

ATLAS-HGTD sensor radiation damage

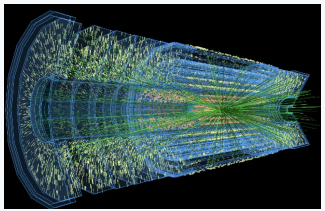
From HGTD production to next-generation LGADs

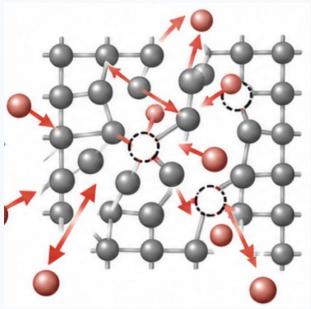
Iskra Velkovska
Jožef Stefan Institute - F9

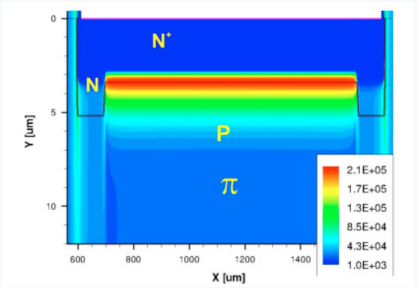
F9 Strategic Meeting · Krvavec · 2026

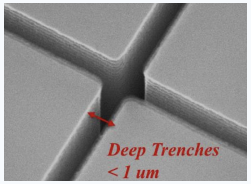
An overview of today's route

PhD thesis: Development of novel measurement methods and radiation hard particle sensors for timing applications

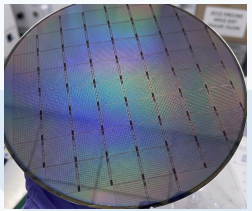








Future colliders



1

HGTD production

How uniform are the sensors?

QC & production

2

Radiation damage

What does irradiation actually change?

Neutron & proton irradiations

3

Detector performance

Test beam characterization
Sr90 source tests & TCT

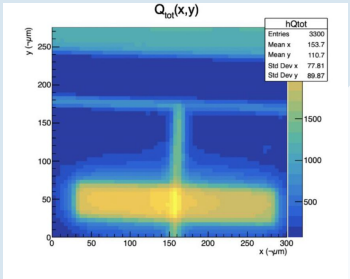
charge · timing · efficiency

4

TI-LGADs

What comes next?

next-generation R&D

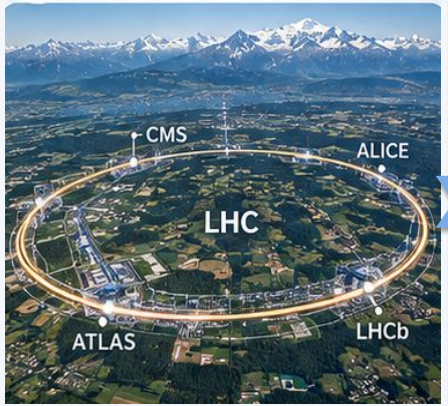


sensor → damage → performance → optimized design

Where my work fits

From HL-LHC detector needs to next-generation timing sensors

1 LHC



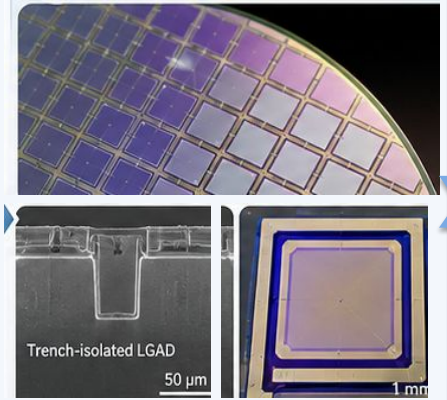
High-energy pp collisions at 13.6 TeV

2 HL-LHC / HGTD



~200 interactions per bunch crossing
precision timing @ HL-LHC

3 DRD3 / silicon R&D



LGAD production
radiation damage
timing performance

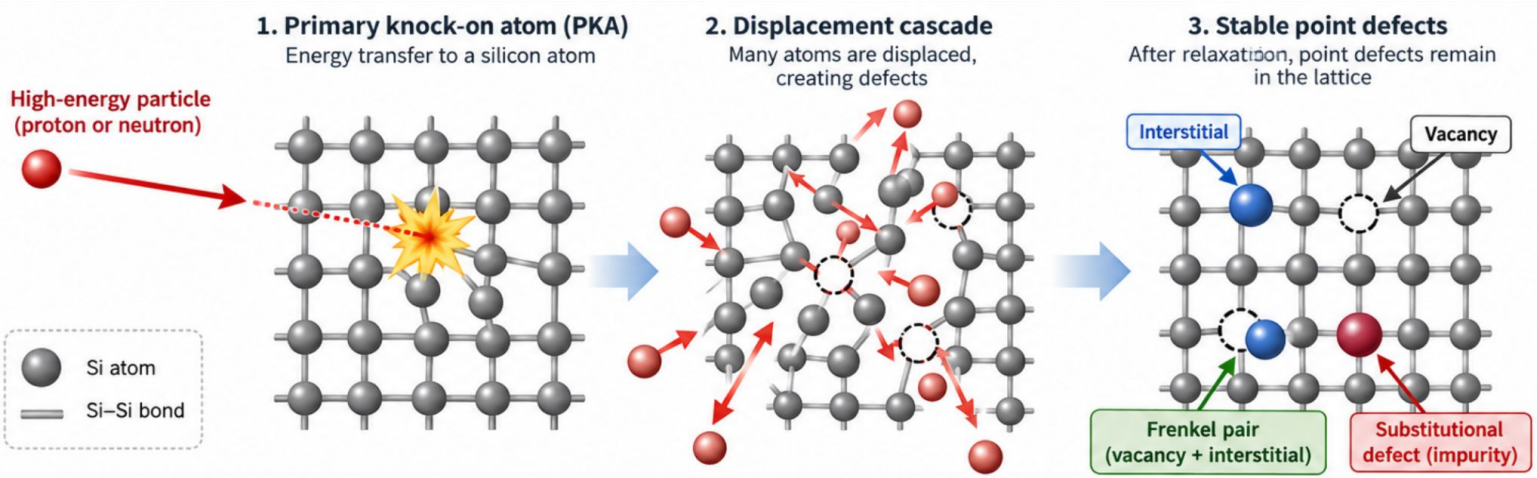
4 Future / FCC

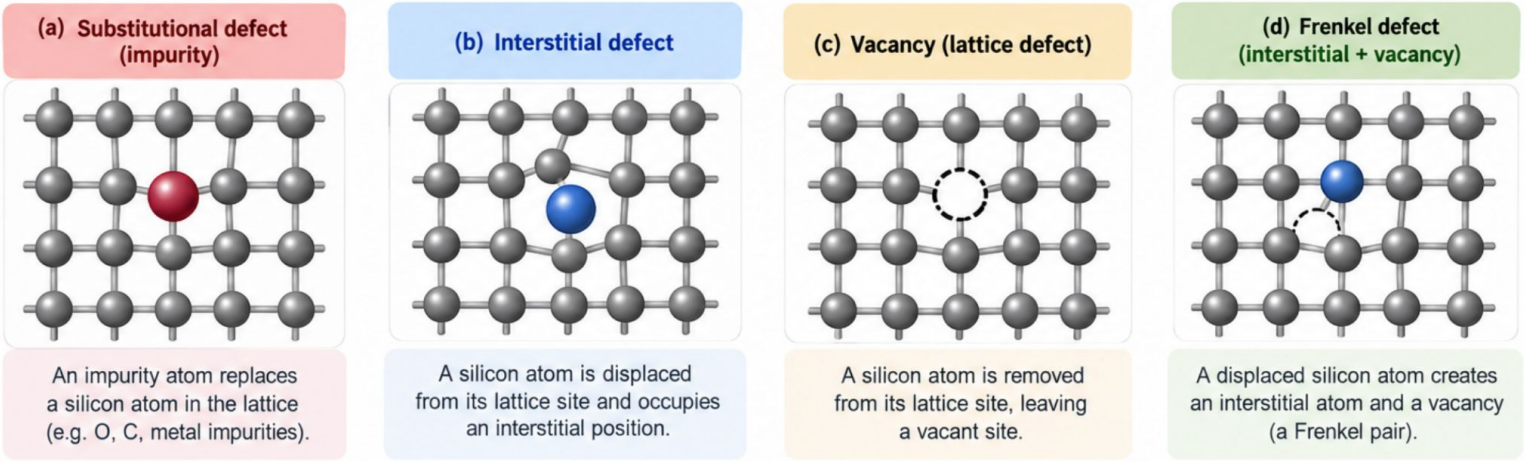


TI-LGADs
4D tracking

My work connects **ATLAS HGTD needs** with **next-generation silicon timing detectors.**

