Development of Ultra-Fast Silicon Detectors (UFSDs) for particle identification using TOPSiDE at the EIC

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Argonne National Laboratory

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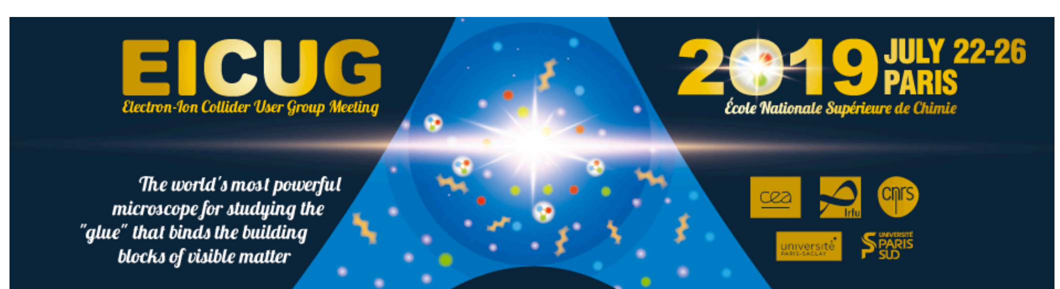
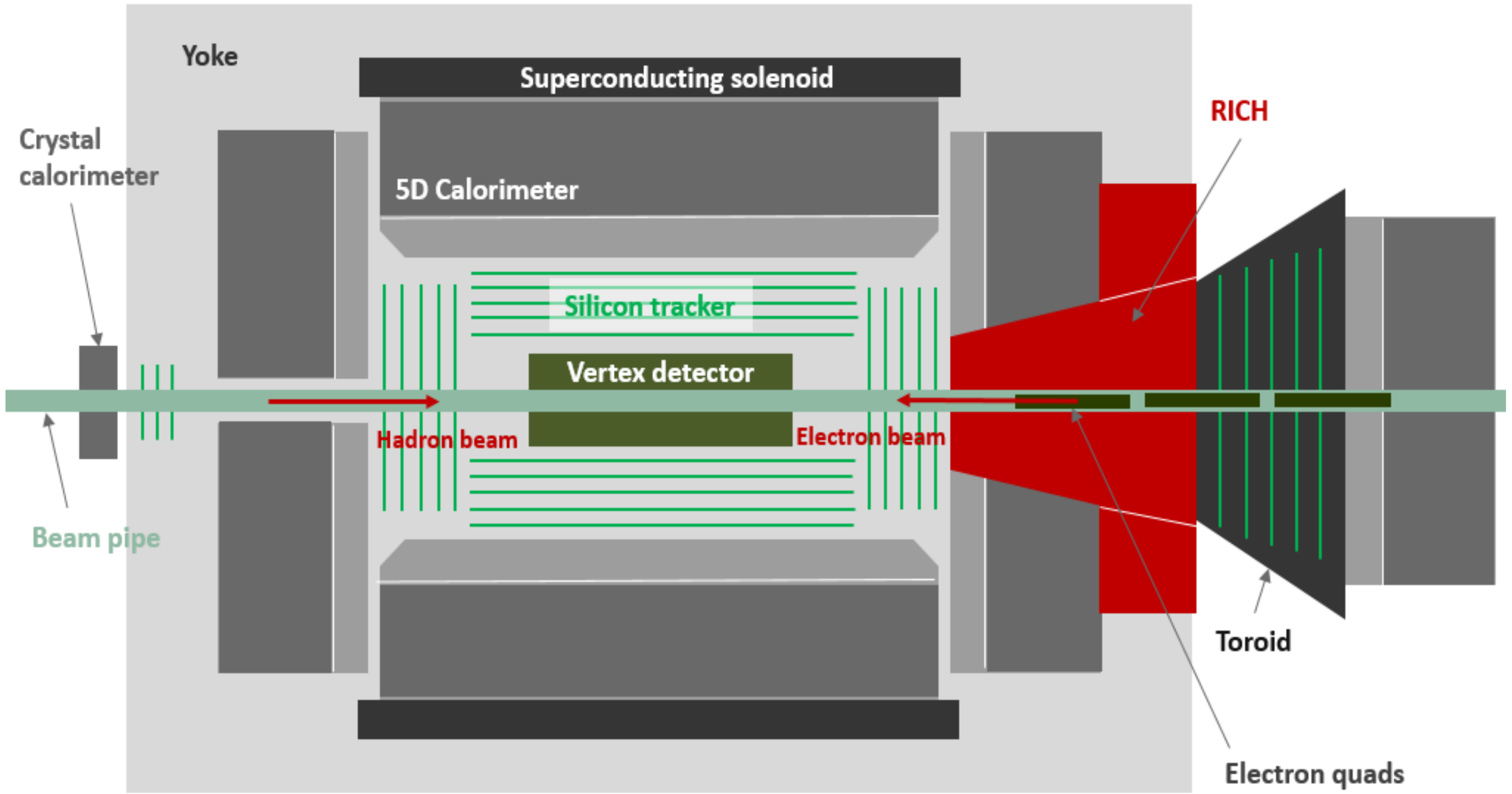


Outline

- TOPSiDE Concept
- Motivation for TOPSiDE
- Ultra-Fast Silicon Detector for the EIC
- Low-Gain Avalanche Detector Design Simulations
- Readout Design Development
- Testing of LGADs at Argonne
- Test Beam Results for LGADs
- Validation of Concept - PENTACAL
- Summary

TOPSiDE concept



5-dimensional information (E, x, y, z, t)

— Silicon tracker+Calorimeter

— Particle identification

Eliminates the need for preshower counters, TRDs, TOF or Čerenkov in front of Calorimeter, and muon chambers in back

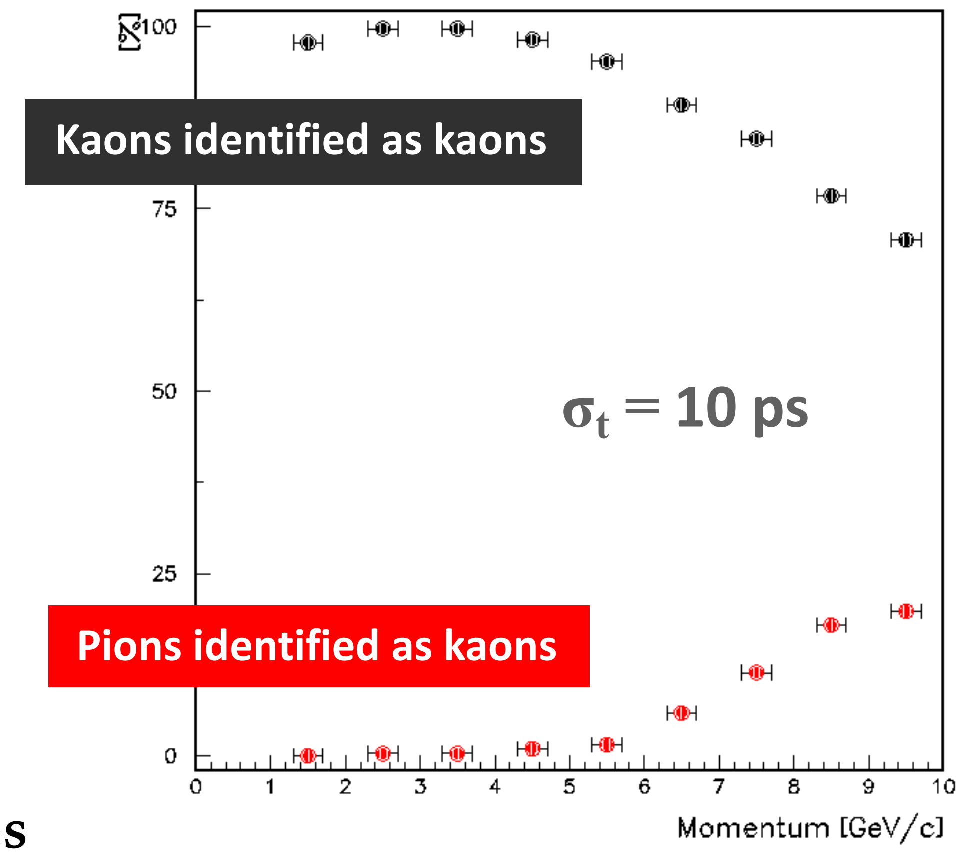
TOPSiDE Sub-Detectors

- Silicon Pixel Vertex
- Silicon Strip Tracker
- Silicon Imaging EM Calorimeter
- Imaging Hadron Calorimeter
- Superconducting Solenoid (3T)
- Forward gaseous RICH
- Forward Dipole + Cloak or Toroid w/o Cloak
- Forward Silicon Disks
- Forward Calorimeter
- Backward Silicon Disks
- Backward Crystal Calorimeter

Motivation for TOPSiDE

Particle Identification:

- Particle momenta < 7 GeV/c
  - most of the solid angle
- Separation of pion-kaon-proton
  - Silicon sensor with time resolution of ~ 10 ps
  - Good separation up to 7 GeV/c
  - Even with 20 ps; good separation up to 5 GeV/c

