Silicon detector upgrades in ALICE: ITS3 and ALICE 3

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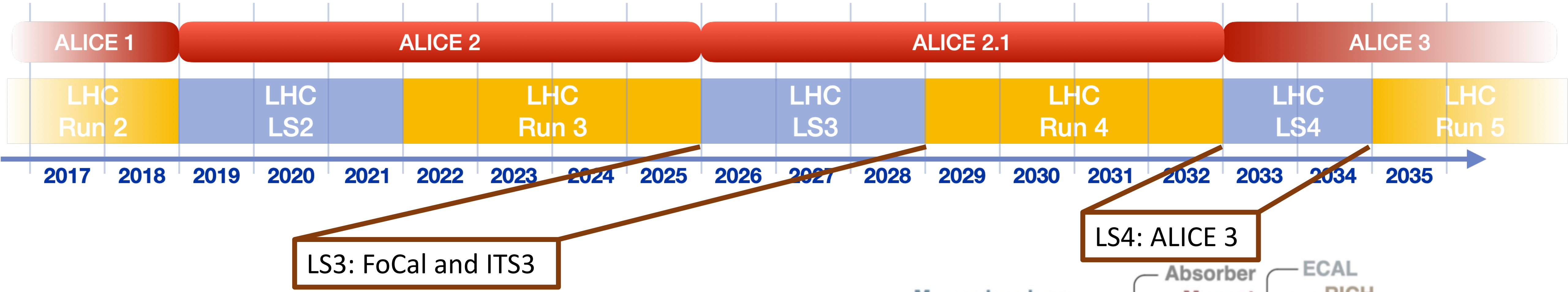
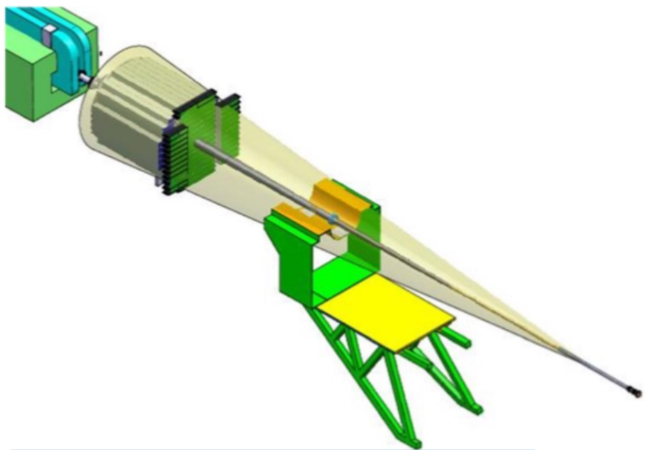
on behalf of the ALICE Collaboration

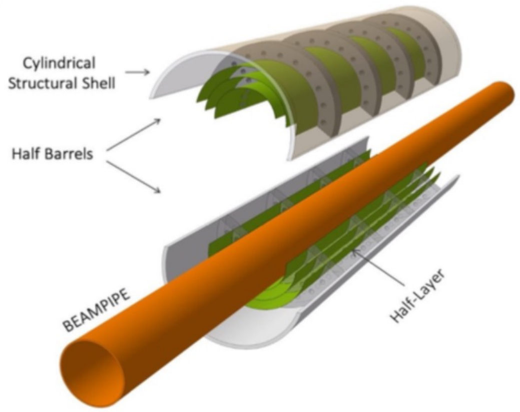
Institute of Physics Joint APP, HEPP and NP Conference 2024

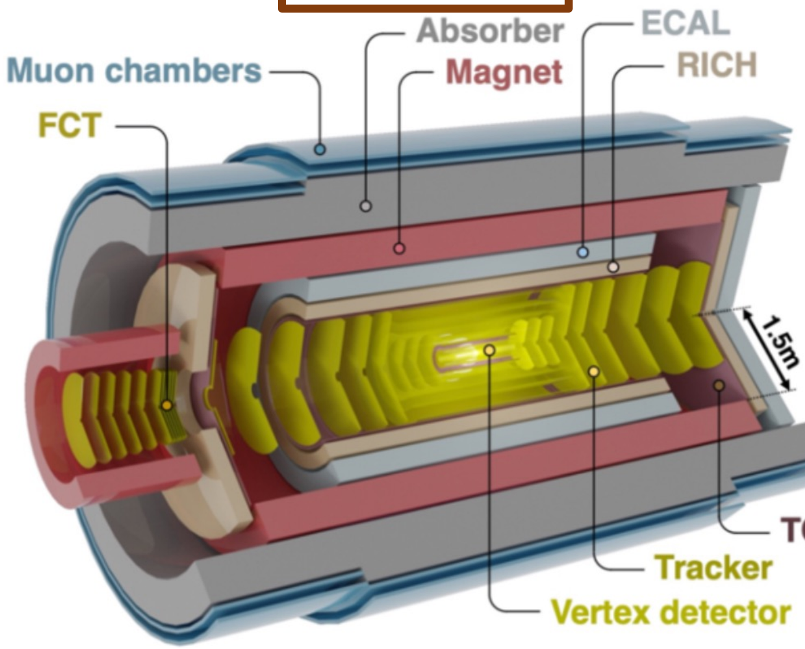
8-11 April 2024, Liverpool, UK

ALICE upgrades timeline









FoCal LoI: CERN-LHCC-2020-009
FoCal TDR: ALICE-TDR-022

Not covered in this talk

ITS3 LoI: CERN-LHCC-2019-018
ITS3 TDR: ALICE-TDR-021

ALICE 3 LoI: CERN-LHCC-2022-009

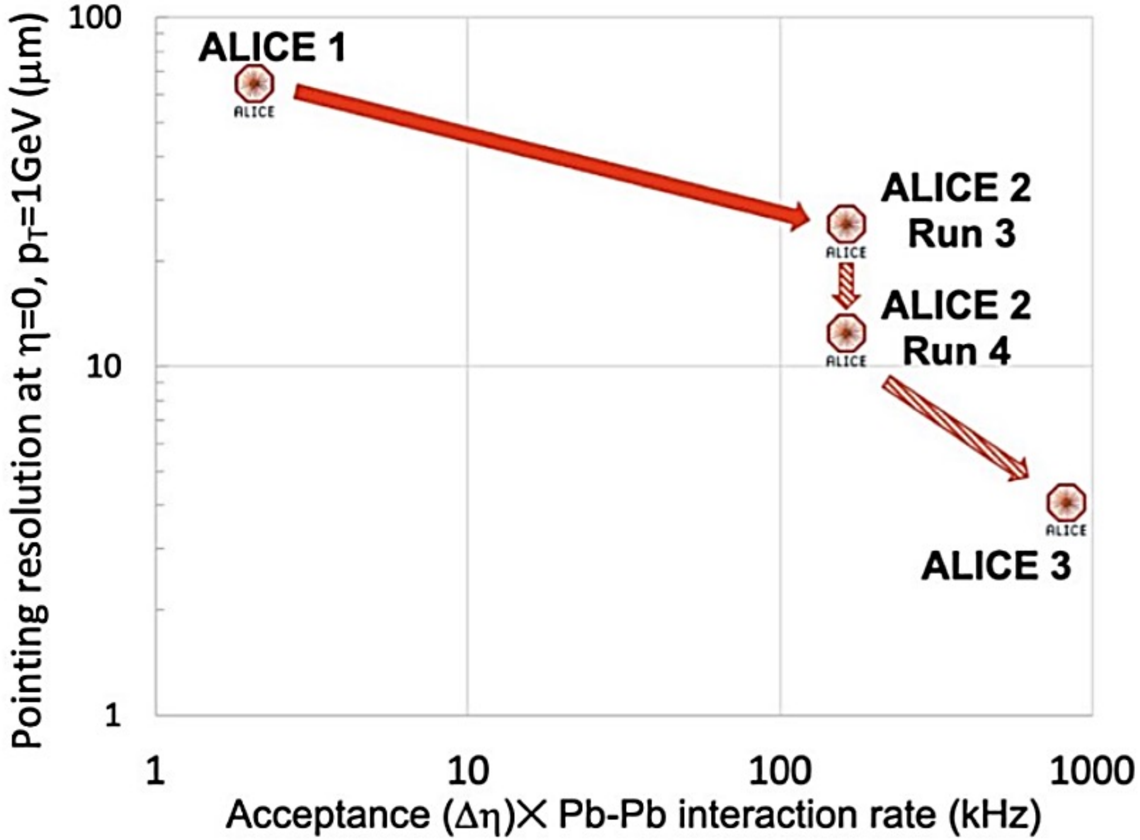
Upgrade motivations and requirements

Main physics motivations

- **Heavy flavours** hadrons at low p_T (charm and beauty interaction and hadronisation in the QGP)
- **Quarkonia** down to $p_T = 0$ (melting and regeneration in the QGP)
- **Thermal dileptons**, photons, vector mesons (thermal radiation, chiral symmetry restoration)
- Precision measurements of **light (hyper)nuclei** and searches for charmed hypernuclei

Main requirements

- Increased effective acceptance (acceptance x readout rate)
- Improved tracking and vertexing performance at low p_T for background suppression
- Preserve in ALICE 2 and enhance in ALICE 3 particle identification (PID) capabilities

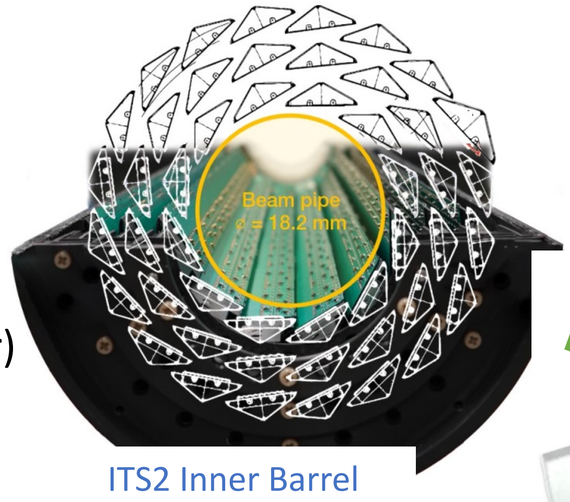


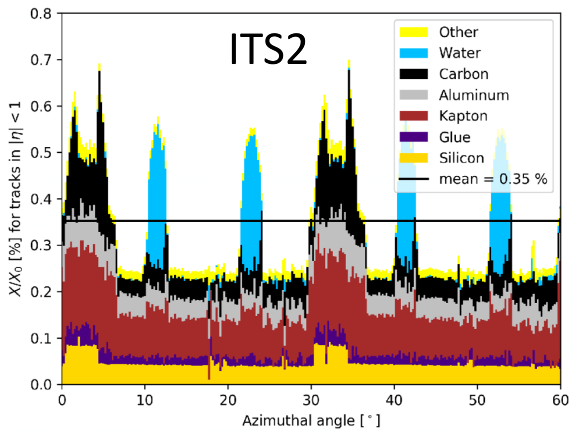
ITS3

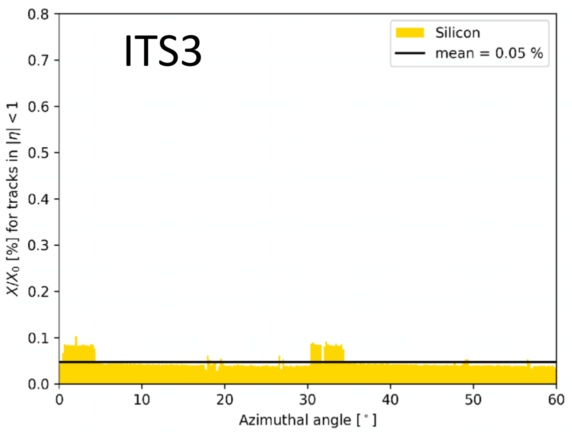
Replacing the 3 innermost layers with new ultra-light, truly cylindrical layers

- Reduced material budget (from 0.36% to 0.07% X_0 per layer) with a very homogenous material distribution by removing water cooling, circuit boards and mechanical support
- Closer to the interaction point (from 23 to 19 mm)

Improved vertexing performance and reduced backgrounds for heavy-flavour signals and for low-mass dielectrons







IB Layer Parameters	Layer 0	Layer 1	Layer 2
Sensor length [mm]		265.992	
Sensitive length [mm]		259.992	
Sensor azimuthal width [mm]	58.692	78.256	97.820
Radial position [mm]	19.0	25.2	31.5
Equatorial gap [mm]		1.0	
Max thickness [μm]		50	

Table 3.3: Design dimensions of the sensor dies and radial position.

ITS3 chip development roadmap

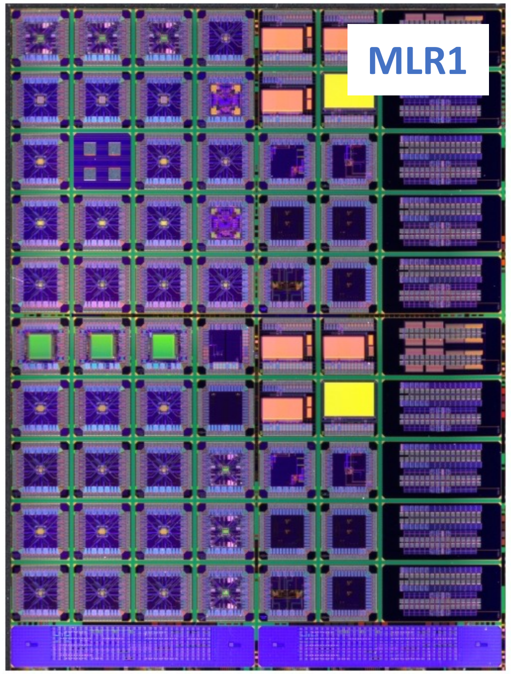
2021 MLR1 (Multi-Layer Reticle 1): first MAPS in TPSCo 65 nm
- Successfully qualified the 65 nm process for ITS3 (and much beyond)

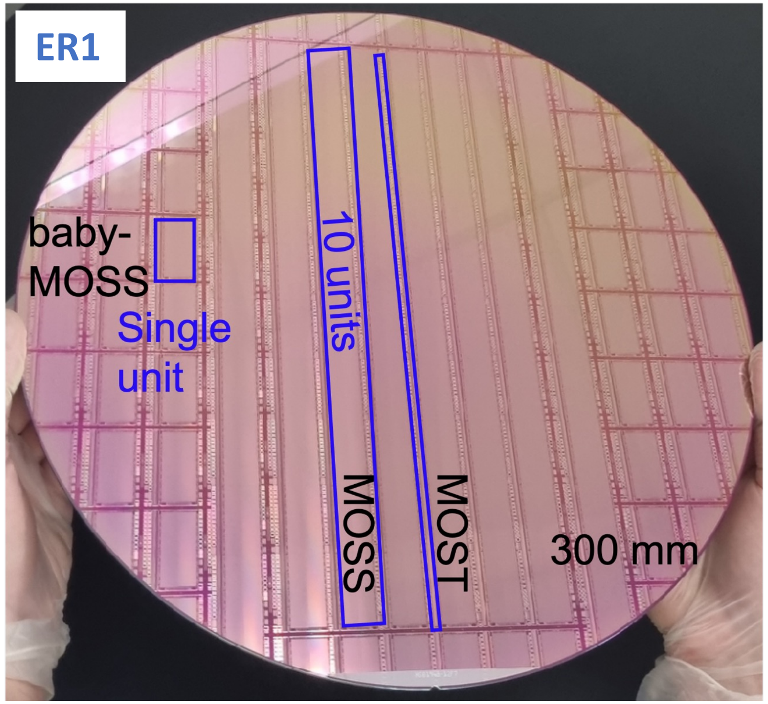
2022 ER1 (Engineering run 1): first stitched MAPS
- Large design “exercise”, stitching was new
- Tests ongoing

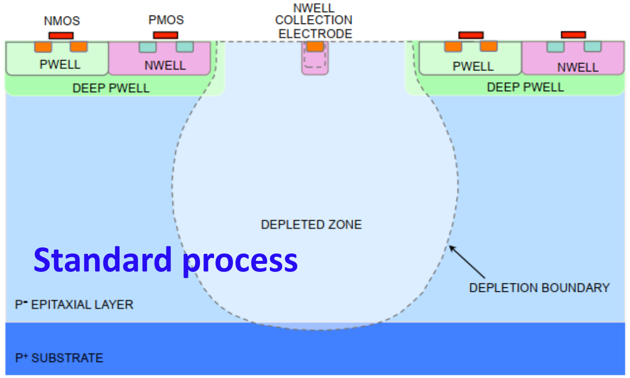
2023

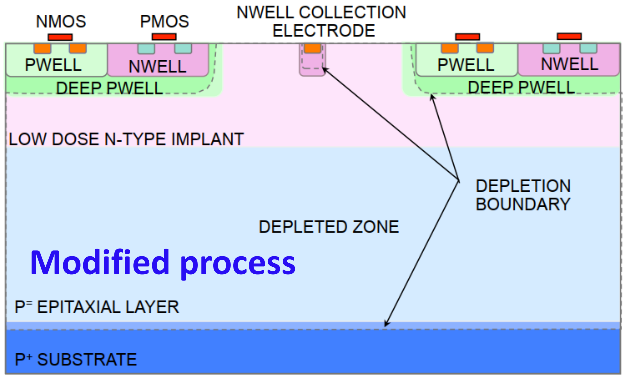
2024 ER2: first ITS3 sensor prototype
- Specifications frozen
- Design ongoing

