Particle Tracking with 3D Monolithically Stacked CMOS Active Pixel Sensors

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(3D and p-type Technologies)
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Outline

- ✓ Introduction: motivation and aim, background.
- ✓ The RAPS04-3D structures: (2D), 3D “not aligned”, 3D “aligned”.
- ✓ Electrical characterization (noise).
- ✓ X-ray characterization (signal).
- ✓ Characterization with 3MeV protons @ LABEC, Florence (Italy).
- ✓ The next prototype: RAPS05-3D.
- ✓ Conclusions.

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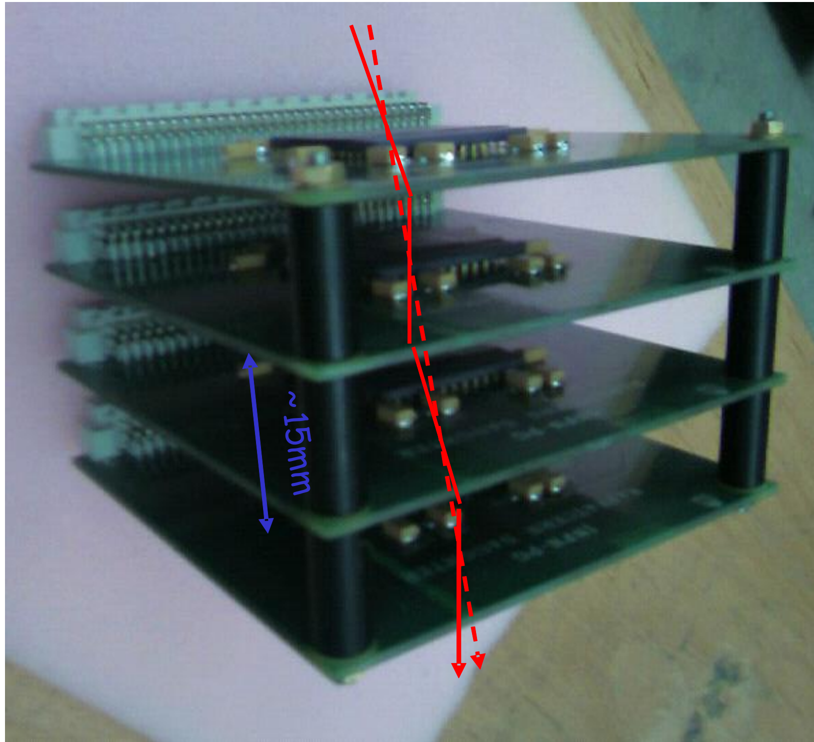
Motivation and Aim

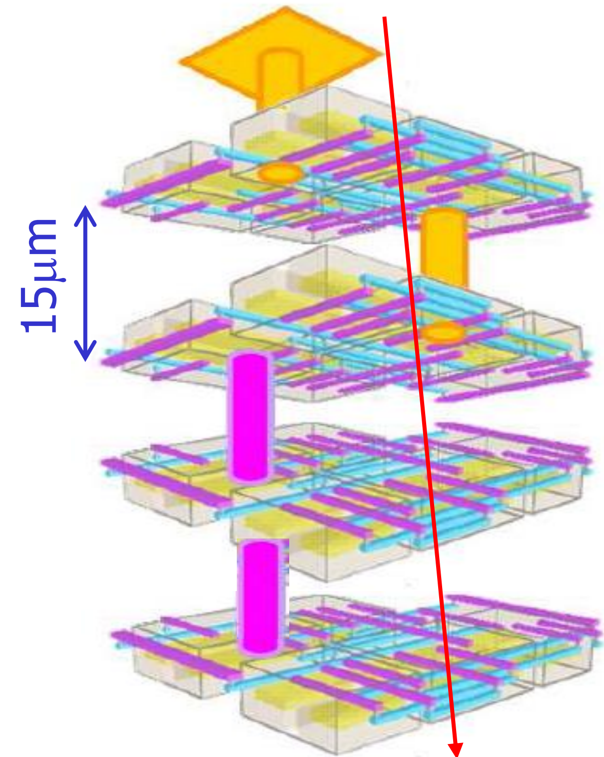
- ✓ The IC technology trend is to move from 3D flexible configurations (package on package, stacked dies) to 3D ICs:
  - increased electrical performances;
  - cost of 3D integration may be cheaper than to keep shrinking 2D.
- ✓ Perspective advantages for particle tracking / vertex detectors:
  - separation of sensor, analog read-out electronics, A/D conversion layers (increased fill-factor, performance).
- ✓ All-in-one chip featuring multiple, stacked, fully functional CMOS APS detector layers:
  - momentum measurement (impact point and trajectory) with a single detector;
  - low material detector (reduced multiple scattering issues).

Basic principle

✓ 3D monolithically-stacked CMOS Active Pixel Sensor detector for single ionizing particle trajectory and momentum identification.



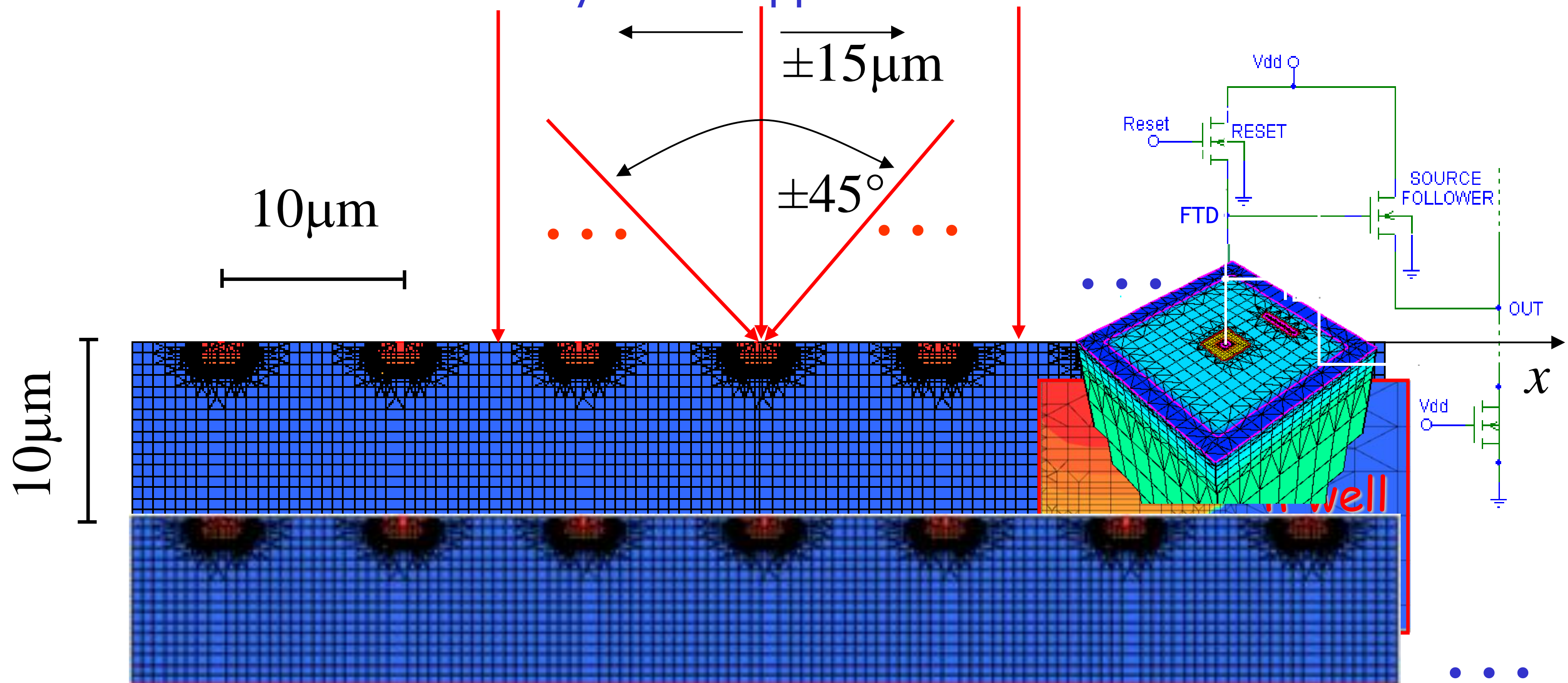
Stack of separate multi-layer CMOS APS detectors.
Worries: multiple scattering and material budget…



Stack of monolithically integrated (vertical scale or 3D) CMOS APS detectors.

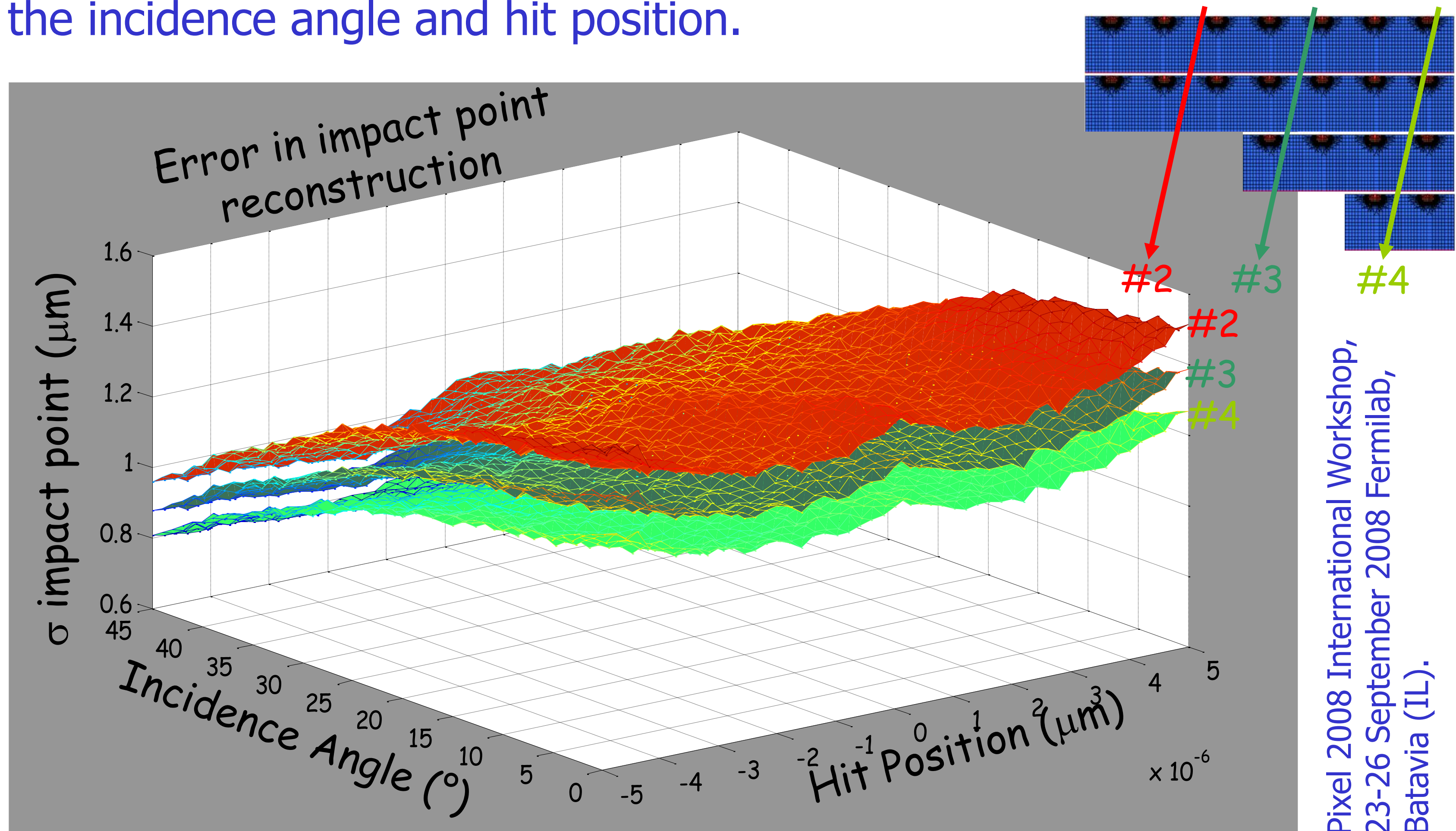
3D Monolithically Stacked CMOS APS

- ✓ Is it possible to gain information (on particle trajectory and momentum) from small pixels / small inter-layer distances?
- ✓ Device/Circuit simulations of a CMOS Active Pixel Sensor to assess the suitability of the approach.