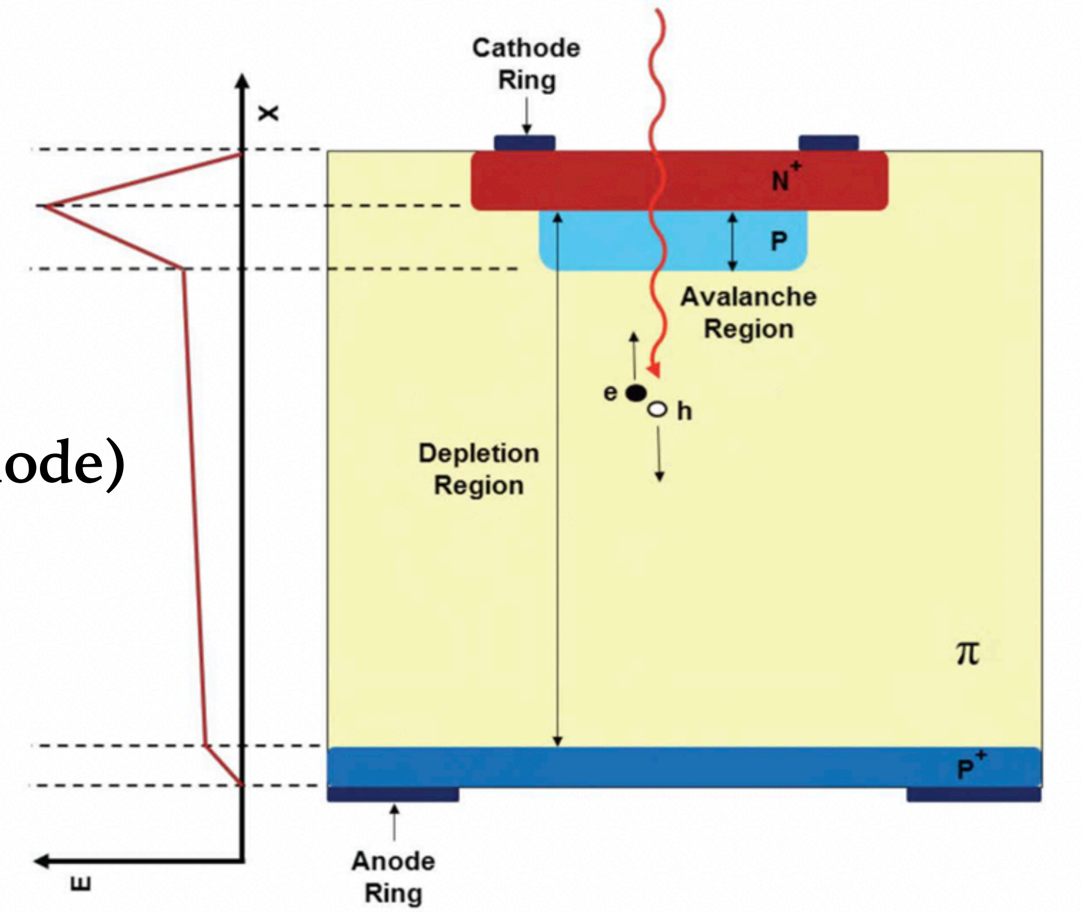


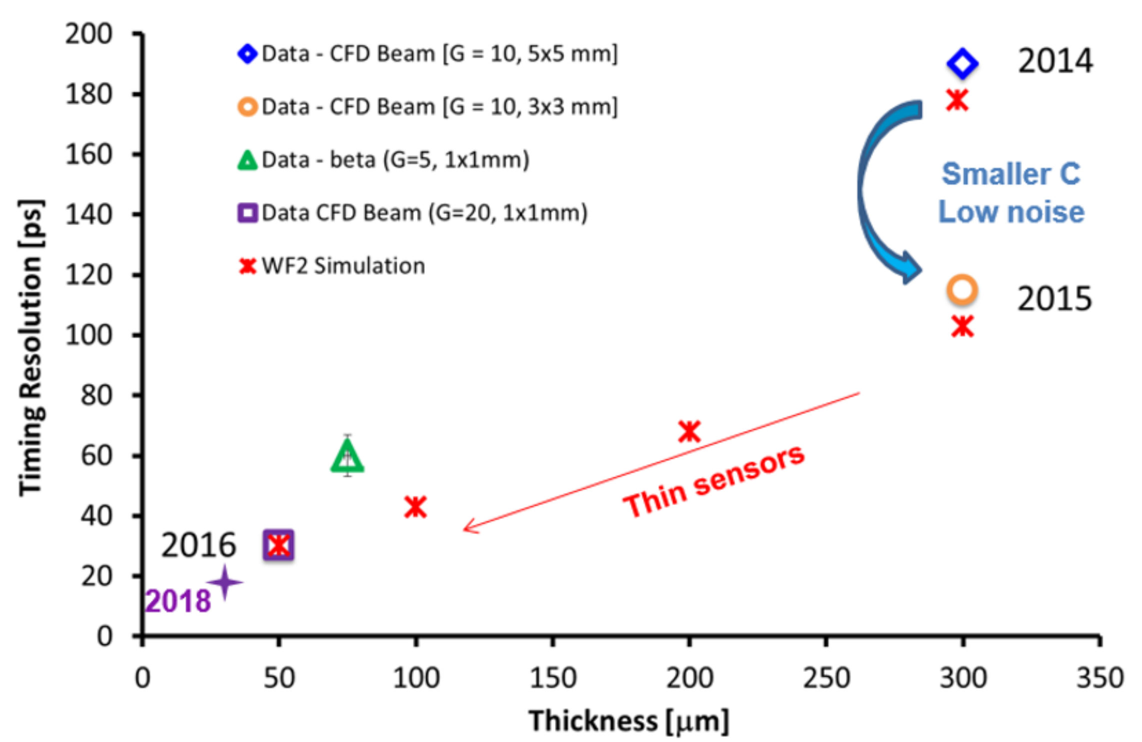
Beauty of TOPSiDE

- **Minimal number of different detector technologies**
  - Silicon, UFSD, Photo sensors for RICH, Xtal calorimeter + forward/backward system
- **Simple design, low material budget**
  - Minimal amount of dead material in front of the calorimeter (do not have preshower counters, TRDs, TOF or Cherenkov)
  - Better photon detection (DVCS)
- **Measurement and identification of all particles individually**
- **Optimized for particle flow algorithms**

Motivation for UFSDs

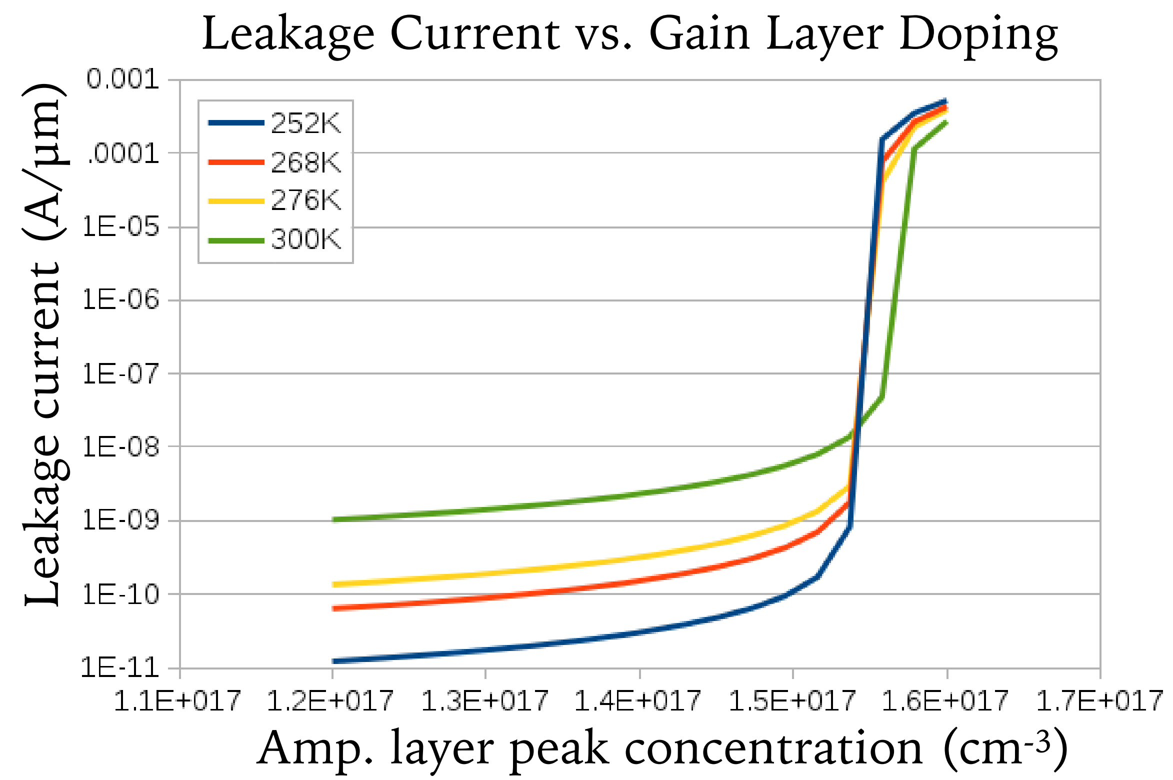
- **Low-Gain Avalanche Diode (LGAD)**
  - EM Calorimeter + silicon tracker
  - Separation of π - K - p for particle identification
- **Internal gain layer (similar to Avalanche Photo Diode)**
  - n++ (N^+) - p+ (P) - p (π) structure
- **High E-field in gain region**
  - multiplication process - provides gain
- **Moderate gain of 10-70 w/o breakdown**
  - increases signal-to-noise ratio (SNR)
- **Improvement in time resolution**
  - 18 ps with 35 μm thick LGAD sensor
  - more thinner sensor - 20 μm
- **Worldwide effort: ATLAS, CMS, EIC**
  - UC Santa Cruz, Kansas, Torino, Geneva, CERN, Bologna, BNL and now Argonne

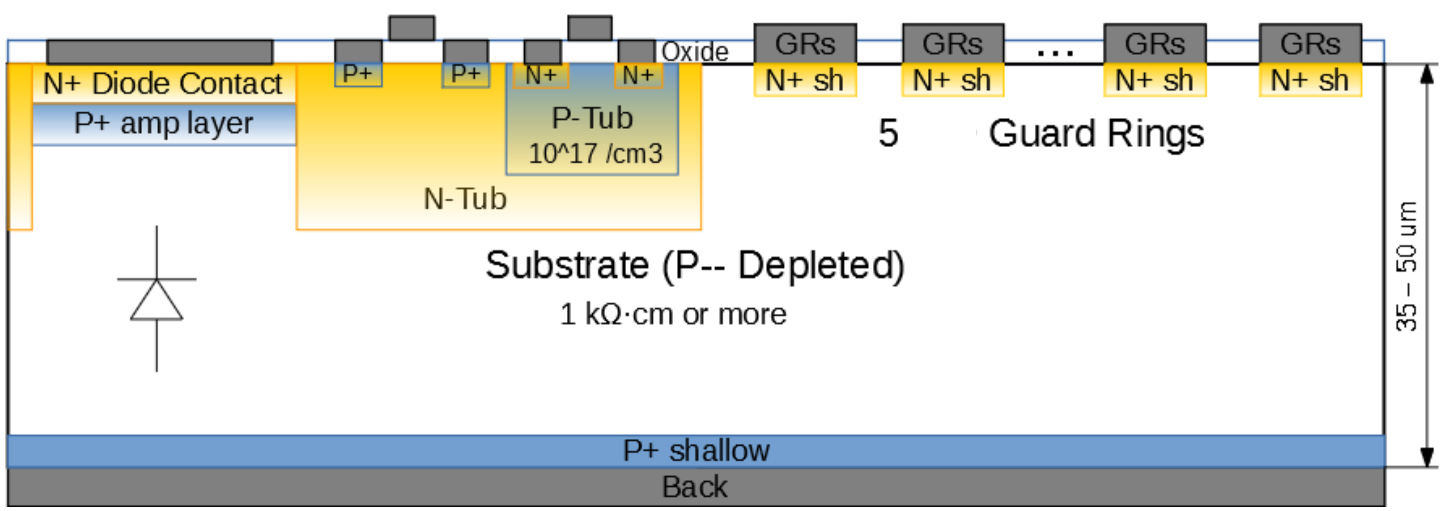


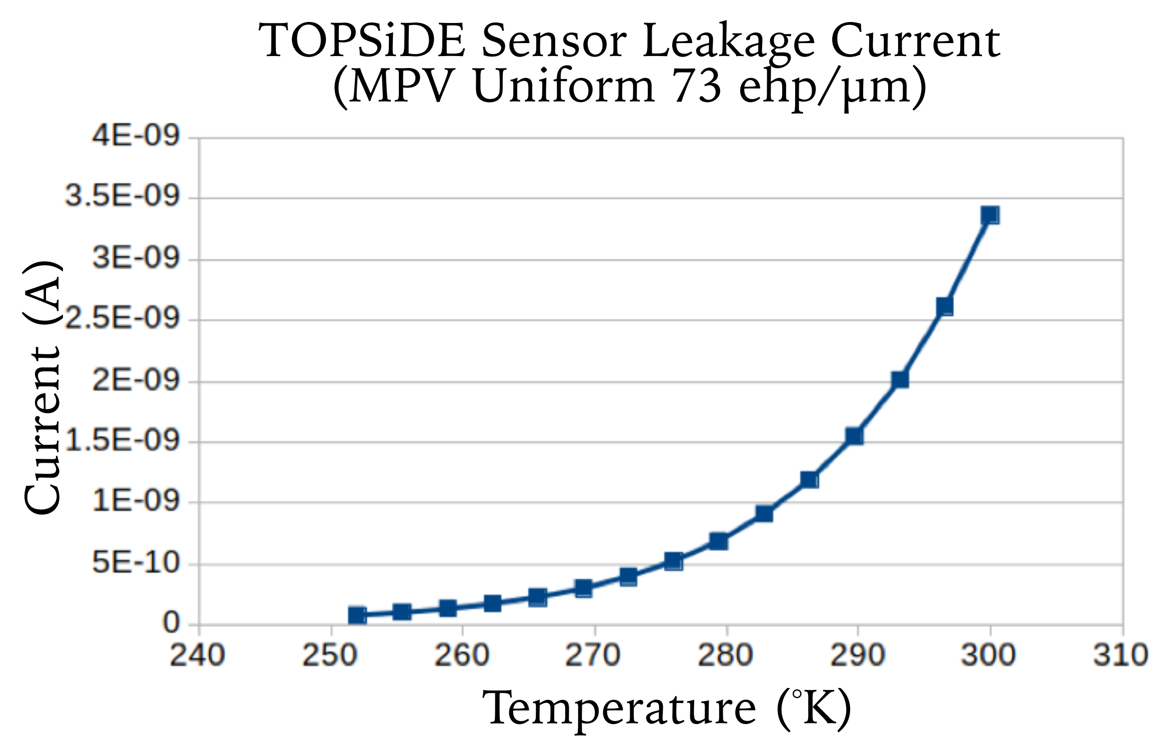


LGAD Sensor Simulations

- **TCAD simulation - ATLAS Silvaco**
- **Sensor Design**
  - Nominal 50 µm
  - 5 guard rings
  - pixel size of 1 × 1 mm^2
  - Bias Voltage ~ 200 Volts
- **In the future will integrate readout electronics using HV-CMOS (PicoPix)**
  - Silicon sensor will accommodate readout

