Low-Gain Avalanche Detectors for the CMS MIP Timing Detector

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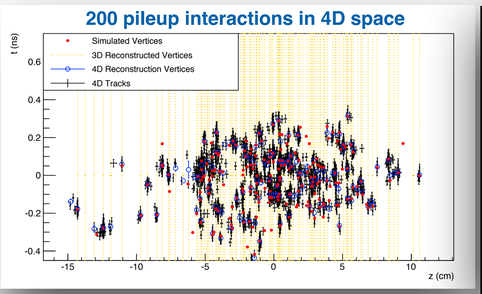
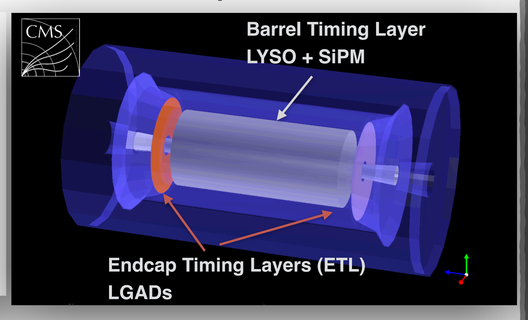
Introduction and motivation

- HL-LHC will reach pileup of approximately 200 simultaneous interactions!
- CMS MIP Timing Detector Phase II Upgrade: provide 40 ps timestamp for every track, maintain detector performance in complex environment.

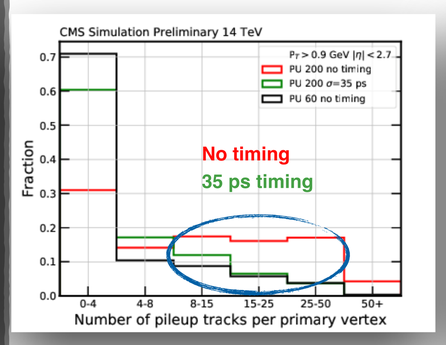
200 pileup interactions in 4D space

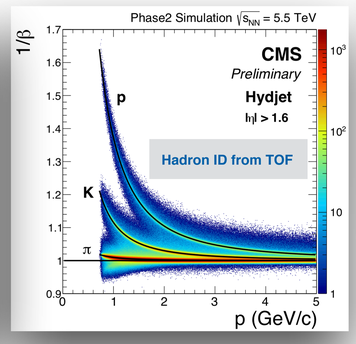




Physics impact of CMS MTD

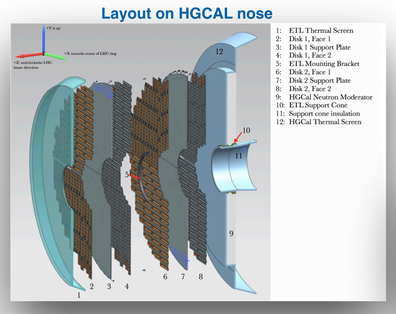
- Reduce PU misassociation rate to Run II levels, critical for lepton isolation, b-tagging & MET resolution
- TOF particle ID for heavy ion/B-physics





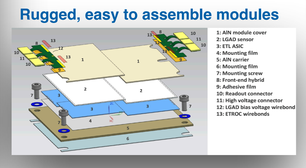
ETL mechanical design

Layout on HGCAL nose



- Two layers provide ~ 1.7 hits per track.
- σ = 50 ps per hit → 35 ps per track.

Rugged, easy to assemble modules

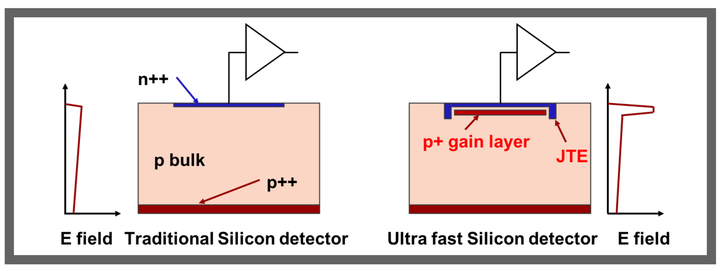


Sensor statistics

Pad size	1.3 x 1.3 mm²
Sensor size	2 x 4 cm² (16x32)
Number of channels	8.5 x 10⁶
Total active surface	16 m²

What are LGADs?

