Hybrid Pixel Sensors for 4D Tracking in AIDAInnova
and
possible application to CMS Inner Tracker Timing Upgrade

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University of Zurich
on behalf of AIDAInnova WP6

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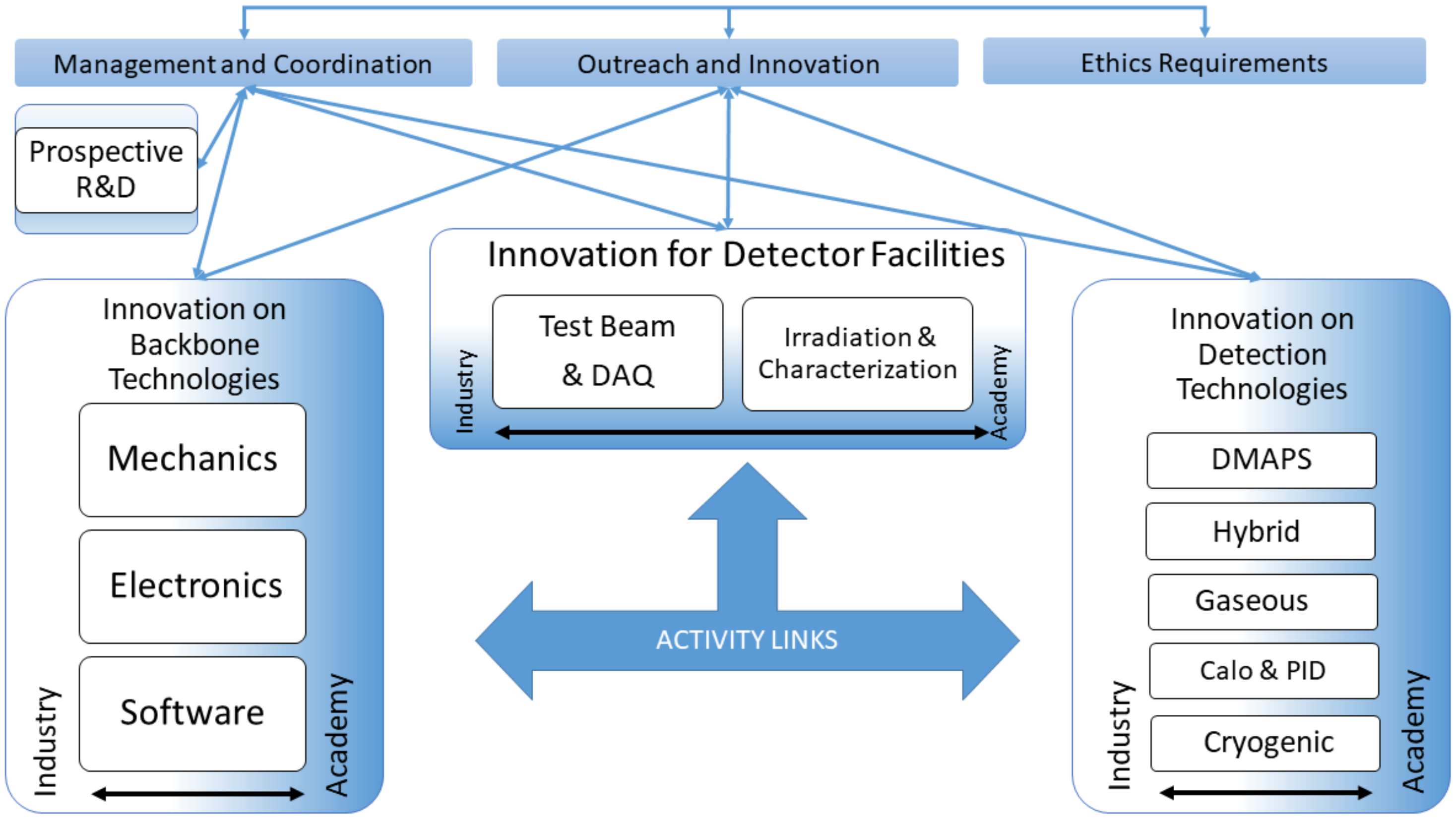
1st MONOLITH Workshop on silicon sensors for timing and their applications, Geneva
https://indico.cern.ch/event/1179742/

The AIDAInnova project



Advancement and Innovation for Detectors at Accelerators

- In the framework of HORIZON-2020
- **To explore applications of novel technologies**
- **To strengthen the synergies between different projects and communities**
- **To increase the efficiency and quality of the beam test and irradiation facilities**
- **To render European Industry ready for large series production** of HEP detectors

WP6: Hybrid Pixel Sensors for 4D Tracking and Interconnection Technologies

WP6 coordination: A.M., Claudia Gemme

Simulation, design and production of common 3D and LGAD productions

- FONDAZIONE BRUNO KESSLER — 3D and TI-LGADs
- Centro Nacional de Microelectrónica IMB — 3D and iLGADs

Innovative Interconnection Technologies

- Wafer to wafer
- Anisotropic Conductive Films

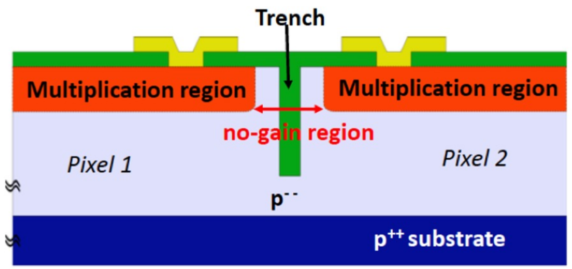
3D validation

LGAD validation

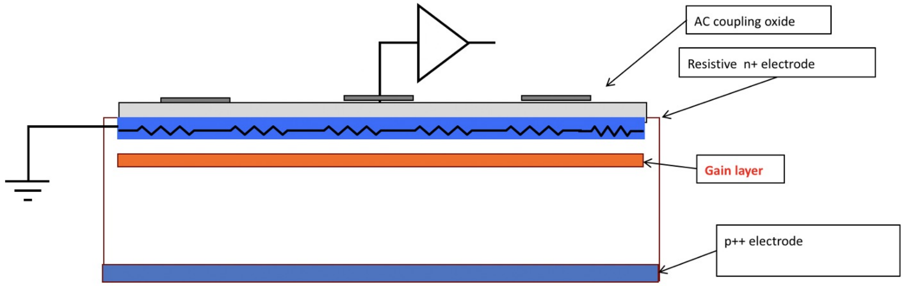
Technologies path towards small pitch LGADs

- Different technologies to be explored to achieve small pitch LGADs necessary for 4D tracking

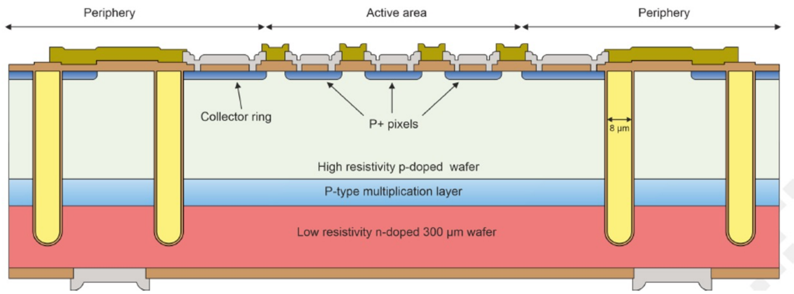
- Trench-isolated LGADs (TI-LGAD)



- Resistive AC-Coupled Silicon Detectors (RSD)
  - AC-pad coupled to the resistive n+ layer via dielectric coupling
  - Not segmented gain layer: 100% fill factor



- Inverse LGAD (iLGAD):
  - multiplication region on the opposite side of the read-out electrodes



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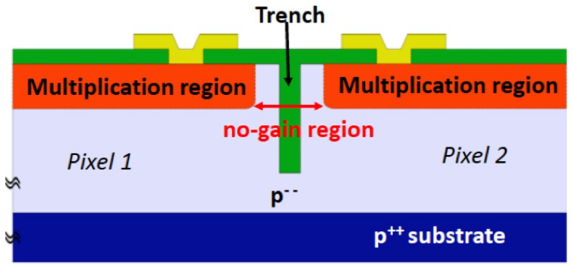

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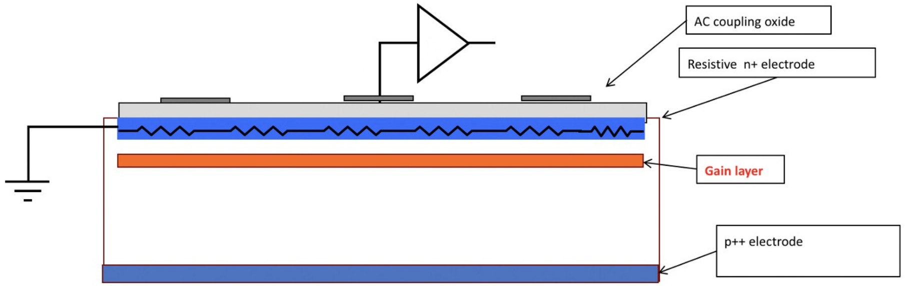

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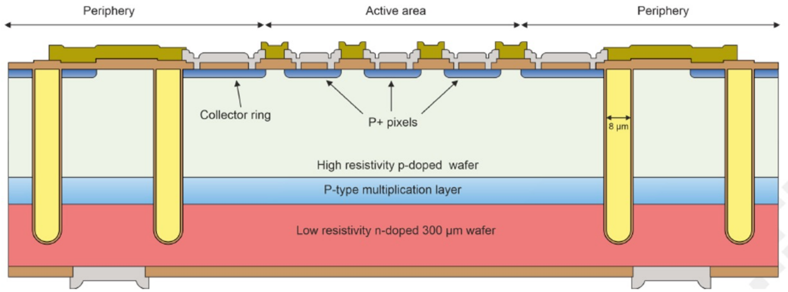


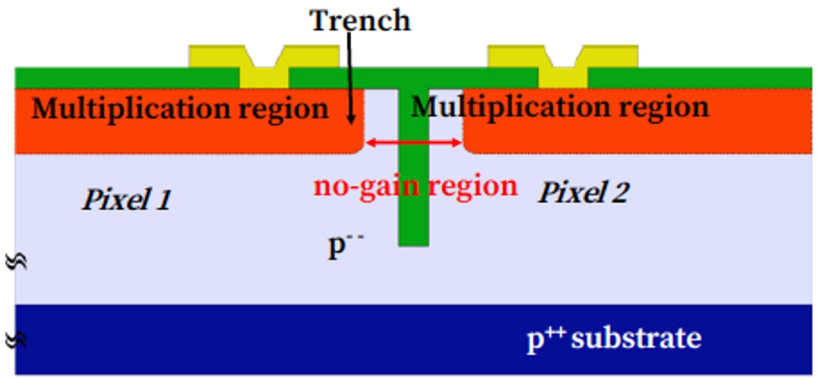
A. Macchiolo, Hybrid Pixel Sensors for 4D Tracking, 1st MONOLITH Workshop, 6 Sept 2022

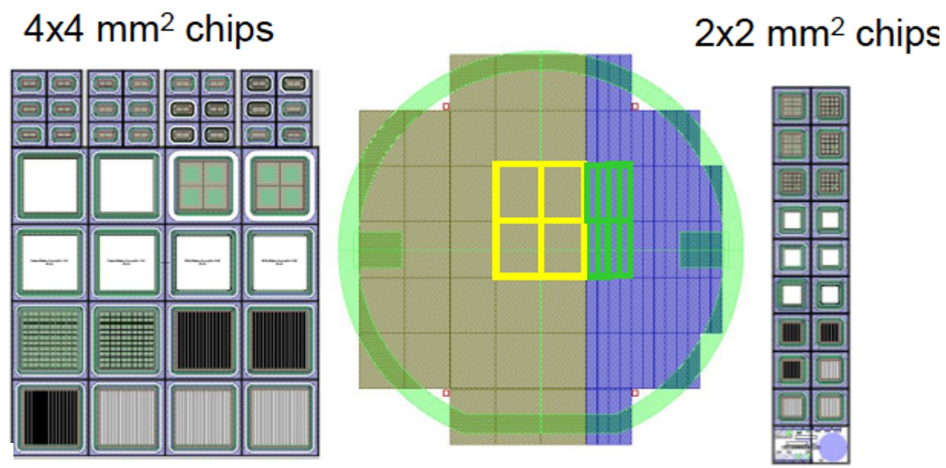
FBK: TI-LGAD productions

A **first batch** to focus on technology validation.