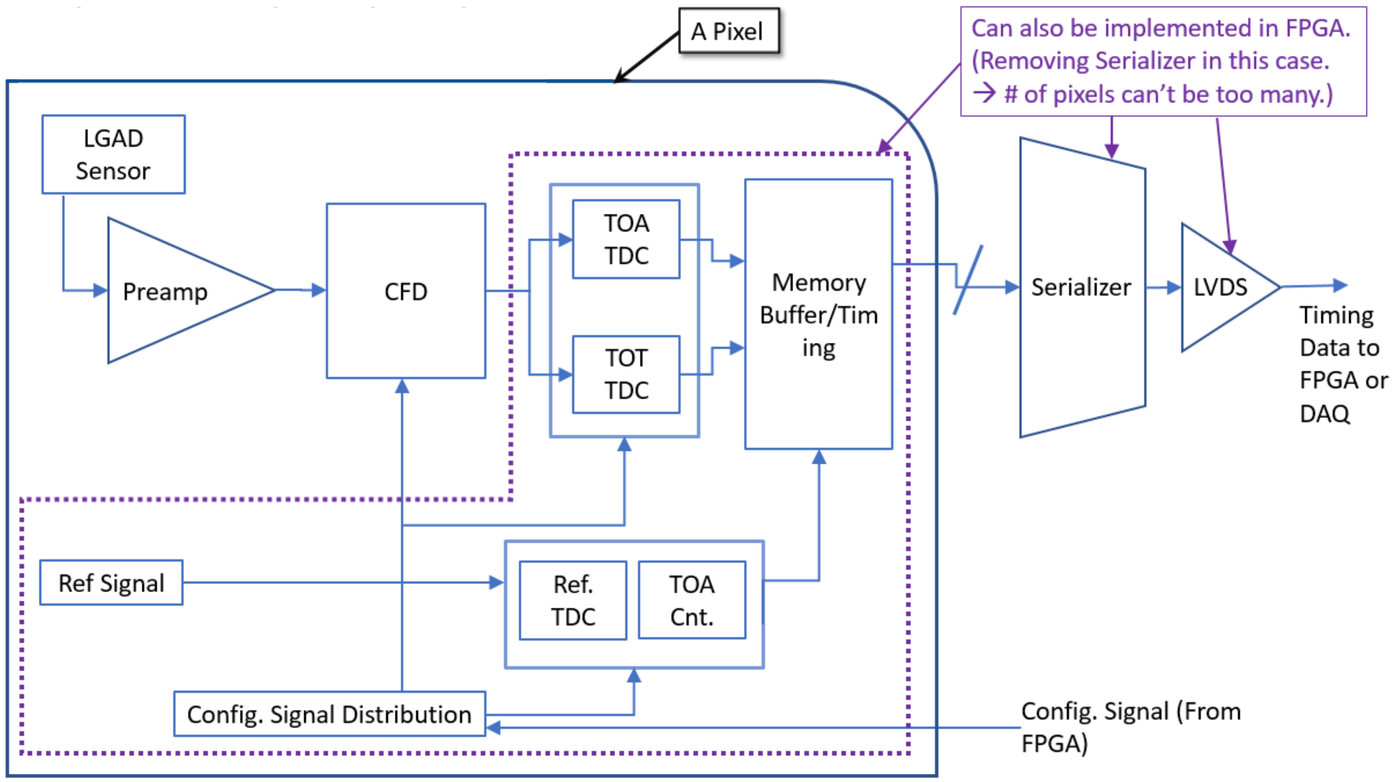


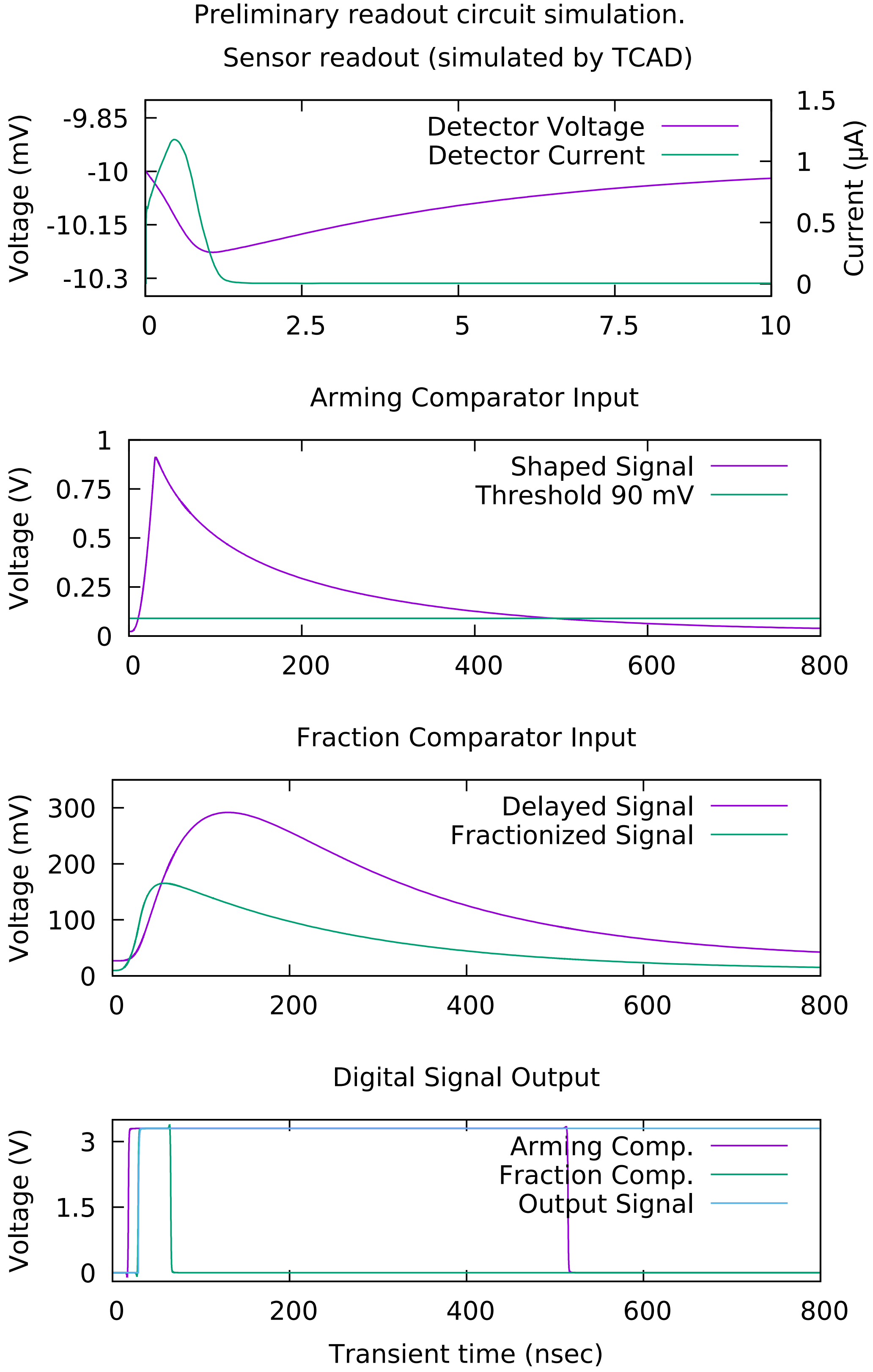




Readout Development

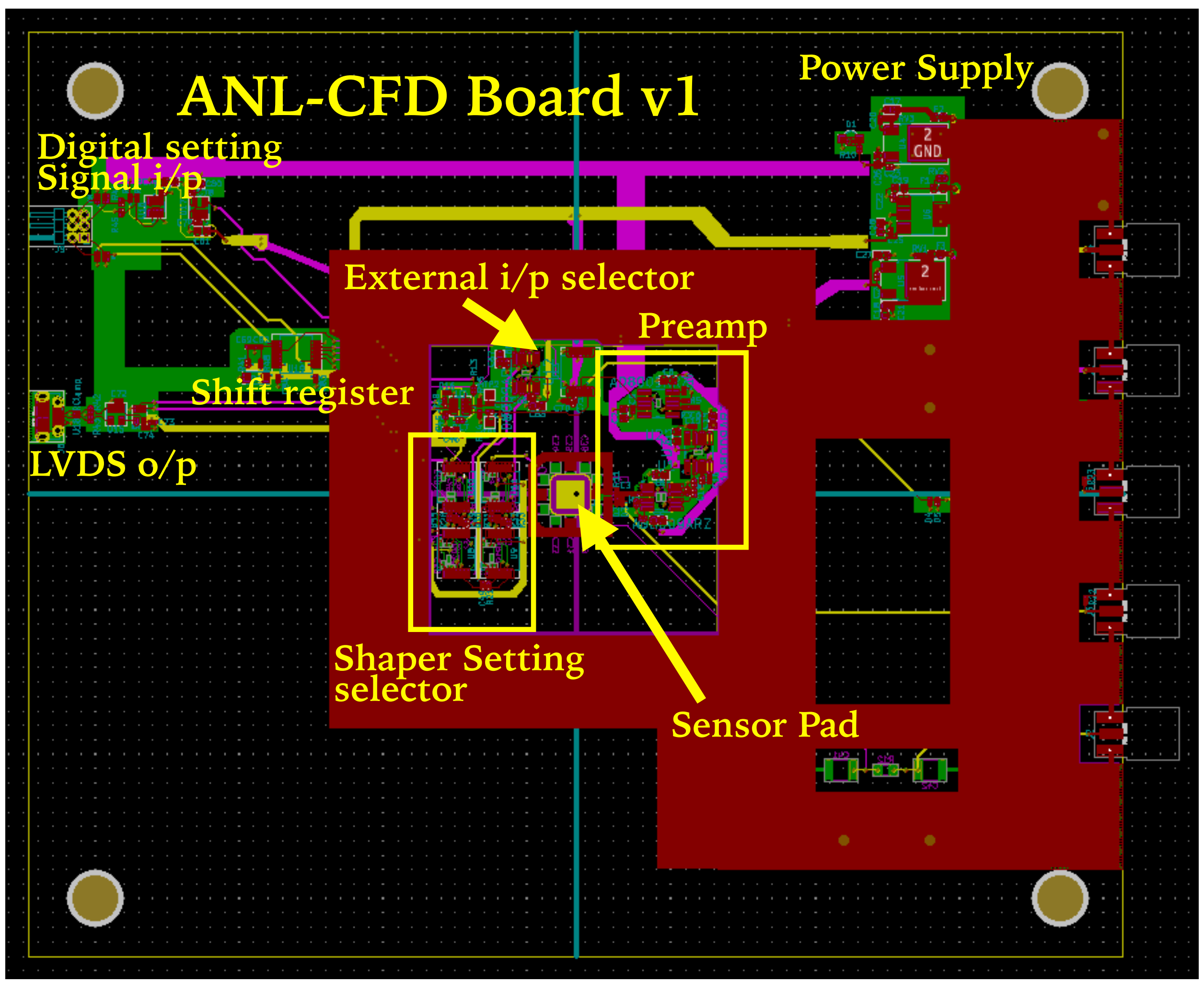
- **Front-end readout components**
  - Shaper, amplifier, discriminators, digitisers (TDC)
  - Time-of-Arrival, Time-over-Threshold
- **LTSpice Simulation**
- **Schematic of complete readout circuit**



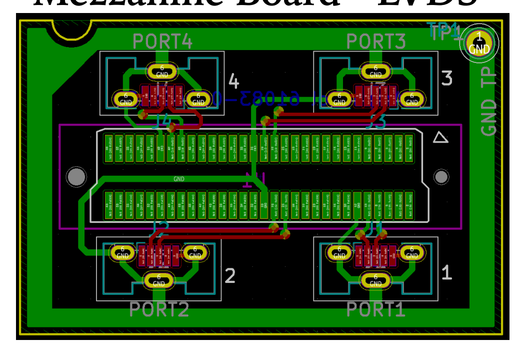


Layout Design

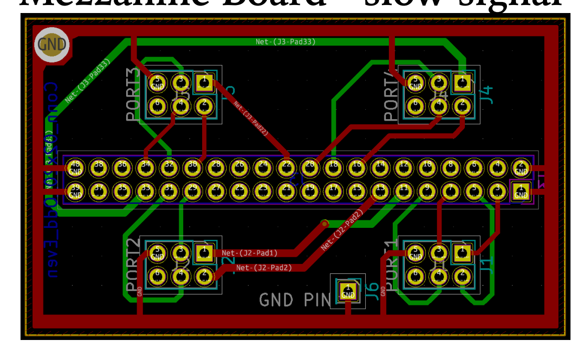
- The first stage includes preamplifiers, shaper, constant fraction discriminator
  - Being prototyped on PCB board before implementation on to pixel
  - TDC not included
- Fabrication of 10 CFD v1 boards complete and one board assembled
- FPGA Ultra 96 - programmable for upto 4 channels



