Development of the ALICE Inner Tracking System 3

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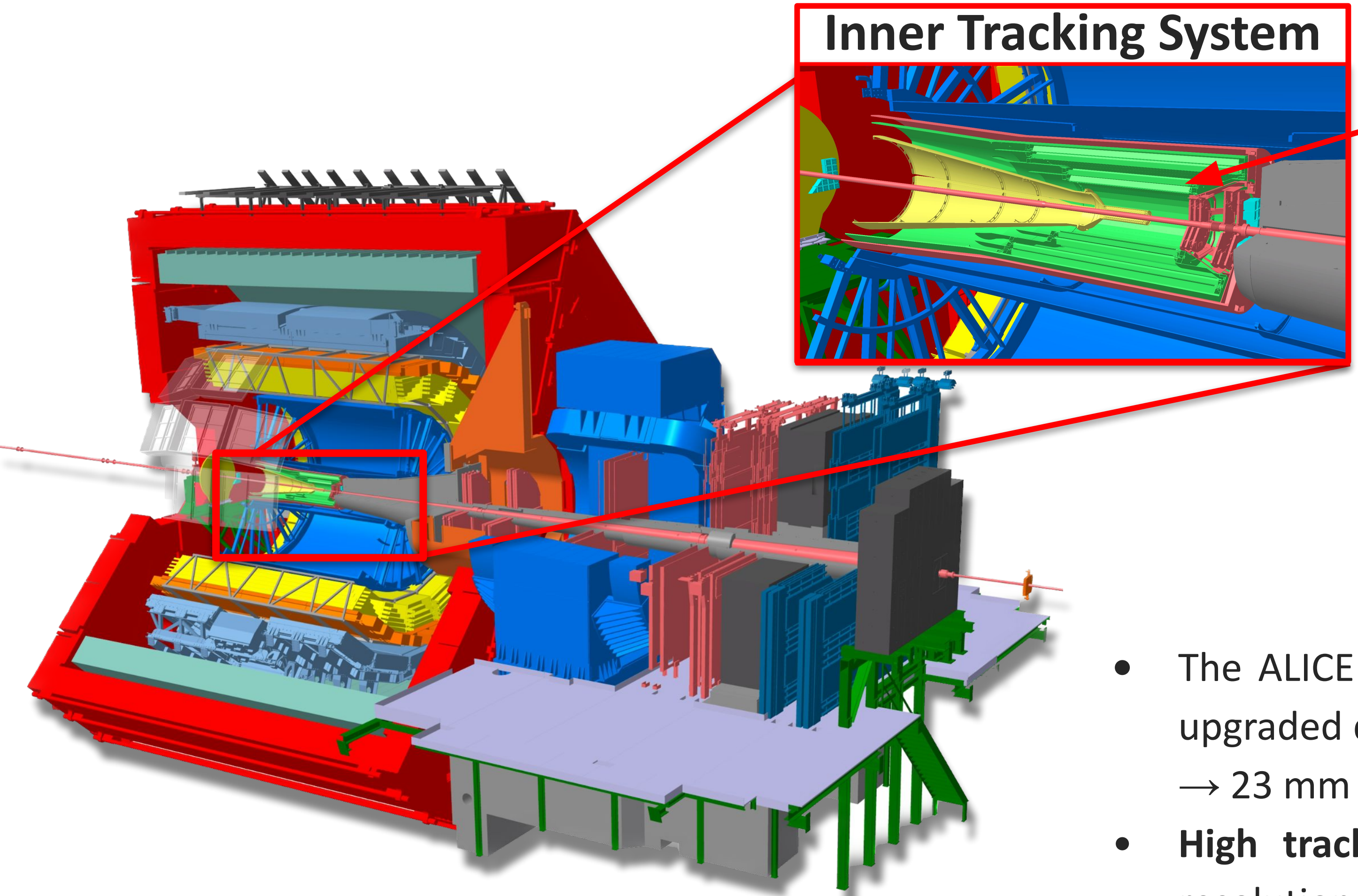
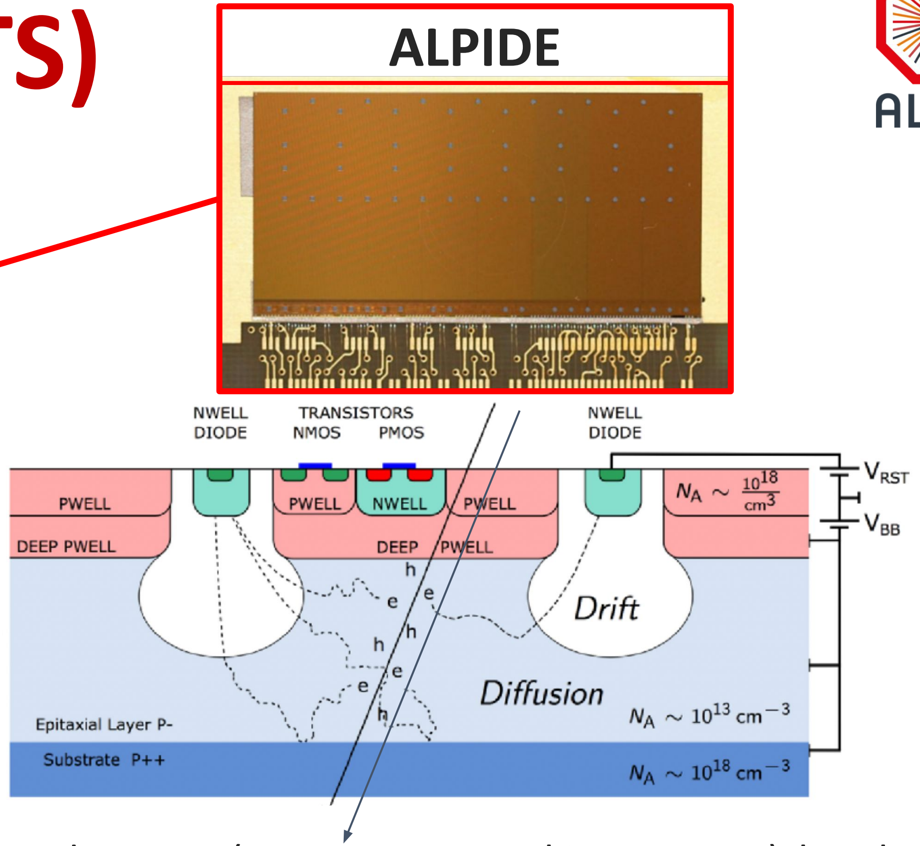
On behalf of the ALICE Collaboration

INFN2024 - Sesto Incontro Nazionale di Fisica Nucleare
Trento - Sala della Cooperazione, 27/02/2024

ALICE Inner Tracking System (ITS)



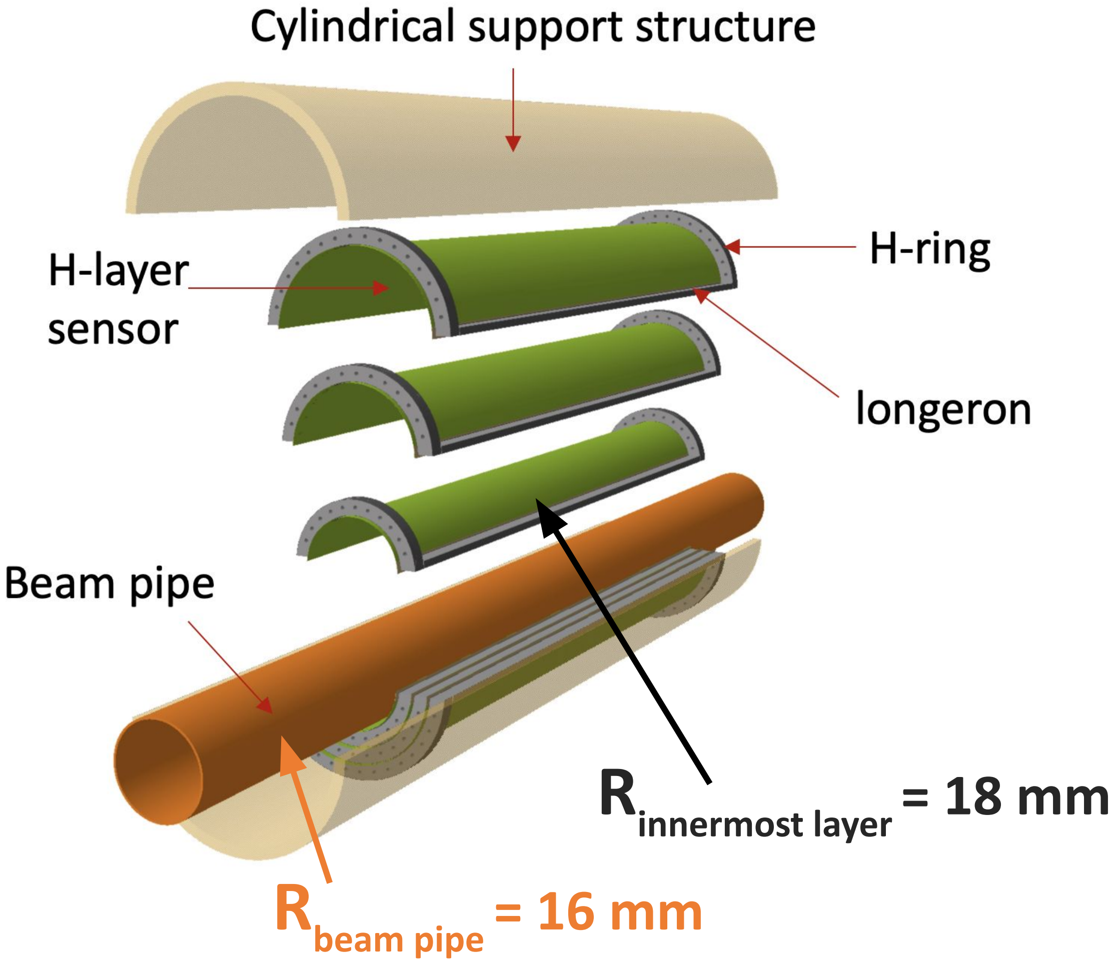


- The ALICE vertex detector (**ITS** = Inner Tracking System) has been upgraded during LHC Long Shutdown 2 (LS2) in preparation for Run3 → 23 mm from the Interaction Point (innermost layer)
- **High tracking performance** also at low p_T (100 μm pointing resolution at p_T = 200 MeV)
- Built using **ALPIDE**, a Silicon pixel chip based on 180 nm Monolithic Active Pixel Sensor (MAPS)

The ITS3 - a bent vertex detector

- Ready for LHC RUN 4 - mounted during LS3
- Built using **wafer-scale MAPS sensors**, fabricated using **stitching**
- **Thinned ≤ 50 μm,** when Si is **flexible**
- Mechanically held in place thanks to carbon foam ribs
- **Bent** to the target radius (18 mm, **closer** to the Interaction Point thanks to the new beam-pipe at 16 mm)
- Better tracking efficiency, less power consumption
- ITS3 will replace 3 innermost ALICE Inner Tracking System 2 (ITS2) layers with only **6 sensors** 26 cm long

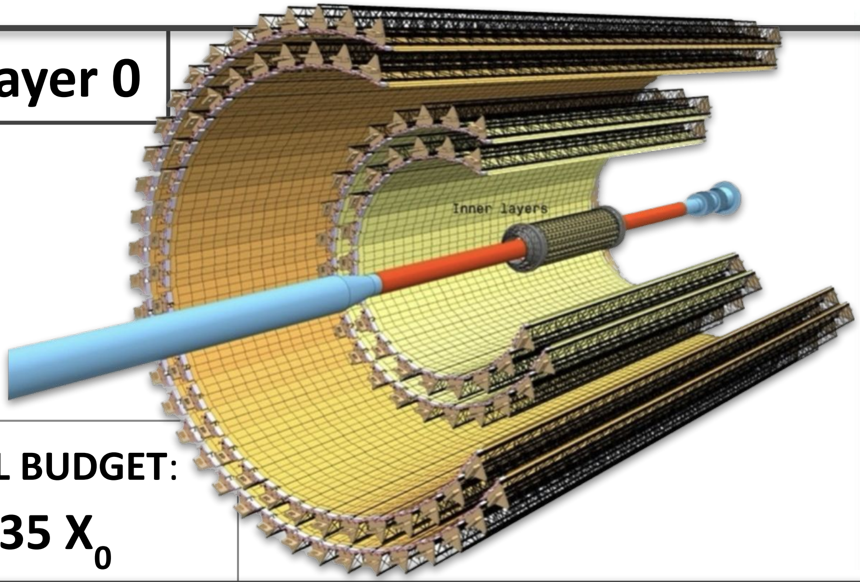
The ITS3 structure



Material budget contribution in the ITS3

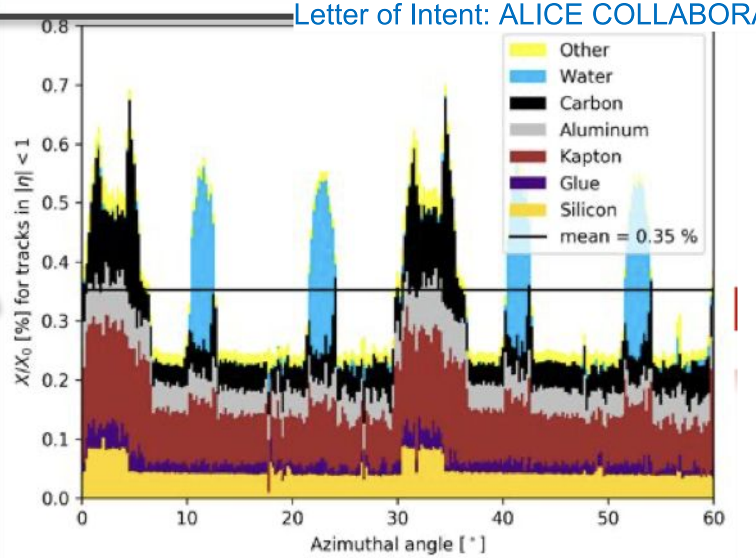
Letter of Intent: ALICE COLLABORATION, CERN-LHCC-2019-018. LHCC-I-034

