LGAD at Collider Experiments

Yanwen Liu

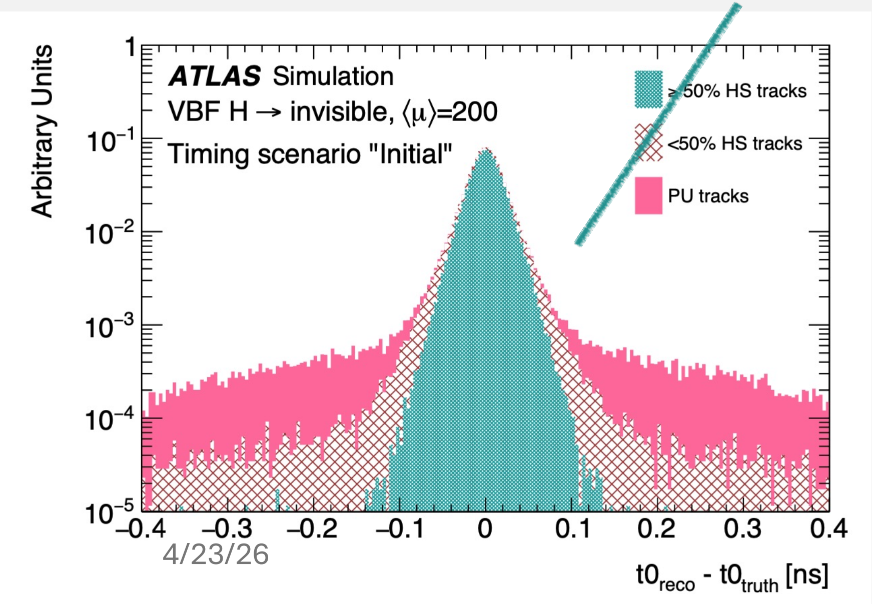
University of Science and Technology of China

Outline

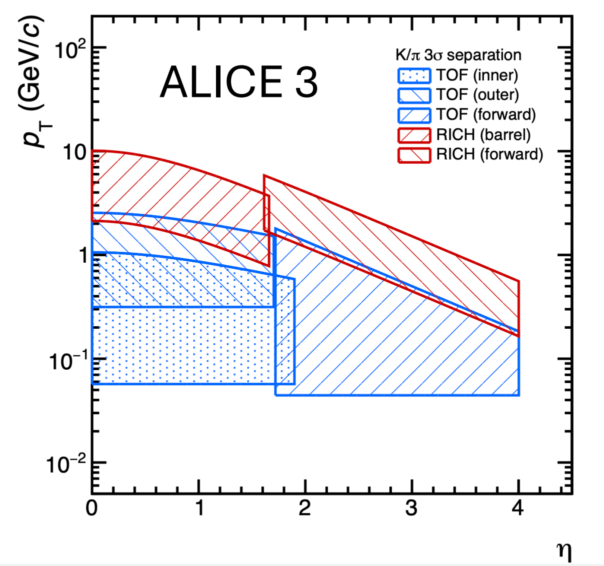
- Work principle of LGAD and early R&D
- Optimization for LHC phase 2 upgrade
- AC-LGAD for electron-ion colliders
- Trench-Isolated (TI) LGAD
- CMOS-LGAD

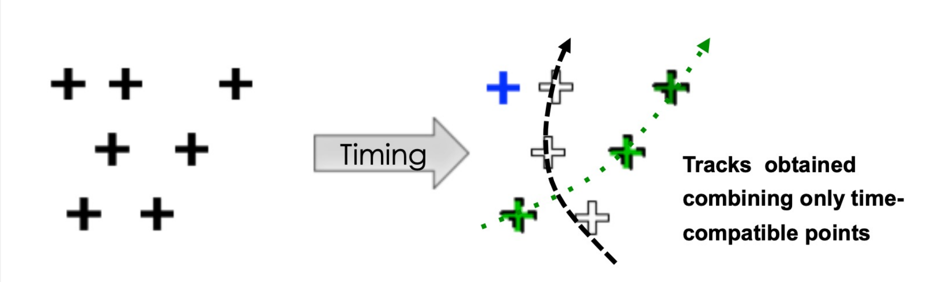
Applications of LGAD at collider experiments

- HL-LHC ATLAS/CMS: time information to tracks, vertices to mitigate pile-up (at peak luminosity, expect 200 pile-up per BX)
- EIC, ALICE 3 TOF for PID
- Future: 4D tracking



RMS = 22 ps



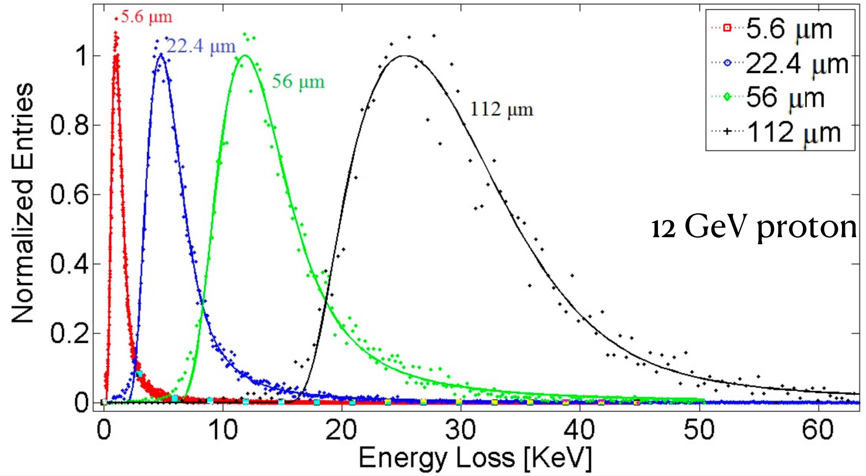


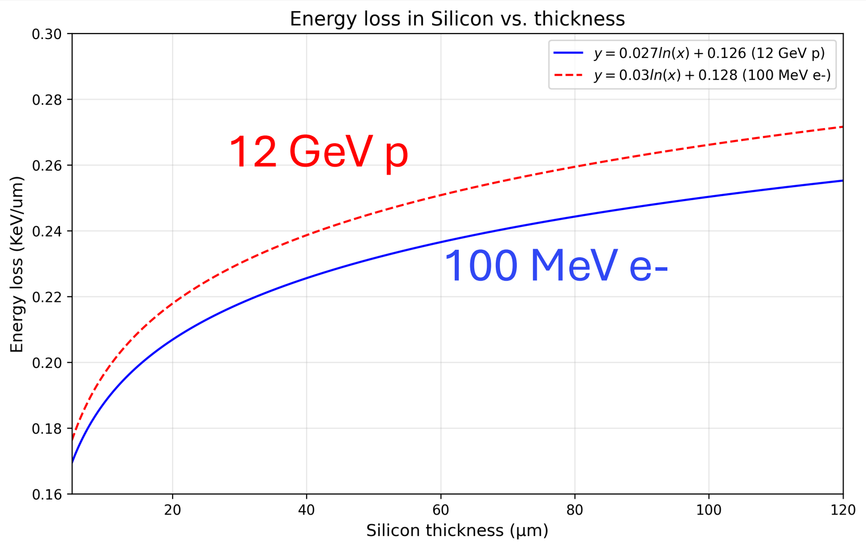
Tracks obtained combining only time-compatible points

Some numbers about Silicon detectors

- MIP E loss : 0.23 keV/μm (MPV for 50 μm thick Si)
- Average ionizing energy: 3.68 eV
- If no gain, 50 μm → ~0.5 fC

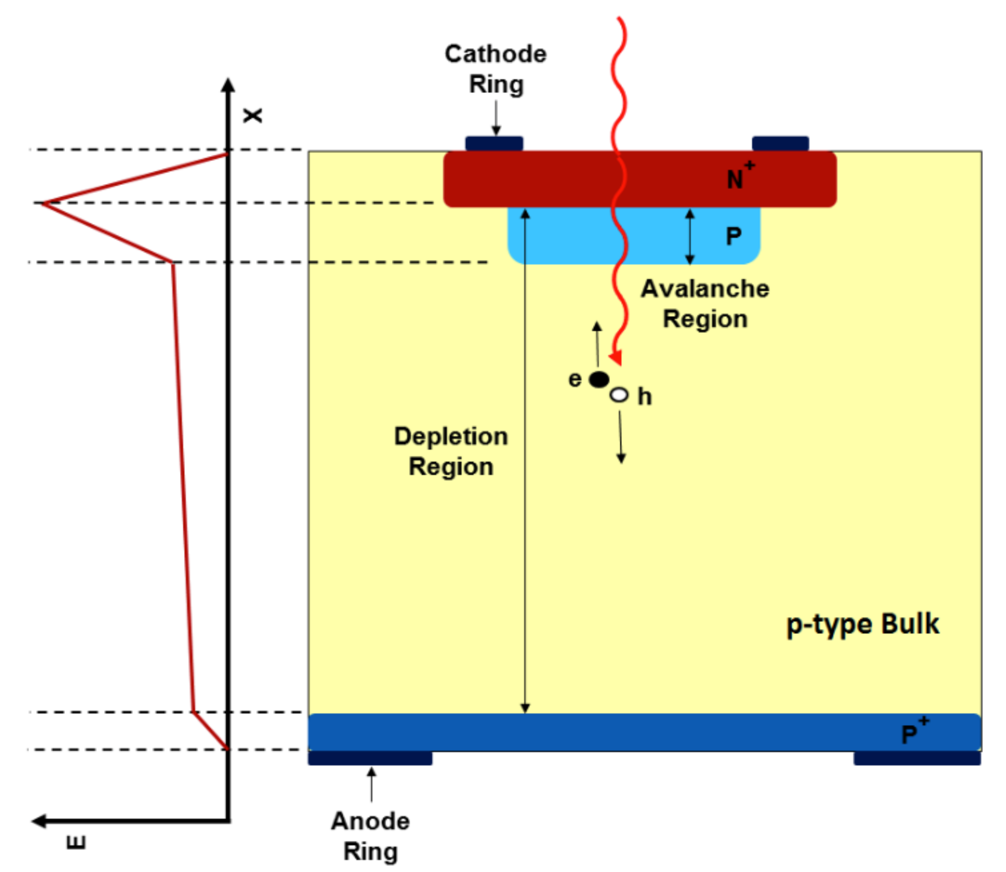
LGAD	Gain:5~20
APD	Gain: 50~1000
SiPM	Gain: 10^5~10^7

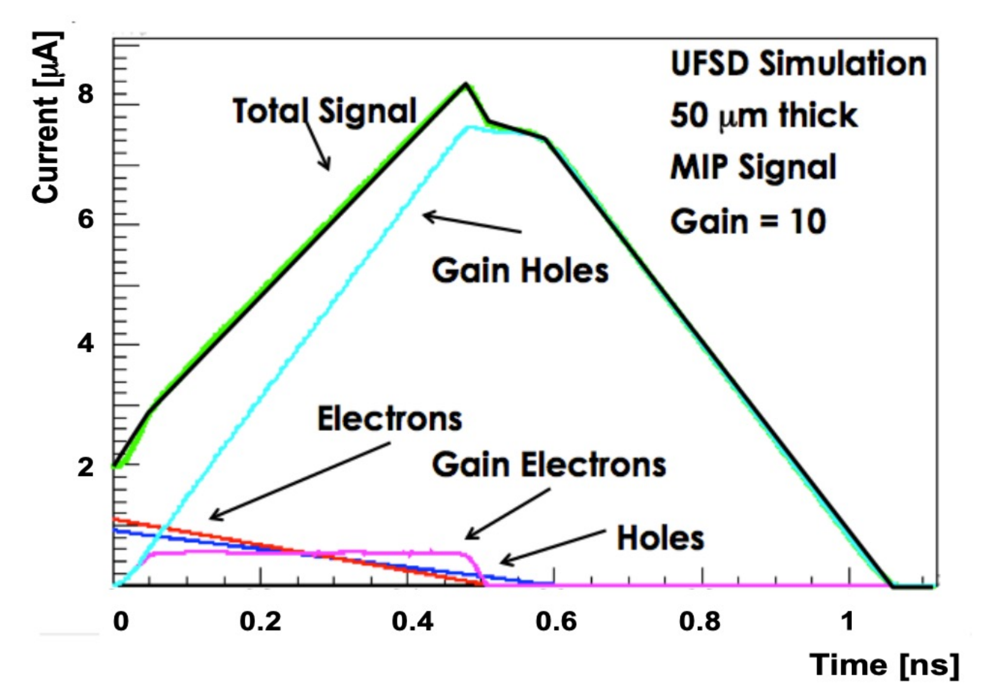




JINST 6 (2011) P06013

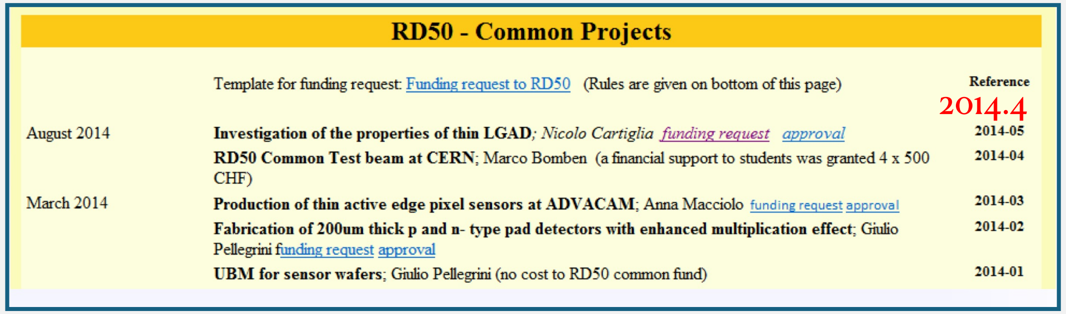
Work principle of Low Gain Avalanche Diode





Invention of LGAD

- 21st RD50 WS **2012**:charge multiplication in irradiated silicon detectors [talk]
- 25th RD50 WS **2014**: Common project to investigate thin LGAD (talk at CB)



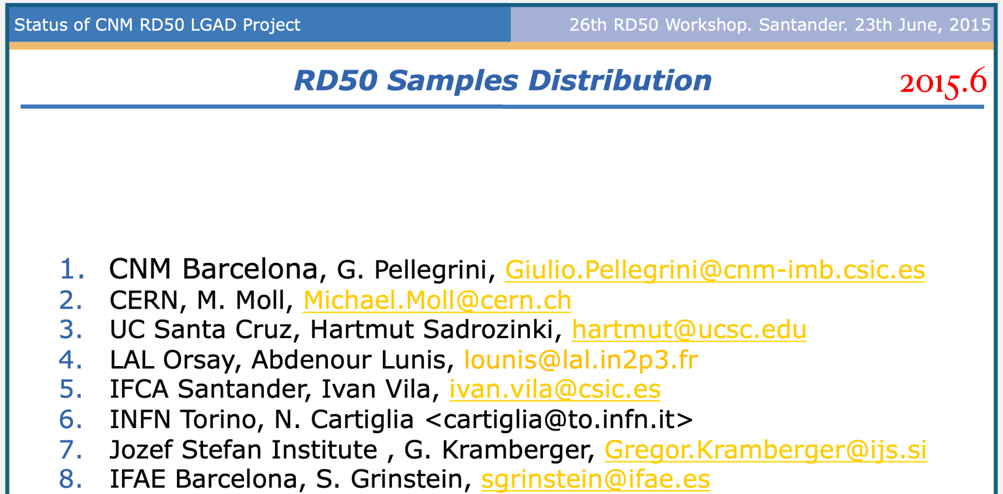
RD50 - Common Projects

	Template for funding request: Funding request to RD50 (Rules are given on bottom of this page)	**Reference**
August 2014	**Investigation of the properties of thin LGAD**; *Nicolo Cartiglia* *funding request* *approval*	**2014-05**
	RD50 Common Test beam at CERN; Marco Bomben (a financial support to students was granted 4 x 500 CHF)	**2014-04**
March 2014	**Production of thin active edge pixel sensors at ADVACAM**; Anna Macciolo funding request approval	**2014-03**
	Fabrication of 200um thick p and n- type pad detectors with enhanced multiplication effect; Giulio Pellegrini funding request approval	**2014-02**
	UBM for sensor wafers; Giulio Pellegrini (no cost to RD50 common fund)	**2014-01**

2014.4

Radiation hard semiconductor devices for very high luminosity colliders

2004-2024 (evolved to DRD3)

