Study of MAPS silicon detector prototypes for the ALICE ITS3 upgrade

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On behalf of the ALICE Collaboration

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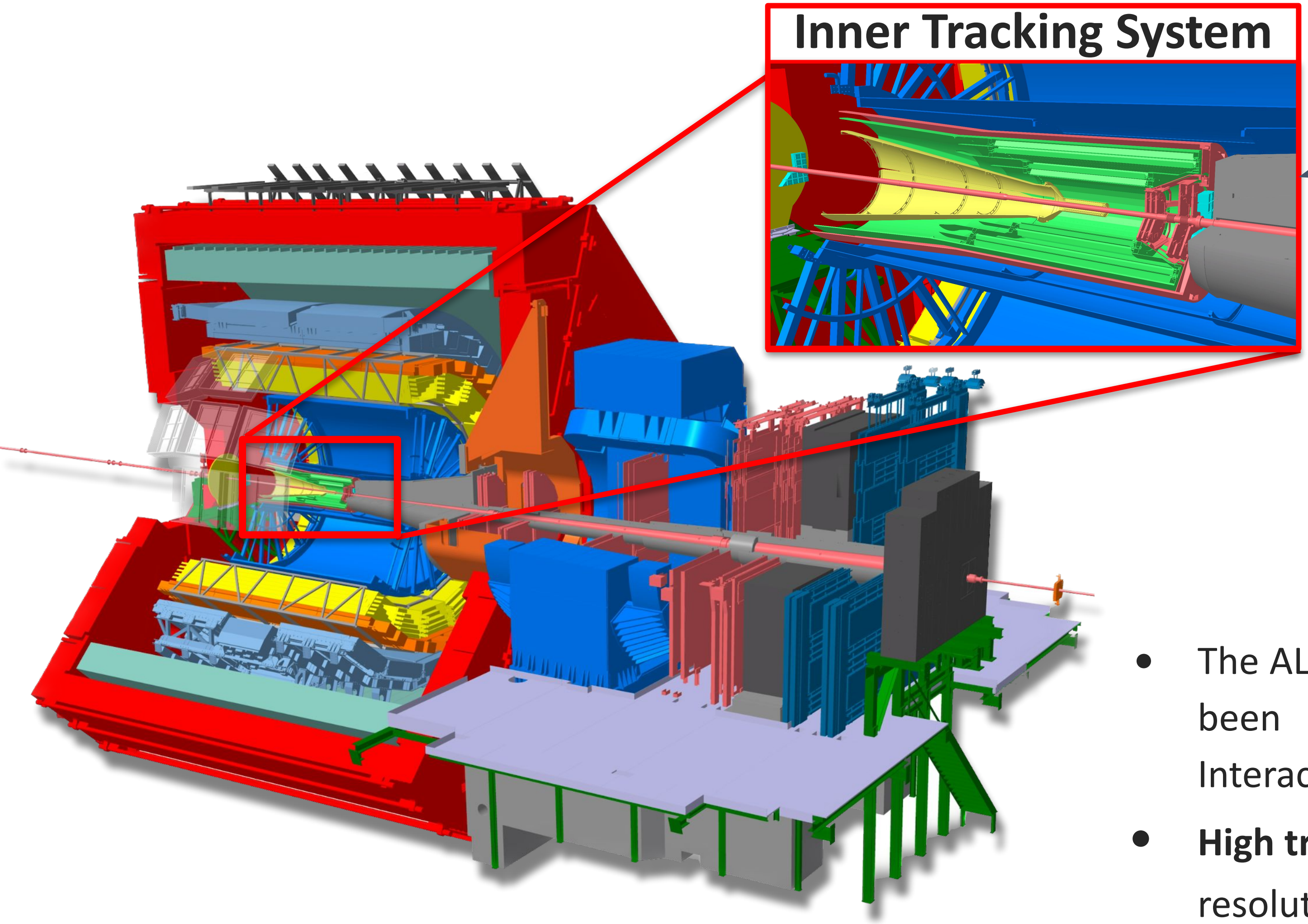
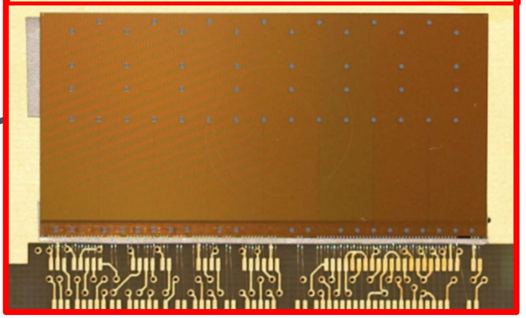
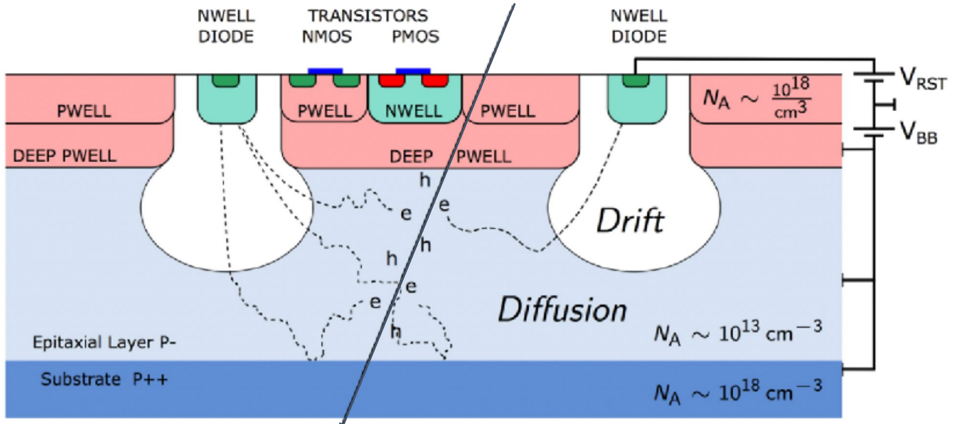
ALICE Inner Tracking System (ITS)



ALPIDE CHIP



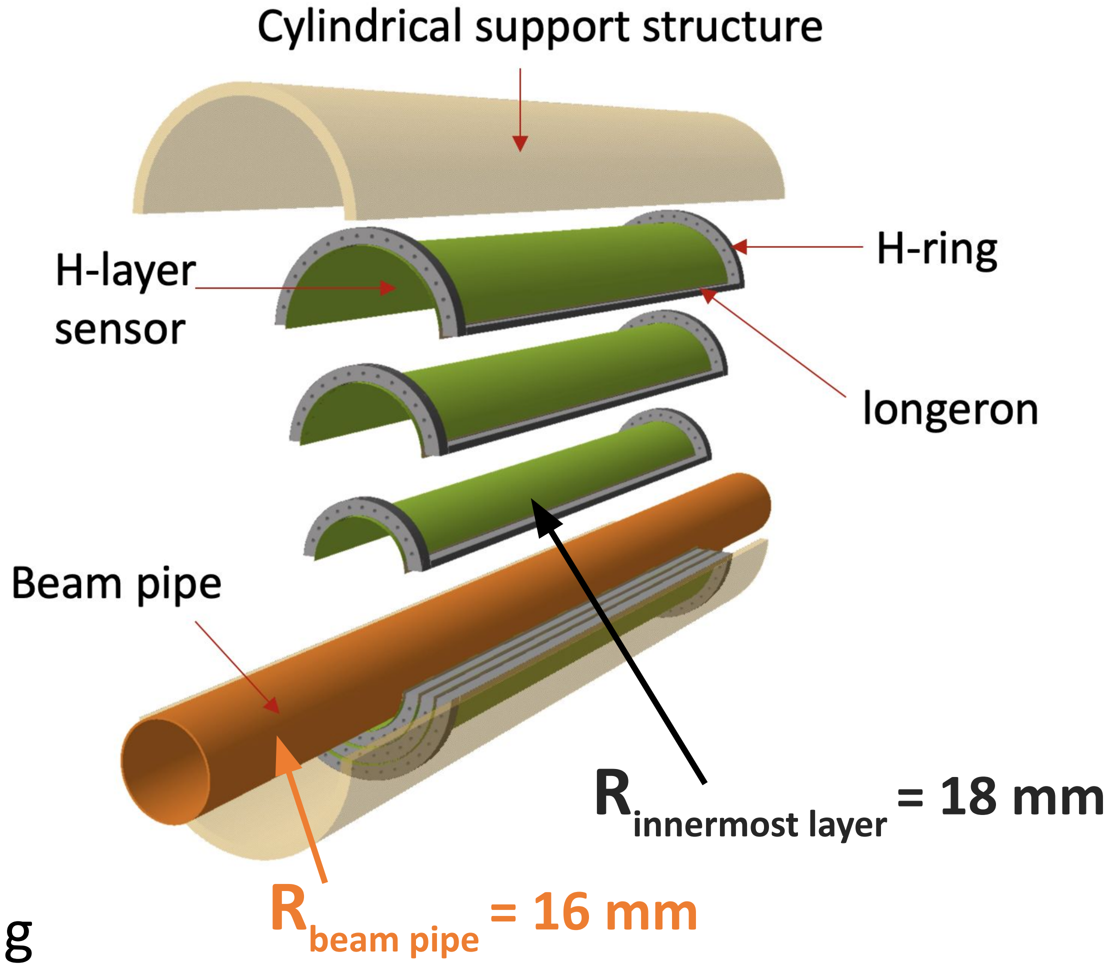


- The ALICE vertex detector (**ITS** = Inner Tracking System) has been upgraded during LHC **LS2** →23 mm from the Interaction Point
- **High tracking performances** also at low p_T (100 µm pointing resolution at p_T=200MeV)
- Built using **ALPIDE**, a Silicon pixel chip based on 180 nm Monolithic Active Pixel Sensor (MAPS)

