ALICE 3 Silicon Tracker
Design, Status And Prospects

Kshitij Agarwal[1], for the ALICE Collaboration

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The 14th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors

Academia Sinica, Taipei (TW); 16 – 21.11.2025

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Dipartimento di Fisica

INFN TRIESTE Istituto Nazionale di Fisica Nucleare Sezione di Trieste

ALICE

Overview

Introduction

- Run 1 … 4: Evolution of the ALICE Inner Tracking Systems
- Run 5 : ALICE 3 Silicon Tracker
  Overview and Layout

Sensor Development

- Requirements and Challenges
- Learnings from ITS3 Sensor R&D
- CMOS 65 nm Technology Qualification
- Sensor R&D and simulations

Module and Stave: Design and Mechanics (incl. cooling)

- Vertex Detector
- Middle Layers and Outer Tracker
- Lightweight Middle Layers Alternatives

Summary and Outlook

INTRODUCTION

Evolution Of The ALICE Silicon Tracker (Run 1 … 4)

Run 1 2009 – 2013	Run 2 2015 – 2018	Run 3 2022 – 2026	Run 4 2030 – 2033	Run 5 2036 – 2041
ALICE 1 Pb-Pb: 1 kHz, pp: 200 kHz		ALICE 2 Pb-Pb: 50 kHz, pp: 1000 kHz	ALICE 2.1 Pb-Pb: 50 kHz, pp: 1000 kHz	ALICE 3 Pb-Pb: 100 kHz, pp: 24 MHz

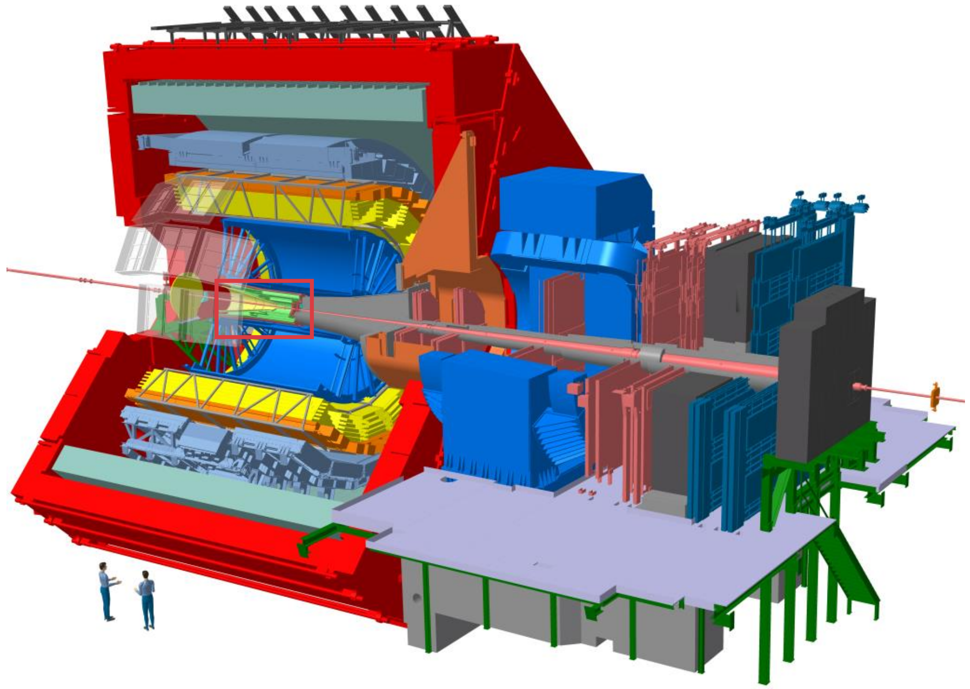

Figure Ref: ALICE-PHO-SKE-2017-001-4

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Upgrades aimed to improve the pointing resolution, while operating at 50 kHz Pb-Pb interaction rate

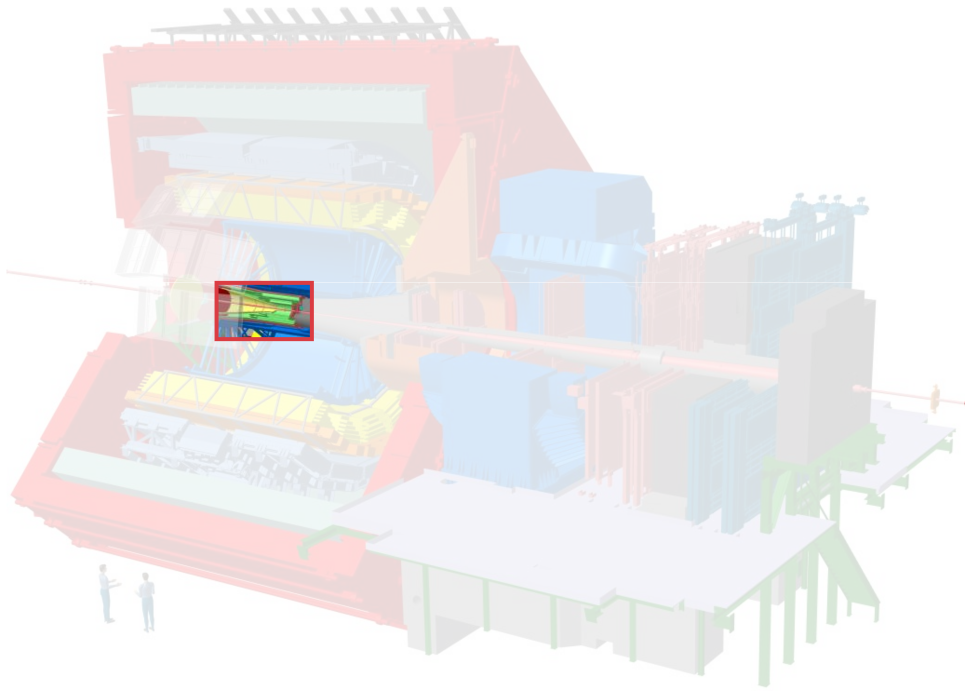
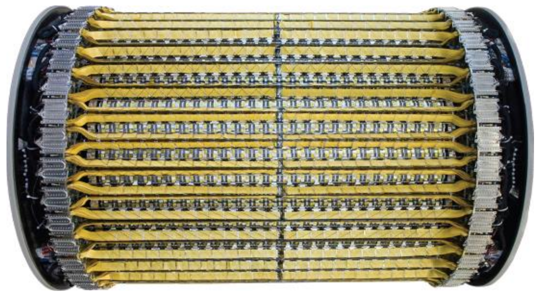


Figure Ref: ALICE-PHO-SKE-2017-001-4

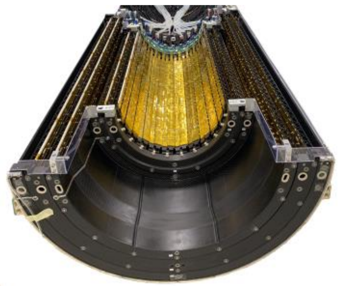
ITS1 @ Run 1, 2 (Pixel, Drift, Strip)



r = 39 … 430 mm, 1.14% X/X_0

ITS2 @ Run 3 (MAPS)

Inner Barrel
r = 23 … 39 mm, 0.36% X/X_0

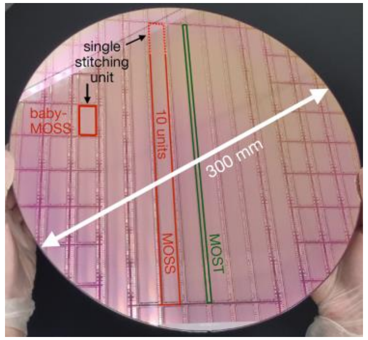


Outer Barrel
r = 196 … 393 mm, 1.1% X/X_0

ITS3 @ Run 4 (Wafer-Scale, Stitched, and Bent MAPS)

r = 19 … 31 mm, 0.09% X/X_0

ITS3 Engineering Model (Outer Barrel as ITS2)



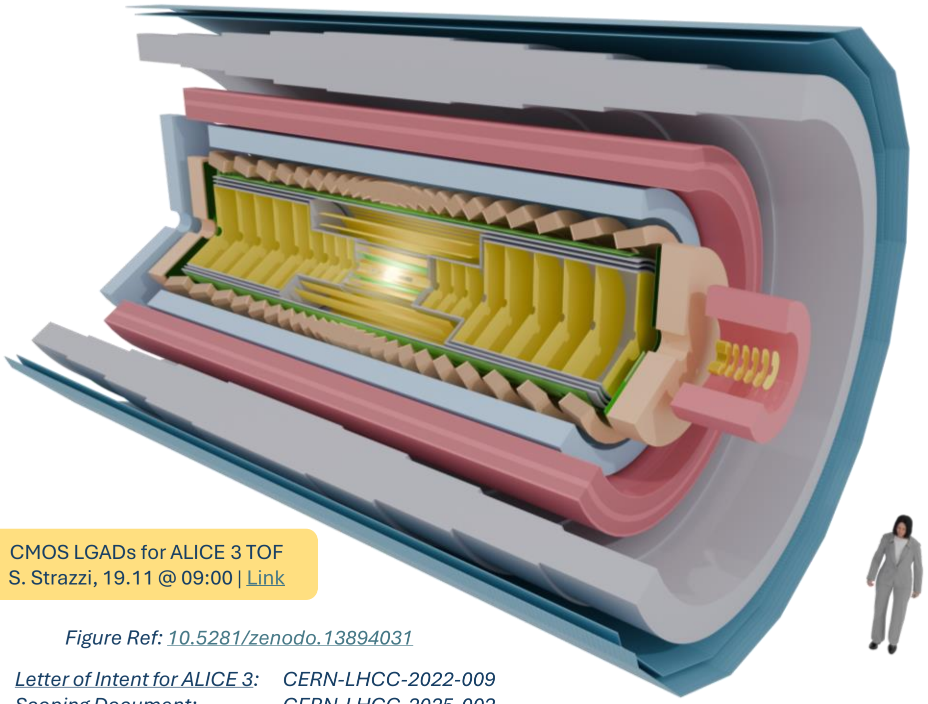
Characterisation of ITS3 Stitched Prototypes (ER1)
N. Tiltmann, 17.11 @ 16:10 | Link

Radiation Performance of ITS3 Prototypes (APTS)
I. Sanna @ Poster Session | Link

ALICE 3 Silicon Tracker (Run 5)

Run 1 2009 – 2013	Run 2 2015 – 2018	Run 3 2022 – 2026	Run 4 2030 – 2033	Run 5 2036 – 2041
ALICE 1 Pb-Pb: 1 kHz, pp: 200 kHz		ALICE 2 Pb-Pb: 50 kHz, pp: 1000 kHz	ALICE 2.1 Pb-Pb: 50 kHz, pp: 1000 kHz	ALICE 3 Pb-Pb: 100 kHz, pp: 24 MHz

ALICE 3 is a new, compact, low mass, all-silicon detector designed to exploit HL-LHC as heavy-ion collider



CMOS LGADs for ALICE 3 TOF
S. Strazzi, 19.11 @ 09:00 | Link

Figure Ref: 10.5281/zenodo.13894031

- *Letter of Intent for ALICE 3*: *CERN-LHCC-2022-009*
- *Scoping Document*: *CERN-LHCC-2025-002*

ALICE 3 Silicon Tracker (Run 5)

Run 1 2009 – 2013	Run 2 2015 – 2018	Run 3 2022 – 2026	Run 4 2030 – 2033	Run 5 2036 – 2041
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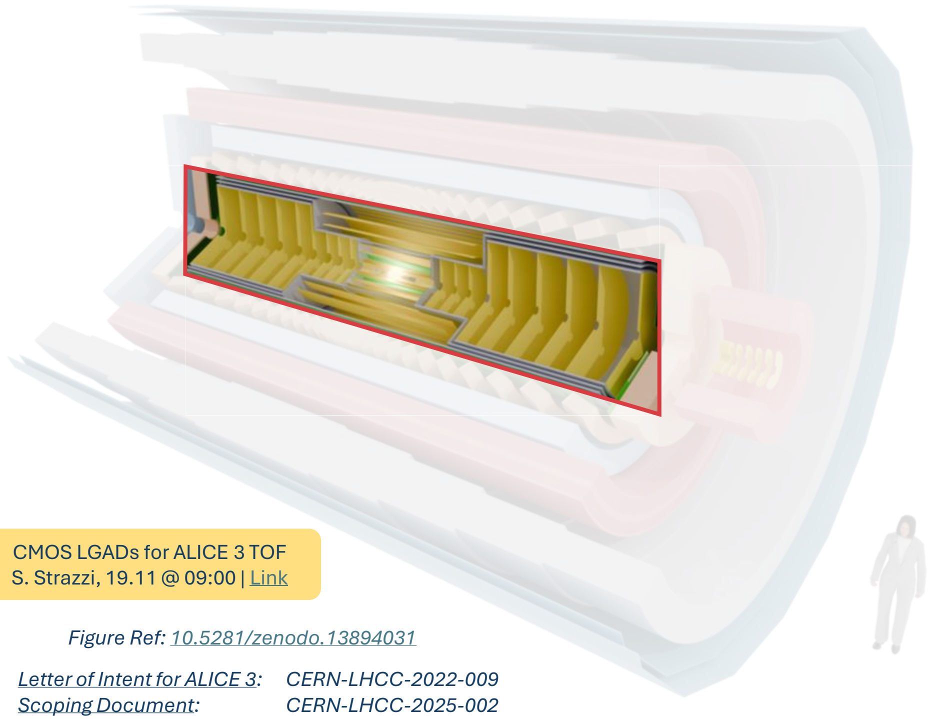
ALICE 3 Silicon Tracker targets unprecedented pointing resolution at even higher Pb-Pb interaction rates (50 → 100 kHz) and acceptance ($\Delta\eta$ = 2.6 → 8)



