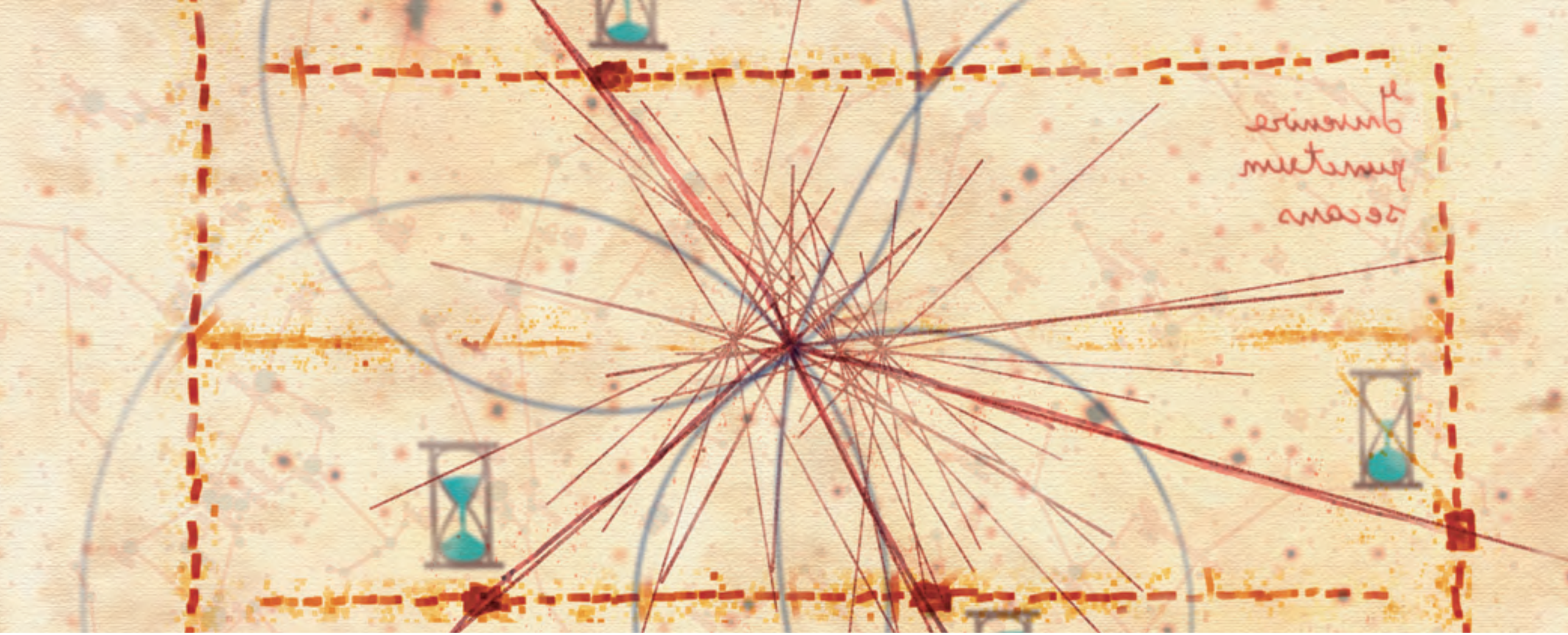


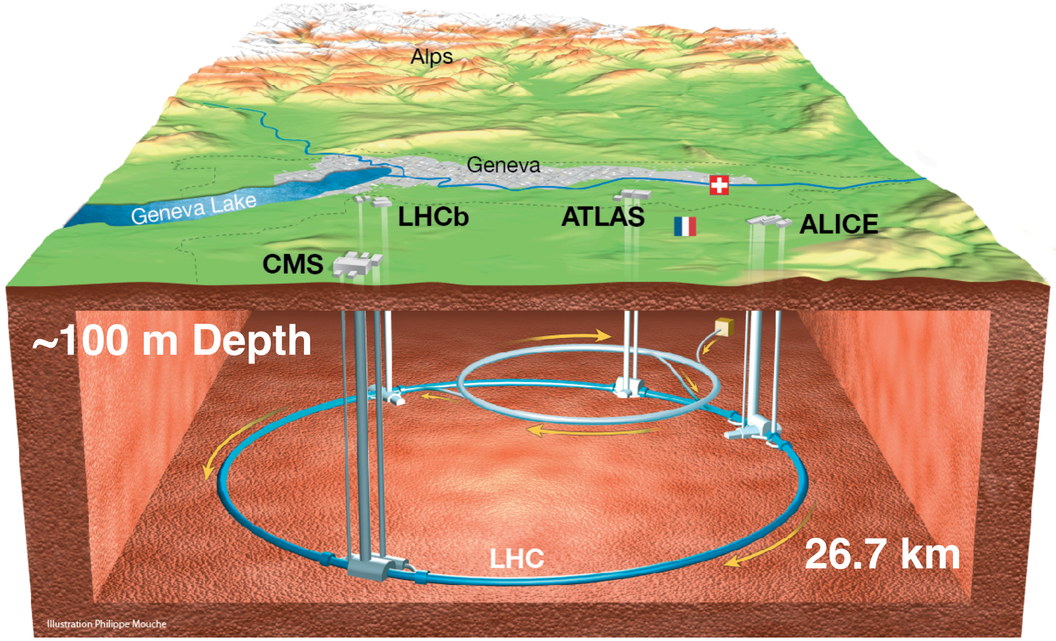
Experience with LGAD sensor development for CMS ETL

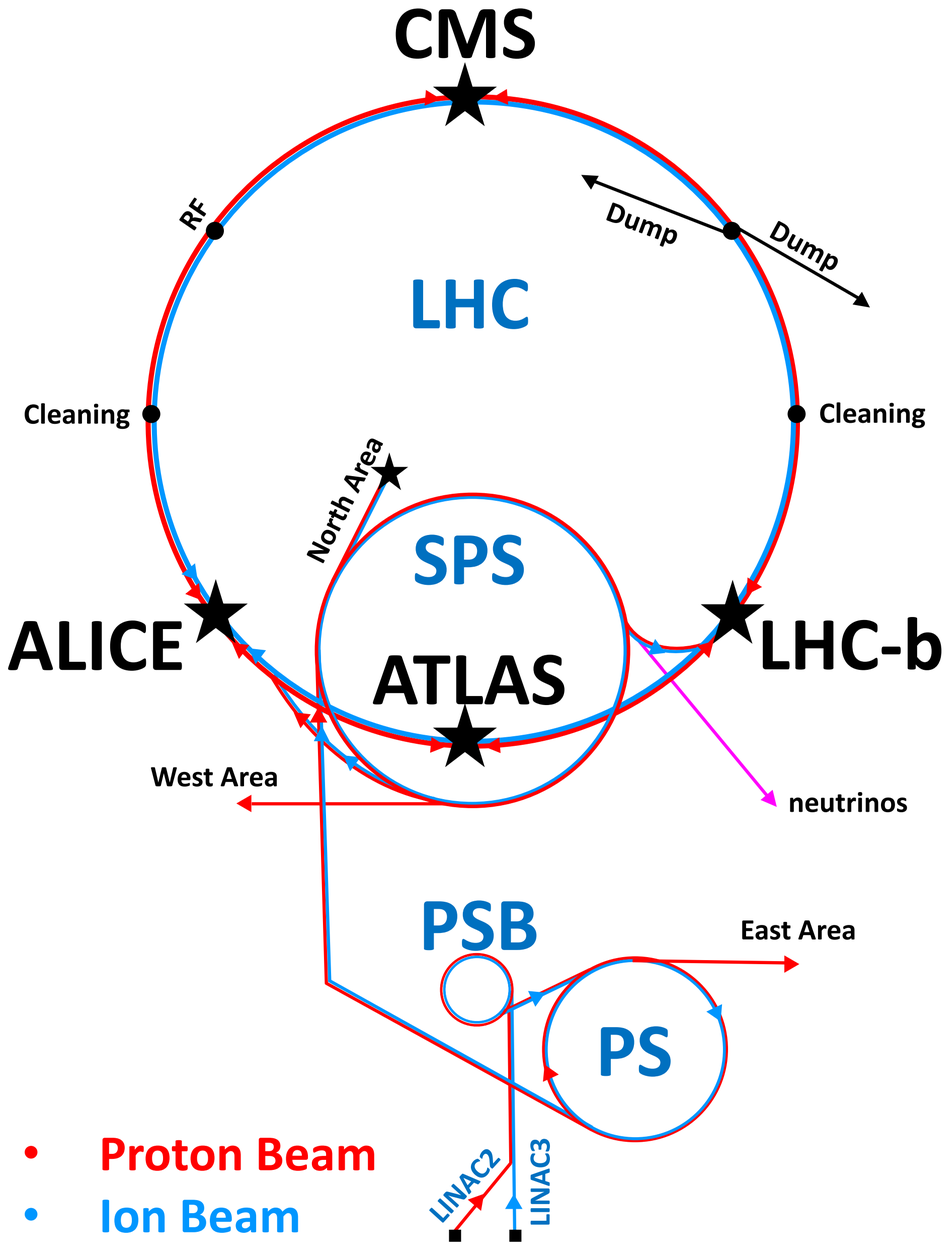
Christopher Madrid

ePIC Collaboration Meeting at Argonne National Laboratory

January 9, 2024

The Large Hadron Collider

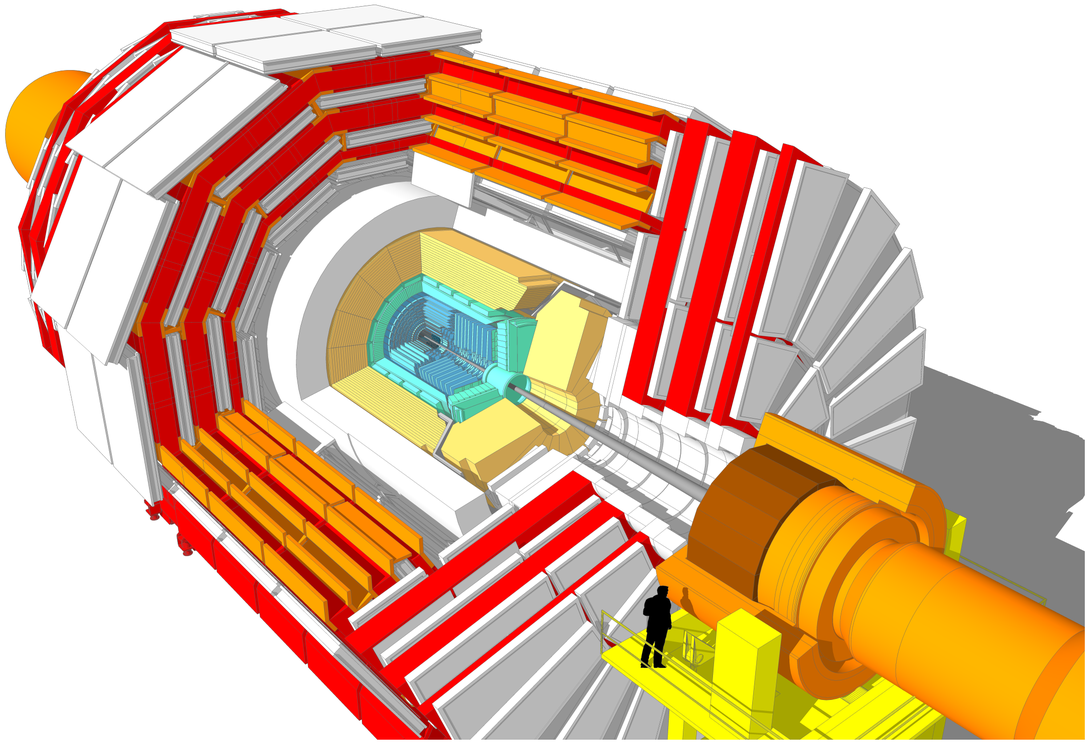


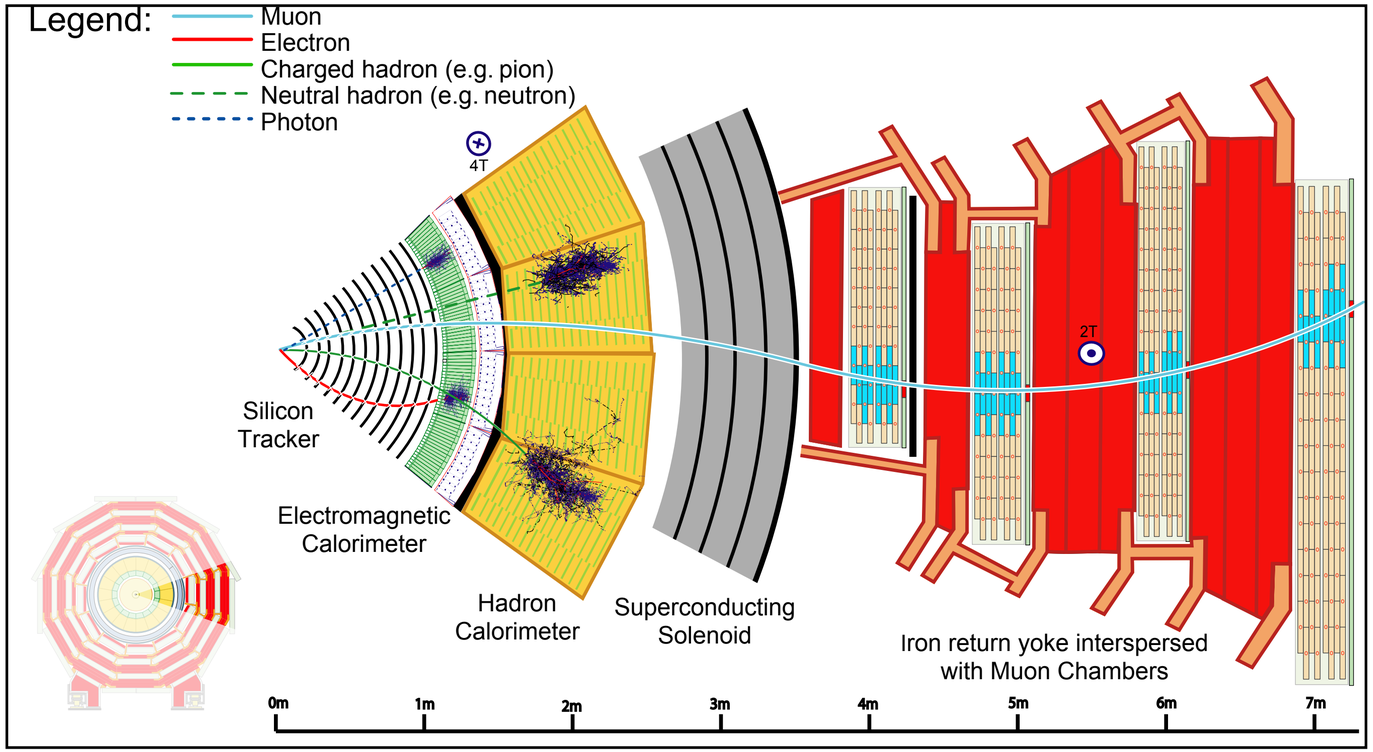


- Located on the border of France and Switzerland near Geneva
  - Hosted by European Organization for Nuclear Research (CERN)
- Currently accelerates protons to 6.8 TeV
  - Collides ~10^{11} protons per bunch every 25 ns
- Collisions occur at 4 points (detectors) along the LHC
  - **Today we will focus on the Compact Muon Solenoid (CMS)**

