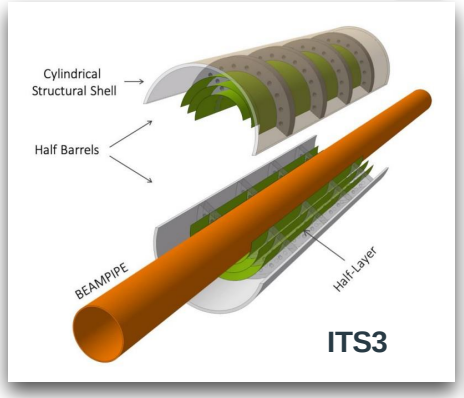
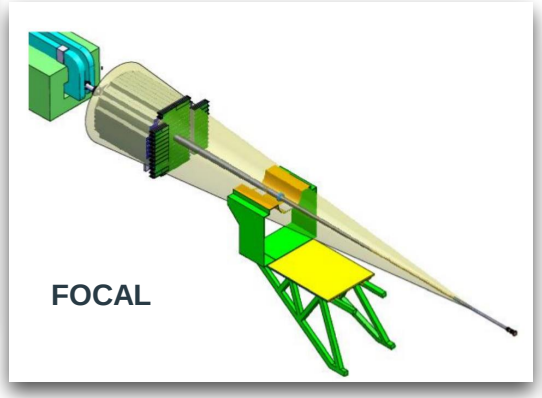
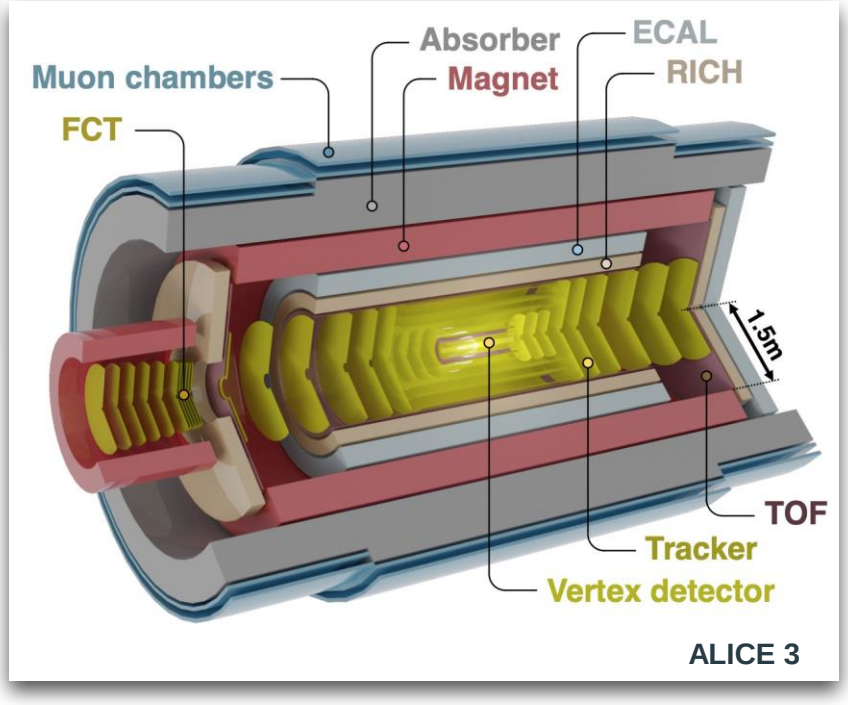
Future for Heavy Ions & ALICE 3



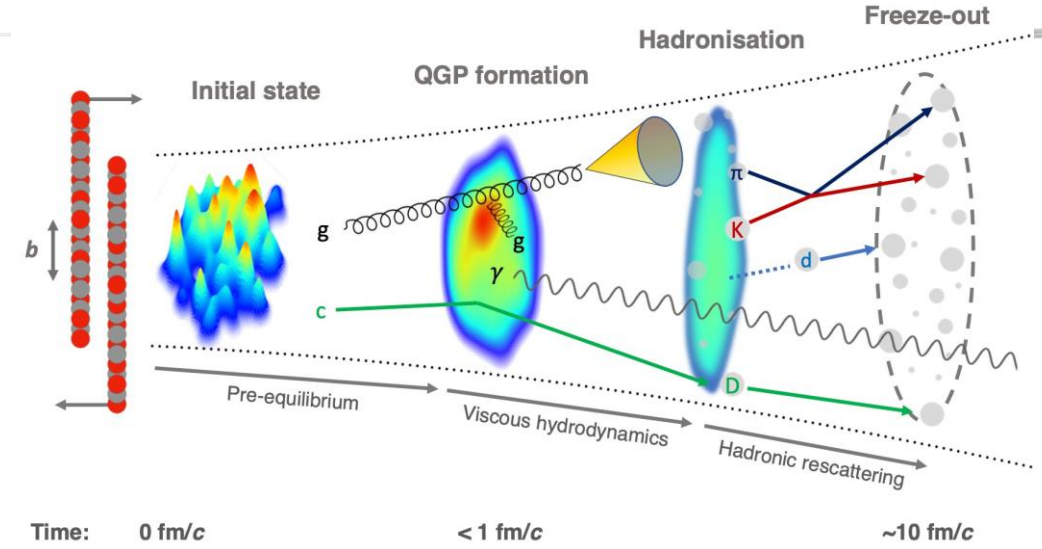




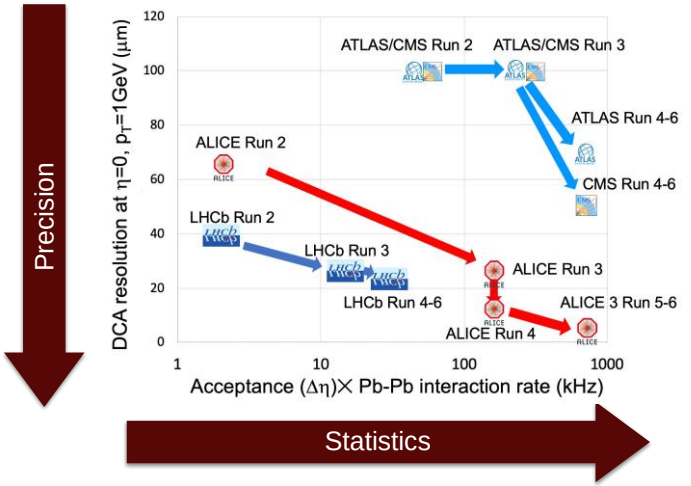
Dieter Roehrich
University of Bergen

on behalf of the ALICE collaboration

Heavy Ion Physics @ LHC



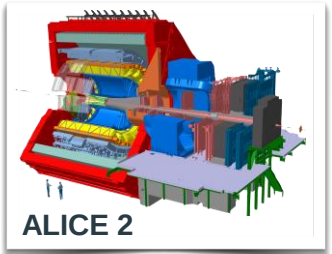
arXiv:2211.04384

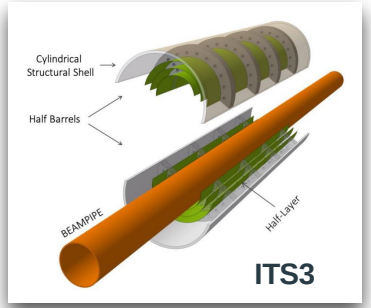


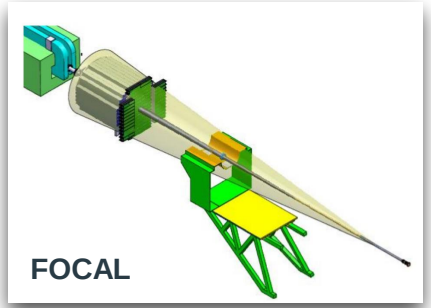
- ALICE is designed to study the quark-gluon plasma produced in heavy-ion collisions at the LHC
- Two main physics goals driving the upgrade strategy:
  - **Heavy flavour (HF)** transport and hadronization in the medium:
    differential measurements of hadron production (suppression, enhancement, flow…) down to vanishing p_T
  - **Electromagnetic radiation** from the medium:
    dileptons below the *J/ψ* mass down to zero p_T: mapping the evolution of the collision

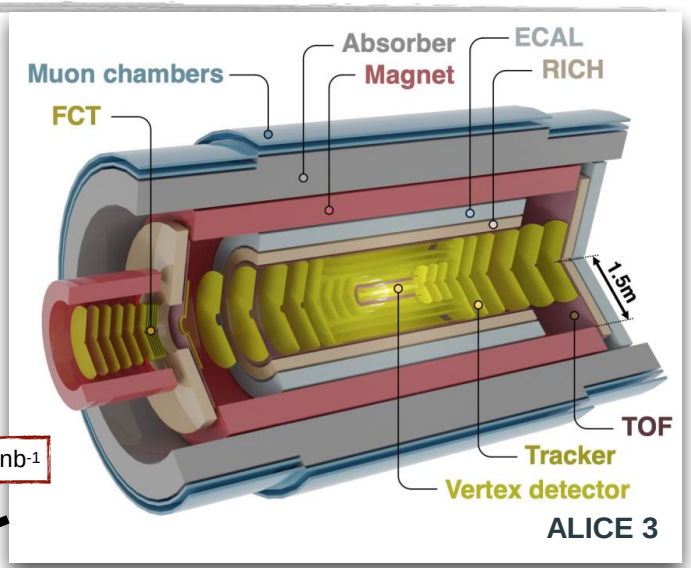
⇒ High-granularity, low-mass detector with continuous readout to access untriggerable signals with very low S/B

ALICE Upgrade Roadmap









Pb-Pb: 6.2 nb^{-1}
O-O: 500 µb^{-1}

Pb-Pb: 6.8 nb^{-1}
p-Pb: 0.6 pb^{-1}

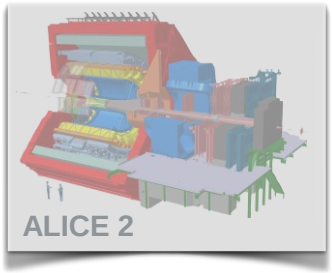
Pb-Pb: ~ 35 nb^{-1}

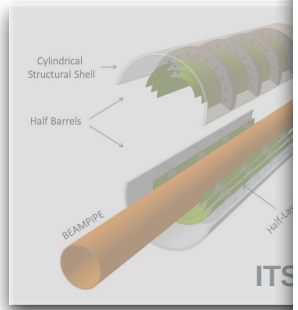
Today

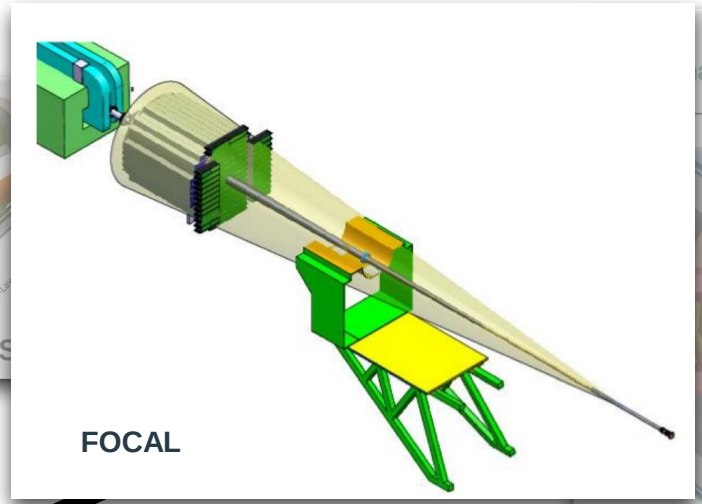
ALICE 2	ALICE 2.1	ALICE 3
LHC Run 3	LHC LS3	LHC Run 4
		LHC LS4
		LHC Run 5
		LHC LS5
		LHC Run 6

