Design and expected performance of the ALICE ITS3 tracker upgrade

Jory Sonneveld on behalf of the ALICE collaboration

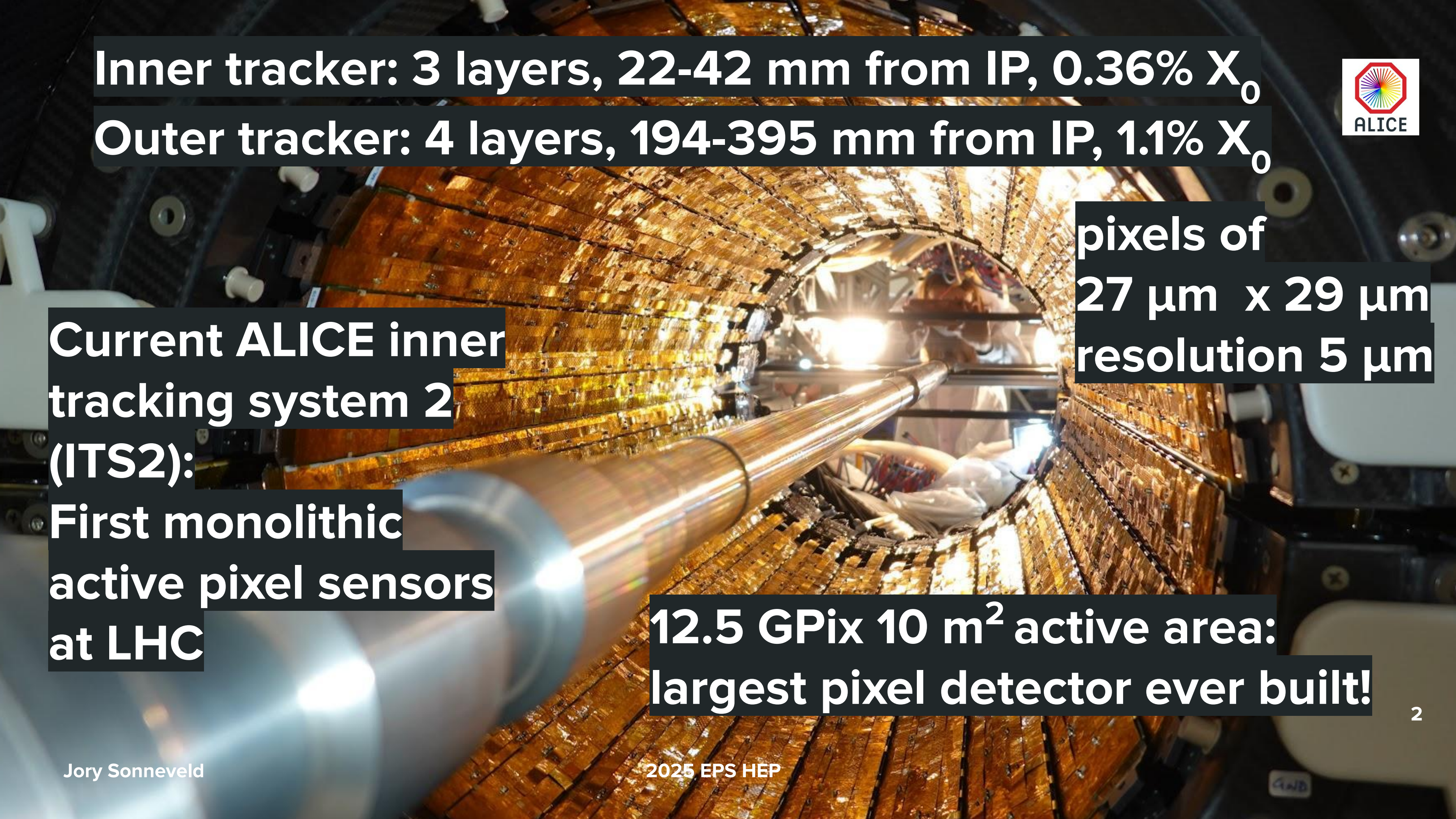
jory.sonneveld@nikhef.nl

EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
MARSEILLE, FRANCE

ALICE

Nikhef

UNIVERSITY OF AMSTERDAM



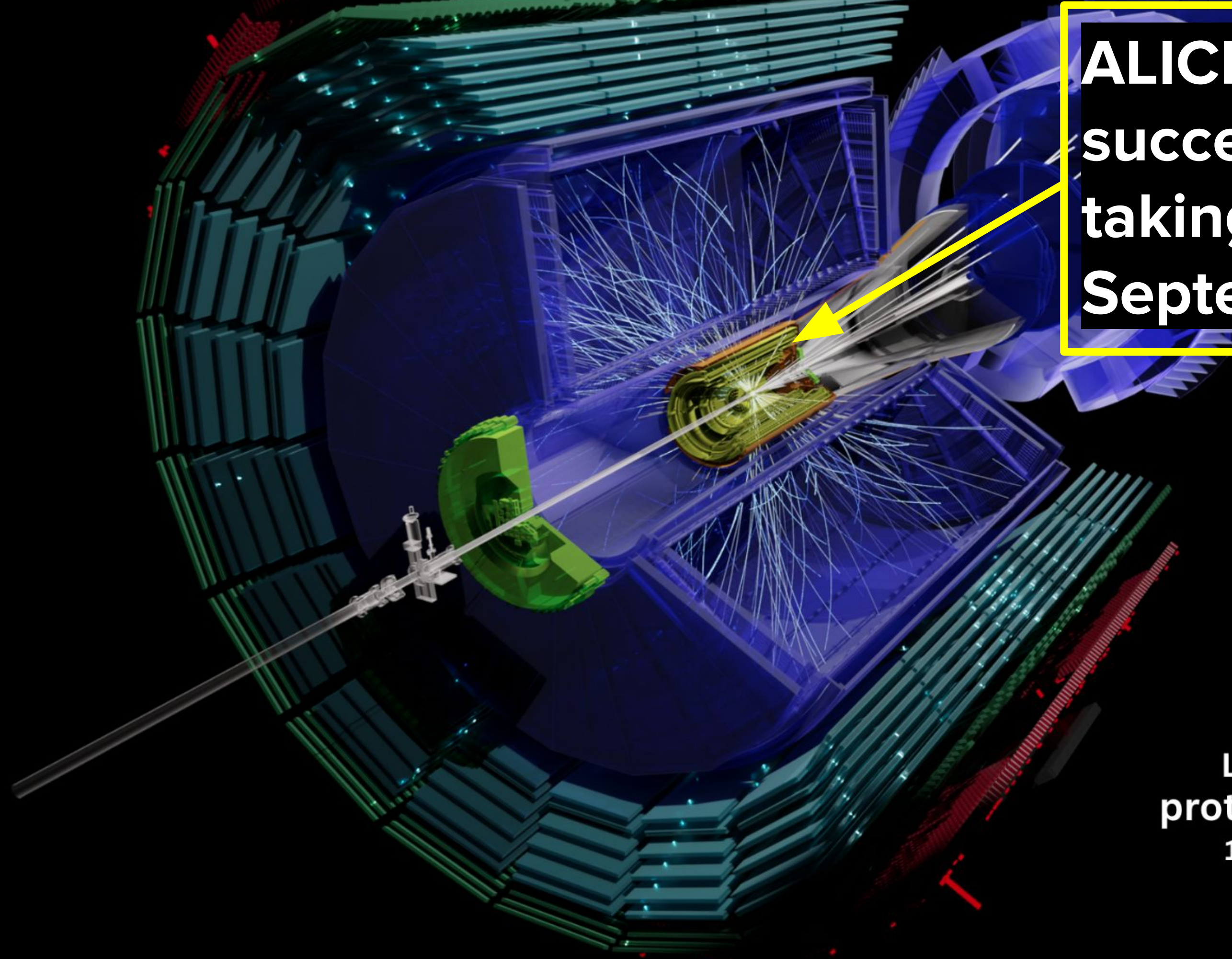
Inner tracker: 3 layers, 22-42 mm from IP, 0.36% X_0

Outer tracker: 4 layers, 194-395 mm from IP, 1.1% X_0

pixels of
27 µm x 29 µm
resolution 5 µm

Current ALICE inner tracking system 2 (ITS2):
First monolithic active pixel sensors at LHC

12.5 GPix 10 m^2 active area:
largest pixel detector ever built!



ALICE ITS2: successfully taking data since September 2021

ALICE

LHC Run3
proton-Oxygen
1 July 2025

ALICE: Quark gluon plasma in heavy ion collisions

Forward photons to prove small-x initial gluons

Low p_T heavy flavor hadrons
for heavy quark thermal equilibrium

Low mass dilepton
precision measurements for QGP temperature

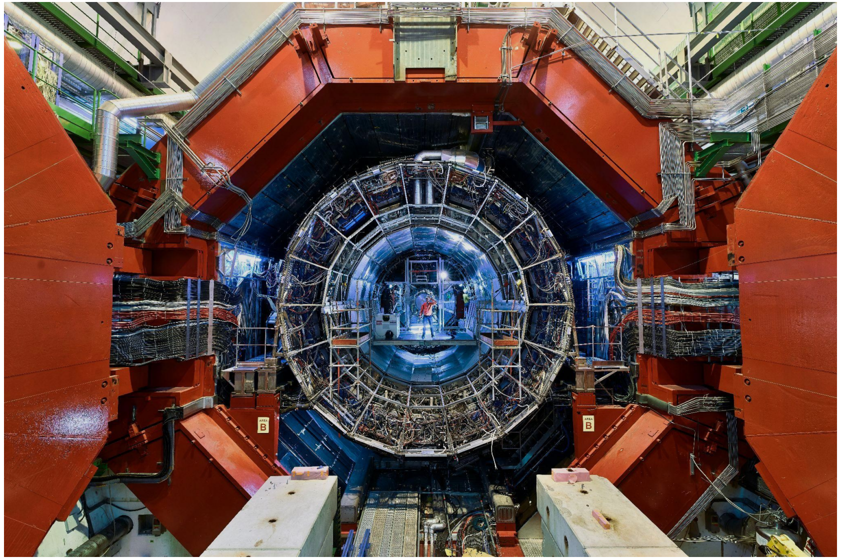


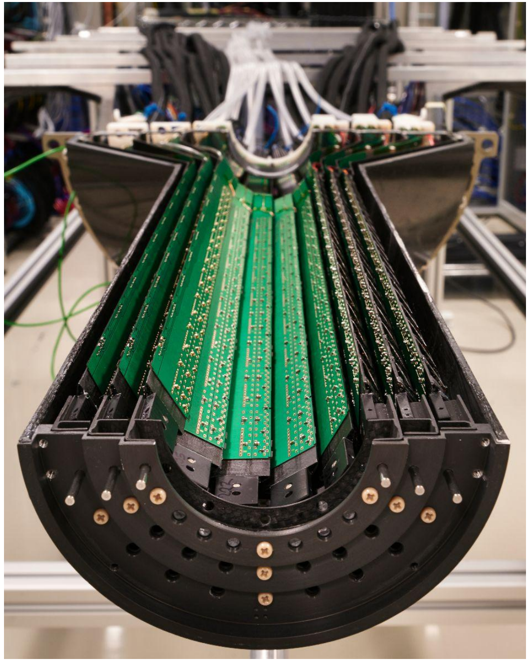
Image from cern.ch

ALICE needs:

Precise vertexing with high impact parameter resolution Of O(100) µm pointing resolution for 100 MeV charged particles

