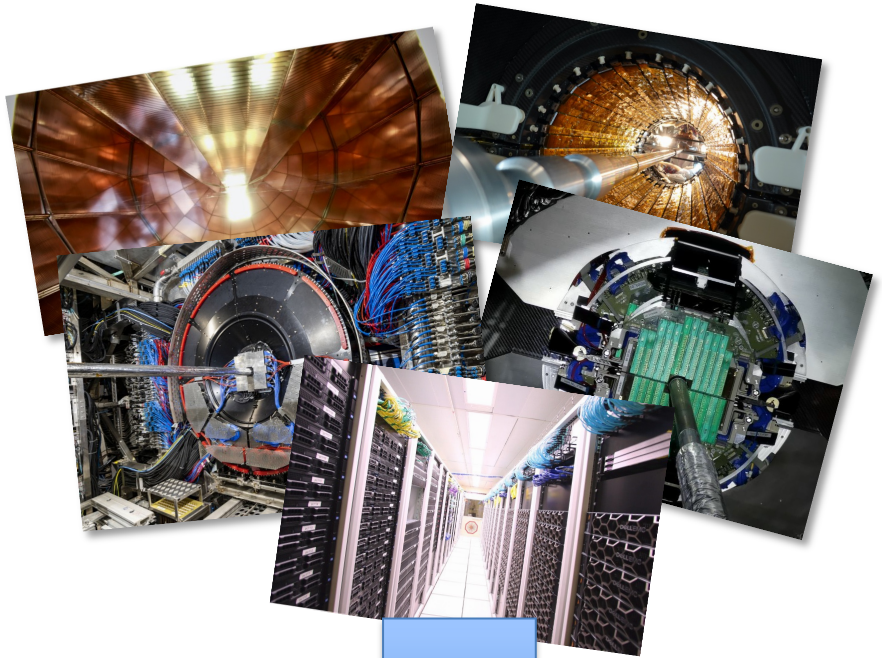
ALICE Upgrades

Antonio Uras
IP2I Lyon – CNRS/IN2P3

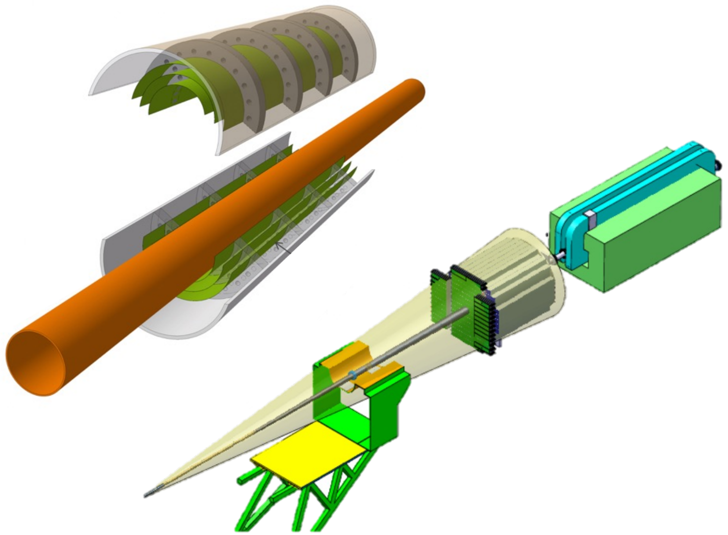
15th FCPPN/L Workshop
Bordeaux – 10-14 June 2024

ALICE Upgrade Timeline

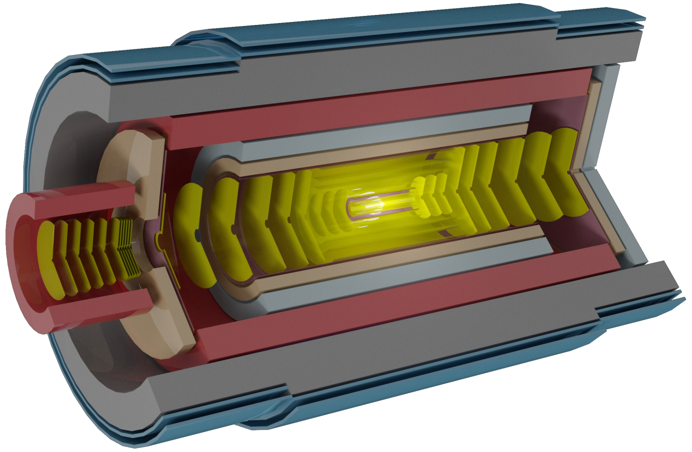
LS2: ITS2, MFT, TPC, FIT, O^2

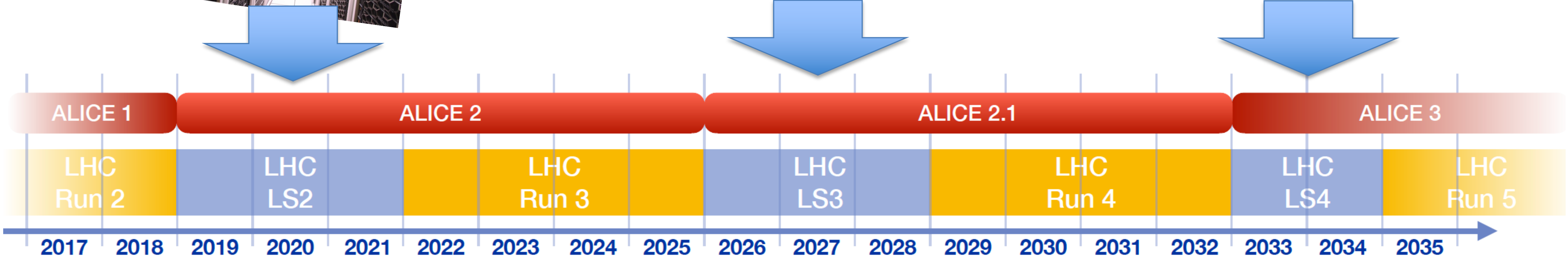


LS3: ITS3, FoCal

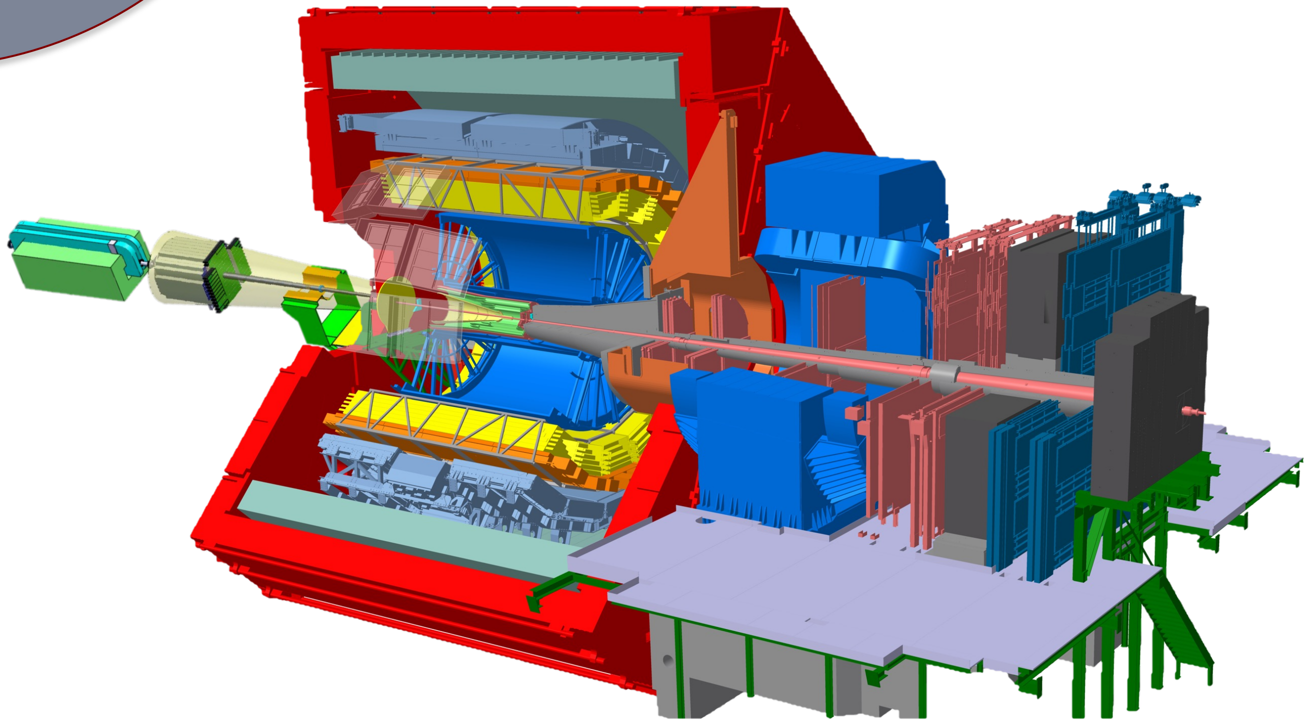


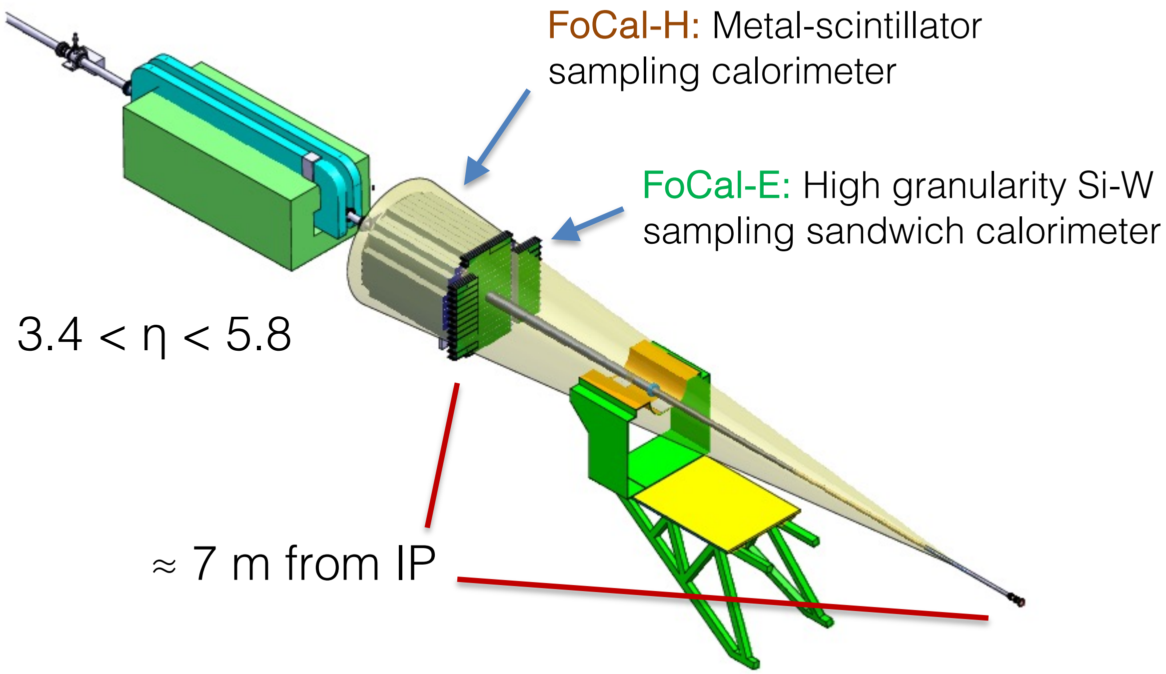
LS4: ALICE 3





FoCal: glue at the smallest x in Run 4





Forward physics at LHC provides an opportunity to study the low-x region

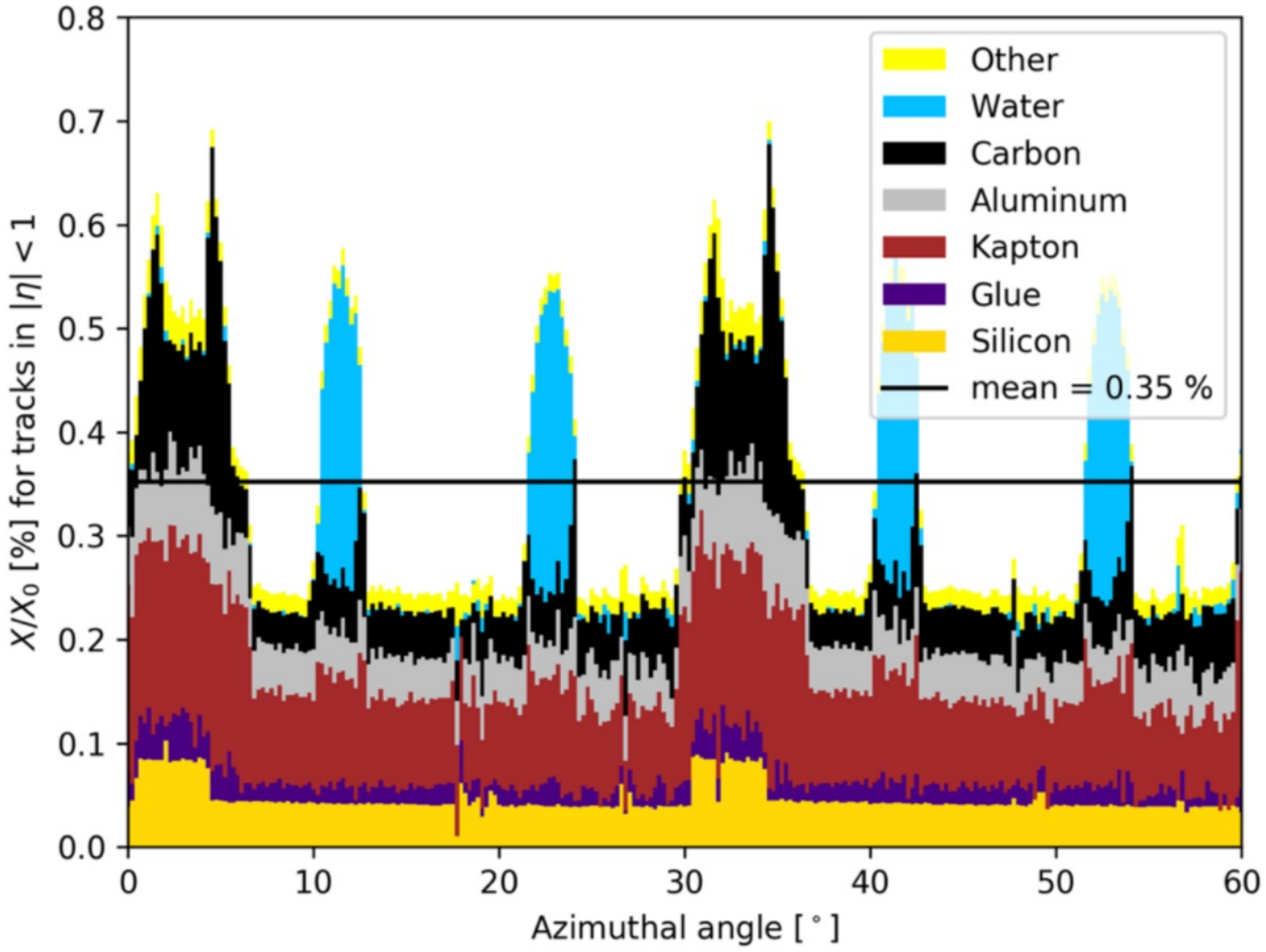
- Access to non-linear QCD mechanisms: investigate the onset of possible of gluon saturation (CGC)
- Quantify and constrain modifications of gluon (n)PDFs at small-x and Q^2
- Direct photons provide a more direct access to the low-x region (10^{-5})

TDR approved (CERN-LHCC-2024-003)

Towards Run 4: ITS3, a truly Cylindrical Inner Tracker

ITS3: replacing the 3 innermost layers of ITS2 with a next-generation vertex detector based on truly cylindrical layers (bent, wafer-scale CMOS sensors)

- **Pointing resolution $\propto r_0 \cdot \sqrt{x/X_0}$**
- Silicon only contributes to 15 % of the material budget for the ITS2 layers
- Pointing resolution can be improved by removing material in the first layers
  - Move from water to air cooling
  - Integrate power and data on chip
  - Self-supporting structure
- **Enhanced precision in the identification of HF signals, and rejection of displaced background for prompt signals (e.g. low-mass dielectrons)**



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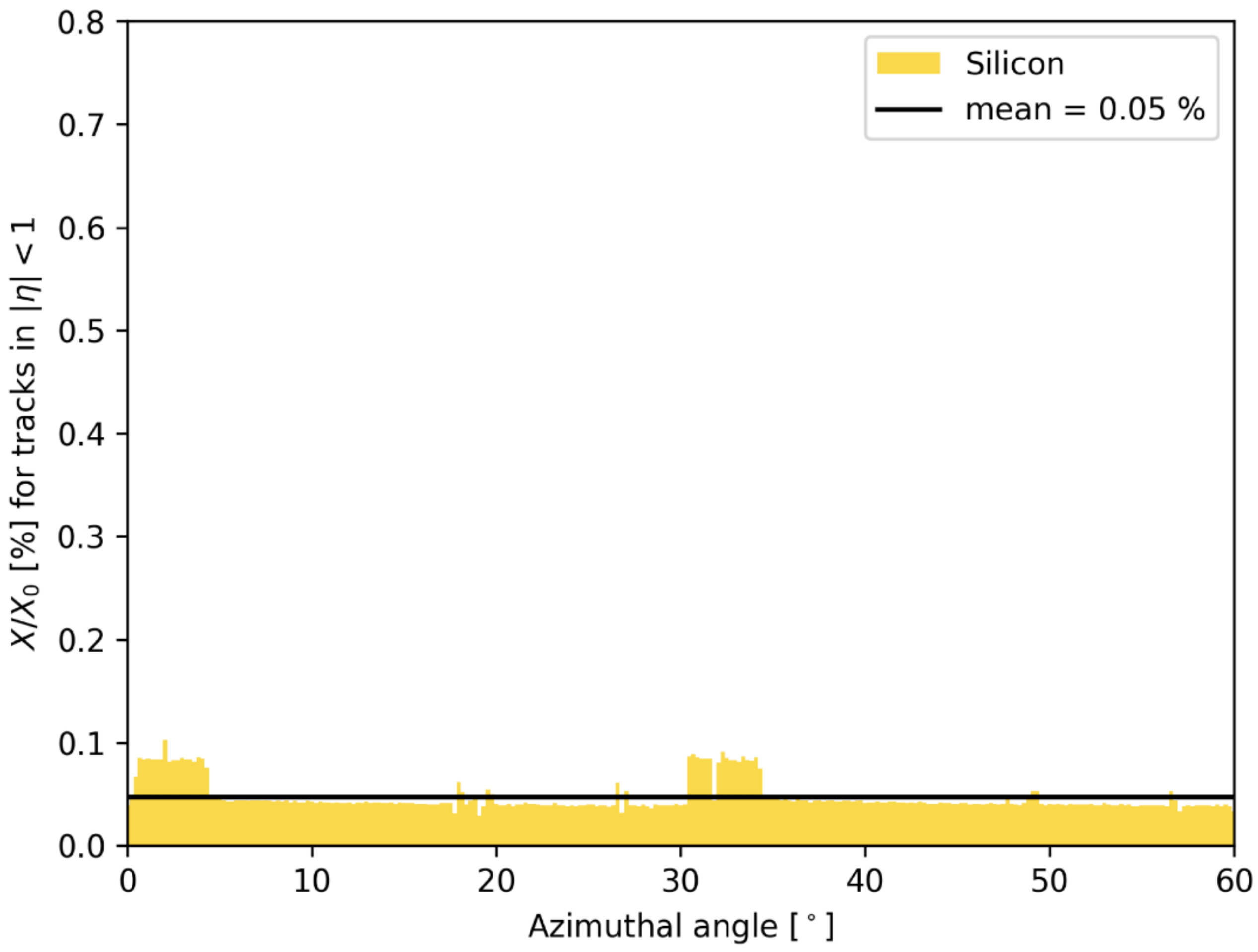
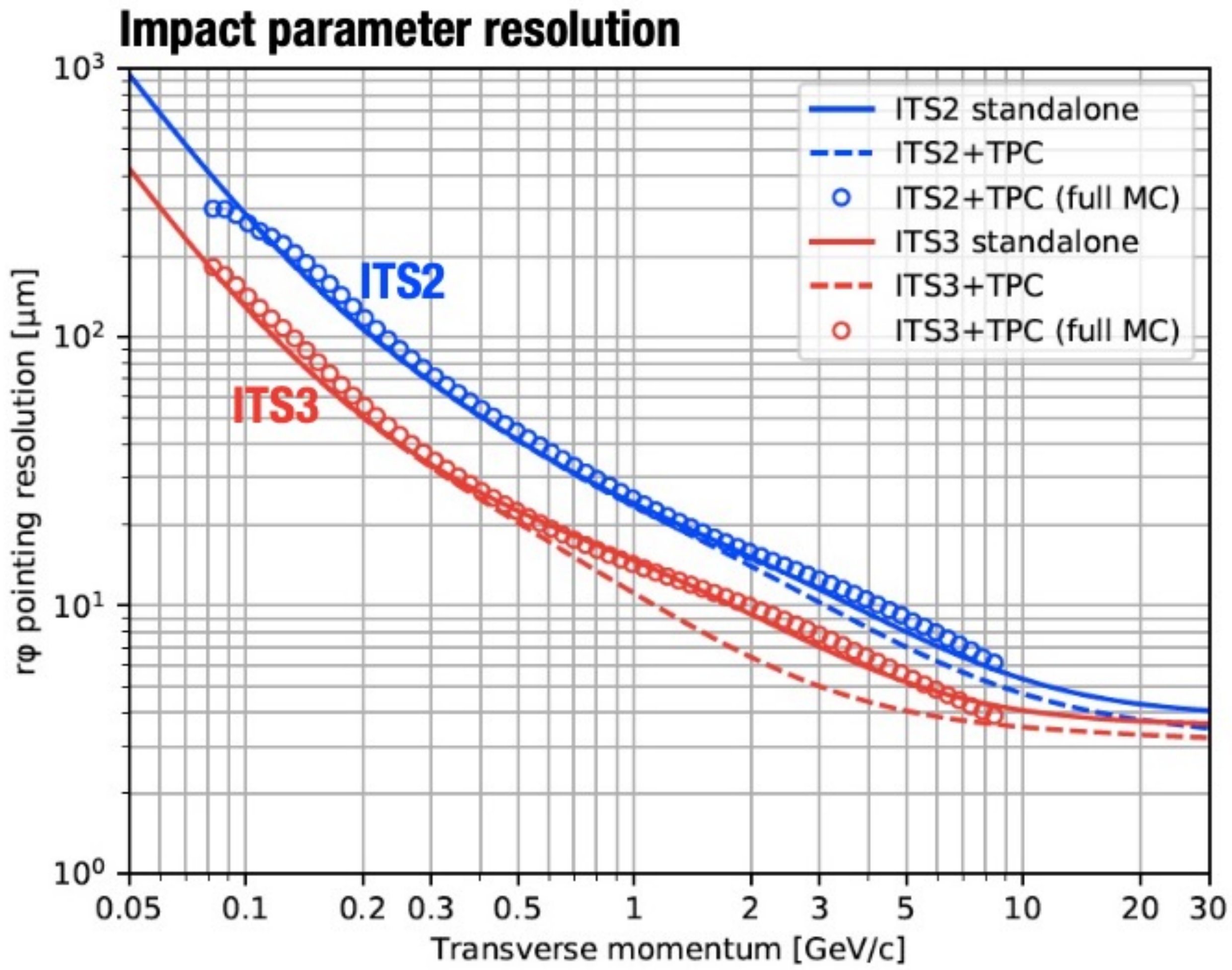
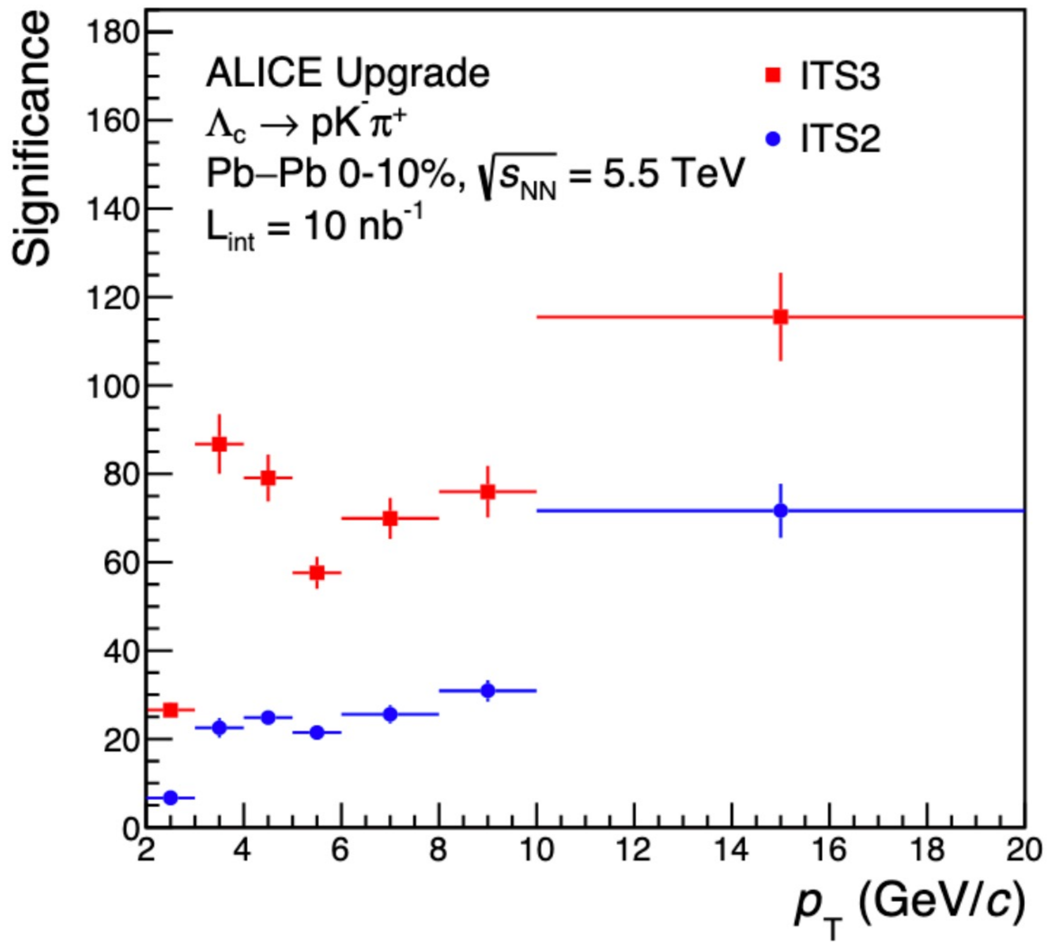