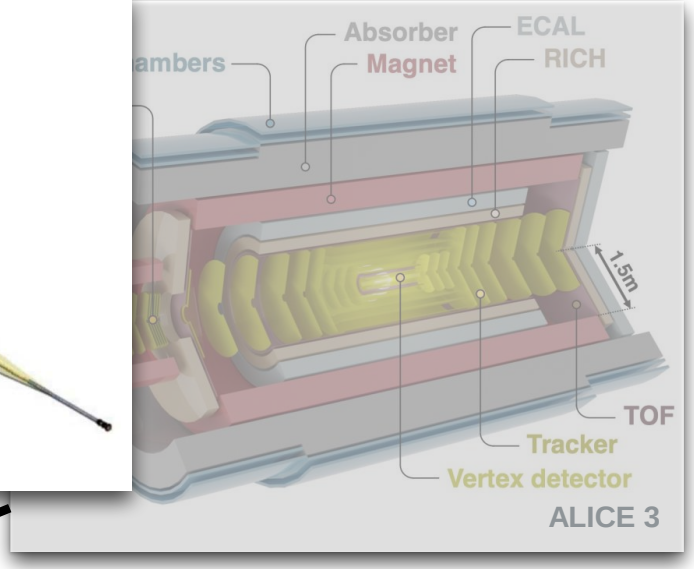
2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041

The Forward Calorimeter (FoCal)









Today

ALICE 2.1

ALICE 3

LHC Run 3

LHC LS3

LHC Run 4

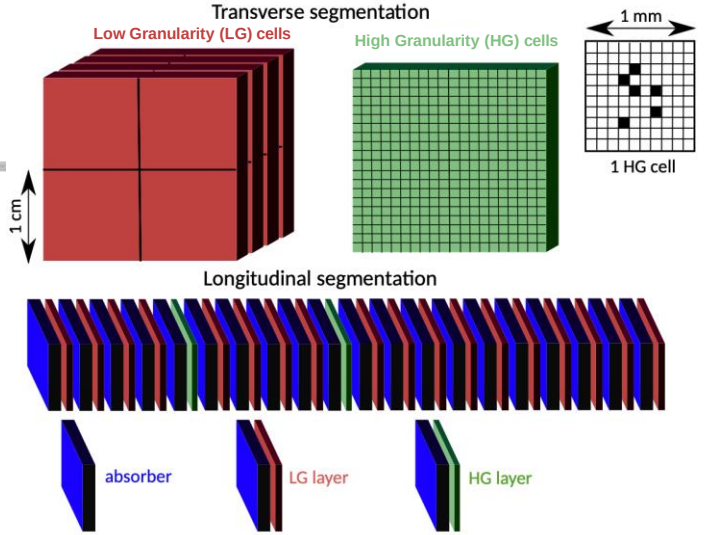
LHC LS4

LHC Run 5

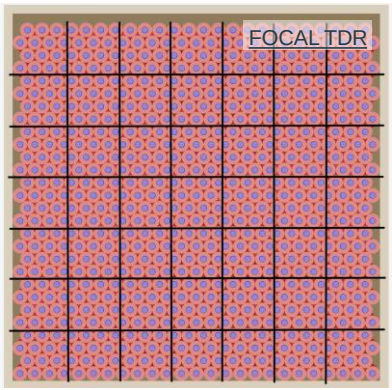
2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041

The Forward Calorimeter (FoCal)

- **FoCal-E:** a compact silicon-tungsten sampling electromagnetic calorimeter with pad (1 x 1 cm^2) and pixel (30 x 30 µm^2)
  - High spatial resolution for discriminating between isolated photons and decay photon pairs
- **FoCal-H:** hadronic calorimeter constructed from copper capillary tubes filled with scintillating fibres
  - Photon isolation, energy and jet measurements
- Coverage: $3.2 < \eta < 5.6$

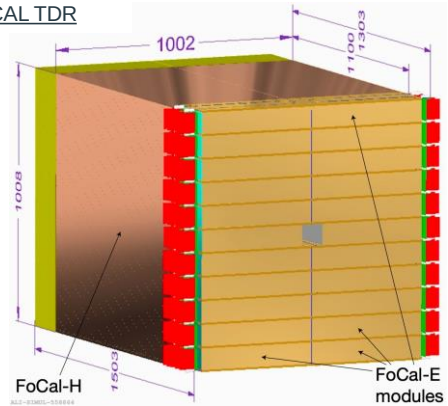


Segmentation of FoCal-E



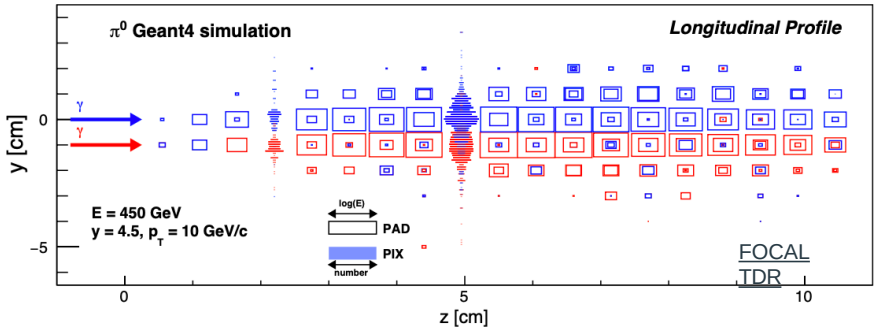
Front view of a FoCal-H module in simulation

FOCAL TDR



3d view of FoCal, dimensions in mm

FOCAL TDR — CERN-LHCC-2024-004



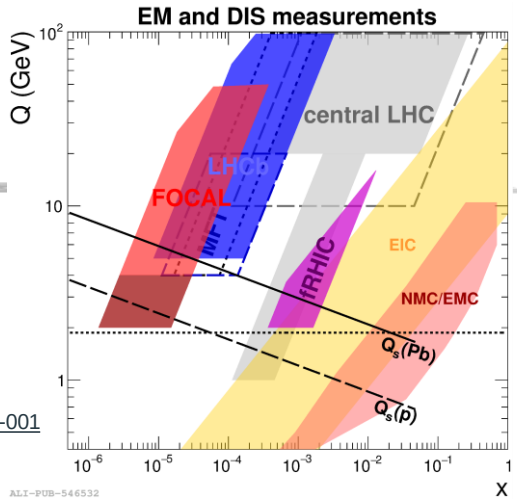
Longitudinal shower profile of two photons in FoCal-E

FoCal — Physics Goals

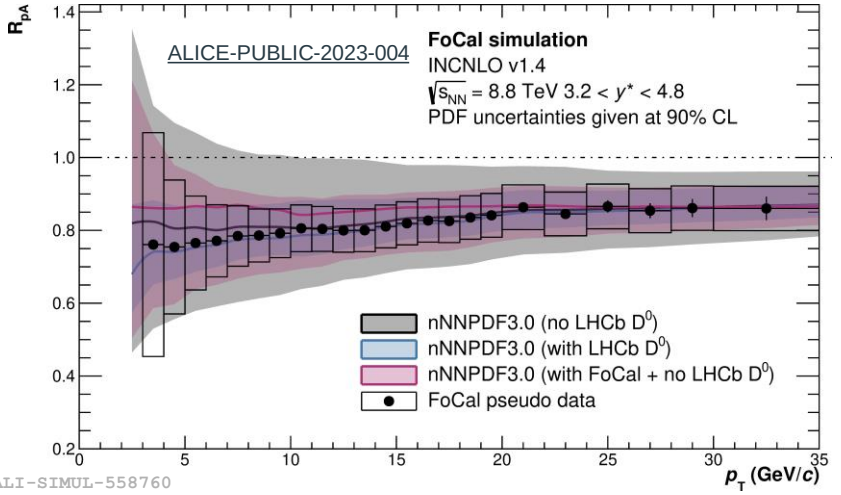
- Search for evidence of gluon saturation due to non-linear PDF evolution in QCD in nucleons and nuclei at low Bjorken-*x* down to ~10^{-6}
- Constrain nuclear PDFs
- Broad phase-space coverage while providing a multi-messenger approach

  → Comprehensive exploration of saturation, complementary to other LHC experiments and to EIC

Wide set of experimental observables:
- Isolated (direct) photons
- π^0 and other neutral mesons
- Jets
- Vector mesons in UPC (J/ψ, Υ,…)
- Correlations (-hadron, hadron-hadron, …)
- … and more

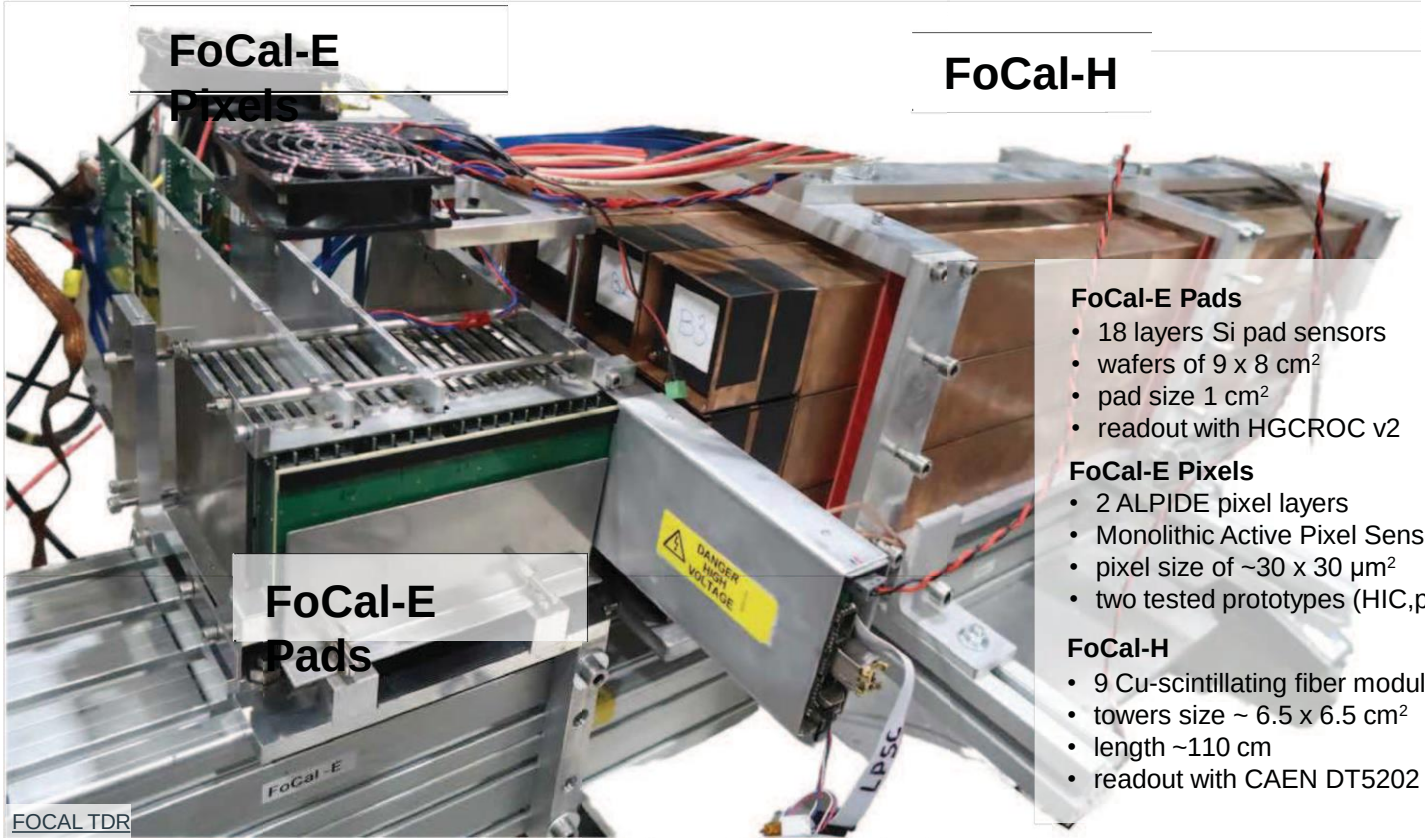


ALICE-PUBLIC-2023-001



Physics of the ALICE Forward Calorimeter upgrade: ALICE-PUBLIC-2023-001
Physics performance of the ALICE Forward Calorimeter upgrade: ALICE-PUBLIC-2023-004