2028 upgrade of the ALICE inner tracking system

Currently: 0.36% X_0 per layer



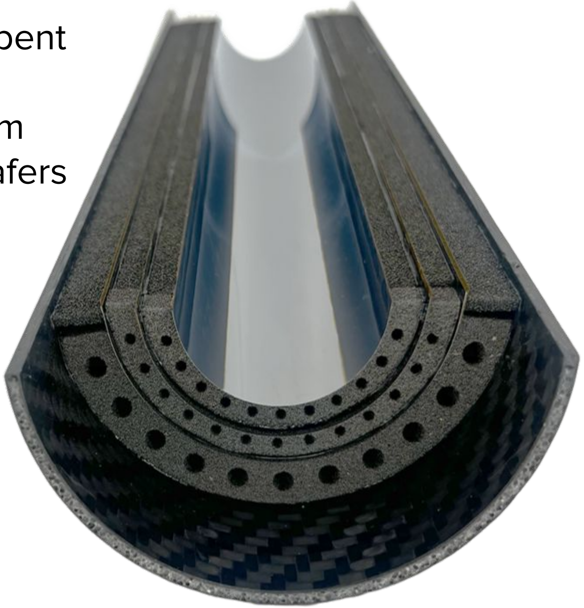
432 chips from 200 mm wafers

22.4 mm from IP
Beam pipe: 18 mm radius, 800 µm Be
0.22% X_0

ITS2 inner barrel

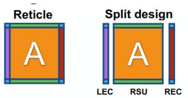
Very low material budget! 0.09% X_0 per layer

6 stitched, bent wafer-scale sensors from 300 mm wafers



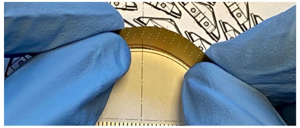
19 mm from IP
New beam pipe:
16.5 mm radius, 500 µm Be,
0.14% X_0

ALICE ITS3 for Run 4 in 2028



Stitching:
- Put design blocks together during processing of silicon
- Can make chip larger than the field of view of the lithographic equipment

Bending

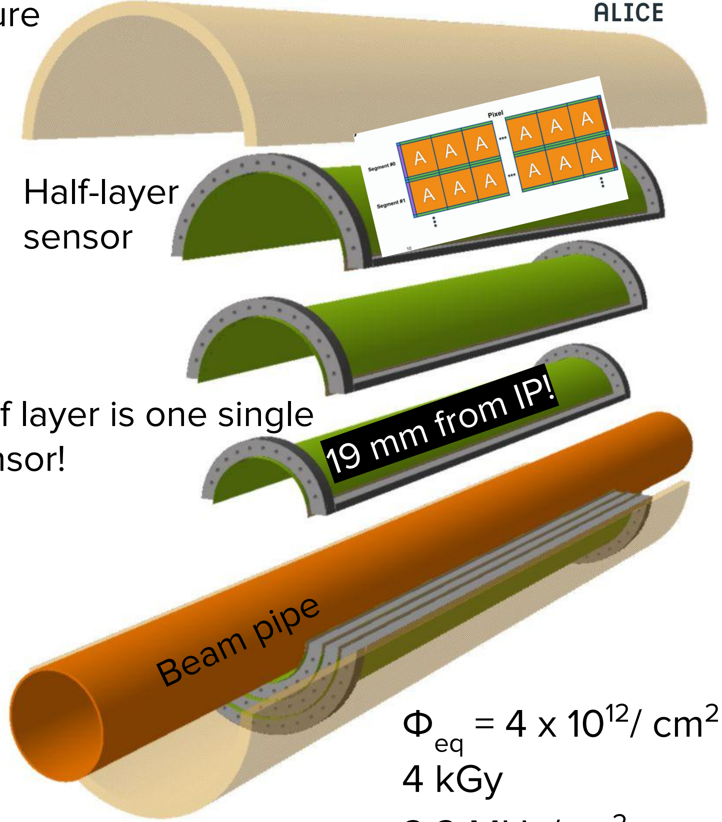


- Material: $X/X_0 \approx 0.09\%$ average per layer
- 6 half-layer sensors with wafer-scale monolithic active pixel sensors (MAPS)
- Half layer sensor of size of 266 x 58.7 mm^2 in layer 0
- Pixel size 22.8 µm x 20.8 µm
- Thinned to 50 µm
- Mechanically held in place by carbon foam

Cylindrical support structure

Half-layer sensor

Each half layer is one single pixel sensor!

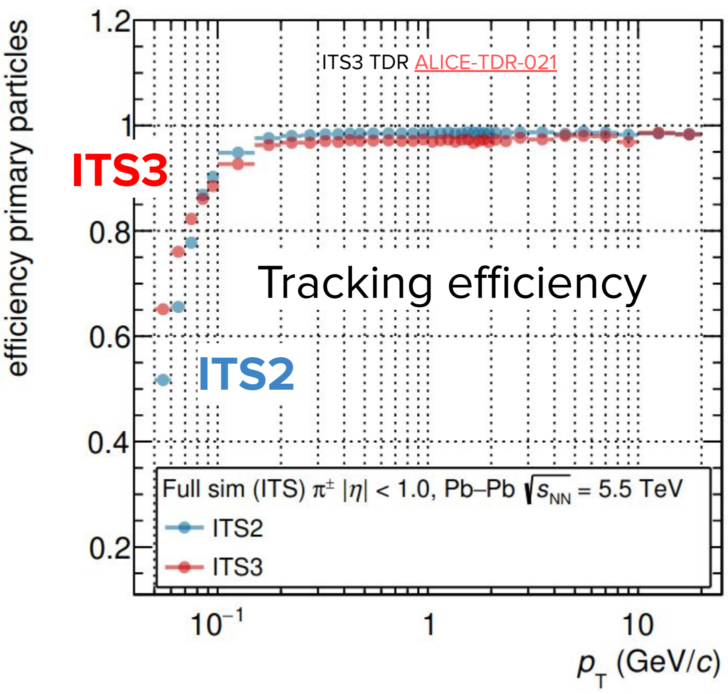


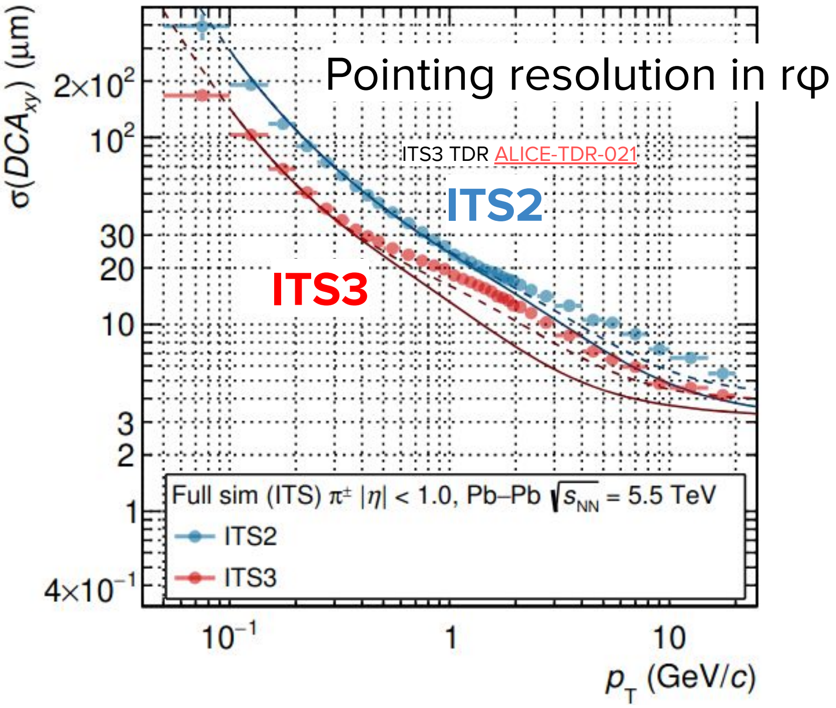
$\Phi_{eq} = 4 \times 10^{12} / cm^2$
4 kGy
2.2 MHz/cm^2

ALICE upgrades LS2 arXiv:2302.01238 ITS3 TDR ALICE-TDR-021

Improved measurements with more precise vertexing and tracking

ITS3: more precise vertexing and tracking





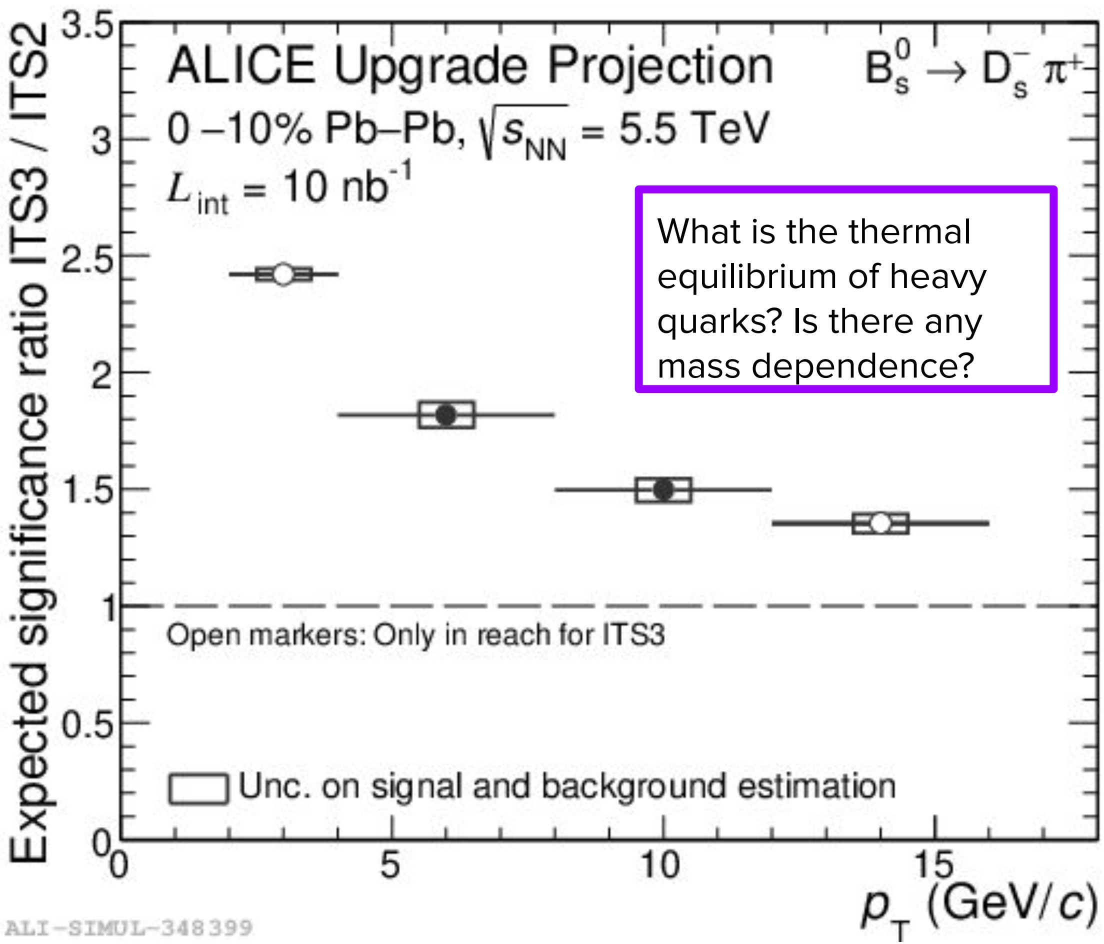
Large improvement at low p_T

Factor 2 improvement over almost all momenta

Strange beauty particles

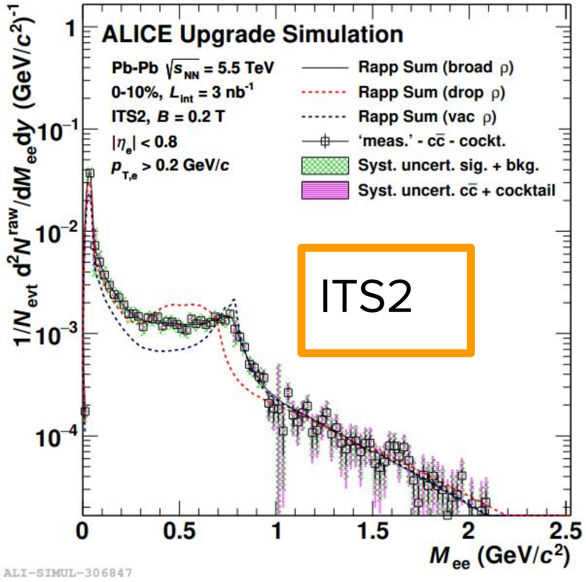
- CMS made first measurement B^0_s / $B_{not\ s}$ in Pb Pb collisions vs pp collisions – with large uncertainties
- ALICE similarly measured non-prompt Ds (Phys. Lett. B 846 (2023) 137561
- Both see an enhancement
- No significant observation
- Large improvement with ITS3
- ITS3 can measure at **lower p_T**