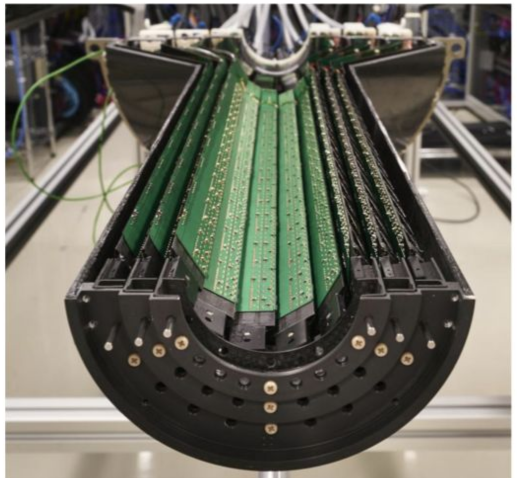
ITS2, Layer 0



MATERIAL BUDGET:

up to 0.35 X_0

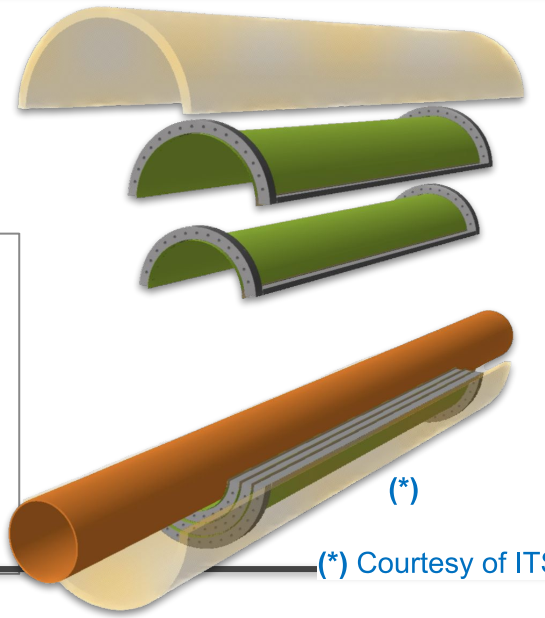




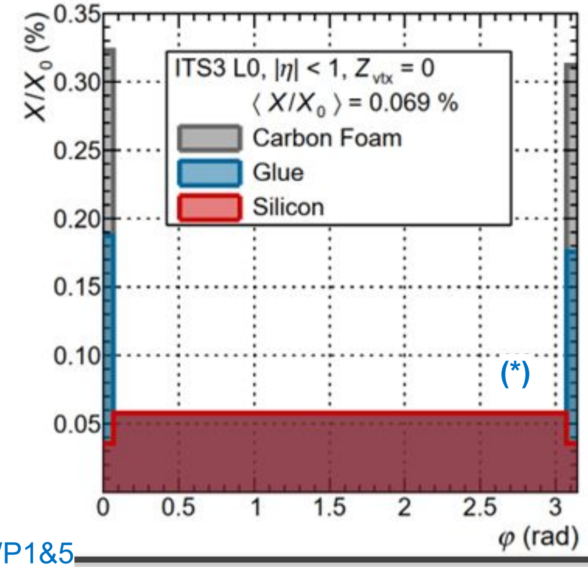
ITS3, Layer 0 Silicon-only contribution

MATERIAL BUDGET

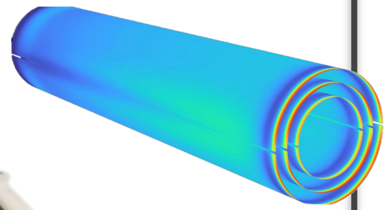
≲0.07 X_0, assuming final sensor thickness ≤ **50 µm**, implementing **air cooling**, removing aluminum structure, glue…



(*) Courtesy of ITS3 WP1&5



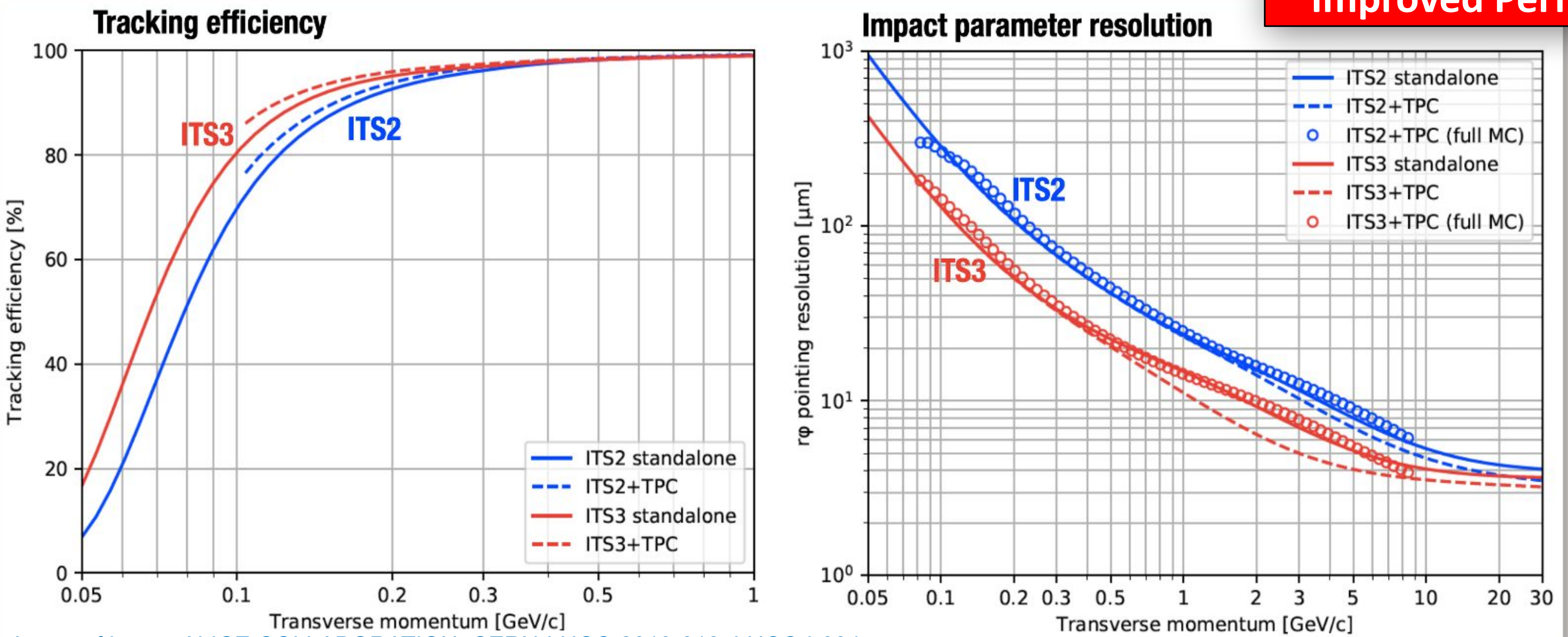
Temperature gradient simulation with air cooling



Carbon foam structure to keep the sensors in place

Performance of the ITS3

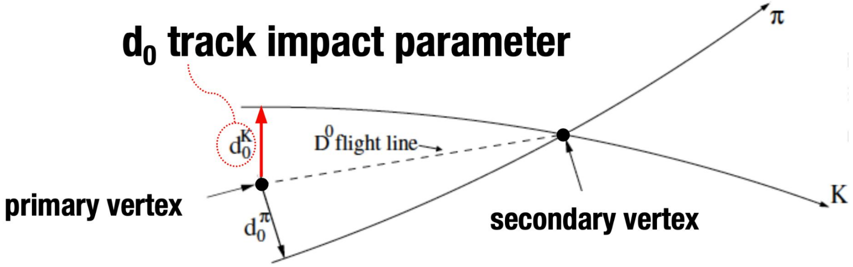
Improved Performance



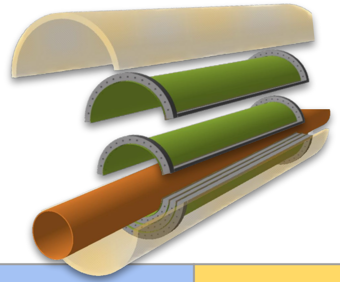
Letter of Intent: ALICE COLLABORATION, CERN-LHCC-2019-018. LHCC-I-034

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

d_0 track impact parameter



ITS3 roadmap



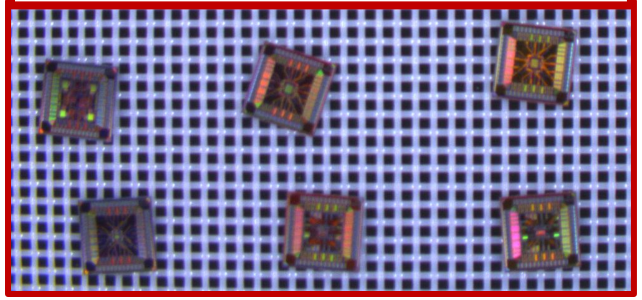
	ITS3													
LS2		RUN3				LS3			RUN4				LS4	
2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
	MLR1		ER1	ER2 + ER3										

You are **here**

Multi Layer Reticle 1 (MLR1)

First submission using a new CMOS TPSCo* 65 nm technology

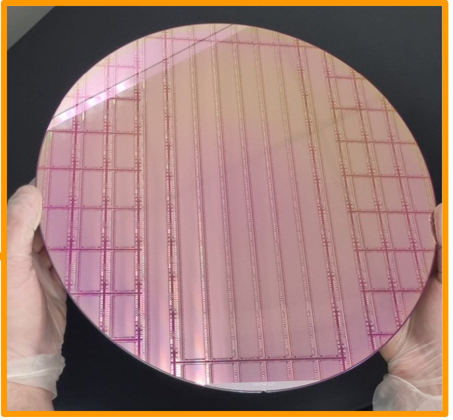
- Many prototypes
- Aim: technology qualification
- Small scale sensors



Engineering Run 1 (ER1)

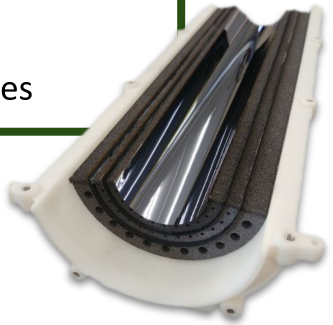
First stitched (wafer-scale) prototype

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



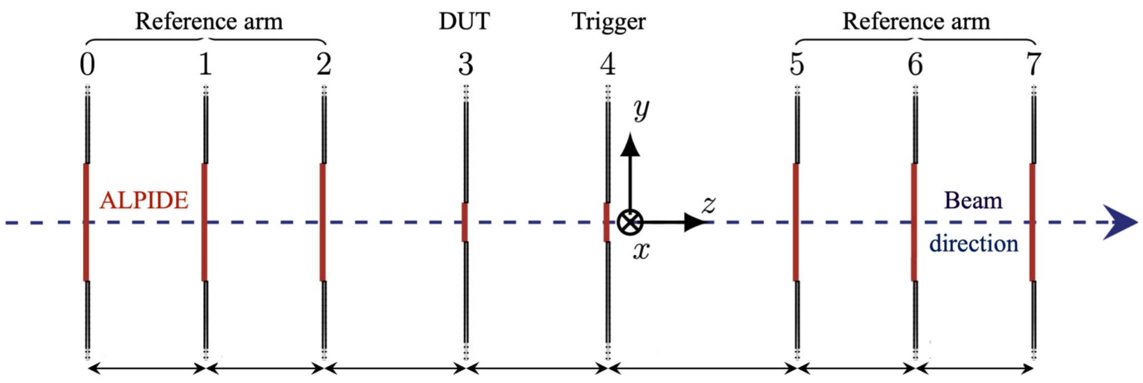
Engineering Run 2 (full sensor) +
Engineering Run 3 (final sensor)

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

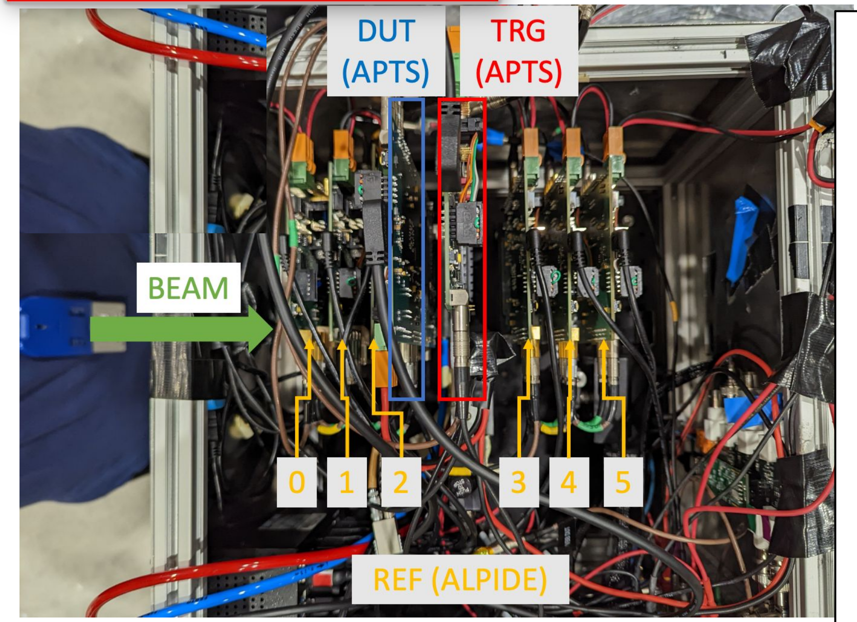


*Tower Partner Semiconductor Co.