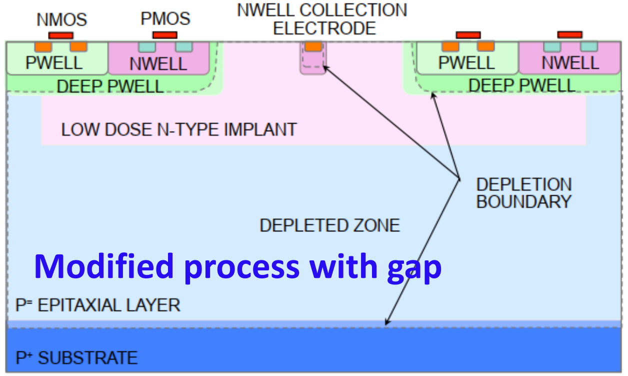
2025 ER3: ITS3 sensor production



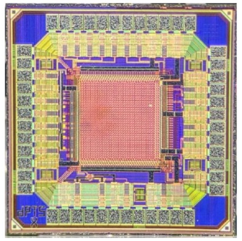




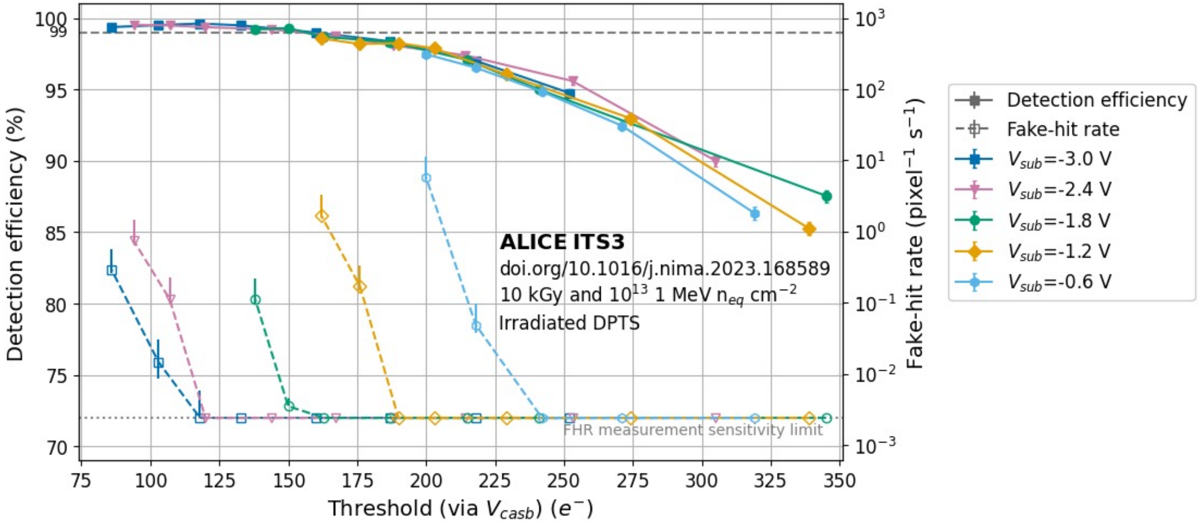


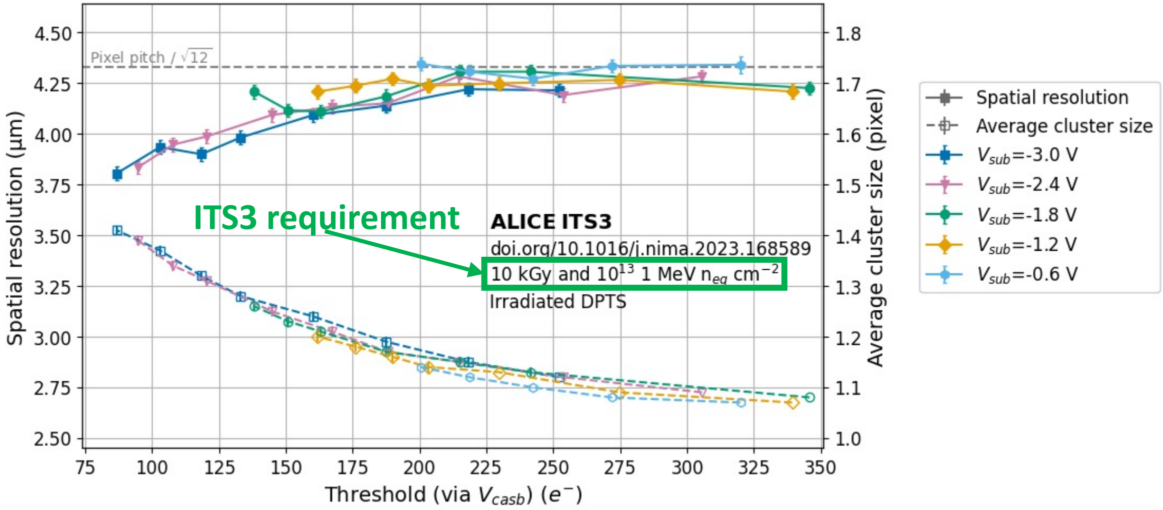


ITS3 MLR1 characterization

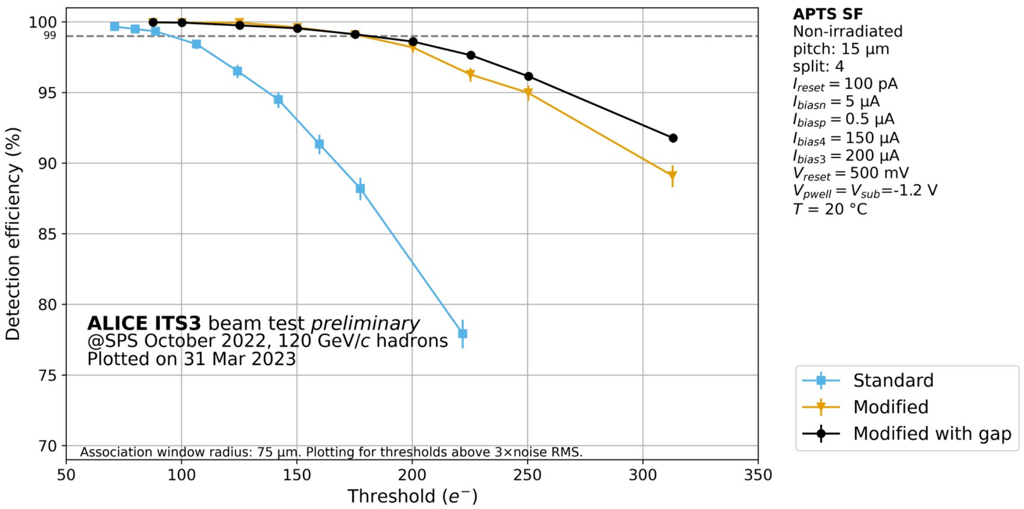


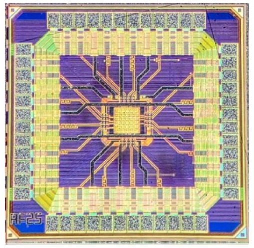
Digital Pixel Test Structure (DPTS)
- 32x32 pixel matrix
- Asynchronous digital readout with Time-over-Threshold information
- Pitch: 15 µm
- Only “modified with gap” process





DPTS: NIM A.2023.168589





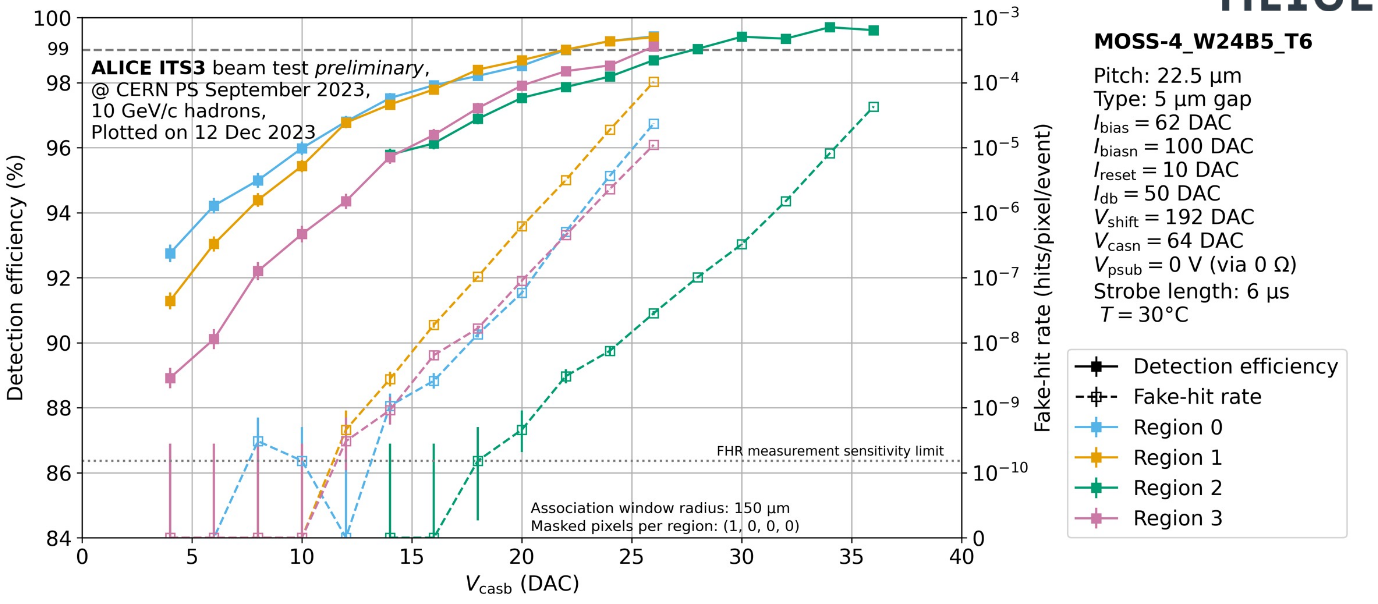
Analogue Pixel Test Structure (APTS)
- 6x6 pixel matrix
- Direct analog readout of central 4x4 pixels
- Two types of output drivers
  - Source follower (APTS-SF)
  - Fast OpAmp (APTS-OA)
- Pitch: 10, 15, 20 and 25 µm

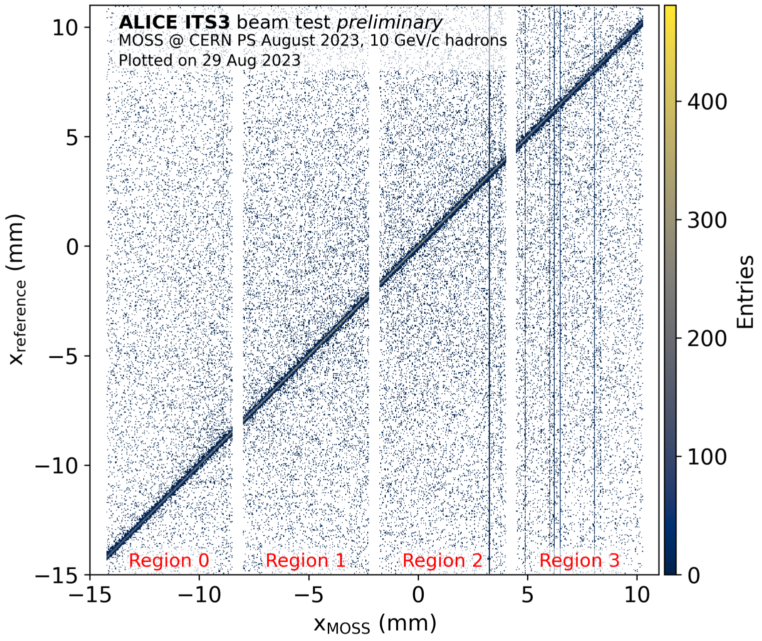
- Validated in terms of charge collection efficiency, detection efficiency and radiation hardness
- Several pixel variants (pitch 10 - 25 µm) were tested both in laboratory and in beam tests
- Excellent detection efficiency over large threshold range for the ITS3 radiation hardness requirement (10 kGy + 10^{13} 1MeV n_{eq} /cm^2)

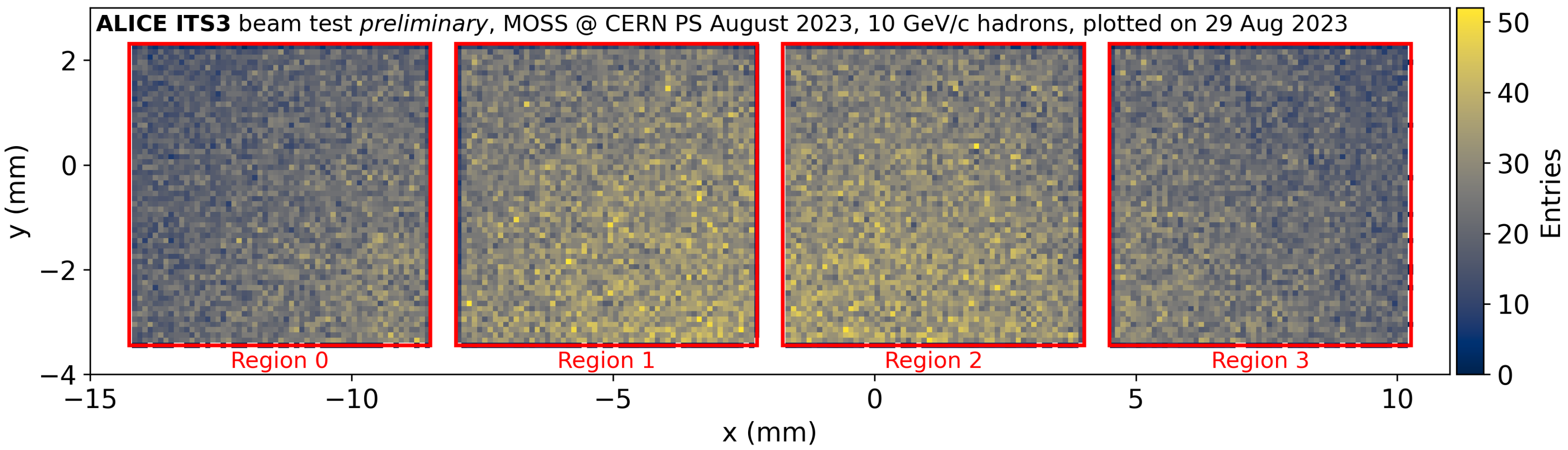
APTS: arXiv:2403.08952

ITS3 MOSS test beams

- Wafer probing and systematic lab tests: verified all basic functionalities, ongoing full characterization to assess yield of different sensor sections
- Three campaigns: July, August and September at PS in 2023
- Data analysis in progress and parameters to be further optimised

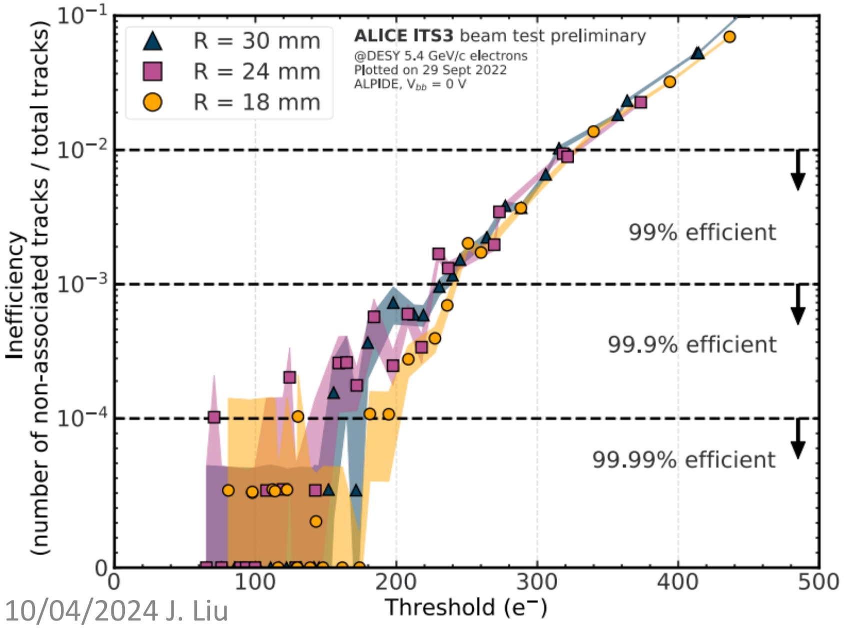


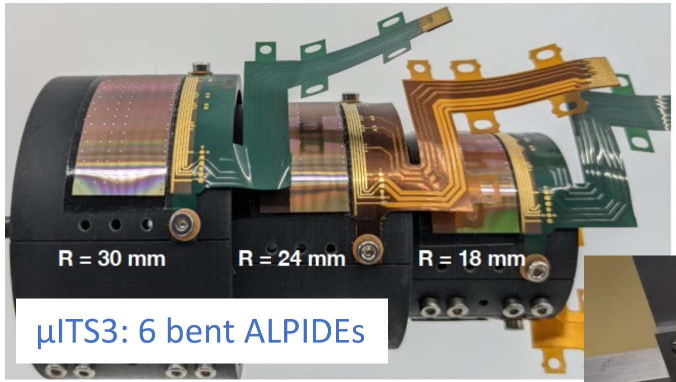




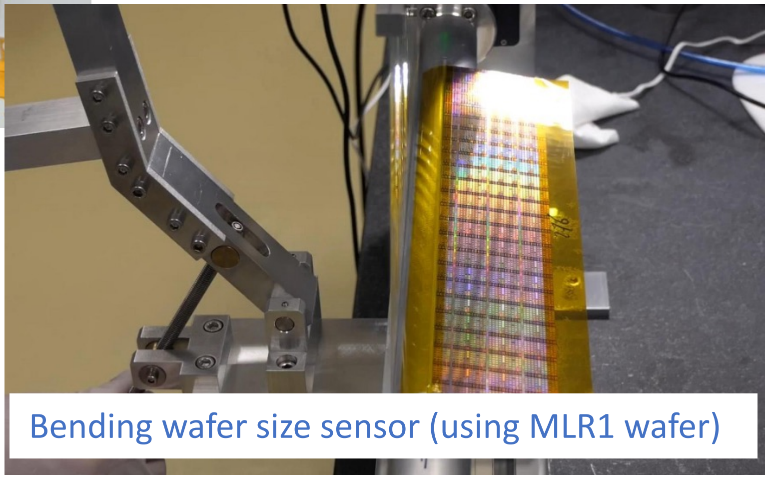
ITS3 sensor bending

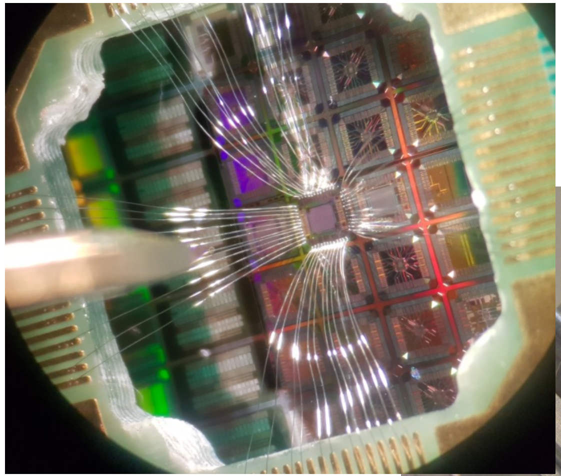
- Functional chips (ALPIDEs) and MLR1 sensors are bent routinely at different labs)
- Full mock-up of the final ITS3, called "µITS3"
  - 6 ALPIDE chips, bent to the target radii of ITS3 tested
- The sensors continue to work after bending
  - Spatial resolution of 5 µm consistent with flat ALPIDEs
  - Efficiency > 99.99 % for nominal operating conditions and compatible with flat ALPIDEs
- Bent MLR1 prototypes are being tested

