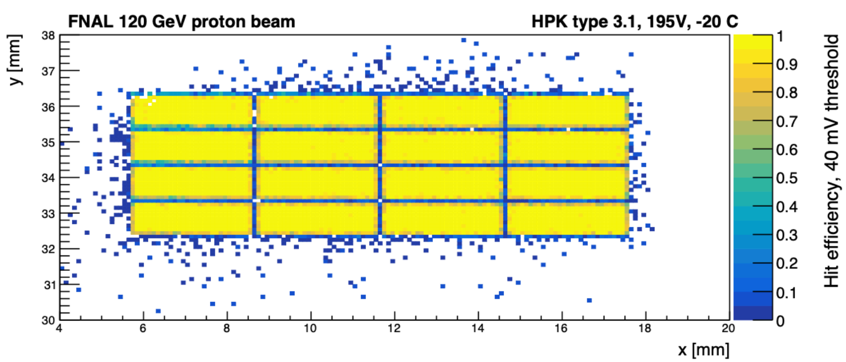
- **International collaborative** developments
  - Development of AC-LGAD sensors and 4D trackers
  - Characterization of irradiated and pre-rad sensors, extensive infrastructure with monitoring all key variables
- Work presented here is based on Snowmass LOI #142 in IF, and US-Japan collaborative consortium
  - A. Apresyan, K. Di Petrillo, R. Heller, R. Lipton, S. Los, C. Madrid, C. Pena, S. Xie, T. Zimmerman (**FNAL**)
  - G. D'Amen, W. Chen, G. Giacomini, E. Rossi, A. Tricoli (**BNL**)
  - K. Nakamura, K. Hara, T. Ueda, S. Kita (**KEK, U. Of Tsukuba**)
  - S. Mazza H. Sadrozinski, B. Schumm, A. Siden (**UCSC**)
  - Y. Degerli, F. Guilloux, C. Guyot, J.P. Meyer, A. Ouraou, P. Schwemling (**Saclay**)

Low-Gain Avalanche Detectors (LGAD)

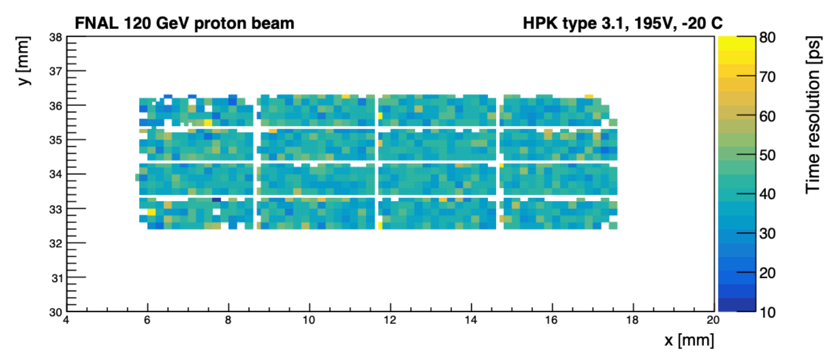


LGAD sensors

- Low-Gain Avalanche Detectors (LGAD): technology for HL-LHC timing detector: ~30 ps
  - Silicon detectors with internal gain
- Sensors developed for CMS and ATLAS show high degree of uniformity and excellent time resolution
  - Gain is uniform within ~5%, high yield, radiation tolerance for HL-LHC
  - No-gain gaps between pixels: due to presence of JTE



Hit efficiency across surface of the 4x4 sensor

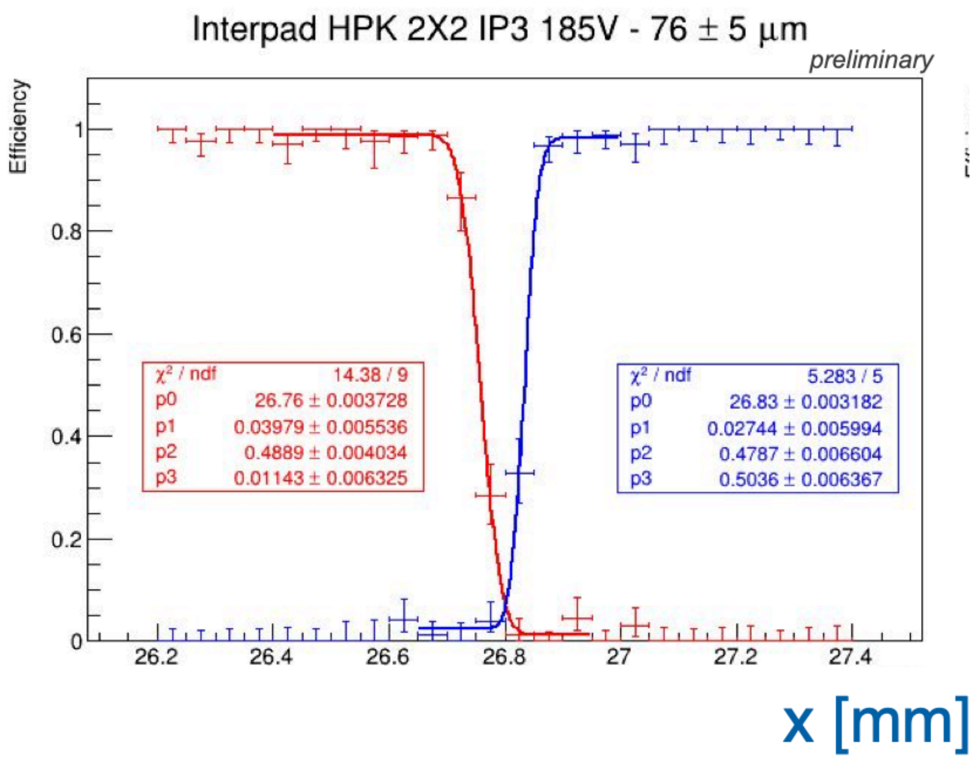


Time resolution across surface of the 4x4 sensor

Fermilab

Low-Gain Avalanche Detectors (LGAD)

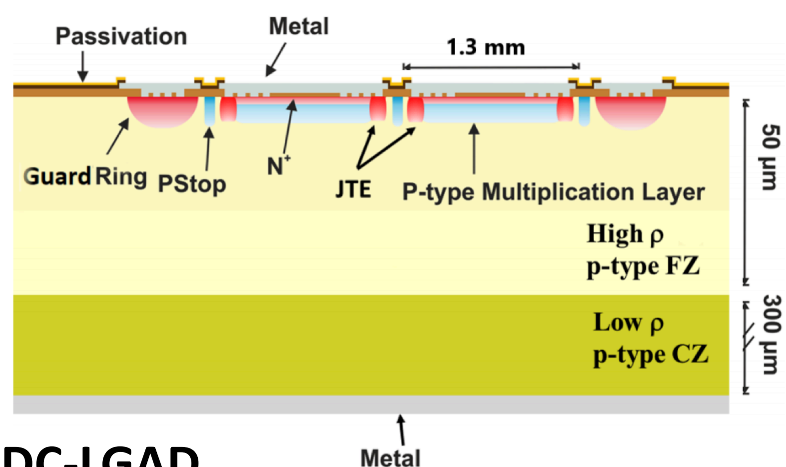
- **Sensors for 4D-trackers should have no dead areas**
  - Traditional LGADs have a gap between pixels, to terminate the field between pixels
  - Improve Gen-1 trackers to achieve 100% fill factor, high position resolution