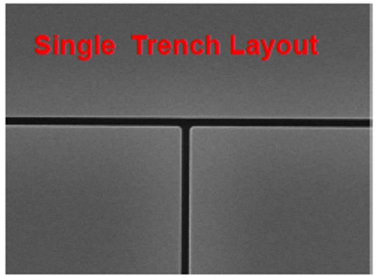
Second batch **in the framework of RD50** based on the experience of the first batch

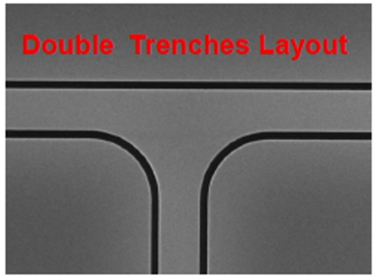
- 18 wafers with process splits
- Devices: Pixels, strips, pad with different geometry





- JTE and p-stop are replaced by a trench structure
- Trench act as a drift/diffusion barrier for electrons and isolate the pixels
- The trenches are a few microns deep and less than < 1 um wide - TCAD simulation to optimize them.
- Filled with silicon oxide

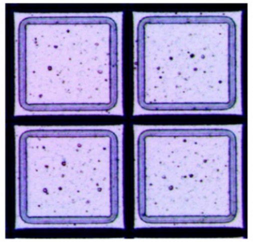




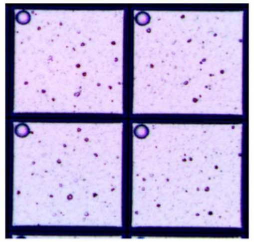
TI-LGAD prototypes

Contact Layout

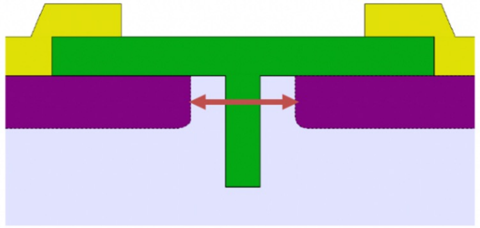
C1
Ring-type contact
GAIN below contacts



C2
Hole-type contact
no GAIN below contact



Gain to Gain distance



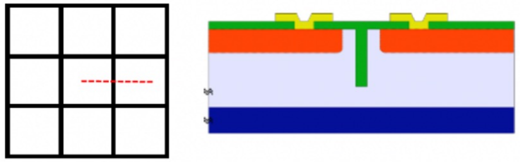
Nominal no-gain width

- V1 < 1um
- V2 < 3um
- V3 < 4um
- V4 < 5 um

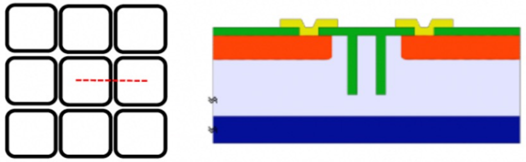
* Referred to 1-trench version

Number of trenches

- **1 Trench Layout (trench grid)**



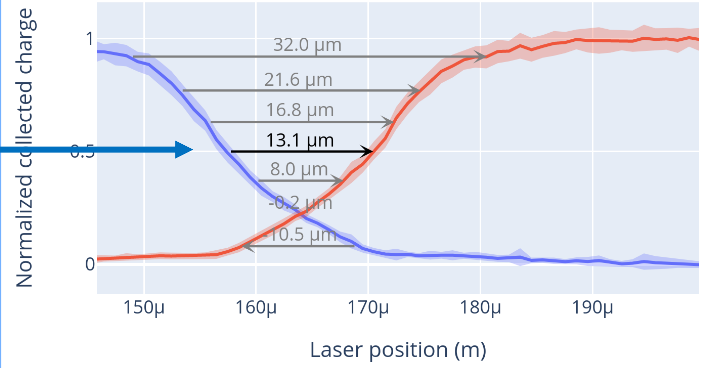
- **2 Trenches Layout**



* 2-trenches version has wider no-gain region

- Three trench depth: **D1 < D2 < D3**

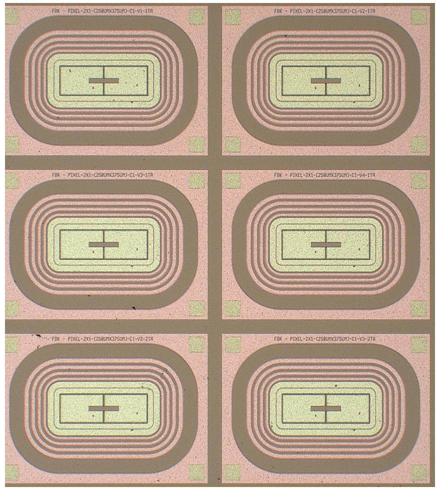
Inter-pixel distance (IPD)



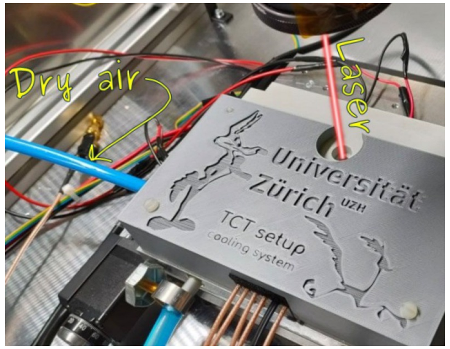
- Inter-pixel distance between 2 and 15µm
  Inter-pixel distance 5-20 times narrower than in LGADs with JTE and p-stop (Fill-Factor improvement)