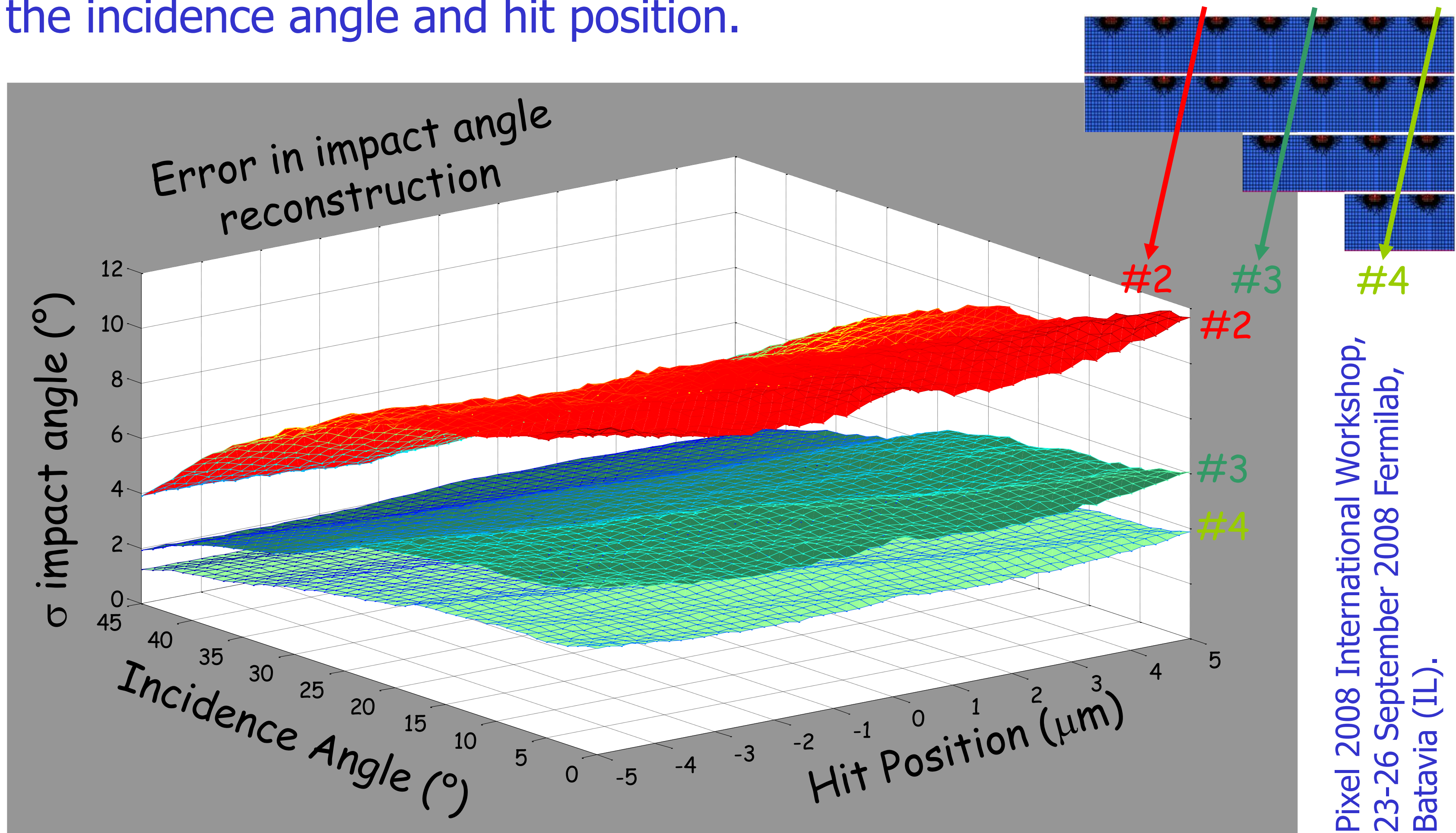
Impact point reconstruction error

- ✓ Standard deviation of the impact point calculation as a function of the incidence angle and hit position.



Incidence angle reconstruction error

- ✓ Standard deviation of the <u>incidence angle</u> calculation as a function of the incidence angle and hit position.



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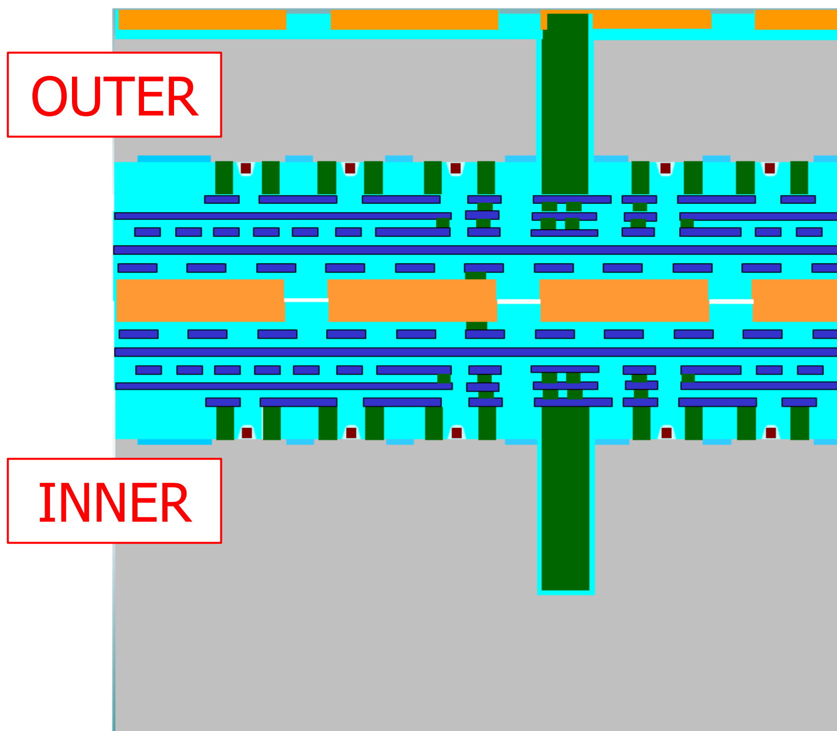
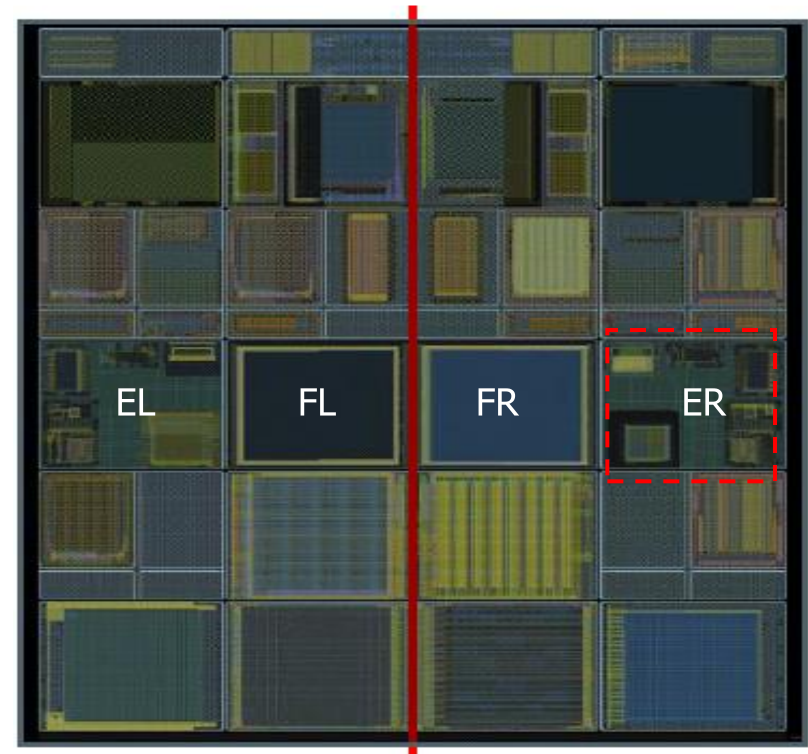
The 3D Tezzaron 130nm Technology

✓ 3D-IC consortium (3dic.fnal.gov)
Access to 3D Tezzaron/Chartered 130nm technology.



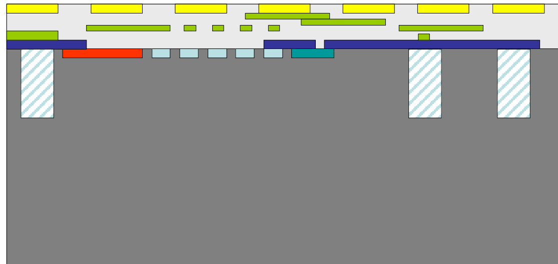
Schematic cross-section of a front-to-front chip bonding (thinned top tier)

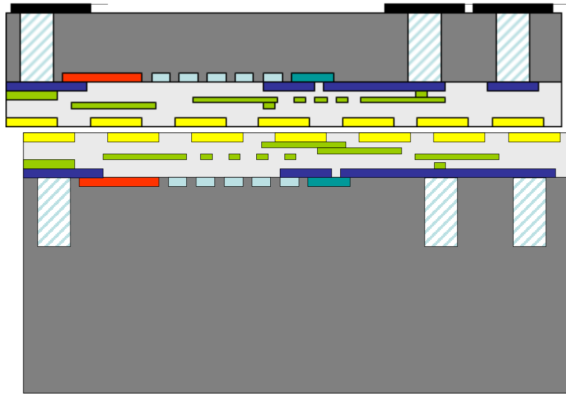


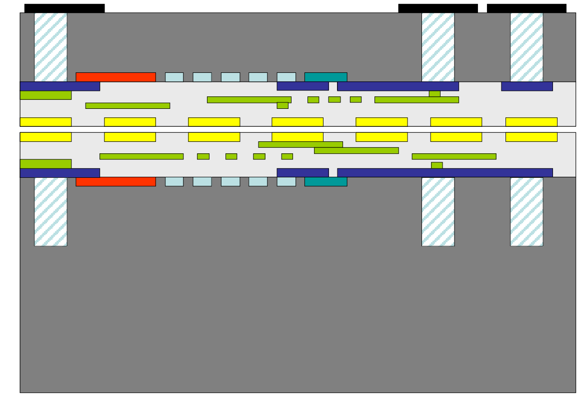
MPW run ("HEP oriented")
VIPIX – INFN gr. V (sub-reticles E & F).

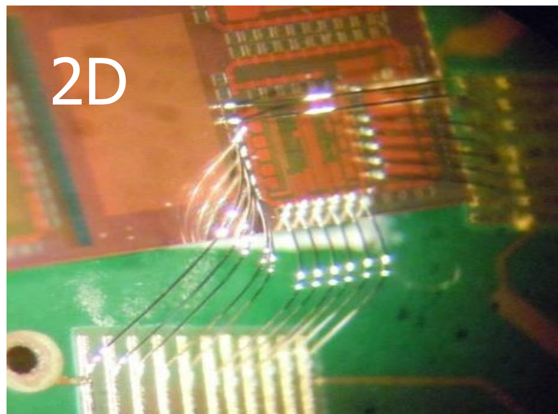
The chip structures

Tezzaron/GlobalFoundries
3D-IC Integrated 2-tier stack
130nm CMOS

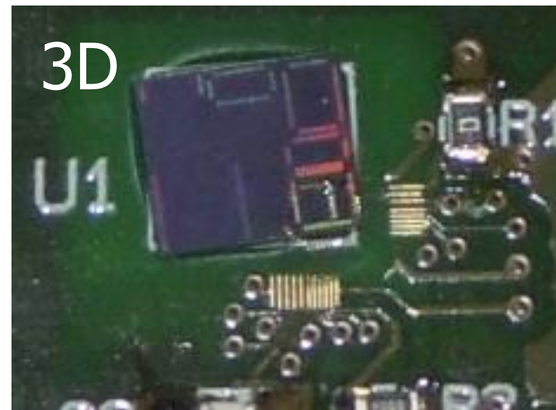




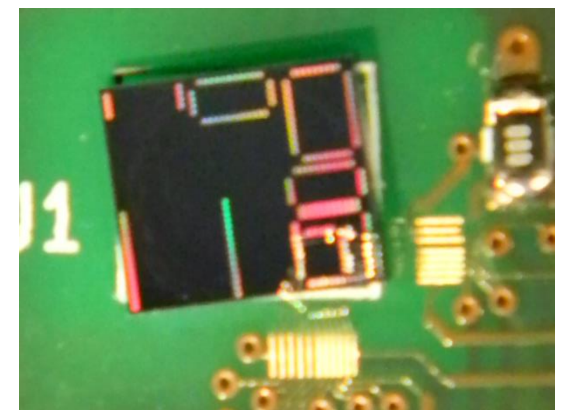




2D.



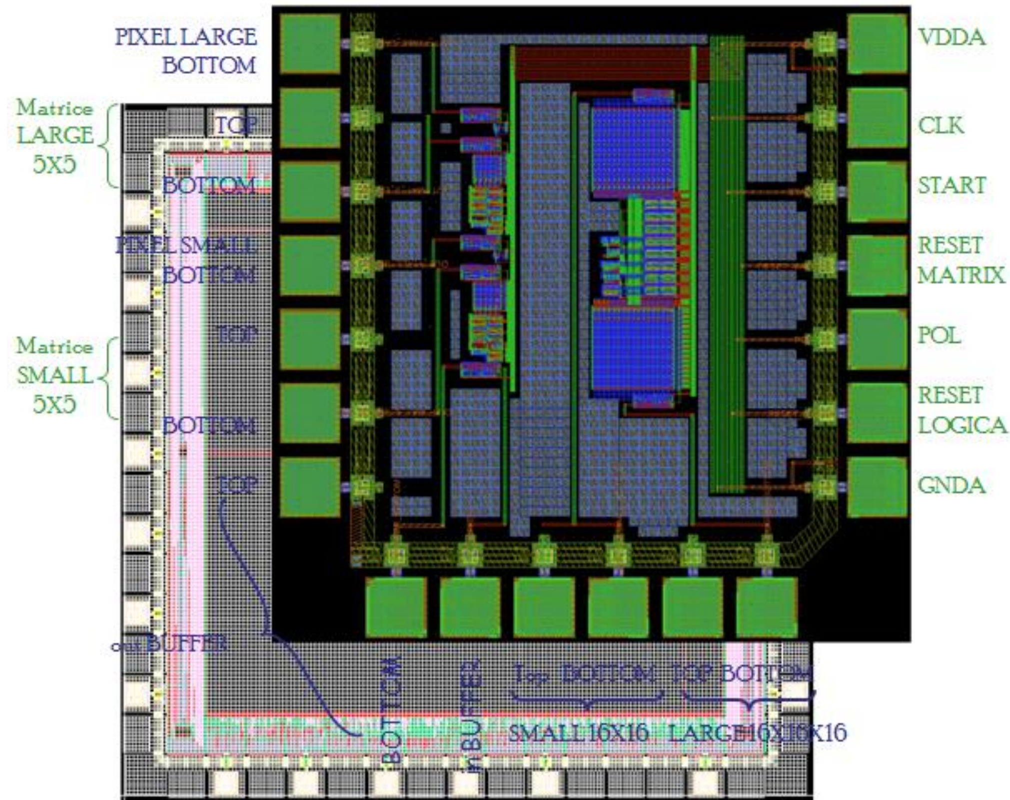
3D Not Aligned.