Mezzanine Board - LVDS

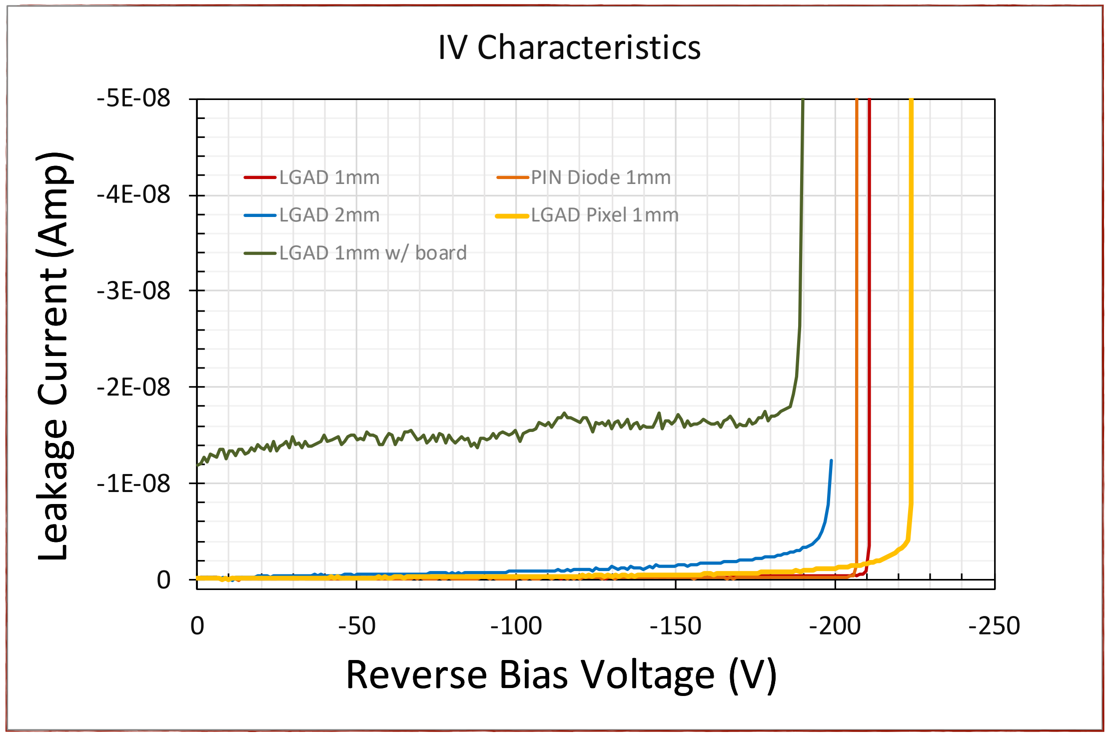


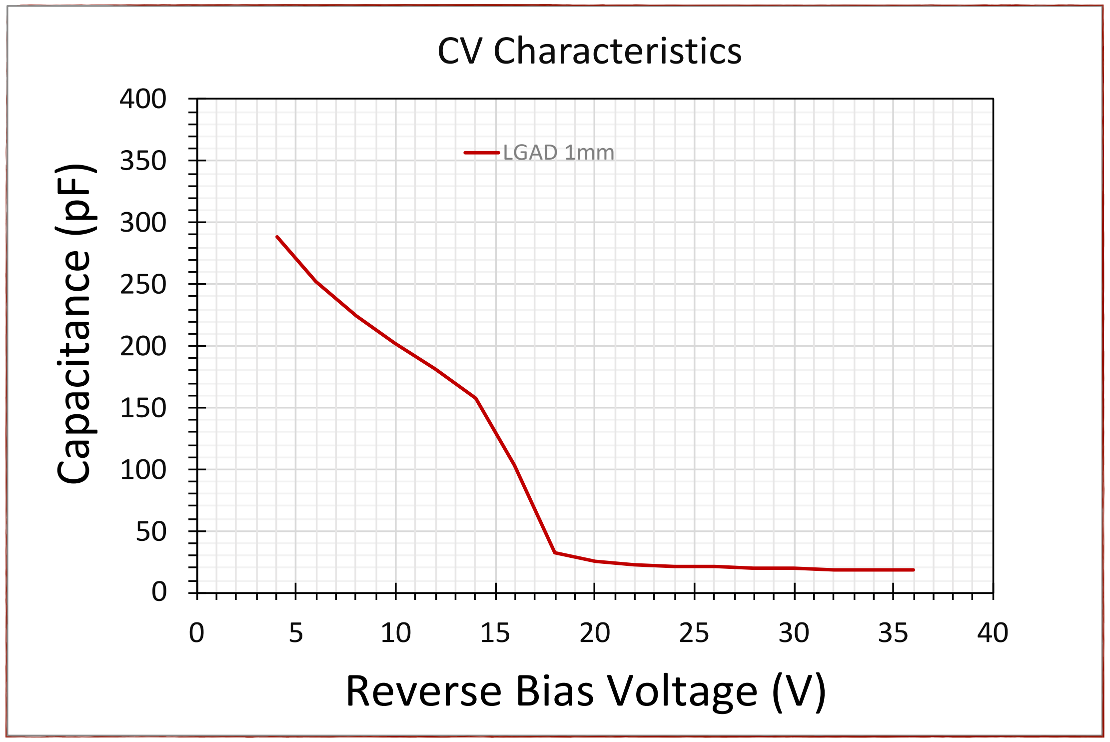
Mezzanine Board - slow signal



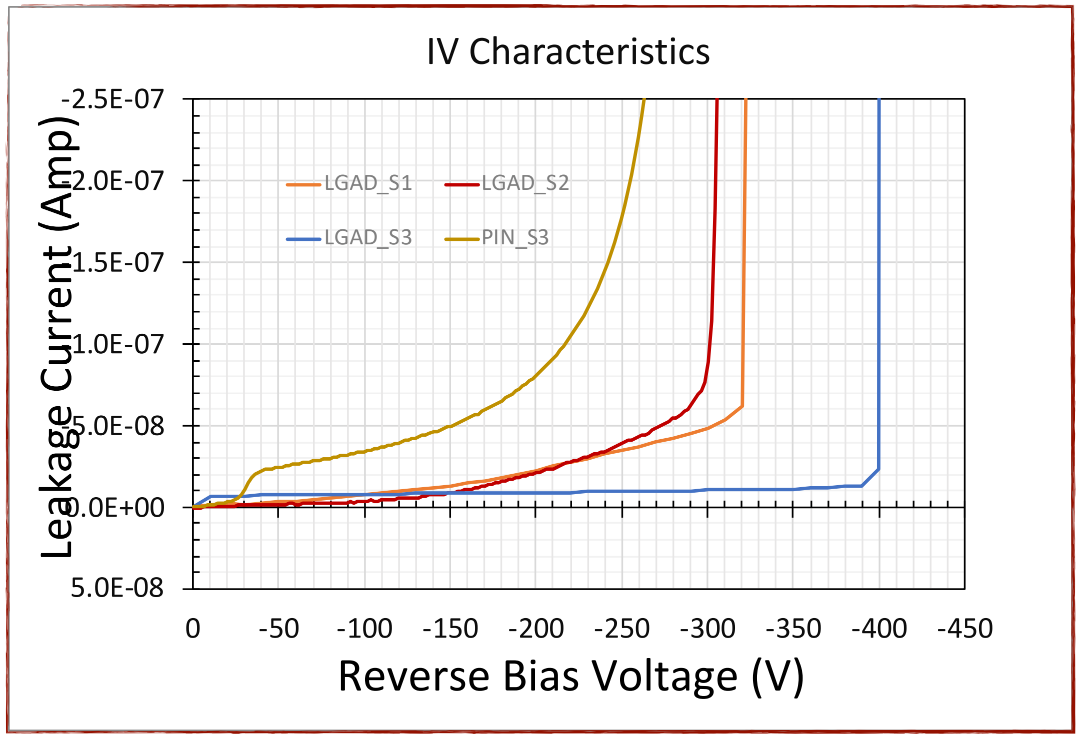
Characterisation of LGADs

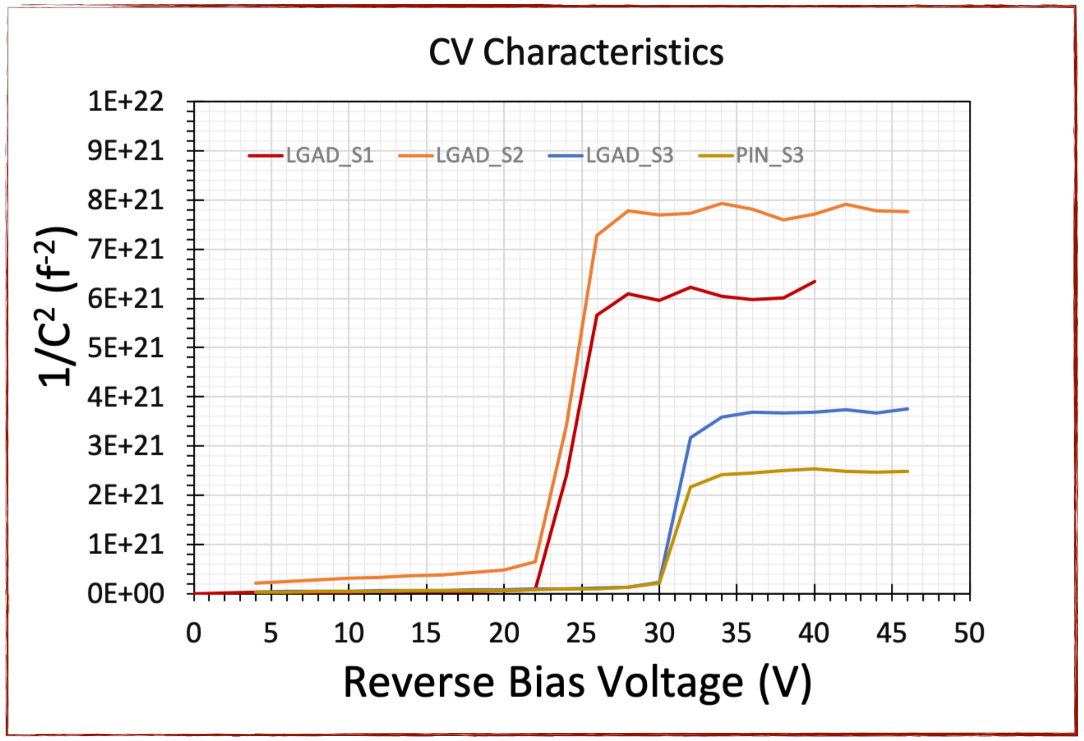
BNL sensors



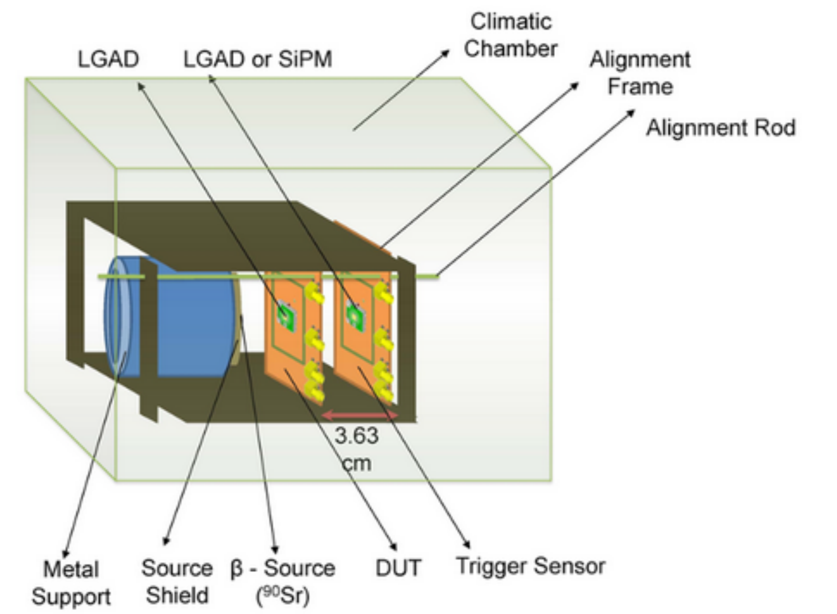


FBK sensors



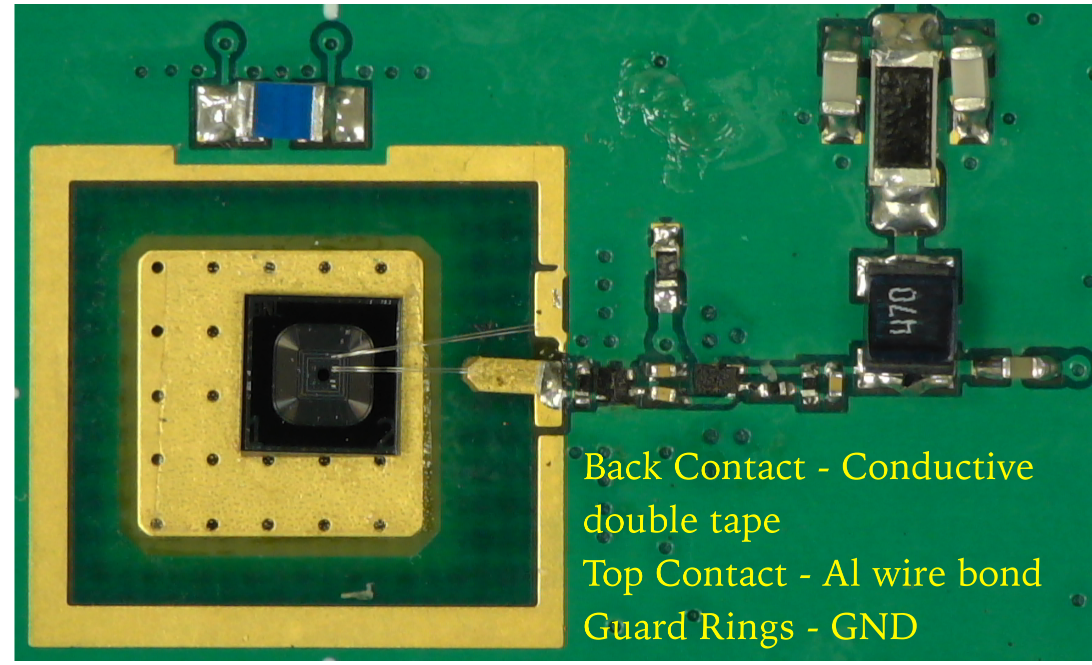


LGAD Measurement Setup



Beta Telescope at ANL

- **Timing measurements for Minimum Ionising Particles (MIPs)**
  - β particles from Sr^{90} source
- **Analog read-out board - Discrete amplifier**
  - 50 ohm i/p impedance, bandwidth > 1 GHz
- **Pulse signal collected with KEYSIGHT oscilloscope**
  - Events recorded using PyVisa
  - Data stored in root files
- **Argonne Micro-Assembly Facility (AMAF)**
  - Clean room facility at Argonne
  - Environmental Chamber for low temperature measurements