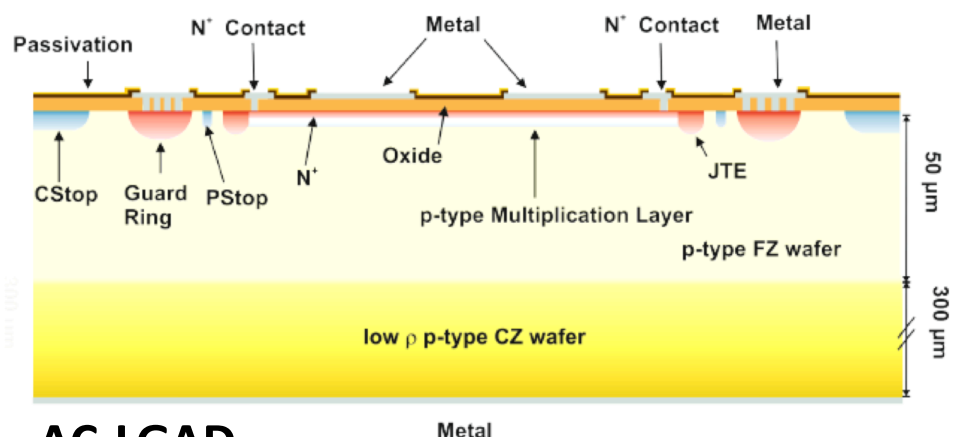
AC-coupled LGADs

- Ongoing R&D to eliminate dead area
  - Simultaneously improve position resolution via charge sharing
- Collaboration with BNL, KEK on AC-LGAD developments
  - 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



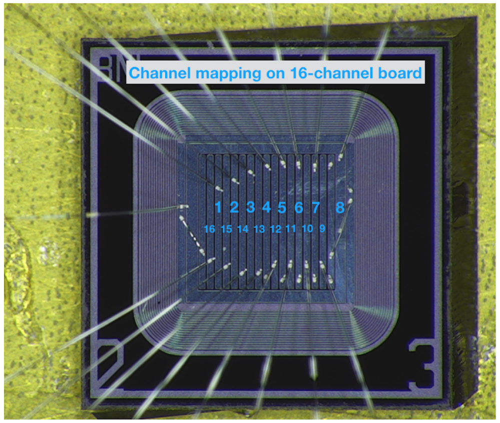
DC-LGAD



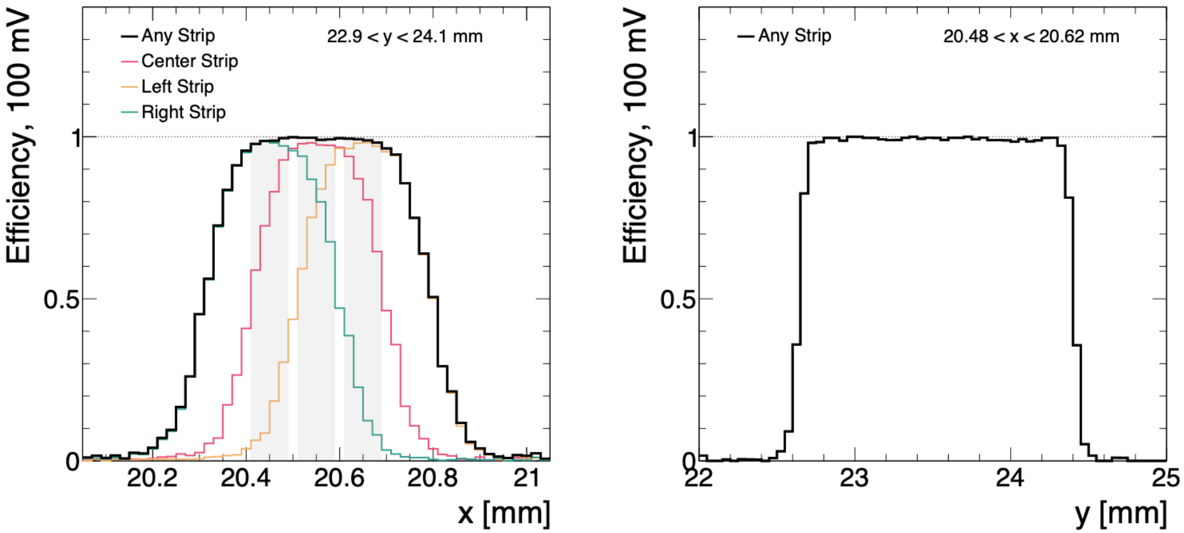
AC-LGAD

AC-LGAD measurements in beams

- Excellent performance in the beam showing high efficiency
  - First measurements in the beam in 2020:
    - BNL sensors: JINST 15 P09038 (2020)
- Time resolution and position resolution achieved targeted goals
  - 100% particle detection efficiency across sensor surface



BNL strip AC-LGAD

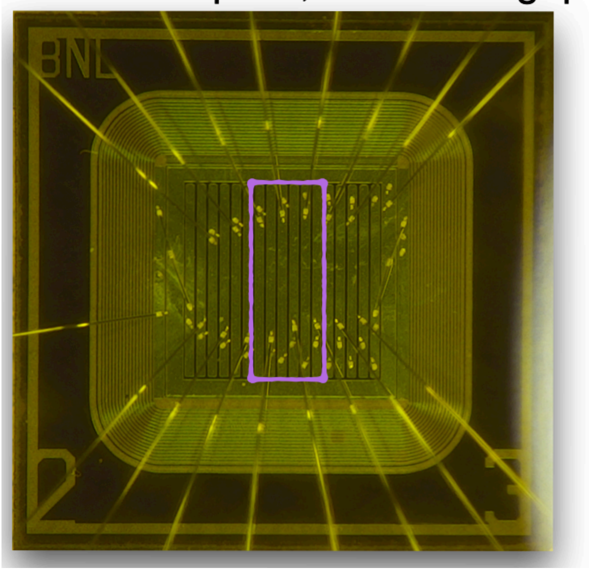


(a) Combined efficiency in x direction (b) Combined efficiency in y direction

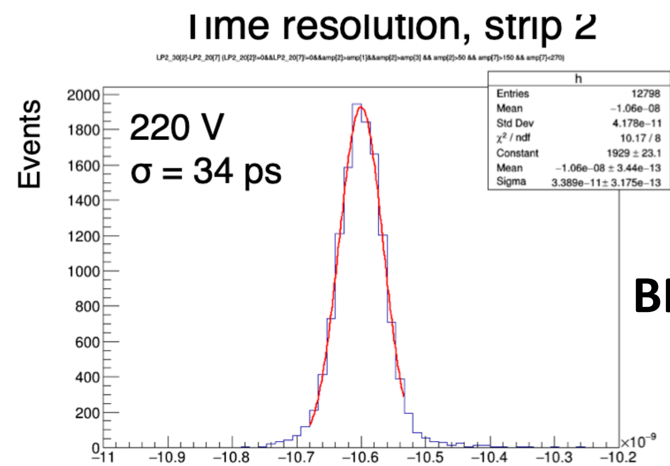
AC-LGAD measurements in beams

- Recent test beam campaign: Mar 2021
  - Measurements of a variety of BNL and HPK sensors
- Read out 6 interior strips + DC ring + MCP reference
- Bias scan from 200 to 225 V