ITS3 design will allow to get closer to the IP w.r.t. ITS2: innermost layer from 22 mm to 18 mm (beam pipe to be replaced around the IP) → **further improvement in the vertex resolution**





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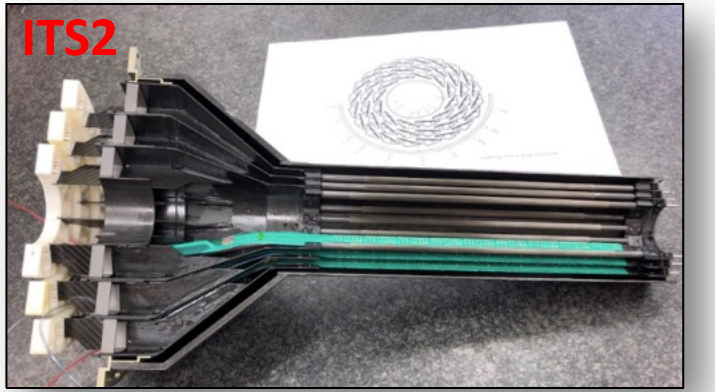
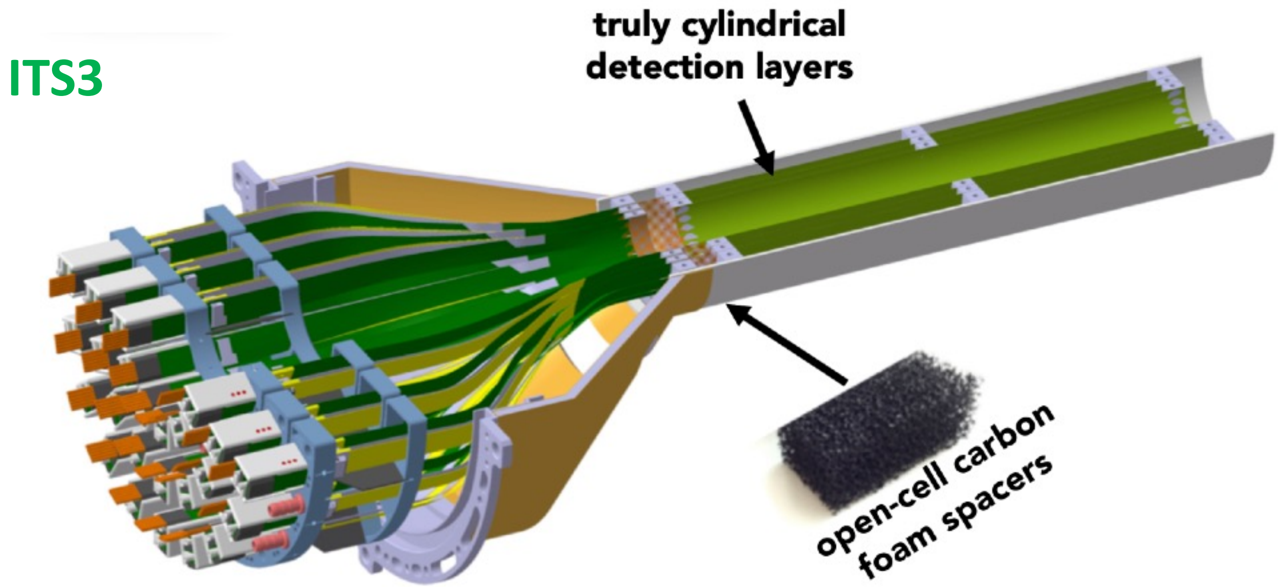
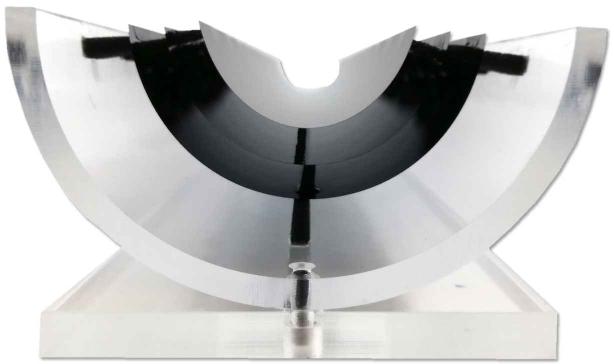




ITS3 Concept

- 280 mm long sensor ASICs out of 300 mm long stitched wafers (2 halves × 3 layers)
- 20-40 µm (0.02 - 0.04% X_0), bent shape with R = 18/24/30 mm
- Carbon foam rib to hold ASICs in place + air cooling



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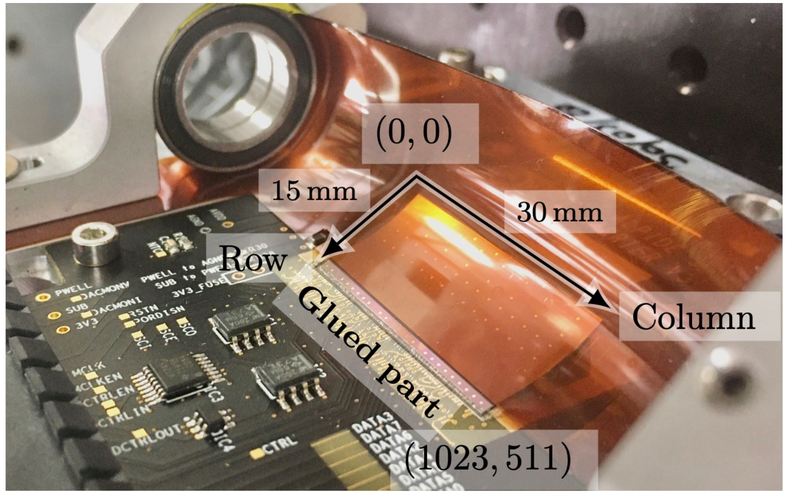
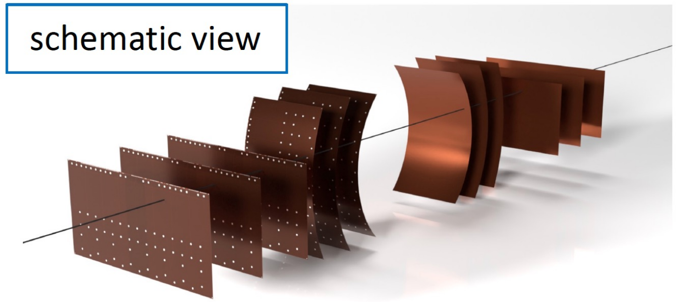
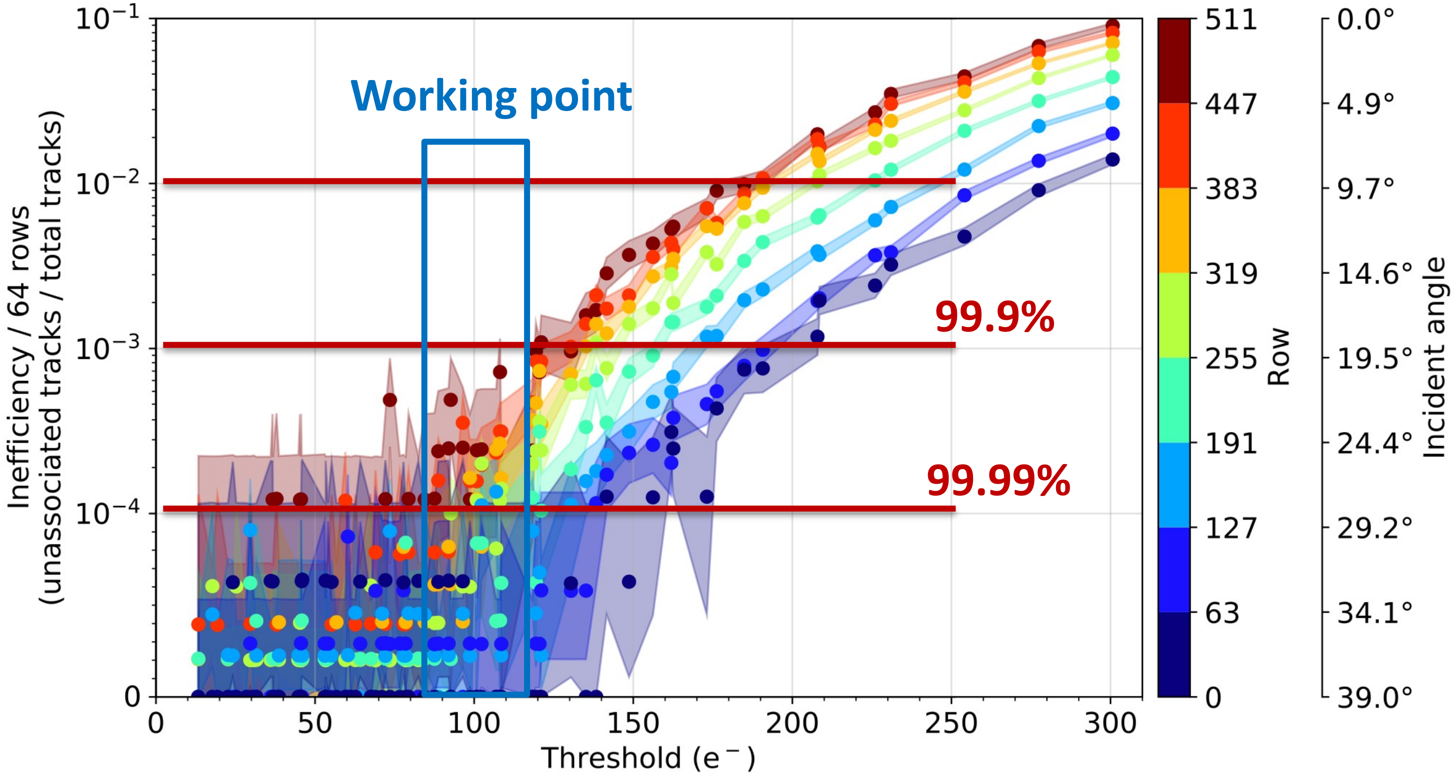




ALPIDE telescope used for the tests

- Bent ALPIDE efficiency > 99.9%
- Digital pixel test structure efficiency > 99 %

(https://doi.org/10.1016/j.nima.2021.166280)



Engineering Run 1 stitched test sensor

- Electrical tests in the lab
- Beam test: successful read out
- Determine yields, optimise design → Engineering Run 2 (2025)

Extreme QCD in Laboratory after Run4

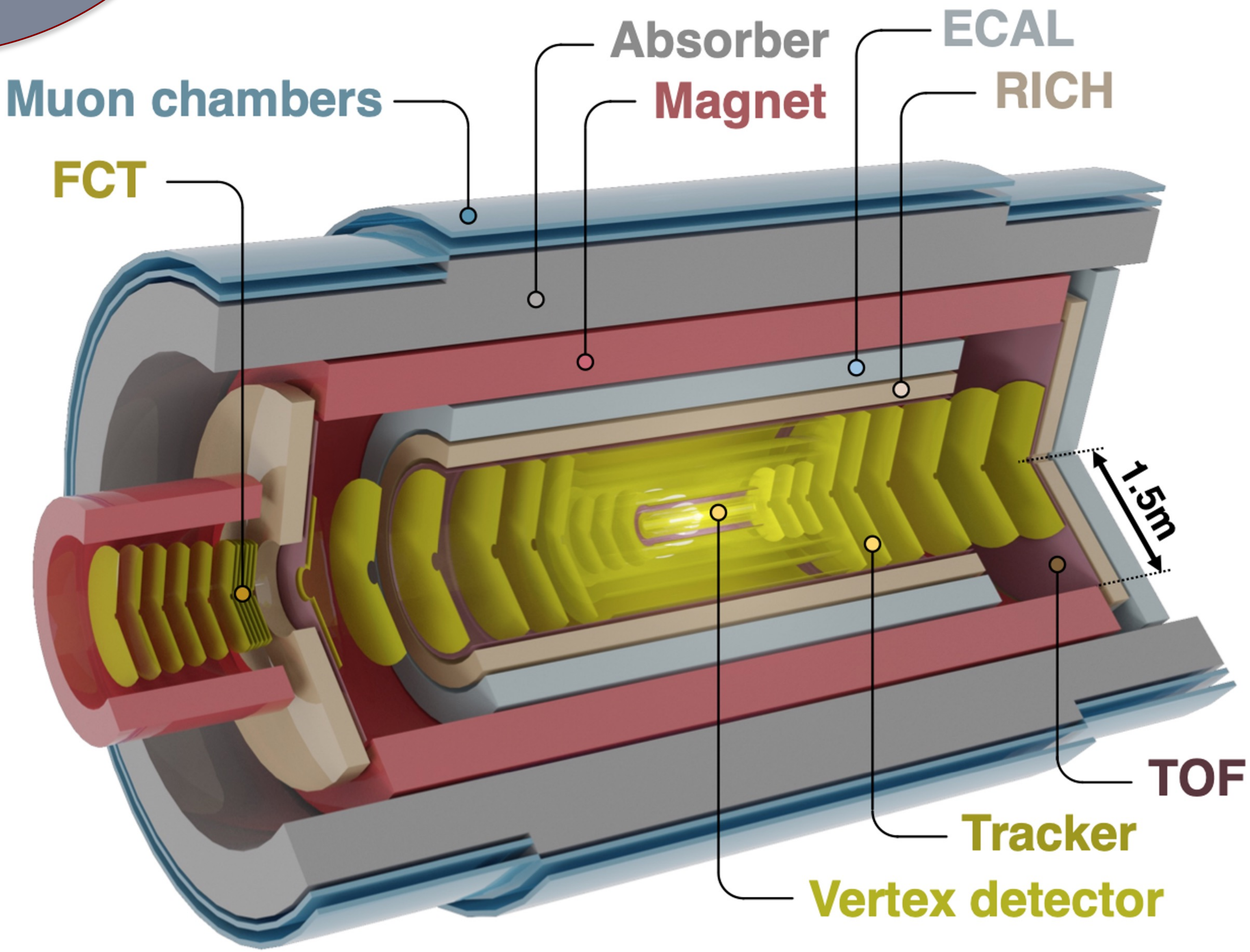
Key QGP findings in last 20 years from RHIC and LHC

- Evolves as almost perfect fluid that quenches jets
- Produces light hadrons in apparent thermal equilibrium
- Readily couples with heavy quarks
- Collective effects found in high-multiplicity events in small systems: QGP droplets or multiplicity-driven mechanisms?

What is ALICE 3 designed to discover and explore?