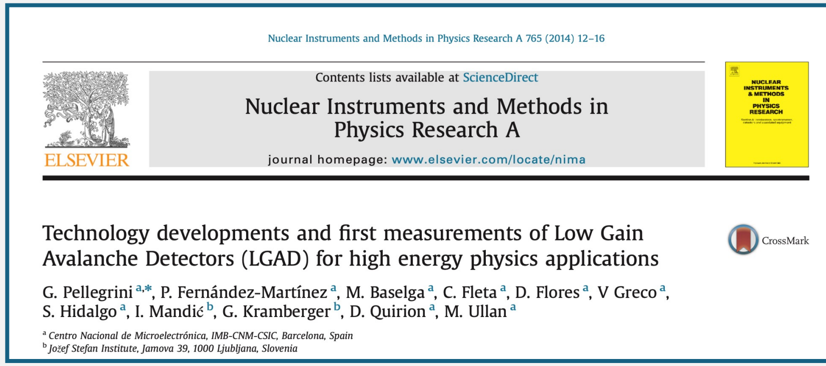


Status of CNM RD50 LGAD Project 26th RD50 Workshop. Santander. 23th June, 2015

RD50 Samples Distribution 2015.6

1. CNM Barcelona, G. Pellegrini, Giulio.Pellegrini@cnm-imb.csic.es
2. CERN, M. Moll, Michael.Moll@cern.ch
3. UC Santa Cruz, Hartmut Sadrozinki, hartmut@ucsc.edu
4. LAL Orsay, Abdenour Lunis, lounis@lal.in2p3.fr
5. IFCA Santander, Ivan Vila, ivan.vila@csic.es
6. INFN Torino, N. Cartiglia <cartiglia@to.infn.it>
7. Jozef Stefan Institute , G. Kramberger, Gregor.Kramberger@ijs.si
8. IFAE Barcelona, S. Grinstein, sgrinstein@ifae.es

First paper on LGAD (2014.6)
300 μm thick!
Establsihed gain layer
No discussion about timing



Nuclear Instruments and Methods in Physics Research A 765 (2014) 12–16

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications

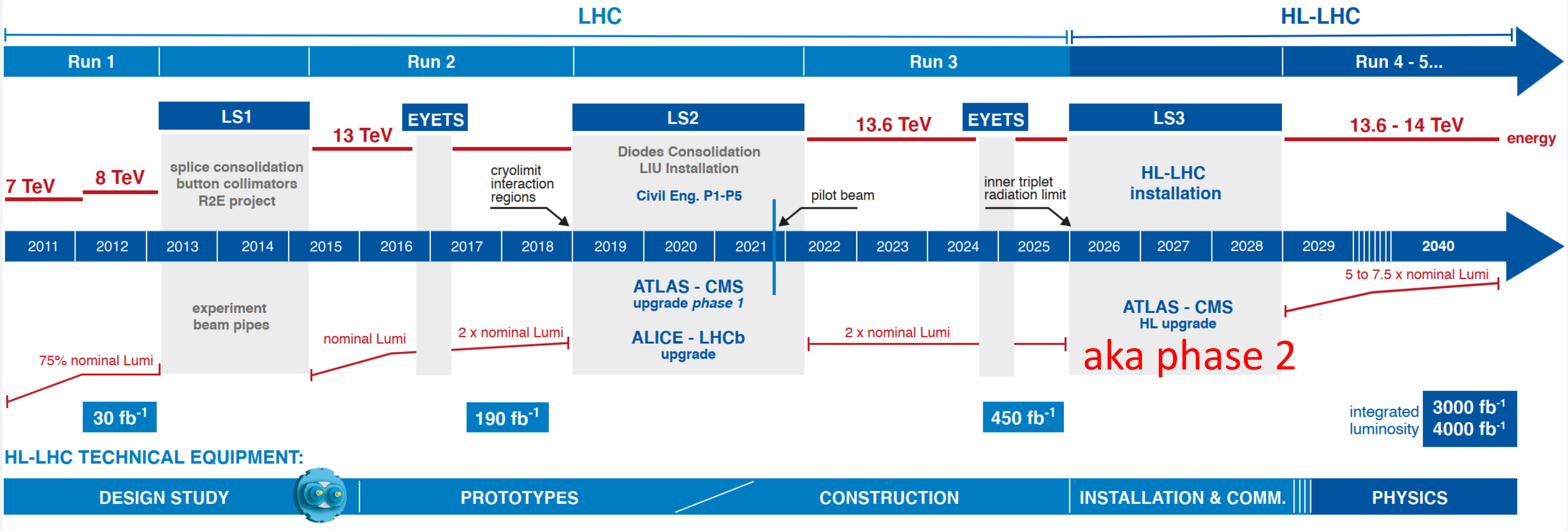
G. Pellegrini [a,*], P. Fernández-Martínez [a], M. Baselga [a], C. Fleta [a], D. Flores [a], V Greco [a], S. Hidalgo [a], I. Mandić [b], G. Kramberger [b], D. Quirion [a], M. Ullan [a]

[a] Centro Nacional de Microelectrónica, IMB-CNM-CSIC, Barcelona, Spain
[b] Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

High-luminosity LHC schedule

Phase 2 = 87% of LHC !

Current LS3 schedule: Jul 2026 ~ Jun 2030



LHC | HL-LHC

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LS1: splice consolidation, button collimators, R2E project; experiment beam pipes

EYETS

LS2: Diodes Consolidation, LIU Installation, Civil Eng. P1-P5; ATLAS - CMS upgrade *phase 1*; ALICE - LHCb upgrade

EYETS

LS3: HL-LHC installation; ATLAS - CMS HL upgrade

aka phase 2

energy: 7 TeV, 8 TeV, 13 TeV, 13.6 TeV, 13.6 - 14 TeV

cryolimit interaction regions

pilot beam

inner triplet radiation limit

2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2040

75% nominal Lumi; nominal Lumi; 2 x nominal Lumi; 2 x nominal Lumi; 5 to 7.5 x nominal Lumi

integrated luminosity: 30 fb^{-1}, 190 fb^{-1}, 450 fb^{-1}, 3000 fb^{-1}, 4000 fb^{-1}

HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY | PROTOTYPES | CONSTRUCTION | INSTALLATION & COMM. | PHYSICS

Rept.Prog.Phys. 81 (2018) 2, 026101

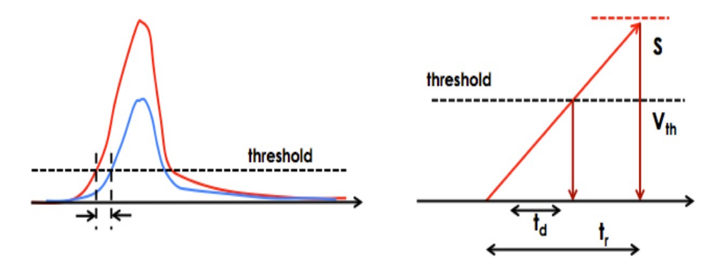
Key points for timing: low gain and thin!

- Time resolution decomposition

$$\sigma_t^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{jitter}}^2 + \boxed{\sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2}$$

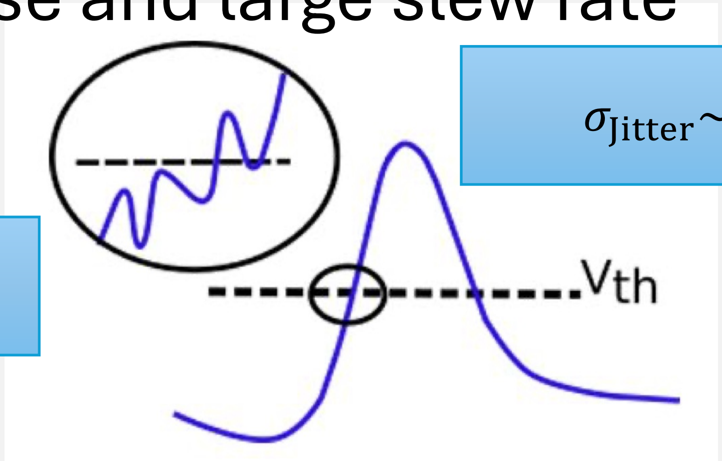
Often negligible

- Landau: fluctuation of energy deposition
  - Mitigation: thin sensors
- Distortion: non-uniformity of drift velocity and weighting field
  - Mitigation: planar and thin sensor, high E-field to saturate drift velocity
- Time-walk and jitter minimized by low noise and large slew rate



$$t_d = \frac{V_{\text{th}}}{S} t_{\text{rise}} \propto \frac{\text{Noise}}{S/t_{\text{rise}}}$$

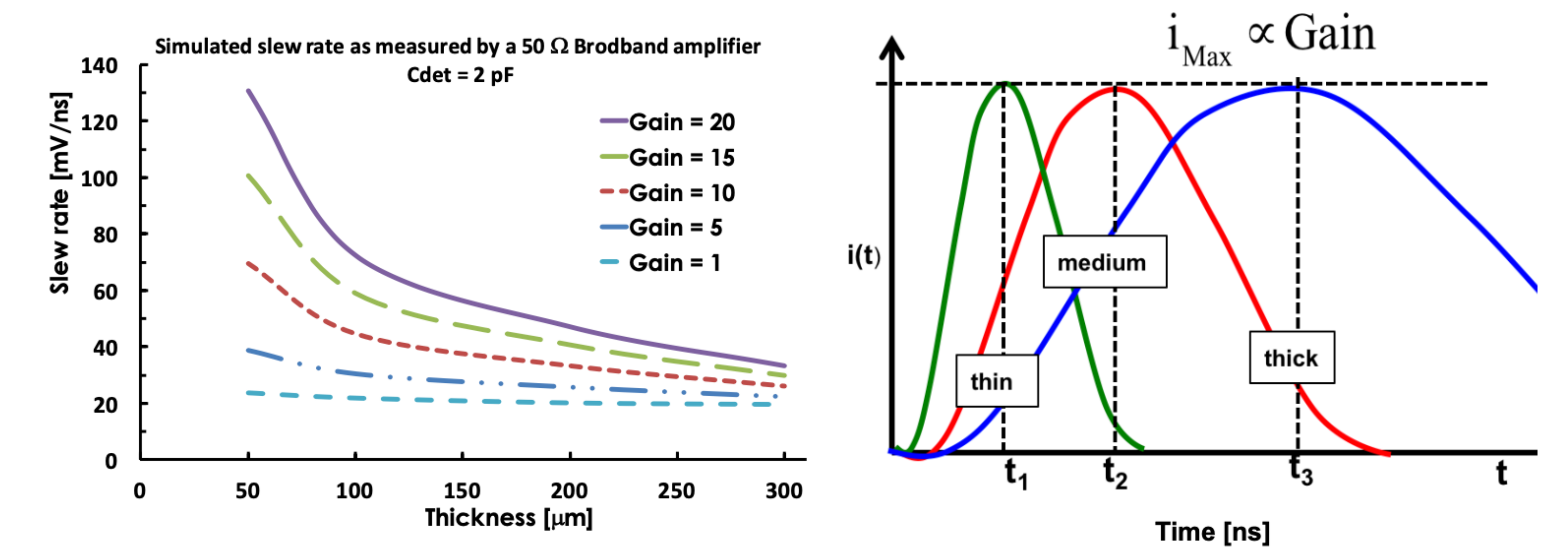
$$\sigma_{\text{TimeWalk}} \sim \text{RMS}[t_d] \sim \text{RMS}[\frac{\text{Noise}}{S/t_{\text{rise}}}]$$



$$\sigma_{\text{Jitter}} \sim \frac{\text{Noise}}{S/t_{\text{rise}}}$$

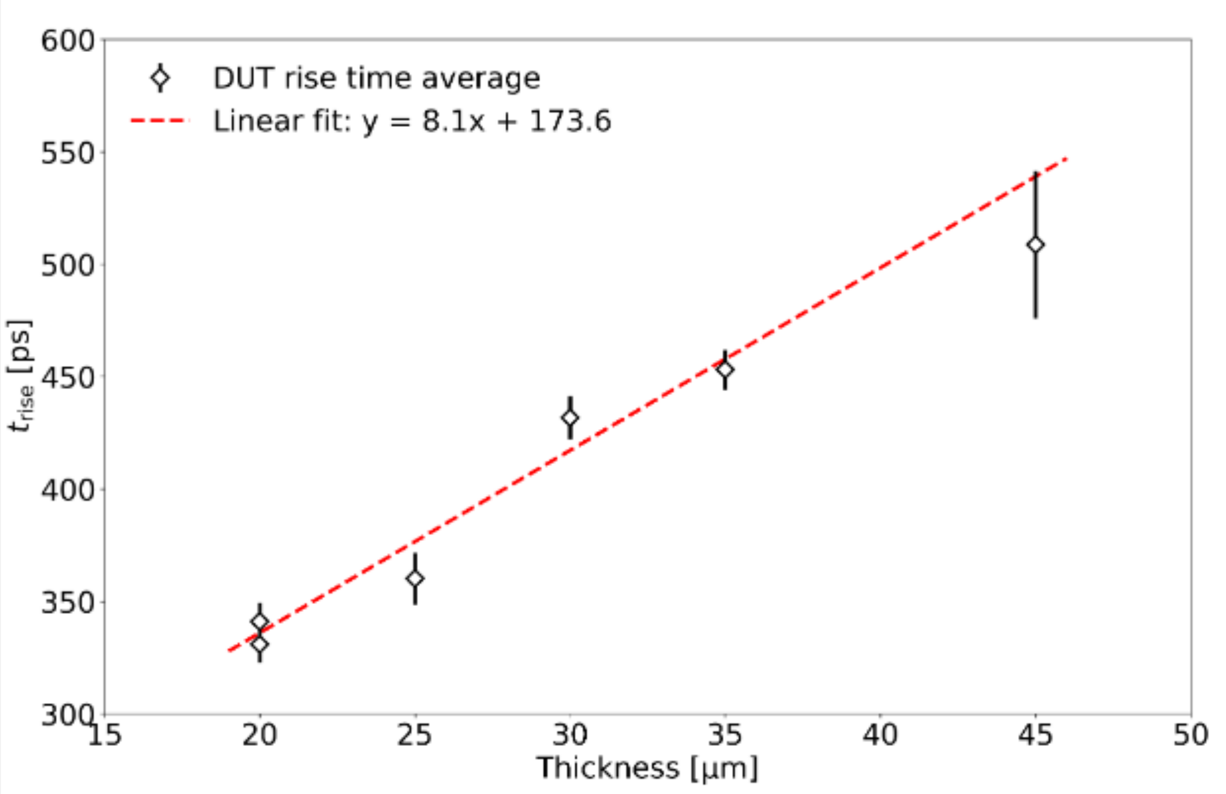
Slew rate vs. thickness

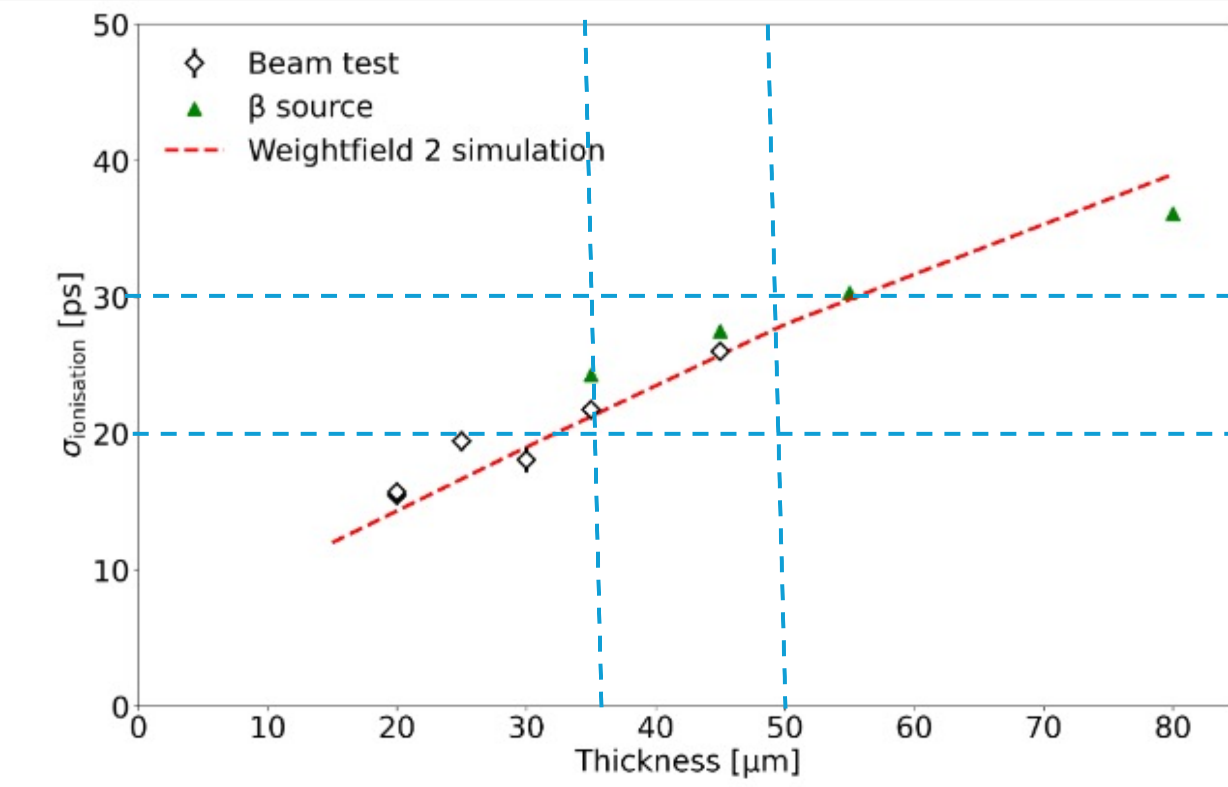
$i_{\max}$ independent of thickness
Thinner sensor => higher slew rate