100 micron pitch, 20 micron gaps



BNL strip AC-LGAD



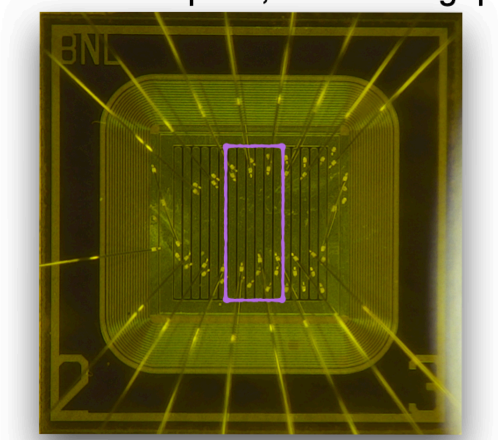
BNL strip AC-LGAD

Reach 30-35 ps timing resolution in the primary hit strip

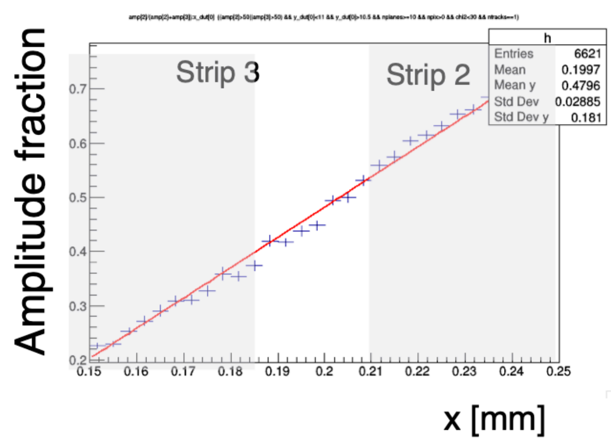
AC-LGAD measurements in beams

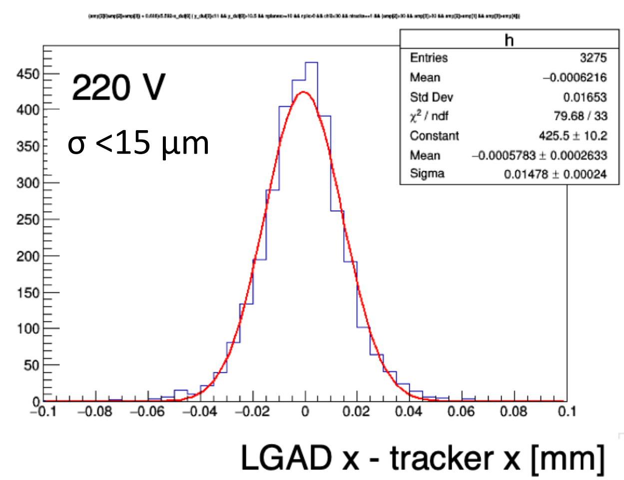
- Basic position reconstruction with 2 strips
  - Plot average amplitude fraction vs X (amplitude[i] / amplitude sum)
  - In each event, calculate amplitude fraction and find corresponding X from fit line

100 micron pitch, 20 micron gaps



BNL strip AC-LGAD

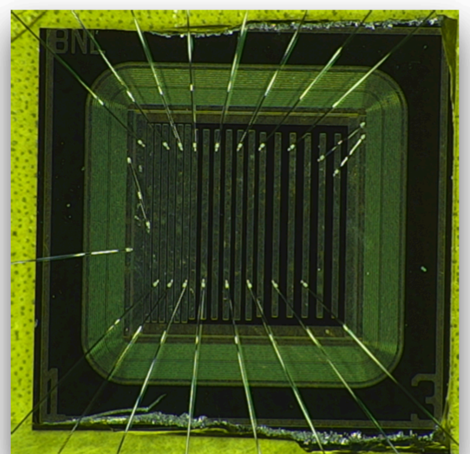




- Reach 15 micron resolution total width, limited by tracker resolution
- Places limit on sensor resolution less than 5-10 microns

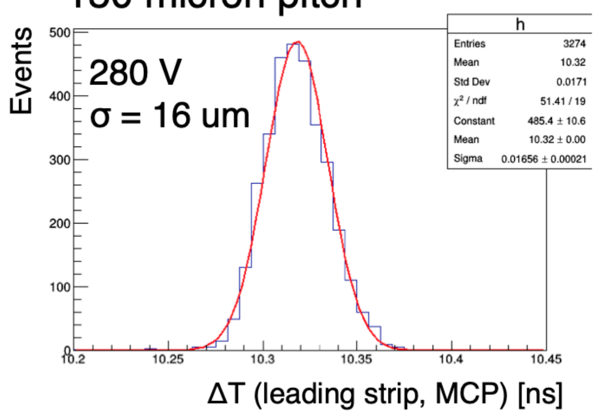
AC-LGAD measurements in beams

- Single BNL sensor with a variety of strips geometries
  - 100, 150 and 200 micron pitch (80 um width)
  - Read out 5-6 strips from each pitch at a time

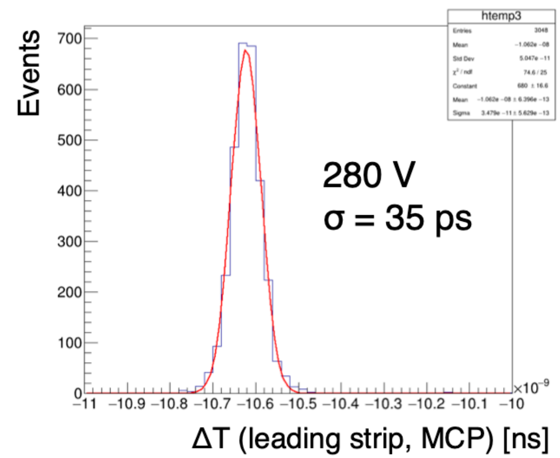


BNL strip AC-LGAD

Space resolution, 2 strips
150 micron pitch



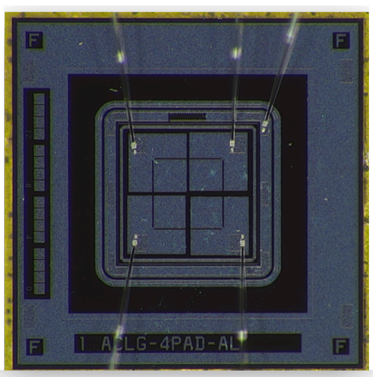
Time resolution, 150 micron pitch



- Reach 16 um and 35 ps resolution even with 50% larger pitch

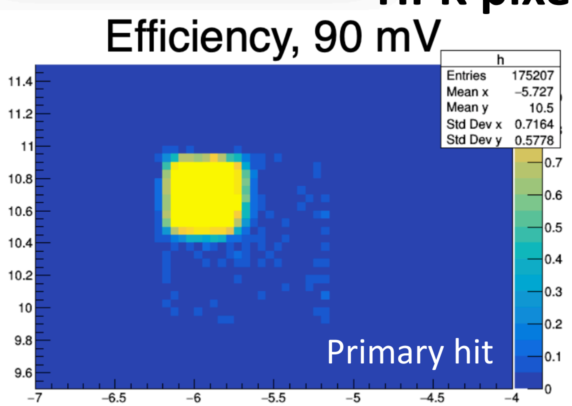
AC-LGAD measurements in beams

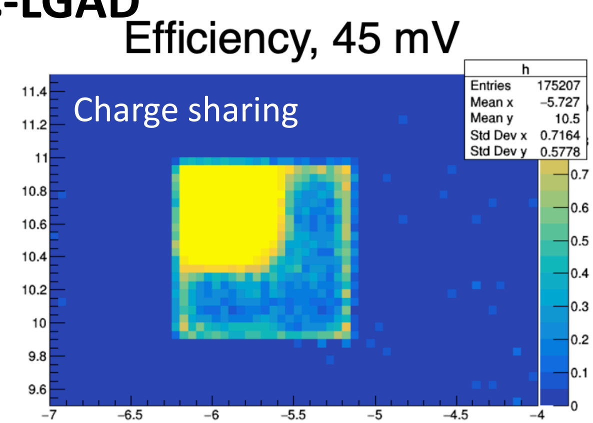
- KEK and U. of Tsukuba group designed AC-LGAD sensors fabricated at HPK with pad, strip and pixel type electrodes.
  - Both pad and strips sensors, compare performance with both geometries, evaluate differences between manufacturers

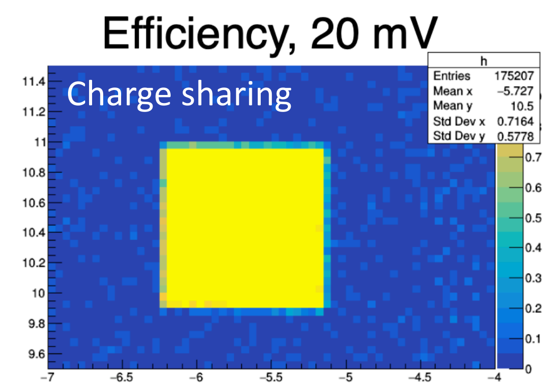


- Large pixels allow more detailed study of position reconstruction, not limited by tracker resolution
- Assess the differences in designs and optimize them, based on experimental performance in lab, test-beams

