ALICE 3: a next-generation heavy-ion detector for LHC Run 5 and beyond

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LHC & ALICE timeline

ALICE: designed to study the physics of **strongly interacting matter** at extreme energy densities.
📚 Eur. Phys. J. C 84 (2024) 813

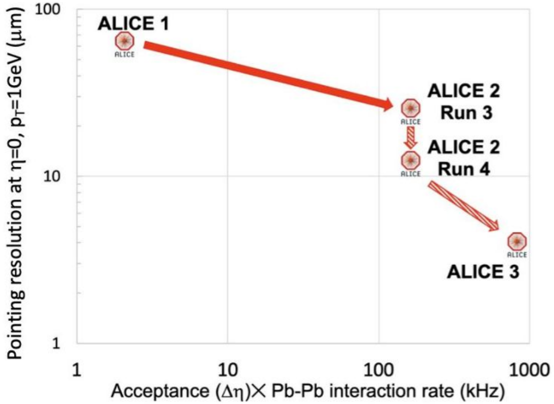
HL-LHC

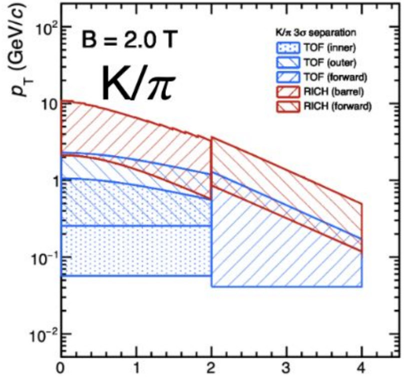
LHC Run 3	LS3	LHC Run 4	LS4	LHC Run 5
2022-2026	2026-2029	2030-2034	2034-2035	2036-2041

Open points after Run 4:
- Heavy-quarks interactions with the QGP, thermalization, hadronization
- QGP temperature as a function of time
- Chiral symmetry restoration
- Nature of exotic hadrons

LS4 upgrades:
- New **ALICE 3** detector, a next-generation heavy-ion detector targeting **unprecedented precision** and **extensive PID**

Letter of Intent: arXiv:2211.02491 Scoping document: CERN-LHCC-2025-002





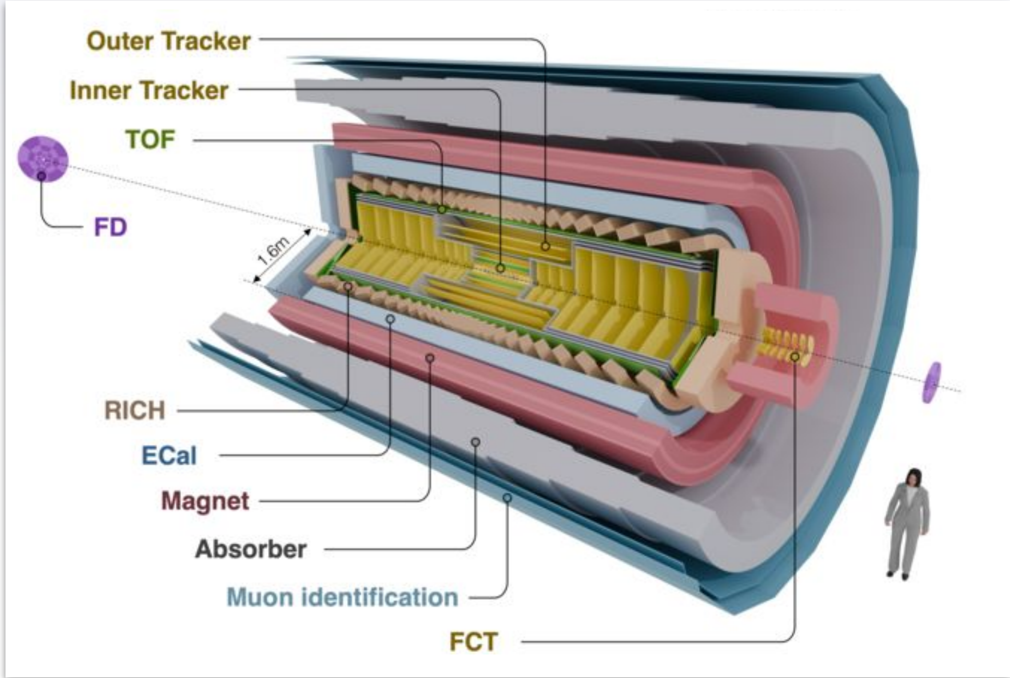
Detector layout

- **B solenoid** = 2.0 T
- **Vertexer + Tracker**,
  compact (R ≈ 85 cm)
  ultra-light (layer 0 ~ 0.1 % X/X_0)
  silicon MAPS-based (≈ 60 m^2) with
  high-performance tracking (Axε, granularity, ...)