arXiv:2511.22308

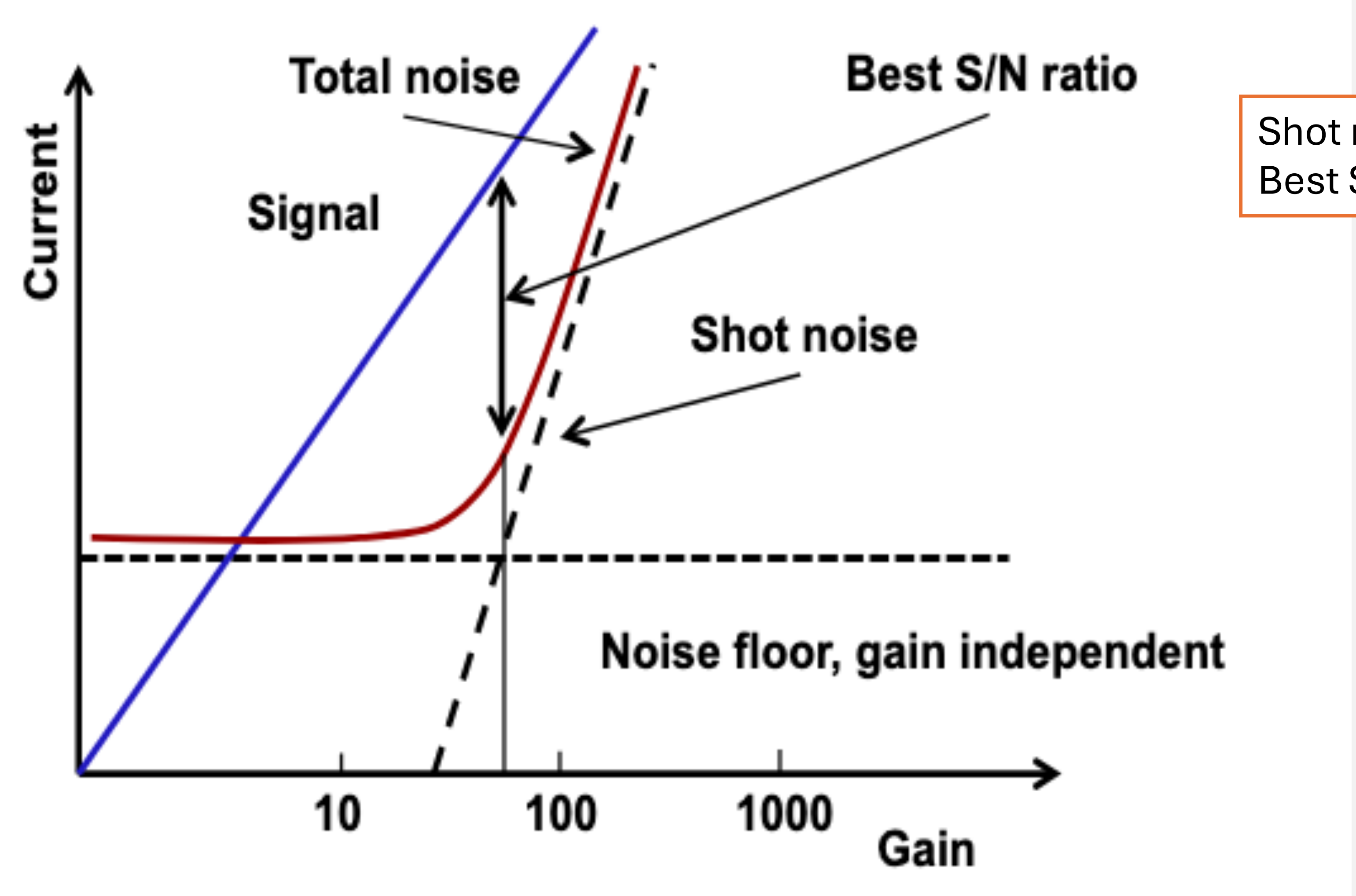
Systematic experimental verification (2025)





50 μm → ~ 30 ps
35 μm → ~ 22 ps

Gain optimization

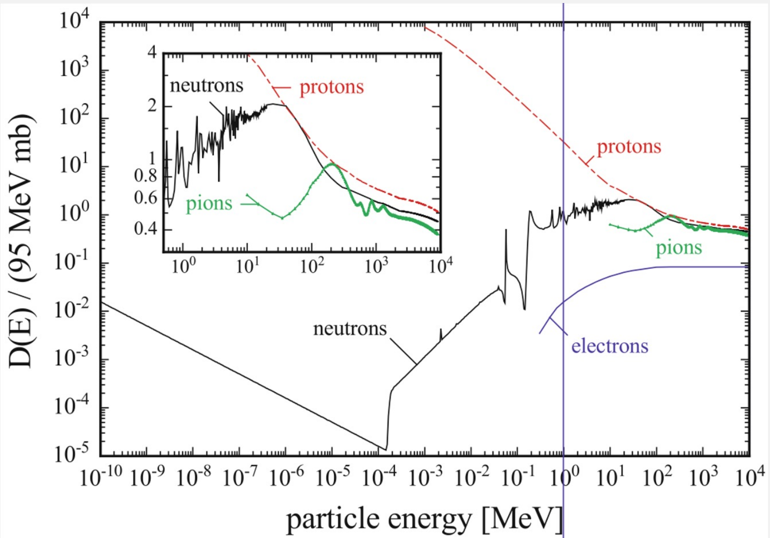


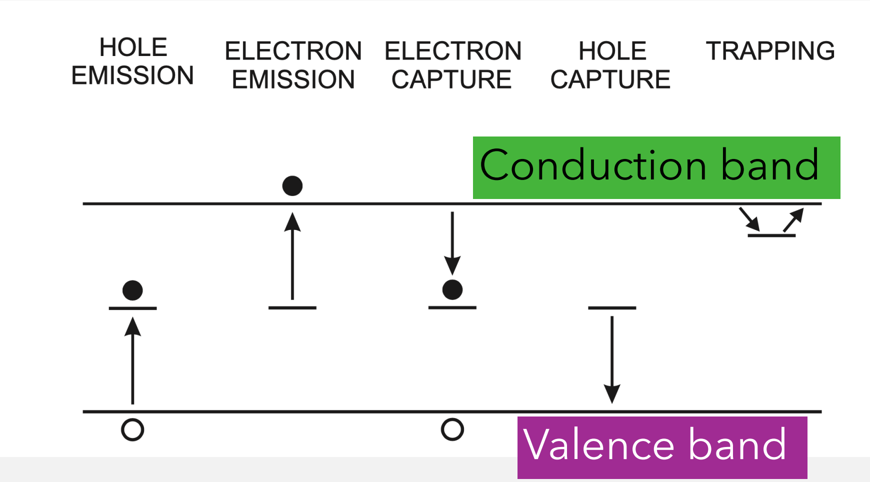
Shot noise increase with bulk leakage current
Best S/N achieved at gain of few 10s

Radiation damages to LGAD

- **Ionizing damage**: energy absorbed by ionizing(1 Gy = 1 J/kg = 100 rad) in insulating layers, liberates charge carriers (less relevant for sensors)
- **Displacement damage**(displaces silicon atoms from their lattice sites)
  - Formation of mid-gap states => increase of leakage current
  - states close to band edges => trapping(decrease charge collection efficiency)
  - Inactivation of Boron doping(Acceptor removal)
  - Energy and particle type dependent (measured in 1 MeV neutron equivalent / cm^2)

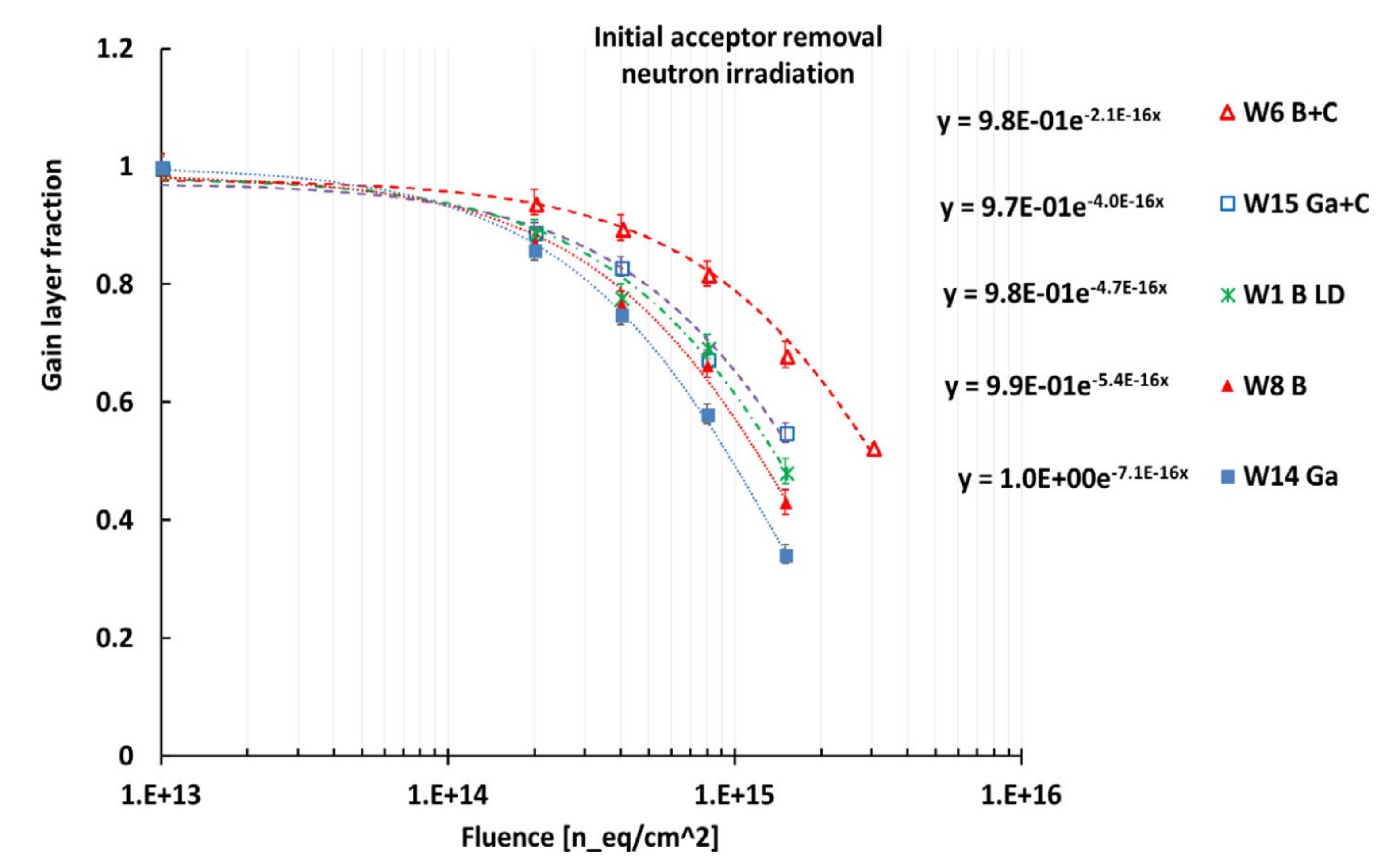
$$D(E) = \sum_{\nu} \sigma_{\nu}(E) \int_{0}^{E_R^{max}} f_{\nu}(E, E_R) P(E_R) \mathrm{d}E_R$$





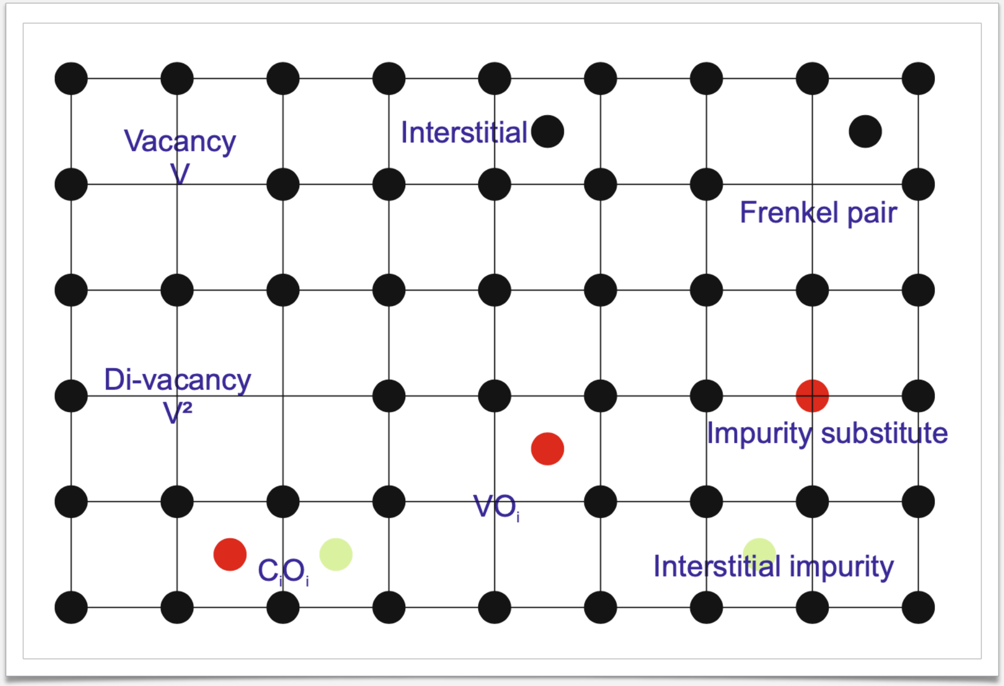
NIMA 910(2019)16

Co-implantation of gain layer

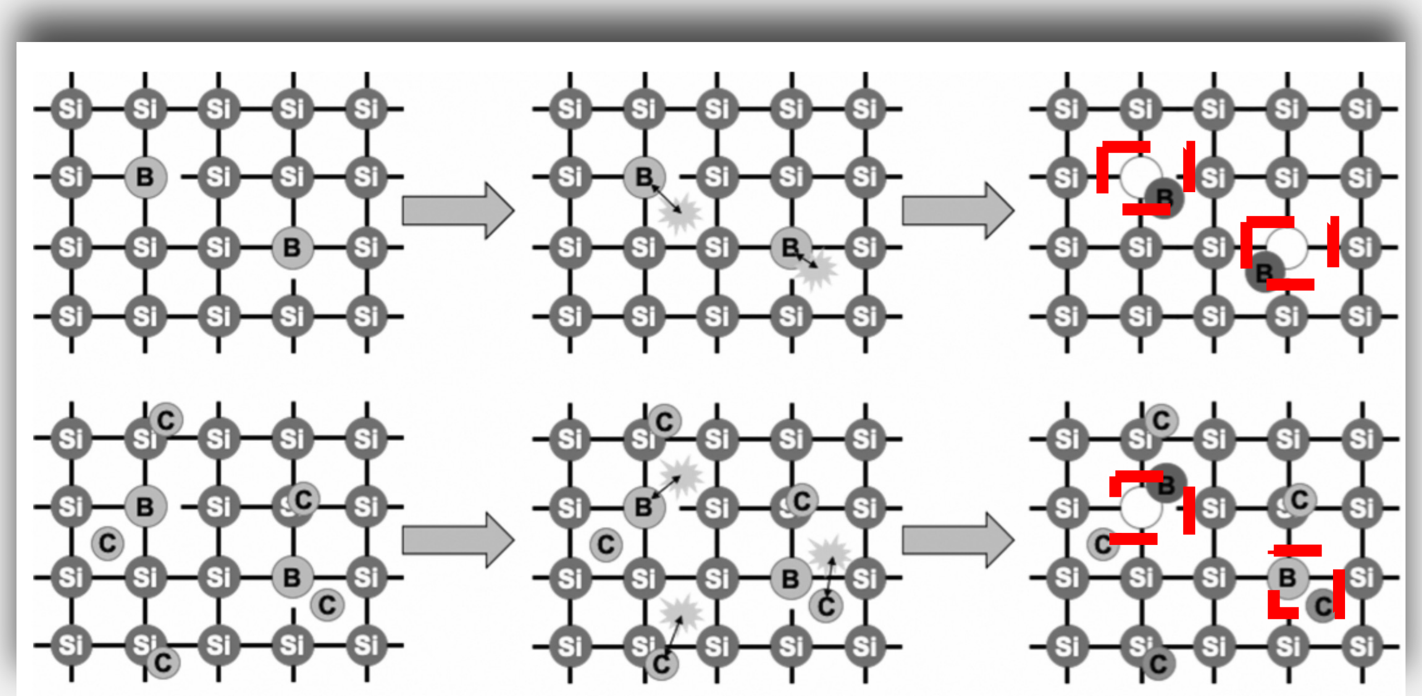


Effects of Carbon in gain layer (conjecture)