Fermilab

The Compact Muon Solenoid (CMS)

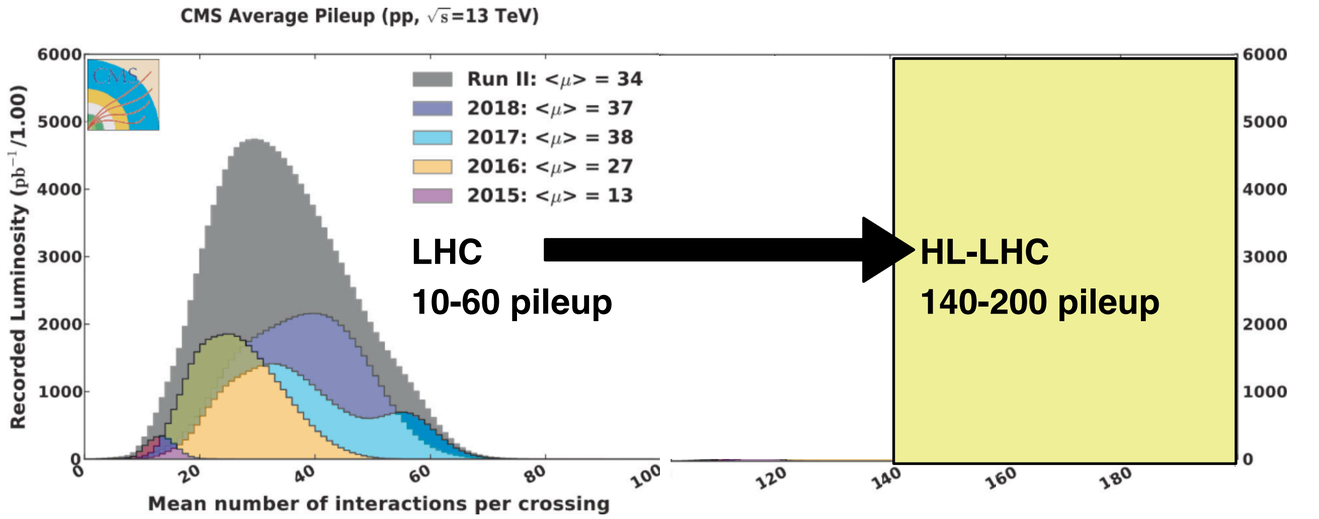


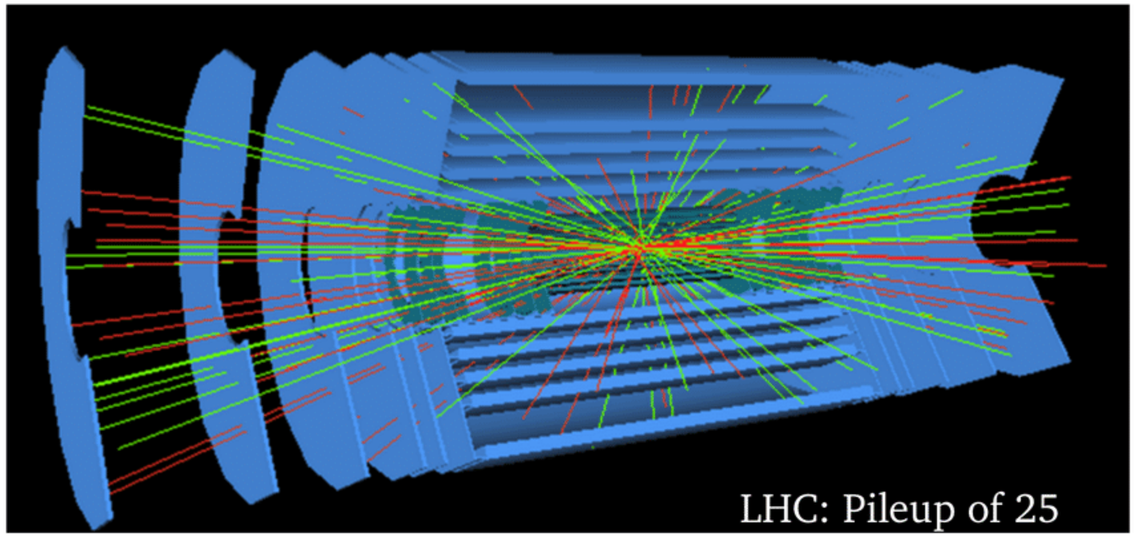


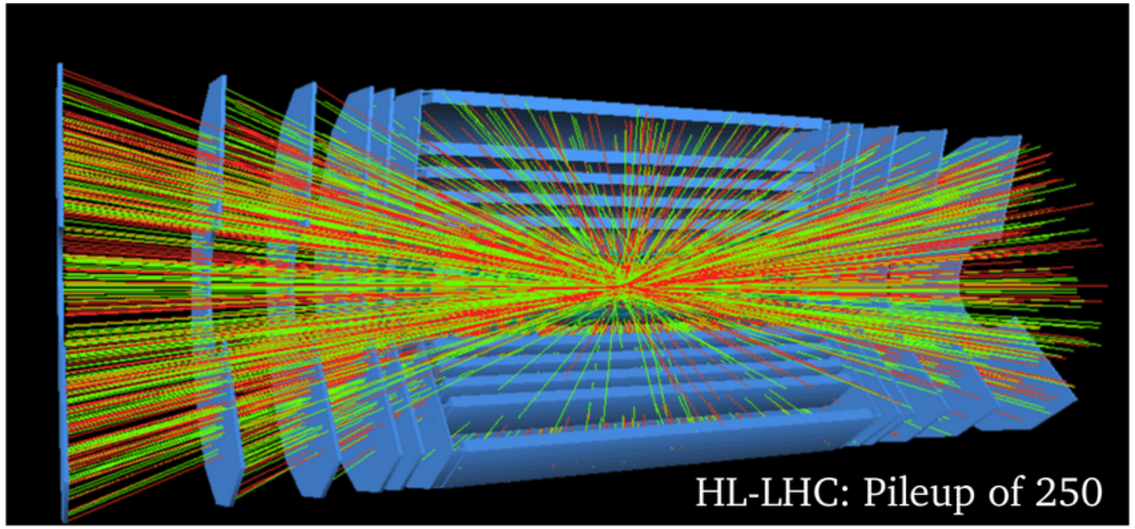
- We measure many particles of varying energies, flavors, charges, and types
- CMS is a general purpose detector and optimized to measure a wide range of particles
- **Actively preparing a massive upgrade for the High Luminosity-LHC era**

The HL-LHC challenge

- HL-LHC will deliver 3-4 times more instantaneous luminosity
  - **Causing enhanced pileup**
- Aiming to have 10x more data by 2040
- **CMS has to be upgraded**