Beam tests - setup and analysis



TESTBEAM TELESCOPE



- After characterisation in laboratory → ionising particle beam
- **Telescope**: 5 or 6 reference ALPIDE chip planes for track reconstruction
- **Trigger**: chip or scintillator depending on specific purpose
- **Goal**: measure tracking efficiency and spatial resolution performance of the sensor

- 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

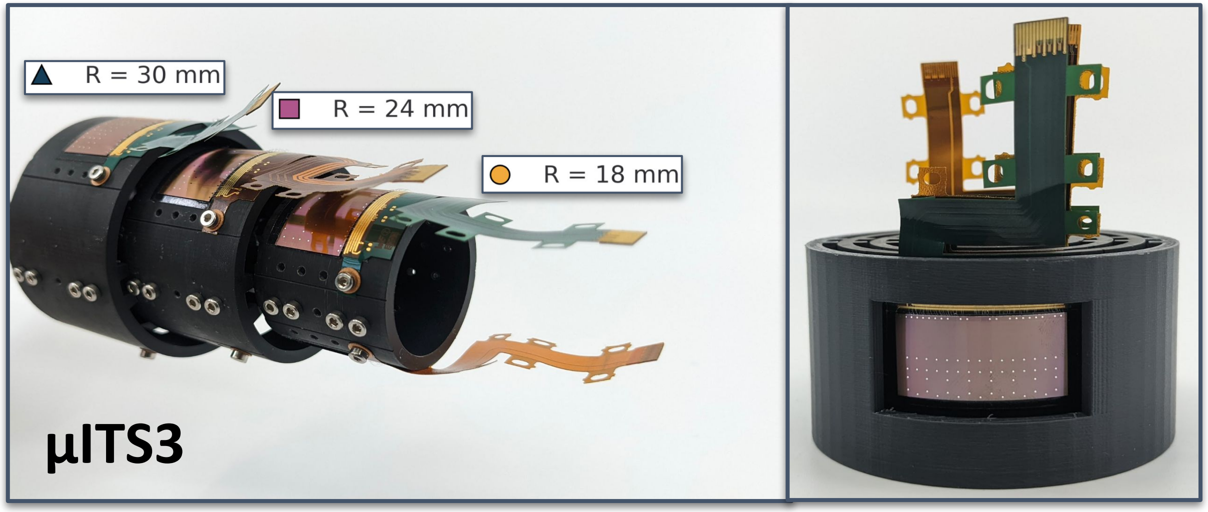
*https://gitlab.cern.ch/corryvreckan/corryvreckan

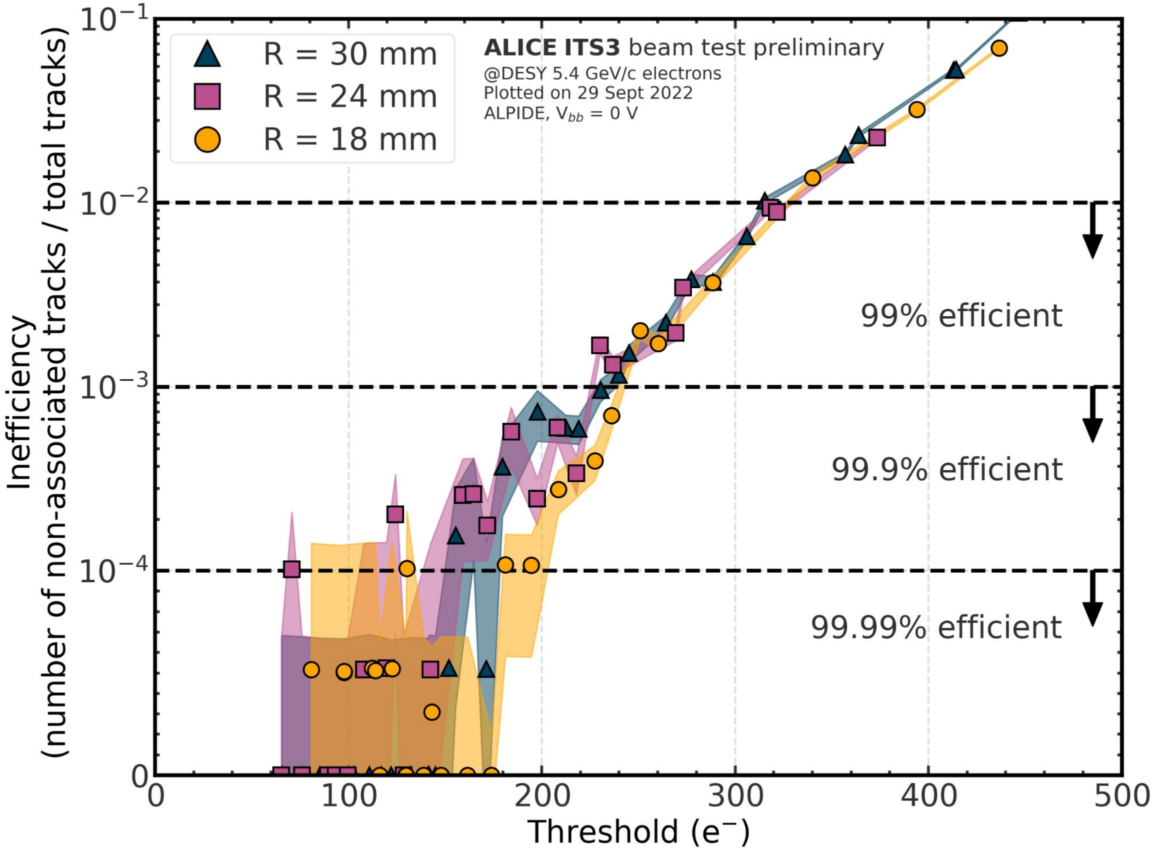
Detection efficiency:

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

Sensor bending

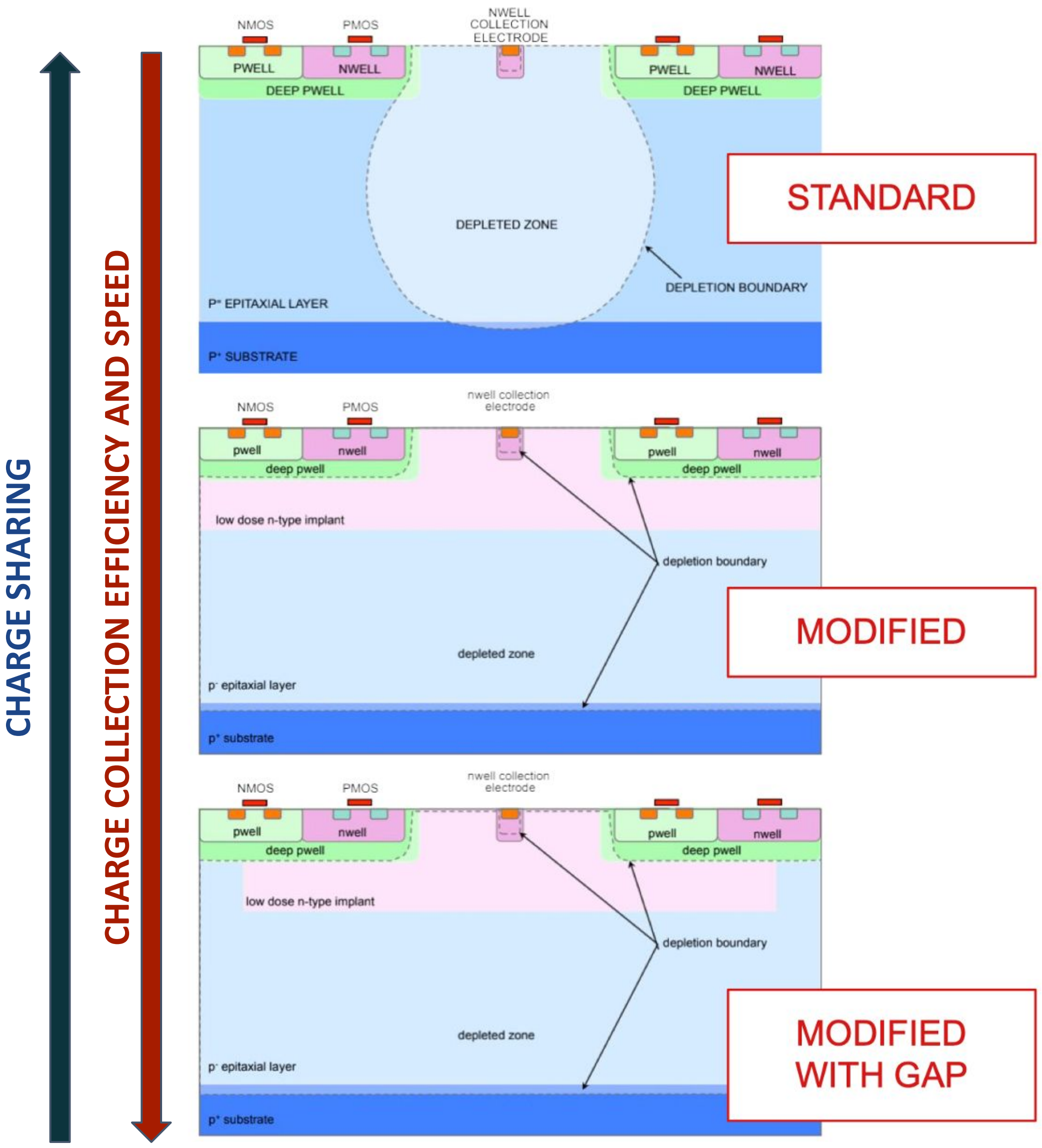
- Bending procedure has been tested in different ways and at different radii on ITS2 ALPIDEs
- No degradation → They work as **flat** chips
- The down-scale model of the final ITS3 was produced with six bent ALPIDEs → **µITS3**
- Results from beam tests show no differences in performance among different bending radii





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

New Monolythic Active Pixel Sensor designs



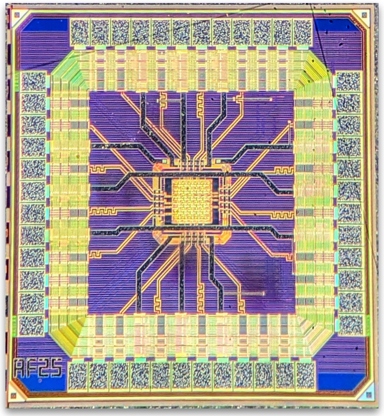
- Based on **MAPS** and **TPSCo 65 nm CMOS** technology
- 50 µm thick
- Three **different chip designs** for characterization and qualification purposes:
  1. Standard type
  2. Modified type
  3. Modified type with gap

Technology validation - MLR1

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

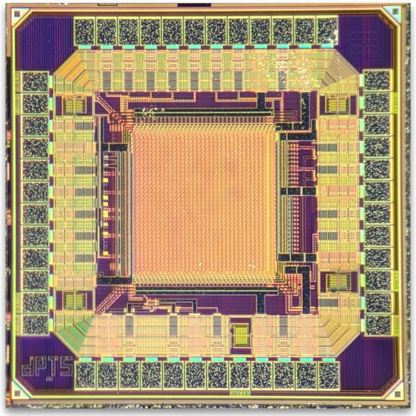
Goal → **test and qualification** (long R&D work done together with CERN EP R&D WP1, WP2)