- with **PID capabilities**
  (iTOF, oTOF, fTOF, bRICH, fRICH ECal, μID)

- over an **acceptance** as **wide** as possible :
  - $|\eta| < 4$ (x5-9 acceptance of ALICE 2 barrel)
  - $p_T \in [\ 0.05\ ; (>10)\ ]$ GeV/c

- able to collect **large integrated MB luminosities** :
  expected recorded readout
  ≈ 24 MHz (pp) (x25-50 ALICE 2 Run 3)
  ≈ 100 kHz (Pb-Pb projection by LHC, x2 Run 3)
  $\mathcal{O}(0.5\ fb^{-1})$ / month pp
  $\mathcal{O}(5.6\ nb^{-1})$ / month Pb-Pb

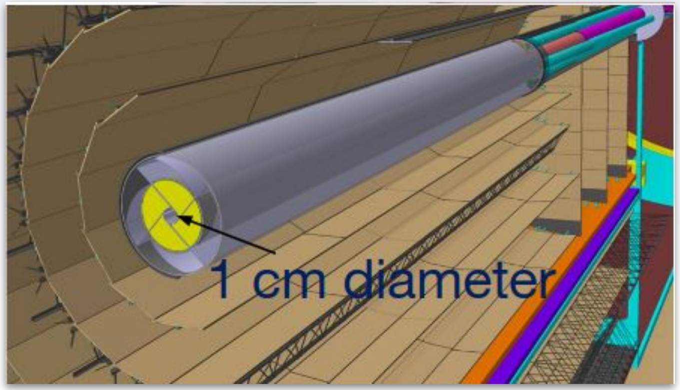


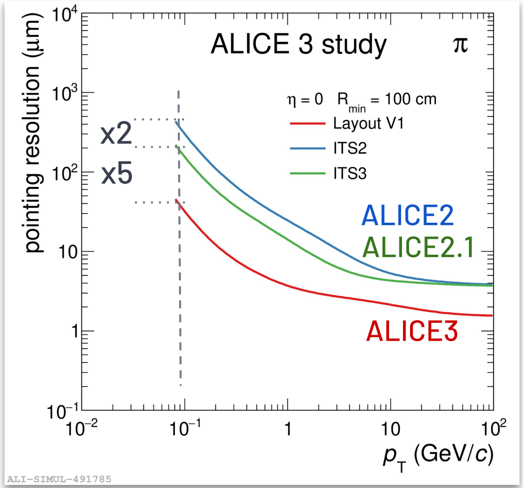
Vertex detector

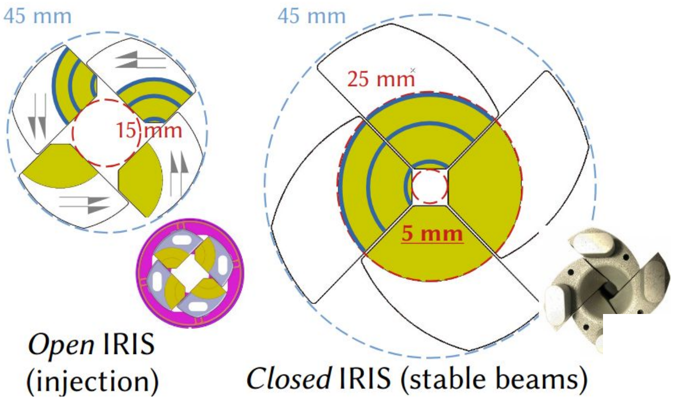
Concept and design:

- Retractable detector:
  3 detection layers (barrel + disks) in secondary vacuum **within the beampipe**
  → up to factor 5 improvement achievable with the 5 mm inner radius
- Wafer-sized, **stitched and bent** 65 nm CMOS Monolithic Active Pixel Sensor (**MAPS**) technology, leveraging ITS3 R&D
- Extremely **low material budget** (0.1 % X/X_0 per layer)