Defects in Silicon lattice



Carbon competes with Boron to form ion-defect states

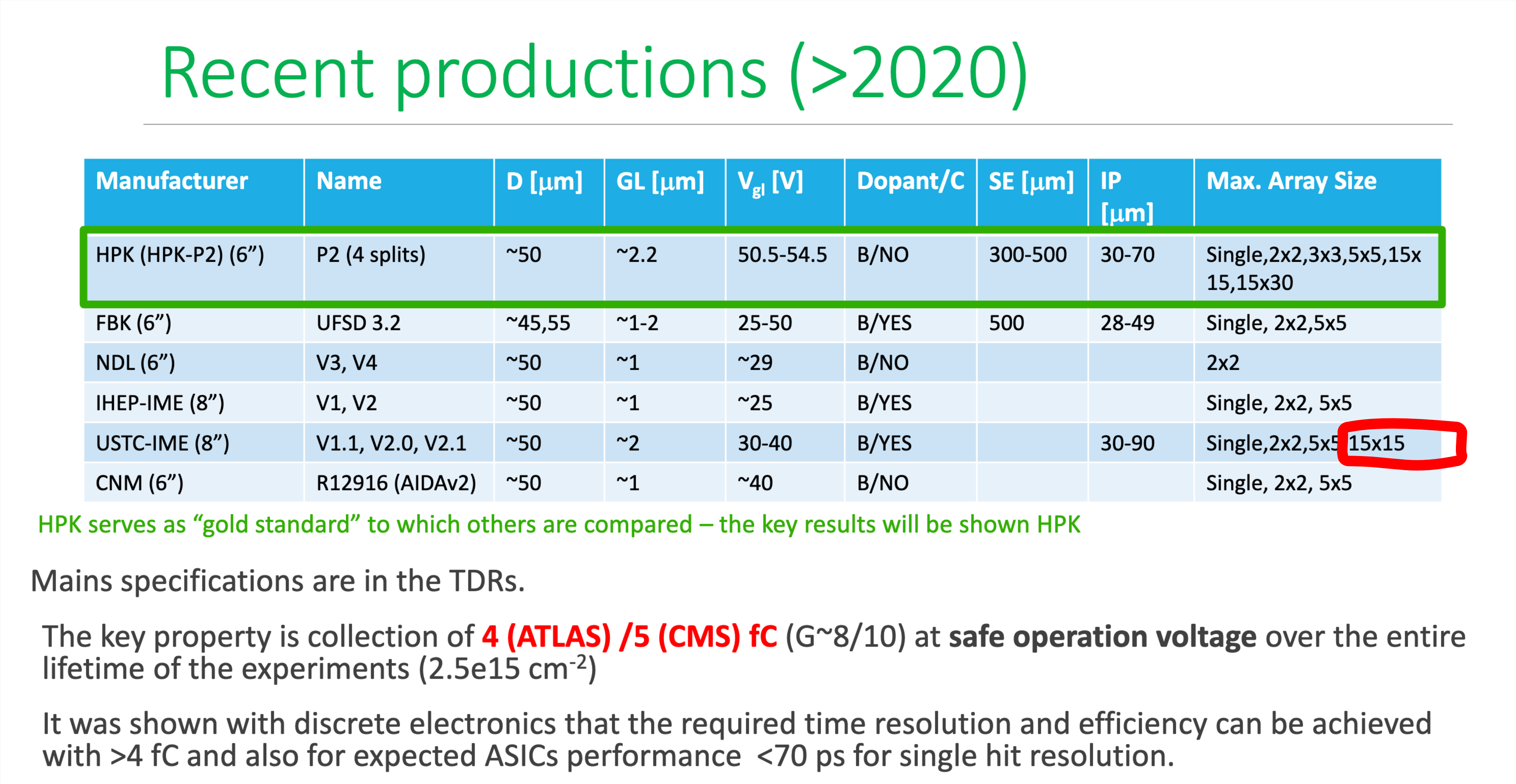


Carbon implantation at gain layer:

1) replace Boron in ion-defect complex formation
2) substitutional carbon pair with interstitial Boron to form centers with energy of 80% acceptor energy level

G. Kramberger CERN seminar talk (Nov. 5 2021)

Snapshot of sensor status in 2021



Recent productions (>2020)

Manufacturer	Name	D [μm]	GL [μm]	V_{gl} [V]	Dopant/C	SE [μm]	IP [μm]	Max. Array Size
HPK (HPK-P2) (6”)	P2 (4 splits)	~50	~2.2	50.5-54.5	B/NO	300-500	30-70	Single,2x2,3x3,5x5,15x15,15x30
FBK (6”)	UFSD 3.2	~45,55	~1-2	25-50	B/YES	500	28-49	Single, 2x2,5x5
NDL (6”)	V3, V4	~50	~1	~29	B/NO			2x2
IHEP-IME (8”)	V1, V2	~50	~1	~25	B/YES			Single, 2x2, 5x5
USTC-IME (8”)	V1.1, V2.0, V2.1	~50	~2	30-40	B/YES		30-90	Single,2x2,5x5,15x15
CNM (6”)	R12916 (AIDAv2)	~50	~1	~40	B/NO			Single, 2x2, 5x5

HPK serves as “gold standard” to which others are compared – the key results will be shown HPK

Mains specifications are in the TDRs.

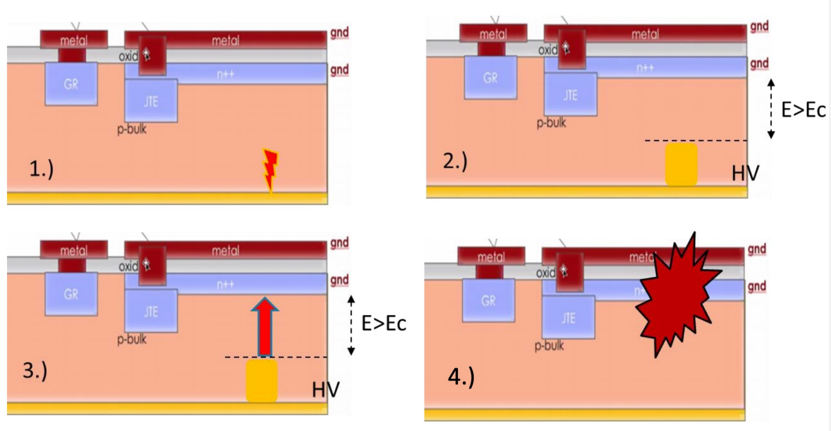
The key property is collection of **4 (ATLAS) /5 (CMS) fC** (G~8/10) at **safe operation voltage** over the entire lifetime of the experiments (2.5e15 cm^{-2})

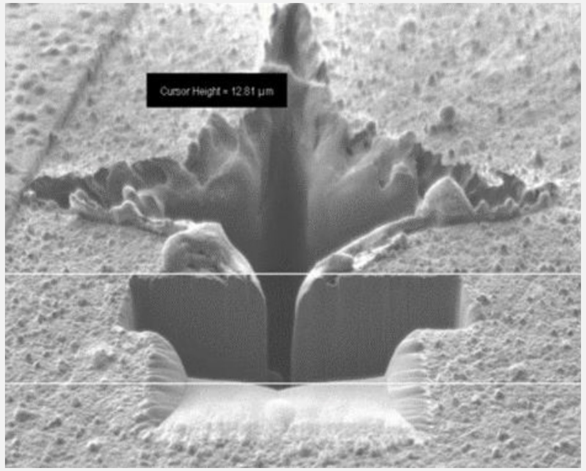
It was shown with discrete electronics that the required time resolution and efficiency can be achieved with >4 fC and also for expected ASICs performance <70 ps for single hit resolution.

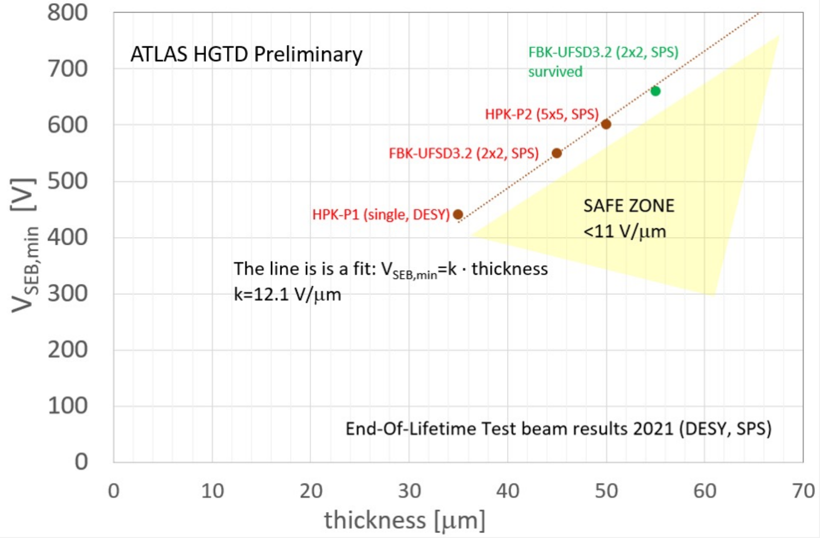
NIMA 1041(2022)167321

Sensor mortality

Large energy deposition →large amount of charge carriers → conductive path
→ localized high E-field (above critical E-field) → irreversible breakdown

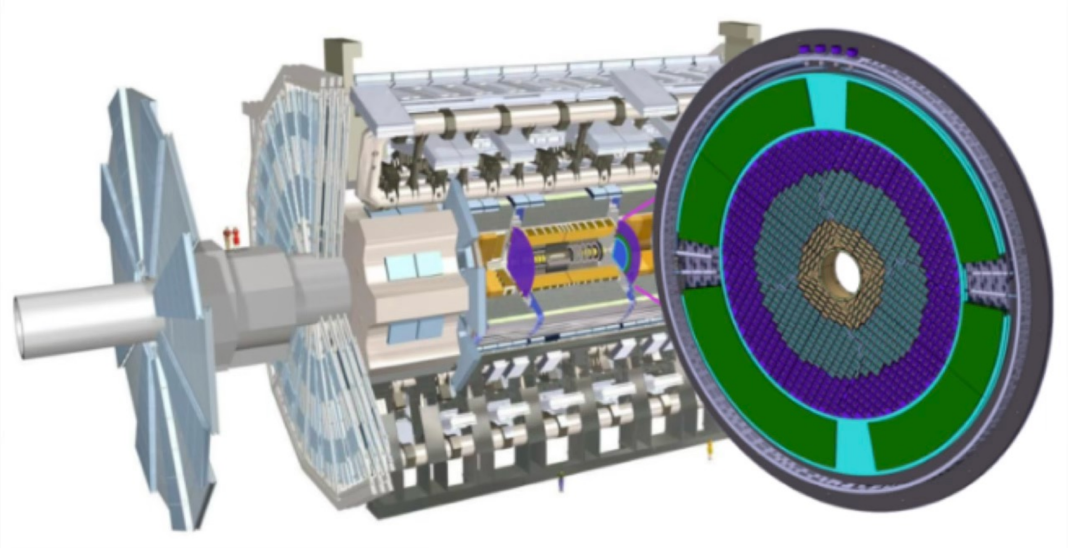




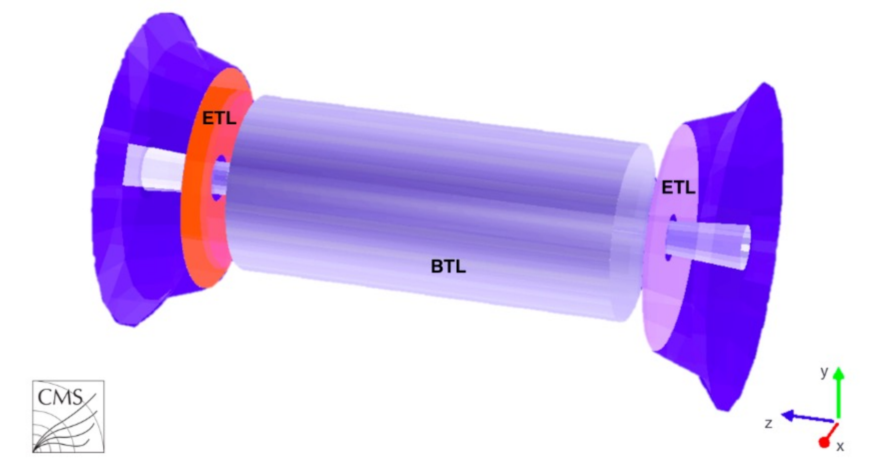


- Unrecoverable breakdown of irradiated sensors observed at proton/electron/laser beam
- “Crater” burn mark at the hit position of the beam particle
- Collaborative investigations at FNAL/DESY/ELI-Prague:
  reproduceable mortality with localized large energy deposition
- Safe bias V < 550 GeV for 50 um sensor

LGAD for ATLAS and CMS



ATLAS HGTD LGAD:15x15 array of 1.3 mm x 1.3 mm
total active area 6.4 m^2
~3.6 M channels
Suppliers: IHEP-IME, USTC-IME