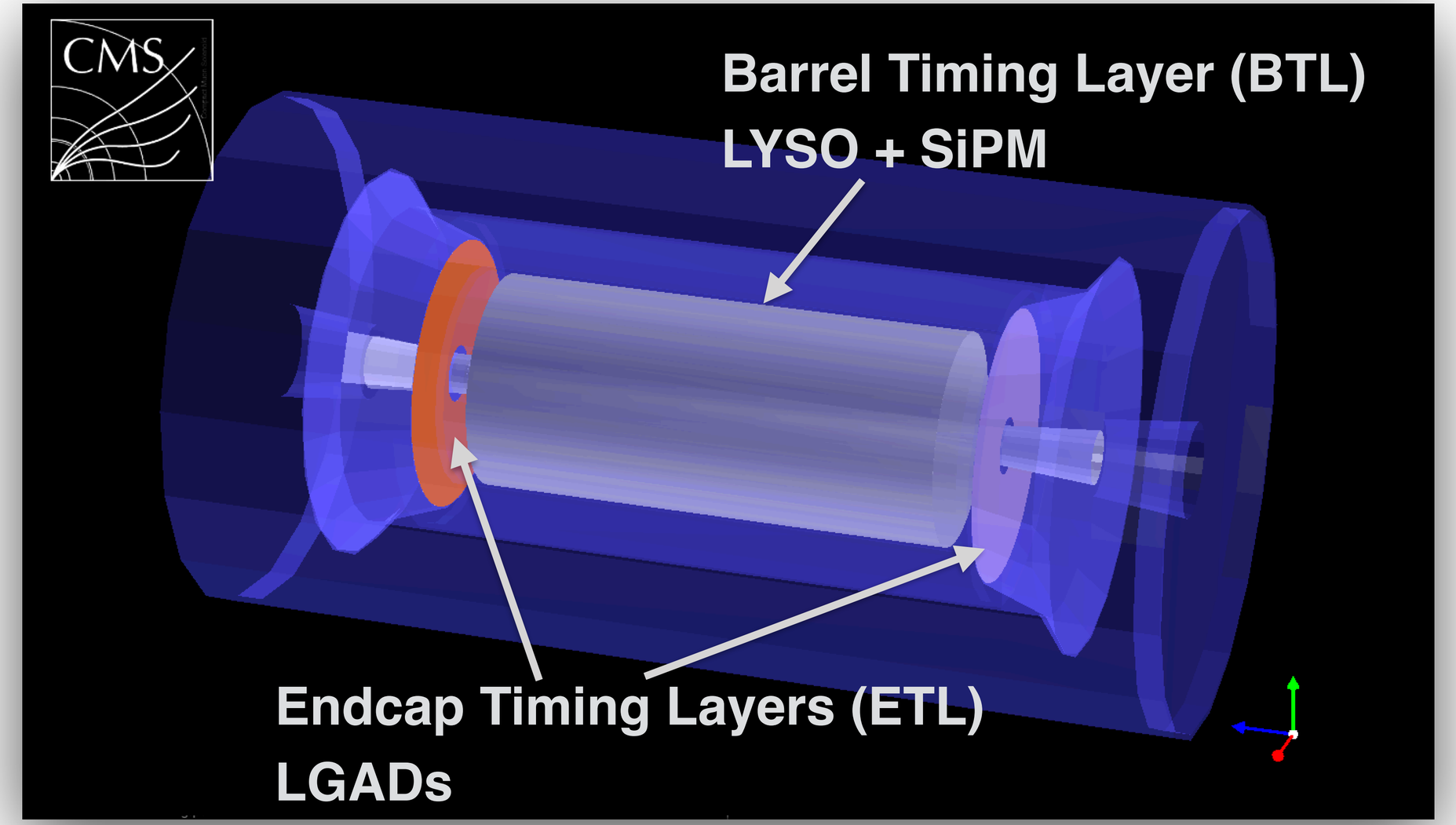




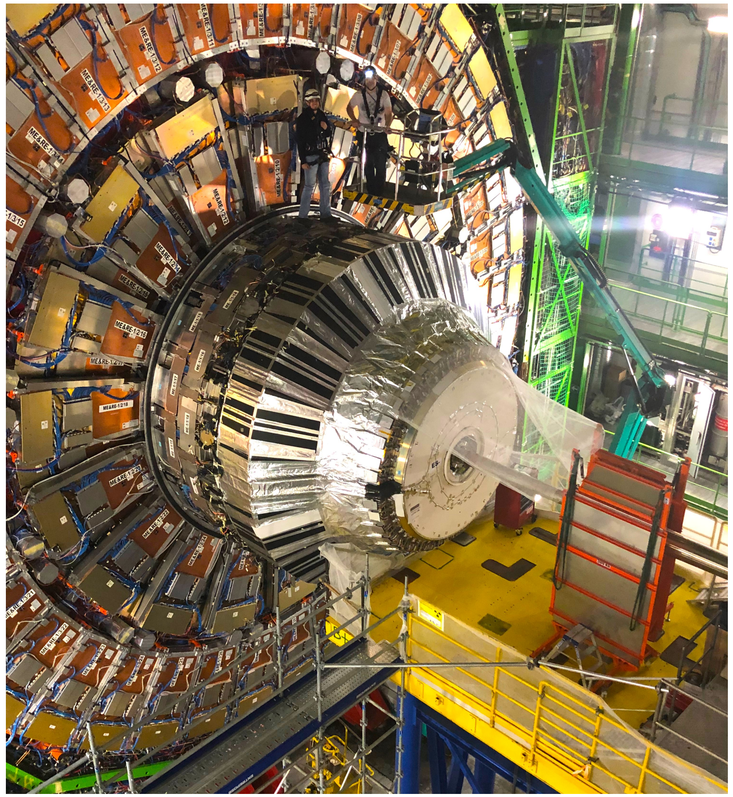
From ATLAS

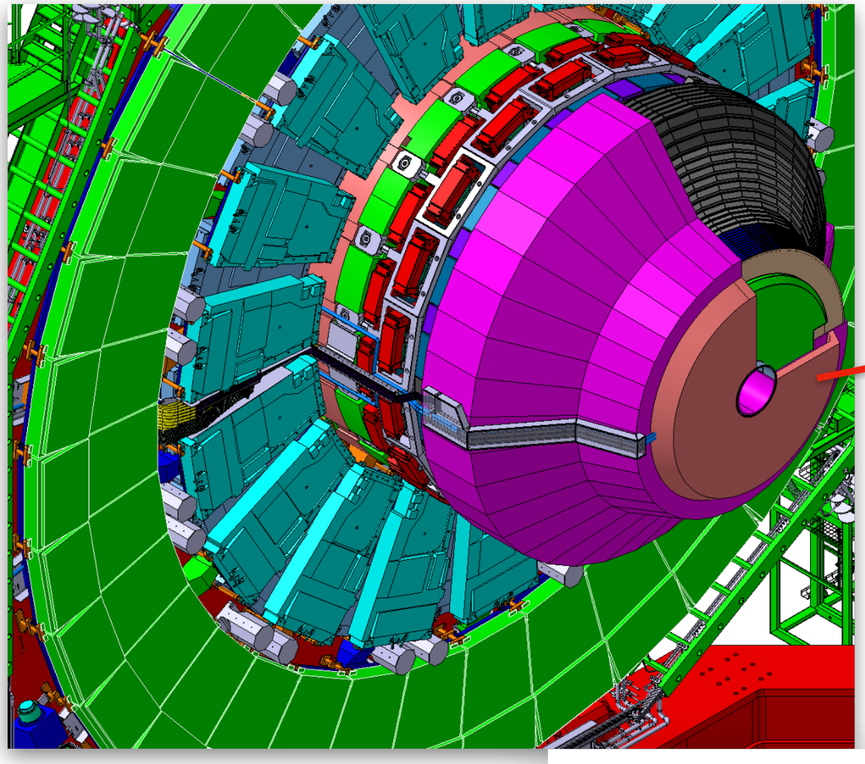
Fermilab

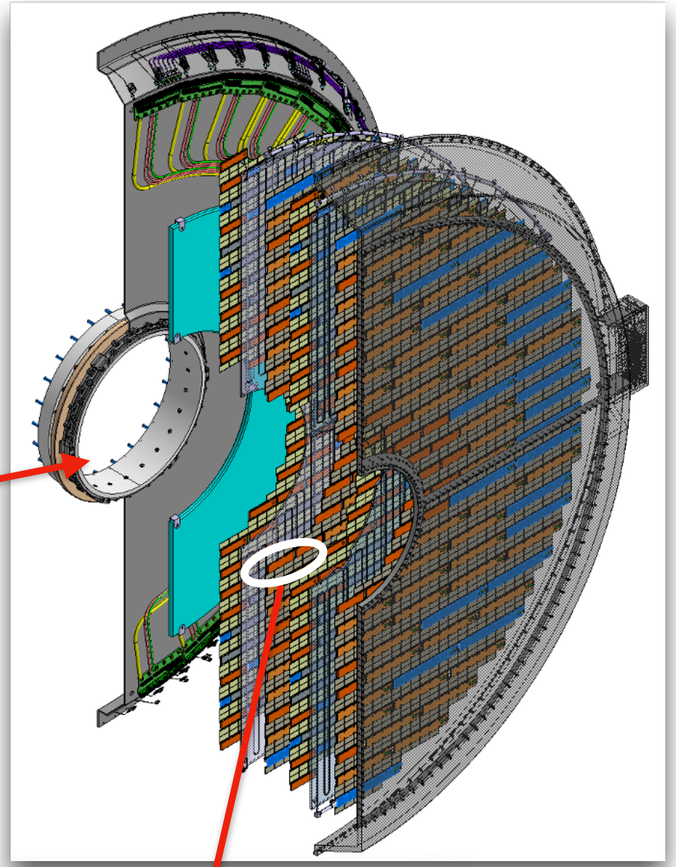
The Mip Timing Detector

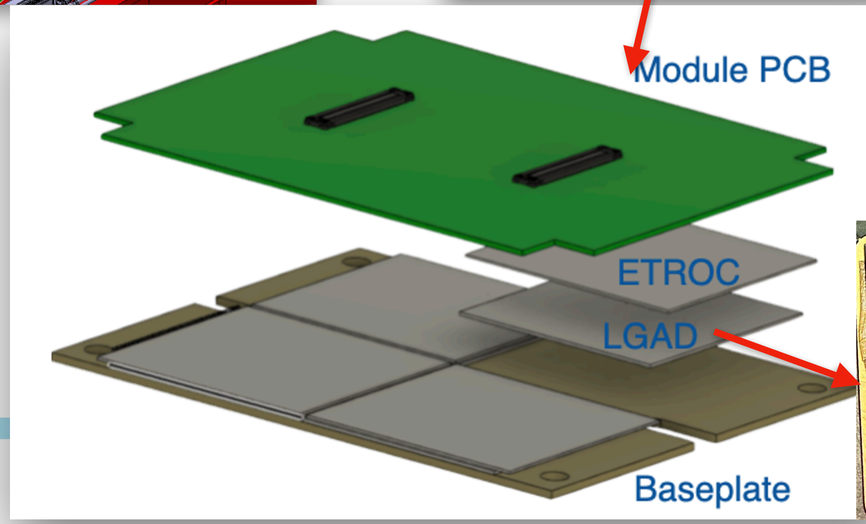


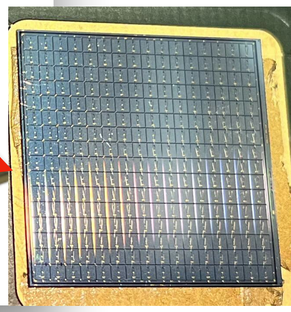
The MTD Endcap Timing Layer







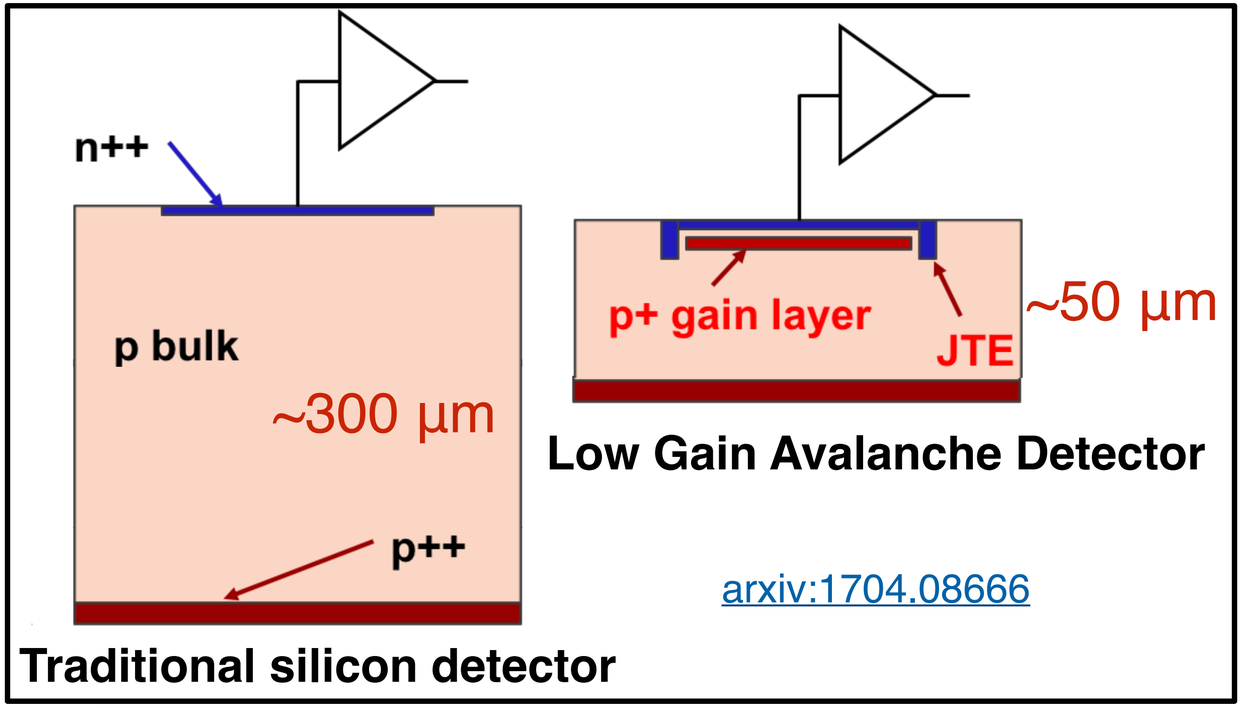


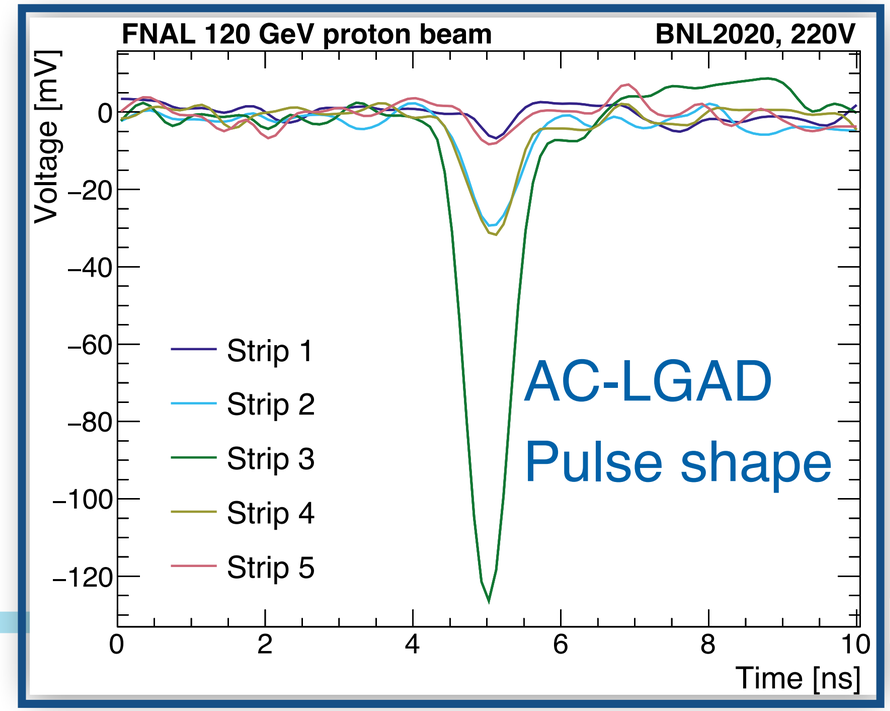


- 2 disks at each endcap: 2 hits per track
- **Single-hit resolution < 50 ps → track resolution < 35 ps**
- Will need ~8000 modules covering ~14 m²
  - **Novel Low Gain Avalanche Diodes (LGAD) sensor**
  - Novel ASIC readout chip (ETROC)

Low Gain Avalanche Detectors

- High occupancy & radiation
  → Highly granular silicon detector
- LGADs: novel ultra-fast silicon detectors
  - Moderate internal gain (10-30)
  - Thin (50 micron depletion region)
- ETL: $(1.3\ mm)^2$ pads, 16x16 channels $(2.1\ cm)^2$ sensors





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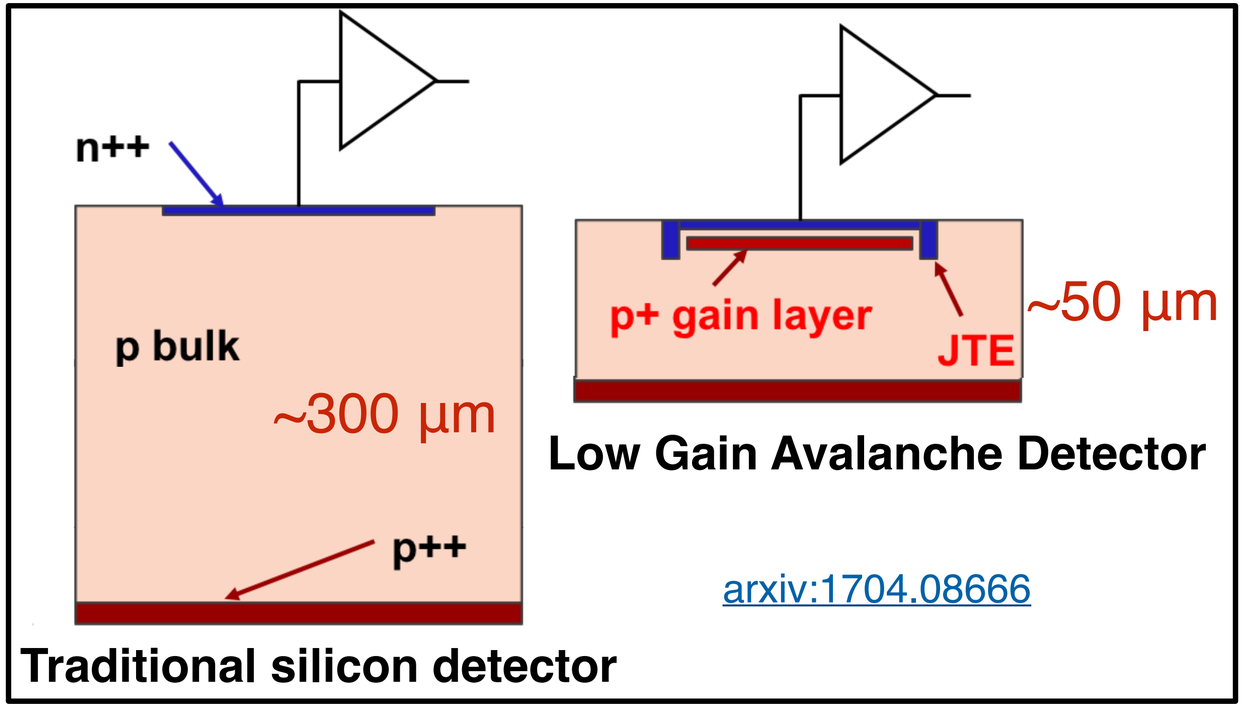

