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Development of inner tracking systems equipped with CMOS pixel sensors for future colliders

Outline:

- Introduction
- The state-of-the-art CMOS sensors and their applications
- Evolution of the technology
- New prototype performances
- Conclusion and outlook

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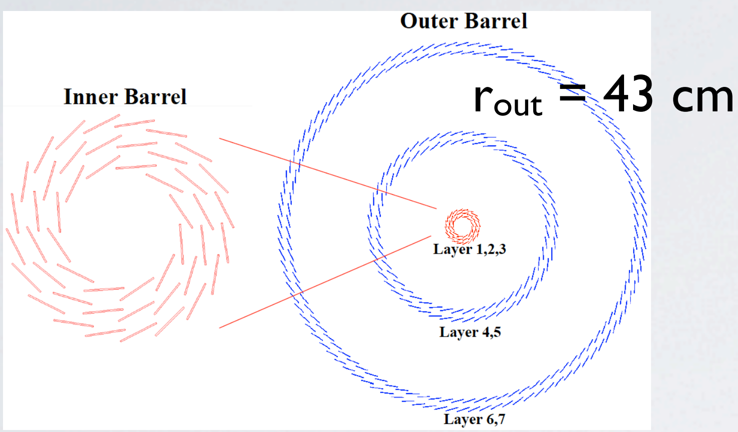
Pixellated inner trackers

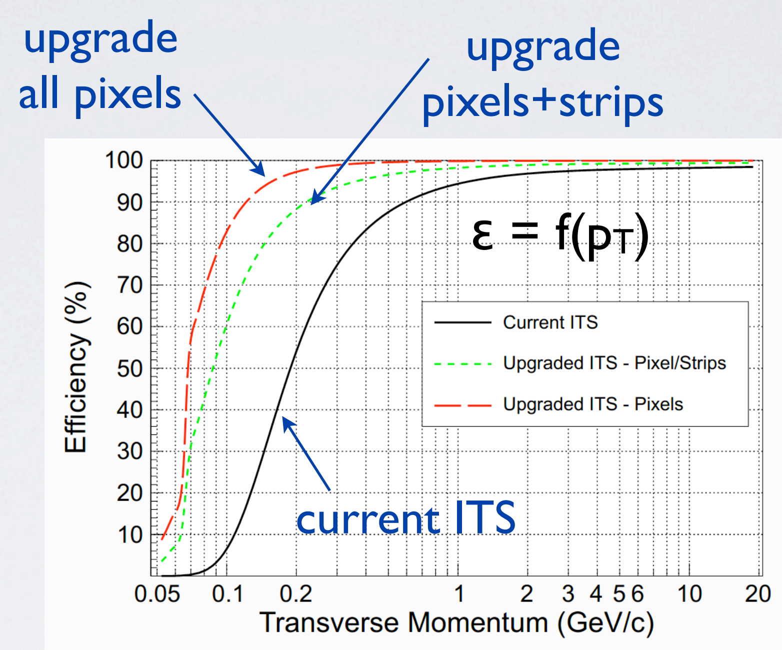
- Added value of designing fully pixellated inner trackers.
  cf. ALICE-ITS upgrade. Experimental environment: B=0.5 T, high hit rate, low momentum tracks.

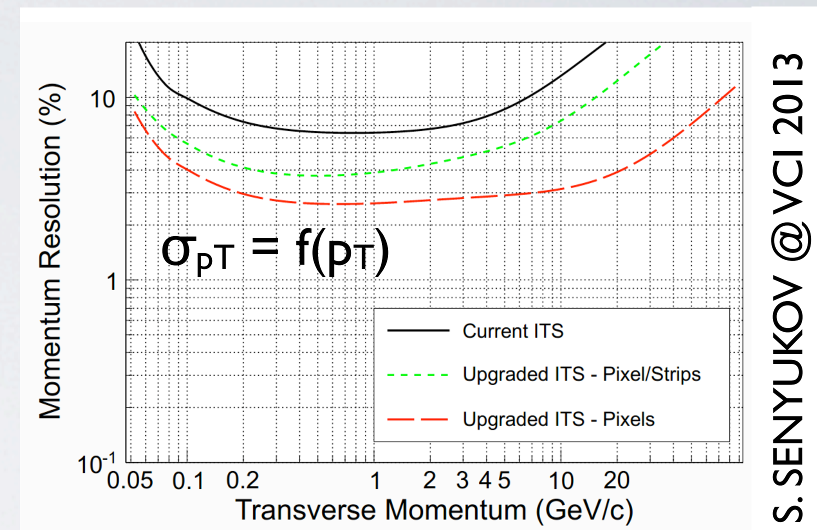
Upgraded ITS:
up to 10 m^2 pixellated inner tracker