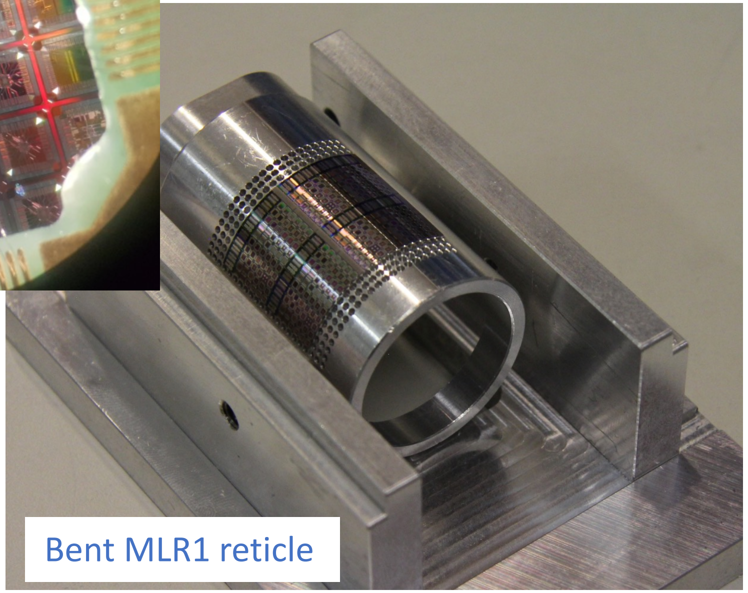




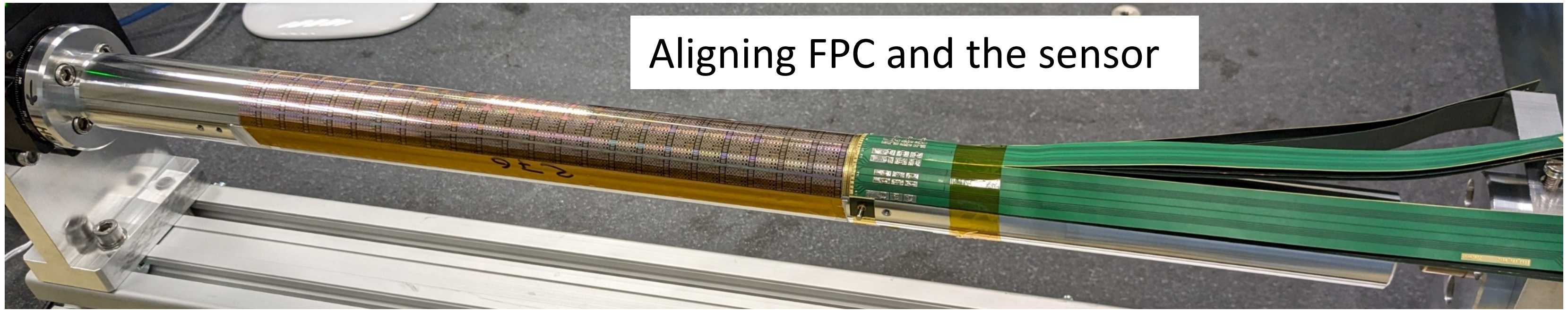
µITS3: 6 bent ALPIDEs

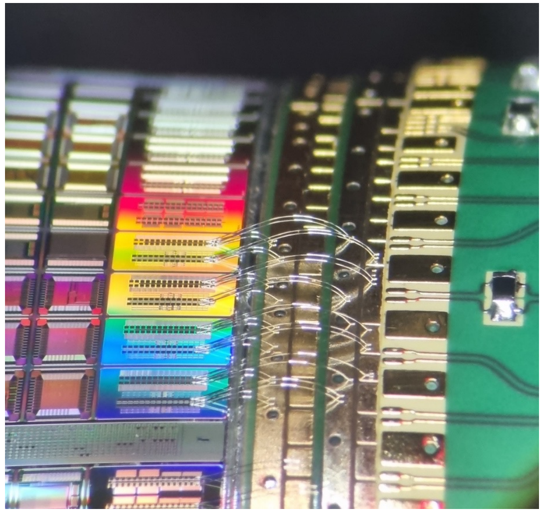

Bending wafer size sensor (using MLR1 wafer)



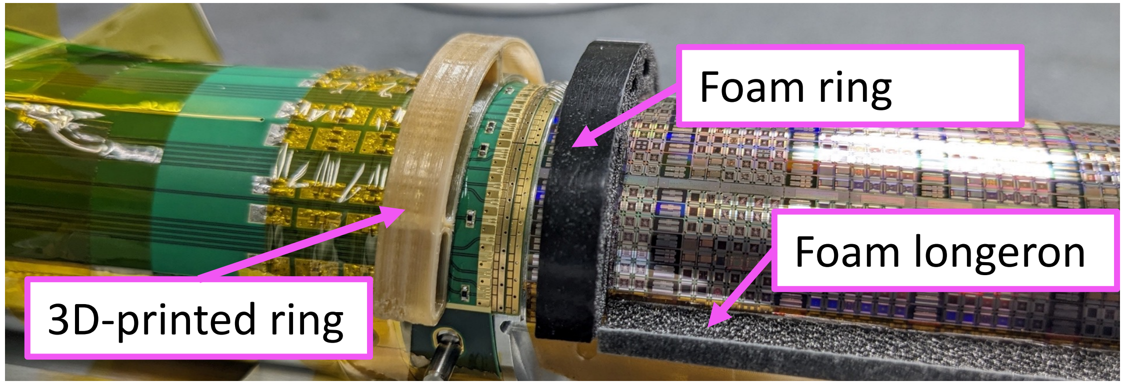

Bent MLR1 reticle

ITS3 assembly practicing

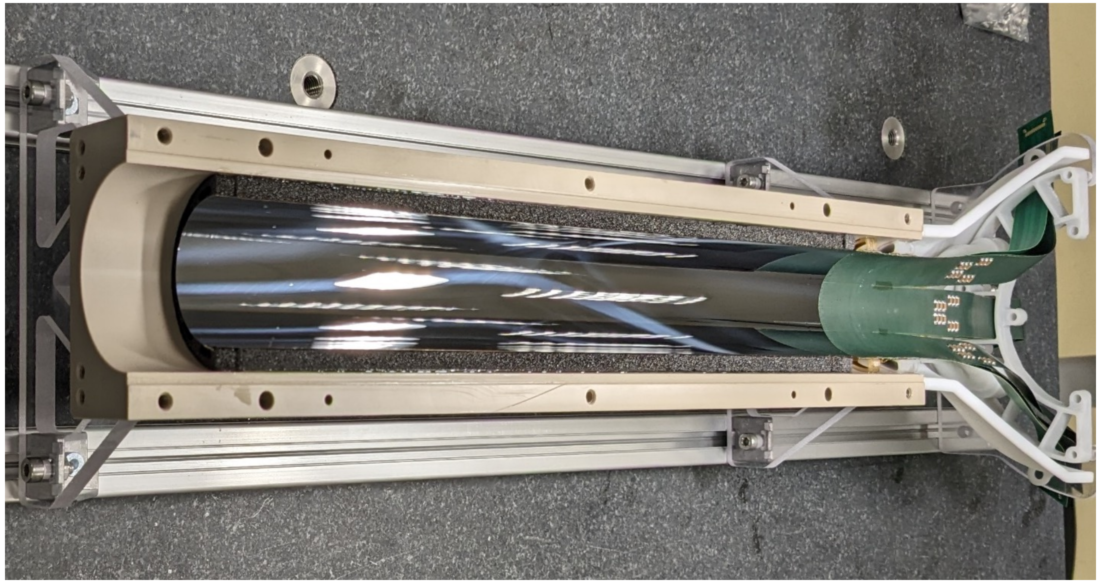




Wire-bonding for the curved sensor



Gluing of foams and additional supports

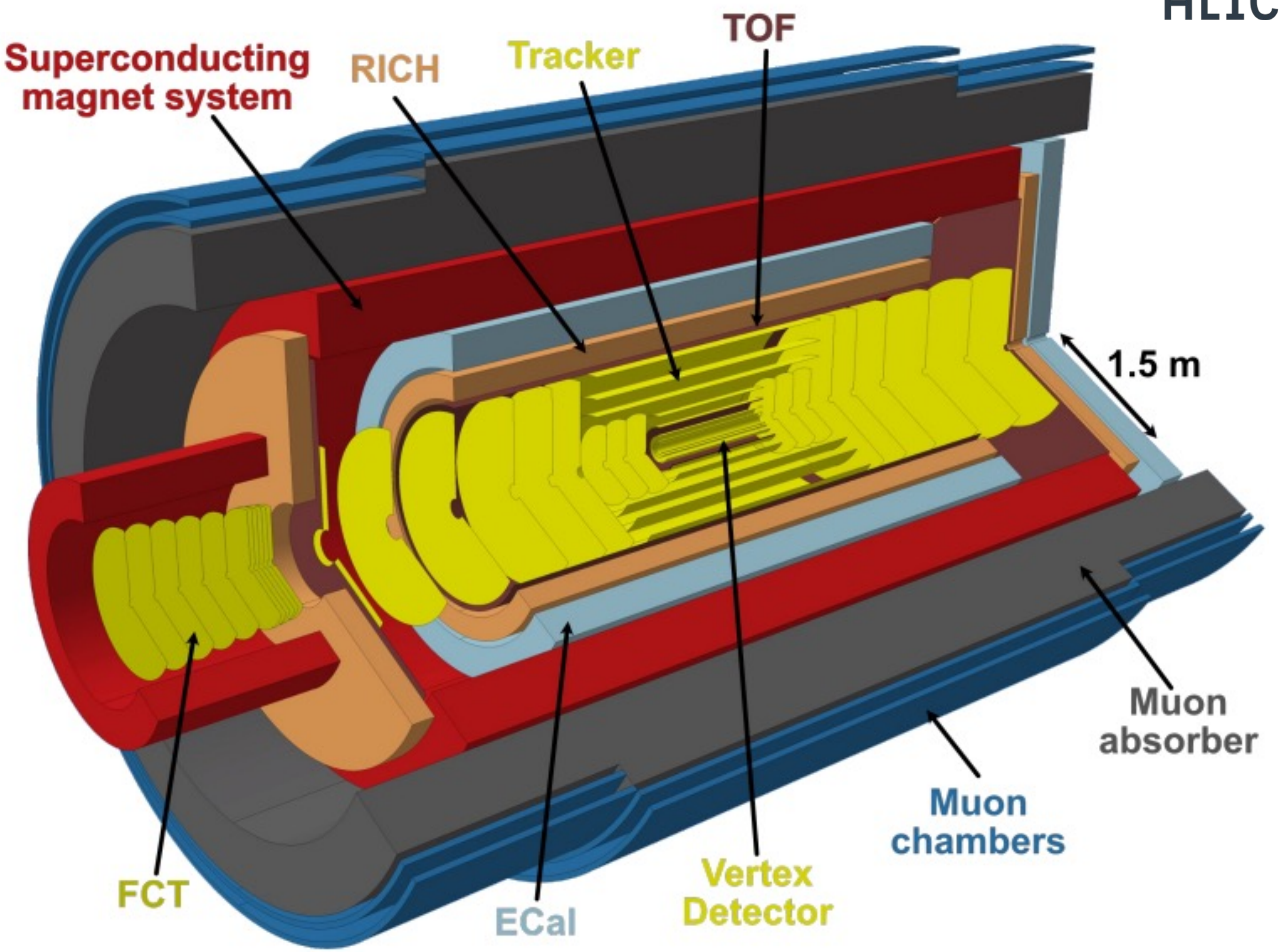


Assembled first layer of ITS3

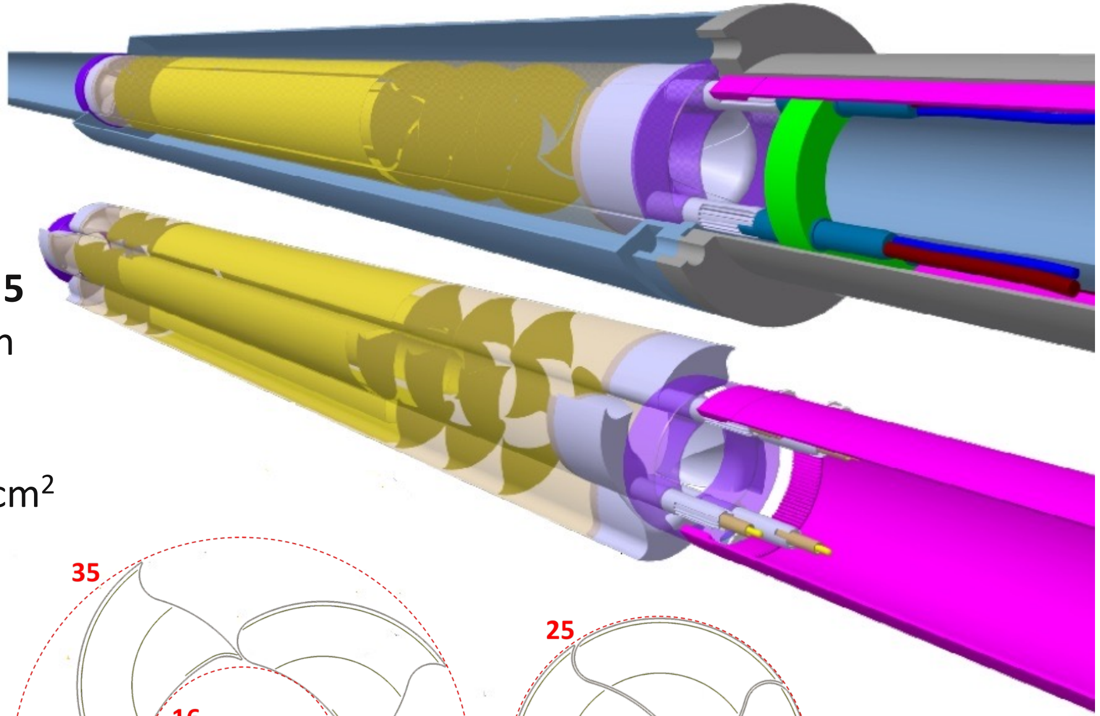
ALICE 3

ALICE 3 LoI: CERN-LHCC-2022-009

- **Compact and lightweight all-silicon tracker**
  - p_T resolution better than 1% @1 GeV/c and ~1-2% over large acceptance
- **Retractable vertex detector** with excellent pointing resolution
  - About 3-4 μm @ 1 GeV/c
- **Large acceptance**: $-4 < \eta < 4$, $p_T > 0.02$ GeV/c
- e/π/K/p particle identification over large acceptance
- Superconducting magnet system
- **Continuous readout** and online processing
  - Large data sample to access rare signals
- Muon Identification system
- Large-area ECal for photons and jets
- Forward Conversion Tracker for ultrasoft photons

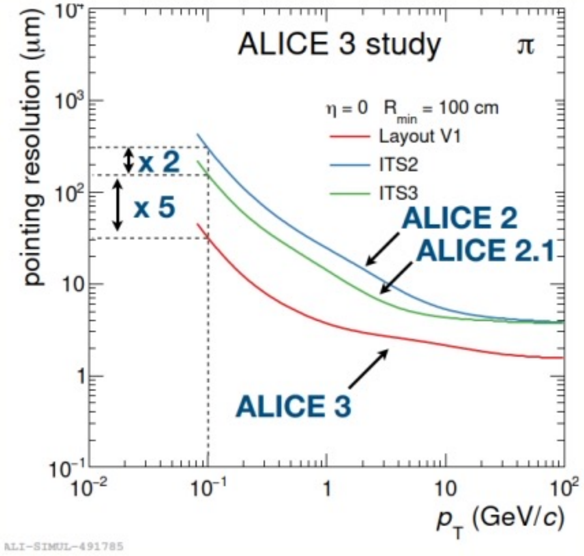


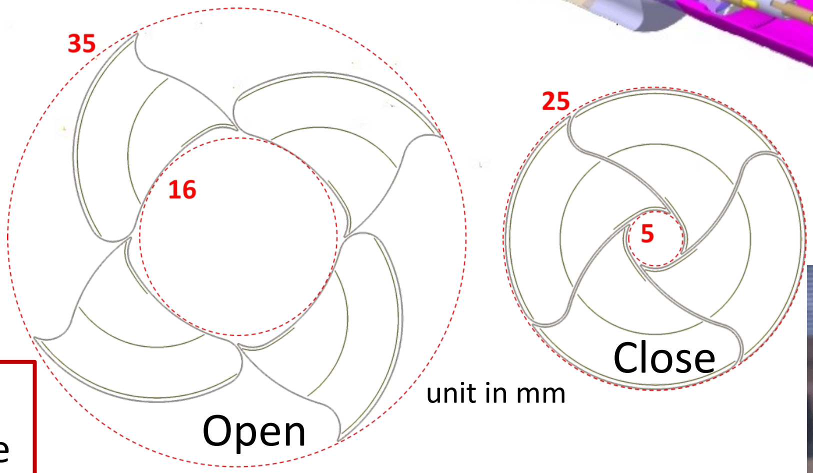
ALICE 3 - Vertex detector



- 3 layers of wafer-size, ultra-thin, curved, CMOS MAPS **inside the beam pipe** in secondary vacuum
- **Retractable** configuration thanks to **movable petals**: distance of **5 mm** from beam axis for data taking and **16 mm** at beam injection
- Unprecedent spatial resolution: $\boldsymbol{\sigma_{pos}}$ **~ 2.5 µm**
- Extremely low material budget: **0.1% per layer**
- Radiation tolerance requirements: 10 Mrad + 2x10^{15} 1MeV n_{eq} /cm^2 (from FLUKA simulations; safety factor to be decided)