FoCal — Test Beams

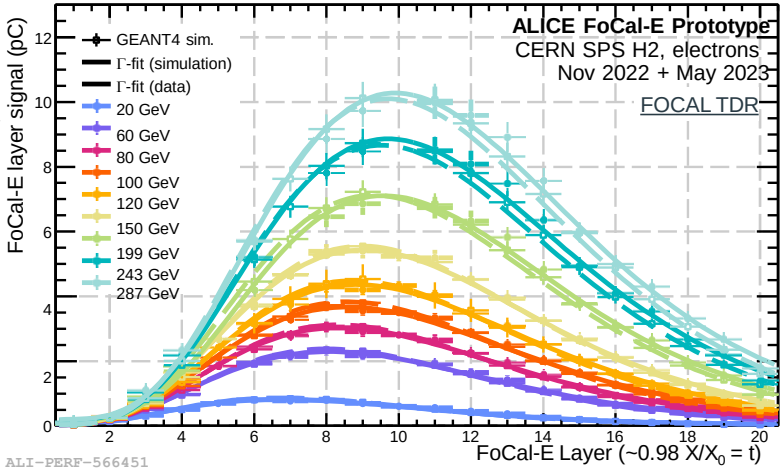


FoCal-E Pads
- 18 layers Si pad sensors
- wafers of 9 x 8 cm^2
- pad size 1 cm^2
- readout with HGCROC v2

FoCal-E Pixels
- 2 ALPIDE pixel layers
- Monolithic Active Pixel Sensors
- pixel size of ~30 x 30 μm^2
- two tested prototypes (HIC,pCT)

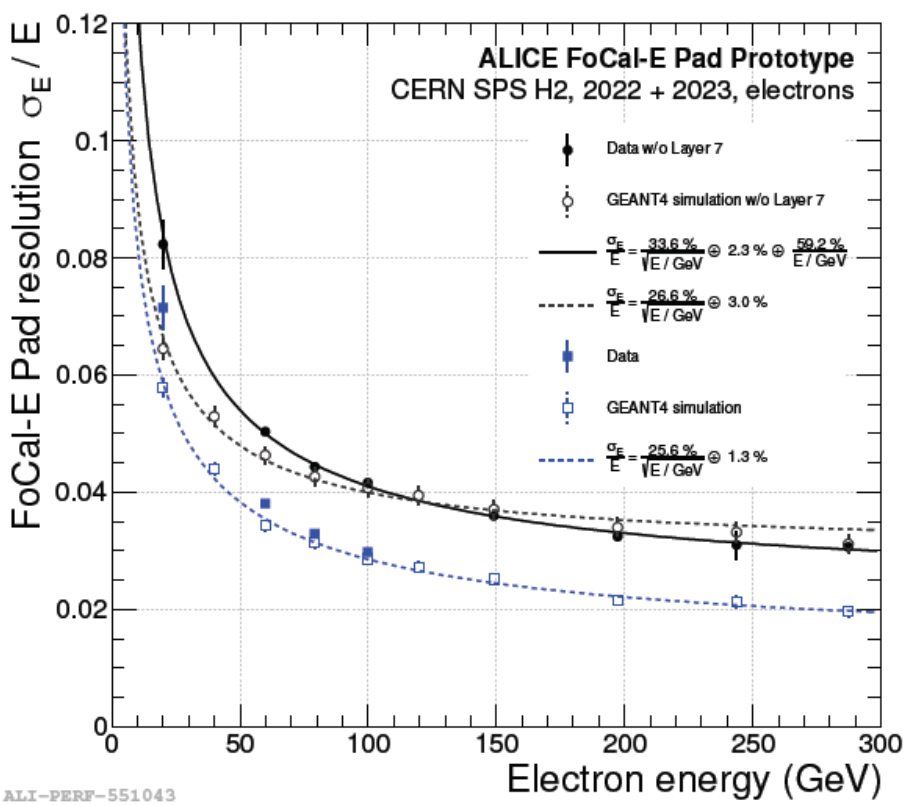
FoCal-H
- 9 Cu-scintillating fiber modules
- towers size ~ 6.5 x 6.5 cm^2
- length ~110 cm
- readout with CAEN DT5202