Inner barrel:
3 layers of pixels.

Outer barrel:
4 layers of pixels.

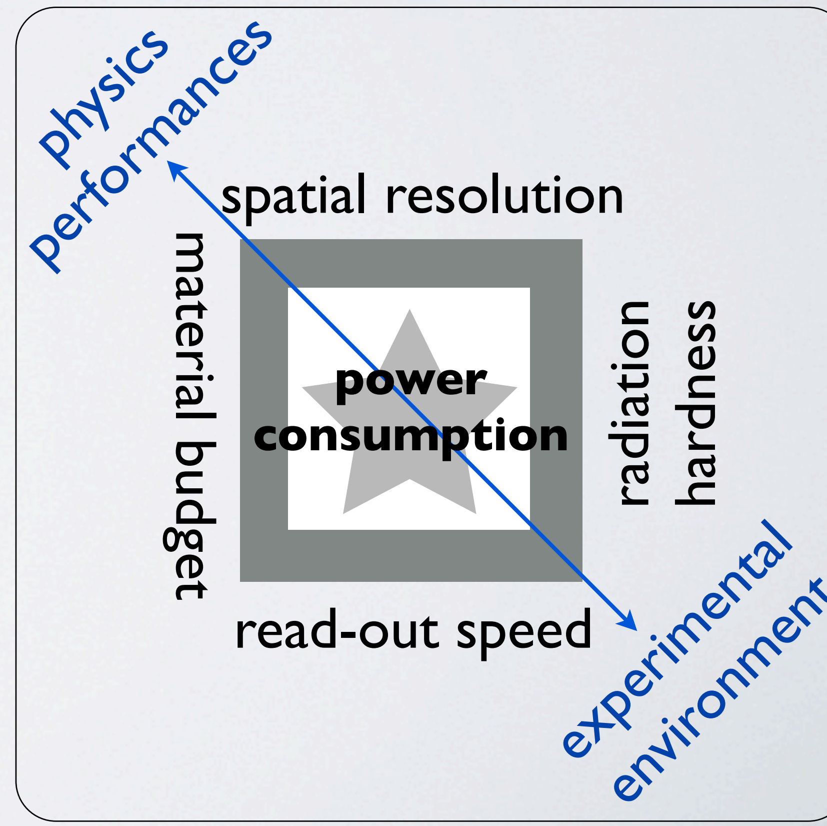




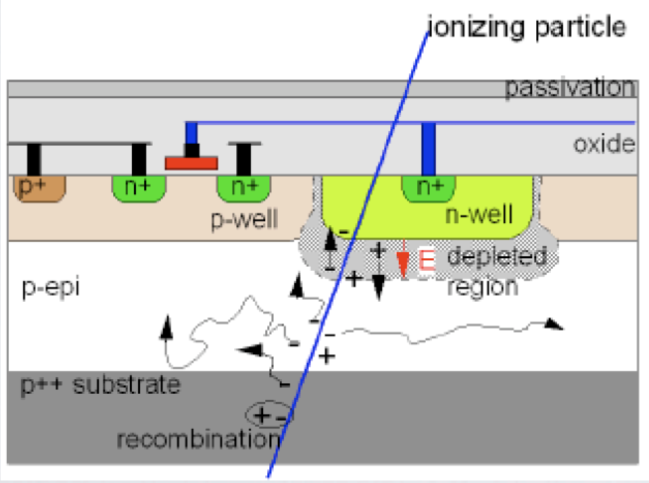
- Constraints when designing sensors for an inner tracker:
  - Performances: spatial resolution, read-out speed, radiation hardness, material budget (power dissipation).
  - Cost.