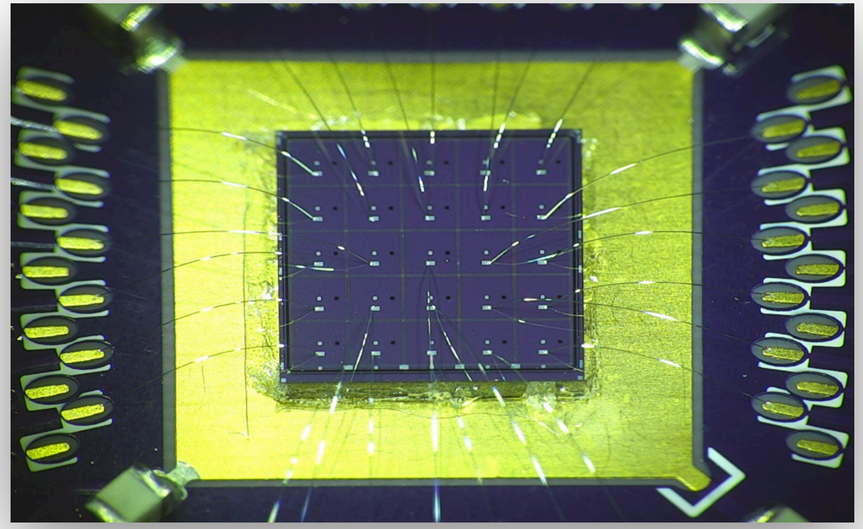

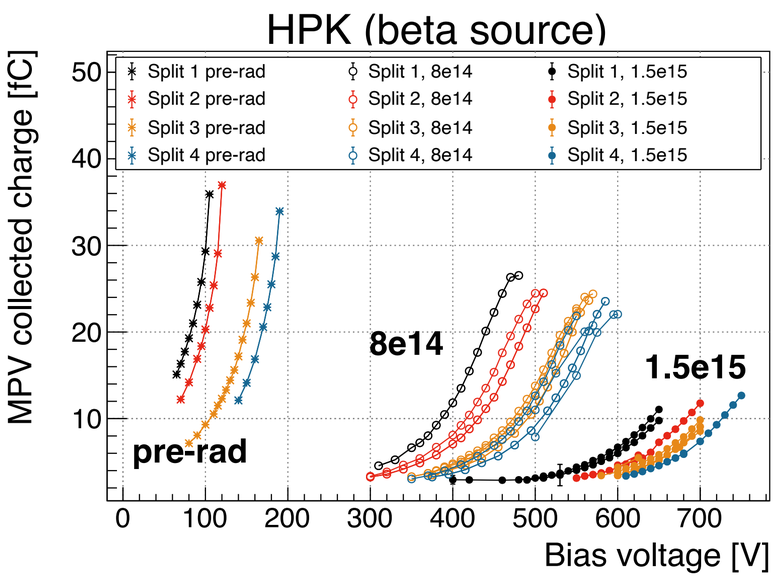

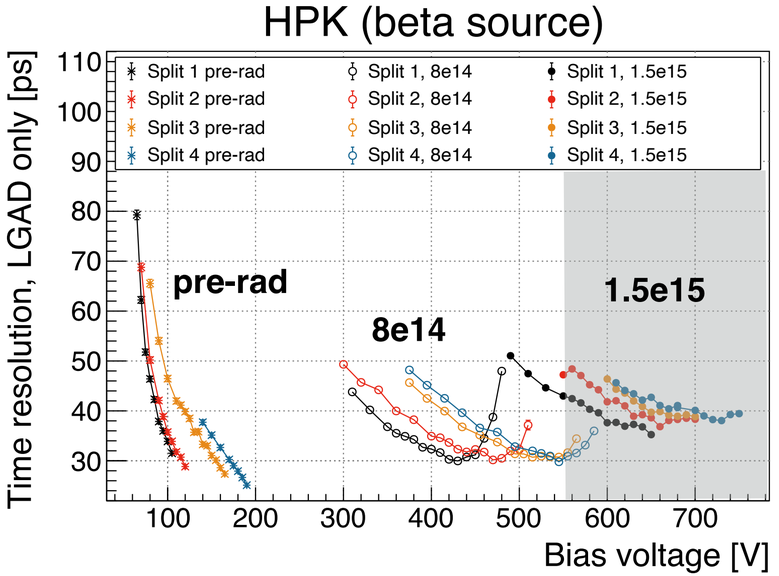

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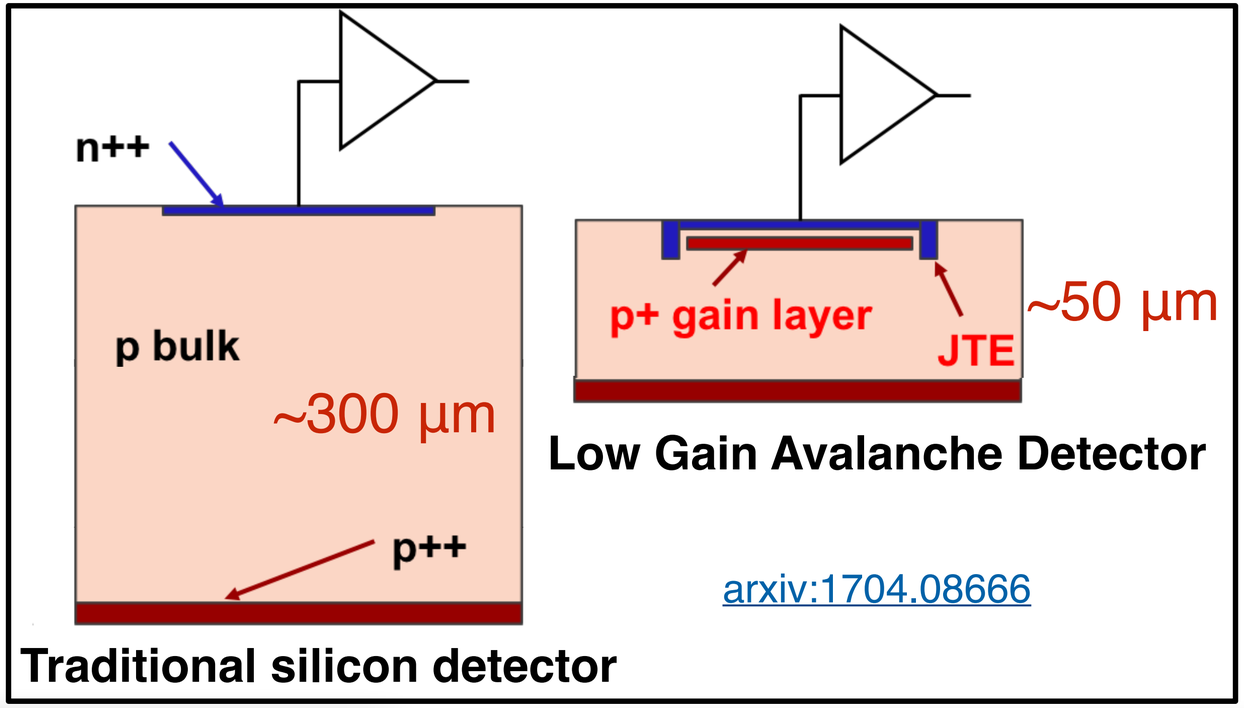
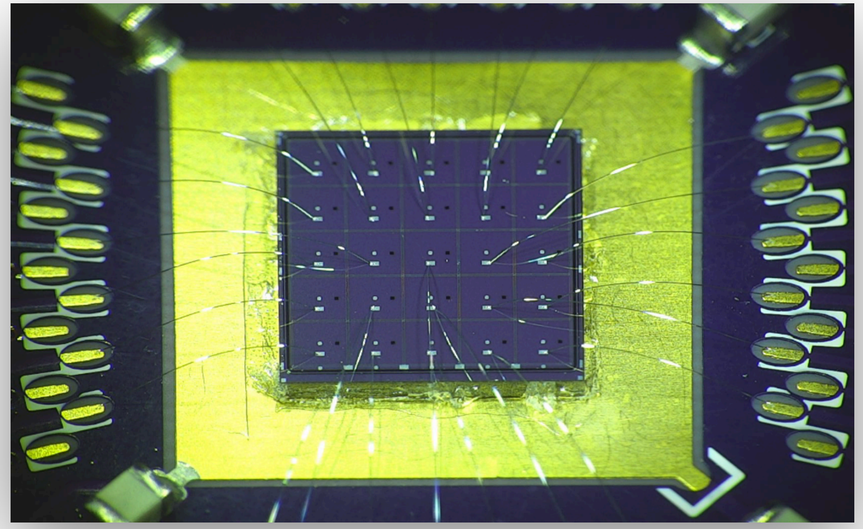
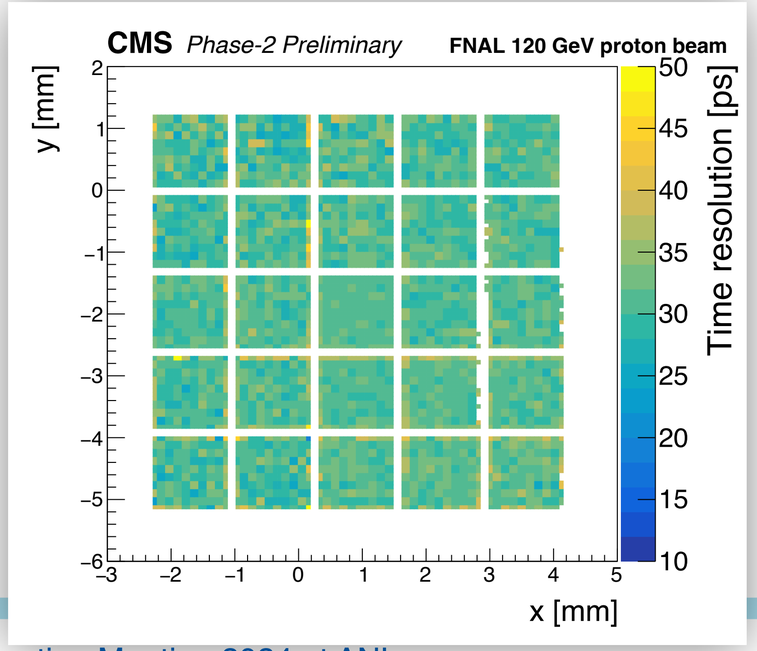
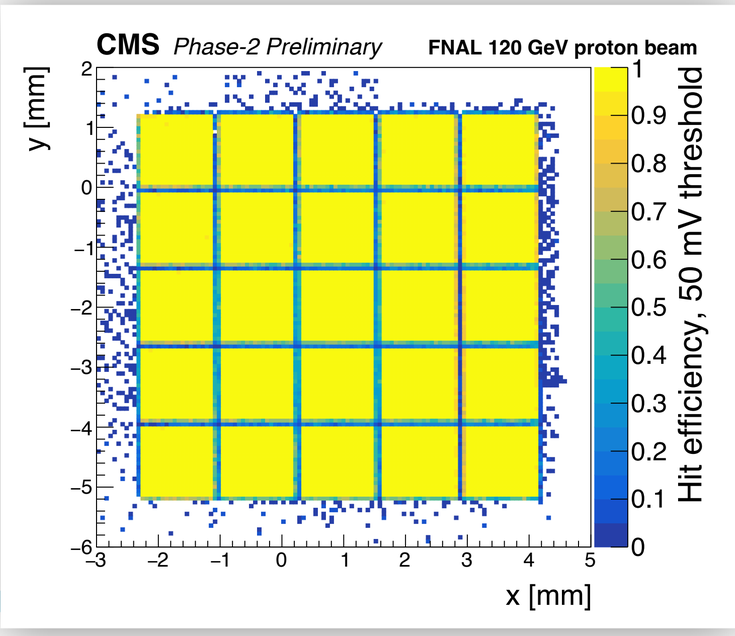


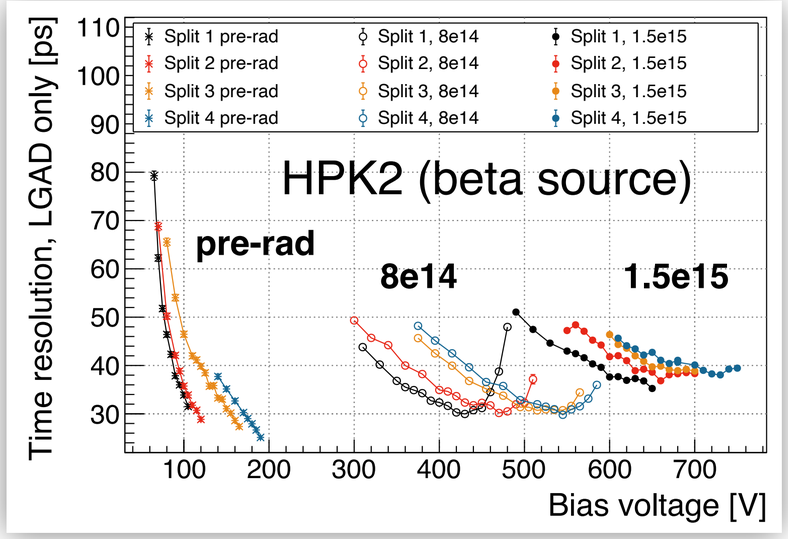


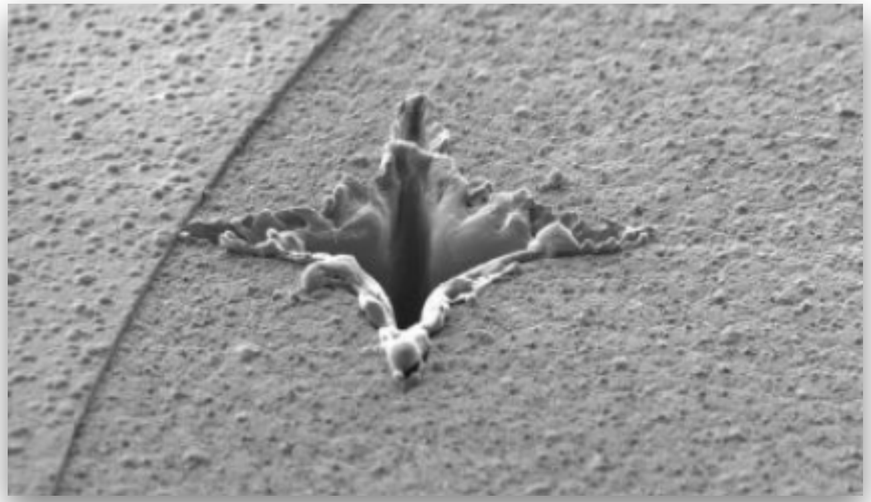


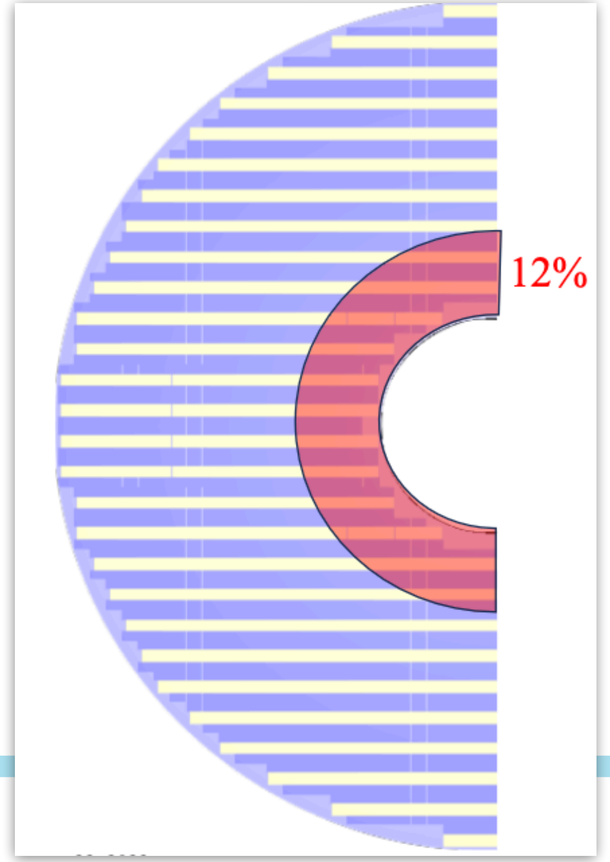


Impact of radiation

- Expect some areas of the detector get a dose up to $3x10^{15}$ n_{eq}/cm^2
- Throughout the lifetime of ETL we will need to increase the bias voltage to compensate and maintain nominal time resolution
  - Can we just keep doing this?
    - **No, the sensors will die**
- We started to call these deaths “Single Event Burnouts” (SEB)
  - **Left behind a hole in the sensor**