Basics of the radiation defects in the Si lattice





Radiation damage in silicon detectors

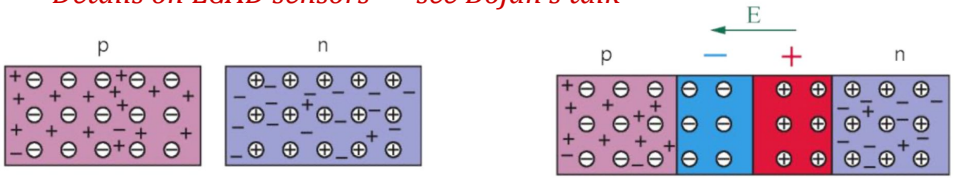
Bulk damage (NIEL->Non-Ionizing Energy Loss), creation of silicon lattice defects expressed as ***1 MeV n_{eq}/cm^2***

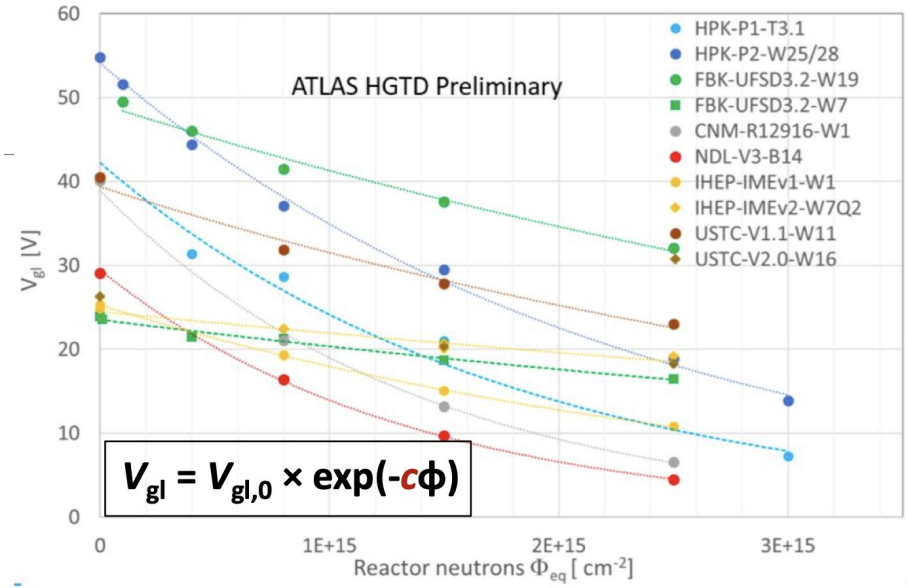
Technology used: Low Gain Avalanche Diodes → 1st concept proposal:
Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications - ScienceDirect

"Acceptor removal"- electrical deactivation of acceptors in material by irradiation → reduced N_{eff}
→ compensated by increasing bias voltage

Gain of the LGAD depends on the doping of the gain layer → doping of the gain layer is affected by radiation, due to acceptor removal

Details on LGAD sensors → see Bojan's talk





Radiation modifies the effective doping of the silicon, reducing the electric field in the gain layer

➔ Different ways to mitigate acceptor removal:
- Dope gain layer with carbon
- Narrow B implantation
- Partial activation of boron (PAB)

c is called acceptor removal parameter

The sensor technology: LGADs

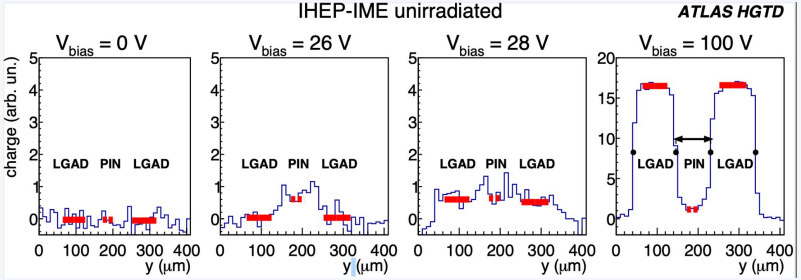
How the sensors work and how we characterise them with TCT and Sr-90 source tests

$$E_{gl} \approx \frac{V_{gl}}{w_{gl}} + \frac{V_{bias} - V_{fd}}{d}$$

V_{gl} ... depletion voltage of the gain layer (≈ 25 V)
V_{fd} ... depletion voltage of the gain layer + bulk
w_{gl} ... gain layer thickness (≈ 1 µm)
d ... active thickness (≈ 50 µm)

Why LGADs?

- Precise timing needs a high signal-to-noise ratio
- Charge multiplication is integrated into the sensor
- LGADs are n-on-p silicon sensors with an extra p+ gain layer
- For HGTD, the active thickness is about 50 µm



Paper published on Irradiation Testing:
https://arxiv.org/pdf/2509.09187

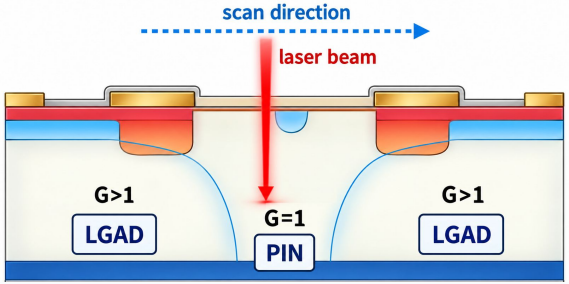


High electric field in the gain layer enables avalanche multiplication

Internal gain improves timing performance at the sensor level.

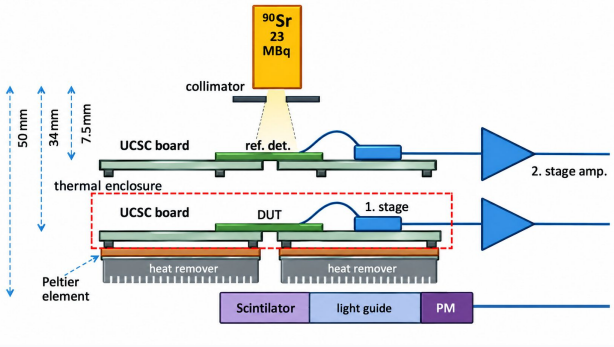
Measurement methods:

Transient Current Technique laser measurements



TCT measurement between two LGAD pads: a focused laser scans the structure from the top, probing charge collection in the **LGAD regions (G > 1)** and in the **inter-pad PIN region (G ≈ 1)**.