But also: flexibility to choose the best suited performances to each detection layer:
  - Low radius layers: specifications governed by occupancy rate.
  - High radius layers: spec. governed by power consumption.

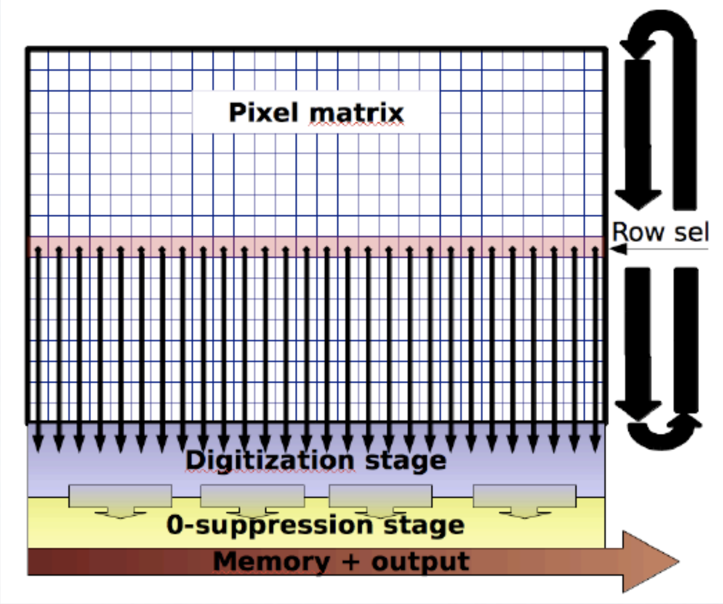
➛ CMOS pixel sensors present attractive performances for inner trackers



MIMOSA 0.35 µm CMOS pixel sensors



- CMOS pixel sensor (CPS) features:
  - Monolithic: signal sensing and analogue processing in pixel array.
  - Very thin: sensitive layer 10-20 µm, total thickness < 50 µm.
  - High granularity: square or elongated pixels.
- The state-of-the art in HEP: MIMOSA series
  - 0.35 µm OPTO process.
  - Partially undepleted.



- Architecture:
  - In-pixel pre-amplification and CDS.
  - End-of-column discrimination, binary charge encoding and 0 suppression.
  - Column parallel rolling shutter read-out

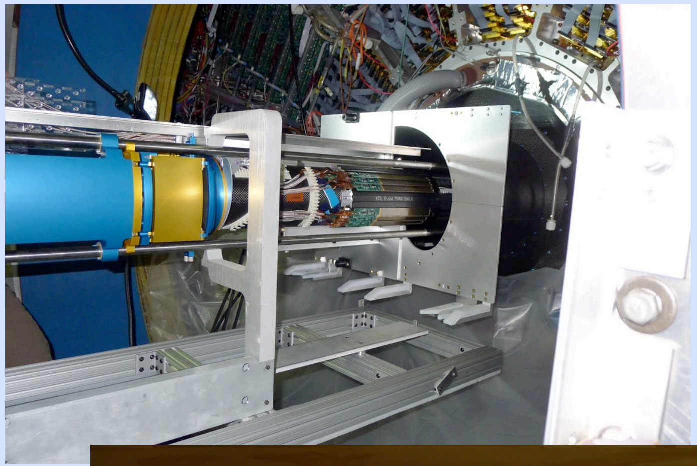
    integration time = # rows × row read-out time (100-200 ns).

