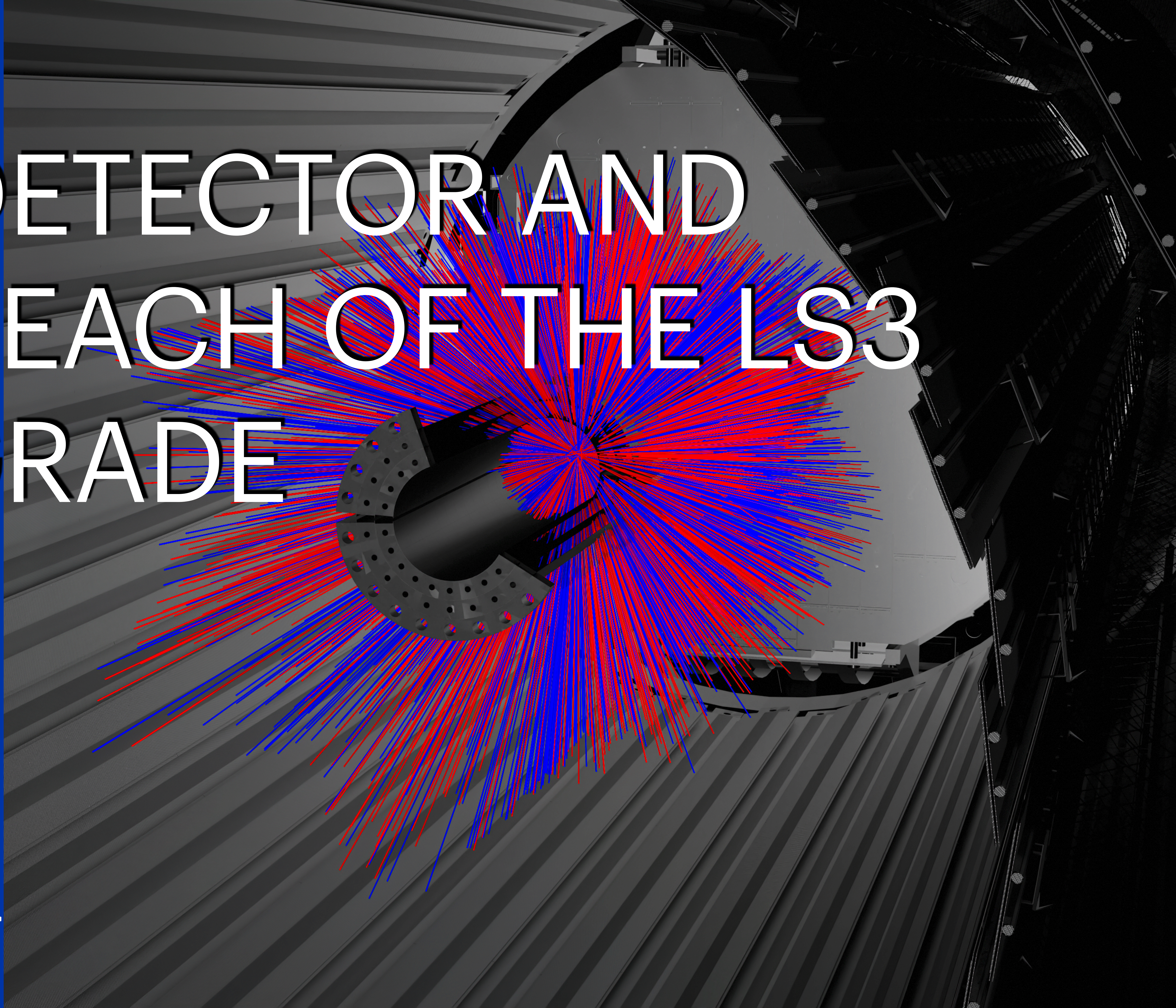
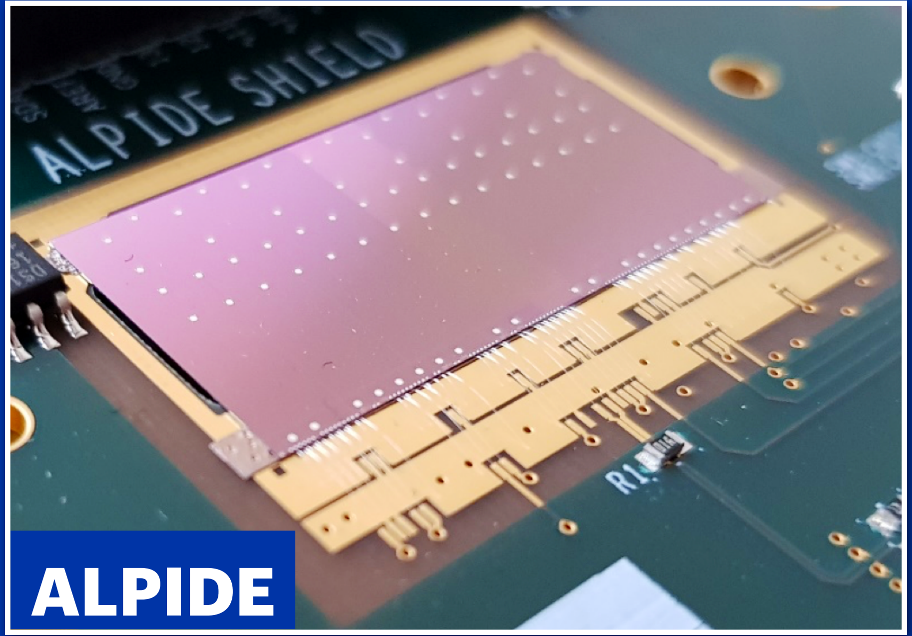
THE ITS3 DETECTOR AND PHYSICS REACH OF THE LS3 ALICE UPGRADE

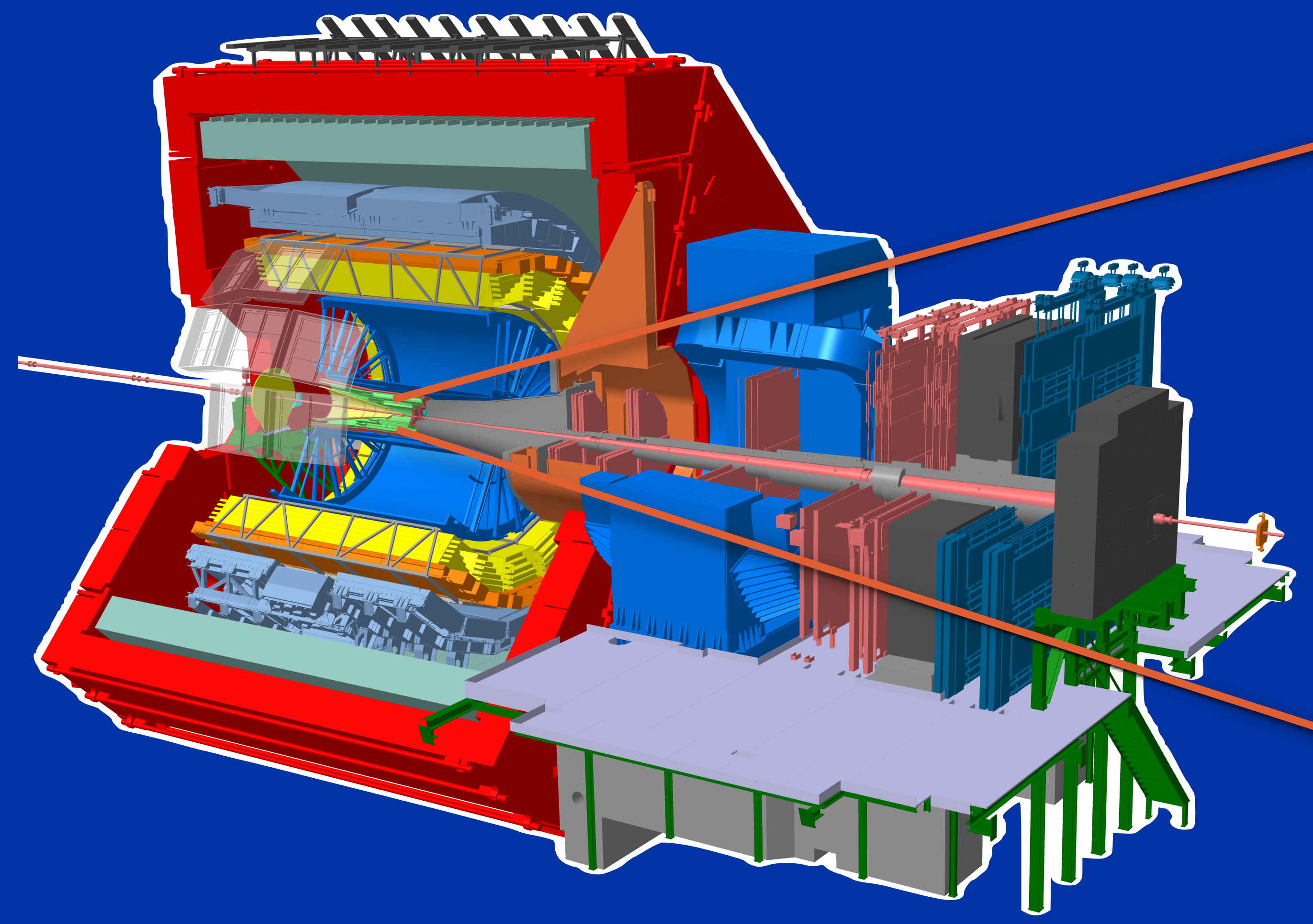


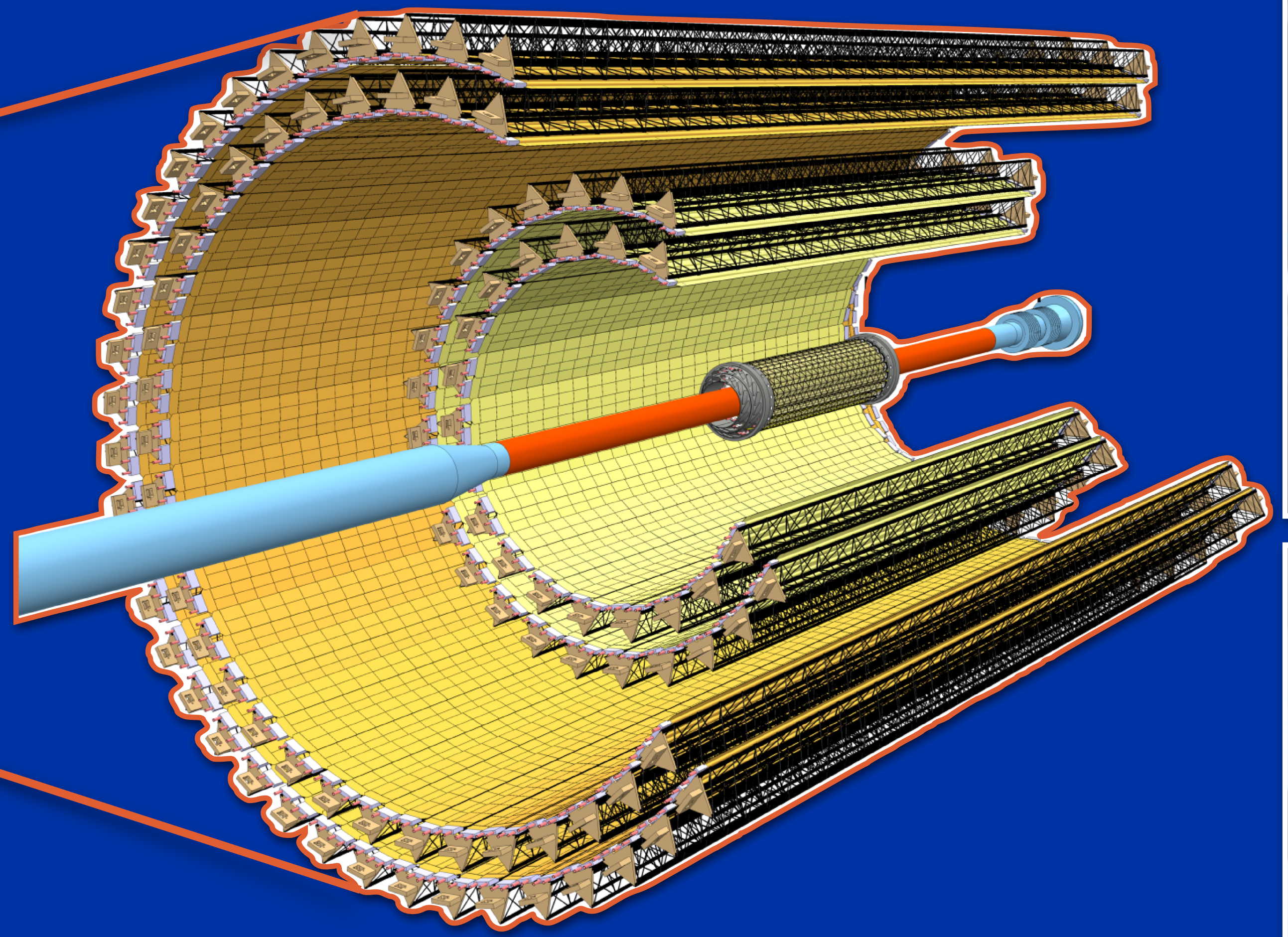
Felix Schlepper
On behalf of the ALICE Collaboration

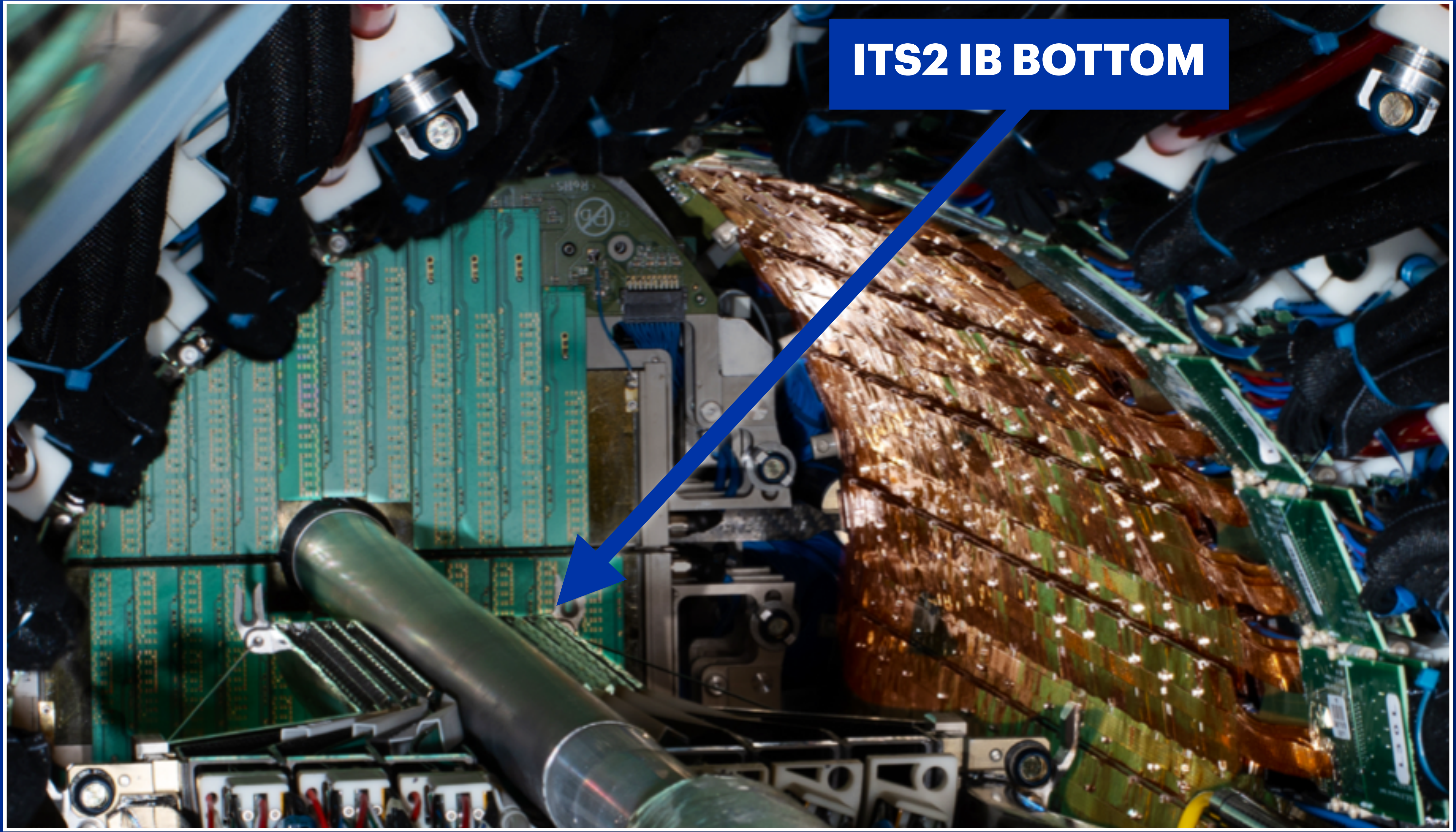
ALICE ICHEP 2024

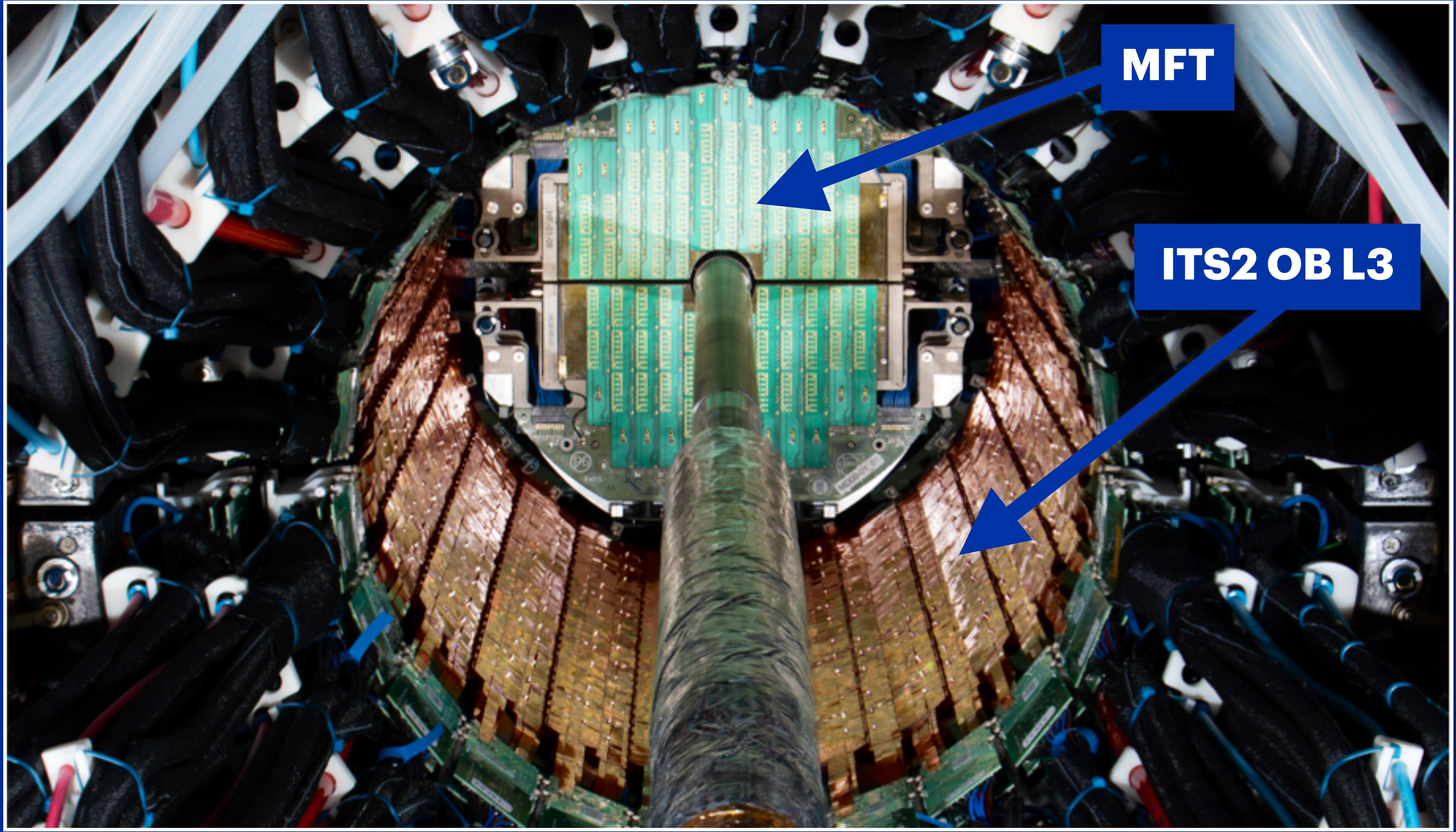
Inner Tracking System 2 (ITS2)











7 Layers

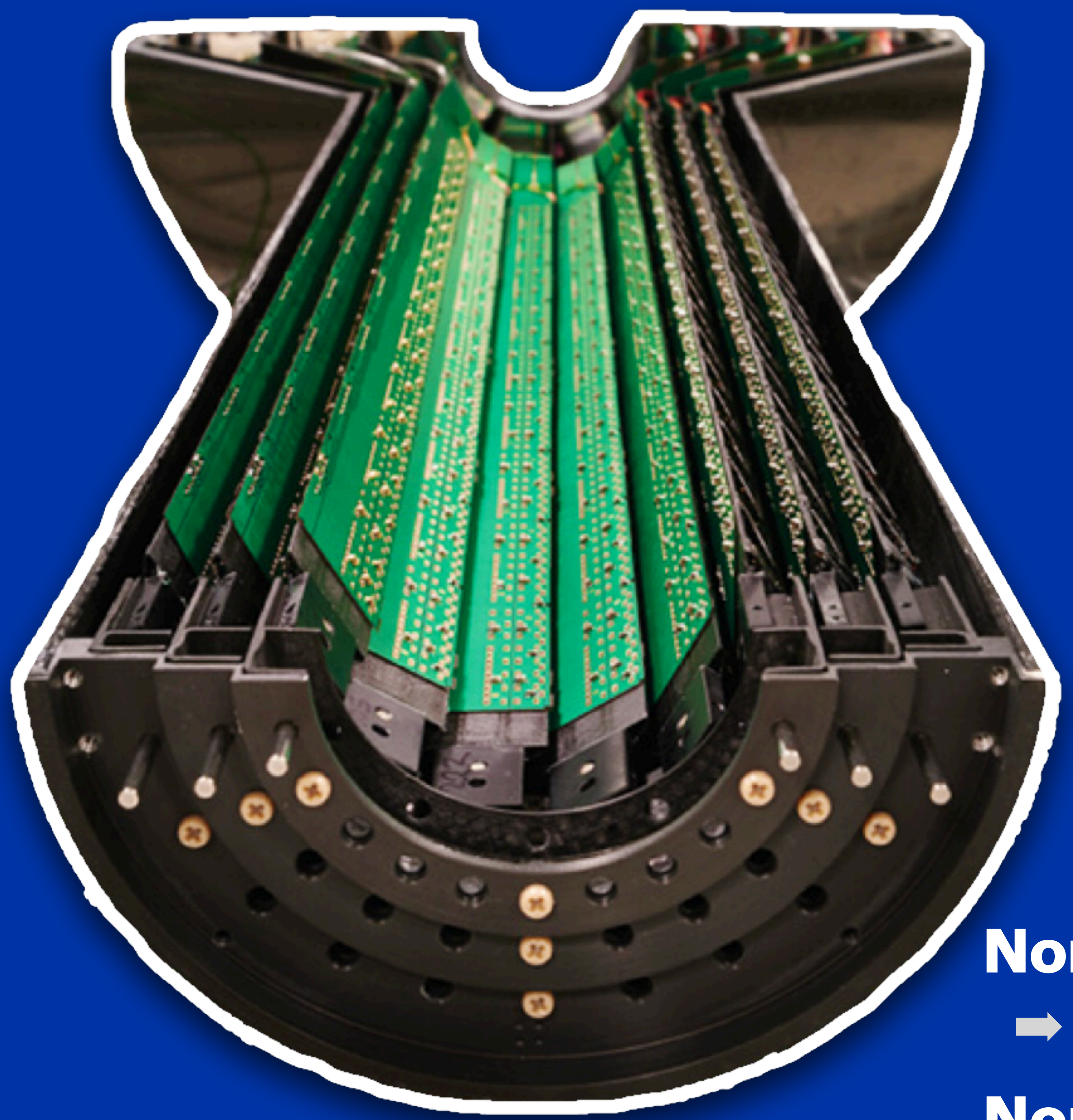
➡ 3 inner barrel (IB) and 4 outer barrel (OB)

Large active area and granularity

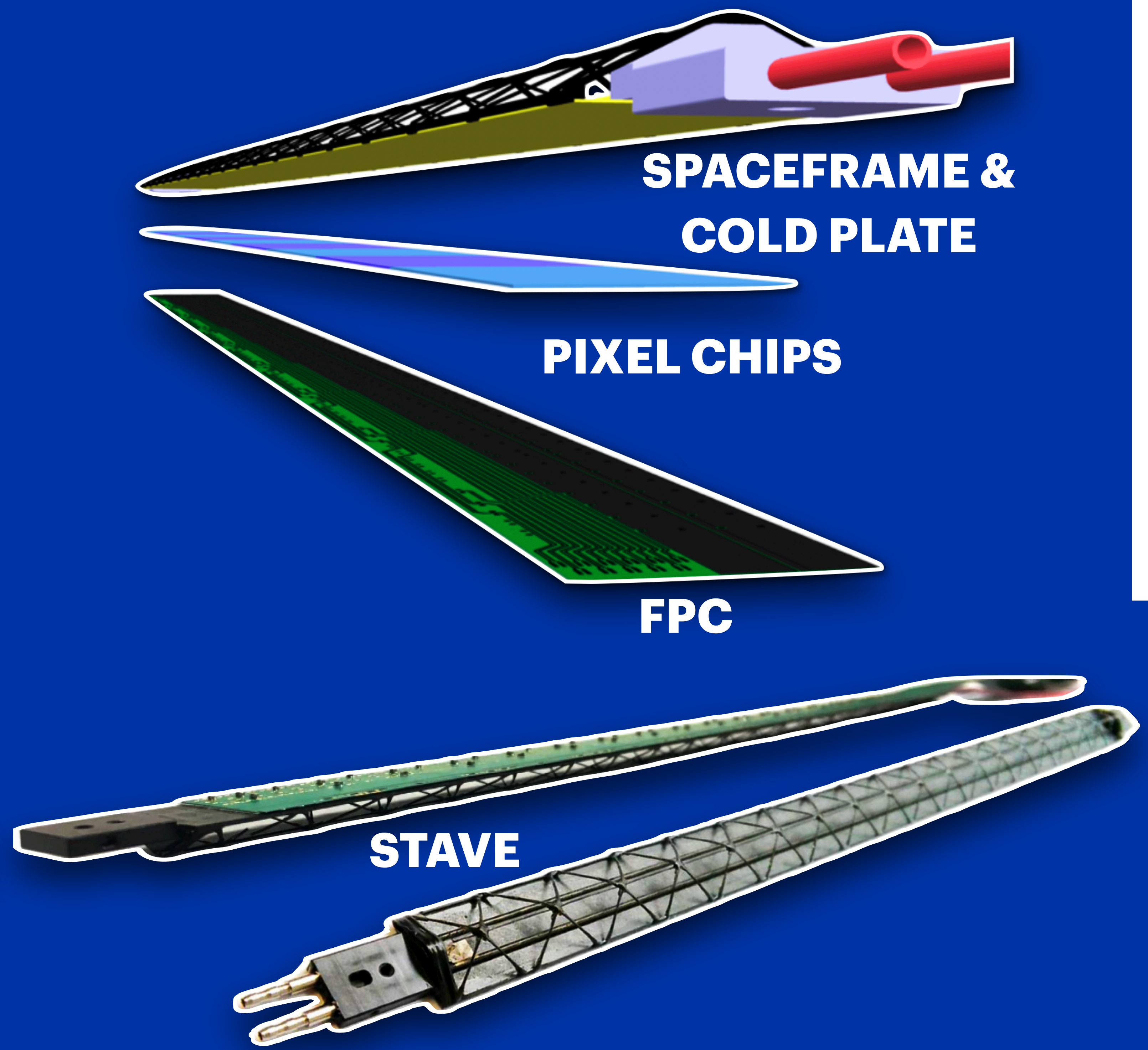
➡ 10 m^2 active silicon area, 12.5 x 10^9 pixels