APTS - Analog Pixel Test Structure



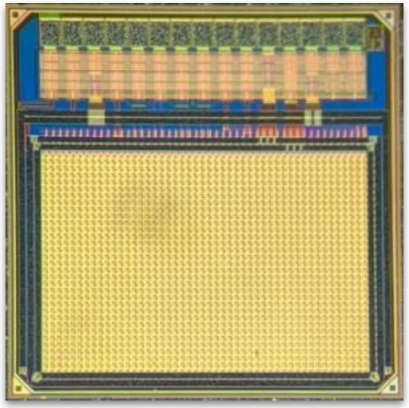
- **matrix**: 6x6 pixels
- **readout**: direct **analogue**
- readout of central 4x4
- **pitch**: 10, 15, 20, 25 µm
- **design**: standard, modified, modified-with-gap

DPTS - Digital Pixel Test Structure



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

CE65 - Circuit Exploratoire 65 nm



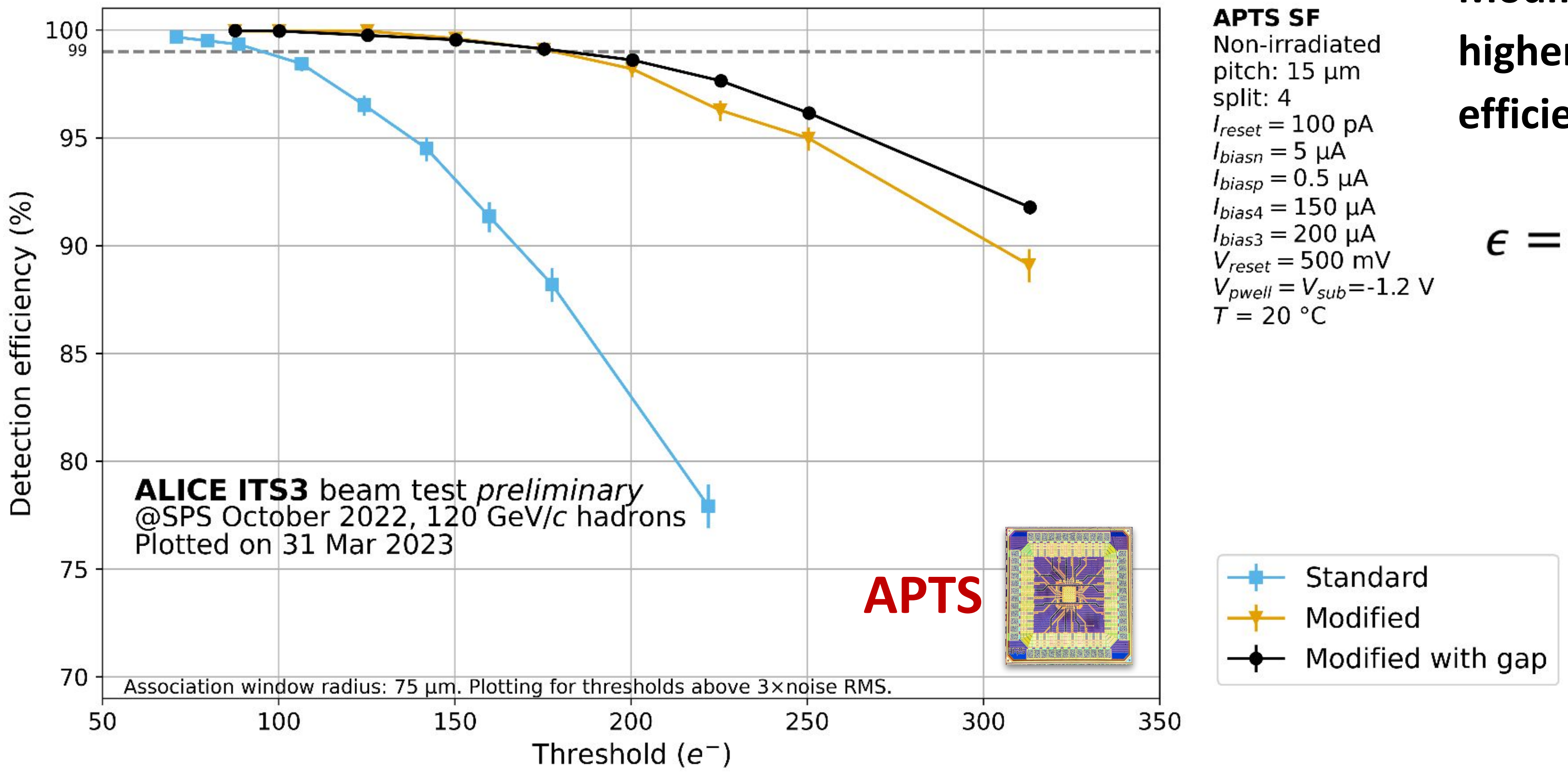
- **matrix**: 64×32 or 48×32
- **readout**: Rolling shutter readout (down to 50 µs integration time
- **pitch**: 15 µm or 25 µm
- **design**: standard, modified, modified with gap

Intensive characterization campaign:

Validation in terms of **charge collection efficiency**, **detection efficiency** and **radiation hardness**

Detection Efficiency - APTS

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

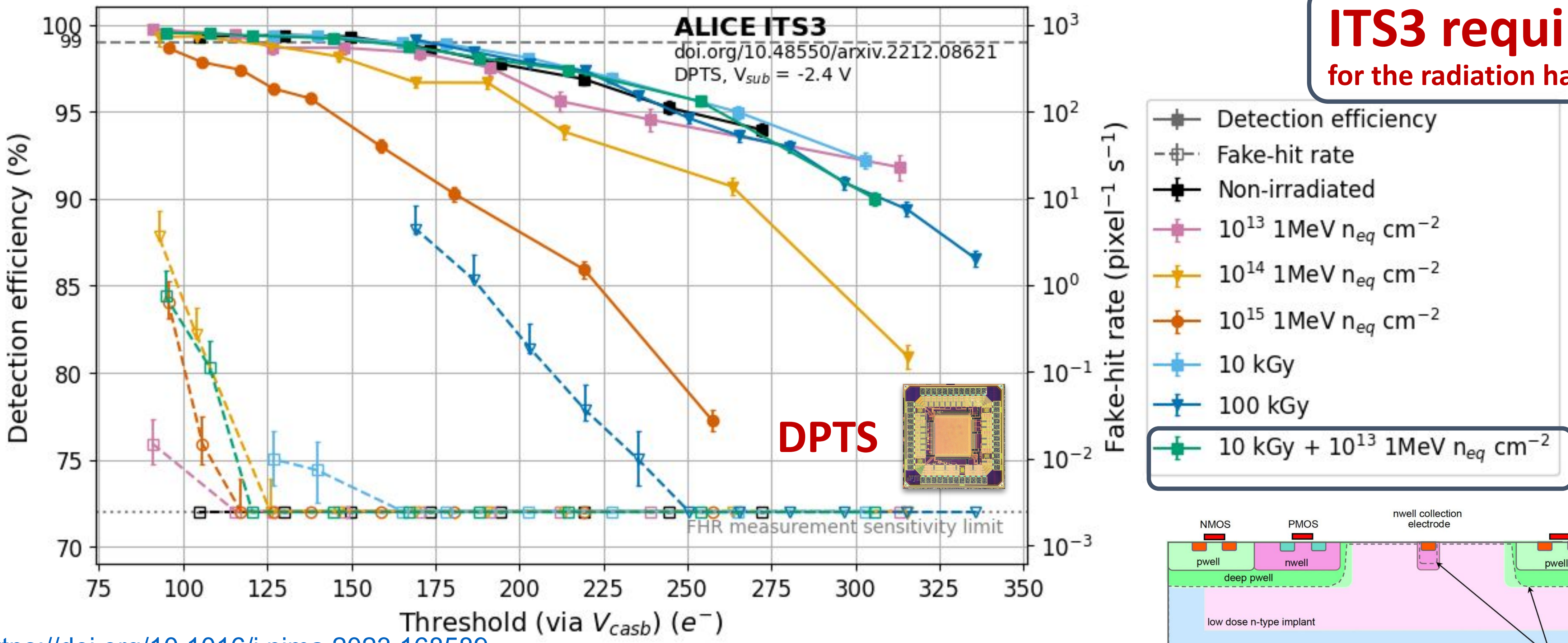
Modified with gap shows also at at higher thresholds the best efficiency values

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

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

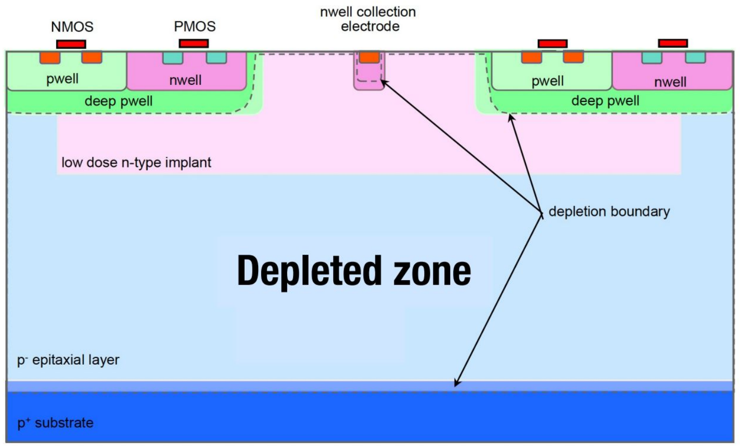
Detection Efficiency - DPTS

Modified-with-gap design



https://doi.org/10.1016/j.nima.2023.168589

ITS3 requirements
for the radiation hardness

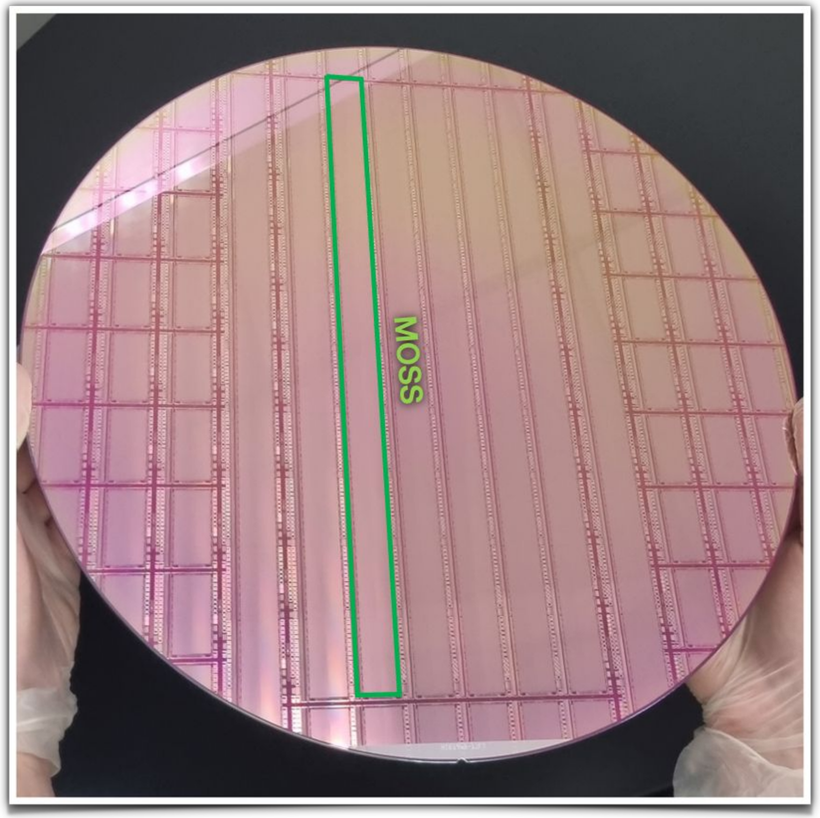


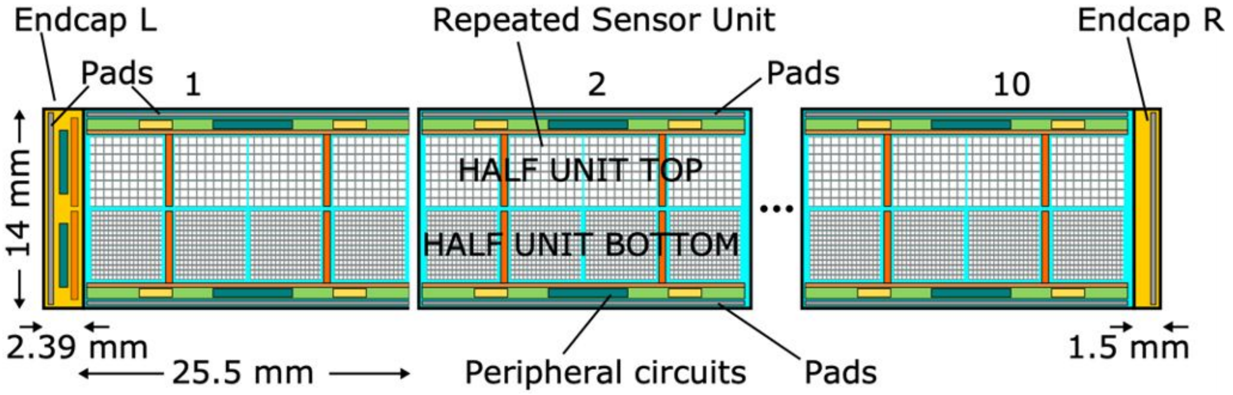
$$\epsilon = \frac{\#\, tracks_{1\, ass.cluster,\ DUT}}{total\ \#\, tracks_{DUT}}$$