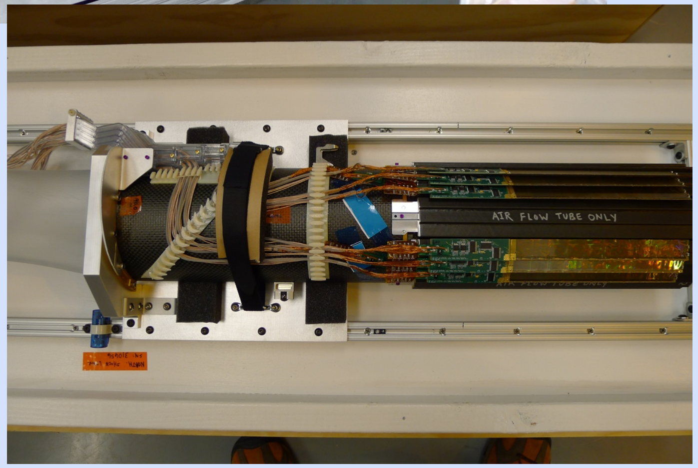
➛ corresponds to one possible optimisation with emphasis on the particle rate to be read out and the power dissipation.

- Advantages and performances:
  - Industrial mass production: excellent manufacturing yields, low costs, technology evolution.
  - Detection efficiency ~ 100 % with very low fake rate ~10^{-5}.
  - Read-out time: $\mathcal{O}$(100 µs), suited to > 10^6 particles/cm^2/s.
  - Running conditions: from ≪0 °C to 40 °C.
  - Low power consumption: 150-250 mW/cm^2 ➛ further allows low material budget.
  - Low material budget: 0.2 % - 0.5 % X_0.
  - Radiation tolerance: 0.1-1 MRad + 10^{12}-10^{14} n_{eq}/cm^2 depending on T°, read-out time, pitch.

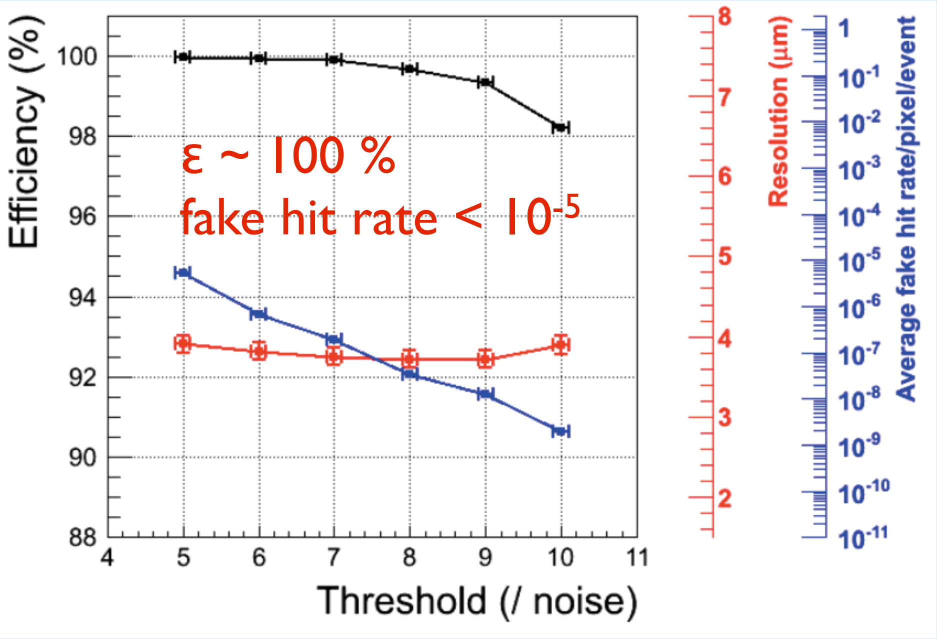
Current applications

- MIMOSA sensors have already been chosen by several projects:
  - EUDET Beam Telescope of the FP6 project: operating since 2008.
  - Hadrontherapy: FIRST (GSI), dose monitoring (Lyon, Strasbourg).
  - STAR @ RHIC: PXL detector ➛ ~1/3 installed in May 2013.
    One month commissioning run completed.
    First vertex detector equipped with CMOS pixel sensors.





- ULTIMATE sensor features:
  - Active area: 960 columns of 928 pixels 19.9×19.2 mm^2, ~ 0.9 million pixels.
  - Pitch: 20.7×20.7 µm^2.
  - Binary output.
  - Power consumption ~ 150 mW/cm^2.
  - Air flow cooling.
  - $t_{r.o.}$ ~ 200 µs.