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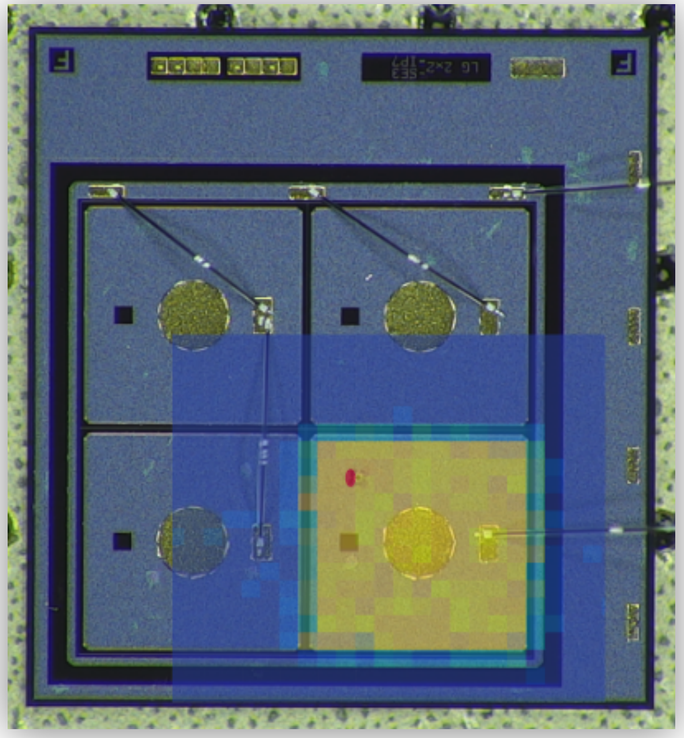
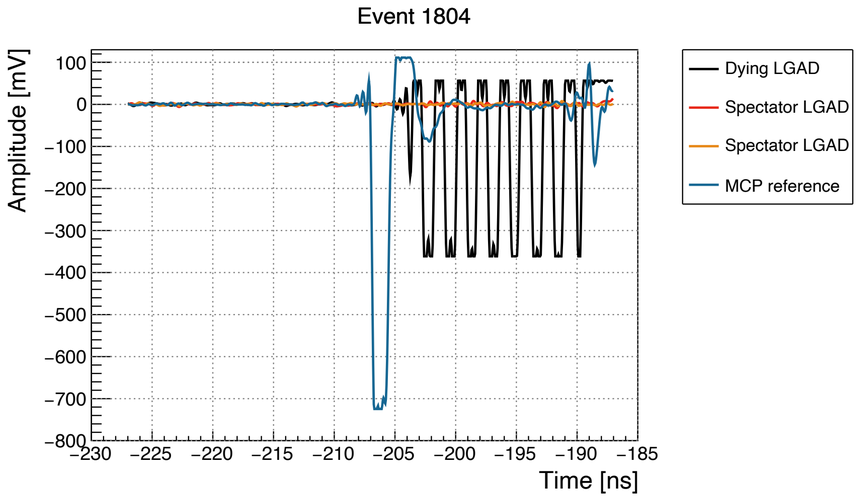
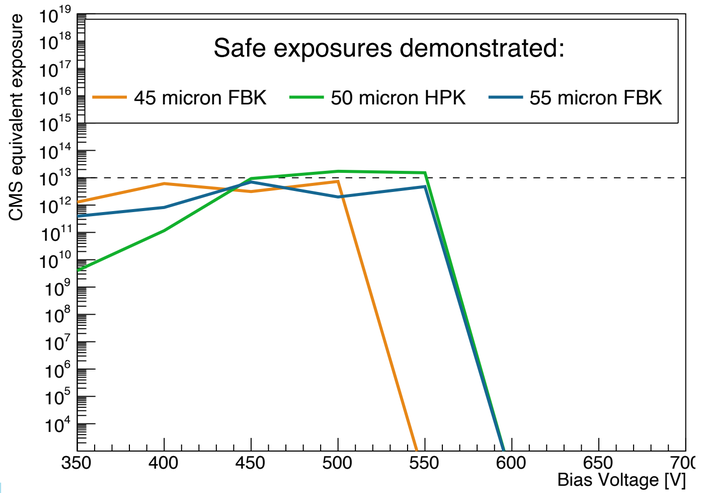
LGAD Single Event Burnouts

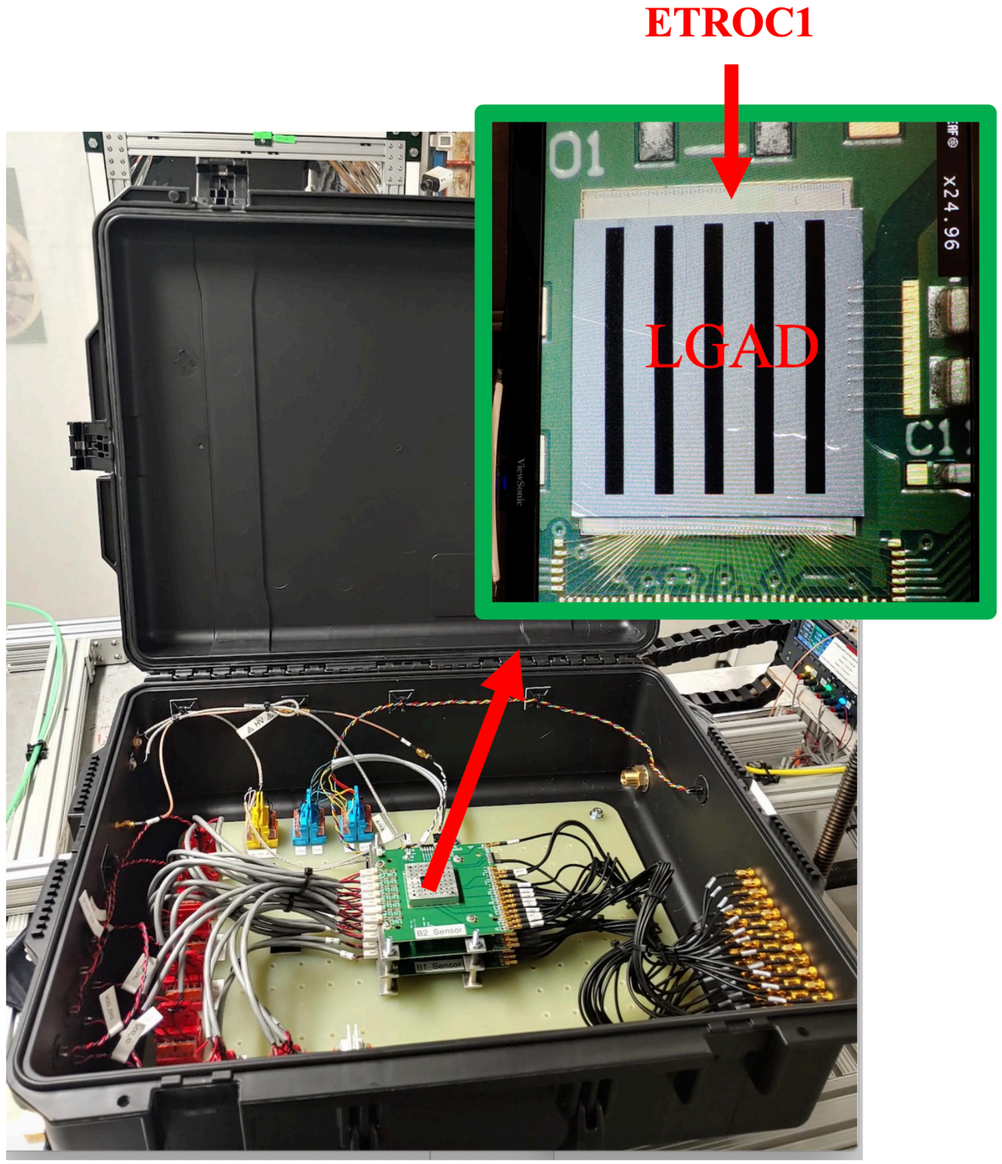
- When operated at high fields ~11.5 V/μm LGADs are susceptible to single event burnout (SEBs)
  - Active area of study
  - Low rate results (38th RD50)
  - High rate results (TREDI 2022)
  - ATLAS results (TREDI 2023)
- Death tends to leave “cross” shape crater where charge particle track points
  - Not always found (different levels of severity?)
- Death has interesting ringing waveforms
- **For 20 μm thick sensor expect death at ~230 V**



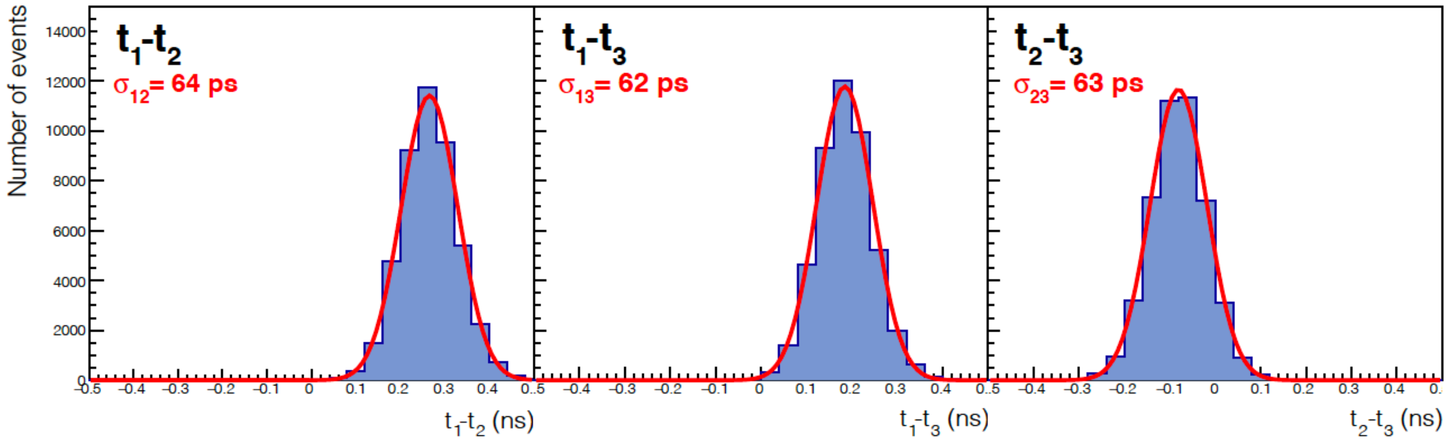




LGAD Readout Electronics: ETROC



- Timing measurement performed by ETROC ASIC (ToA + ToT correction)
- Test beam results with LGAD and ETROC1 prototype: **σ = 42-46 ps**



Extract single-layer resolution from 3-layer ΔT:

$$\sigma_i = \sqrt{0.5 \cdot \left(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2\right)}$$