The ITS3 - a bent vertex detector

The ITS3 structure

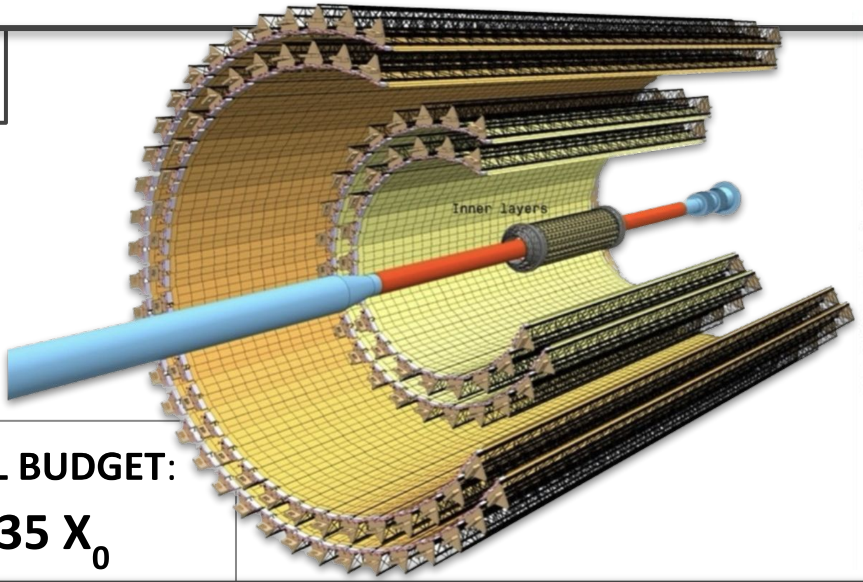
- Ready for LHC RUN 4 - mounted during LS3
- Built using **wafer-scale MAPS sensors**, fabricated using **stitching**
- Mechanically held in place thanks to carbon foam ribs
- **Thinned ≲ 50 μm,** when Si is **flexible**
- **Bent** to the target radius (18 mm, **closer** to the interaction point thanks to the new beampipe at 16 mm)
- Goal: more efficiency, less power consumption
- ITS3 will replace 3 innermost ALICE Inner Tracking System 2 (ITS2) with only **6 sensors** of 26 cm length



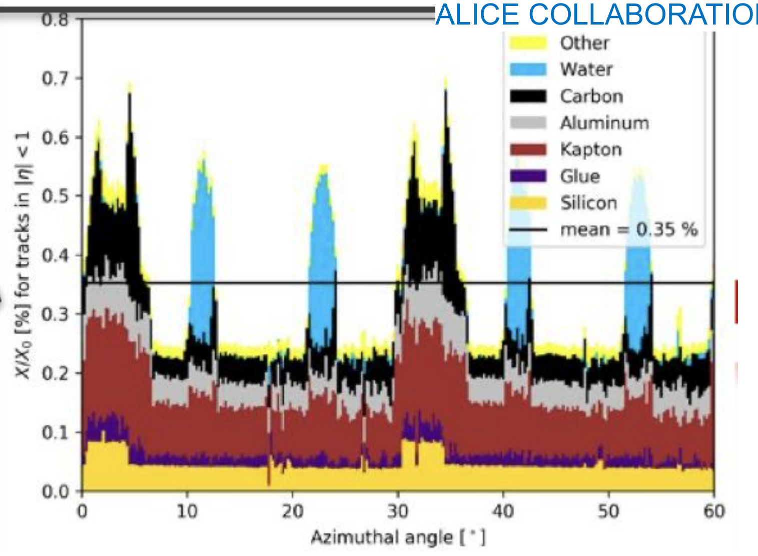
Material budget contribution in the ITS3

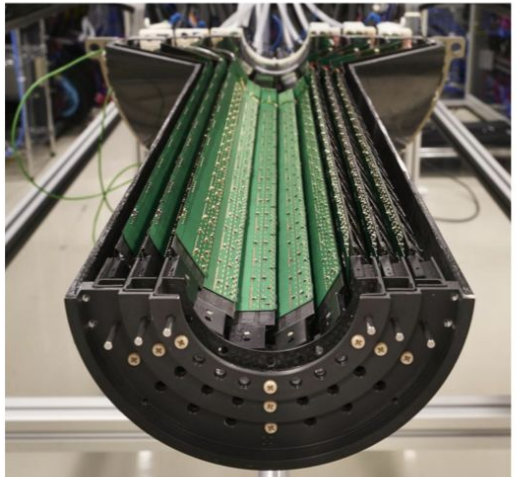
ALICE COLLABORATION, CERN-LHCC-2019-018. LHCC-I-034

ITS2



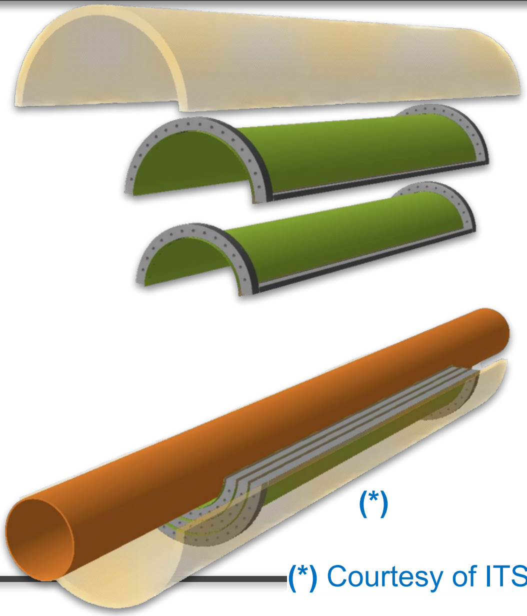
MATERIAL BUDGET: up to 0.35 X_0

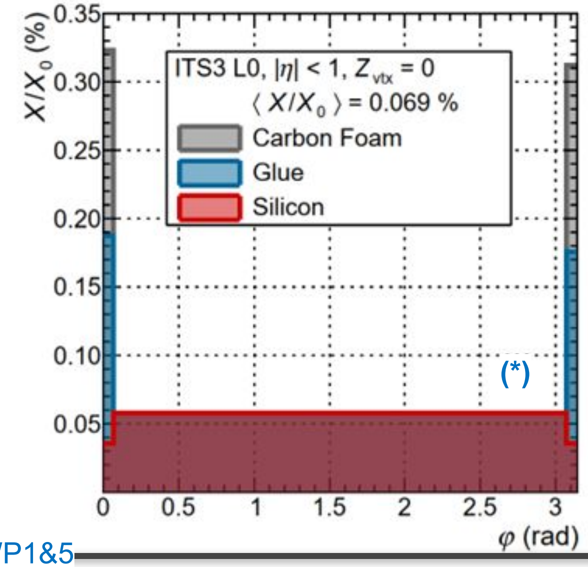




ITS3: Silicon-only contribution

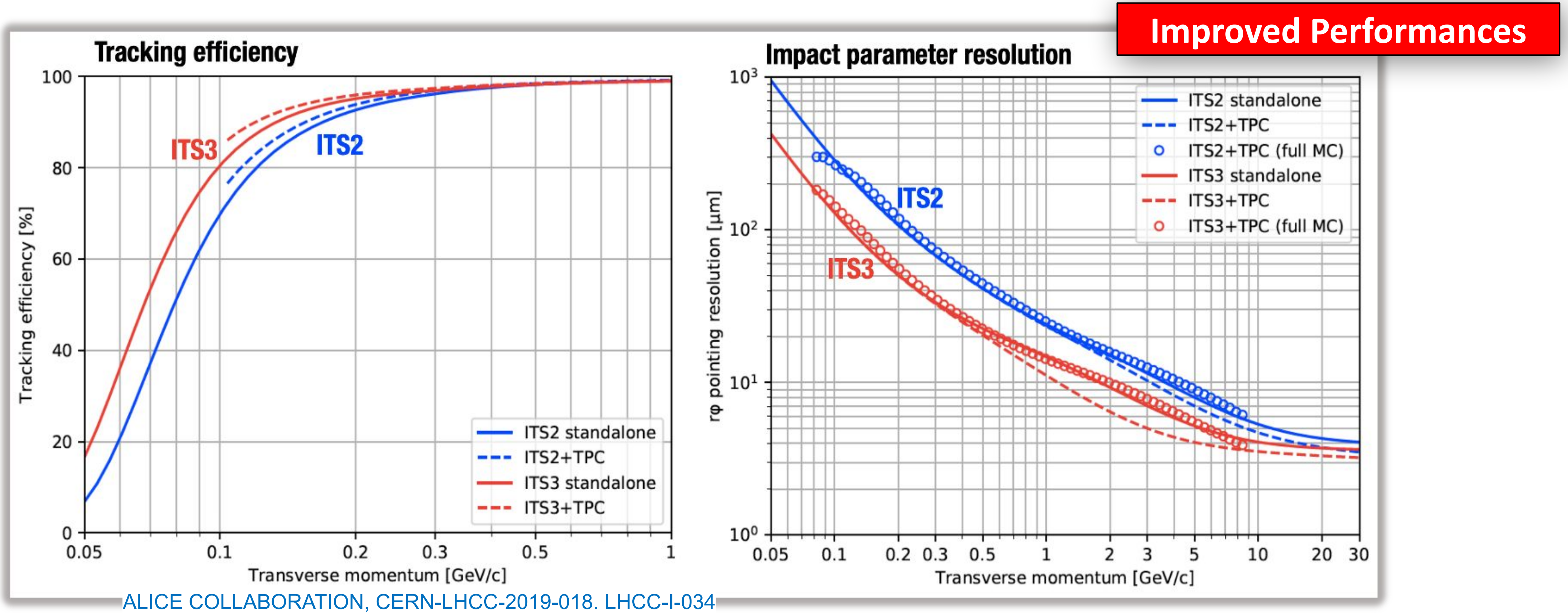
MATERIAL BUDGET ≲0.07 X_0 assuming final sensor thickness ≤ **50 µm**