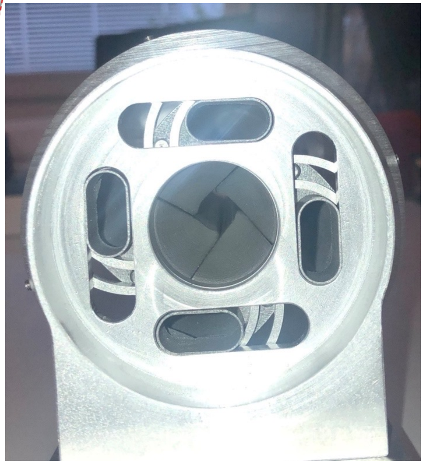
ITS3 prototype already achieved 10^{15} 1MeV n_{eq} /cm^2





R&D challenges: radiation hardness, technology feature size and cooling

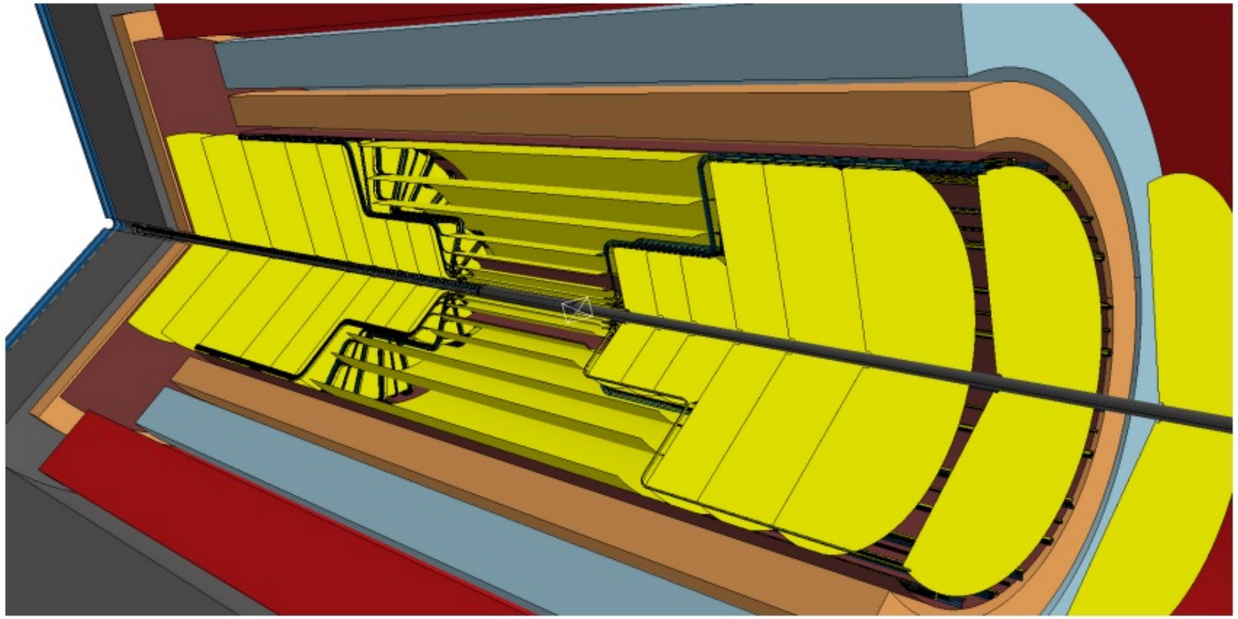
Plans in 2024: new irradiation tests (NIEL, TID), sensor specs, lab tests (mechanics, services, vacuum, etc.)



Bread-Board Model 3
3D-printed aluminium petals
0.5 mm wall thickness

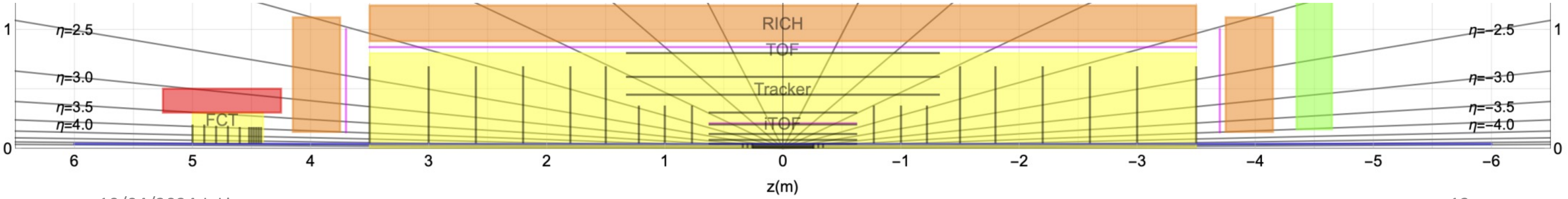
ALICE 3 - Tracker

- 8 + 2 x 9 tracking layers (barrel + disks)
- **60 m^2 silicon pixel detector based on CMOS MAPS technology**
- Compact: r_{out} ~80 cm, z_{out} ± 3.5 m
- Large coverage: ± 4 η
- Time resolution: ~100 ns
- Sensor pixel pitch of ~50 µm for σ_{POS}= 10 µm
- **Low power consumption**: ~ 20 mW/cm^2
- **Very low material budget**: ~1% X_0 per layer



R&D challenges: module integration, timing performance and material budget

Plans in 2024: module concept (with dummy sensors), full-scale sector prototype, sensor specs and lab tests

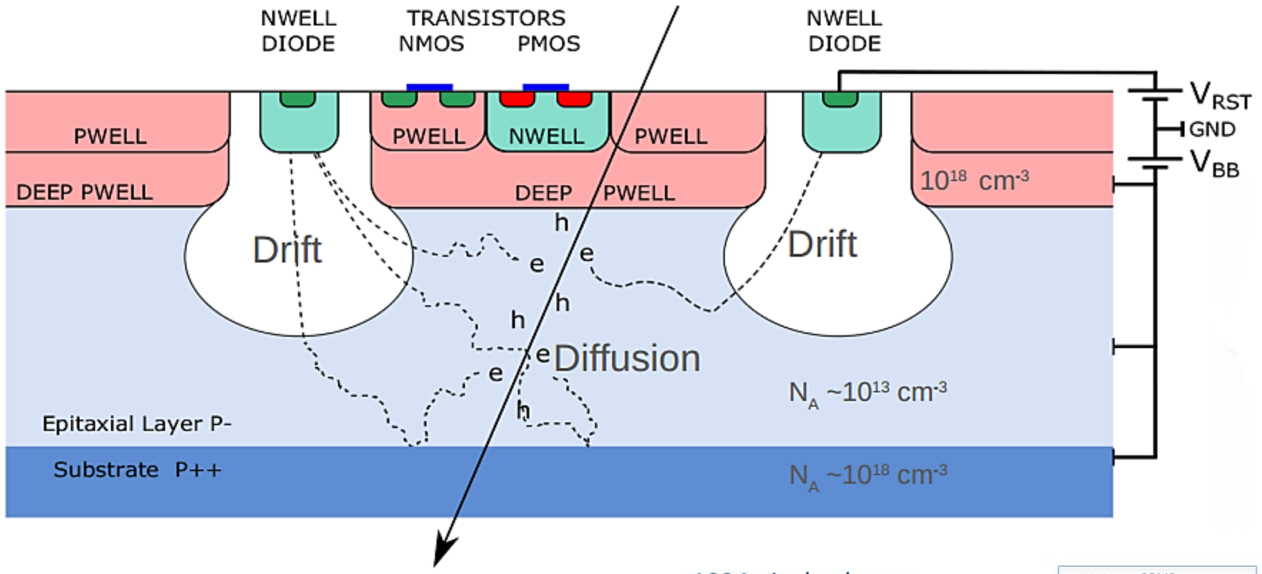


Summary

- **ITS3**: replacement of inner barrel of ITS2 with stitched wafer-scale 65 nm CMOS sensors to reduce material budget and improve pointing resolution
  - **ITS3 project is on track for installation in LHC LS3**
  - Technical baseline for precise detector layout is defined
  - TDR is approved by LHCC and Research Board
- **ALICE 3**: innovative detector concept focusing on silicon technology
  - **R&D activities started** on several strategic areas
- **ITS3 and ALICE 3 pioneer several R&D directions that can have a broad impact on future HEP experiments** (e.g., EIC, FCC-ee)

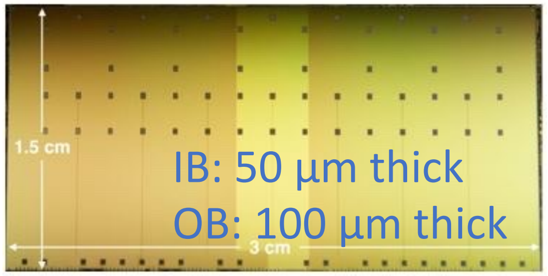
Backup

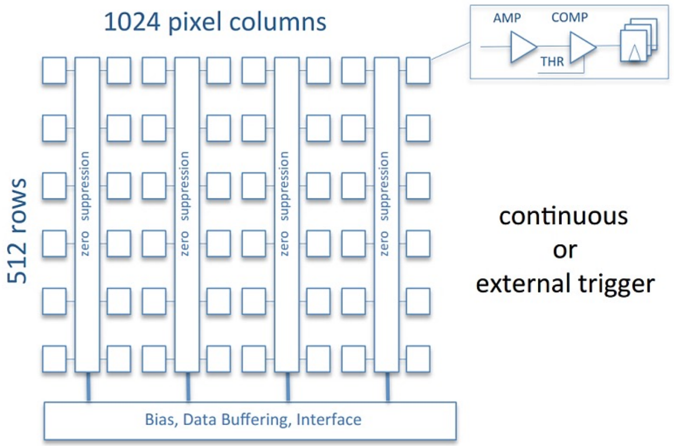
ALPIDE: ALICE PIxel DEtector



ALPIDE technology features:

- TowerJazz 180 nm CiS Process, full CMOS
- Deep P-well implementation available
- High resistivity epi-layer (>1 kΩ·cm) p-type, thickness 25 µm
- Smaller charge collection diode → lower capacitance → higher S/N
- Possibility of reverse biasing
- Substrate can be thinned down

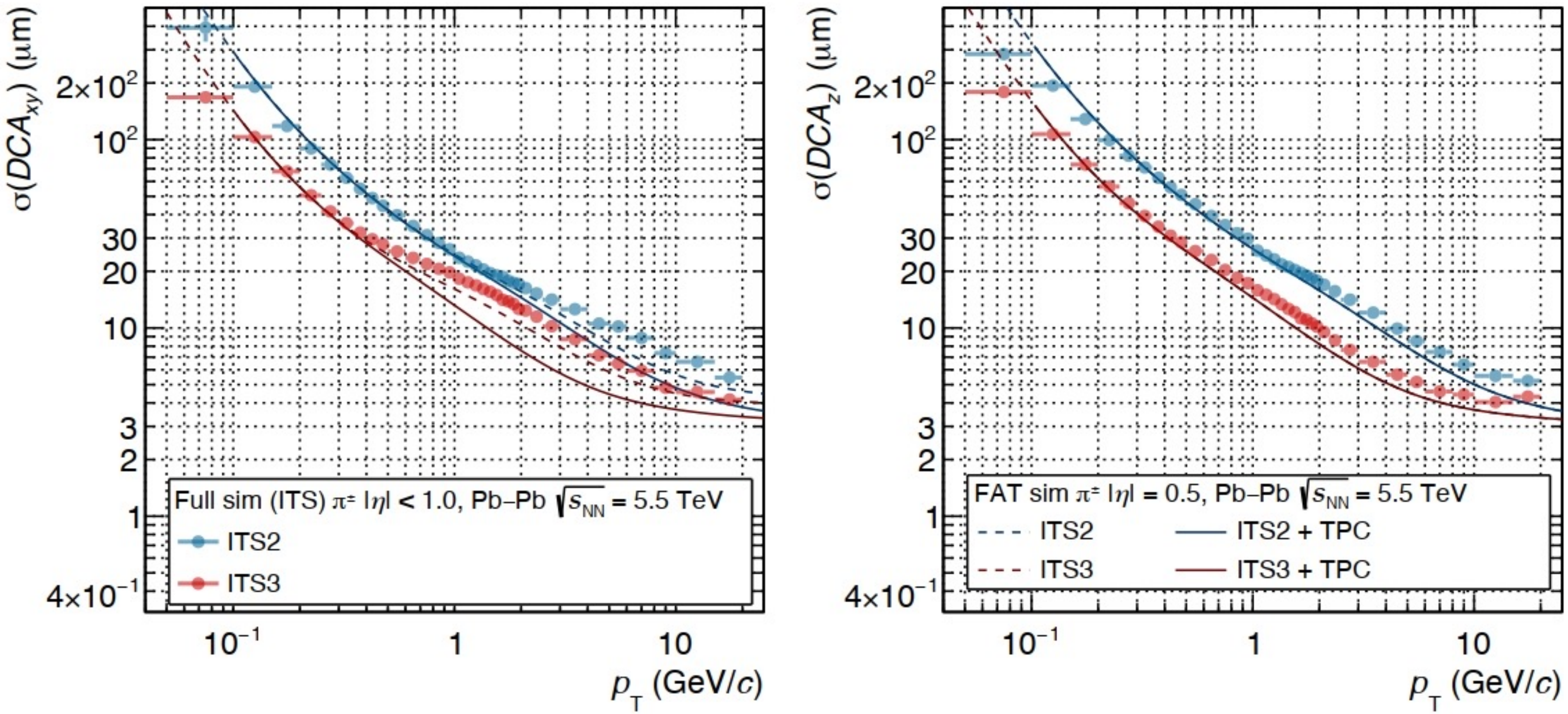




Sensor specification:

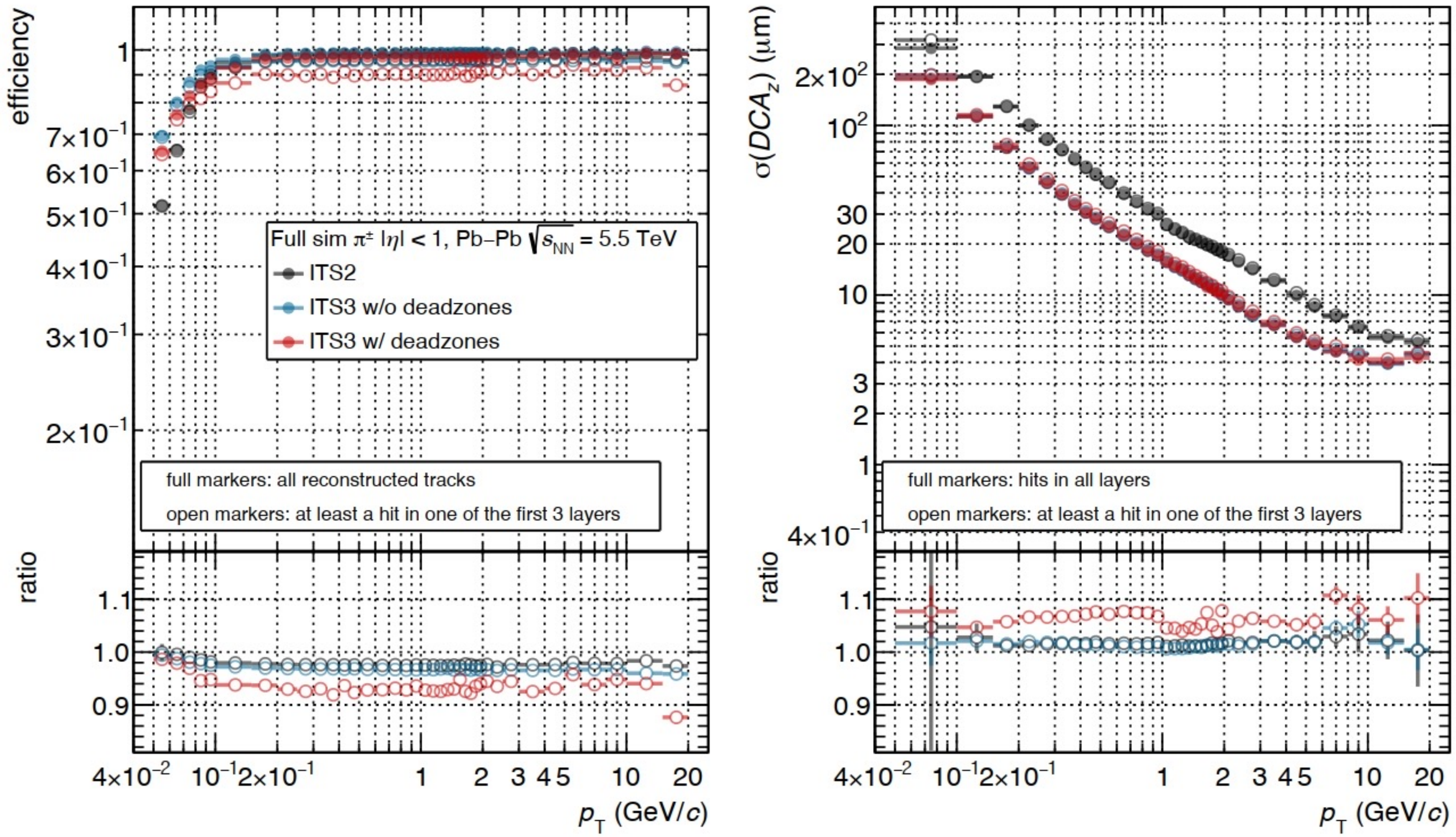
- Pixel pitch 27 µm x 29 µm → spatial resolution 5 µm x 5 µm
- Priority Encoder Readout
- Power: 40 mW/cm^2
- Trigger rate: 100 kHz
- Integration time: < 10 µs
- Read out up to 1.2 Gbit/s
- Continuous or triggered read-out

ITS3 performance – pointing resolution



- Improvement in pointing resolution by a factor of 2 over all momenta
- Increase of tracking efficiency for low-p_T particles and extension of the low-p_T reach