Sensor stitching
MOSS

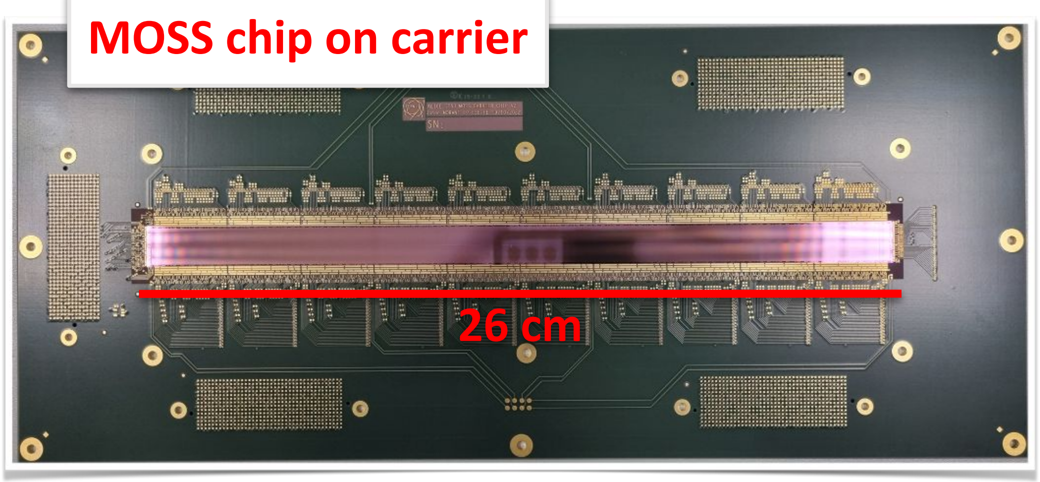
First **large-scale** stitched sensor, **MO**nolithic **S**titched **S**ensor (**MOSS**) received on June 2023:

- Repeated identical but functionally independent units, with **in-silicon** interconnections and peripheral structures of the sensor
- **Laboratory tests**: once checked the basic functionalities, full characterization to assess yield of different sensor sections





MOSS chip on carrier

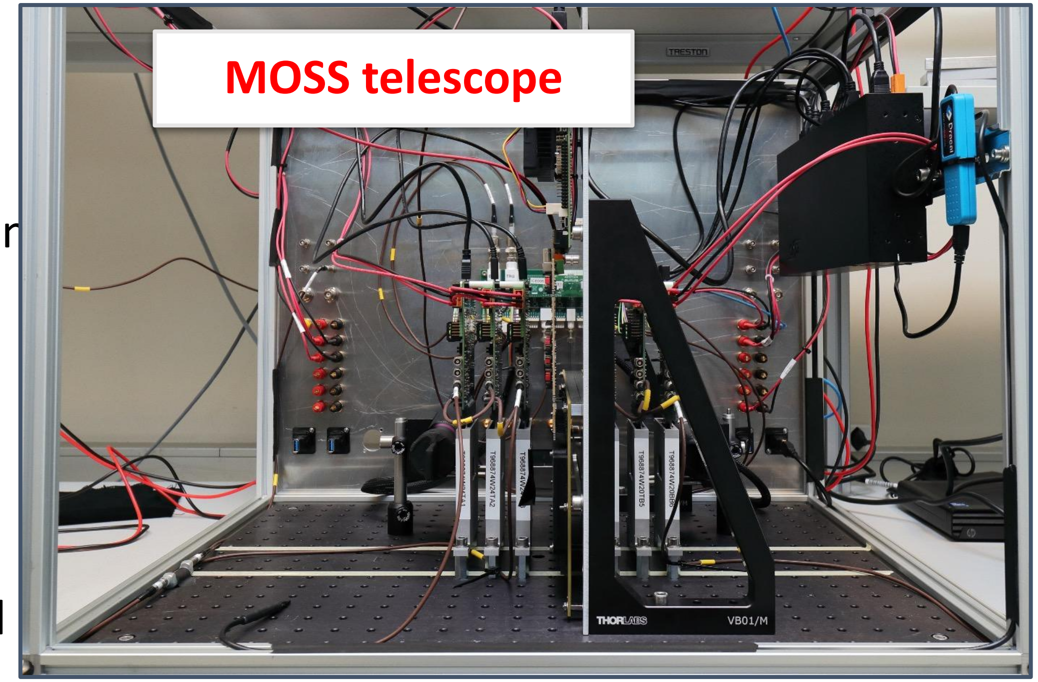


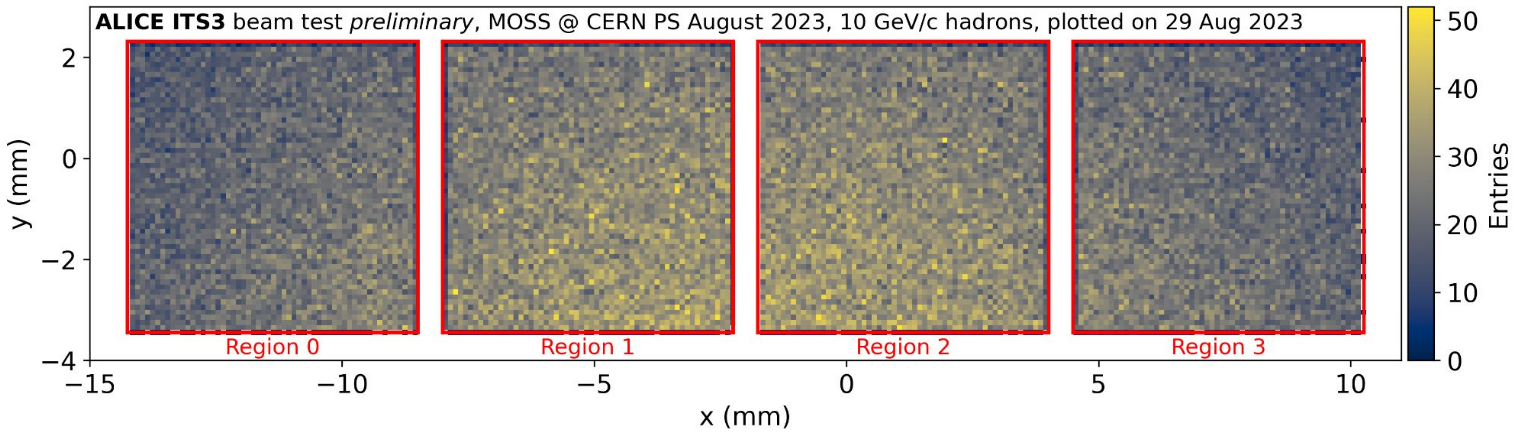
Sensor stitching

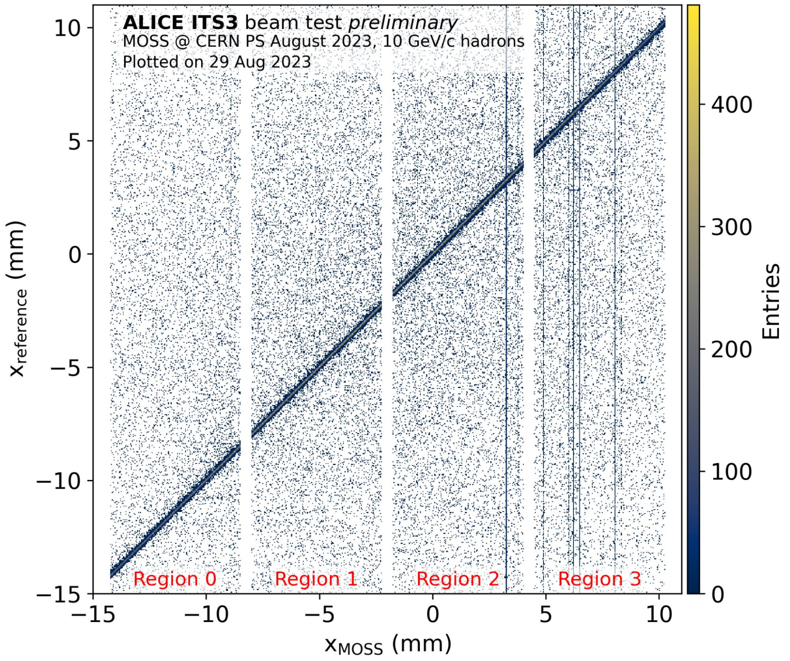
MOSS

First stitched unit **MO**nolithic **S**titched **S**ensor (**MOSS**) received on June 2023:

- Repeated identical but functionally independent units, with **in-silicon** interconnections and peripheral structures of the sensor
- **Laboratory tests**: once checked the basic functionalities, full characterization to assess yield of different sensor sections
- **First beam tests** @CERN PS and SPS: system fully functional, analysis ongoing







Summary

ITS3 will be installed during LS3 to be ready for LHC Run 4 (2029-2032).
The sensor qualification has shown that:

- **Bent sensors** show the same performance of **flat chips** for all the radii values of the foreseen final ITS3 structure
- **65 nm** technology has been validated for the use in ITS3:
  - **modified-with-gap** design is more efficient compared to the modified and standard design
  - all the tested chips show detection excellent efficiency over large threshold range term for the ITS3 radiation hardness requirements (10 kGy + 10^{13} 1 MeV n_{eq} /cm)
- **Stitching** qualification is ongoing:
  - First studies on first **large-scale stitched sensors** performance (**ER1**) shows promising result → to be extended on more chip and wafers

Next steps

- Continue and finalize studies on ER1 chips
- 2nd production of stitched sensors by 2025

INFN Gruppo Collegato di Salerno

ALICE

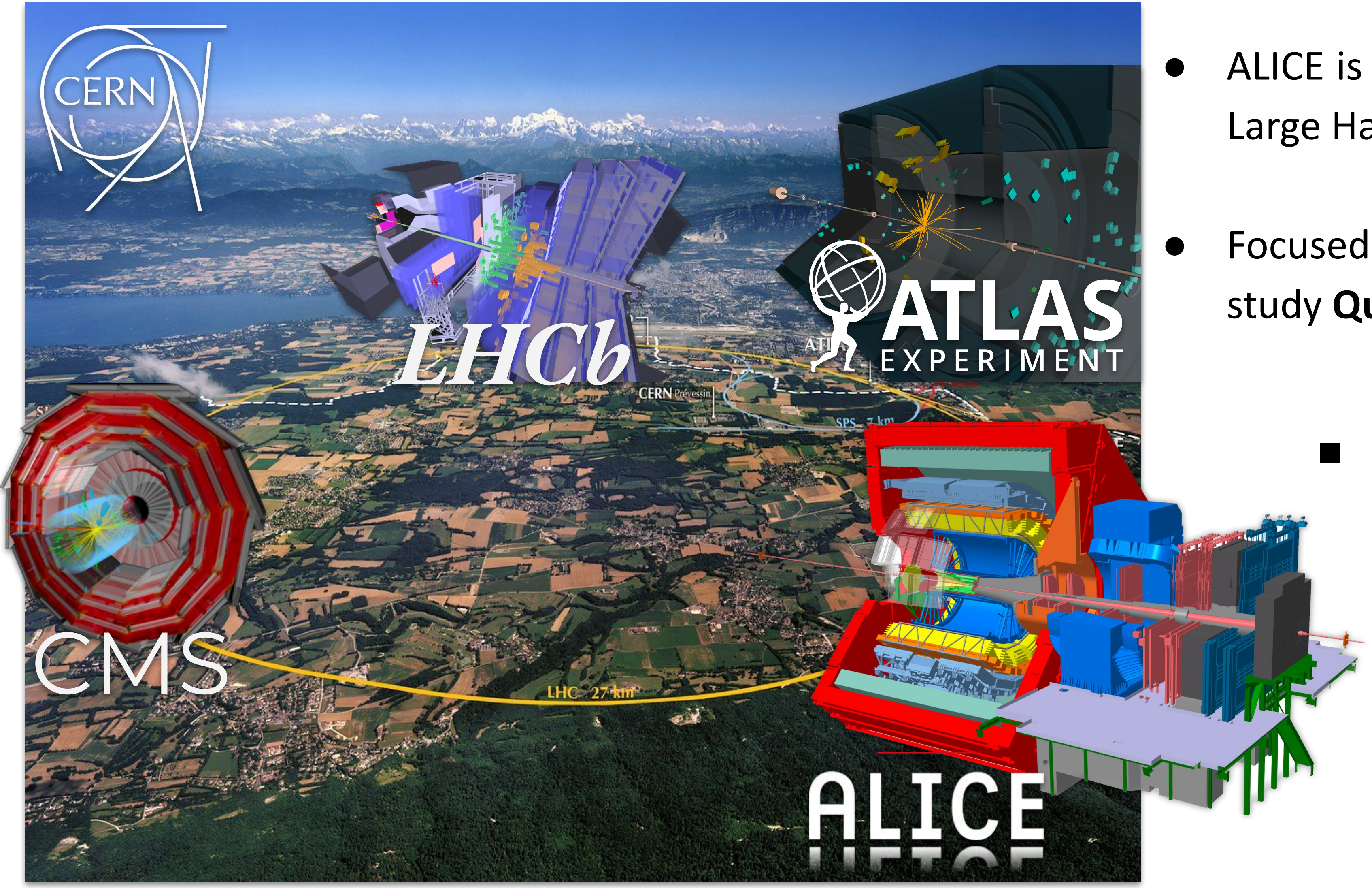
Thanks for your attention

Sala della Cooperazione
via G. Segantini 10
TRENTO
26 | 28 Febbraio

INFN BOLOGNA

Backup

ALICE - A Large Ion Collider Experiment



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

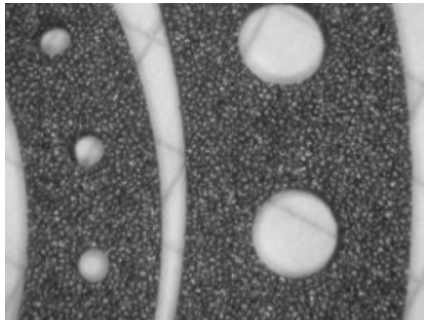
- Focused on heavy-ion interactions physics to study **Quark-Gluon Plasma** (QGP)