Longitudinal shower profile in FoCal-E



ALI-PERF-566451

FoCal-E energy resolution

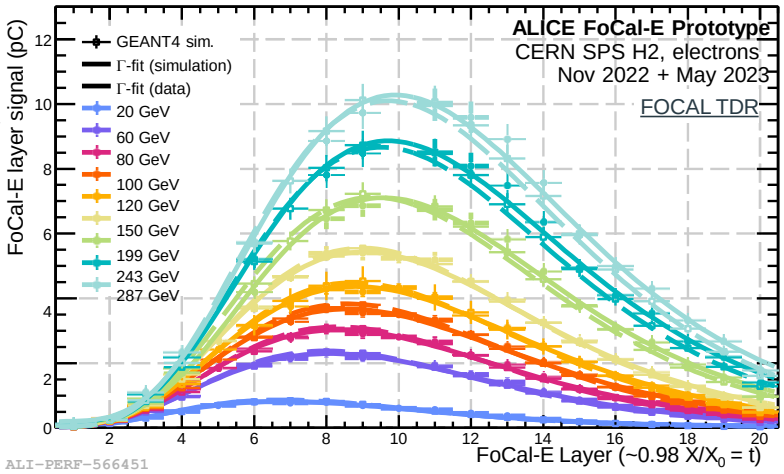


ALI-PERF-551043

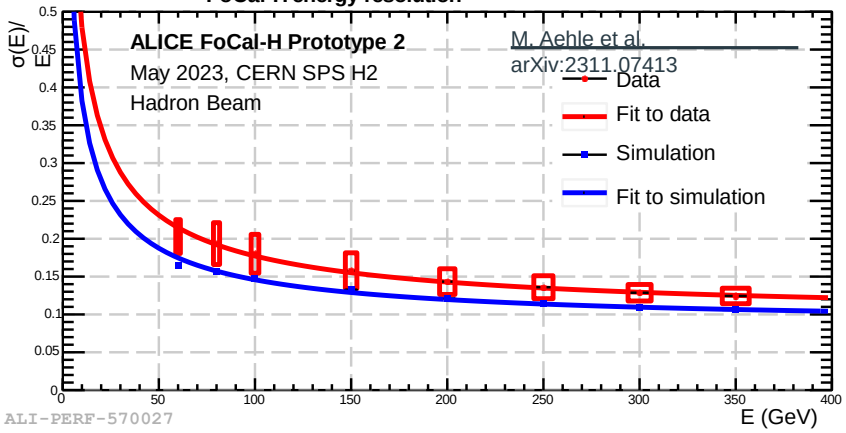
ALI-PERF-569144

FOCAL TDR

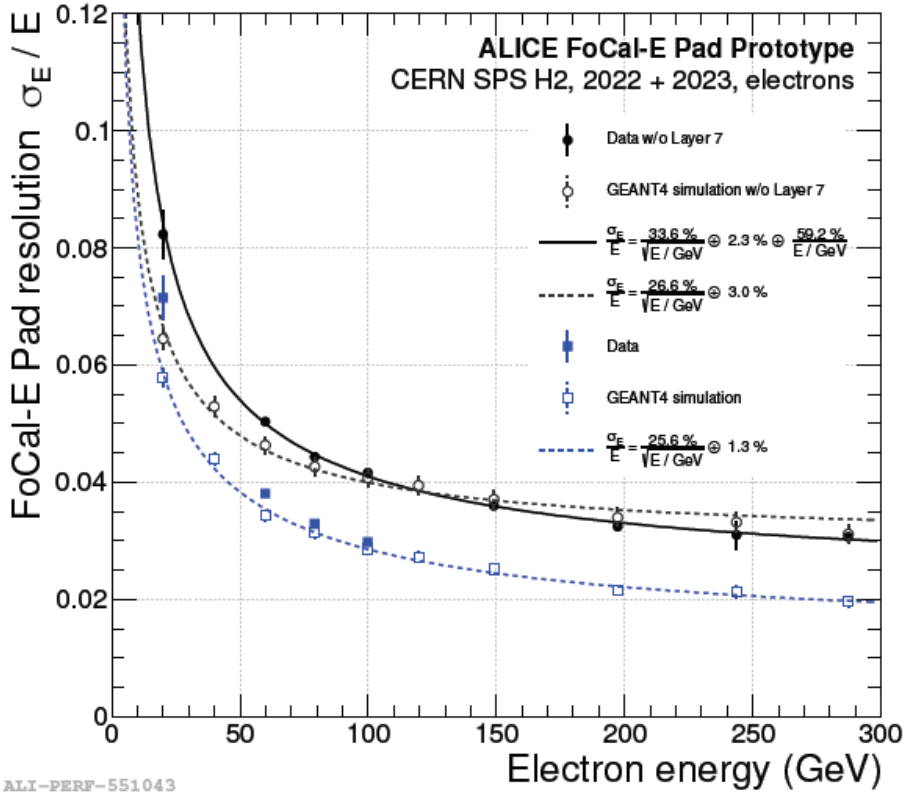
Longitudinal shower profile in FoCal-E



FoCal-H energy resolution

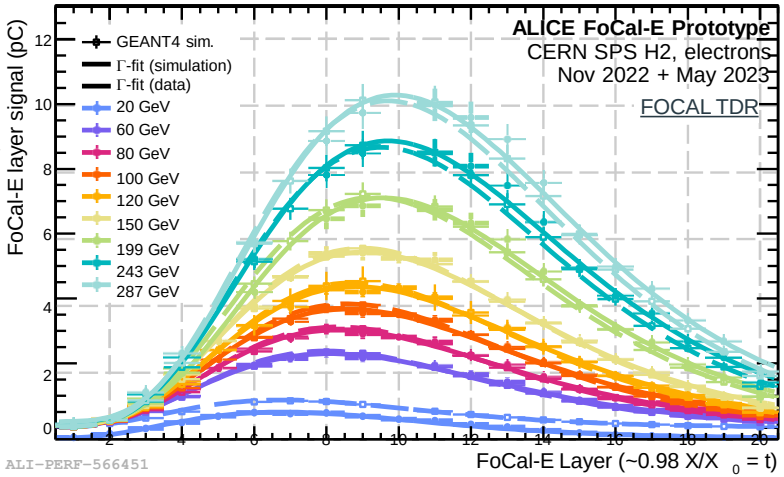


FoCal-E energy resolution

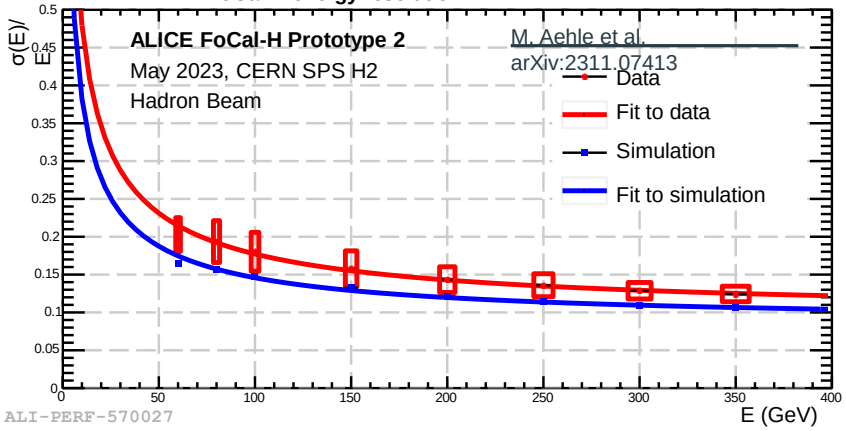


Resolution < 15% at high energies, data/MC discrepancy under investigation

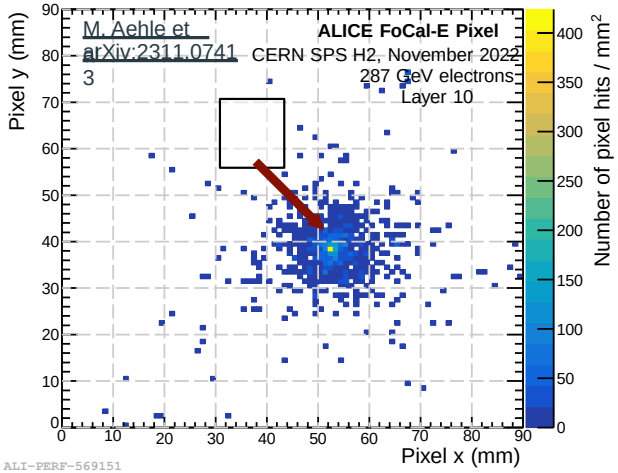
Longitudinal shower profile in FoCal-E

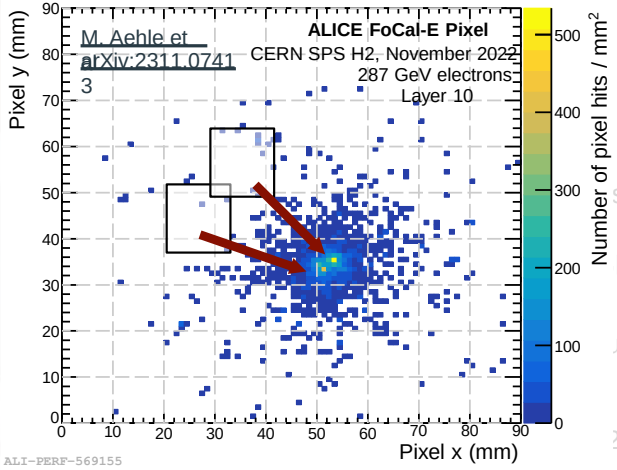


FoCal-H energy resolution



Resolution < 15% at high energies, data/MC discrepancy under investigation

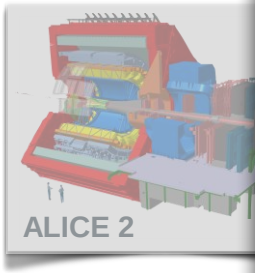


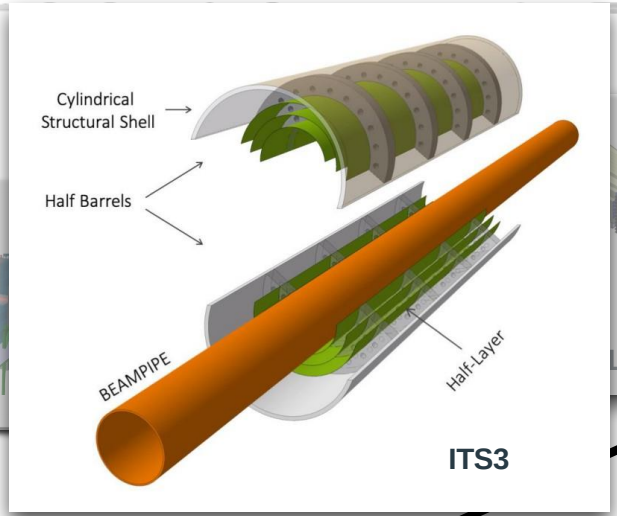


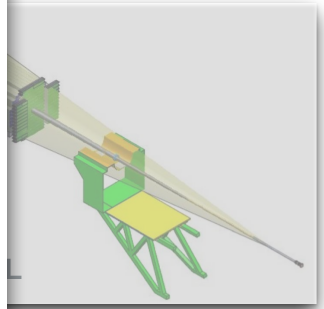
Event display of one- and two-electron showers in the 2nd pixel layer

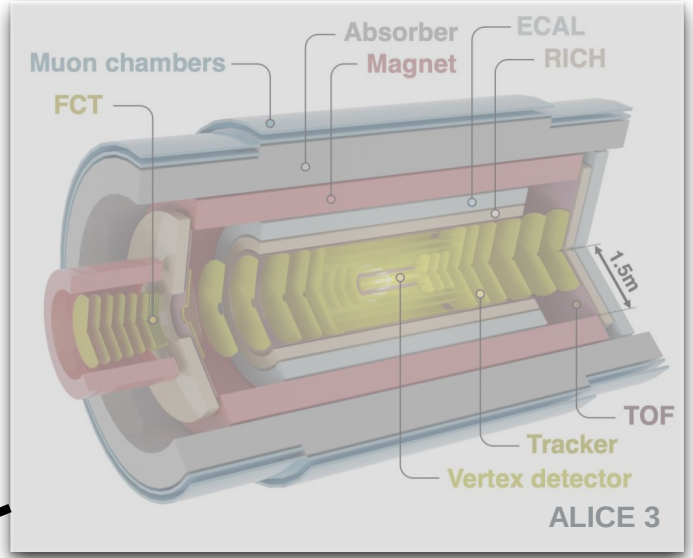
FoCal-E pixel

Inner Tracking System 3 (ITS3)









Today

ALICE 2.1

ALICE 3

LHC Run 3

LHC LS3

LHC Run 4

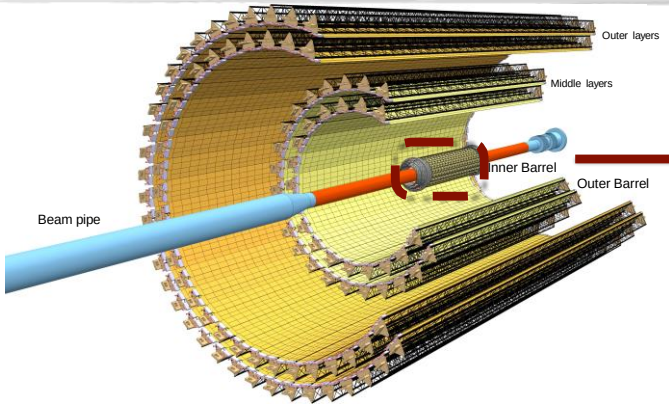
LHC LS4

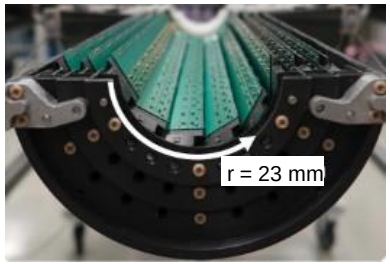
LHC Run 5

2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041

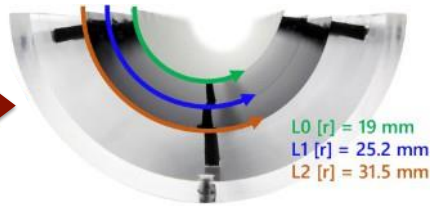
The Inner Tracking System 3 (ITS3)

ALICE



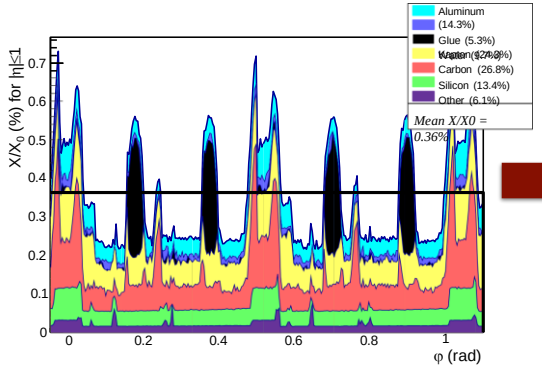


ITS2 Inner Barrel

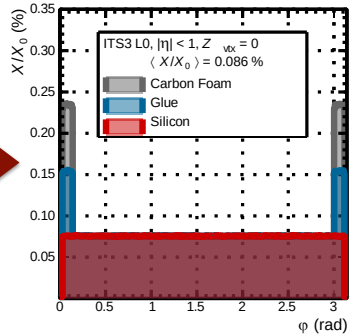


ITS3 Engineering Model 1

- Replacement of ITS2 Inner Barrel with 3 layers of curved 50 µm thick wafer-scale MAPS
- Air cooling and ultra-light mechanical supports
- Reduced material budget of **0.09% X_0** instead of **0.36% X_0** per layer
- Smaller radius of the innermost layer: **19 mm** instead of **23 mm**