→ unprecedented **spatial resolution 2.5 μm**







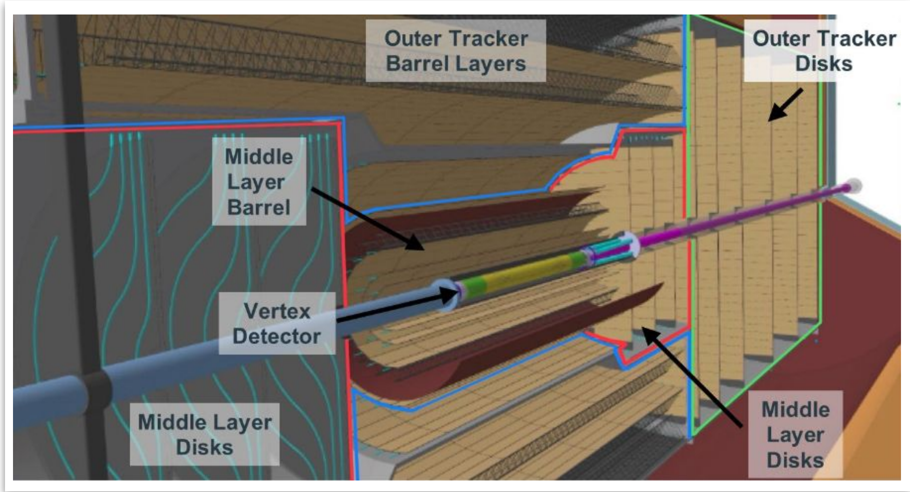
Middle and Outer Trackers

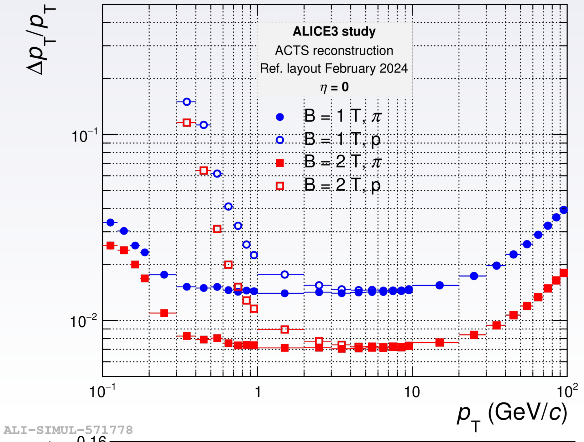
Design:

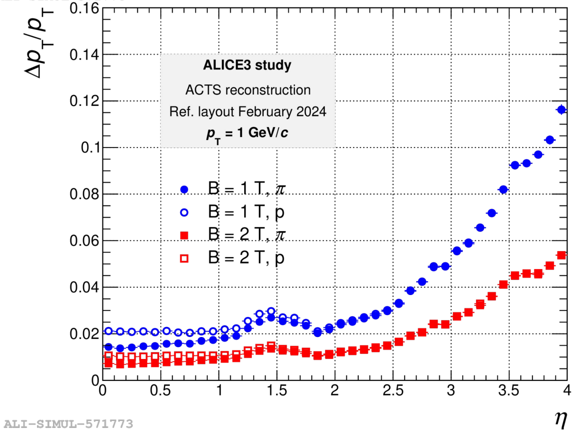
- 60 m^2 of CMOS MAPS
- R_{out} ~ 80 cm, |z| < 350 cm
- 8 barrel layers + 2x9 disks
- ~1% X/X_0 per layer material budget

Performance:

~10 μm spatial resolution (up to 50 μm pitch)







Particle Identification detectors

TOF

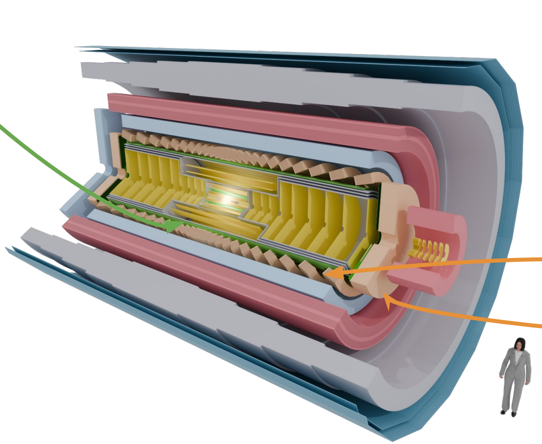
Requirements

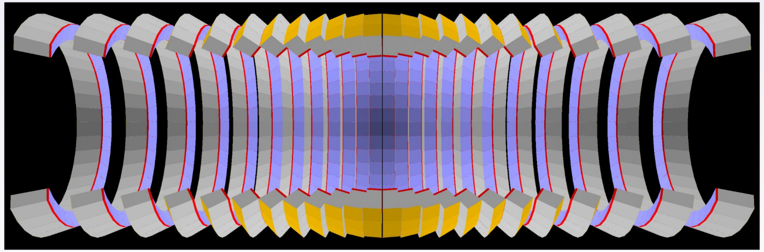
- e/π, π/K, K/p 3σ separation up to ≈ 0.2, 2, 4 GeV/c

$\rightarrow f(L/\sigma_{TOF})$, calling for $\sigma_{TOF} \approx 20$ ps

Layout:

- barrel : Inner TOF ($1.5\ m^2$), Outer TOF ($37\ m^2$)
- forward + backward: disks ($2\times 3.1\ m^2$)





Projective cylindrical bRICH

RICH

PID beyond TOF limits:

- 3σ separation e/π, π/K and K/p up to ≈ 2, 10 and 16 GeV/c, respectively

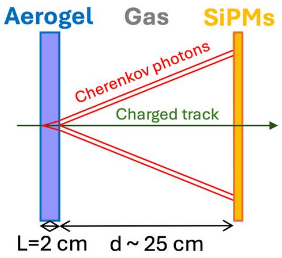
$\rightarrow n = 1.03$ (barrel)

$\rightarrow n = 1.015$ (forward)