➛ Measured performances:
- N ~ 15 e- ENC at T°= 35 °C.
- $\sigma_{s.p.} \gtrsim 3.5$ µm.
- Radiation tolerance validated: 3×10^{12} n_{eq}/cm^2 + 150 kRad at 35 °C.

Future experiments

- Now CPS are also being considered by forthcoming projects (e^+e^-, heavy ions collisions):
  - · ALICE @ LHC: baseline to equip the entire upgraded ITS (~10 m^2).
  - · CBM @ FAIR: data taking > 2016 (SIS-100).
  - · ILD @ ILC: option to equip the VD.
  - · BES-3 @ BEPC: option to equip an inner tracker.

	$\sigma_{single\ point}$	read-out time	TID	Fluence n_{eq}/cm^2	$T_{coolant}$ °C
STAR-PXL	5 µm	~200 µs	150 kRad	3×10^{12}	30
future projects	3-5 µm	1-30 µs	up to 10 MRad	up to 10^{14}	< 0 - 30

Considering: hit rate, data flow and trigger rate:
Correlation between all specifications + strong dependence on the extrapolated track quality

➛ a global design of the inner tracking system geometry enables to go beyond current technology limits.

- Next generation of experiments call for higher read-out speed and radiation tolerance:
  - Smaller feature size technology: switch to 0.18 µm.
  - Higher epitaxial layer resistivity.

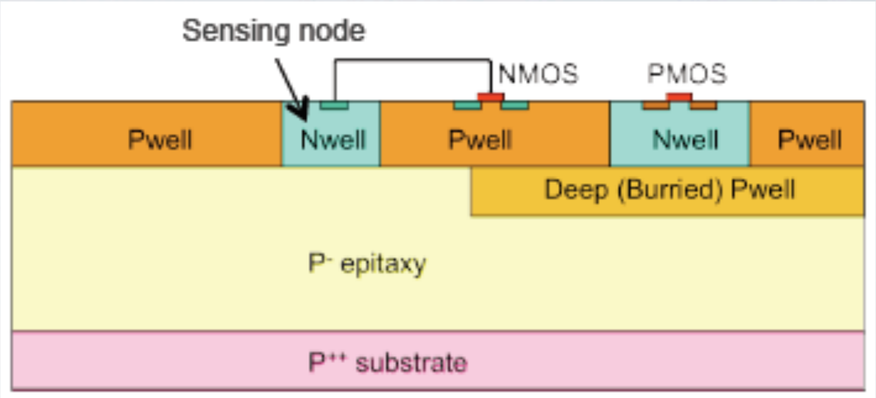
Evolution of the technology

- Performances of monolithic planar technology: global optimisation of all functionalities: sensing, analogue amplification, digital treatment.
  Specifications are not driven by HEP but by commercial concerns.
  ➛ full potential of CPS for HEP not reached yet.

- Path defined to improve radiation hardness and to accelerate read-out speed while keeping low power consumption:
  - Parallelised rolling shutter: sensor divided in sub-arrays read out in //, and several rows read out in //.
  - Elongated pixels: thanks to excellent charge collection.
  - Smarter pixels: row read-out fasten to 100 ns with in-pixel digitization thanks to smaller feature size.
  - Binary signal transmission: to maintain power consumption low.
  - High resistivity epitaxial layer.

- Pixel dimension increased in that direction ↕: less rows to be read.
  r.o. time = # rows × row read-out time (100 ns)
  ➛ higher read-out speed.
- Pixel dimension increased in that direction ↔: less pixels in a row.
  ➛ limited power consumption.

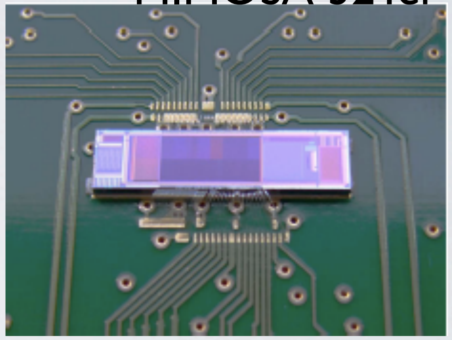
0.18 μm sensor prototypes



- TowerJazz® CIS 0.18 μm process:
  - Epitaxy: 18 μm thick, high resistivity 1-5 kΩ.cm.
  - Quadruple well.
  - Up to 6 metal layers.