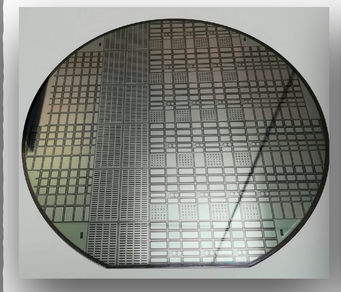
- LGADs: novel ultra-fast silicon detectors
  - Moderate internal gain (10-20): Large signals, but low noise
  - Thin (50 micron depletion region): Uniform field, fast rise-time



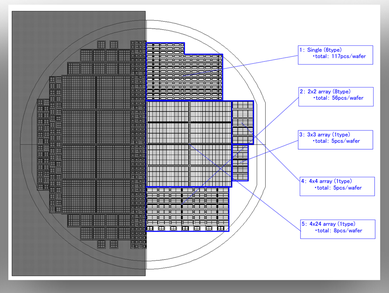
LGAD sensors for CMS ETL

- Two main producers: Hamamatsu (HPK), Fondazione Bruno Kessler (FBK)
- Main R&D focus: improving radiation hardness & developing large, uniform arrays

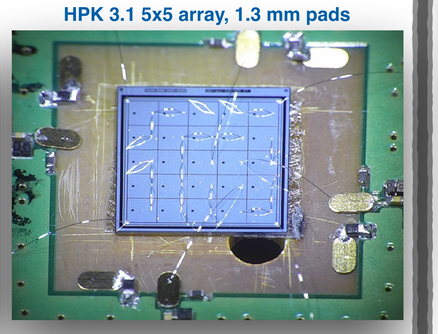
FBK UFSD3 wafer



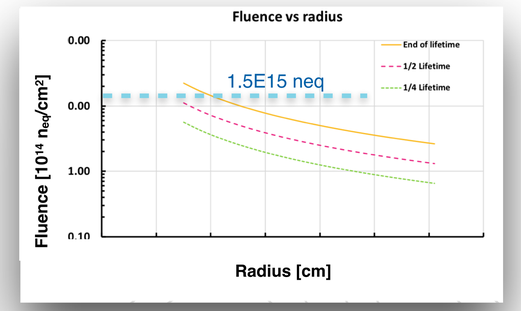
HPK 3.1 layout



HPK 3.1 5x5 array, 1.3 mm pads



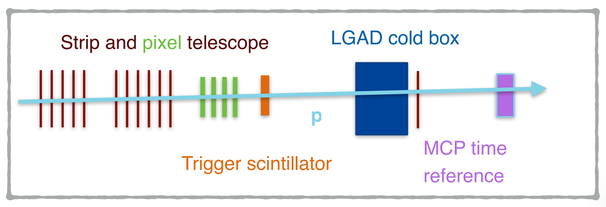
CMS ETL fluence vs radius



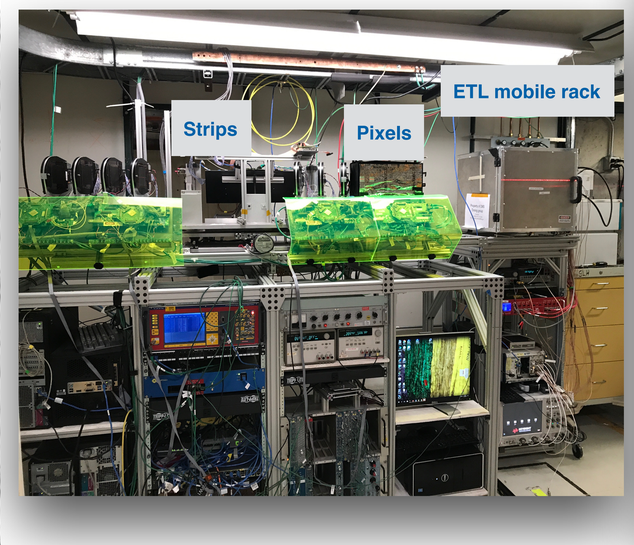
80% of sensors: < 8 x 10¹⁴ neq/cm²
15% of sensors: > 1 x 10¹⁵ neq/cm²