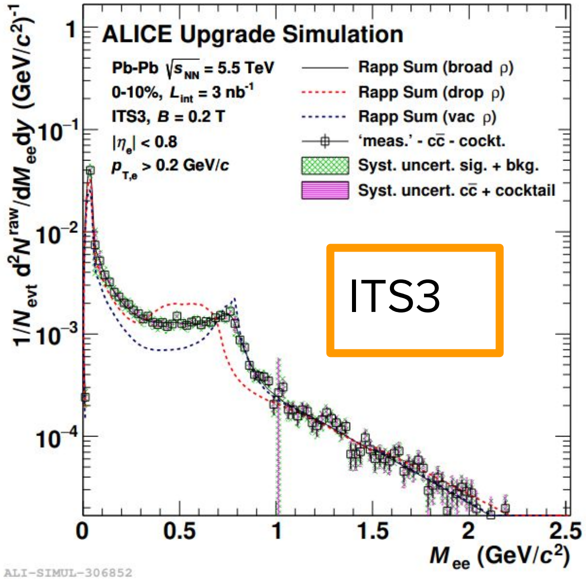
This all thanks to a close proximity to IP and a very low material budget!

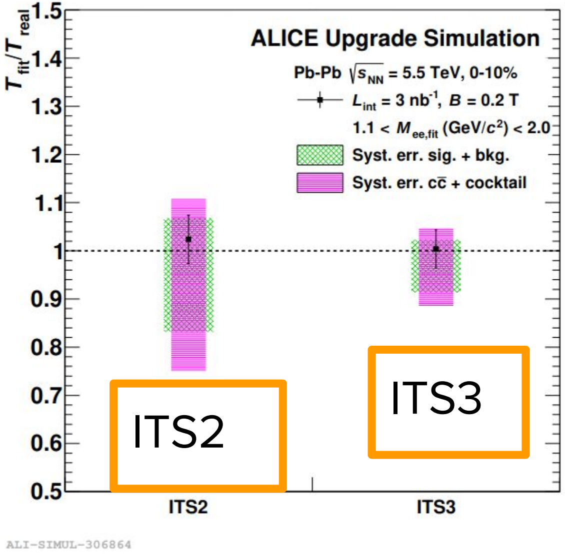


What is the thermal equilibrium of heavy quarks? Is there any mass dependence?

Thermal dielectrons







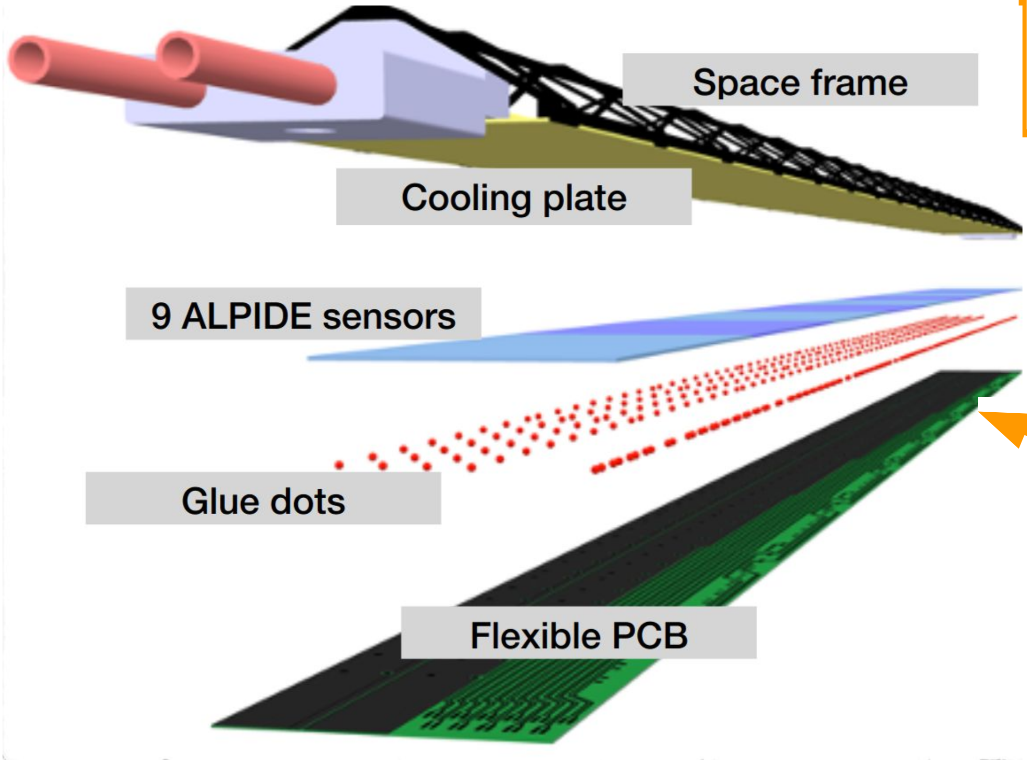
Syst. err down by factor 2

What is the temperature of the QGP radiation?

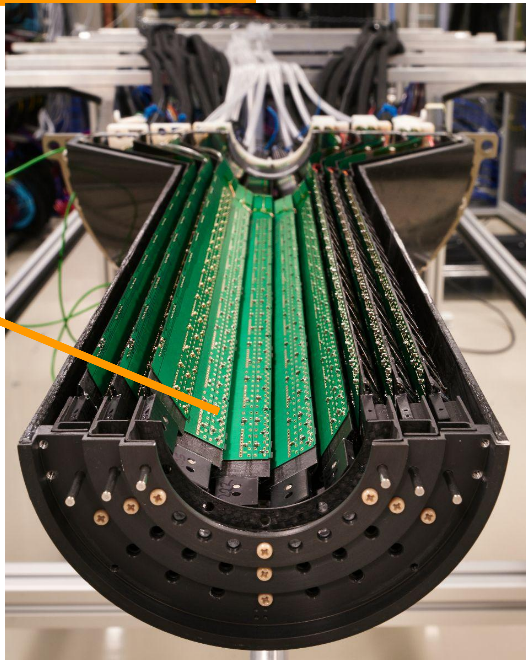
- ITS3 low-pT tracking improves photon conversion reconstruction efficiency
- Very good electron tagging efficiency with improved pointing resolution

How to reduce the material?

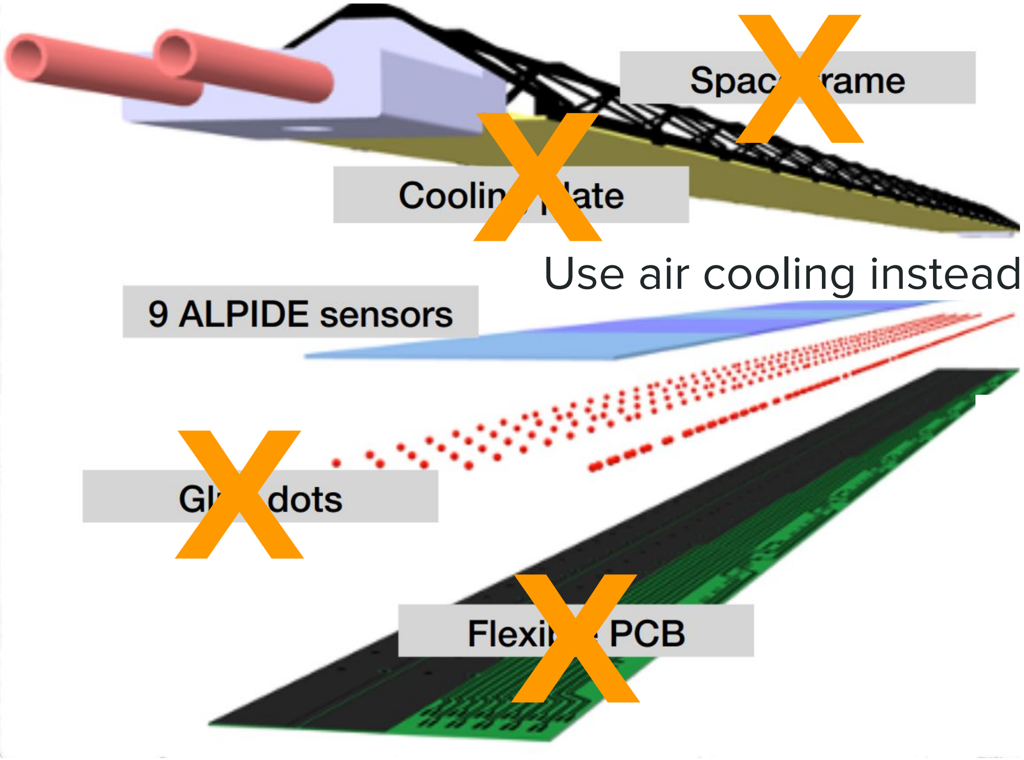
Remove “unnecessary” material from ITS2



Current ITS2 detector



Remove “unnecessary” material from ITS2



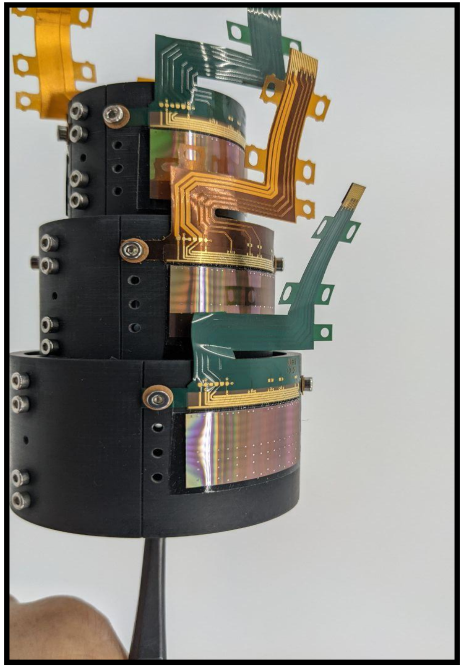
Less mechanical support needed for large bent sensors