ITS3 performance – impact on dead zones

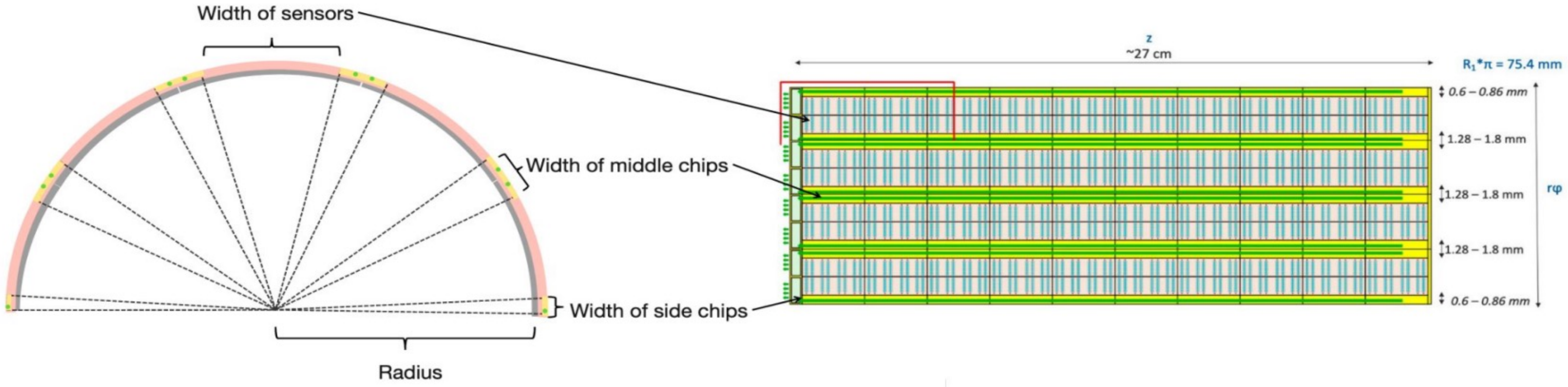


Assumptions here:

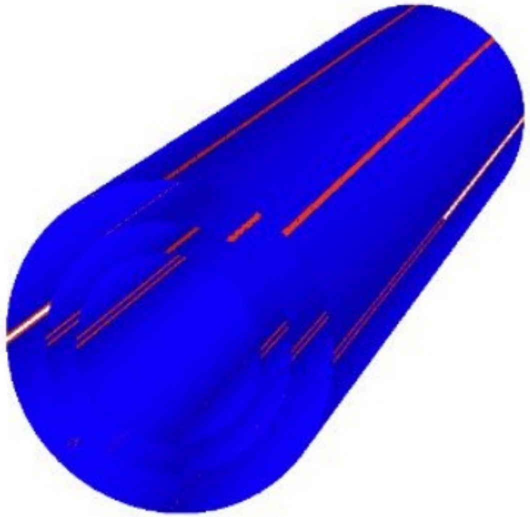
- 1mm gap between top and bottom
- Total: 8-9% dead area

- Dead zones (on chip and between halves) have direct impact on efficiency → important to optimise mechanics and chip design in this parameter

ITS3 geometry - dead zones



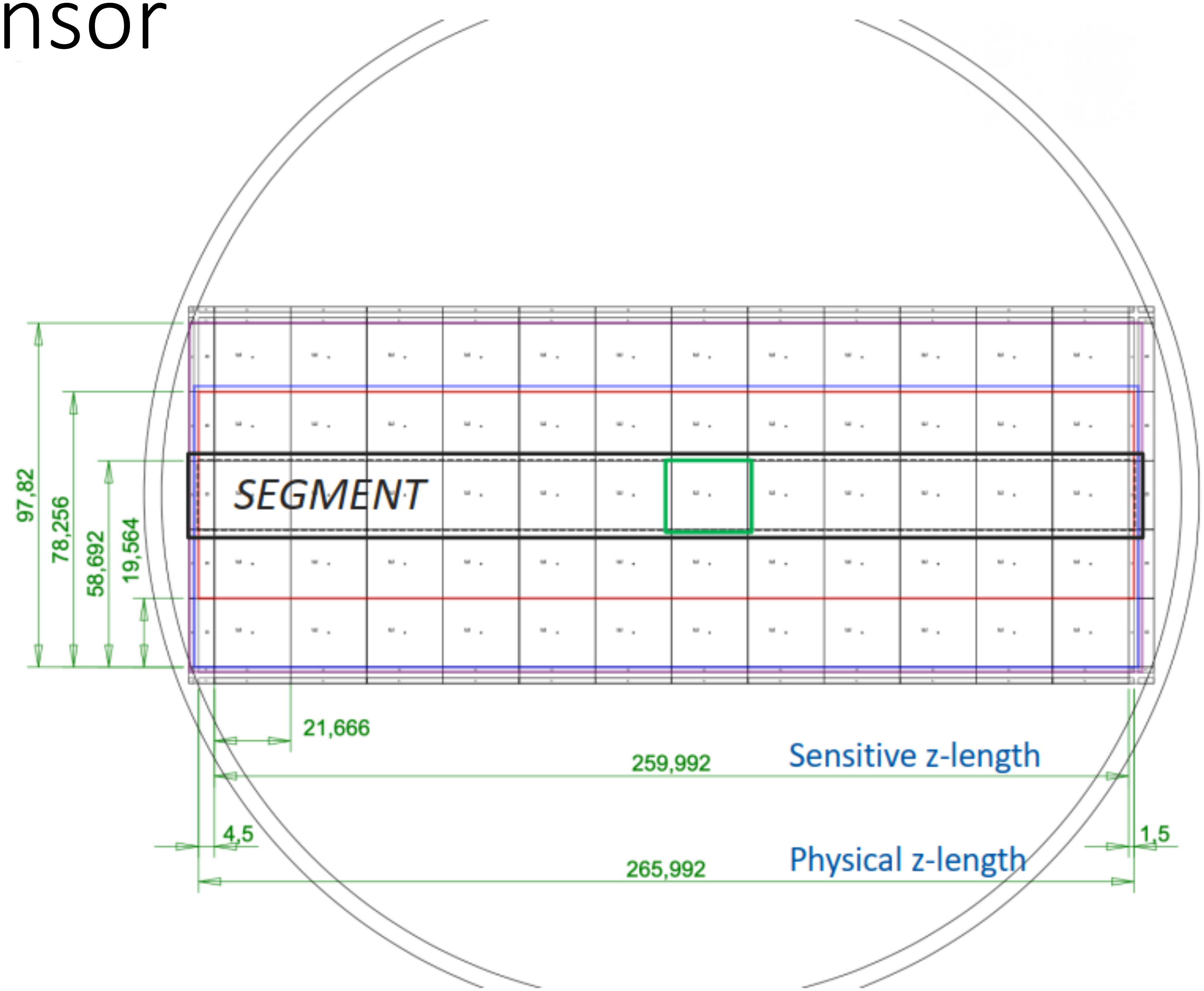
- Blue: sensitive areas
- Red: dead areas
- Gap between the two hemicylinders



ITS3 ER2 stitched sensor

Layer 0: 12 x 3 repeated units+endcaps
Layer 1: 12 x 4 repeated units+endcaps
Layer 2: 12 x 5 repeated units+endcaps

Repeated (Stitched) Sensing Unit

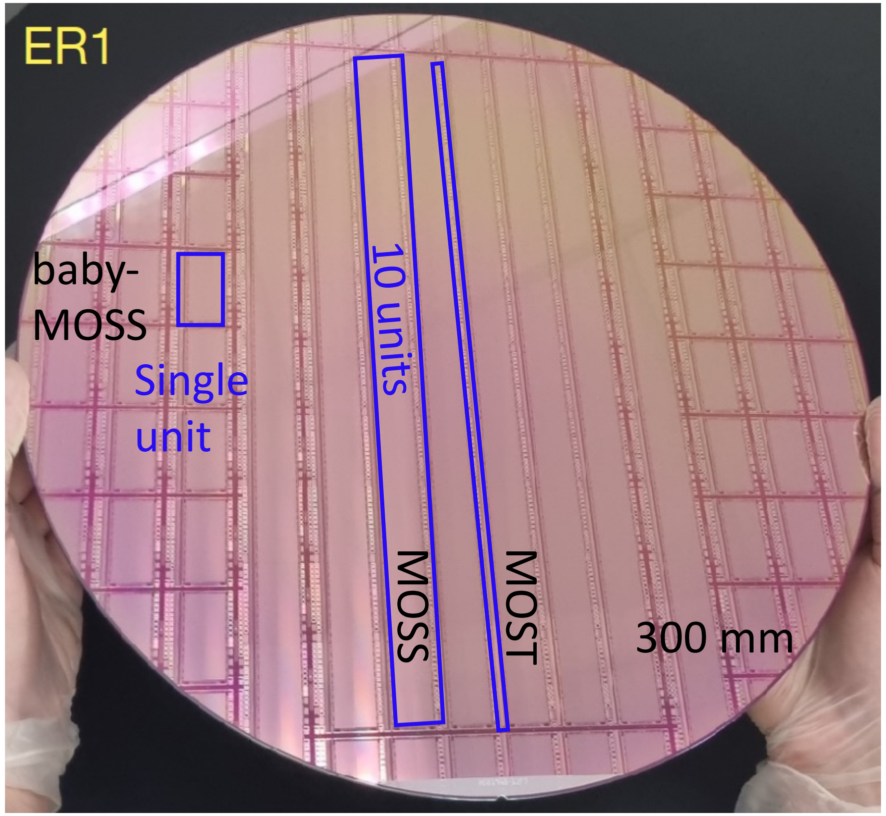


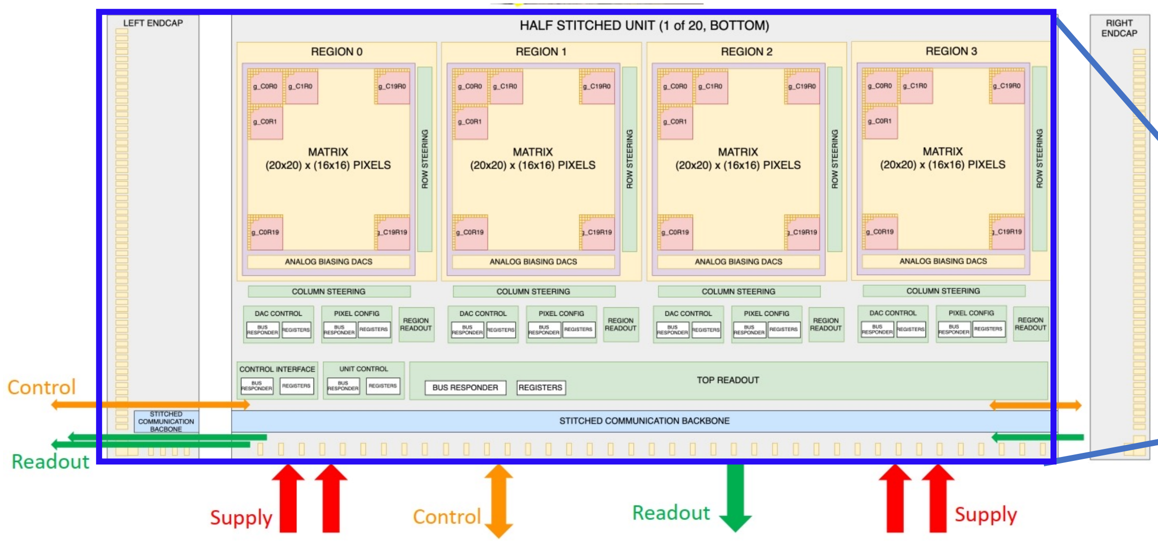
ITS3 ER1

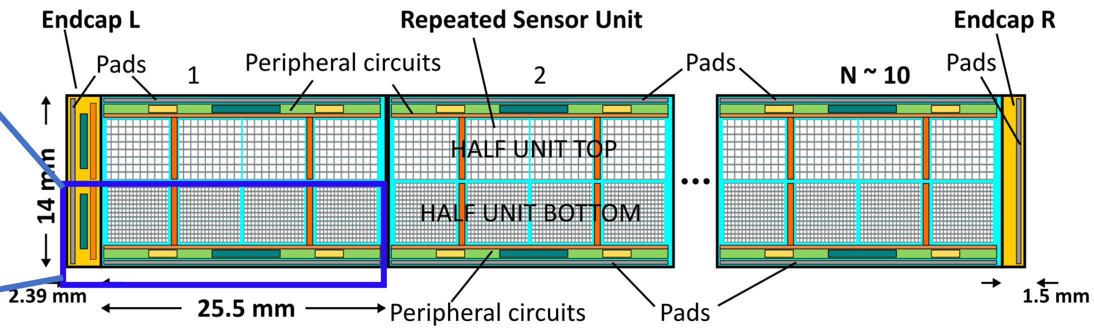
First MAPS for HEP using stitching
- One order of magnitude larger than previous chips

"MOSS": 14 x 259 mm, 6.72 MPixel (22.5 x 22.5 and 18 x 18 μm^2)
- Conservative design, different pitches