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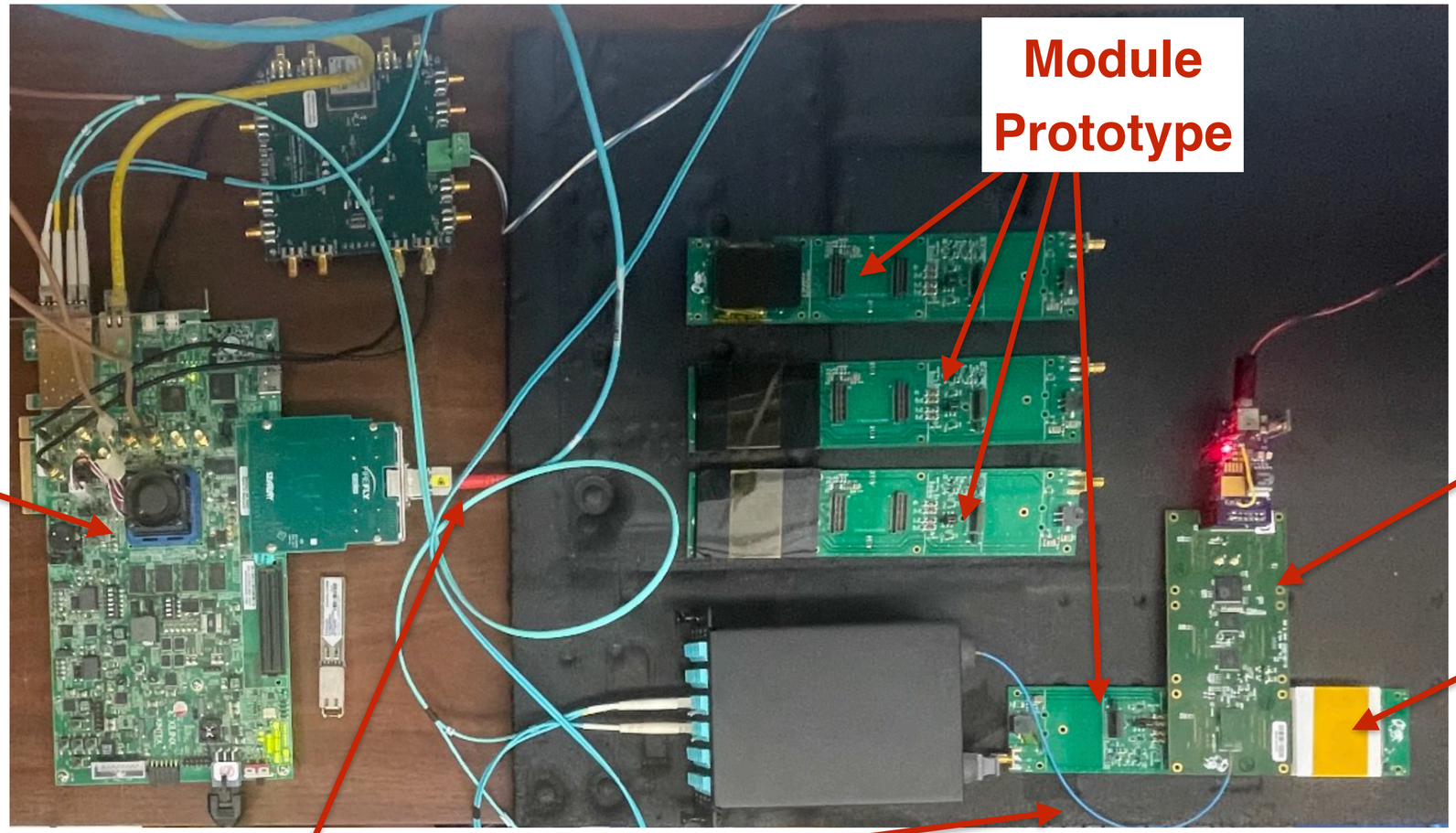
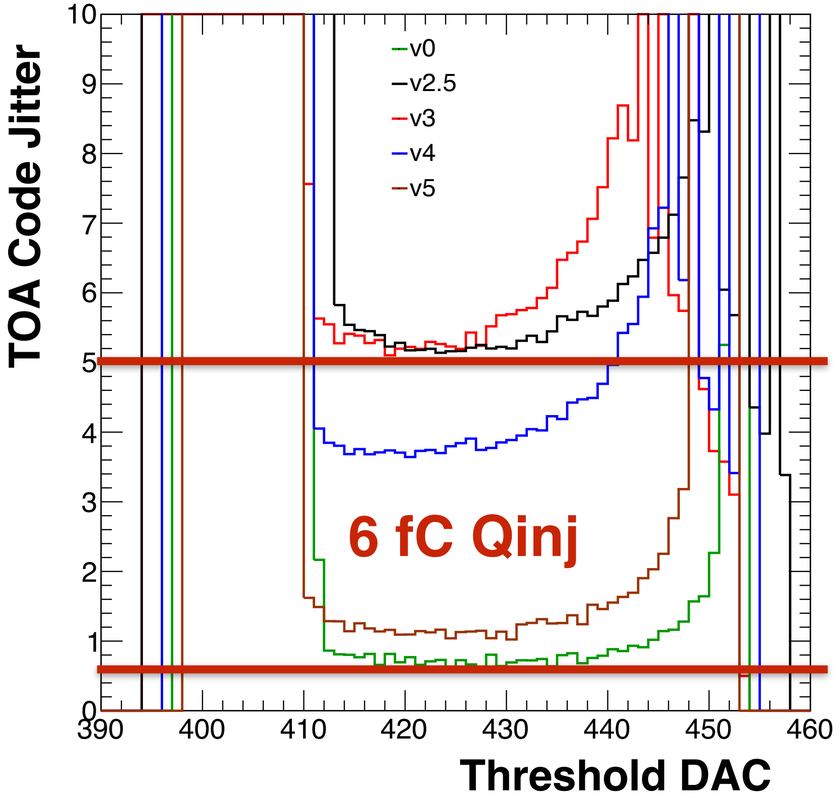
Building the Full System

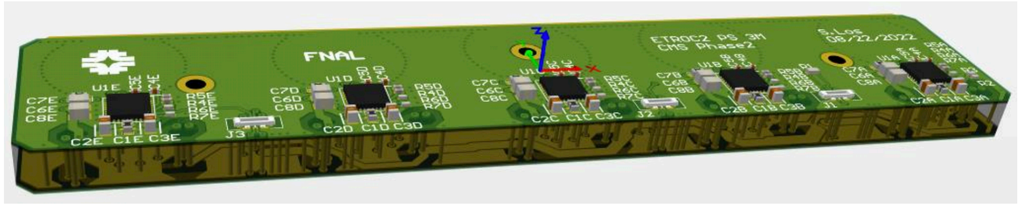


Fermilab

Building the Full System



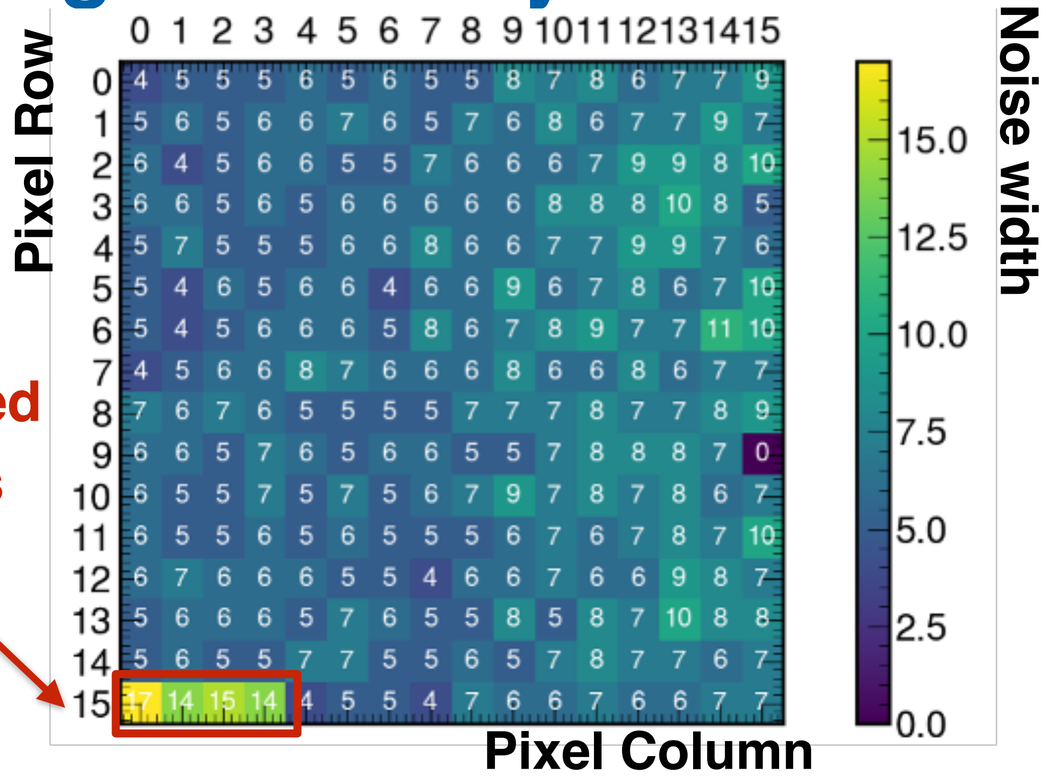
Wire bonded ETROC1 System Prototype



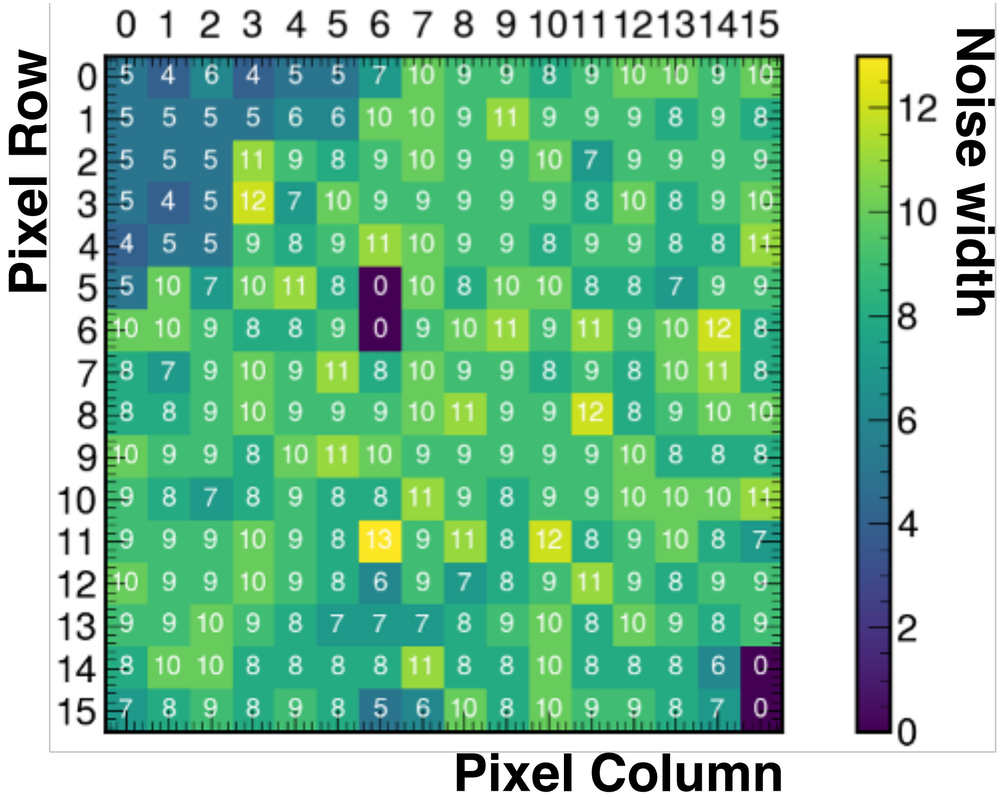
ETL front end power board

- Full system did not work out of the box
  - System is very sensitive to thermal and pickup noise
- After appropriate modifications to module design we now achieve sufficient performance

Building the Full System



Wire bonded ETROC2 System Prototype



Bump bonded ETROC2 System Prototype

- Full system did not work out of the box
  - System is very sensitive to thermal and pickup noise
- After appropriate modifications to module design we now achieve sufficient performance
- **Observe decrease noise for bump bonded devices vs. wire bonded (~50%)**

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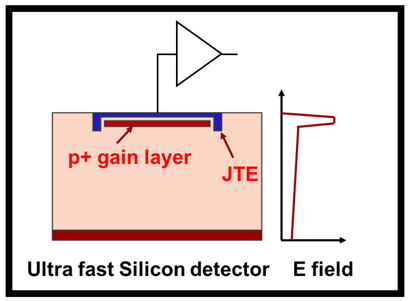
4D tracking research

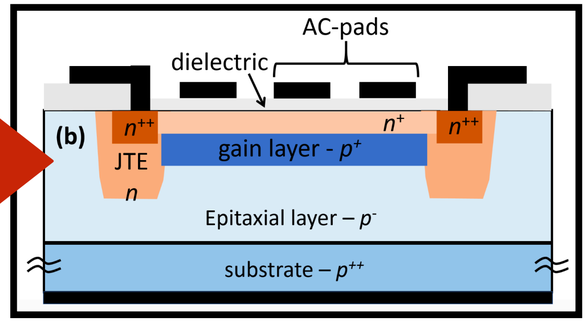
CMS ETL



$\sigma_x = 375\ \mu m$
$\sigma_t = 30\ ps$

Low Gain Avalanche Detector (LGAD)

ePIC at EIC



$\sigma_x = 20\ \mu m$
$\sigma_t = 20\ ps$

AC-coupled LGAD

FCC or µC

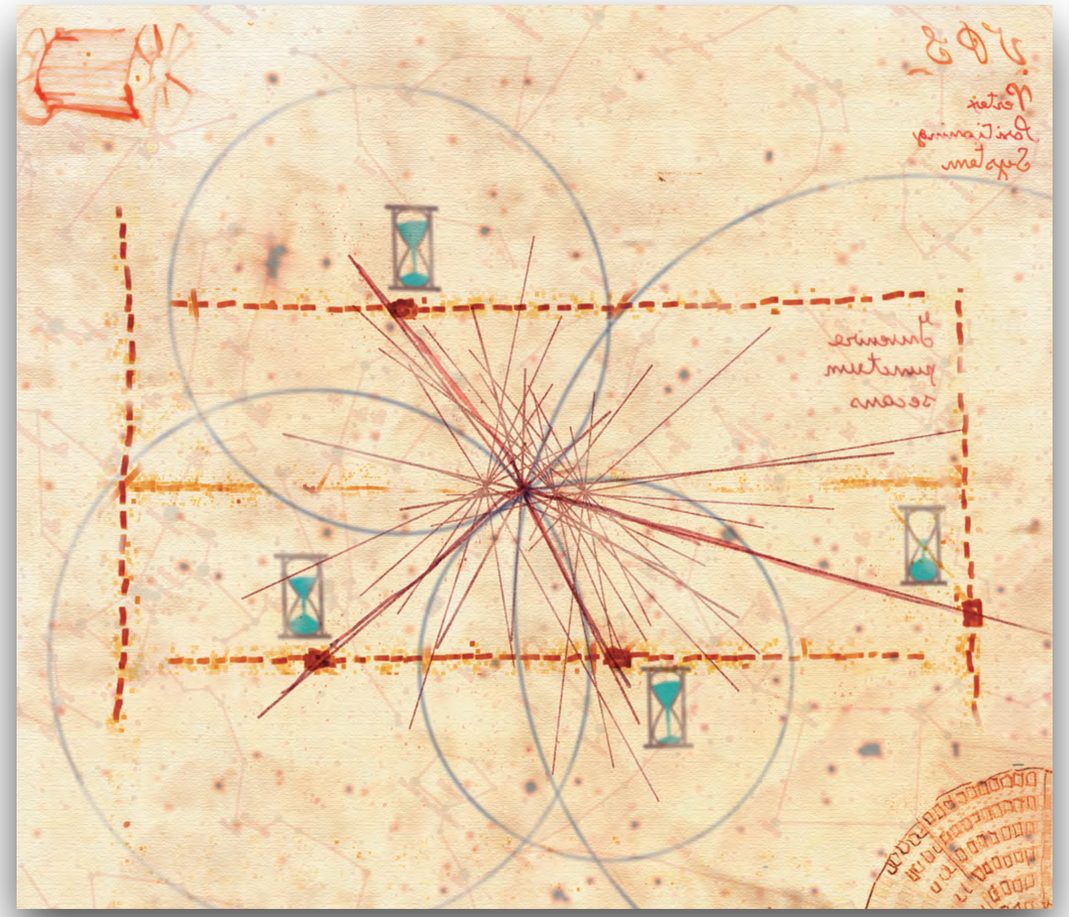
?