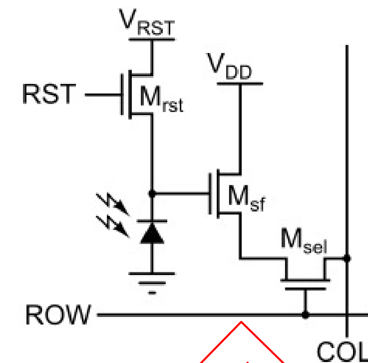


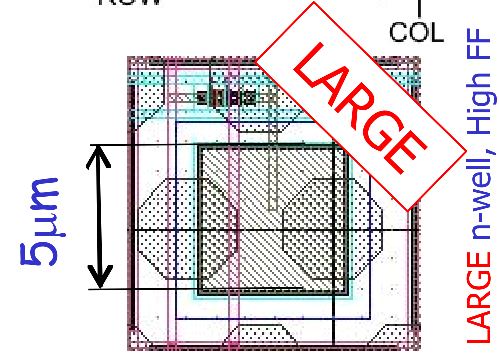
3D Aligned (Ziptronix/Tezzaron).

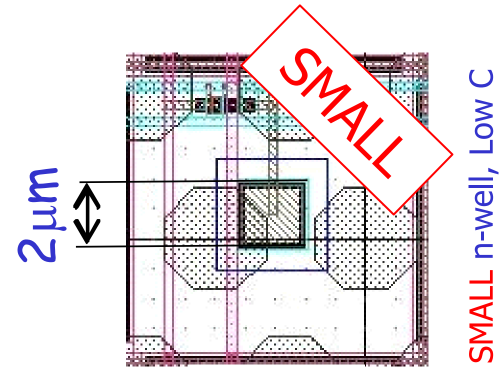
The RAPS04-3D structures

- ✓ Active Pixel Sensor 3T architecture with different photodiode area.









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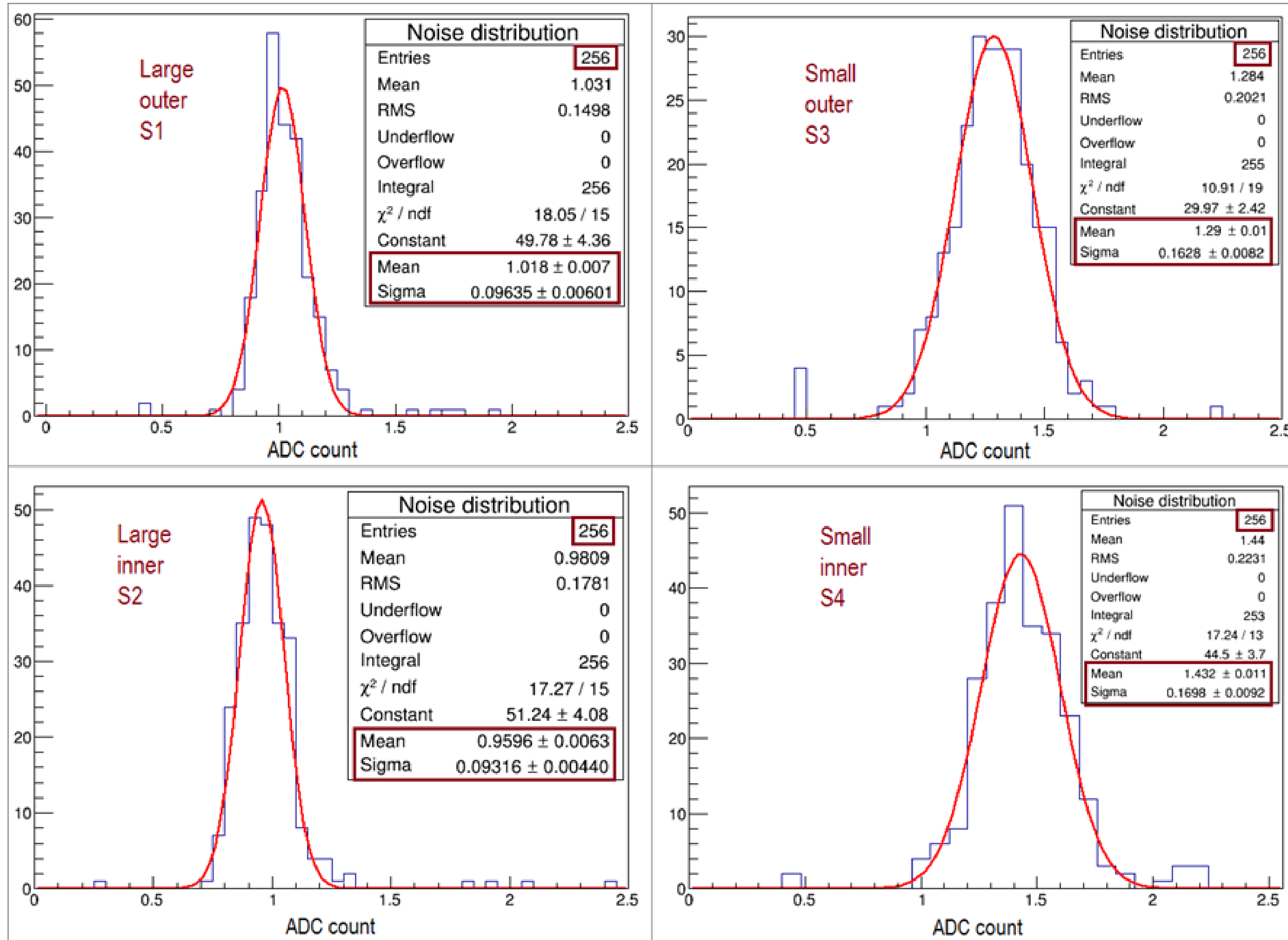
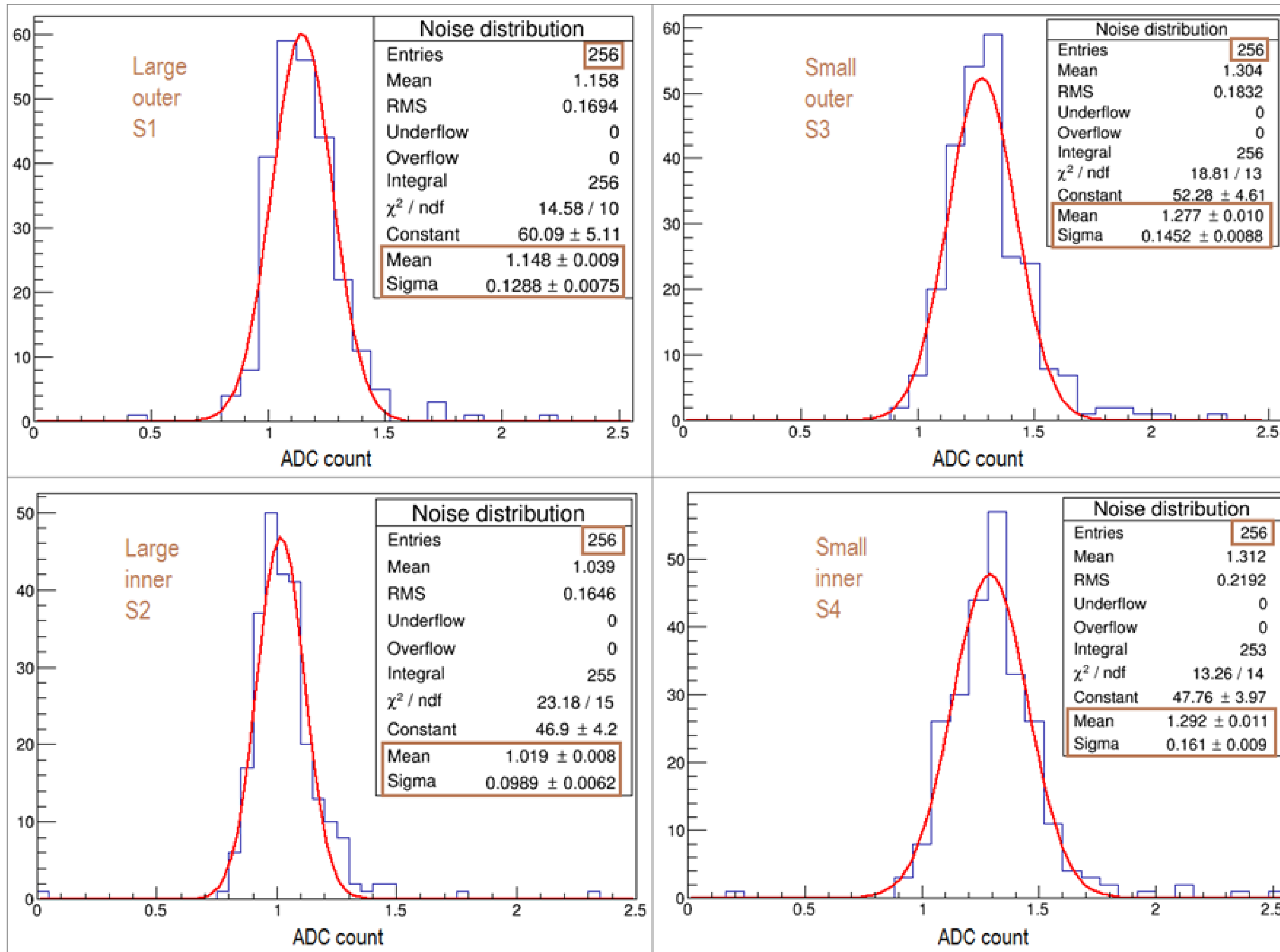
Electrical Characterization

✓ Noise distribution 16x16 pixel matrices – Tezzaron bonded chip



Electrical Characterization (2)

✓ Noise distribution 16x16 pixel matrices – Ziptronix bonded chip



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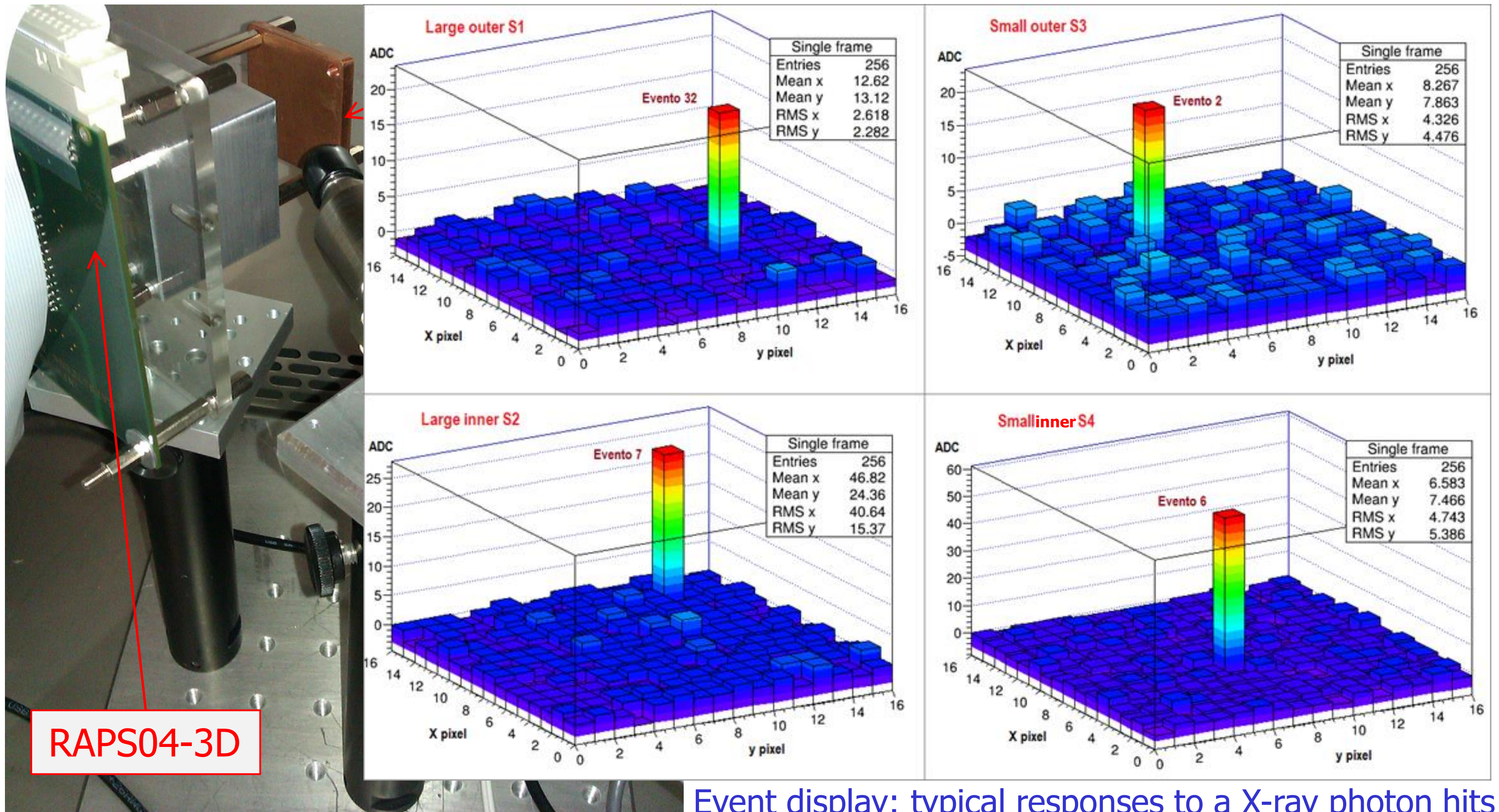
Functional Characterization (X-rays)