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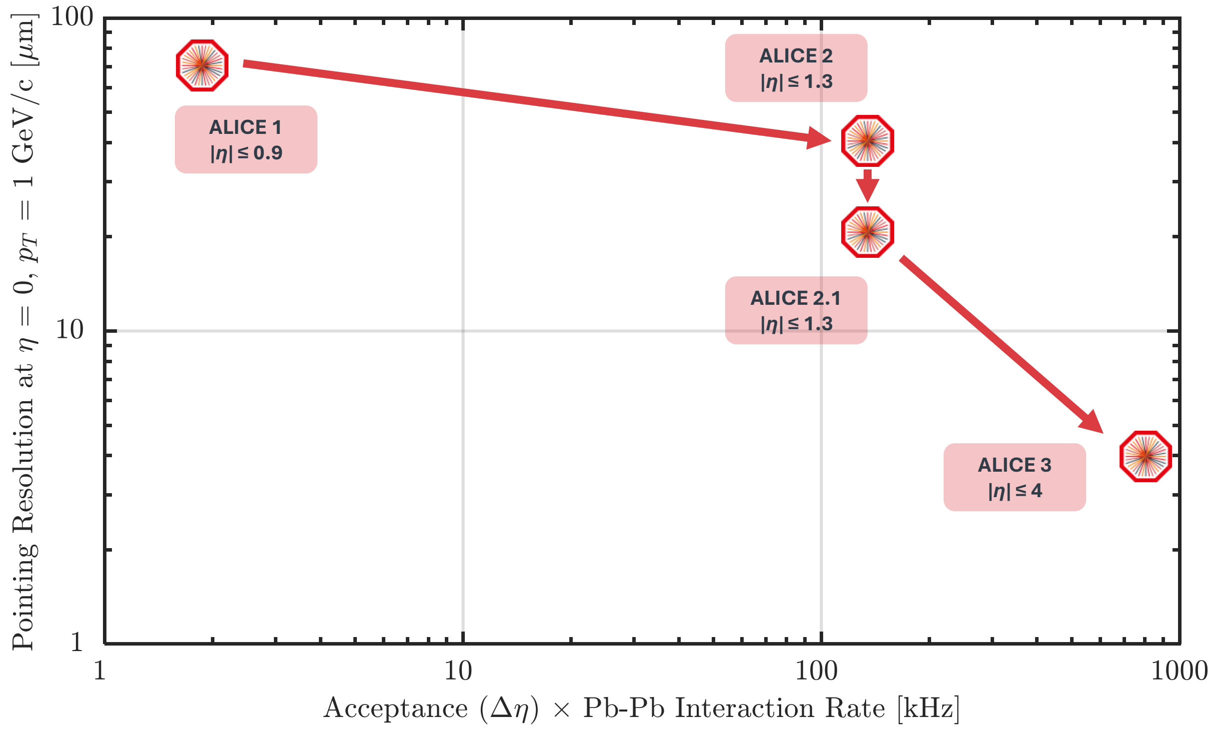
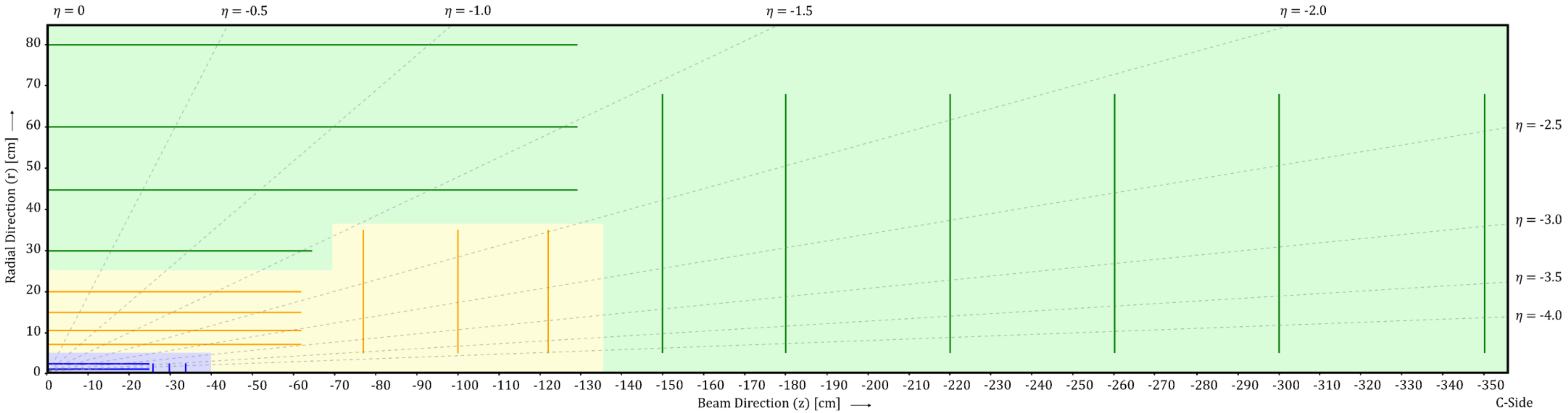
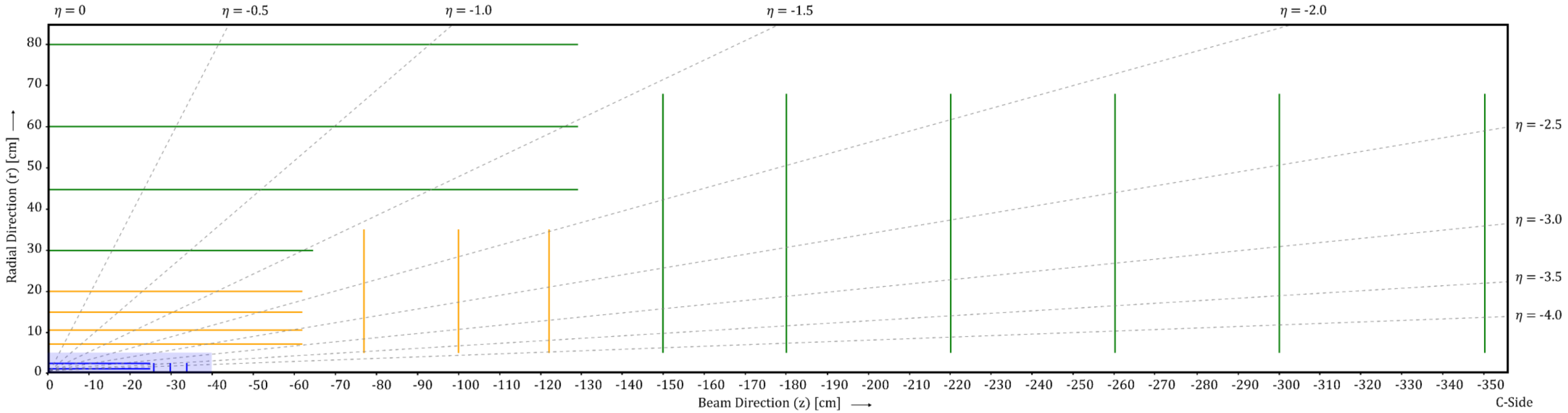


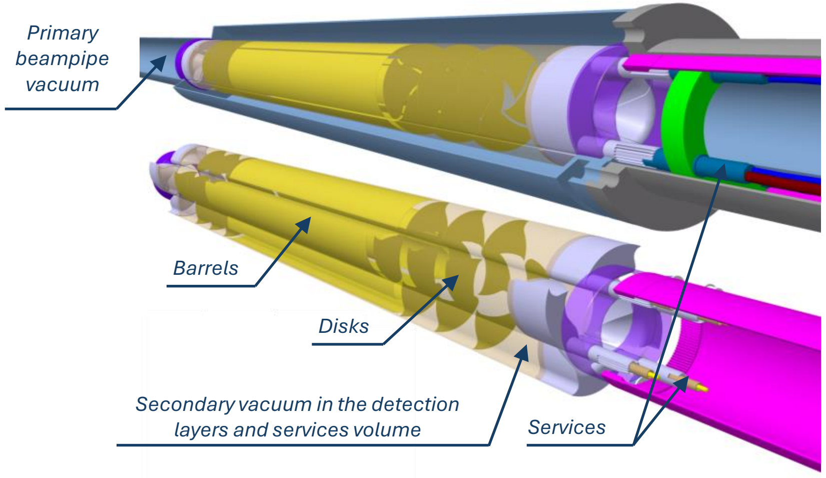
ALICE 3 Silicon Tracker : Layout

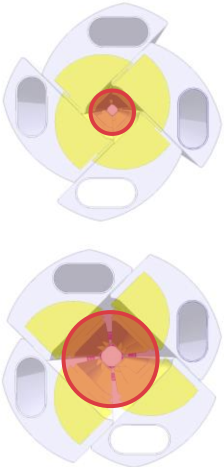


Tracker Sub-Systems		No. of Layers (Barrels + Disks)	Intrinsic Resolution [μm]	Barrel Layers		Disks		Roles
				Length Δ*z* [cm]	Radius *r* [cm]	Position |*z*| [cm]	R_{in} ... R_{out} [cm]	
Inner Tracker	Vertex Detector	3 + (3 x 2)	2.5	50	0.5 ... 2.5	26 ... 34	0.5 ... 2.5	Vertexing
	Middle Layers	4 + (3 x 2)	10	124	7 ... 20	77 ... 122	5 ... 35	Tracking
Outer Tracker		4 + (6 x 2)	10	129, 2 x 129	30 ... 80	150 ... 350	5 ... 68	

VERTEX DETECTOR : OVERVIEW



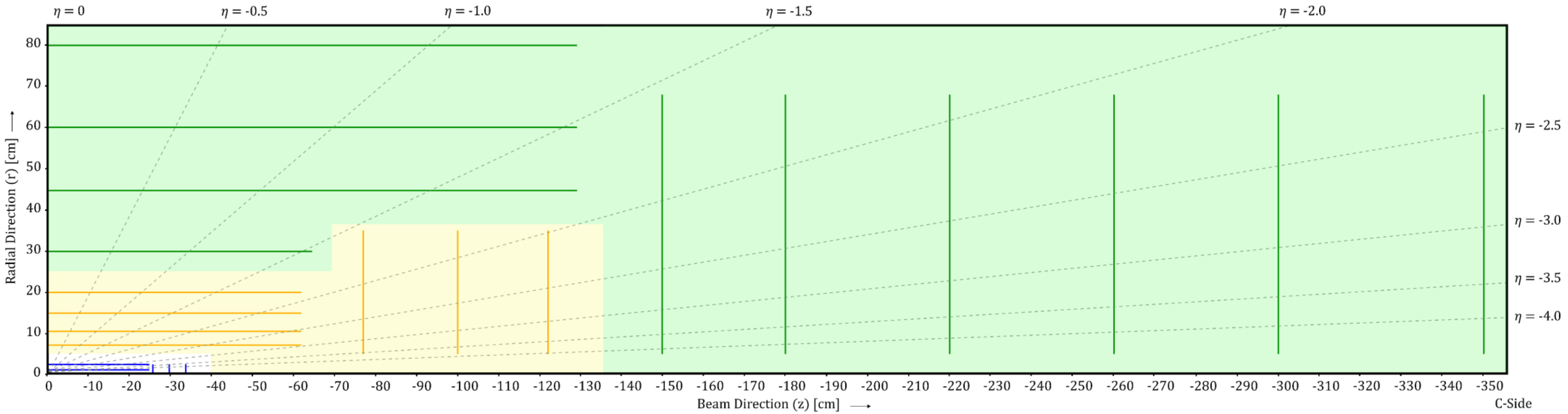


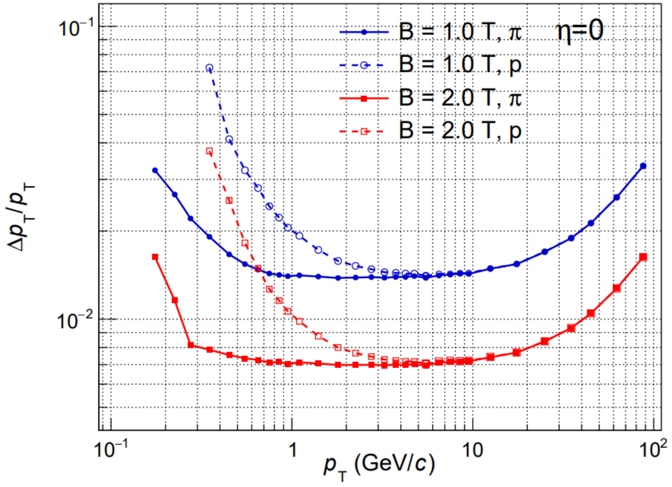


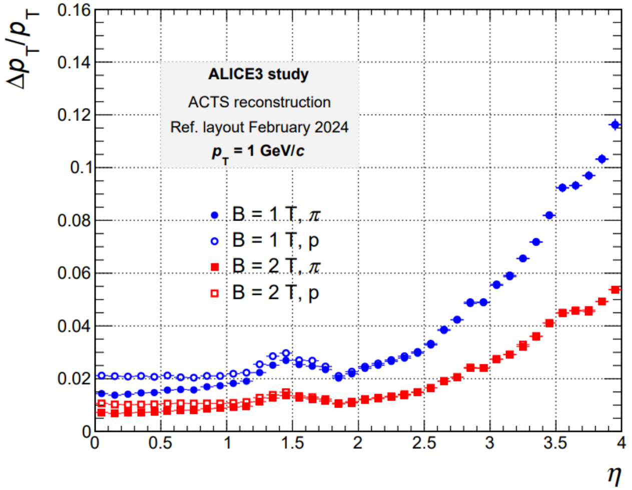
Vertex Detector

- Based on wafer-scale, ultra-thin, curved MAPS
- Radial distance from beam: 5 mm (inside beam pipe, retractable)
- Unprecedented spatial resolution: ≈ 2.5 µm
- Stringent material budget: ≈ 0.1% X/X_0 per layer
- Small pixel pitch: 10 µm
- High radiation levels: 3×10^{15} 1MeV n_{eq}/cm^2 + 200 Mrad
- High hit rates: 100 MHz/cm^2, ≈ 35 MHz/cm^2 (avg.)