β-^{90}Sr MIP-like laboratory source



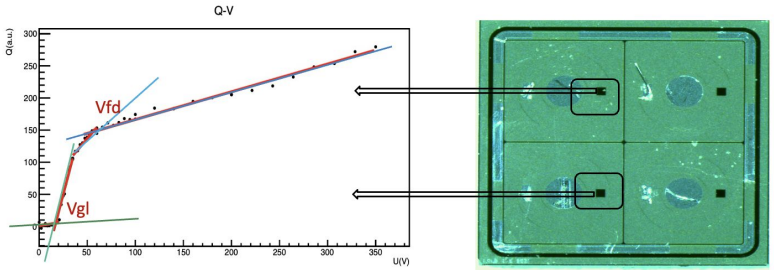
What we measure?
- Collected charge
- Time resolution

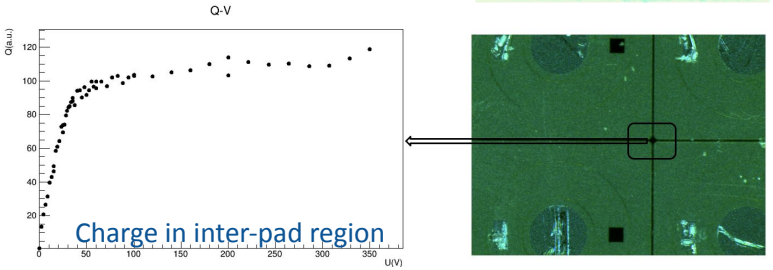
Why ^{90}Sr?
- MIP-like β particles for laboratory testing
- Measures **collected charge** and **time resolution**
- DUT cooled to **−30 °C**
- Trigger: **PMT + reference LGAD**

My work connects **sensor structure** to **charge and timing performance before and after irradiation**

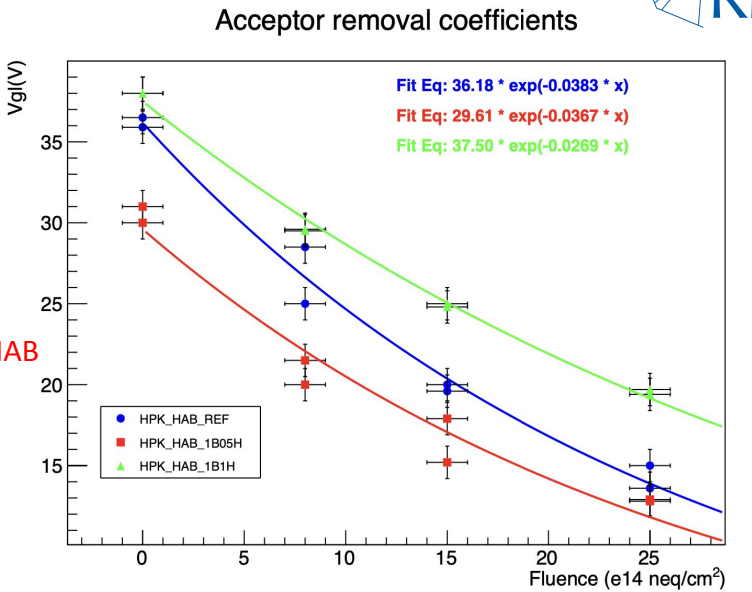
R&D studies on acceptor removal: LGADs with Partially Activated Boron

- Part of boron implanted, but not electrically activated in the gain layer
- **Radiation hardness improvement → inactive boron shielding the electrically active boron, hence reducing acceptor removal**





- No HAB
- Medium HAB
- High HAB



2x2 LGAD array
1.3x1.3 mm²
50 um thickness

Acceptor removal coefficients
c (REF)= 3.8e-16 cm²
c (1B05H)= 3.4e-16 cm²
c (1B1H)= 2.6e-16 cm²

Conclusion from studies: Small effect of PAB on acceptor removal!

Why HGTD?

See more in Bojan's talk from Monday!

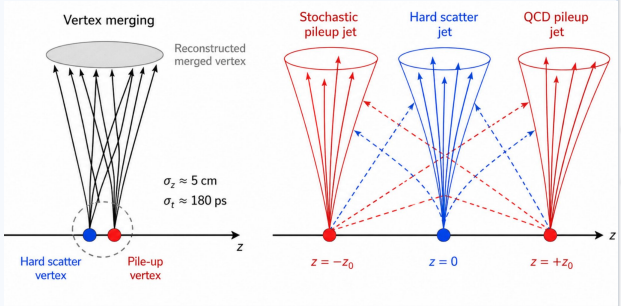
Proceedings paper under review "Development and characterization of sensors and electronics for the ATLAS High-Granularity Timing Detector" - I.Velkovska

HGTD

From pile-up at HL-LHC to precision timing in the forward region

Detector upgrades > 2026-2030

1 Pile-up problem



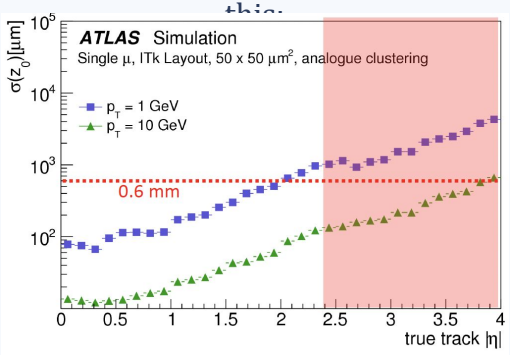
Many vertices become difficult to separate **using position alone.**

track-to-vertex association becomes ambiguous

2 Forward-region limitation

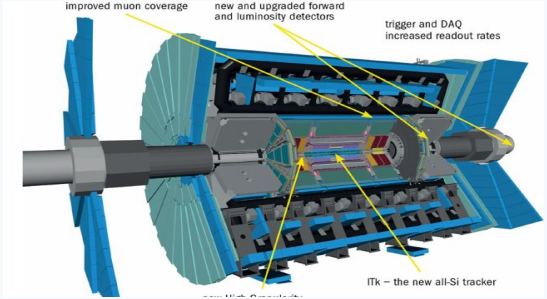
average vertex separation at μ≈200
0.6 mm

When ITk z-resolution exceeds this:

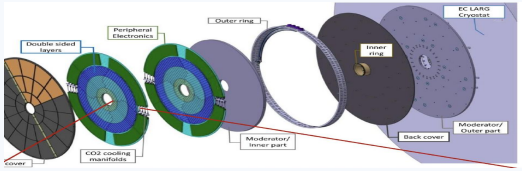


ITk spatial resolution degrades at high |η|

3 HGTD solution



HGTD between ITk and LAr calorimeter



double-sided silicon timing layers

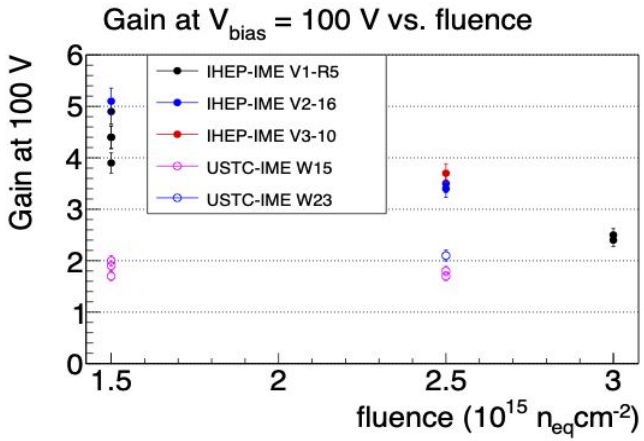
Coverage: 2.4 < |η| < 4.0

Position: z ≈ ±3.5 m

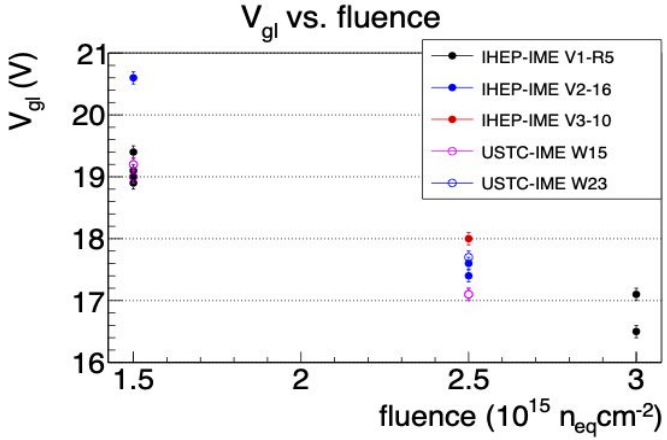
Timing: track time resolution < 50 ps at EoL