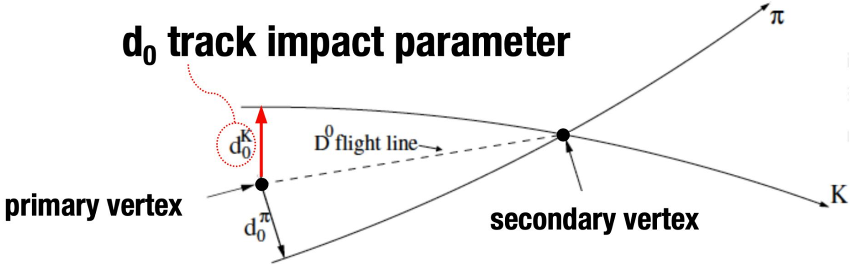
(*) Courtesy of ITS3 WP1&5

The ITS3 - a new golden vertex detector

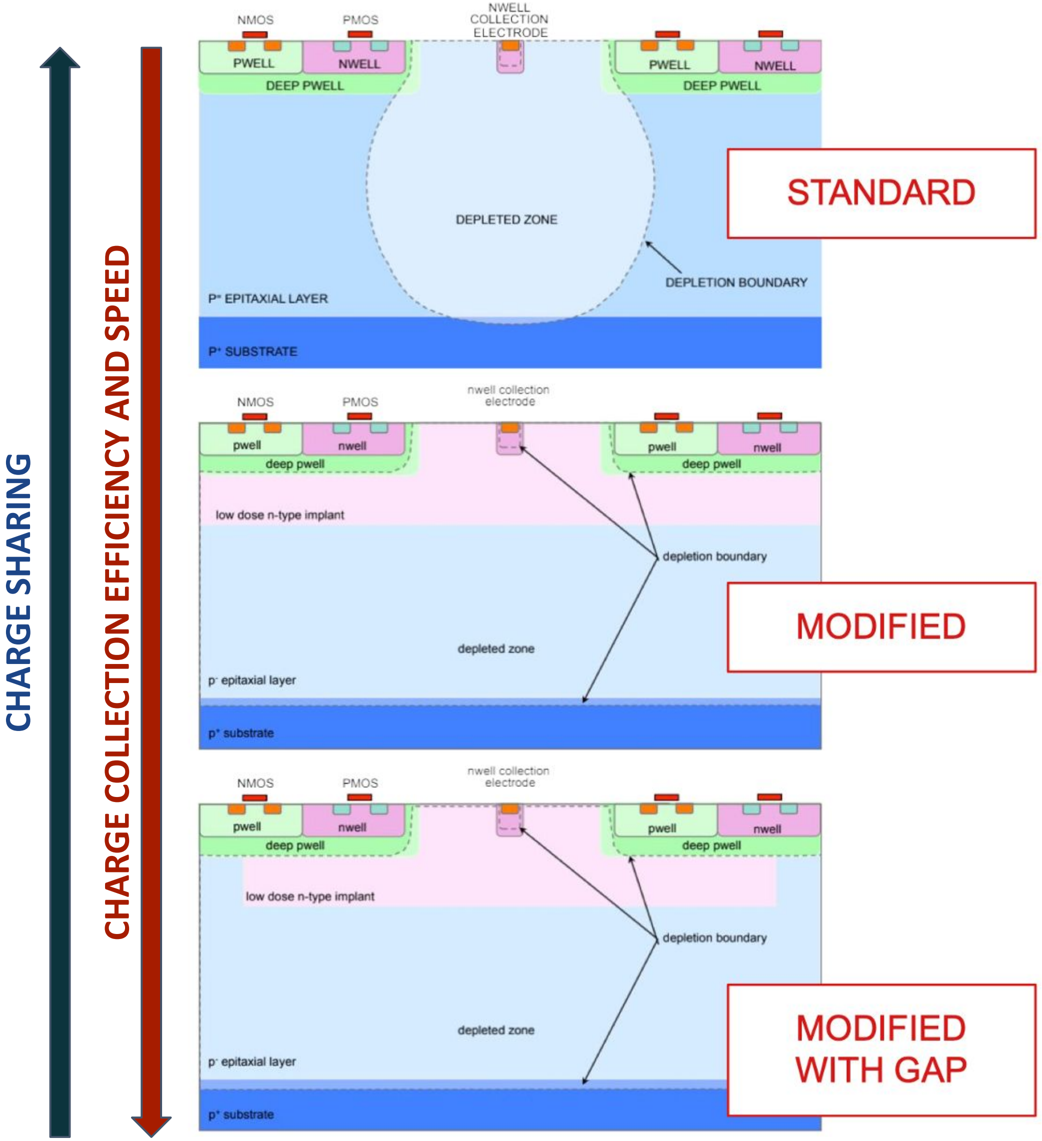


ALICE COLLABORATION, CERN-LHCC-2019-018. LHCC-I-034

- less material budget, closer to the IP, less inhomogeneities
- impact-parameter resolution improved by a factor two with respect to the current ITS2



New Monolythic Active Pixel Sensor prototypes



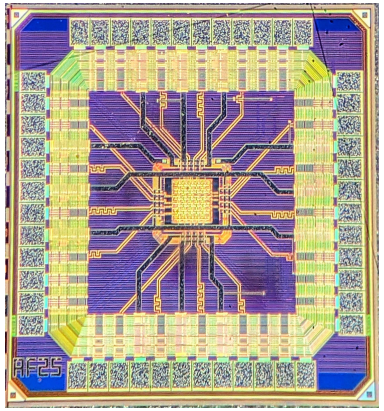
- Based on **MAPS** and **65 nm CMOS** technology
- 50 µm thick
- Three **different chip designs** for characterization and qualification purposes:
  1. Standard type
  2. Modified type
  3. Modified type with gap

MLR1 Sensors characterization and qualification

Multi Layer Reticle 1 - First submission in the **65 nm** MAPS technology for the ITS3

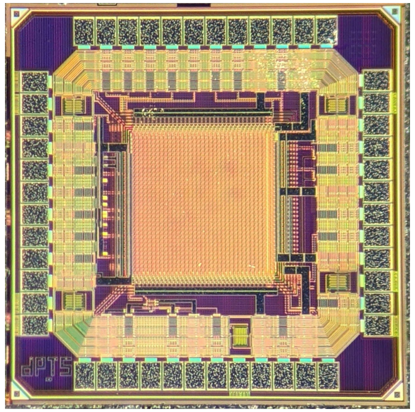
Goal → **test and qualification** (long R&D work done together with CERN EP R&D WP1, WP2)

APTS - Analog Pixel Test Structure



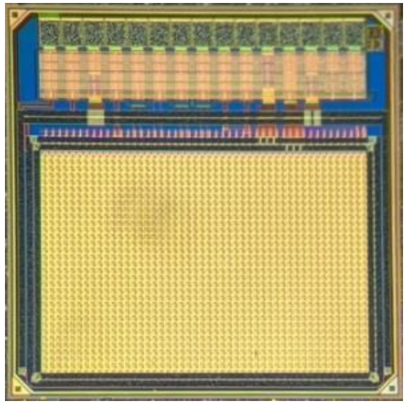
- **matrix**: 6x6 pixels
- **readout**: direct analogue
- readout of central 4x4
- **pitch**: 10, 15, 20, 25 µm
- **process**: standard, modified, modified with gap

DPTS - Analog Pixel Test Structure



- **matrix**: 32x32 pixels
- **readout**: digital with ToT
- **pitch**: 10, 15, 20, 25 µm
- **process**: standard, modified, modified with gap

CE65 - Circuit Exploratoire 65 nm

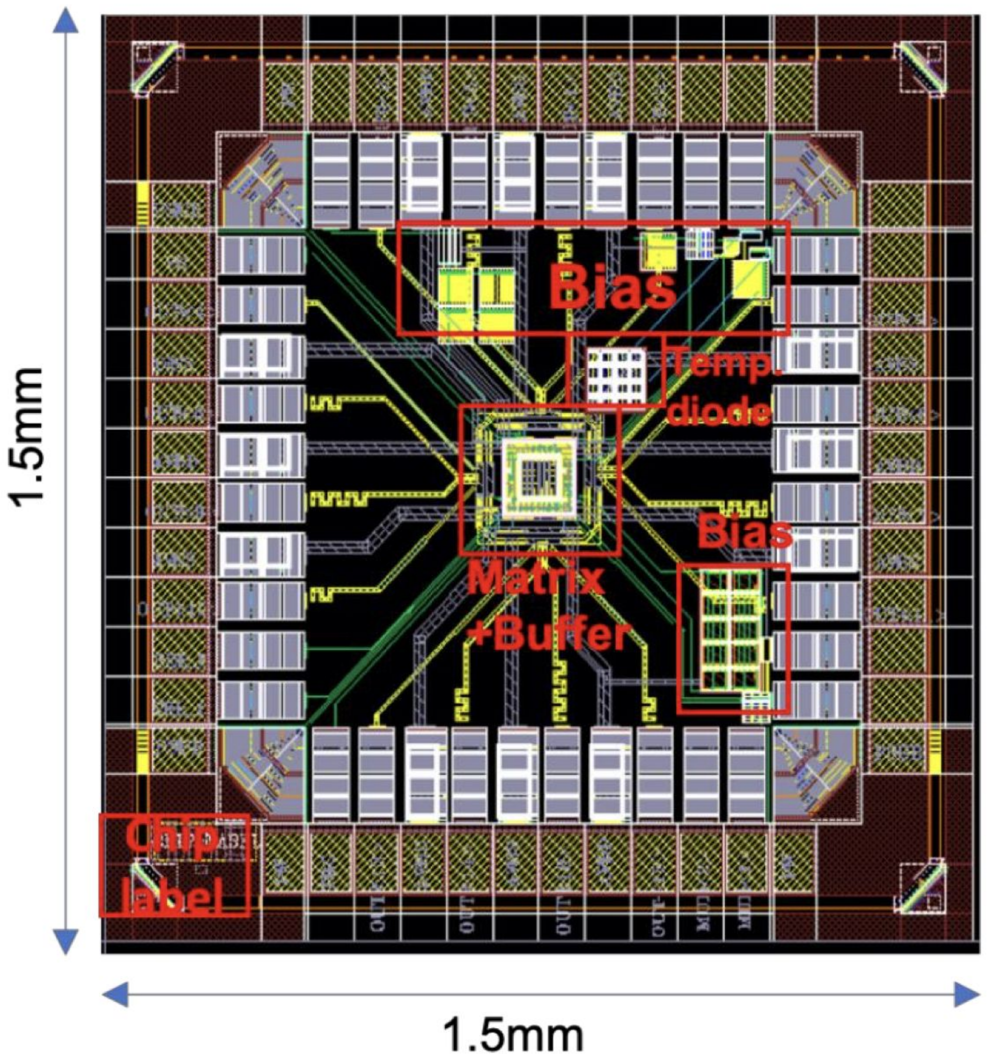


- **matrix**: 64×32 or 48×32
- **readout**: Rolling shutter readout (down to 50 µs integration time
- **pitch**: 15 µm or 25 µm
- **process**: standard, modified, modified with gap