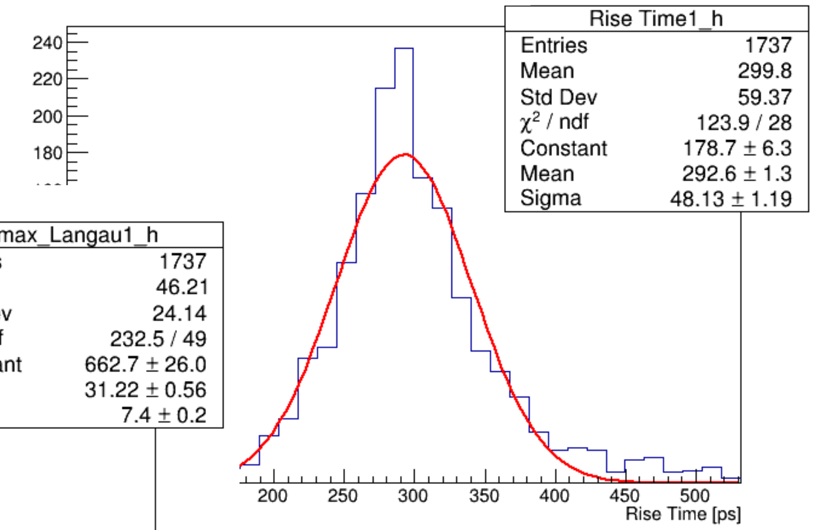


Detector+Readout → Oscilloscope ↔ PyVISA - DAQ Data → TROOT - Data Analysis

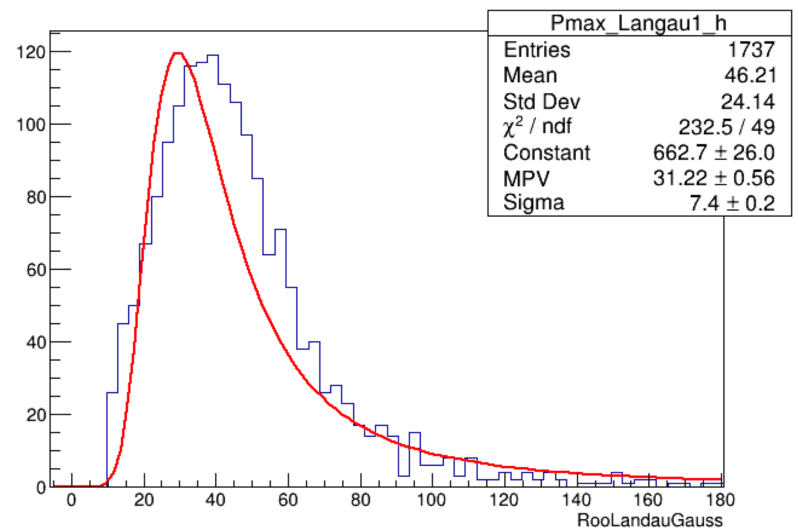
Measurements with Beta-telescope

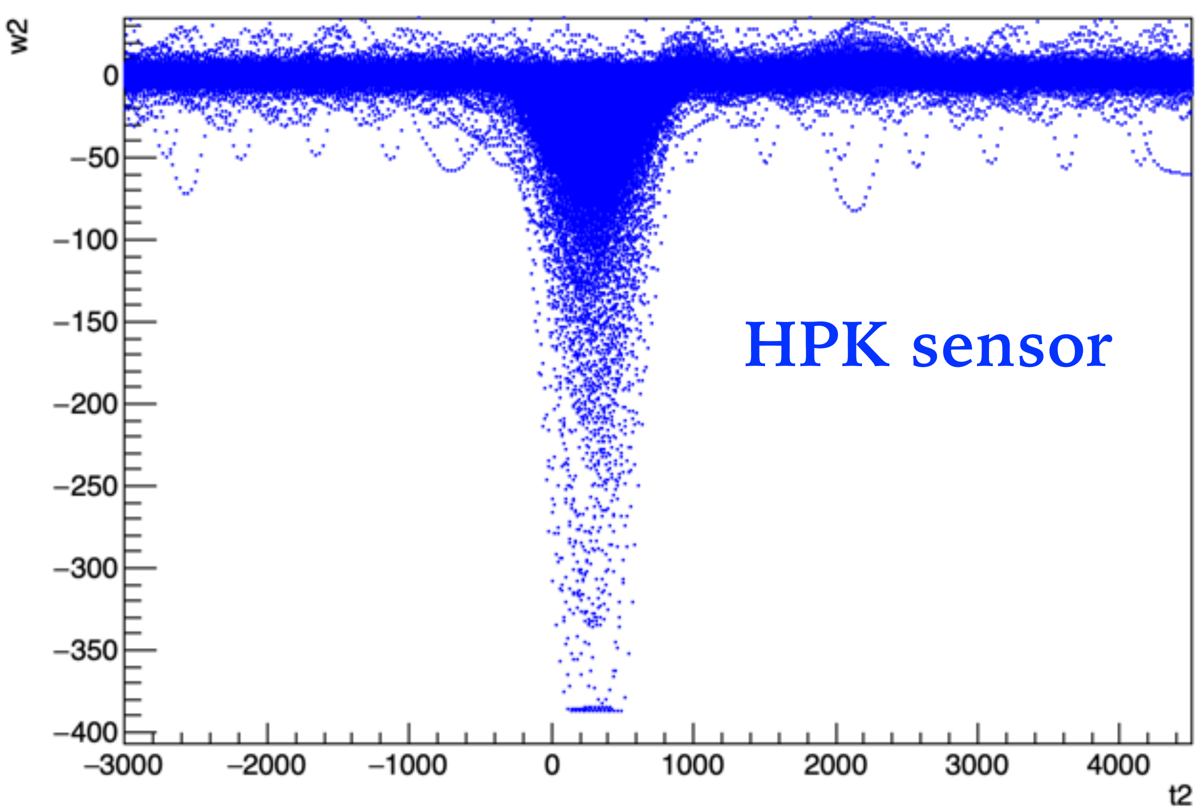
- **Measurements for LGAD sensors**
  - HPK and BNL for different bias voltages
- **A fast HPK LGAD trigger ~ 16.5 ps**
  - Coincidence for event selection
- **Time Resolution using CFD method**
  - sqrt(σ_{det}^2 — σ_{trg}^2)
  - 25 ps for HPK