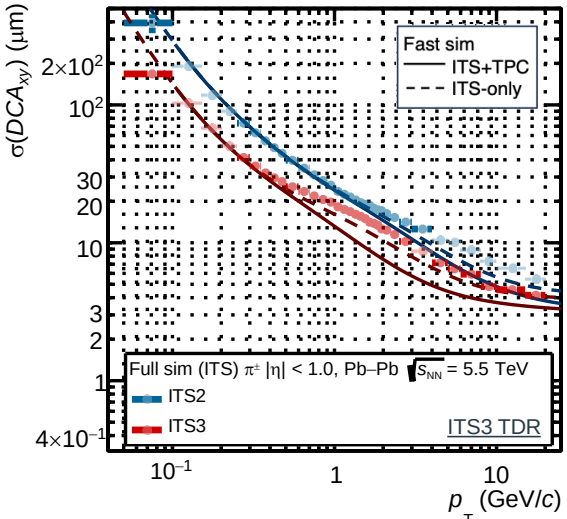
ITS2 Layer 0



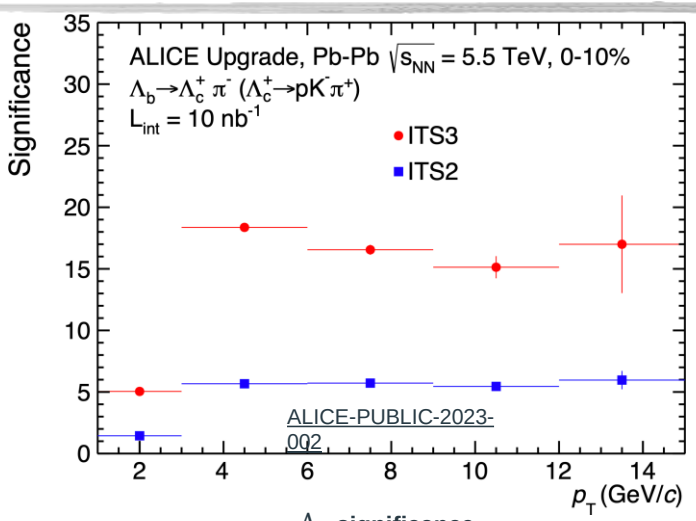
ITS3 Layer 0

ITS3 TDR — CERN-LHCC-2024003

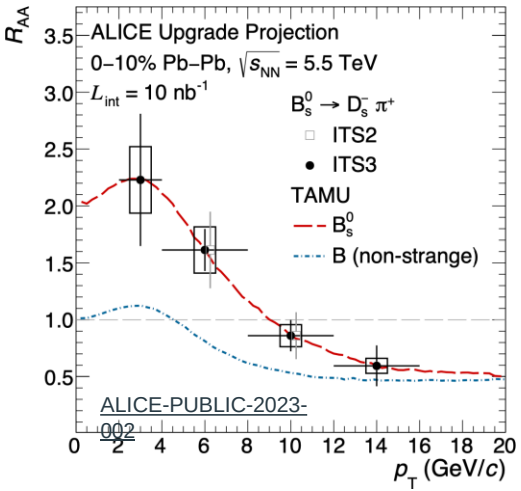
ITS3 — Physics Impact



Impact parameter resolution



Λ_b **significance**

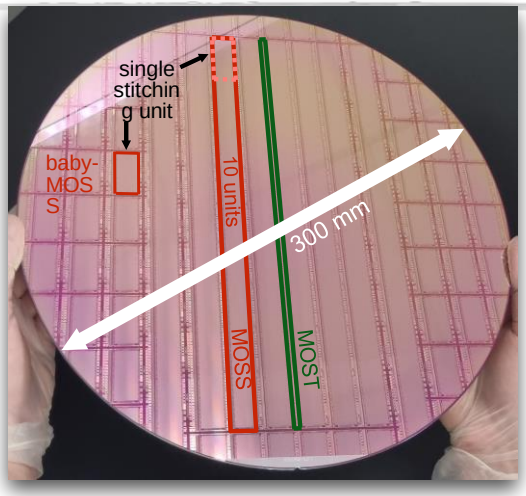


B_s^0 **nuclear modification factor**

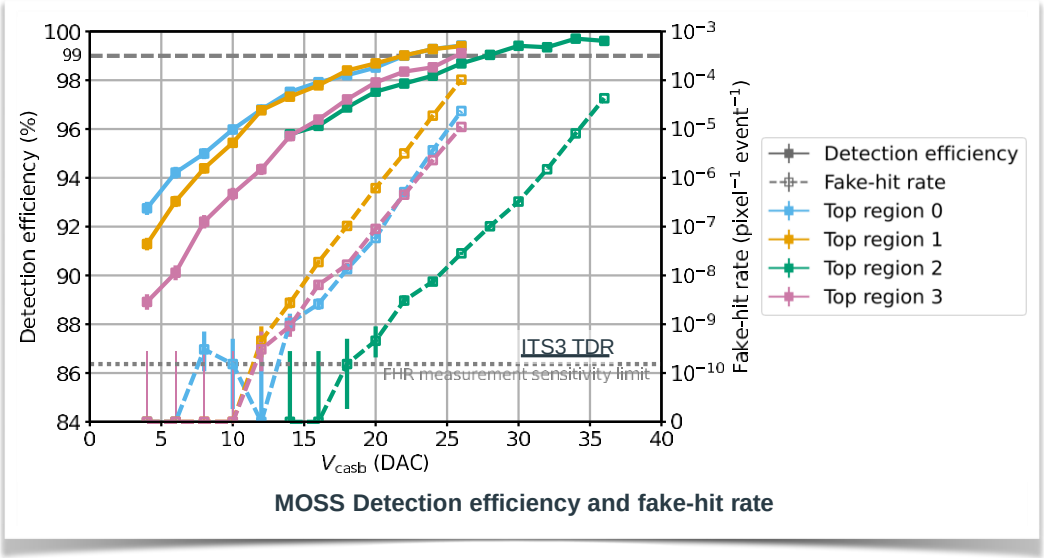
- DCA resolution improved by a about a factor of 2 → improved separation of secondary vertices
- Many fundamental observables strongly profiting or becoming in reach
  - Charmed and beauty baryons
  - Low-mass di-electrons
  - Full topological reconstruction of B_s

ITS3 physics performance studies: ALICE-PUBLIC-2023-002

ITS3 — Stitched Wafer-Scale MAPS — Recent Results



Engineering Run 1 wafer with various dies



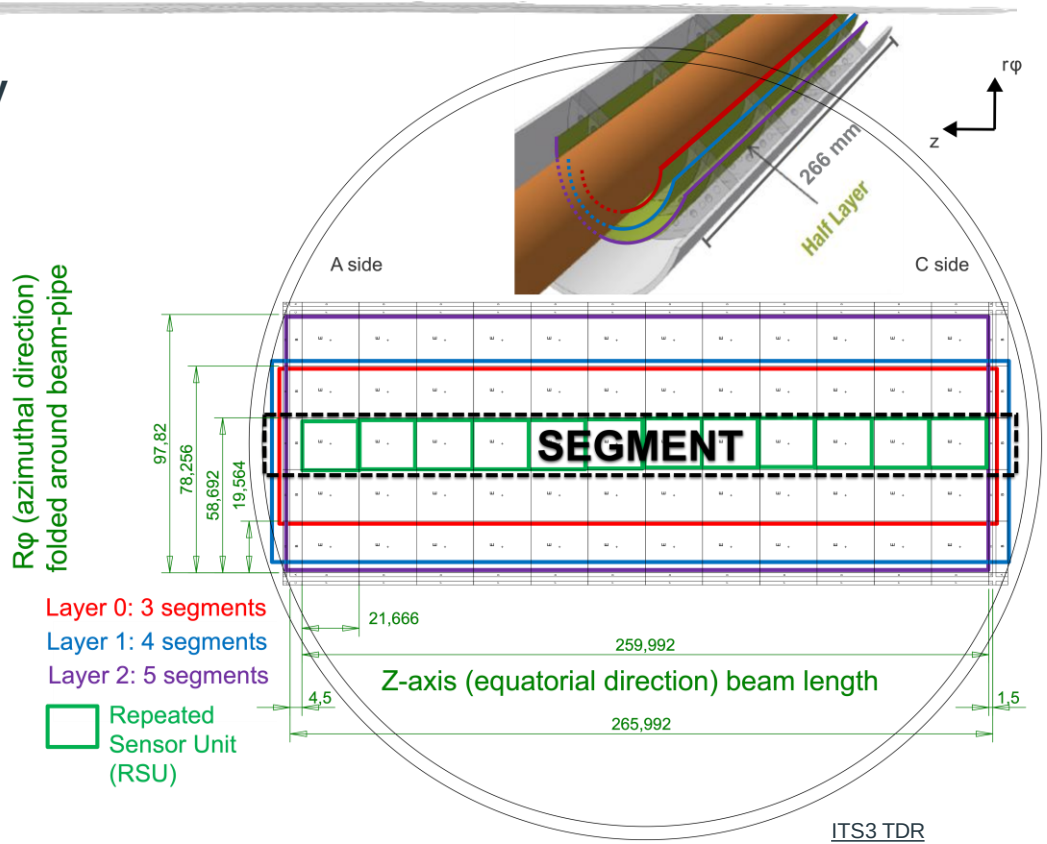
MOSS Detection efficiency and fake-hit rate

Monolithic Stitched Sensor (MOSS)

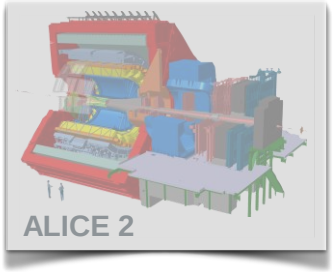
- First stitched MAPS for high-energy physics
- 10 Repeated Sensor Units (RSUs) stitched together: **259 mm x 14 mm** per **sensor**
- 2 pixel pitches (18 µm and 22.5 µm) and 5 front-end variants, a total of **6.72 MPixel** per chip
- Chip is **operational** and reaches **full efficiency**
- Yield currently being studied in detail, main failure mechanism expected to be mitigated in the next submission

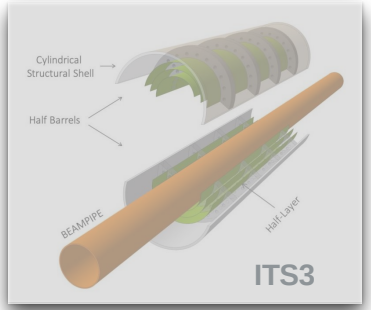
ITS3 — Stitched Wafer-Scale MAPS — Next Steps

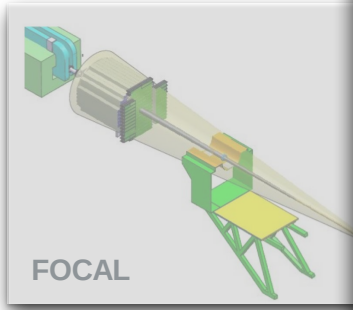
- Design of the final **full size**, **full functionality sensor** called MOSAIX is ongoing
  - Modular design:
    - Sensor divided into 5 segments (allowing to use 3, 4 or 5 segments for layers 0, 1 and 2, respectively)
    - Each segment is constituted of 12 Repeated Sensor Units (RSUs)
    - Each RSU is divided in turn into 12 fully independent tiles (powering, control and readout)
  - Interfacing from the Left End Cap (LEC) and Right End Cap (REC)
    - Powering from both sides
    - Control and readout from the LEC only
  - Yield target: >98% of pixels active
  - Submission to foundry planned for fall 2024

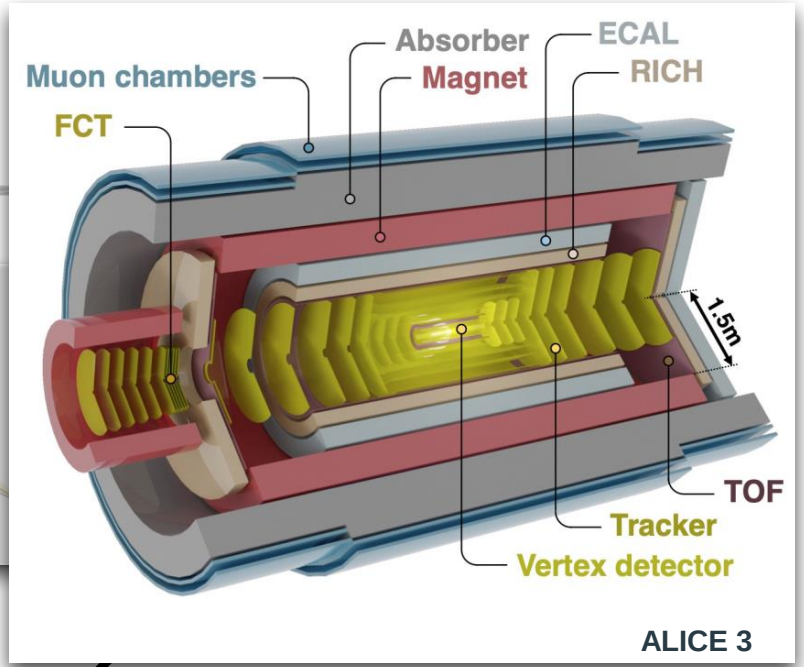


ALICE 3







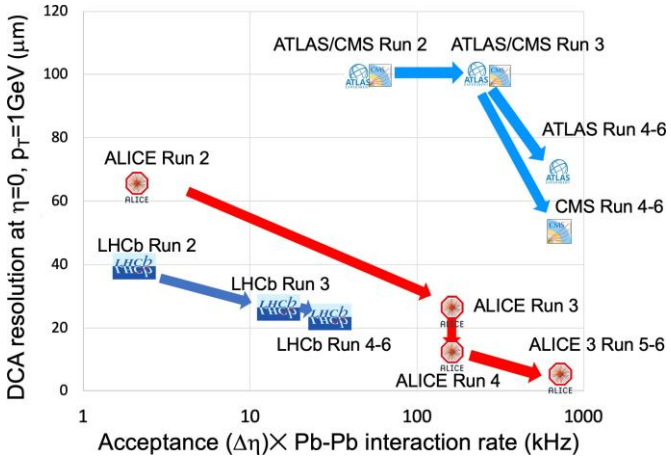


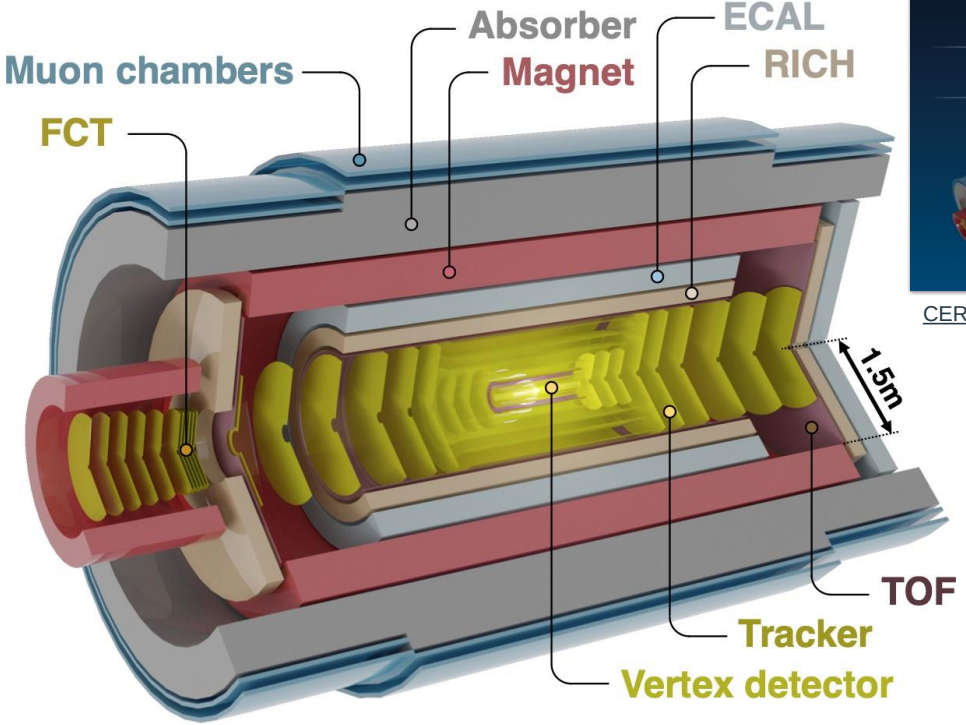
Today

ALICE 2				ALICE 2.1							ALICE 3								
LHC Run 3				LHC LS3				LHC Run 4			LHC LS4		LHC Run 5				LHC LS5	LHC Run 6	
2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041