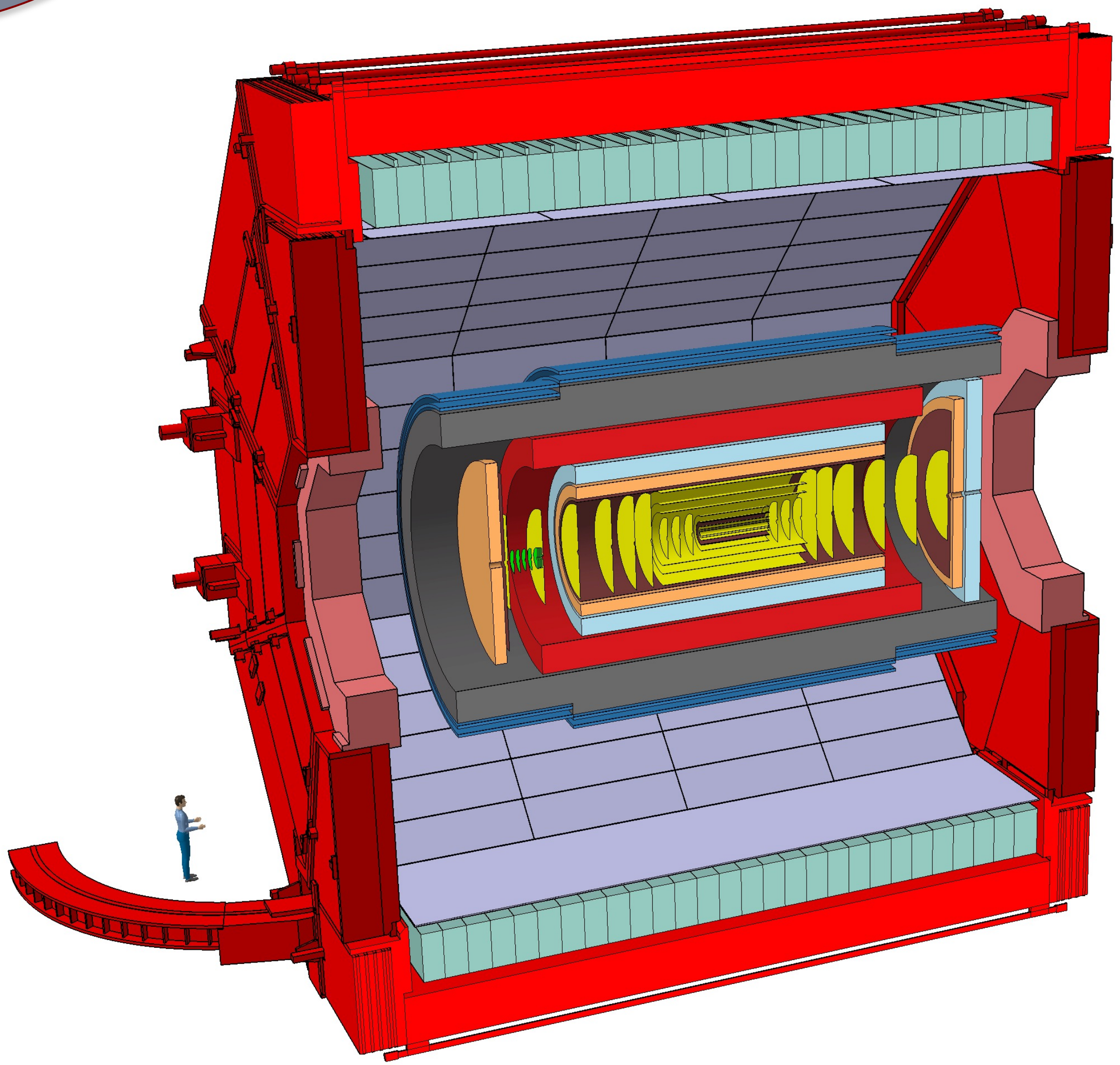
- QGP temperature evolution and when "local" equilibrium achieved
- Precision measurements on heavy quark diffusion and hadronization in the QGP
- Nature of QCD phase transition at $\mu_b \approx 0$
- Rare hadron production mechanisms and hadronic interactions
- Beyond Standard Model searches…

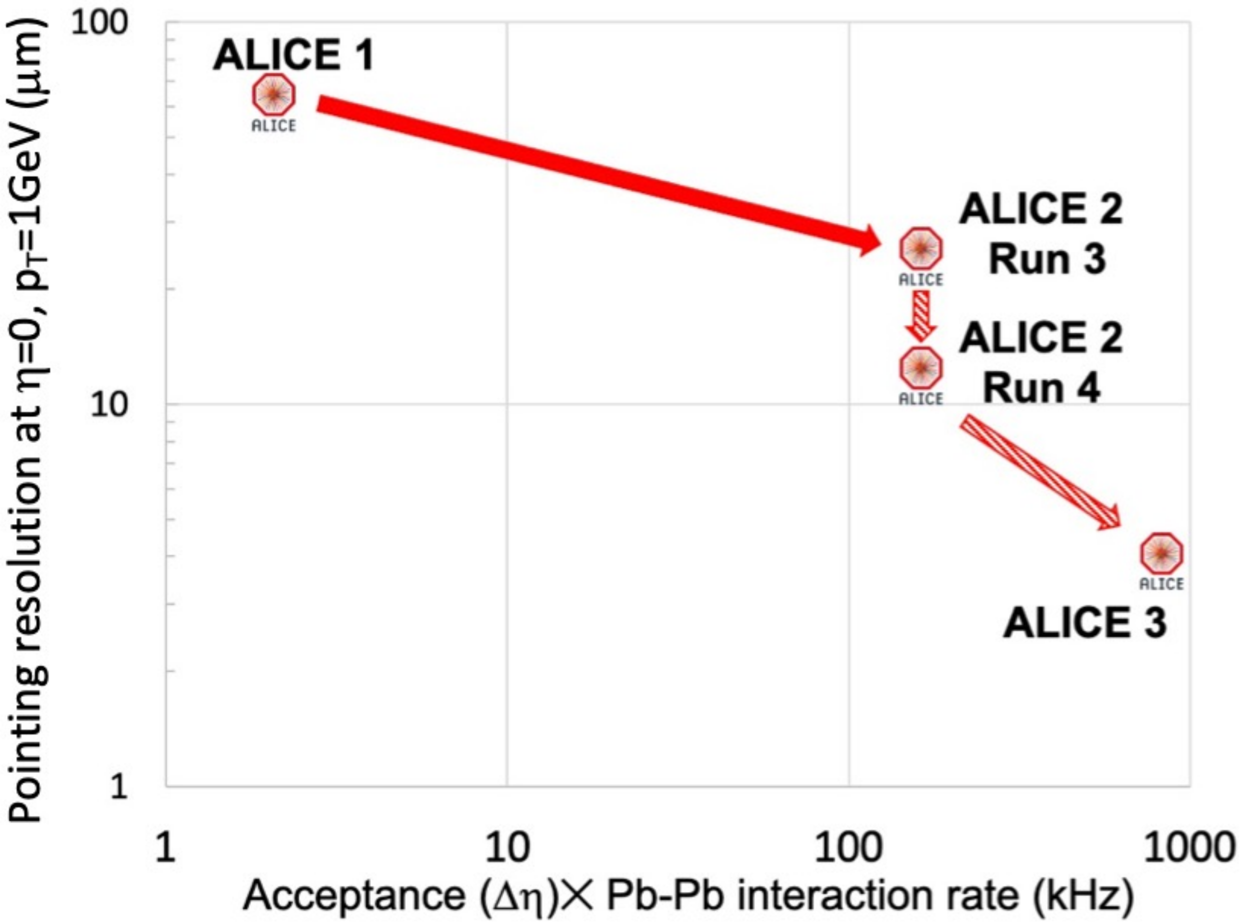
ALICE 3: a new Heavy-Ion experiment for Run 5 and beyond



- **Compact and lightweight all-silicon tracker with a restractable vertex detector**
- **Superconducting magnet system**
- **Particle identification down to vanishing p_T over 6 > units of pseudorapidity**
- **Continuous readout and online processing**

Detector Setup



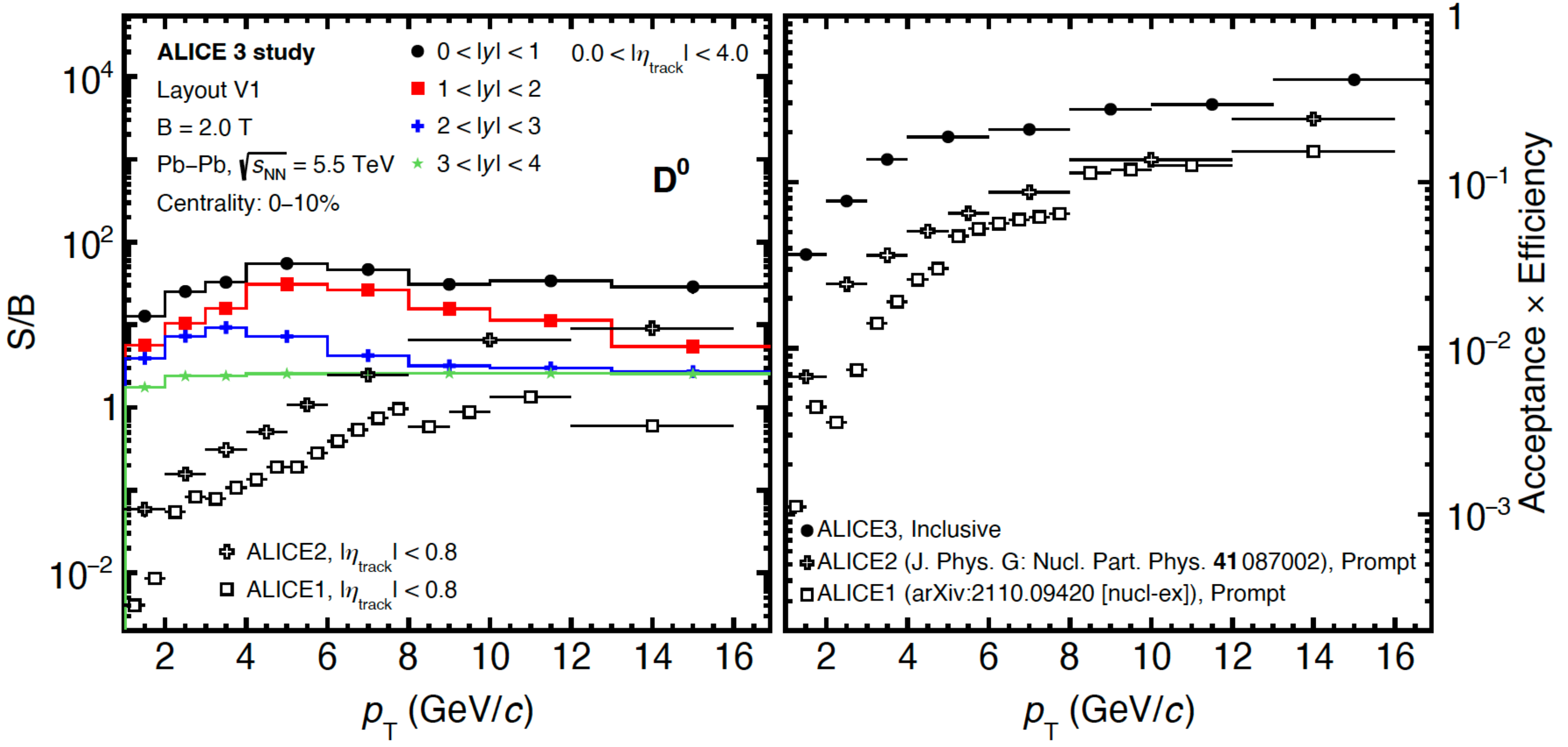


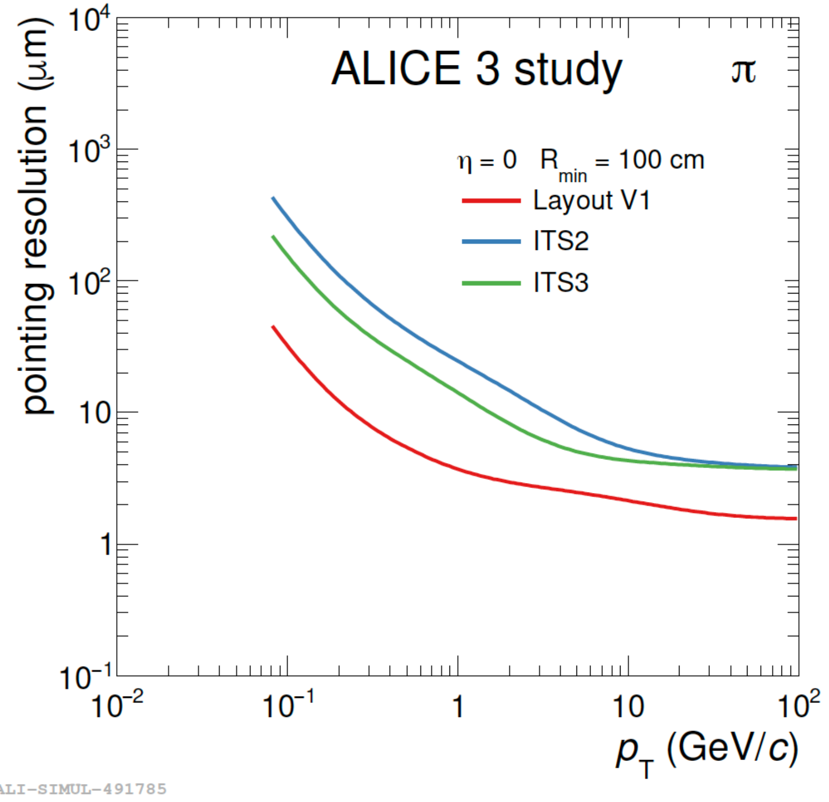
Heavy-Flavour Benchmark: D^0

Excellent pointing resolution and PID: **large S/B and efficiency** 10-20 × w.r.t. Run 3 (i.e. ITS2) for $p_T < 4$ GeV/c

Experimental benchmark giving access to the measurement of:

- Beauty meson and baryon v_2
- DD correlations
- Multi-charm baryons

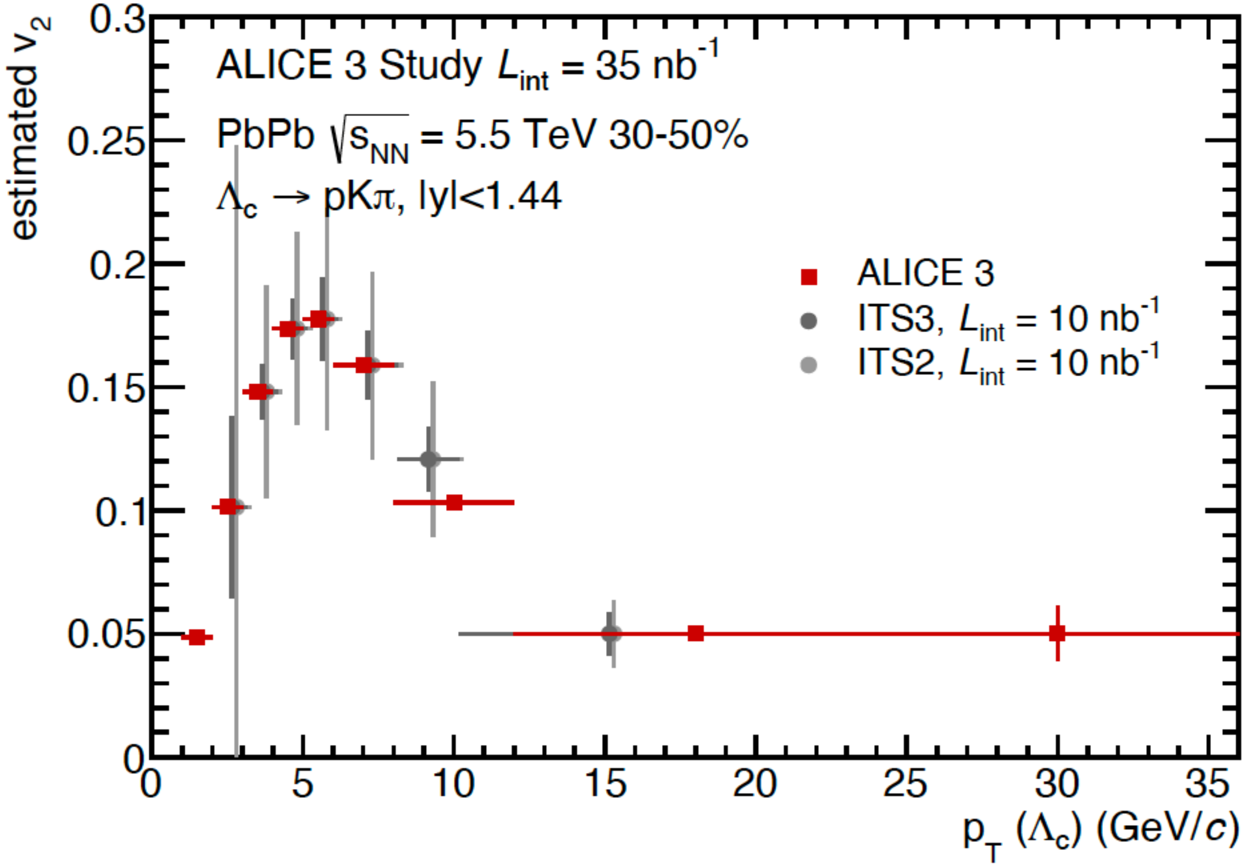


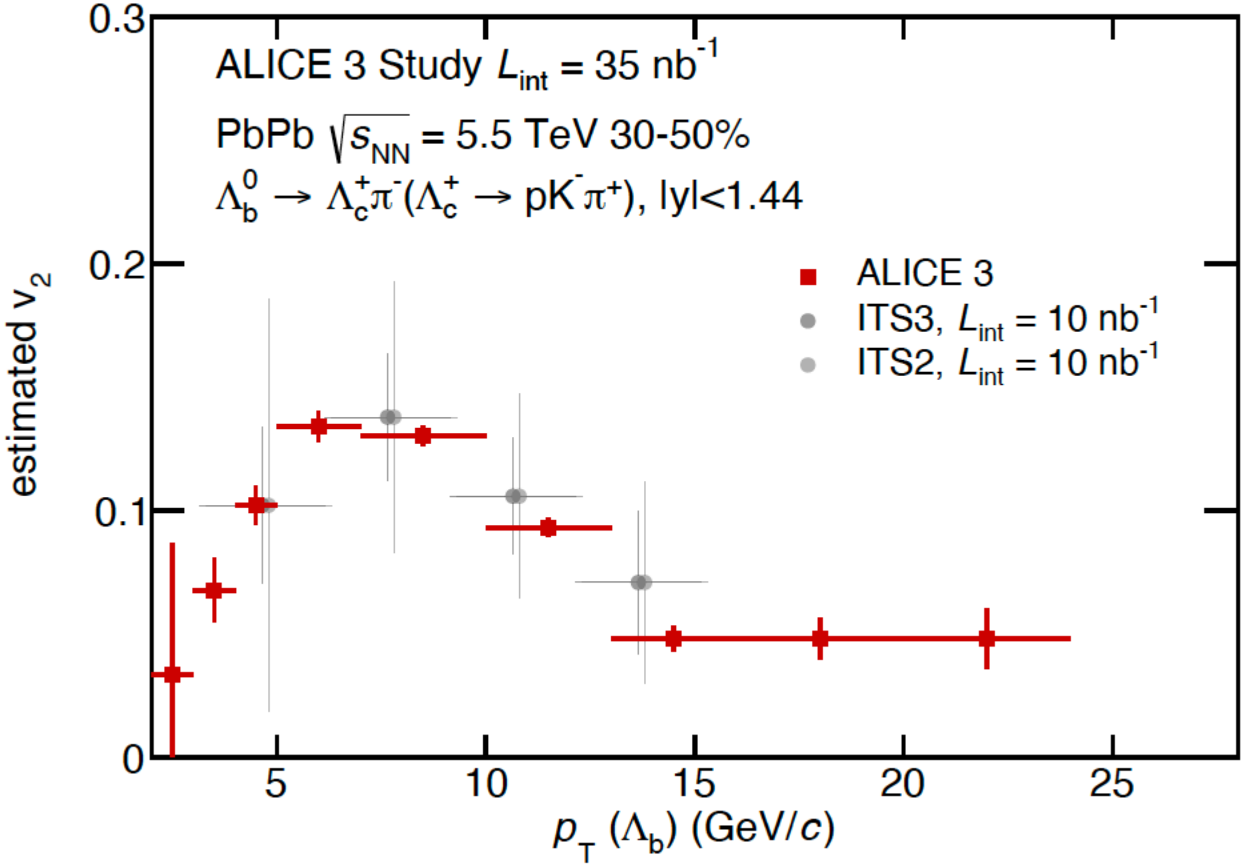


HF Baryon v_2

Goal: disentangle effects of quark transport and hadronization

- Expect beauty thermalization slower than charm — does this affect hadronization?
- First measurements of Λ_b coupling to hydrodynamic flow (via v_2 parameter) in Run 3 and 4
- Need ALICE 3 performance for precision measurement