$\sigma_x < 5\ \mu m$
$\sigma_t < 10\ ps$

- The CMS ETL is a stepping stone to 4D trackers
- AC-coupled LGADs for the ePIC detector
- **Need to push the limit of 4D trackers for future colliders**

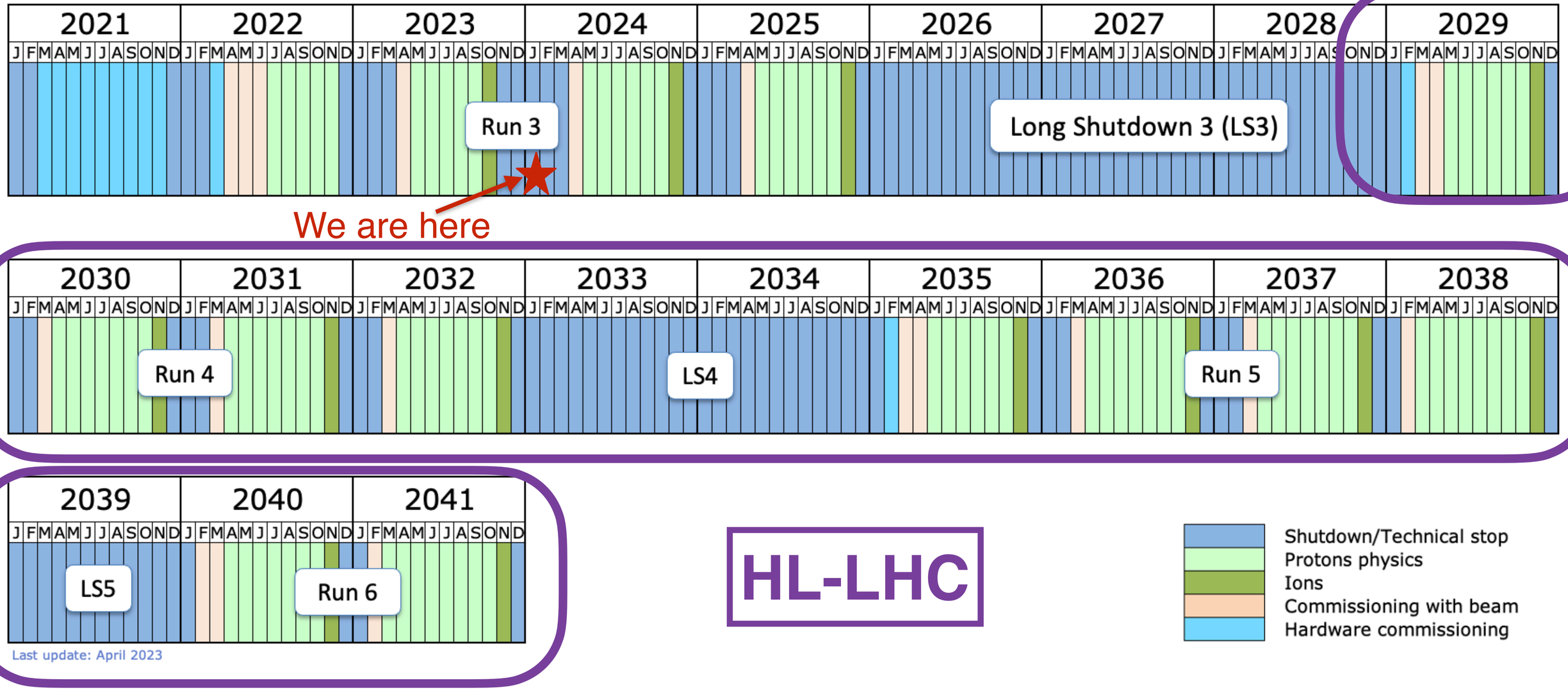
Summary

- The upgrade for HL-LHC is fast approaching
- Endcap timing layer will use LGADs readout by the novel ETROC
- Overcame many challenges and well positioned for production
- Timing detectors have a bright future
- **Thank you!**



Backup

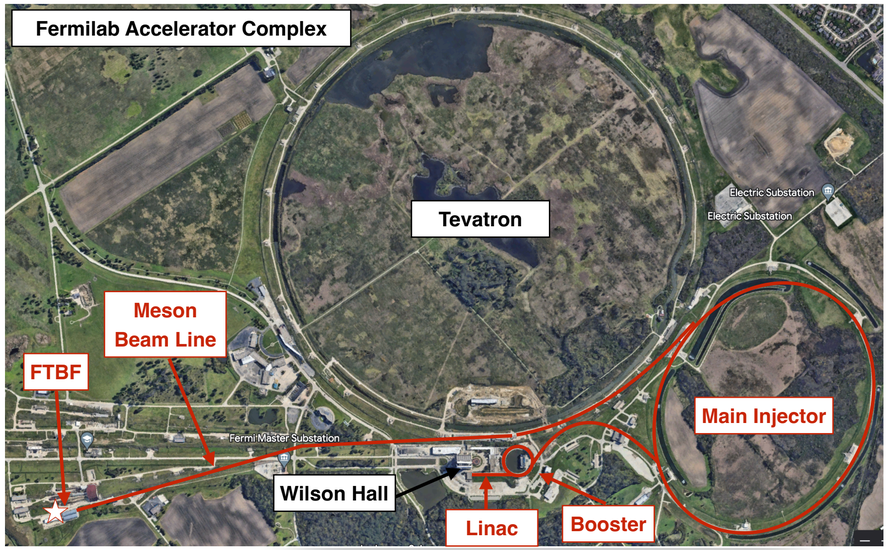
LHC Timeline

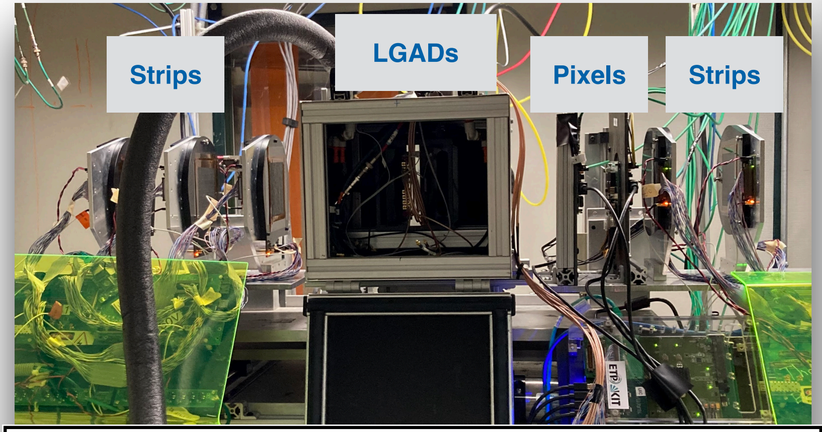


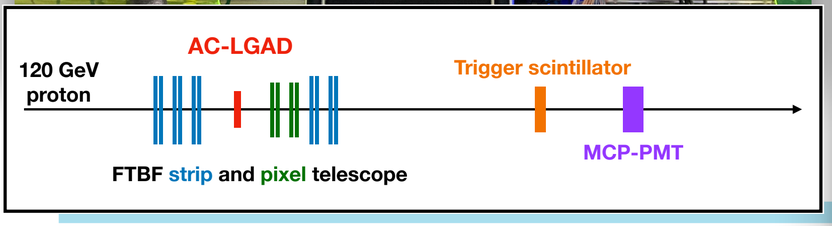
Fermilab

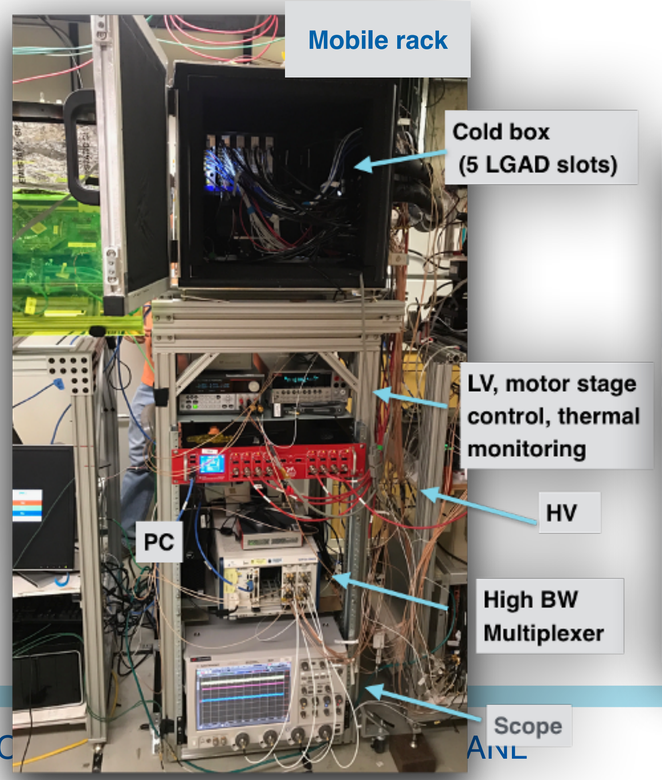
Fermilab 4D-trackers test beam infrastructure

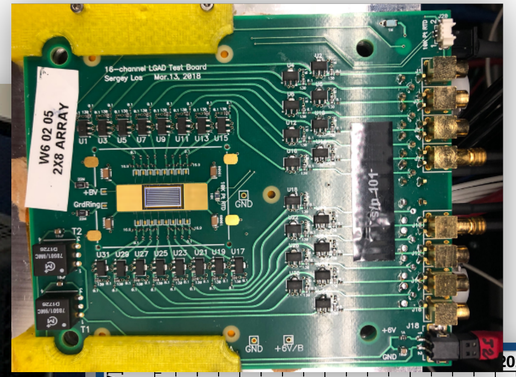
- Permanent setup in FNAL test beam facility (FTBF)
  - Movable: slide in and out of beamline as needed, parasitic use of beam
  - Environmental controls: sensor temperature (-25 C to 20 C), and humidity, monitoring
  - **Time reference with ~ 10 ps resolution (MCP)**
  - DAQ: high bandwidth, high ADC resolution **8-channel scope**
  - Record 20k events during 4 s spill,
  - **Tracker with ~5 µm resolution**
- Developed **readout boards** for the characterization of LGADs
  - Without complex ASIC and DAQ