Rise_Time

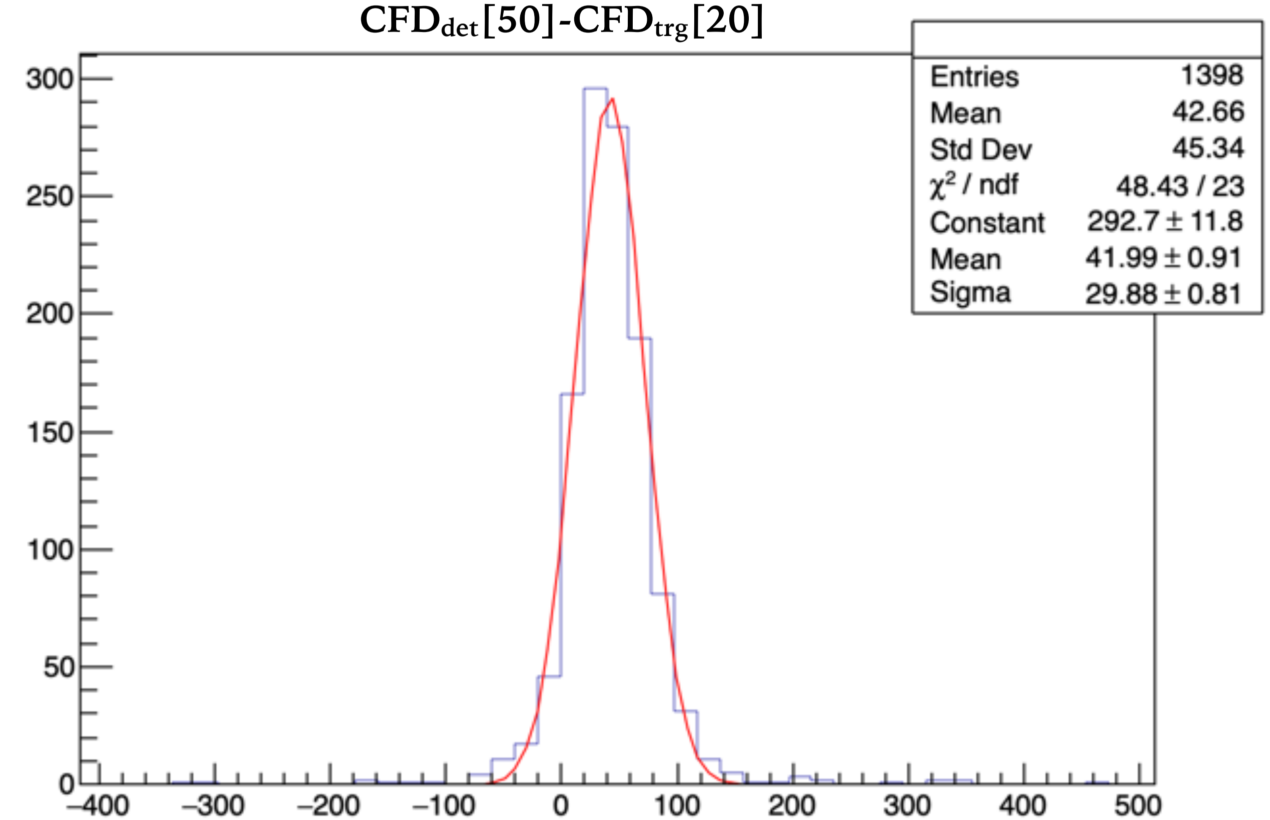


Pmax_Landau

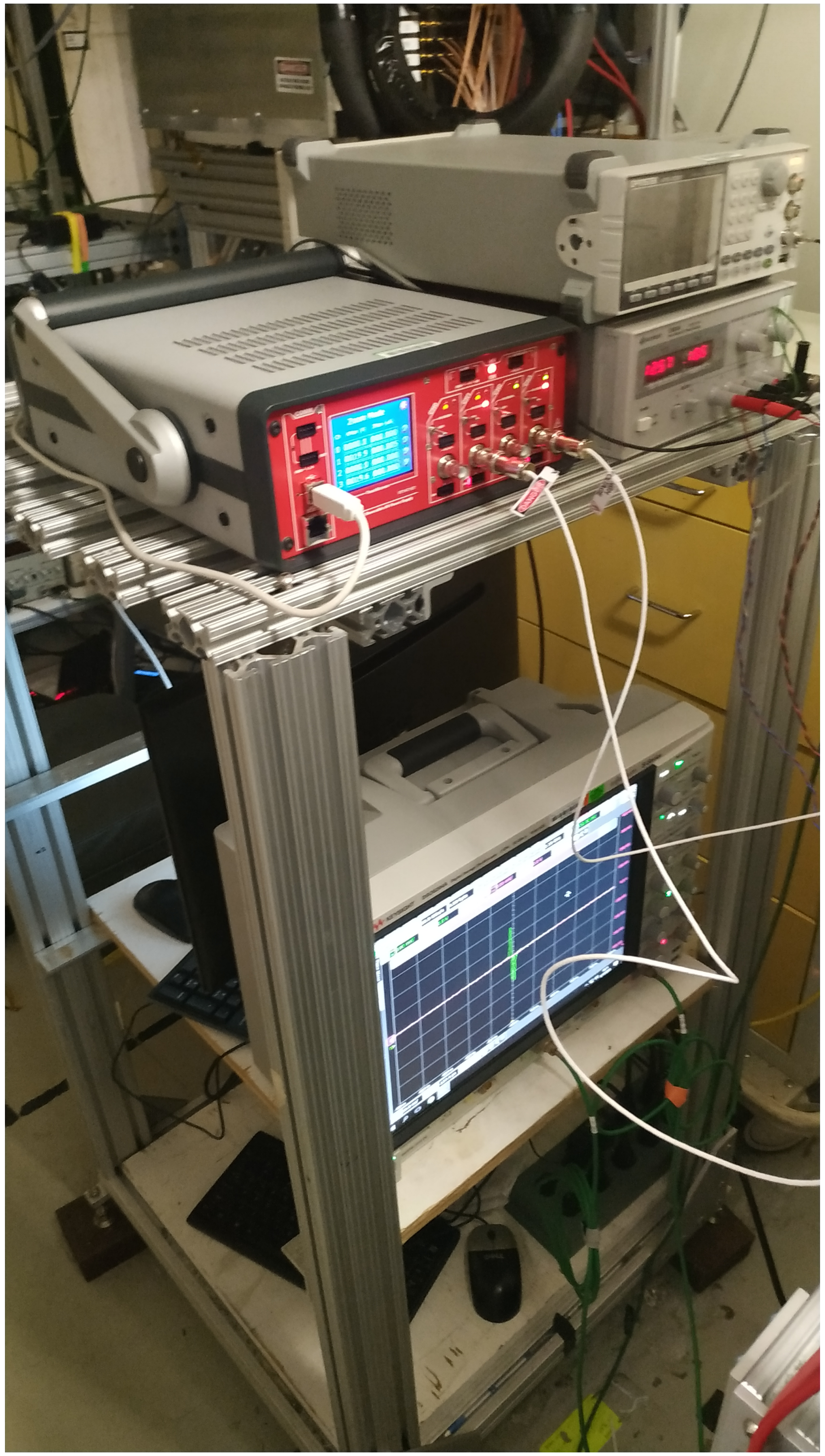


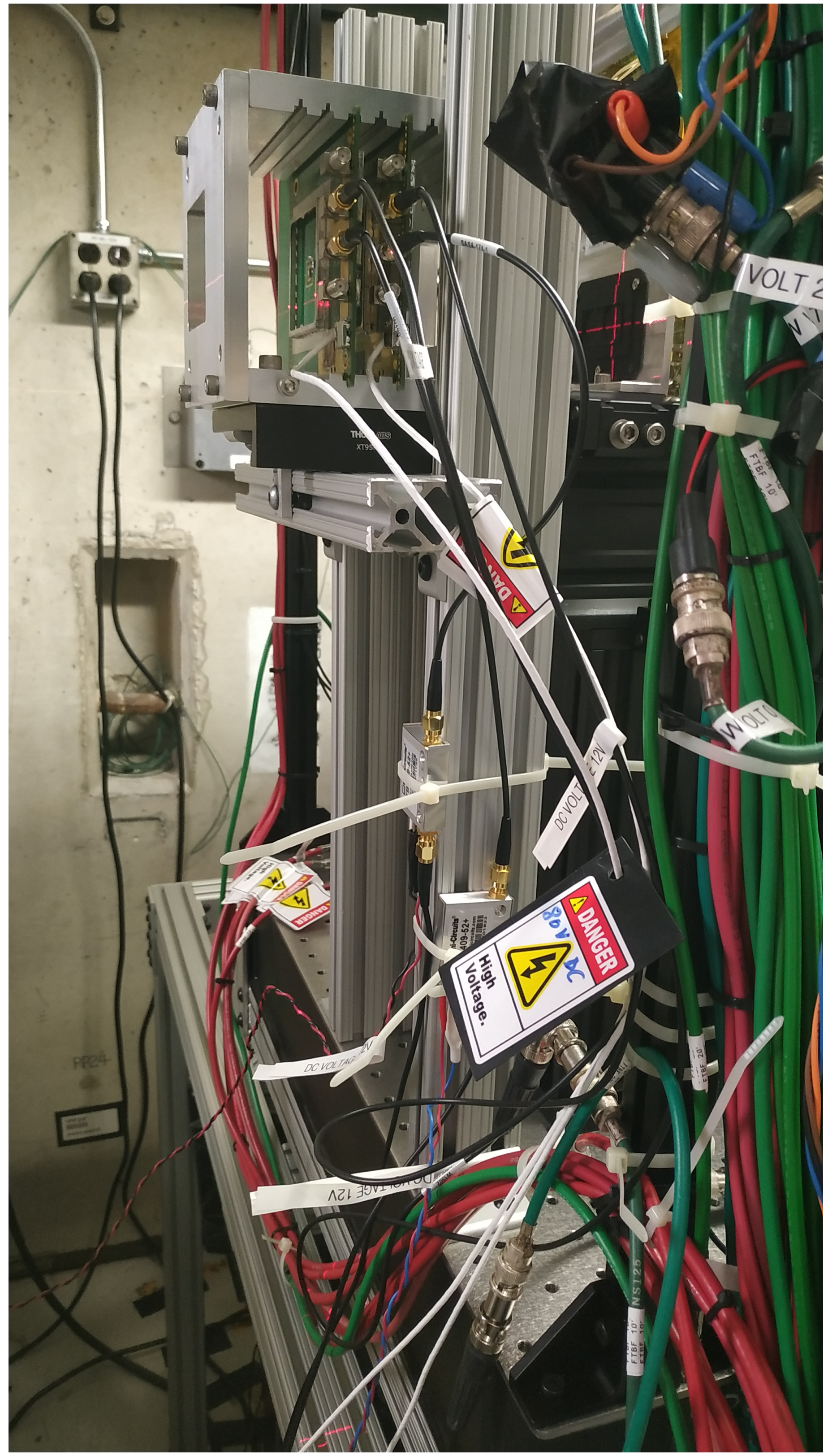


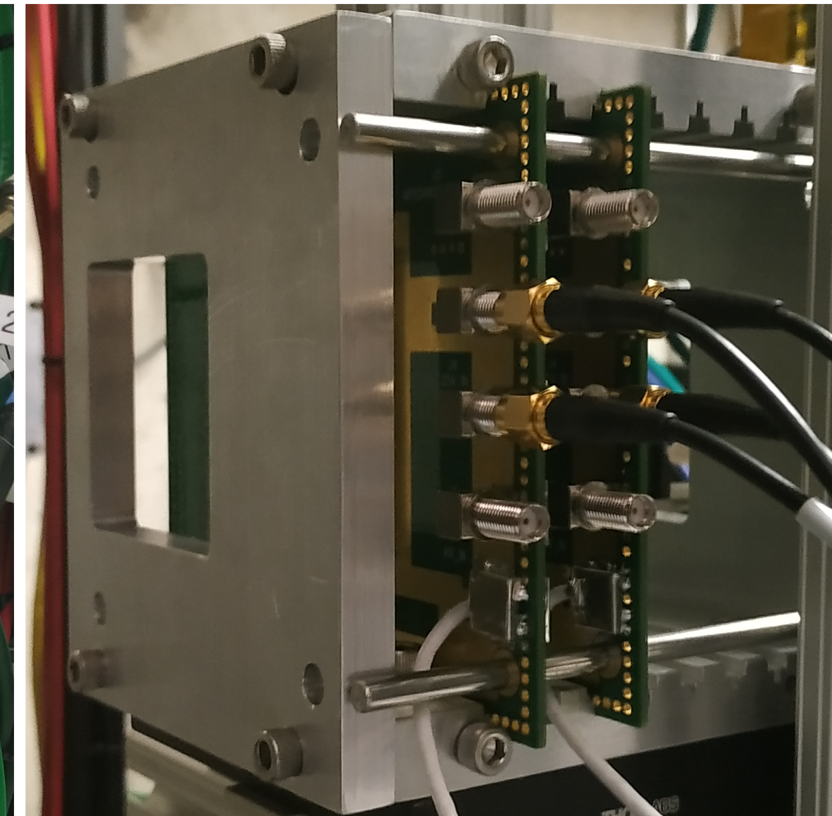
CFD$_{det}$[50]-CFD$_{trg}$[20]