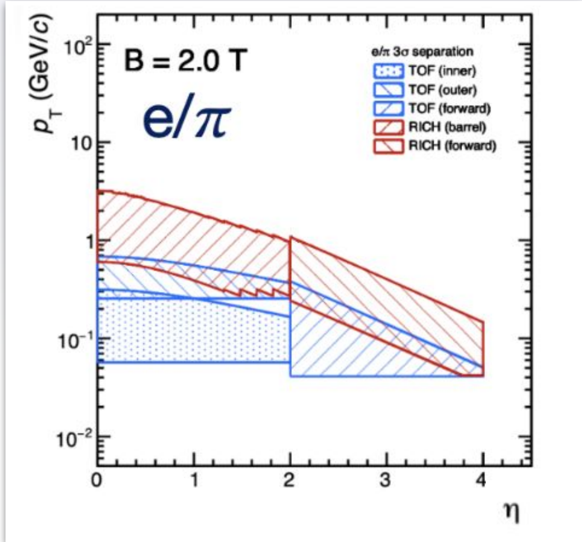
$\rightarrow \sigma_{RICH} \approx 1.5$ mrad at saturation

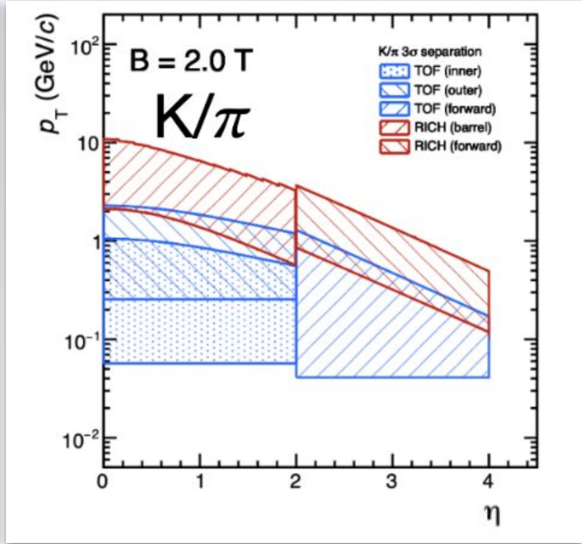
Layout:

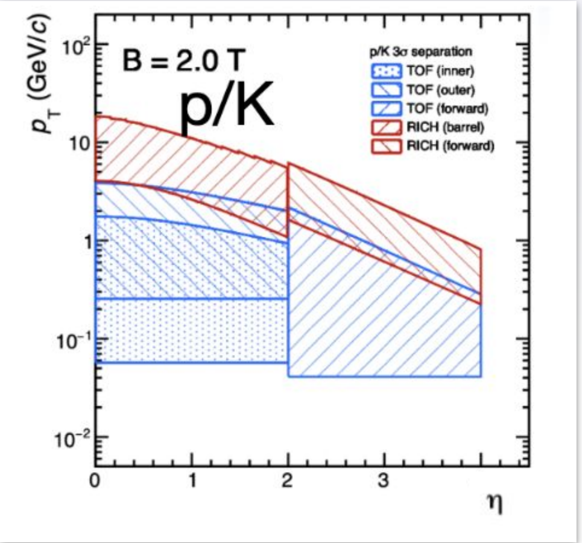
- bRICH : Aerogel + SiPMs ($\approx 30\ m^2$)
- fRICH : Aerogel + HRPPDs ($\approx 8\ m^2$)



Combined TOF+RICH PID performance







3σ e/π separation:

TOF $p_T \lesssim 0.5$ GeV/c
RICH $p_T \lesssim 2$ GeV/c

3σ K/π separation:

TOF $p_T \lesssim 2$ GeV/c
RICH $p_T \lesssim 10$ GeV/c

3σ p/K separation:

TOF $p_T \lesssim 4$ GeV/c
RICH $p_T \lesssim 16$ GeV/c

Multi heavy-flavor hadrons production

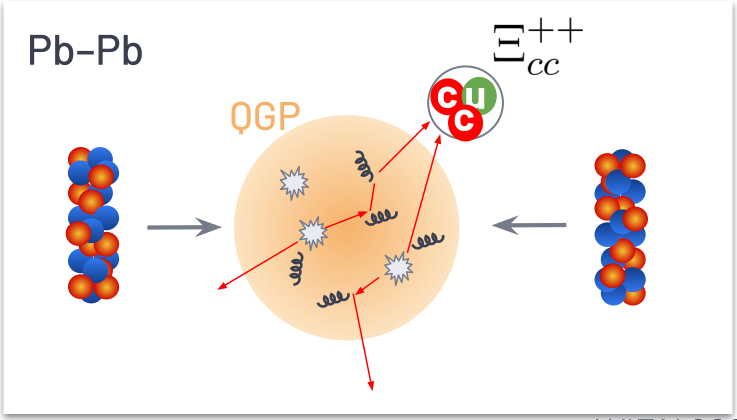
Heavy quarks (HF) produced only via **hard scatterings** before **QGP** formation:

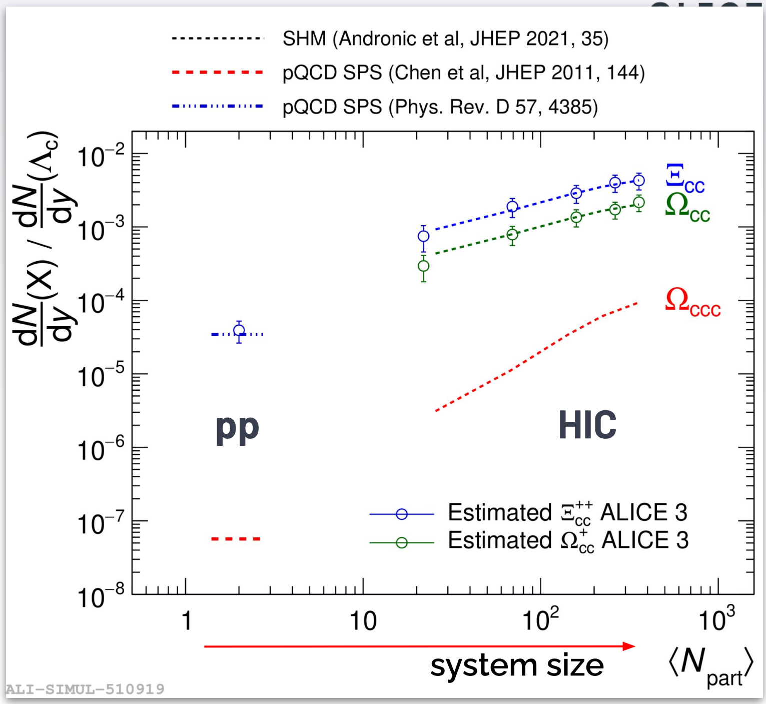
→ experience the full evolution of the medium interacting with its elementary constituents

→ **partial thermalisation** brings heavy quarks close in phase space

→ **coalescence** (recombination) main hadronisation mechanism at low-p_T

Multi-charm hadron yields in HIC > 100x larger than in pp



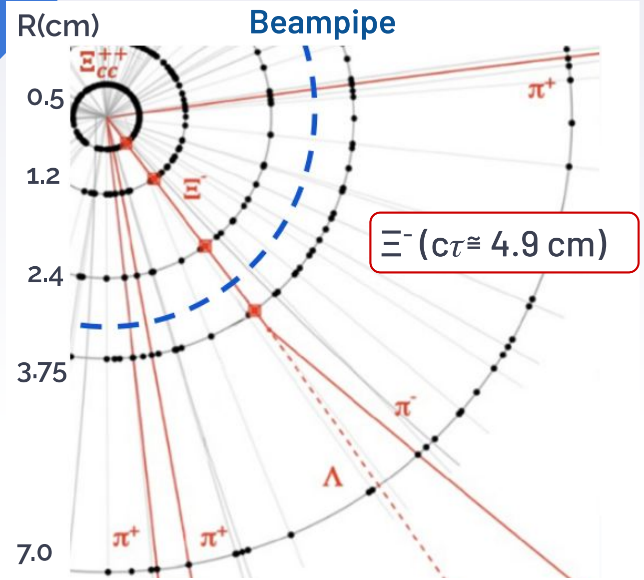


Yield ratios (Ξ_{cc}/D, Ω_{cc}/Ξ_c) sensitive to:

→ charm-quark density in the medium

→ degree of heavy-quark thermalisation

Strangeness tracking



Novel approach for the reconstruction of **multi-charm baryons:**

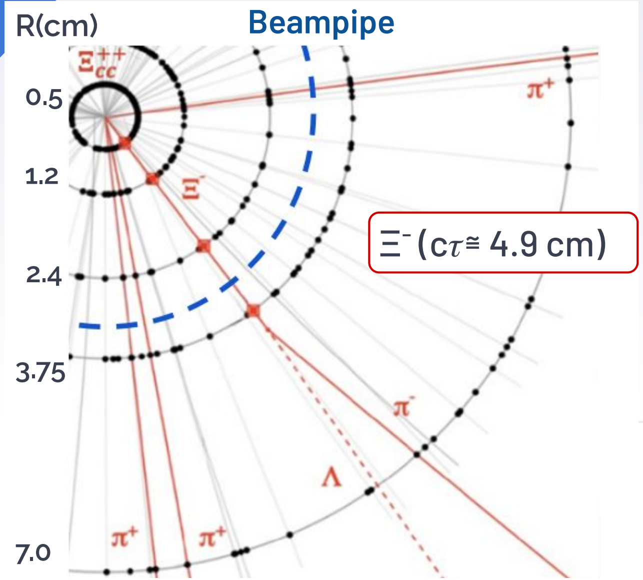
$$\left.\begin{array}{l}\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+} \rightarrow \Xi^{-}3\pi^{+} \rightarrow \Lambda\, 3\pi^{+}\pi^{-} \\ \qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow p\,\pi^{-}\end{array}\right\}$$