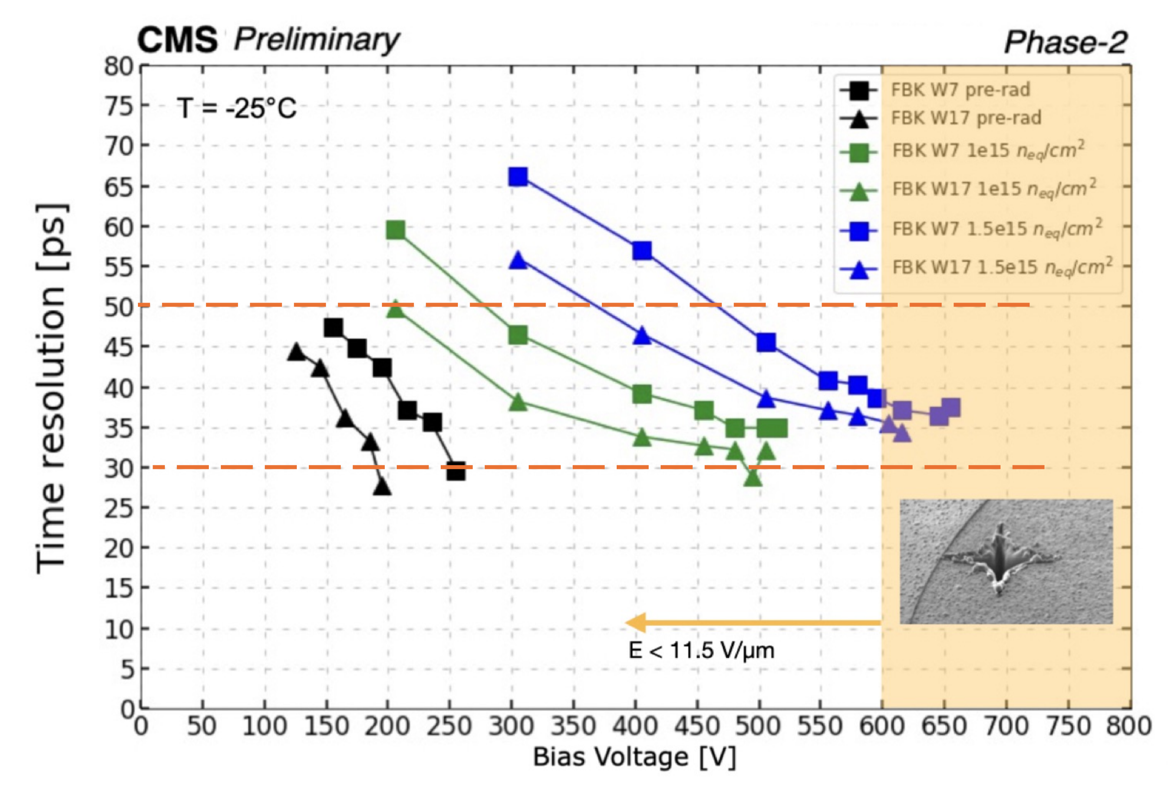


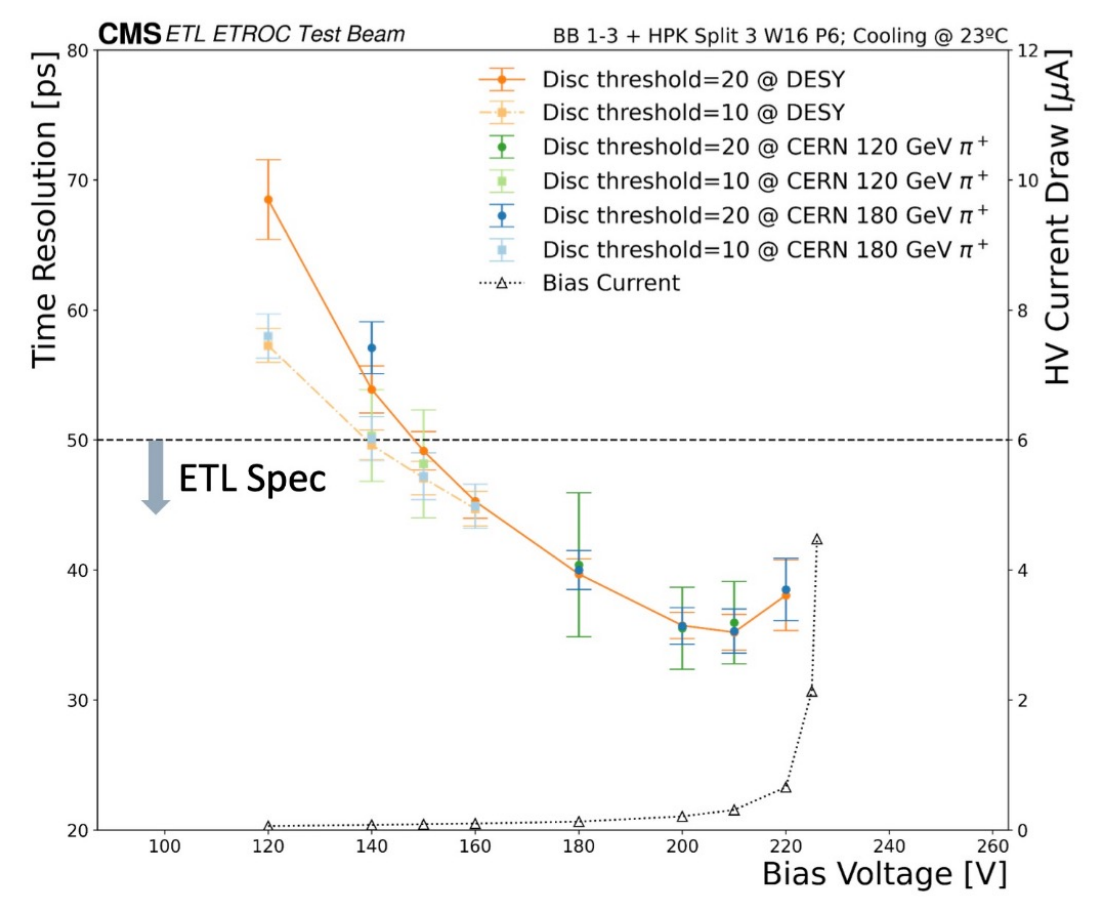
CMS ETL LGAD: 16x16 array of 1.3 mm x 1.3 mm
total active area 14.4 m^2
~8.5 M channels
Suppliers: FBK (LFoundtry), HPK

Some test results of production LGAD (CMS)

EPS HEP 2025

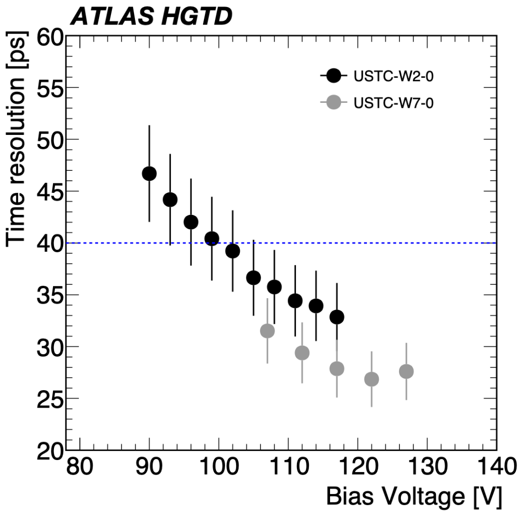
LP 2025 conference report

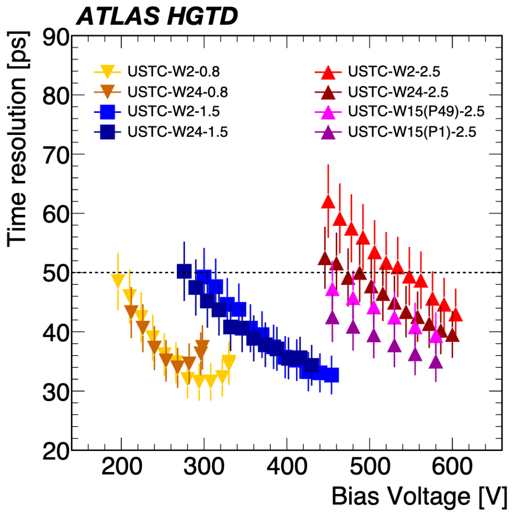


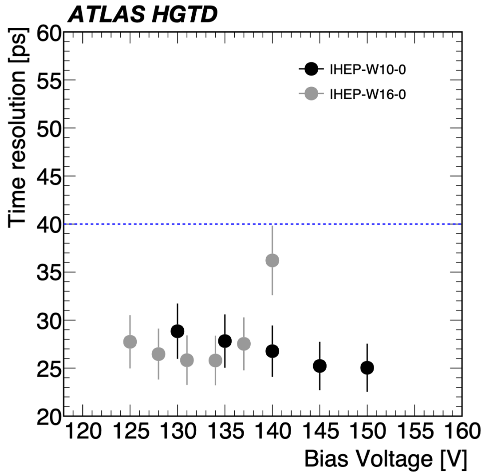


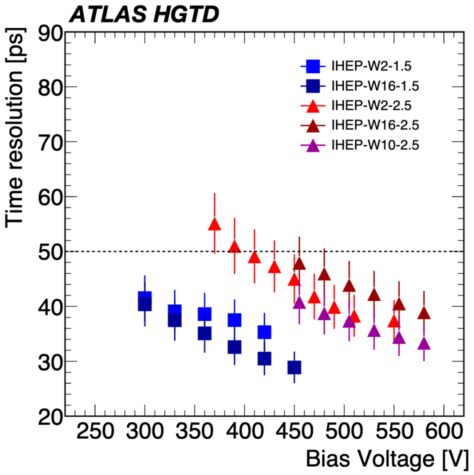
JINST 21(2026)P03021

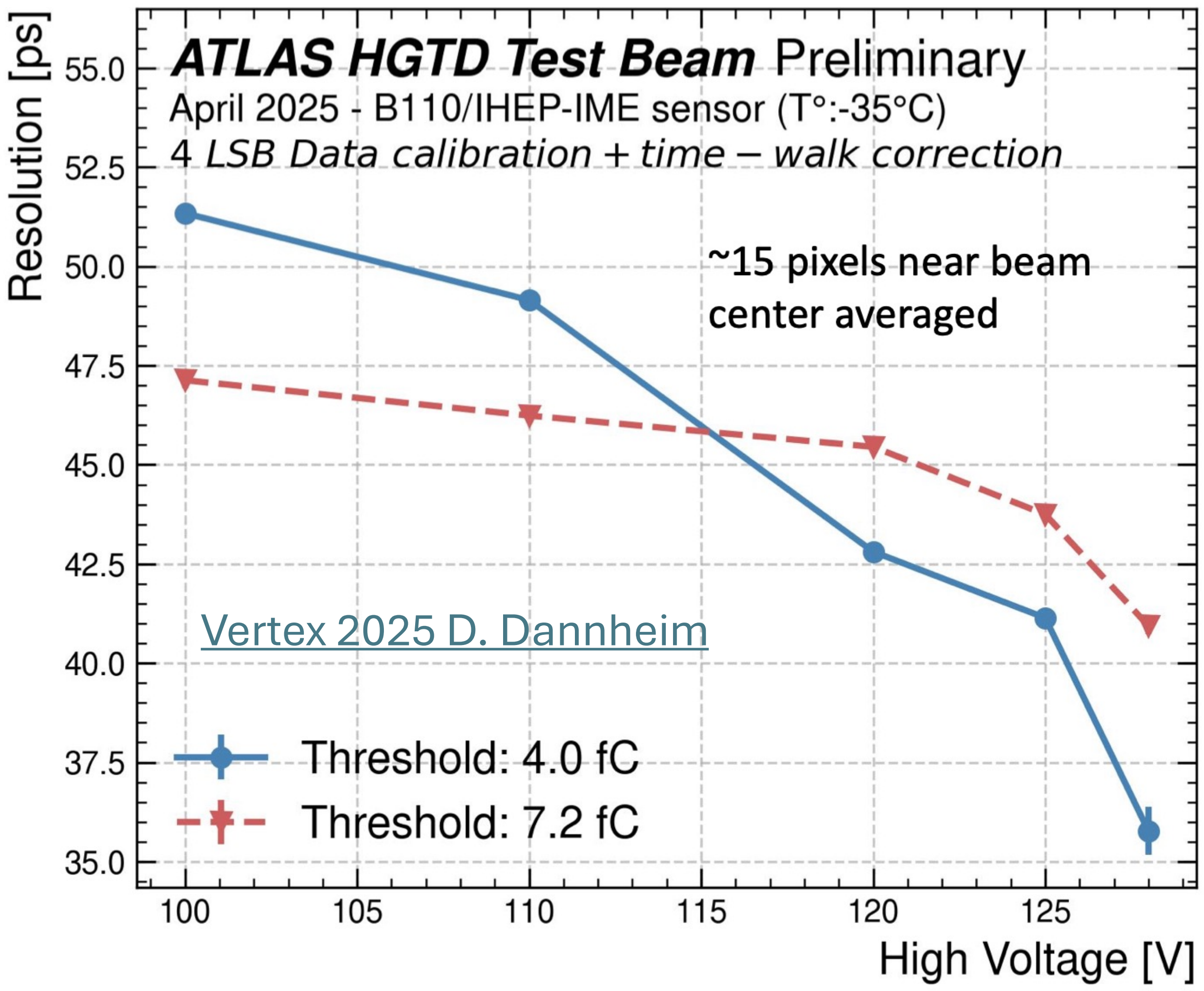
Some test results of production LGAD (ATLAS)





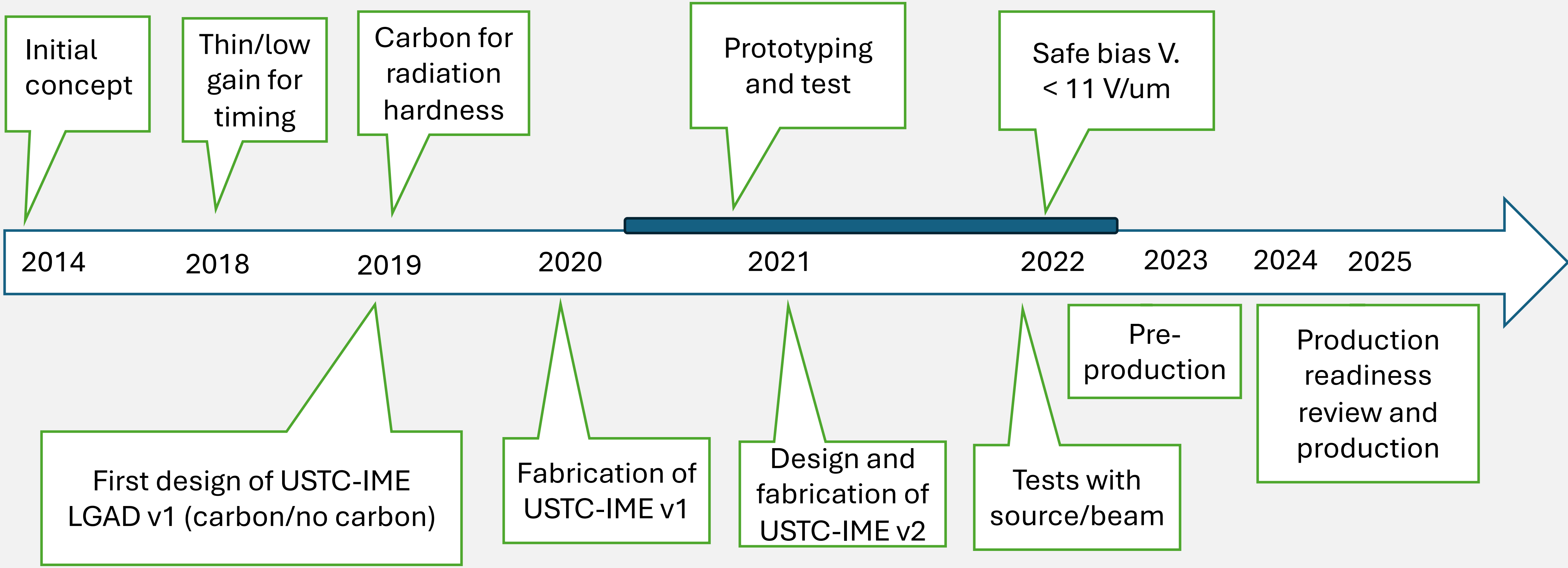






Vertex 2025 D. Dannheim

Recap of the LGAD RD for ATLAS/CMS



Initial concept

Thin/low gain for timing

Carbon for radiation hardness

Prototyping and test

Safe bias V. < 11 V/um

2014

2018

2019

2020

2021

2022

2023

2024

2025

First design of USTC-IME LGAD v1 (carbon/no carbon)