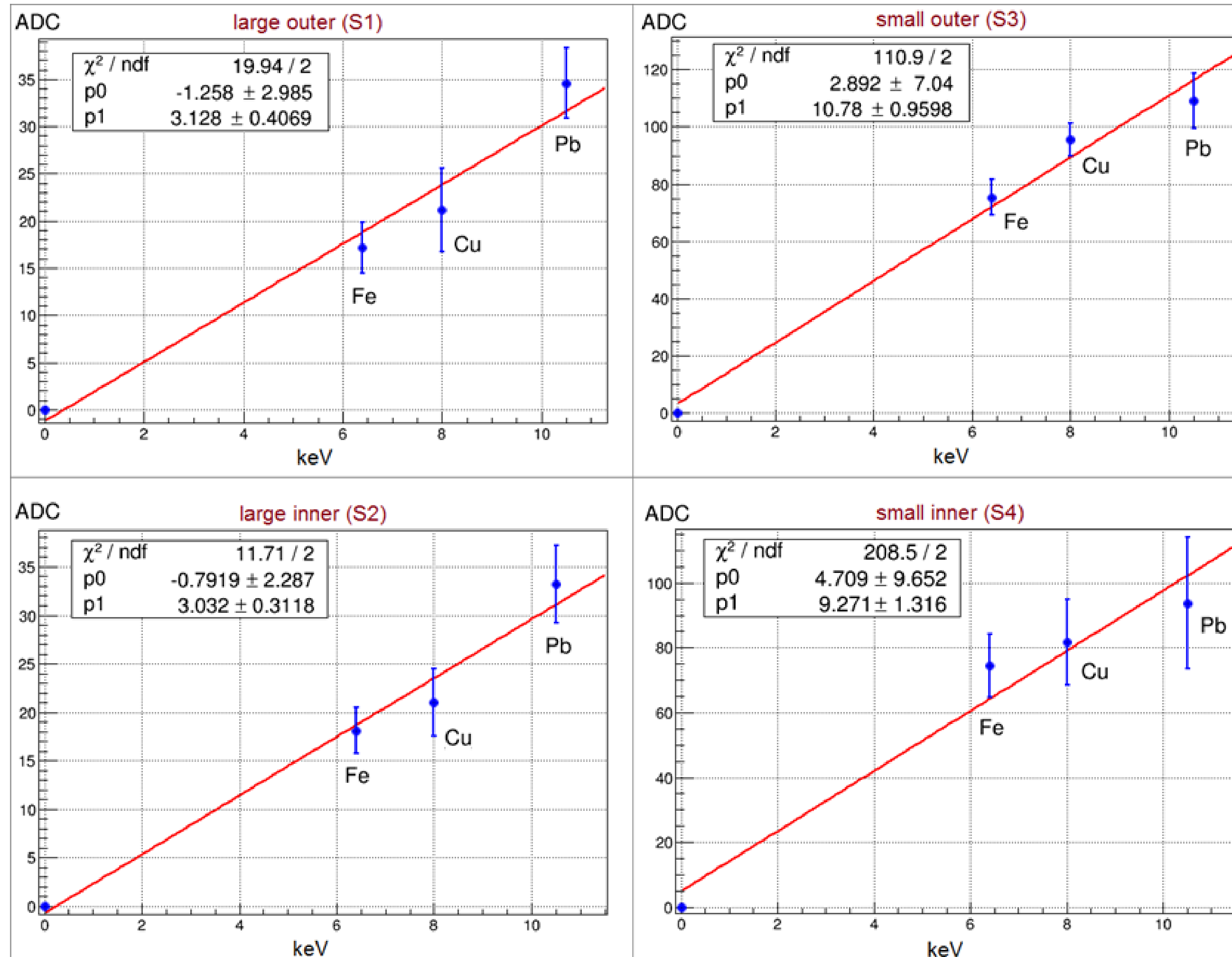
✓ The X-ray set-up @ INFN Perugia Laboratories.



Event display: typical responses to a X-ray photon hits

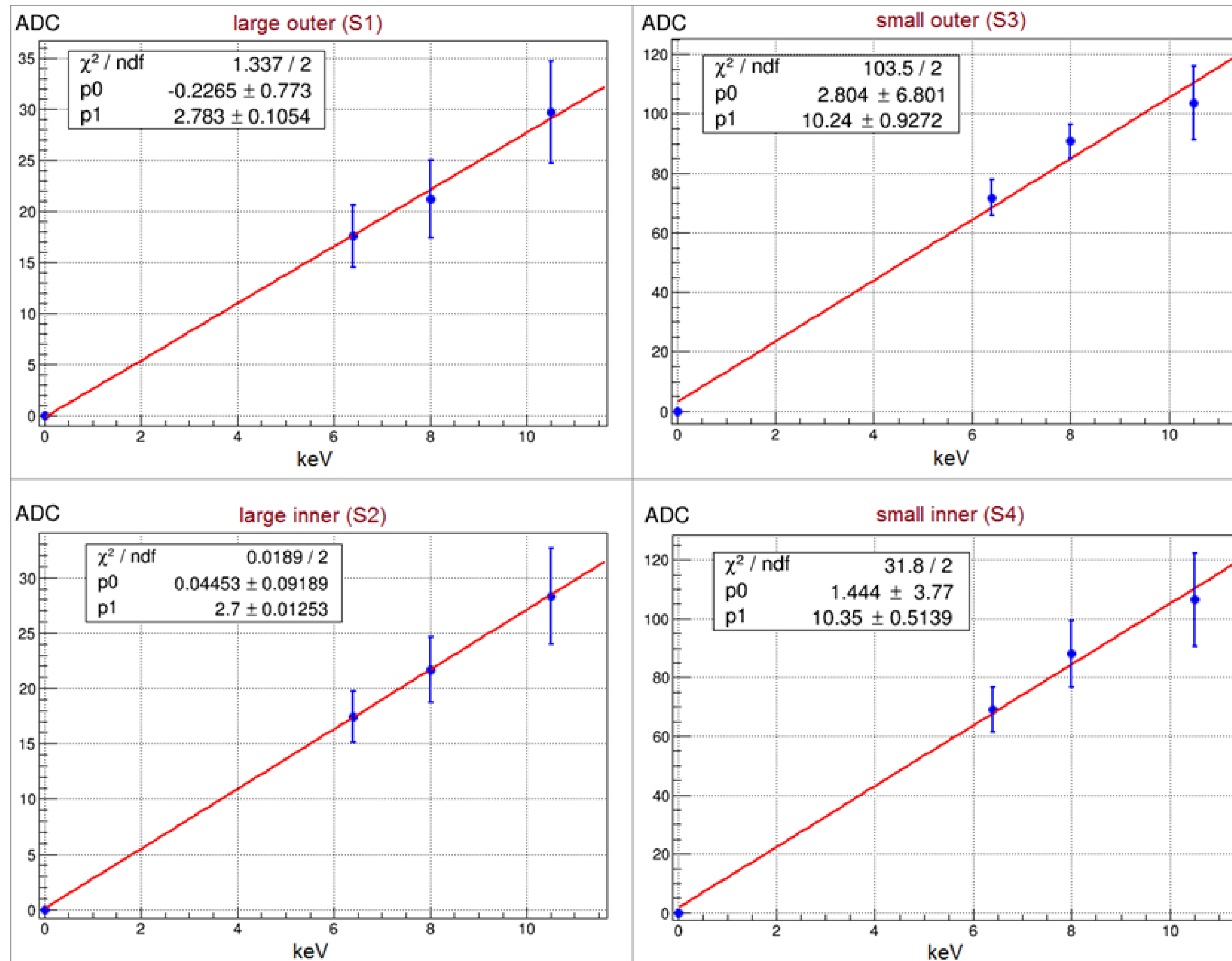
Sensor Calibration

✓ X-ray photon energy -> ADC count – Tezzaron bonded chip



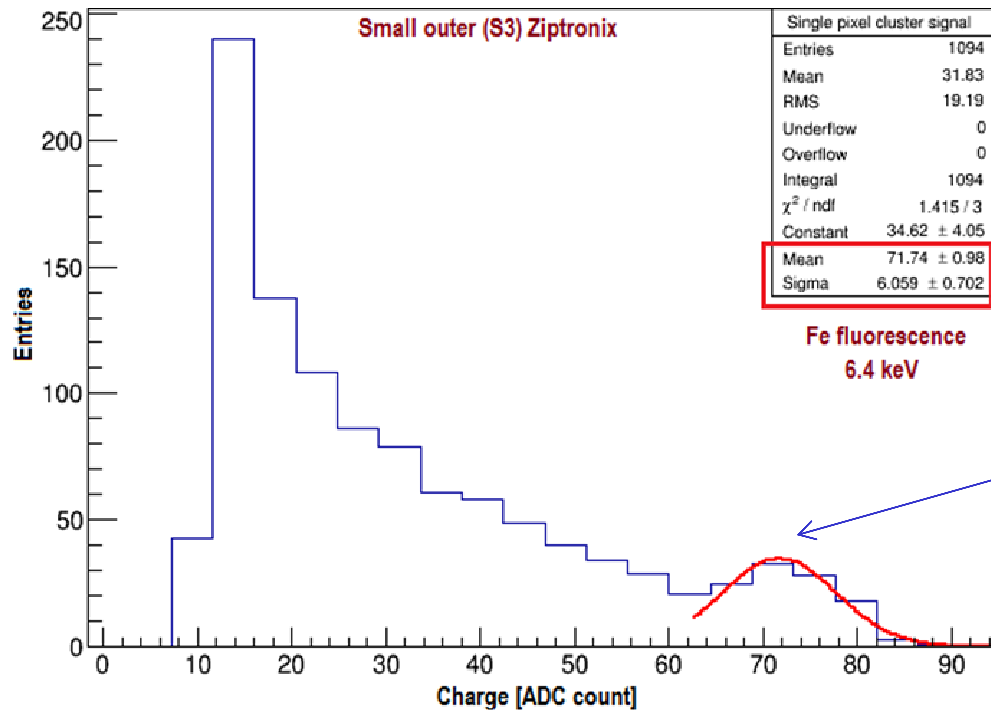
Sensor Calibration (2)

✓ X-ray photon energy -> ADC count – Ziptronix bonded chip



Sensor Calibration (3)

✓ Electrons -> ADC counts



Fe peak energy

$$e/h = \frac{6.4\ keV}{3.6\ \mathrm{eV}} = 1777$$

Energy for e/h creation in Si

$$1777/Mean = [e/ADC]$$

✓ 1 ADC count -> ~102e for the large photodiode pixel layout

✓ 1 ADC count -> ~25e for the small photodiode pixel layout

Better conversion gain

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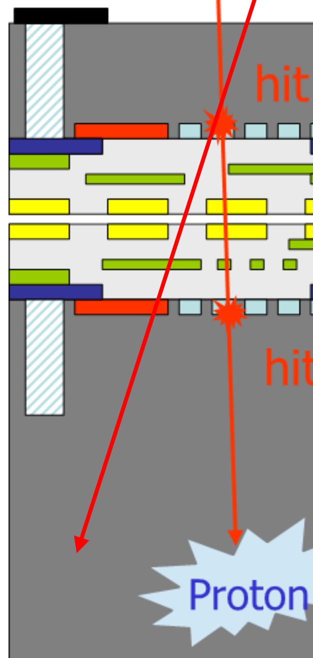
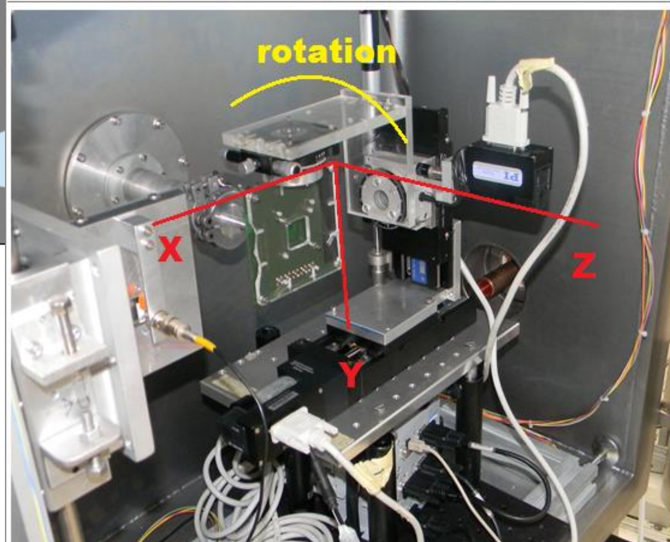
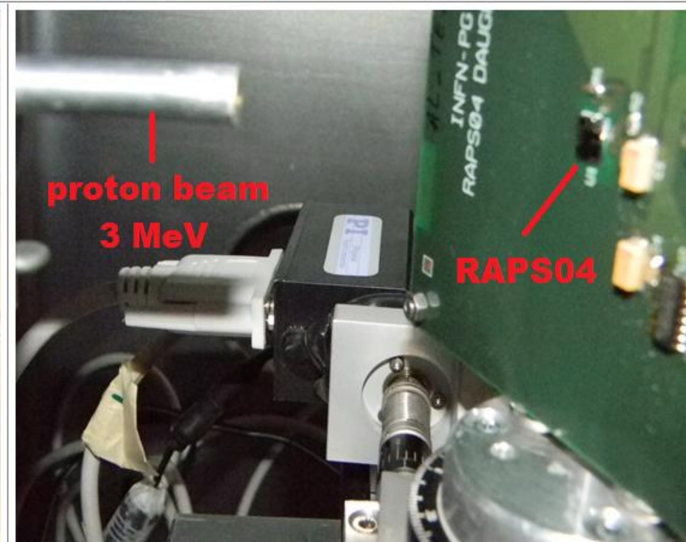
The set-up at LABEC (Florence, Italy)