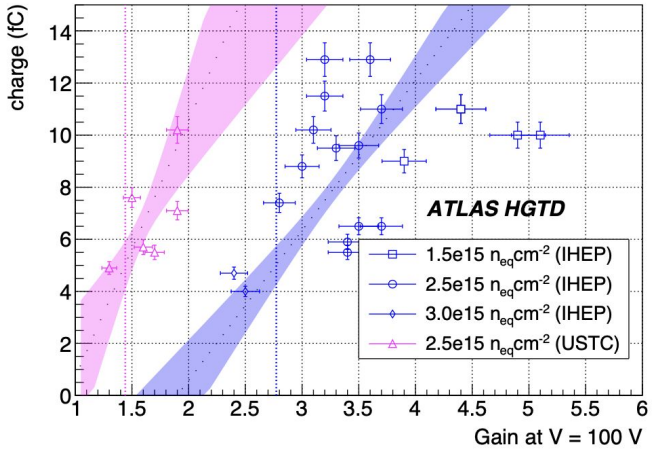
Takeaway: add time where space is not enough

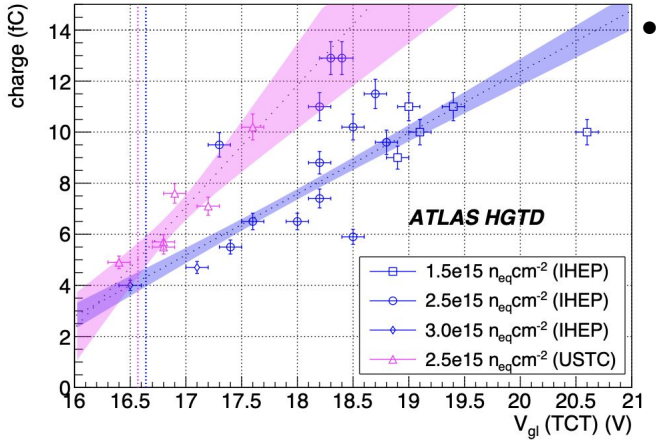
Irradiation results on a QCTS sample irradiated to 2.5 × 10^{15} n_{eq} cm^{-2}



Only neutrons







Neutron irradiations done @TRIGA reactor in Ljubljana

TCT–^{90}Sr correlation

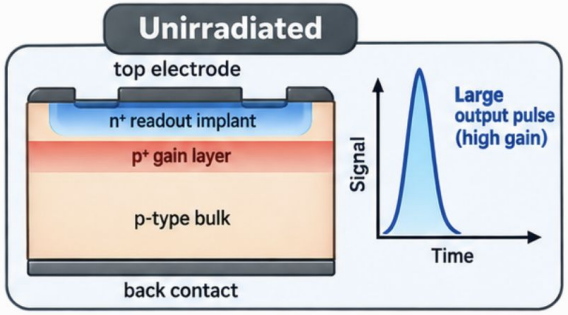
- V_{gl} and G_{100} correlate with the ^{90}Sr most probable collected charge.
- V_{gl} and gain decrease with fluence
- The **5 fC charge requirement** is projected onto the fits to define TCT-based wafer acceptance thresholds.
- This enables fast radiation-hardness qualification during HGTD production.

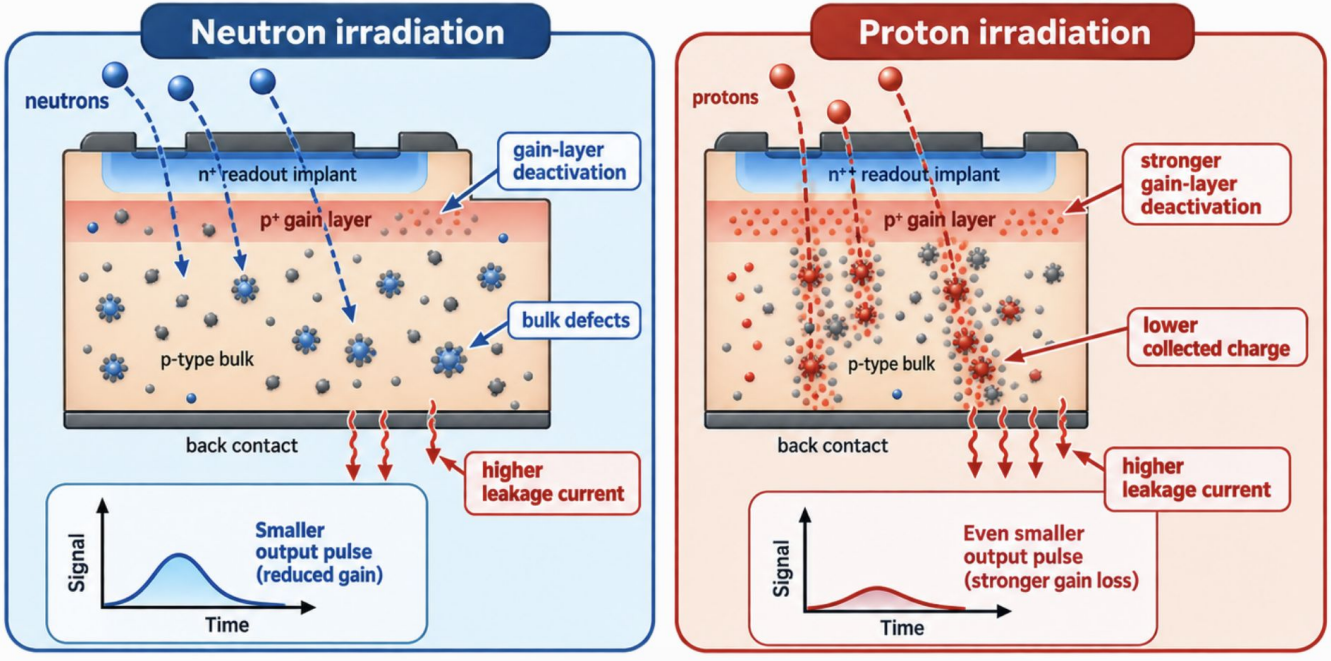
Paper published presenting this work:

https://arxiv.org/pdf/2509.09187

How do particle type and energy affect LGAD radiation damage?

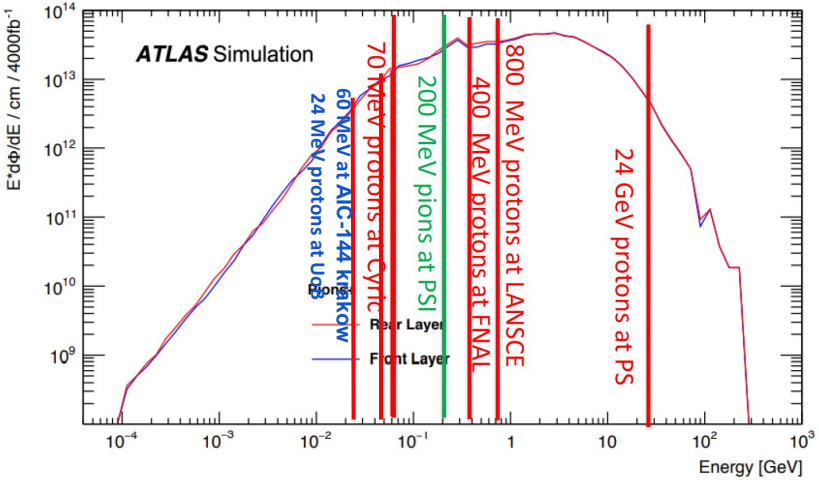
Sensors irradiated with protons:
24 GeV, 24 MeV, 60 MeV