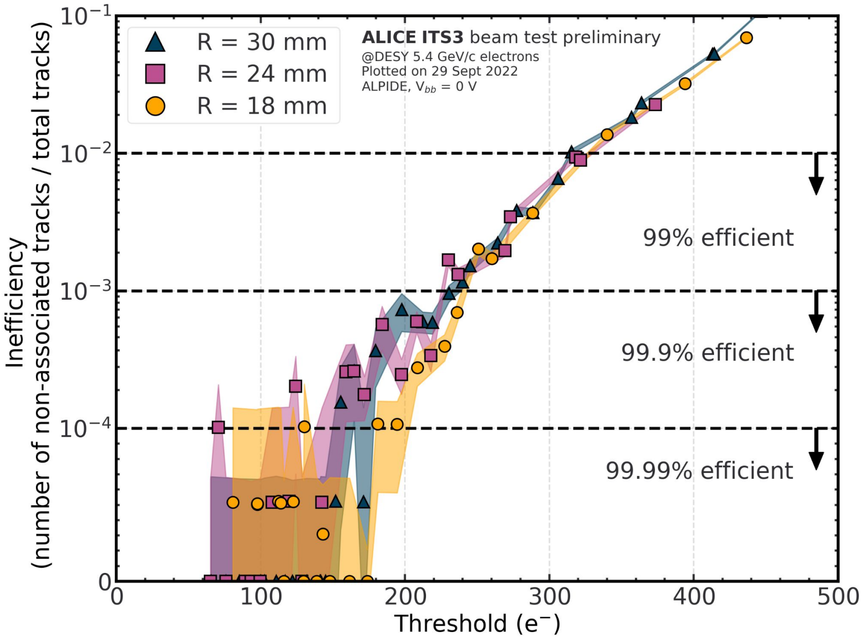
Use air cooling instead of water. Requires ~40 mW/cm^2

Power and data are integrated into silicon

Beam test studies with bent sensors

- Bending silicon wafers and functional ALPIDEs is now routine
- Full mock-up of the final ITS3: “µITS3” bent to ITS3 radii tested
- Spatial resolution uniform among different radii
- Efficiency and resolution consistent with flat ALPIDEs

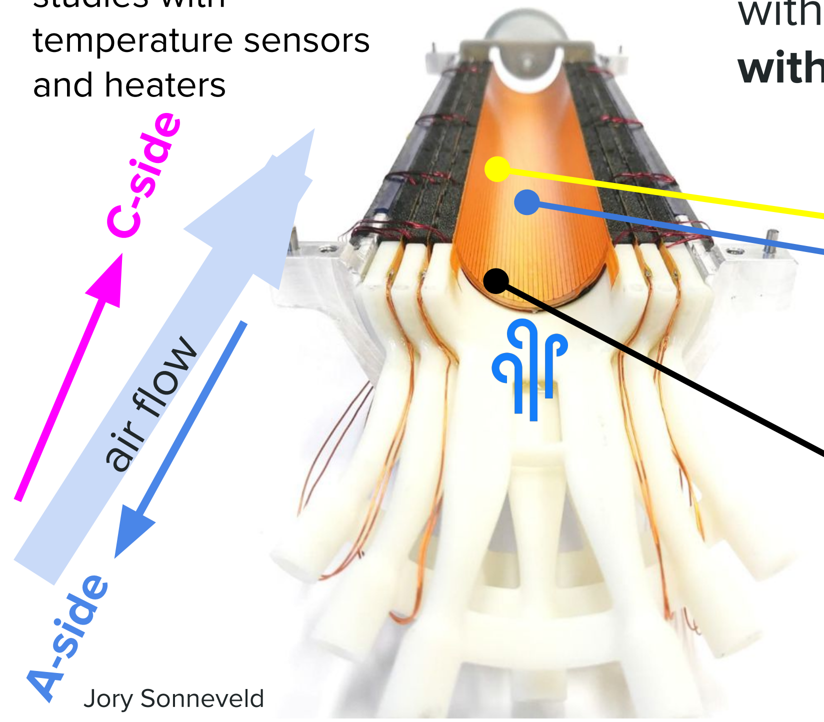




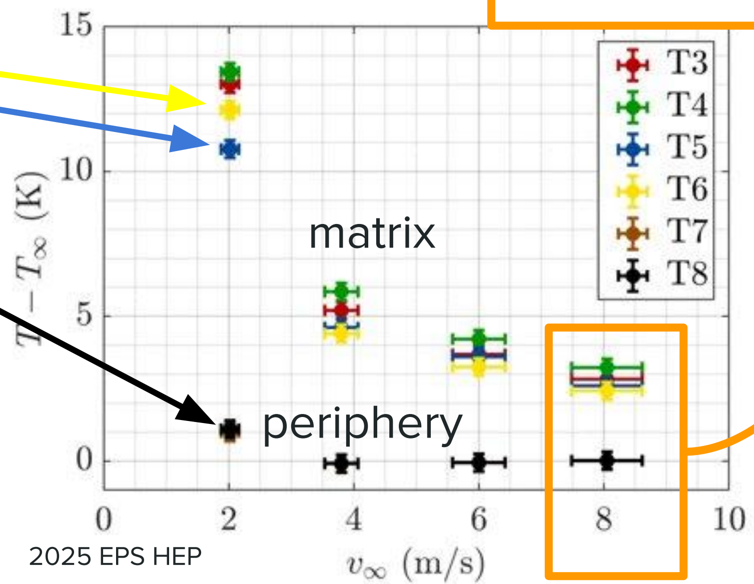
More results in doi:10.1016/j.nima.2021.166280

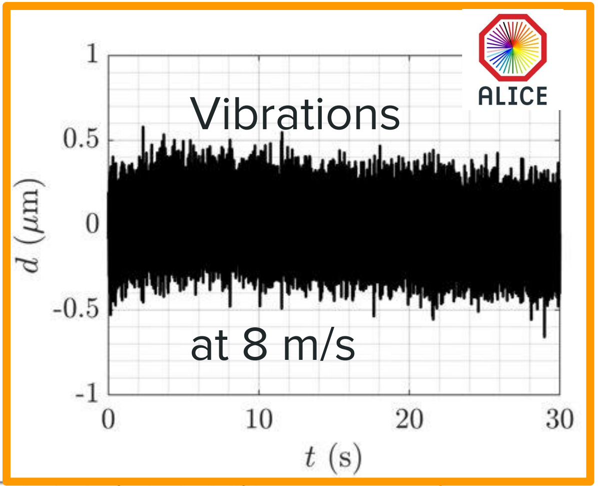
Performance under air cooling

Model for thermal studies with temperature sensors and heaters



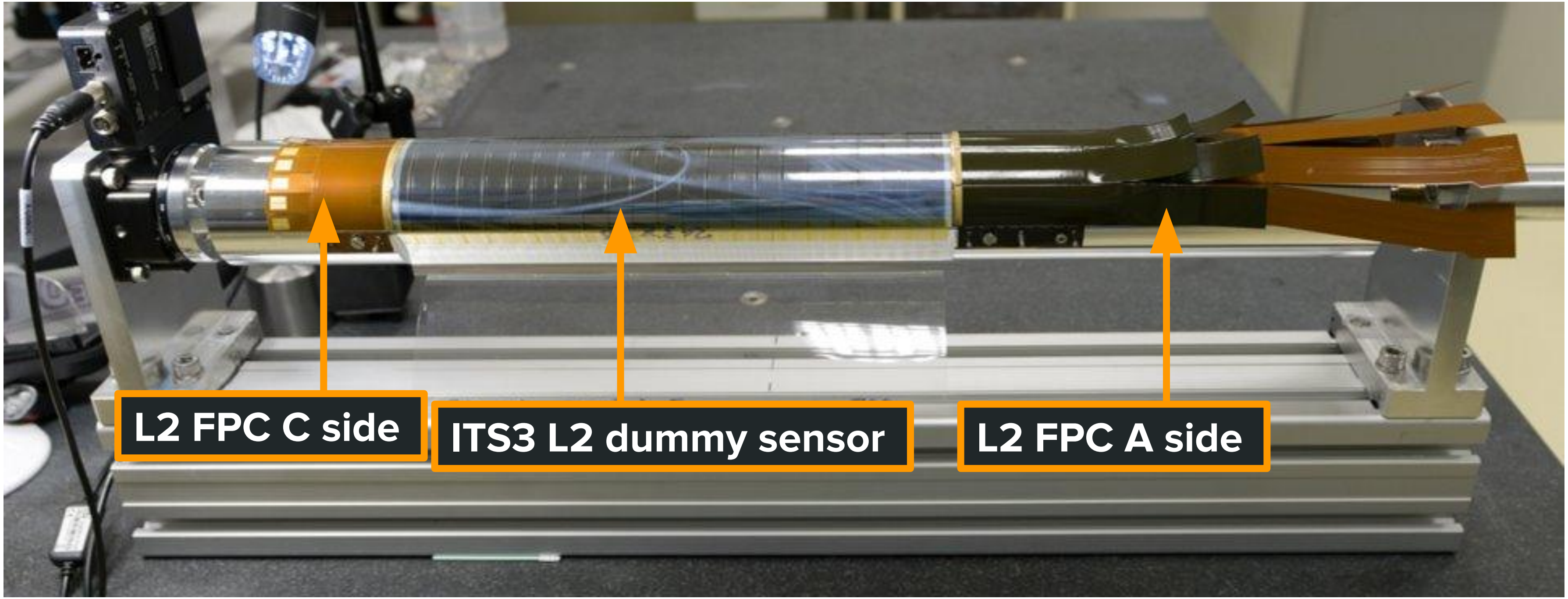
Demonstrated air-cooling with vibrations **within 1 µm peak-to-peak**