HPK pixel AC-LGAD







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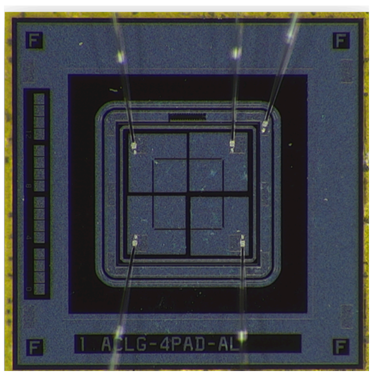
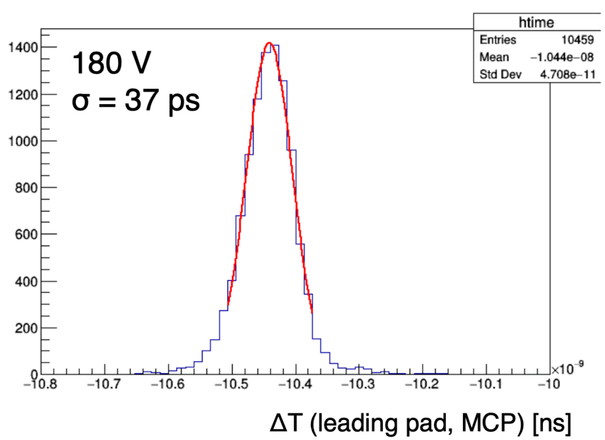


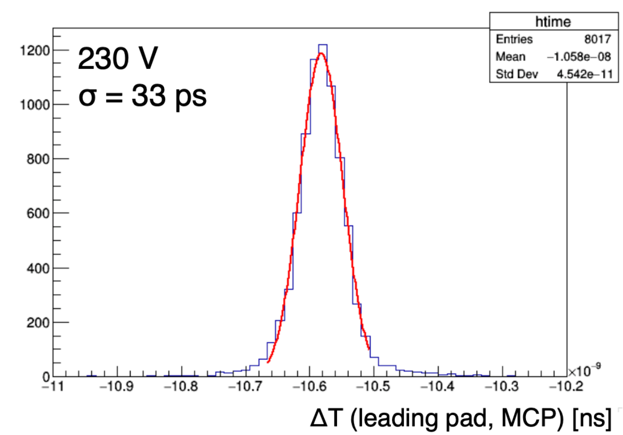
HPK pixel AC-LGAD

- Large pixels allow more detailed study of position reconstruction, not limited by tracker resolution
- Assess the differences in designs and optimize them, based on experimental performance in lab, test-beams

C-2, primary pad only, 180 V



B-2, primary pad only, 230 V



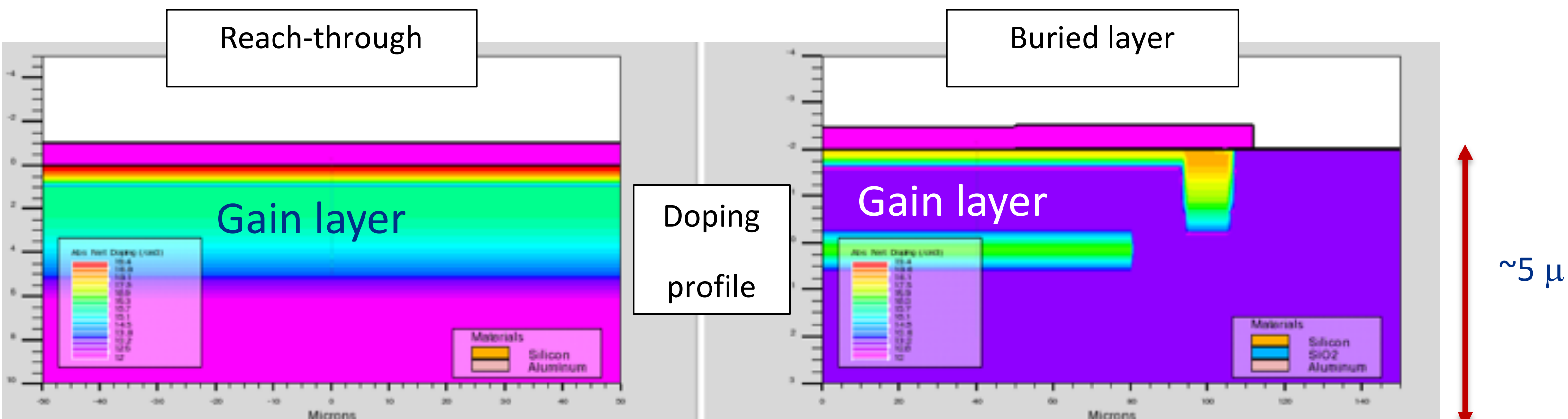
Buried layer LGADs

We can engineer the silicon substrate to tailor the characteristics of the device

- Buried gain layer LGAD can provide a more radiation hard, stable device
- Gain layer is below epitaxy – AC coupling or more sophisticated topside processing can be integrated
- Combine with small pixels, or CMOS MAPS to design specialized sensors.

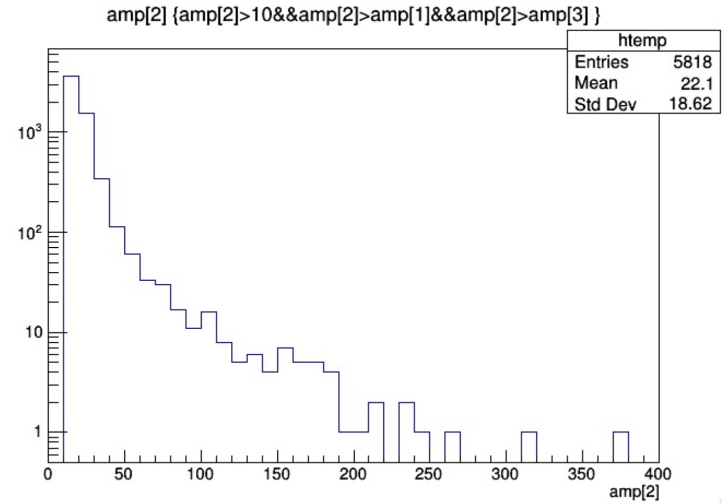
Usual reach-through implanted from top – limited options

Gain layer grown over implant – can be denser, top can be custom processed



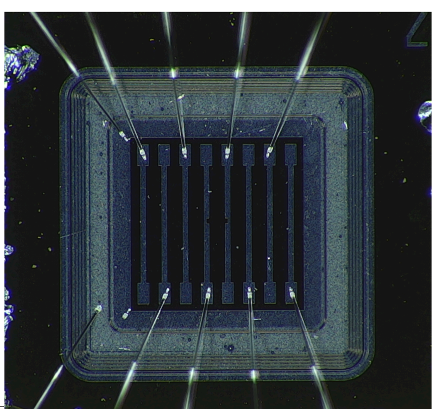
Buried gain layer AC-LGAD sensors in test beam

- First test beam measurements
  - Signal size is not optimal for good time resolution
  - Higher leakage current, probably need to improve the processing of wafers
- Very successful SBIR collaboration with Cactus Materials, Inc
  - Will follow up with another round production