Middle Layers & Outer Tracker : Overview







Middle Layers and Outer Tracker

- Large area and coverage: $60\ m^2$, $|\eta| \leq 4$
- High momentum resolution: 1-2%
- Less stringent material budget: $\lesssim 1\%\ X/X_0$ per layer
- Fast time resolution: 100 ns RMS
- Minimise sensor power: 30 … 50 mW/cm^2
- Industrially scalable production (10k modules)
- Minimise off-stave supplies and services

SENSOR DEVELOPMENT

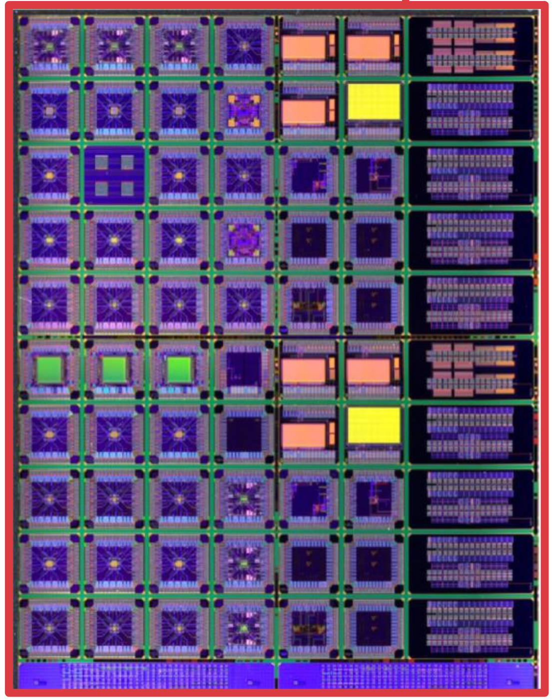
ALICE 3 Silicon Tracker : Sensor Requirements

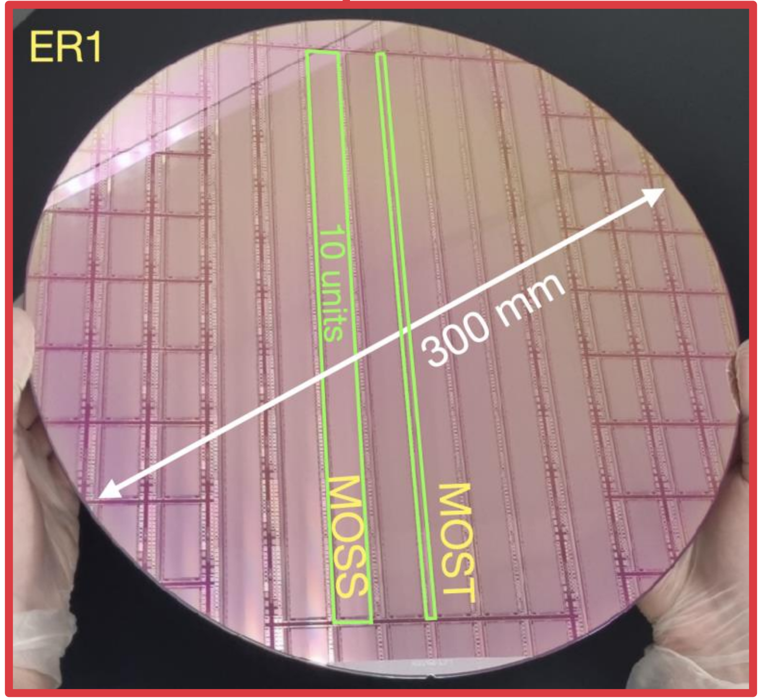
	ALICE ITS3	ALICE 3 Silicon Tracker	
		Vertex Detector	Tracker (ML/OT)
Position resolution (μm)	5	2.5	10
Pixel size (μm^2)	*O*(20 x 20)	*O*(10 x 10)	*O*(50 x 50)
Time resolution (ns RMS)	O(1000)	100	100
In-pixel hit rate (Hz)	54	94	42 (barrel)
Fake-hit rate (/ pixel / event)	$< 10^{-7}$	$< 10^{-7}$	$< 10^{-7}$
Power consumption (mW/cm^2)	35	70	20
Particle hit density (MHz/cm^2)	8.5	94	0.6
Non-Ionising Energy Loss (1MeV n_{eq}/cm^2)	3×10^{12}	3×10^{15}	6×10^{13}
Total Ionising Dose (Mrad)	0.3	200	3 (barrel)
X/X_0 per layer	0.09% (average)	0.1%	1.0%

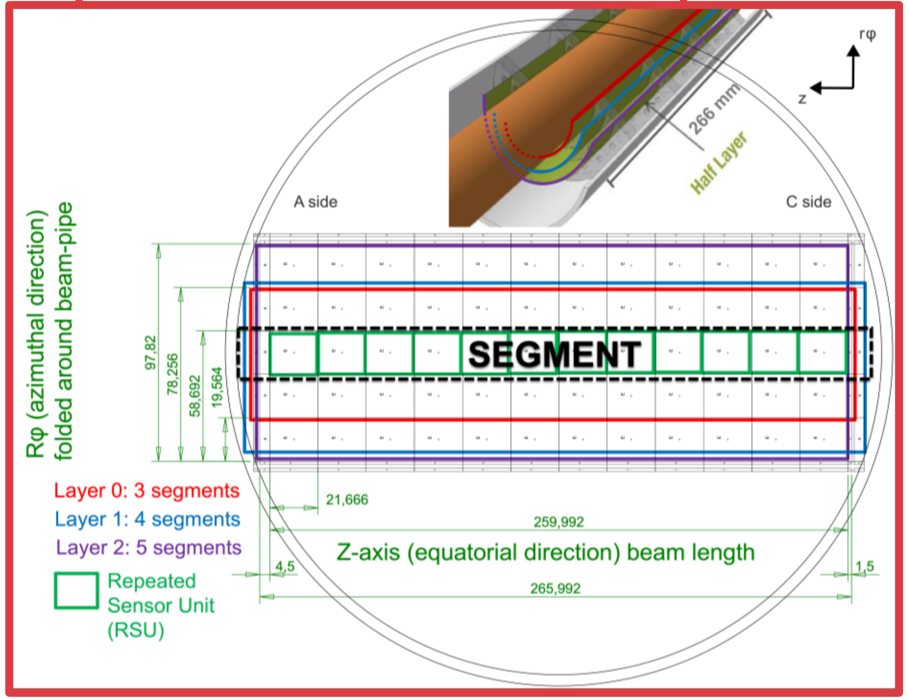
- Some of the parameters span across a wide range: specific optimisation
- ITS3 sensor development providing preliminary information

ITS3 Sensor Development Roadmap

Multi Layer Reticle 1 MLR1 – 2021	Engineering Run 1 ER1 – 2023	Engineering Run 2 ER2 – 2025	Engineering Run 3 ER3 – 2027
65 nm MAPS Tech. Qualification	Stitched MAPS (MOSS, MOST)	Full scale ITS3 prototype (MOSAIX)	ITS3 Final Sensor Production







DPTS: Nucl.Instrum.Meth.A 1056 (2023) 168589
Nucl.Instrum.Meth.A 1083 (2026) 171082
APTS-SF: Nucl.Instrum.Meth.A 1069 (2024) 169896
APTS-OA: Nucl.Instrum.Meth.A 1070 (2025) 170034

Characterisation of ITS3 Stitched Prototypes (ER1)
N. Tiltmann, 17.11 @ 16:10 | Link

MOSS: e-Print: 2510.11463 [physics.ins-det]

ITS3 Technical Design Report
CERN-LHCC-2024-003 | Link

LEARNINGS FROM ITS3 → ALICE 3 SENSOR R&D

Multi Layer Reticle 1
MLR1 – 2021

Engineering Run 1
ER1 – 2023

Engineering Run 2
ER2 – 2025

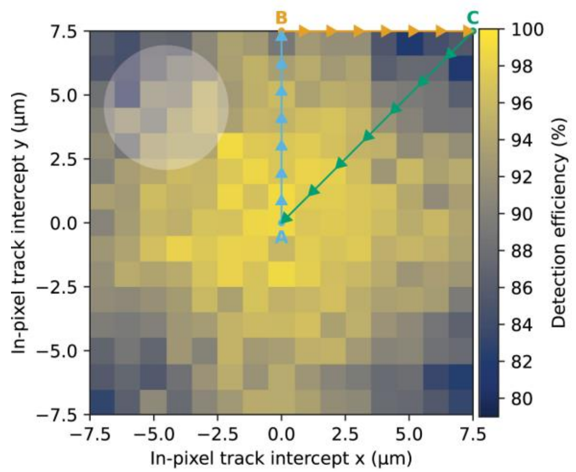
Engineering Run 3
ER3 – 2027

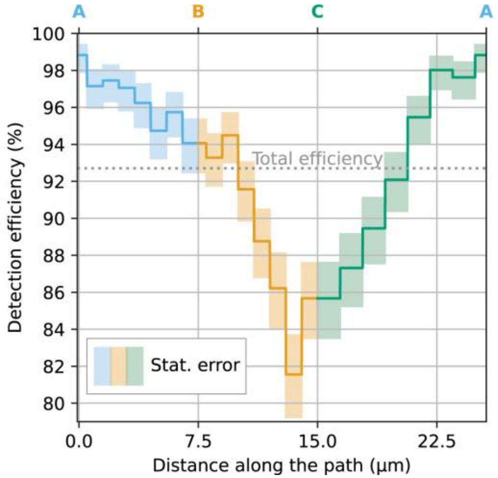
Detection Efficiency:

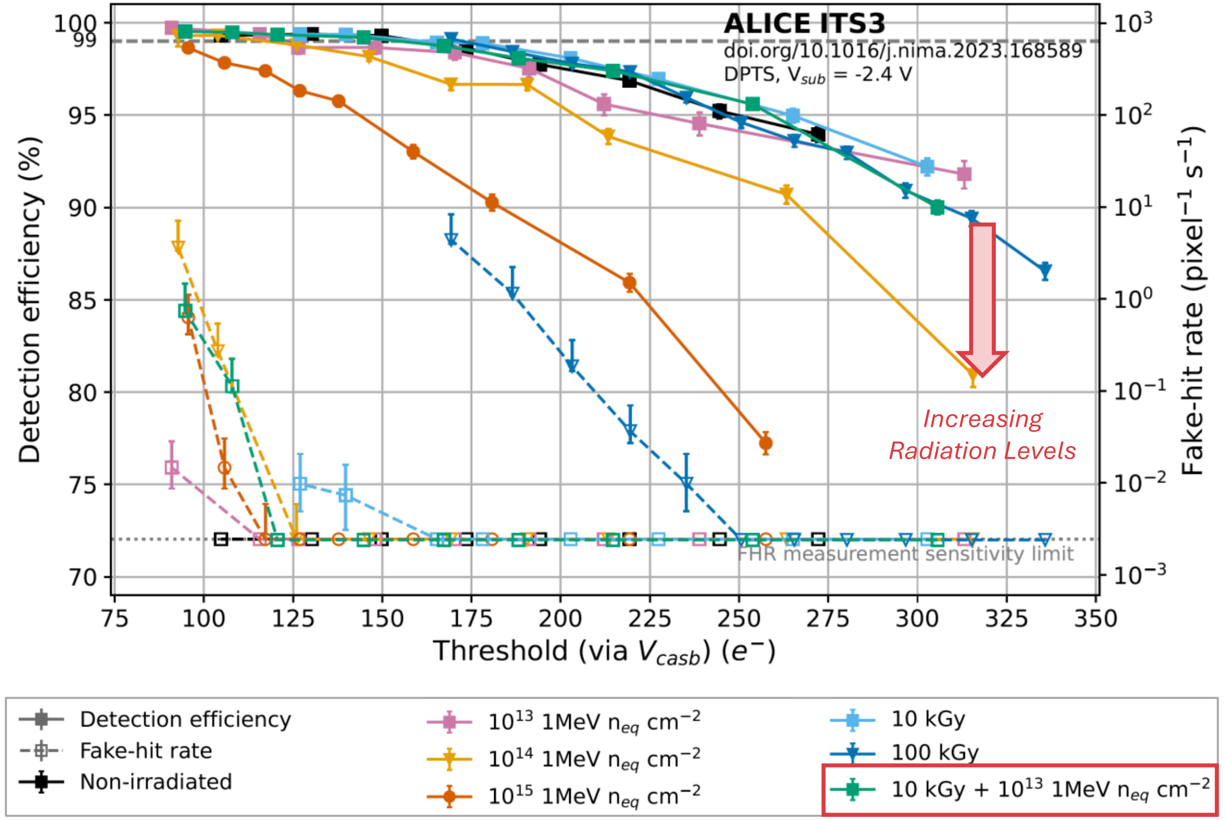
- Fulfils ITS3 requirements at 20°C for 10 kGy + 1 × 10^{13} n_{eq}/cm^2
- Notable deterioration for higher irradiation at pixel corners

Time Resolution:

- Fast intrinsic charge collection at ≈ 70 ps (10 µm pixel; ~ 3 µW in-pixel)







ITS3 Radiation Level

Top: Detection efficiency (filled symbols, solid lines) and fake-hit rate (open symbols, dashed lines) as a function of average threshold, measured at various radiation levels with DPTS.
Left: In-pixel detection efficiency for 15 µm pitch DPTS irradiated at 10^{15} 1 MeV n/cm^2.
Figures from: Nucl.Instrum.Meth.A 1056 (2023) 168589.