✓ 3MeV protons



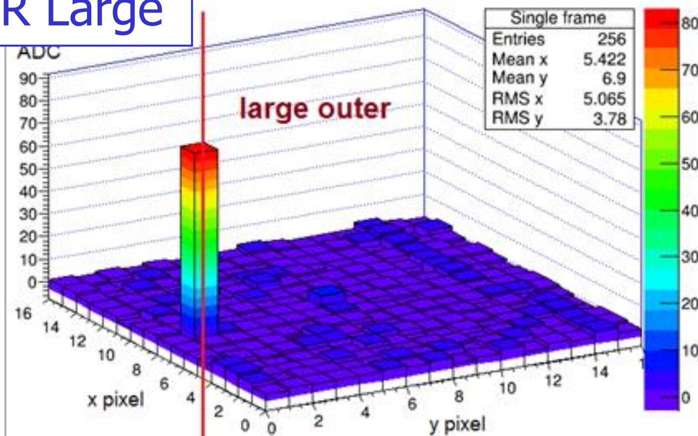




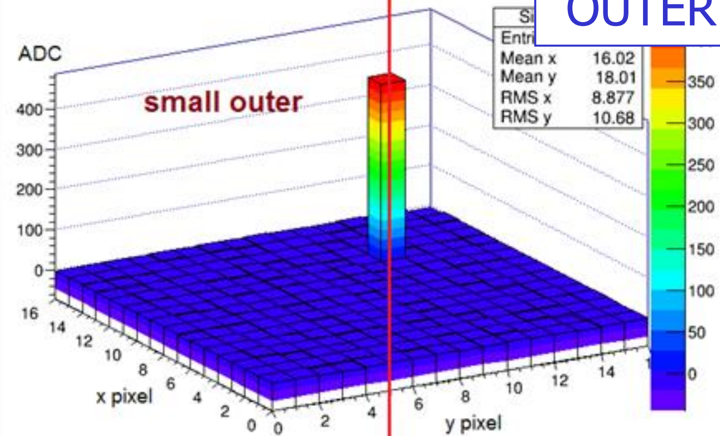
3 MeV protons response

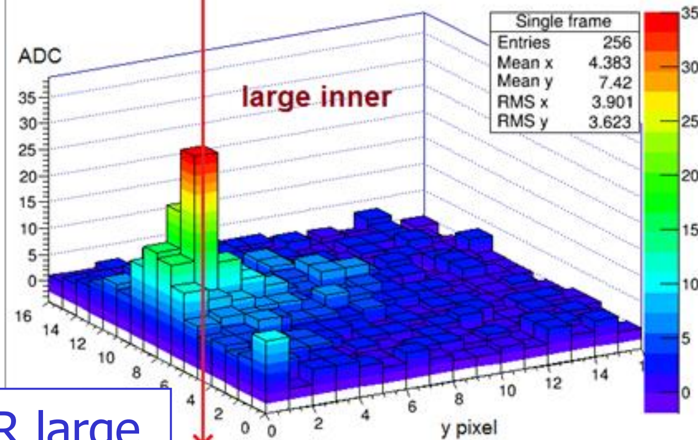
✓ RAPS04-3D 3MeV protons – Outer & Inner tier coincidence responses

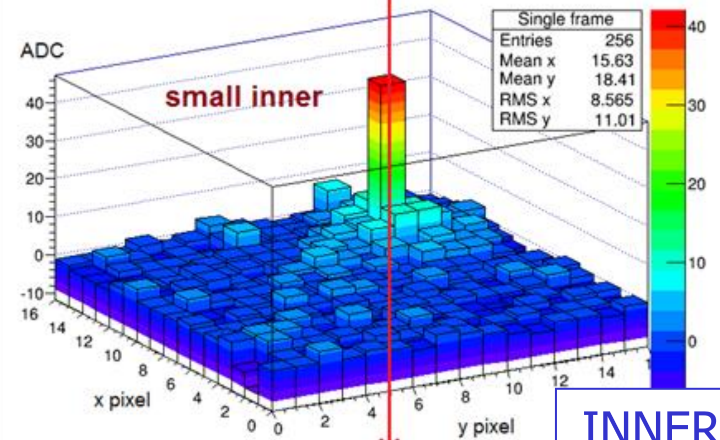
OUTER Large



OUTER Small



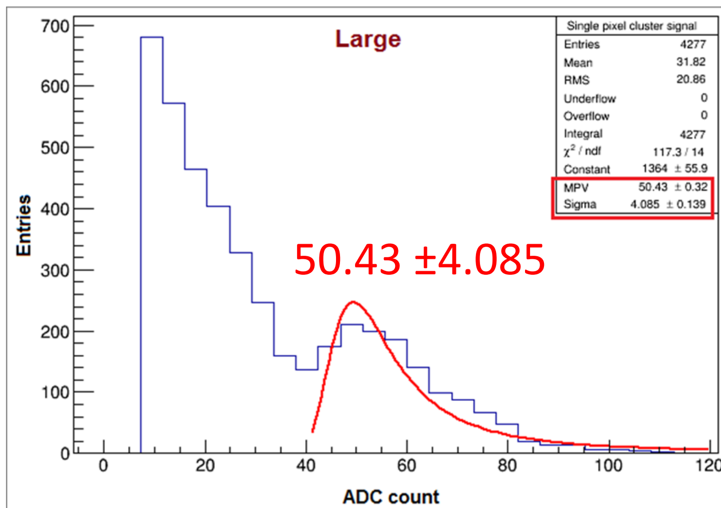


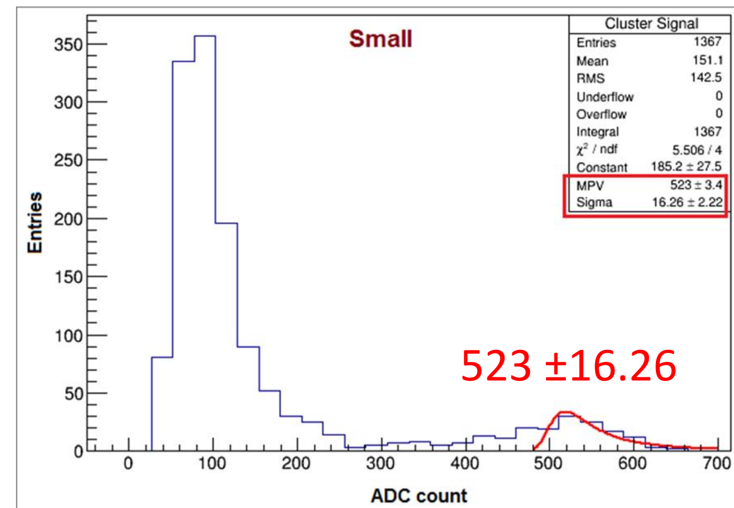


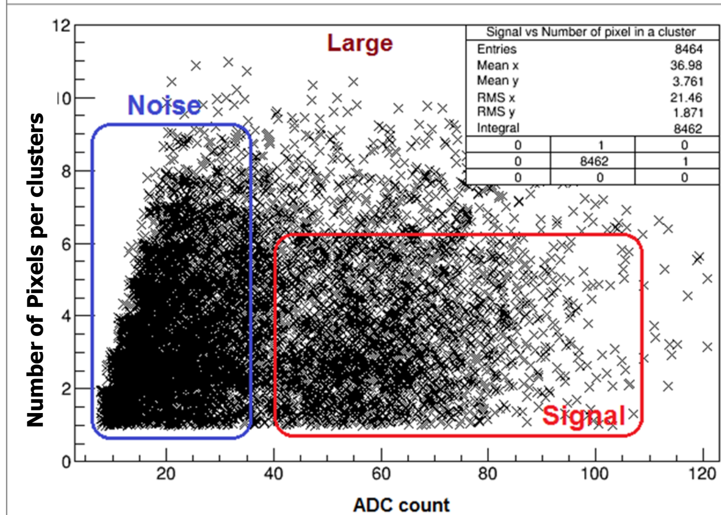
INNER large

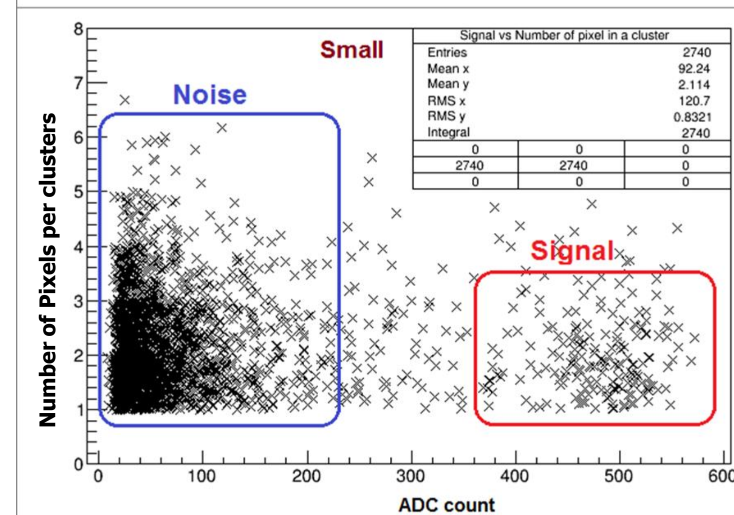
INNER Small

3 MeV protons response (2)



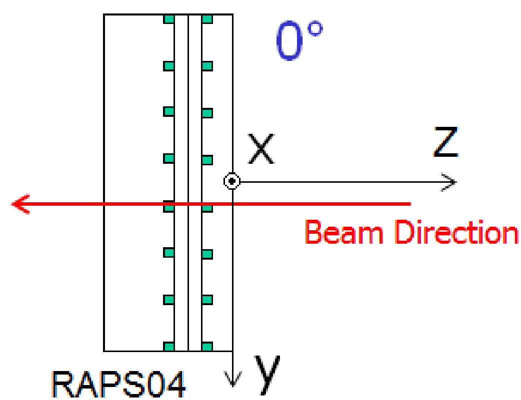


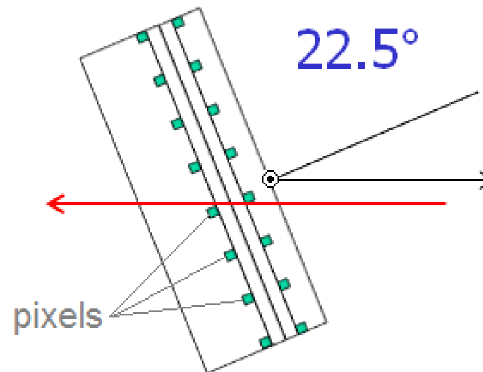


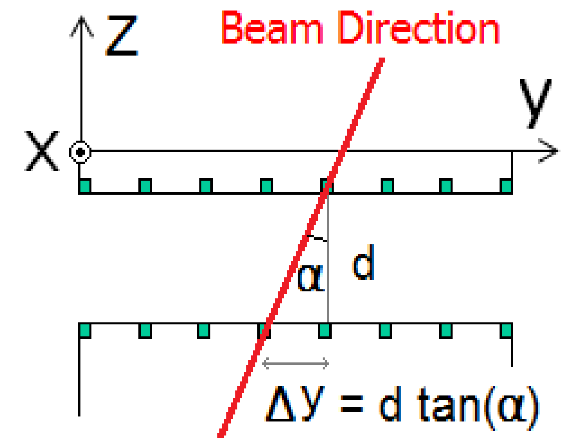


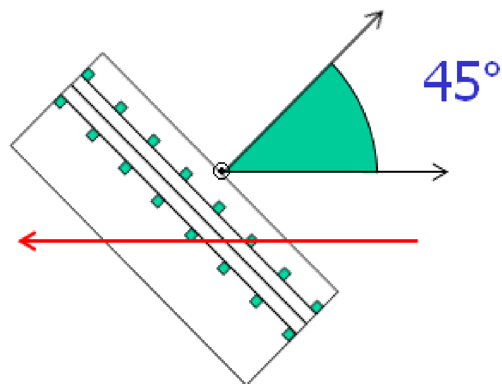
Signal distribution & Landau Fit (LARGE) Signal distribution & Landau Fit (SMALL)