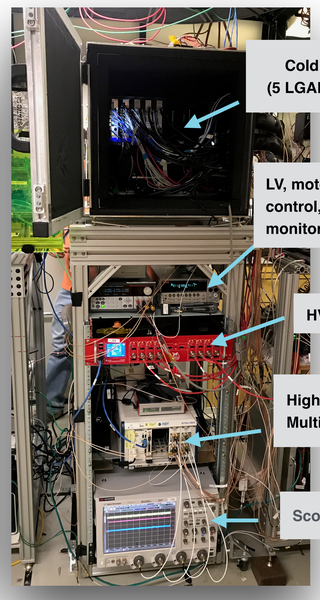
CMS ETL setup at Fermilab Test Beam Facility

- Main Injector provides 120 GeV protons
- Strip telescope: track position (σ ~ 30-50 μm)
- Multi-channel plate: time reference (σ ~ 10 ps)



- Key features:
  - High resolution Keysight scope
    - Fully exploit "burst" beam structure: record 100k events to memory at once
  - Permanent mechanical structure moves in and out of beam as needed; enables parasitic operation

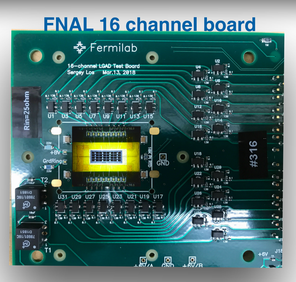




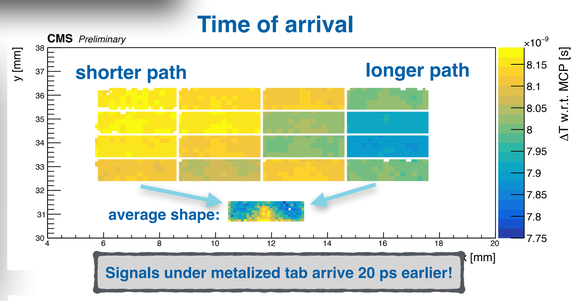
LGAD test beam results

- FNAL 16-channel board enables measurements with large arrays for the first time!
- Series of measurements with HPK type 3.1 arrays (4x4 grid of 3x1 mm² pads)

FNAL 16 channel board

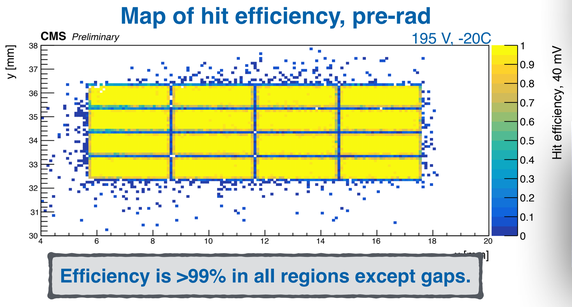


Time of arrival



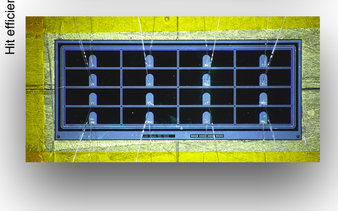
Signals under metalized tab arrive 20 ps earlier!

Map of hit efficiency, pre-rad

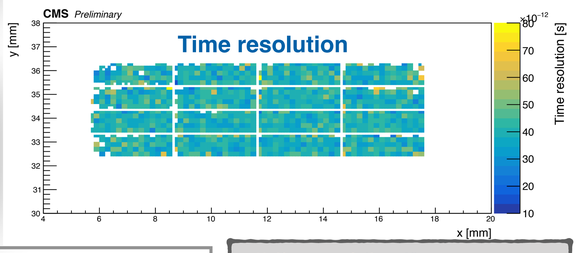


Efficiency is >99% in all regions except gaps.

HPK 3.1 4x4 array



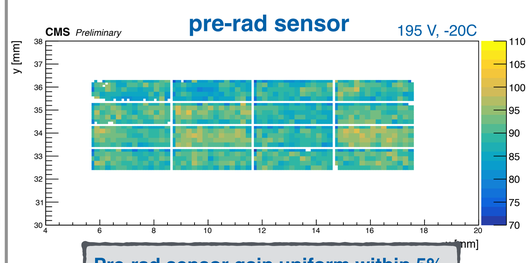
Time resolution



- Uniform resolution, 40 ps.
- On low-noise 1-chan board: 30ps.
- → Infer intrinsic resolution uniform at 30 ps.