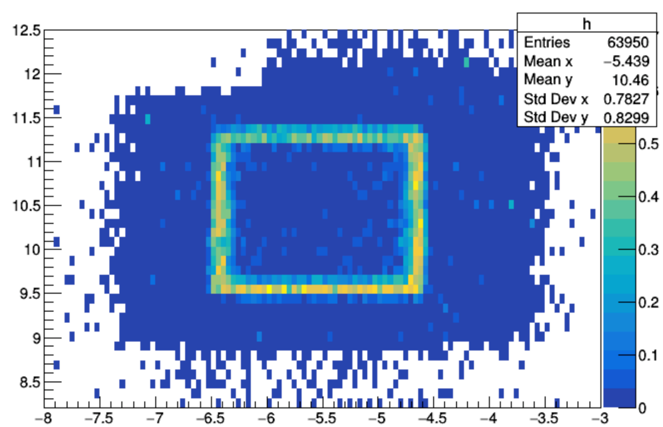


Signal amplitude distribution

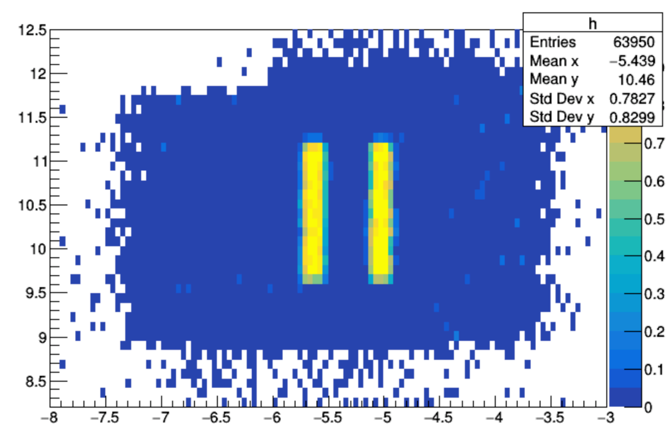
8-channel strips,
200 micron pitch,
50 micron metal



Efficiency for DC ring



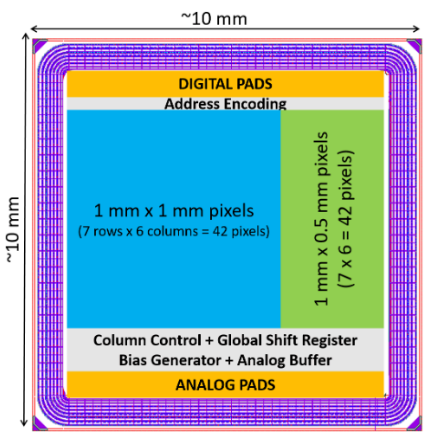
Efficiency for leading hit in strip 2 or 5

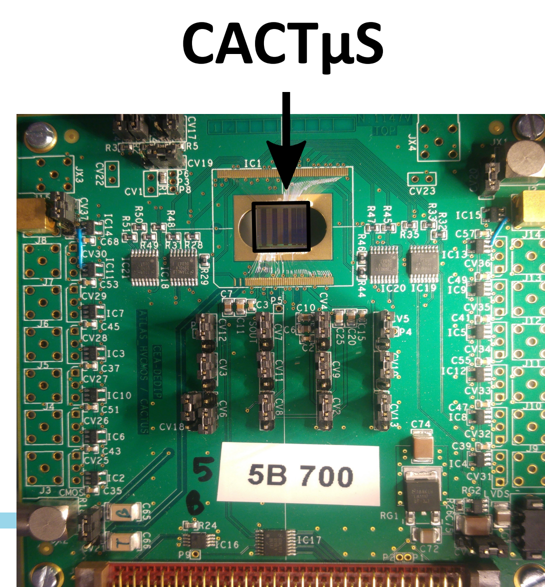


MAPS sensors: CACTμS detector

- Collaboration with CEA Saclay
  - Depleted monolithic active timing sensor using a CMOS 150 nm radiation hard technology from LFoundry
  - Promises to be: low cost, radiation hard, and with good time resolution
  - Originally intended for ATLAS HGTD detector, but could be used for EIC, future colliders
- The in-pixel front-end electronics of each pixel is made of a fast charge-sensitive amplifier(CSA) followed by a leading-edge discriminator.
  - The analog output of the CSA and the digital output of the discriminator can be monitored out of the chip through dedicated on-chip buffers.

Simplified block diagram of Cactus detector.

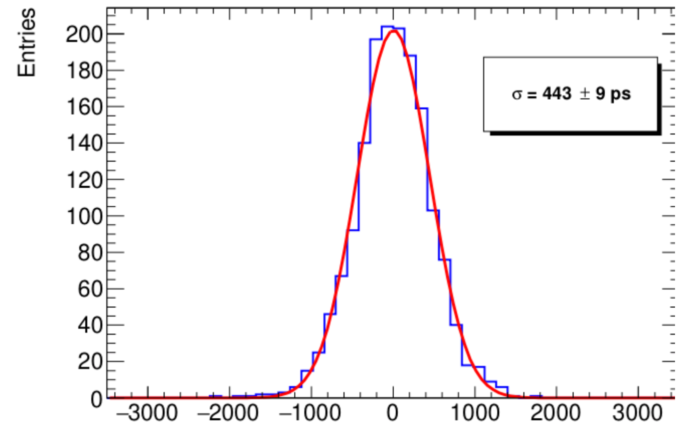




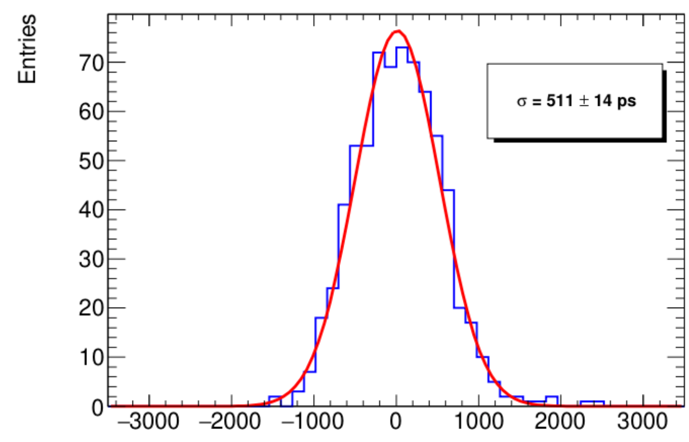
JINST 15 P06011

MAPS sensors: CACTμS detector

- Detailed measurements performed in the lab and in beam: JINST 15 P06011
  - Test results are promising but some problems observed
  - Analog S/N is lower than expected from simulations
  - This effect is likely due to the in-pixel power metal rails, increase the capacitance of the charge collection diode
  - New version is being designed
- Ideas to integrate LGAD and MAPS detectors:
  - G. Deptuch in Snowmass meeting: https://indico.fnal.gov/event/45625/



Time resolution with analog signal



Time resolution with digital signal

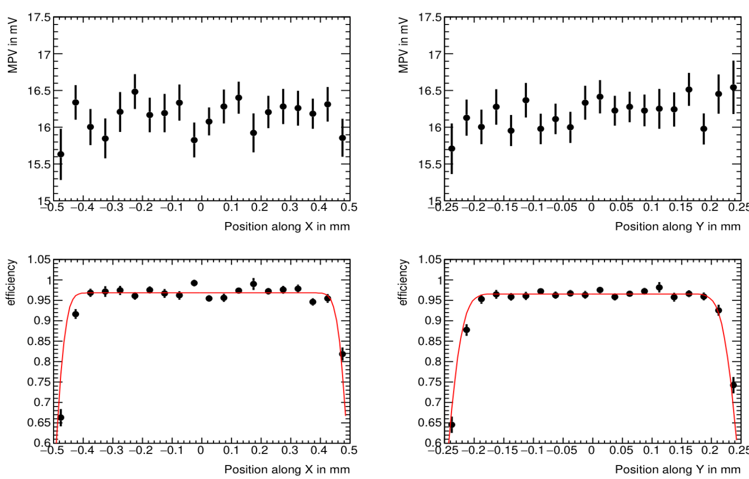
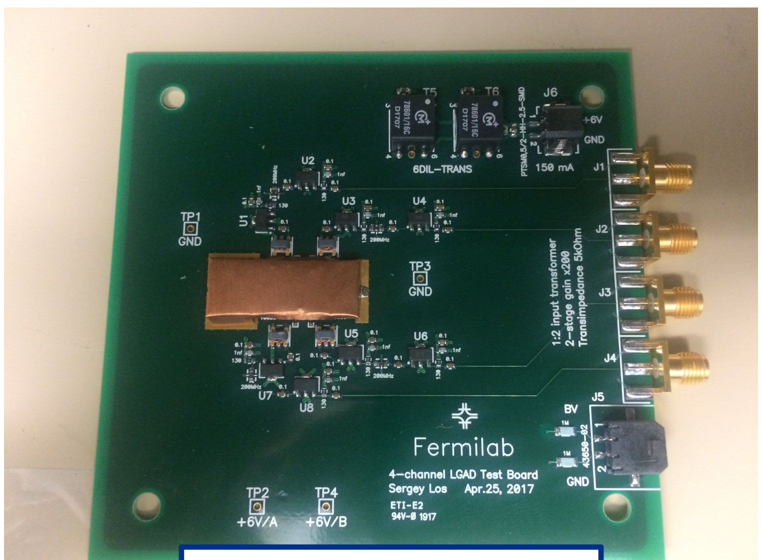