  - 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)

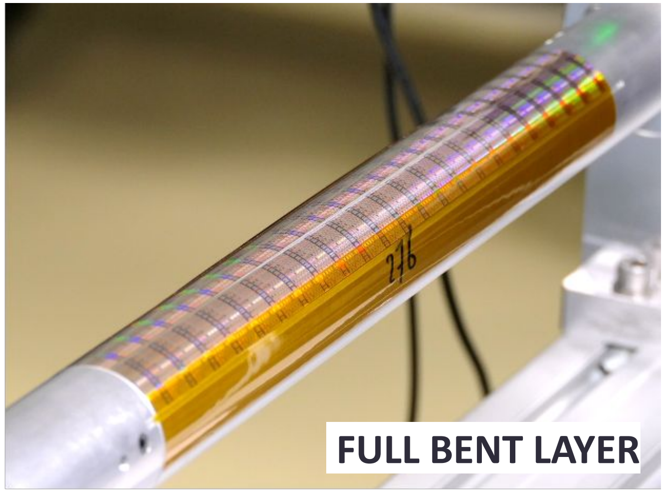
ITS3 - mechanical structure

Many tests ongoing to check mechanical stability, final bending procedure, thermal variations, air cooling… configuration…

SUPPORT



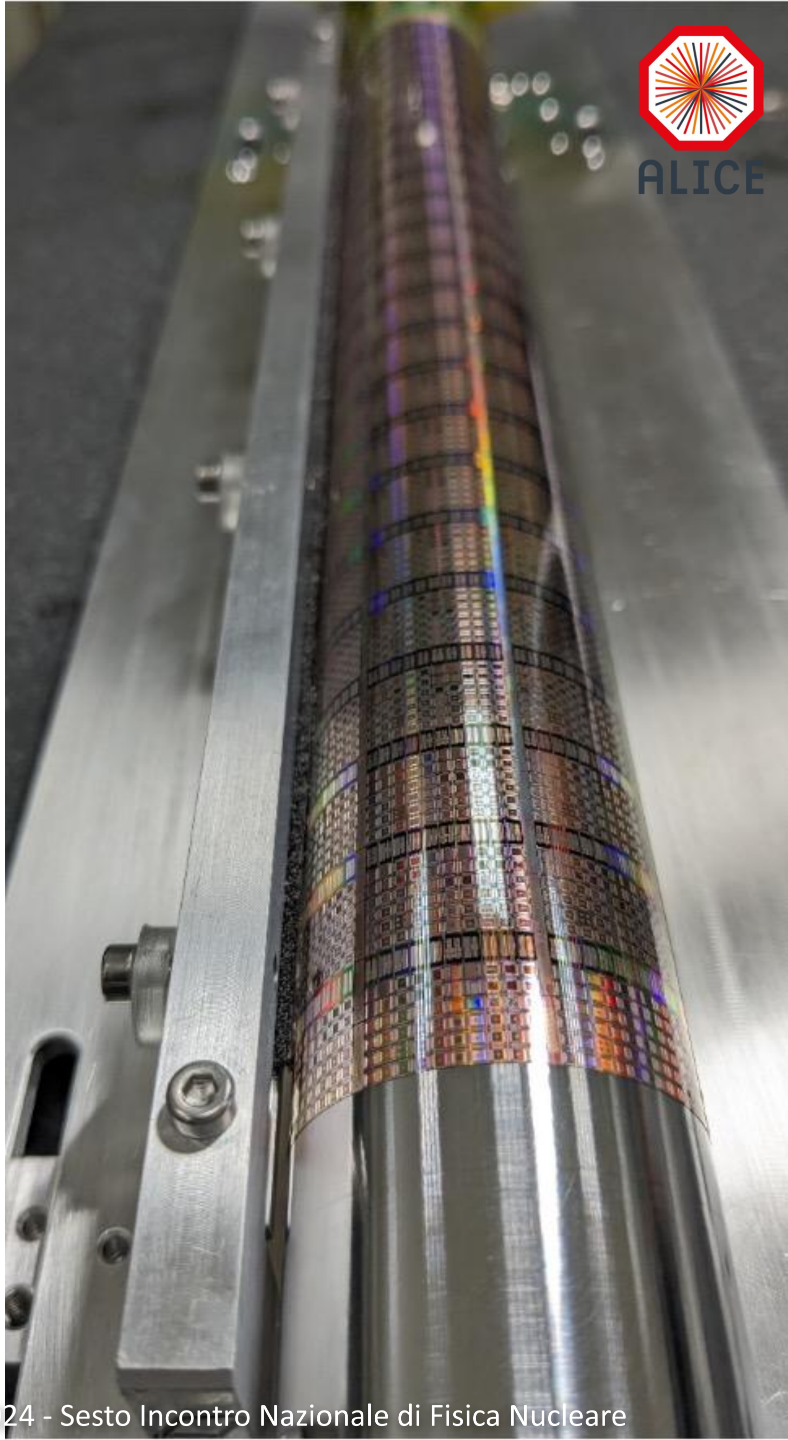
SUPPORT&COOLING



FULL BENT LAYER

Courtesy of ITS3 WP5

ENGINEERING MODEL INCLUDING THE THREE LAYERS

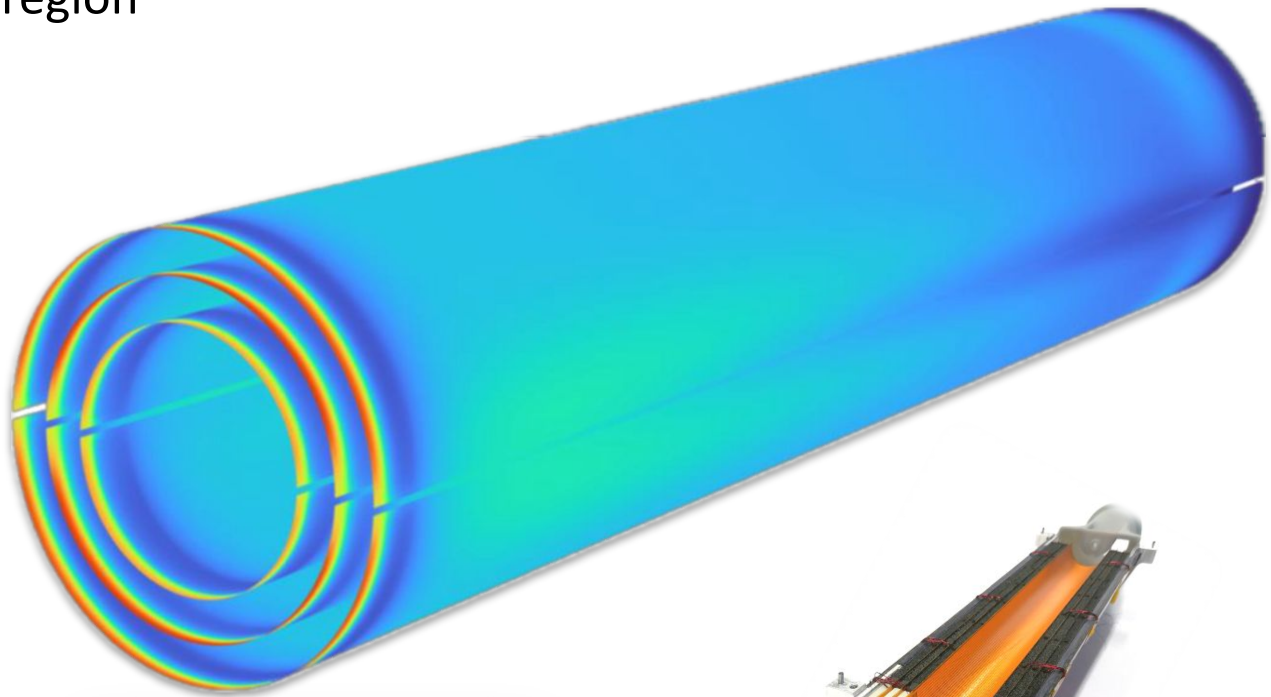


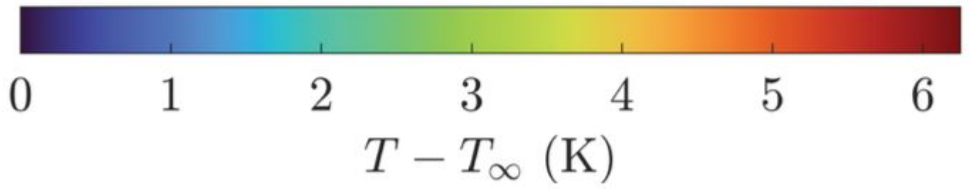
ITS3 - air cooling implementation

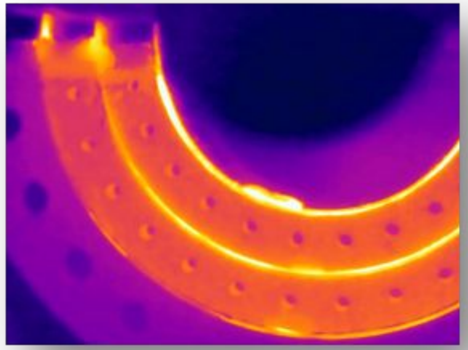
Air cooling avoids introducing structures in the active region
→ keeps the material budget low

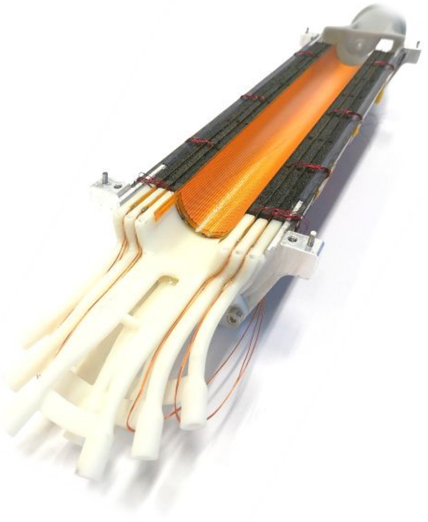
These requirements must be reached:

- Sensor **operating temperature <30°C**
- **Temperature gradient** in the matrix region **<5°C**
- Sensor **power density < 40 mW/cm2**
- Placed in a custom wind tunnel, thermal and mechanical properties are being studied