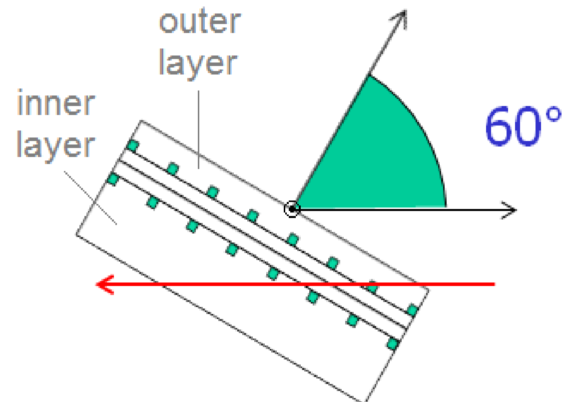
Angular measurements







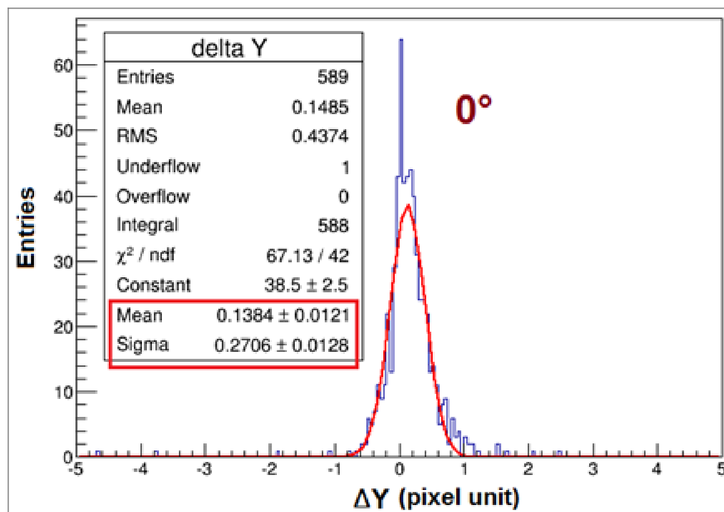


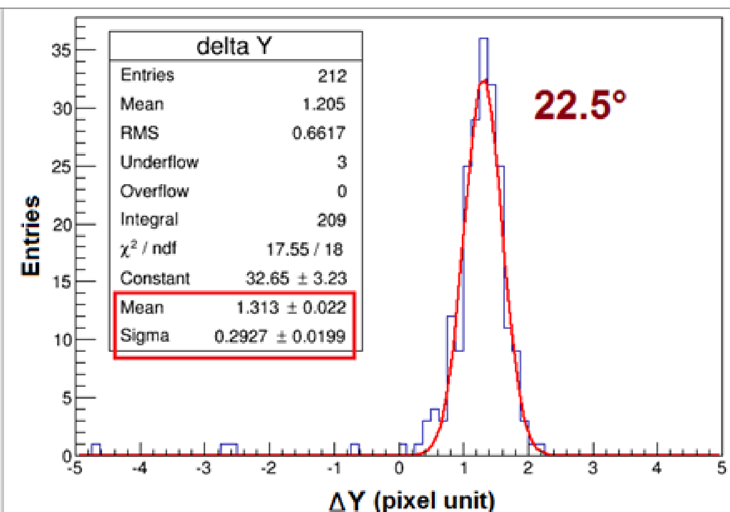


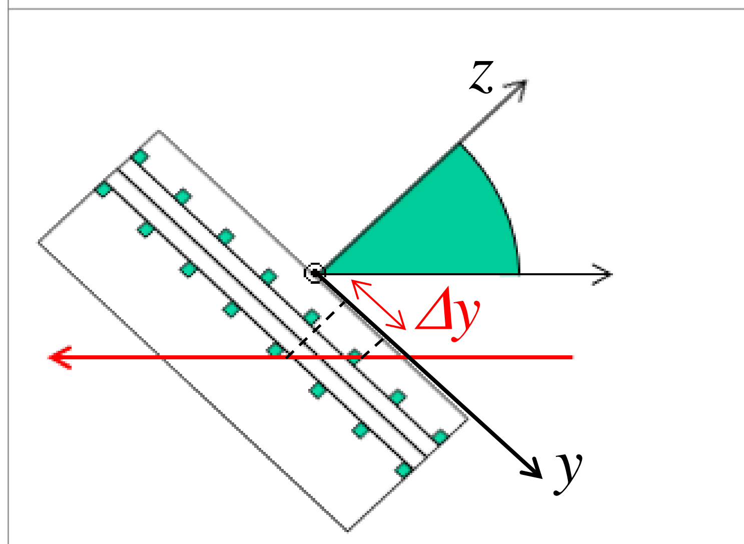
$$\alpha = \tan^{-1}\left(\frac{\Delta y}{d}\right)$$

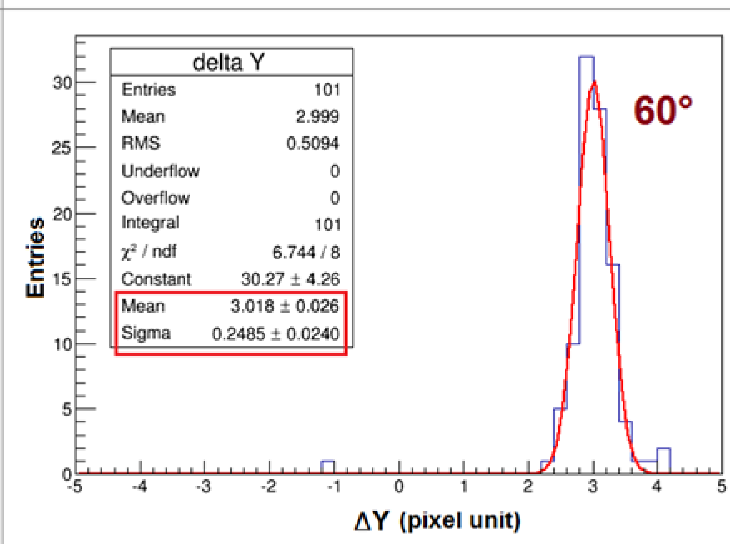
✓ Residuals (outer – inner coordinates) for both directions.