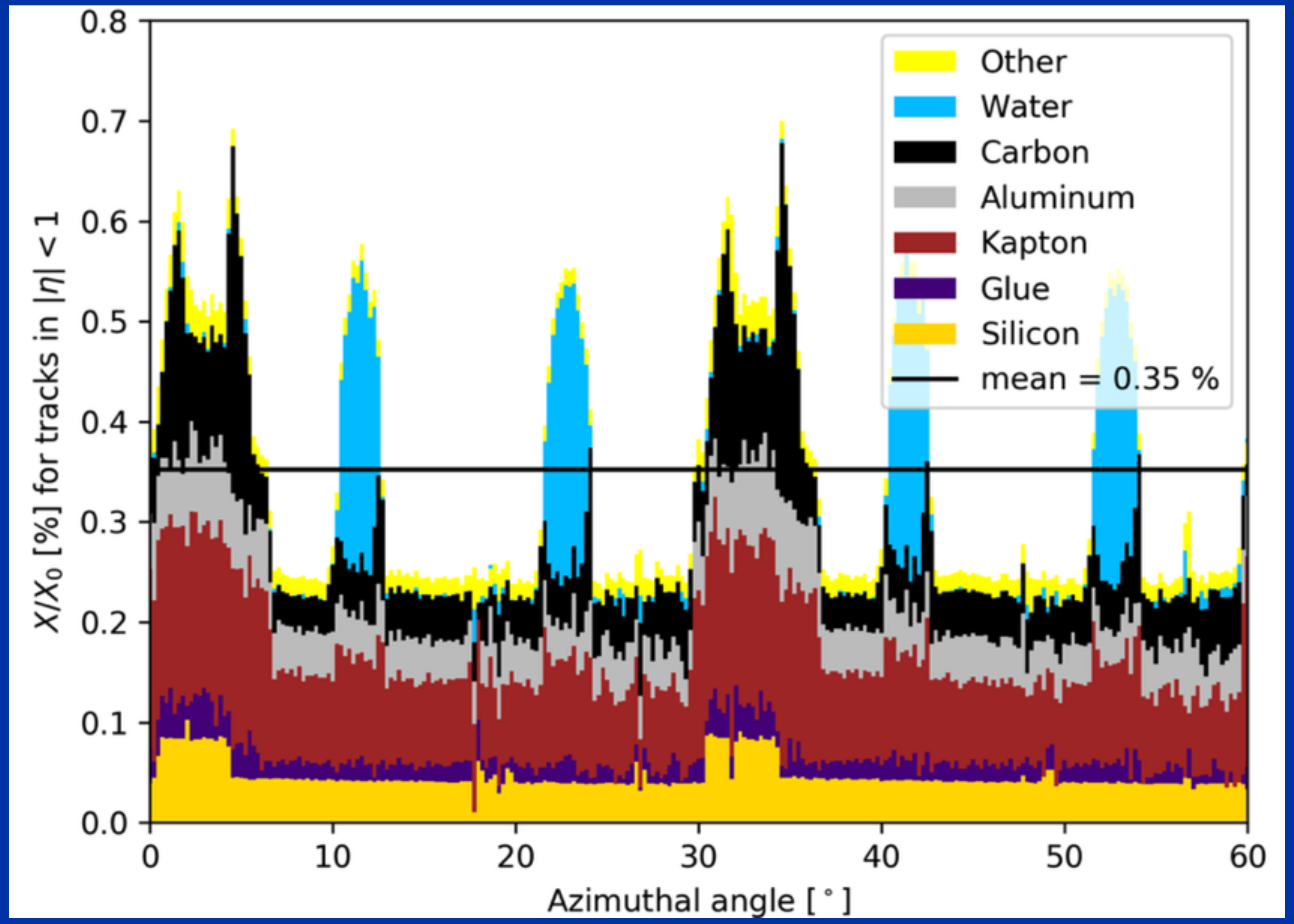
➡ 180 nm CMOS MAPS (Monolithic Active Pixel Sensors) 15 x 30 mm^2, 512 x 1024 pixels

Looking at ITS2



ITS2 IB





Non-sensitive material
- ➡ Silicon has 1/7 of total material budget

Non-uniformly distributed material
- ➡ Staves overlapping, support and water cooling structure

Unable to be closer to the interaction point
- ➡ Mechanical constraints

Remove water cooling
- ➡ New processing chip (with lower power consumption) requiring air cooling

Remove circuit board
- ➡ New technology integrating data, control and power distribution on a single chip

Remove mechanical support
- ➡ New mechanical design

ITS3 replacement for ITS2 IB

New Sensor

Bent wafer-scale sensor ASIC

- ➡ 65 nm CMOS MAPS
- ➡ Fabricated with stitching
- ➡ Power density < 40 mW/cm²

3 layers with 6 sensors

Air cooling between layers

Key benefits

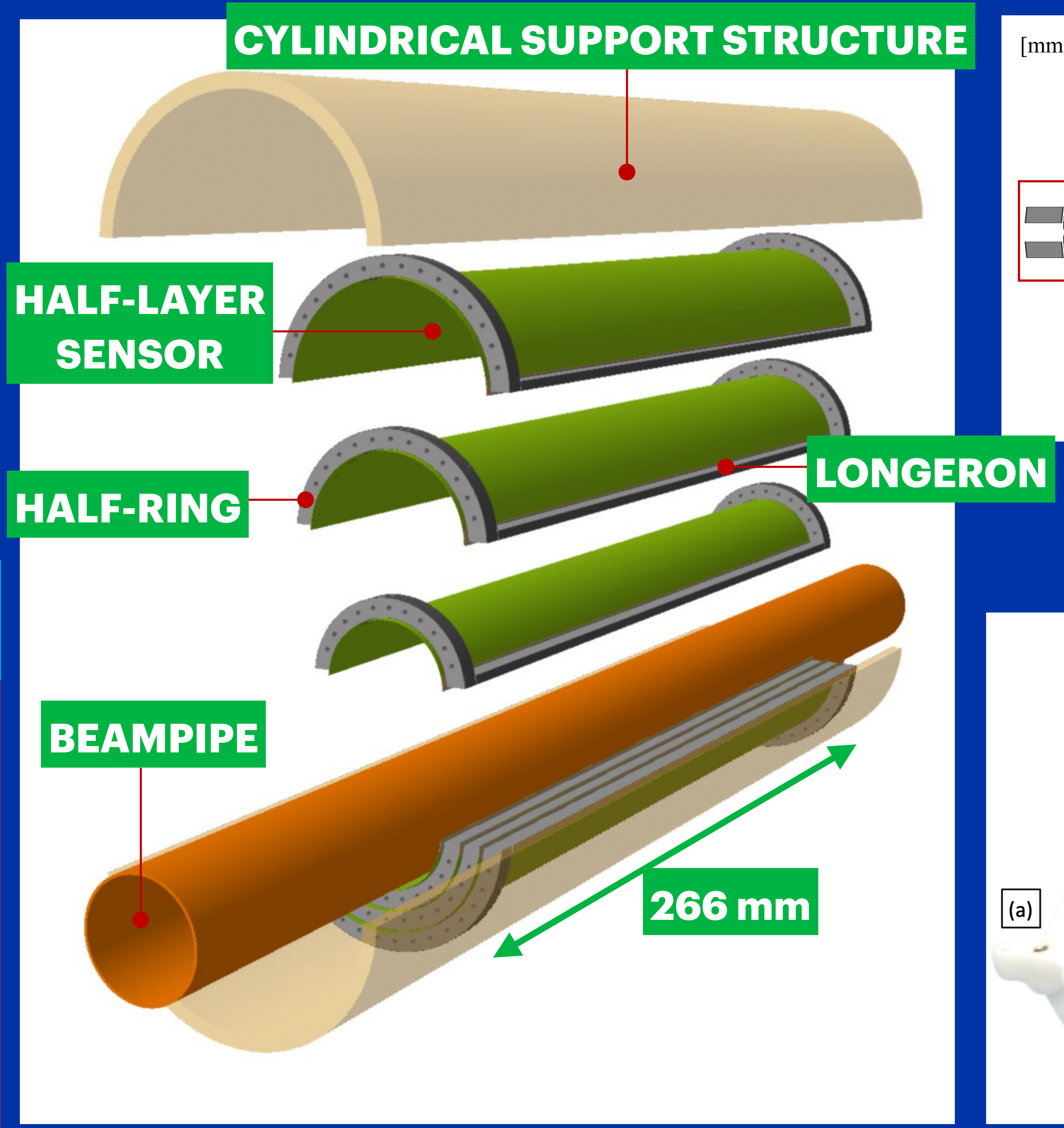
Lower material budget

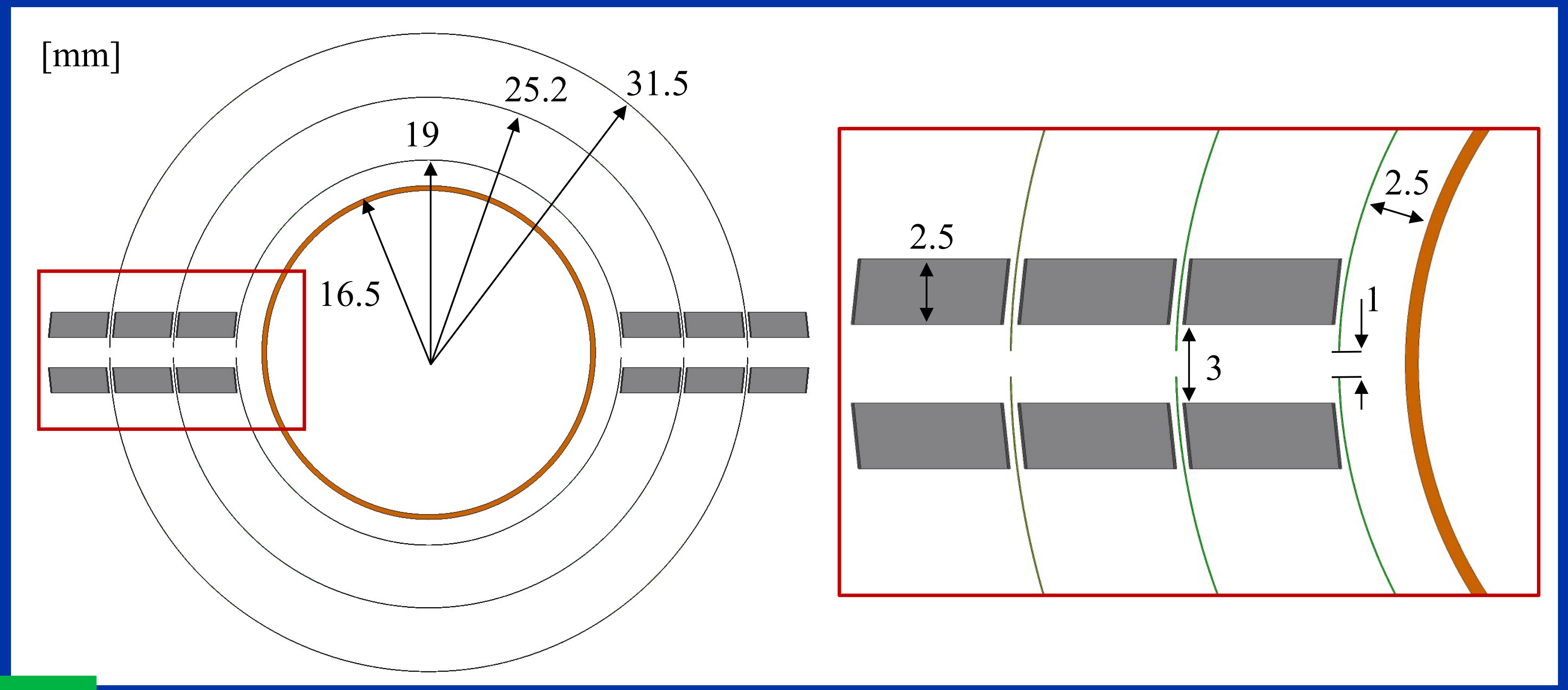
- ➡ 0.35% X_0 → 0.07% X_0 per layer for most of the area