ALICE 3 — Concept

- Compact, low-mass all-silicon tracker
- Retractable vertex detector
- Excellent vertex reconstruction and PID capabilities
- Large acceptance
- Super-conducting magnet system
- Continuous read-out and online processing

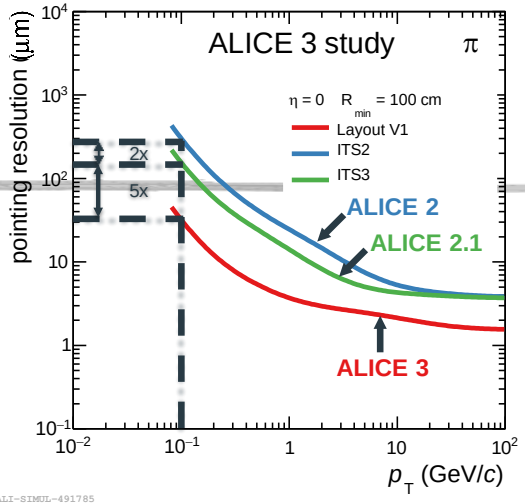


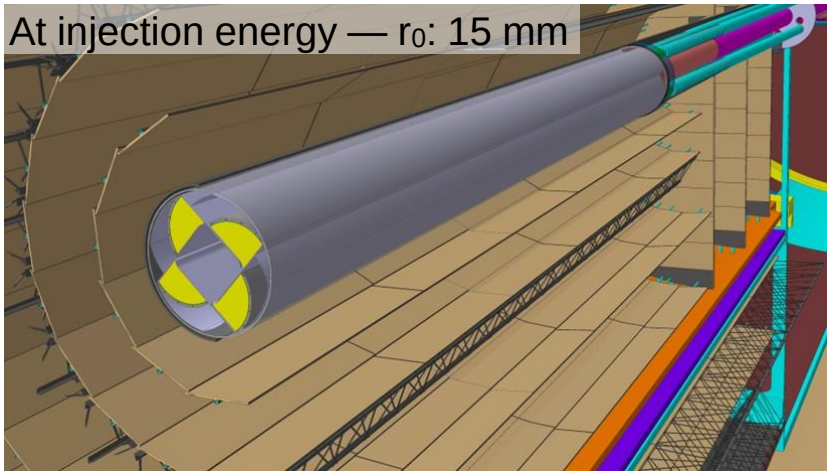


CERN-LHCC-2022-009

ALICE 3 — Vertex Detector (VD)

- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$ (multiple scattering regime)
  - Radius and material of first layer crucial
  - Minimal radius given by required aperture:
    R ≈ 5 mm at top energy,
    R ≈ 15 mm at injection energy
    → **retractable vertex detector**
- **Key detector characteristics**
  - 3 detection layers (barrel + disks)
  - Retractable: **r_0 = 5 mm**
  - Material budget: **0.1% X_0 / layer**
  - Unprecedented spatial resolution: **2.5 µm**
- **Main R&D challenges**
  - Light-weight in-vacuum mechanics and cooling
  - Radiation hardness* (10^{16} 1 MeV n_{eq}/cm^2 + 300 Mrad)
  - Pixel pitch of 10 µm
- **R&D will build upon ITS3 experience**





* LOI values, further simulation studies ongoing

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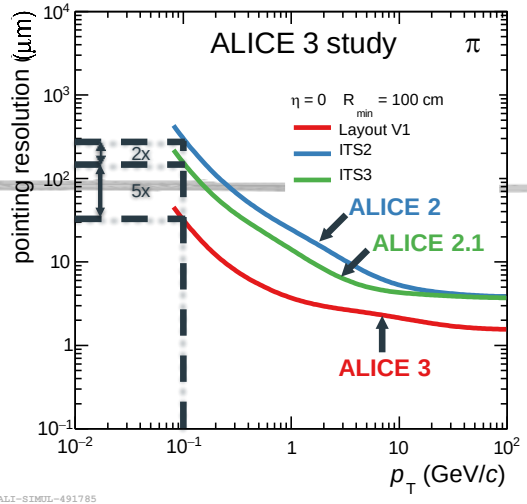

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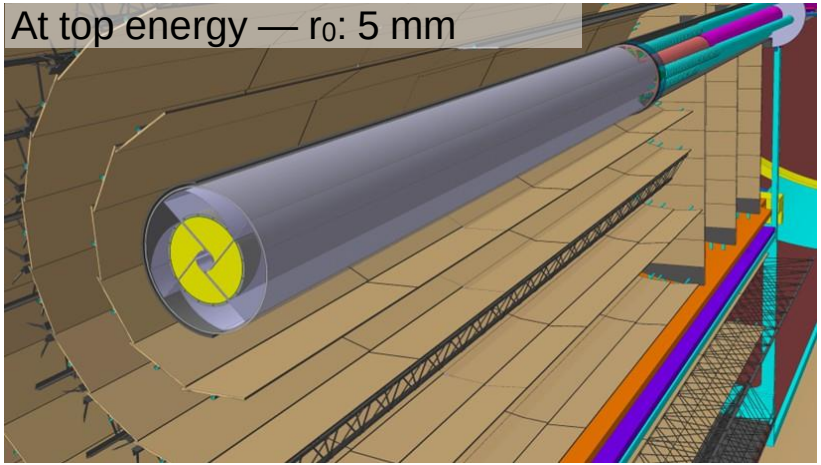

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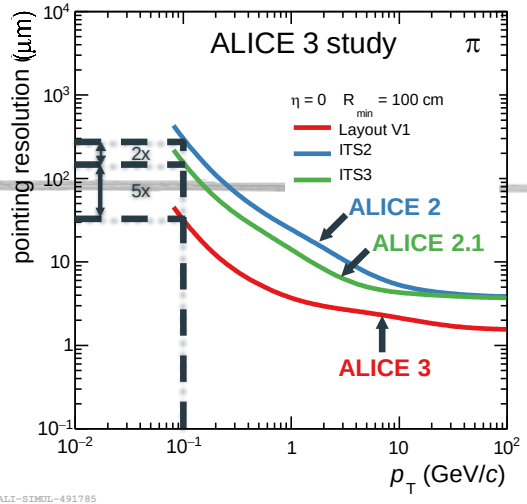

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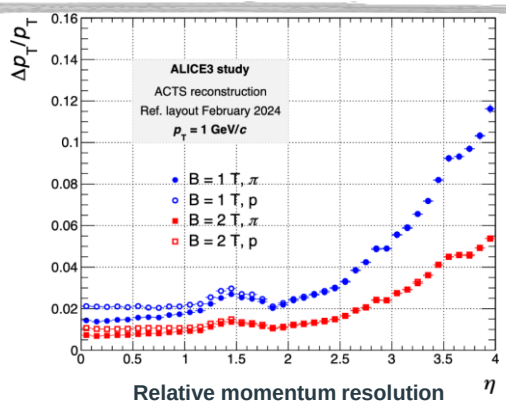
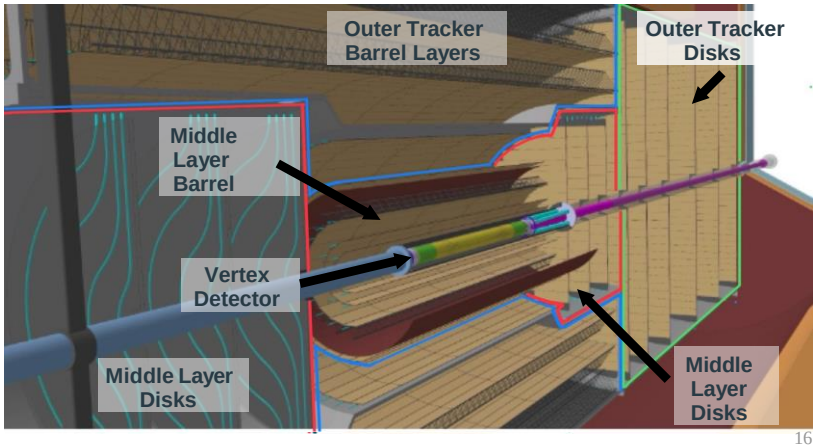
ALICE 3 — Tracking detectors (Middle Layers and Outer Tracker)

- **Relative p_T resolution** $\propto \frac{\sqrt{x/X_0}}{B \cdot L}$
  (limited by multiple scattering)
  - Integrated magnetic field crucial
  - Overall material budget critical
- **Key detector characteristics**
  - 8 barrel layers (3.5 cm < R < 80 cm)
  - 2 x 9 forward disks
  - Total surface: ~ 60 m²
  - Material budget: 1% X_0 / layer
  - Spatial resolution: 10 µm / 50 µm pixel pitch
  - Low power consumption: 20 mW/cm²
  - 100 ns time resolution
- **Main R&D challenges**
  - Module design for high yield industrial mass production
  - Low power consumption while maintaining timing performance



Relative momentum resolution


Automated module assembly tests



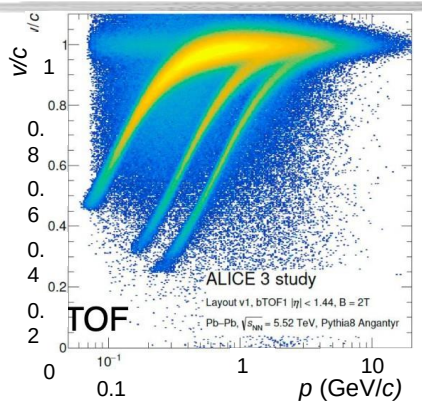
ALICE 3 — Particle Identification

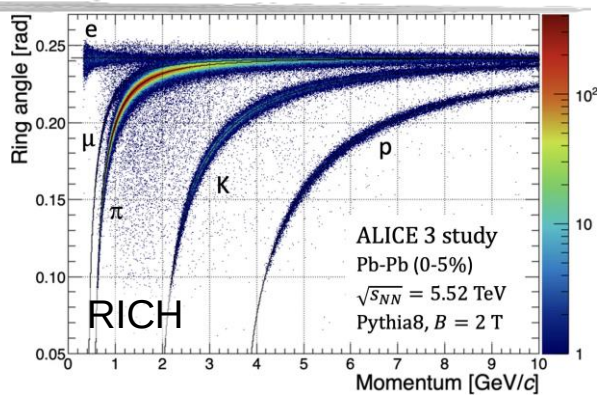
Time of Flight

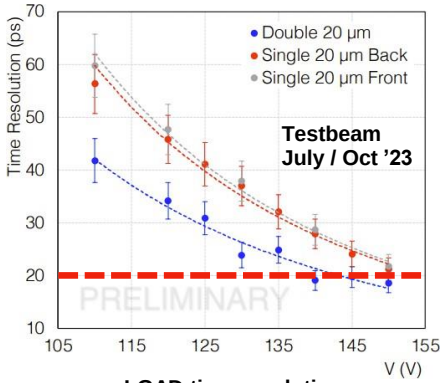
- Time resolution target: 20 ps
- Low material budget 1-3% X_0/layer
- Total surface: ~45 m^2
- **R&D streams:**
  - SiPM coated with different resins (type, thickness)
  - Single and double LGADs
  - 50 µm thick CMOS-LGAD (ARCADIA / MADPIX)