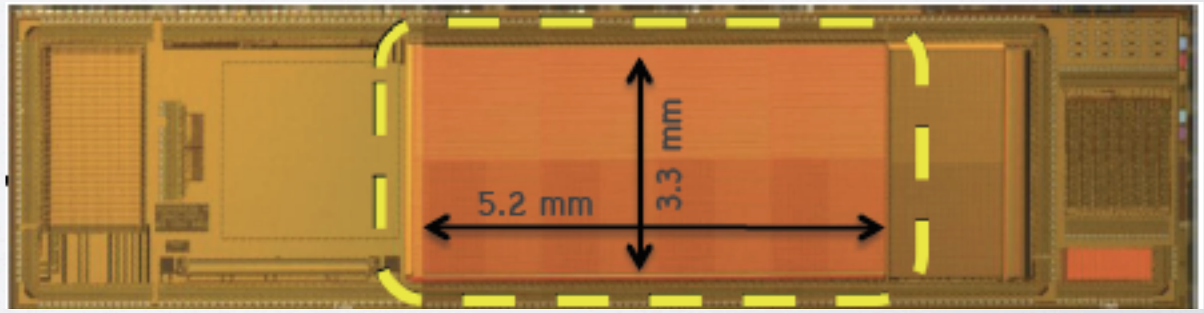
- Different prototypes submitted and tested in 2012:
  - Explore pixel sizes: 20x20, 20x40 and 20x80 μm^2.
  - Explore charge amplification and collection system: diode sizes ~9-15 μm^2, NMOS and PMOS transistor based amplifiers.
  - Explore discrimination: 1 discriminator at each column end, in-pixel discrimination.
  - Integration time = 32 μs (per sub-matrix).

MIMOSA 32Ter



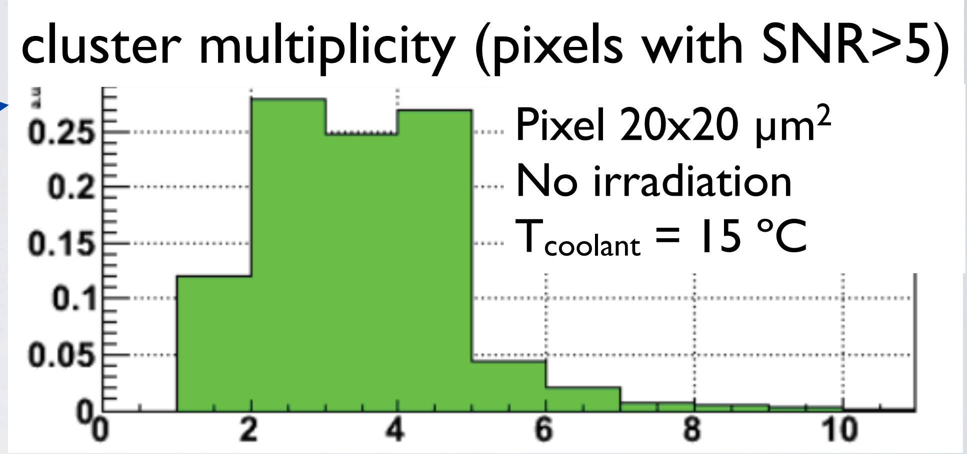
- Tests performed with ^{55}Fe source and with CERN SPS T4-H6 beam line, 60-120 GeV π^-:
  - $T_{coolant}$ = 15, 20 and 30 °C.
  - Total Ionising Doses: 1 and 3 MRad.
  - Non-ionising fluences: 0.3 - 1.0 - 3.0 $\times 10^{13}$ n_{eq}/cm^2.
  - Combined irradiations: up to 1 MRad + 10^{13} n_{eq}/cm^2.