"MOST": 2.5 x 259 mm, 0.9 MPixel (18 x 18 μm^2)
- More dense design

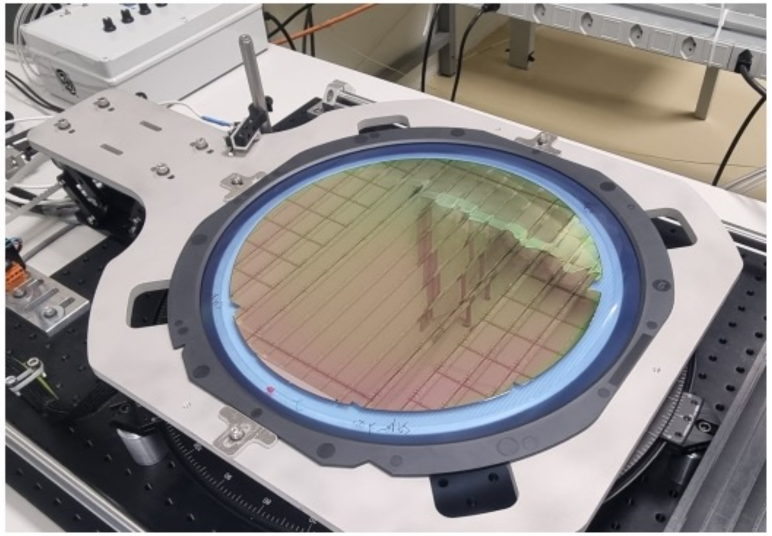


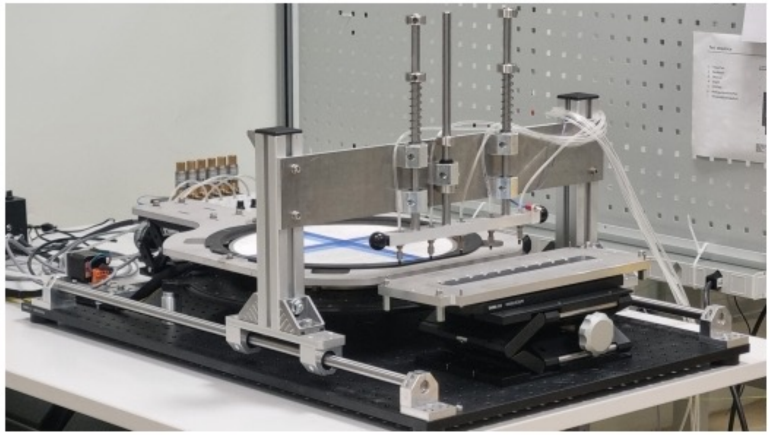


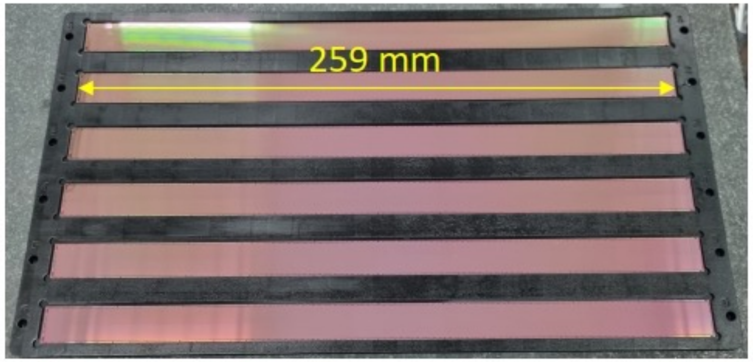


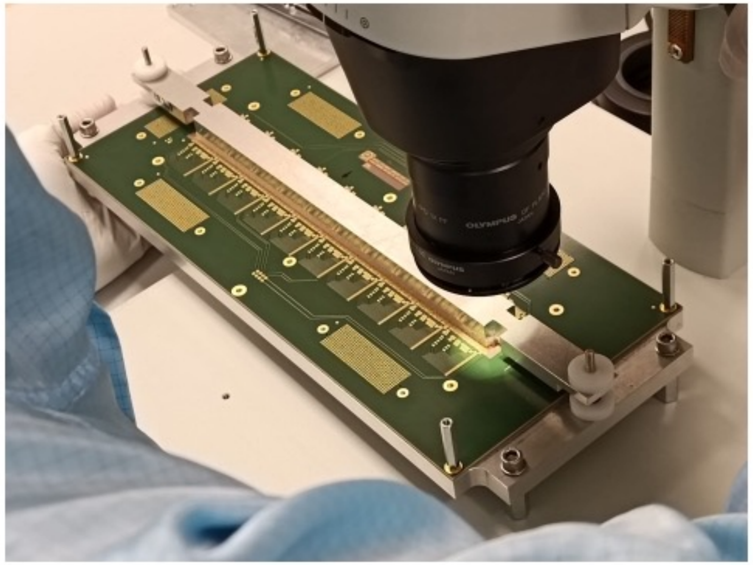
ITS3 ER1 postprocessing

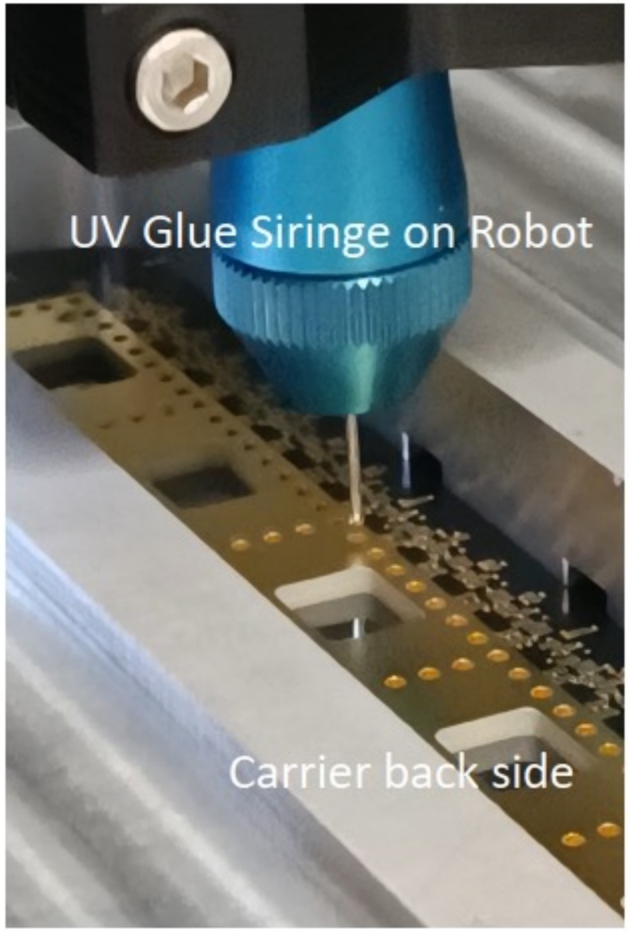
Pick, align, glue MOSS on Carrier





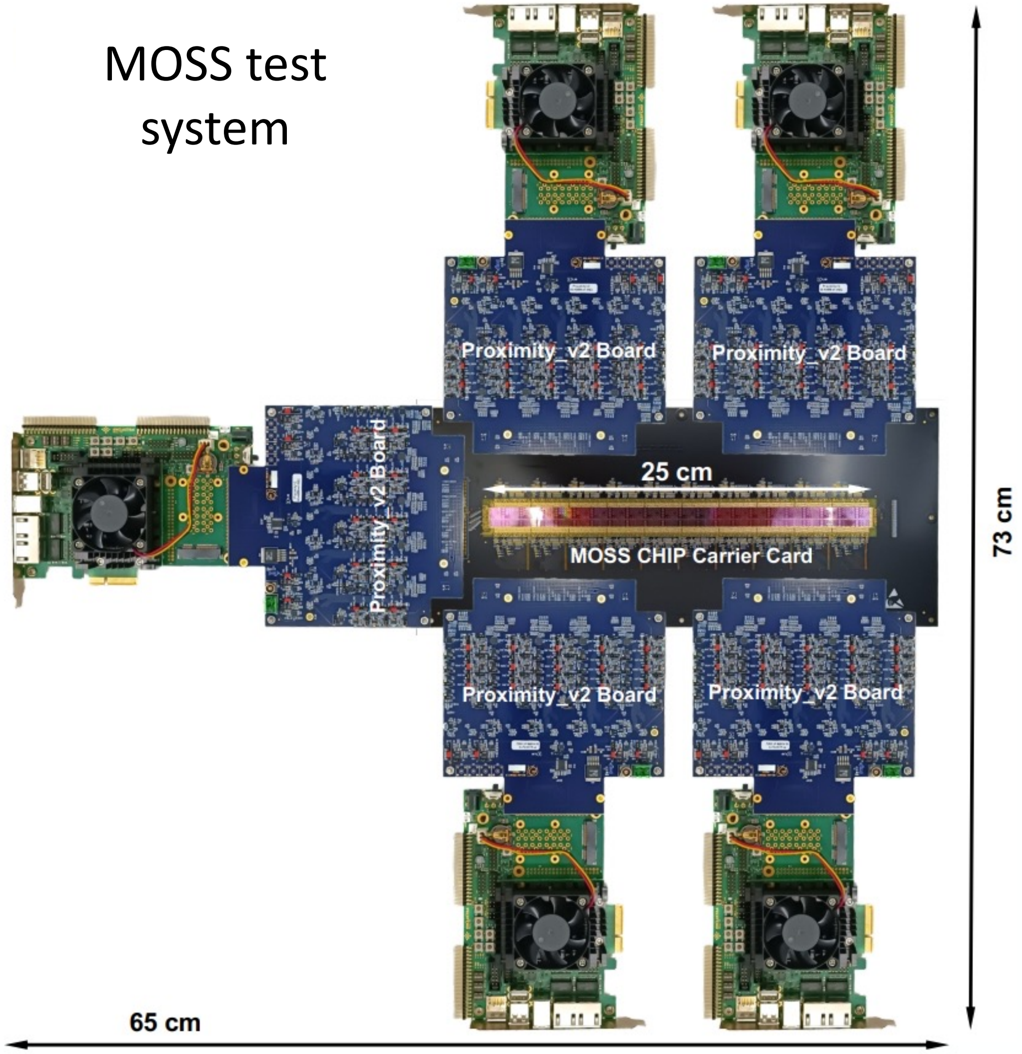


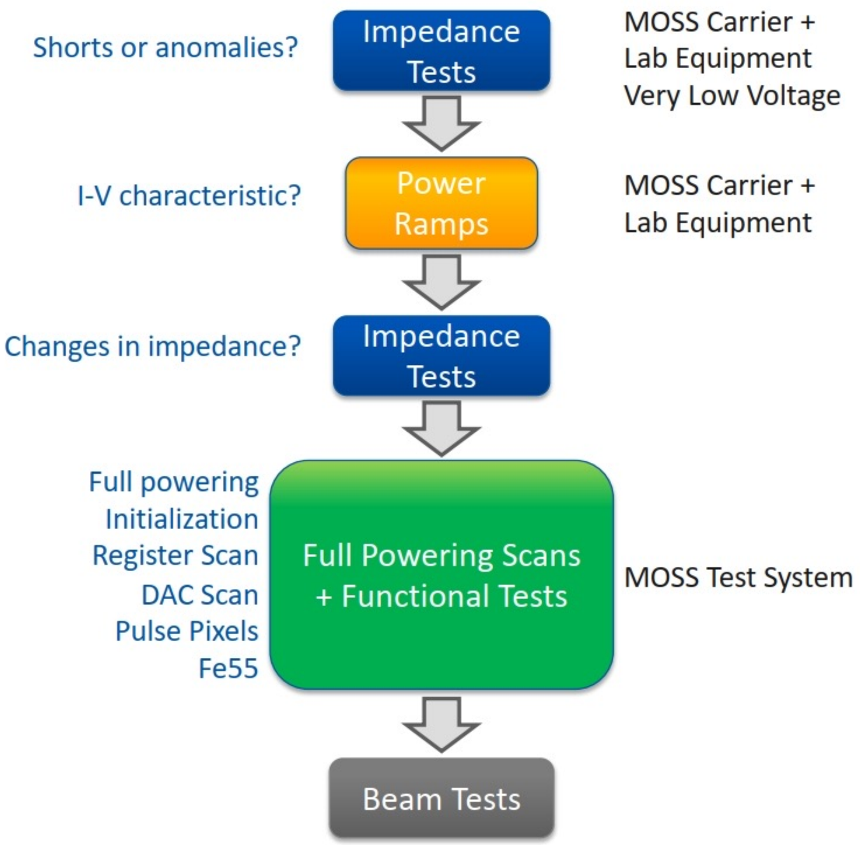


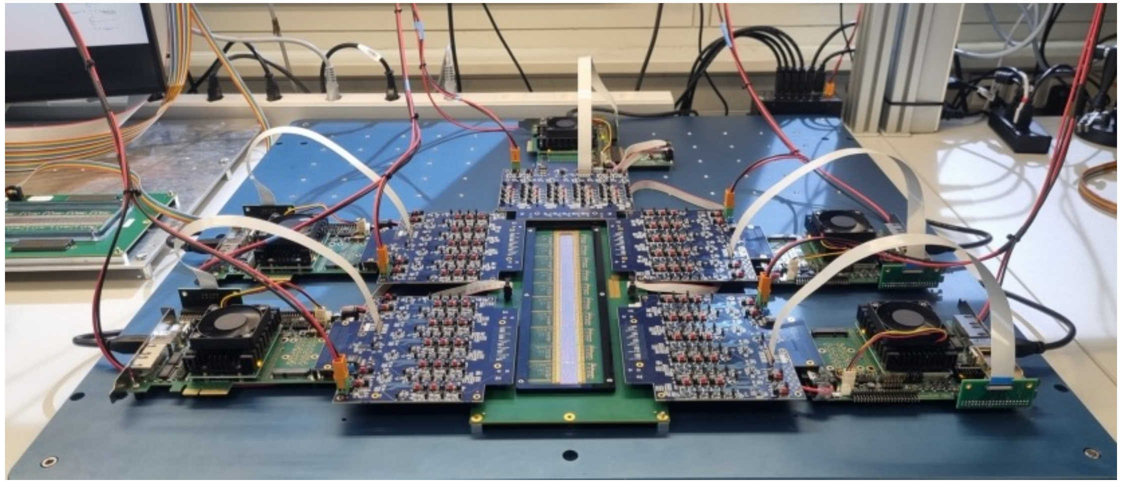


ITS3 MOSS testing

MOSS test system

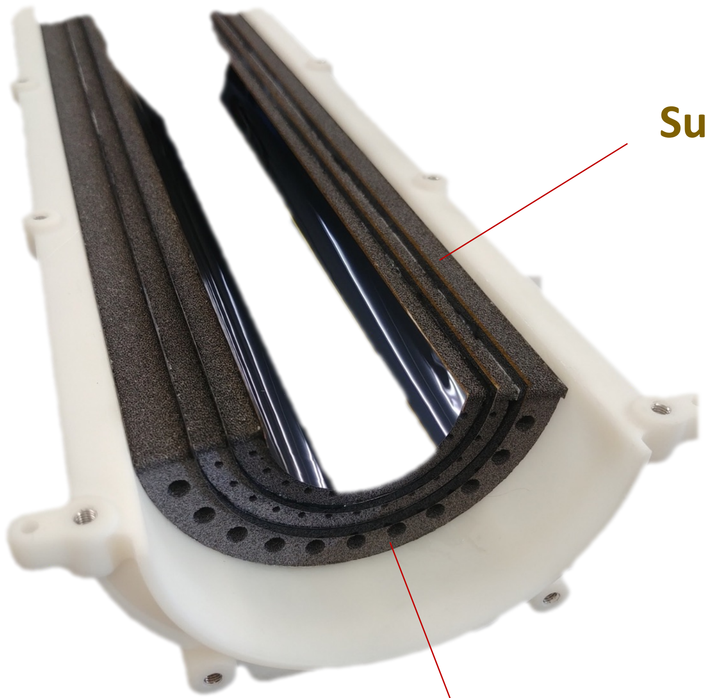






ITS3 mechanics and cooling solutions

- The limited dissipated power allows for the use of air cooling at ambient temperature (colder gas are also being considered as back up)
- The material budget requirement call for a unpalpable support structure i,.e. carbon foam used as support and radiator (carbon fiber truss support being considered as backup)



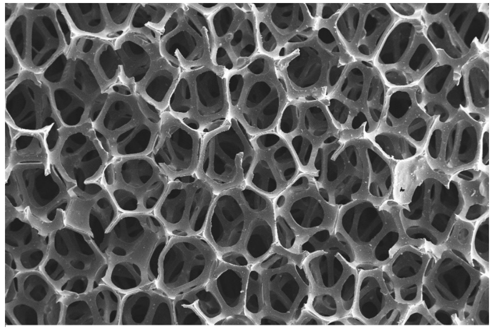
Support

ERG Carbon

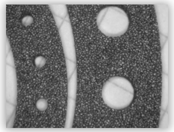
@Duocel

ρ = 0.045 kg/dm³

k = 0.033 W/m·K



Support & cooling

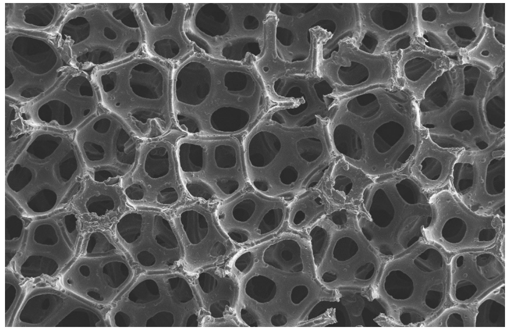


K9

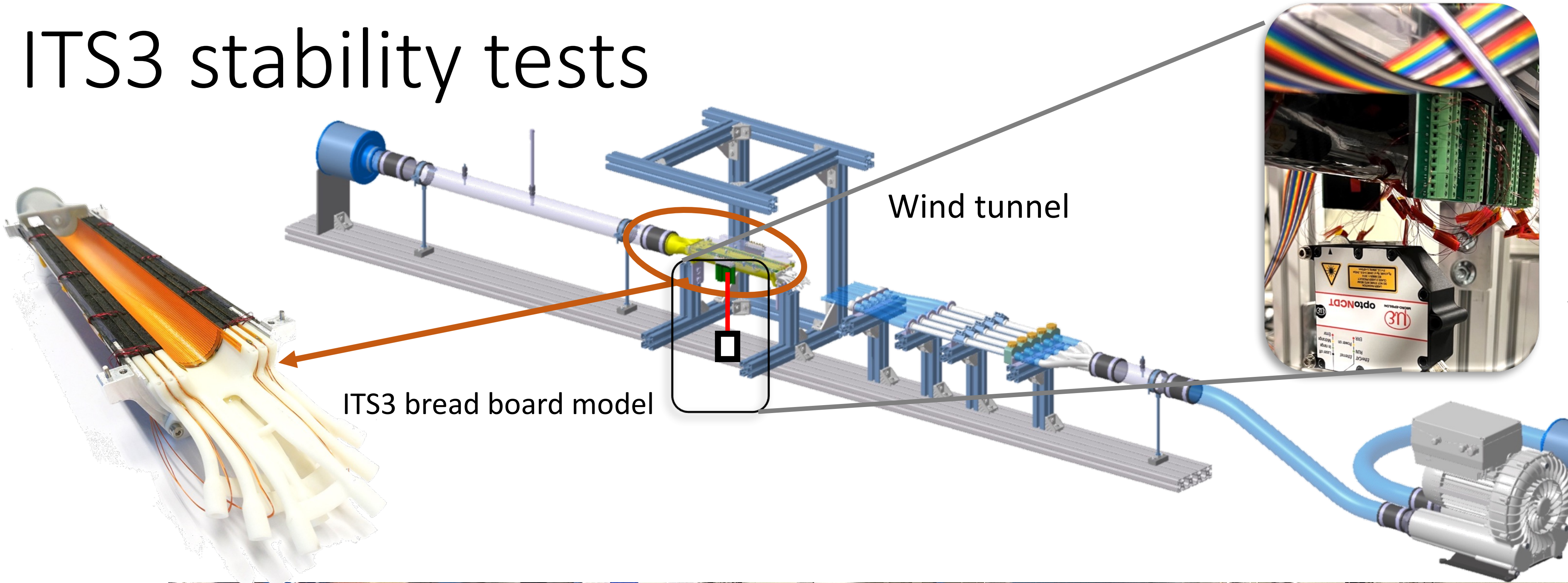
Standard Density

ρ = 0.2-0.26 kg/dm3

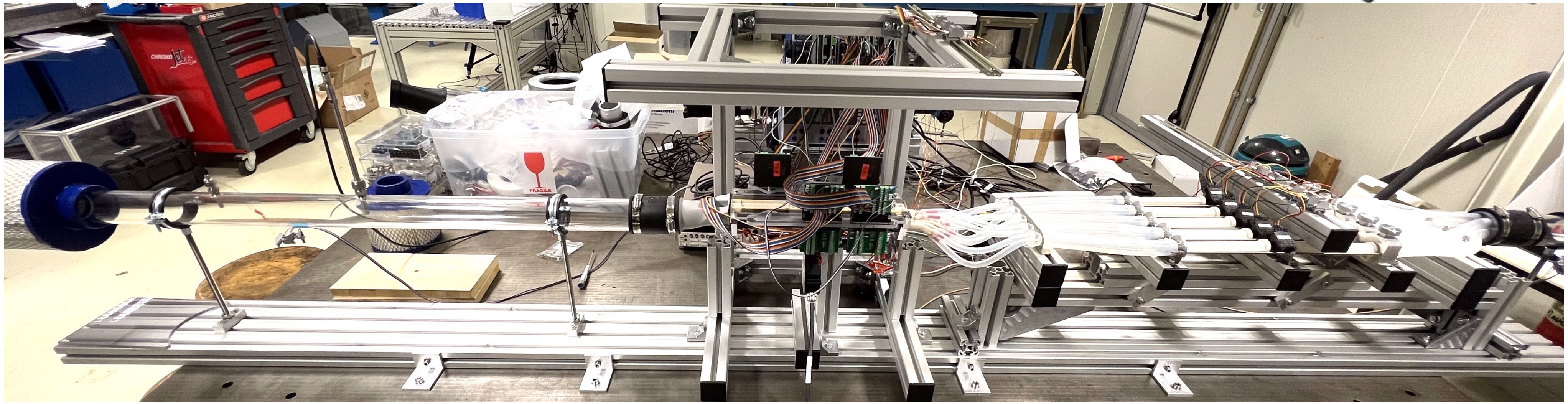
k = >17 W/m·K



ITS3 stability tests



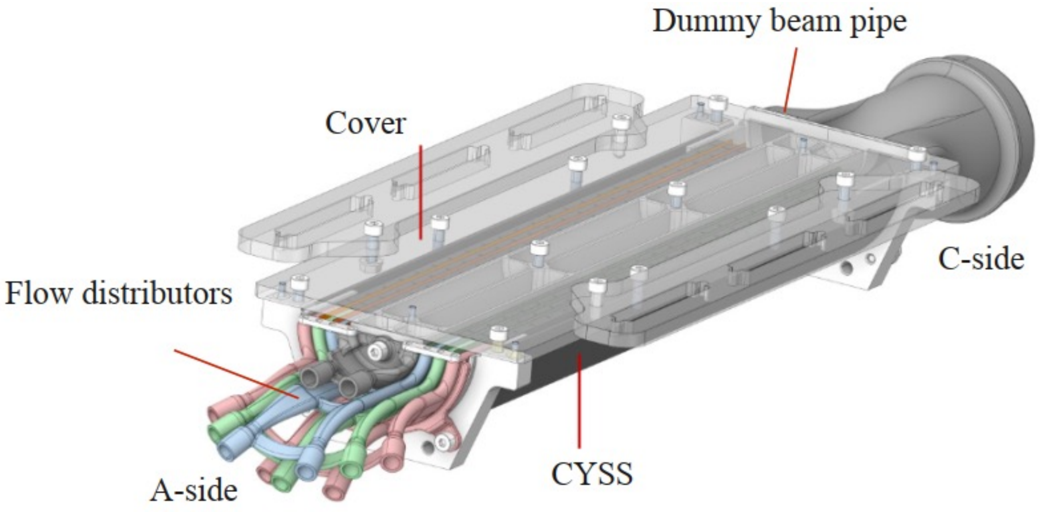
Laser measurement machine for vibration analysis