Fabrication of USTC-IME v1

Design and fabrication of USTC-IME v2

Tests with source/beam

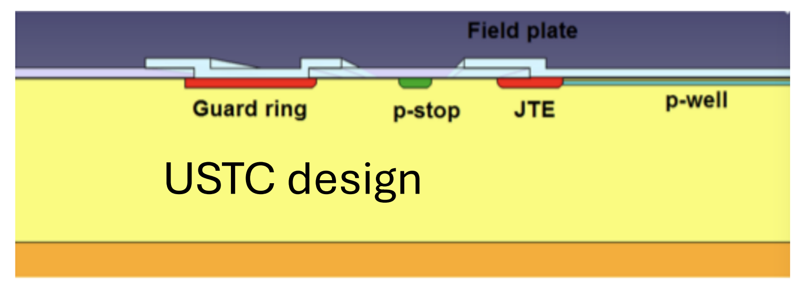
Pre-production

Production readiness review and production

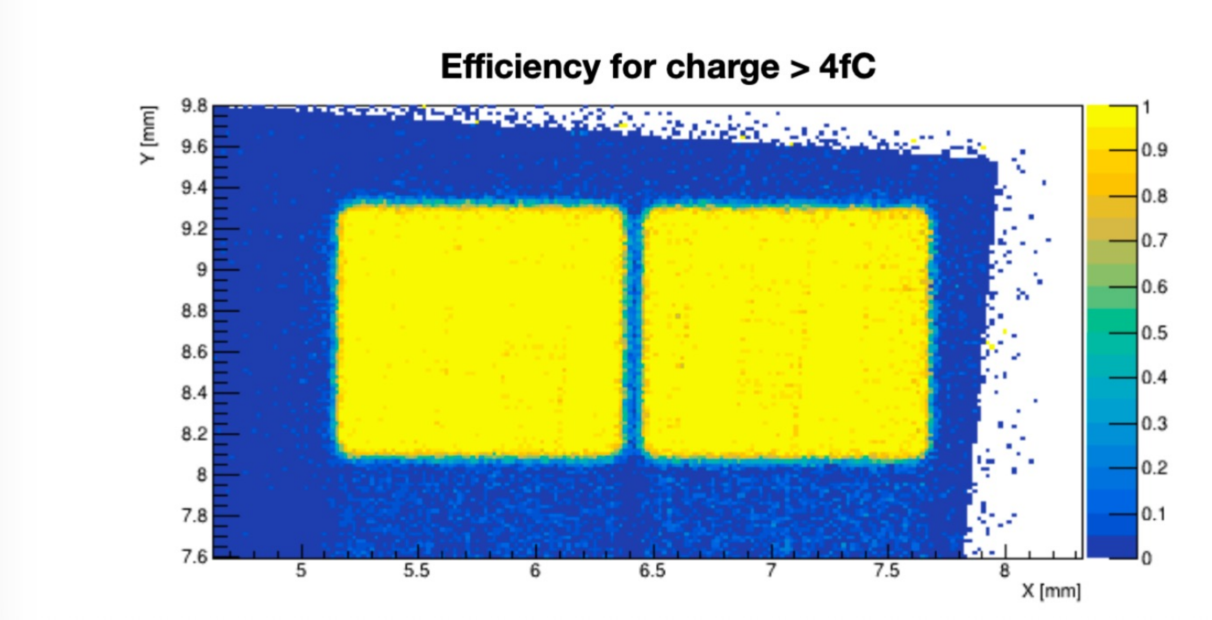
CMS ETL TDR: CERN-LHCC-2019-003
ATLAS HGTD TDR: CERN-LHCC-2020-007

Fill-factor of LGAD

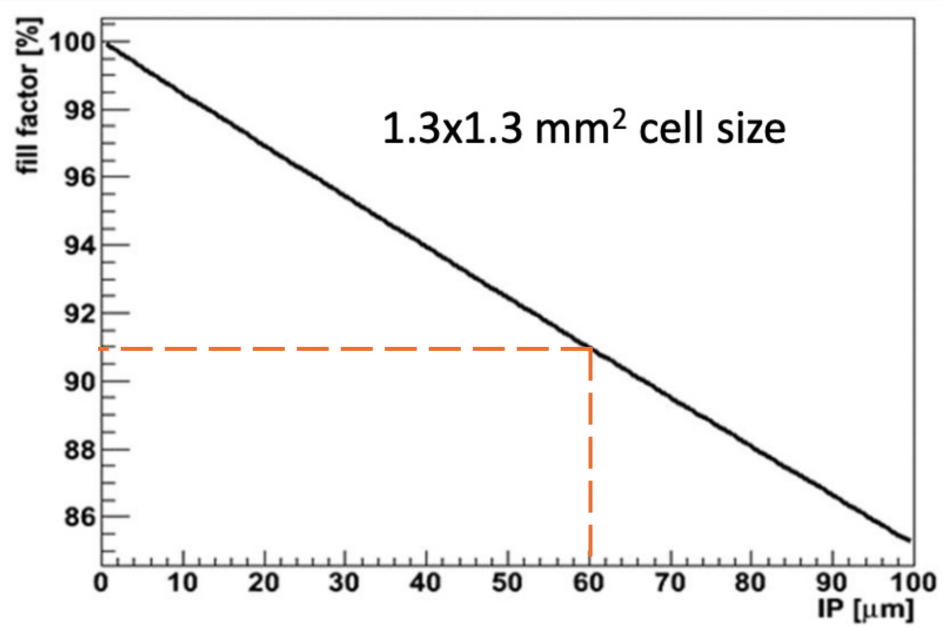
- Structures at peripheral region
  - Isolation, protection and field adj. at edge
- Fill-factor = [area w. gain]/[total area]
- Limiting the pitch size of LGAD



USTC design



USTC-IME v2 W17-2x2 IP3:
inter-pad width = 62 um

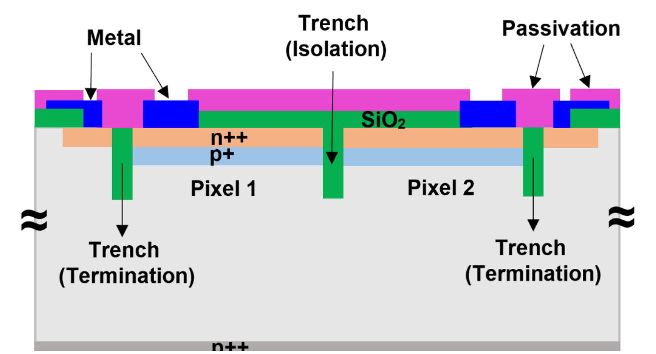


1.3x1.3 mm^2 cell size

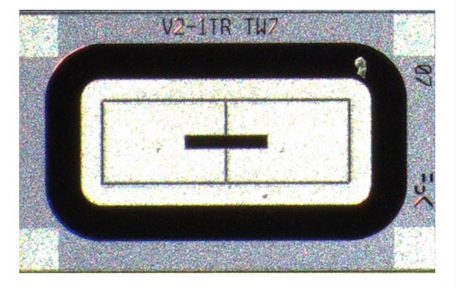
Trench-Isolated LGAD (TI-LGAD)

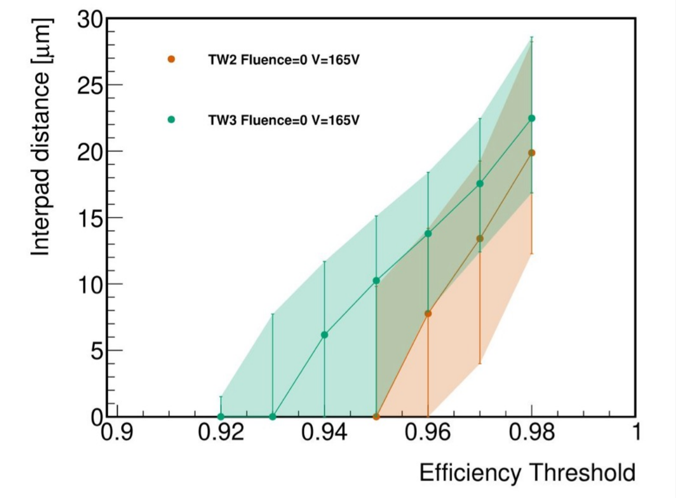
A. Carrera @ Trento 2026

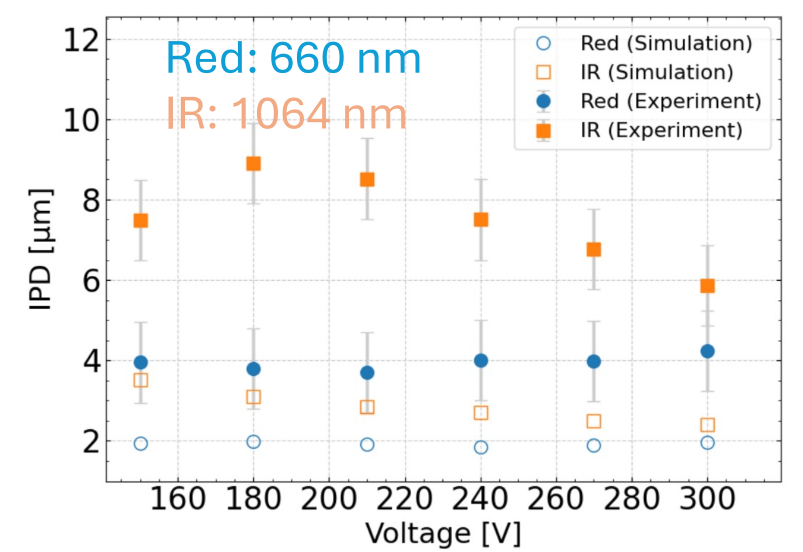
Micron Semiconductor Ltd.



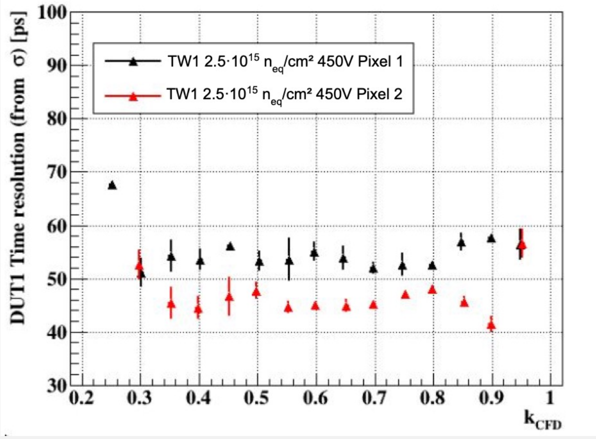
FBK AIDAInnova



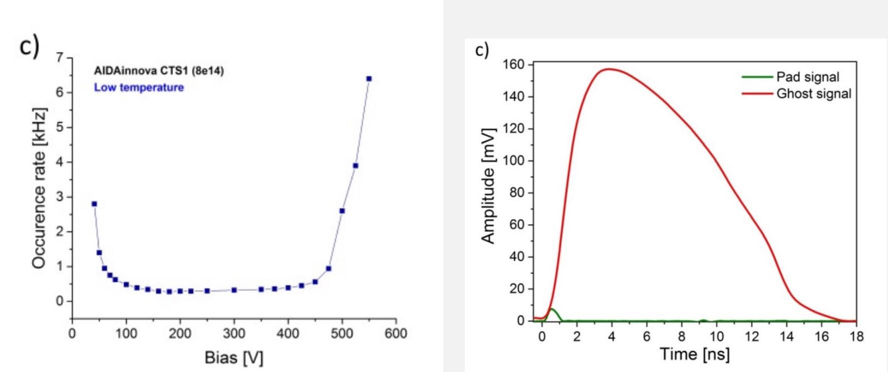




$2.5\cdot10^{15}$ n_{eq}/cm^2 (V = 450 V)



Self induced signal after irradiation



2025 JINST 20 P07037

2025 JINST 20 C07015

AC-LGAD

- Continuous gain layer, segmented electrodes
  - Solve the fill factor issue
  - Flexibilities in sensor design
  - Capacitively coupled readout:charge sharing

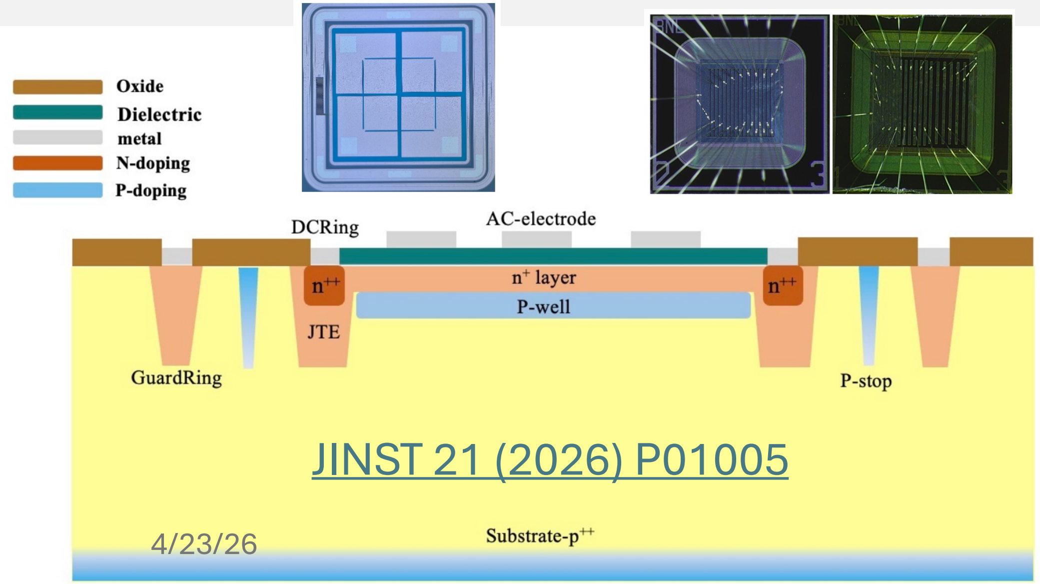
EIC requirement

Subsystem	Timing	Spatial	Geometry
Barrel TOF	~30 ps	~30 μm	1 cm strip,500-1000 μm pitch
Forward TOF	~25 ps	~30 μm	500 x 500 μm^2 pixels

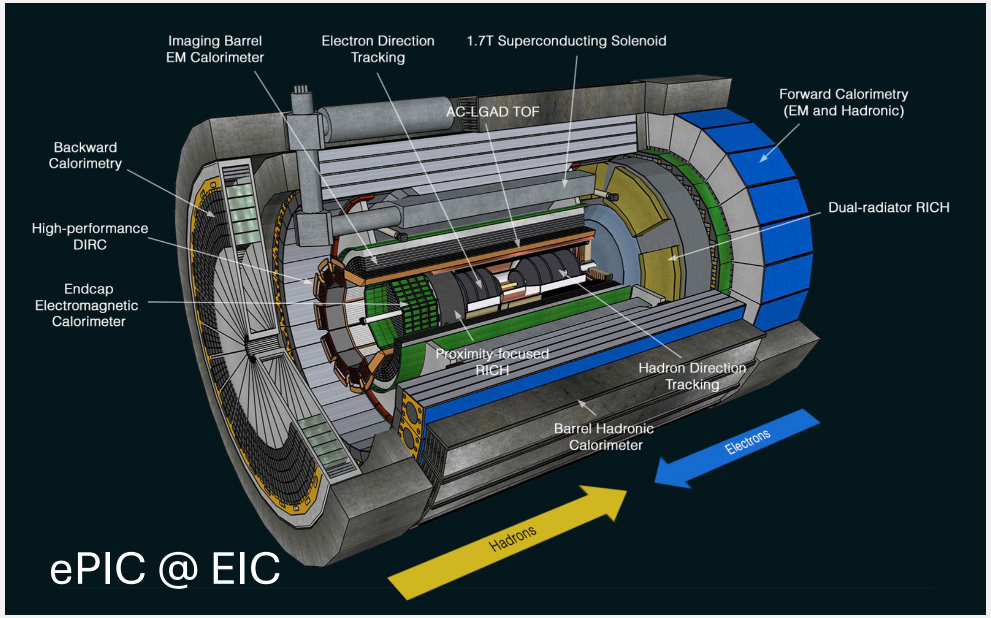
HPK: Pad size 500 μm x 500 μm
inter-pad gap: 20,30,40,50 μm
Thickness 50 μm

BNL: Pitch:100/150/200 μm, strip: 80 μm x 1.7 mm
thickness: 50 μm

2022 JINST 17 P05001



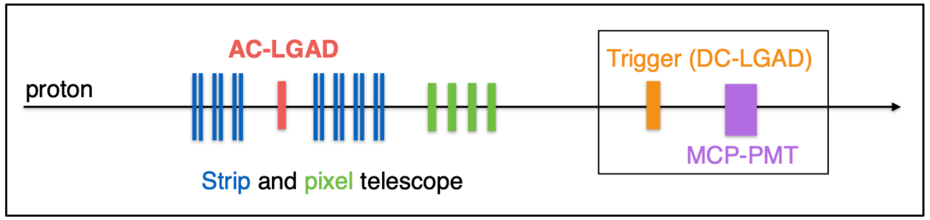
JINST 21 (2026) P01005

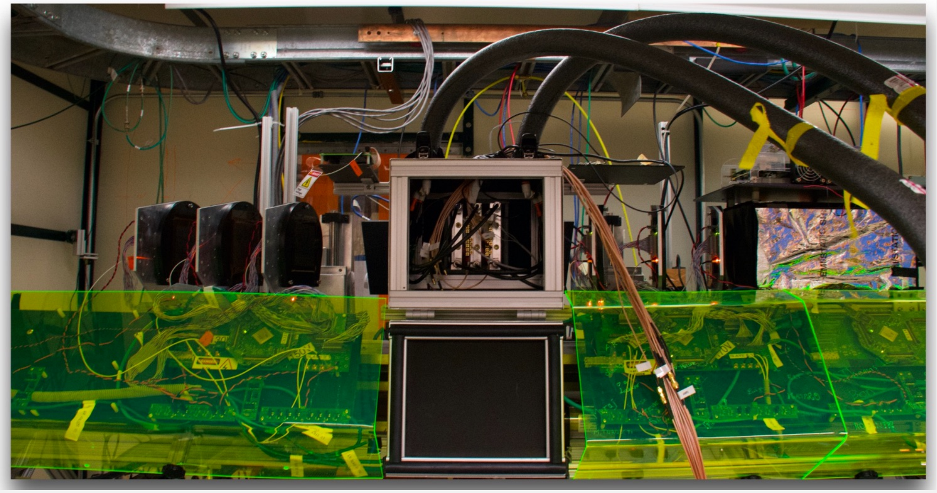


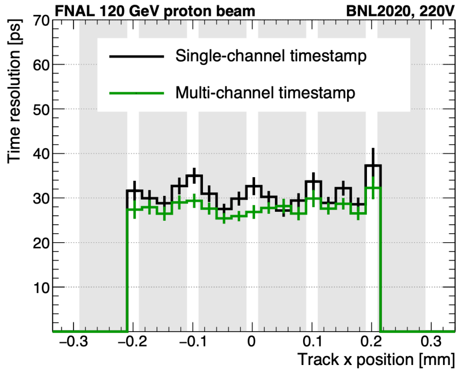
ePIC @ EIC

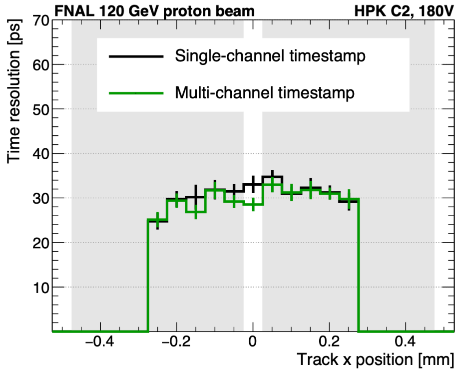
JINST 17 (2022)P05001

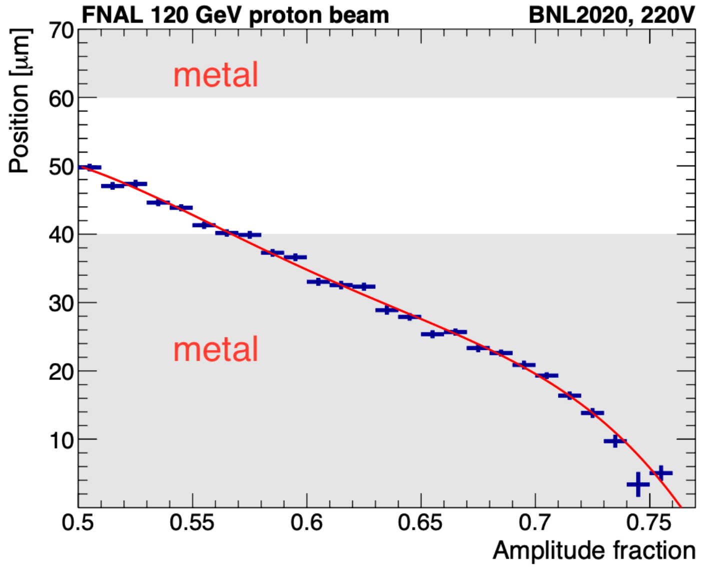
Performance from test beam(prototypes)