Learnings From ITS3 → ALICE 3 Sensor R&D

Multi Layer Reticle 1
MLR1 – 2021

Engineering Run 1
ER1 – 2023

Engineering Run 2
ER2 – 2025

Engineering Run 3
ER3 – 2027

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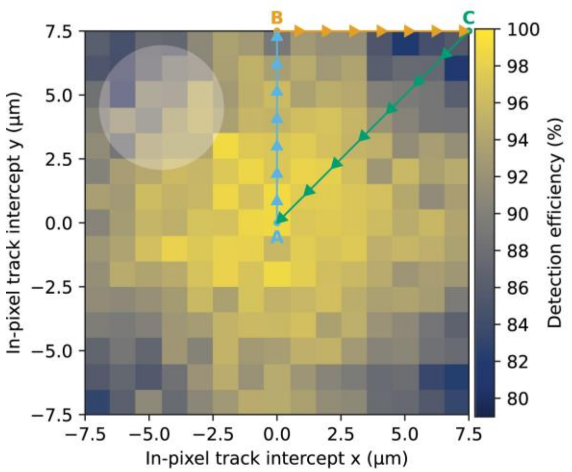
- Notable deterioration for higher irradiation at pixel corners

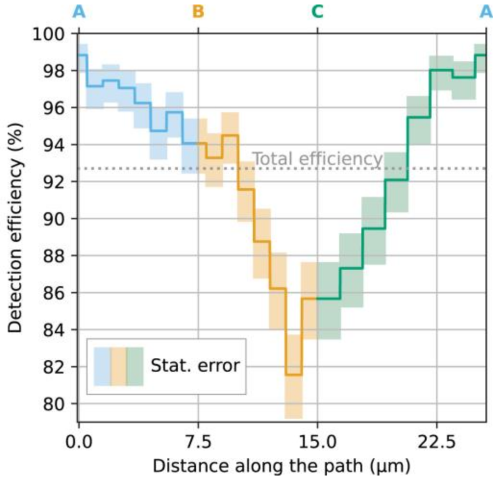
Time Resolution:

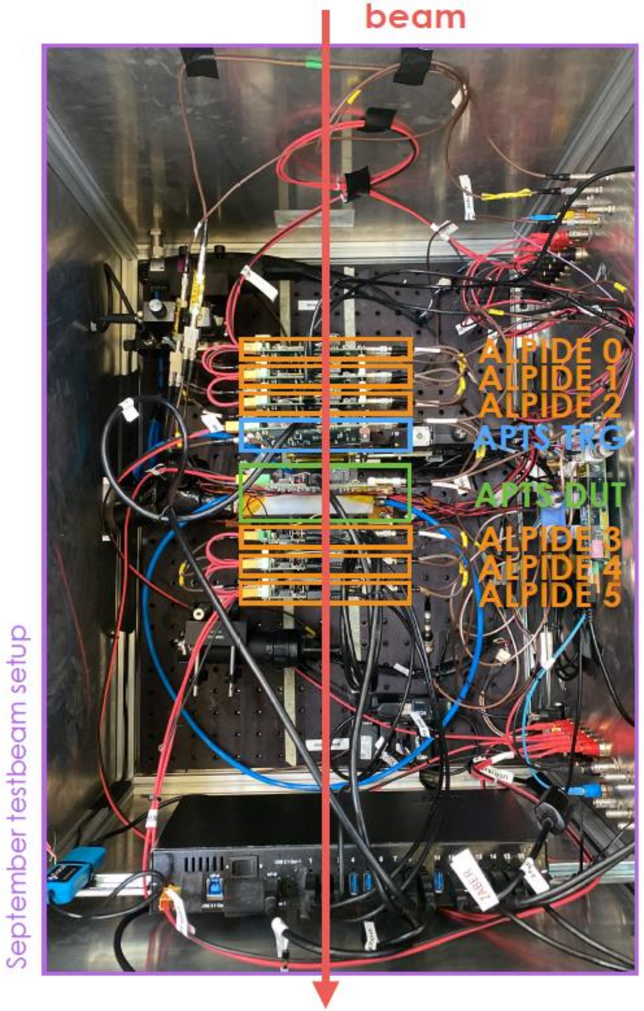
- Fast intrinsic charge collection at ≈ 70 ps (10 μm pixel; ~ 3 μW in-pixel)

R&D for ALICE 3 Silicon Tracker:

- Tests ongoing to recover pixel performance at < 0°C for higher irradiation







Two test-beams at PS (10 GeV mixed protons/pions) to commission the setup with cold box

LEARNINGS FROM ITS3 → ALICE 3 SENSOR R&D

Multi Layer Reticle 1
MLR1 – 2021

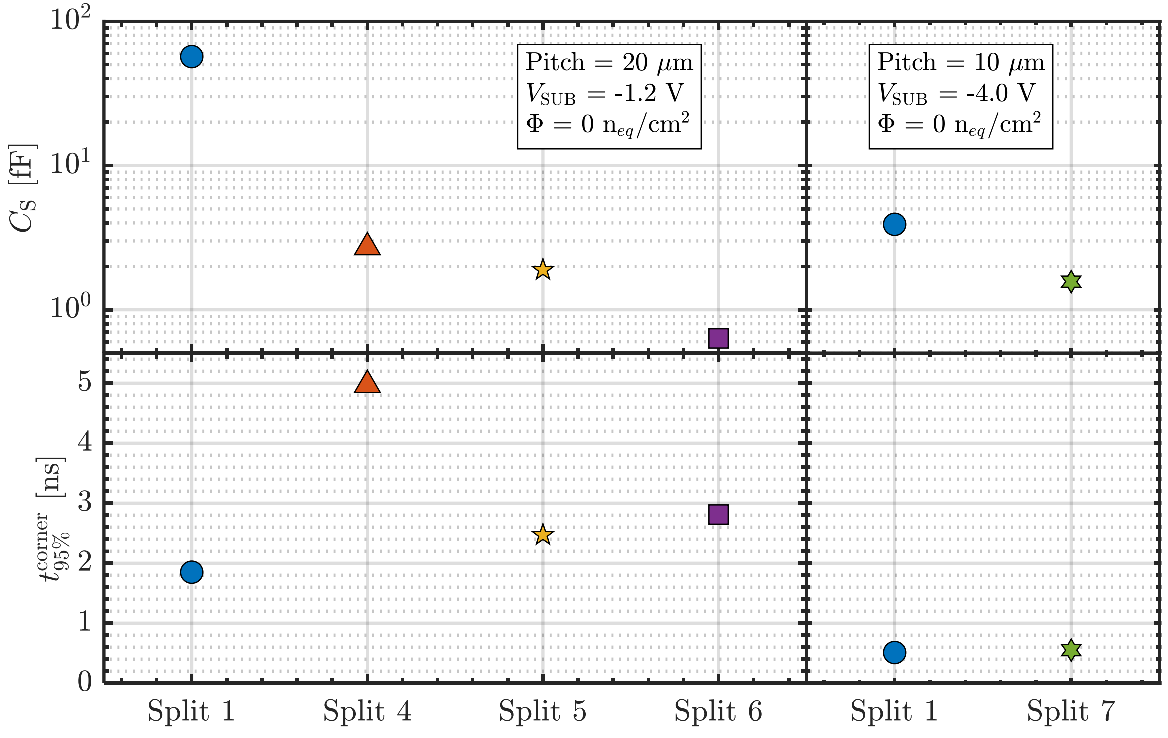
Engineering Run 1
ER1 – 2023

Engineering Run 2
ER2 – 2025

Engineering Run 3
ER3 – 2027

Potential Prototypes for ALICE 3 Silicon Tracker in ER2 and beyond

- VD: 10 µm analogue pixels and optimized splits
- ML, OT: Larger pixels (APTS; 30 … 50 µm)
- SPARC: Asynchronous Priority Arbiter for timing



Top: 3D TCAD Simulations showing the variation of sensor capacitance and and charge collection time (95% of total charge) from pixel corner. Figure adapted from: G. Boghello, JINST 20 (2025) 07, C07053.
Left: Charge Sharing in Dual Diode Pixel (16 x 32 μm^2). Figure from: J. Hensler (Uni. Heidelberg).

LEARNINGS FROM ITS3 → ALICE 3 SENSOR R&D

Multi Layer Reticle 1
MLR1 – 2021

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- VD: 10 µm analogue pixels and optimized splits
- ML, OT: Larger pixels (APTS; 30 … 50 µm)
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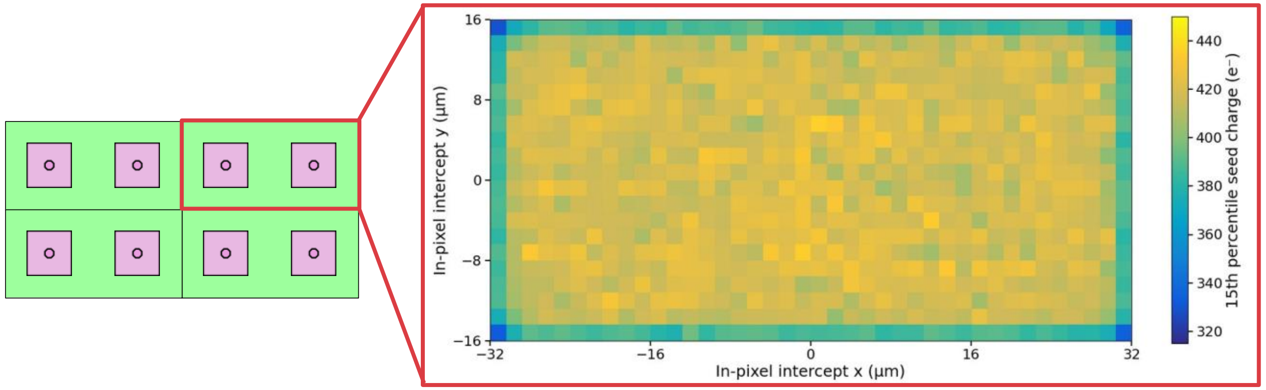
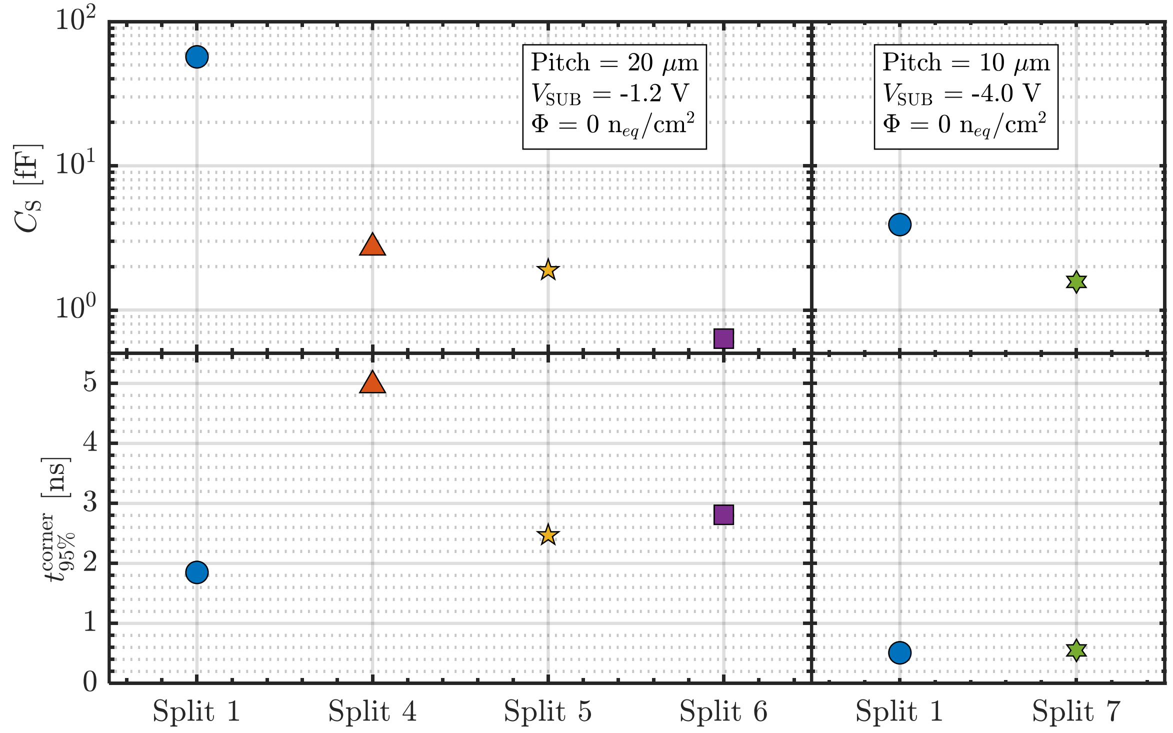
Design and Simulations Ongoing

- Optimise efficiency and readout speed for a given power budget
  - Analog front-end: Grouping of neighbouring pixels
  - Readout architecture: Asynchronous readout
- Modular pixel matrix unit to facilitate construction of large sensors
- Minimise footprint of digtal pixel down to 10 µm





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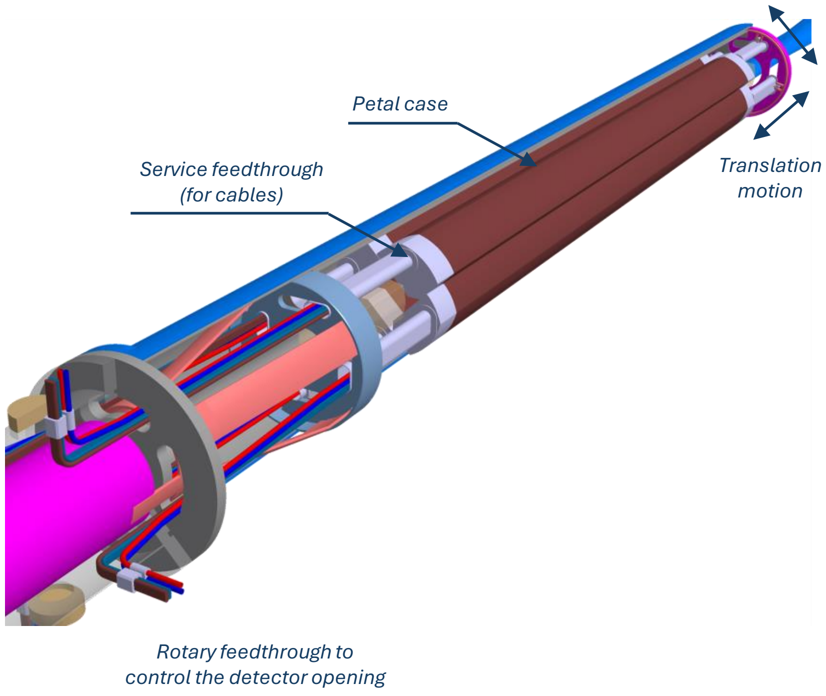
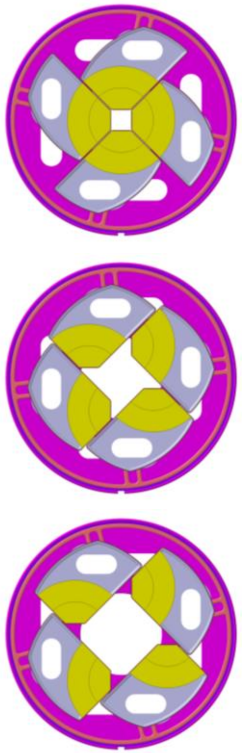
Module And Stave
Design, Mechanics And Thermal Management

VERTEX DETECTOR : MECHANICS

Concept:

- Petals in primary beam vacuum; secondary vacuum inside
- Petals in 0.15 mm thick beryllium case with service feedthrough
- Petals opening ($r_0 \approx 15$ mm) and closing ($r_0 \approx 5$ mm) based on their translations driven by rotary motor device and feedthrough