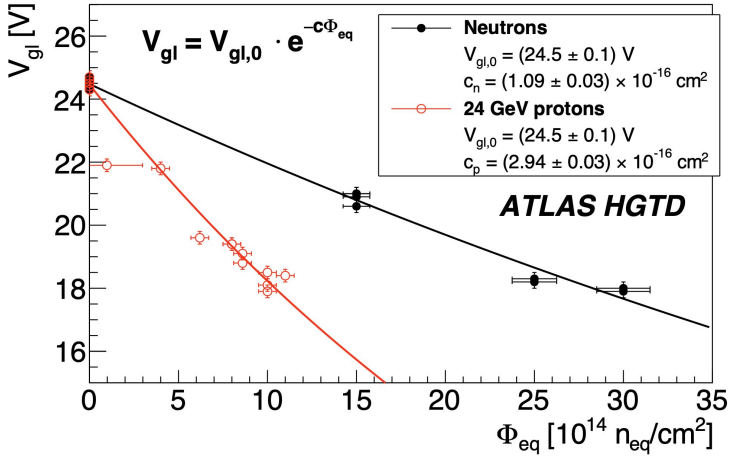
Charged-hadron damage in HGTD

- In HGTD, a significant fraction of the damage is also expected to arise from charged hadrons, in particular pions with energies of a few GeV
- LGAD performance degrades with irradiation due to **acceptor removal in the gain layer :** $V_{gl}=V_{gl,0} \times e^{-c\varnothing}$
  - Acceptor removal depends on particle type (neutrons vs charged hadrons)
  - Charged hadrons are generally more damaging than neutrons ($c_p > c_n$), consistent across many manufacturers; rate also shows energy dependance
  - In ATLAS: at η=2.4, **n:h**=90:10; at η=4, **n:h**=50:50

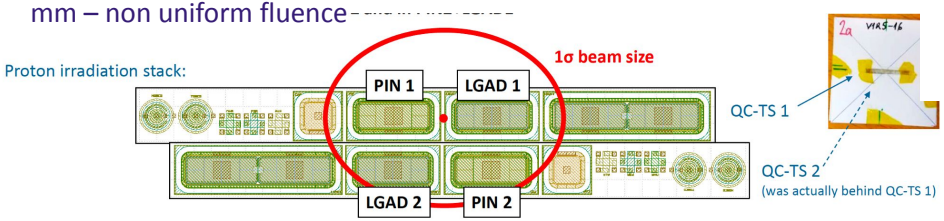


Pion spectra averaged over the rear (outermost) and front (innermost) silicon layer of the HGTD. The uncertainties are of the order of 5 %

Comparison of acceptor removal with 24 GeV IRRAD proton beam

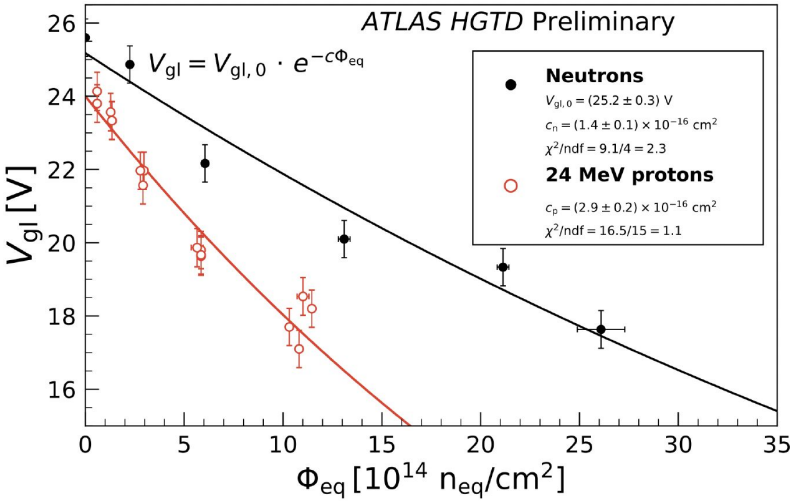


Gaussian shaped beam with σ= 3-4 mm – non uniform fluence



Proton irradiation paper in preparation

Irradiations @UoB **MC40 cyclotron with 24 MeV protons**



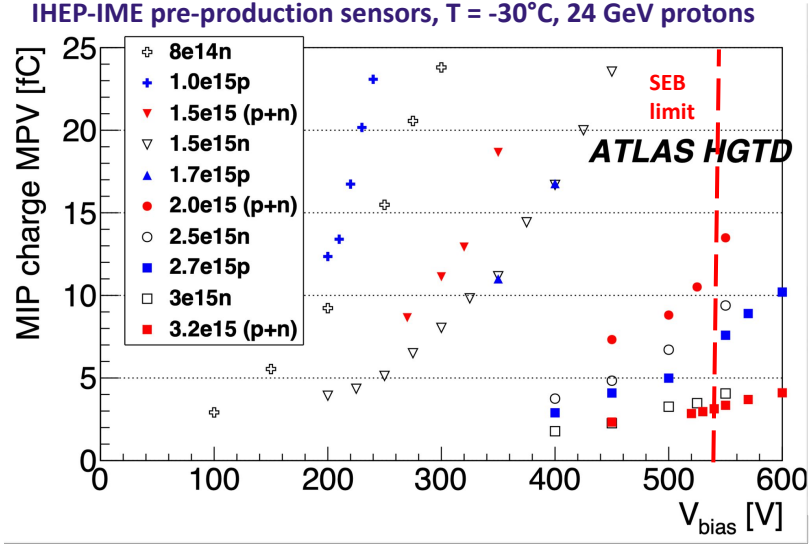
- 24 MeV protons: c_p = (2.9 ± 0.2) × 10^{-16} cm²
- 60 MeV protons: c_p = (2.3 ± 0.2) × 10^{-16} cm²
- 24 GeV protons: c_p = (2.94 ± 0.03) × 10^{-16} cm²

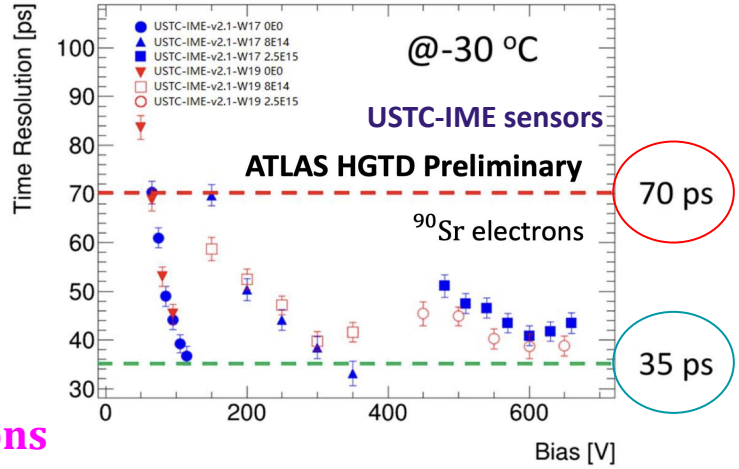
Only protons

The value of the acceptor removal coefficient for neutron irradiation is 1.2 x 10^{-16} cm² , whereas preliminary results for proton irradiation indicate a c-value between 2 and 3 times that of neutrons, depending on the proton energy.