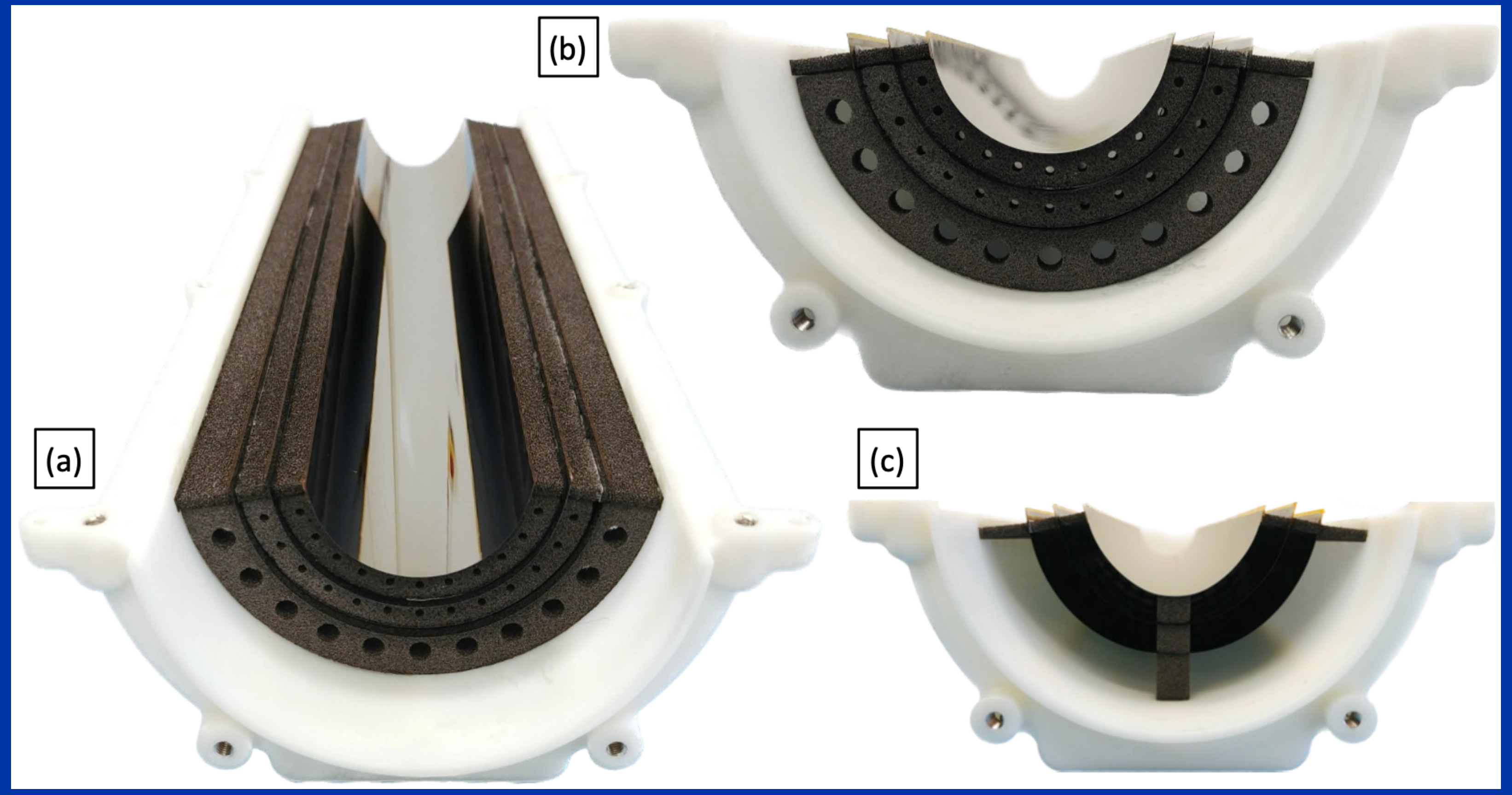
Uniformly distributed material

Closer to interaction point

- ➡ Beampipe: 18.2 mm → 16.0 mm
- ➡ Layer 0 position: ~24 mm → 19 mm



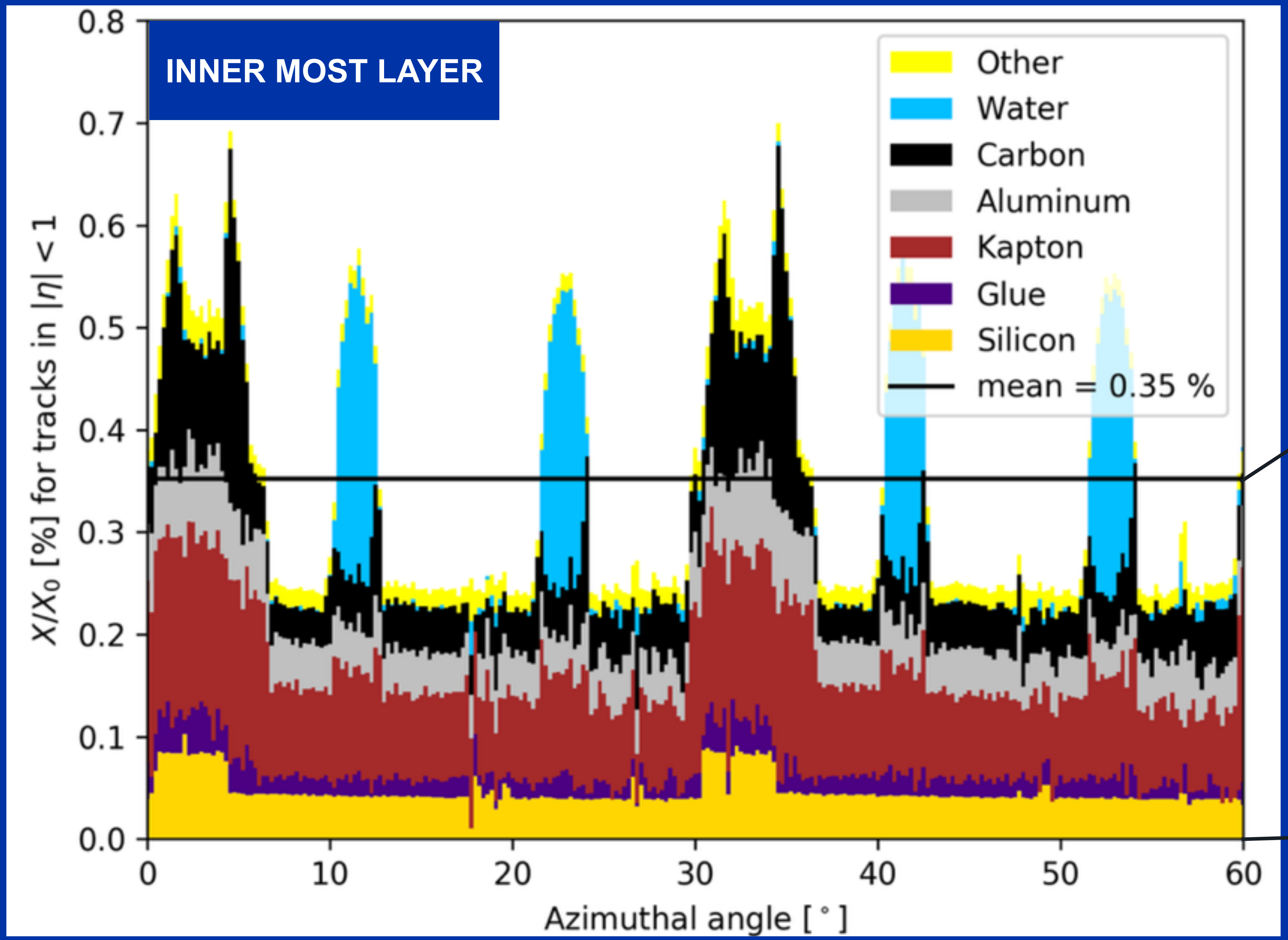


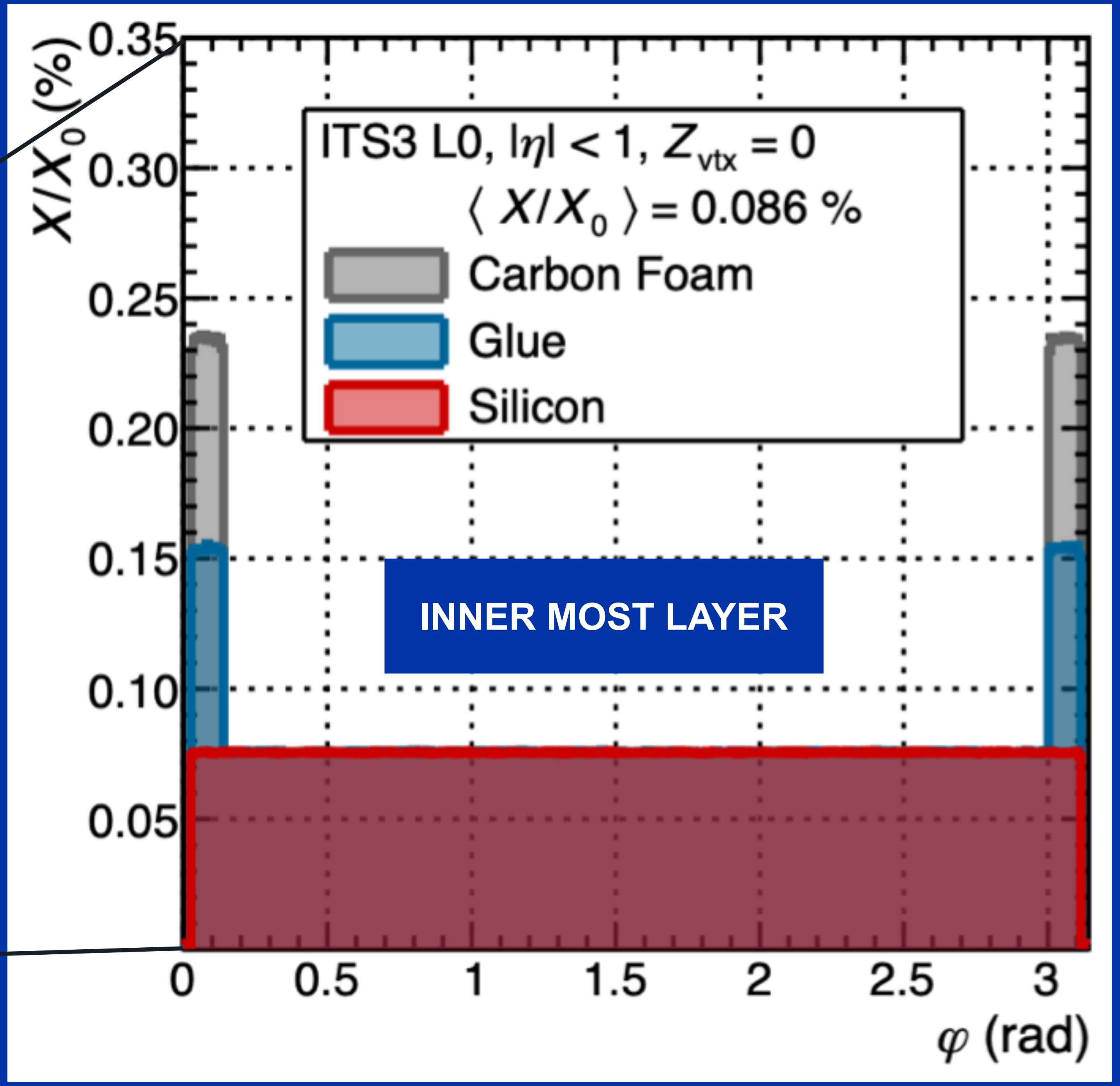


ITS3 TDR: CERN-LHCC-2024-003

ITS3 material budget

ITS3 TDR: CERN-LHCC-2024-003





ITS2 IB

Non-sensitive materials

➡ Silicon has 1/7 of total material budget

Non-uniformly distributed material

➡ Staves overlapping, support, water cooling

ITS3

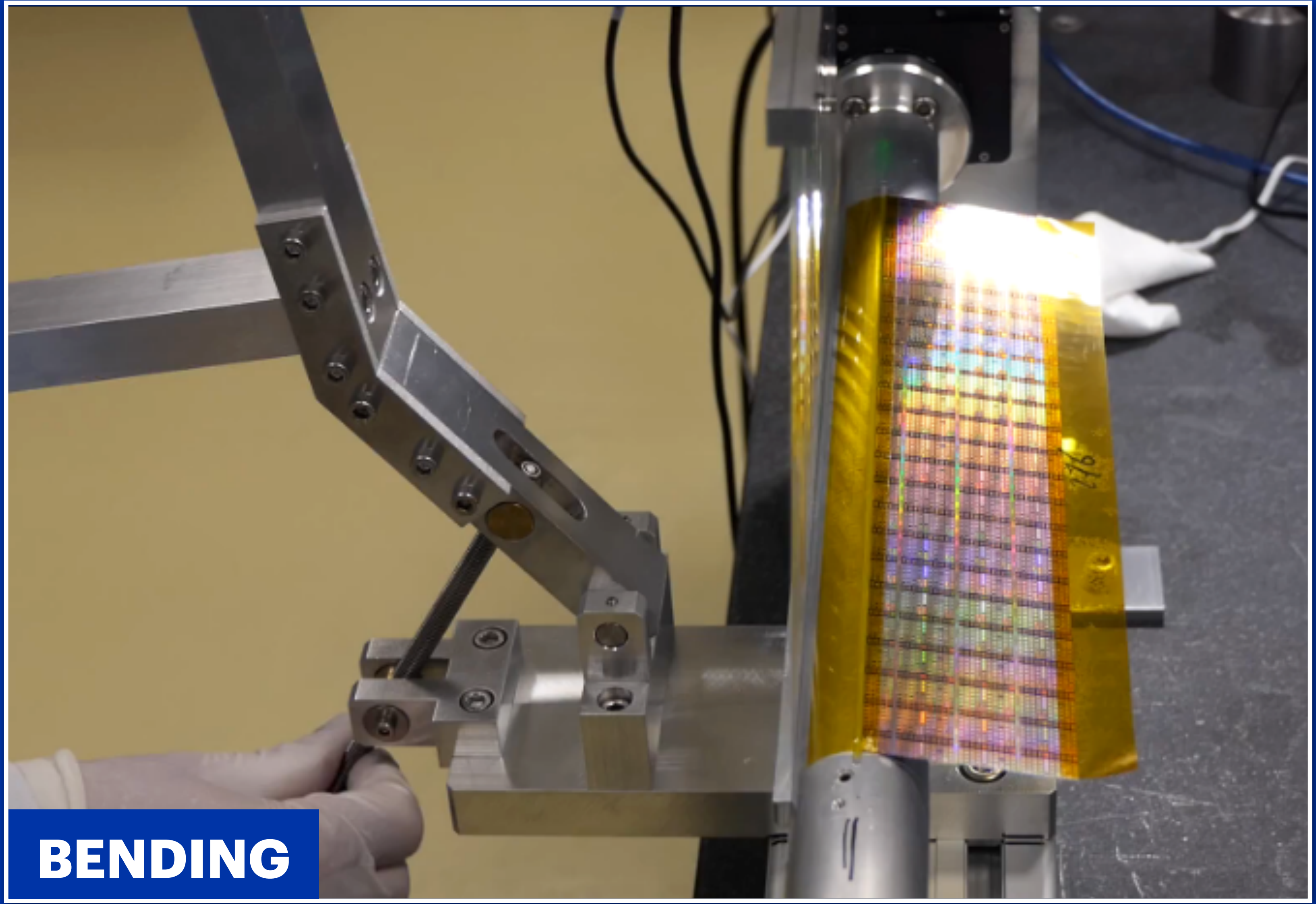
Non-sensitive materials

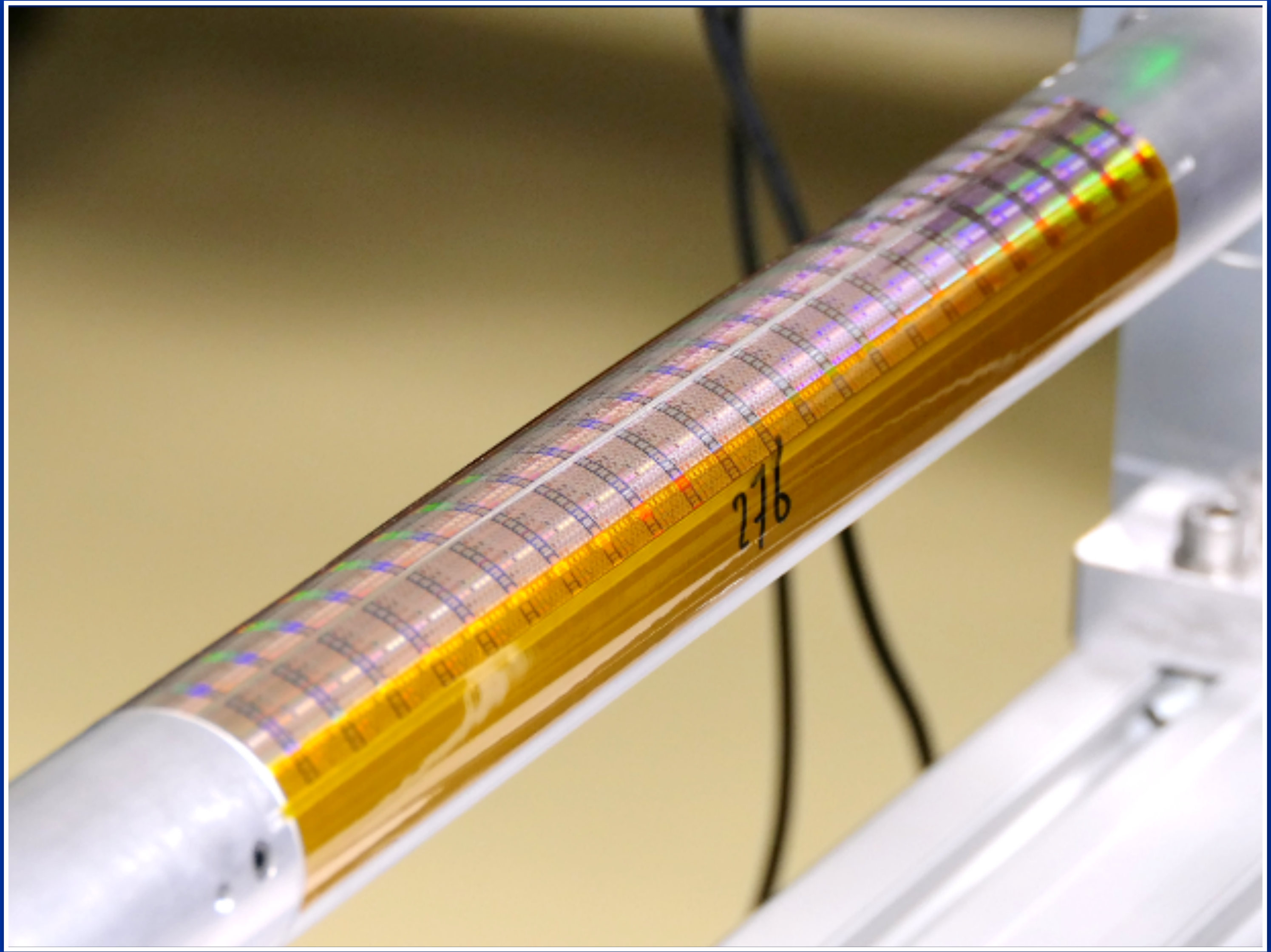
➡ Sillicon dominates

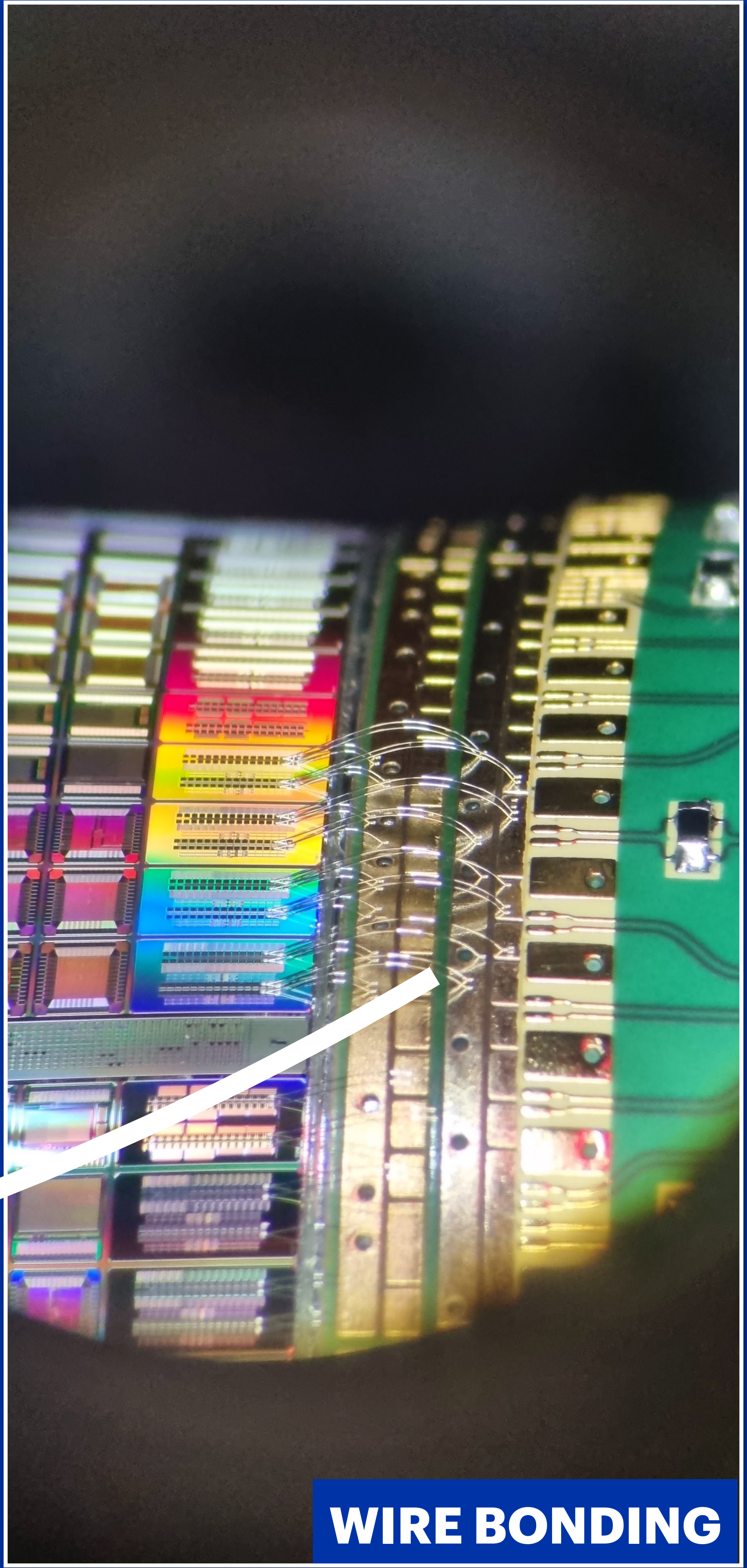
Uniformly distributed material

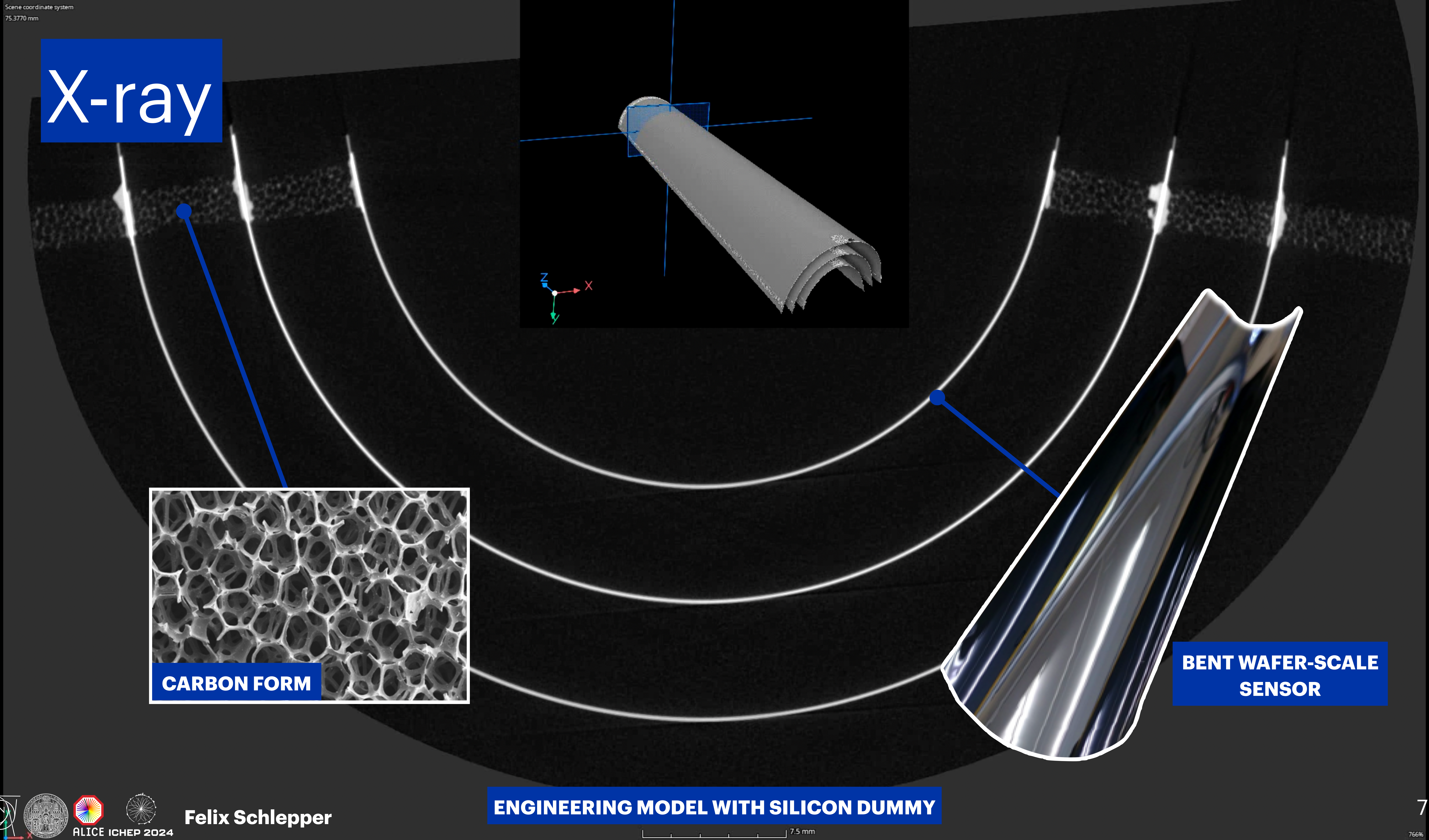
➡ Only lightweight carbon foam and glue distributed on the edge of the sensitive area

ITS3 bending/interconnection procedure








Scene coordinate system
75.3770 mm
X-ray
Z
X
Y
CARBON FORM
BENT WAFER-SCALE SENSOR
ENGINEERING MODEL WITH SILICON DUMMY
7.5 mm

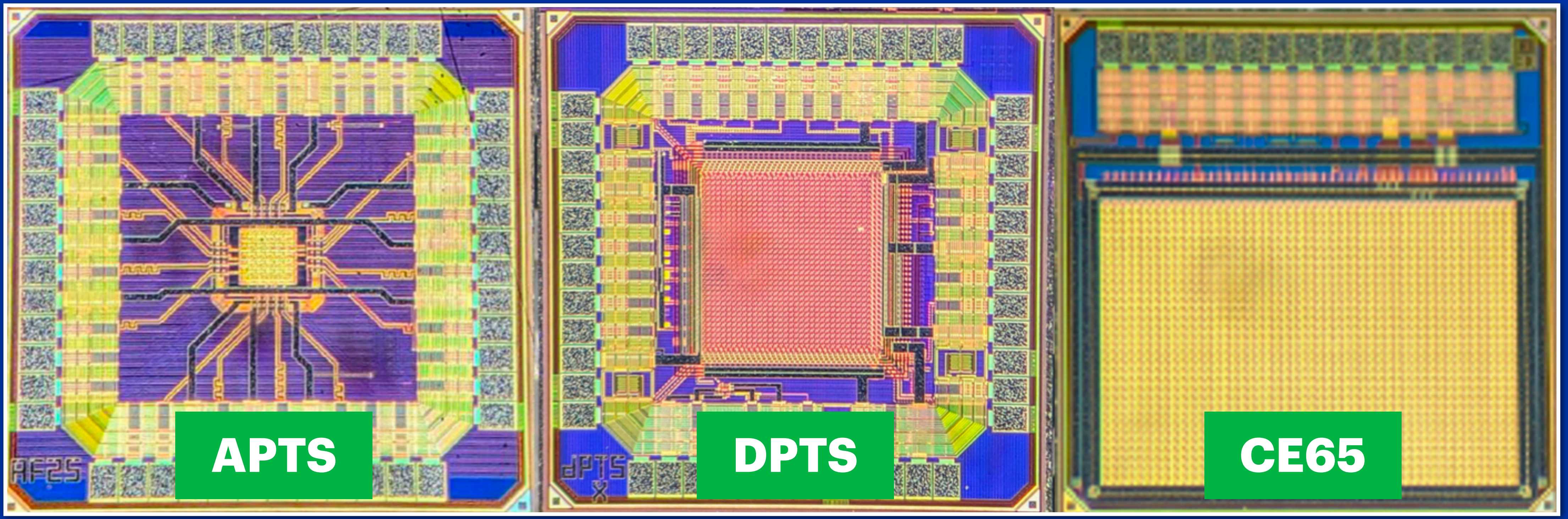
Chip development roadmap

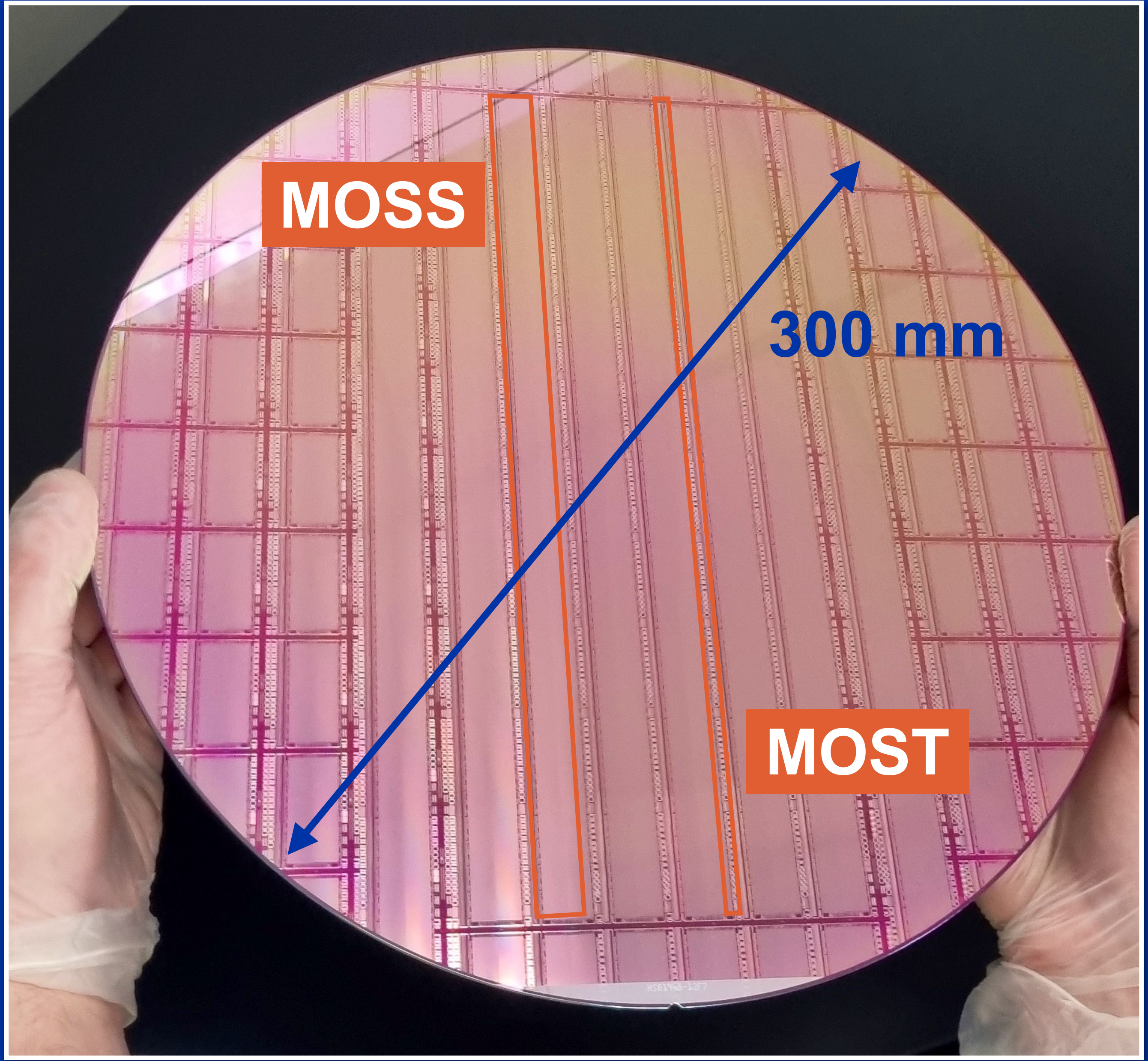
MLR1 (Multi-reticle Layer Run 1)
- ➡ First 65 nm process MAPS
- ➡ APTS, DPTS, CE65
- ➡ Successfully qualified the 65 nm process for ITS3

ER1 (Engineering Run 1)
- ➡ First stitched MAPS
- ➡ MOSS, MOST
- ➡ Successfully qualified the large scale sensor design

ER2 (Engineering Run 2)
- ➡ ITS3 sensor prototype
- ➡ Design ongoing

ER3 ITS3 sensor production





APTS
- ➡ Analogue Pixel Test Structure

DPTS
- ➡ Digital Pixel Test Structure

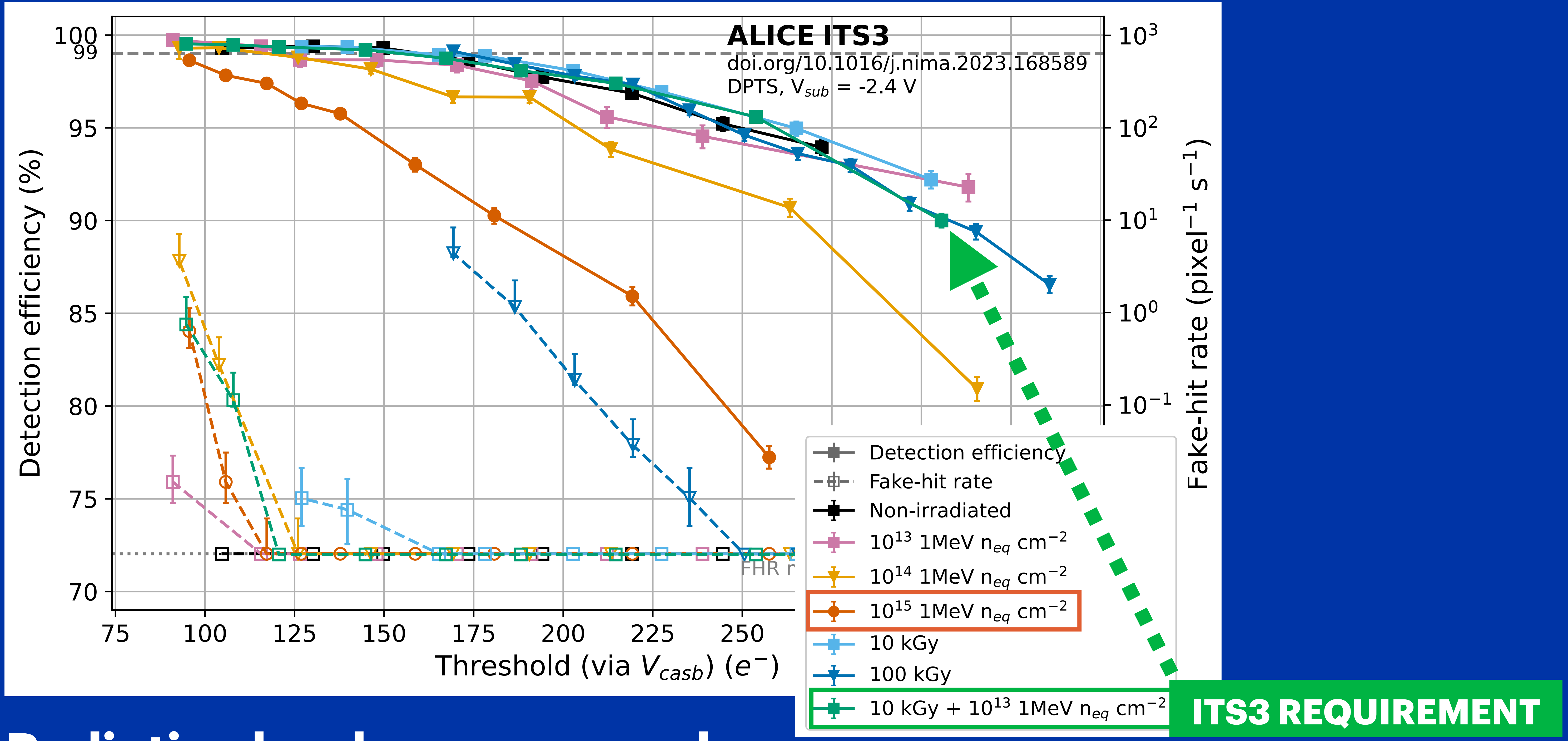
CE65
- ➡ Circuit Exploratoire 65 nm

MOSS
- ➡ Monolithic Stitched Sensor

MOST
- ➡ Monolithic Stitched Sensor Timing

MLR1 selected testing results

G. A. Rinella et al., arXiv:2403.08952
G. A. Rinella et al., NIM-A 1056, 168589 (2023)



Radiation hardness assessed

➡ Under the irradiation requirements of ITS3, and even under higher levels, the chip operates normally

MLR1 selected testing results

G. A. Rinella et al., arXiv:2403.08952
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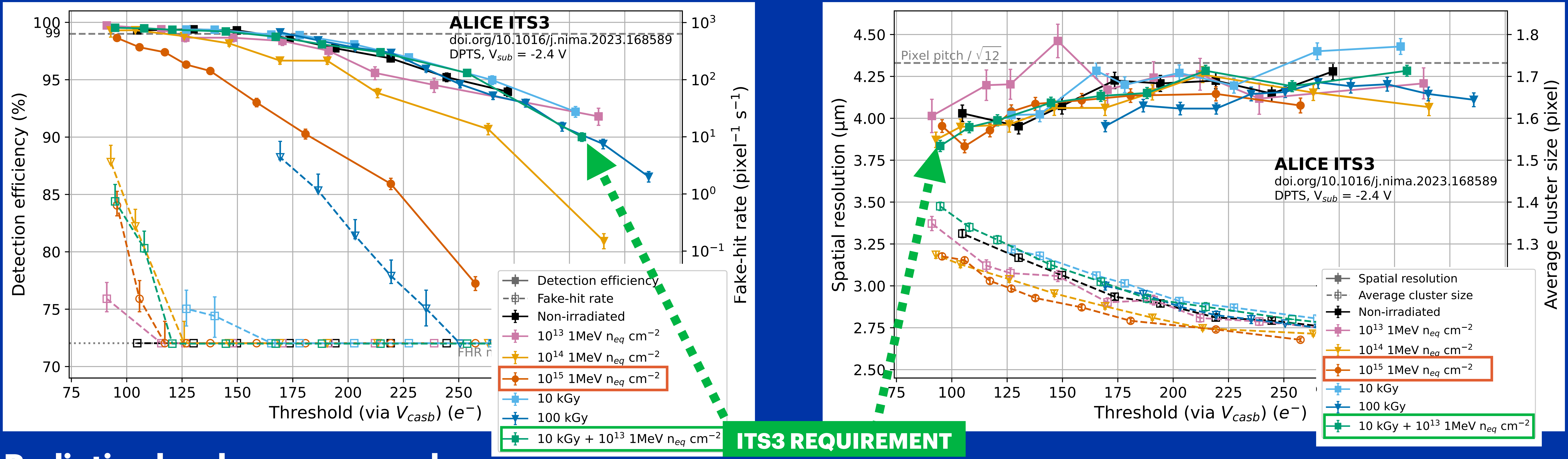