Angular measurements: *y*-axis displacement

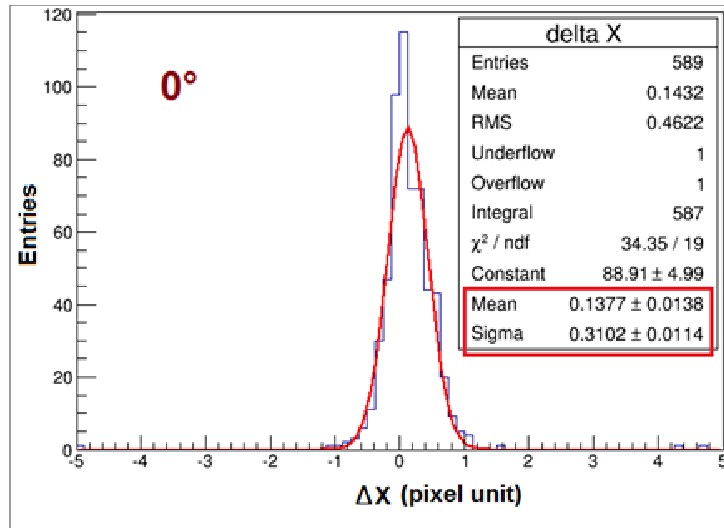


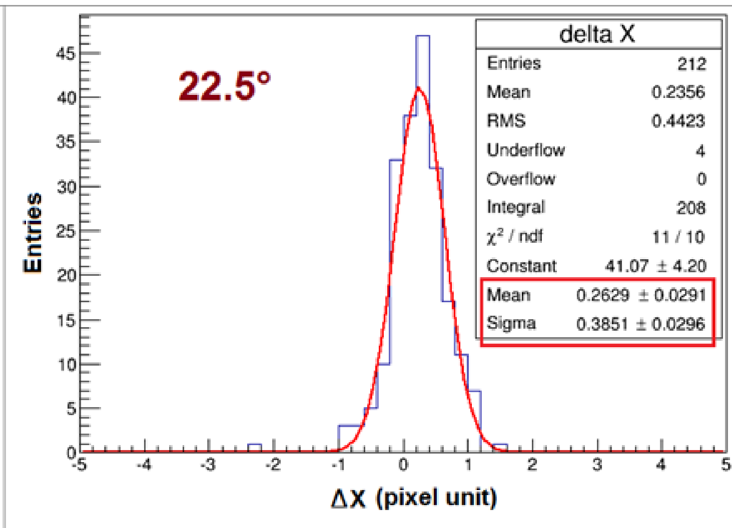


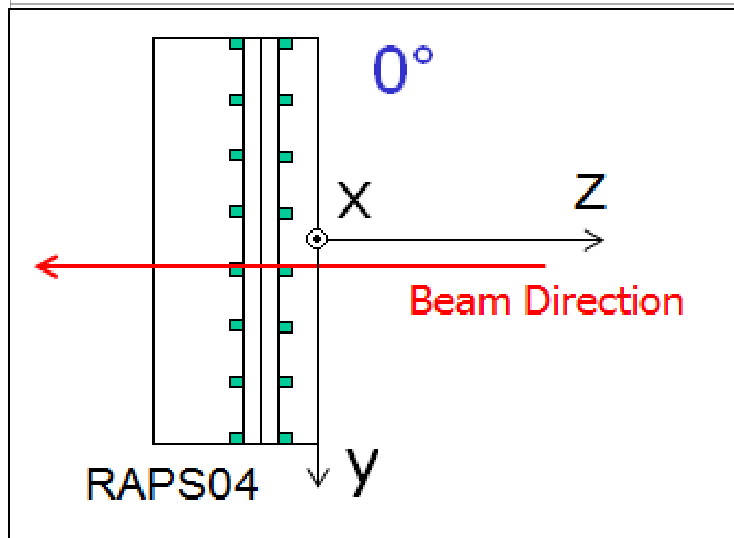


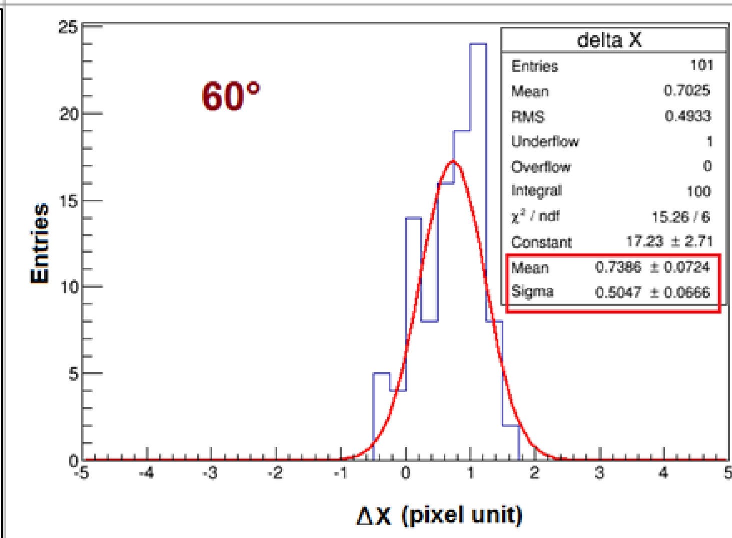


Angular measurements: x-axis displacement

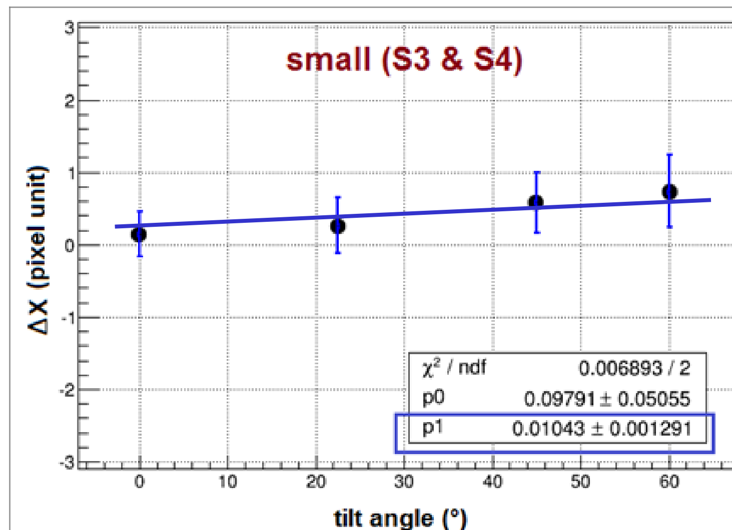


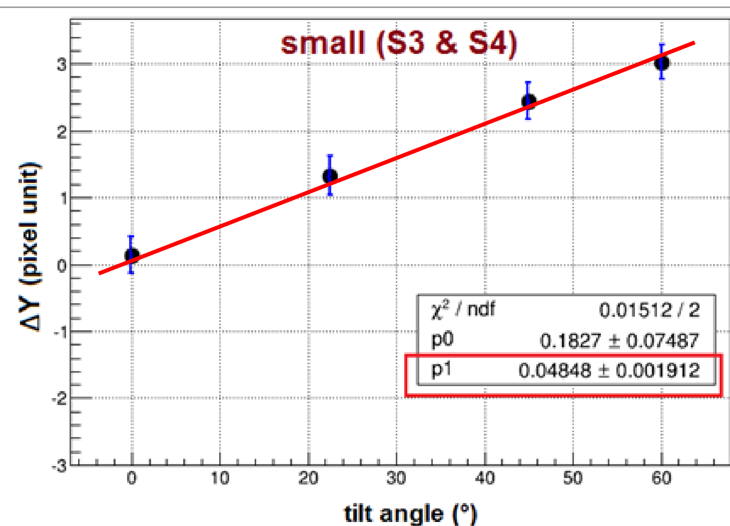


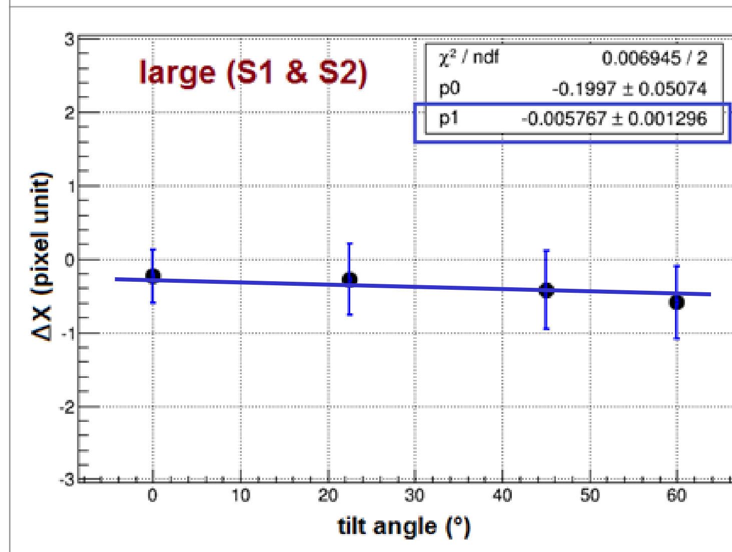


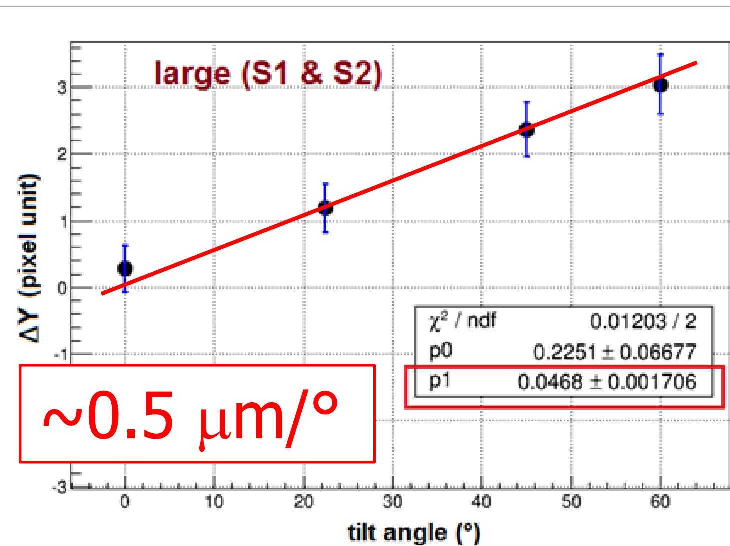


Angular measurements: Δx and Δy vs. tilt angle









~0.5 μm/°

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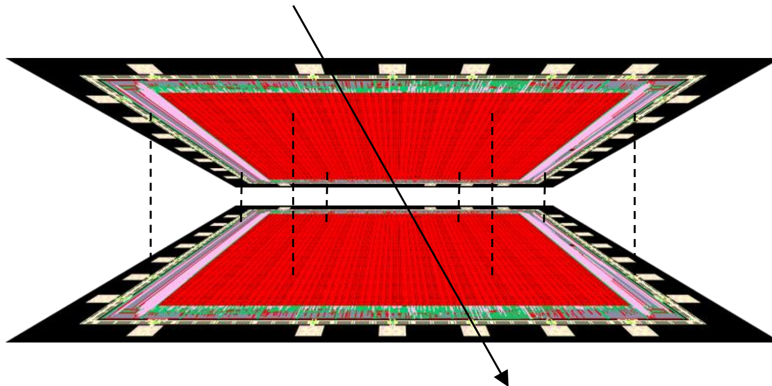
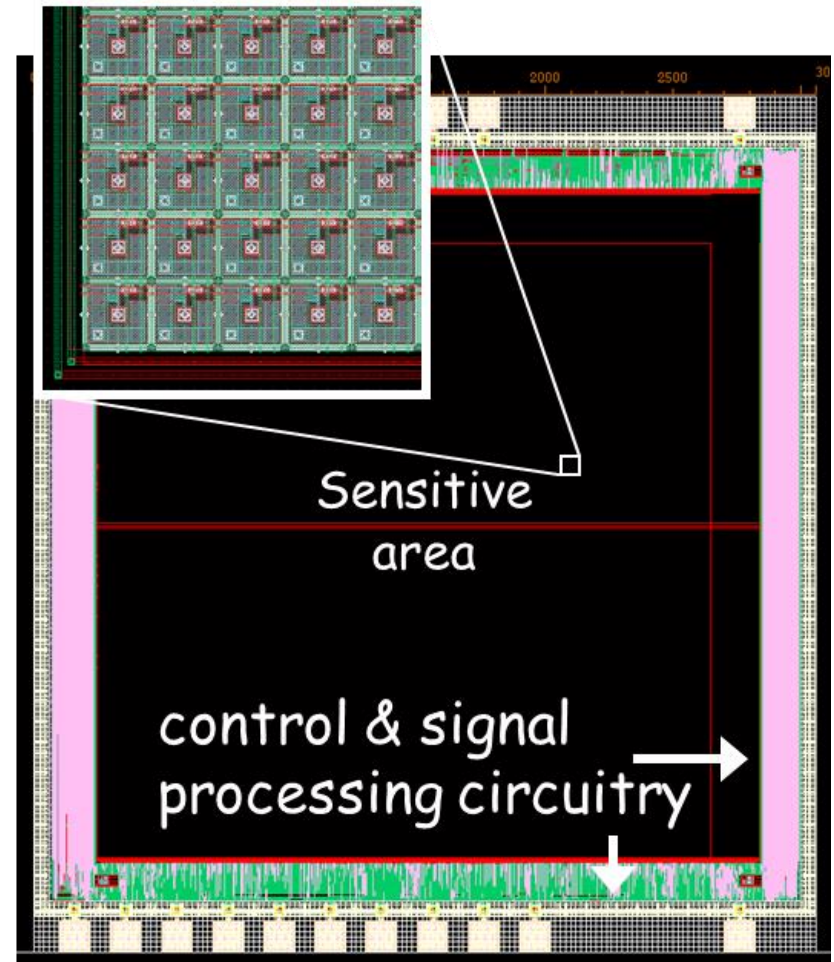
RAPS05-3D

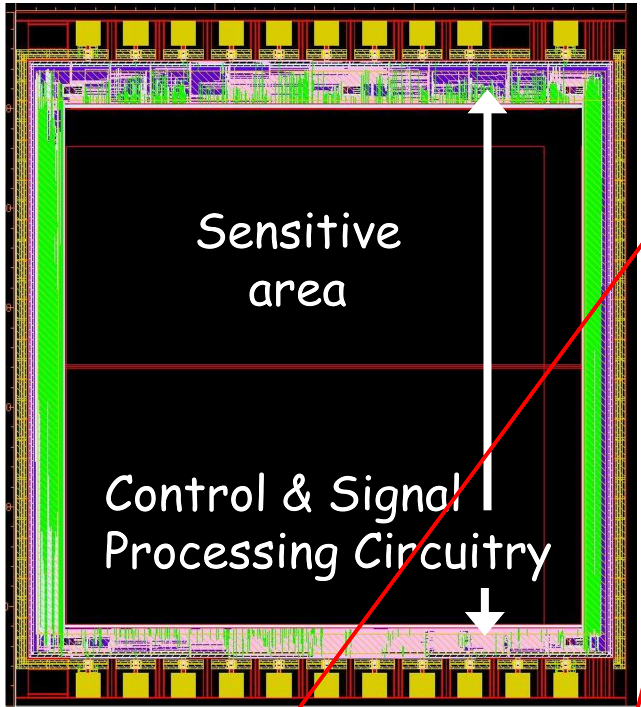
- ✓ New pixel design.
- ✓ Bigger matrix.

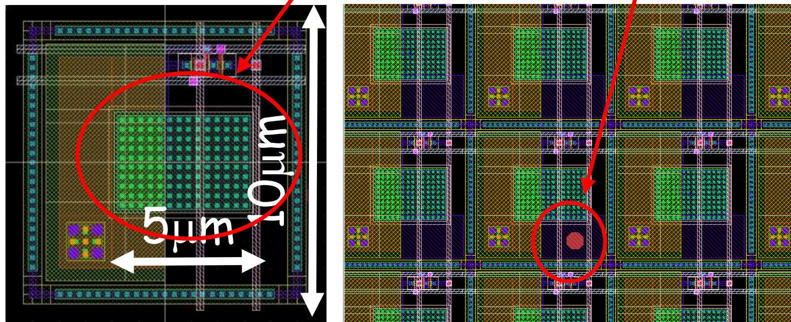
- ✓ 256x256 pixels (~6.5mm^2 area).
- ✓ APS - 3T pixel (10μm x 10μm).
- ✓ 4-parallel analog outputs.
- ✓ Control&signal processing circuitry: ARM (Artisan) SC library.



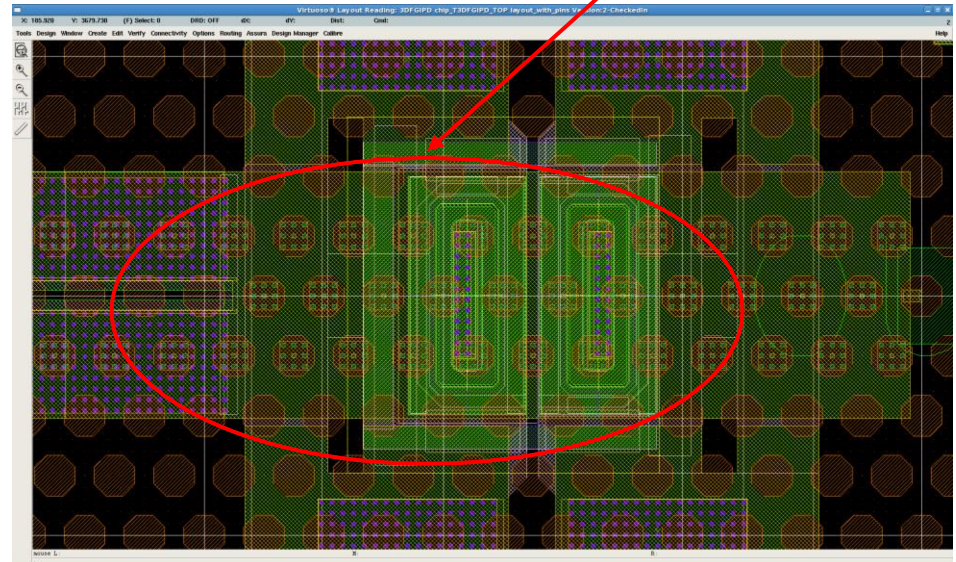


RAPS05-3D (2)

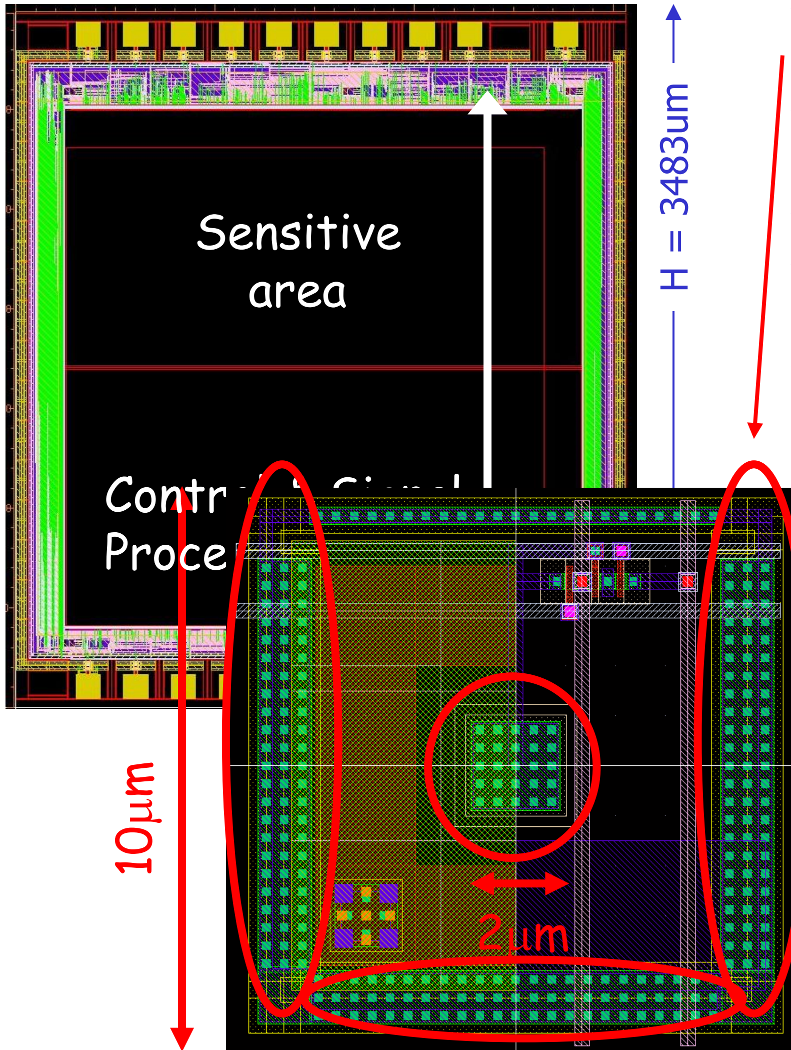




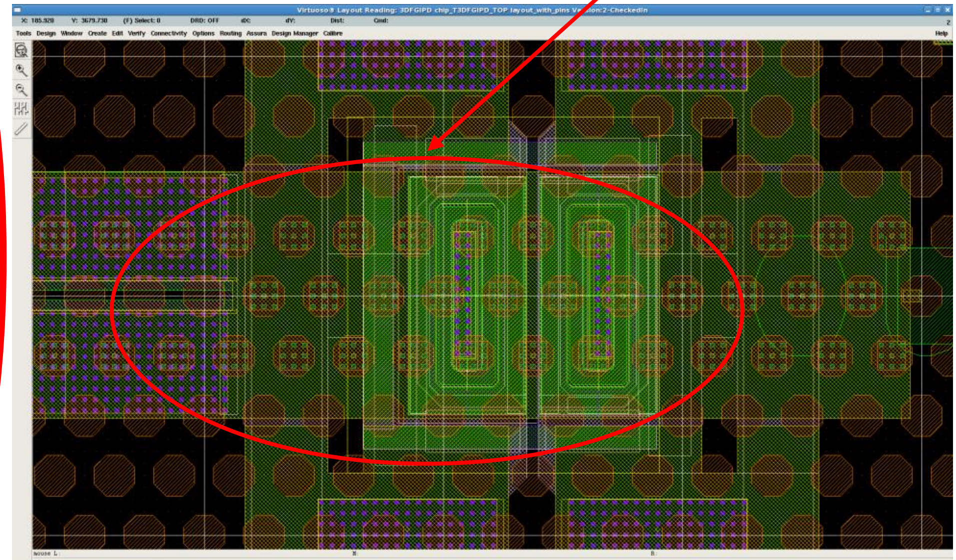
- ✓ COMP (local) density rules -> wider pixel sensitive area (n-well)
- ✓ Metal&Poly density -> non-uniform (local) metal dummy filling
- ✓ TSV density rules -> TSV dummies on array
- ✓ Contacts between tiers are located only at the chip periphery (e.g. within I/O PADs).
- ✓ Redundant bondpoint scheme has been adopted (as for RAPS04).