Silicon bending: full scale engineering model

C side: Powering　　**A side**: Powering & data transmission

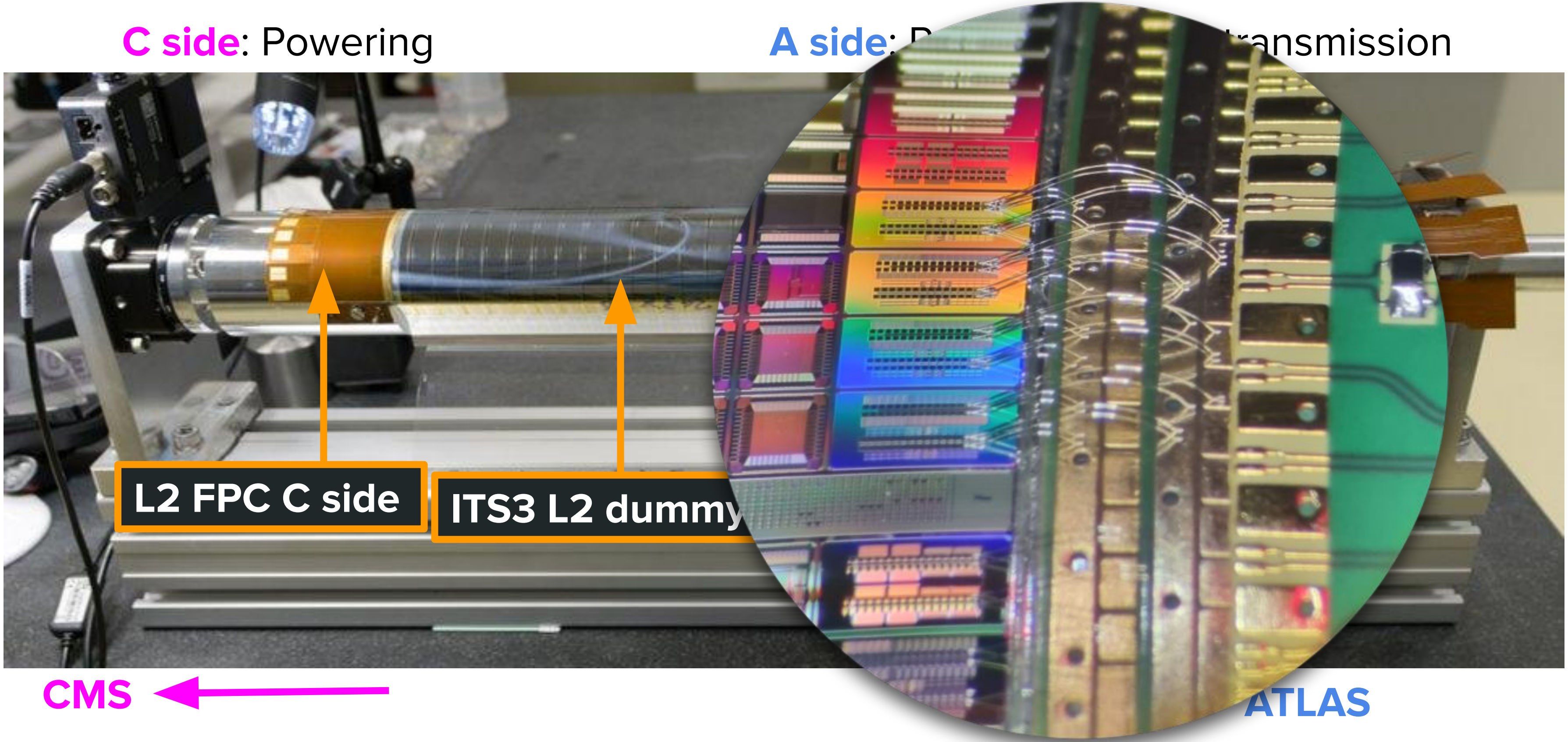


CMS ←　　→ **ATLAS**

Silicon bending: full scale engineering model

C side: Powering

A side: D… ransmission



CMS ←

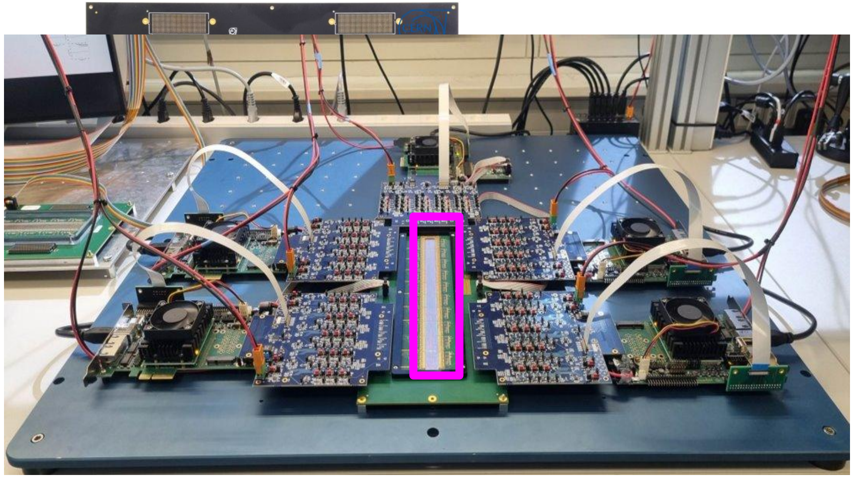
ATLAS

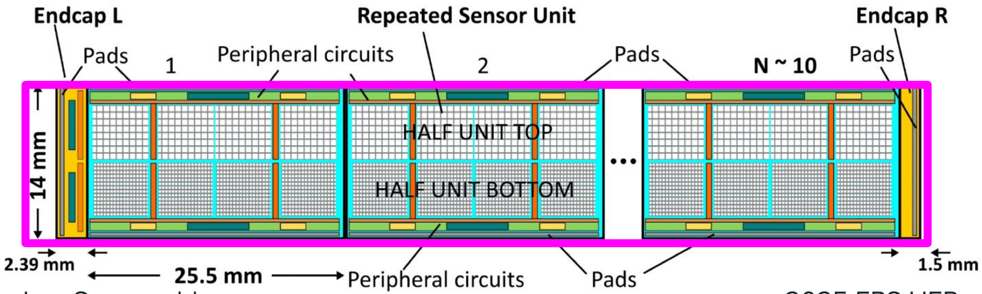
Sensor R&D

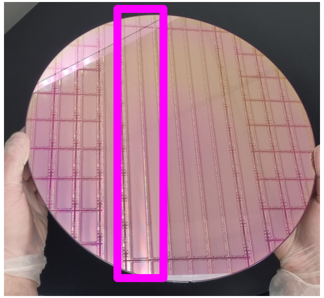
Stitched sensor prototypes

ALICE

- TPSCo CIS 65 nm → 300 mm wafers
- Engineering Run 1 (ER1):
  - Monolithic Stitched Sensor (MOSS)
  - with Timing (MOST)
- MOSS 14 x 259 mm^2, 6.72 MPixel
- MOST 2.5 x 259 mm^2, 0.9 MPixel
- Final structure 2.5 times as large
- Pixels of 22.5 x 22.5 μm^2 and 18 x 18 μm^2
- Processing issue found:
  - understood, and fixed for next submission
- Yield in unaffected sensors > 90%
  - → failure tolerant structures







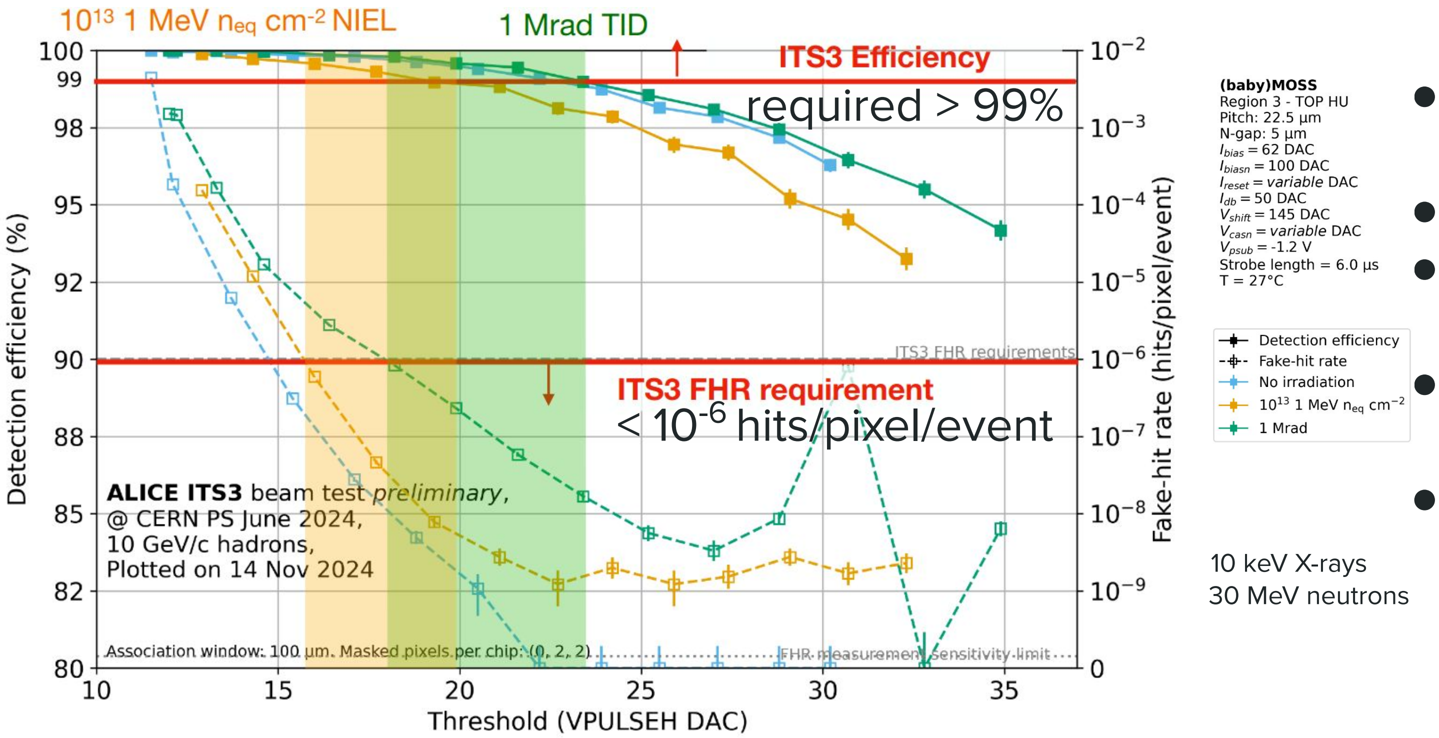
65 nm technology:

Validated to ITS3 fluences: Nucl.Instrum.Meth.A, 1069 (2024) 169896

Time resolution 67 ps: Nucl.Instrum.Meth.A, 1070 (2025) 170034

Validation of digital test structure: Nucl.Instrum.Meth.A, 1056 (2023) 16858

Performance of 259 mm stitched sensors



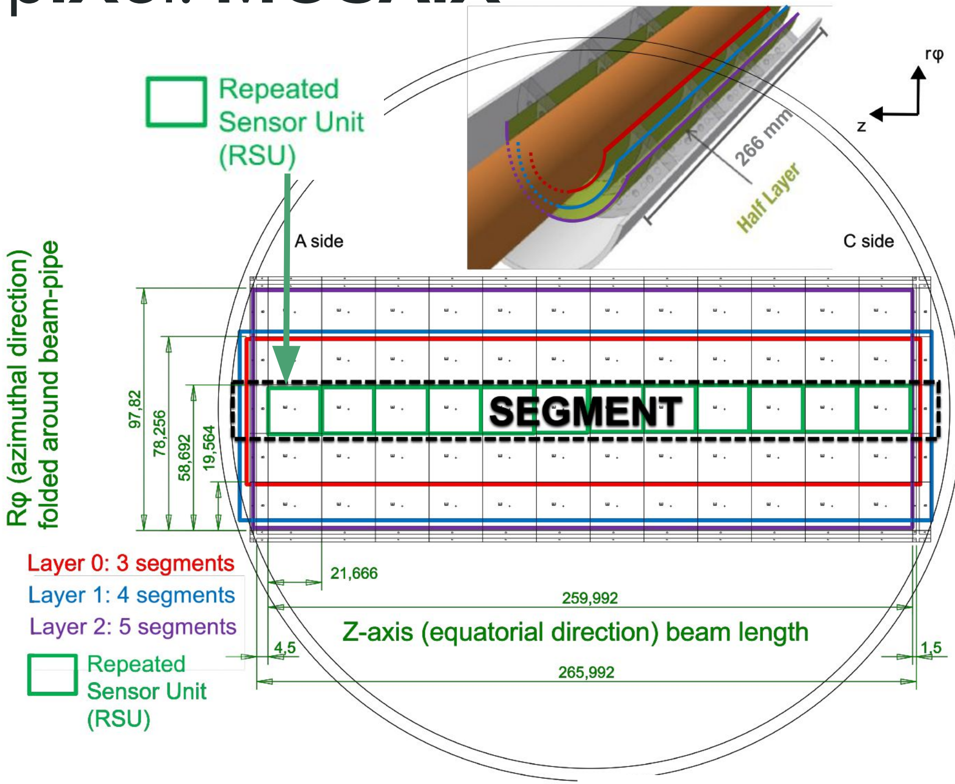
10 keV X-rays
30 MeV neutrons

- 82 days of in-beam data
- 17 chips
- 2 process variations
- 5 irradiation levels
- Many settings

- Fully functional 259 mm stitched sensor even after irradiation
- ITS3 requirements met at 4 x 10^{12} 1 MeV n_{eq} cm^{-2} and 400 krad

MOnolithic **S**titched **A**ctive p**IX**el: **MOSAIX**

- R&D towards ITS3:
  Engineering Run 2 MOSAIX
- Final prototype before ITS3 production to be tested with bending
  - Includes features of both MOSS and MOST
- MOSAIX has modular design: 3, 4, or 5 segments for layers 0-2