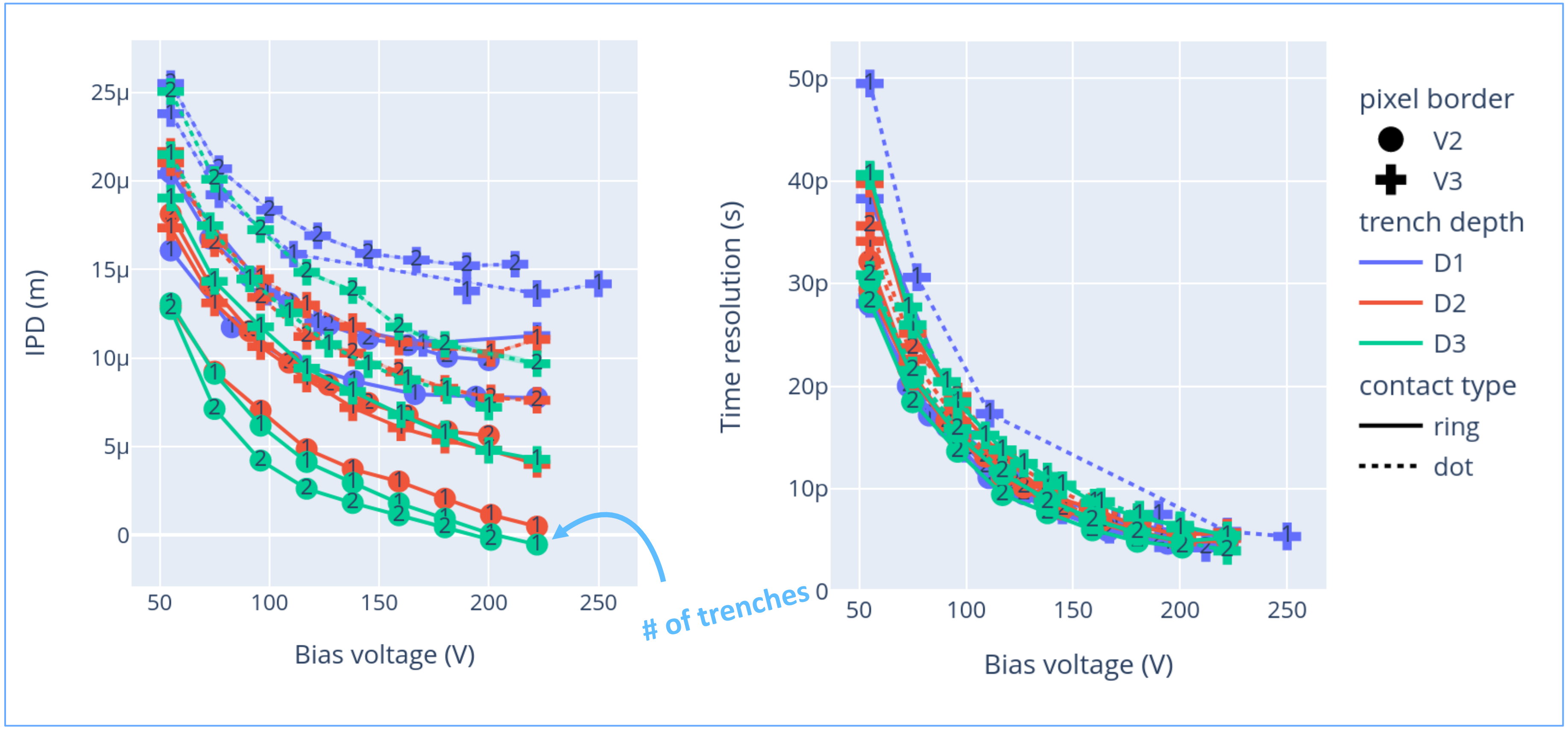
TI-LGAD characterization

TCT set-up, before irradiation



TCT system by Particulars



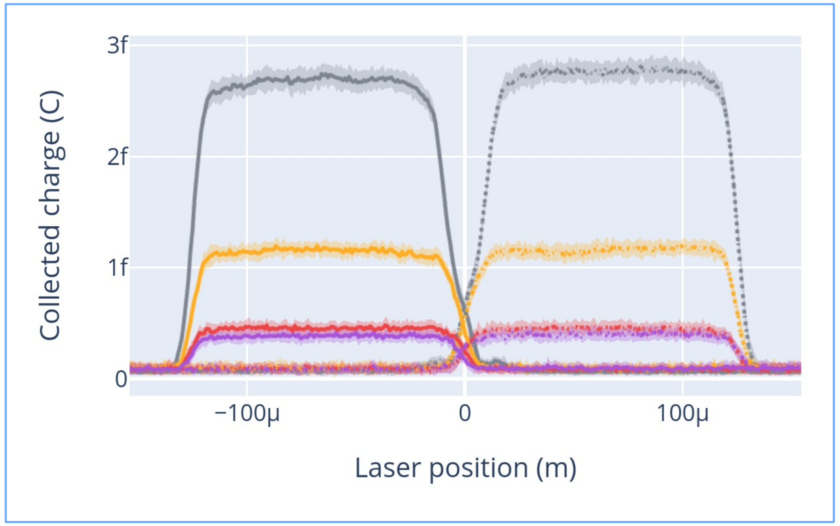


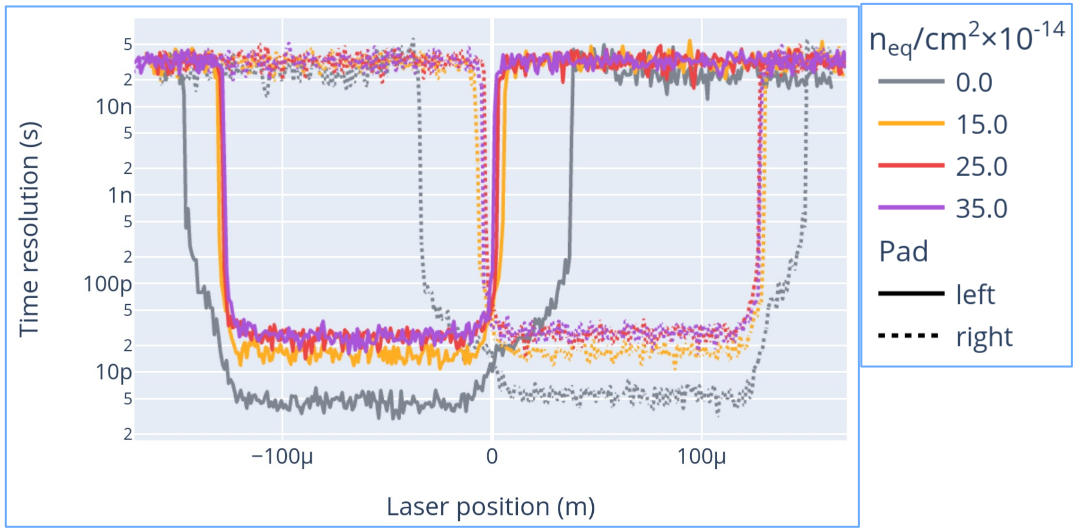
- Border V2 is always better than V3
- Deeper trenches are better.
- Contact type “ring” is better.

- Time resolution does not seem to depend systematically on these design and process parameters.

TI-LGAD irradiation campaign

- TI-LGADs aimed towards future trackers.
  - Possible replacement of pixel disks of the CMS experiment in Phase-3, with fluence range 3-4×10^{15}.
- We irradiated with reactor neutrons at JSI to 3 fluences:
  1) 1.5×10^{15} n_{eq}/cm^2
  2) 2.5×10^{15} n_{eq}/cm^2
  3) 3.5×10^{15} n_{eq}/cm^2
  4) 5.0×10^{15} n_{eq}/cm^2



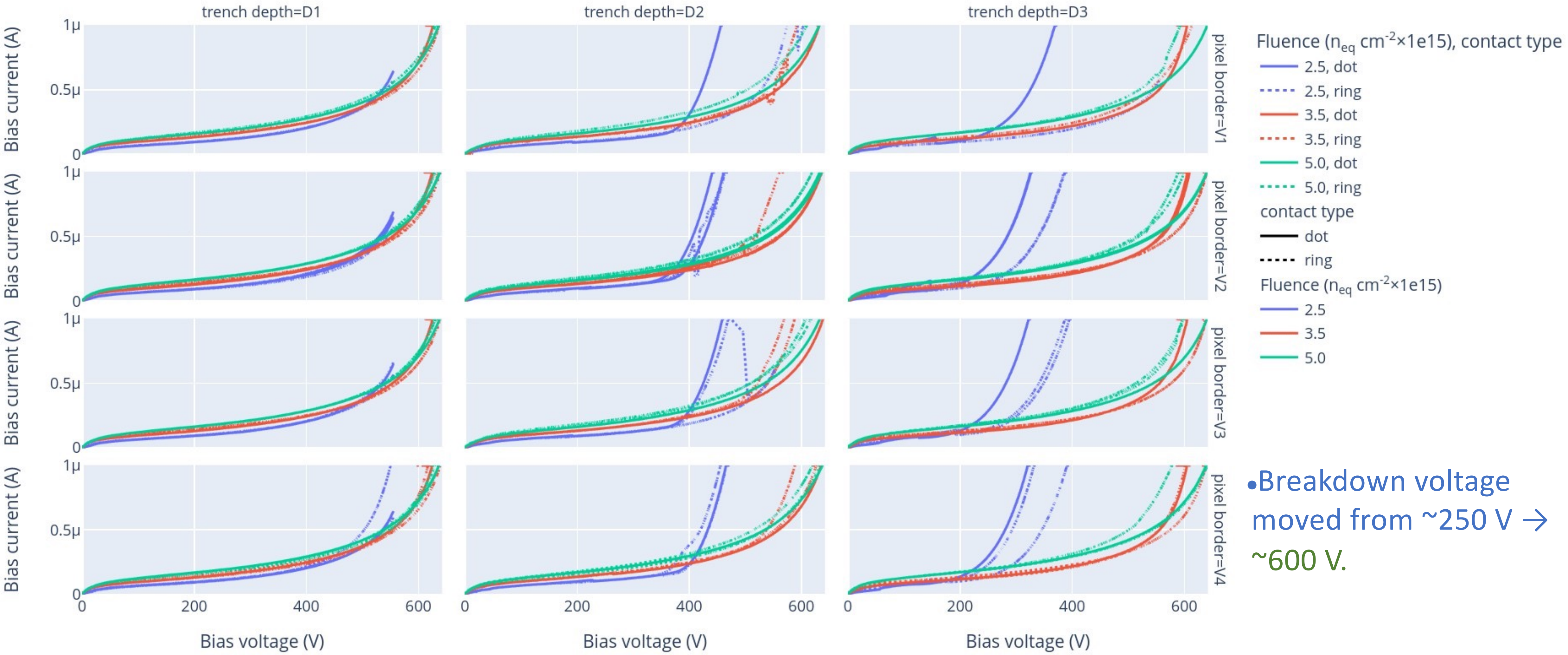


- Gain is significantly reduced
- Time resolution degraded by radiation but still uniform until the edges
- The time resolution is the value in the plateau, for this split:
  - Not irr ~ 5 ps
  - Irr ~ 15-30 ps

M. Senger, AIDAInnova Annual meeting

IV curves after irradiation

- Curves measured in a probe-station at T=-20C

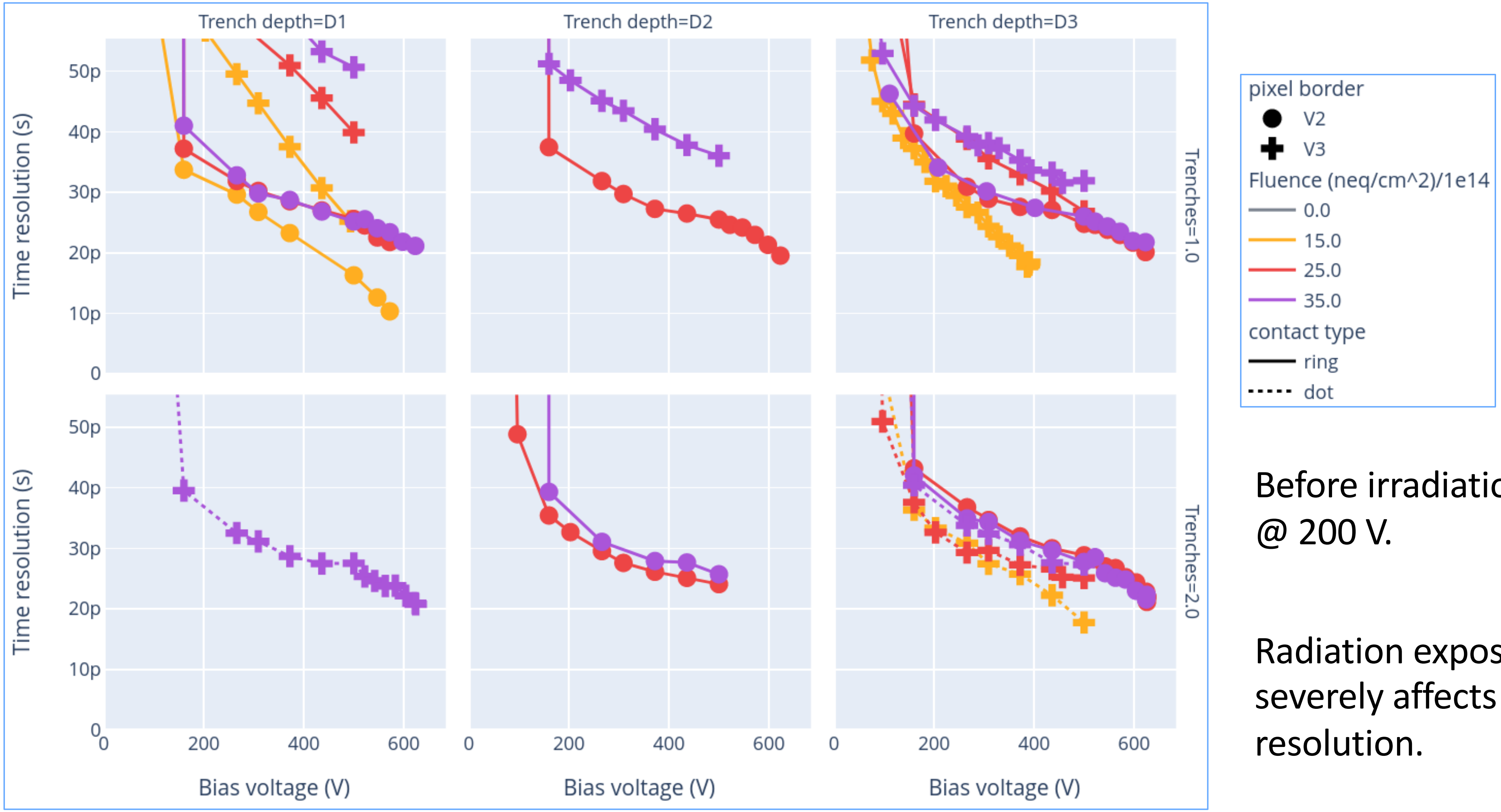


- Breakdown voltage moved from ~250 V → ~600 V.