~~6-prong decay~~

4-prong

→ Ξ^- (strange particles) tracked before their decay thanks to VD inside the beam pipe

Strangeness tracking



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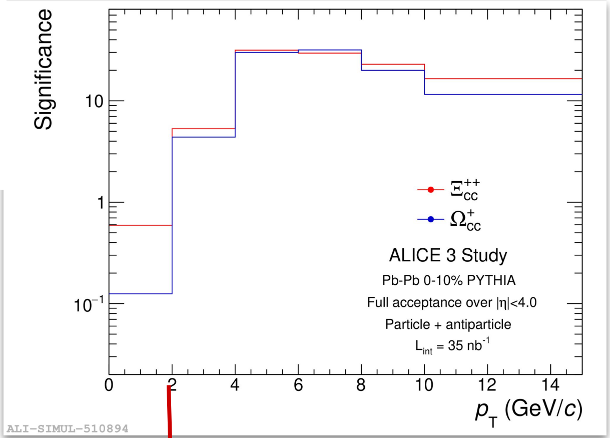
~~6-prong decay~~ 4-prong

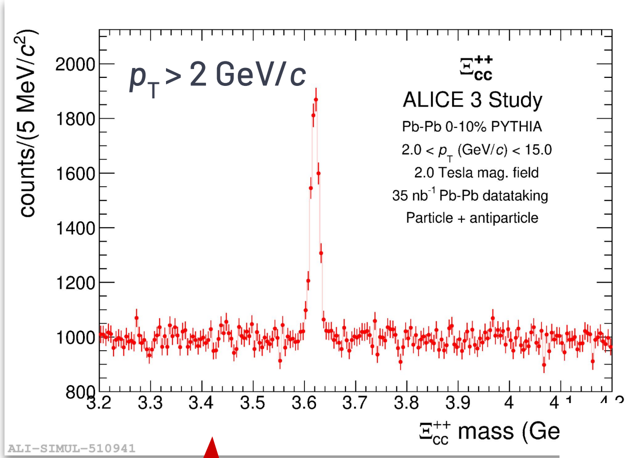
→ Ξ^- (strange particles) tracked before their decay thanks to VD inside the beam pipe

The ultimate challenge: Ω_{ccc}

- unknown branching ratios,
- unknown lifetimes

Detector capable, but large integrated luminosity needed



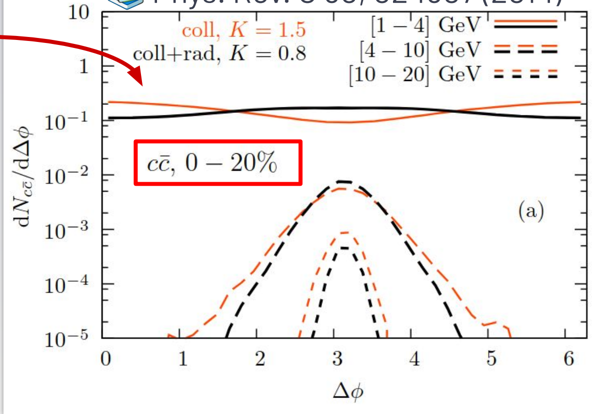


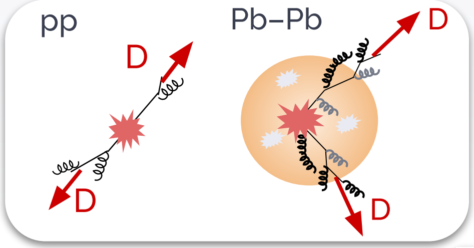
D-$\bar{\mathrm{D}}$ angular correlations

Sensitive to charm energy loss and degree of thermalization in medium:

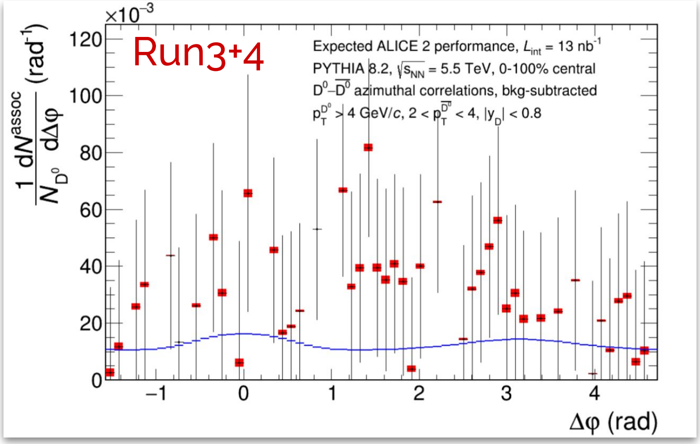
→ momentum decorrelation between charm hadrons keep traces of charm interactions with the medium