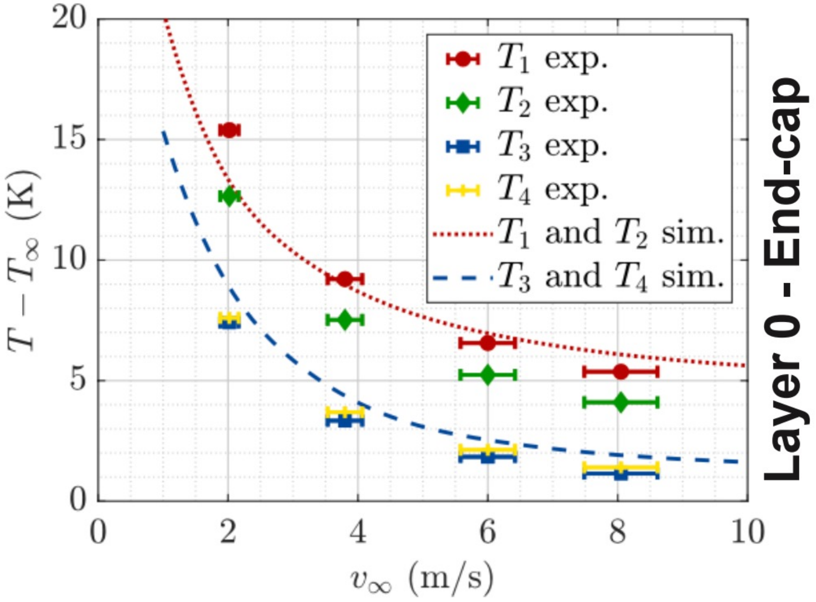


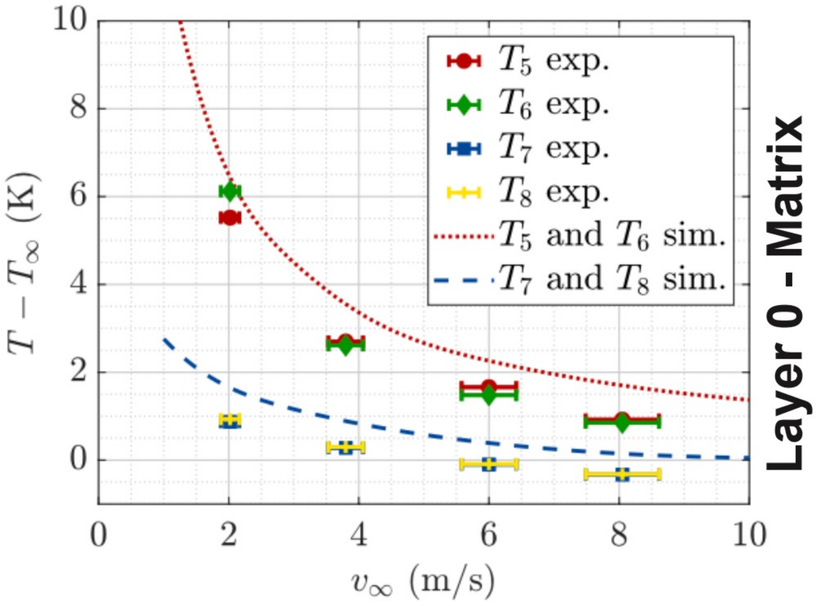
ITS3 air cooling analysis

Thermal characterization setup

- Dummy silicon equipped with copper serpentine simulating heat dissipation in matrix (25 mW/cm^2) and end-cap (1000 mW/cm^2) regions
- 8 PT100 temperature sensors distributed over the surface of each half-layer







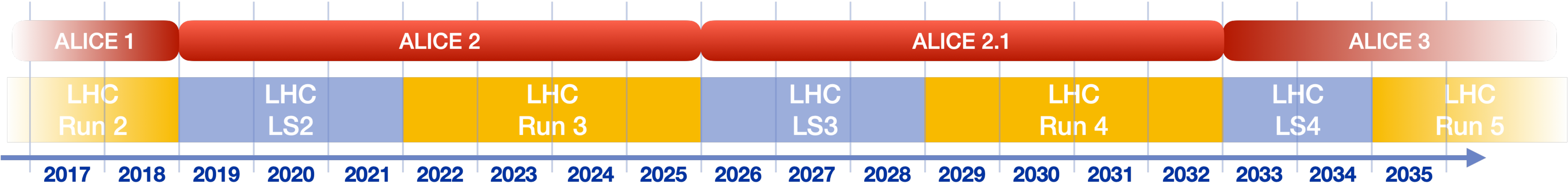
Temperature sensor position and nomenclature

- **With an average airflow free-stream velocity between the layers of about 8 m/s,** the detector can be operated at a temperature of 5 degrees above the inlet air temperature
- Temperature uniformity along the sensor can be also kept within 5 degrees

ALICE 3 timeline

Long-term schedule

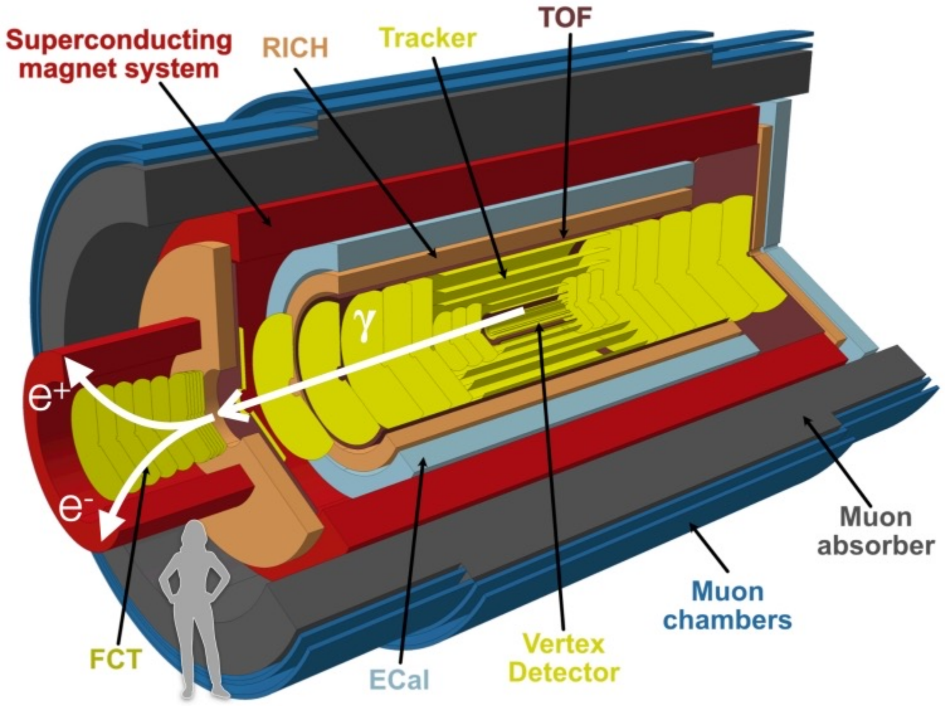
- **2023-25**: selection of technologies, small-scale proof of concept prototypes (~25% of R&D funds)
- **2026-27**: large-scale engineered prototypes (~75% of R&D funds) → Technical Design Reports
- **2028-30**: construction and testing
- **2031-32**: contingency and pre-commissioning
- **2033-34**: preparation of cavern, installation

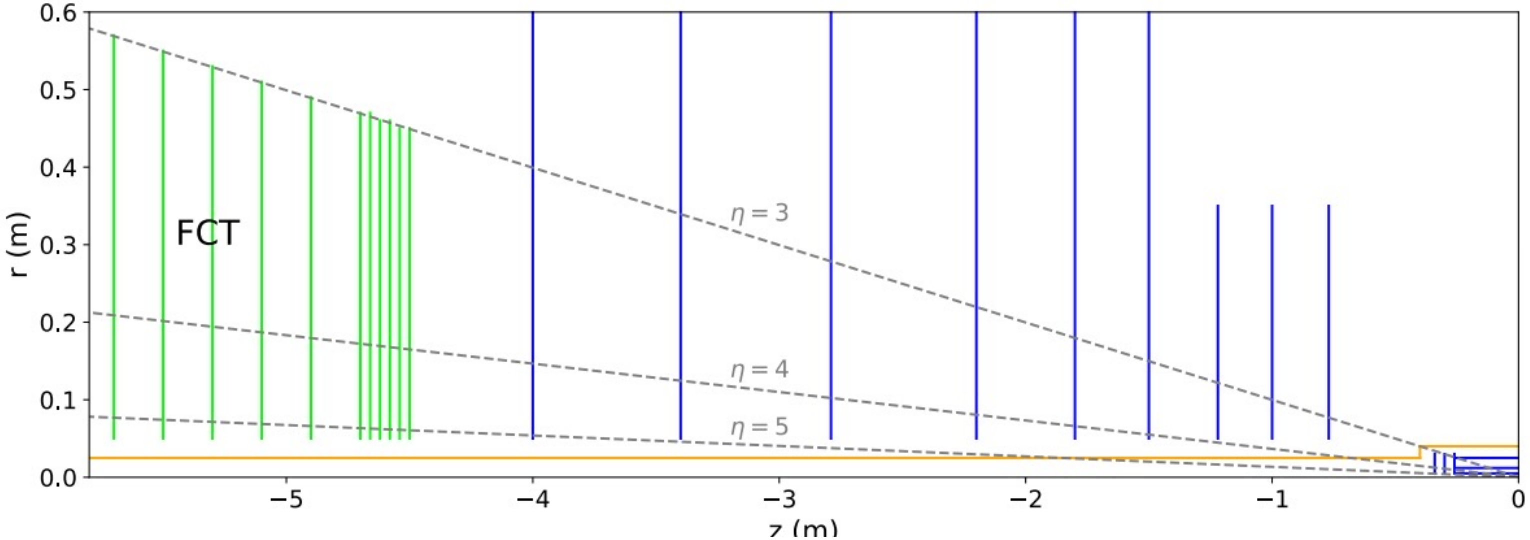


ALICE 3 - Forward conversion tracker

Prime motivation: resolve the soft-photon puzzle

- Thin tracking disks to cover $3 < \eta < 5$: few ‰ of a radiation length per layer, position resolution < 10 μm
- R&D programme on large area, thin disks, minimisation of material in front of FCT, operational conditions





ALICE 3 - Particle identification - TOF

Time of Flight (TOF) detectors concept based on **silicon timing sensors**:

- Outer TOF at R ≈ 85 cm
- Inner TOF at R ≈ 19 cm
- Forward TOF at z ≈ 405 cm
- Total silicon surface ~45 m^2
- Time resolution of ~20 ps

Separation power ∝ L/σ_{TOF}

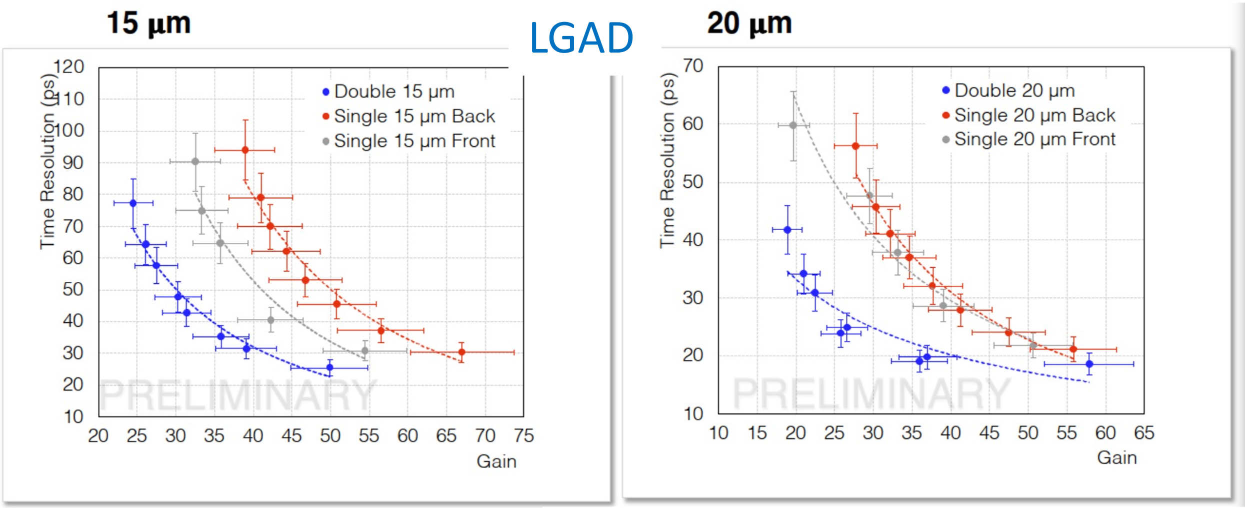
- Distance and time resolution are crucial
- Separation up to 100 MeV/*c*

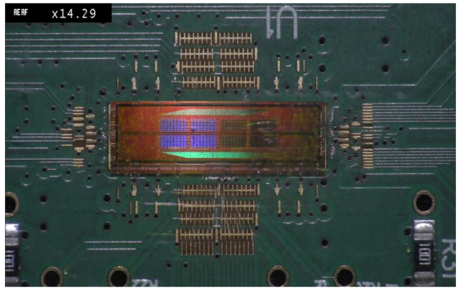
Silicon timing sensors

- R&D on LGAD and on CMOS with gain layer
- Double LGAD reaches 20 ps almost independently of sensor thickness

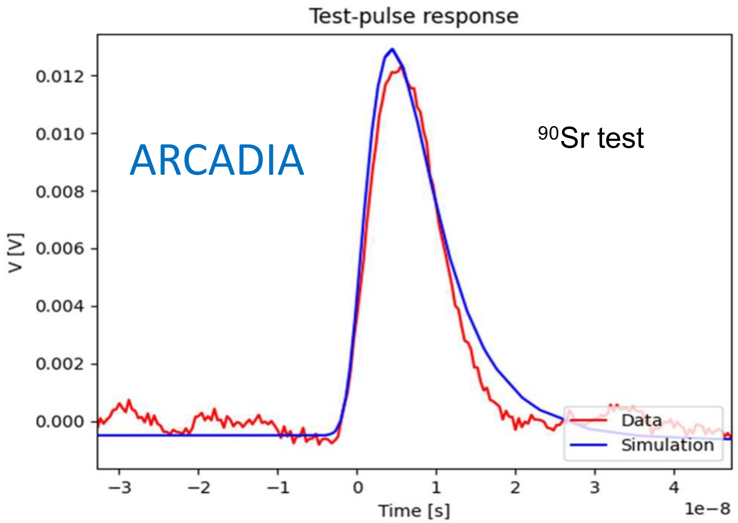
R&D challenges: optimisation of geometry, time distribution at system level and powering concept

LGAD





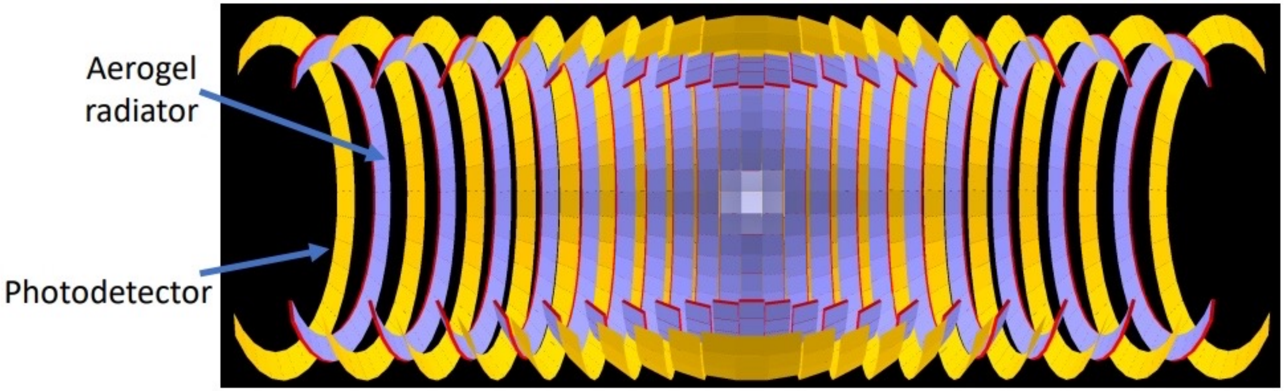
ARCADIA (LFoundry CMOS 110 nm with 48 μm active thickness)+ gain layer