HGTD LGAD hadron irradiation results

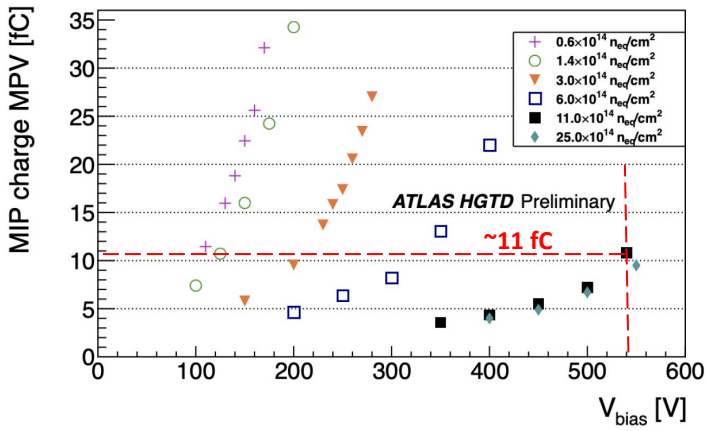
IHEP-IME pre-production sensors, T = -30°C, 24 GeV protons





protons+ neutrons

IHEP-IME production sensors, T = -30°C, 24 MeV protons



- LGAD performance degrades with radiation exposure due to a loss of gain
  - Recovered by increasing the bias
    - Limit imposed by ***Single Event Burnout*** **(SEB)** effect (local breakdown of electric field) → V_{max} ~ 550 V for 50 µm thickness
- Carbon-enriched gain layer → **slower acceptor removal** → better radiation hardness

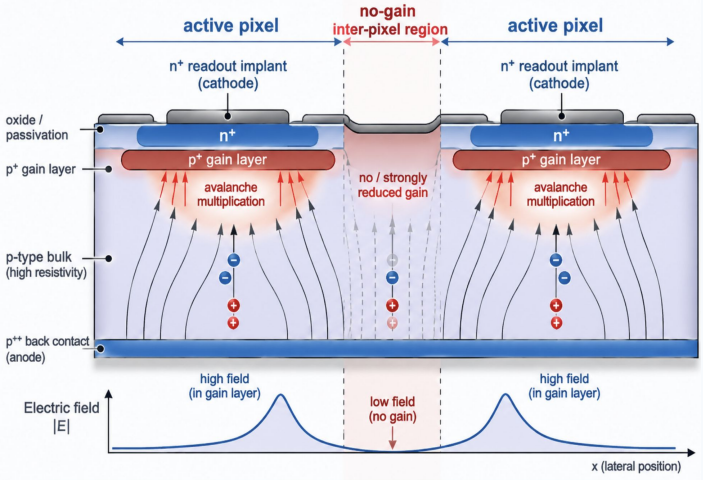
Mixed irradiation in HGTD paper submitted

Sensors meet 4 fC MIP MPV requirement up to ~2.5×10^{15} n_{eq}/cm² (End-of-Lifetime fluence)

Beyond HGTD: TI-LGADs for future 4D tracking

See Gregor's slides on DRD3; see more: I. Velkovska *et al* 2025 *JINST* 20 C08023

1 LGAD challenge

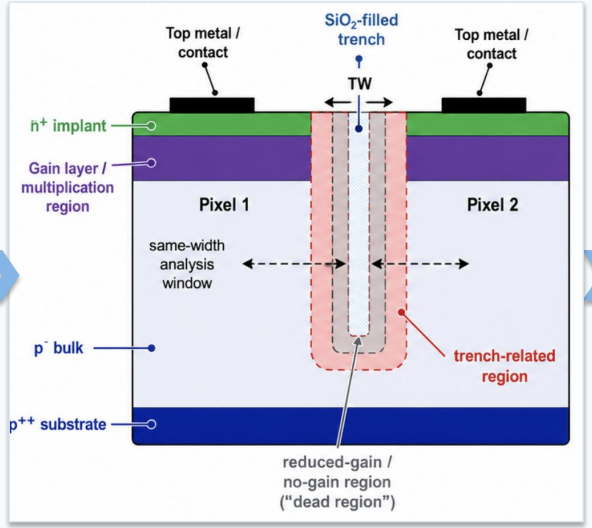


Reduced fill factor due to inactive area
Effect becomes more severe for smaller pixel pitch.

The inactive inter-pixel region reduces the fill factor, with a larger relative impact as pixel pitch decreases. TI-LGADs address this by using trench isolation to minimize the dead area.

2 TI-LGAD solution

Trench isolation pushes the inactive region to a minimum.

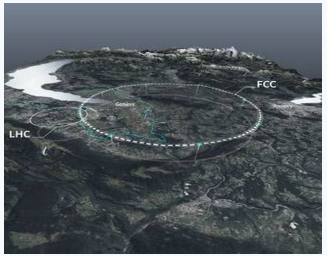


- **Sensor with small pixels (~100×100 µm² or smaller)**
- **high fill factor (95 % or higher)**

3 Why this is exciting?



Candidate technology for future 4D tracking
ATLAS HGTD replacement of damaged sensors during HL-LHC/outer disk layers in CMS/ATLAS Phase 3
· future lepton colliders

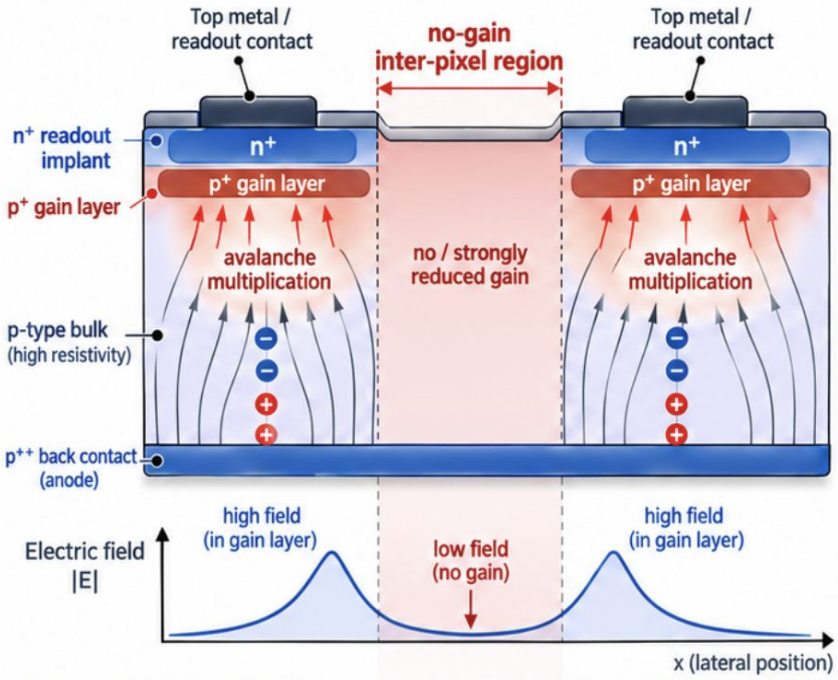


• future collider trackers need time + position with minimal dead area

TI-LGADs target the combination of **high fill factor**, **small pixels** and **precision timing** for next-generation tracking.

Standard segmented LGAD

Wide no-gain inter-pixel region limits the fill factor, especially for small pixel pitch.

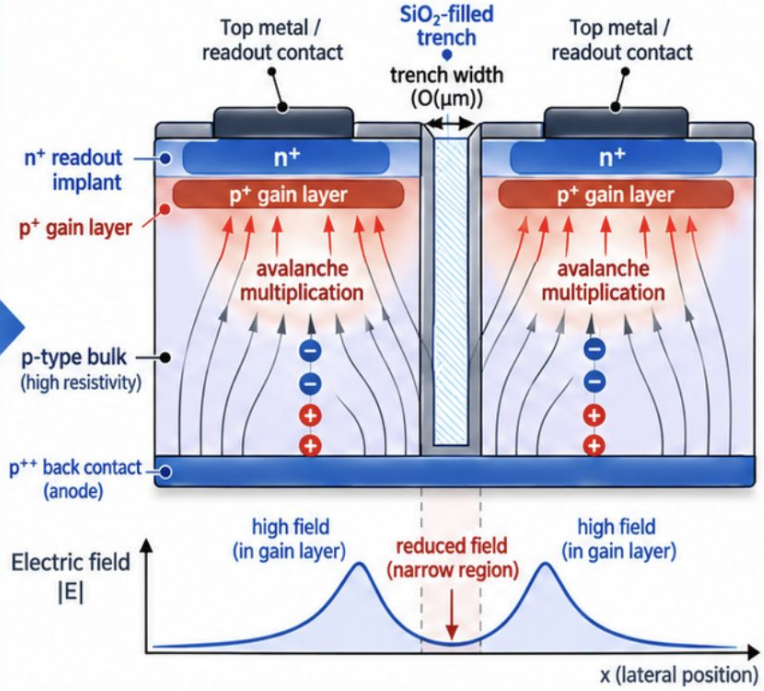


Reduced fill factor

Larger relative dead area for smaller pixel pitch.