RAPS05-3D (2)



- ✓ COMP (local) density rules -> different p-well guard layout & smallest n-well
- ✓ Metal&Poly density -> non-uniform (local) metal dummy filling
- ✓ TSV density rules -> TSV dummies on array
- ✓ Contacts between tiers are located only at the chip periphery (e.g. within I/O PADs).
- ✓ Redundant bondpoint scheme has been adopted (as for RAPS04).



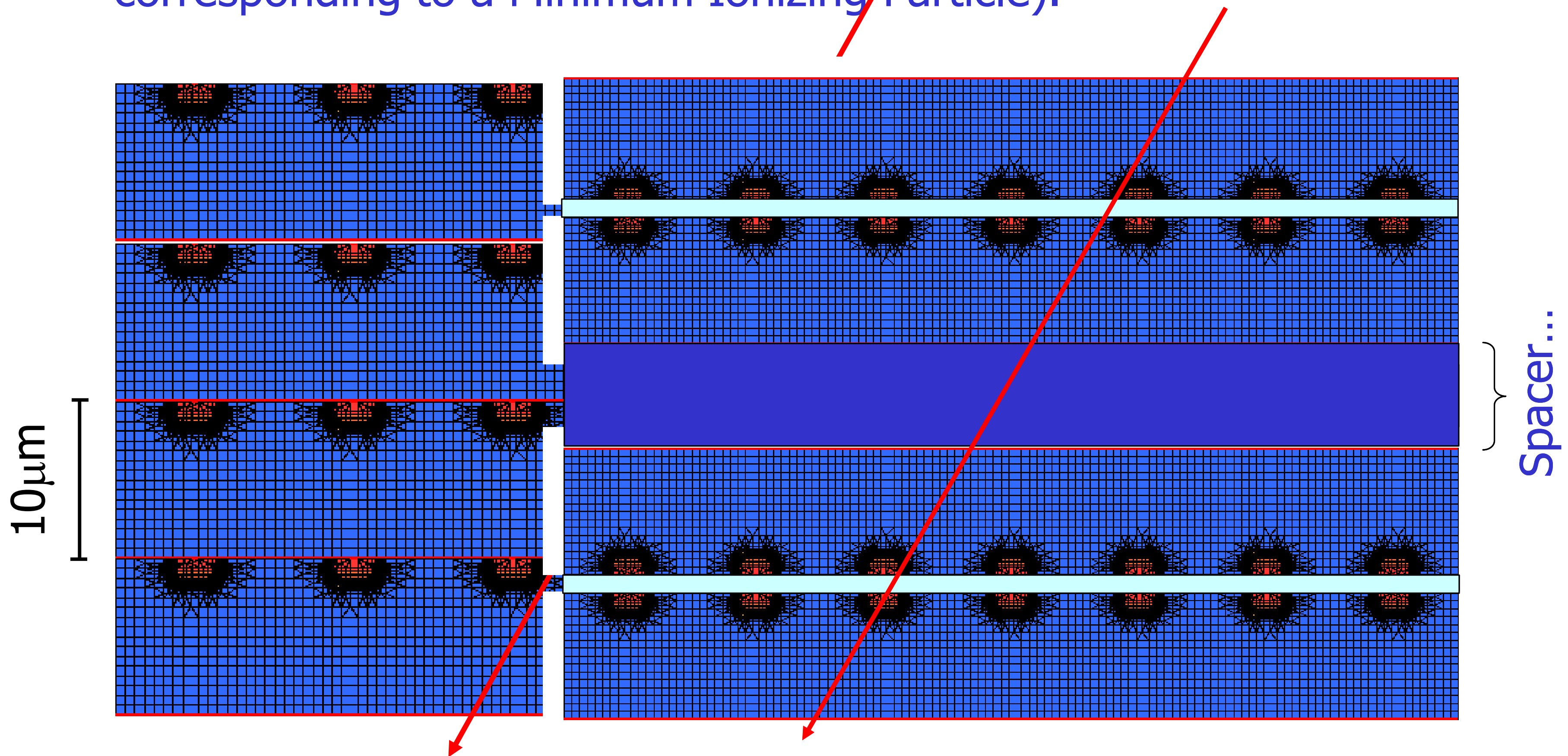
Conclusions

- ✓ Functional characterization of 3D monolithically stacked CMOS Active Pixel Sensors layers (beam test) fabricated in Chartered/Tezzaron 130nm 3D technology for particle tracking purposes.
- ✓ Coincidence responses between bottom and top matrices have been obtained with 3MeV protons from aligned tiers.
- ✓ Particle angular measurement can be carried out by parallel read-out of corresponding outer and inner pixel matrices.
- ✓ Momentum measurement with a single, multiple layers, 3D vertically stacked APS CMOS detector.
- ✓ Next prototype: bigger sensitive area (efficiency…) and optimized charge to voltage conversion gain (w.r.t. the technology node).

Backup Slides

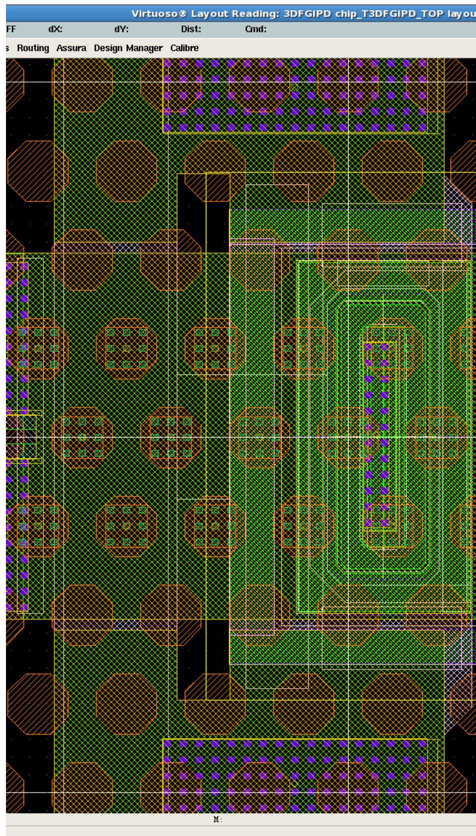
3D Monolithically Stacked CMOS APS

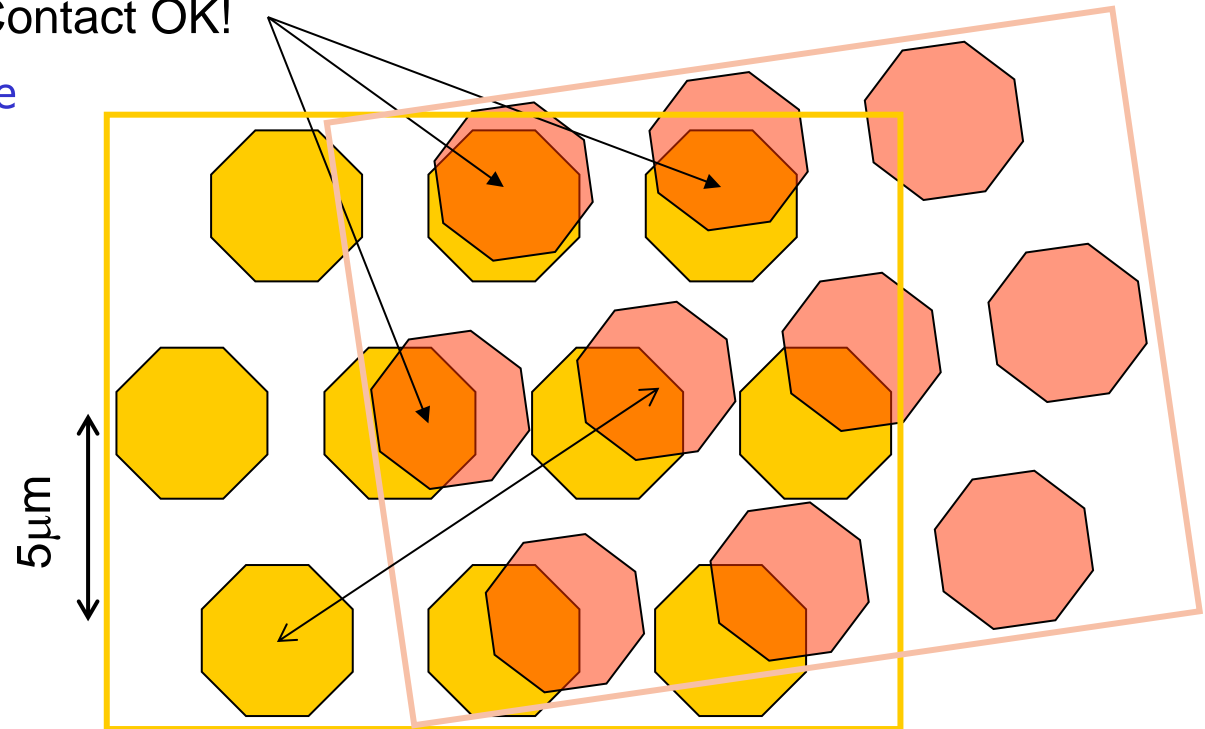
- ✓ Up to four (isolated) sub-arrays.
- ✓ Voltage response as a function of a particle hit (e/h pairs generation corresponding to a Minimum Ionizing Particle).

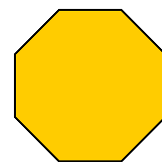


The 3D Not Aligned is anyway ok…

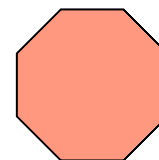
Redundant bondpoint scheme







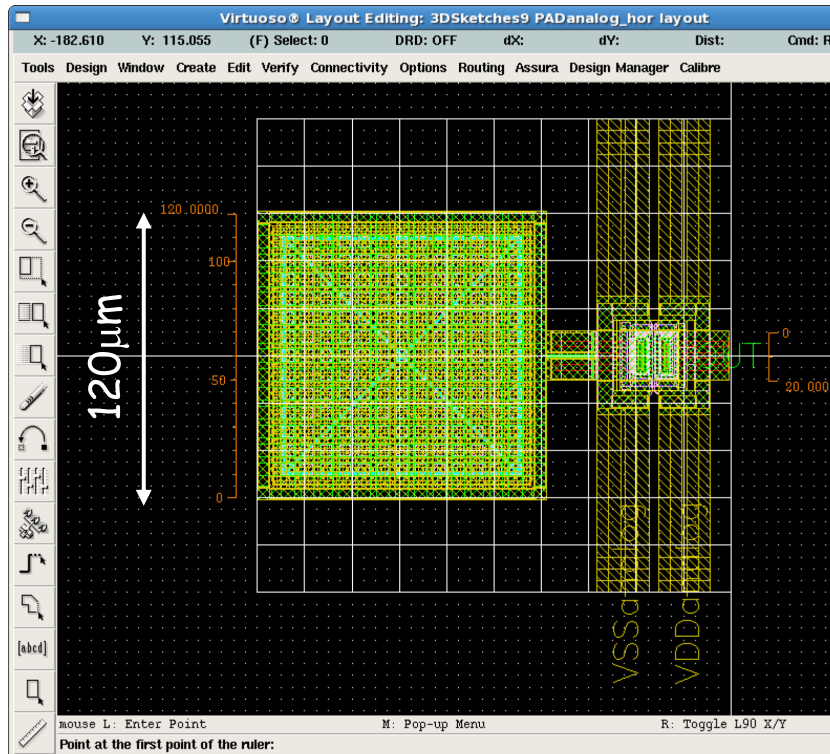
bottom tier bondpoint



top tier bondpoint

Top & Bottom tiers (mis)alignment!

- ✓ TOP/BOTTOM tier misalignment…
- ✓ RAPS04 3D tomography (courtesy of DESY - Hamburg)



~12μm

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