Radiation hardness assessed

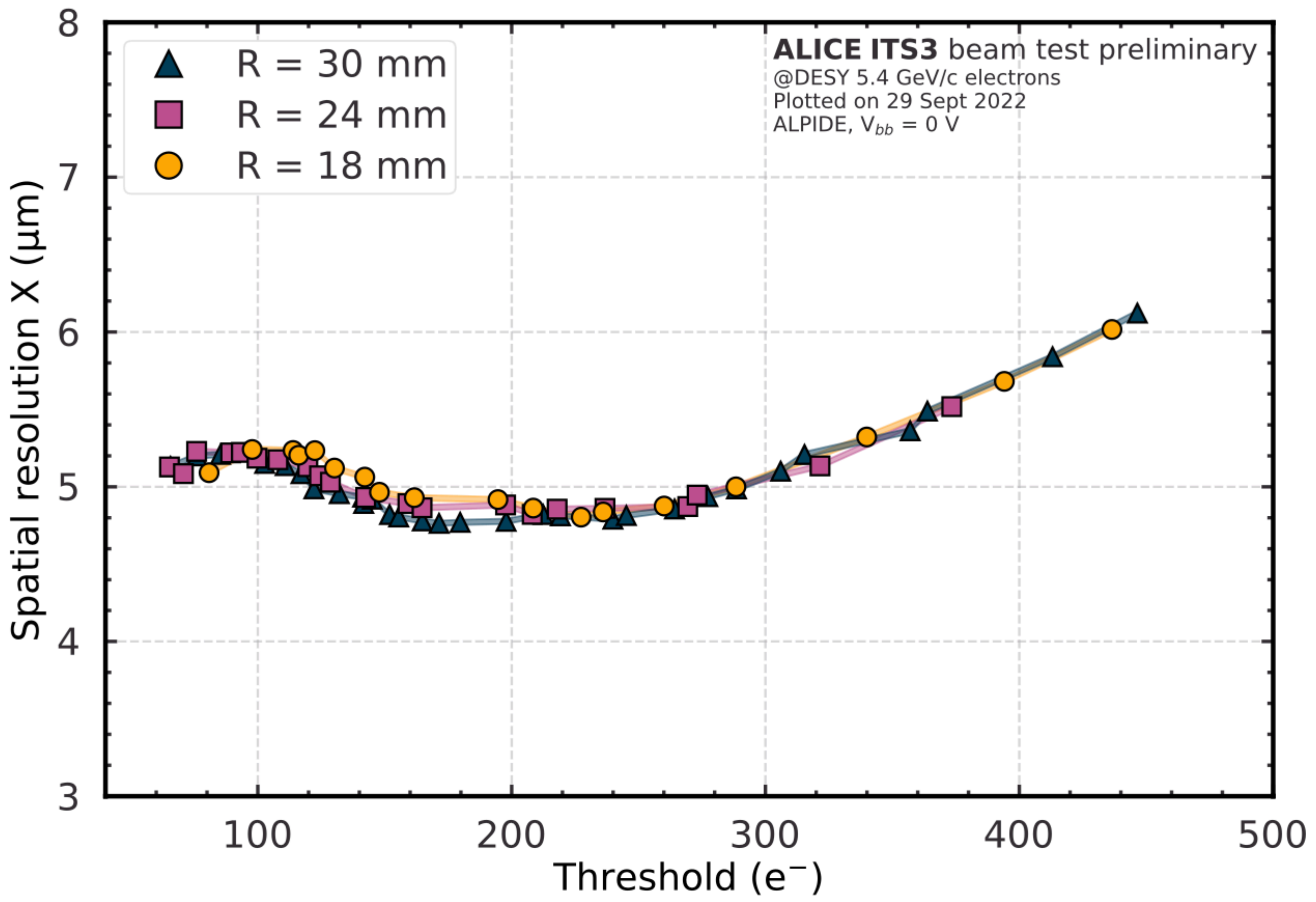
➡ Under the irradiation requirements of ITS3, and even under higher levels, the chip operates normally

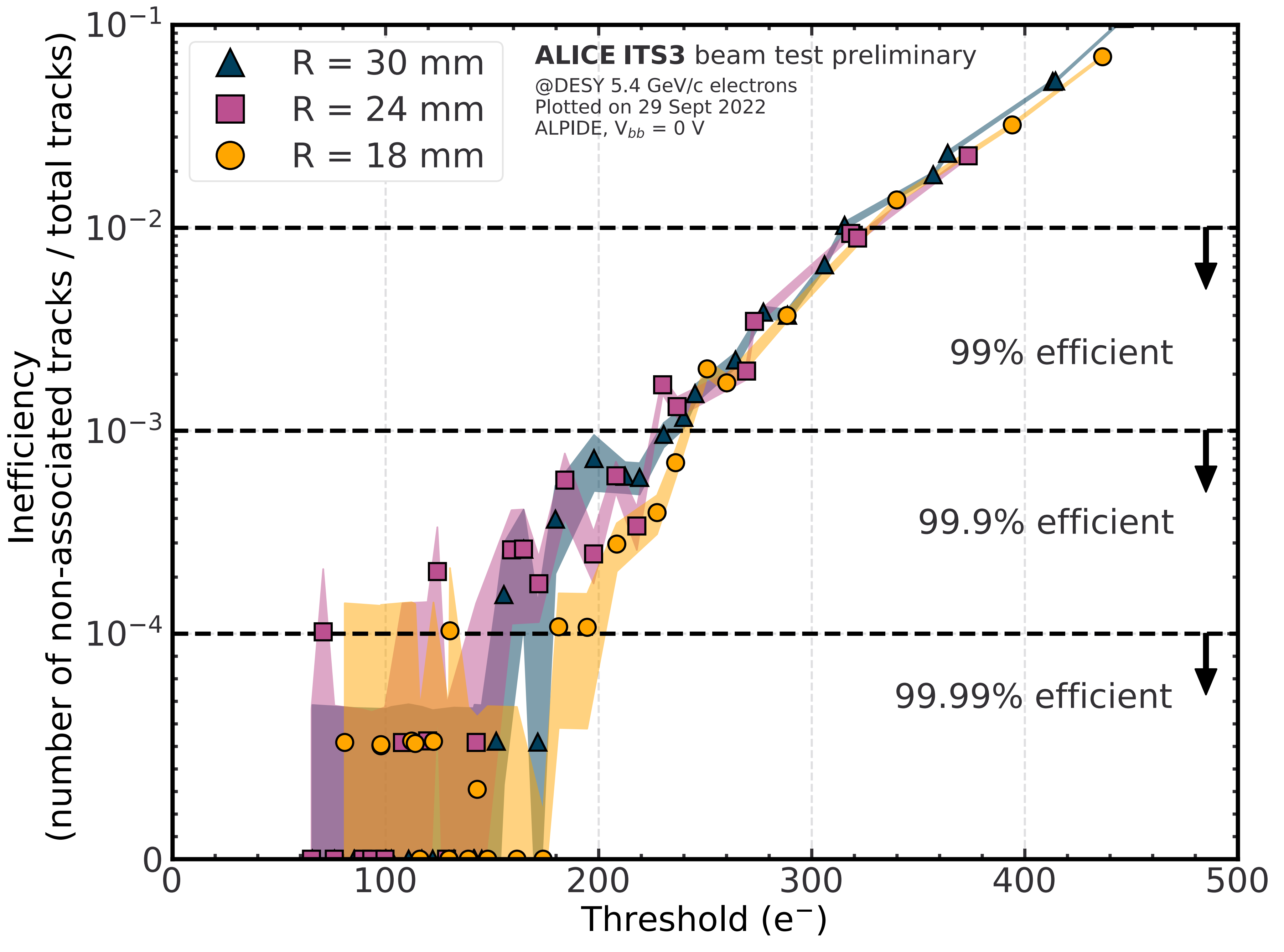
Spatial resolution and cluster size

➡ Evaluated for different levels of irradiation: spatial resolution not affected by irradiation, average cluster size slightly increases with irradiation

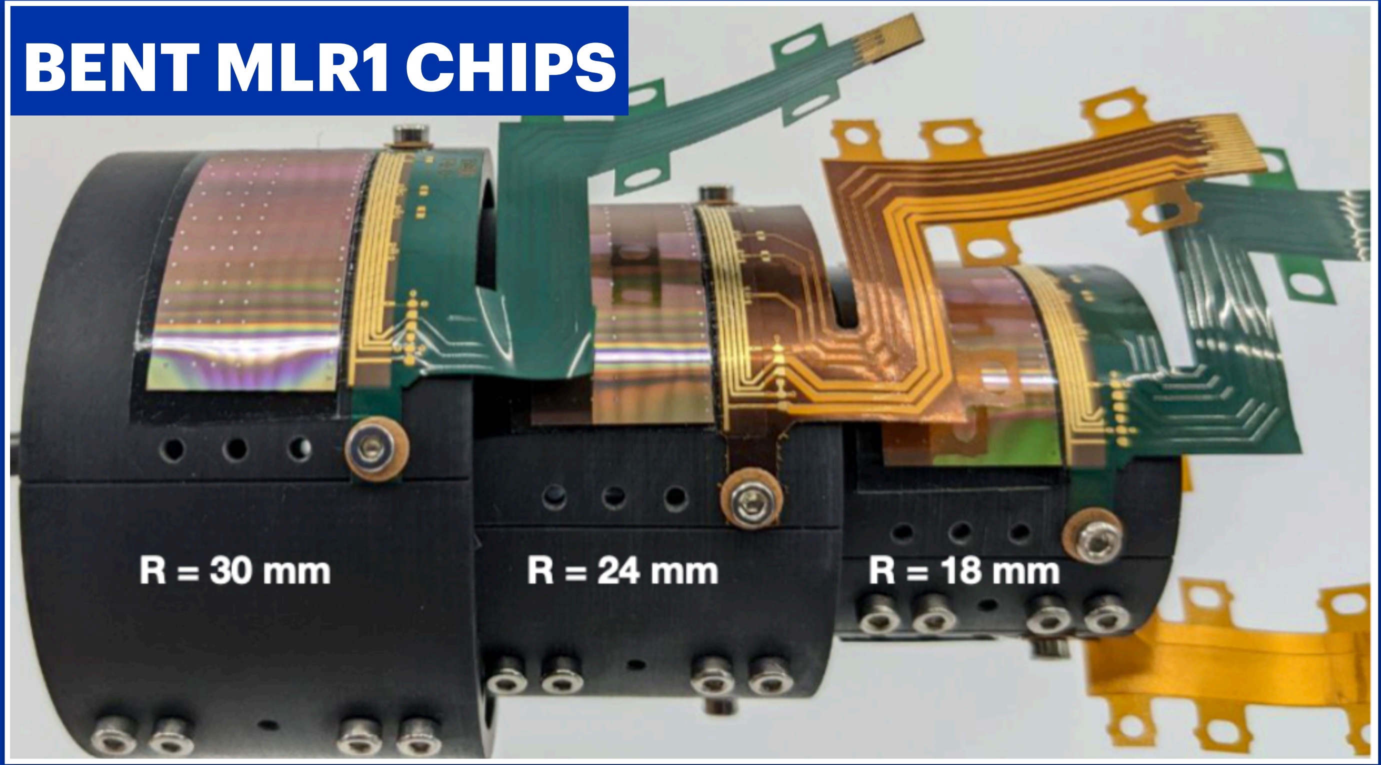
Excellent performances of the 65 nm technology have been established experimentally

Bent MAPS characterisation





Bent MAPS work

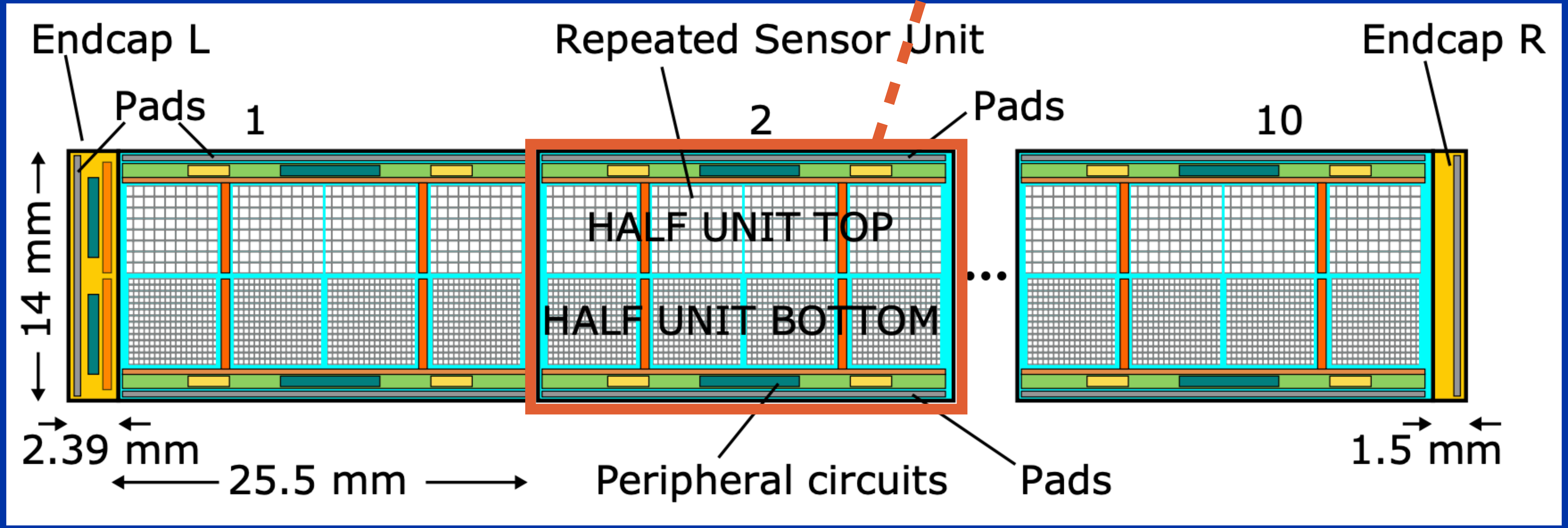


No performance degradation observed when bending

- ➡ Spatial resolution of 5 µm consistent with flat ALPIDEs
- ➡ Efficiency > 99.99% for nominal operating conditions
- ➡ Inefficiency compatible with flat ALPIDEs

MLR1 chips (65 nm process) were also tested and the results were consistent

ER1 MOSS



First stitched chips

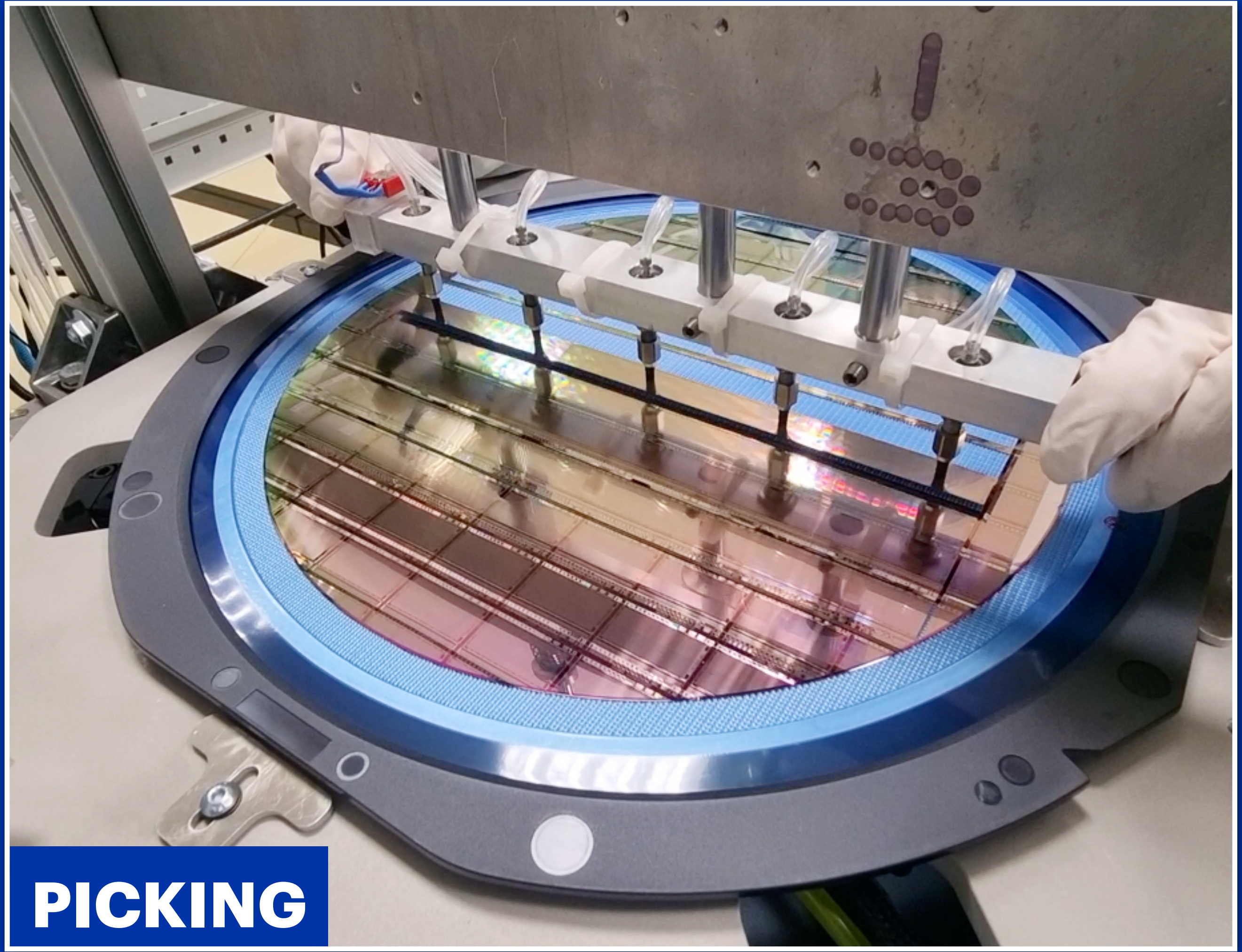
- Full module on a single chip
- Wafer-scale (14 x 259 mm^2), 6.72 million pixels

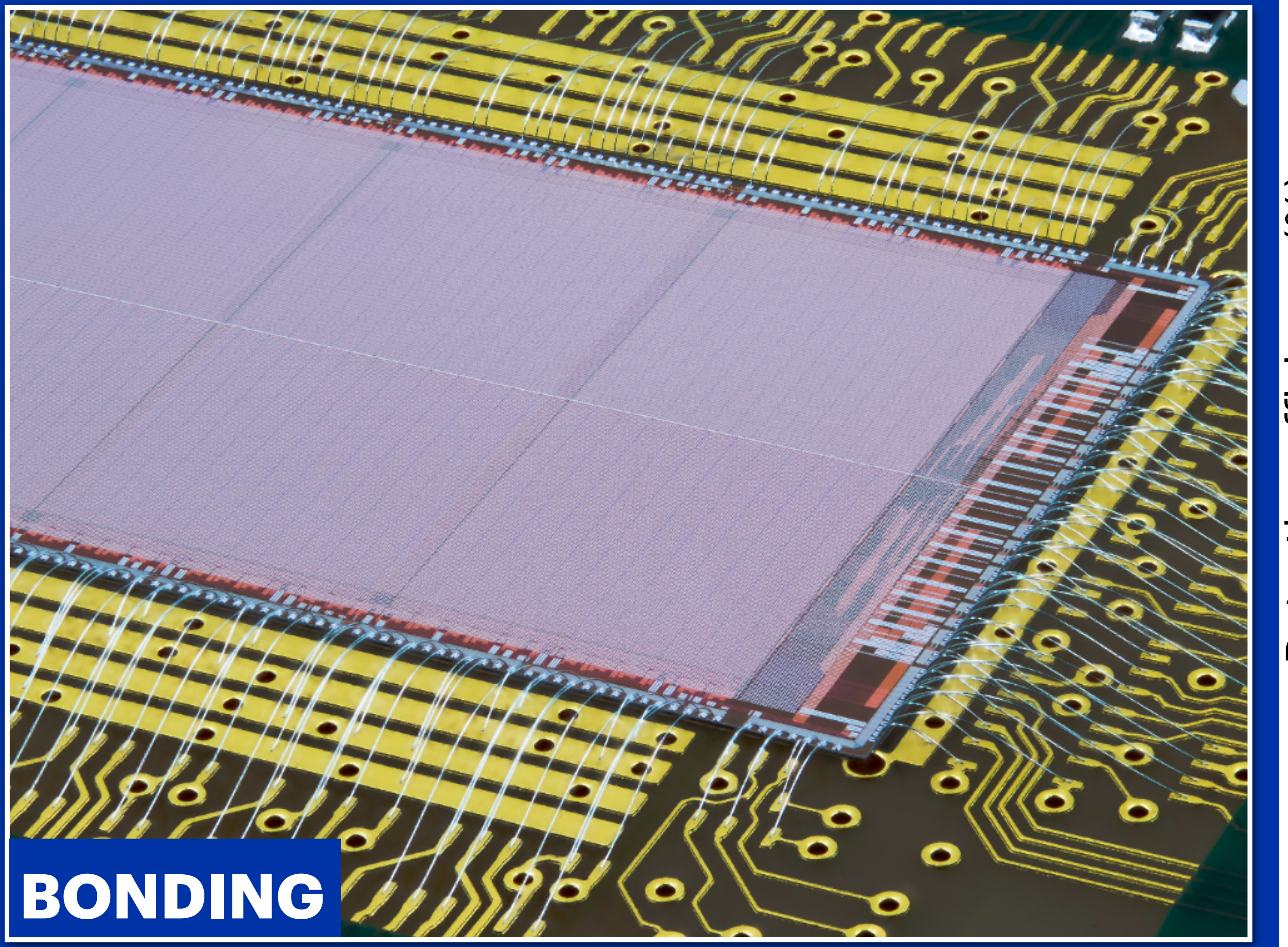
MOSS segmented into 10 repeated sensor units (RSU)

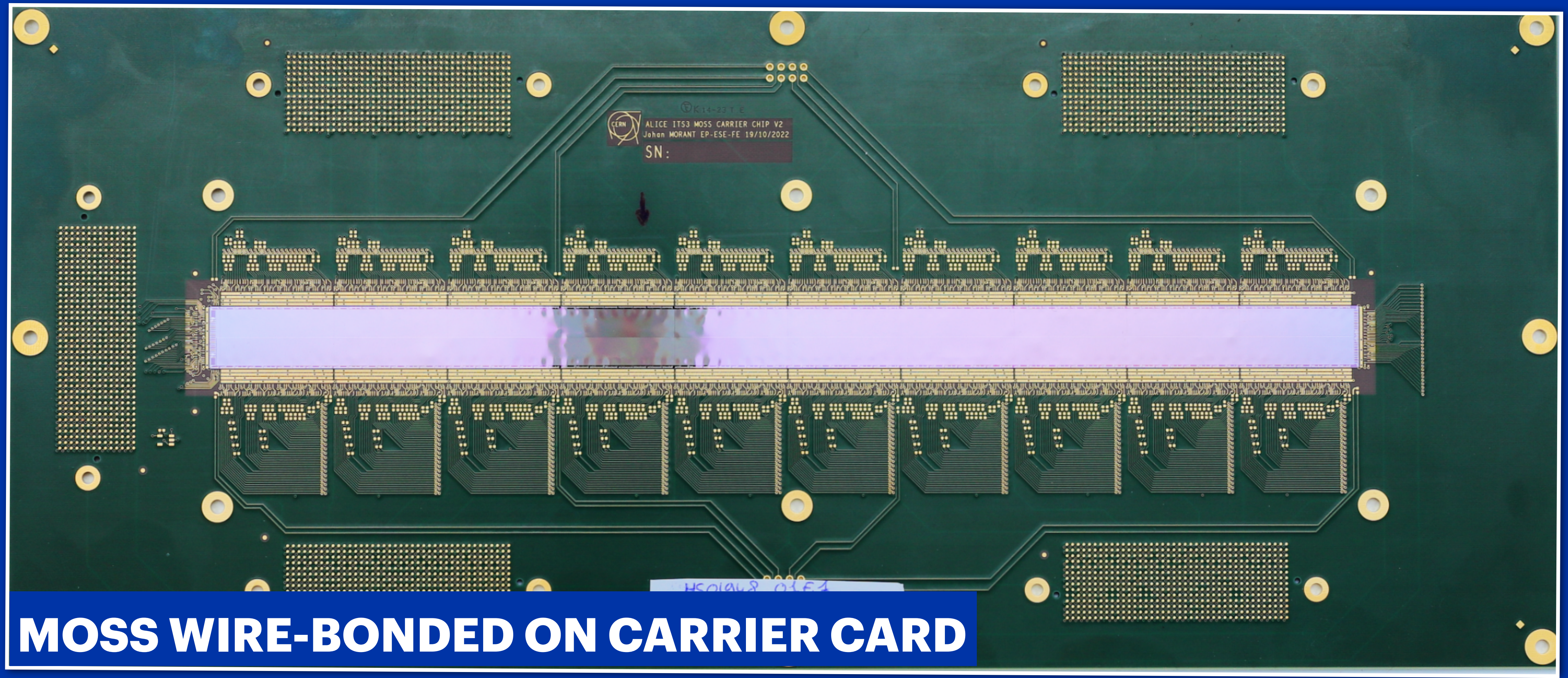
- RSUs are divided into top and bottom half units with different pitch sizes