TI-LGAD

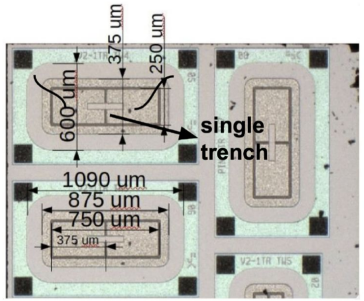
Trench isolation confines the inactive region to a minimum, maintaining a high fill factor even for small pixels.



Inactive region pushed to a minimum

High fill factor, enabling small pixels.

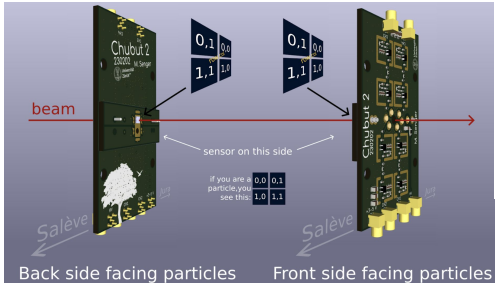
2–year extensive beam-test characterization of TI-LGADs

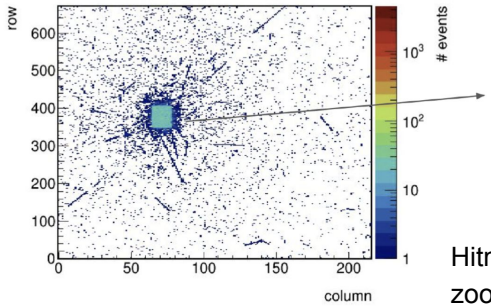


- Tested various designs of trench depth and trench width
- **375 µm × 250 µm pixel pitch, 45-55 µm thickness**
- Multiple TI-LGAD designs tested at normal incidence and at different tilt angles

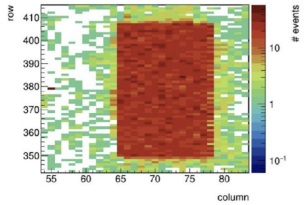


@ DESY Bremsstrahlung/conversion beam with electron energy up to 6 GeV



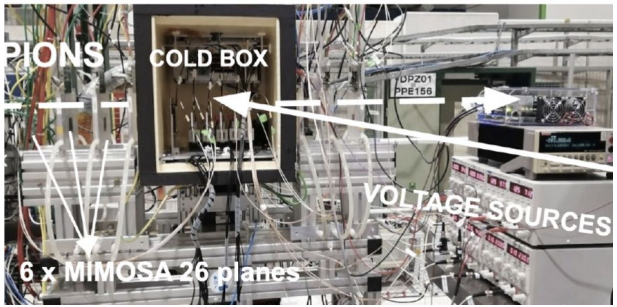


@ CERN SPS



Hitmap of the CROC; zoomed-in ROI corresponding to the position of the HPK LGAD





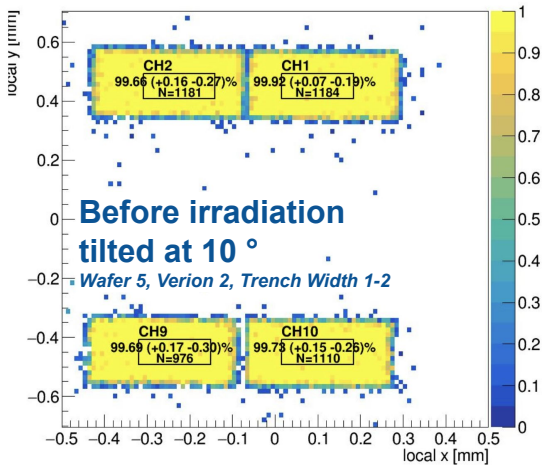
- 120 GeV pion beam
- EUDET beam telescope with MIMOSA26 sensors (18 µm pitch)
- CMS ReadOut Chip for ROI selection (CROC); Chubut readout boards
- Track reconstruction using **Corryvreckan software**
- CAEN DT5742 digitizer, 500 MHz @ 5 GS/s