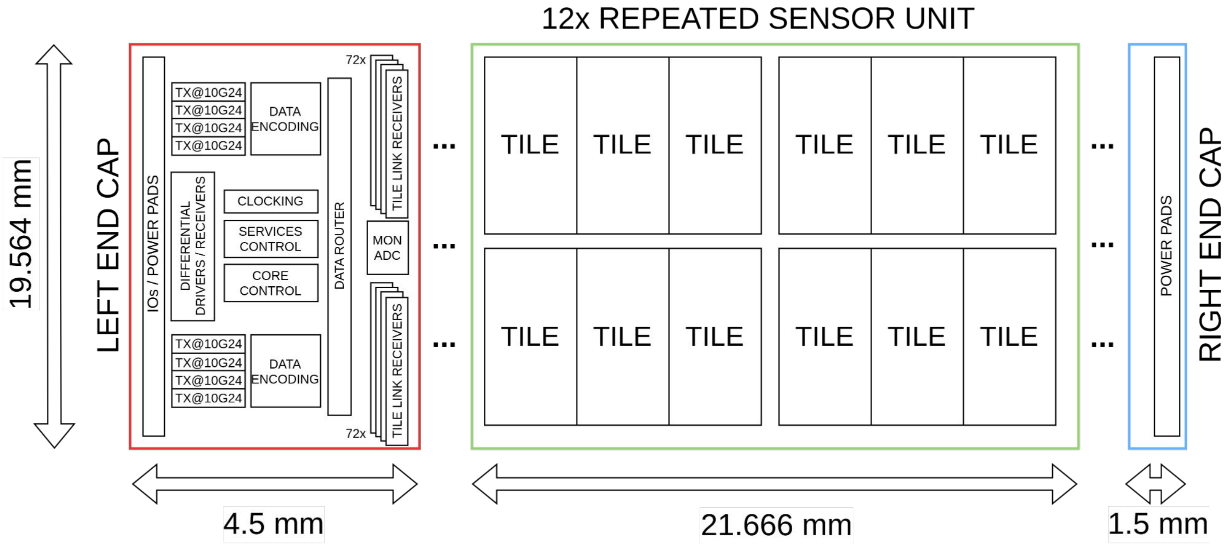


ITS3 TDR

MOSAIX sensitive area and powering scheme

Readout through **left end cap**

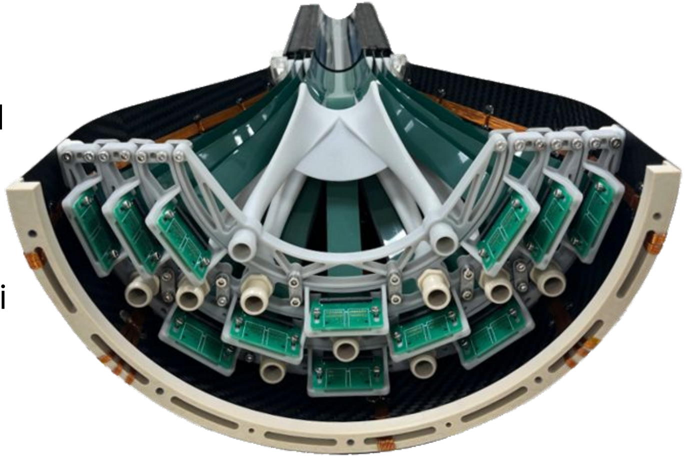
Powering through **LEC** and **REC**



- 12 RSUs, **12 tiles per RSU** with independent powering, control, and readout
- 144 tiles → 0.7% of sensor per tile that can be switched off individually in case of a short or issue
- 93% sensitive area in total

Summary and outlook

- ALICE will install **new inner layers for ALICE inner tracking system 3** (ITS3) for LHC Run 4 in 2028
- Aim for **truly cylindrical wafer-scale monolithic active pixel sensors**
- **Silicon flexibility and bending proven** with routine bending tests
- **Full mockup of ITS3 efficient** when bent to ITS3 target radii



- Sensor prototypes reach **>99% detection efficiency and less than 10^{-6} hits/pixel/event fake hit** rate at room temperature **at ITS3 fluence requirement** of $\Phi_{eq} = 4 \times 10^{12}$ / cm^2
- **First stitched sensors successfully tested,** final prototype coming next year
- ITS3 R&D will pave the way to thin 50 µm low-power 40 mW/cm^2 sensors that **could be used in ALICE 3** (see talk by Antonin Maire in this session) **and beyond** at FCC

ITS3 is a successful R&D project enabling a wealth of new precision measurements.

Additional material

Large Hadron Collider

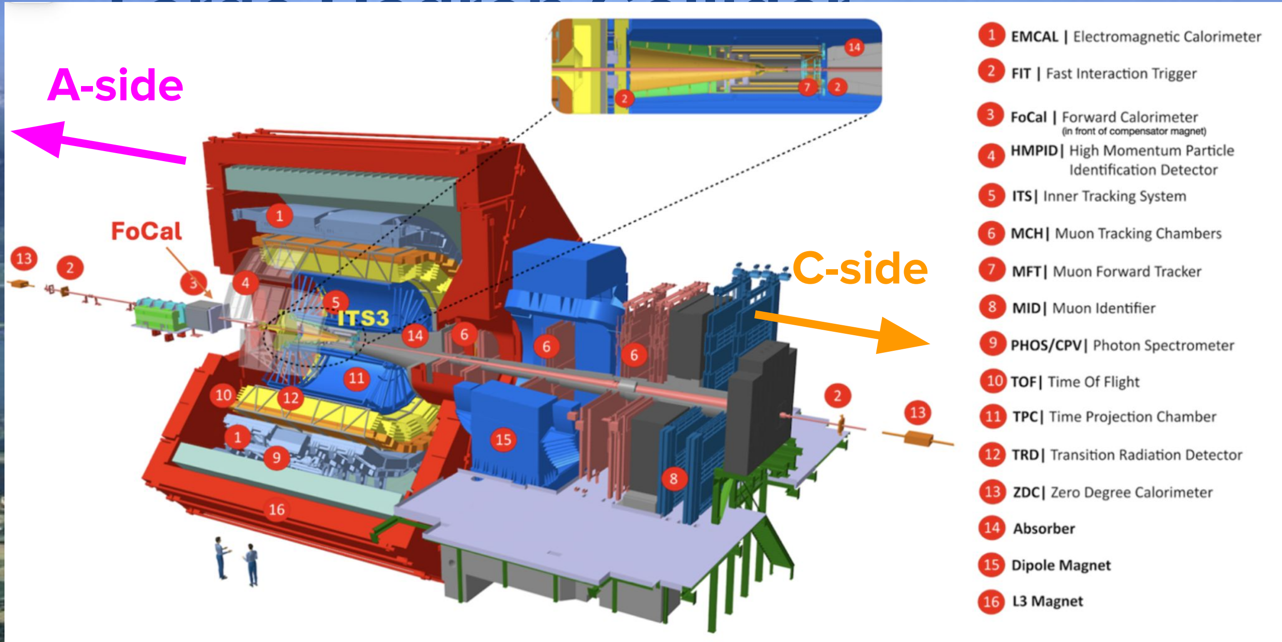
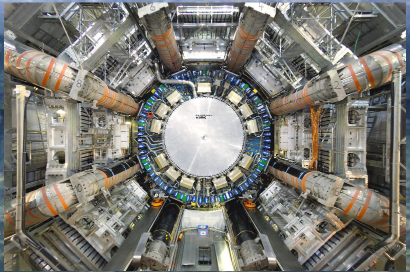


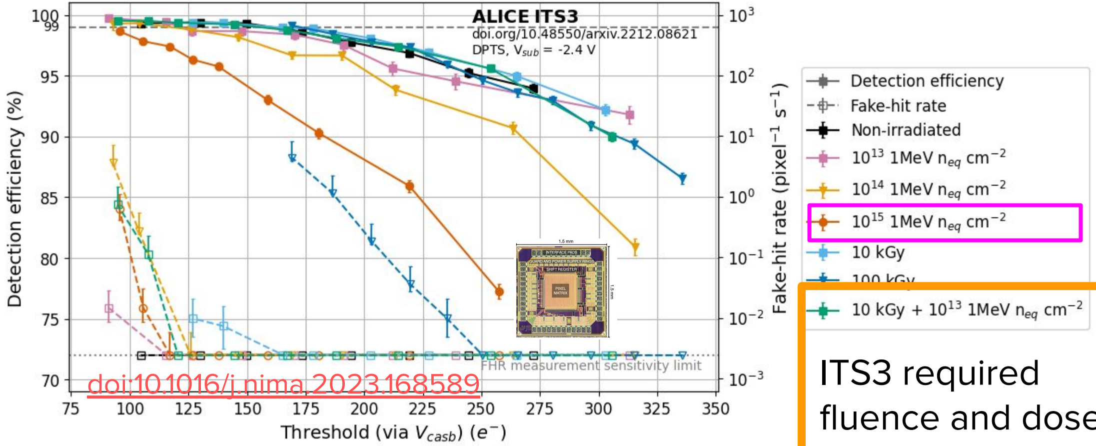
Image from cern.ch



https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg
Http://sites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg
https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG
https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg
https://www.youtube.com/watch?v=NhXMXiXOWAA

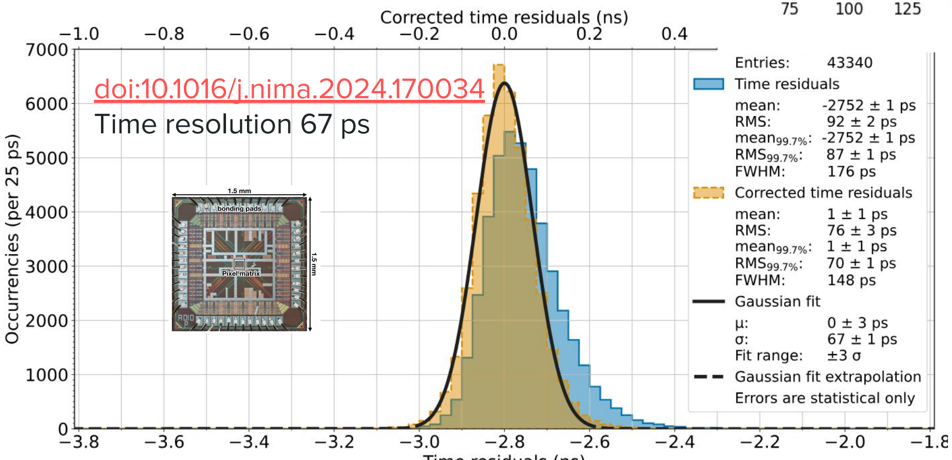
Qualification of new 65 nm technology for ITS3