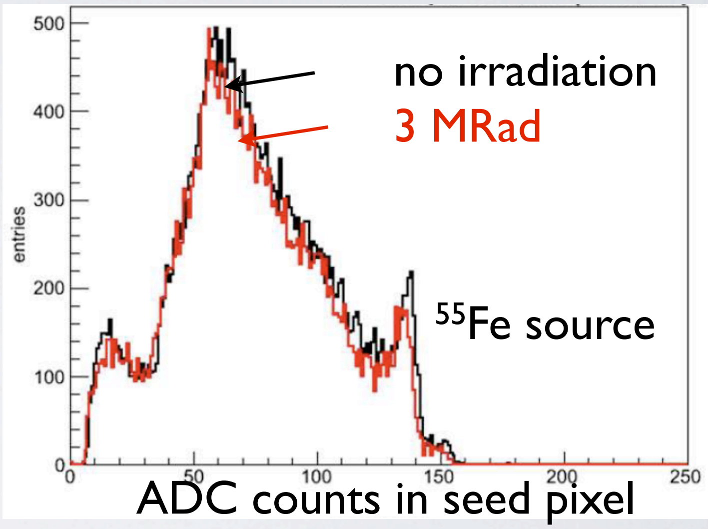
➛ First evaluatation of this technology:
- Validation of the charge collection performances, before and after irradiation.
- Validate the different steps required for a final sensor: enlarged pixels, in-pixel discri, parallelised rolling-shutter.