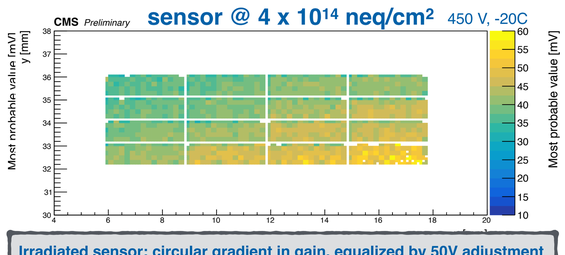
Maps of most probable signal amplitude

pre-rad sensor



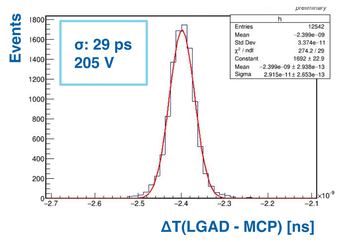
Pre-rad sensor gain uniform within 5%.

sensor @ 4 x 10¹⁴ neq/cm²

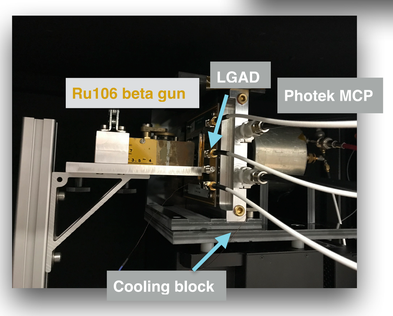


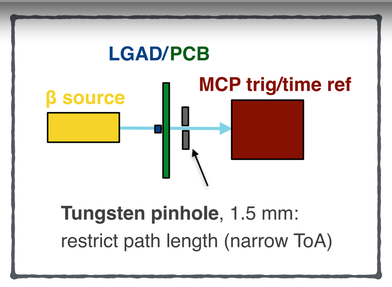
Irradiated sensor: circular gradient in gain, equalized by 50V adjustment
Unknown if intrinsic or induced by irradiation

Low-noise UCSC board

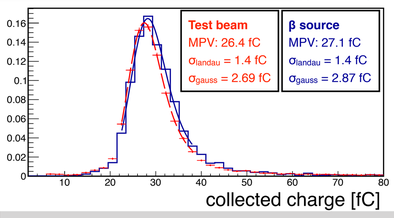


Beta source LGAD characterization





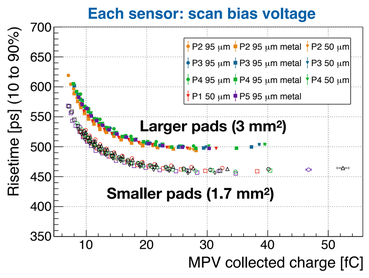
Test beam vs β, two similar sensors (HPK 3.1)

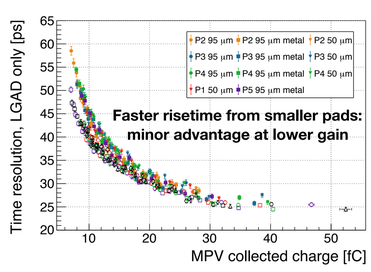


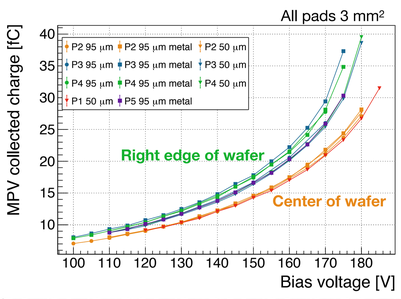
Ru106 β ionization extremely similar to MIP!

- Beta source allows high statistics sampling of sensors
- Complete characterization of 22 HPK 3.1 sensors: study wafer uniformity & prepare for systematic irradiation campaign.