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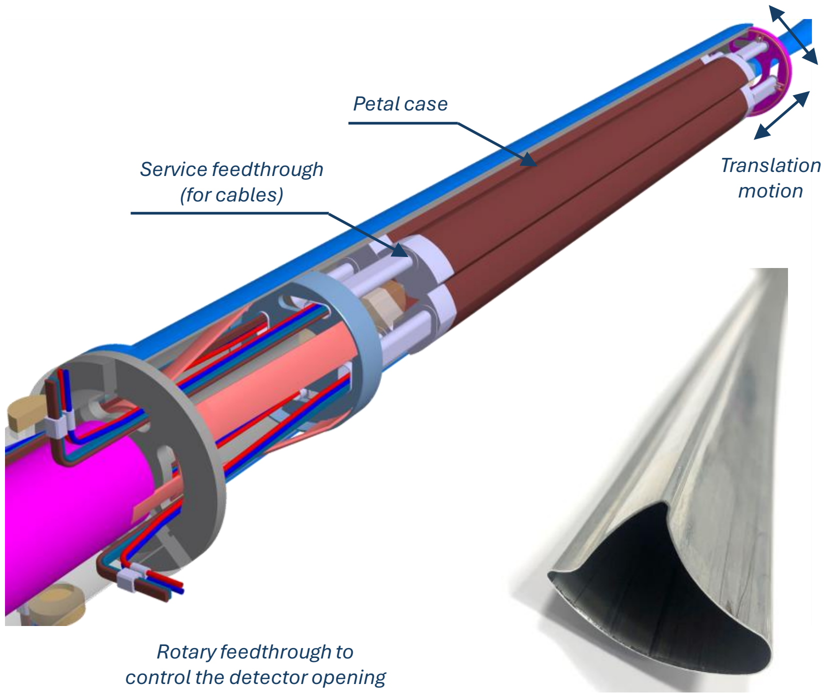
- Petals opening ($r_0 \approx 15$ mm) and closing ($r_0 \approx 5$ mm) based on their translations driven by rotary motor device and feedthrough

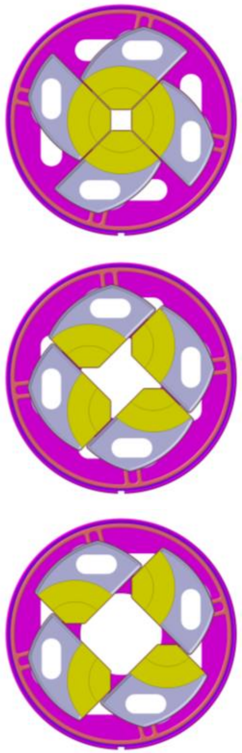
Prototyping and Testing

- Full scale prototypes produced in aluminium (0.3 mm thick)
- Ongoing tests to characterise materials in $\approx 5 \times 10^{-10}$ mbar double-vacuum setup (observing outgassing and mass loss)
- Upgrades ongoing to test larger-scale prototypes

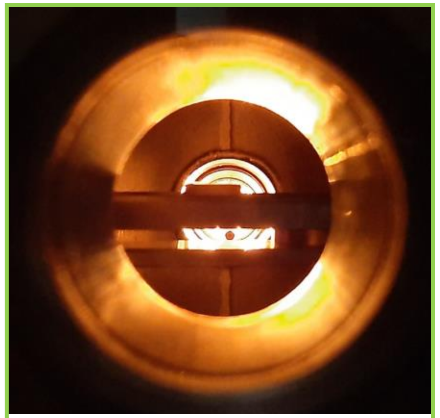


Rotary feedthrough to control the detector opening

Full scale petal prototype (0.3 mm aluminium Al 5083)



4.0×10^{-10} Torr $\approx 5.33 \times 10^{-10}$ mbar



Al_2O_3 sample inside the UHV system

VERTEX DETECTOR : THERMAL MANAGEMENT

Concept:

- Cold plate located outside the L2 sensors
- Evaporative CO_2 cooling to maximise volumetric heat transfer
- Carbon foams and foils provide thermal contact between cold plate, detection layers (70 mW/cm^2) and petal case
- Beam-induced power (100 mW/cm^2) cooled via the petal case

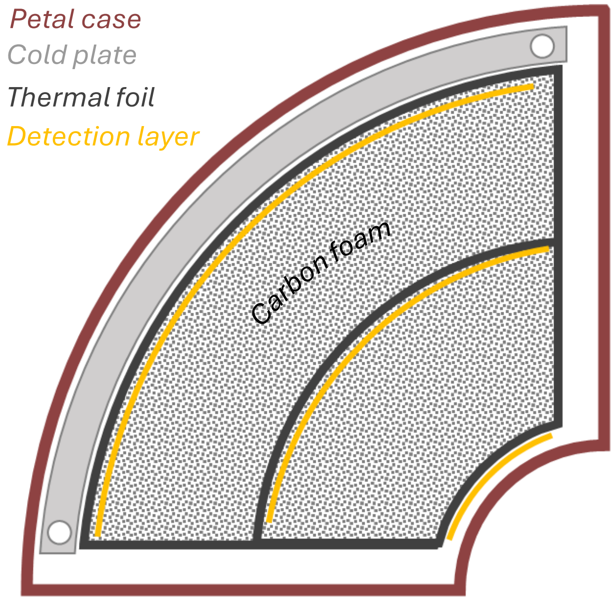


Figure from: C. Gargiulo, Forum on Tracking Detector Mechanics (2024).

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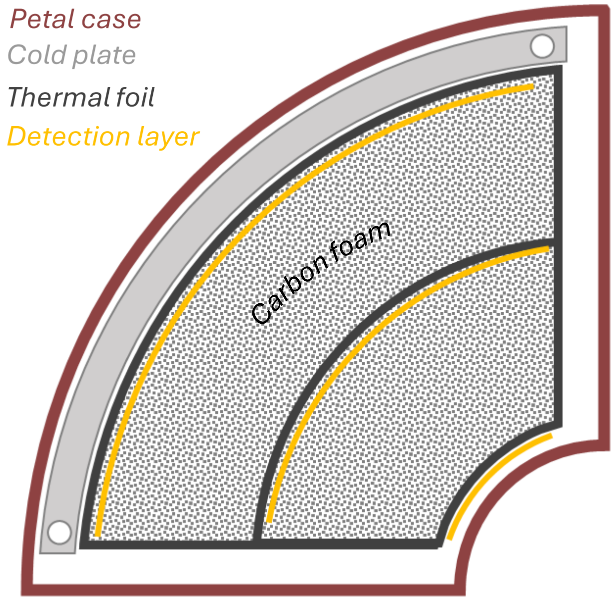
Computational Fluid Dynamics Simulations:

- Max. sensor temperature < -25°C, with -35°C inlet
- Uniform temperature gradient over a sensor (1-2°C)



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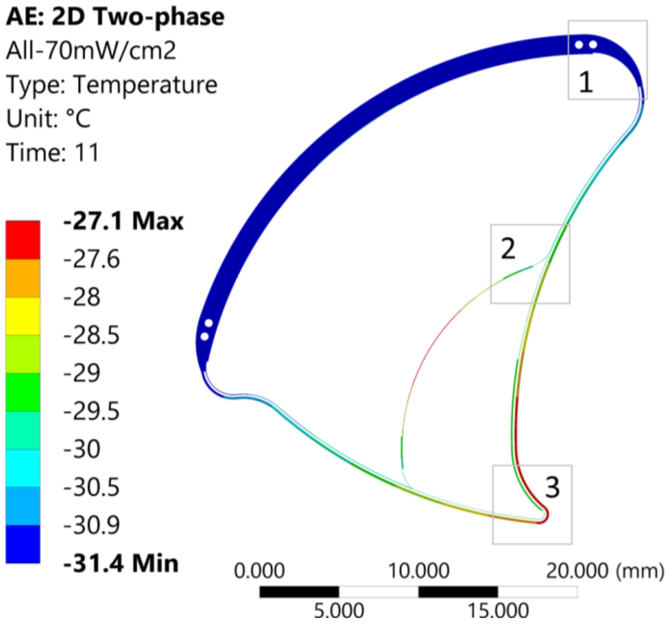

Figure from: Letter of Intent for ALICE 3, CERN-LHCC-2022-009, LHCC-I-038 | Link.

Vertex Detector : Thermal Management

Concept:
- Cold plate located outside the L2 sensors
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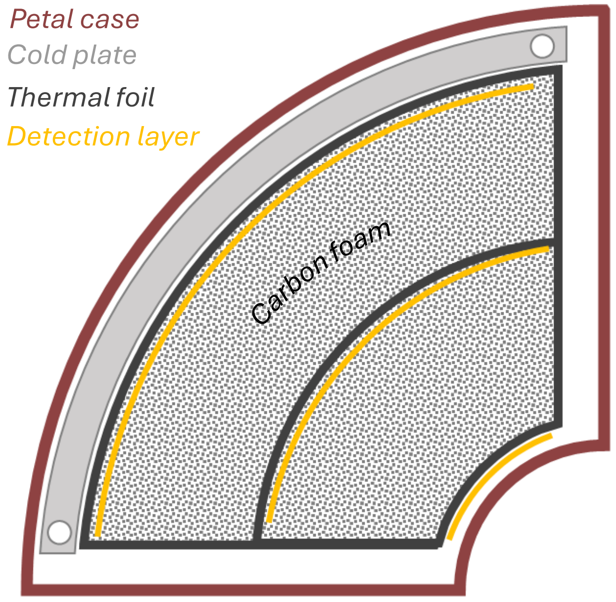
Computational Fluid Dynamics Simulations:
- Max. sensor temperature < -25°C, with -35°C inlet
- Uniform temperature gradient over a sensor (1-2°C)

Prototyping and Testing
- Carbon cold plate with Kapton pipes (exp. burst pressure 150 bar)
- 3D printed ceramic plate with engraved cooling channels



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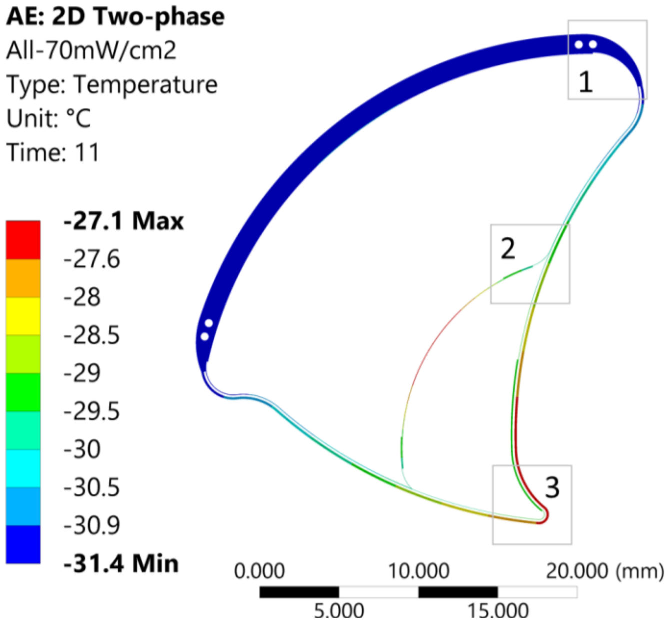


Figure from: Letter of Intent for ALICE 3, CERN-LHCC-2022-009, LHCC-I-038 | Link.

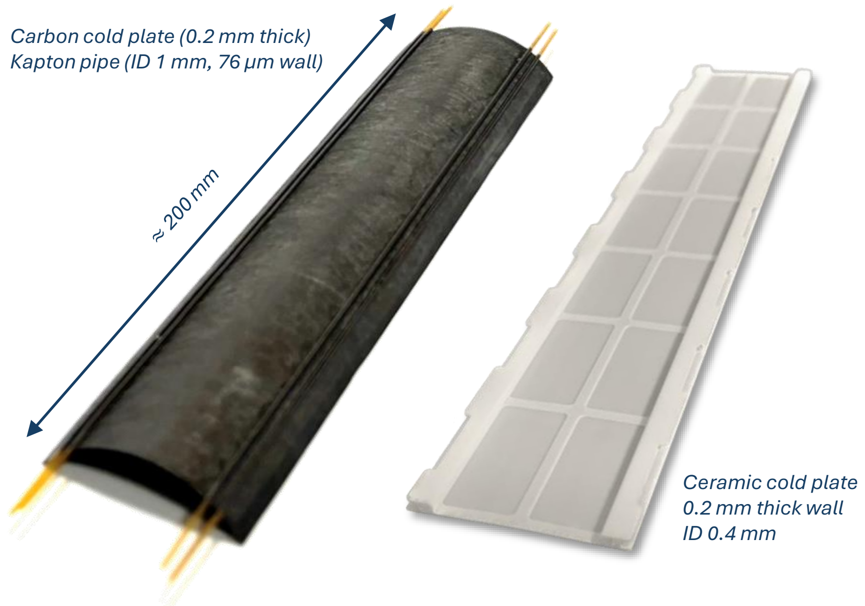
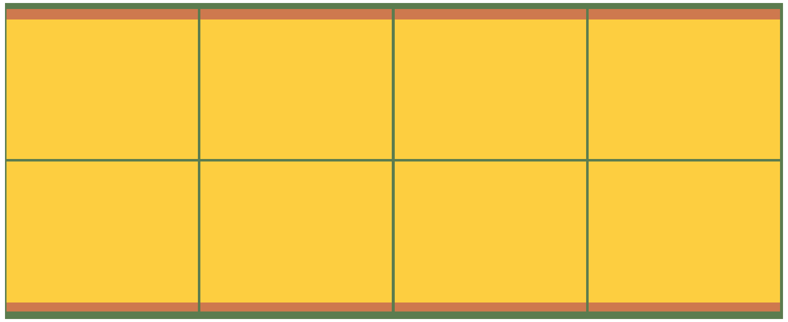


Figure from: C. Gargiulo, Forum on Tracking Detector Mechanics (2024).