A. Macchiolo, Hybrid Pixel Sensors for 4D Tracking, 1st MONOLITH Workshop, 6 Sept 2022

M. Senger, AIDAInnova Annual meeting

Time resolution (TCT) after irradiation

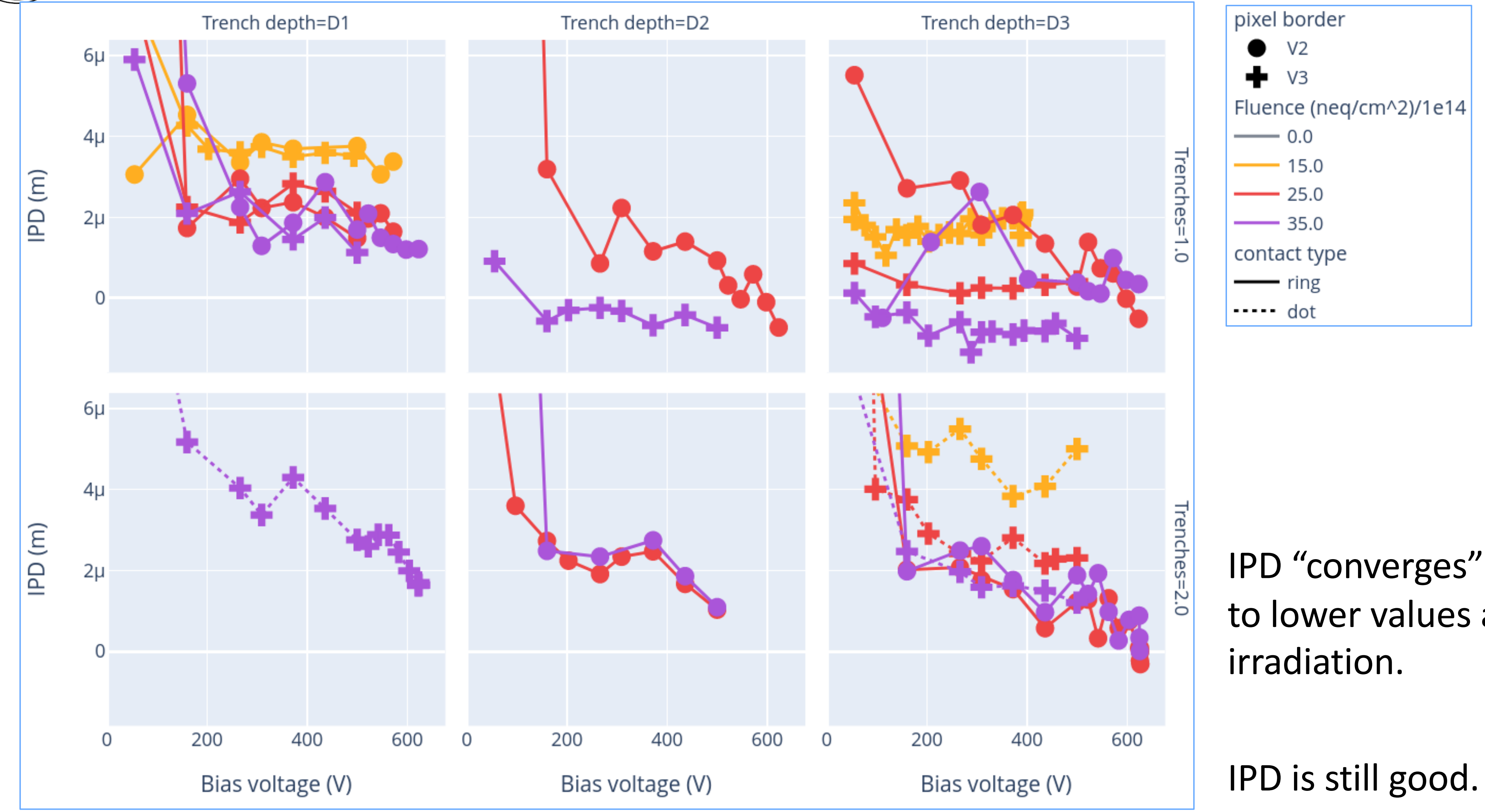


Before irradiation 4-6 ps @ 200 V.

Radiation exposure severely affects time resolution.

[M. Senger, AIDAInnova Annual meeting]

Inter-pixel distance after irradiation



IPD “converges” faster to lower values after irradiation.

IPD is still good.

A. Macchiolo, Hybrid Pixel Sensors for 4D Tracking, 1st MONOLITH Workshop, 6 Sept 2022

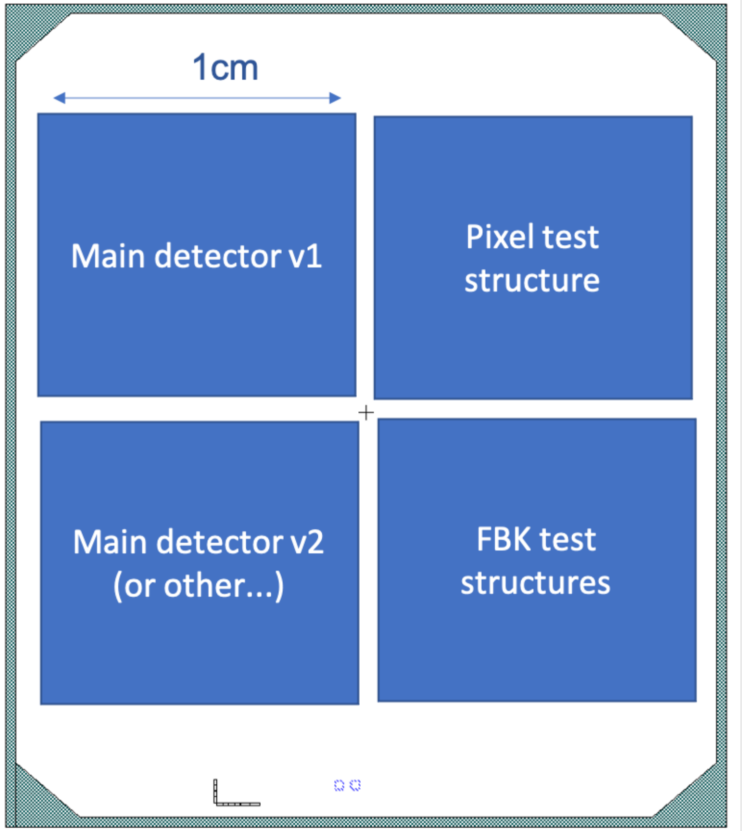
M. Senger, AIDAInnova Annual meeting

FBK LGAD activities in AIDAInnova

- 12 wafers (6 inch)
- With and without carbon doping of the multiplication layer
- Temporary metal to test the large devices

- Active thickness: 45-55 um
- Process start: November 2022
- To be completed in about 6/8 months

- Technological Splits:
  - Gain
  - Carbon co-implantation
  - Trench depth
  - Trench isolation



- Stepper technology = max area 2x2 cm^2
- Reticles divided in fourth sectors

- Shot1: Main detector v1
  - 1x1 cm^2
  - 55 micron pitch

- Shot 2: Pixel small structures
  - 55 μm pitch
    - Matrix 64x64; 32x32
    - Compatible with Timespot and Picopix
  - Strips
  - 2x2 matrix of 1.3x1.3 mm^2 pads

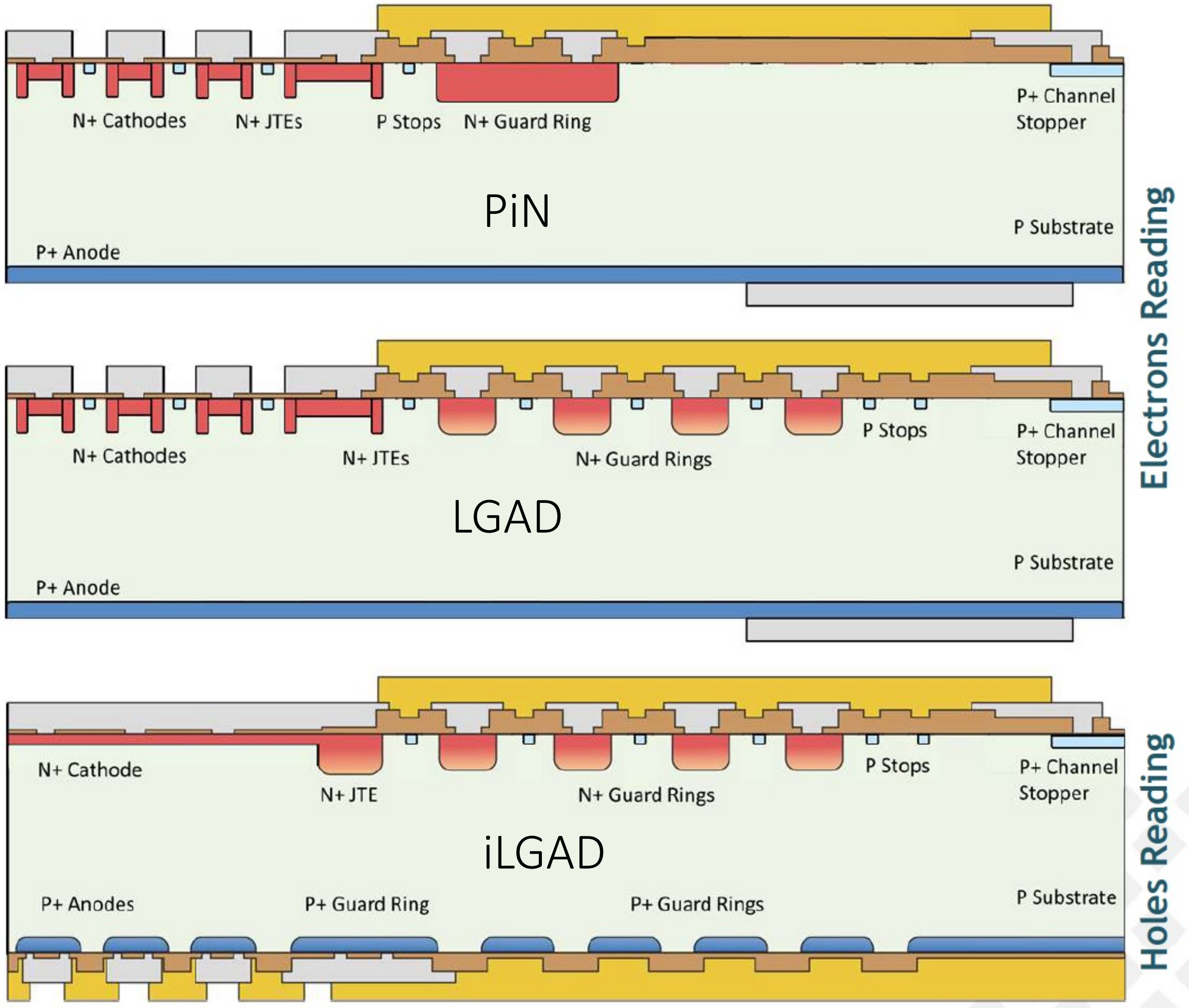
- Shot 3: Main Detector v2 (or alternative structure)

- FBK test structures

M. Boscardin, WP6 meeting, July 6th 2022

CNM LGAD activities in AIDAInnova

- PiN devices as initial step for single Timepix4 timing layer for WP3 Telescope
- LGAD and iLGAD devices as second step for WP3



- iLGAD:
  - JTE and Guard ring structure on the multiplication side, 100% fill factor
  - Hole read-out

A. Macchiolo, Hybrid Pixel Sensors for 4D Tracking, 1st MONOLITH Workshop, 6 Sept 2022

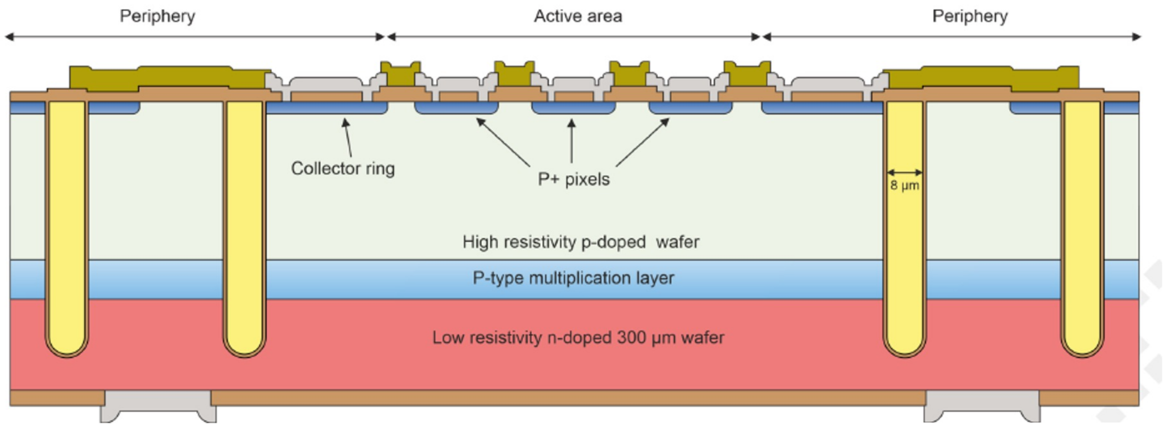
Giulio Pellegrini, WP6 meeting

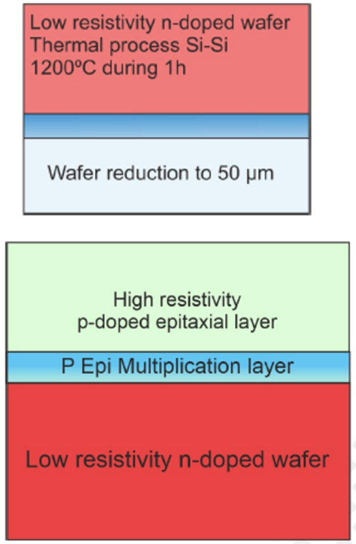
CNM iLGAD

- In the iLGAD Third Generation (ILG3) we are going to use trenches to isolate the active area

  ✓ Multiplication region is fully isolated.
  ✓ Simpler single-side process and 50% less fabrication steps.
  ✓ Devices are able to sustain higher voltages.
  ✓ Slim-edge technology.
  ✓ Optimization of the multiplication layer is independent of charge collection and cross-talk at the electrodes.