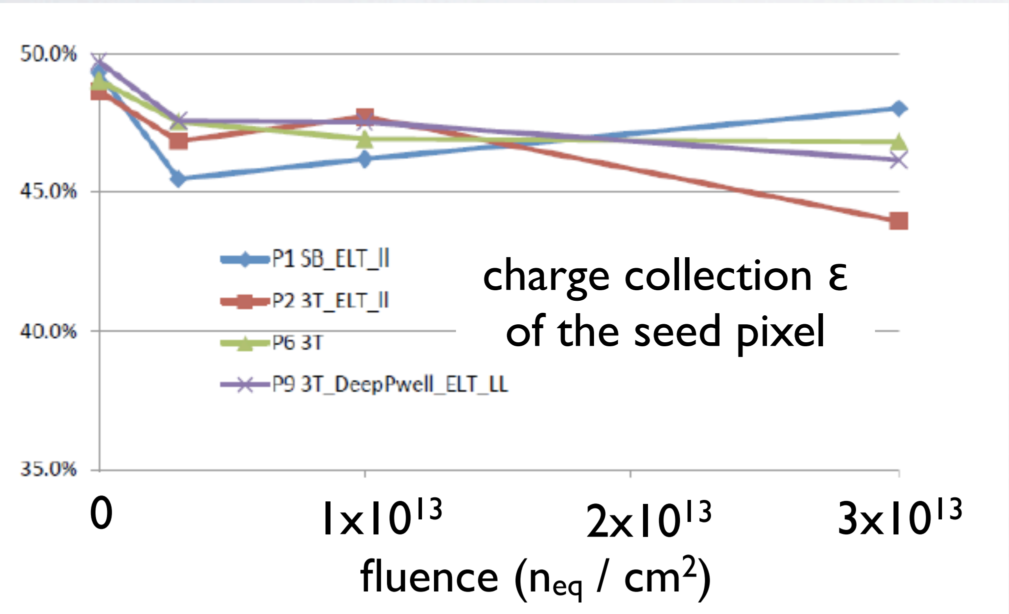


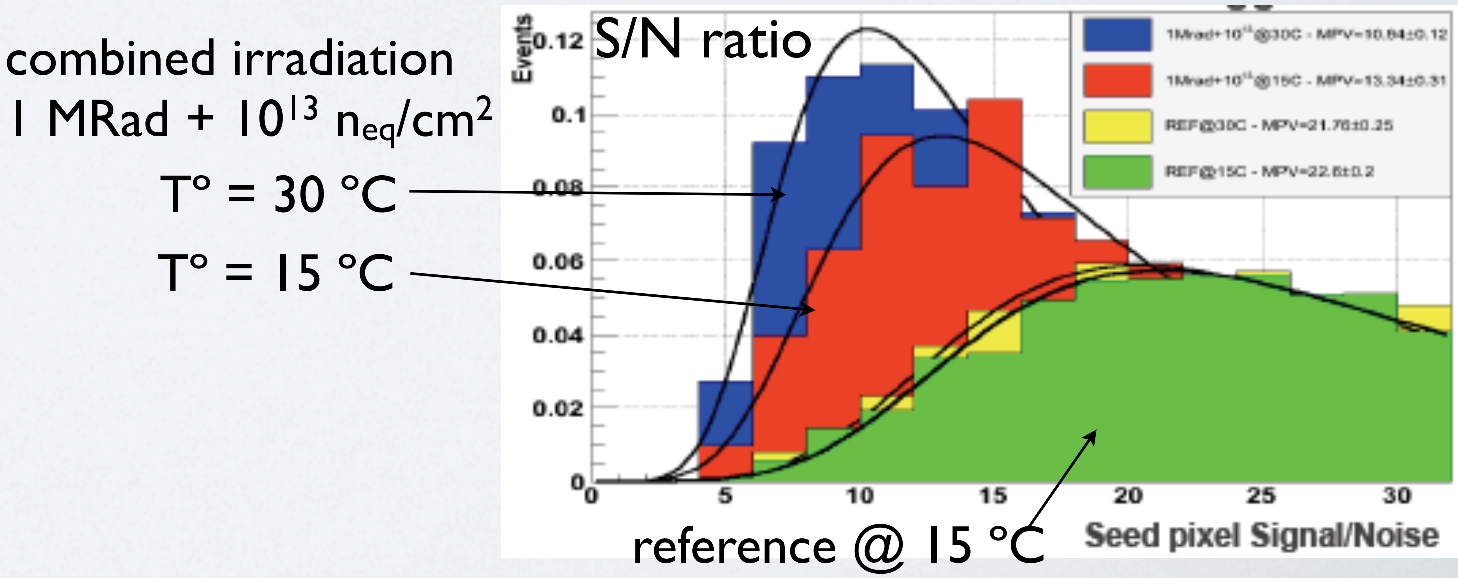
0.18 μm sensor test results

- Charge collection:
  - High resistivity confirmed, limited thermal diffusion and total charge collected within 4 pixels.
  - Deep P-well does not parasite charge collection.
- Radiation hardness:
  - Irradiation has no impact on charge collection even at 30 °C. Signal not degraded by traps induced by bulk damages after NI rad.
  - Evolution of noise with fluence is a typical effect of leakage current.
- Impact of pixel dimension:
  - Square pixels: detection ε ~ 100 % even at 30 °C and after combined I+NI irradiation.
  - Elongated 20x40 μm^2 pixels: still detection ε ≥ 99 % at 15 °C (~ 98 % at 30 °C) after combined I+NI irradiation.









Conclusion and outlook

- CMOS pixel sensors (CPS) are a mature technology to equip high performances inner trackers whose specifications are governed by spatial resolution, material budget, power dissipation and cost.

- The STAR-PXL detector is the first operating vertex detector equipped with CMOS pixel sensors: CPS well suited for tracker innermost layers.
  The ALICE-ITS upgrade is based on CPS: CPS also well suited to equip a complete inner tracker.

- Exploration of 0.18 µm technology, to design CPS aiming at equipping future inner trackers (upgrade of ALICE-ITS, CBM-MVD, etc.):
  - 2011-12: Charge collection performances and radiation hardness validation.
  - 2013-14: Architecture validation.
  - 2014-16: MISTRAL (30 µs read-out time) and ASTRAL (15 µs r.o. time).

- CPS new 2D-technologies, with deep sub-micronic feature size, thicker epitaxy and higher resistivity offer conditions of a potential breakthrough in performances:
  - integration time ~ 1 µs.
  - radiation hardness up to 10 MRad + 10^{14} n_{eq}/cm^2.

  ➛ open the door to future possible applications: X-ray imaging.
  and motivate further performance improvement: applications to HL-LHC with $t_{r.o.}$ << 1 µs.


thank you for your attention