- Multi-Layer Reticle 1 (MLR1): first submission in Tower Partner Semiconductor (TPSCo) 65 nm technology
- 65 nm wafers are 300 mm: allows for large scale sensors
- 55 small-scale analog and digital pixel test structure variants of processes and pitches



doi:10.1016/j.nima.2023.168589

ITS3 required fluence and dose



doi:10.1016/j.nima.2024.170034

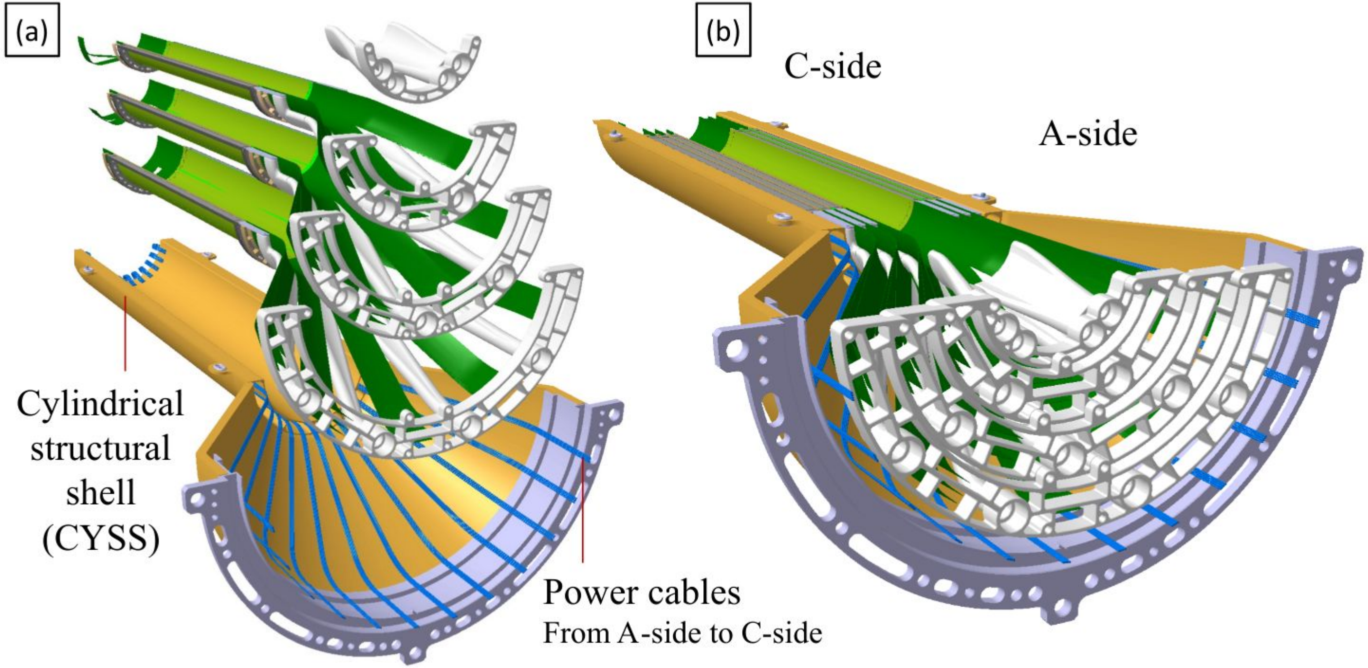
Time resolution 67 ps

Validated for
- charge collection efficiency
- detection efficiency
- radiation hardness

See also doi:10.1016/j.nima.2024.169896

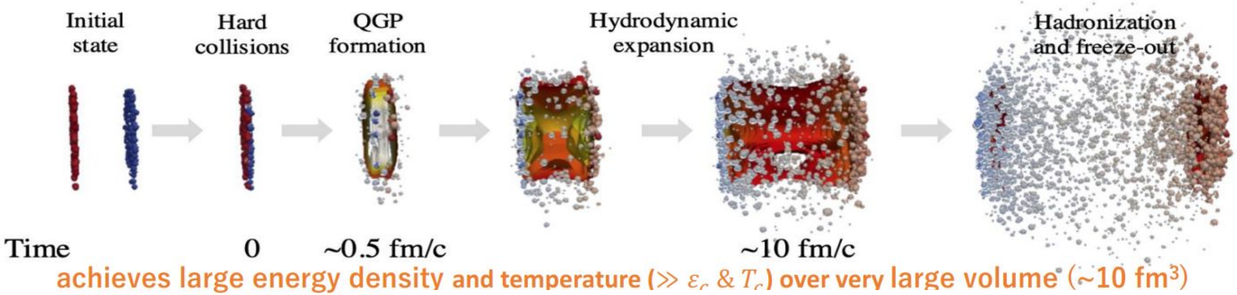
Sensor still operable at 99% efficiency at 20°C after $\Phi_{eq} = 10^{15}$ / cm^2 !

Powering ITS3



Power lines travel along CYSS to reach the C-side

ALICE: Quark gluon plasma in heavy ion collisions



Some open questions:

https://arxiv.org/pdf/1804.06469

Forward photons to prove small-x initial gluons

What is the initial state of collisions and QGP formation? Is the gluon density saturated at small x?

Low p_T heavy flavor hadrons

What is the thermal equilibrium for heavy quarks? What is the mass dependence?

Low mass dilepton precision measurements

What is the temperature of QGP radiation? How is chiral symmetry restored in QGP?

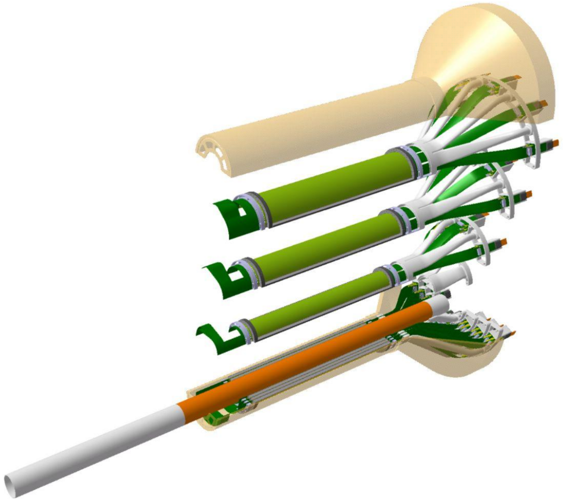
From Ken Oyama

ITS3 geometry

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	

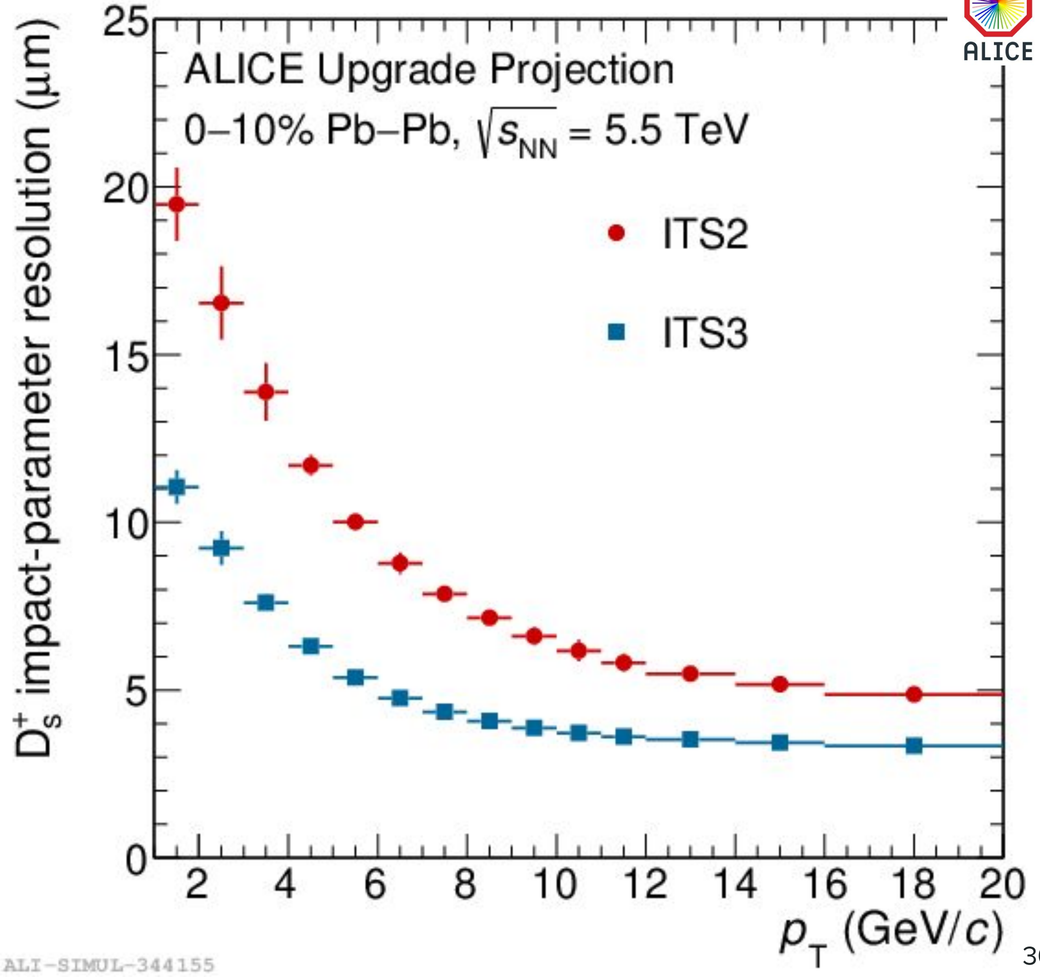
[a] The pseudorapidity coverage of the detector layers refers to tracks originating from a collision at the nominal interaction point ($z = 0$).



ITS3 TDR CERN-LHCC-2024-003

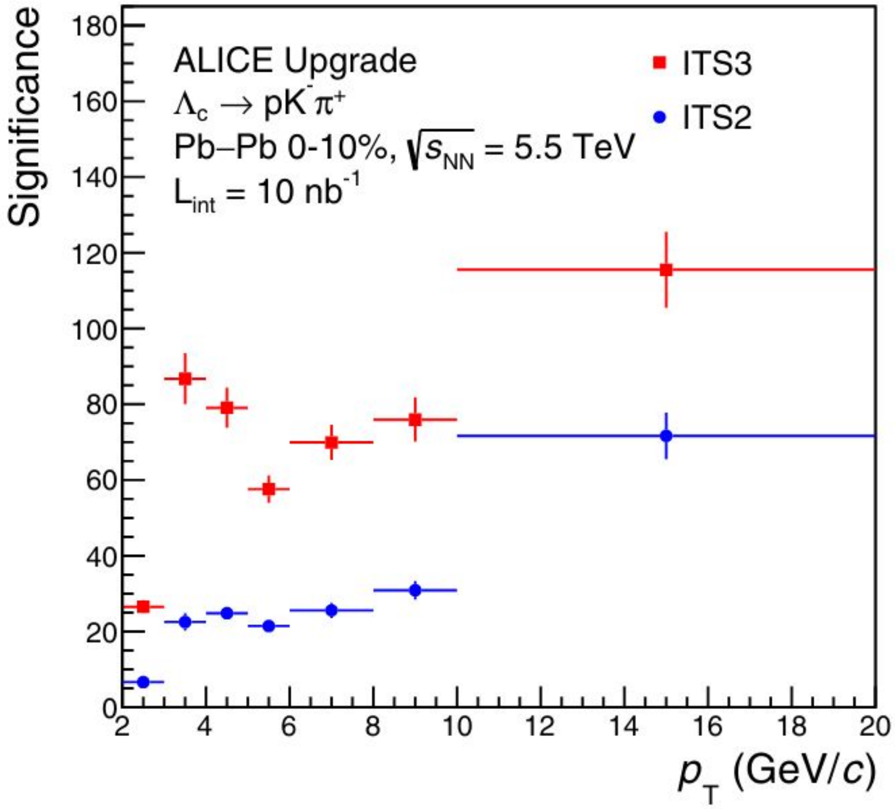
Non-prompt D mesons

- Highly sensitive to beauty-strange hadron production in quark gluon plasma
- $Br(B^0_s \rightarrow D^+_s + X) = (93 \pm 25)\%$
- Higher background rejection resulting from improved track spatial resolution