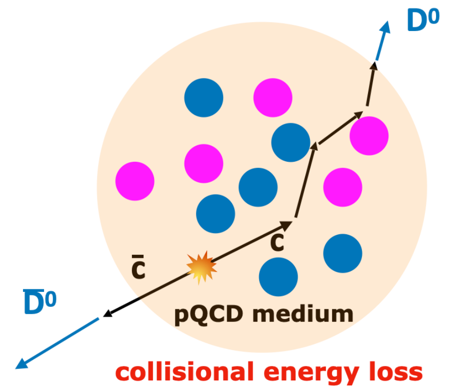




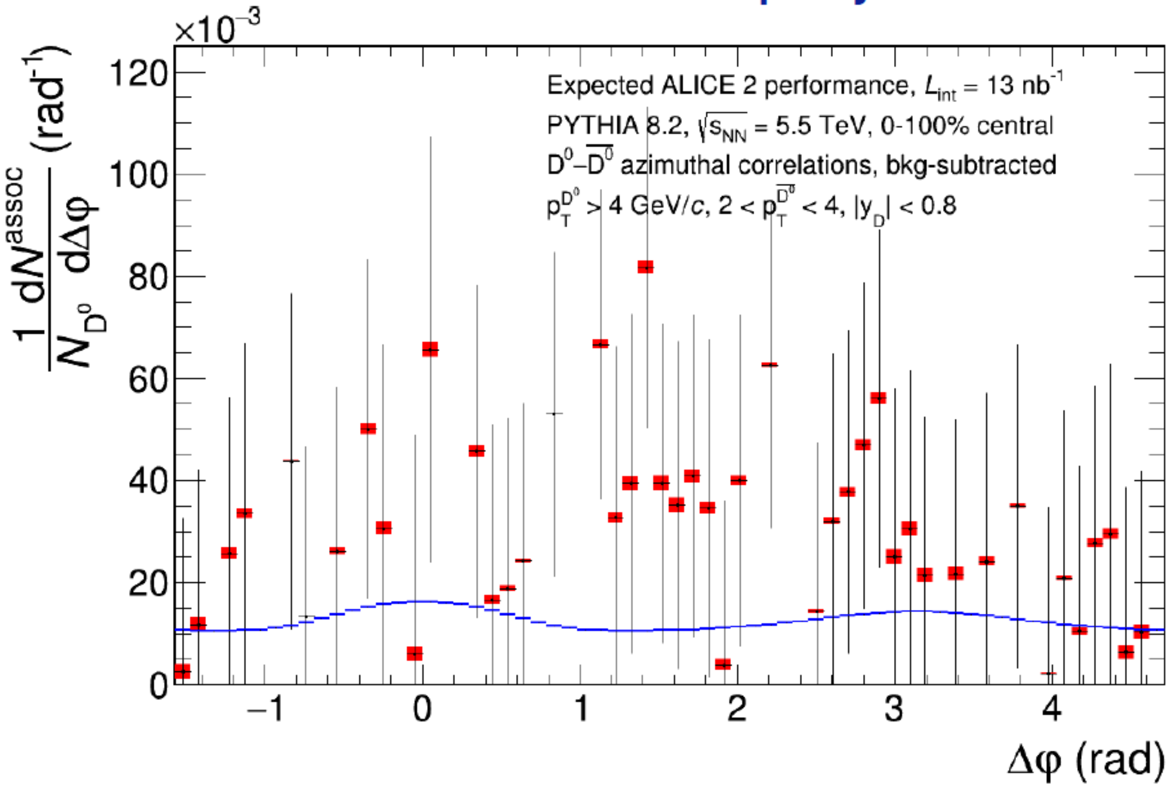
$D\bar{D}$ Azimuthal Correlations

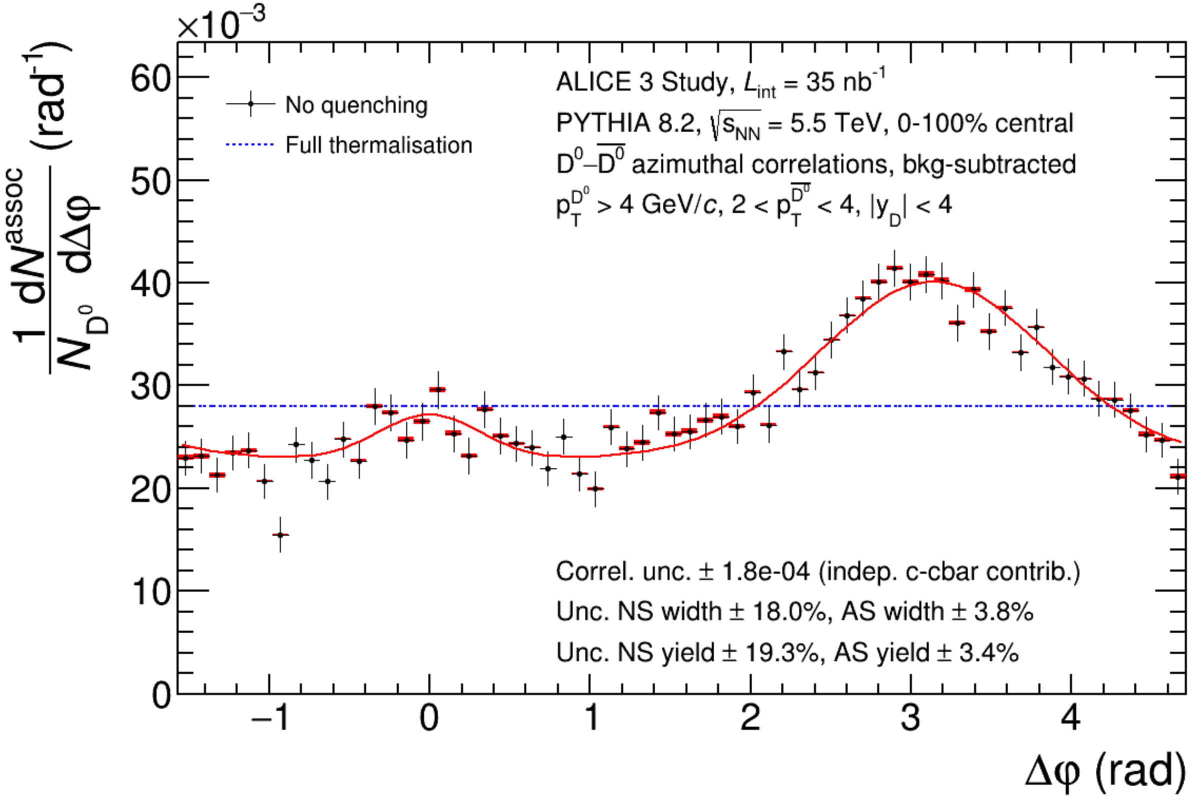
Goal: measure angular (de)correlations — direct probe of QGP scattering

- Very challenging measurement: need good purity, efficiency and η coverage
- Heavy-ion measurement only possible with ALICE 3



ALICE Run 3&4 projection

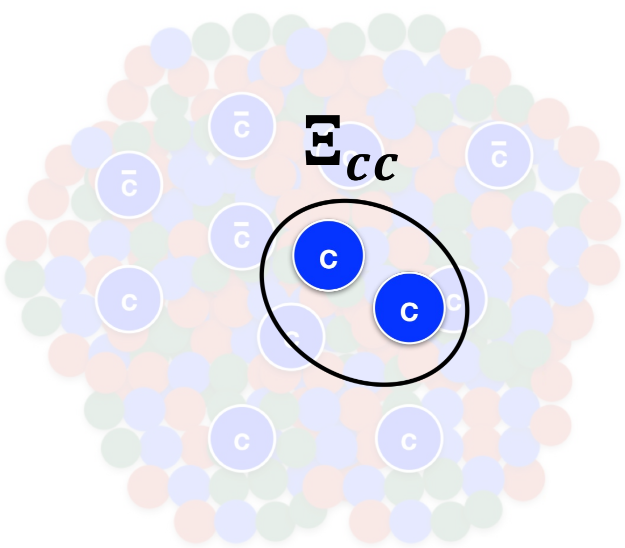




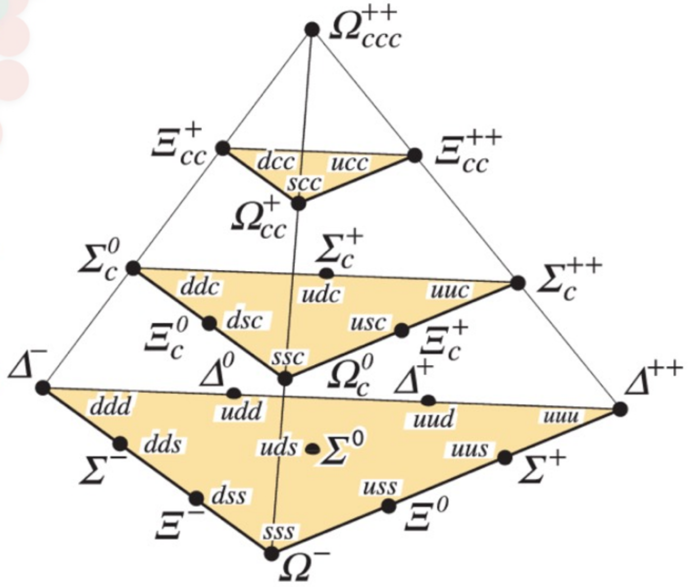
HF Hadronization Mechanisms

- In heavy-ion collisions, large increase of multi-HF baryons ($\approx \times 1000$) expected via coalescence **with charm quarks from different hard scatterings ($N_{ccbar} \approx 100$ in central Pb-Pb)**

Discrimination power on the role of the various hadronization mechanisms: multi-charm baryon factory (almost purely produced out of quark coalescence)



Ω_{cc} and Ω_{ccc} not yet observed. Ω_{ccc} may only be accessible in heavy-ion collisions



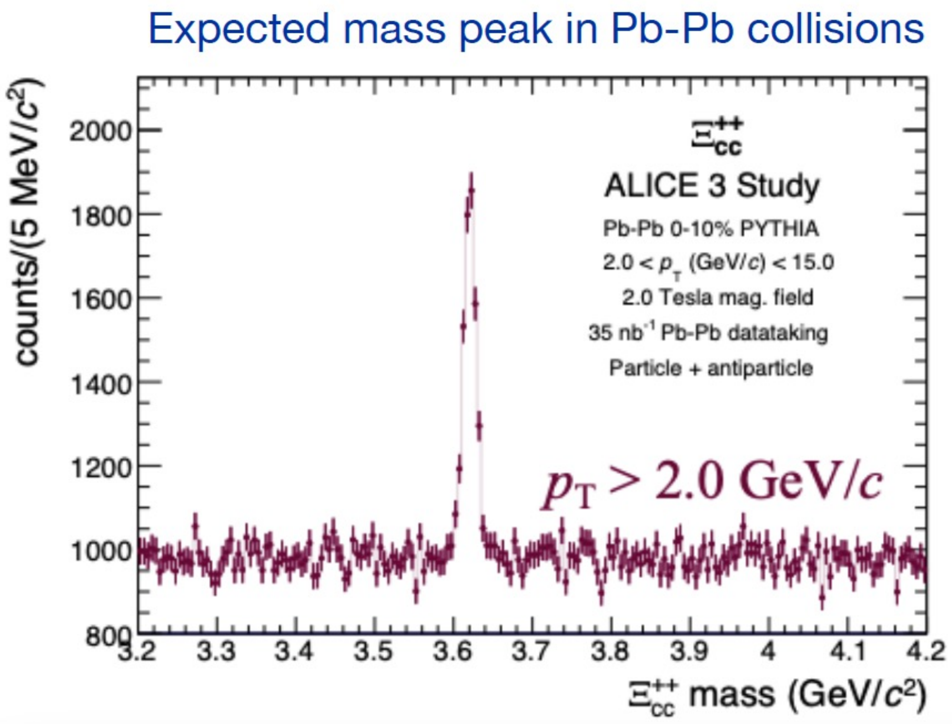
Challenging **reconstruction of cascade decay,** exploiting state-of-the-art vertexing and tracking

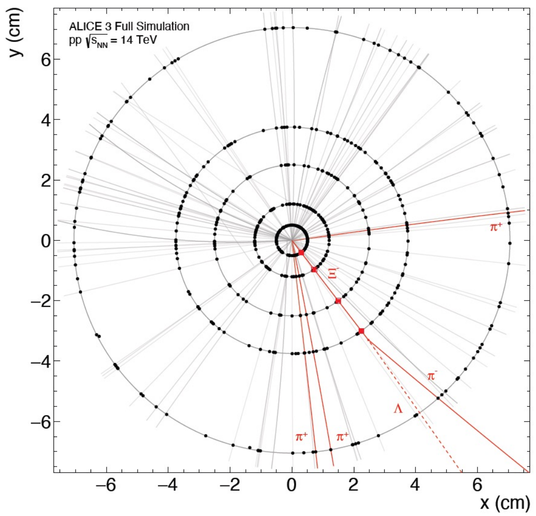
$$\Omega^{++}_{ccc} \to \Omega^{+}_{cc} + \pi^{+}$$
$$\Omega^{+}_{cc} \to \Omega^{0}_{c} + \pi^{+}$$
$$\Omega^{0}_{c} \to \Omega^{-} + \pi^{+}$$
$$\Omega^{-} \to \Lambda + K^{-}$$
$$\Lambda \to p + \pi^{-}$$

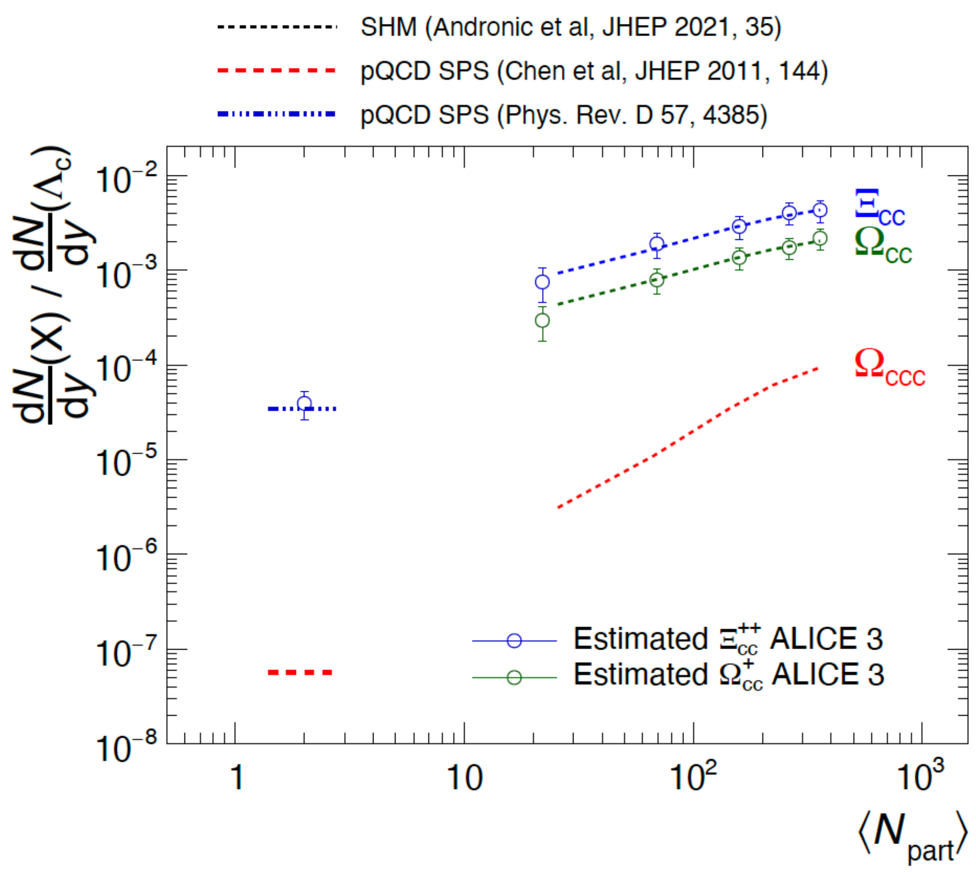
Multi-Charm Baryon Reconstruction

New technique: strangeness tracking with Ξ baryon provides high selectivity

$$\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+} + \pi^{+}$$
$$\Xi_{c}^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$







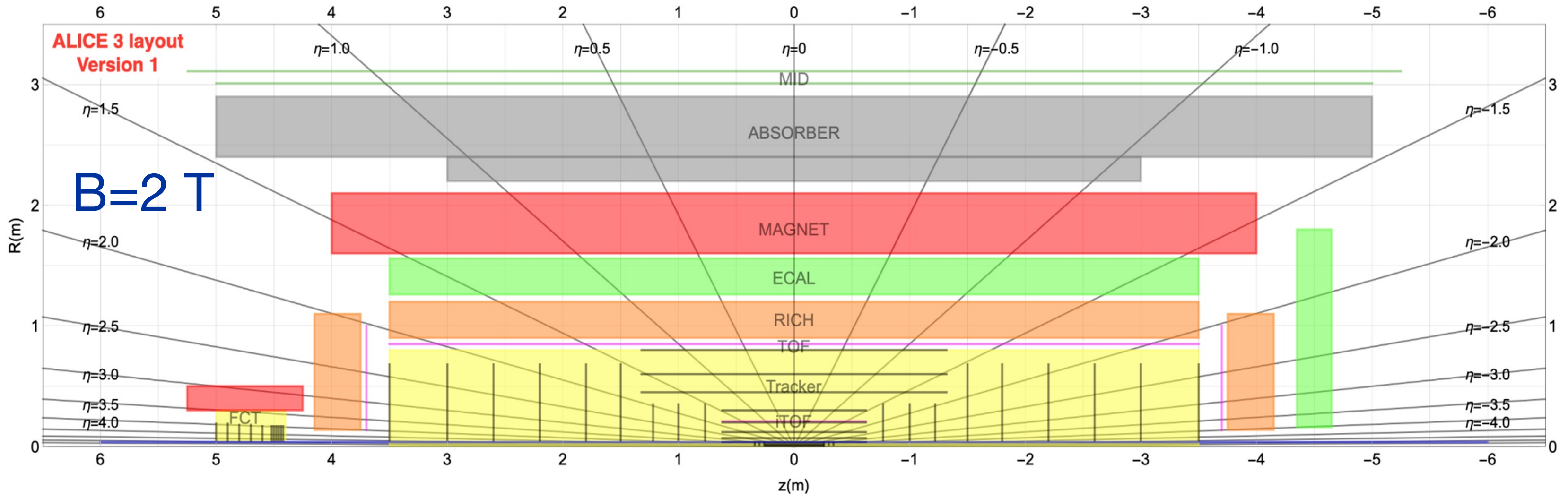
- **Multi-charm baryons vs system size: unique insight in thermalization and hadronization dynamics.**
- ALICE 3: unique experimental access in Pb-Pb collisions

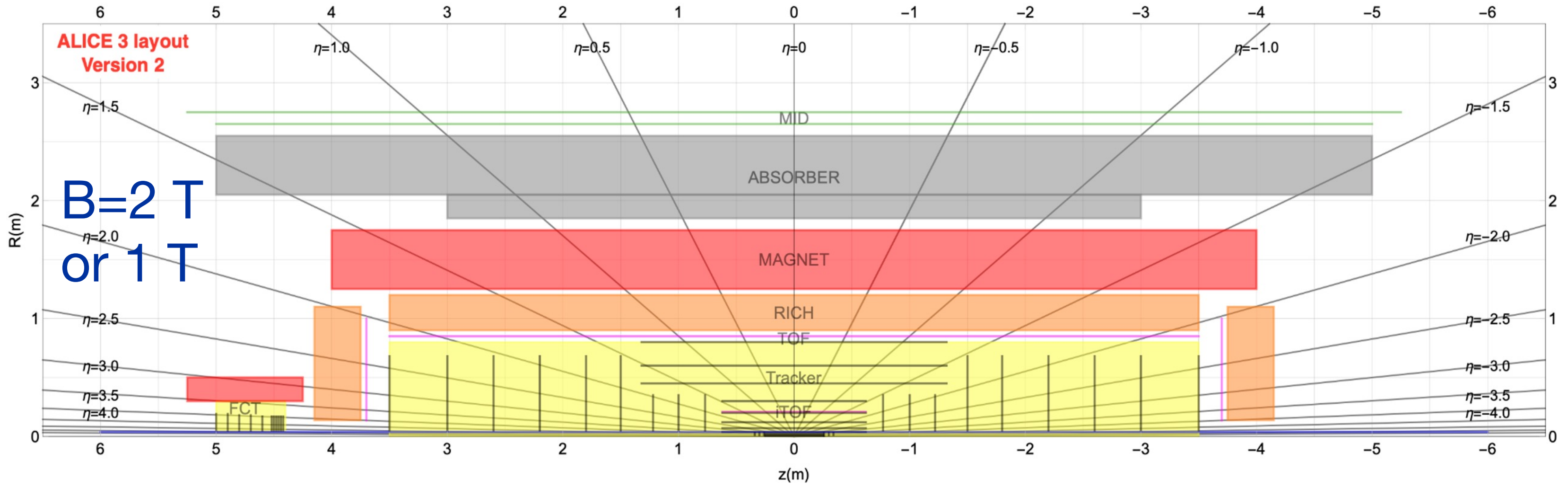
Further Topics

- **Quarkonium Measurements beyond S-wave States**
- **Dileptons: Accessing QGP Temperature**
- **New nuclear states**: existence of bound states of a charm baryon and a nucleon without Coulomb repulsion (c-deuteron n-Λ_c and c-triton n-n-Λ_c) sheds light on the charm-nucleon potential
- **Ultra-soft photons (down to $p_T \approx 2$ MeV/c)**: Low's theorem predictions violated in previous experiments by an excess of soft-photon production
- **Ultra-peripheral collisions:** rare single-resonance and resonance-pair production (e.g. $\rho' \rightarrow 4\pi$, ρ-J/ψ), light-by-light scattering
- **Net-baryon fluctuations:** baryon number conservation, baryon number susceptibility and critical behavior
- **BSM searches**: ALPs, dark photons, long-lived particles

Towards the Scoping Document

A tale of two Setups





Version 1
(LoI)

Version 2
(no ECal, smaller magnet)

Version without ECal as de-scoped layout

Version without ECal and with reduced field (1 T) as further de-scoping

A tale of two Setups

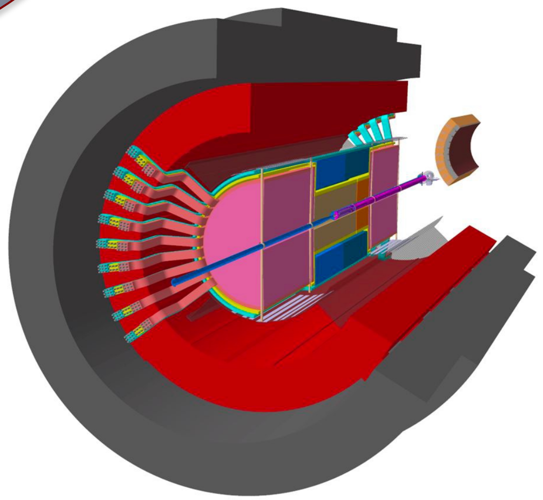
Measurement	Layout v2-2T	Layout v2-1T
ALPs searches in $\gamma\gamma \to \gamma\gamma$	strongly limited ($m_a < 2$ GeV/c^2, $1/\Lambda_a > 0.2$ TeV^{-1})	
$\chi_{c1,2} \to J\psi\gamma$	measurement limited to $p_T > 4$ GeV/c	
		minor additional impact
γ–jet correlations	limited improvement w.r.t. ALICE 2	
$\chi_{c1}(3872) \to J\psi\pi\pi$	not affected	minor impact
Ξ_{cc} yield	not affected	minor impact
Ξ_{cc} rapidity dependence	not affected	large impact
B^+ yield and flow	not affected	moderate impact at low and high p_T
Λ_c and Λ_b flow	not affected	large impact at $2 < \|y\| < 4$
D^0–$\overline{D^0}$ vs. $\Delta\varphi$	not affected	minor impact
D–D* vs. k^*	not affected	significant impact
Dielectrons	not affected	can exploit full integrated luminosity