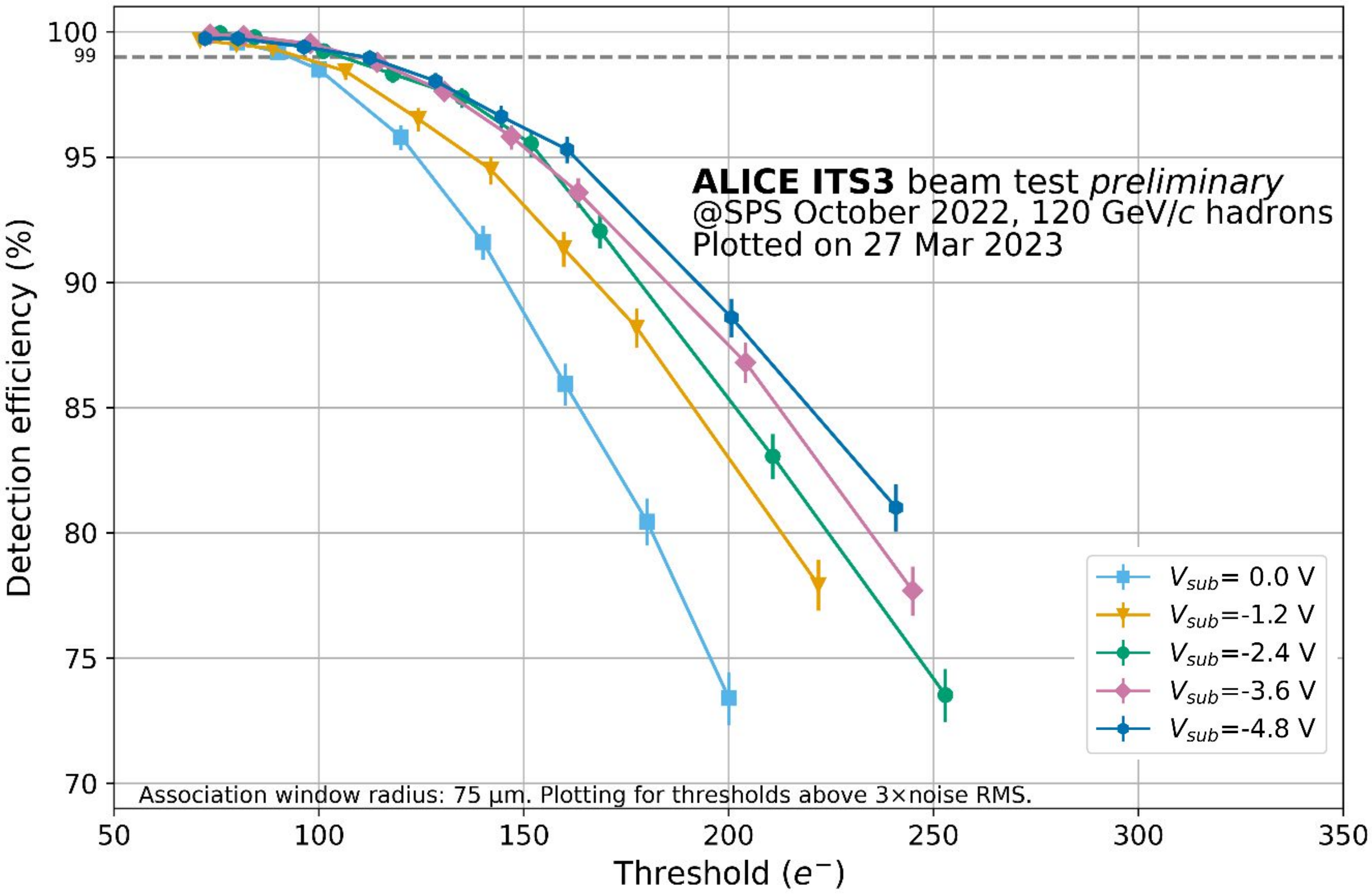




Courtesy of ITS3 WP5

Detection Efficiency - APTS

Standard design

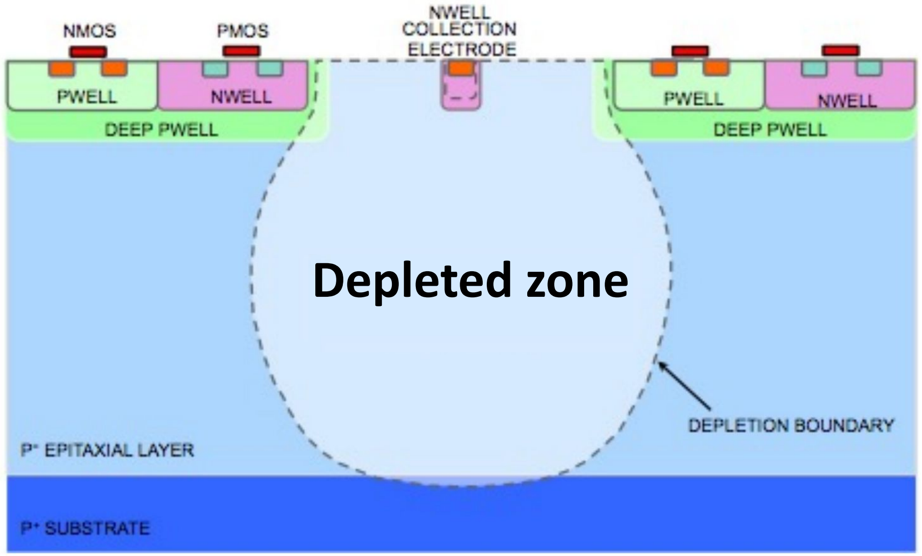


$$\epsilon = \frac{\# \, tracks_{1 \, ass.cluster, \; DUT}}{total \, \# \, tracks_{DUT}}$$

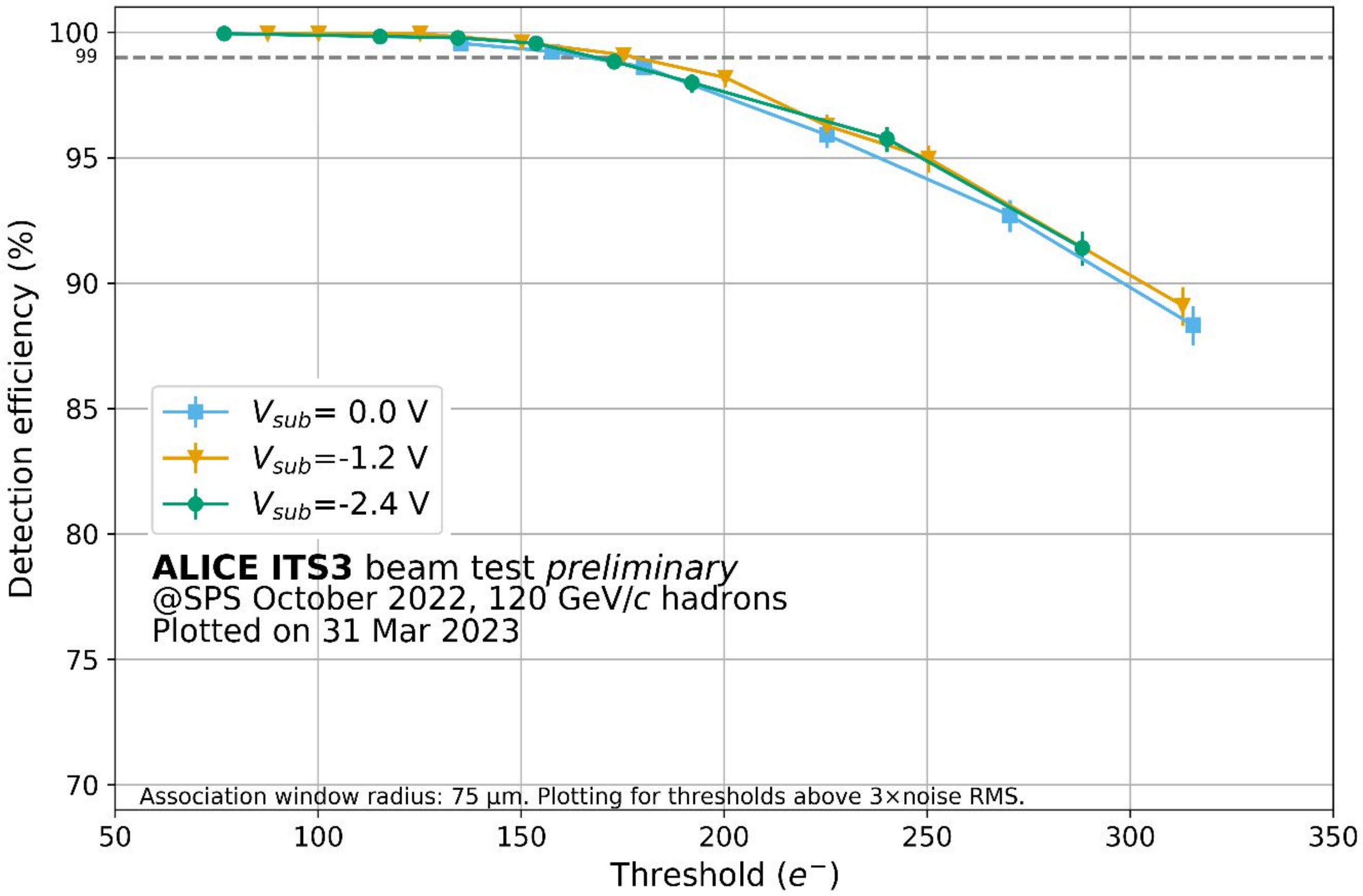
APTS SF
Non-irradiated
type: standard
pitch: 15 µm
split: 4
$I_{reset} = 100$ pA
$I_{biasn} = 5$ µA
$I_{biasp} = 0.5$ µA
$I_{bias4} = 150$ µA
$I_{bias3} = 200$ µA
$V_{reset} = 500$ mV
$V_{pwell} = V_{sub}$
T = 20 °C

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 - APTS
Modified design



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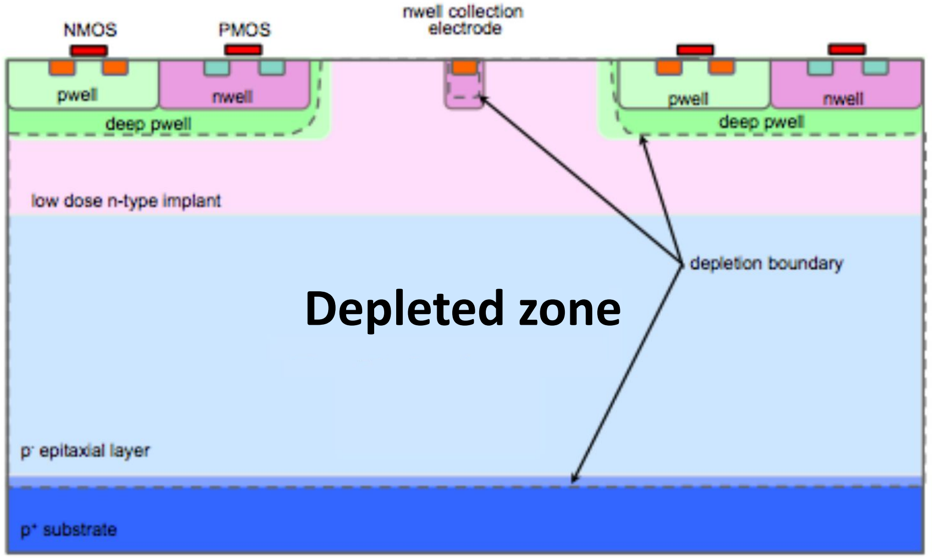
$I_{bias4} = 150$ µA
$I_{bias3} = 200$ µA
$V_{reset} = 500$ mV
$V_{pwell} = V_{sub}$
T = 20 °C

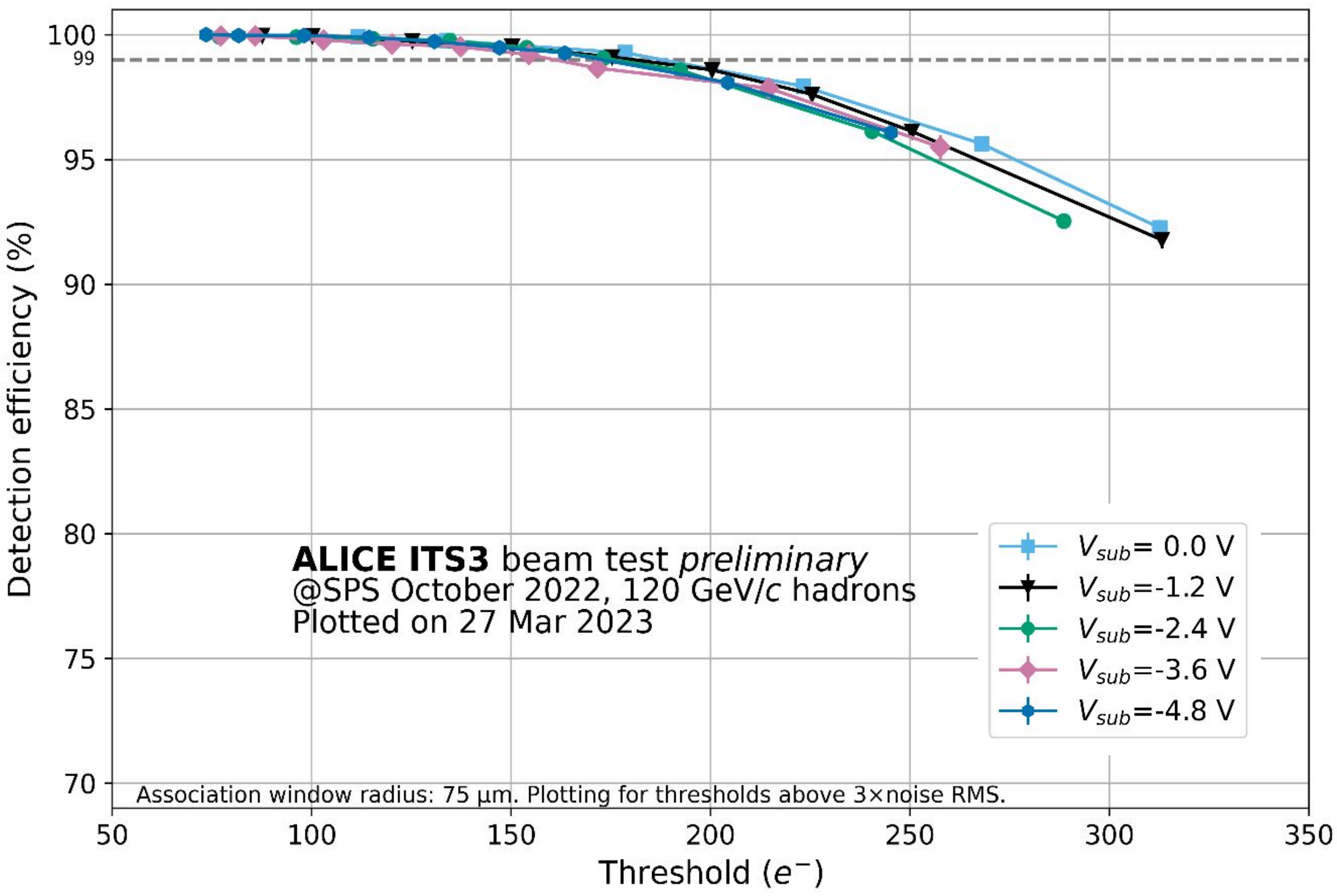
Almost same efficiency also at different reverse biases