Middle Layers & Outer Tracker : Module Design

Concept:

- Module comprising 2 × 4 sensors (≈ 13 × 5 cm^2)
- Facilitate industrial production (60 m^2; 10k modules)
- Material minimization with aluminium FPCs and serial powering



Sensor Width = 25 mm
Sensor Length = 32 mm
Periphery Width = 1.5 mm

Module Width = 128.8 mm
Module Length = 52.2 mm
Inter-Sensor Gap = 0.2 mm

Sensor-FPC Gap = 0.1 mm (short-edge)
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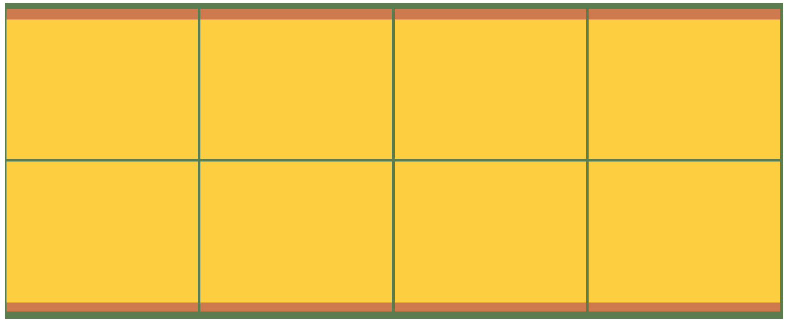
Prototyping and Testing

- Serial powering demonstration of ALPIDEs with ALPOSE
- Module assembly demonstration with dummy components

MEMPACK (KR) : multi-purpose machine

C-ON tech (KR) : customized assembly machine



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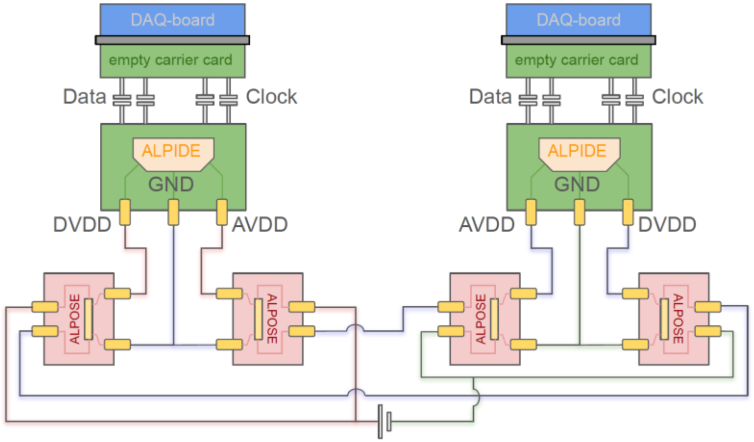
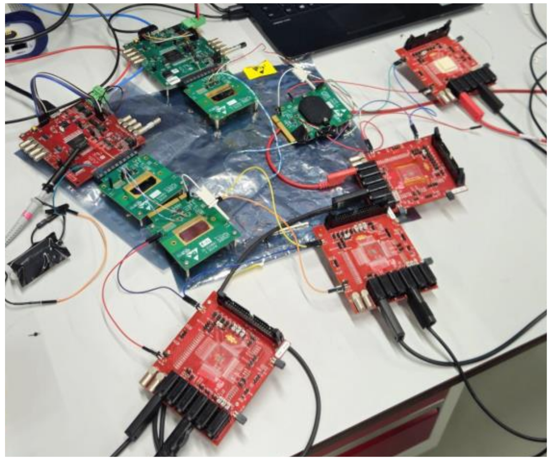
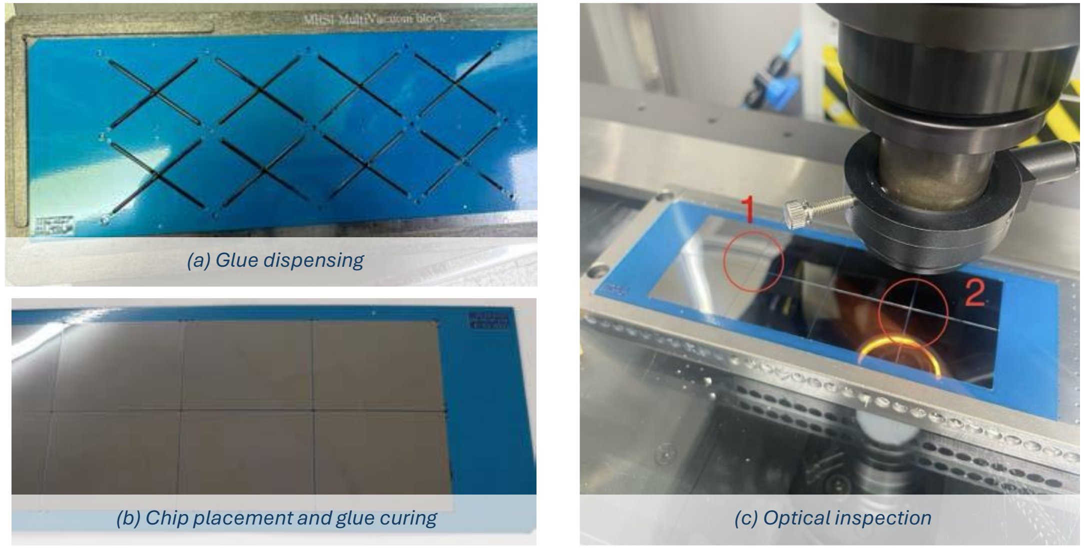




Serial powering qualification schematic (left) and setup (right) with ALPIDE and ALPOSE.

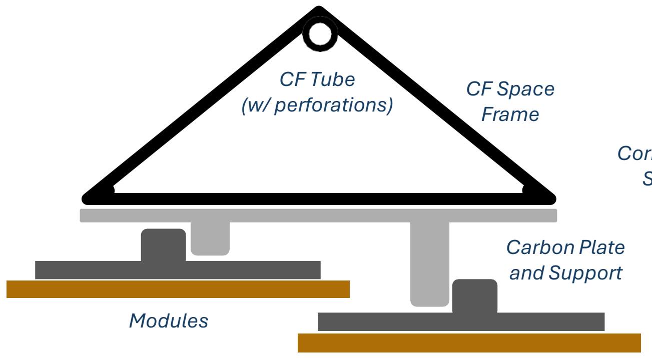


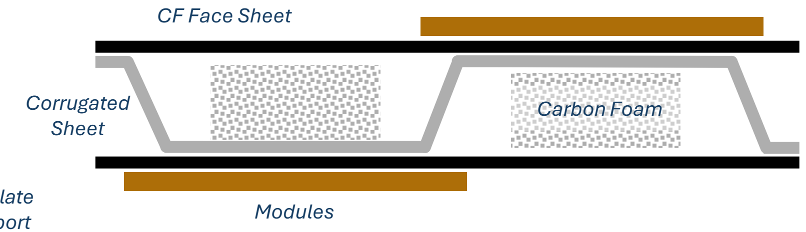
Module assembly procedure with dummy components by using MEMPACK multi-purpose machine die bonder.

Middle Layers & Outer Tracker : Mechanics

Concept:

- Large-area, lightweight CF support structures (< 1% X/X_0)
- Air cooling elements integrated into support structures
- Barrel Layers: Space-frame (à la ITS2 and CBM-STS)
- Disk Layers: Corrugated structures (à la ePIC-SVT)





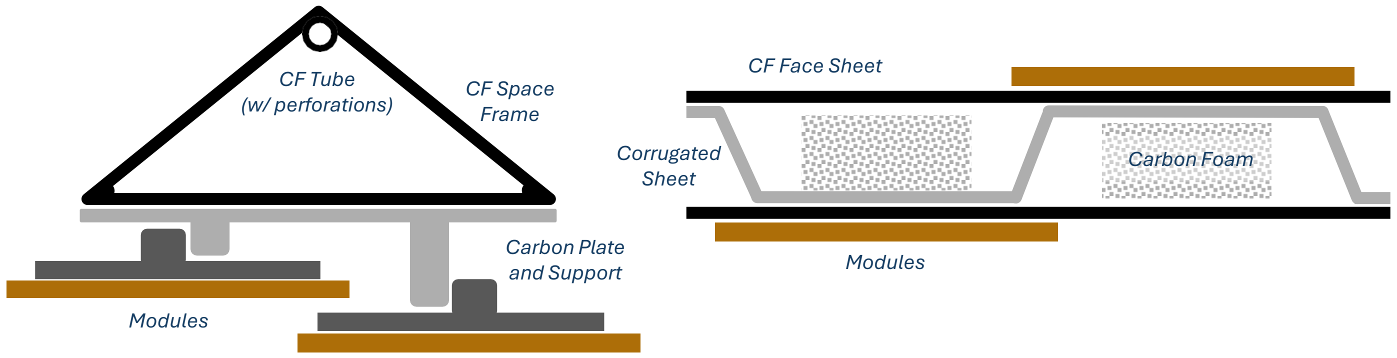
MIDDLE LAYERS & OUTER TRACKER : MECHANICS

Concept:

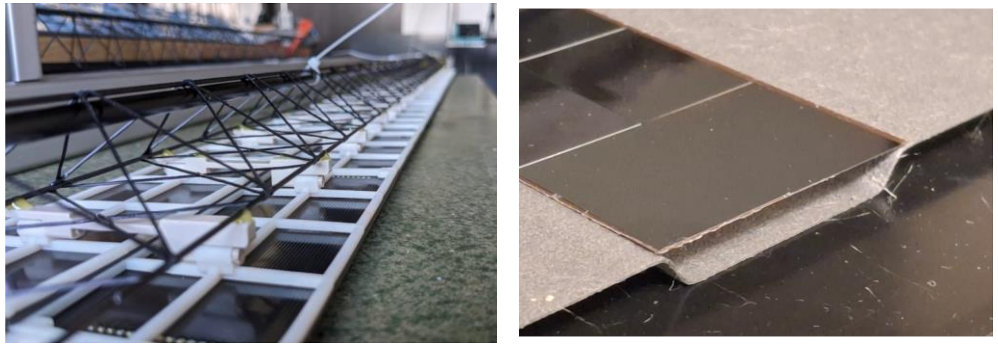
- Large-area, lightweight CF support structures (< 1% X/X_0)
- Air cooling elements integrated into support structures
- Barrel Layers: Space-frame (à la ITS2 and CBM-STS)
- Disk Layers: Corrugated structures (à la ePIC-SVT)

Prototyping and Testing

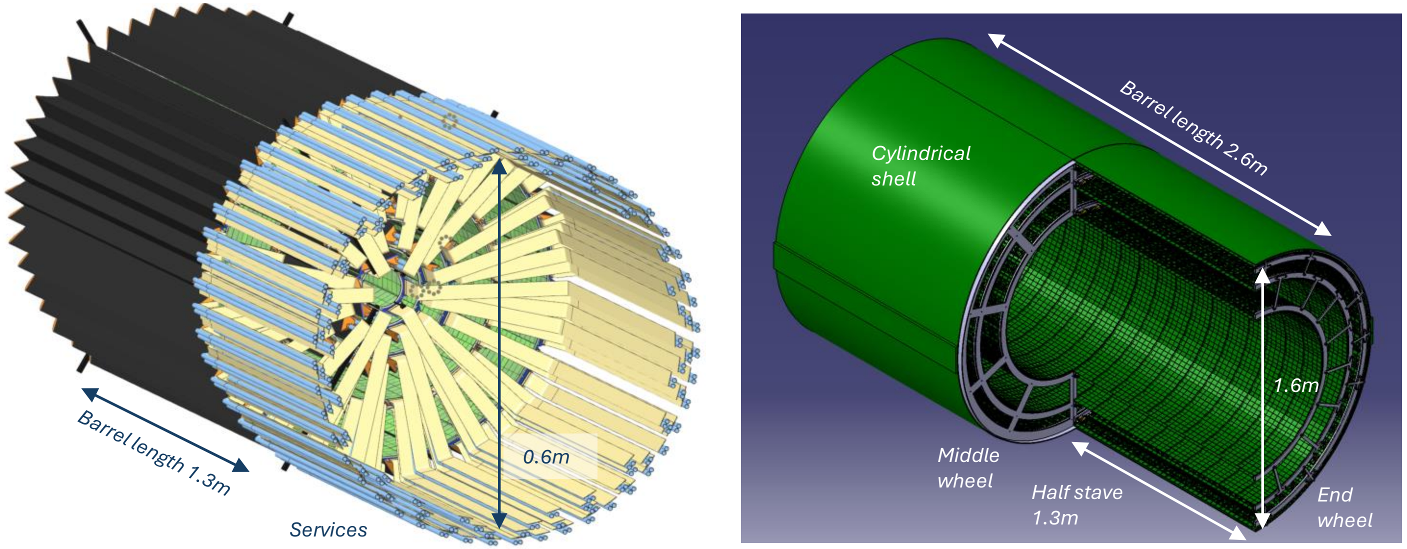
- Stave assembly procedures under development
- Stave metrology with load
- Detector integration and installation being studied
- CAD drawings finalization (incl. service routing)



Cross-sectional illustration of the stave assembly and cooling principle of barrel (left) and disk layers (right).



Mechanical prototypes to test the stave assembly procedures for barrel (left) and disks (right).

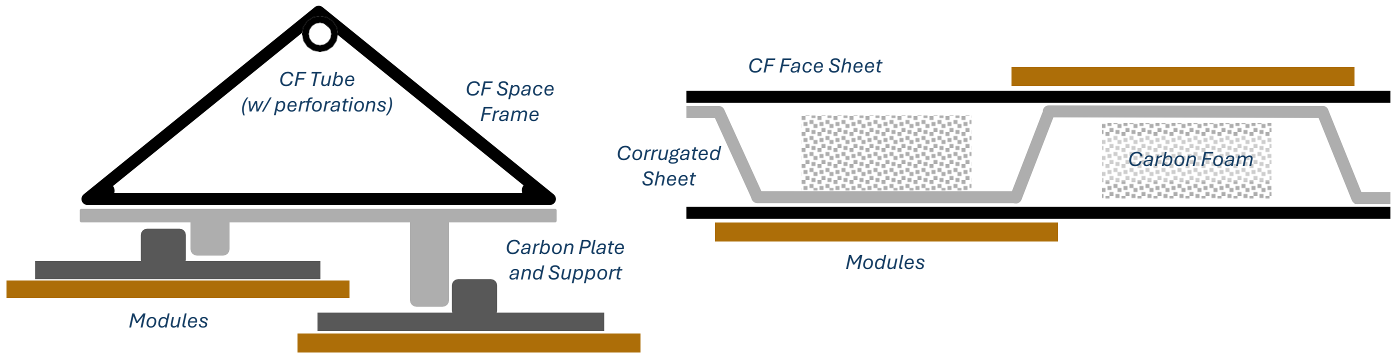


CAD drawings of the middle (left) and the outer tracker barrels (right).

Middle Layers & Outer Tracker : Thermal Management

Concept:

- Air cooling elements integrated into support structures
- Barrel Layers: Perforated CF tube integrated into the CF space frame for impinging air jets on module surface
- Disk Layers: CF corrugated structures with internal air channels with carbon foam for turbulence



Cross-sectional illustration of the stave assembly and cooling principle of barrel (left) and disk layers (right).