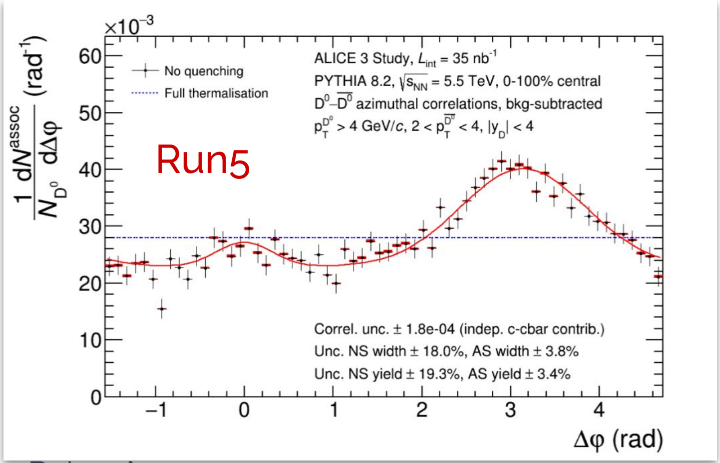
Phys. Rev. C 90, 024907(2014)



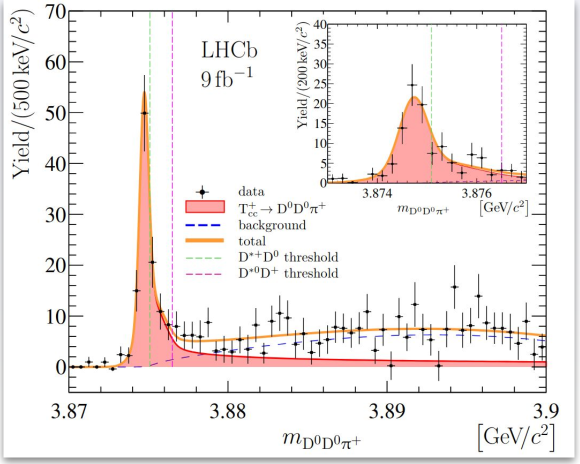


Measurement projections:



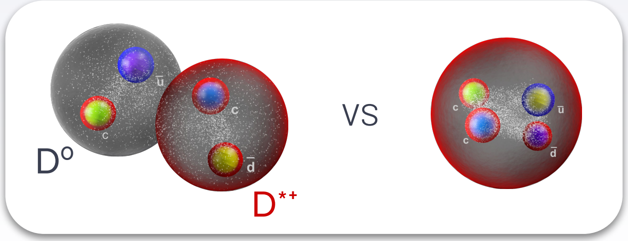


Heavy-flavour exotica



Nature Communications, 13, 3351 (2022)

Understanding the molecular vs. tetraquark nature of exotic states (T_{cc}^{+}).



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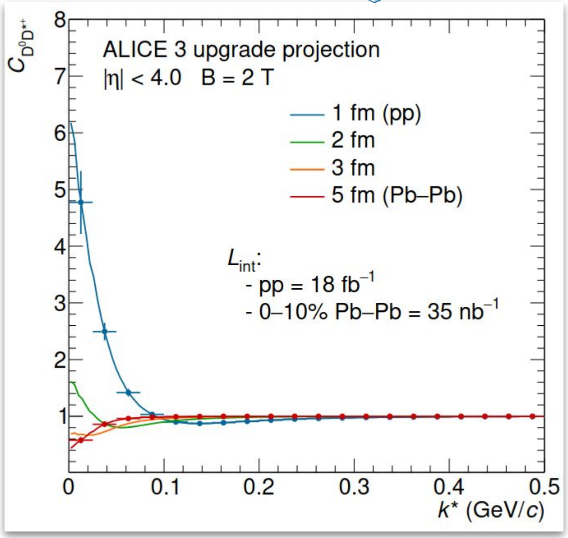
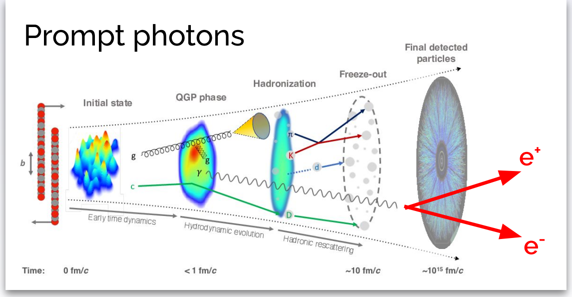


D^0D^{*+} momentum correlations of charm hadrons provide direct access to the hadron–hadron interaction potentials in the heavy-flavour sector.