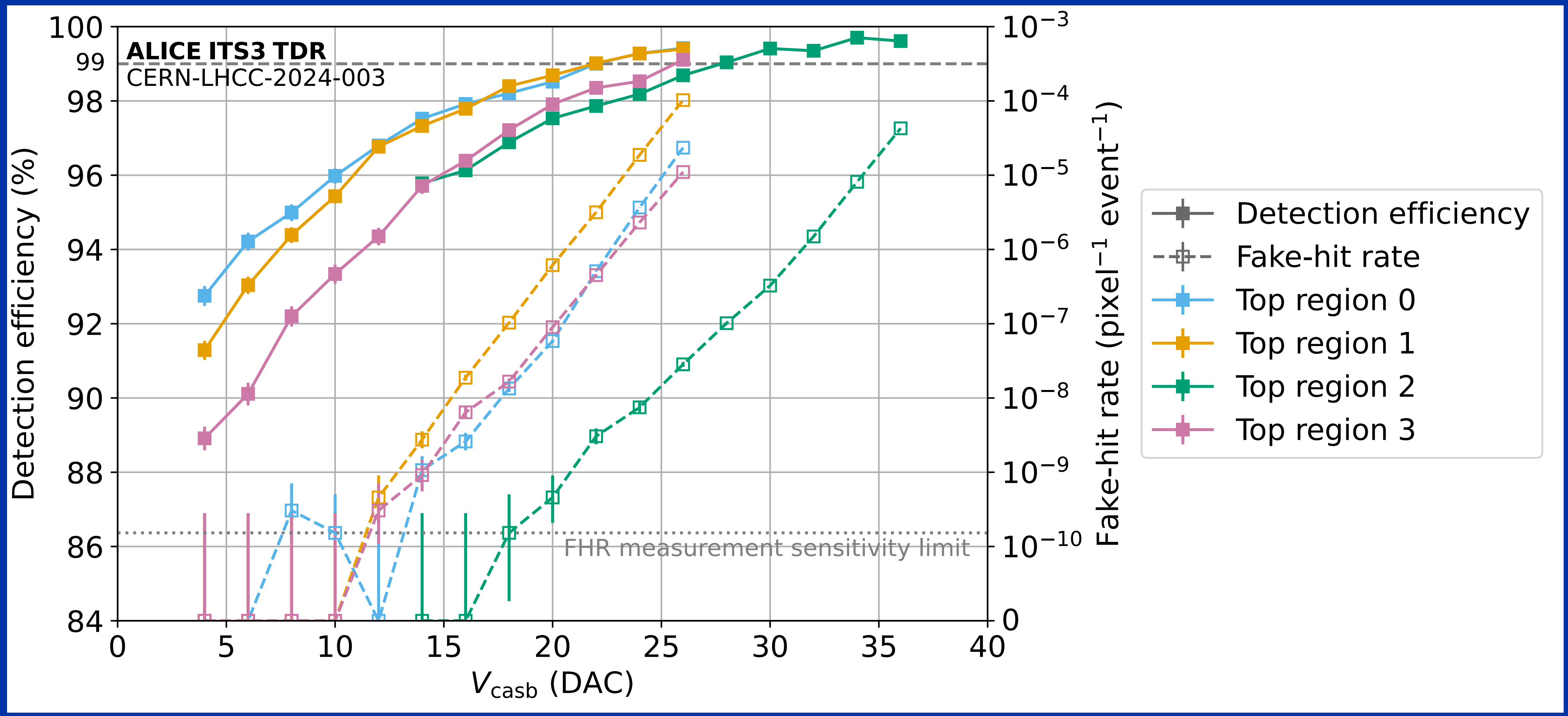
Matrices	Pixel matrix	Pitch size (µm)
Top	256×256	22.5
Bottom	320×320	18

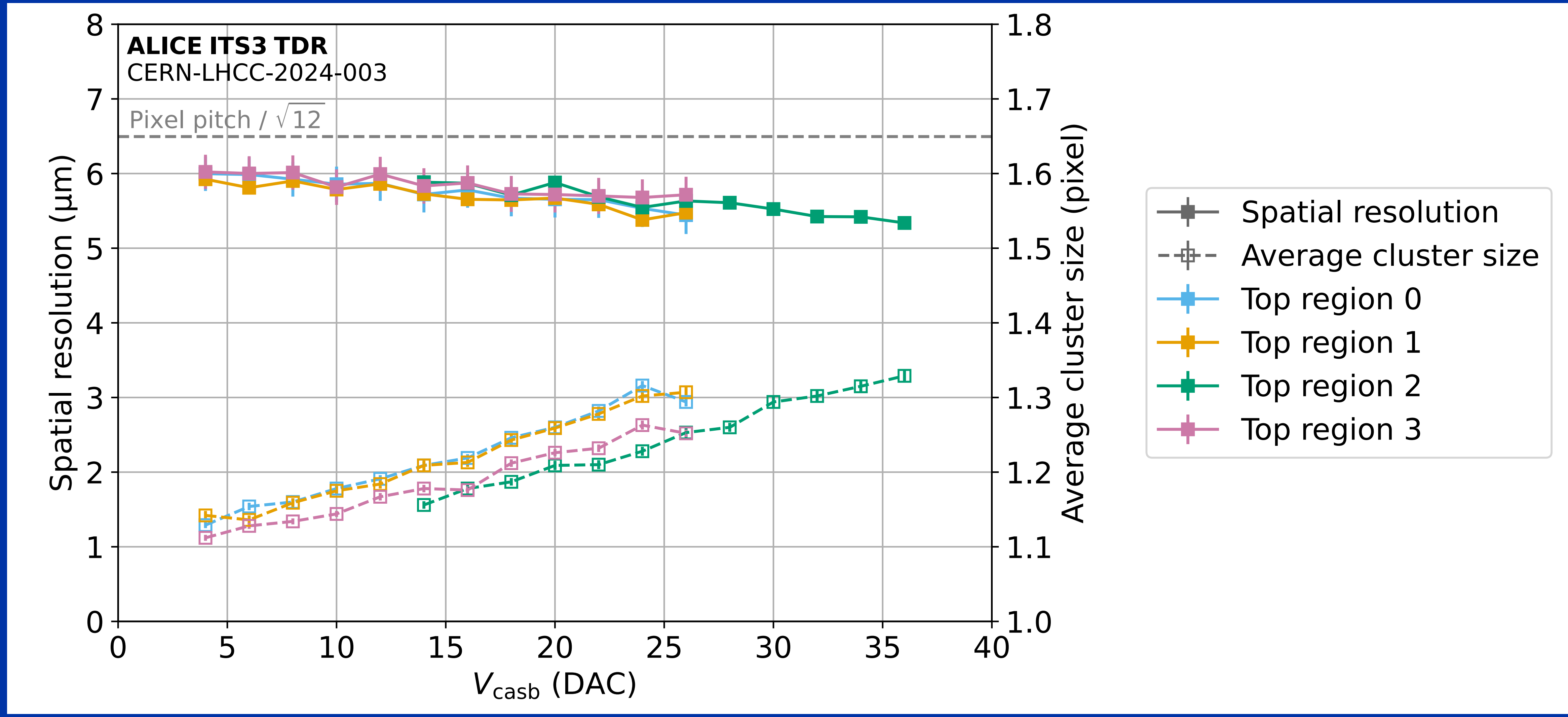
ER1 MOSS selected testing results





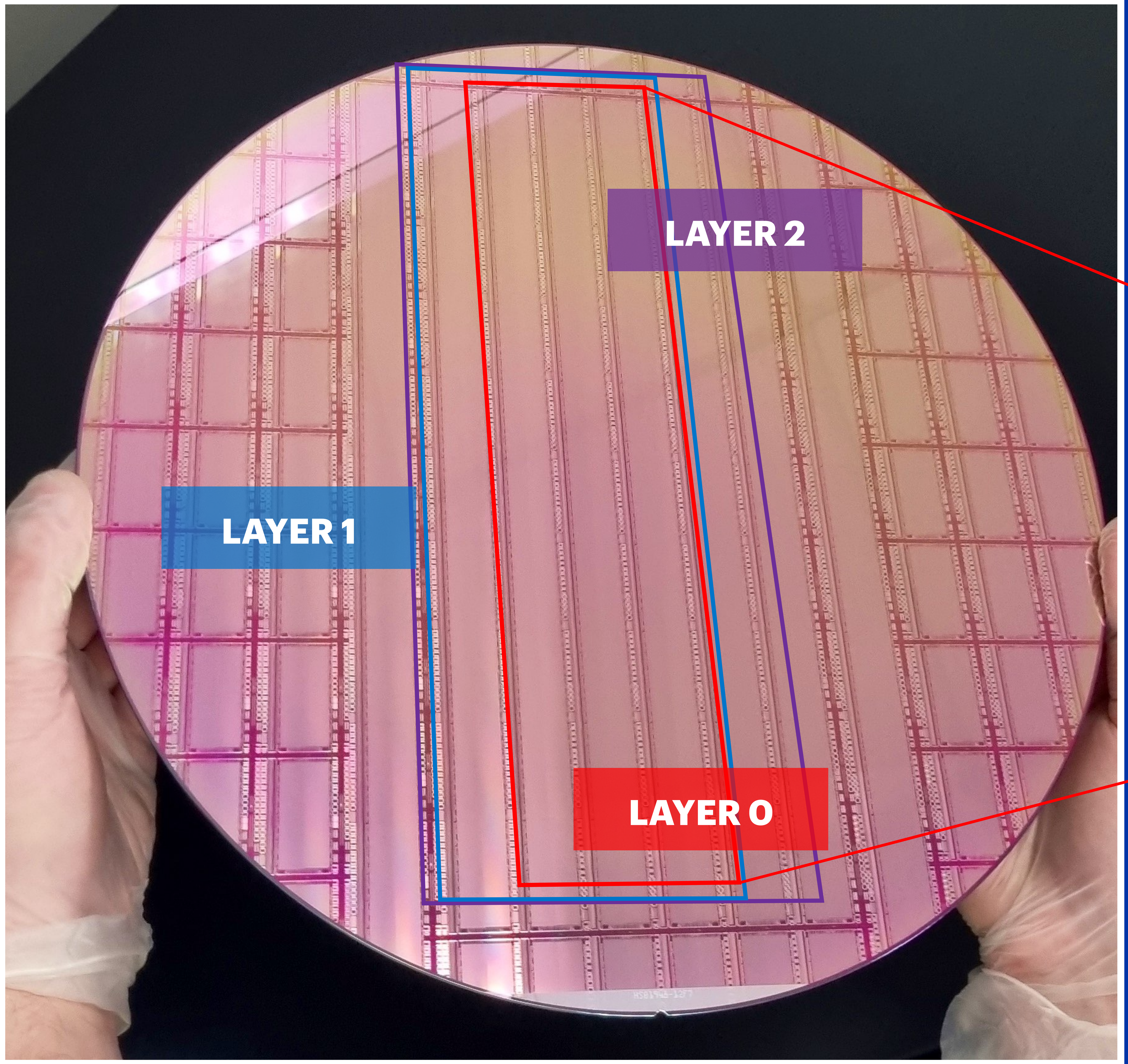


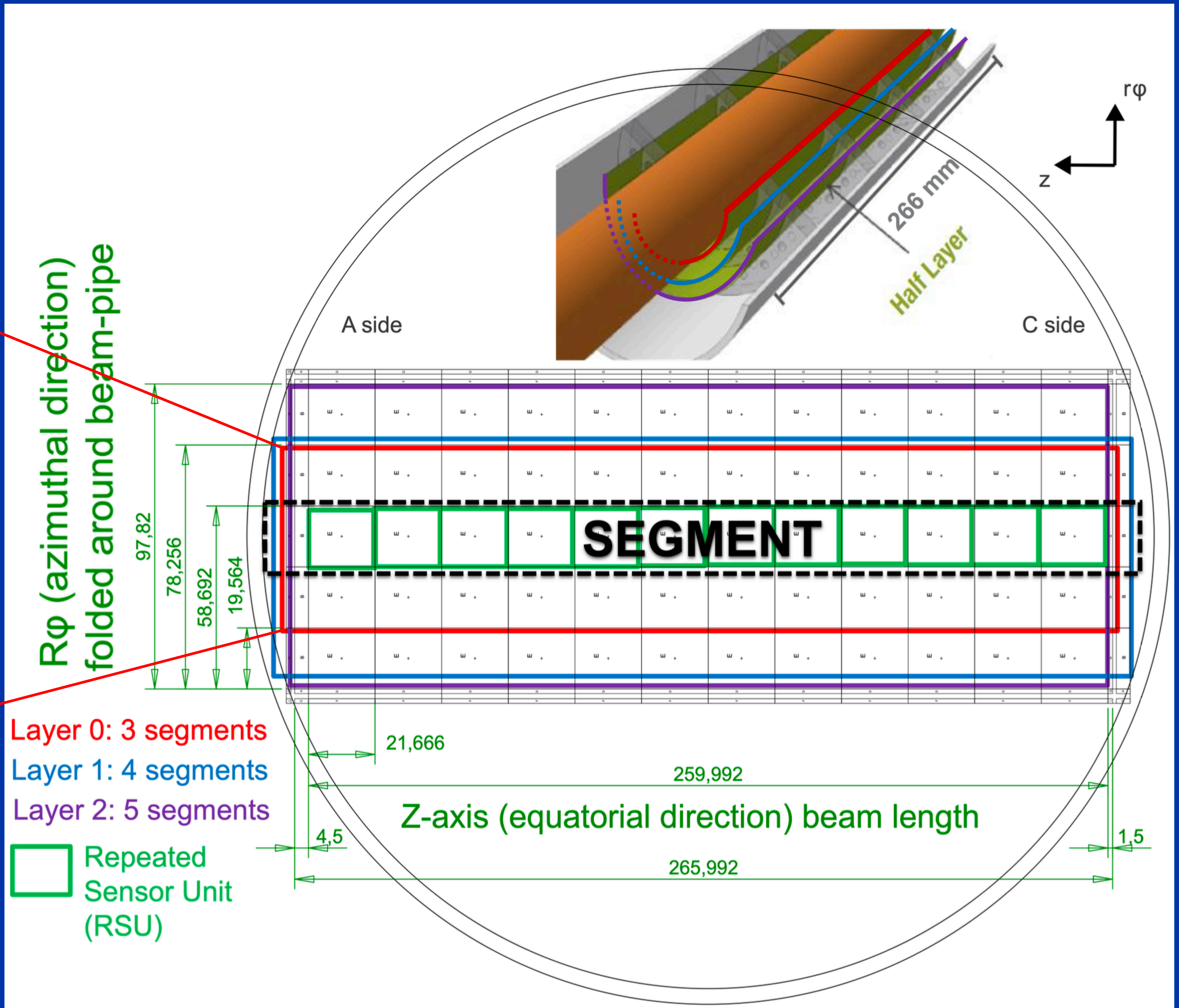




Excellent efficiency and spatial resolution

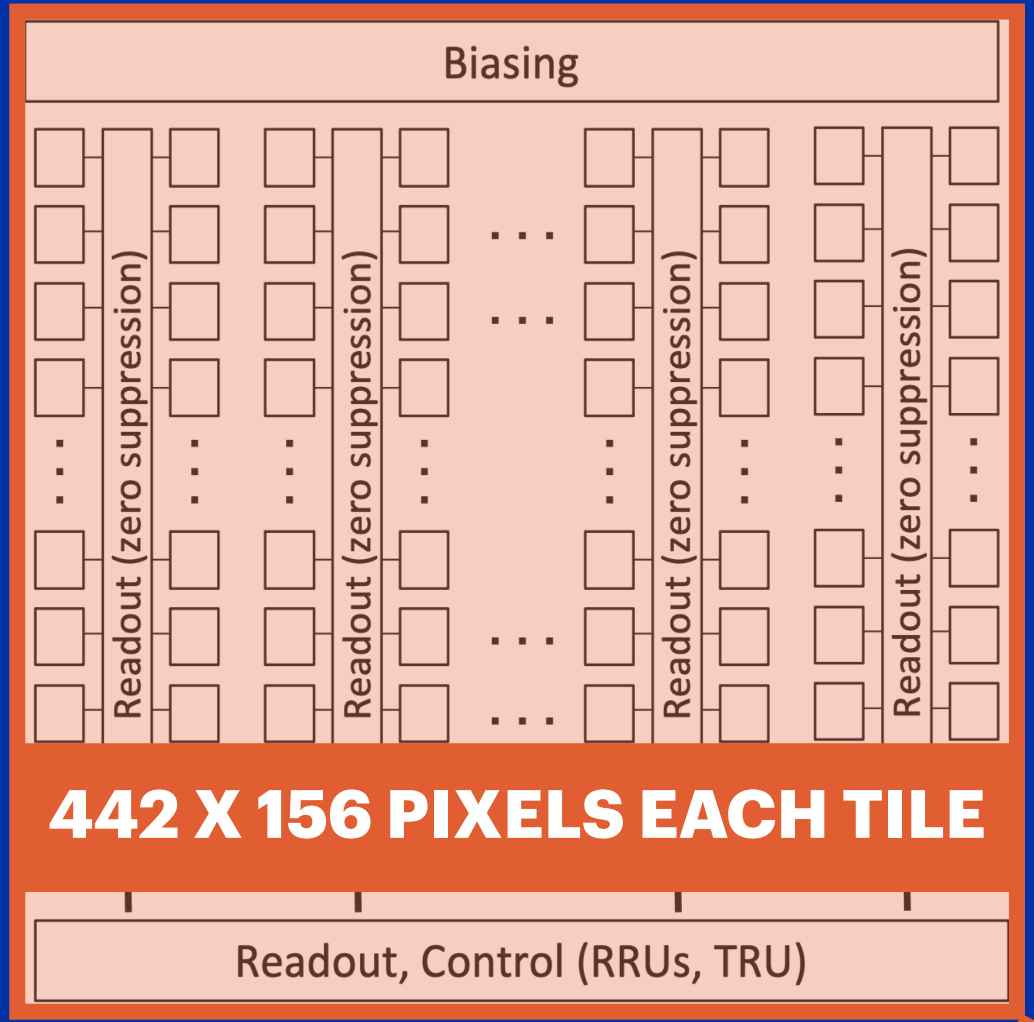
ITS3 final wafer-scale sensor design





ITS3 TDR: CERN-LHCC-2024-003

ITS3 final wafer-scale sensor design



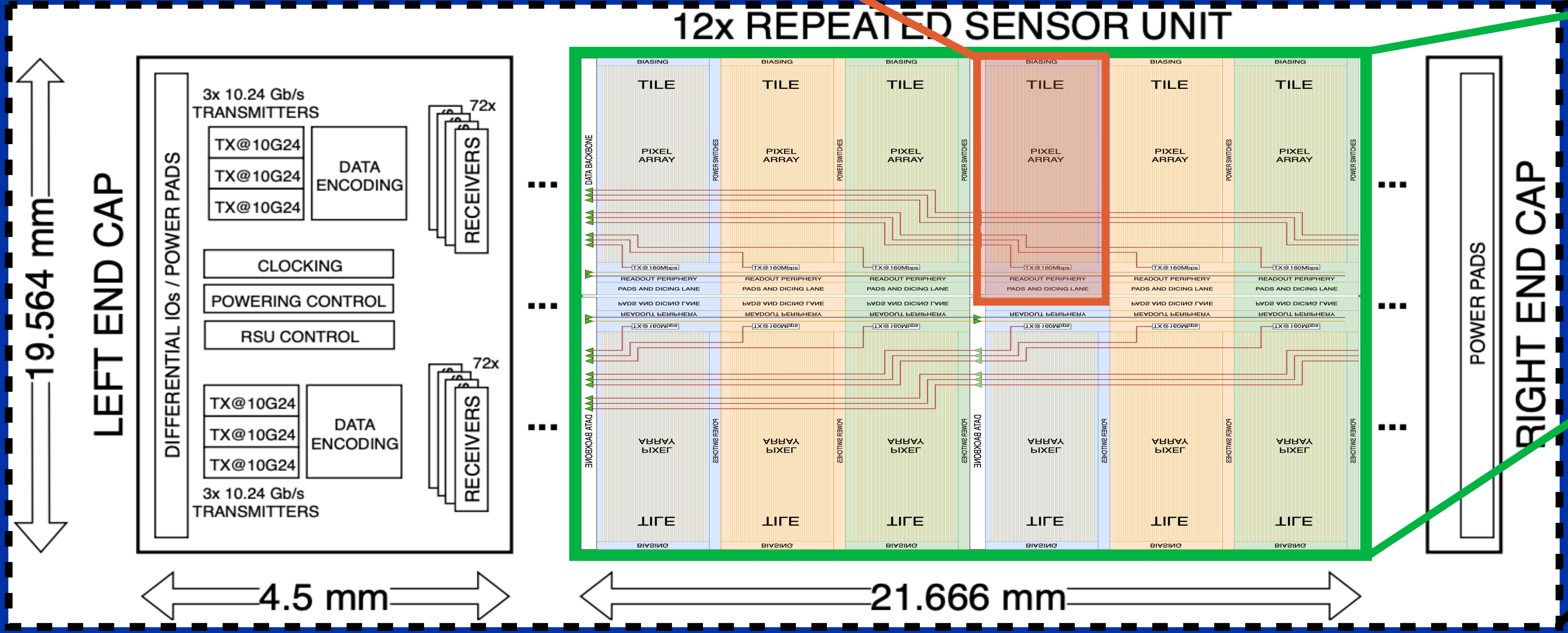
Power consumption

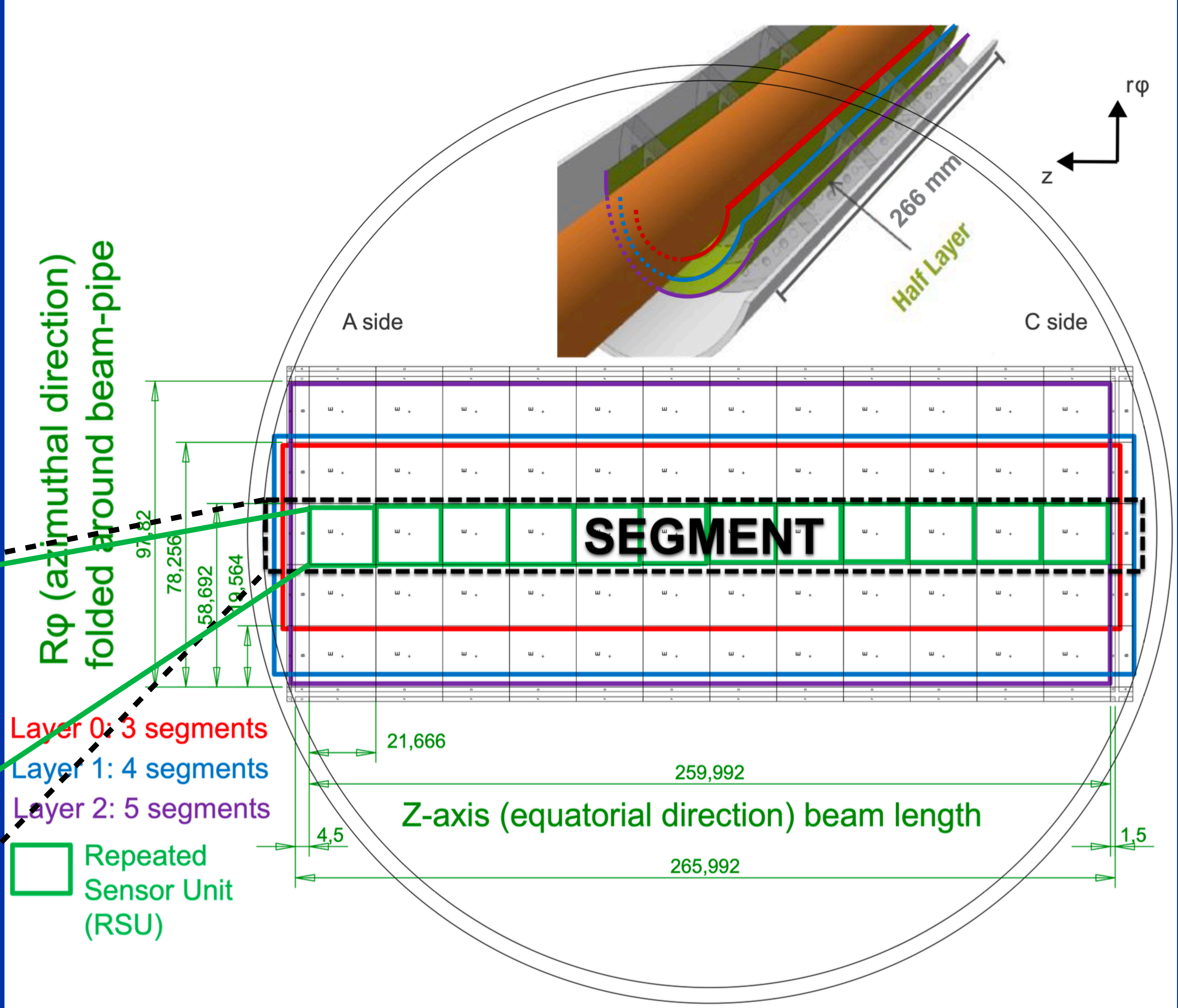
➡ < 40 mW/cm²

Total fill factor: ~93%

➡ possibly ~95.5% depending on ER2 test results

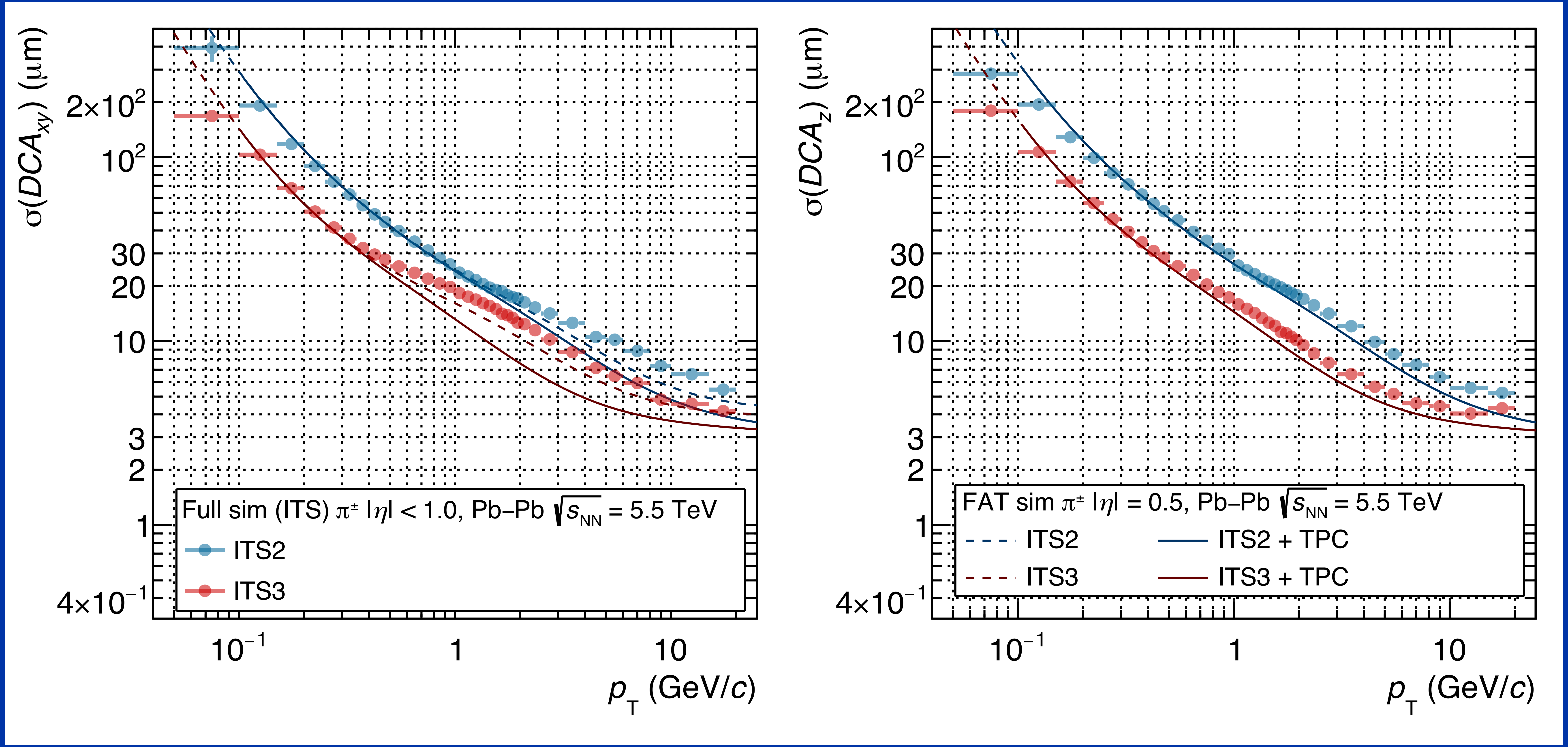
➡ i.e., deadzone area: ~4.5-7%





ITS3 TDR: CERN-LHCC-2024-003

Physics performance — Pb-Pb collisions



Single Track Performance

Detailed description of geometry and material

Two independent simulation methods used

- ➡ Full simulation
- ➡ Fast simulation (FAT)