Intensive characterization campaign:

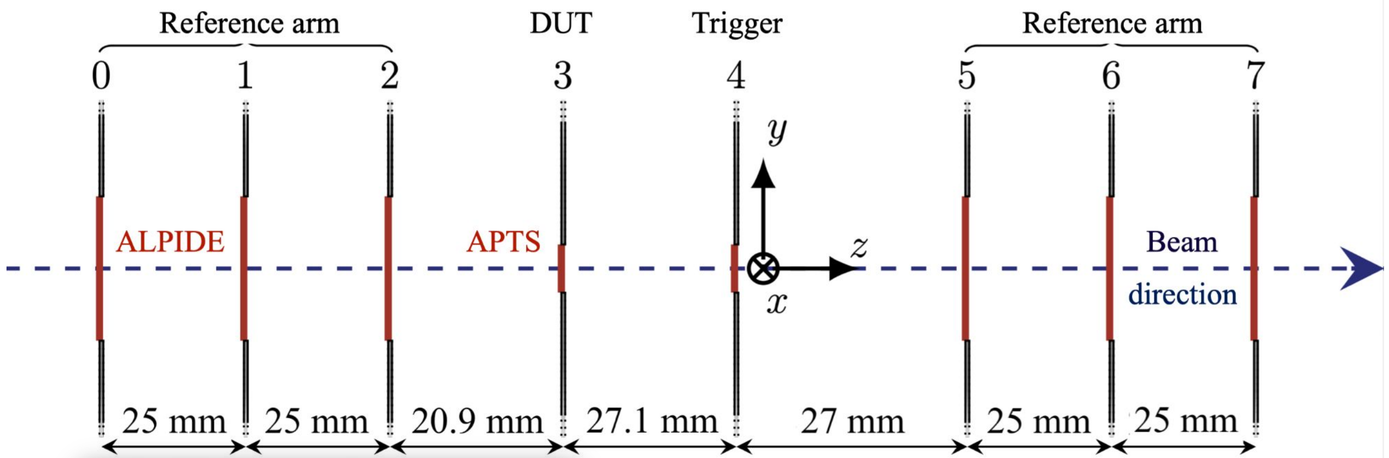
Laboratory tests (also with Fe-55 source), **Testbeams** (efficiency and spatial resolution studies)

APTS - Analogue Pixel Test Structure for the ITS3 upgrade

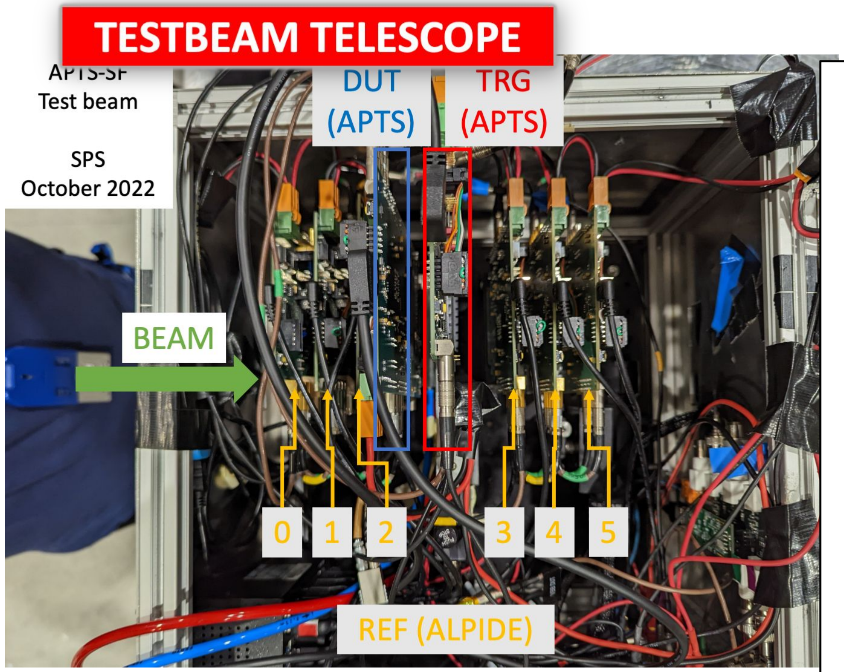


- APTS (Analog Pixel Test Structure)
- Based on **MAPS** and **65 nm CMOS** technology
- 6x6 pixel matrix, readout of **central 4x4** (16 analog outputs)
- 50 µm thick
- Can operate at different back bias voltages (from 0 to -4.8 V)
- Different chip designs for characterization purposes:
    1. Standard, Modified, Modified with gap
    2. Pixel pitch size: 10, 15, 20, 25 µm
- Characterization done in **laboratory** (also with Fe-55) and with **testbeams** (CERN PS and SPS)

Testbeam Setup and analysis



- After characterisation campaign in laboratory → ionising particle beam
- **Telescope**: 6 reference ALPIDE chip planes for track reconstruction
- **Goal**: measure tracking efficiency and spatial resolution performances of APTS



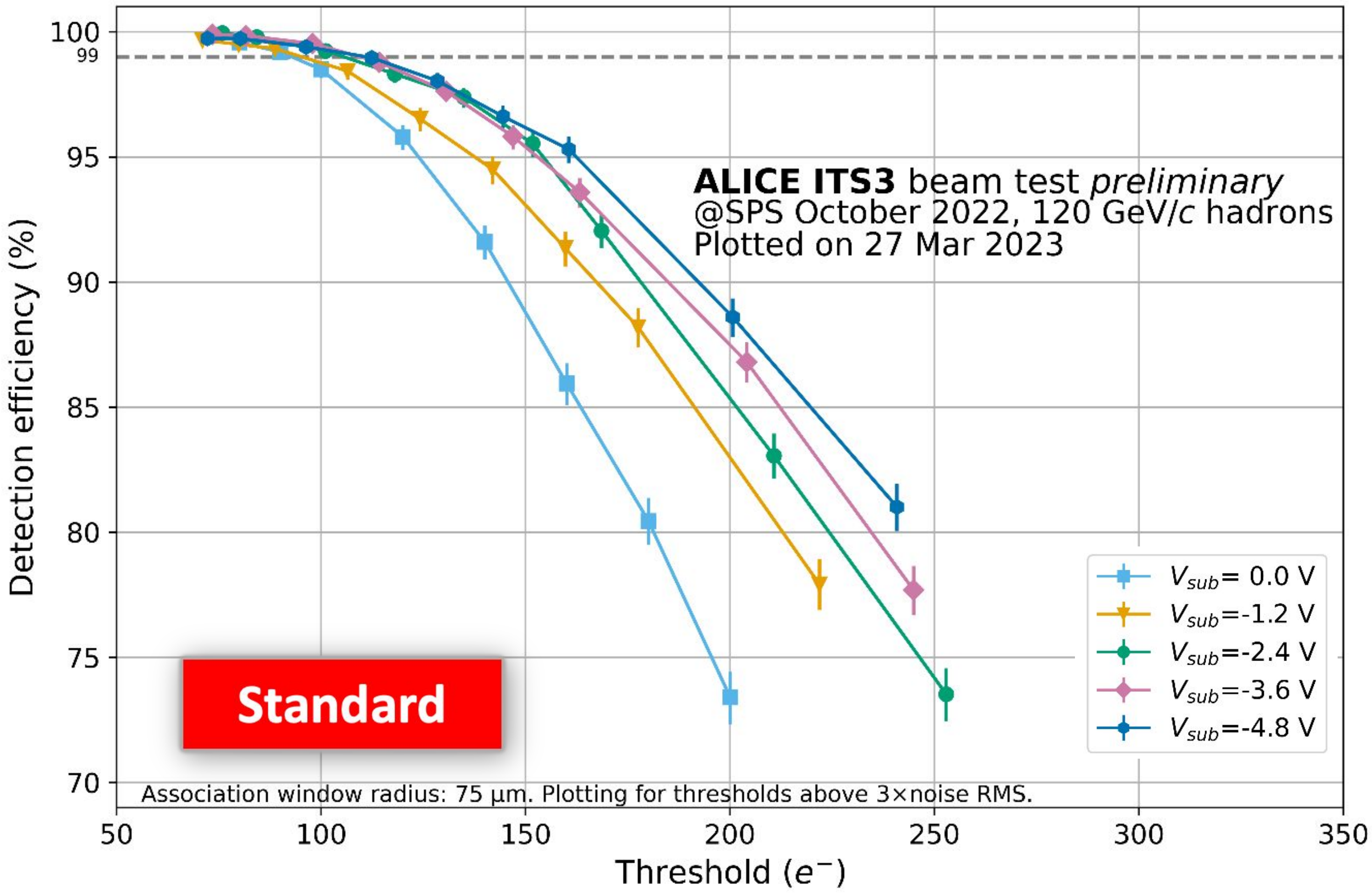
- Data analysis performed using *Corryvreckan**
  - software written in C++
  - used for test beam data reconstruction and analysis
  - it performs offline event building also in high complexity data-taking conditions