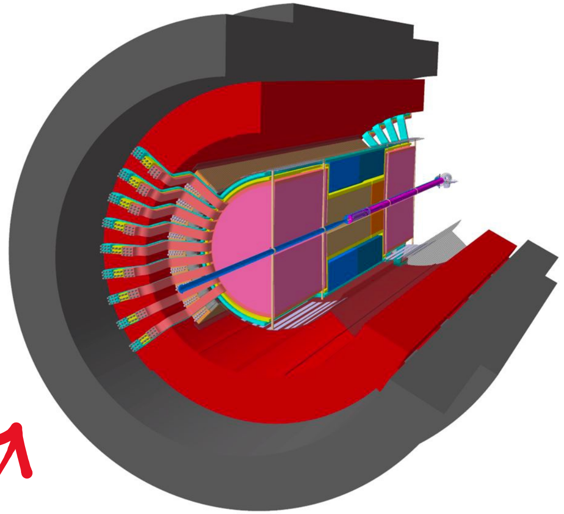
ALICE 3 Timeline

	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
	Run 3			LS3			Run 4				LS4	
	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
ALICE 3	Scoping Document, WGs kickoff	Selection of technologies, R&D, concept prototypes		R&D, TDRs, engineered prototypes		Construction				Contingency and precommissioning		Installation and commissioning

- **2023-25:** Scoping Document, selection of technologies, small-scale prototypes (≈ 25% of R&D funds)
- **2026-27:** large-scale engineered prototypes (≈ 75% of R&D funds) → TDRs and MoUs
- **2028-30:** construction and testing
- **2031-32:** contingency and pre-commissioning
- **2033-34:** preparation of cavern, installation

Layout Update: Services and Installation



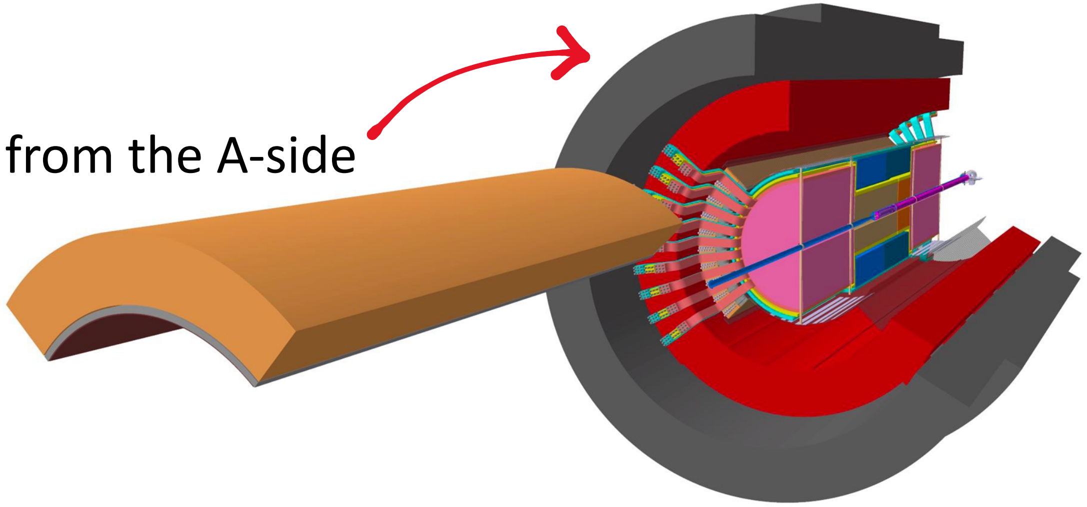


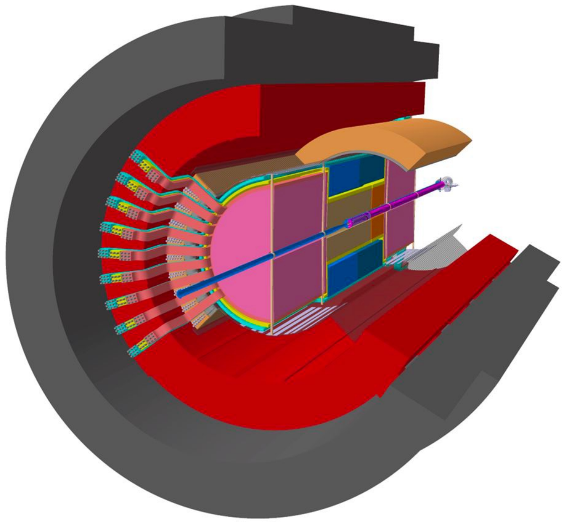
Insertion from the C-side

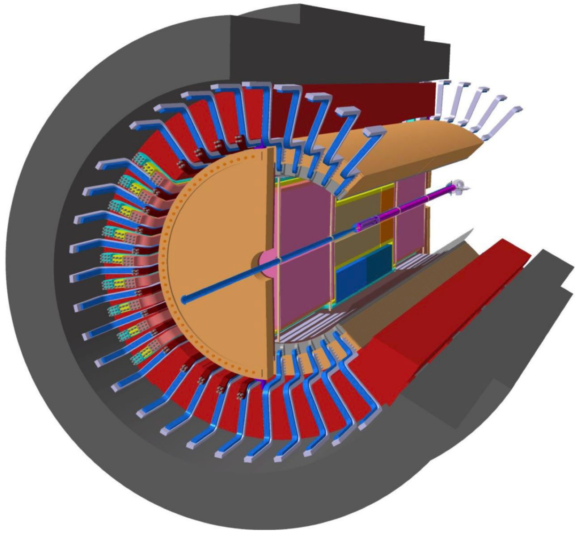
Study of integration scheme with alternating services enabling for modular and independent installation of OT endcaps, RICH and oTOF barrel, fRICH and fTOF endcaps

- In case of delay, any of these components can be installed during a YETS, without affecting the LHC schedule

Insertion from the A-side







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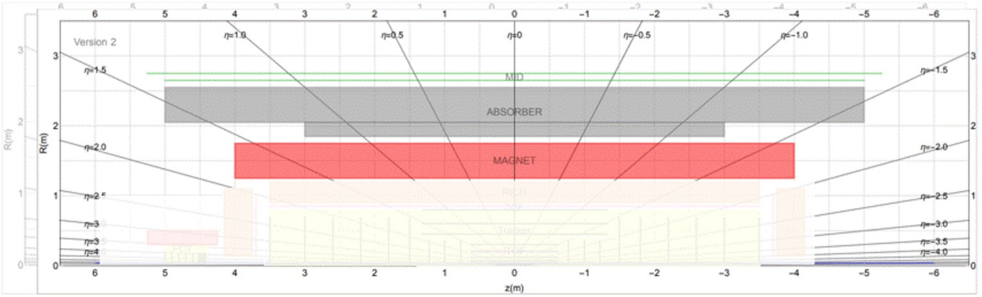
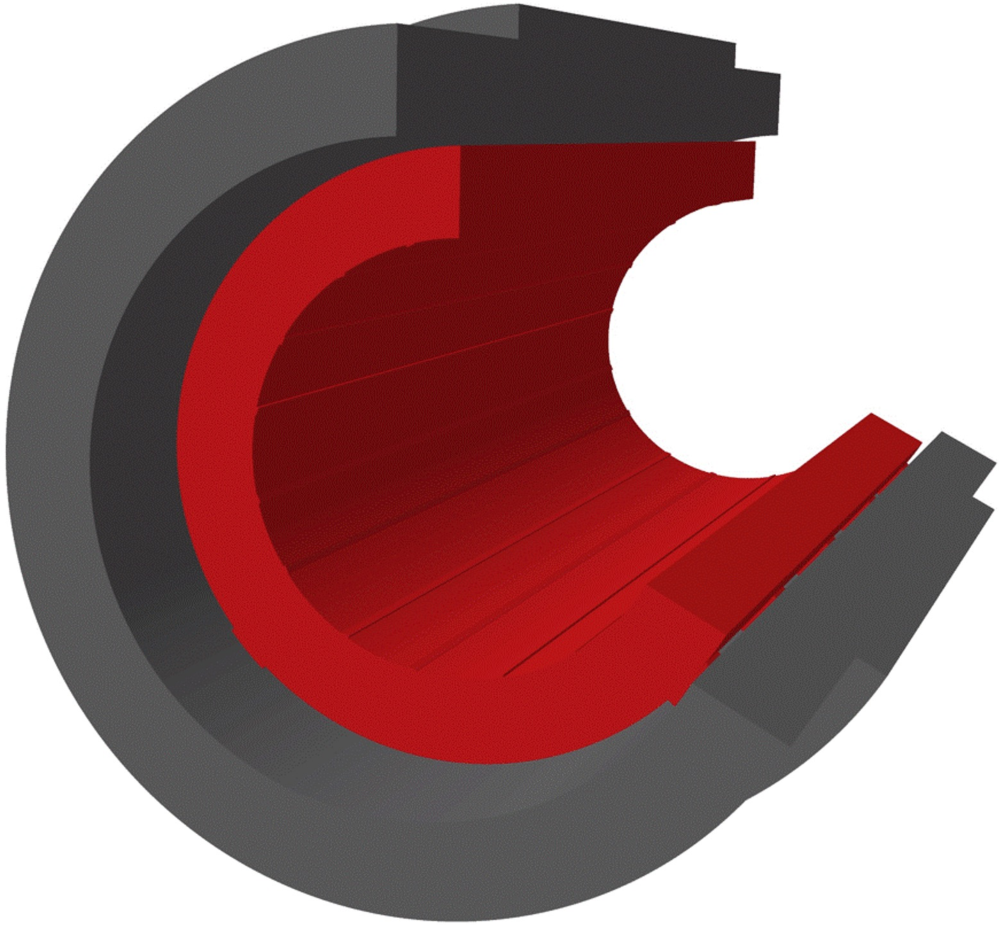
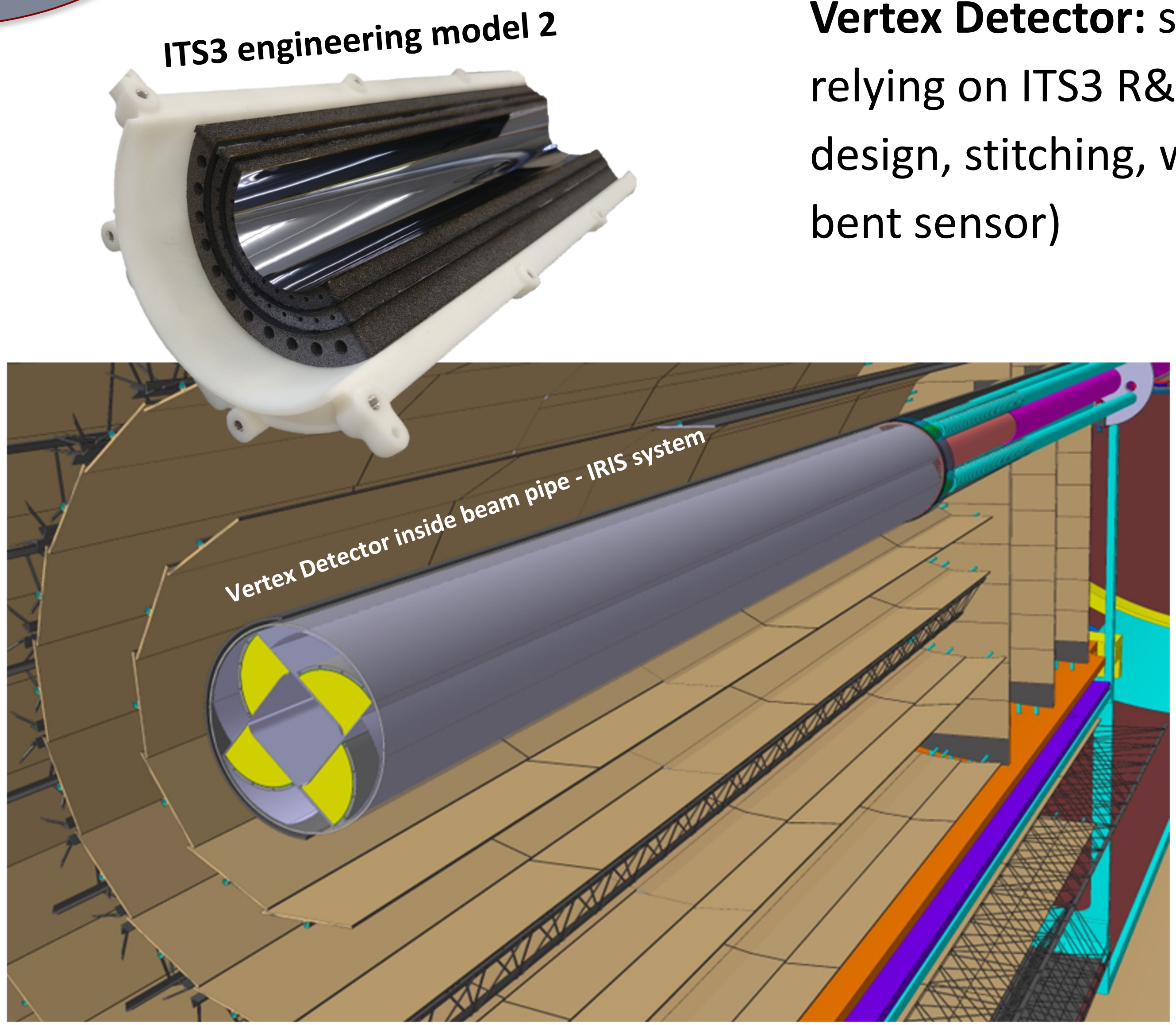


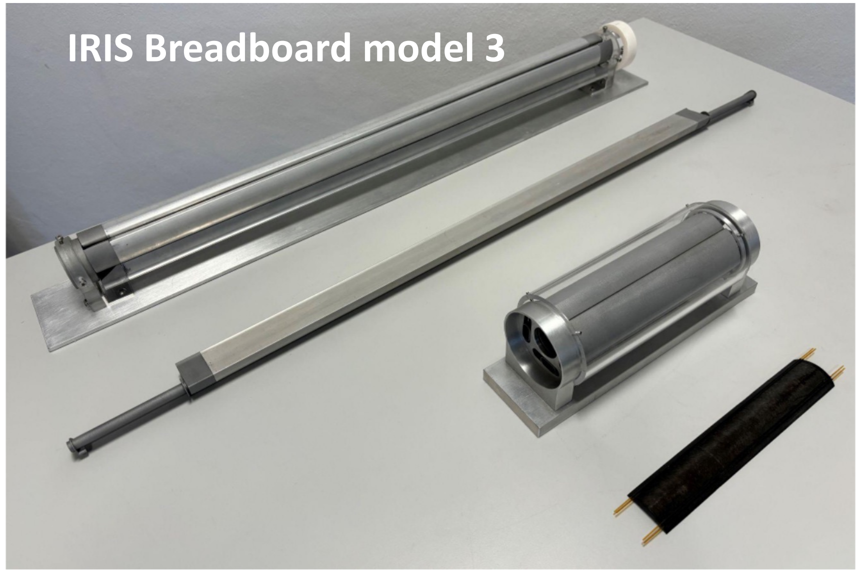


Magnet

R&D for the Inner Tracker



Vertex Detector: strongly relying on ITS3 R&D (sensor design, stitching, wafer-scale bent sensor)



IRIS system:

- Services integration being detailed
- Study of protection between primary and secondary vacuum
- mpact of vacuum on components, wire bonding, glued parts

R&D for the Outer Tracker

OT barrel design studies:

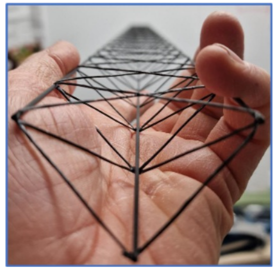
- Full-scale stave model
- Air and water cooling studies
- Mechanical support

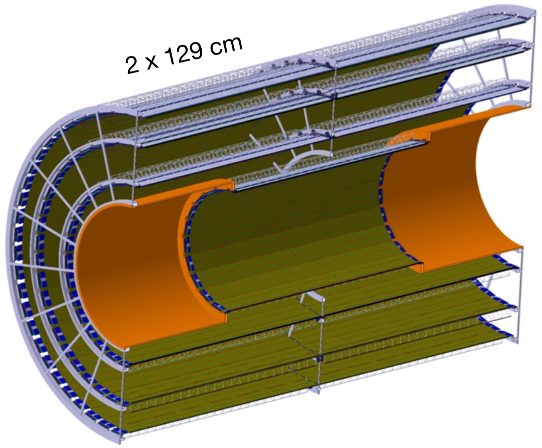
OT endcaps with disks:

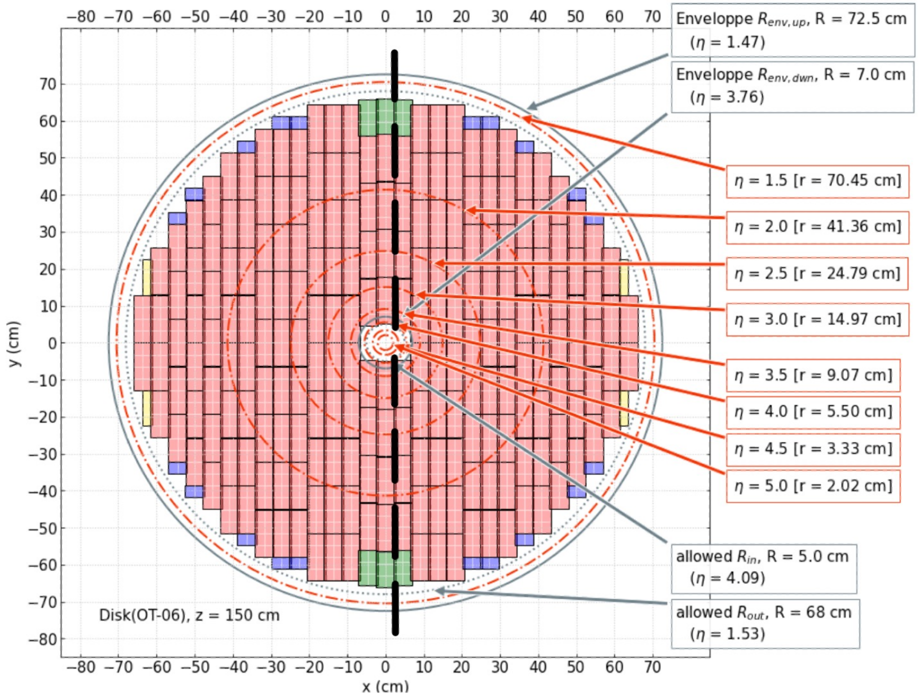
- “Paving” with modules
- Mechanical layout (double-sided disks?), carbon-fibre support

Automated module assembly:

- General-purpose die-bonder machine
- Flexible printed circuit, sensor gluing and interconnections



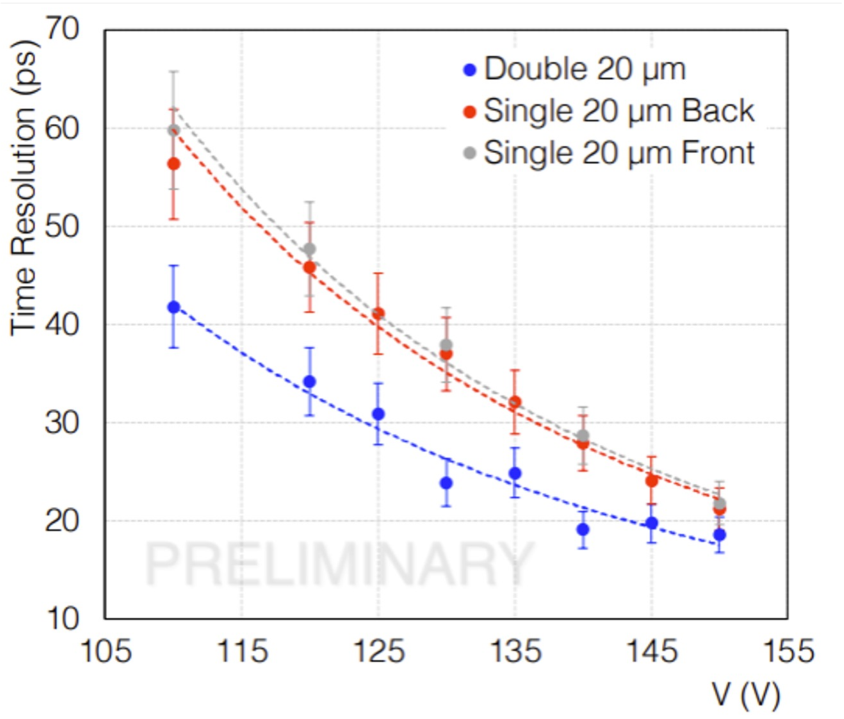


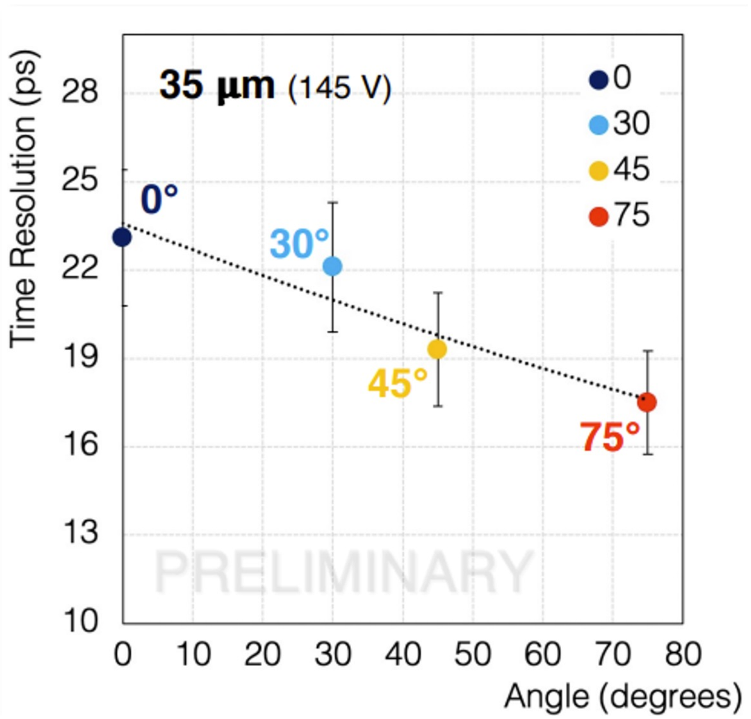


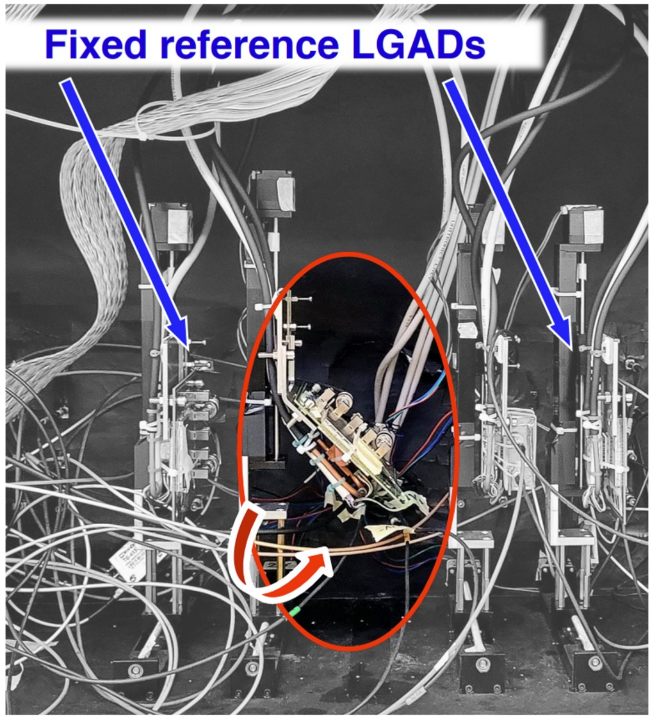
R&D for the TOF

Time resolution target: 20 ps. **Testbeams in July and Oct '23:**

- SiPM coated with different resins (type, thickness)
- Single and double LGADs 20 μm, 25 μm, 35 μm thick
- 50 μm thick CMOS-LGAD (ARCADIA MAPS with gain layer) and with integrated FEE (MADPIX)