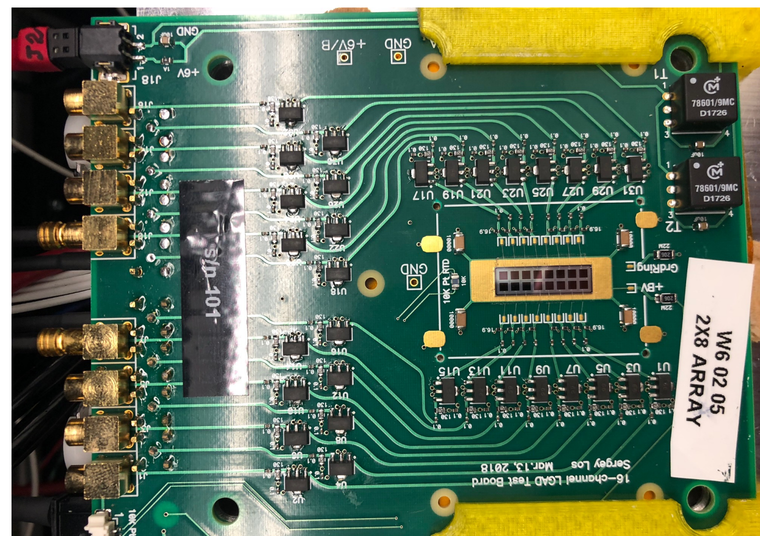
Figure 12: MPV and efficiencies determined in slices of X or Y. For the efficiencies, the red curves show the expected efficiency when a 97 % plateau efficiency is convoluted with a 25 μm telescope resolution.

Readout electronics for precision timing sensors

- Need appropriate *"tools"* to perform high precision position and timing measurements, without complicated ASIC and DAQ
  - Developed readout boards for the characterization of LGADs
  - 4-,16- and 26-channel boards are a **cost-effective and simple way to test** large channel count sensors
- Several iterations produced and improved over time
  - Have been critical in measurement campaigns for LGAD, and AC-LGAD sensors



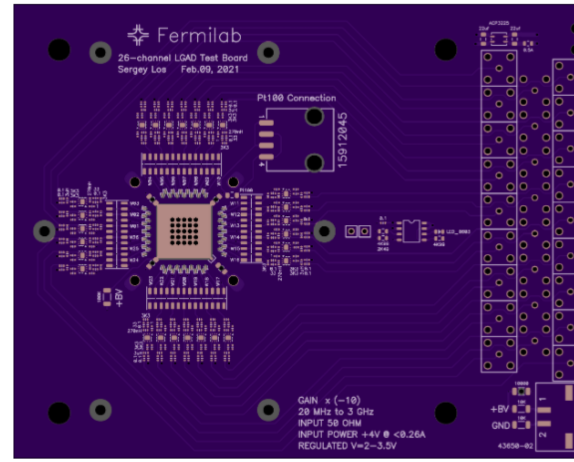
FNAL 4-ch readout board



16-ch sensor LGAD on Fermilab readout board

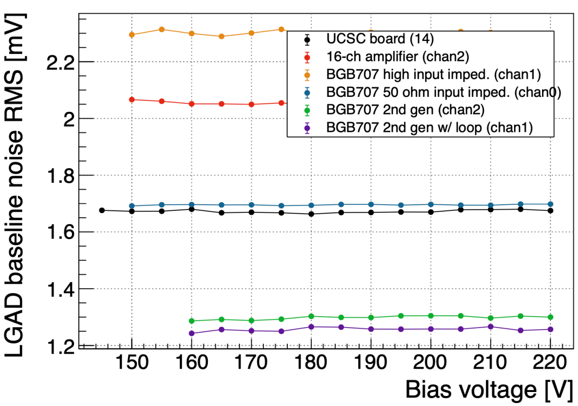
Readout electronics

- New development: low power 26-ch board
  - Goals: Increase the channel count, reduce power consumption, improve time resolution performance
  - Maintain low noise, and low jitter
  - Achieve sensor’s intrinsic limitation on time resolution: around 30 ps resolutions (for 50 μm thickness)
- Measurements of 4-ch prototypes showed very good performance with particles
  - Full-size boards produced, being tested now