*https://gitlab.cern.ch/corryvreckan/corryvreckan

Detection efficiency:

$$\epsilon = \frac{\#\ tracks_{1\ ass.cluster,\ DUT}}{total\ \#\ tracks_{DUT}}$$

Detection Efficiency - Standard type

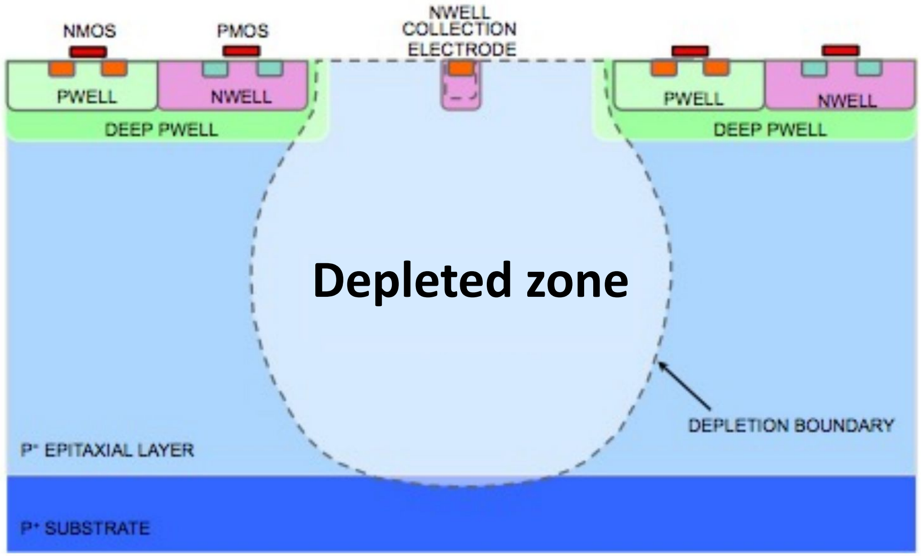


APTS SF
Non-irradiated
type: standard
pitch: 15 µm
split: 4
$I_{reset} = 100$ pA
$I_{biasn} = 5$ µA
$I_{biasp} = 0.5$ µA
$I_{bias4} = 150$ µA
$I_{bias3} = 200$ µA
$V_{reset} = 500$ mV
$V_{pwell} = V_{sub}$
T = 20 °C

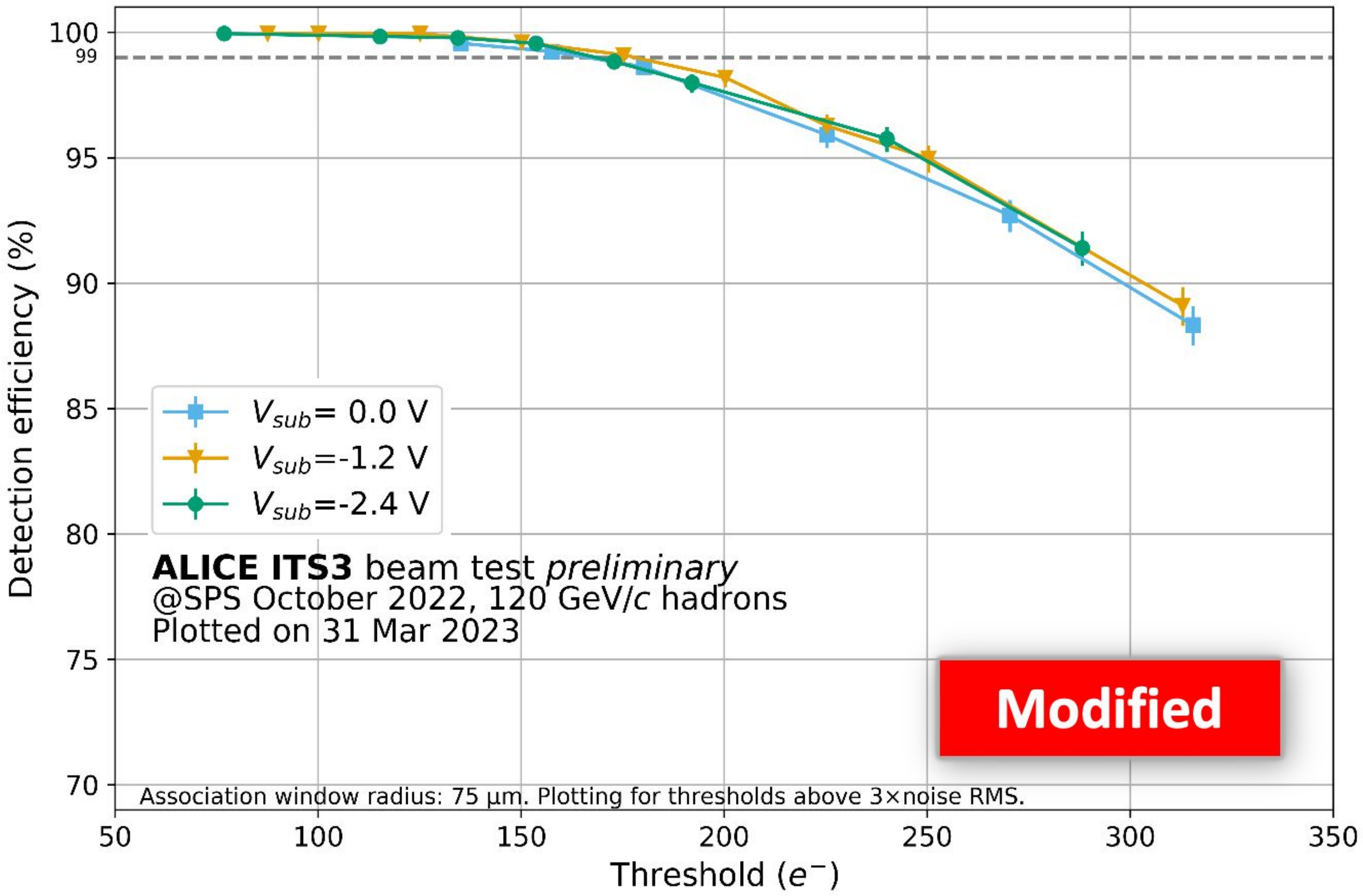
$$\epsilon = \frac{\#\, tracks_{1\, ass.cluster,\ DUT}}{total\ \#\, tracks_{DUT}}$$

Efficiency changes depending on the applied reverse bias voltage

Vbb (V)	Noise (e^-)
0.0	25
1.2	24
2.4	24
3.6	23
4.8	23



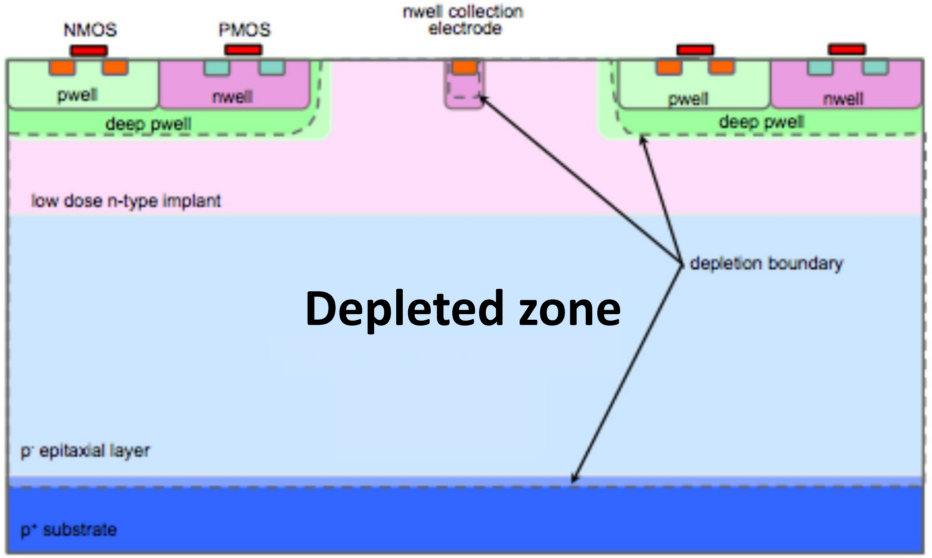
Detection Efficiency - Modified type



APTS SF
Non-irradiated
type: modified
pitch: 15 µm
split: 4
I_{reset} = 100 pA
I_{biasn} = 5 µA
I_{biasp} = 0.5 µA
I_{bias4} = 150 µA
I_{bias3} = 200 µA
V_{reset} = 500 mV
V_{pwell} = V_{sub}
T = 20 °C