RICH

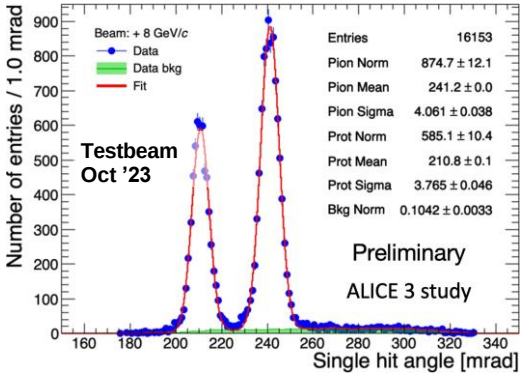
- Extending PID to higher p_T
- Aerogel radiator
  - n = 1.03 (barrel)
  - n = 1.006 (forward)
- Total SiPM area: ~ 35 m^2
- **R&D challenge:** SiPM radiation hardness







LGAD time resolution

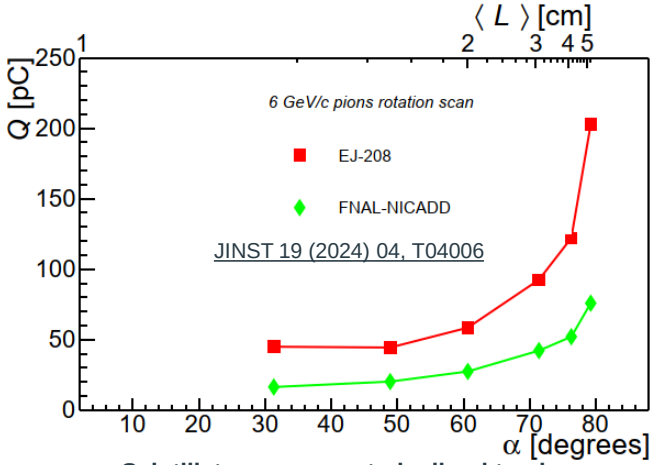


Cherenkov angle of pions and protons:
4 mrad angular resolution

ALICE 3: Muon and Photon ID

Muon IDentification (MID) at central rapidity

- Optimised for charmonia reconstruction down to zero p_T
- ~ 70 cm steel hadron absorber
- 2 layers with 5 x 5 cm^2 pad size
- Baseline: plastic scintillator bars w/ wave-length shifting fibres + SiPMs
- Options: RPCs or MWPCs
- Test beam results: R. Alfaro et al. JINST 19 (2024) 04, T04006



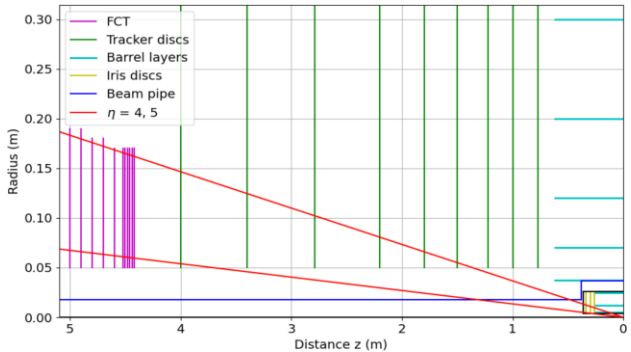
Scintillator response to inclined tracks

Large acceptance Electromagnetic Cal (ECal)

- 2π coverage
- Sampling calorimeter, $O(100)$ layers of 1 mm Pb + 1.5 mm plastic scintillator
- $PbWO_4$-based high energy-resolution segment

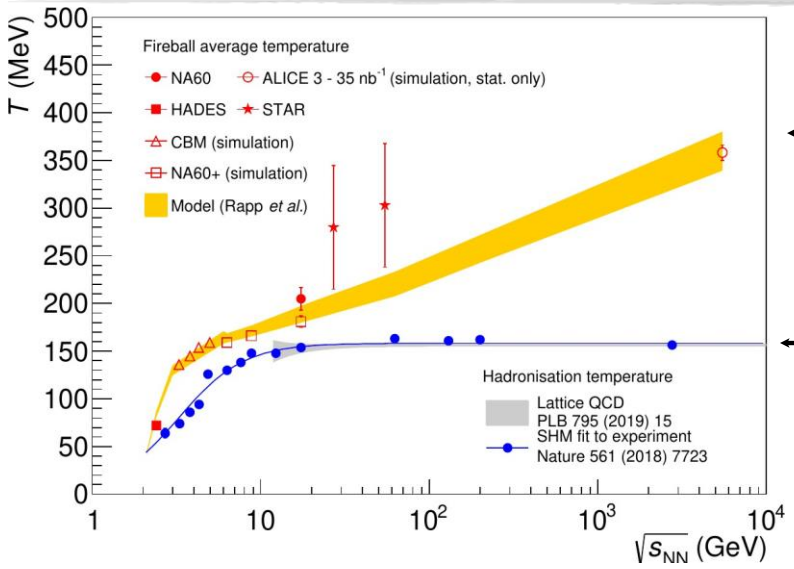
Forward Conversion Tracker (FCT)

- Thin tracking disks in $4 < \eta < 5$ in a dedicated dipole magnet
- Very low pT photons (< 10 MeV/c)



Schematic drawing of the FCT

Accessing the QGP temperature

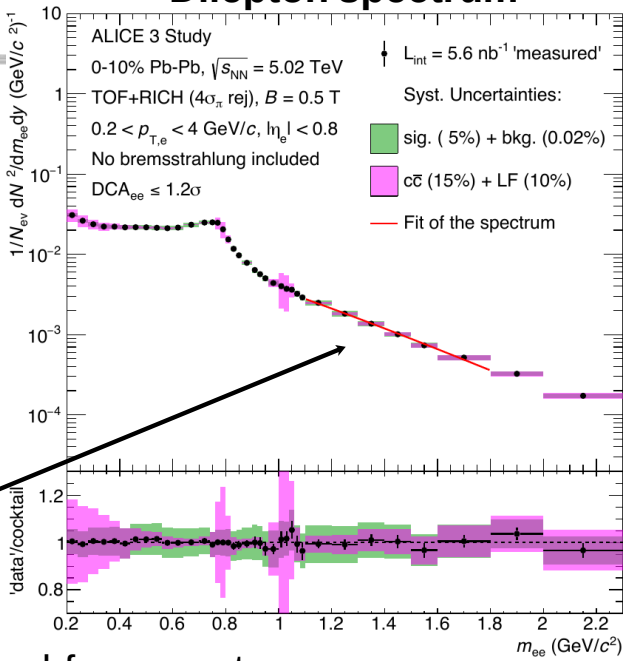


← **Projected temperature from electromagnetic radiation**

← **Temperature from hadron abundances 'chemical freeze-out'**

The slope measures the temperature

Dilepton spectrum



- Light flavour hadron abundances consistent with common chemical freeze-out
  - Limiting temperature: ~155 MeV
- Electromagnetic radiation gives access to temperature of QGP before hadronisation
- Dilepton pairs provide an unique probe for the time evolution of T
  - Temperature expected at the LHC: 300-400 MeV

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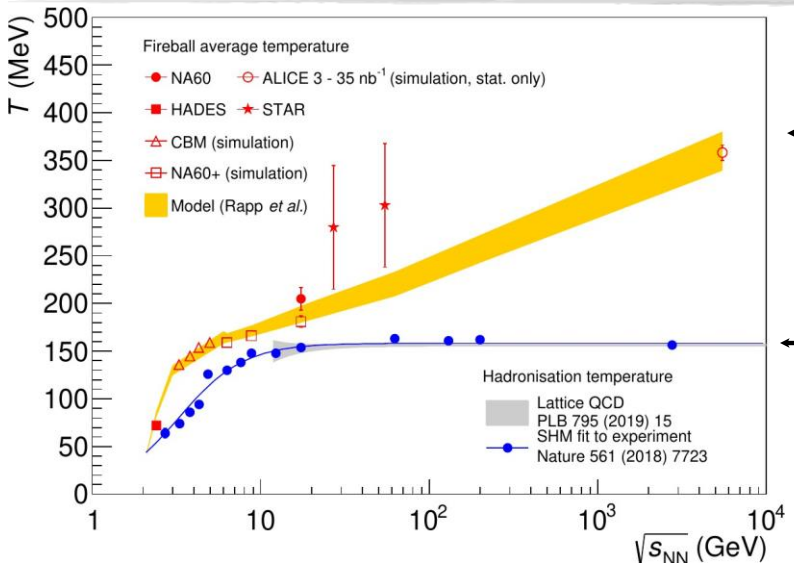

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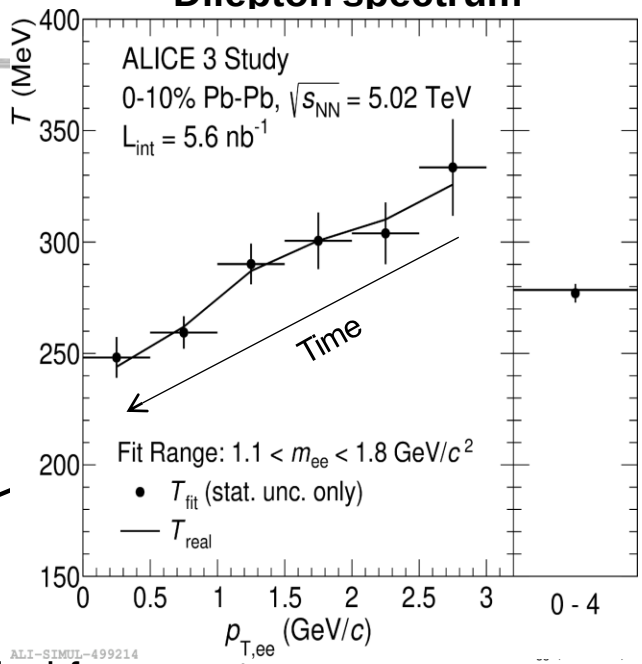

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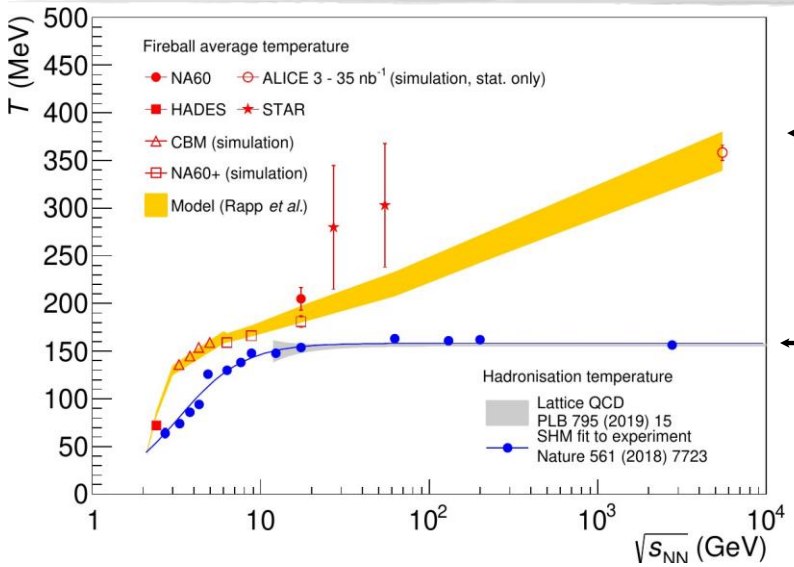