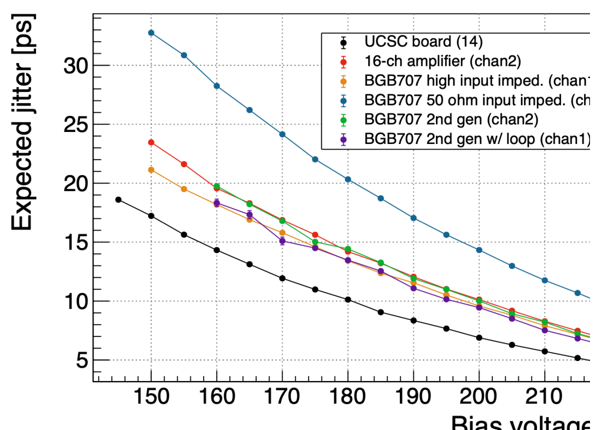


26-channel board design

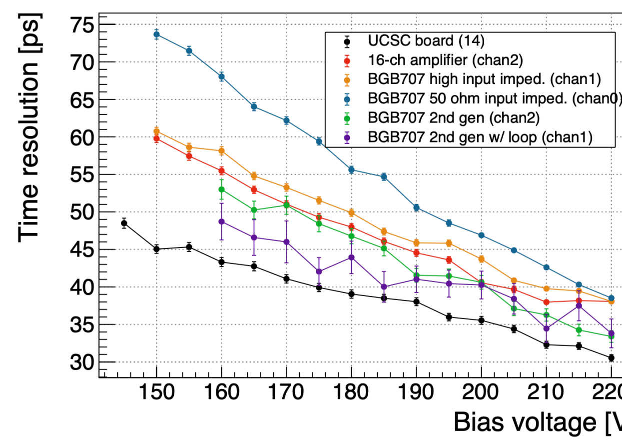
Noise



Noise / dV/dt

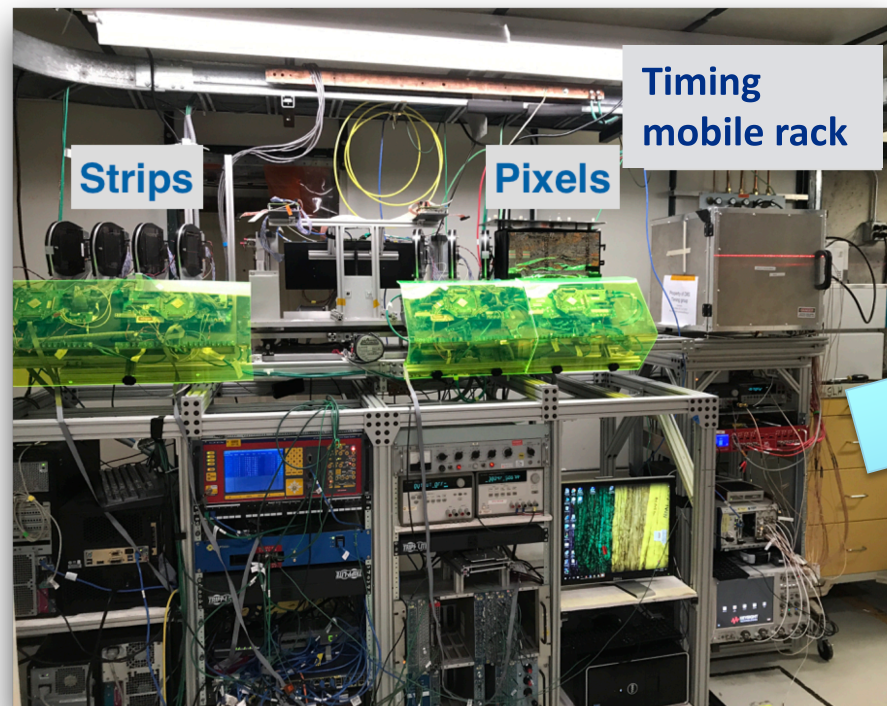


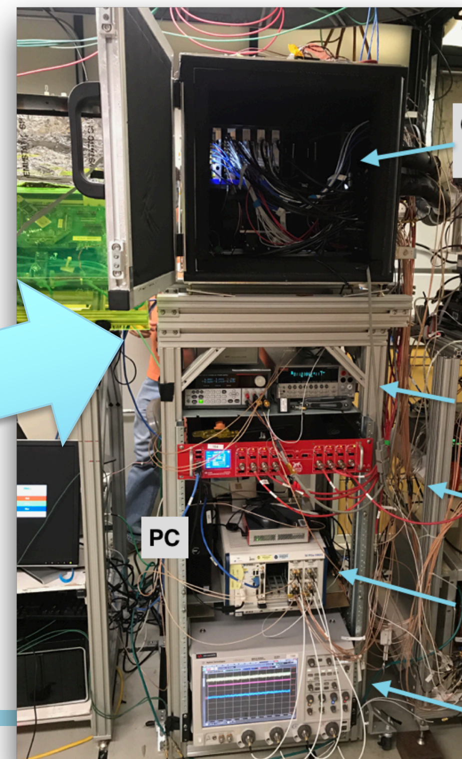
Time resolution



Fermilab 4D-trackers test beam infrastructure

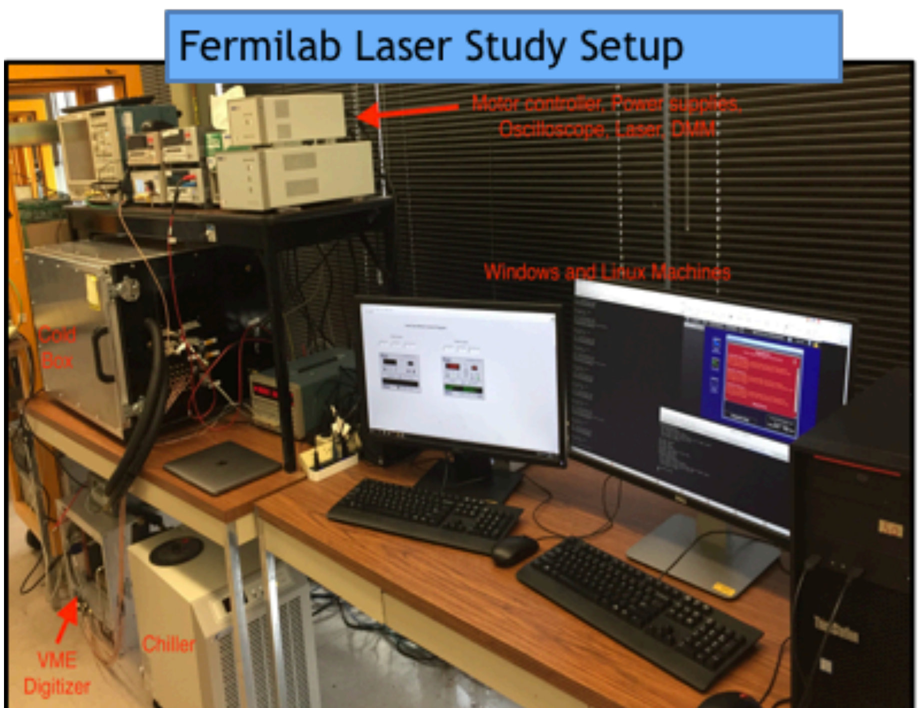
- Permanent setup in FNAL test beam facility (FTBF)
  - Movable: slide in and out of beamline as needed, parasitic use of beam
  - Environmental controls: sensor temperature (-25 C to 20 C), and humidity, monitoring
  - Remote control (stages, HV, LV), logging & reconstruction; $\sigma_T \sim 10$ ps time reference (MCP)
  - Cold operation of up to 10 prototypes at the same time
  - DAQ: high bandwidth, high ADC resolution scope 4- or 8-channel scope
  - Record 100k events per minute, tracker with ~10 µm resolution

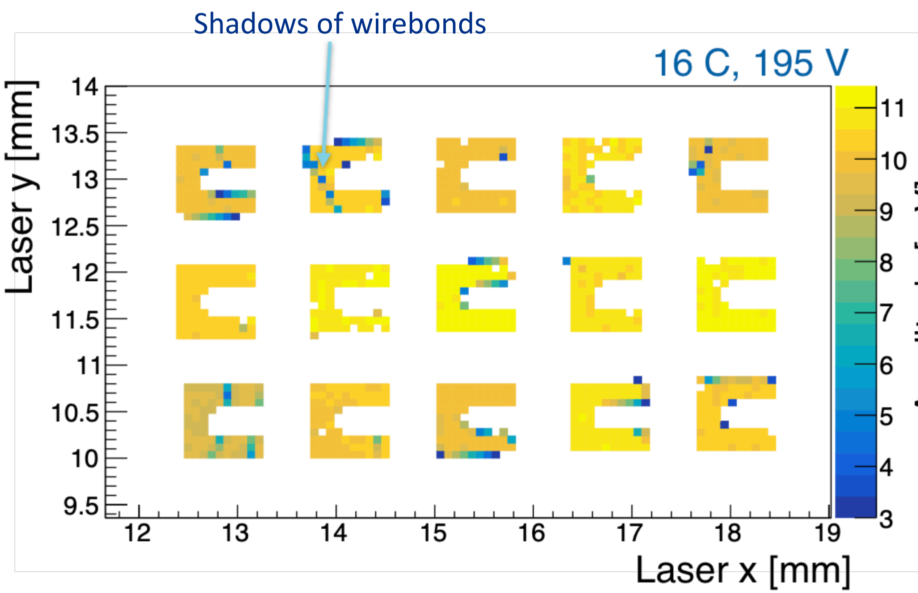




Infrastructure at SiDet

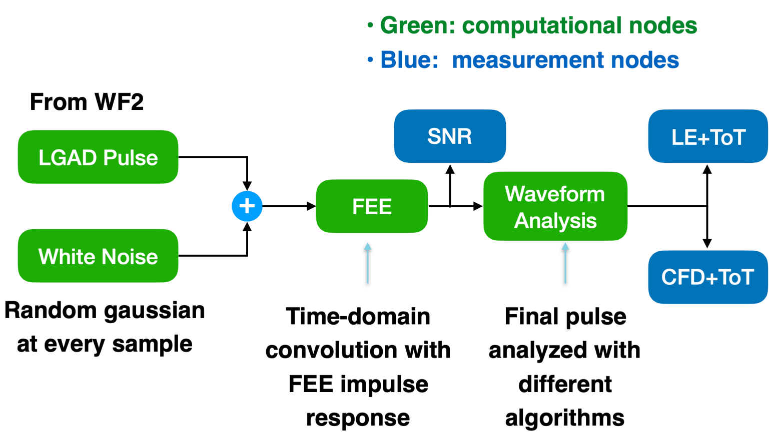
- LGAD sensors characterization facility
  - Environmental chamber with the same capabilities and DAQ as in MTest
  - Infrared laser with 15 µm beamspot and XYZ motion stages for scanning
  - Sr^{90} and Ru^{106} beta-sources for gain, time resolution measurements
  - Studies of large samples of sensors, stability and detailed understanding without the rush of beam tests