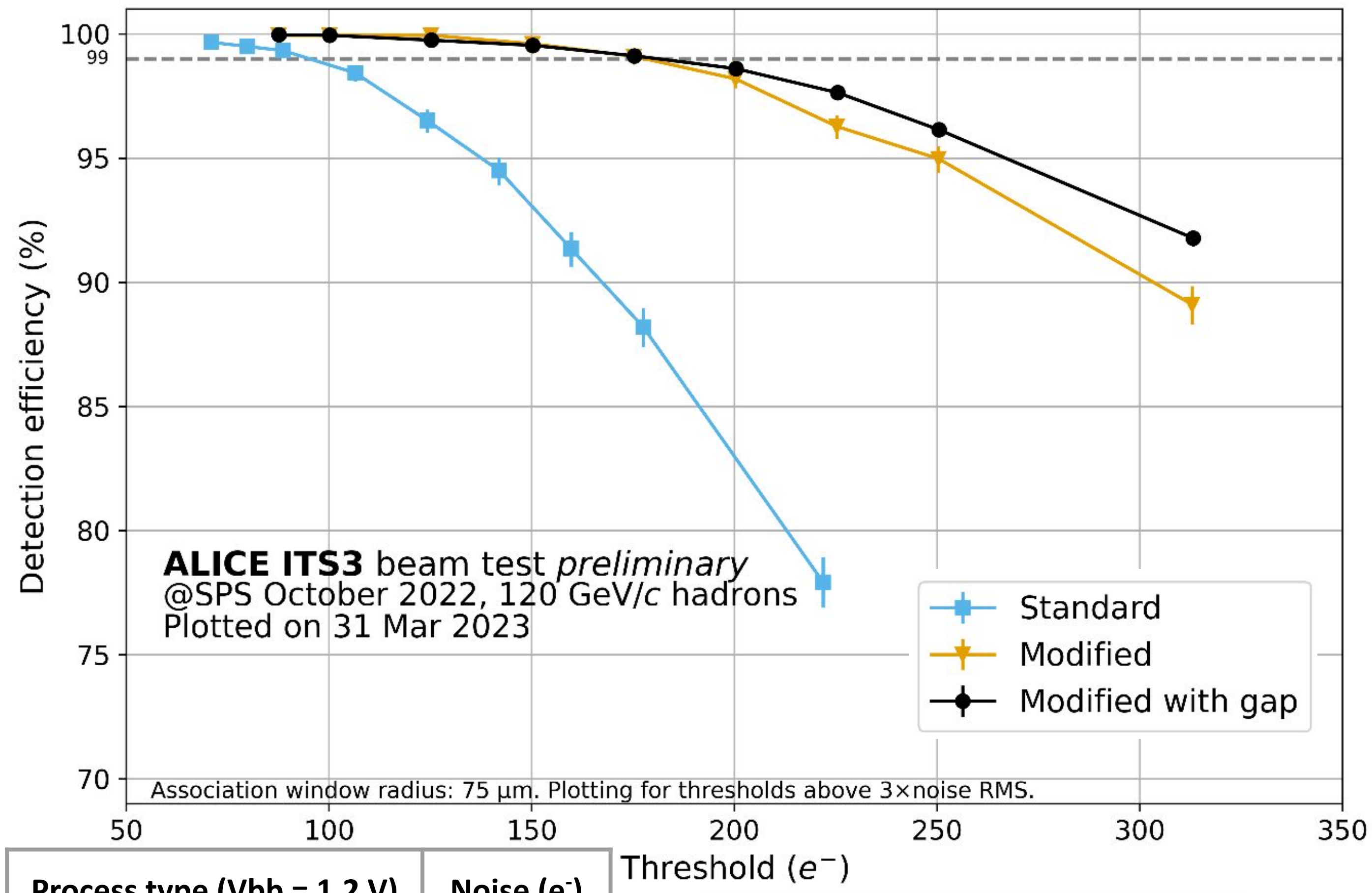
Almost same efficiency also at different reverse biases

Vbb (V)	Noise (e^-)
0.0	34
1.2	28
2.4	24



$$\epsilon = \frac{\#\, tracks_{1\, ass.cluster,\ DUT}}{total\ \#\, tracks_{DUT}}$$

Detection Efficiency - design comparison



APTS SF
Non-irradiated
pitch: 15 µm
split: 4
$I_{reset} = 100$ pA
$I_{biasn} = 5$ µA
$I_{biasp} = 0.5$ µA
$I_{bias4} = 150$ µA
$I_{bias3} = 200$ µA
$V_{reset} = 500$ mV
$V_{pwell} = V_{sub}$=-1.2 V
T = 20 °C

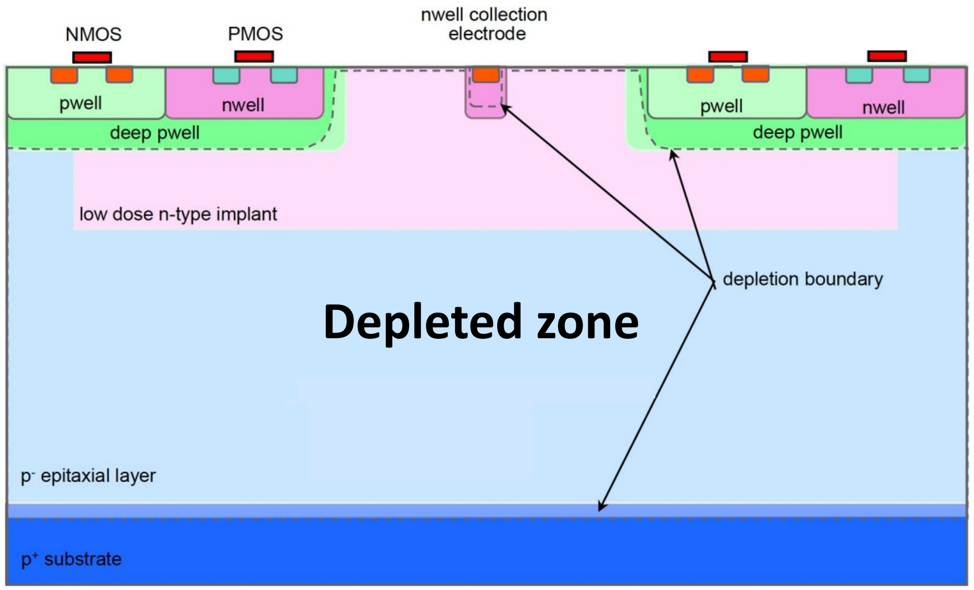
Modified with gap shows also at at higher thresholds the best efficiency values

$$\epsilon = \frac{\#\, tracks_{1\, ass.cluster,\ DUT}}{total\ \#\, tracks_{DUT}}$$

Process type (Vbb = 1.2 V)	Noise (e⁻)
Standard	24
Modified	28
Mod.Gap	28

Comparison among the three types

Modified type with gap



ITS3 roadmap

ITS3

LS2		RUN3					LS3			RUN4				LS4	
2020	2021	2022	2023	2024	2025		2026	2027	2028	2029	2030	2031	2032	2033	2034
	MLR1	MLR1 - test	ER1	ER2 + ER3											

You are **here**

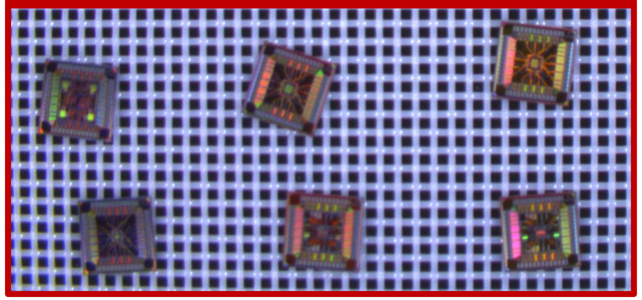
Engineering Run 2 (full sensor) +
Engineering Run 3 (final sensor)

- 2D stitching
- **final size** sensor studies

Multi Layer Reticle 1 (MLR1)

First submission using 65 nm technology

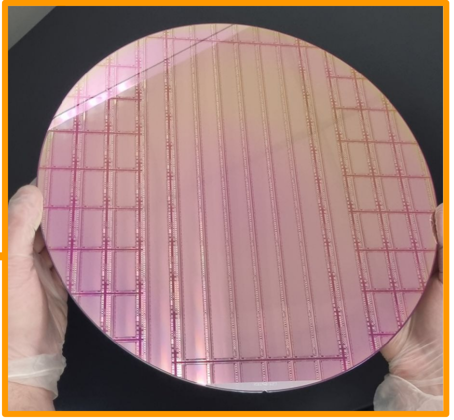
- Many prototypes (55 sensors)
- Aim: technology qualification



Engineering Run 1 (ER1)

First stitched (wafer-scale) prototype

- 1D stitching
- First working stitching prototype in HEP
- First tests in 2023, July



Summary

- **Results on MLR1 chips qualified the 65 nm technology for the use in ITS3 and put the basis for studies on new ER1 sensors**
- **In particular, results of data analysis from the APTS beam tests show:**
  - Better tracking efficiency when increasing the reverse bias voltage for the **standard process technology**
  - Almost the same efficiencies among different reverse bias voltages for the **modified process**
  - **Better tracking efficiencies** for the **modified with gap** type compared to the modified and standard type processes