- Fabrication run on 4” wafers (Si-Si+Epi) in preparation, run on 6” wafers as AIDAinnova production





- **TimePix3.** 55x55 µm pitch, 256x256 pixels: 12
- **TDCPix.** 300x300 µm pitch, 40x45 pixels: 8
- **UZH-PSI.** 100x100 µm pitch, 30x30 pixels: 36
- **iStrip.** 80 µm pitch, 20 strips: 40

Giulio Pellegrini, WP6 meeting

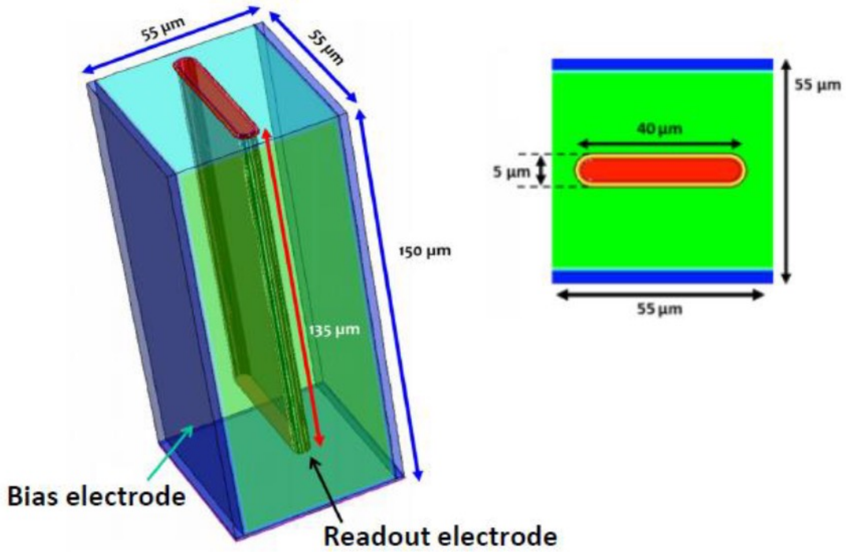
3D sensors for timing

FBK: trenched 3D optimization

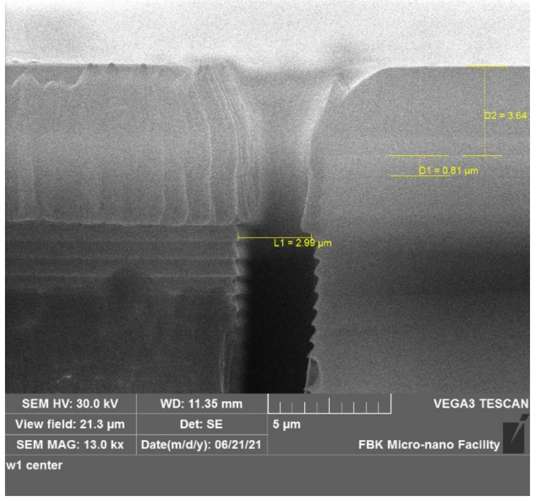
- The idea is to use a 3D based on trenches instead of columns in order to obtain a more uniform electric / weighting field between electrodes
- This reduces the dependence of timing on the impact position of particles

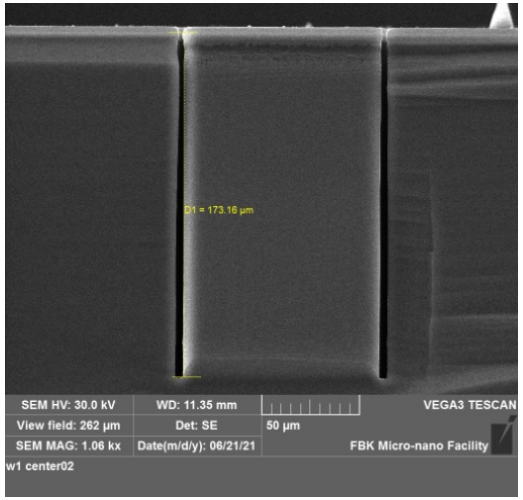
- Technological tests performed at FBK to address the following aspects:

Reduction of trenches width	Down to 3 micron
Passivation optimization	Increase the step coverage: - Optimisation of PECVD deposition - Metal definition optimization
Temporary metal	Optimisation of the etching process
Device planarization	TEOS Reflow
Wafer layout optimisation	Increasing the number of devices per wafers but reducing the bow
Resist coating	Spray coating in FBK



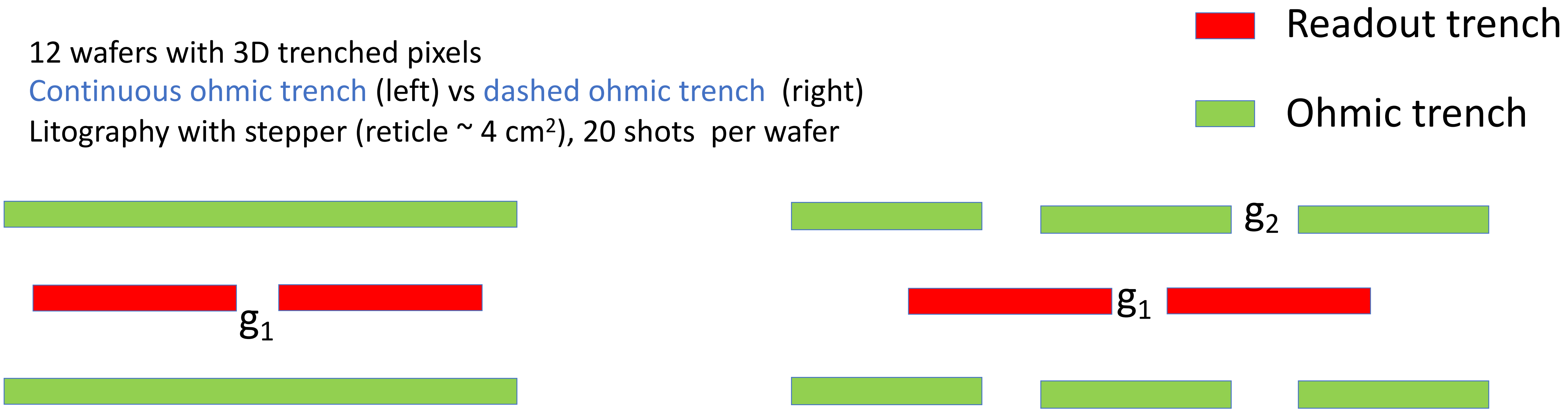
3 micron trench etching





G. Dalla Betta, AIDAInnova WP6 meeting, 06/07/2002

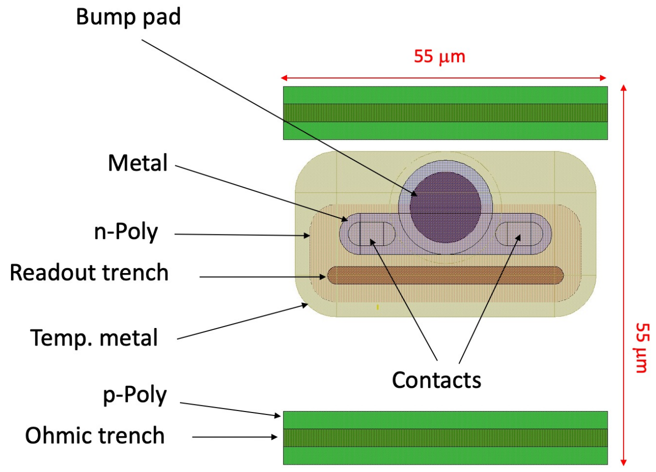
AIDAInnova FBK 3D production



- 12 wafers with 3D trenched pixels
- Continuous ohmic trench (left) vs dashed ohmic trench (right)
- Litography with stepper (reticle ~ 4 cm^2), 20 shots per wafer

- Pixels 70% of the area
  - Baseline 55 micron pitch
    - 32x32 pixels (TIMESPOT1)
    - 64x64 pixels (TIMESPOT2, Picopix)
- Test structures: single/multiple pixels, strips, diodes

Planned start October 2023



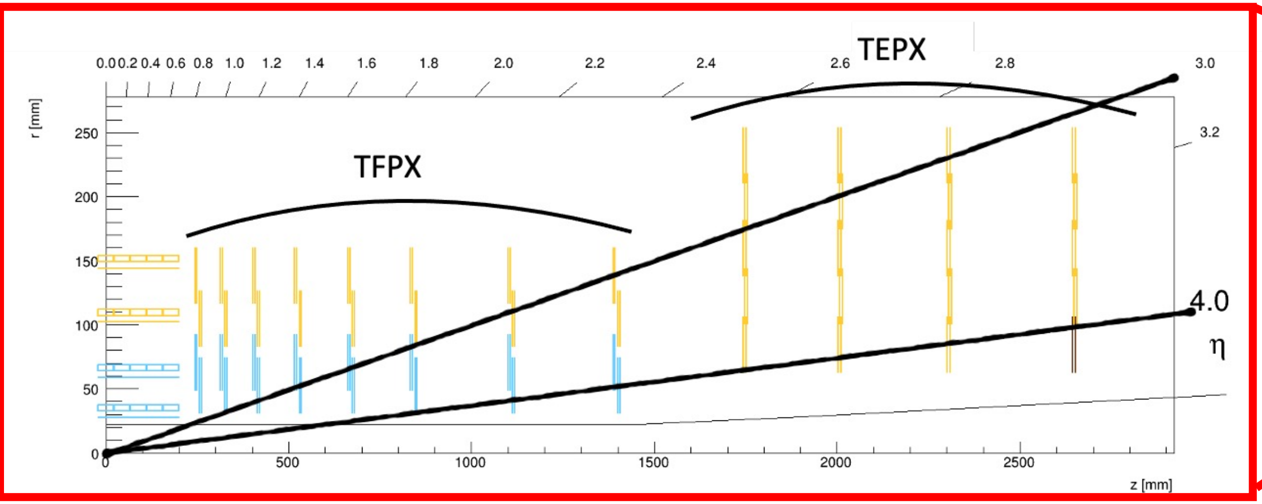
G. Dalla Betta, AIDAInnova WP6 meeting, 06/07/2002