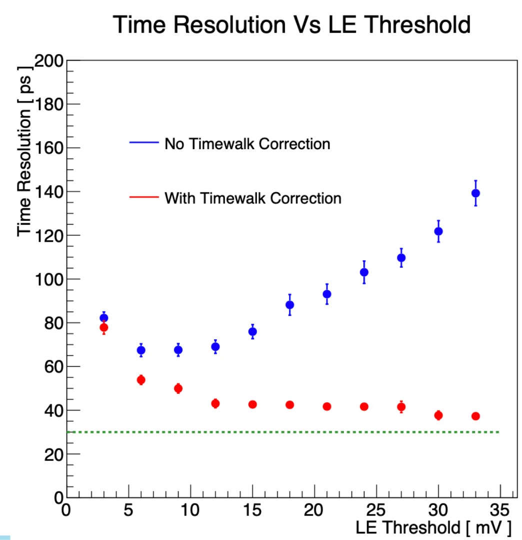


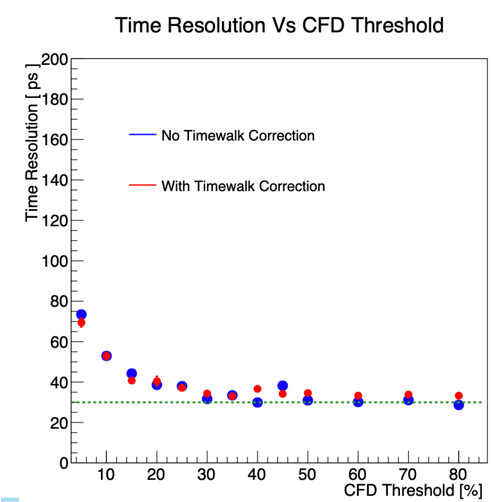


Timing ASIC approaches: LE or CFD

- Simulation Model of Front-end Electronics for High-precision Timing Measurements with LGADs
  - LGAD pulses are from Weightfield2 (WF2) simulation
  - Different pulse shape as a function of irradiation
- Consider various options for the pre-amp:
  - Simulation scans BW, SNR, and compare LE vs CFD approaches







Analysis Summary of Results (ST = 0.5 ns)

Leading Edge

ST (ns)	SNR=20	SNR=30	SNR=100	
0.5	38 ps	35 ps	29 ps	Pre-rad
0.5	37 ps	32 ps	26 ps	5×10^{14} n/cm^2
0.5	48 ps	38 ps	27 ps	1×10^{15} n/cm^2

Constant Fraction

ST (ns)	SNR=20	SNR=30	SNR=100	
0.5	37 ps	35 ps	30 ps	Pre-rad
0.5	33 ps	31 ps	25 ps	5×10^{14} n/cm^2
0.5	42 ps	34 ps	24 ps	1×10^{15} n/cm^2

- 30-35 ps target resolution achieved by LE and CFD up to SNR = 30
- Target resolution achieved up to irradiations of 1×10^{15} n/cm^2
- 40-50 ps resolution achieved when SNR = 20 at the largest dose

Analysis Summary of Results (ST = 1.0 ns)

Leading Edge

ST (ns)	SNR=20	SNR=30	SNR=100	
1.0	45 ps	37 ps	29 ps	Pre-rad
1.0	41 ps	34 ps	29 ps	5x10^{14} n/cm^2
1.0	60 ps	47 ps	28 ps	1x10^{15} n/cm^2

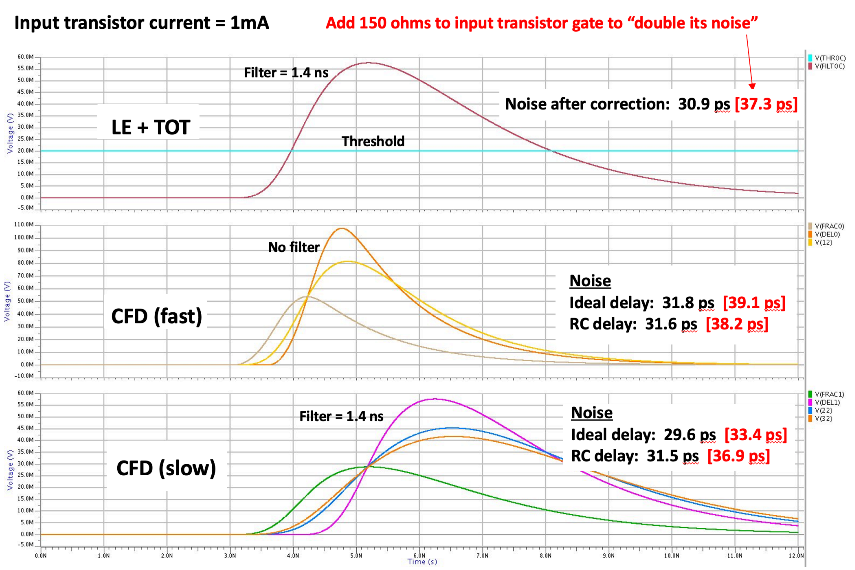
Constant Fraction

ST (ns)	SNR=20	SNR=30	SNR=100	
1.0	36 ps	33 ps	26 ps	Pre-rad
1.0	33 ps	31 ps	26 ps	5x10^{14} n/cm^2
1.0	47 ps	37 ps	23 ps	1x10^{15} n/cm^2

- 30-35 ps target resolution achieved by LE and **CFD** up to SNR = 30
- ST = 1 ns → observe a large performance gap when using CFD
- 40-50 ps resolution (CFD only) when SNR = 20 at the largest dose

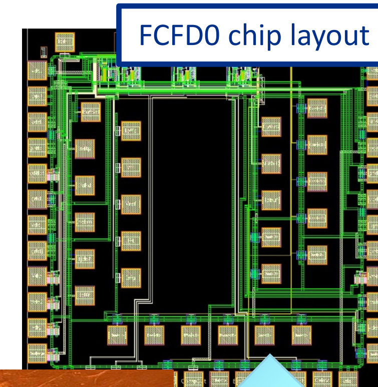
Timing ASIC with CFD: FCFD0

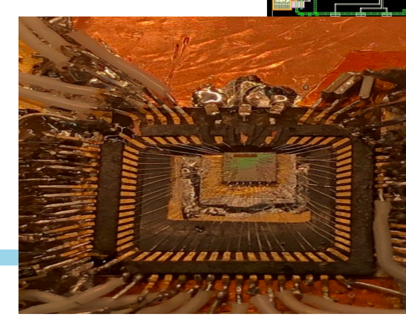
- Develop a CFD based ASIC for LGAD fast timing readout
  - Expect better performance for low S/N after irradiation, no need for time-walk correction, stability, simplicity of operation,
  - Many innovative solutions designed and implement by T. Zimmerman (FNAL)
- The chip recently received from TSMC
  - Currently being tested, and then will mount on dedicated readout board for testing with sensor, betas and beams.
  - Follow up with subsequent productions of full chips, with more channels



Fraction peak	Ideal delay	RC delay	
1.36 ns	31.8 ps	30.9 ps	← Too fast
1.58 ns	30.5	30.7	
1.76 ns	30.2	30.8	← Ideal
1.97 ns	30.3	31.2	← OK
2.17 ns	30.4	32.0	
2.33 ns	30.5	32.9	

FCFD0 chip layout





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Summary

- Timing is an enabling technology for future experiments
  - The last dimension to be used in collider experiments!
  - Will bring improvements in event reconstruction, triggering, and new handles in searches for new physics!

- Future tracking detectors will likely be required to have significant timing precision: both lepton and hadron colliders
  - Timing precision of 20-30 ps achieved with several Si-based technologies
  - Collaborative efforts are a key for the progress in many challenging directions