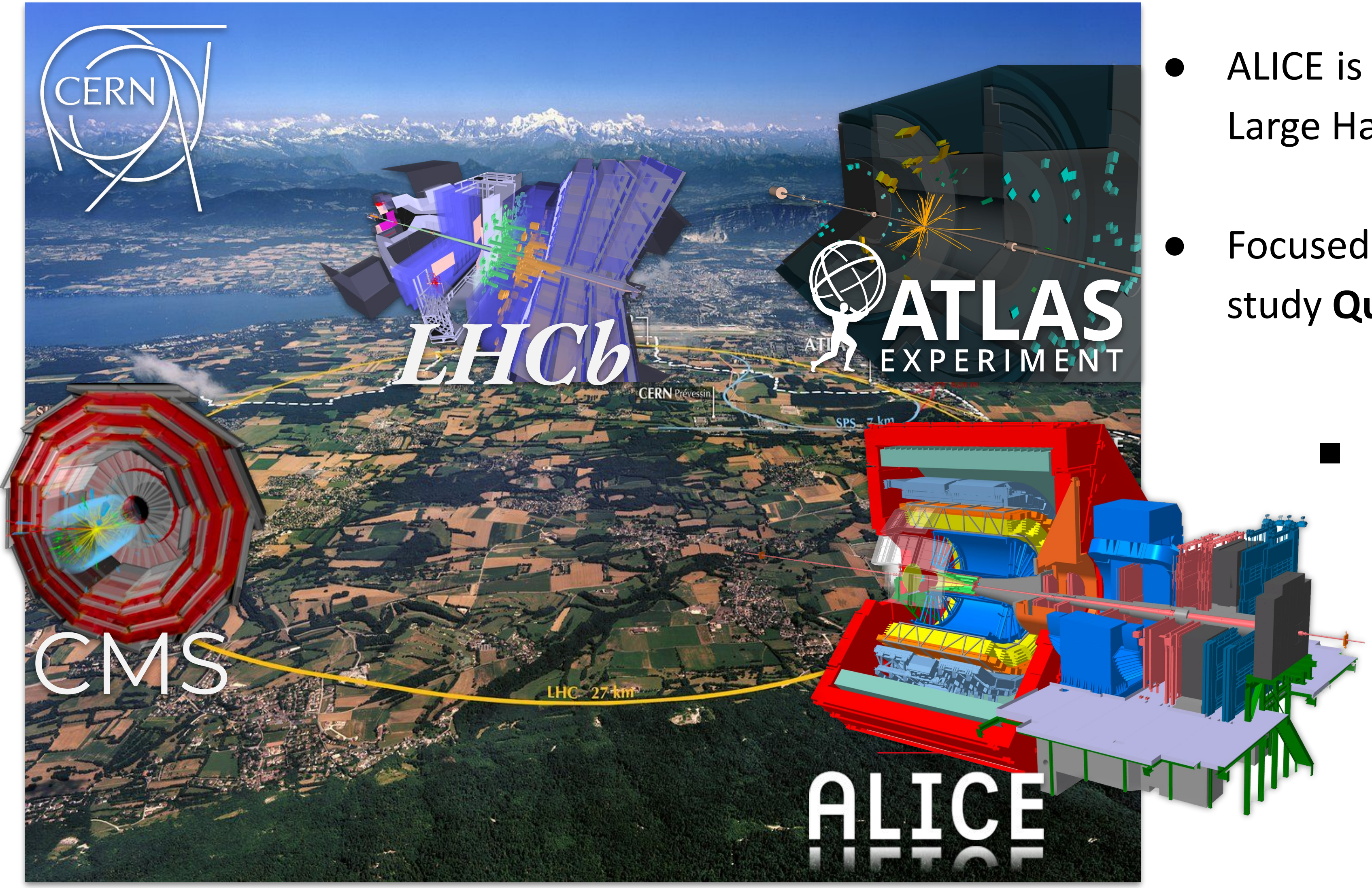
Next steps

- Finalize studies on spatial resolutions and Non Ionizing Energy Loss (NIEL) irradiation for the different APTS variants
- Study of first **large-scale stitched sensors** performance (ER1)

Thanks for your attention

Backup

ALICE - A Large Ion Collider Experiment

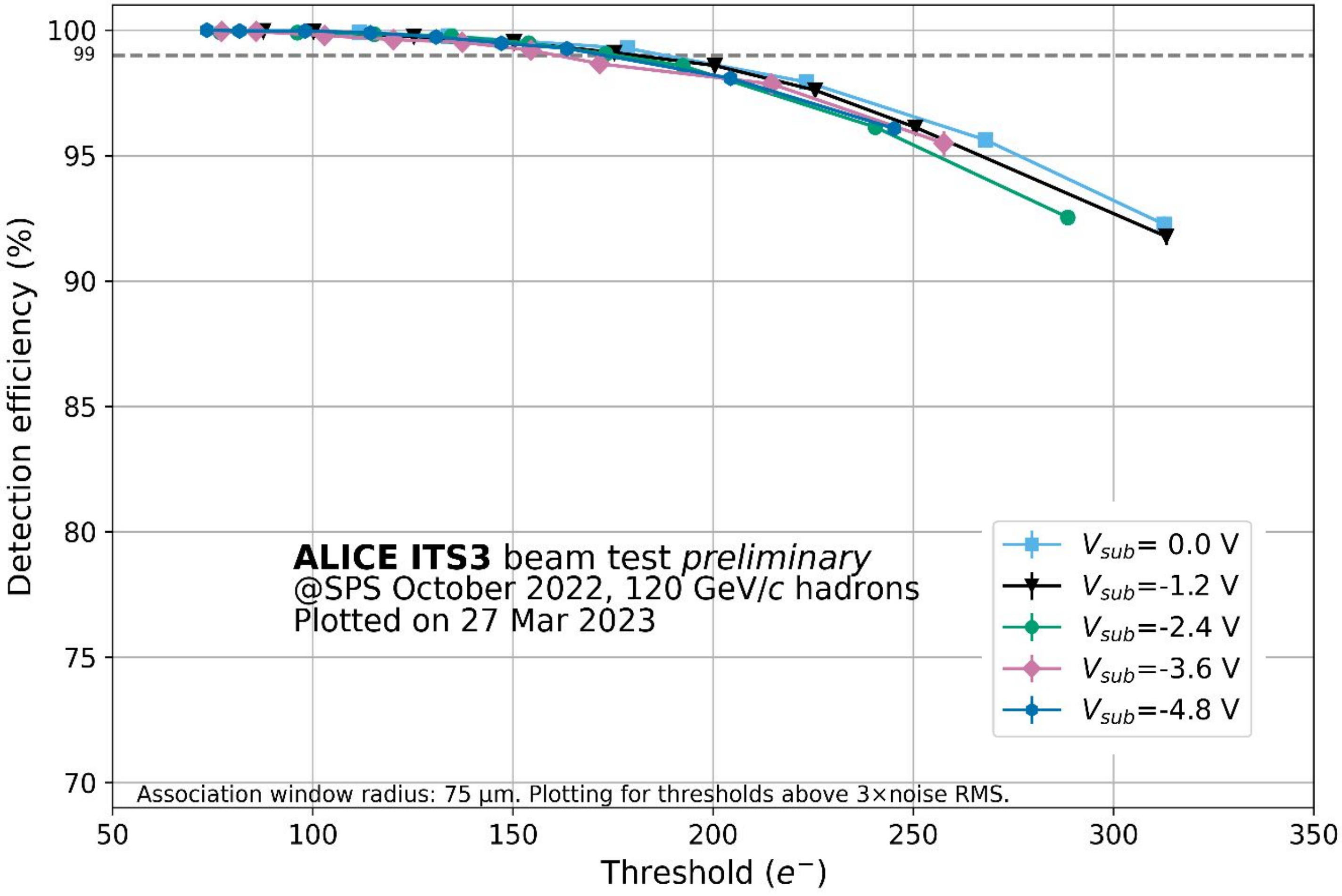


- ALICE is one of the main 4 experiments at the Large Hadron Collider (LHC) at CERN

- Focused on heavy-ion interactions physics to study **Quark-Gluon Plasma** (QGP)

  - The collision product is a "**fireball**" which should reproduce:
    - early Universe evolution stages
    - transition from partonic deconfined matter into confined hadrons (few **μs** after the Big Bang)

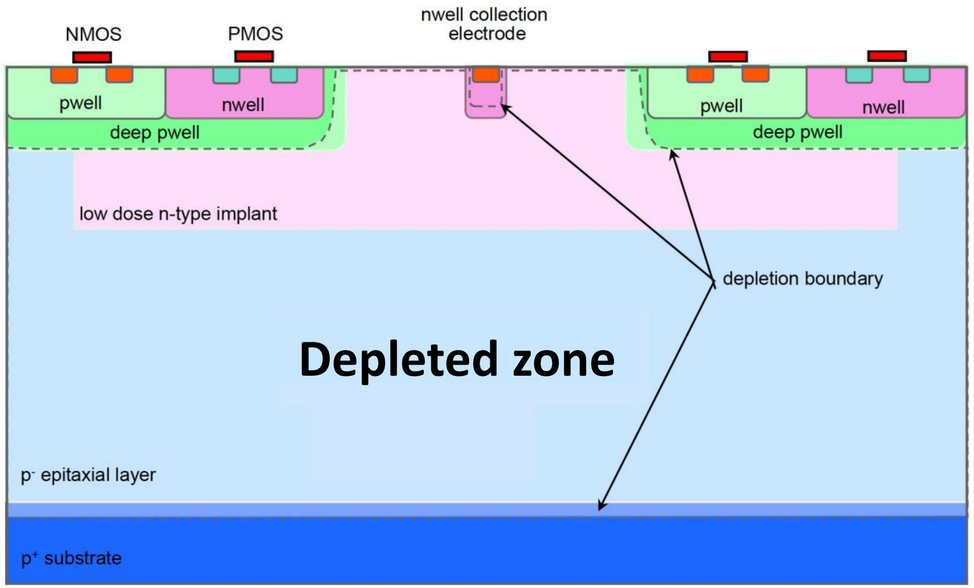
Detection Efficiency - modified with gap type



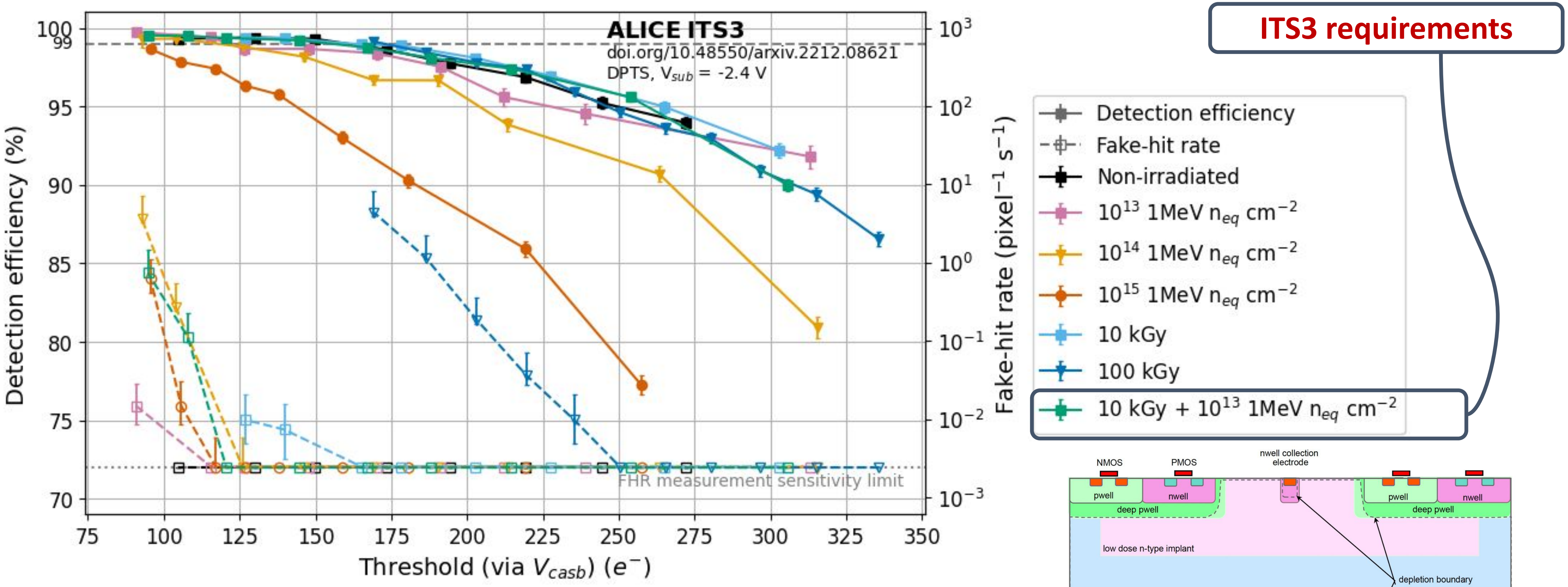
APTS SF
Non-irradiated
type: modified with gap
pitch: 15 µm
split: 4
I_{reset} = 100 pA
I_{biasn} = 5 µA
I_{biasp} = 0.5 µA
I_{bias4} = 150 µA
I_{bias3} = 200 µA
V_{reset} = 500 mV
V_{pwell} = V_{sub}
T = 20 °C