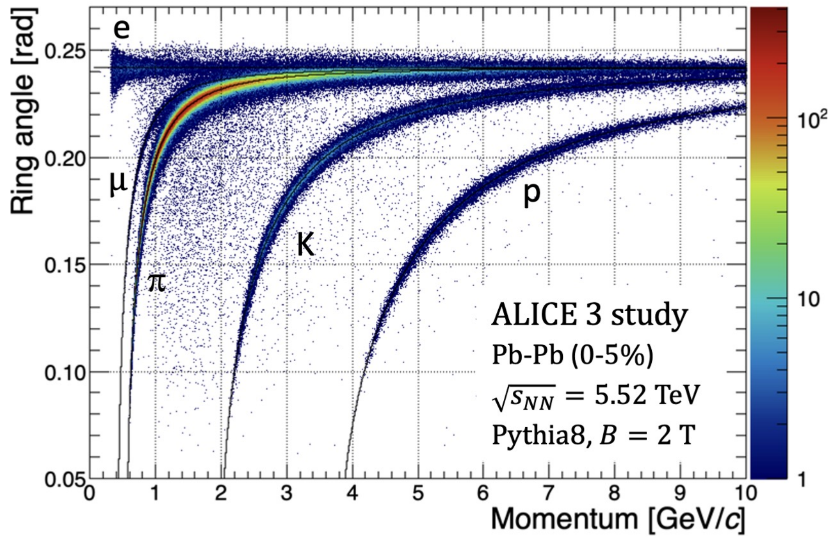


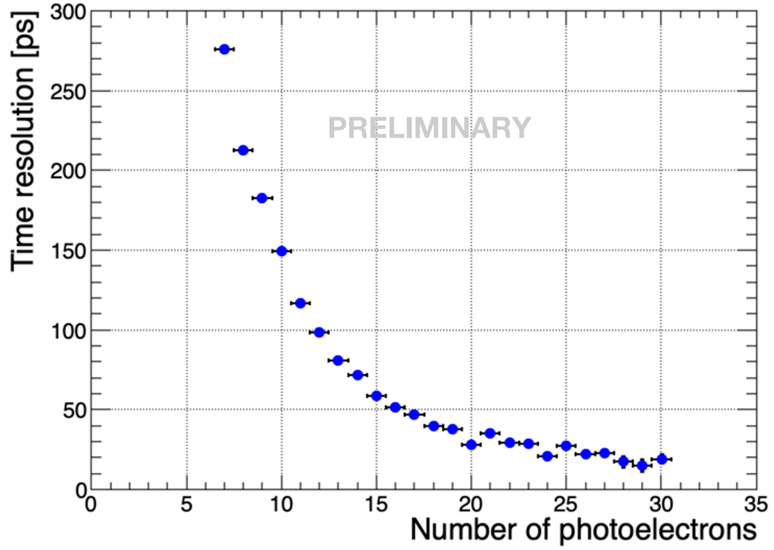


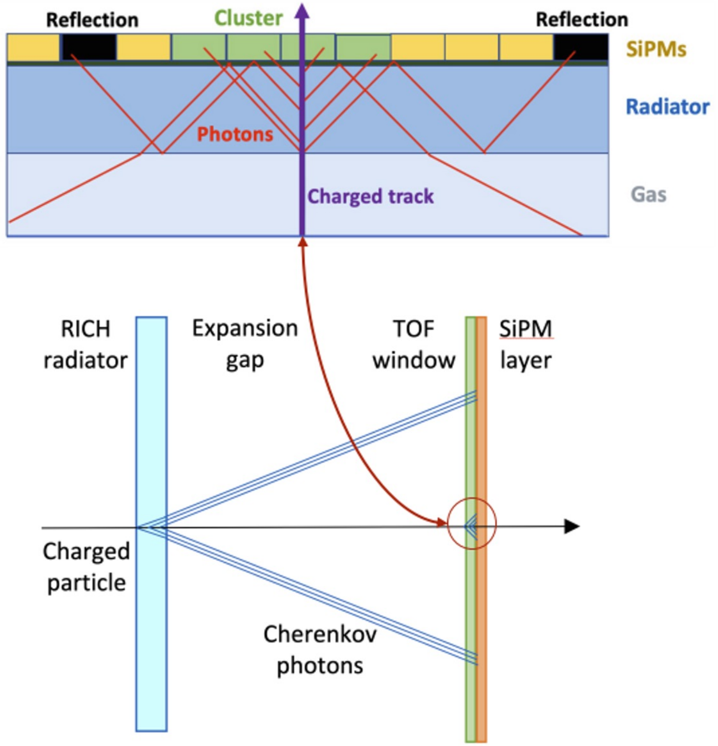
Target resolution achieved on individual sensor

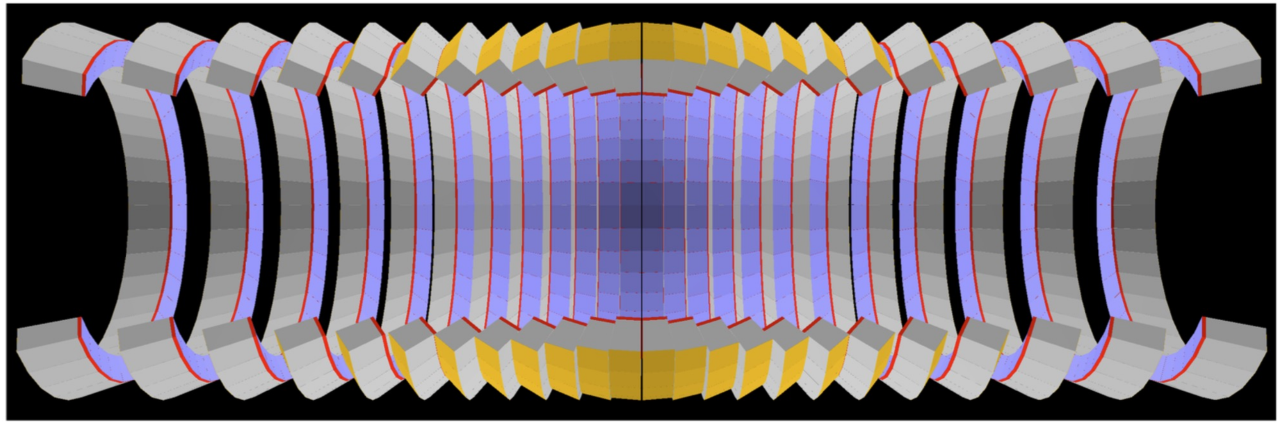
Small dependence on track inclination

R&D for the RICH









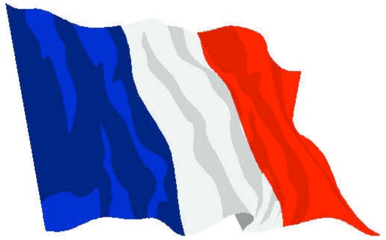
- **Possible layout optimization: outer TOF layer integrated with RICH** (thanks to the the generation of Cherenkov photons inside the protective layer detected by the sensor)

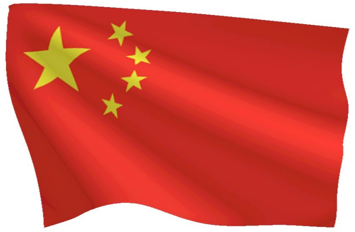
Summary of ongoing R&D 2024

Detectors	Activities	Plans for 2024
SC Magnet	Conceptual design of SC magnet	Initial design, investigation of cable options (Nb-Ti/Cu, Nb-Ti/Al, MgB_2)
Inner Tracker	Sensor rad. hard. (ITS3 MLR1), mechanics (IRIS), components outgassing	New irradiation tests (NIEL, TID), sensor specs, lab tests (mechanics, vacuum,...)
Outer Tracker	Module concept, mechanics, cooling	Sector mechanical prototype, sensor specs, lab tests
TOF	LGAD and SiPM time resolution, CMOS-LGAD design and characterization	New FEE with picoTDC, new CMOS-LGAD, PS testbeam in Apr, July, Oct
RICH	Angle resolution, time resolution for TOF (SiPM+window)	Focusing aerogel, new FEE with picoTDC, PS testbeam in Oct
ECal	SiPM timing, test new FEC32 with HPTDC	PbWO4 crystal +dual chan. photodet. +FEC32, energy and time resolution, SPS testbeam in May
MID	Scintillator selection, SiPM response, MWPC, RPC	Scintillator prototype module, new FEE, PS testbeam in Oct of all options

Plans for ALICE 3 in France and China

3 French institutes (IPHC, LPSC, IP2I) **and 5 Chinese institutes** (CCNU, CIAE, CUG-Wuhan, USTC, Fudan Univ.) **aim at participating in the ALICE 3 project**





- **Common scientific program** based on heavy-flavor measurements, allowing for the study of the interaction of heavy quarks with the medium (energy loss + hadronization) and the characterization of the mechanisms driving the formation and dissociation of bound states inside the medium

- **France:** technical project focused on the R&D and construction of the **outer tracking layers (CMOS)**, capitalizing the experience and the efforts deployed in the ITS3 project (recently approved by IN2P3). **Ongoing discussions with the IN2P3 directorate: converging in the next months towards a technical proposal illustrating the plans for the contribution to the detector R&D and construction**

- **China:** technical project focused on the R&D and construction of the **tracking layers (CMOS) and TOF (based on LGAD technology)**

Summary

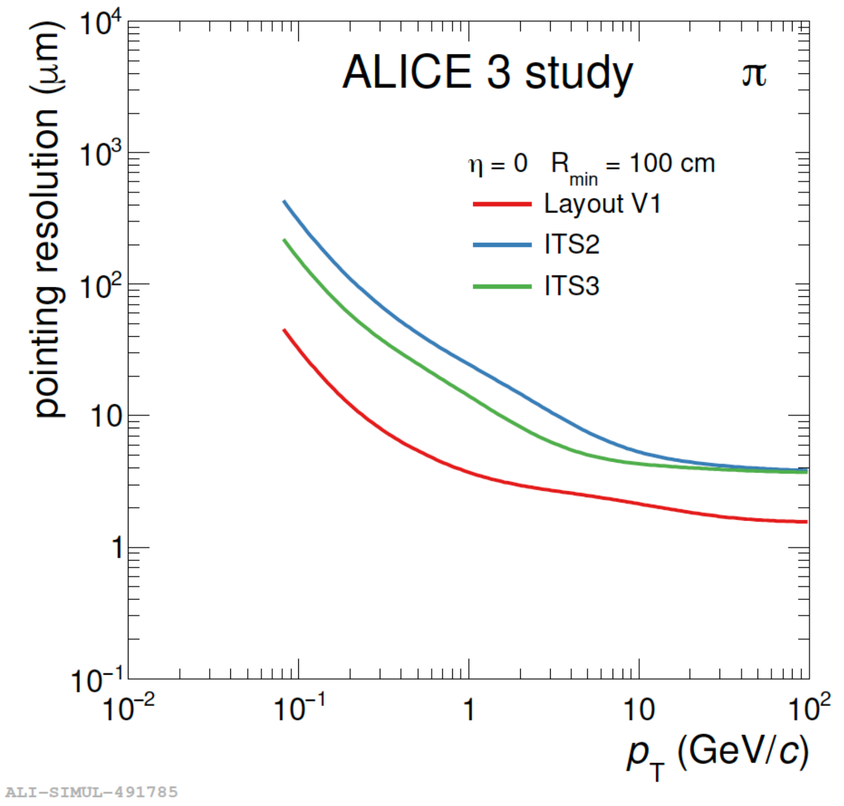
- **ALICE LS3 upgrade program under finalization: next-generation vertex detector with truly cylindrical layers (ITS3), forward calorimeter (FoCal). Significant R&D progress:**
  - Operation of bent silicon sensors in test beams
  - Demonstration of FoCal concept in test beams
  - Complete prototype under construction

- **ALICE LS4 upgrade program already well defined:**
  Letter of Intent of ALICE 3 → CERN-LHCC-2022-009
- Detector layout updated: increased modularity introduces flexibility on installation schedule
- **Scoping document under finalization, pinning down the detector configuration**
- R&D: several prototypes and test beams planned for 2024

Backup Slides

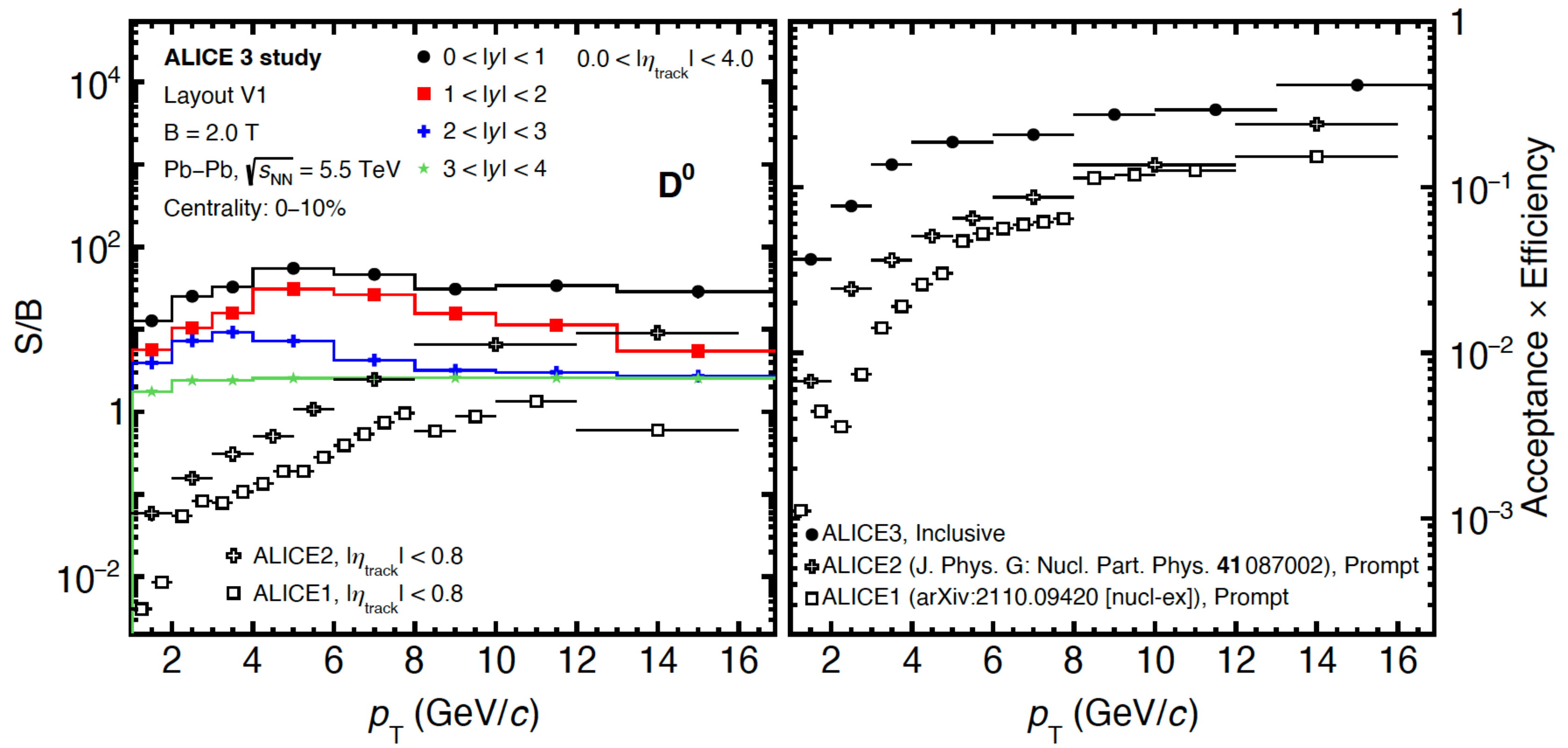
Heavy-Flavour Benchmark: D^0

Excellent pointing resolution and PID: **large S/B and efficiency** 10-20 × w.r.t. Run 3 for p_T < 4 GeV/c



Experimental benchmark giving access to the measurement of:

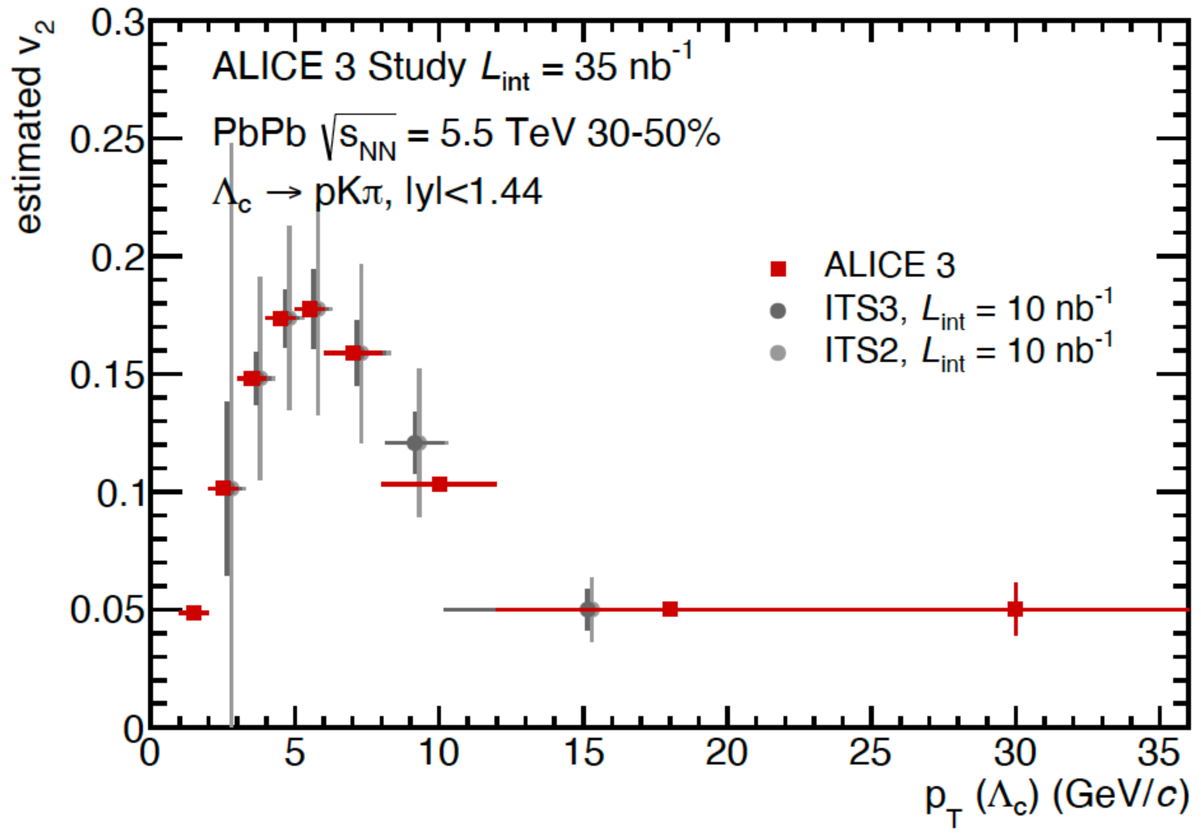
- Beauty meson and baryon v_2
- DD correlations