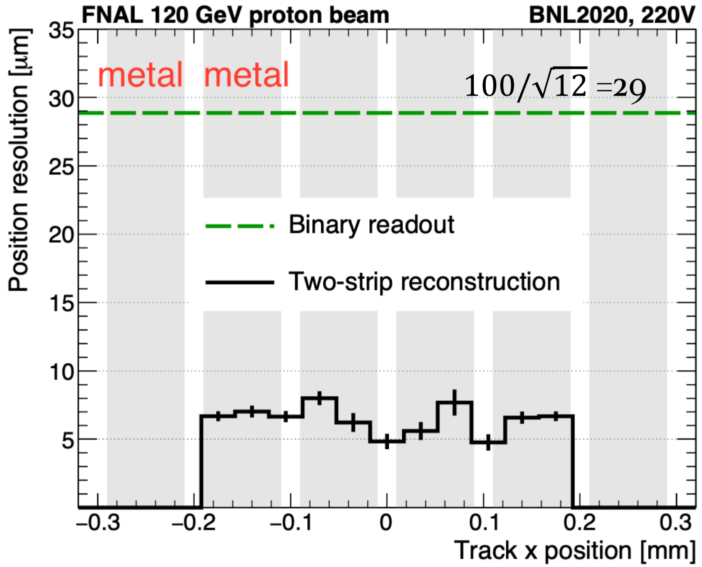




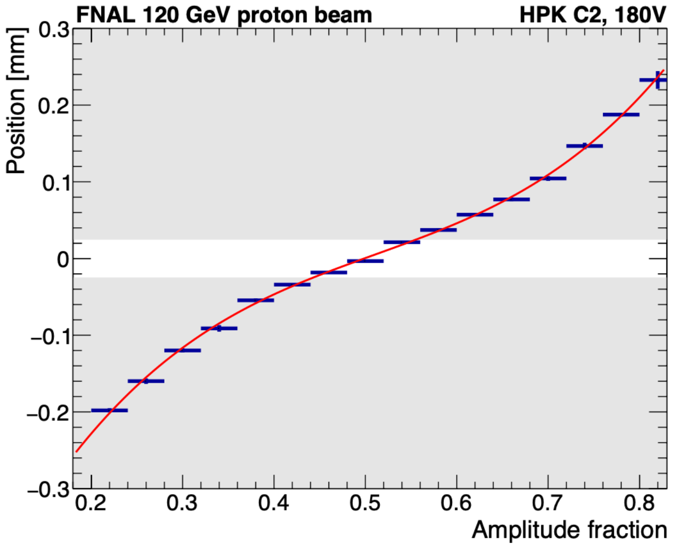


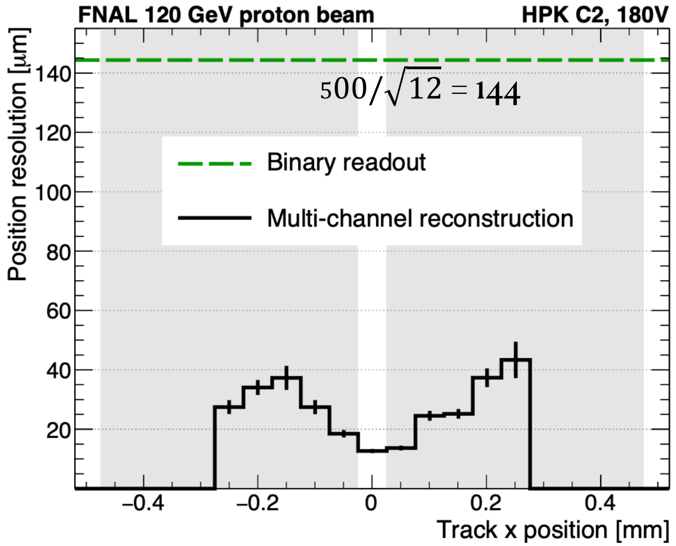






$100/\sqrt{12}=29$

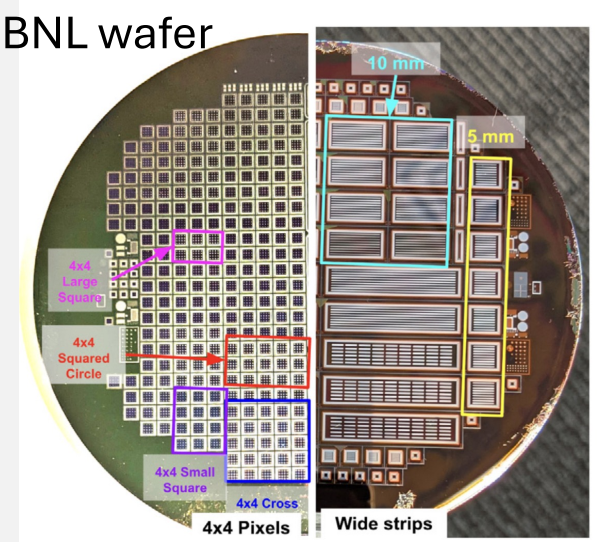


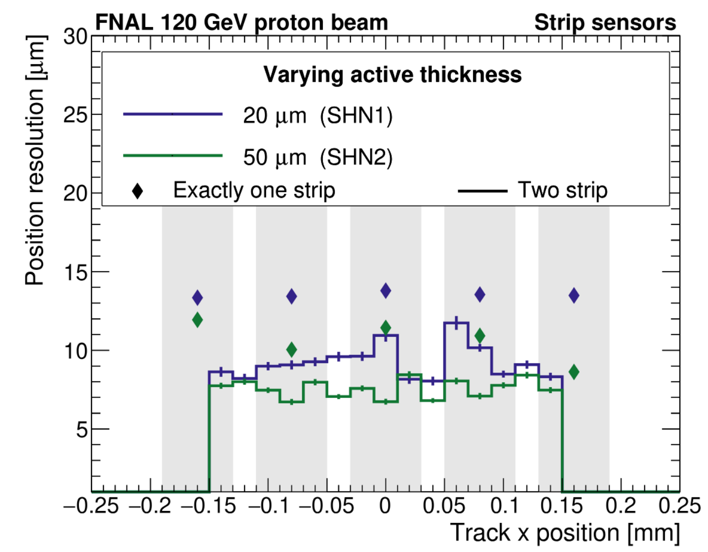


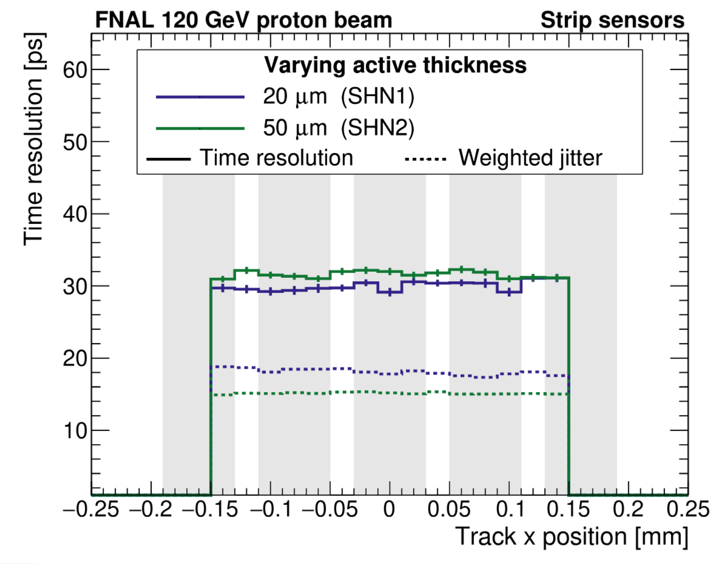
$500/\sqrt{12}=144$

Test results of cm-scale AC-LGAD for ePIC

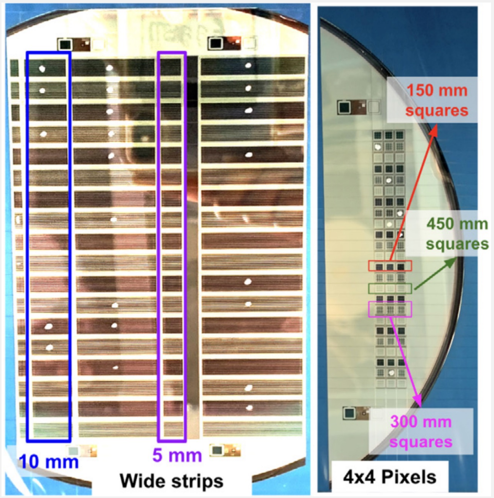
BNL wafer

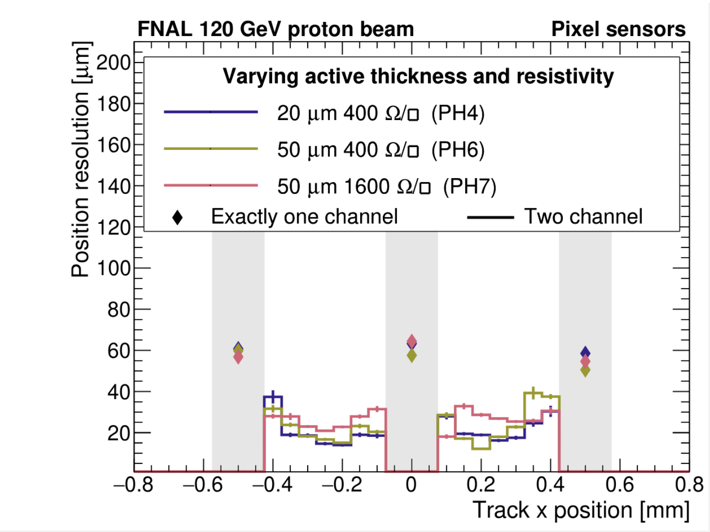


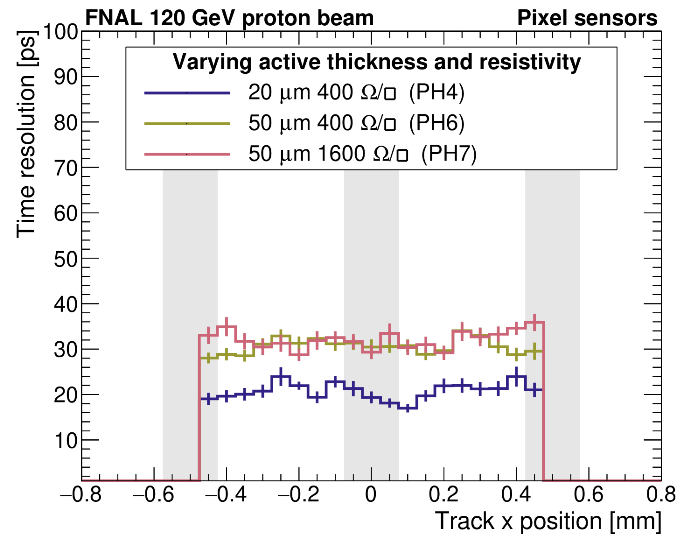




HPK wafer







R&D mostly completed. Large-scale production and testing on-going

AC-LGAD R&D at USTC

- USTC made some AC-LGAD in house during the R&D for ATLAS HGTD
- Finished characterization and started developing AC-LGAD for EICC

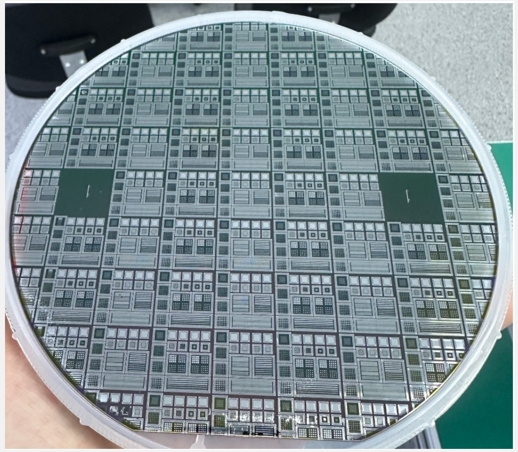
V1: thickness = 50 μm JINST 21(2026)P01005

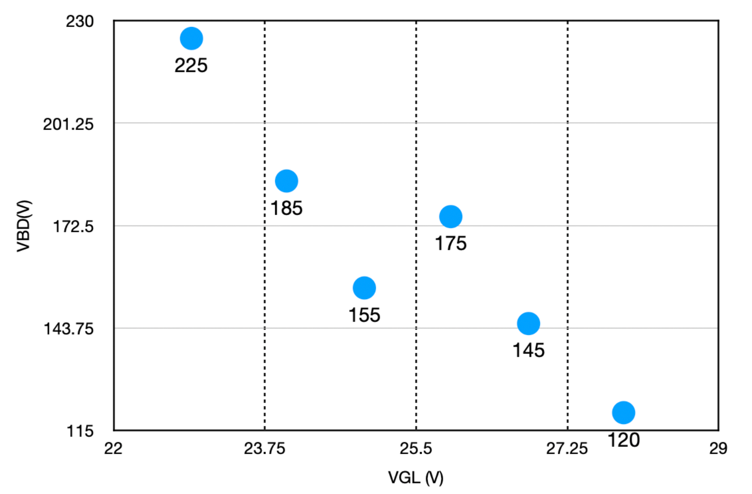
V2: thickness = 35 μm
Characterization on-going

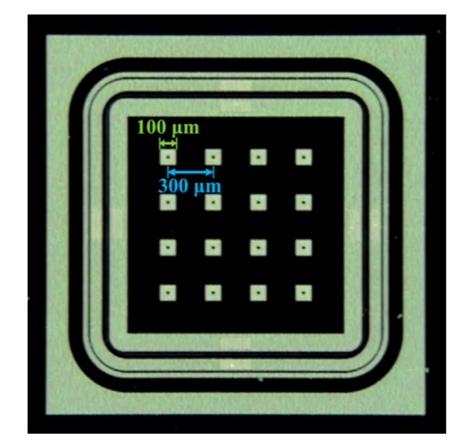
6 splits, very good correlation of VBD~VGL