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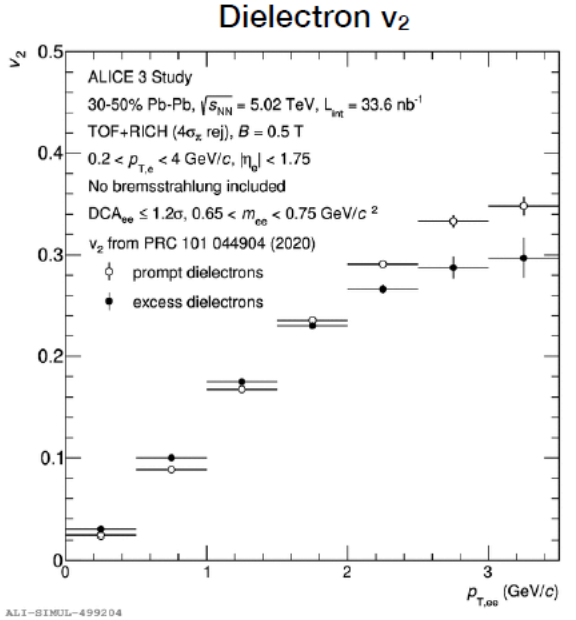

Unique access to **time evolution of temperature**
via v_2, p_T dependence of T

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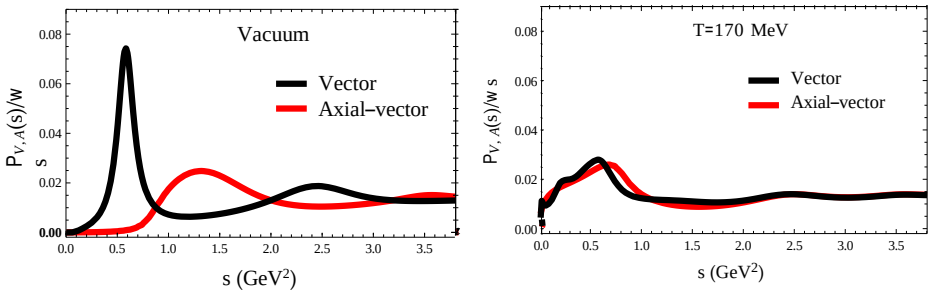
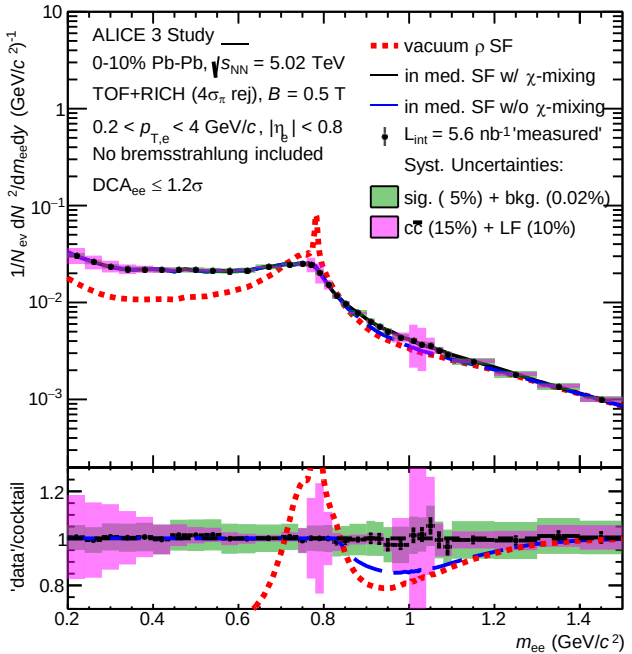
Chiral symmetry restoration: $\rho - a_1$ mixing

- Spontaneous breaking of chiral symmetry generates **hadron masses in QCD**
  - Large mass difference between
    ρ(770 MeV) and a_1(1260 MeV)
- **Chiral symmetry restored in QGP**
  - ρ and a_1 degenerate: mixing
- ALICE 3 provides experimental access to chiral symmetry restoration mechanism

ρ and a_1 spectral function



Hohler and Rapp, PLB 731,103

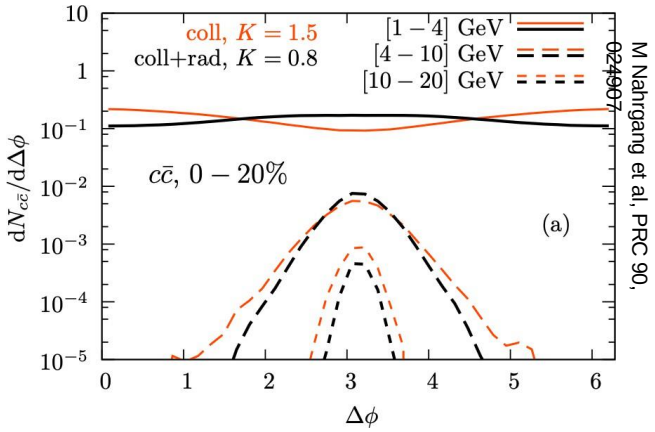


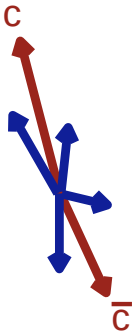
$\rho - a_1$ mixing affects mass spectrum above ρ peak

ALICE 3 provides necessary precision

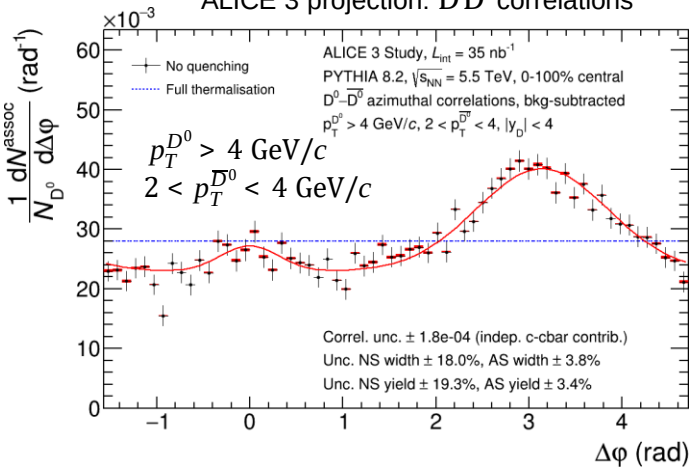
Heavy-flavour diffusion in the QGP: $D\bar{D}$ azimuthal correlations

Charm azimuthal correlations





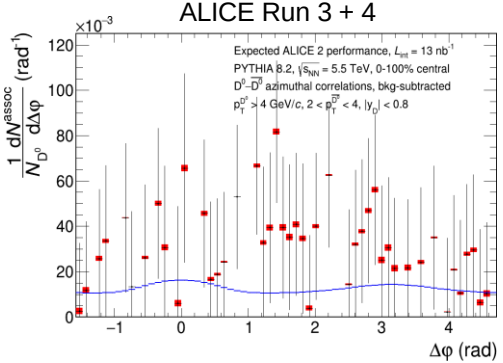
ALICE 3 projection: $D\bar{D}$ correlations



- Angular decorrelation directly probes QGP scattering
  - Signal strongest at low p_T
- Very challenging measurement:
  - need good purity, efficiency and η coverage

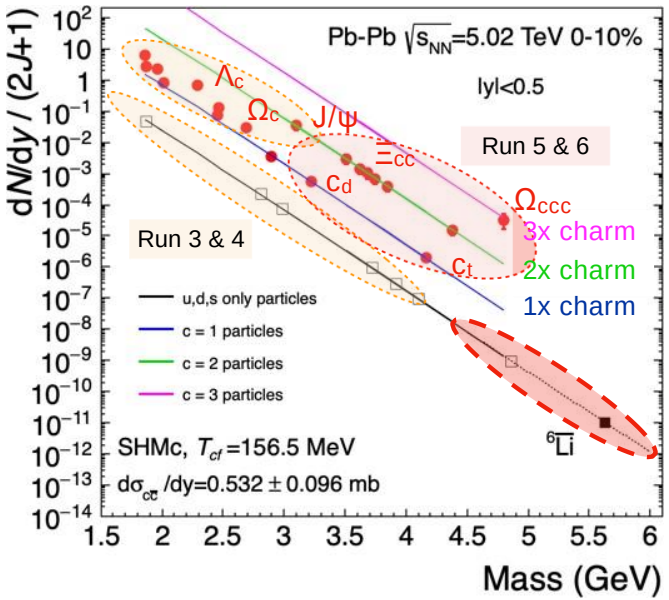
→ **heavy-ion measurement only possible with ALICE 3**

ALICE Run 3 + 4



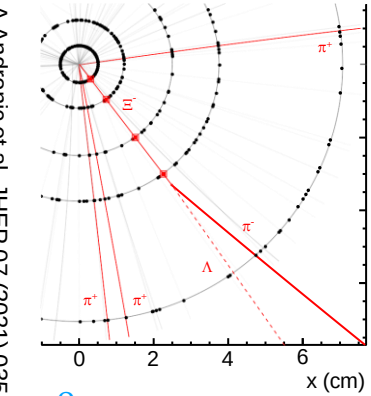
Hadron formation: multi-heavy-flavour hadrons

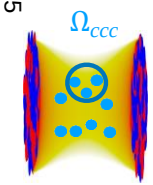
Yield vs mass



A Andronic et al, JHEP 07 (2021) 035

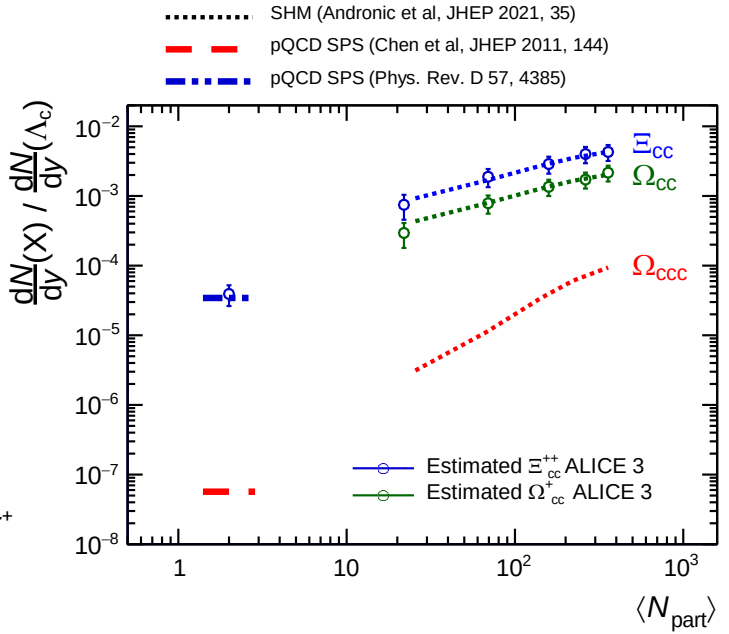
Strangeness tracking





$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+$$

$$\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$$



Multi-charm baryons: unique probe of hadron formation

Statistical hadronisation model: **very large enhancement** in AA

- Specific relation between yields: g_c^n for *n*-charm states

ALICE 3: unique experimental access to multi-charm baryons

Summary

- ALICE has an ambitious upgrade program, aiming at furthering our understanding of the QGP in particular with precise measurements of heavy flavour and electromagnetic radiation

- **LS3 (2026-2028):** new upgrades for LHC Run 4 approaching construction phase
  - **FoCal**: γ, π^0, jets in the forward region to constrain the gluon nPDF at low *x*
  - **ITS3**: ultra-thin, truly cylindrical, wafer-scale MAPS
    improved secondary vertex reconstruction

- **Beyond Run 4:** ALICE 3 to fully exploit the HL-LHC as a heavy-ion collider until Run 6
  - Novel, silicon-based detector concept
  - Pioneering several R&D directions with broad impact on future HEP experiments (e.g. FCC-ee)
  - Enabling precision measurements of dileptons, (multi-)heavy-flavour hadrons
    and hadron correlations