MIDDLE LAYERS & OUTER TRACKER : THERMAL MANAGEMENT

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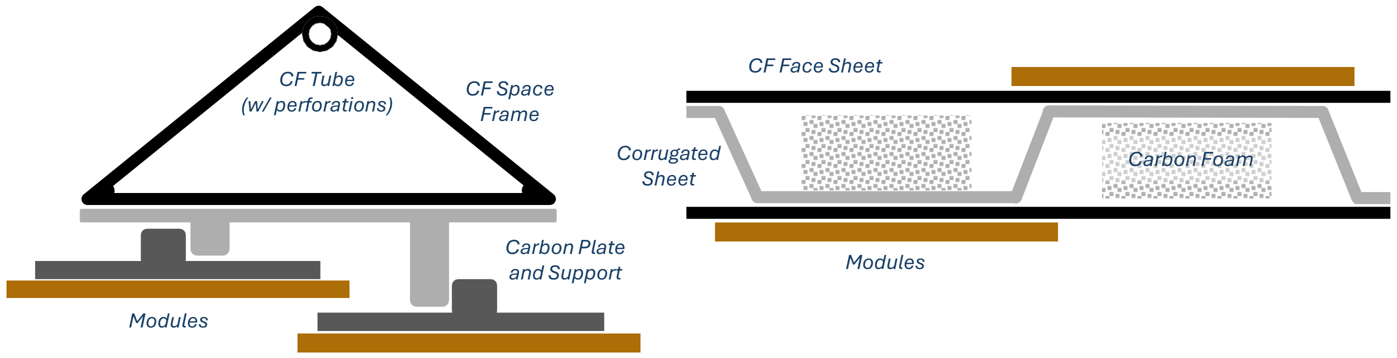
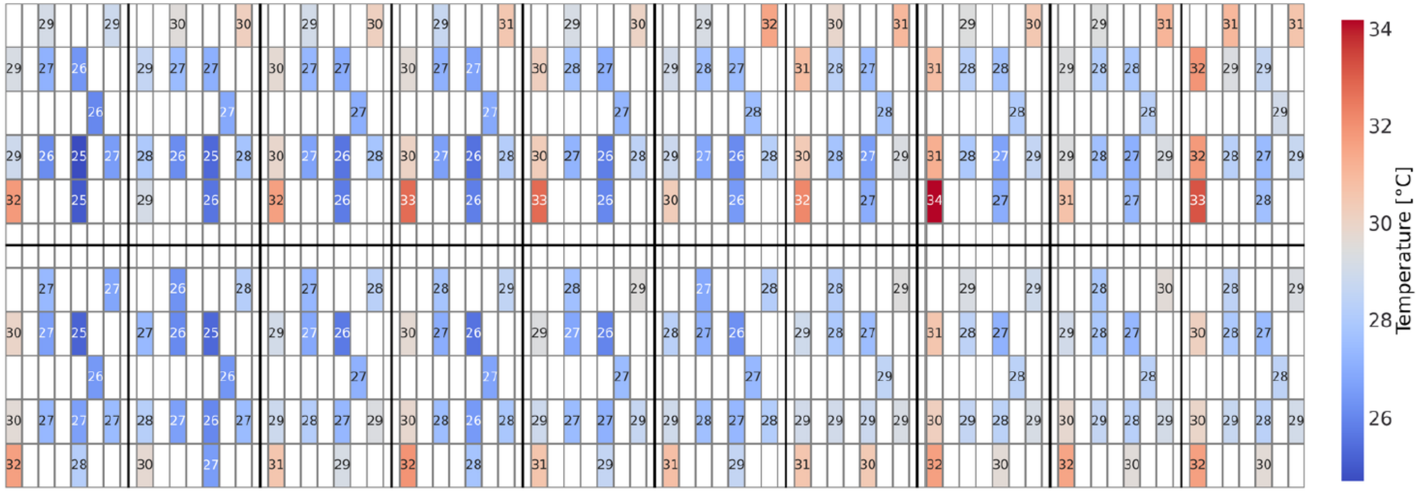


Cross-sectional illustration of the stave assembly and cooling principle of barrel (left) and disk layers (right).

Prototyping and Testing

- Tests with realistic thermal prototypes
- Max. sensor temp. < 35°C for nominal power dissipation

Realistic thermal dummies for cooling tests produced for barrels (left; silicon) and disks (right; FPC), with dedicated regions for matrix and peripheral power dissipation.



Measured temperature distribution over a half-stave (1.3 meter long) for nominal operation conditions.
P_{matrix} = 30 mW/cm^2, $\dot{V}$ = 20 l/min, T_{inlet} = 16°C

Middle Barrel Layers : Lightweight Versions

Feasibility studies towards lightweight middle layers barrels, offering significant improvement in track reconstruction parameters

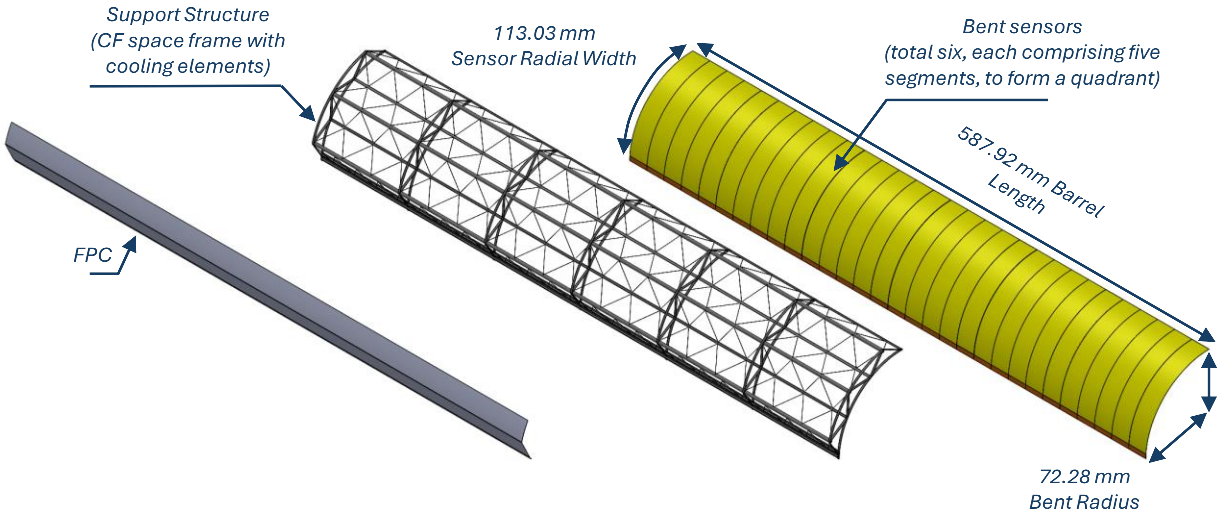
MIDDLE BARREL LAYERS : LIGHTWEIGHT VERSIONS

Feasibility studies towards lightweight middle layers barrels, offering significant improvement in track reconstruction parameters

Bent middle layer version

Avg. material budget of < 0.25% X/X_0 per layer

- Sensor Design: MOSAIX-like 5 segments x 5 RSUs; LECs along the z-axis
- Stave and Integration Design: Bent sensors glued onto light CF supports
- Thermal Management: Bi-phase CO_2 (LEC) + impinging air jets (RSU)
- Sensor-level (inter-segment) data aggregation and serial powering



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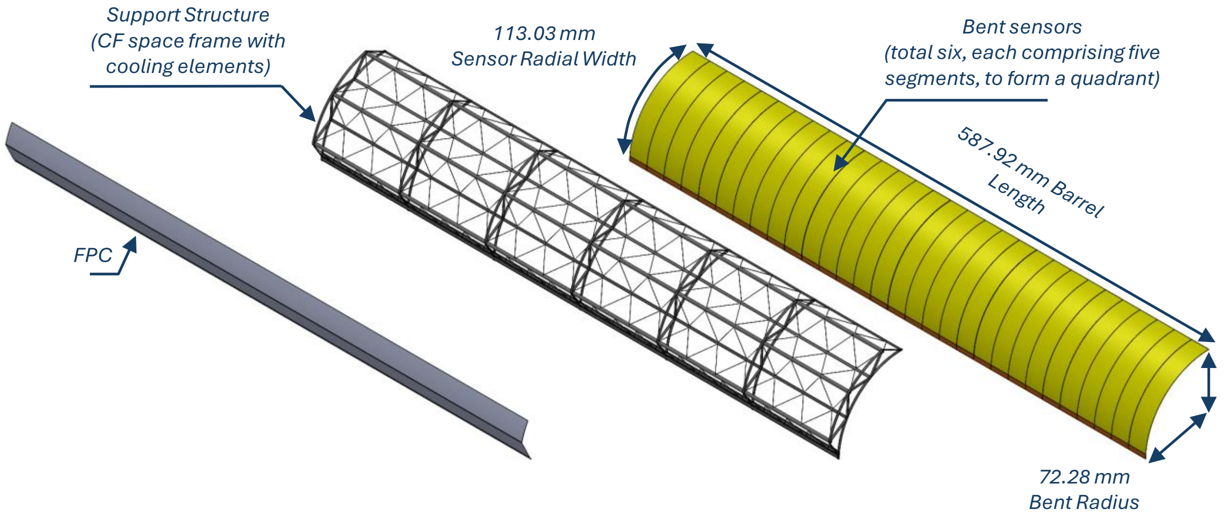
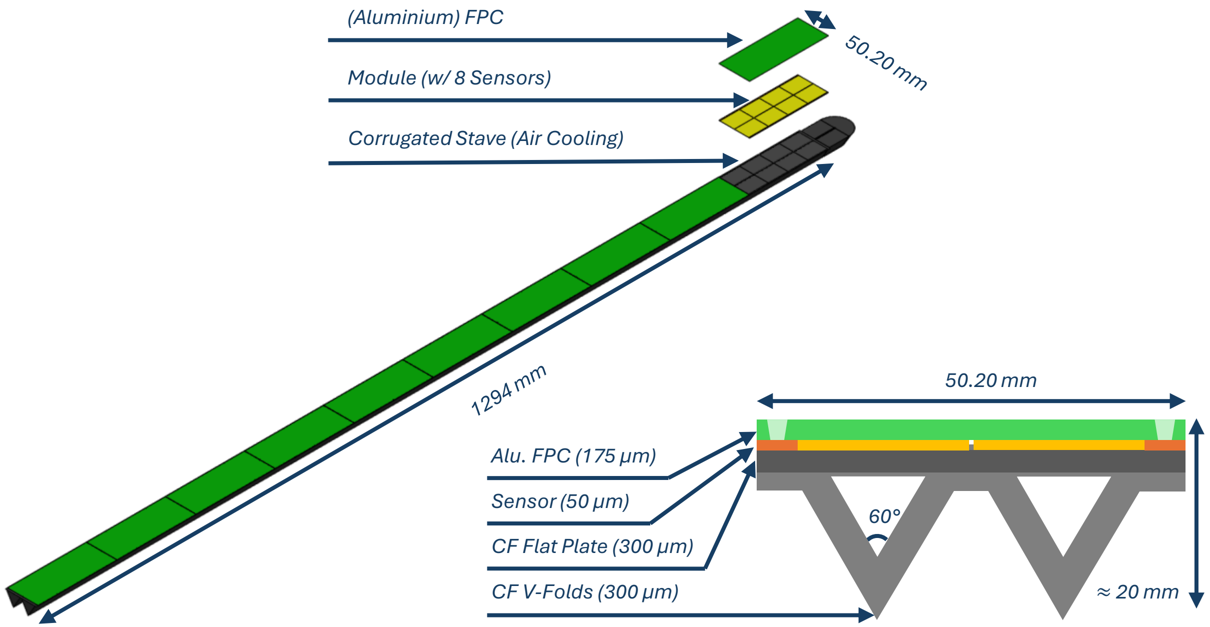


Planar middle layer version
Avg. material budget of < 0.45% X/X_0 per layer

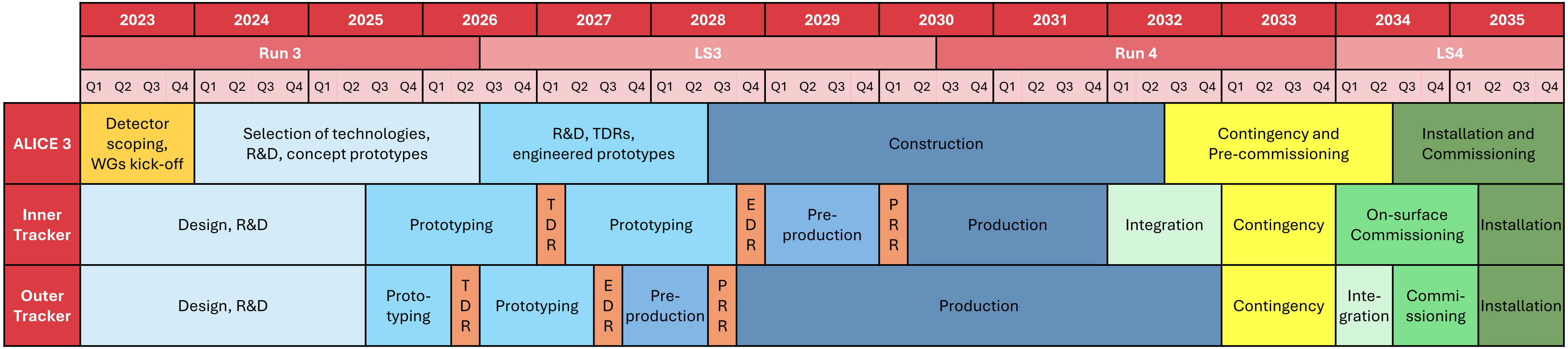
- Sensor Design: Single-reticle sensor (32 x 25 mm^2; 1.5 mm periphery)
- Module Design: Sensors arranged in 4x2 layout with aluminium FPCs
- Thermal Management: Air-cooled CF staves; cooling ≈ 60 mW/cm^2
- Readout and Powering: Off-stave lpGBT and VTRx+, and serial powering



Summary And Outook

ALICE 3 Silicon Tracker, with its unique detector concept, pushes the limits of MAPS technology and large-area integration methods, and has a very aggressive R&D program to ramp up towards TDRs in 2026 for eventual data taking in Run 5!