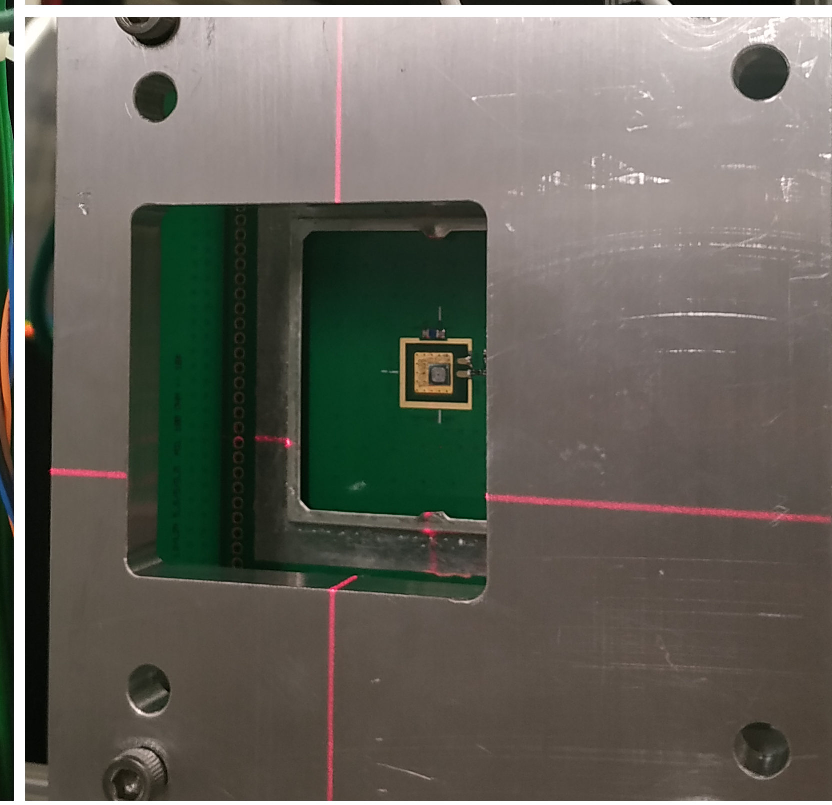


Fermi-Lab Beam Test Setup



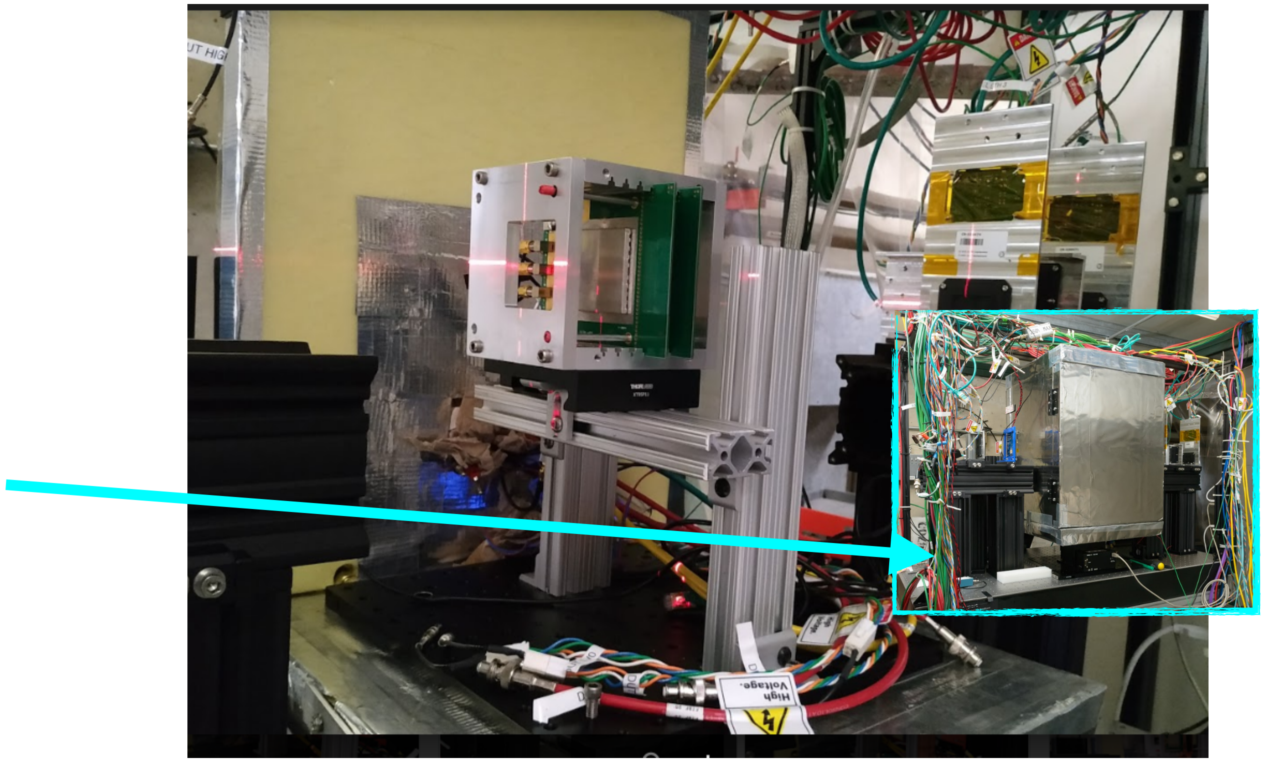


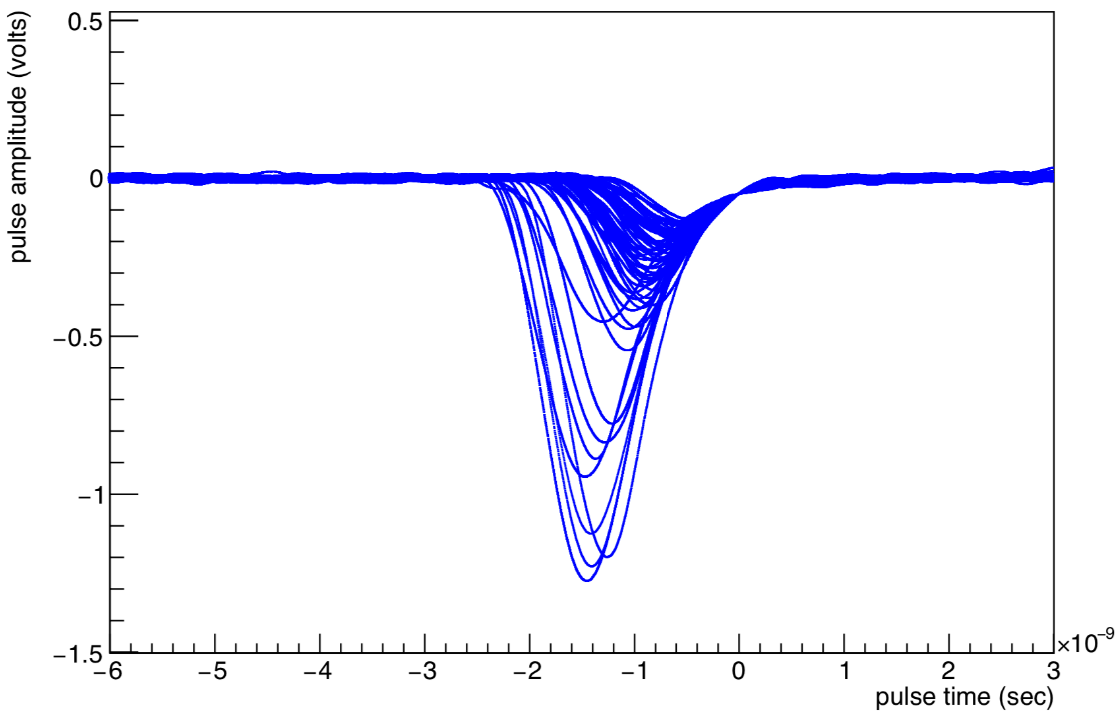


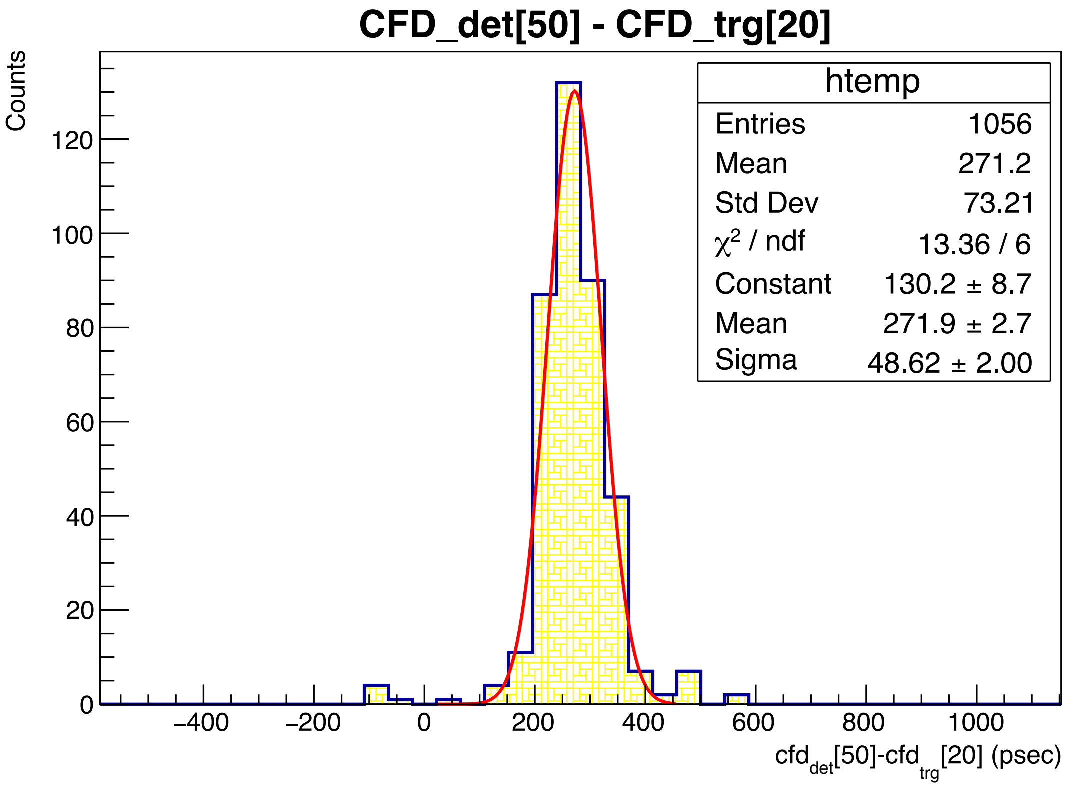


Measurements with Proton Beam

- Proton Beam, 120 GeV
- LGAD sensors separated by 1 cm
- data taken at different temperature
  - Room temperature to -10 °C (inside cold box)
- Example data shown for 50 μm HPK LGAD
  - Time resolution of 42 ps at room temperature
- More data to be analysed!



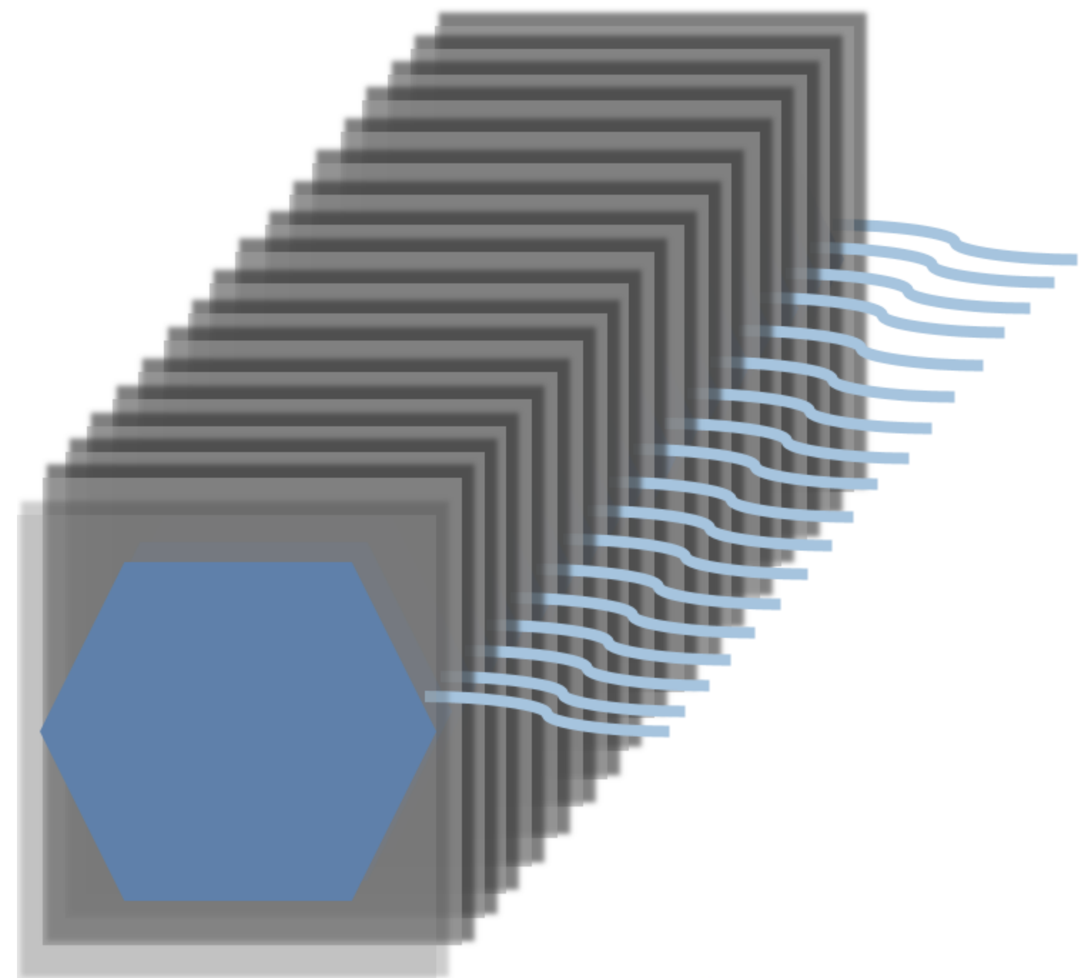




Validation of Concept - PENTACAL

5D Electromagnetic Calorimeter

- **Structure**
  - 20 active layers
  - Interleaved with Tungsten (smaller Moliere radius)
  - Copper sheets - efficient cooling
- **5D information**
  - Position (x,y,z), energy, and precision time
- **Active layers**
  - 8" wafers - total area 324 cm^2
  - 1 × 1 mm^2 pixels
  - Number of pixels per wafer - 32,400
  - Total number of readout channels - 650,000
- **Cooling estimate**
  - 500 mW/cm^2 -> 90 W/layer
  - 1800 W/Calorimeter; total power consumption
- **COMPASS++ (AMBER) at CERN is also interested in this technology**



Summary

- **TOPSiDE with precision timing**
  - Reconstruction and identification of all particles produced in collisions
  - Separation of π - K - p for particle identification
- **UFSD LGAD sensors as timing detector can play a major role**
- **LGAD sensor with integrated readout circuitry - PicoPix**
  - The sensor simulation is done
  - The readout design is complete
  - The first iteration is fabricated with PCB - CFD Board
- **LGAD sensors from HPK, BNL, FBK**
  - Characterisation for IV and CV measurements
  - Beta telescope testing
  - Test Beam at Fermi lab for temperature dependence
- **More data to be analysed!**
- **PENTACAL**
  - Validation of concept with 5D electromagnetic calorimeter prototype

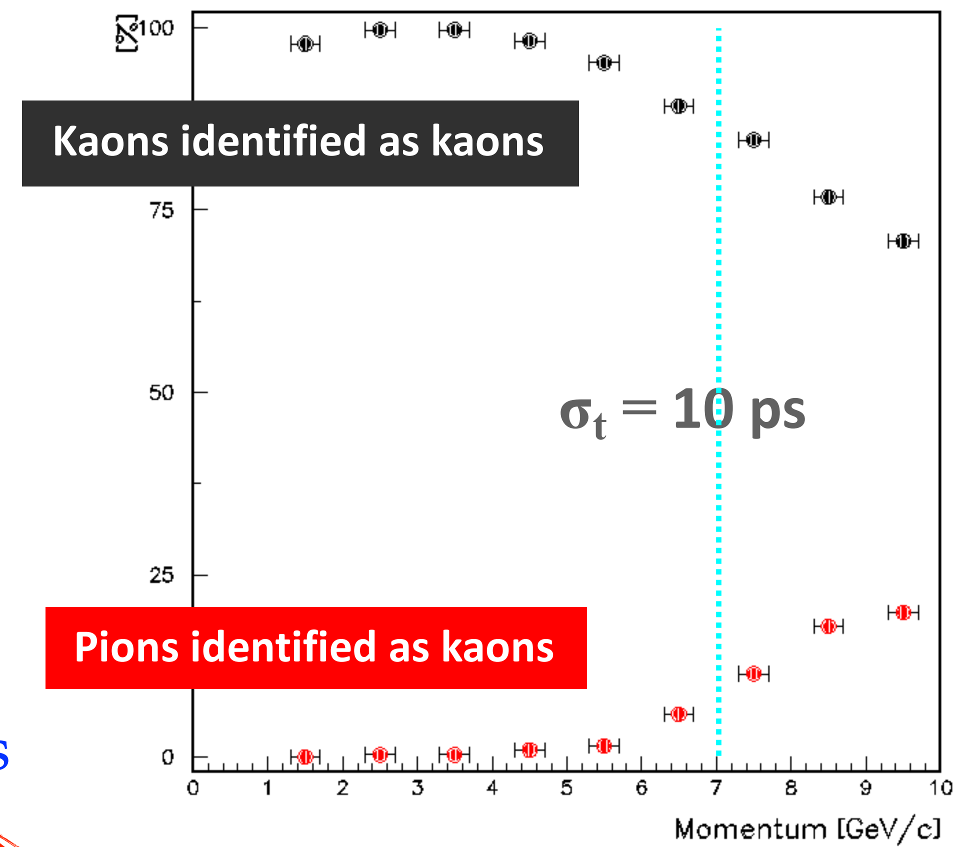
Thank you!