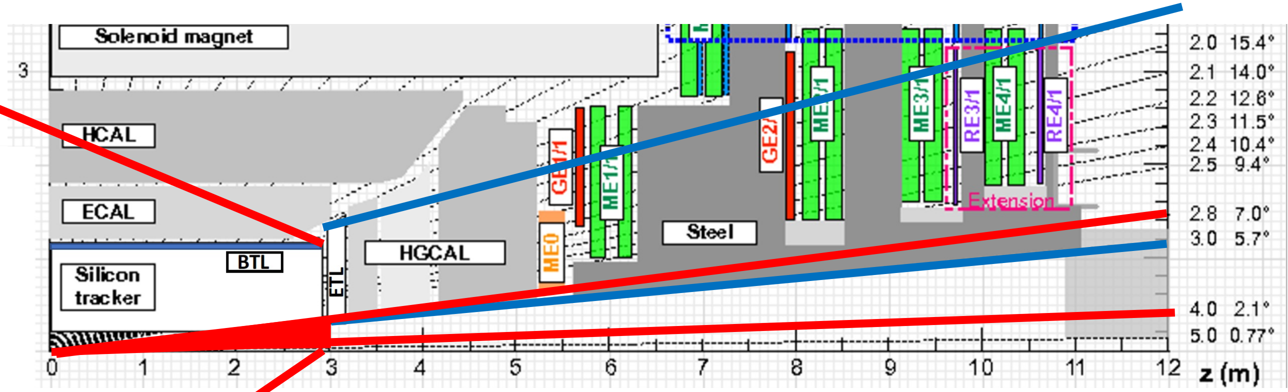
4D timing in CMS Inner Tracker Disks?

4D Tracking in TEPX

- MTD will provide timing in barrel and endcap
  - ETL covering a region from 1.6 < |η| < 3.0
  - HGTD in ATLAS covers 2.4 < |η| < 4.0
- Extension of timing to higher rapidity in Phase-3 will greatly improve detector performance

A. Albrecht, DPG Conference, March 2022



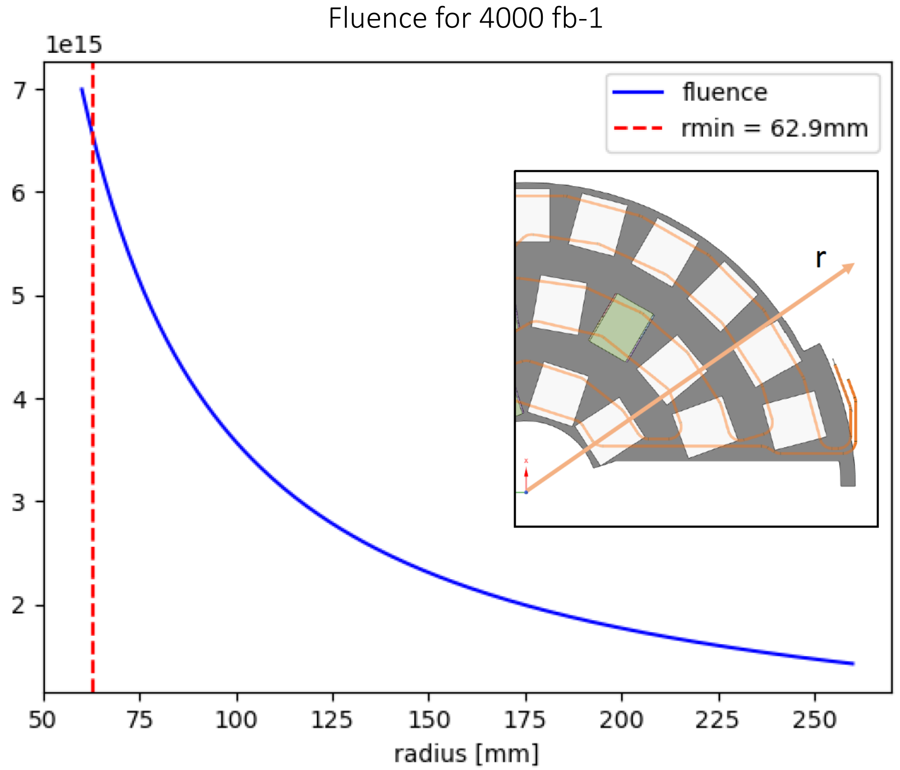


- Options in TEPX:
  - Replace one or two disks with LGADs pixels
    - Implement timing capabilities but spatial resolution can worsen if larger pitch 4D pixels have to be adopted with respect to 25x100 μm^2
  - Adding one disk with LGAD pixels: increase material budget but original disks retain standard hit spatial resolution

Environment in TEPX

Hit rate and occupancy

part	hits / roc	hits/cm²	occupancy (100 x25)	occupancy (100 x100)
ring 1	46	13	3.19E-04	1.27E-03
ring 2	27	7.3	1.87E-04	7.48E-04
ring 3	20	5.5	1.39E-04	5.54E-04
ring 4	15	4.2	1.04E-04	4.16E-04
ring 5	13	3.6	9.01E-05	3.60E-04



- Depending on the time of replacement the fluence level in R1 could be around **3-4E15 neq/cm^2**

Technologies under investigation

option A : Replacement of two disks with 100x100 μm^2 pixels + 65nm CMOS ASIC

- TI-LGAD: loss in position resolution for a better pileup mitigation
- AC-LGAD could deliver good position resolution: radiation hardness? Occupancy?
- development of an ASIC “CROC like” with a TDC per pixel is likely possible, low cost

option B : Replacement of two disks with 25x100 μm^2 TI-LGAD pixels + 28nm CMOS ASIC

- Keep same granularity as present disk design, no loss in position resolution
- development of ASIC quite challenging, high cost, need to be compatible with serial powering and present CMS DAQ

Conclusions

- Different technologies for 3D and LGAD common sensor productions for 4D Tracking are being identified in AIDAInnova WP6 thanks to the characterization of prototype productions

- Productions should be completed within the end of 2023

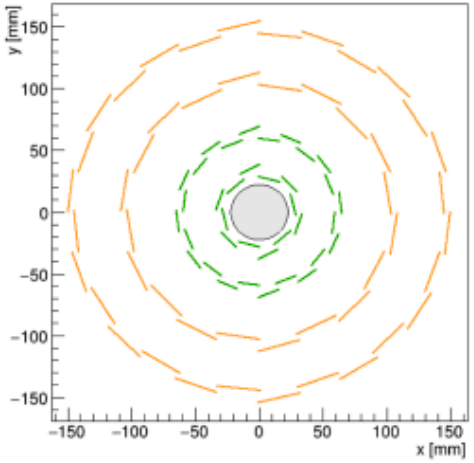
- The performance will be assessed and compared with lab and beam tests, before and after irradiation

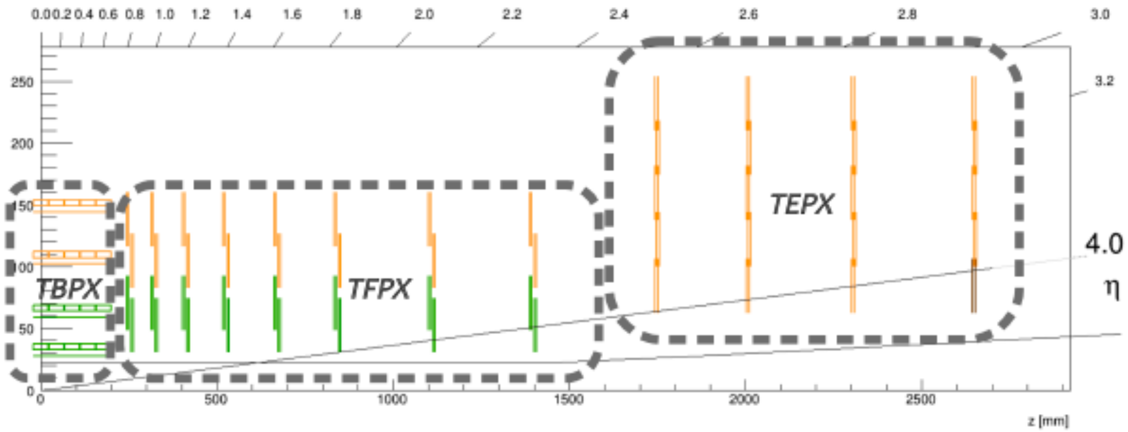
- First (inofficial!) thoughts on replacement of Inner Tracker disks with timing layers in CMS for HL-LHC Phase-3
    - Extension of timing capabilities for CMS in $3 < |\eta| < 4.0$
    - Different sensor and chip technologies being considered

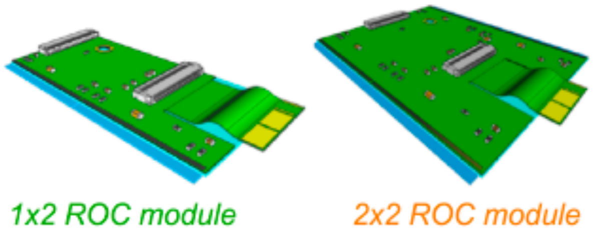
Additional slides

Inner Tracker – Detector Layout

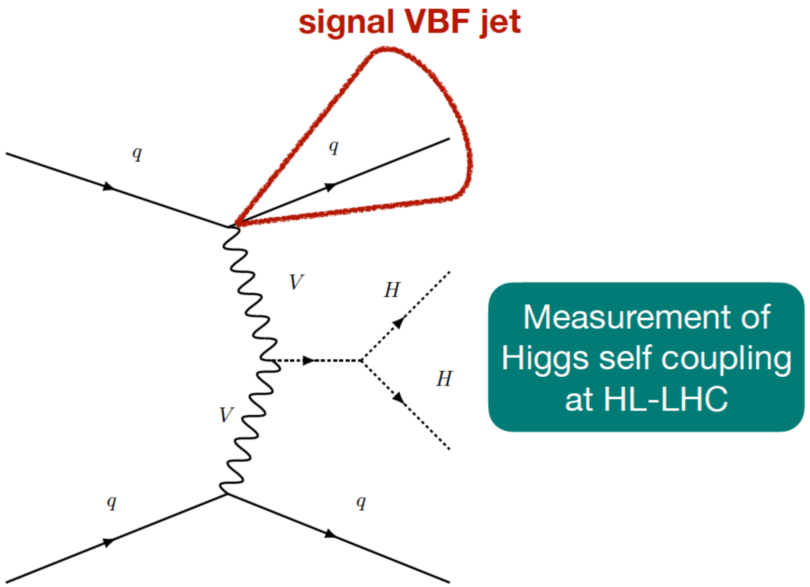
- Extended coverage up to |η|=4
- Innermost modules located at r=2.75 cm from the beamline
- 4 barrel layers (TBPX) + 2x8 small discs (TFPX) + 2x4 large discs (TEPX)
  - TBPX: no crack at z=0, two ladders per layer skewed in rϕ for the insertion in CMS
  - TFPX and TEPX: each disc made of 4 identical dees
- Hybrid pixel modules:
  - Two module types: 1x2 and 2x2 readout chip per module