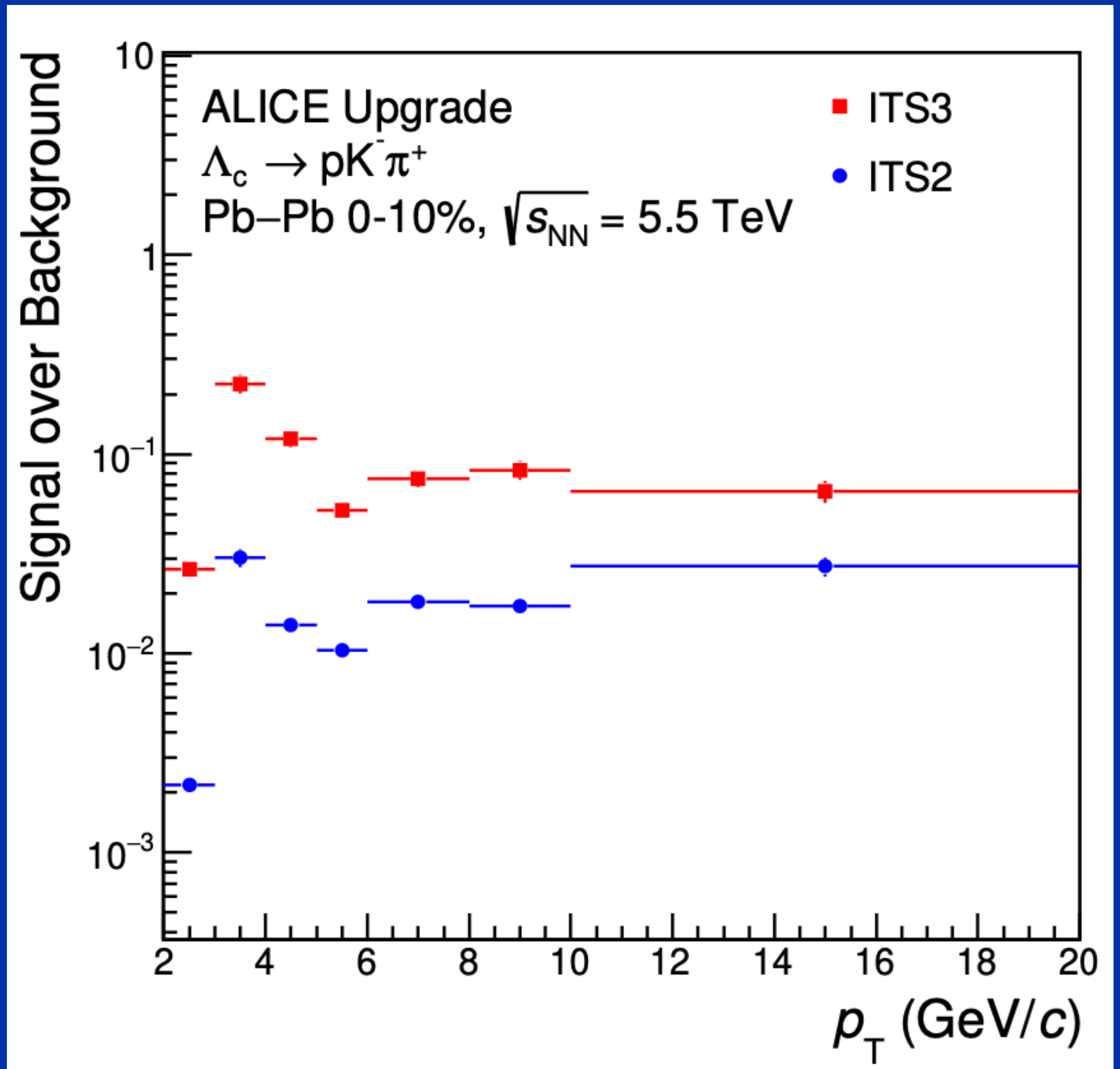
ITS Standalone

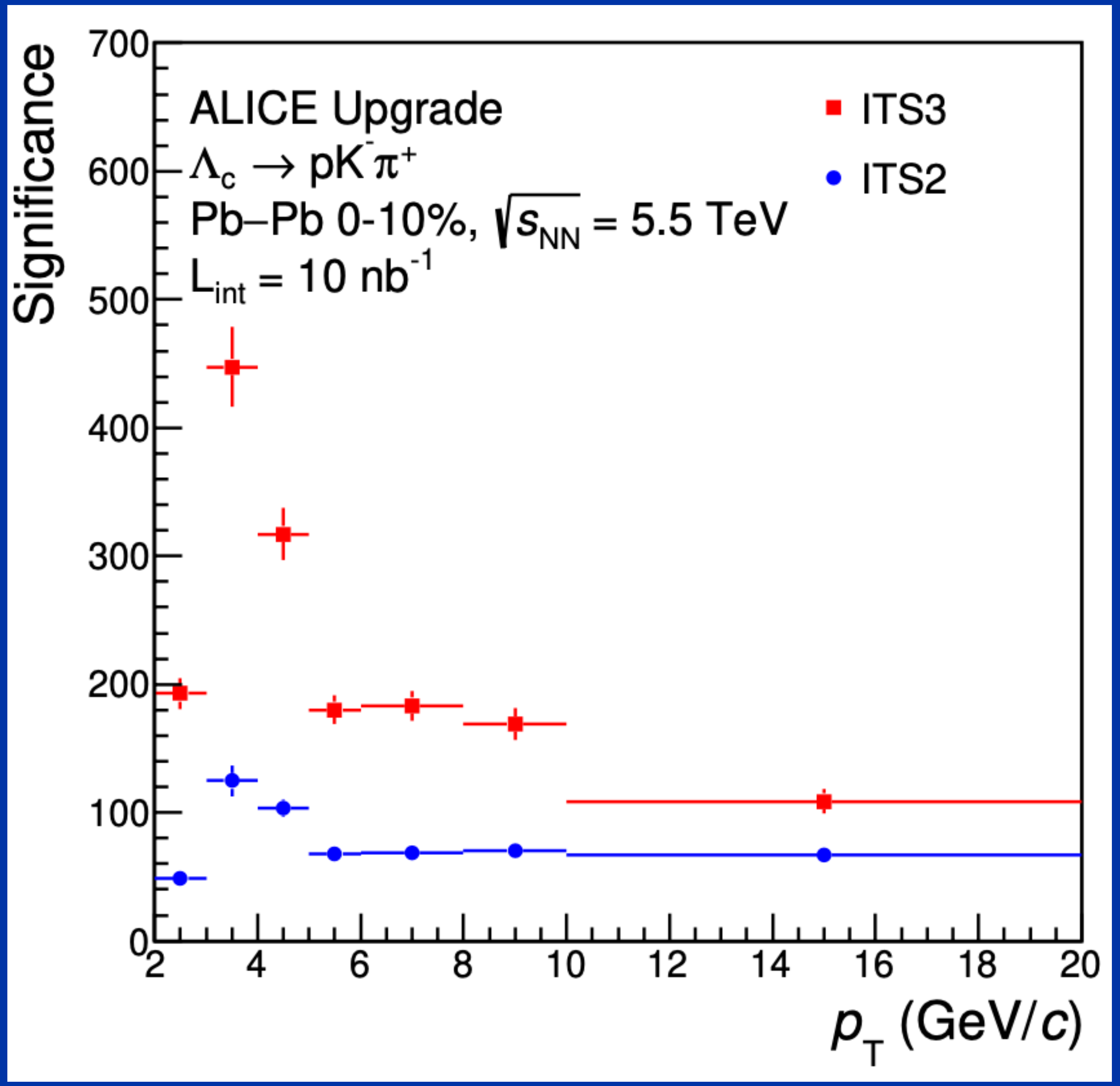
- ➡ Full simulation and FAT results agree for DCA_{xy} and DCA_z
- ➡ Differences due to more accurate material description in Full simulation and tracking model

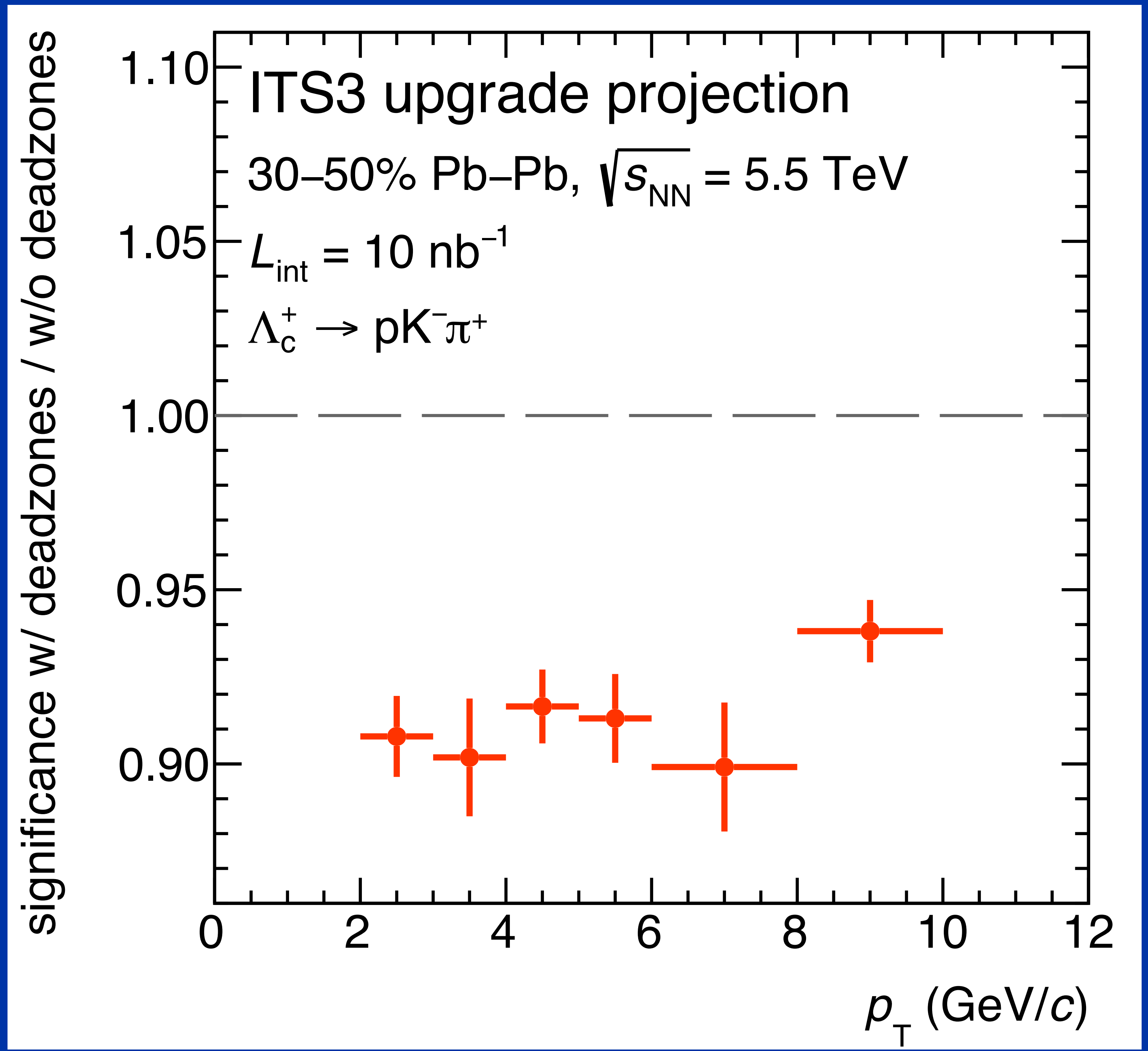
ITS-TPC matching recovers excellent impact parameter resolution at intermediate p_T

Twofold improvement in impact parameter resolution over ITS2

Physics performance — Heavy flavour







Signal and Background yields estimated in $\pm 3\sigma$ interval around Λ_C^+ mass

Public Note on ITS3 Physics Performance ALICE-PUBLIC-2023-002

Λ_C^+ reconstruction as an example for possible improvement

- ➡ Large three-prong combinatorial background
- ➡ Can be better suppressed with improved primary and secondary vertex reconstruction

Factor 10 improvement for S/B
Factor 4 improvement for the significance
Impact of deadzones negligible compared to the improvement over ITS2

Summary and Outlook

ITS3 — a bent wafer-scale monolithic pixel detector

ITS3 project is on track for installation in LS3

- ➡ Proved silicon bending
- ➡ Technology qualified
- ➡ Wafer-scale stitched MAPS

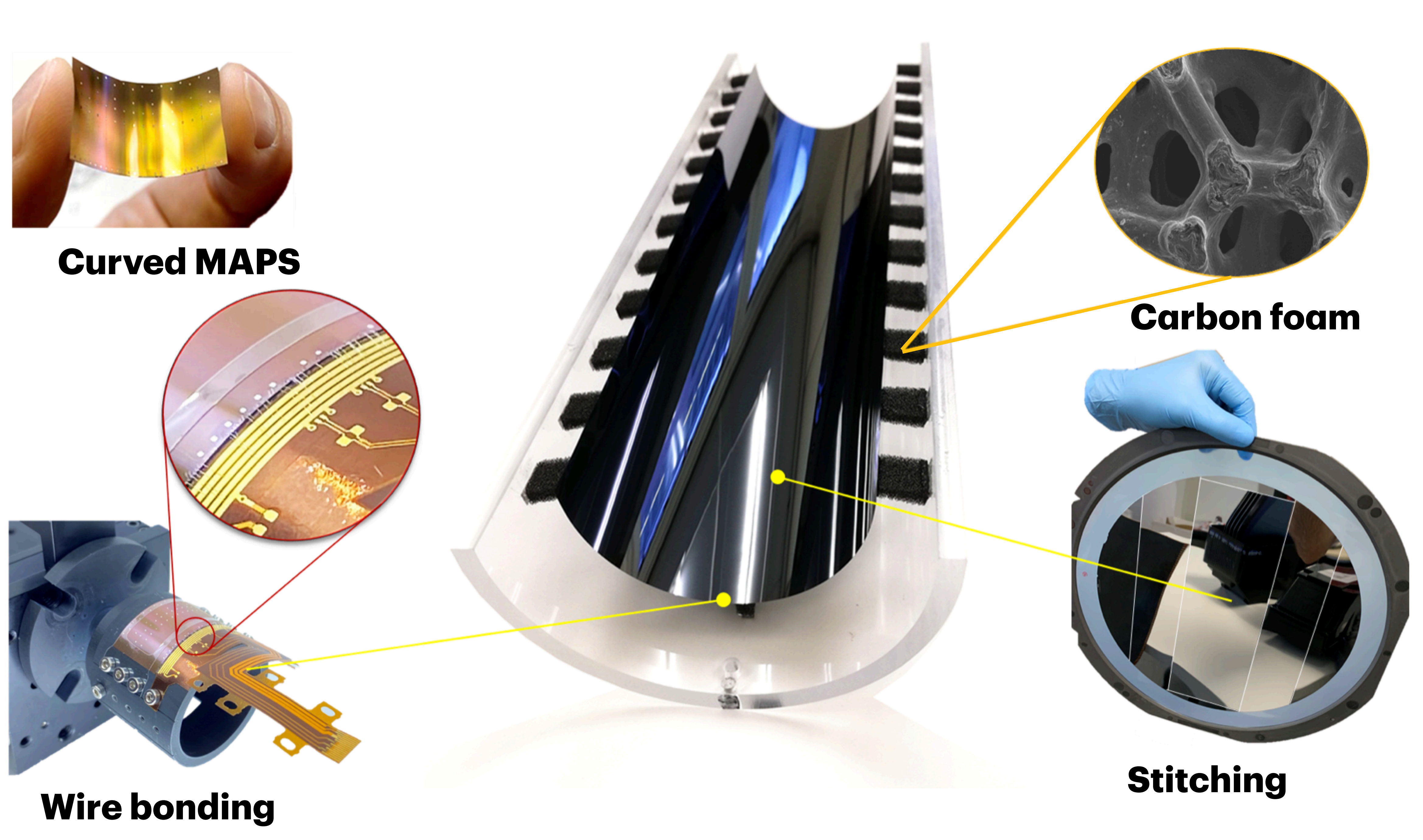
Technical Design Report approved

A twofold improvement in spatial resolution wrt. ITS2

- ➡ Significant improvement in reconstructing heavy flavour hadrons

Analysis benefiting from ITS3

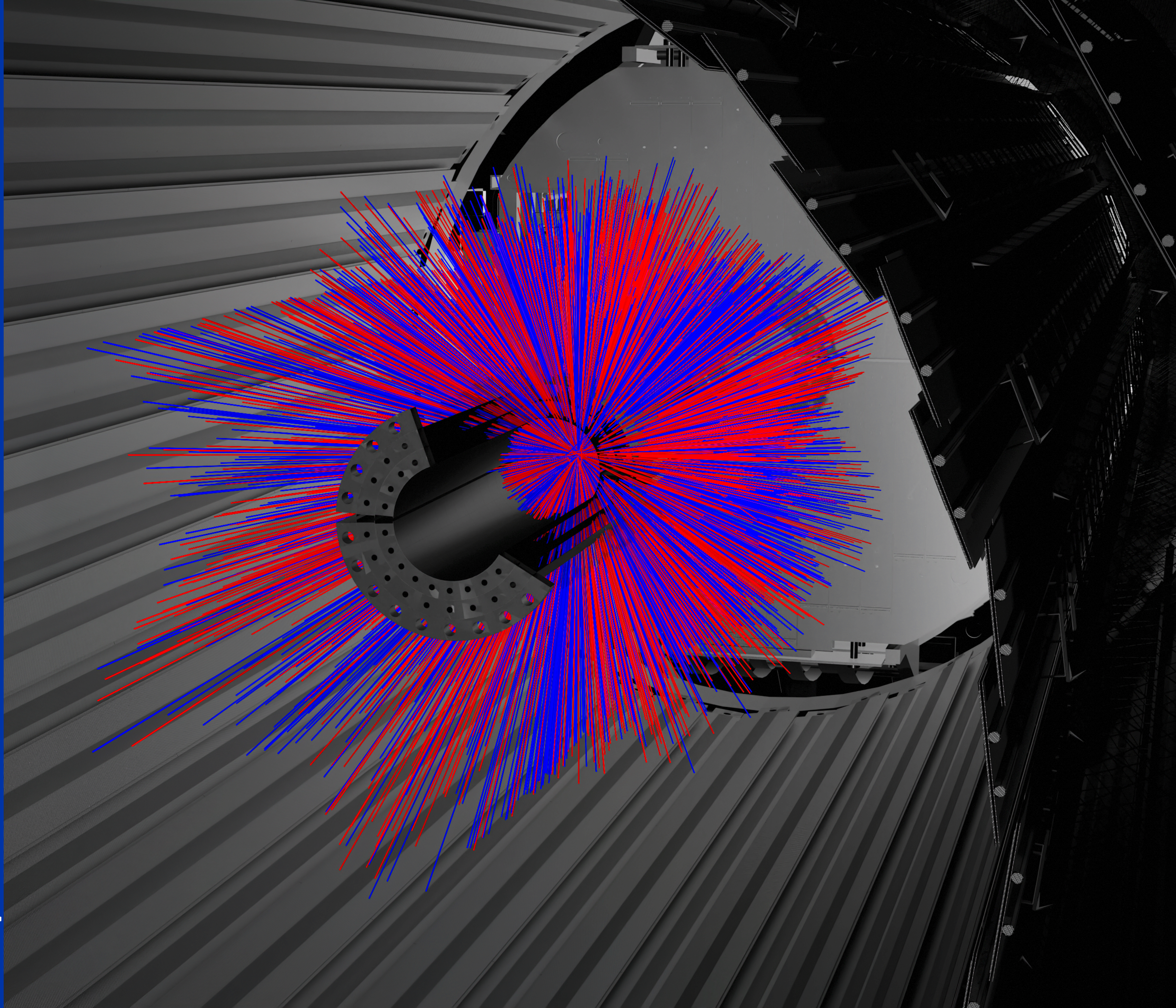
- ➡ Heavy flavour collectivity
- ➡ Thermal radiation via dielectron measurements
- ➡ And many more analyses...



ITS3 TDR: CERN-LHCC-2024-003

THANK YOU!

BACKUP



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ITS3 — Sensor ASIC design specifications

Table 2.1: ITS3 general parameters.

Beampipe inner/outer radius (mm)	16.0/16.5		
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	19.0	25.2	31.5
Length (sensitive area) (mm)	260	260	260
Pseudo-rapidity coverage[a]	±2.5	±2.3	±2.0
Active area (cm^2)	305	407	507
Pixel sensors dimensions (mm^2)	266 × 58.7	266 × 78.3	266 × 97.8
Number of pixel sensors / layer		2	
Material budget ($\%X_0$ / layer)		0.07	
Silicon thickness (µm / layer)		≤50	
Pixel size ($µm^2$)		$O(20 \times 22.5)$	
Power density (mW/cm^2)		40	
NIEL (1 MeV n_{eq} cm^{-2})		10^{13}	
TID (kGray)		10	

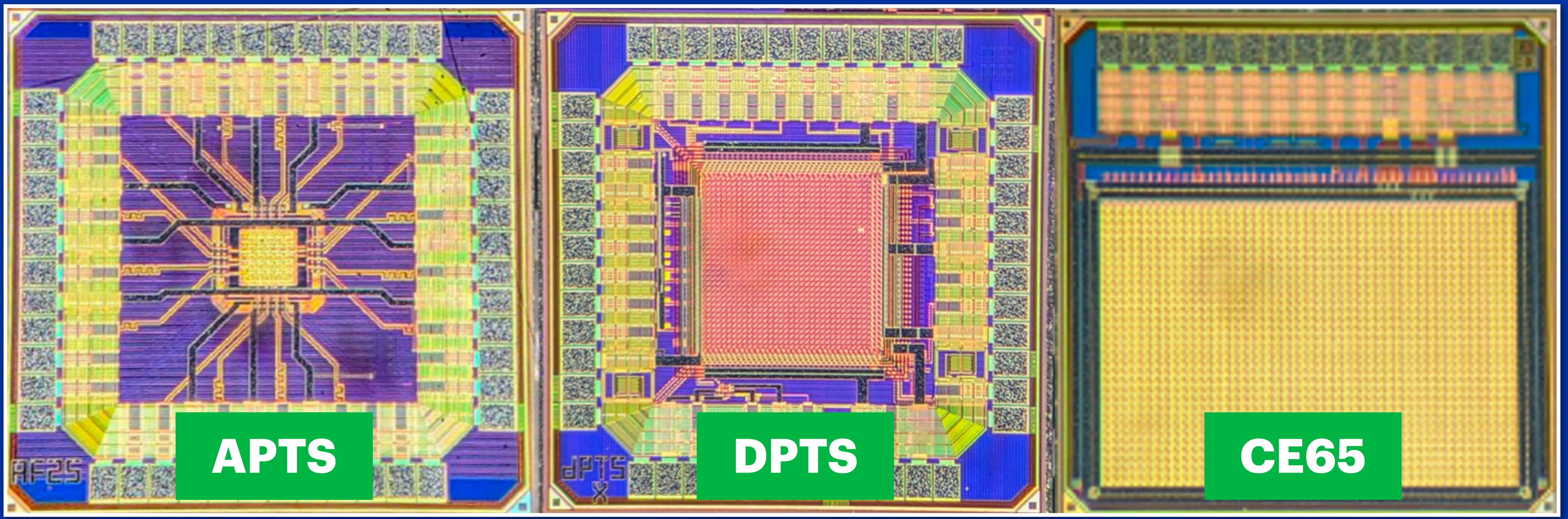
[a] The pseudorapidity coverage of the detector layers refers to tracks originating from a collision at the nominal interaction point ($z = 0$).

ITS3 TDR: CERN-LHCC-2024-003

Table 3.2: General requirements for the sensor ASIC design.