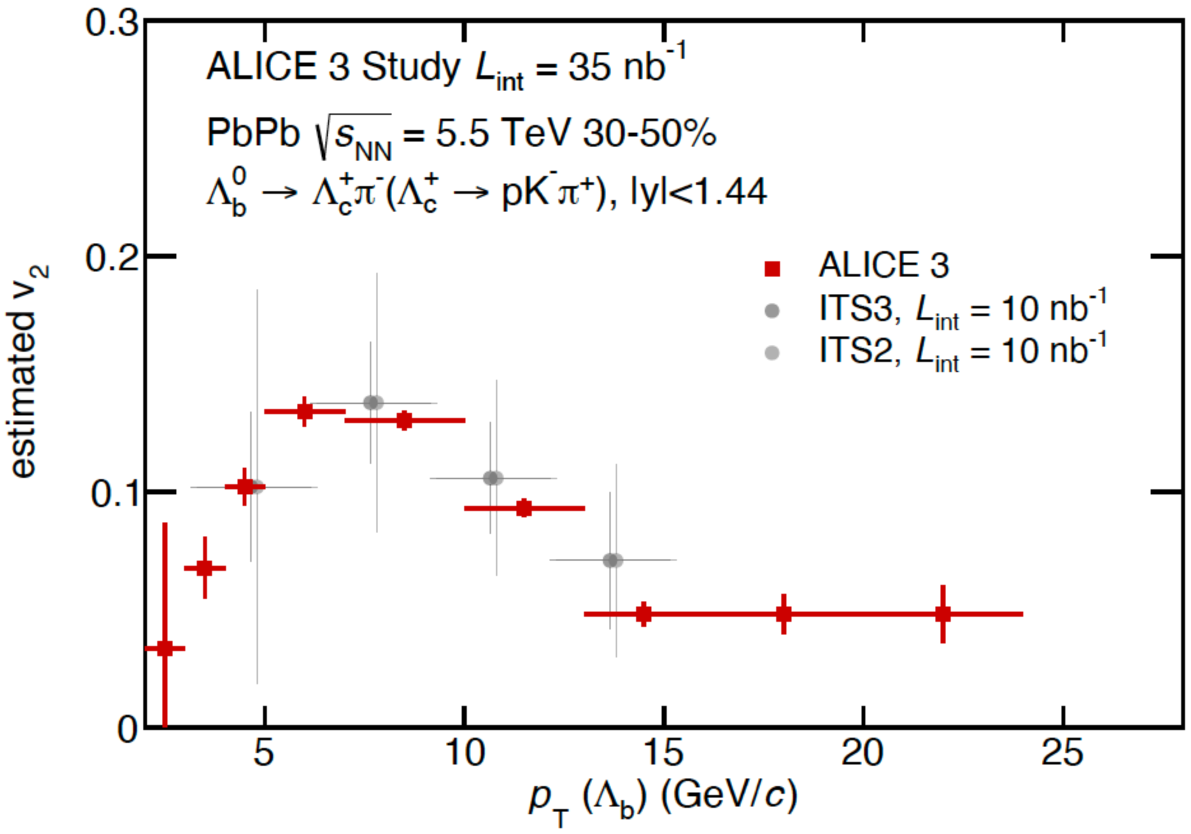


HF Baryon v_2

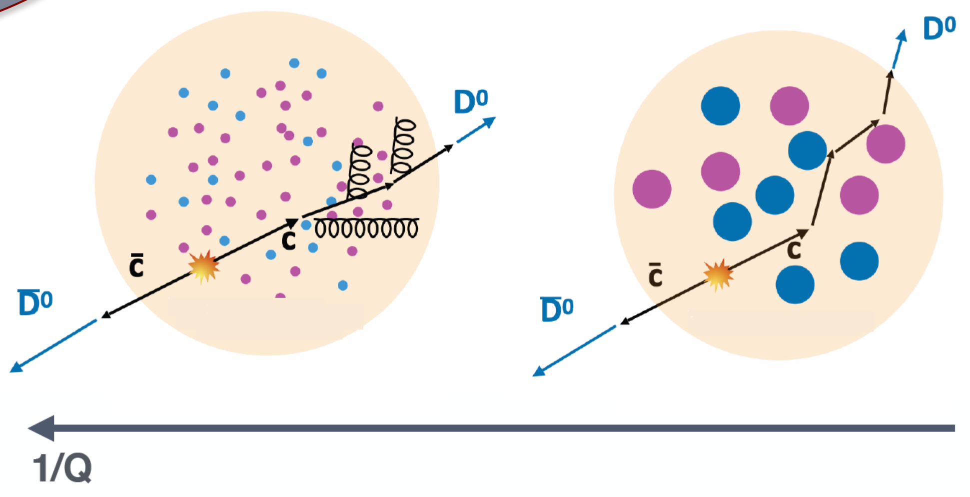
Goal: disentangle effects of quark transport and hadronisation

- Expect beauty thermalisation slower than charm — does this affect hadronization?
- First measurements of Λ_b v_2 in Run 3 and 4
- Needs ALICE 3 performance for precision measurement





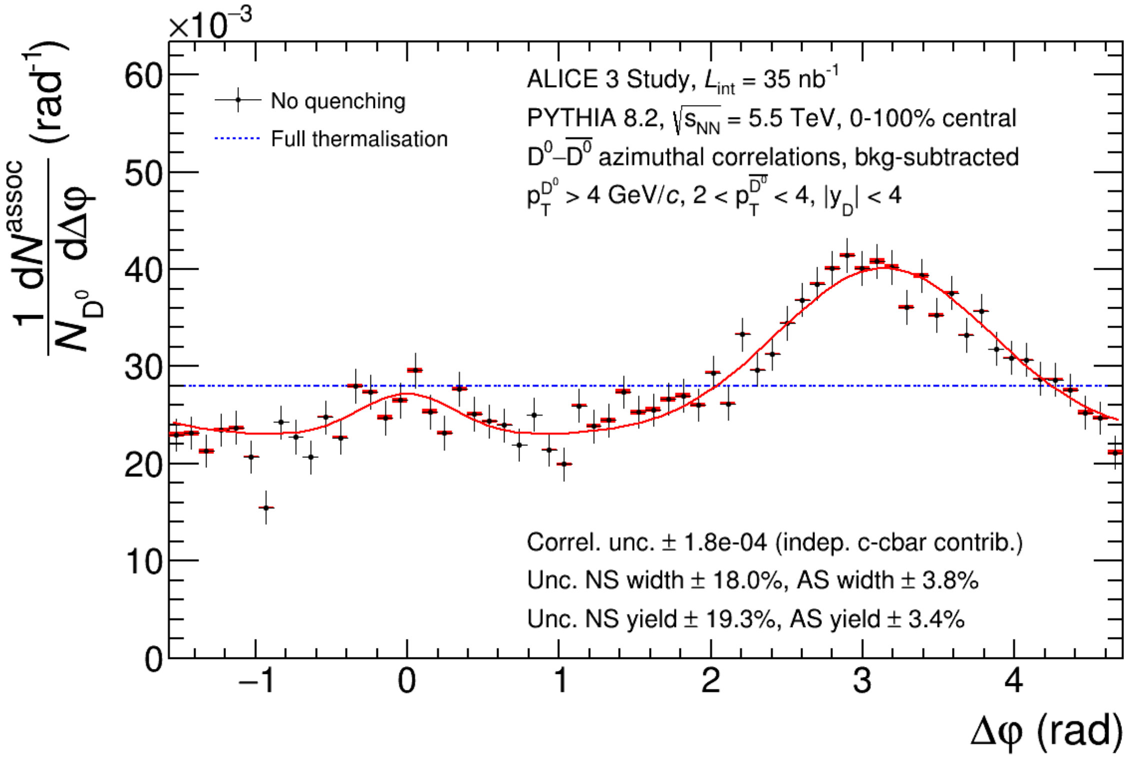
$D\bar{D}$ Azimuthal Correlations



Goal: measure angular (de)correlations — direct probe of QGP scattering

- Very challenging measurement: need good purity, efficiency and η coverage
- Heavy-ion measurement only possible with ALICE 3

- Insight on the relative importance of the **different energy loss mechanisms** as a function of p_T
- Shed light on the quasi-particle nature of the QGP at different momentum scales
- In the limit of **full thermalisation**, the flight direction of the charm quarks would be **fully randomized**, and no remnant of the initial correlation would be visible



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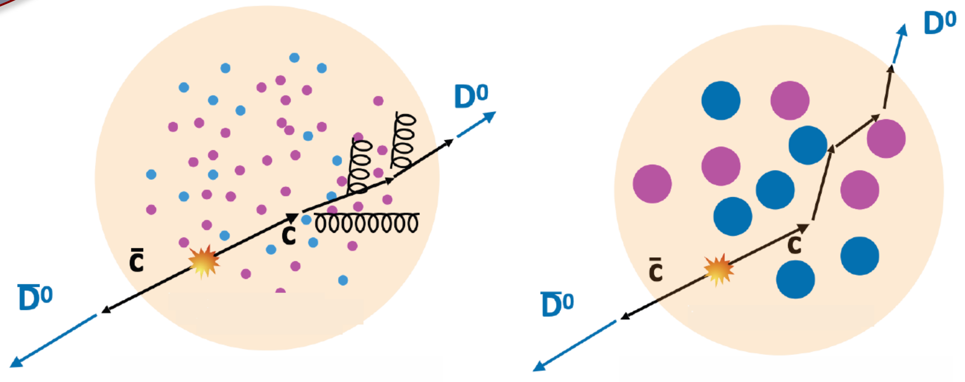

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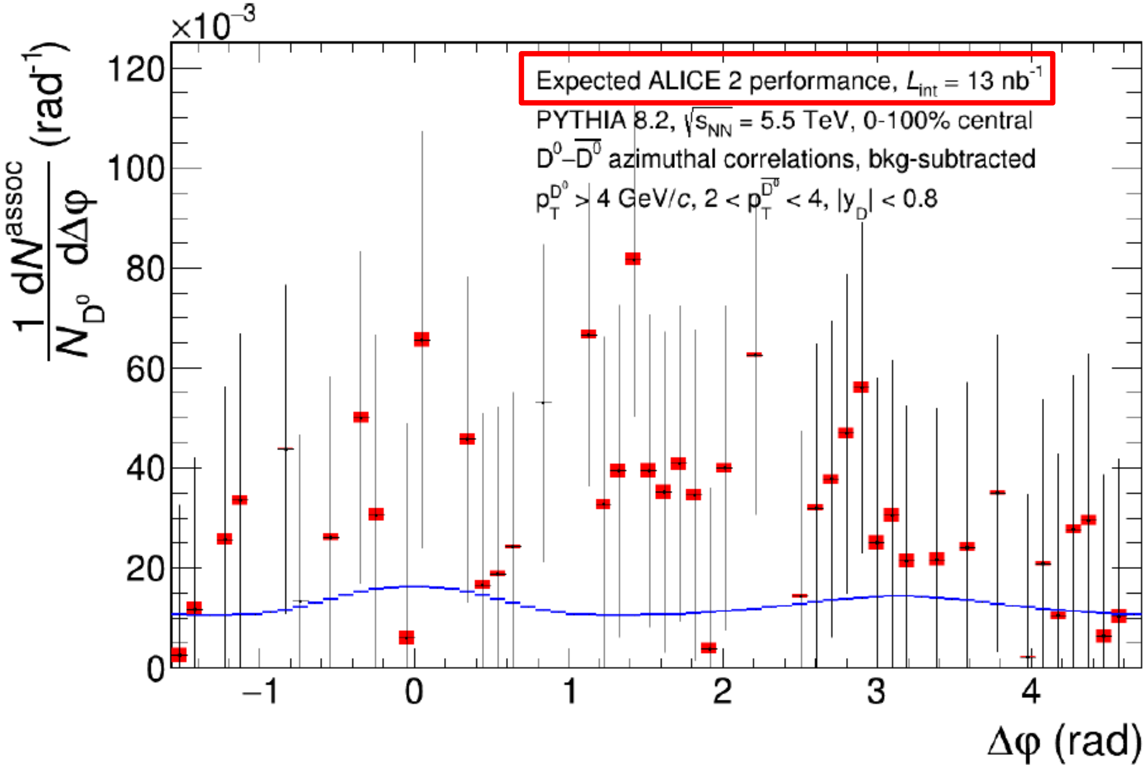
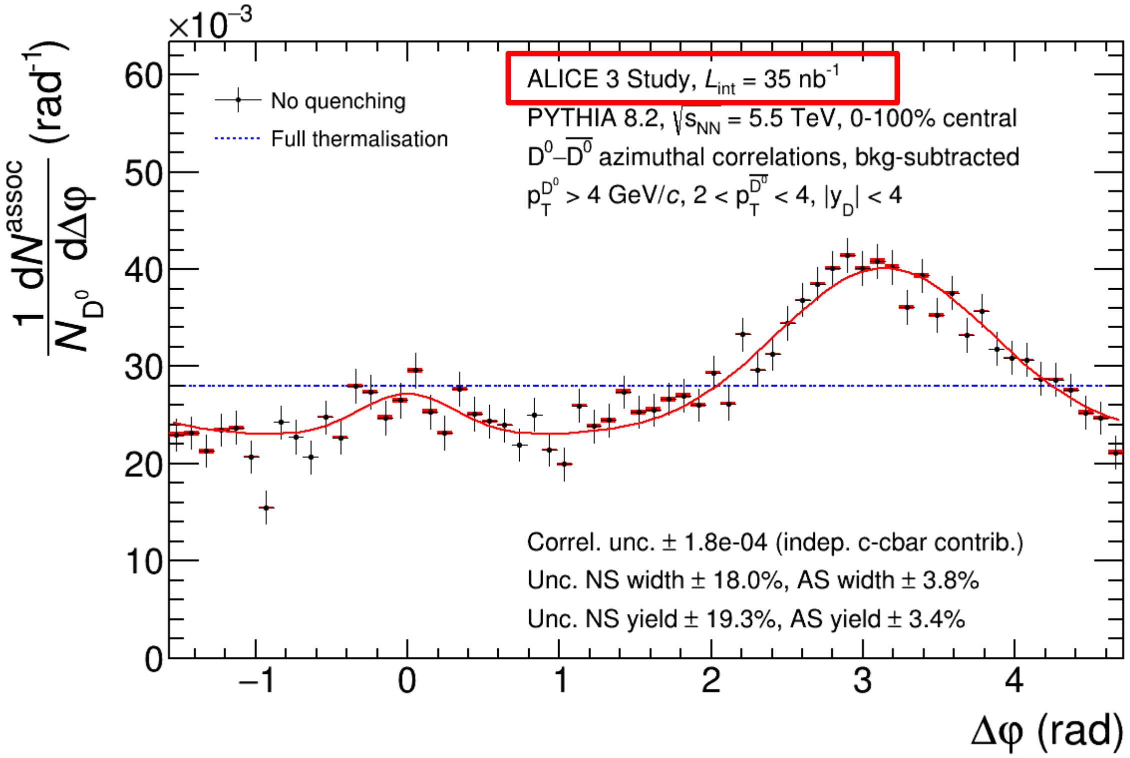


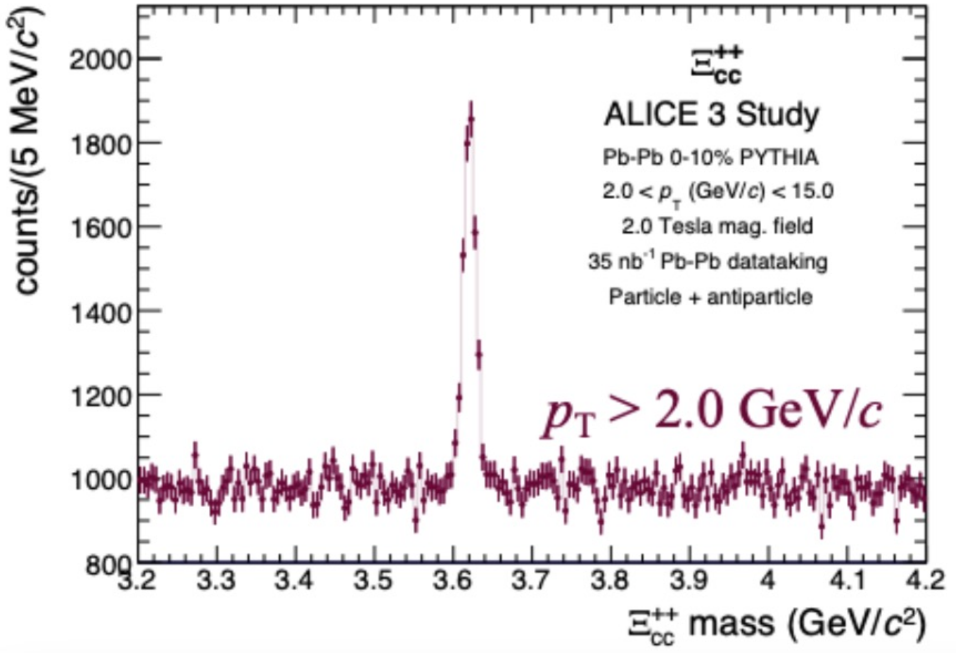


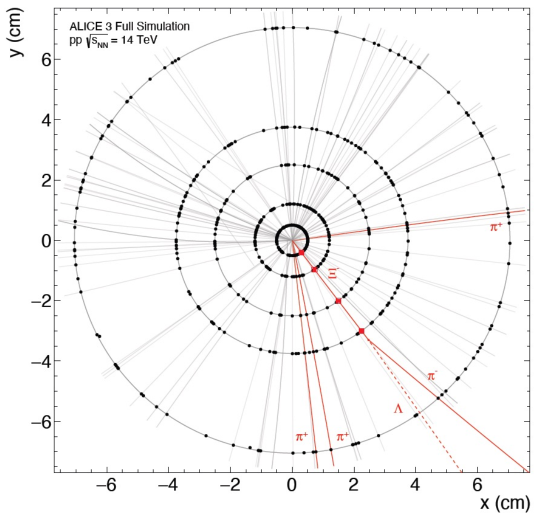
Multi-Charm Baryon Reconstruction

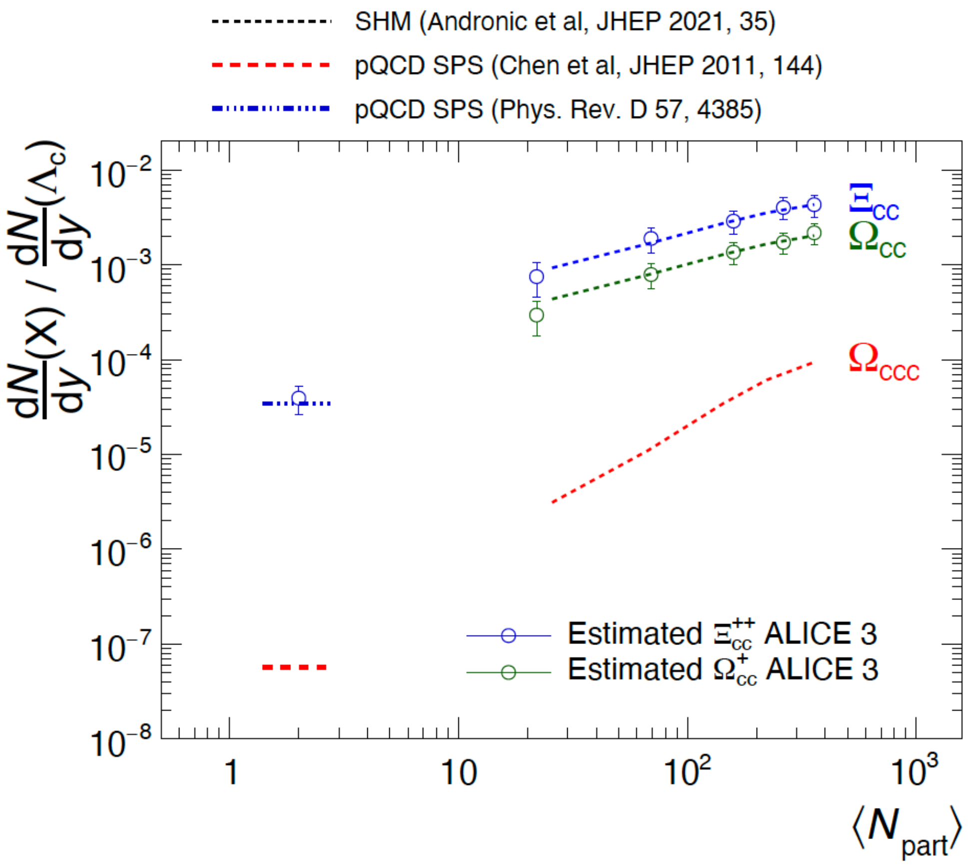
New technique: strangeness tracking with Ξ baryon provides high selectivity

$$\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+} + \pi^{+}$$
$$\Xi_{c}^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$

Expected mass peak in Pb-Pb collisions







- **Multi-charm baryons vs system size: unique insight in thermalization and hadronization dynamics.**
- ALICE 3: unique experimental access in Pb-Pb collisions