Physics case for forward timing



Signal: VBF→ HH → bbbb (Signal VBF and b jets defined with matching to signal genparticles)

Background: QCD sample (PU jets if R(reco, gen) >0.6)

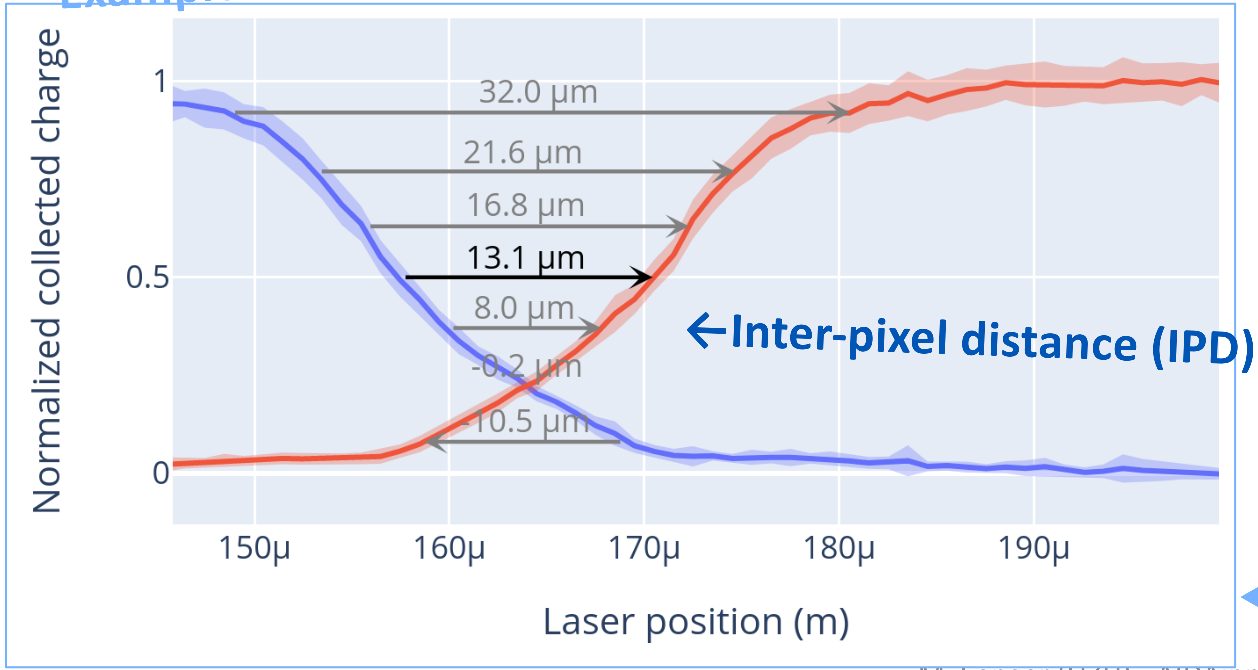
Can PU mitigation be improved by timing up to |η|<4?

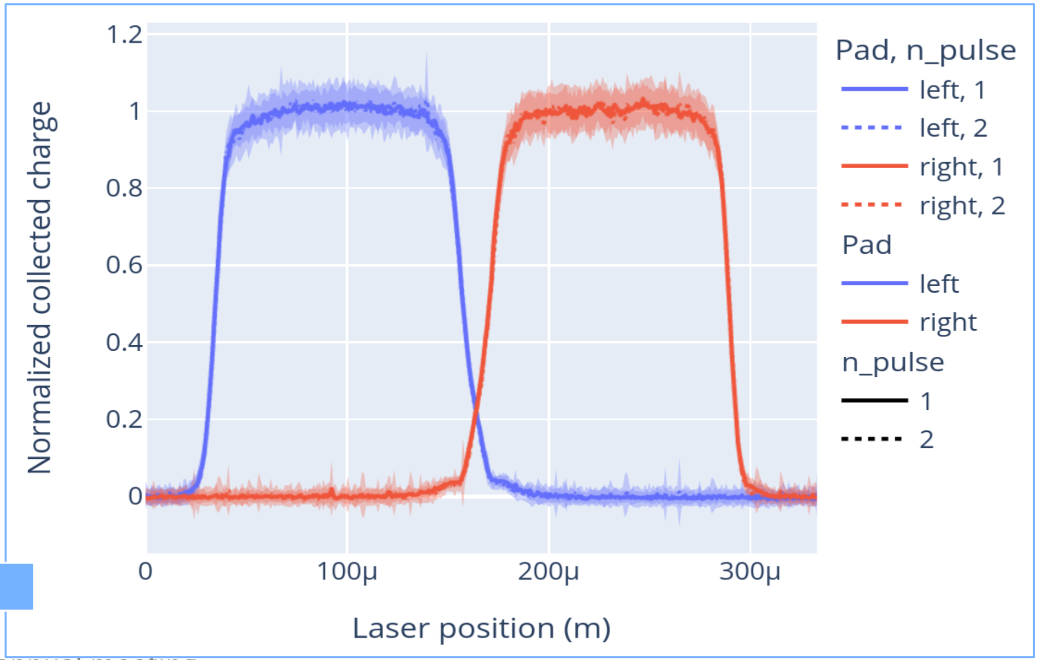
A. Albrecht, DPG Conference, March 2022

Inter-pixel distance (IPD)

- IPD: Distance between 50 % of normalized collected charge of each channel.
- Linear interpolation, not “S function”.
  - Observed deviations from “S”, different for each design pattern and dependent on the bias voltage.

Example from a random scan (non irradiated device)

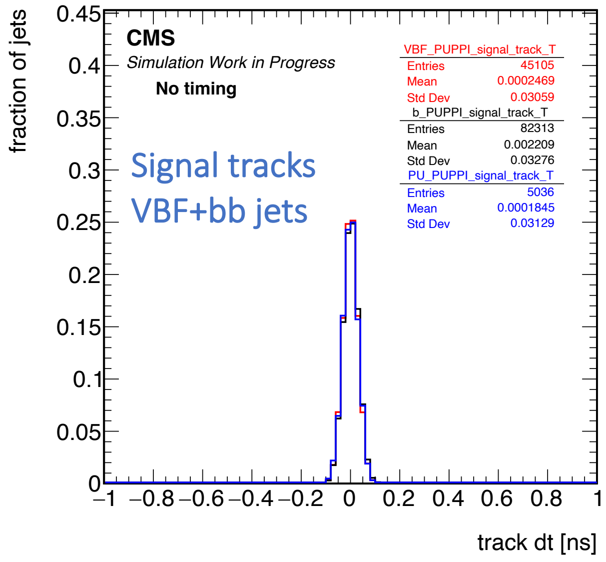


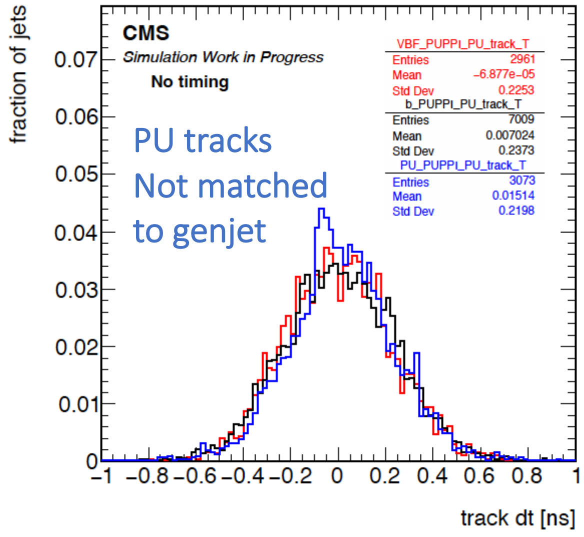


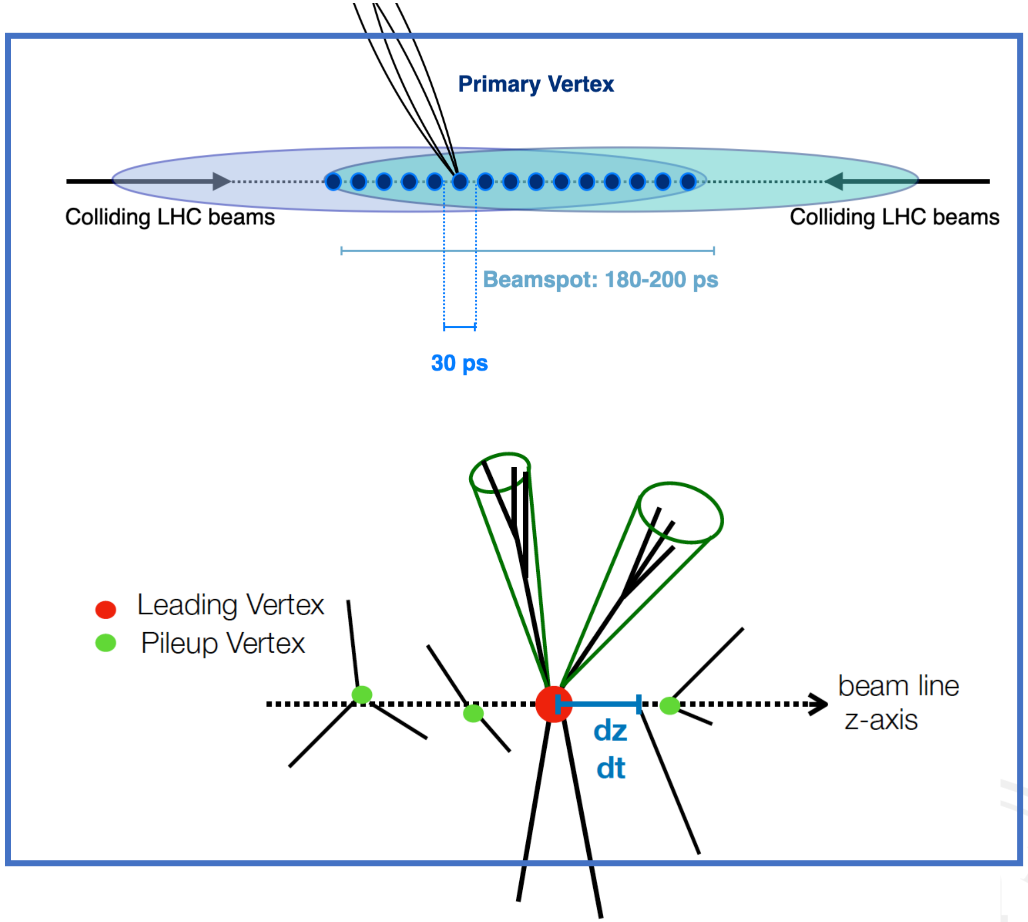
Pile-up mitigation

Test 3 different scenarios:
Charged tracks (signal and PU) removed if **dz > 0.1 cm** …

1. … with no timing requirement
2. … or dt > 0.1 ns for |η|< 3 BTL+ETL
3. … or dt > 0.1 ns for |η|< 4 BTL+ETL+Timing EPX