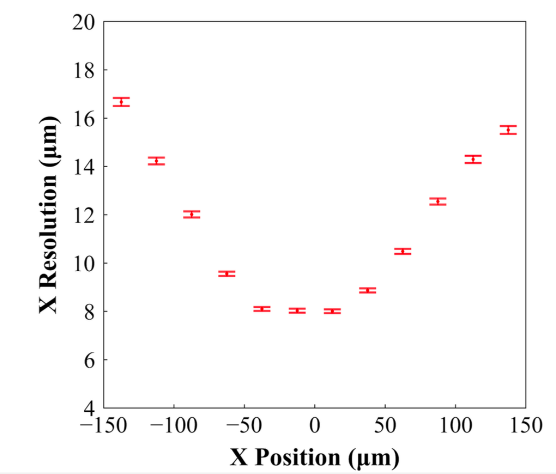
ChinaXiv:202602.00195V1

ML on waveform

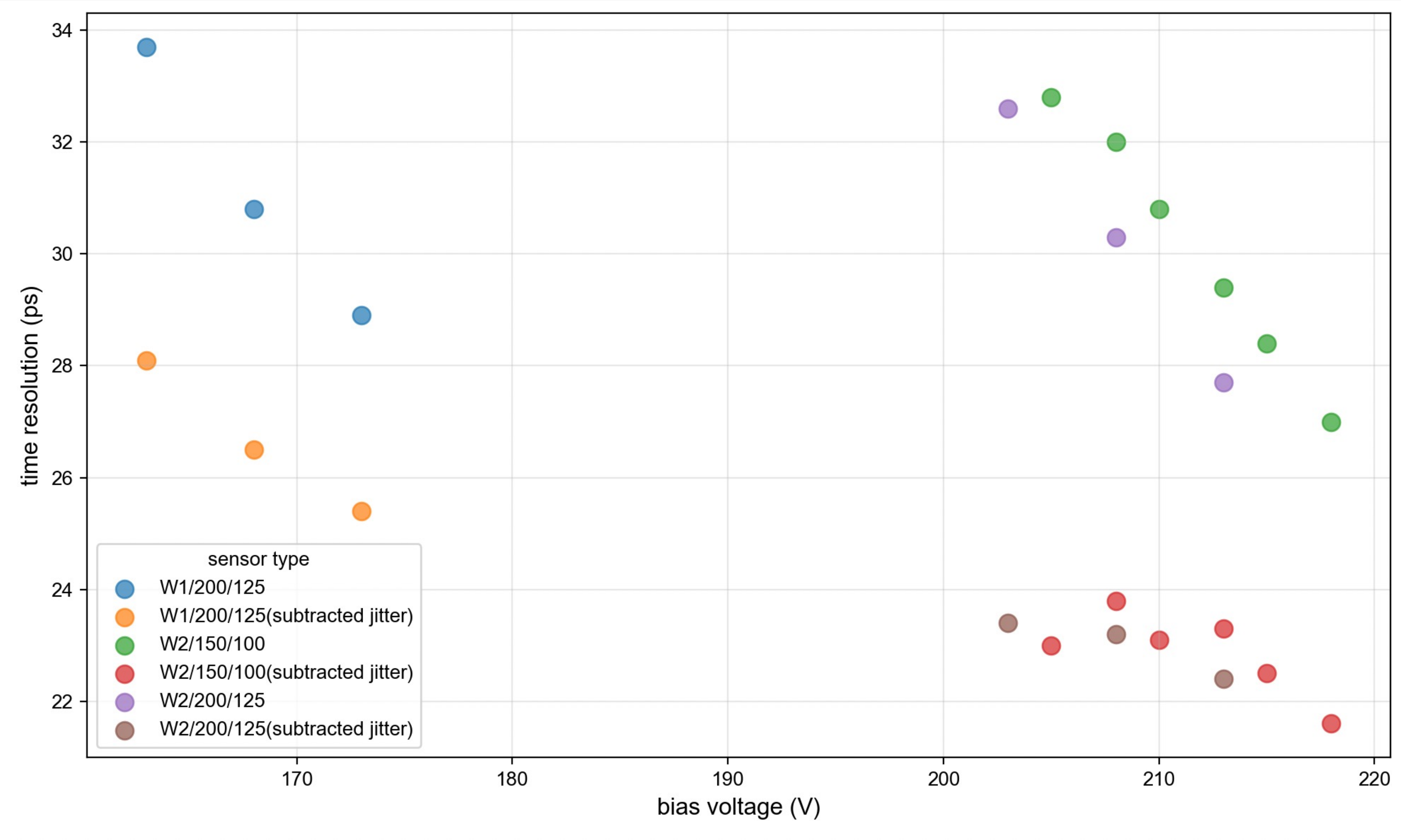






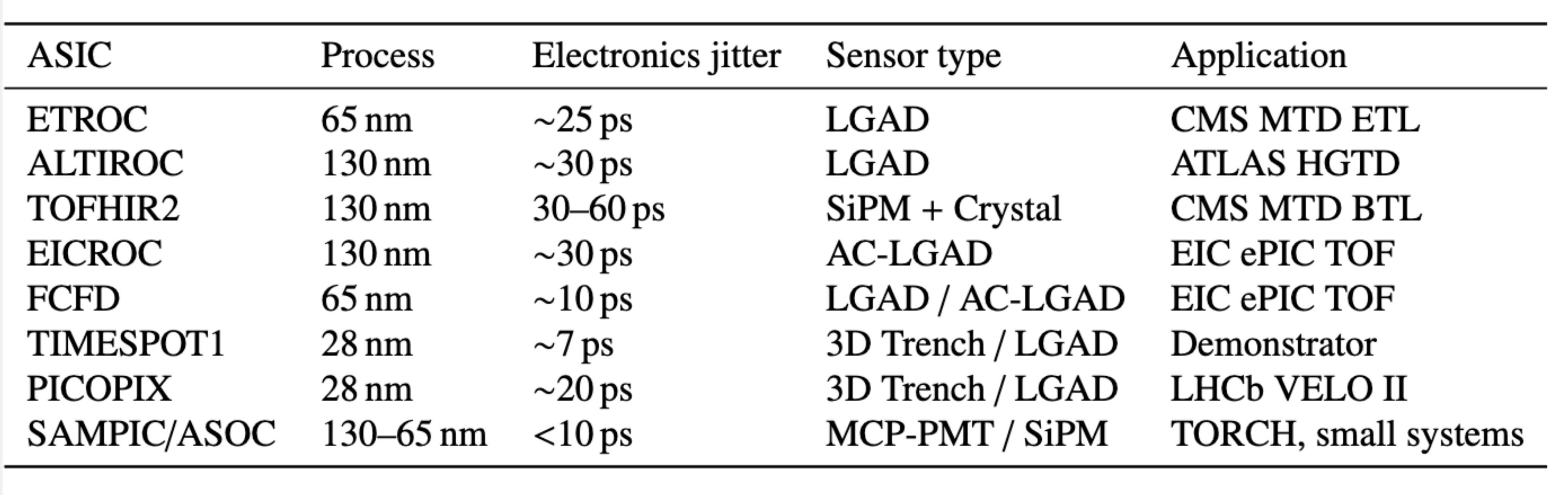


Very Preliminary Results on time resolution



1.2 mm strips

Readout ASIC chips for LGAD

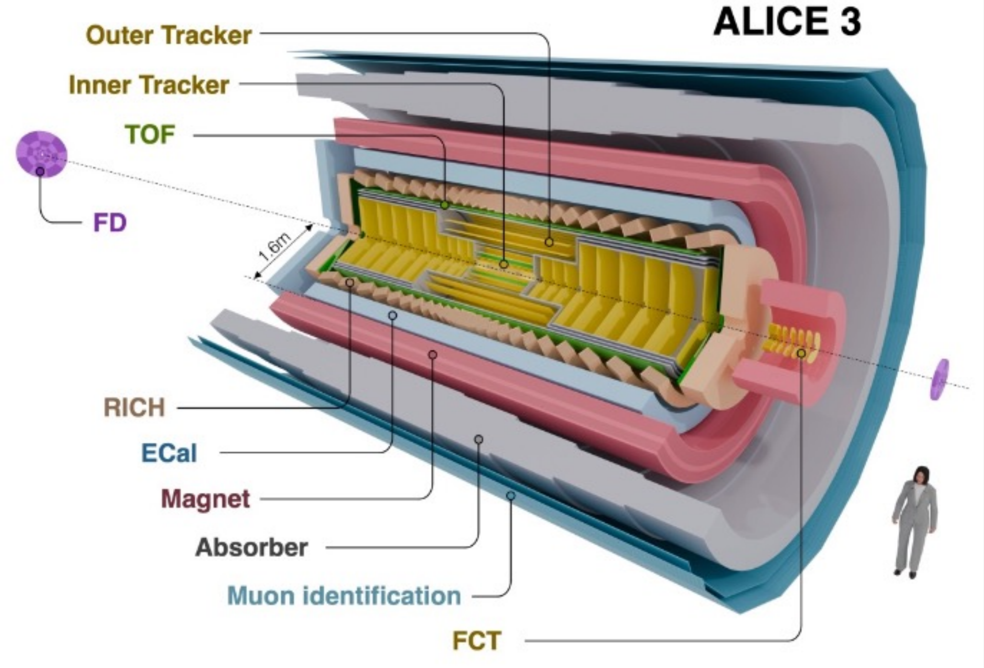


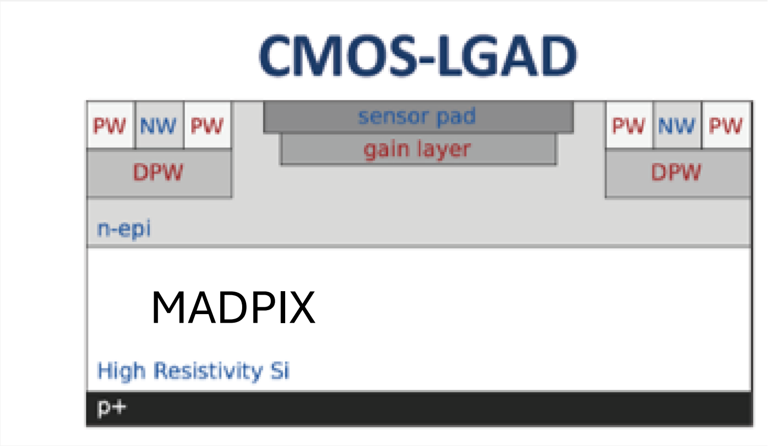
ASIC	Process	Electronics jitter	Sensor type	Application
ETROC	65 nm	~25 ps	LGAD	CMS MTD ETL
ALTIROC	130 nm	~30 ps	LGAD	ATLAS HGTD
TOFHIR2	130 nm	30–60 ps	SiPM + Crystal	CMS MTD BTL
EICROC	130 nm	~30 ps	AC-LGAD	EIC ePIC TOF
FCFD	65 nm	~10 ps	LGAD / AC-LGAD	EIC ePIC TOF
TIMESPOT1	28 nm	~7 ps	3D Trench / LGAD	Demonstrator
PICOPIX	28 nm	~20 ps	3D Trench / LGAD	LHCb VELO II
SAMPIC/ASOC	130–65 nm	<10 ps	MCP-PMT / SiPM	TORCH, small systems

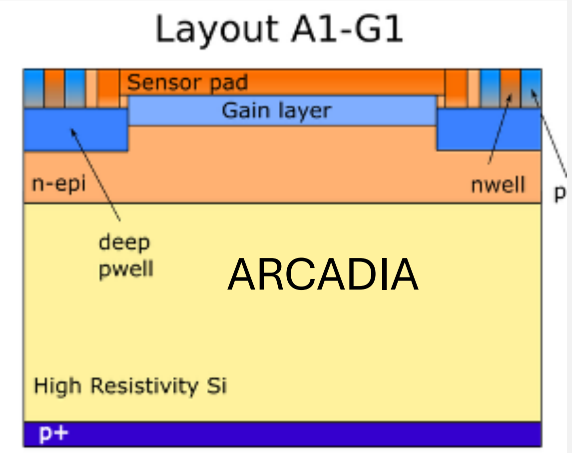
Development of ASIC in China
LATRIC (IHEP)
LATIC (USTC)
ALGROC (NWPU)
…

CMOS-LGAD / Monolithic LGAD

- Implement both sensor and IC on a same silicon wafer
- Application for ALICE LS4 upgrade (2034 ~ 2035)
  - Requirements: $\sigma_t \leq 20\ \mathrm{ps}$,power consumption: 50 mW/cm^2







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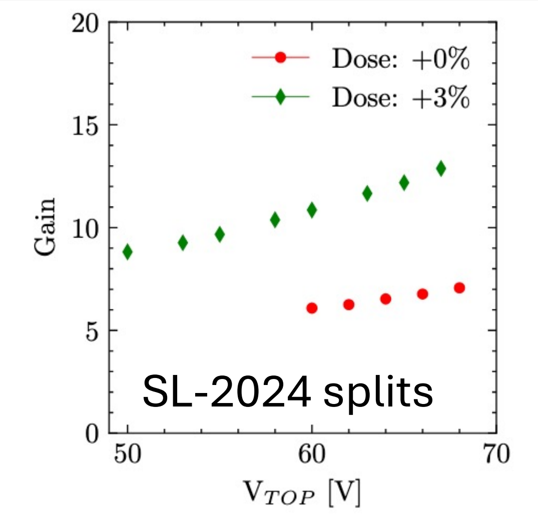
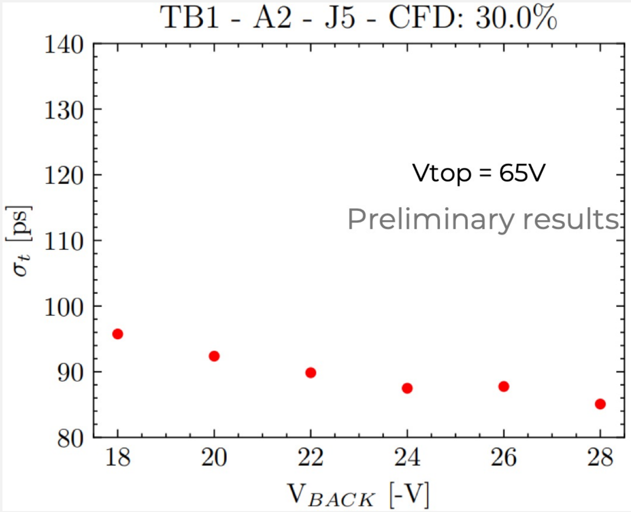
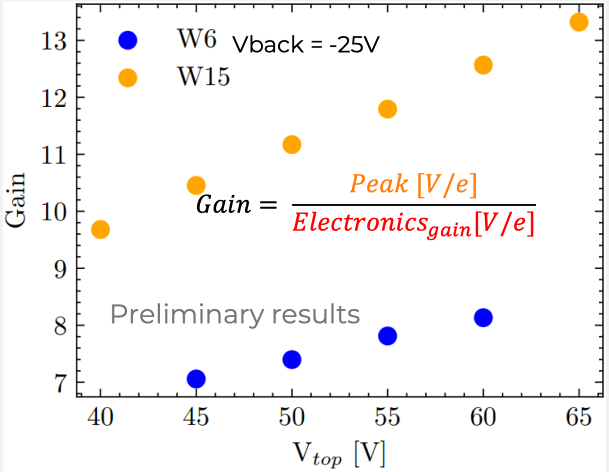
JINST 21(2026) C01056

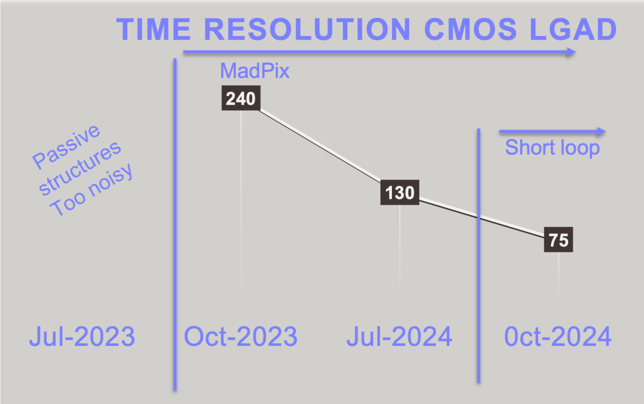
Status of MadPix for ALICE 3

- ER-2023: σ_t = 120 ps, power consumption 0.17 mW/ch gain ~ 3, 48 μm
- SL-2024: calibrated the gain to 10-20 σ_t=75 ps(subtracted jitter)
- SL-2025: thickness = 15 μm, expect ~30 ps time resolution
- ER-2027: full-size chip, optimal pitch to achieve 20 ps
- Backup solution: hybrid LGAD being developed at USTC









U. Follo talk at Trento 2025

Summary

- Very intensive R&D of LGAD technology in the past 10+ years
- Extremely good progress (excellent teamwork of the community!)
- DC-LGAD ➔ AC-LGAD ➔ CMOS LGAD
- Current state-of-art resolutions: 20 ~ 40 ps / ~10 μm
- Applications at Collider experiments
  - HL-LHC (pile-up mitigation)
  - EIC (TOF for PID)
  - Future (4D –tracking)