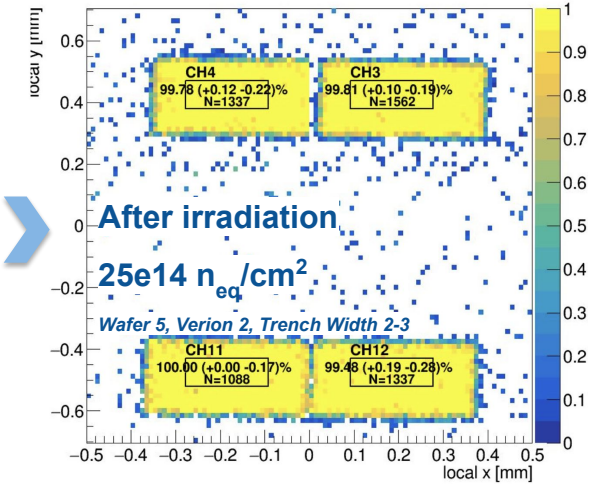


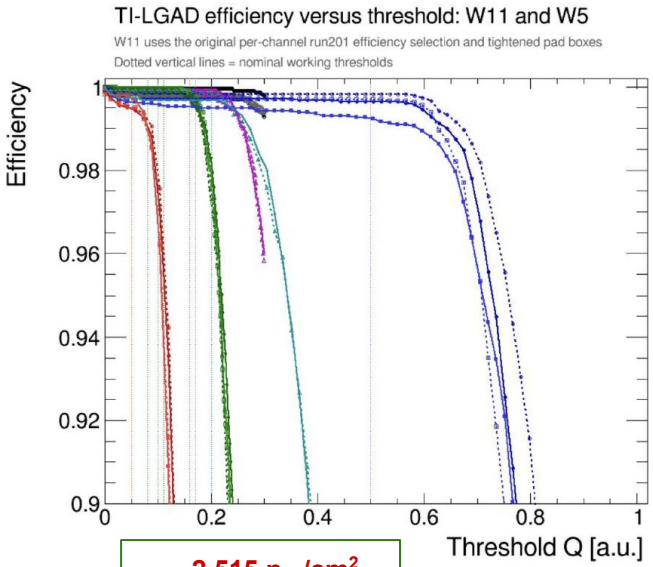


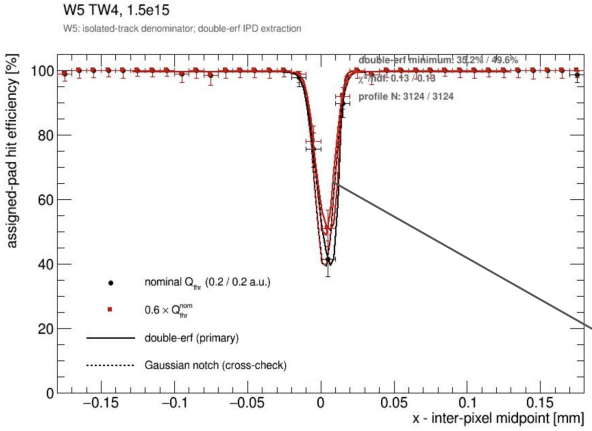
TI-LGADs beam test results

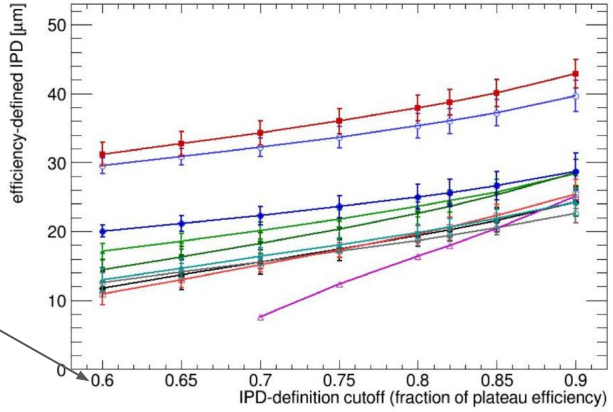
Efficiency results









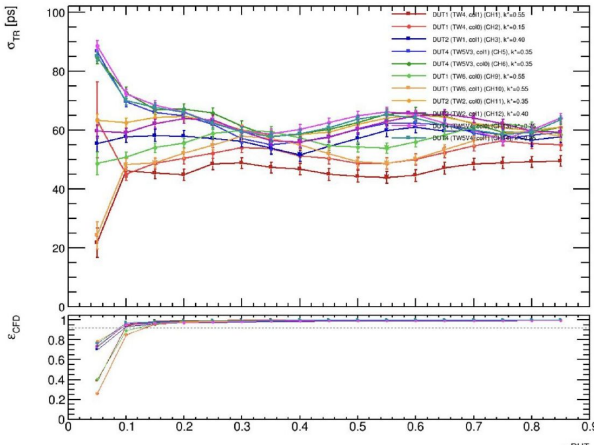


AIDAInnova Test beam paper in preparation

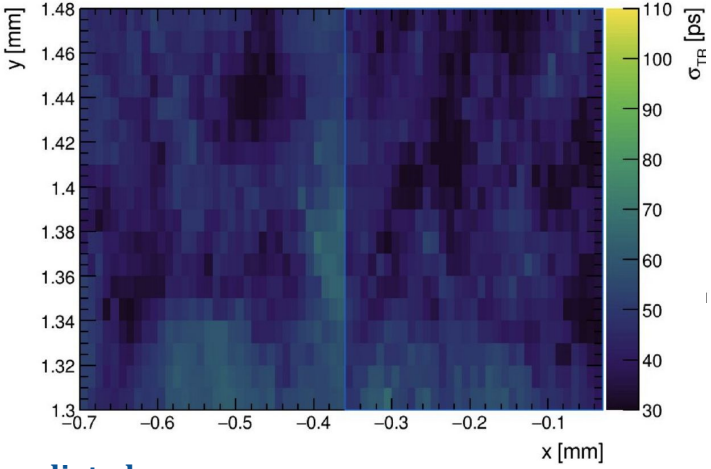
Lots of data analyzed…
13 TB of raw data in March alone

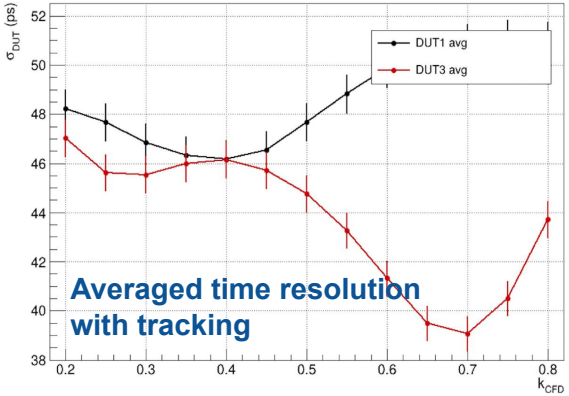
Timing performance before irradiation

Bulk time resolution ~ 40 - 42 ps

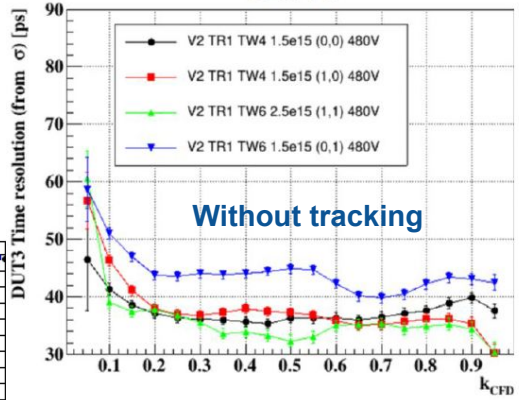


Timing across 2 pixels



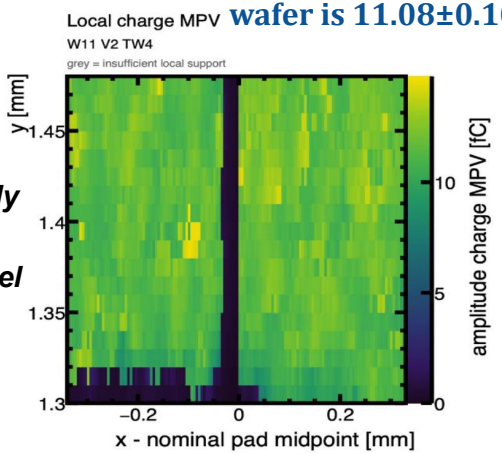


Averaged time resolution with tracking

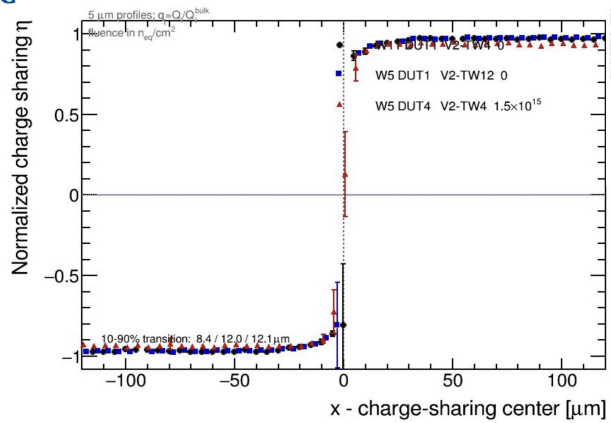


Without tracking

MPV for unirradiated wafer is 11.08±0.10 fC



The signal transfers sharply from one neighboring pixel to the other.

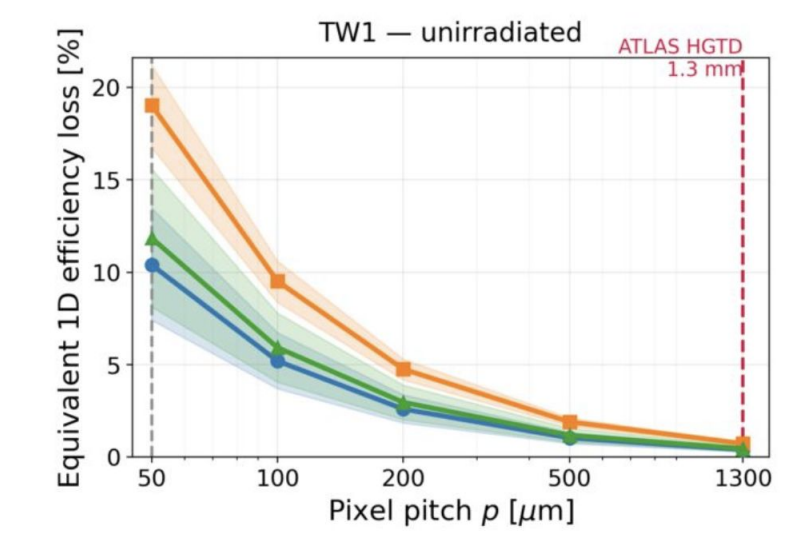


After irradiation: reduced gain → larger jitter → degraded time resolution **higher bias can compensate**

Future plans and objectives

Thank you for the attention!

Parametrisation of inter-pixel efficiency loss



Main message: the effective inactive width determines how much efficiency is lost as pixel pitch becomes smaller.

Key objectives

- Validate the parametrisation with existing test-beam data
- Use TCT to link local charge collection with expected beam efficiency
- Compare trench geometries and identify robust small-pixel designs

For published papers check:
https://orcid.org/0009-0009-4142-3409

Research timeline

- **Now** — Finalising measurements and analysis of testbeam data overall
- **2027** — Selecting best trench designs for high-fill-factor operation
- **Longer term** — design guidance for future 4D tracking sensors

Strategic goal: Generate and discuss predictive design rules for next-generation 4D trackers