Momentum Smearing for Phase 2 tracker

- Phase 2 (25x100) resolution for dz
- Time smeared by 30 ps resolution

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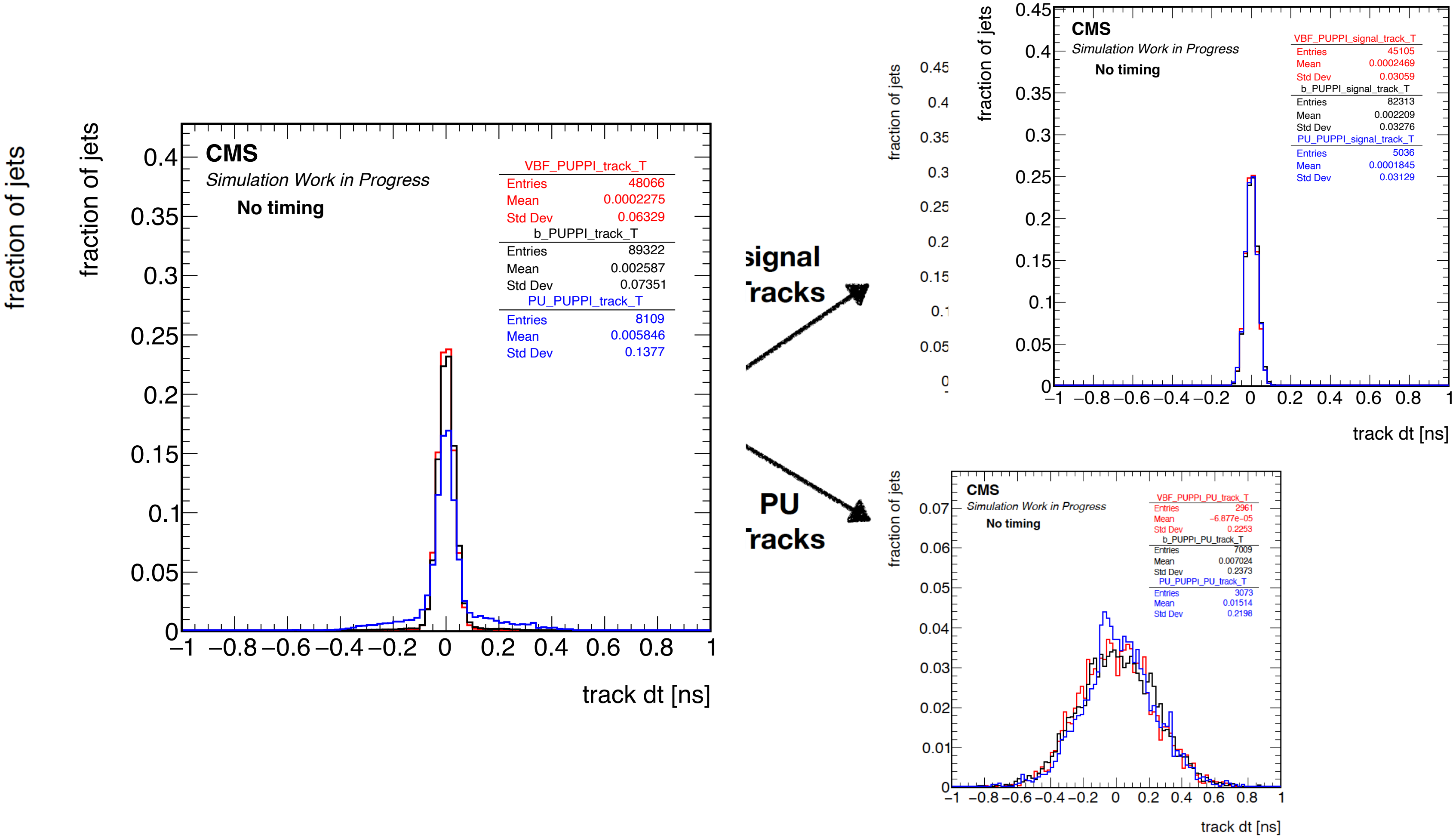
Signal/Pile-up timing distribution



PU jets show tails in dt distribution PU tracks.
Signal tracks dt < 0.1 ns

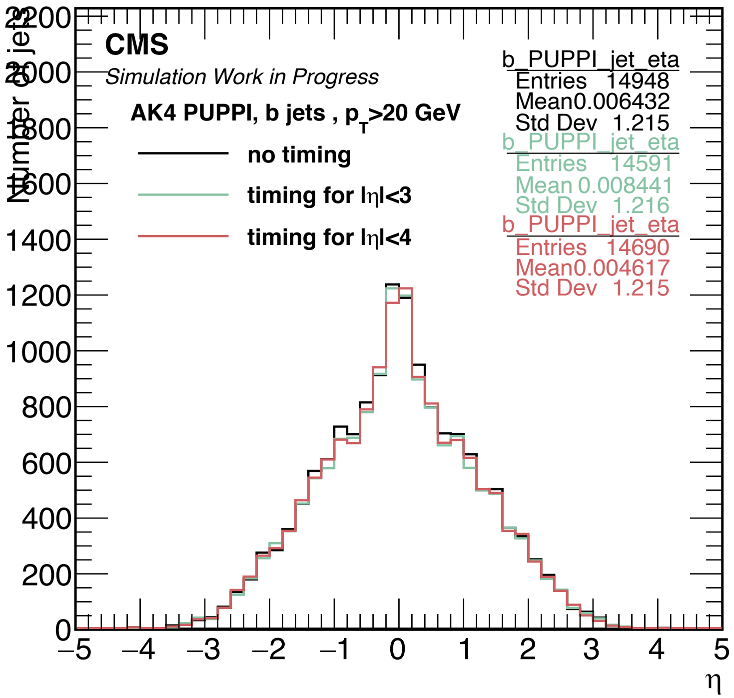
PU tracks dt distribution broader gaussian

PU tracks can be removed with timing requirement

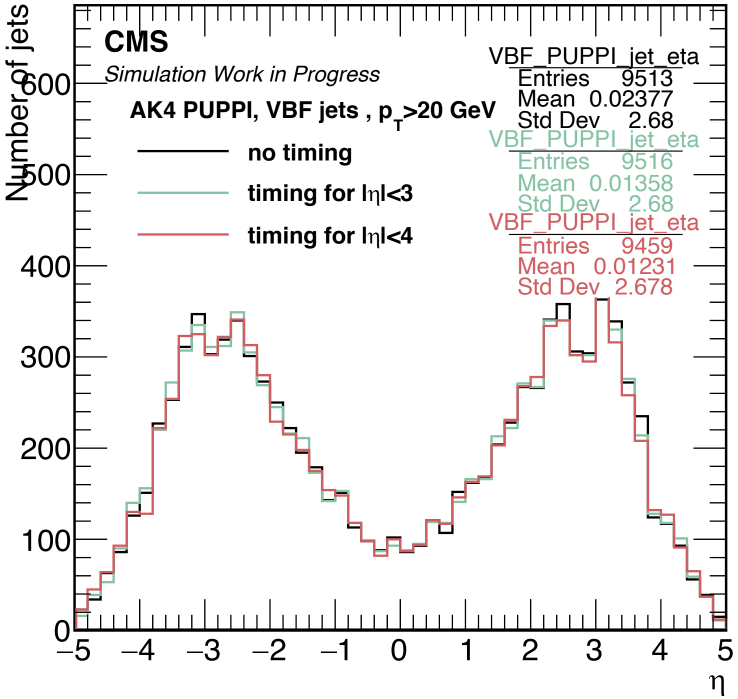
Signal: VBF_HH_bbbb sample PUPPI jets matched to **b (R<0.2)** or **VBF** quarks (R<0.4)
Background: QCD sample PUPPI jets not matched to genjet (R>0.6) **(PU jets)**

Pile-up rejection

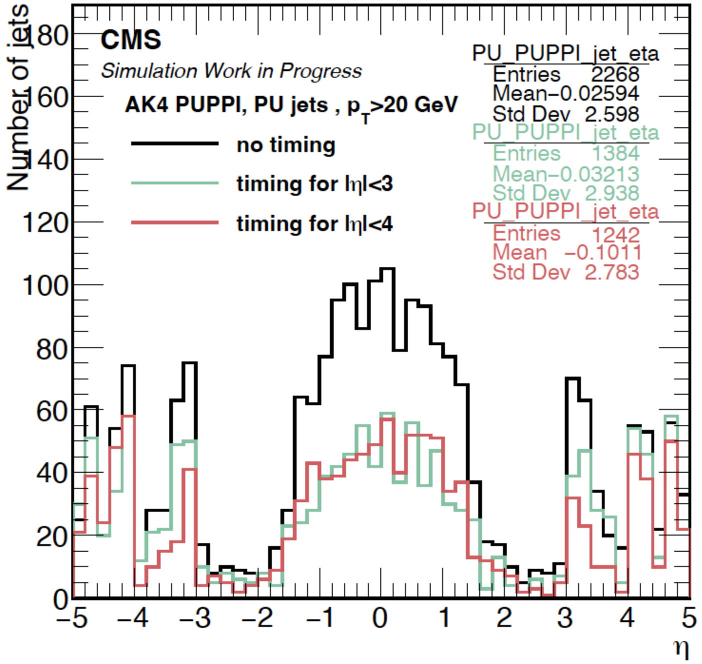
b jet (R<0.2)



VBF jet (R<0.4)



PU jets (R>0.6)



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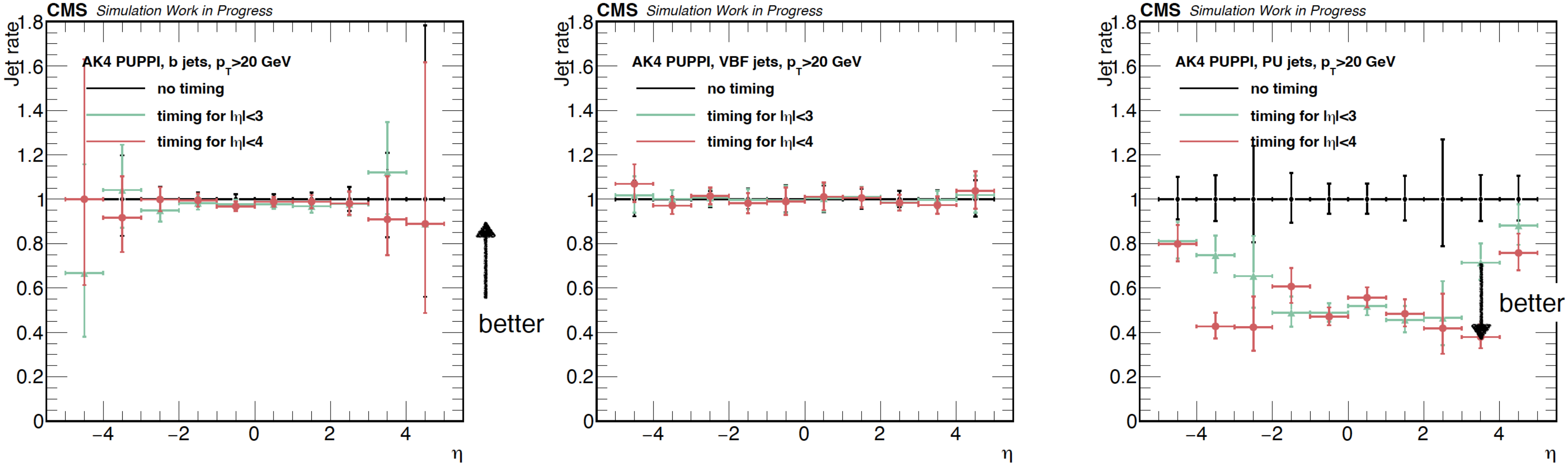
Pile-up rejection

Central region (up to $|\eta| < 3$): Signal rates similar for all scenarios; reduced PU jet rate with timing
Forward region ($4 < |\eta| < 3$): With timing up to 4 the PU jet rate is reduced even more than with timing up to 3; Some signal efficiency lost



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