Back-Up

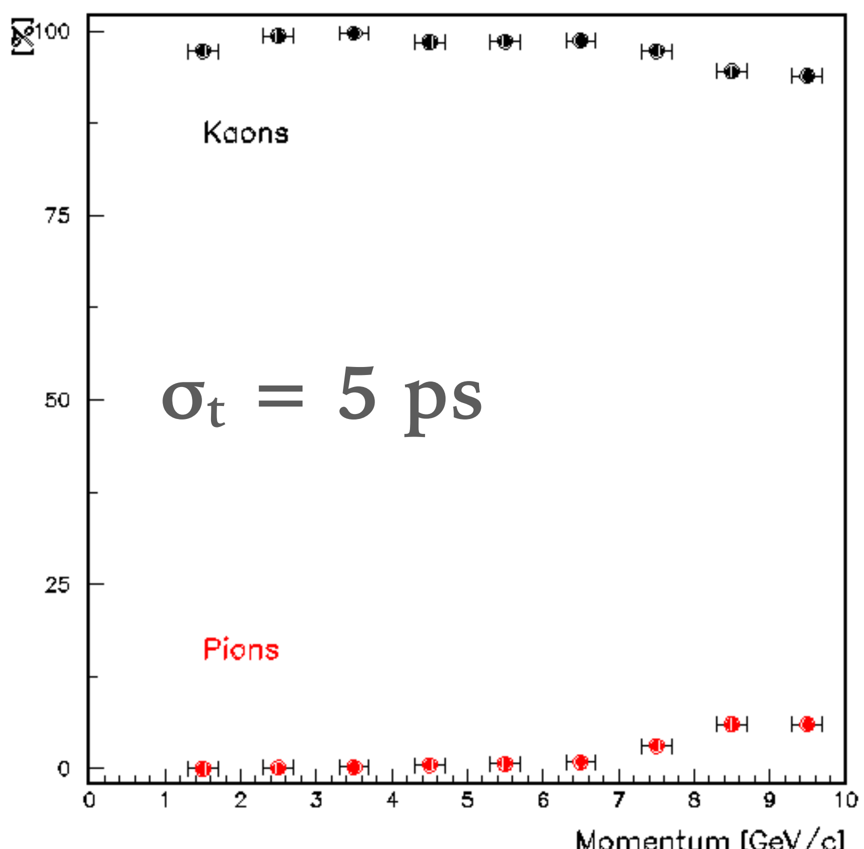
Motivation for TOPSiDE

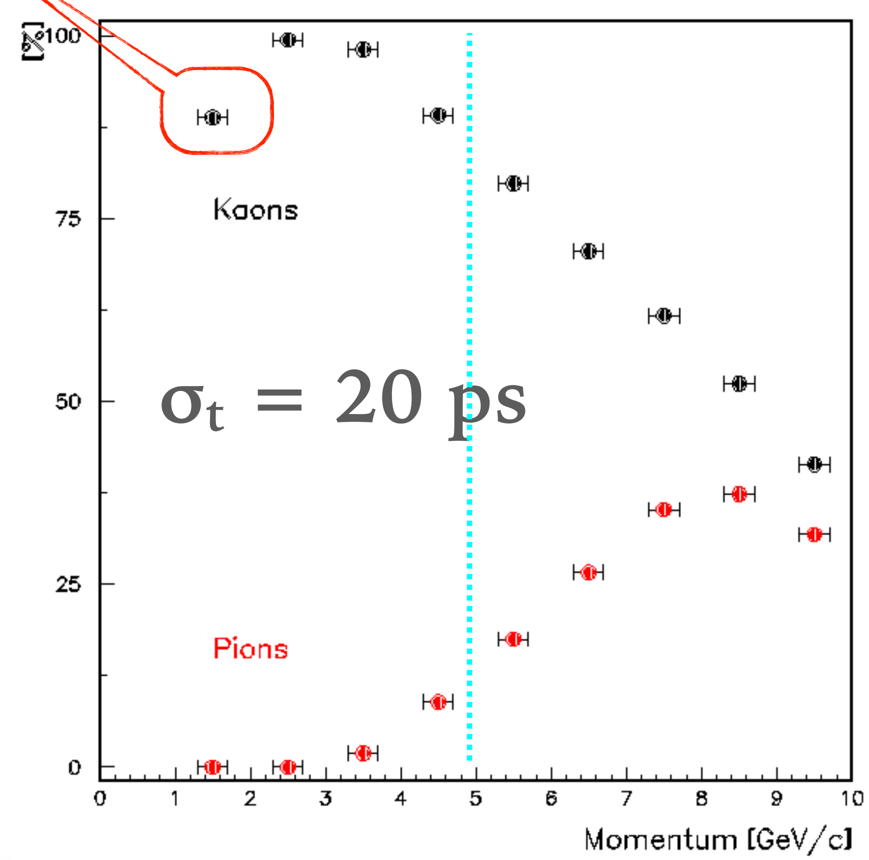
Particle Identification:

- Particle momenta < 7 GeV/*c*
  - most of the solid angle
- Separation of pion-kaon-proton
  - Silicon sensor with time resolution of ~ 10 ps
  - Good separation up to 7 GeV/*c*

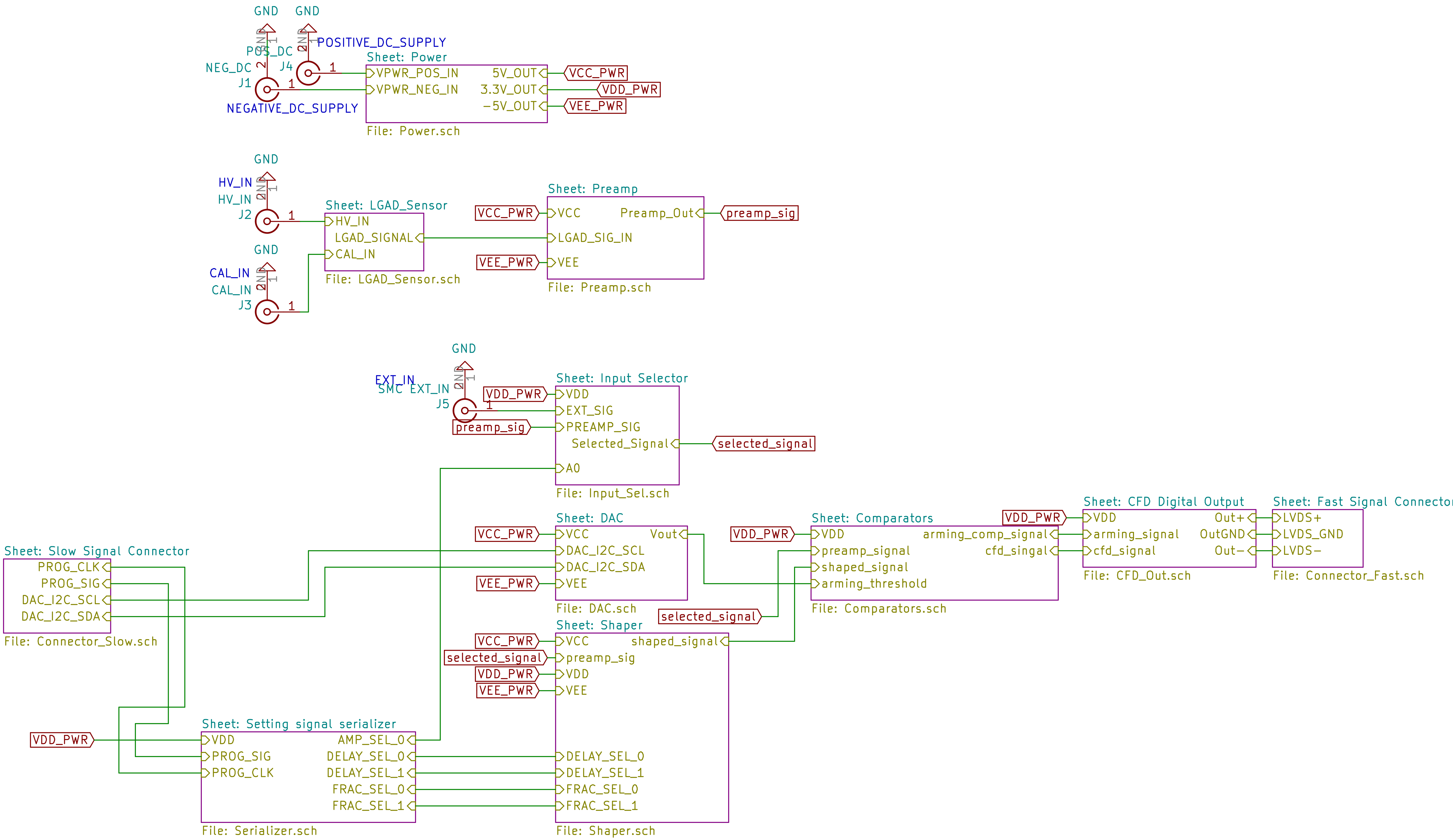


Not optimized with selection cuts

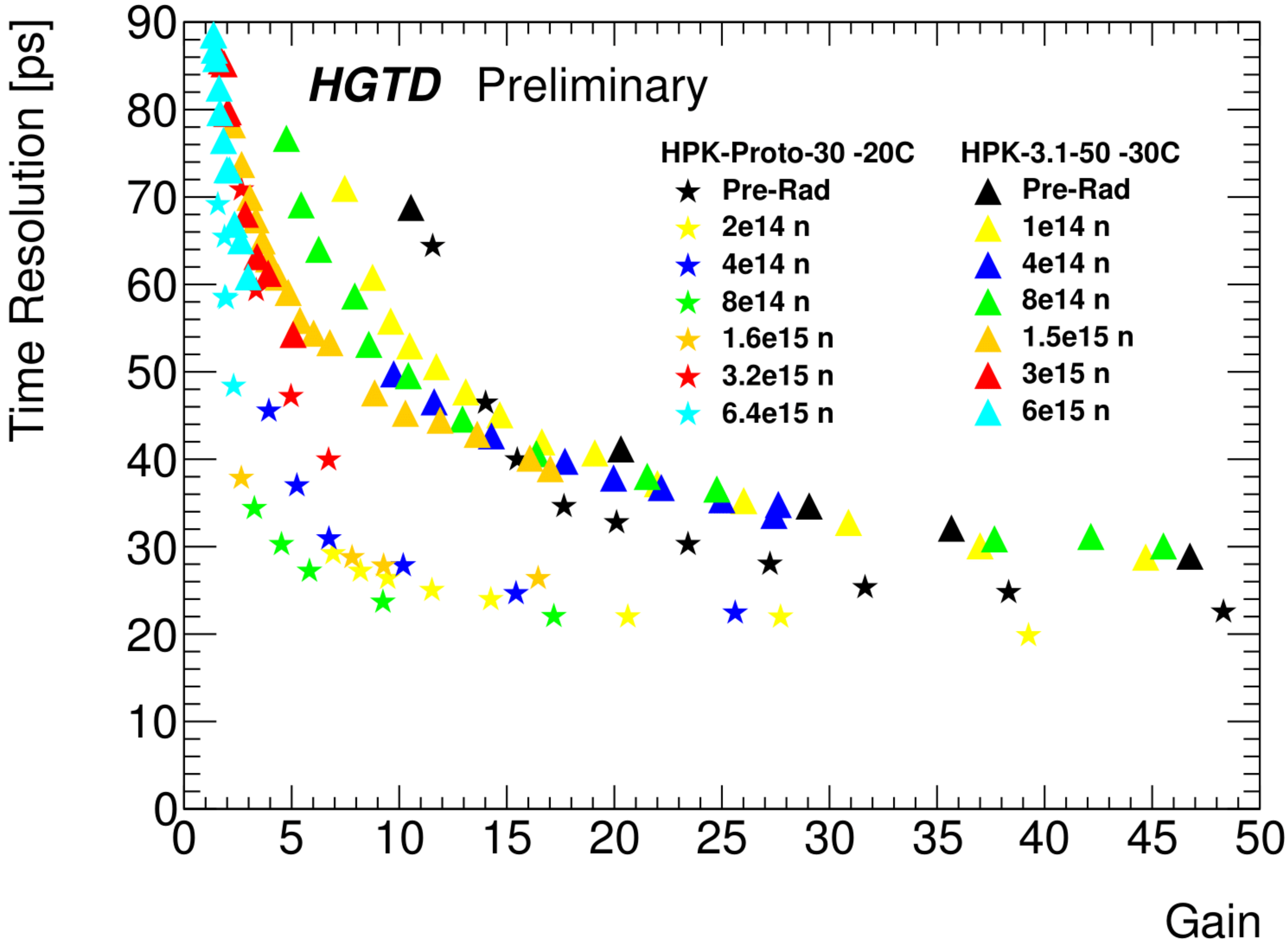




CFD Circuit Design



ATLAS R&D for UFSD-LGADs



Measurements with Beta-telescope

- **Measurements for LGAD sensors**
  - HPK, BNL, and FBK for different bias voltages
- **A fast HPK LGAD trigger ~ 16.5 ps**
  - Coincidence for event selection
- **Example data shown for 2 sensors; HPK and BNL**
  - At room temperature and -30 °C