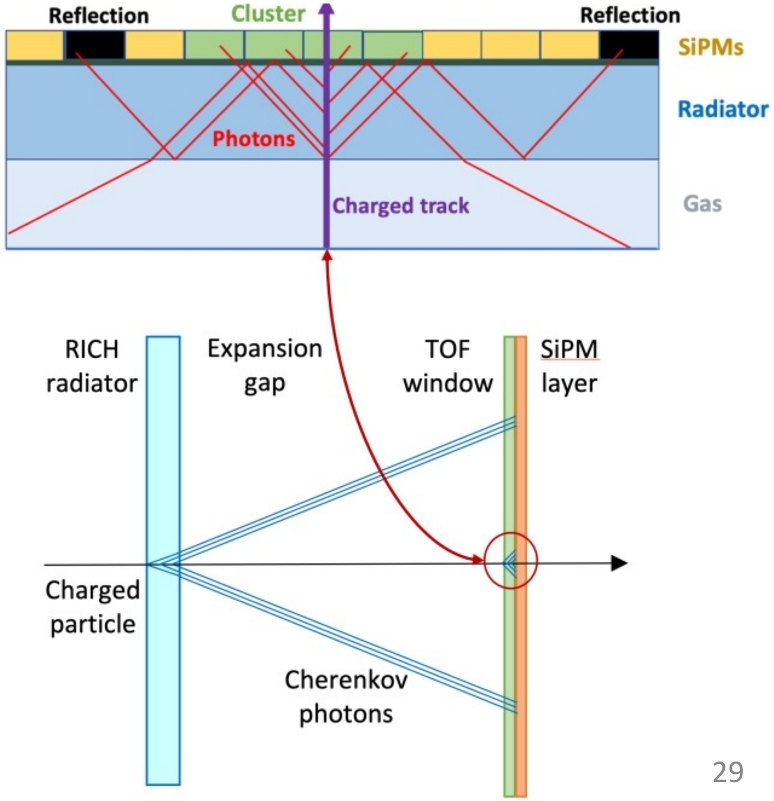


ALICE 3 - Particle identification - RICH

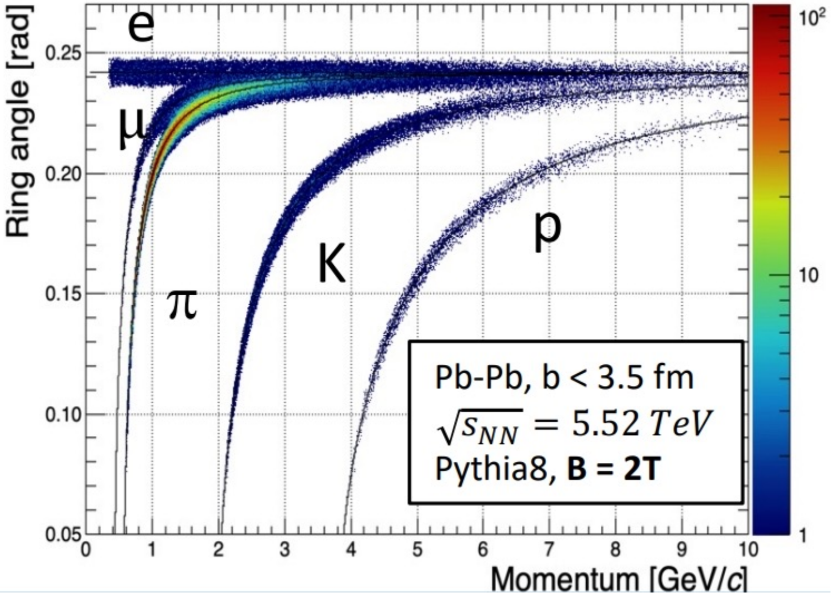
Complement TOF PID with Ring-Imaging Cherenkov detector (RICH)

- **Extend charged PID beyond the TOF limits**
  - p/e up to $p_T \approx 2.0$ GeV/c
  - K/p up to $p_T \approx 10.0$ GeV/c
  - p/K up to $p_T \approx 16.0$ GeV/c
- Detectors concept (barrel + forward):
  - Aerogel radiator + SiPM photodetector
  - Total SiPM area ~40 m^2





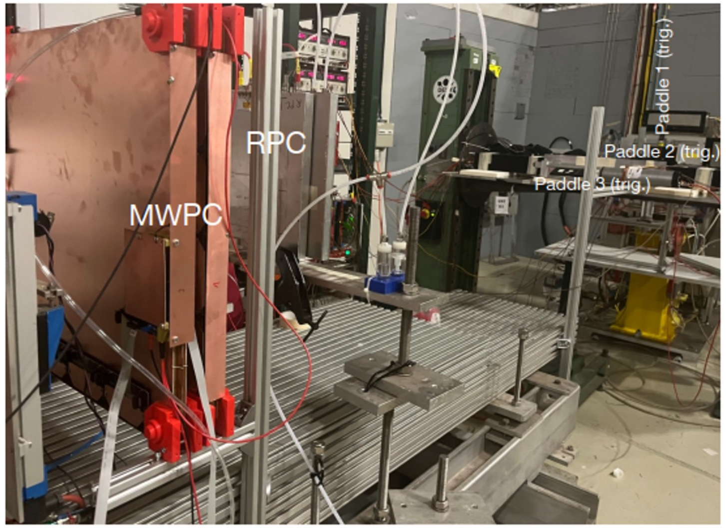
R&D challenges: cost-effective large-area high-granularity photon detection, detector optimisation and simulations, and combined TOF-RICH readout



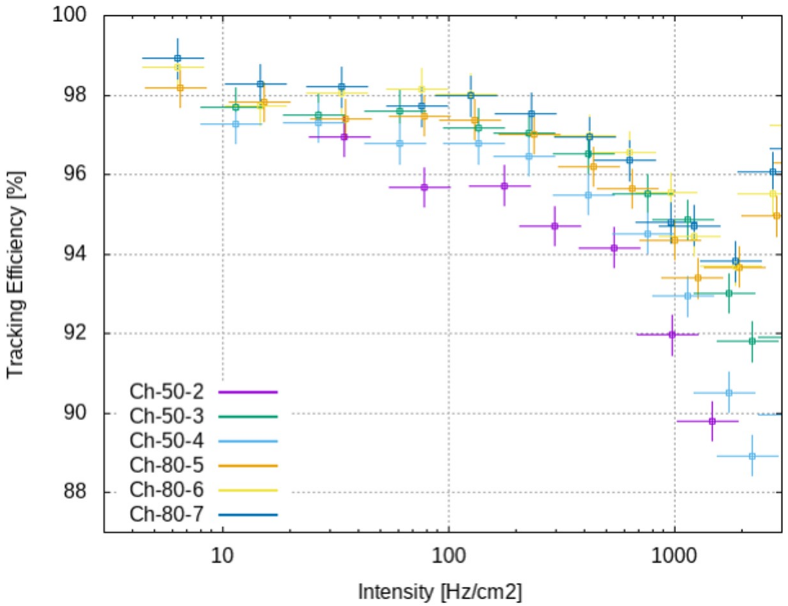
ALICE 3 - Muon identification

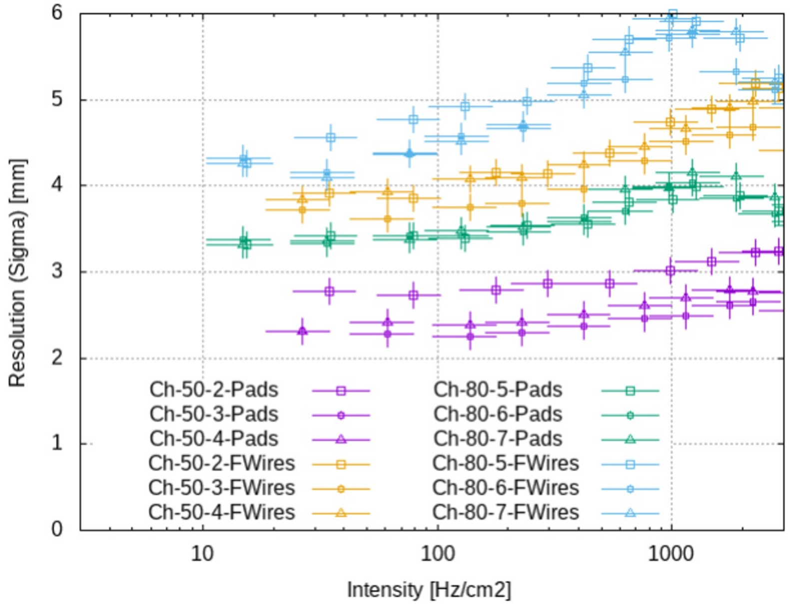
Muon chambers at central rapidity optimized for reconstruction of charmonia down to p_T = 0 GeV/c

- ~70 cm non-magnetic steel hadron absorber
- Granularity $\Delta\eta - \Delta\varphi = 0.02 \times 0.02$
- Considered technologies options: scintillators, MWPC and RPC
- SiPM readout



R&D challenges: assess options for detection layers and refine requirements on segmentation, integration time, and efficiency



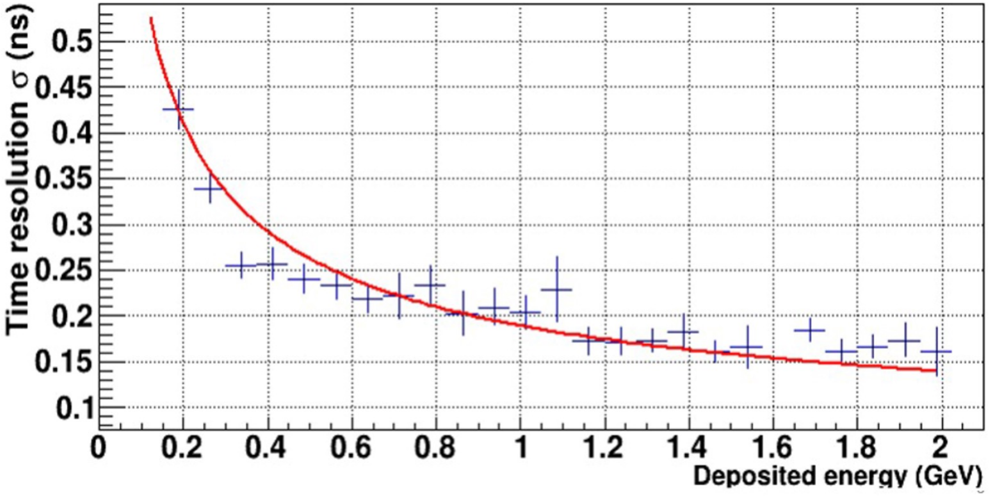


- MWPC: satisfactory efficiency (>97%) and position resolution (<1cm) for particle rates of up to 300 Hz/cm^2
- Data analysis concerning ACORDE scintillators and RPCs is in progress

ALICE 3 - Electromagnetic calorimeter

Large acceptance ECal (2π coverage) is critical for measuring P-wave quarkonia and thermal radiation via real photons

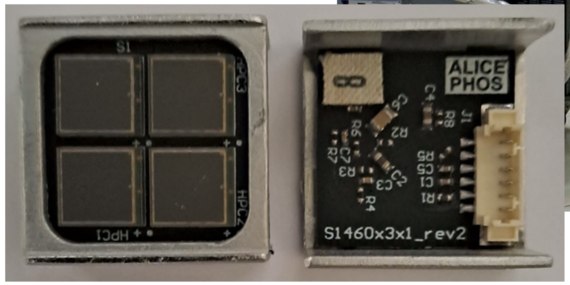
- $PbWO_4$-based high energy resolution segment
- Different hybrid photodetectors based on SiPM studied @PS and SPS: $\sigma_t < 200$ ps



Letter of intent for ALICE 3 (CERN-LHCC-2022-009)

ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 0.33$
geometry	$R_{in} = 1.15$ m, $\lvert z\rvert < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\lvert z\rvert < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV

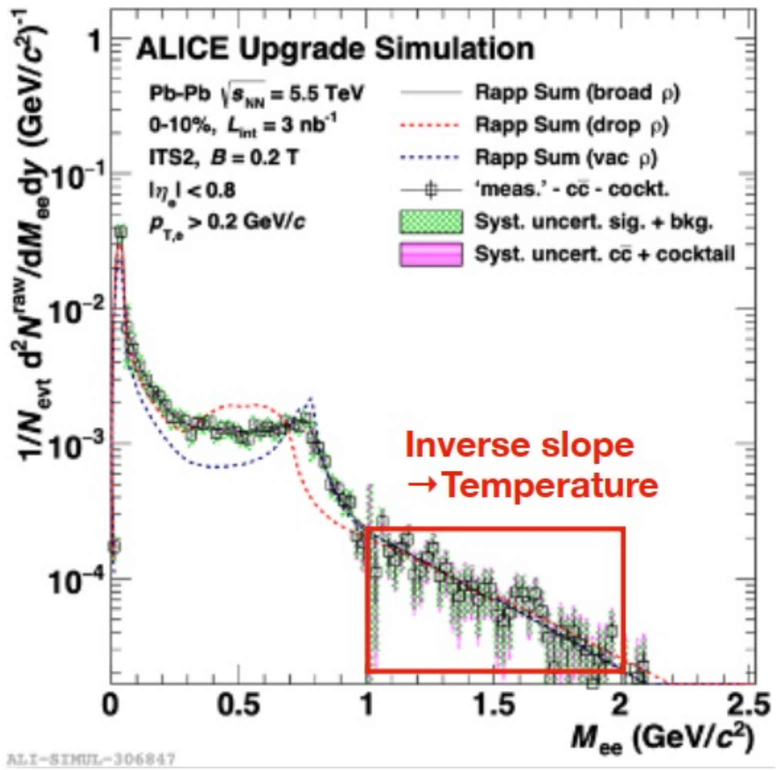
R&D challenges: optimisation of sampling stack, readout design and physics performance

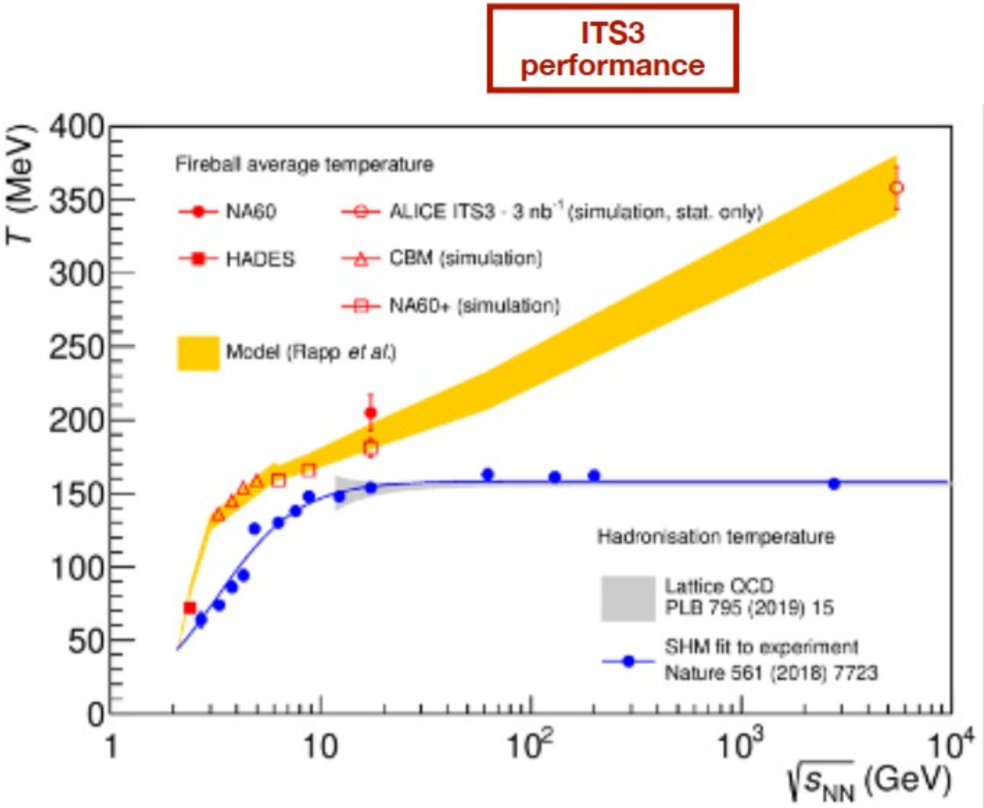


ITS3 - Physics goals - Dileptons

Thermal dileptons, photons, vector mesons (thermal radiation, chiral symmetry restoration)

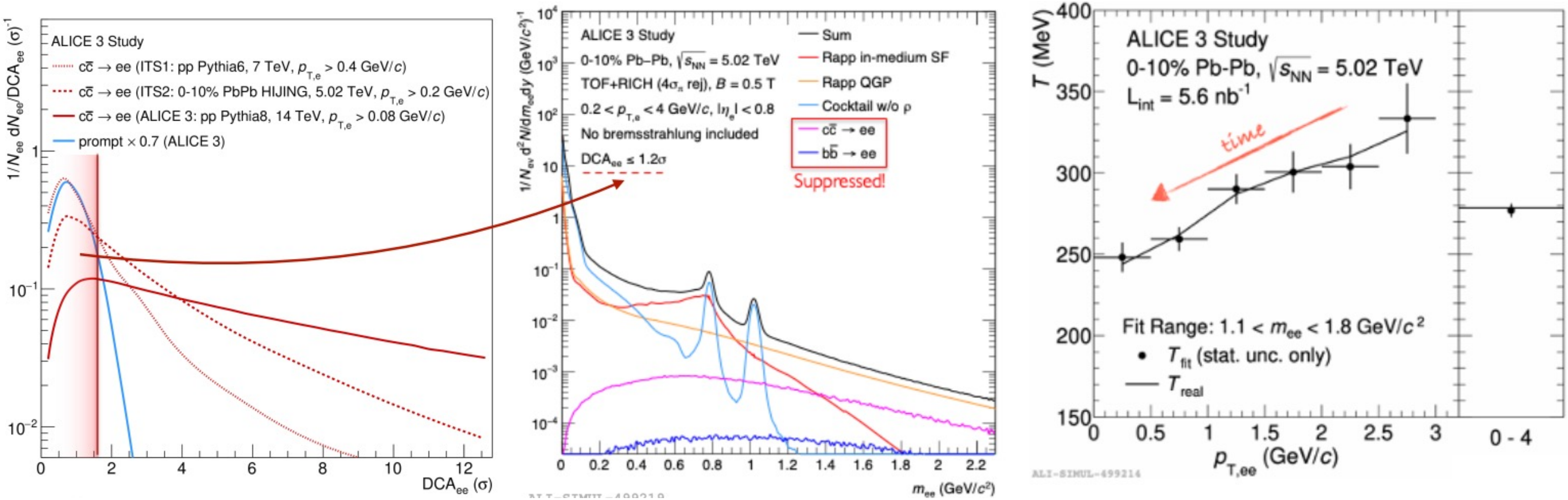
- High precision measurement of temperature in mass region $1<M_{ee}<2$ GeV/c^2





ALICE3 - Physics goals - Dileptons

- ALICE 3 high precision tracking results in an unprecedented HF rejection and low-p_T electron ID → background suppression allows a very precise temperature measurement
- Differential analysis in $p_{T,ee}$: **only** accessible with ALICE 3



ALICE3 - Physics goals - Heavy flavours

- **Heavy flavour** hadrons at low p_T (charm and beauty interaction and hadronisation in the QGP)
- SHM: hierarchy with **n** number of charms (**g_c^n**) → multicharm hadrons (e.g., Ξ^{++}_{cc})
- Silicon layers inside the beam pipe allow for **direct tracking** of **Ξ/Ω** baryons (**strangeness tracking**) -> full reconstruction of multi-charm baryon decay vertices