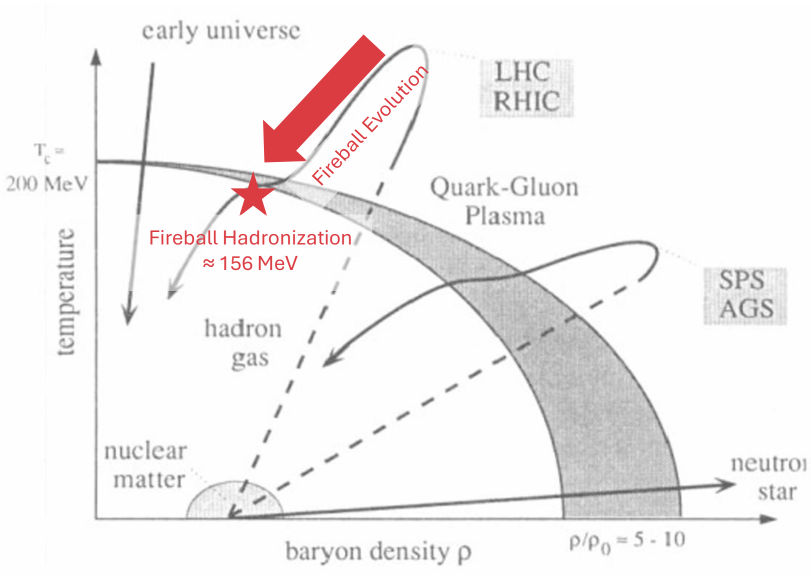
- Targets pointing resolution of 10 μm at p_T = 200 MeV/c at midrapidity
  - ✓ compact: 11 barrel layers (0.5 ≤ r ≤ 80 cm) and 2 x 12 disks (|z| ≤ 350 cm)
  - ✓ large area: ≈ 60 m^2 spanning |η| ≤ 4
  - ✓ lightweight: ≈ 0.1 % X/X_0 per layer for the Vertex Detector (in-vacuum); ≈ 10 % X/X_0 for all Silicon Tracker layers
  - ✓ housed in 2T solenoidal magnet
- R&D will build upon ALICE ITS3 experience, where wafer-scale MAPS based on the TPSCo 65 nm process have been qualified
- Challenges and opportunities
  - ✓ improve radiation hardness and rate capabilities
  - ✓ achieve smaller pixel pitches and spatial resolution
  - ✓ retractable mechanics and operation in beam pipe
  - ✓ reduce power consumption
  - ✓ industrial and automatized module assembly methods
- Developments are of broad interest for next-gen upgrades and experiments



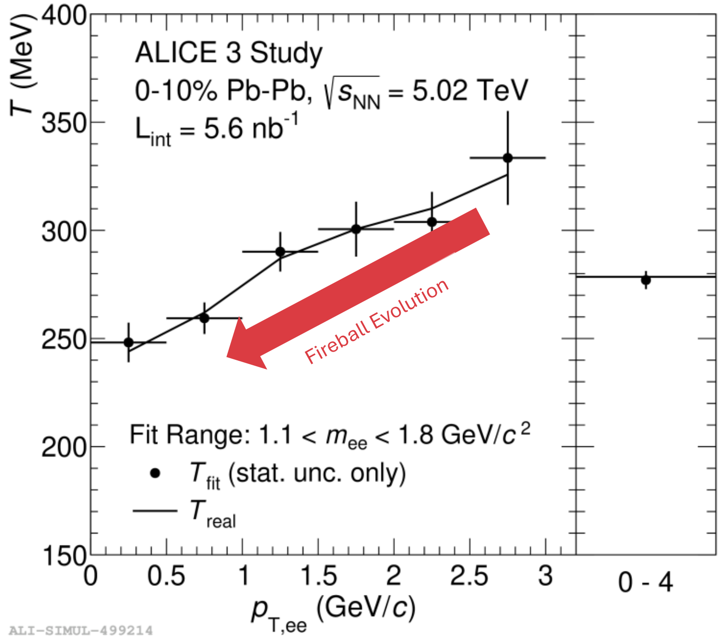
Thank You

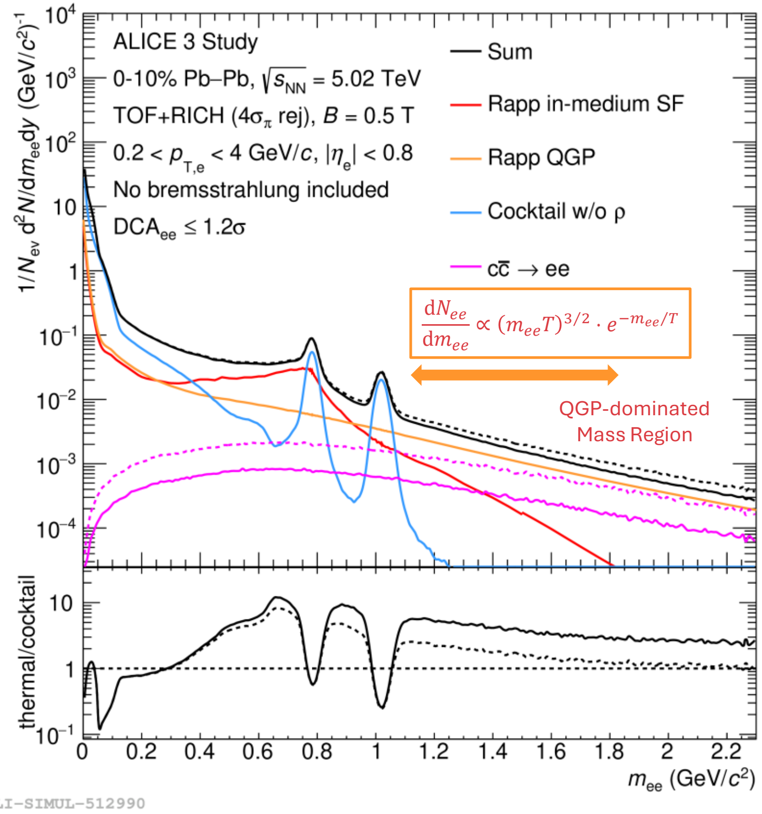
EXTRA SLIDES

Motivation For Lightweight Silicon Tracker

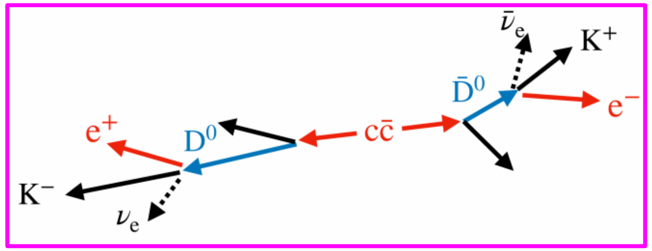


H.R. Schmidt, J. Schukraft, J.Phys.G 19 (1993) 1705-1796
[ALICE], Eur.Phys.J.C 84 (2024) 8, 813
F. Gross et al., Eur.Phys.J.C 83 (2023) 1125



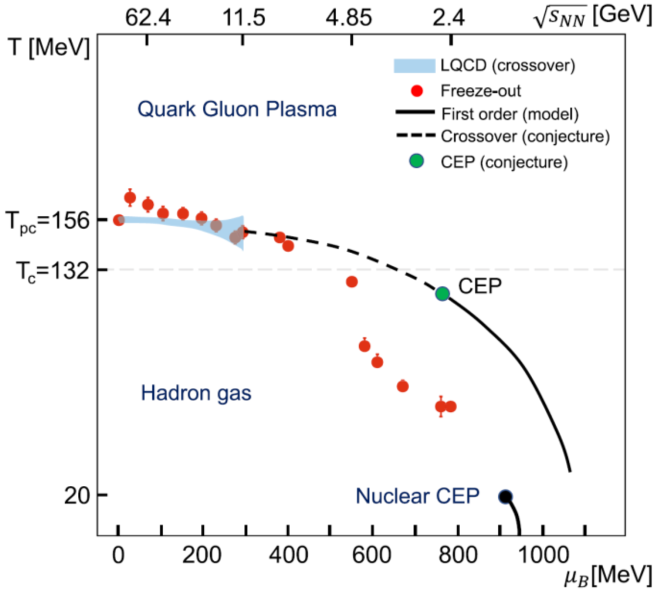


- Current experimental info about fireball temp. at LHC energies (Pb-Pb) is at hadronization (T_{chem} ≈ 156 MeV)
- Source temperature can be extracted from the inverse slope of dilepton excess spectra
- Semi-leptonic heavy-flavour hadronic decays ($c/b \xrightarrow{W^{\pm}} e^{+/-}X$) dominate the di-electron spectrum (B.R. ~ 10%)
- Unfold spectra through characteristic weak-decay topologies of heavy-flavour hadrons (DCA_{ee} separation between prompt and non-prompt di-electrons; $c\tau$ ~ 100 μm)

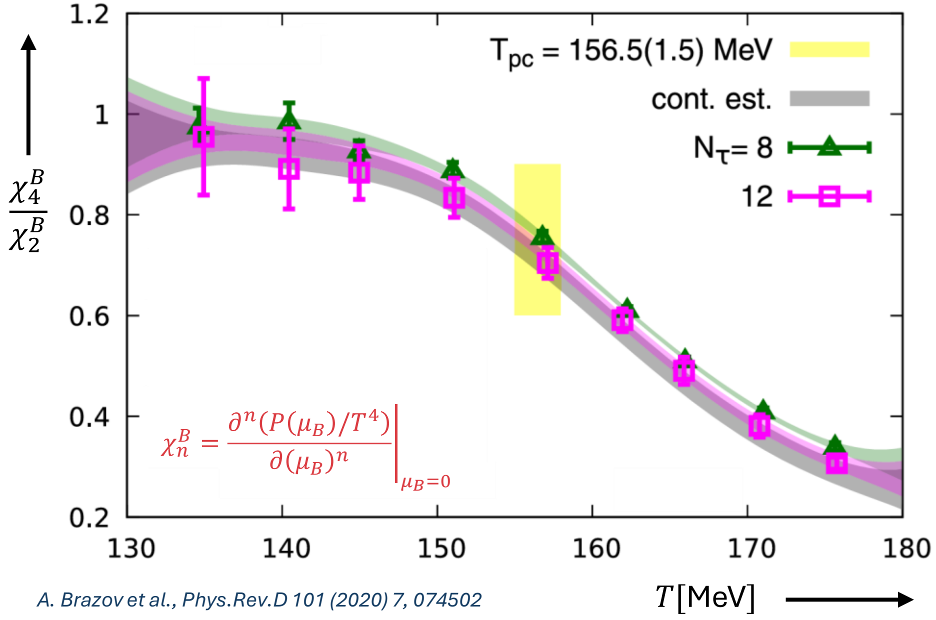


Low-material ALICE 3 tracker is crucial for achieving ≈ 10μm pointing resolution, enabling identification of non-prompt heavy-flavour decays (background) and di-electron excess yield (temp.) with p_T (evolution time)

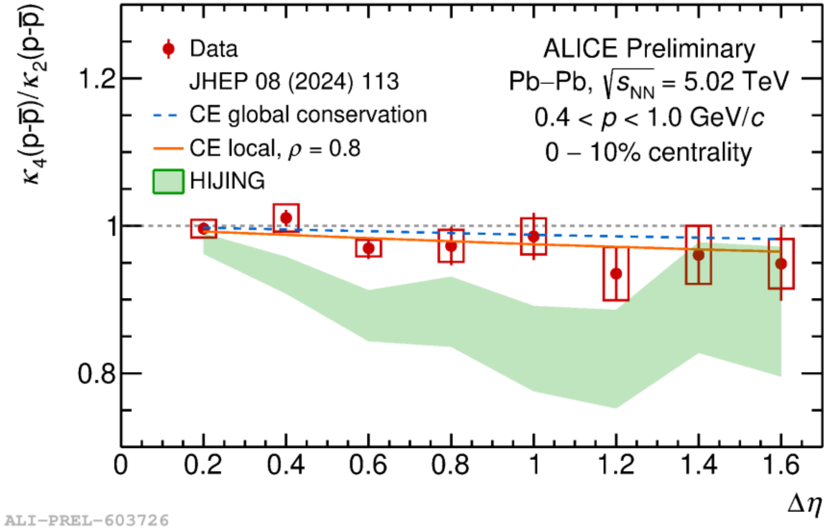
Motivation For Large-Acceptance Silicon Tracker

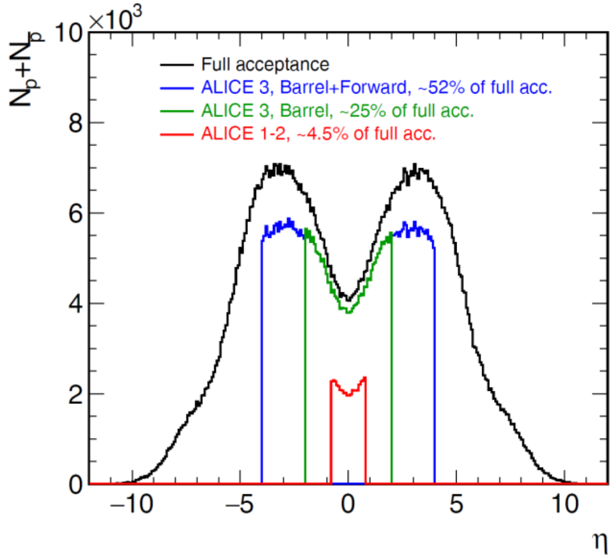


F. Gross et al., Eur.Phys.J.C 83 (2023) 1125
P. Braun-Munzinger et al., arXiv: 2211.08819 [hep-ph]



A. Brazov et al., Phys.Rev.D 101 (2020) 7, 074502





- At LHC energies ($\mu_B \approx 0$), current info about partonic phase transition is only available from lQCD ➡ Massless Quarks: 2nd-order ($T_c \approx$ 132 MeV); Finite Quark Masses: Cross-over ($T_{pc} \approx$ 156 MeV)
- Varying correlation length in vicinity to phase transition ➡ lQCD: Susceptibilities (χ_4^B/χ_2^B); Experiments: Cumulants (κ_4/κ_2)
- Sensitivity to phase transition, i.e., deviation from the Poissonian baseline, is highly dependent on detector acceptance (for ALICE 1-2 setup, |η| ≤ 0.8, or Δη ≤ 1.6)

Large acceptance (Δη) of ALICE 3 tracker would enable mapping the higher-order fluctuations of conserved charges (related to susceptibilities in lQCD), thereby characterizing the nature of hadron-to-parton phase transition at the LHC