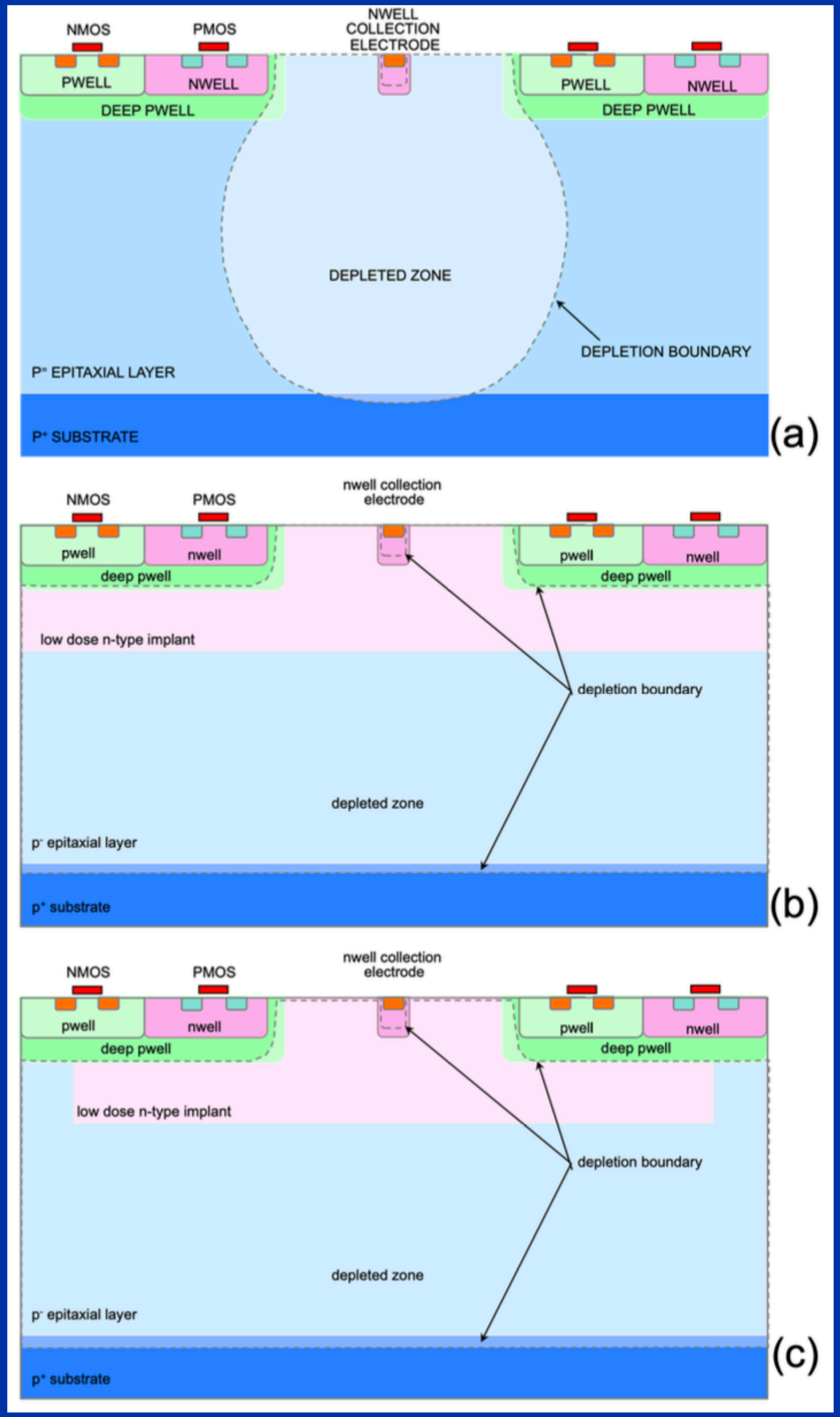
Particle Rate	
Pb-Pb Interaction Rate (average)	50 kHz
Pb-Pb Interaction Rate (expected peak rate including safety factor of 2)	164 kHz
Total particle flux (@164 kHz, Layer 0, z=0 cm)	5.75 MHz cm^{-2}
Hadronic flux (all centralities, @164 kHz, Layer 0, z=0 cm)	2.55 MHz cm^{-2}
QED electrons flux (@164 kHz, Layer 0, z=0 cm)	3.20 MHz cm^{-2}
Detection Performance	
Single point resolution	$\lesssim$ 5 µm
Pixel pitch	< 25 µm
Fill factor (fractional sensitive area)	> 92%
Detection efficiency	> 99%
Fake-hit rate	< 0.1 $pixel^{-1}$ s^{-1}
Fake-hit occupancy (10 µs Frame Duration)	< 10^{-6} $pixel^{-1}$ $frame^{-1}$
Frame duration programmable	2 – 10 µs
Readout Efficiency	
Fraction of Pb-Pb interactions fully recorded, Layer 0	> 99.9%
Fraction of incomplete Pb-Pb interactions, Layer 0	< 1×10^{-3}
Power Budget	
Power Dissipation Density, Active Region	< 40 mW cm^{-2}
Power Dissipation Density, Peripheral Region	< 1000 mW cm^{-2}
Radiation Load	
NIEL	10^{13} 1 MeV n_{eq} cm^{-2}
TID	10 kGy
Environmental Conditions	
Target Operating Temperature	15 °C to 30 °C

MLR1 chips



After an incredible work and effort from all the institutes involved, the 65 nm technology is validated for ITS3

- ➡ **APTS-SF** allowed us to establish the **most suited chip** variant in terms of performance: modified with gap, split 4, reference collection diode geometry
- ➡ **APTS-OA** enabled all the time response studies, useful beyond ITS3
- ➡ **CE65** explored different processes and pitches, confirming what observed also in other test structures
- ➡ **DPTS** was crucial for detection efficiency, spatial resolution, cluster size and radiation hardness evaluation, satisfying all the ITS3 requirements



ER1 MOSS details

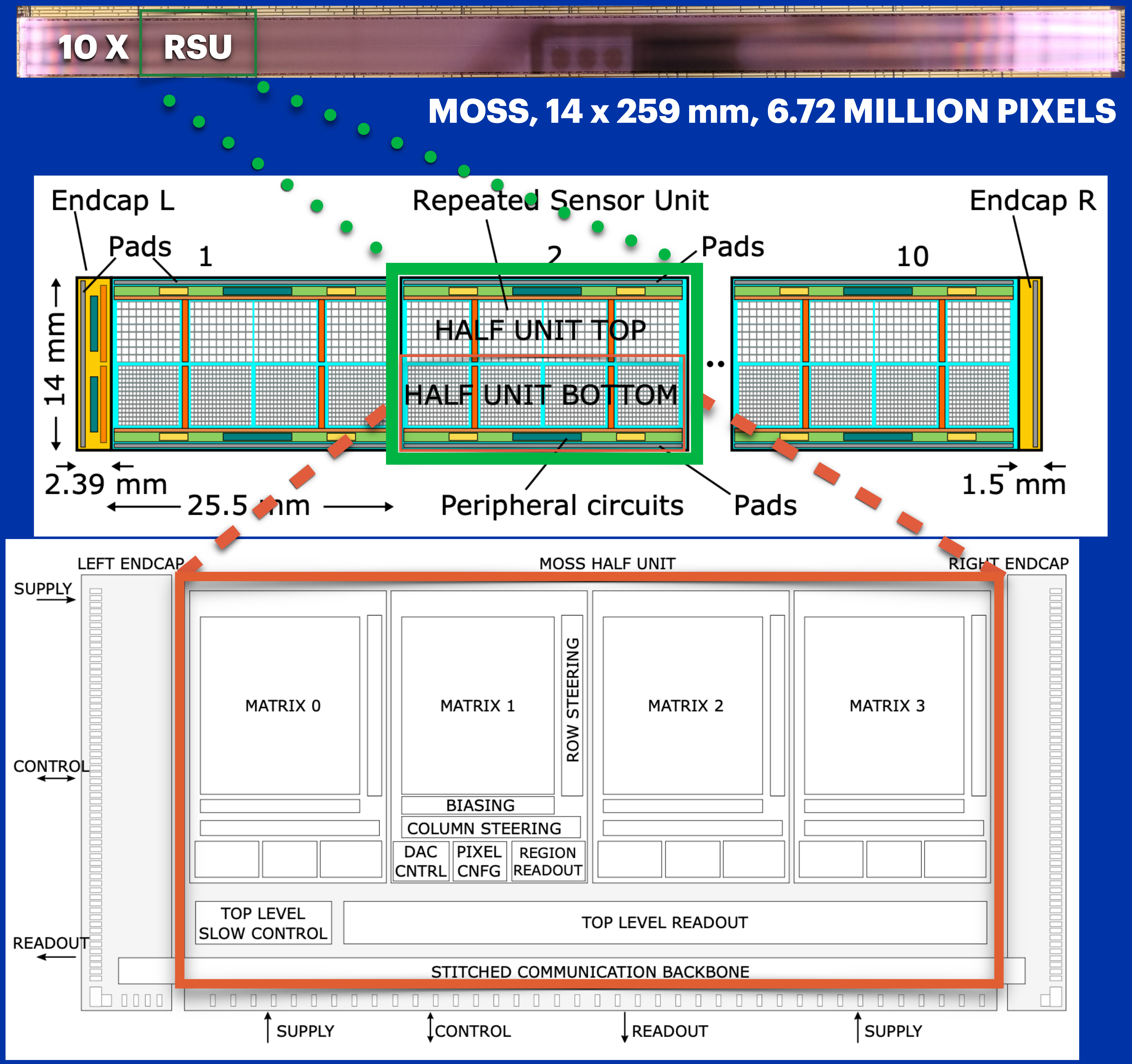
MOSS is segmented into 10 RSUs and left / right end-caps

- ➡ Each RSU is split into top and bottom half units with different pitches
  - ➡ Each half unit contains 4 matrices with different distinct analog components and a top level peripheral control and readout

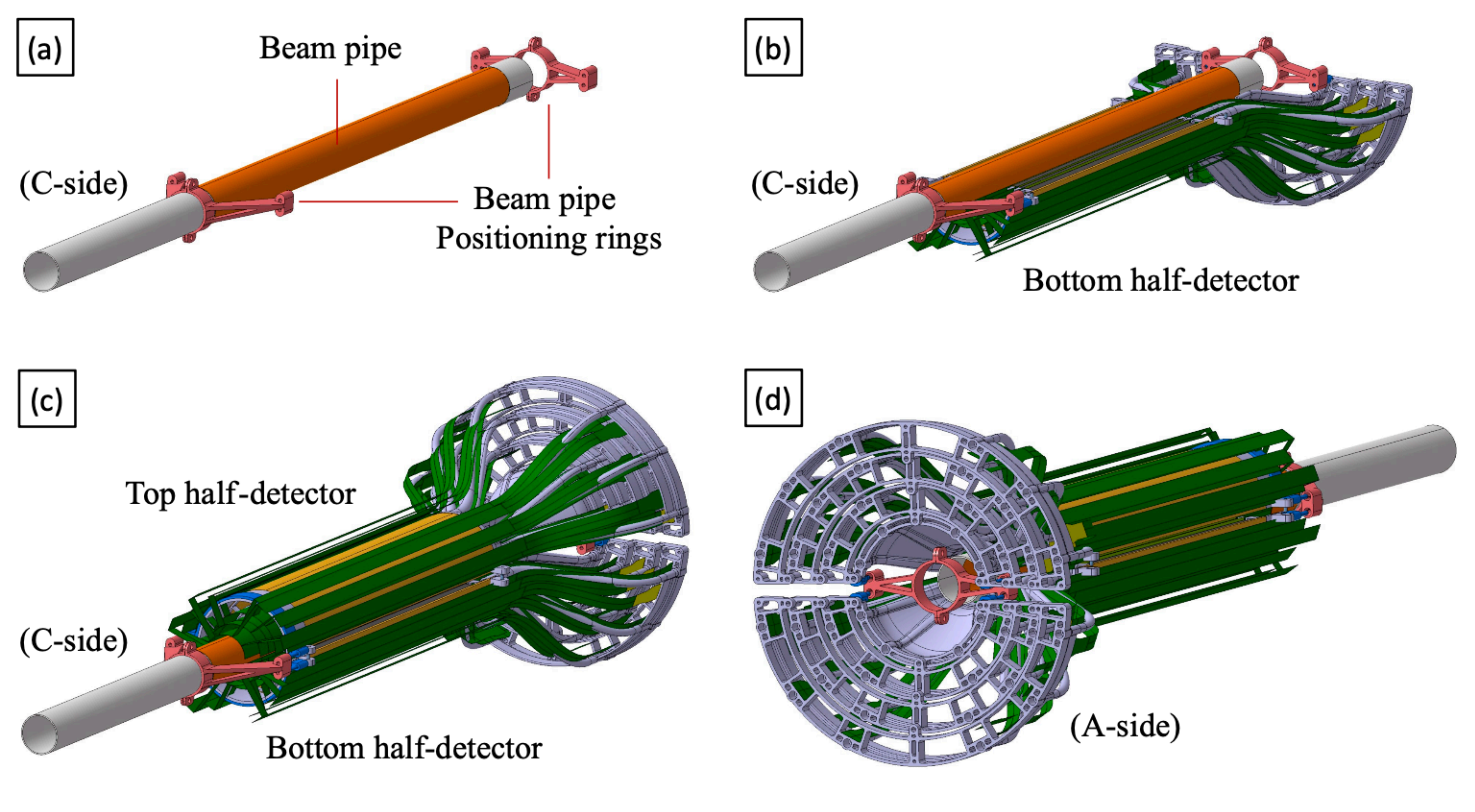
Each half unit can be controlled, read out and powered

- ➡ By left end-cap via stitched communication backbone
- ➡ Independently, enabling separate testing to identify yield discrepancies and potential defects

Matrices	Pixel matrix	Pitch size
Top	256×256	$22.5\ \mu m$
Bottom	320×320	$18\ \mu m$

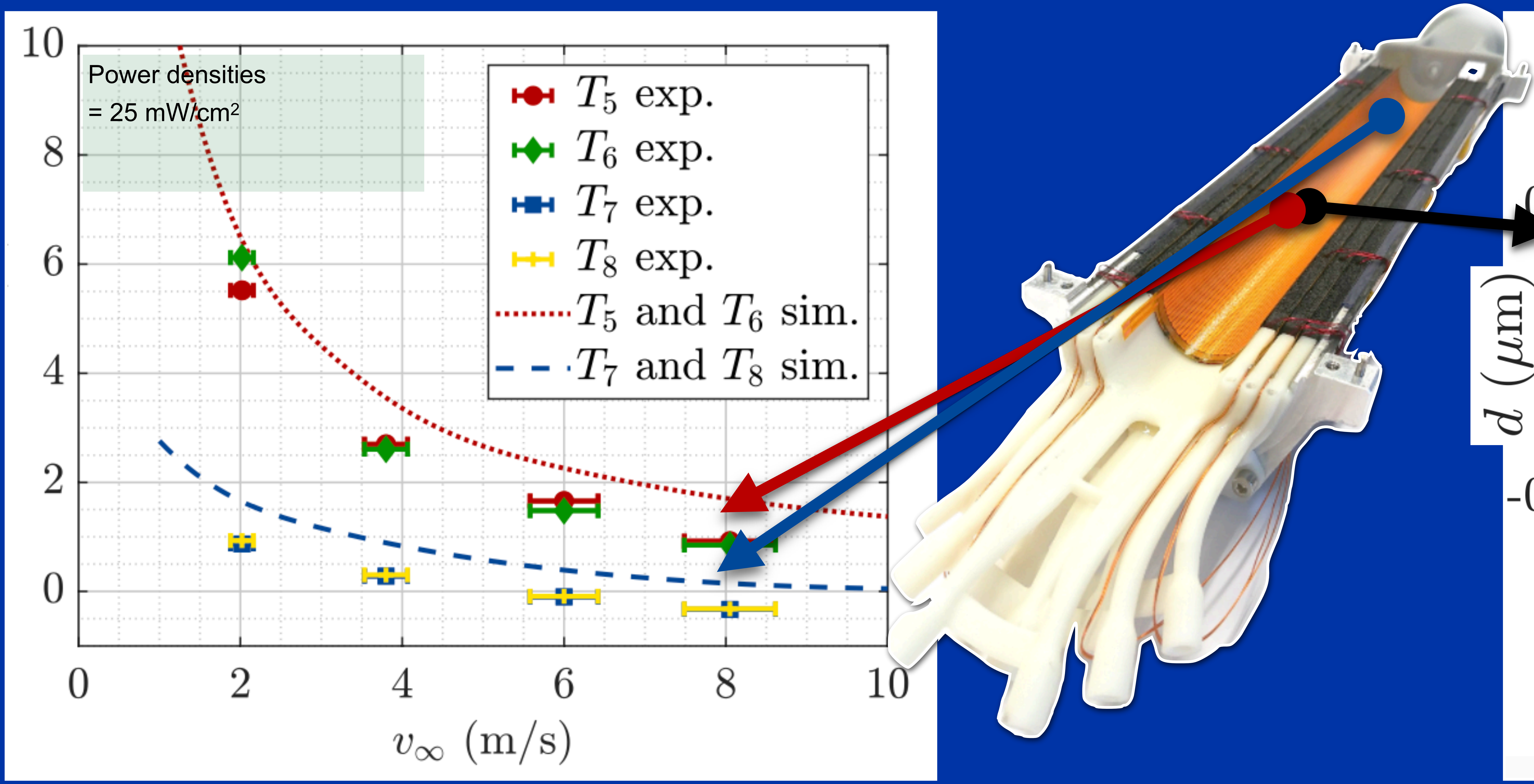


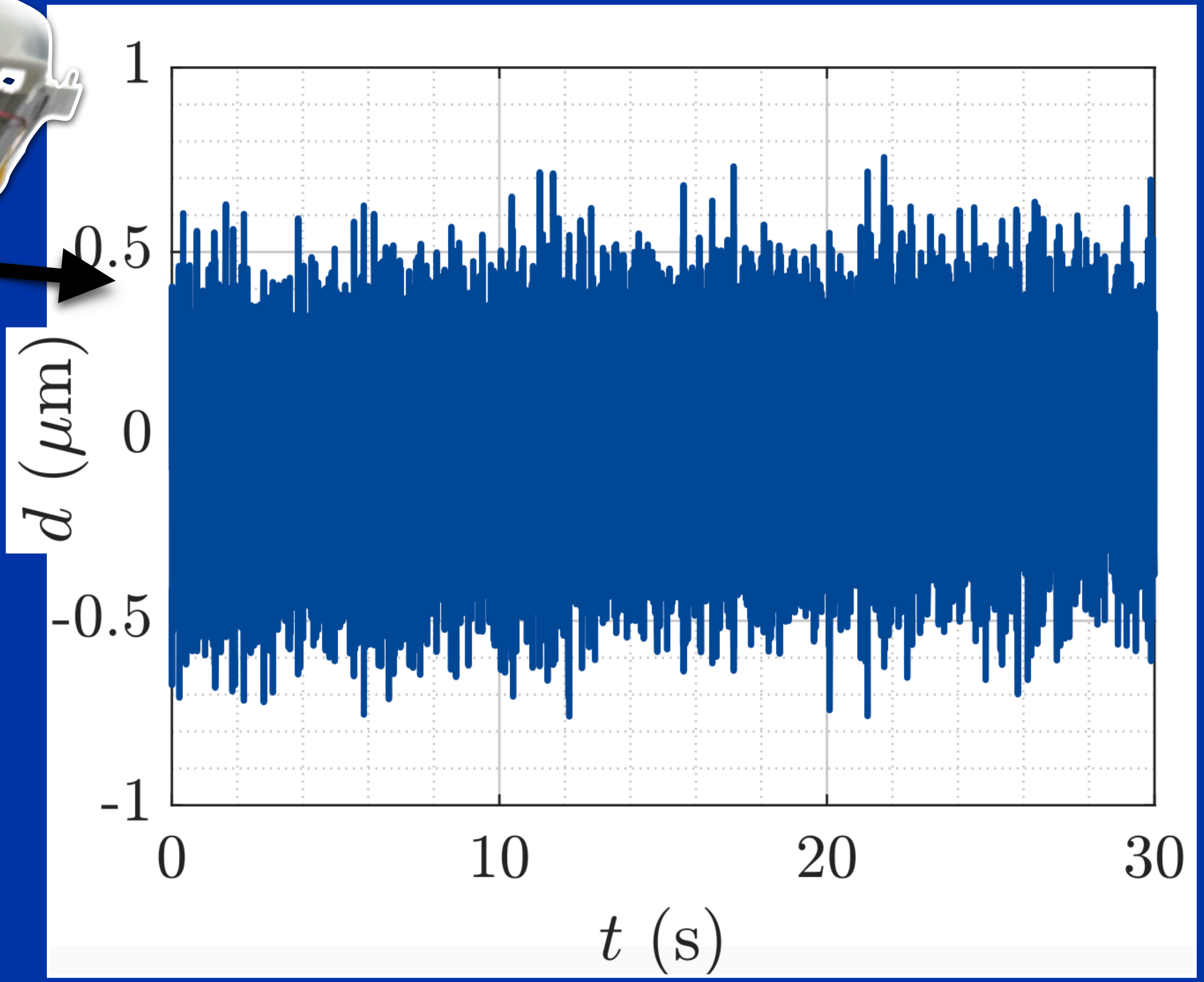
ITS3 — Detector services



ITS3 TDR: CERN-LHCC-2024-003

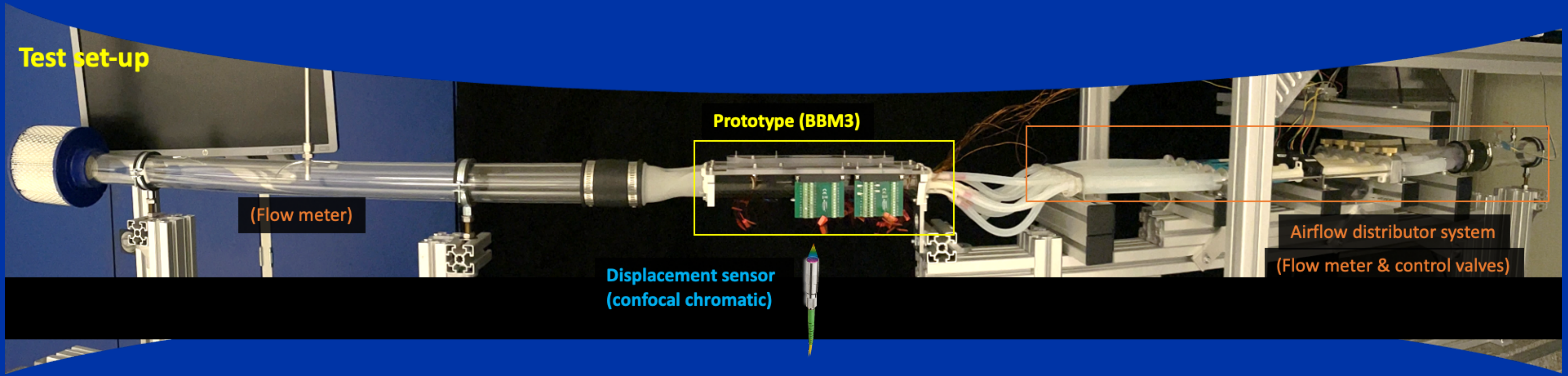
ITS3 — Air cooling



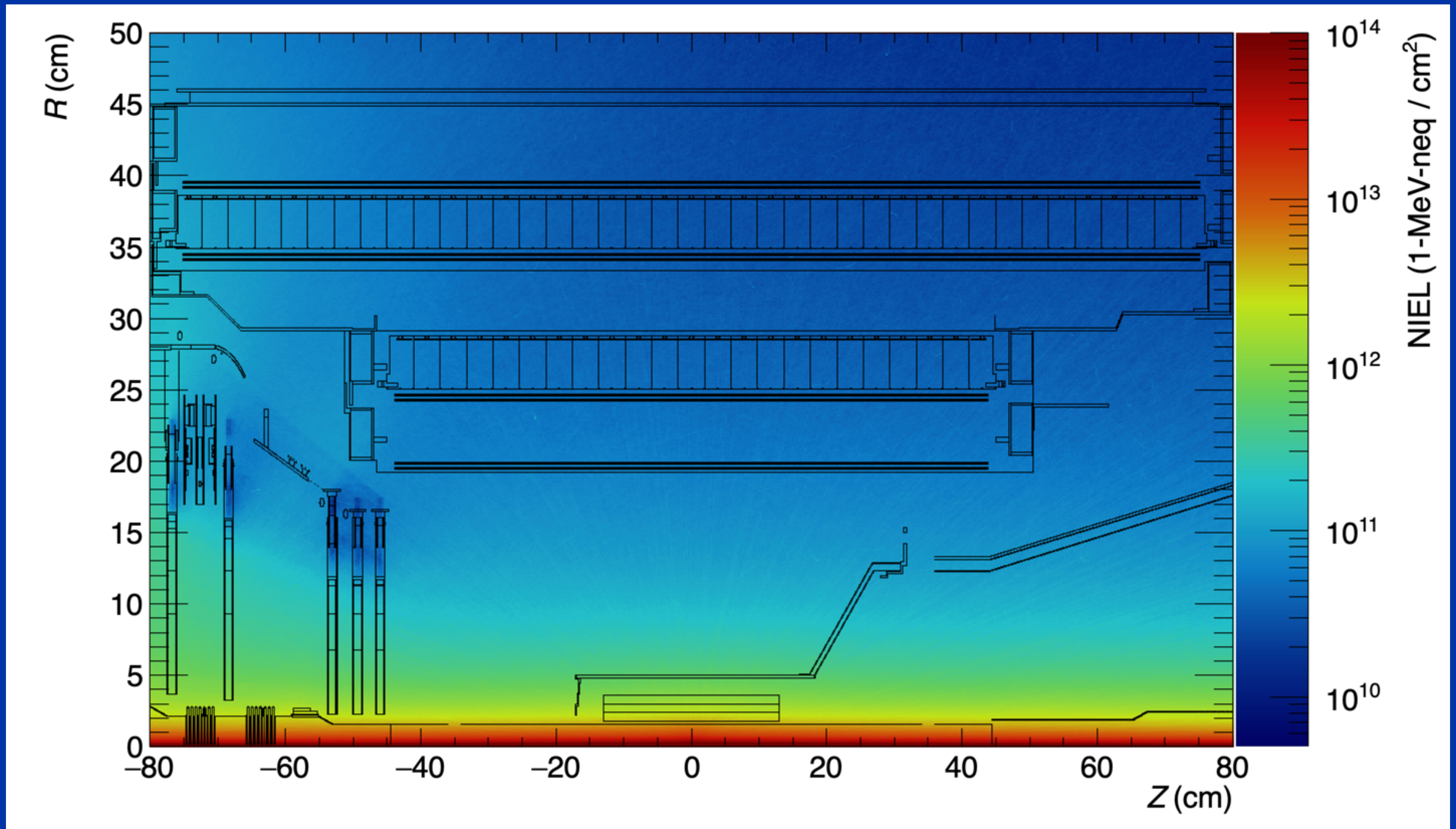


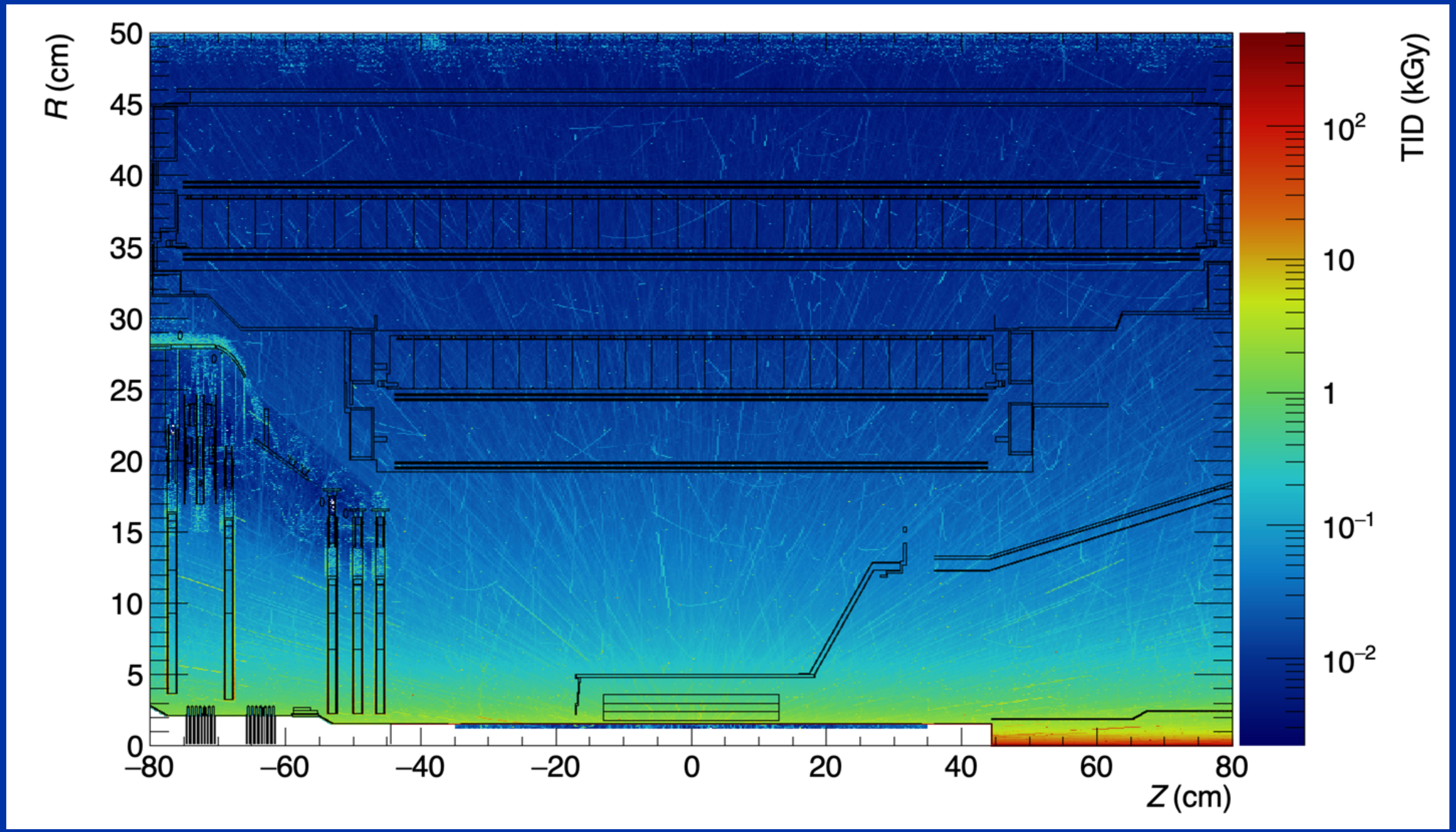
Temperature uniformity along the sensor within $5°C$