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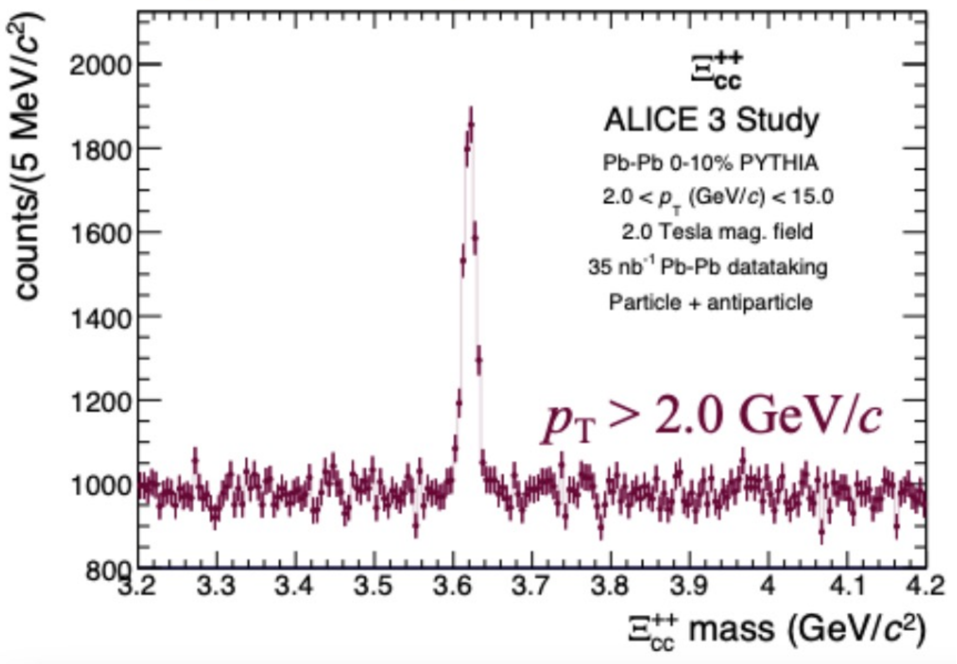
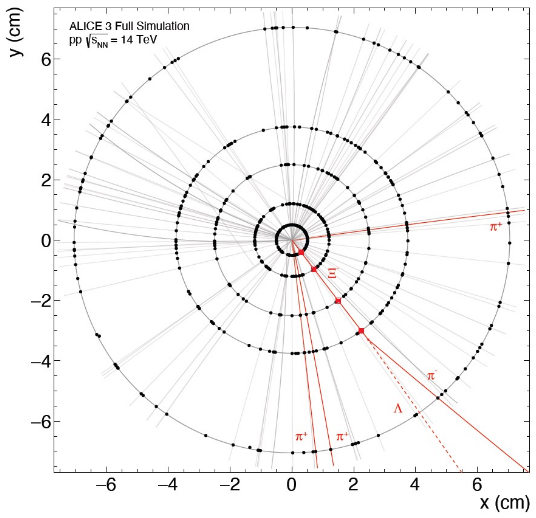
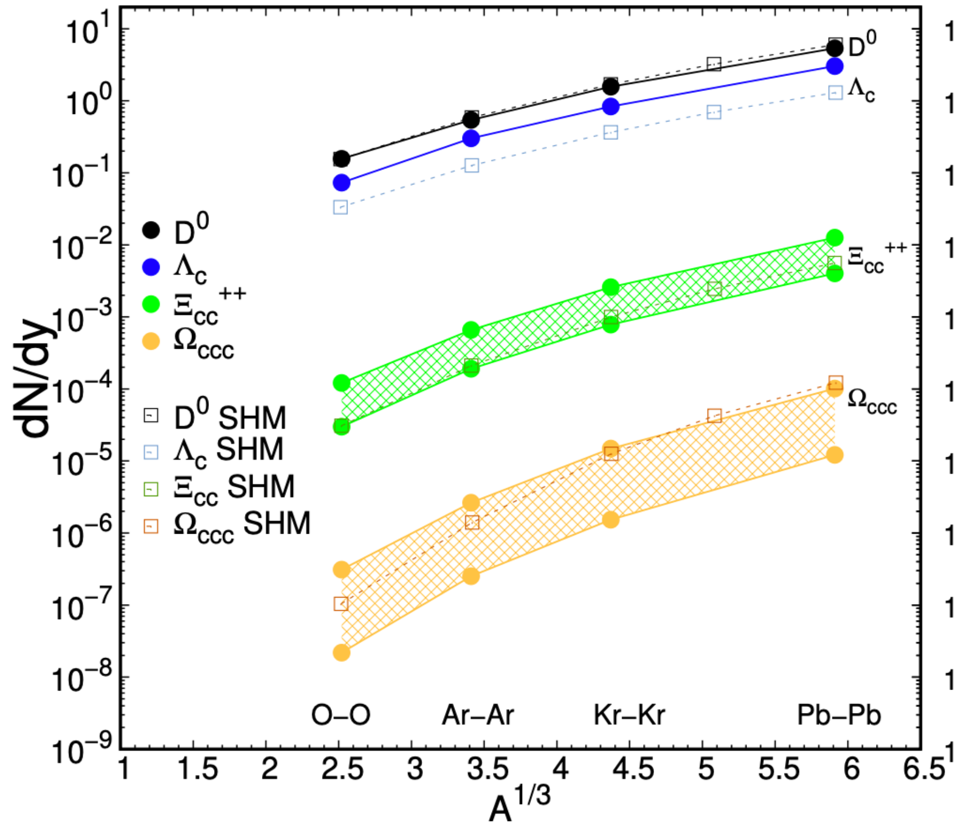




https://arxiv.org/abs/2305.03687

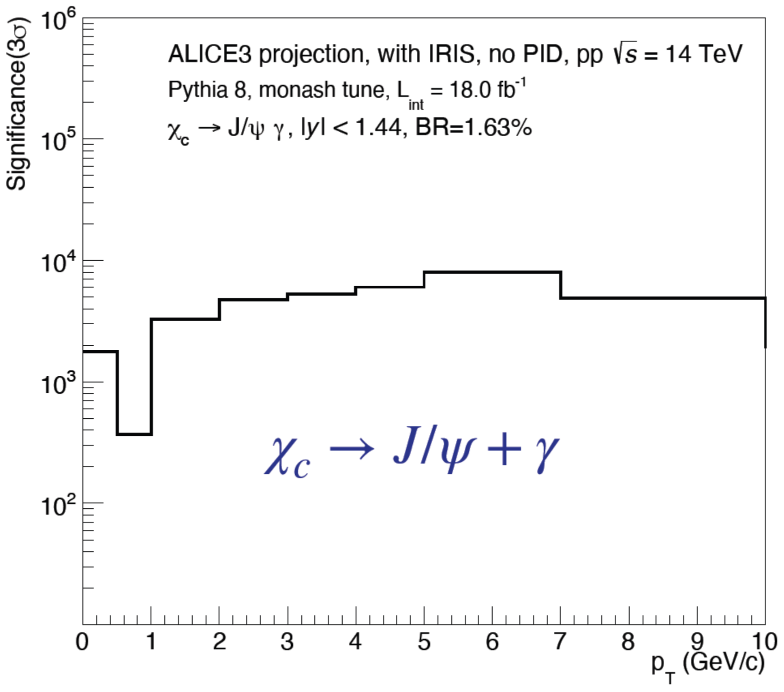


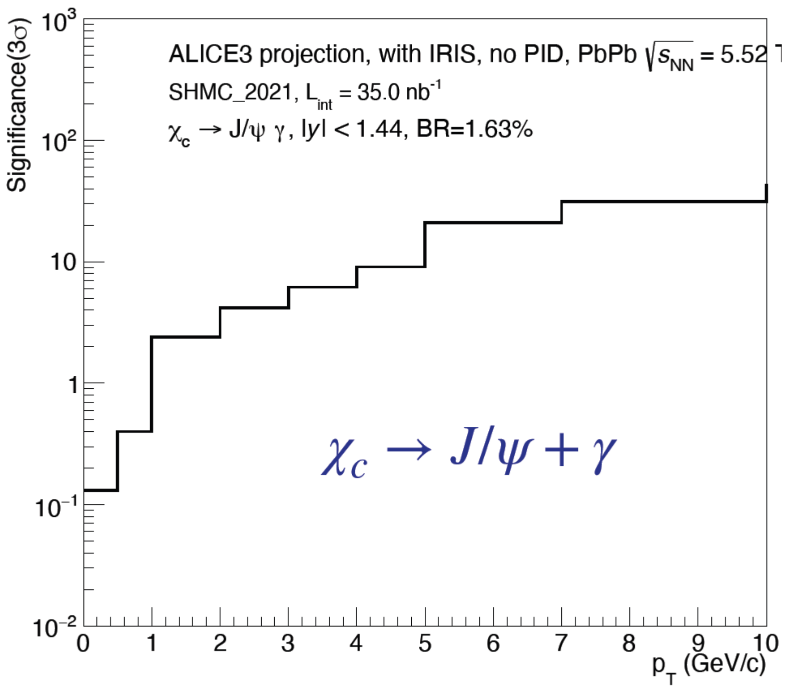
- **Multi-charm baryons vs system size: unique insight in thermalization and hadronization dynamics.**
- ALICE 3: unique experimental access in Pb-Pb collisions

Quarkonium Measurements beyond S-wave States

Quarkonium measurements in Heavy-Ion collisions are currently limited to S-wave states decaying into dileptons: J/ψ, ψ(2S), ϒ(nS)

χ (and η) state measurements: unique tool to constrain the dynamics of bound-state interactions with the QGP, where different predictions are available from the existing approaches

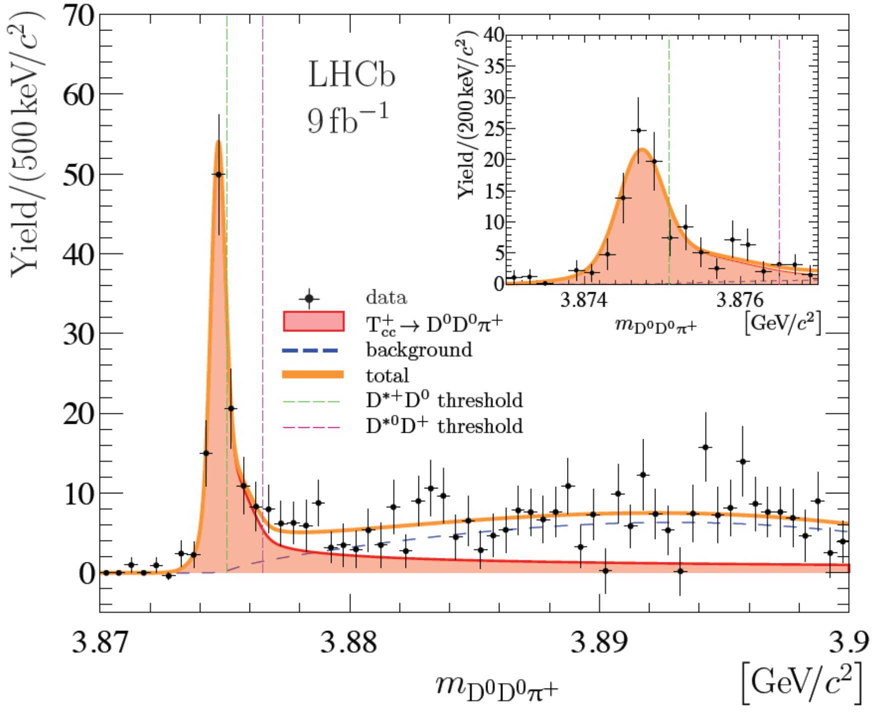




χ_c states:

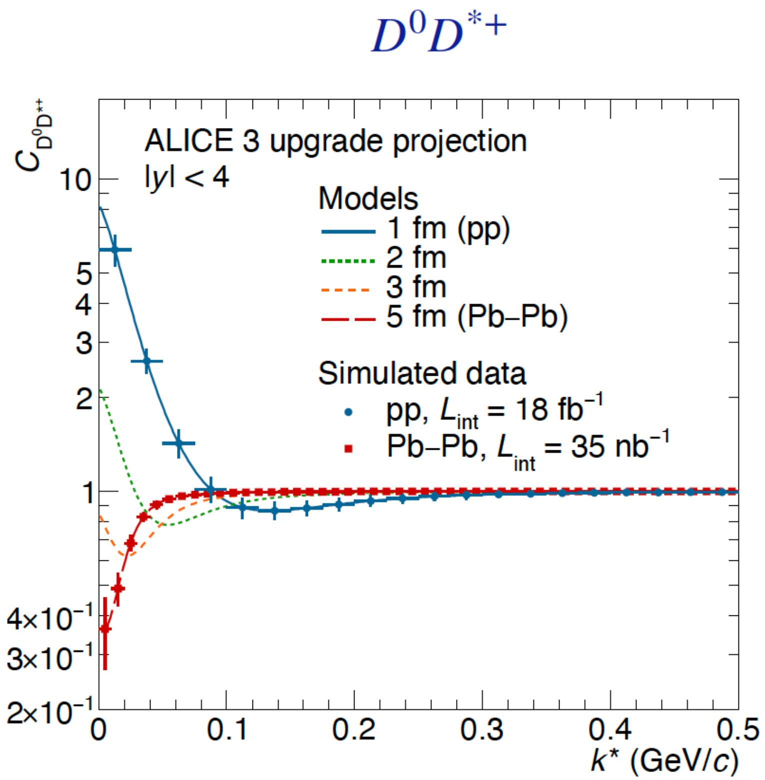
- Binding energy in between J/ψ and ψ(2S)
- Sizable feed-down contribution to J/ψ
- **Most promising decay mode: $\chi_c \to$ J/ψ γ (γ measured with calorimetry and/or pair conversion)**

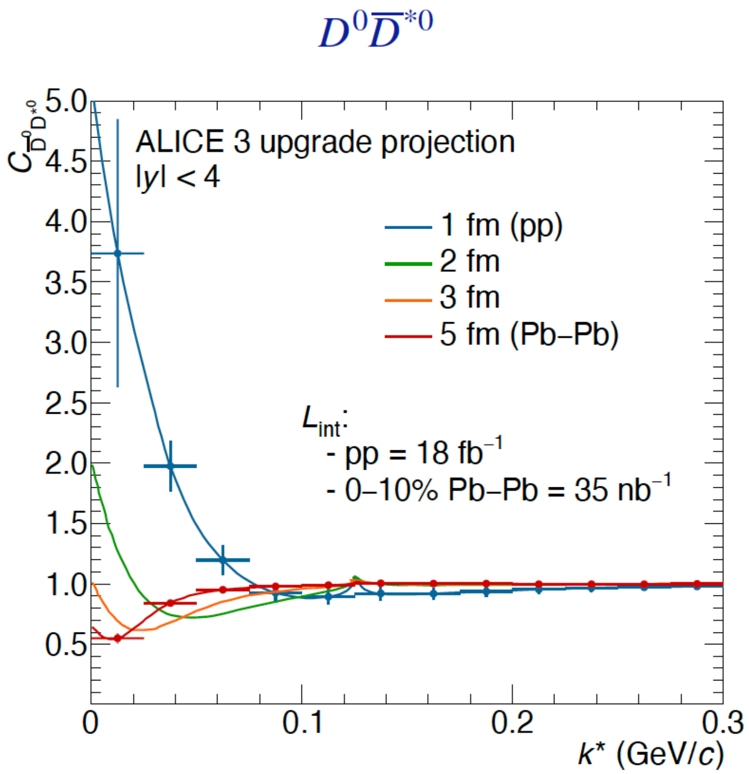
DD* Momentum Correlations



- Several exotic heavy flavour states identified: loosely bound meson molecule or tightly bound tetraquark?
- Can we pin down the nature of the states other than performing direct observations?

Studying binding potential with final state interactions through femtoscopic correlations

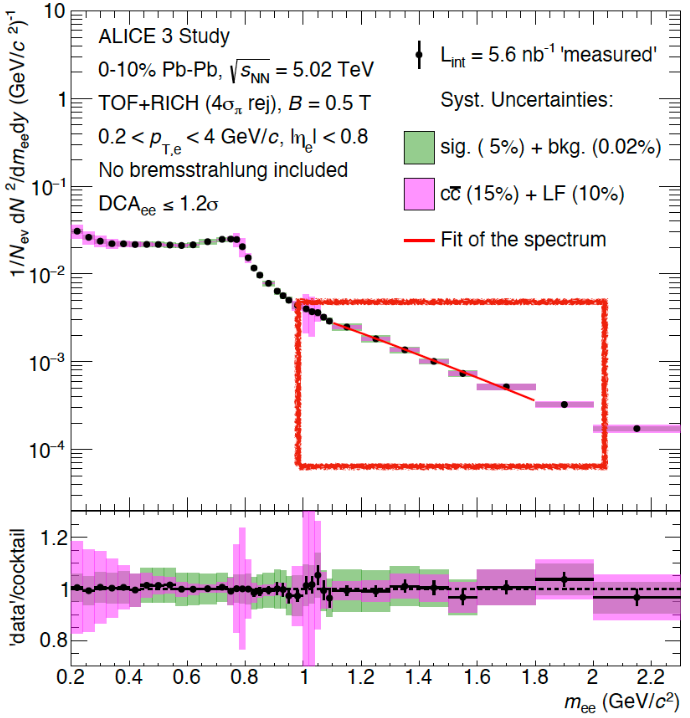




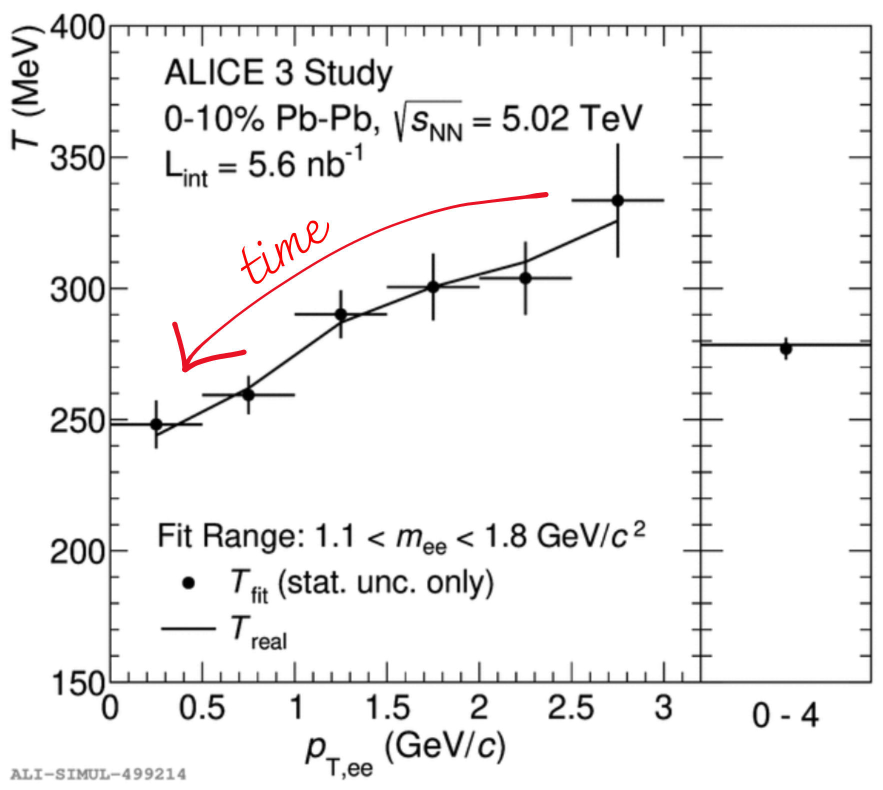
Dileptons: Insight on QGP temperature evolution

- **Improved pointing resolution** → significant reduction of charm contribution and associated uncertainty: unique opportunity at the LHC
- **Precision measurement of dielectrons as function of mass and p_T**
- Excellent precision for dilepton v_2 vs p_T in different mass ranges → time evolution of emission

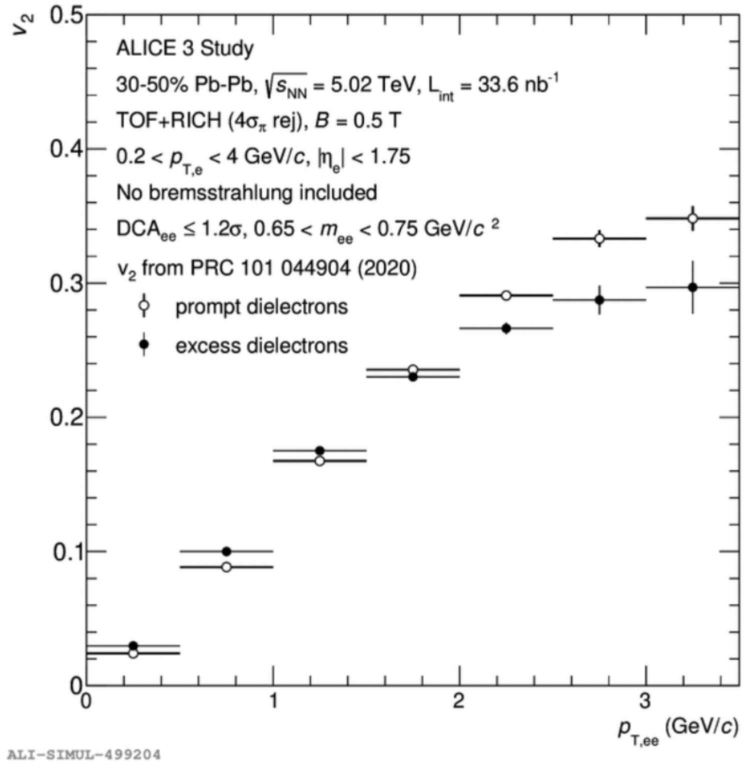
Dielectron mass distribution



Temperature from slope (M_{ee})

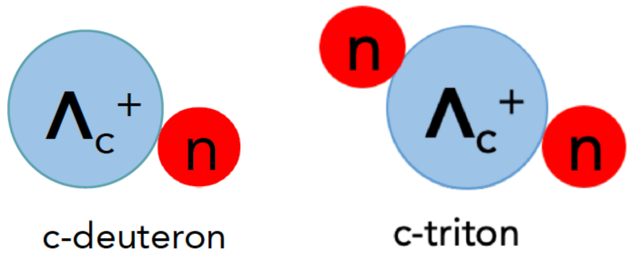


Dielectron v_2



Nuclear States: Charm-Deuteron

The lightest possible bound states of a charm baryon and a nucleon without Coulomb repulsion are bound states of Λ_c and a neutron: **c-deuteron and c-triton**



Their possible (non) existence is widely and controversially discussed in the literature and can shed light on the charm-nucleon potential

Most promising decay channels:

- $c_d \rightarrow d + K^- + \pi^+$
- $c_t \rightarrow t + K^- + \pi^+$