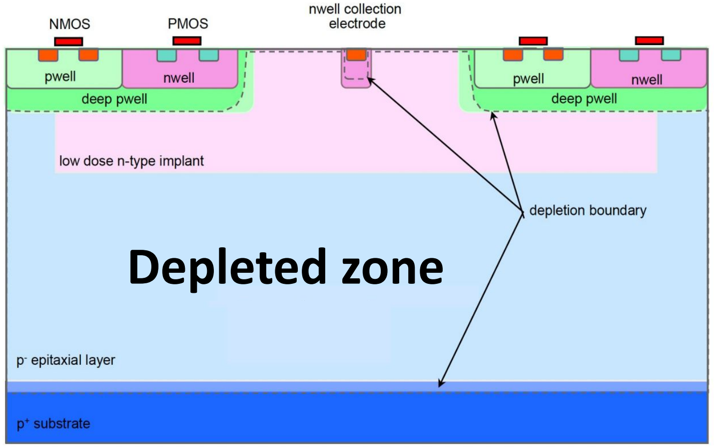
Trend similar to modified type

$$\epsilon = \frac{\#\, tracks_{1\, ass.cluster,\ DUT}}{total\ \#\, tracks_{DUT}}$$



Detection Efficiency - DPTS



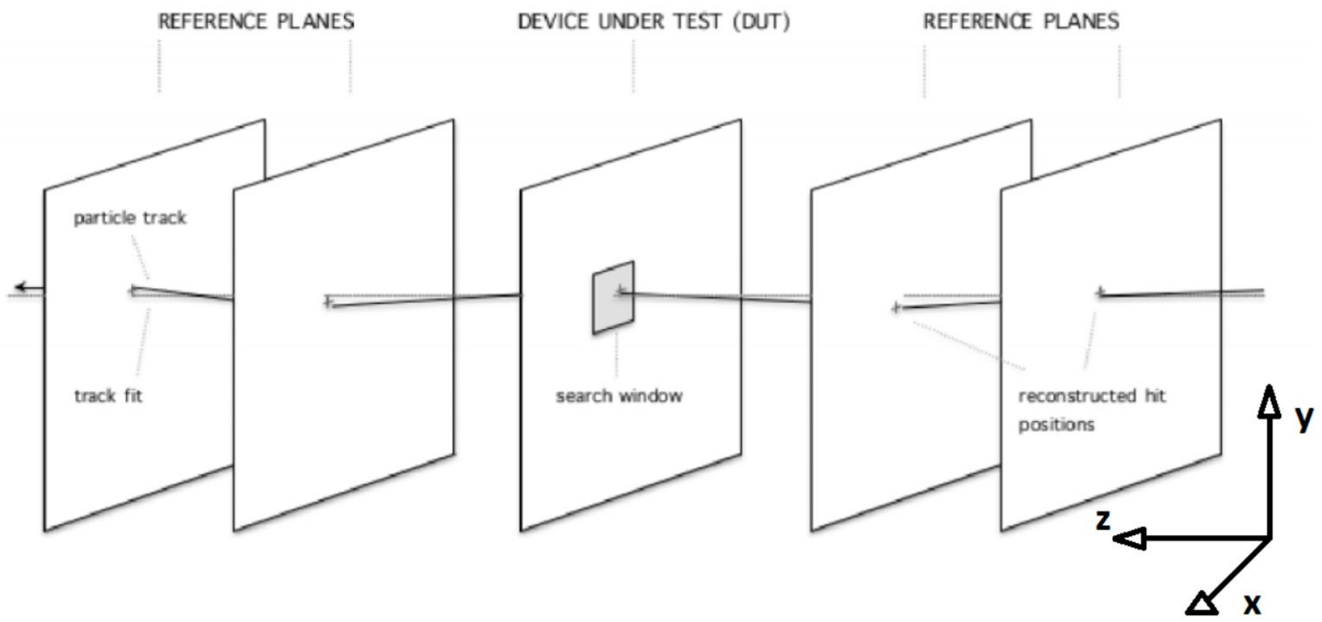


$$\epsilon = \frac{\# \, tracks_{1 \, ass.cluster, \; DUT}}{total \, \# \, tracks_{DUT}}$$

Corryvreckan

Framework used to analyze data from the beam test. Analysis steps are:

1. Masking: pixels with firing rate 1000 times than the average are «masked»;
2. Prealignment: correlation of the hits on all the planes of the telescope with the hits on the first reference plane;
3. Clustering: adjacent fired pixels grouped in clusters center-of-gravity technique to calculate the hit



Corryvreckan

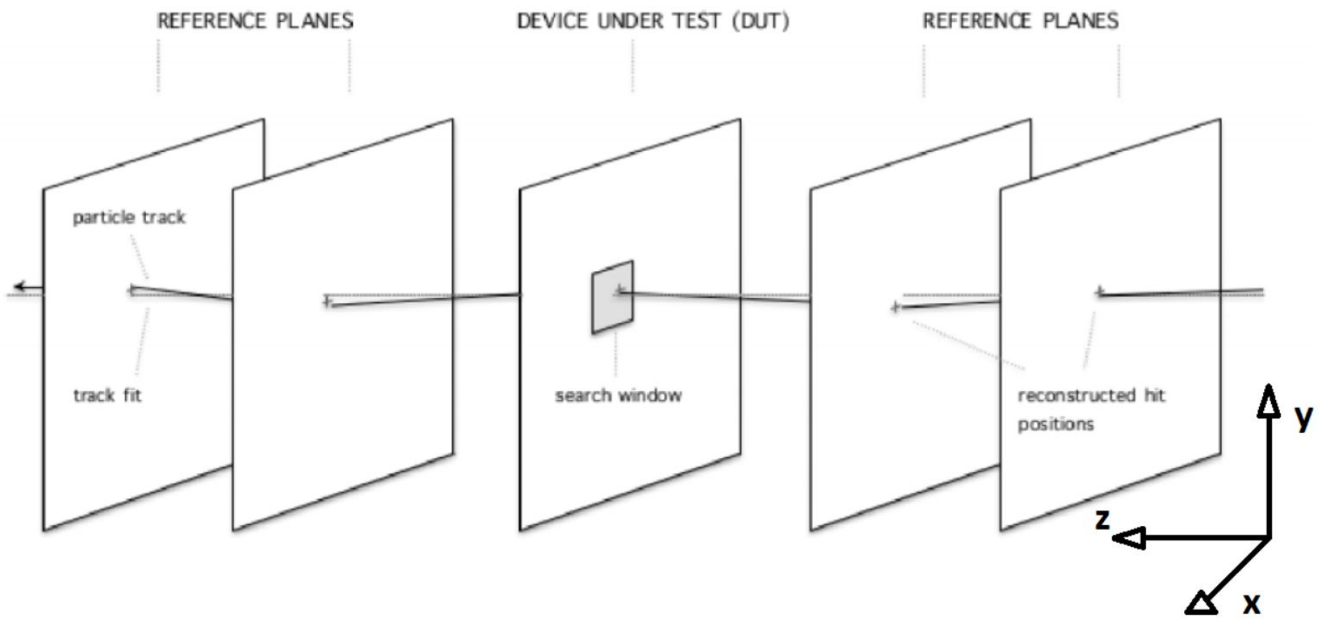
4. Pre-tracking: building of straight-line pre-tracks using the cluster on all the detectors, including also the DUT;

5. Alignment: the pre-tracks in 3 degrees of freedom (x-shift, y-shift, z-rotation) are used to align the detectors, using the updated pre-aligned coordinates.;

6. Tracking association: for each event, the clusters in the reference planes are used to reconstruct the straight-line tracks. Then, a chi-square test is used for the goodness-of-fit;

7. Residuals calculation;

8. Efficiency calculation



Pointing resolution and vertex detectors layers

The pointing resolution σ_p can be written as:

$$\sigma_p \sim \sigma_p^{sp} \oplus \sigma_p^{ms}$$

where σ_p^{ms} is the contribution due to the multiple scattering and σ_p^{sp} the one given by the structure of the detector (number of layers ad proximity to the Interaction Point.)

This indicates that is possible to achieve a better σp by having a better spatial resolution of the detector, going closer to the IP, and having a lower material budget (in this particular case, of the beampipe and the innermost layer).

$$\sigma_p^{ms} \sim r_1 \theta_{RMS}$$

$$\sigma_p^{sp} = \sqrt{(\frac{r_2}{r_2 - r_1}\sigma_1)^2 + (\frac{r_1}{r_2 - r_1}\sigma_2)^2}$$