→ determination of the residual strong interaction between charm mesons and exploration of possible charm nuclei

Expected to be fully within the experimental reach of the ALICE 3 detector

Medium temperature evolution



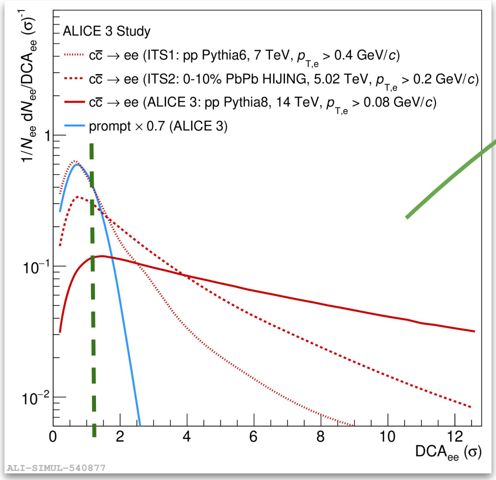
Dileptons are produced at all stages of heavy-ion collisions,

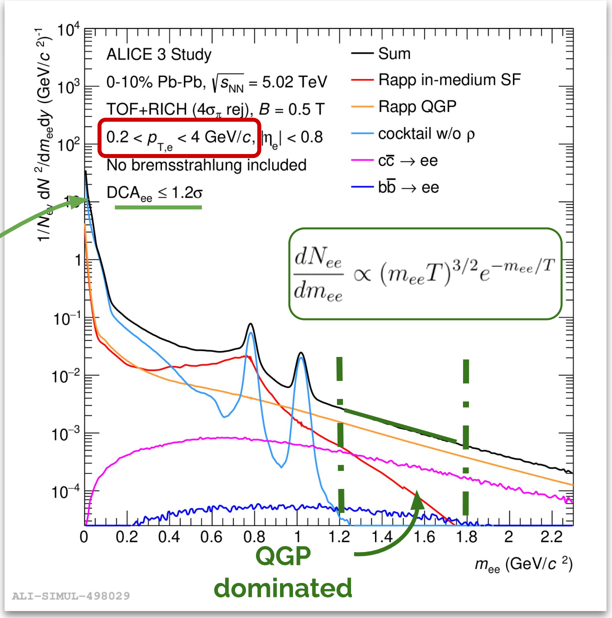
→ escape the QGP with minimal interaction:

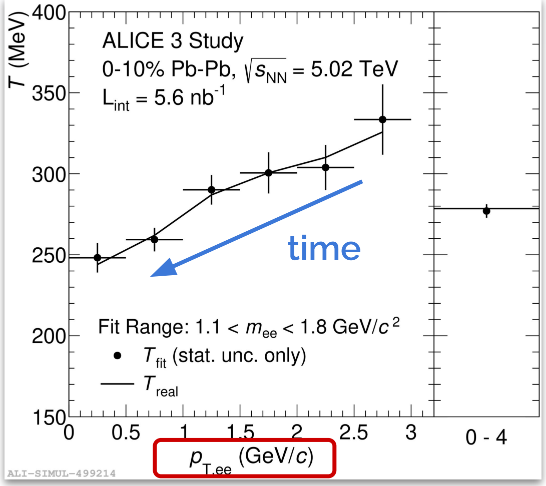
→ providing direct access to the properties of the early stages of collision

→ tracing the time evolution of the QGP temperature

Effective prompt / non-prompt separation
→ excellent DCA_{ee} resolution of ALICE 3





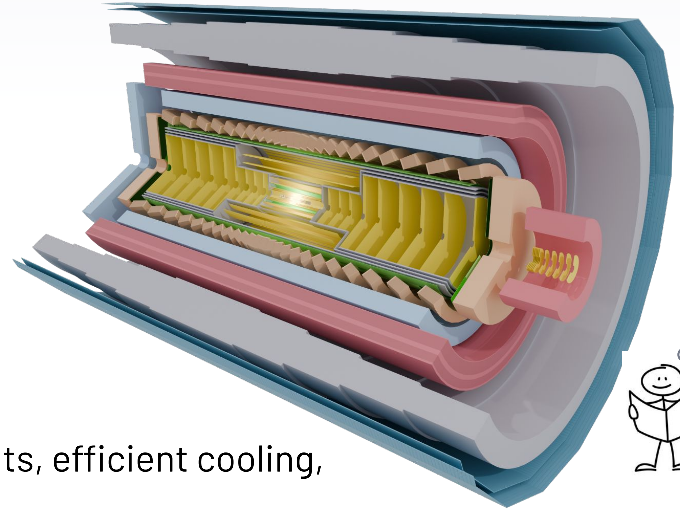


Conclusions

The **HL-LHC** provides unique conditions to study heavy-ion collisions, enabling the exploration of QCD matter under extreme conditions with unprecedented precision.

ALICE 3 will grant access to a rich and diverse physics programme to address open questions in hot and dense QCD and beyond:

- Production of multi-heavy-flavor baryons
- Heavy-flavor correlations
- Exotica
- Temperature evolution of the QGP fireball
- Signatures of chiral symmetry restoration
- ...



Pioneering R&D for future HEP experiments:

- Radiation tolerance, low-material budget requirements, efficient cooling, lightweight mechanics, ...