Integrated displacement RMS $\leq 0.4\,\mu m$



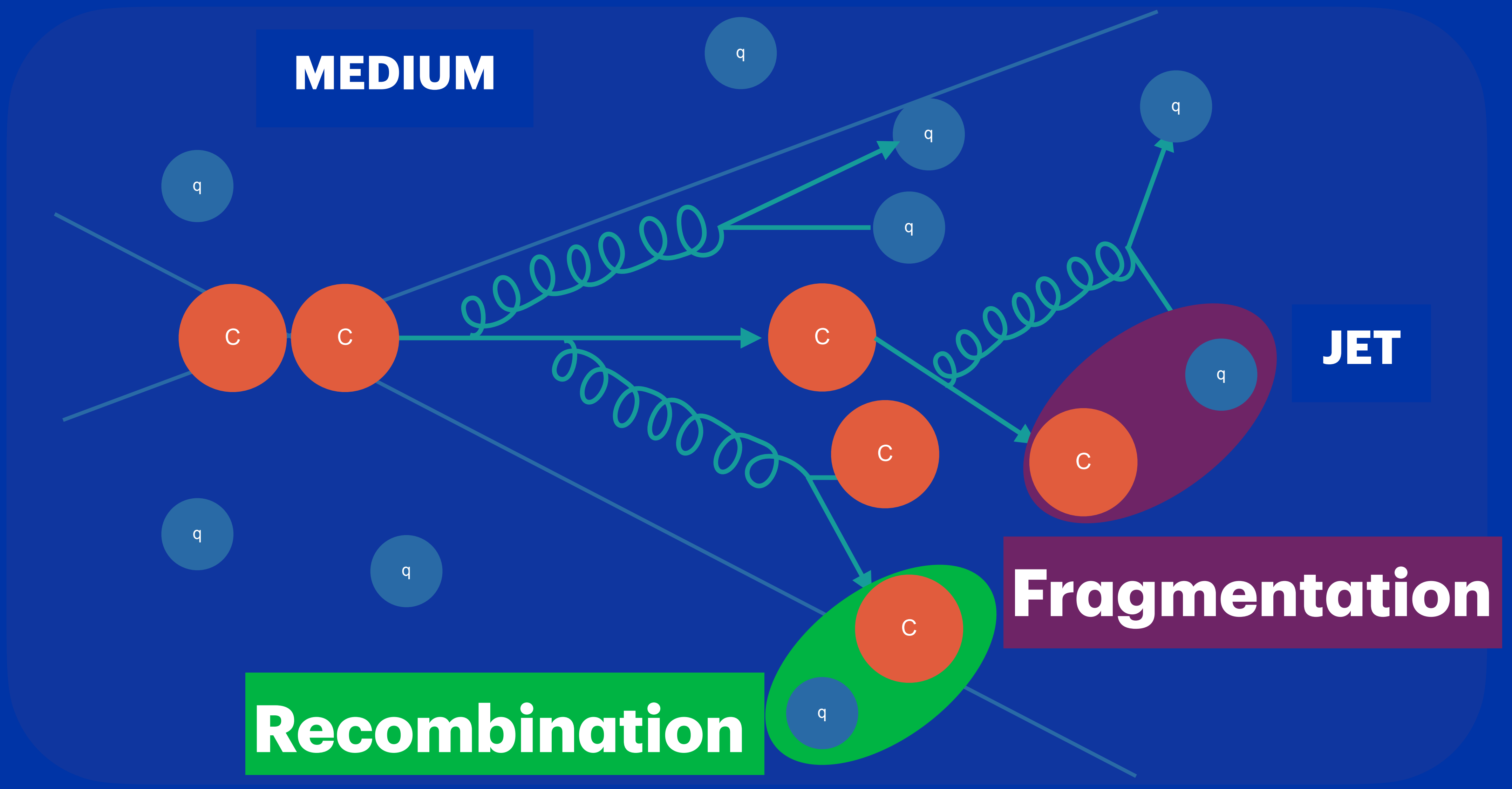
ITS3 — Radiation load simulation





ITS3 TDR: CERN-LHCC-2024-003

Physics reach — Heavy flavour collectivity



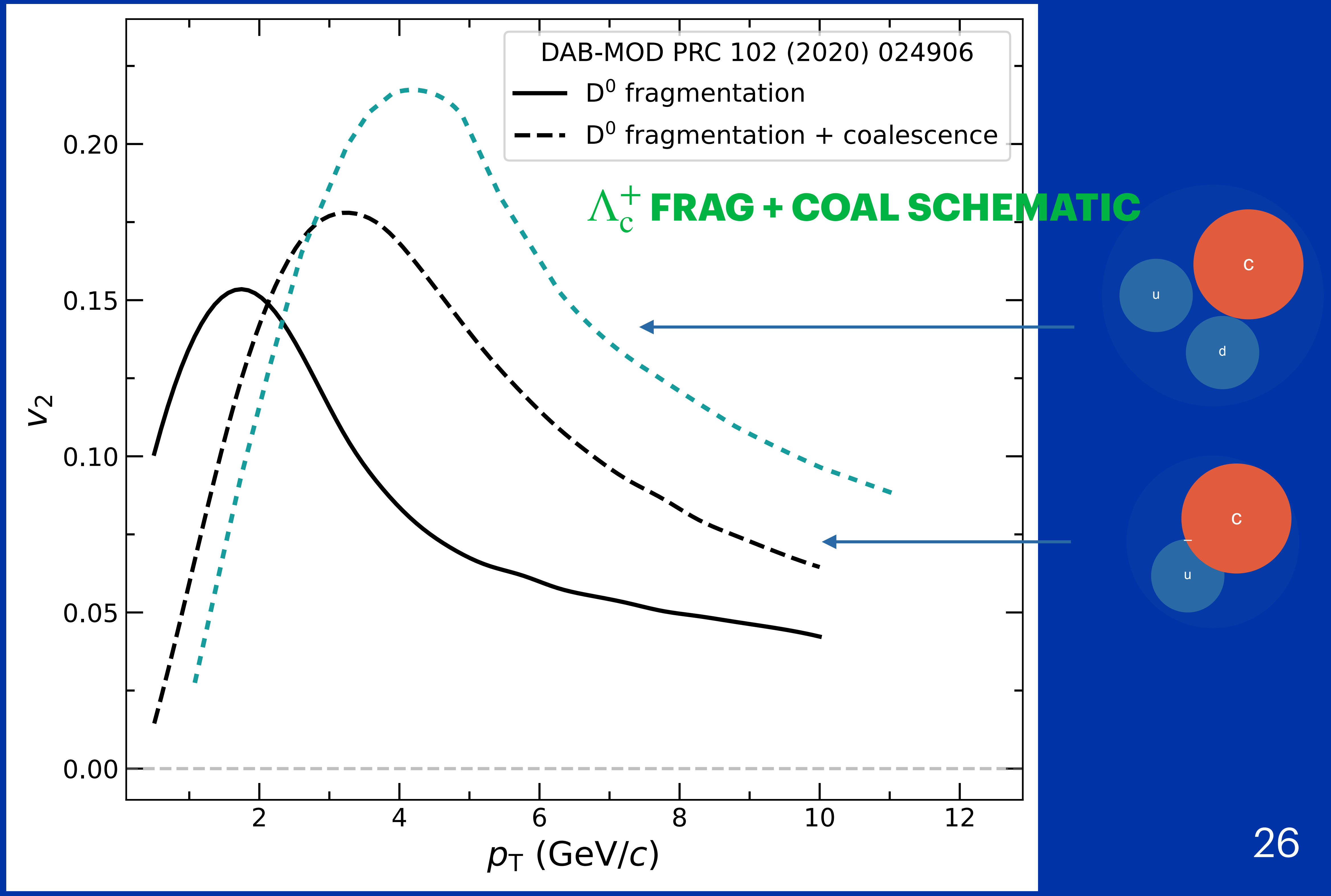
Heavy flavour hadronization from the medium

Fragmentation

➡ A fraction of the Parton momentum is taken from the hadron

Recombination/coalescence

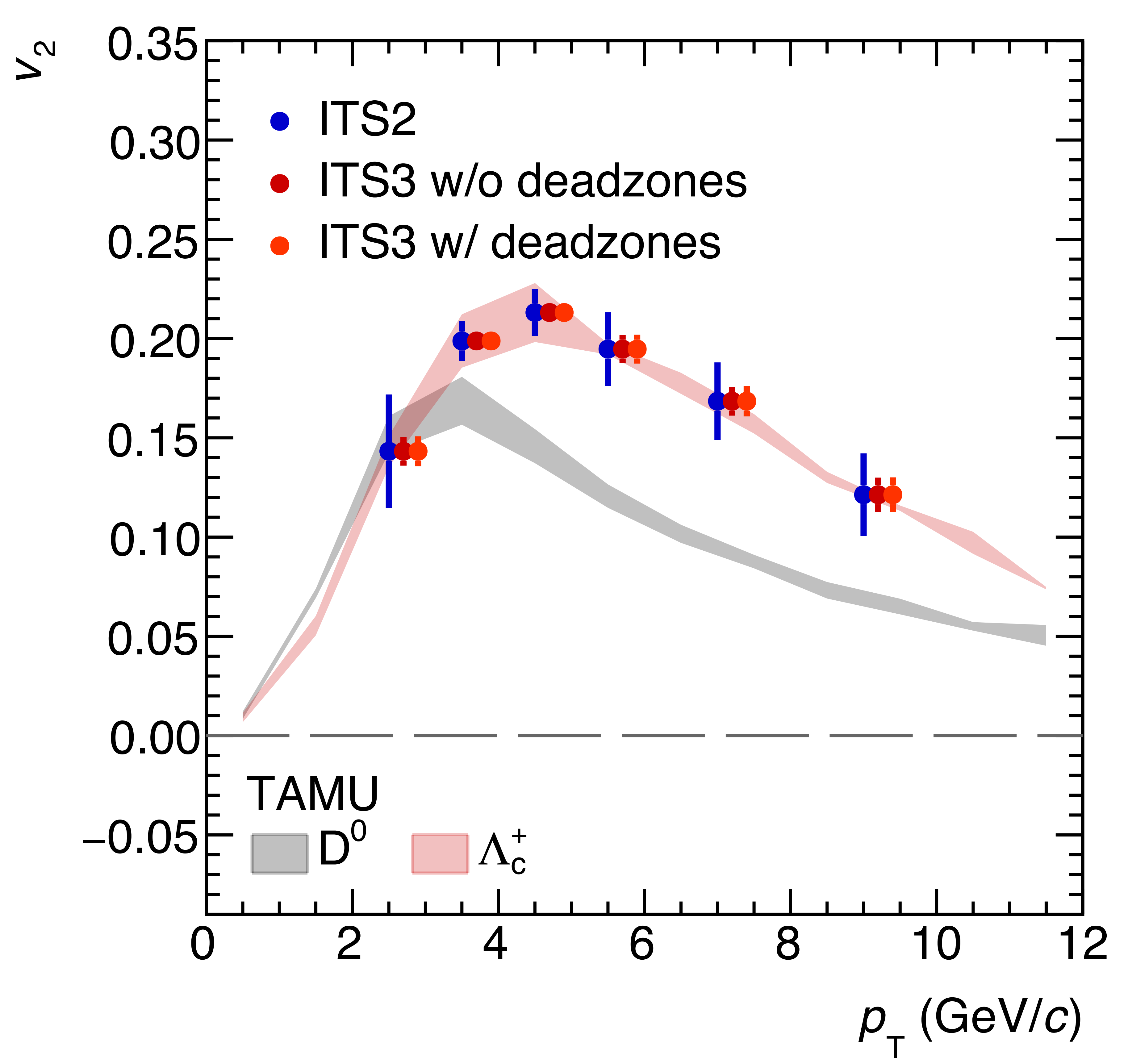
➡ Partons close in phase-space can recombine



Recombination of c-quarks with the medium light quarks could cause charm hadrons to partly inherit the flow of light quarks

Λ_c^+ (udc) has one more light quark than D^0, may inherit more "collective" characteristics of light quarks

Physics reach — Heavy flavour collectivity



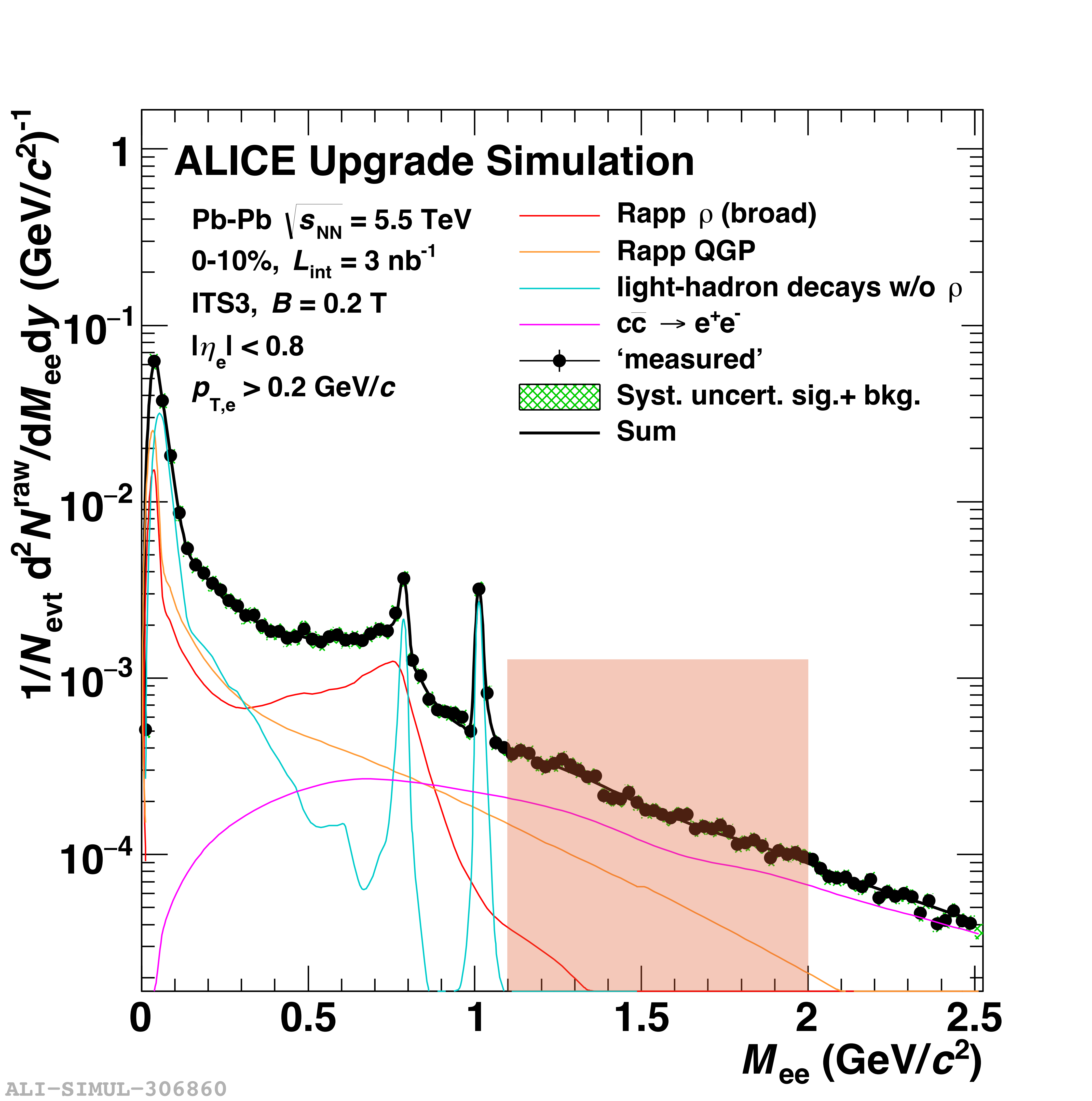
Expected to get a difference $\Delta v_2 \approx 0.03$ between D^0 and Λ_c^+ by TAMU Model*

- ➡ Up to a factor of 4 reduction of the statistical uncertainty
- ➡ Impact of deadzones in ITS3 is negligible

Able to constrain the modeling of charm diffusion and hadronization in the QGP

* M. HE AND R. RAPP, PRL 124, 042301 (2020)

Physics reach — Thermal dielectrons



Complex invariant mass spectrum of e^+e^- pairs

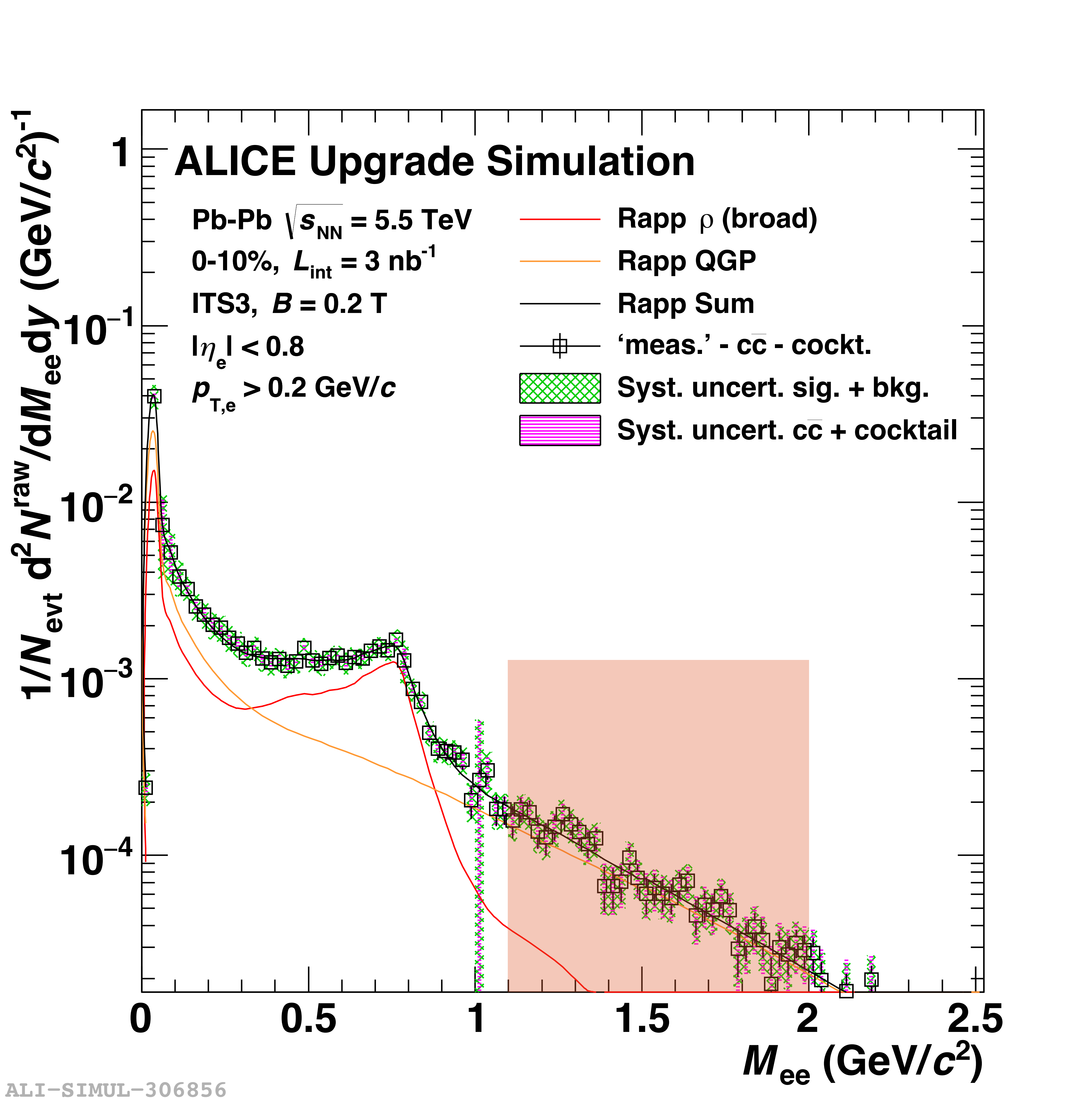
- ➡ Light flavour hadron decays
- ➡ Heavy flavour hadron decays
  - ➡ Suppressed by using DCA to primary vertex
- ➡ Thermal radiation
  - ➡ From hadron gas
  - ➡ From quark gluon plasma (QGP)

In the region $M_{ee} \geq 1.1$ GeV/c^2

- ➡ Dominated by $c\bar{c} \rightarrow e^+e^-$ process and thermal radiation from the QGP

Perfect for extracting the QGP temperature

Physics reach — Thermal dielectrons



Less material

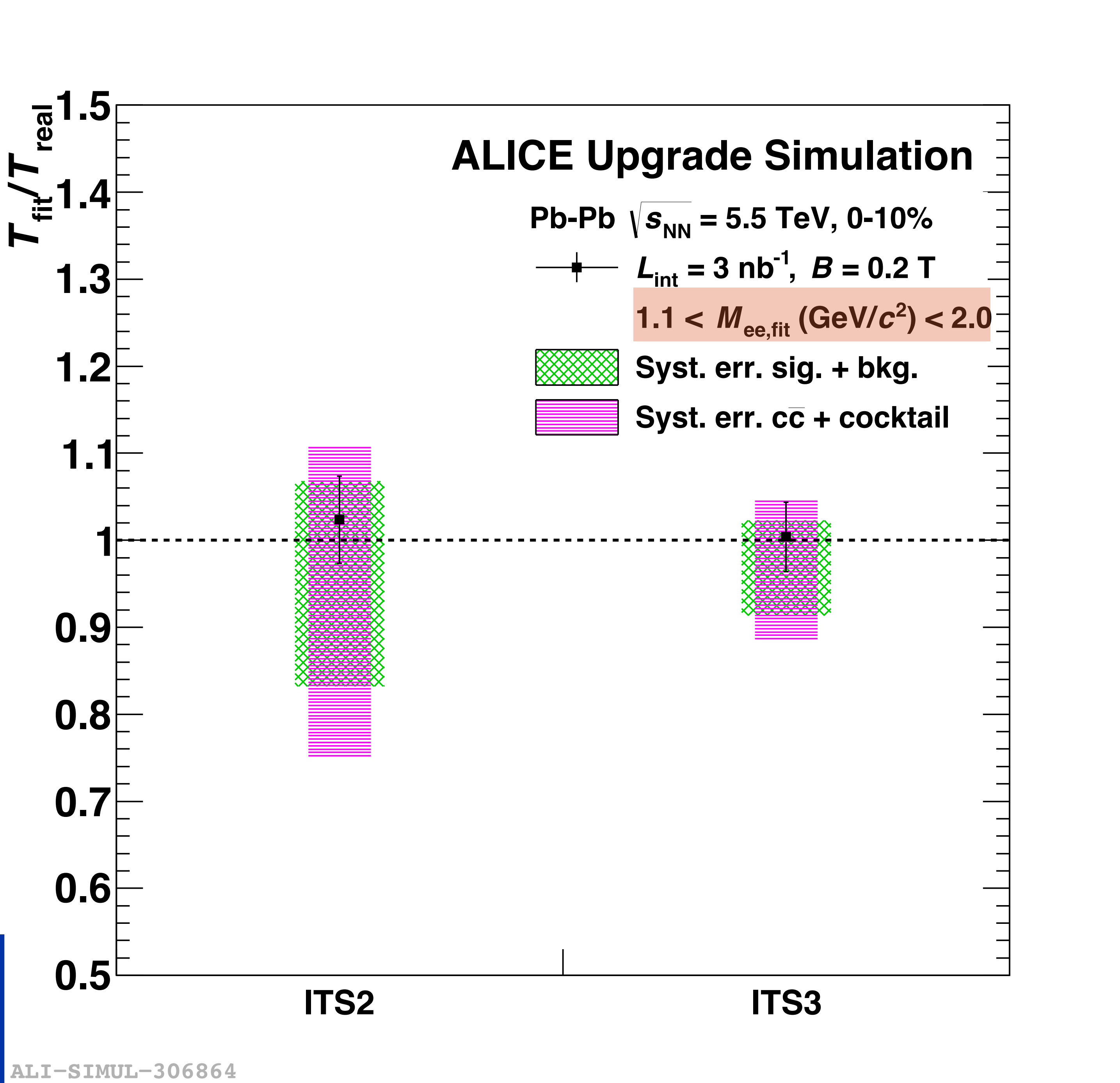
- ➡ Less electrons from photon conversions

Enhanced low-p_T electron tracking

- ➡ Improved photon conversion reconstruction, reducing combinatorial background

Improved impact parameter resolution

- ➡ Suppress contributions from heavy-flavour hadron decays



Systematic uncertainty with ITS3 reduces by a factor of two compared to ITS2