Each sensor: scan bias voltage

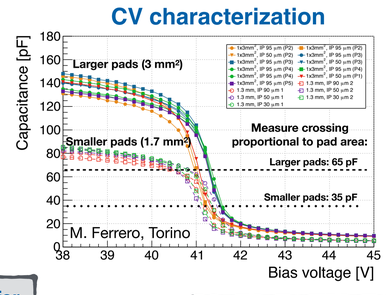




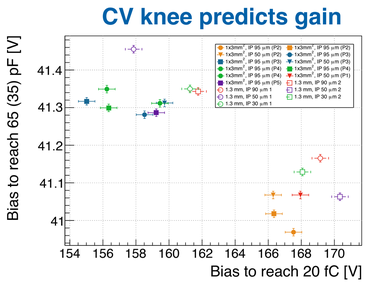


Small non-uniformity of gain observed across wafer
Offset by 10V difference in operating voltage.

CV characterization

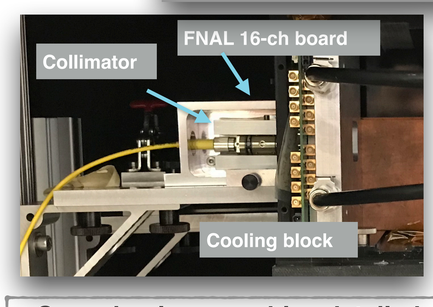


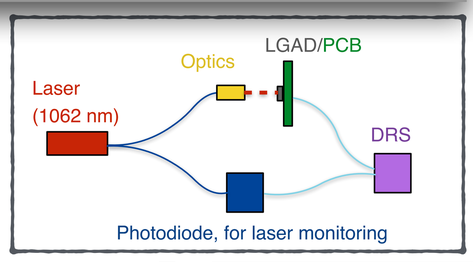
CV knee predicts gain



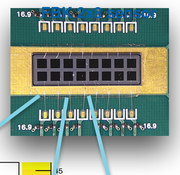
CV knee transition accurate predictor of gain!
→ highly efficient for high volume testing.

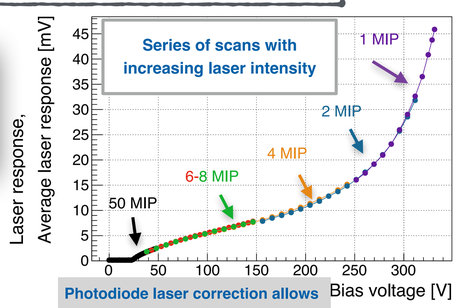
Scanning laser uniformity studies



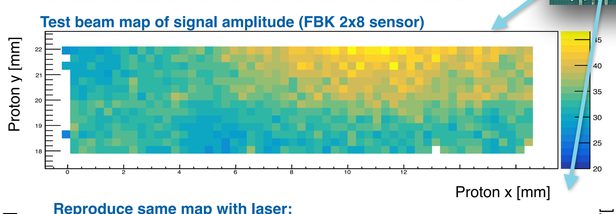


- Scanning laser enables detailed studies of spatial features without TB, in the comfort of the lab.

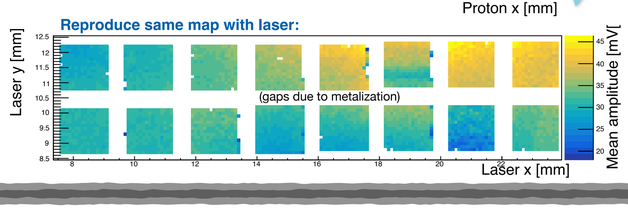




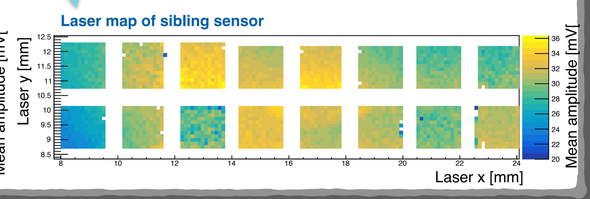
Test beam map of signal amplitude (FBK 2x8 sensor)



Reproduce same map with laser:



Laser map of sibling sensor



Summary & conclusions

LGAD development on track for CMS ETL!
Prototypes satisfy all ETL requirements:
- Time resolution < 40 ps beyond 10¹⁵ neq
- Fill factor > 85%
- Large, uniform arrays are achievable

Strong characterization capabilities lead towards promising future:
- Large area uniformity studies with scanning laser
- Detailed timing & irradiation studies with beta source
- High volume uniformity studies with probe CV
- Complete test beam characterization as anchor for all measurements.

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