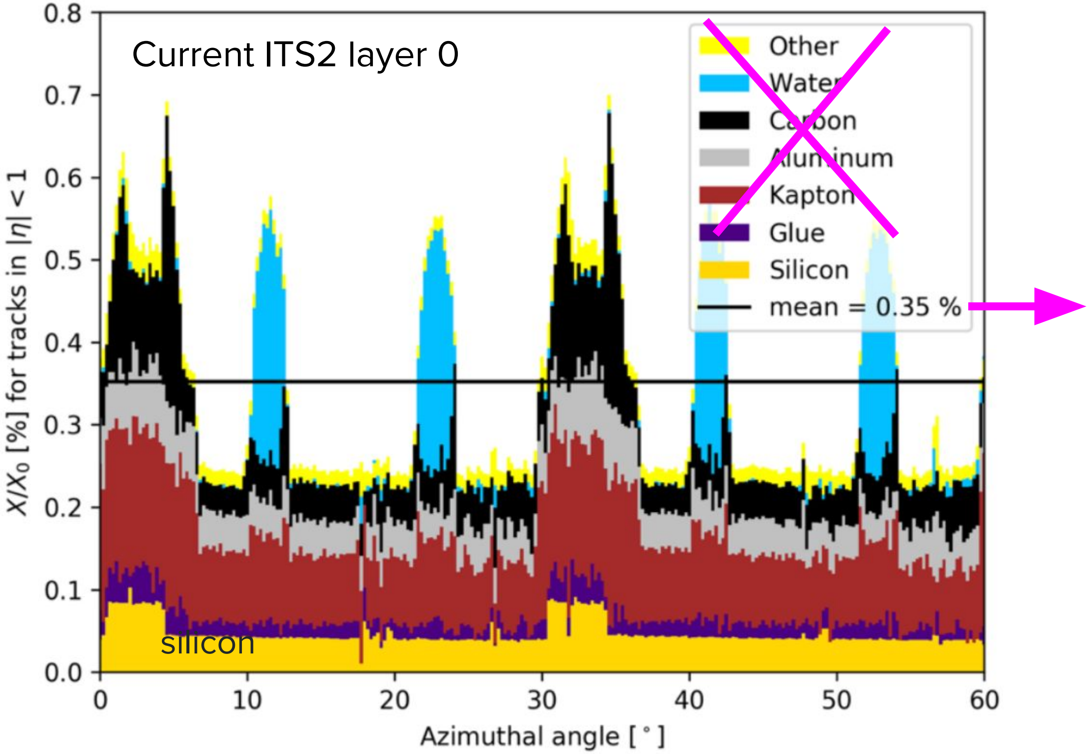


Better reconstruction of short-lived hadrons in ITS3

- Short lifetime:
  $c\tau(\Lambda^{+}_{c}) \sim 59\ \mu m$
  twice smaller than D^0 meson
- Decay tracks displaced O(10) µm from IP
- Significance of Λ_c in pion decay channel more than doubles in ITS3 for low momenta



Remove “unnecessary” material from ITS2



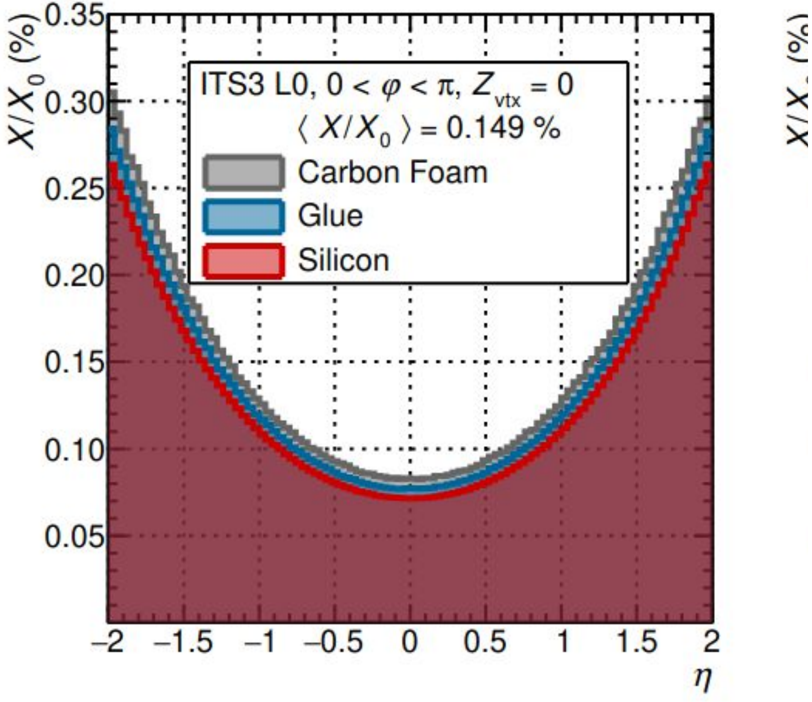
- Circuit board (kapton, aluminum): not required if power and data are integrated into the silicon

Mean 0.05% per layer

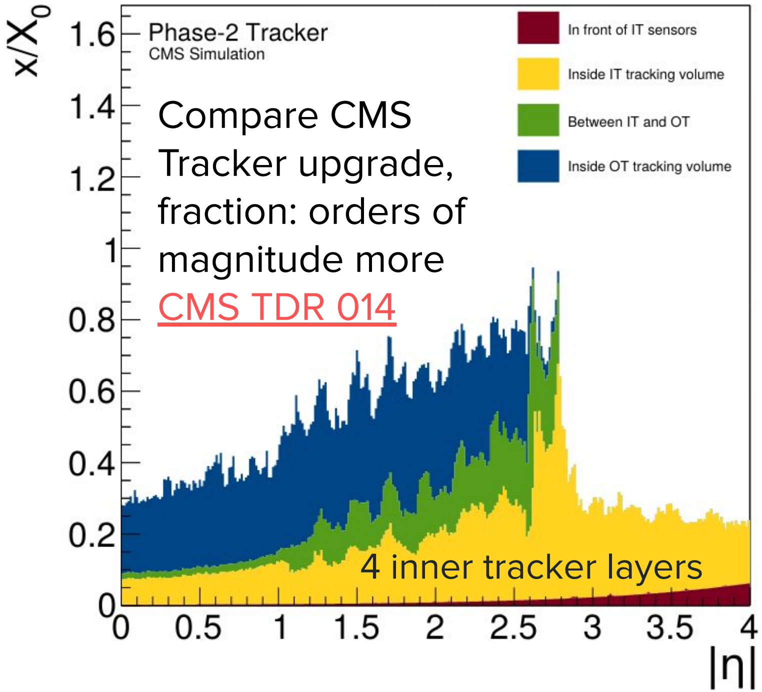
- Water cooling ➔ replace with air cooling. Requires < 40 mW/cm^2
- Less mechanical support (carbon, glue) needed for large, bent sensors!

ITS3 Letter of intent CERN-LHCC-2019-018

Remove “unnecessary” material from ITS2



[ITS3 TDR]



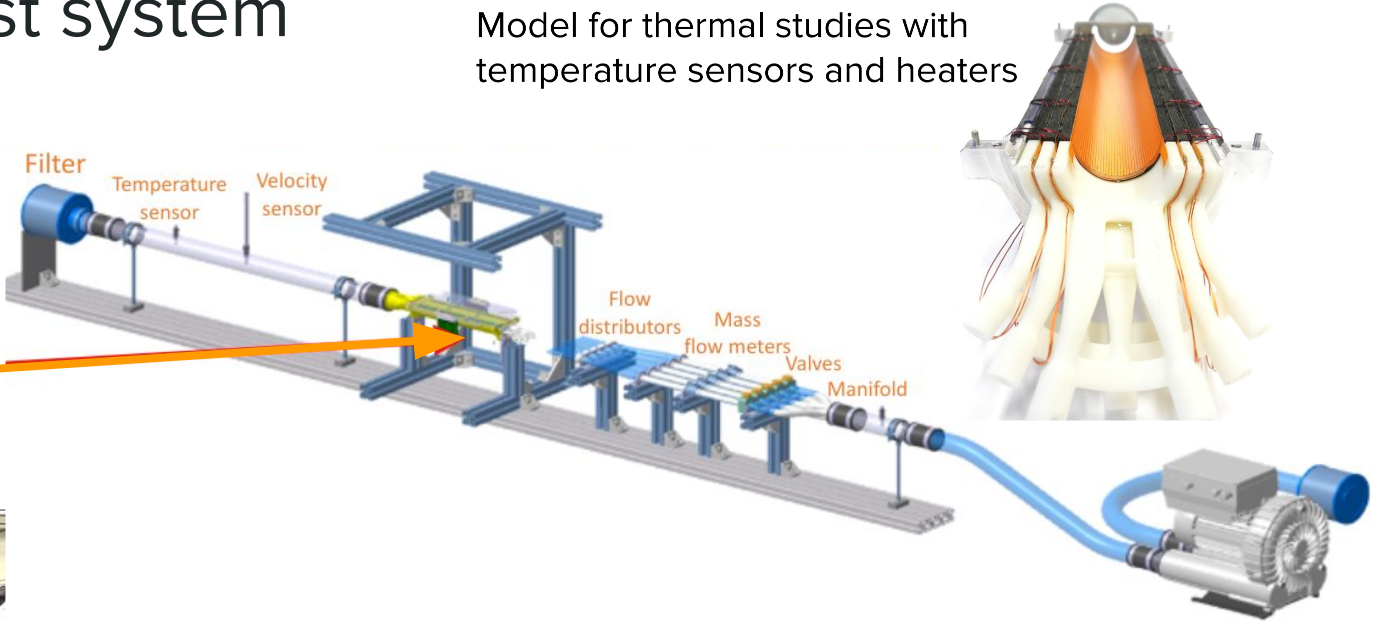
Compare CMS Tracker upgrade, fraction: orders of magnitude more

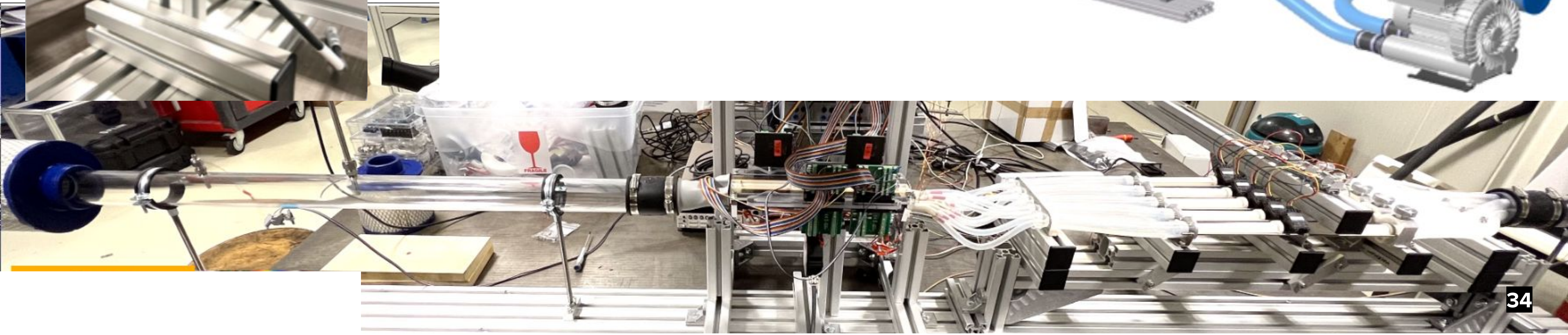
[CMS TDR 014]

ITS3 Letter of intent [CERN-LHCC-2019-018]

Air cooling test system

Model for thermal studies with temperature sensors and heaters





Different process modifications

- Motivated by better charge collection
- Higher speed may serve for monolithic sensors with timing functionality that could be applied in ALICE3