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



Detection Efficiency - APTS

Modified-with-gap design



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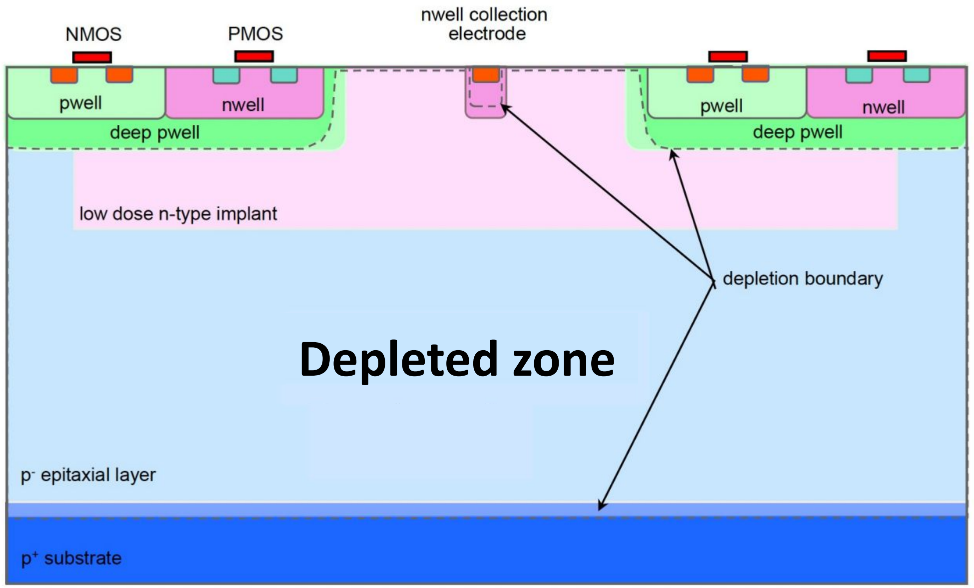
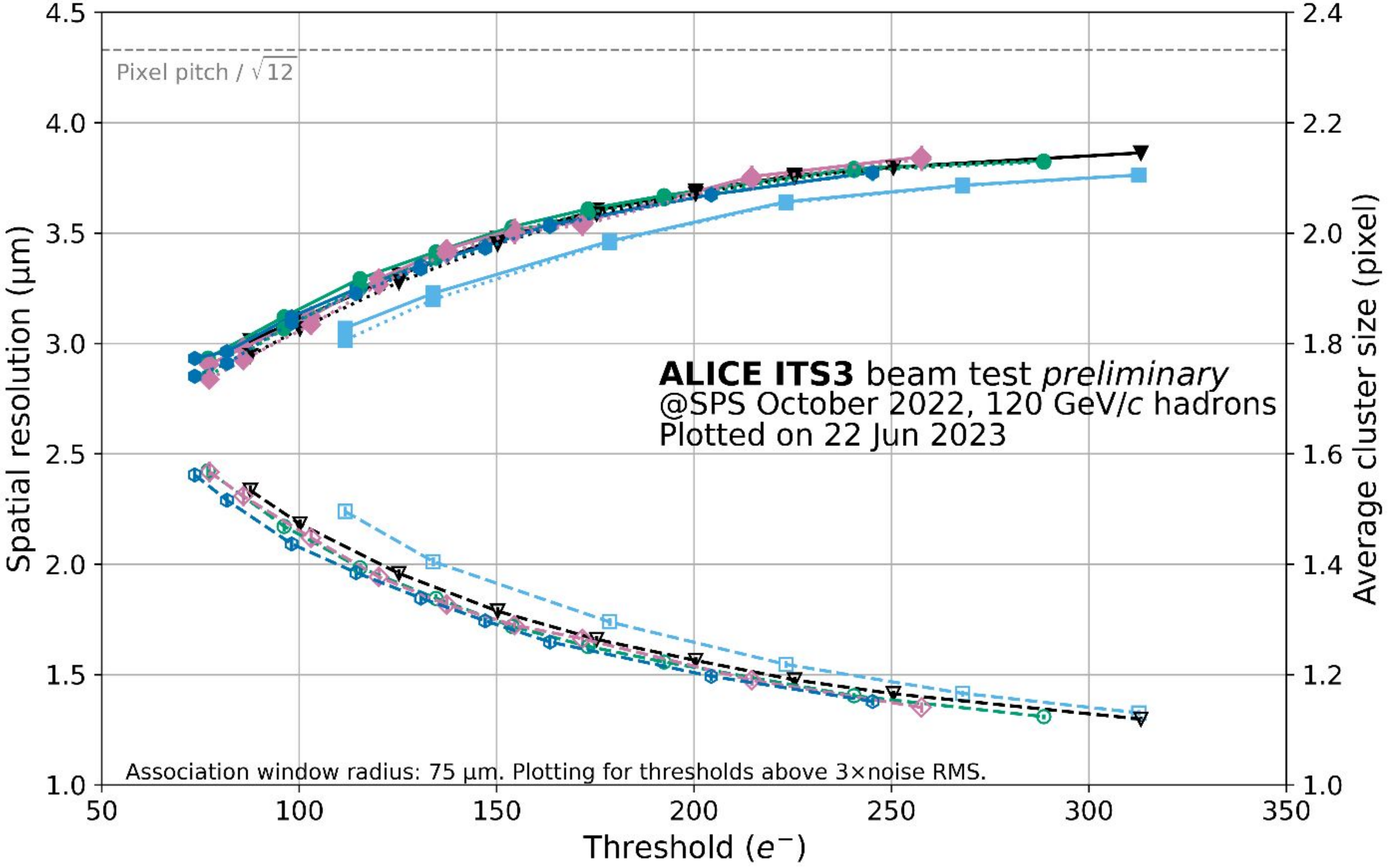
$I_{biasp} = 0.5$ µA
$I_{bias4} = 150$ µA
$I_{bias3} = 200$ µA
$V_{reset} = 500$ mV
$V_{pwell} = V_{sub}$
$T = 20$ °C

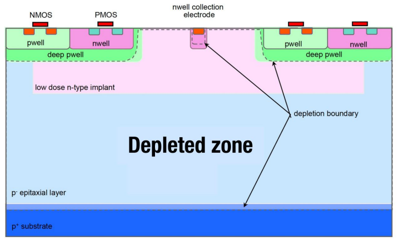
Trend similar to modified type

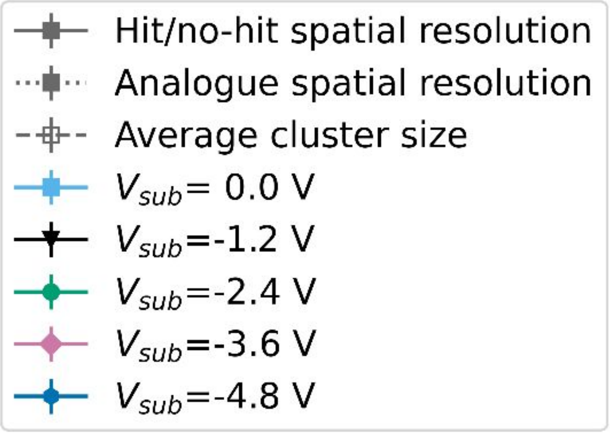


Spatial resolution - APTS
Modified-with-gap design



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



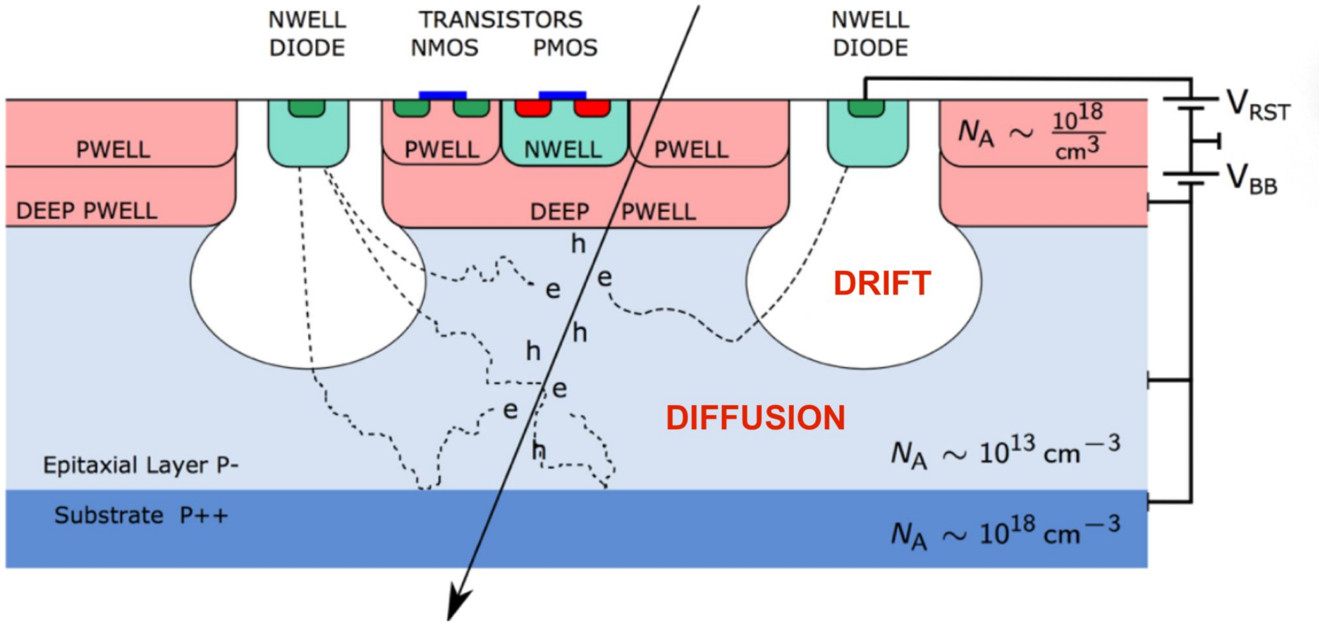


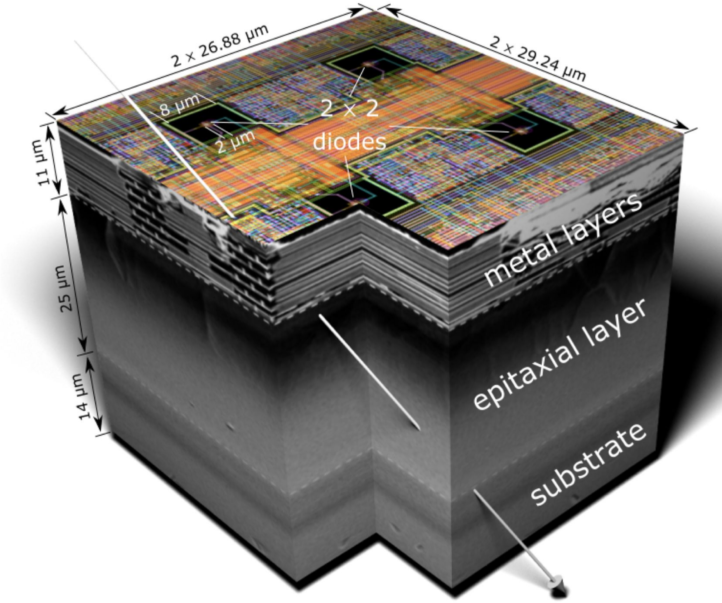
Benefits in ALICE measurements from ITS3

- Low-mass dileptons
  Beauty-strange mesons
  - exclusive reconstruction of B_s^0
  - non-prompt D_s^+ (50% from $B^{0,+}$ and 50% from B_s^0)
- Beauty baryons
  - non-prompt Λ_c^+
  - exclusive reconstruction of Λ_b^0
- Charm strange and multi-strange baryons
  - Ξ_c^0 (cds), Ξ_c^+ (cus), Ω_c^0 (css)
- Searches for light charm hypernuclei
  - bound state of a Λ_c^+ and a neutron (c-deuteron)
  - bound state of a Λ_c^+ and a deuteron (c-triton)

Monolithic Active Pixel Sensors (MAPS)

- The single Si chip includes both detection volume and readout electronics (instead of connecting two different units - hybrid pixel sensors)
- Many advantages:
  - small pixel pitch O(10-30 µm)
  - lower power consumption O(10-100 mW/cm^2) thanks to lower capacitance
  - thin: <50 µm (0.05% X_0)
  - commercial process





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).

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

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