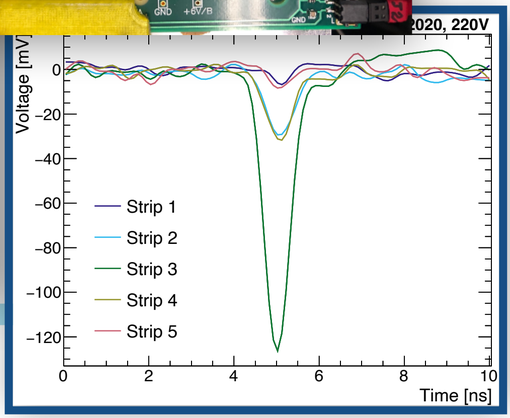






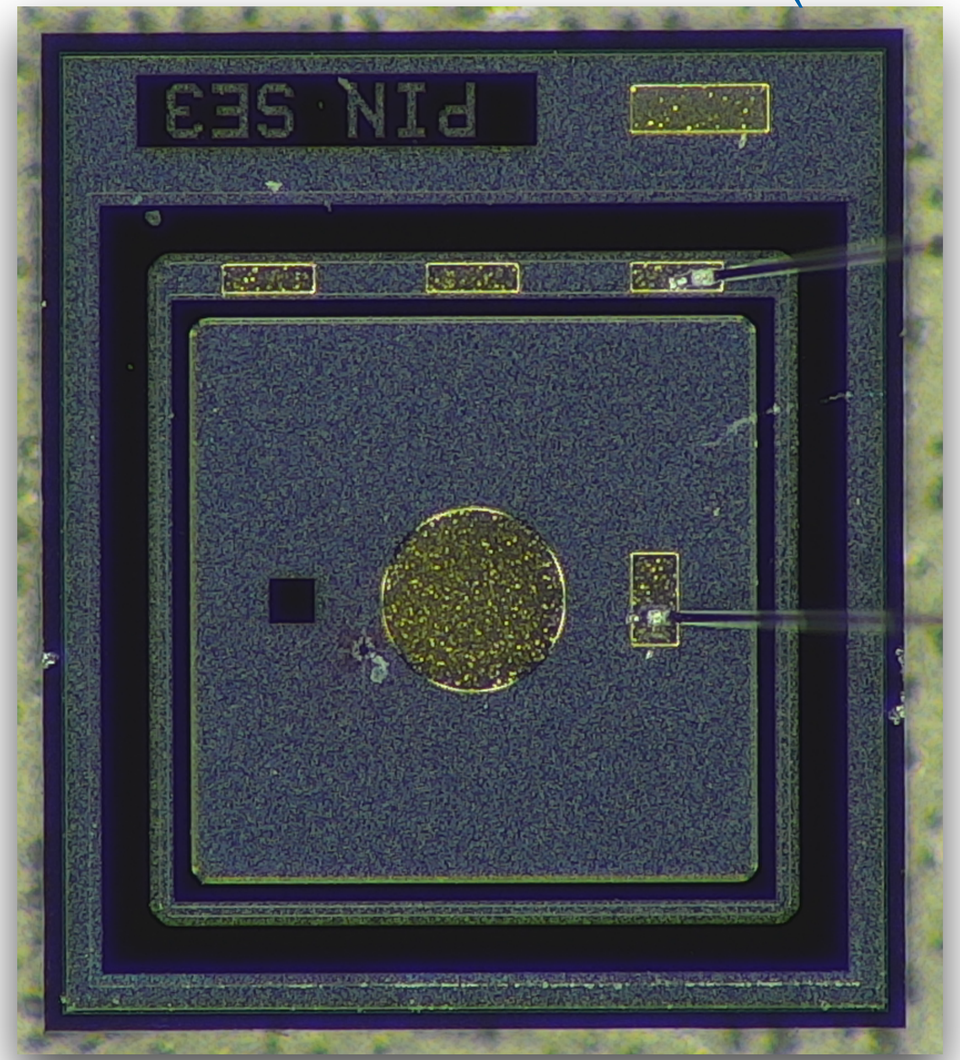


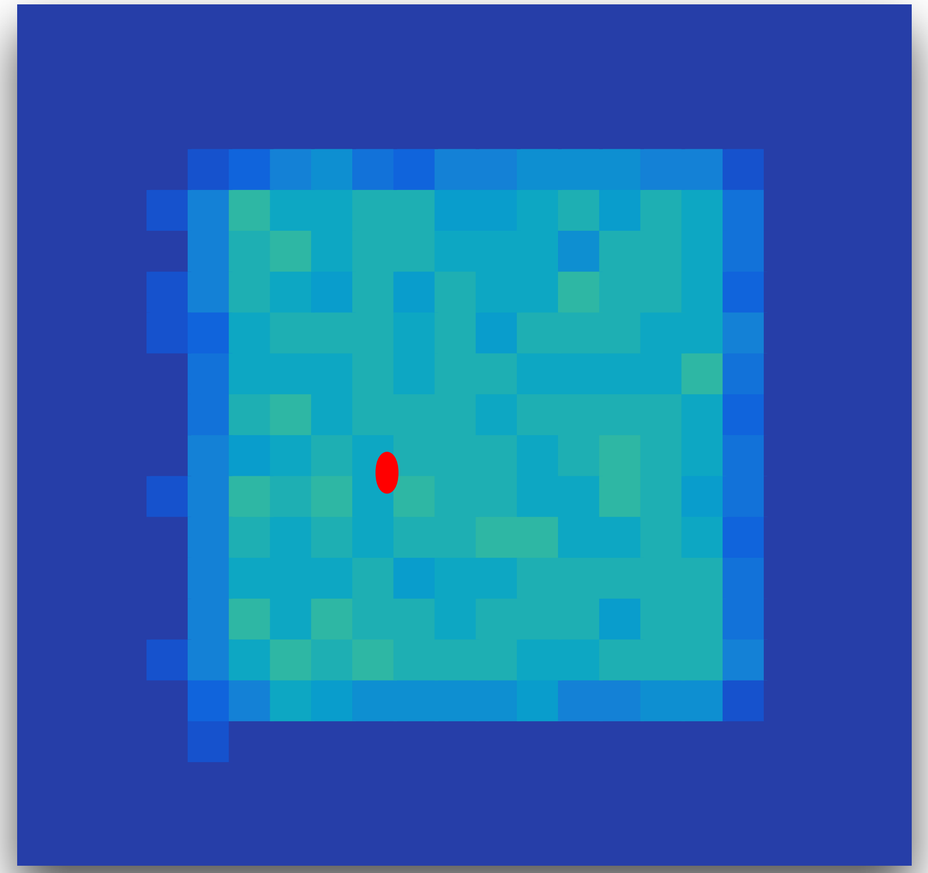
8-channel oscilloscope,
2 GHz, 10 GSa/s



Burnout in PIN diode

Gamma-irradiated HPK PIN diode (50 micron)





Even diodes die the same way→ gain is not needed.

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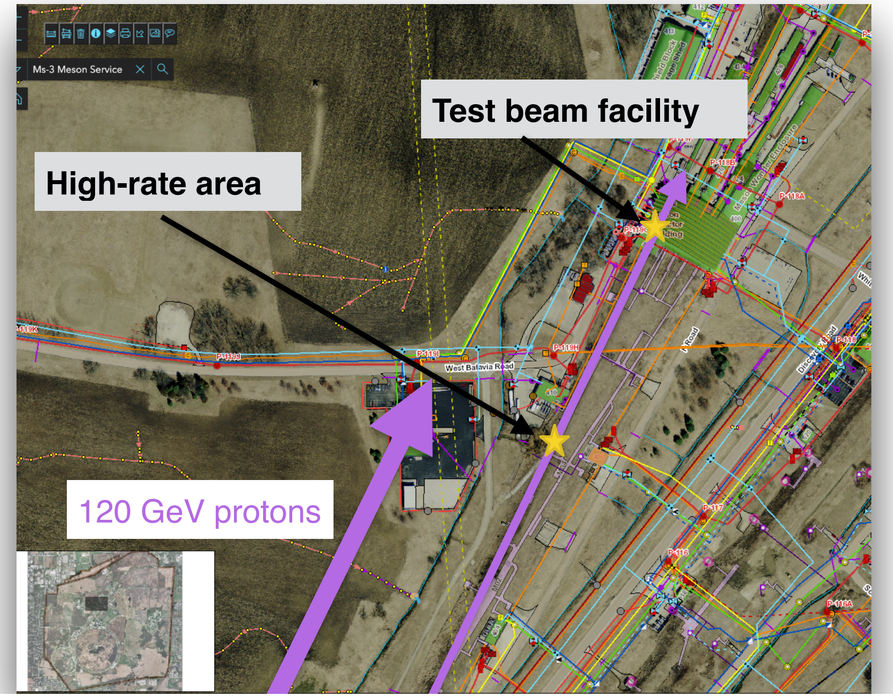
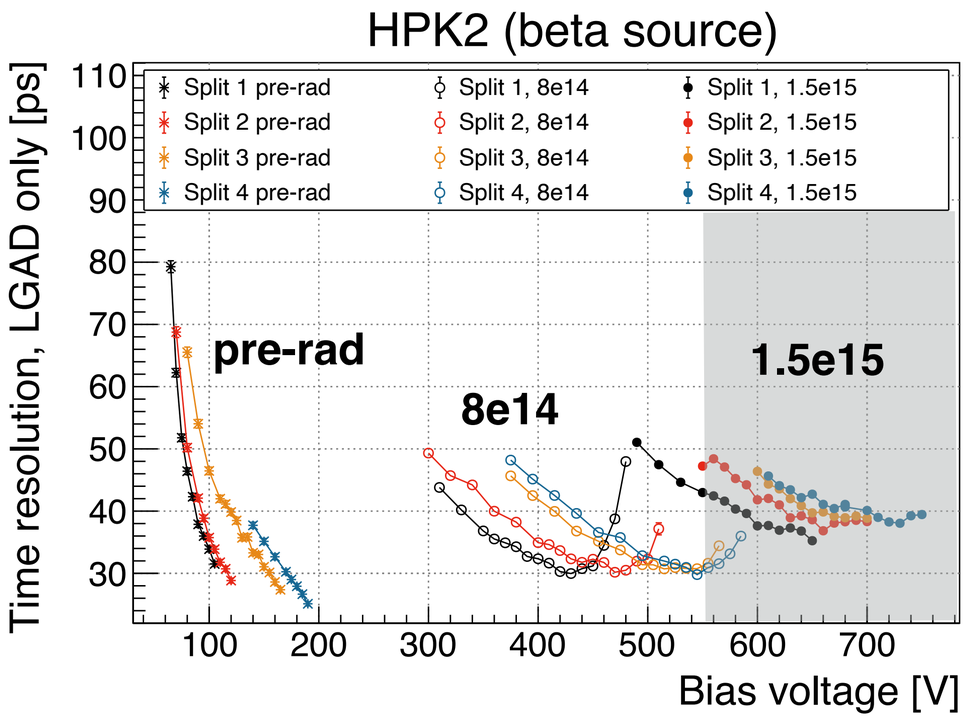
High-rate survival demonstration

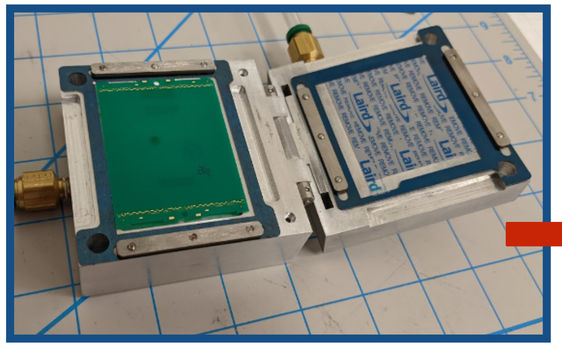
- Next performed a test beam to replicate SEB death for 20 sensors
- Needed to expose sensors to emulate lifetime exposure levels

- **Bottom line can not operate 50 μm thick sensor above 550 V**

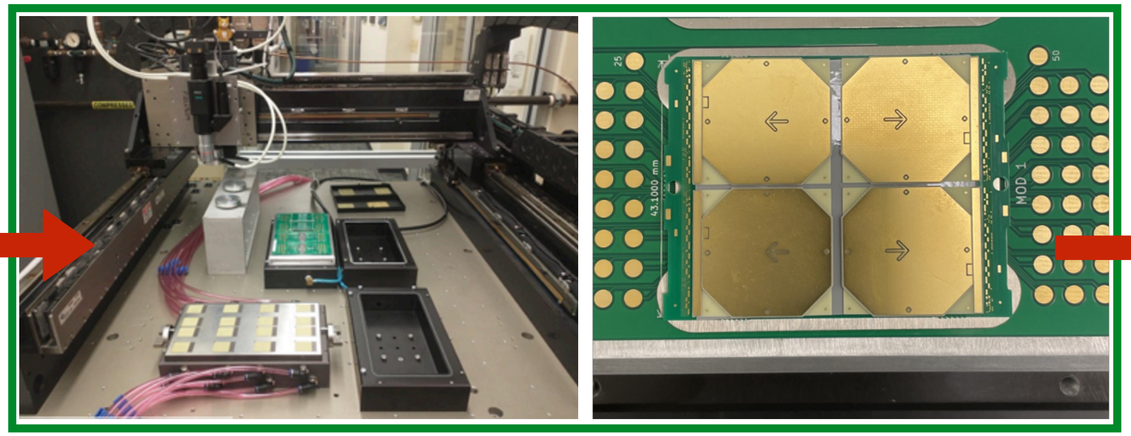




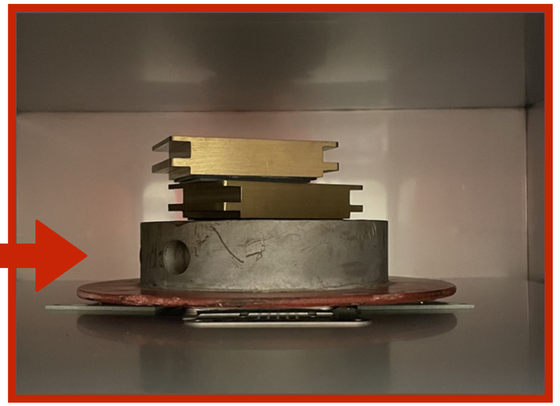
Module assembly using a gantry



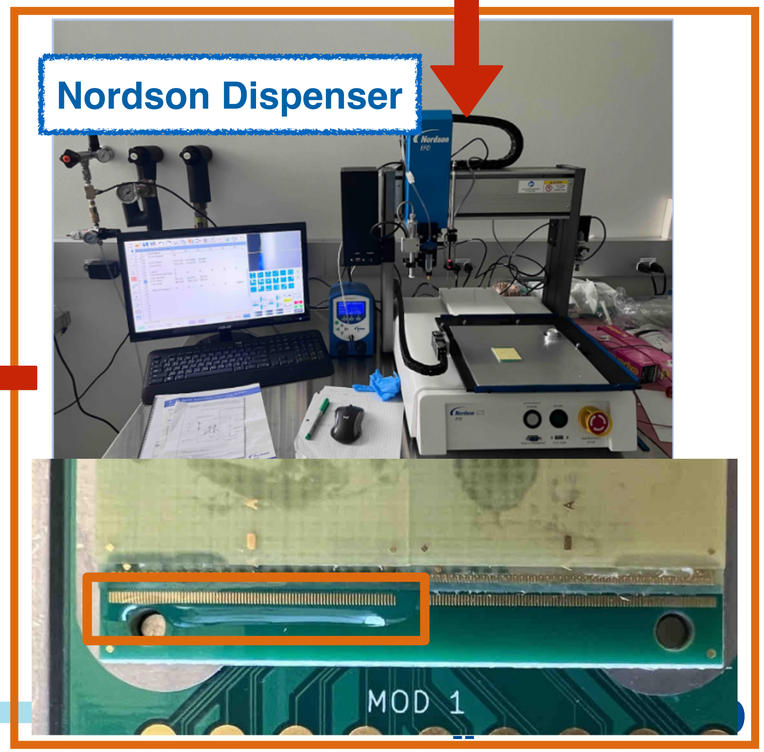
Step 1: Apply film to module PCB



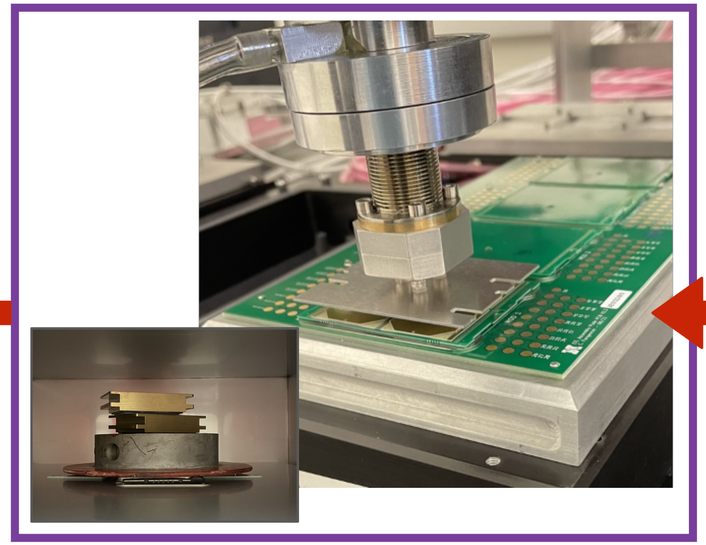
Step 2: Pick and place sensor+ETROC



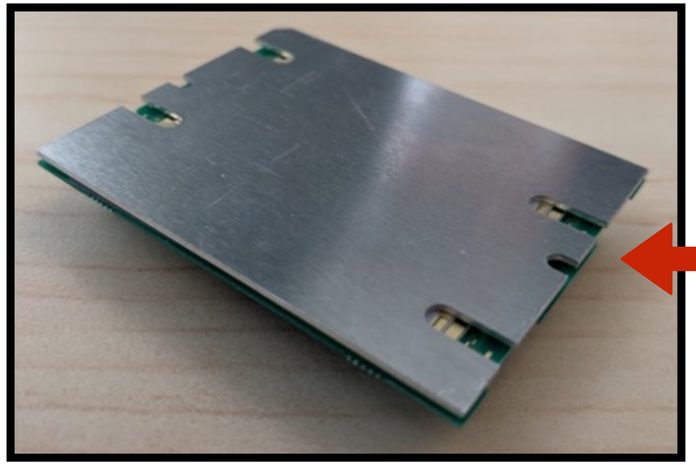
Step 3: Cure film in vacuum oven



Step 4-5: Wirebond and Encapsulate



Step 6-8: Apply film to baseplate,
Pick and place, and cure film



Assembled Module