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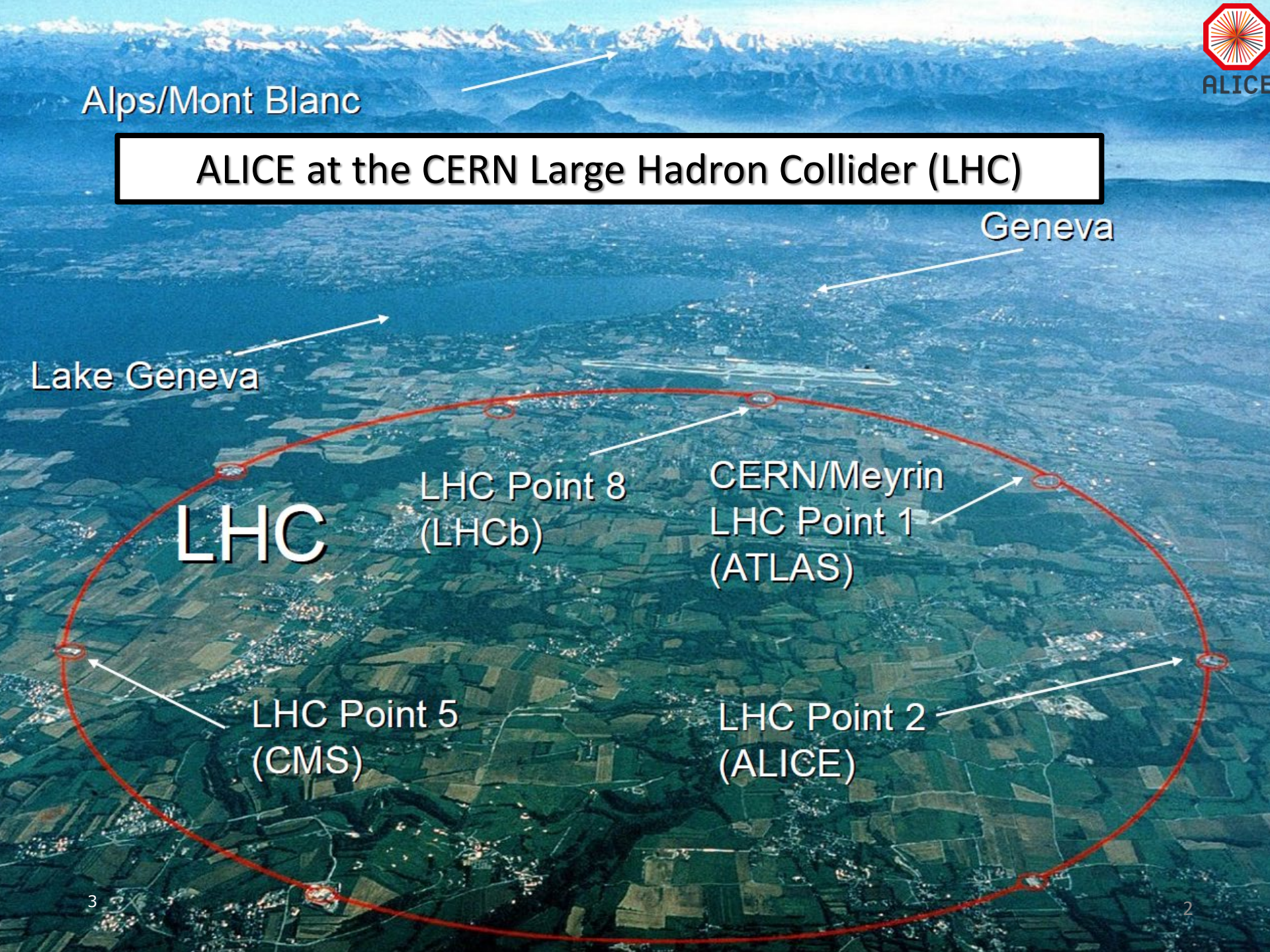
Highlights of ALICE results from heavy-flavour measurements at LHC energies

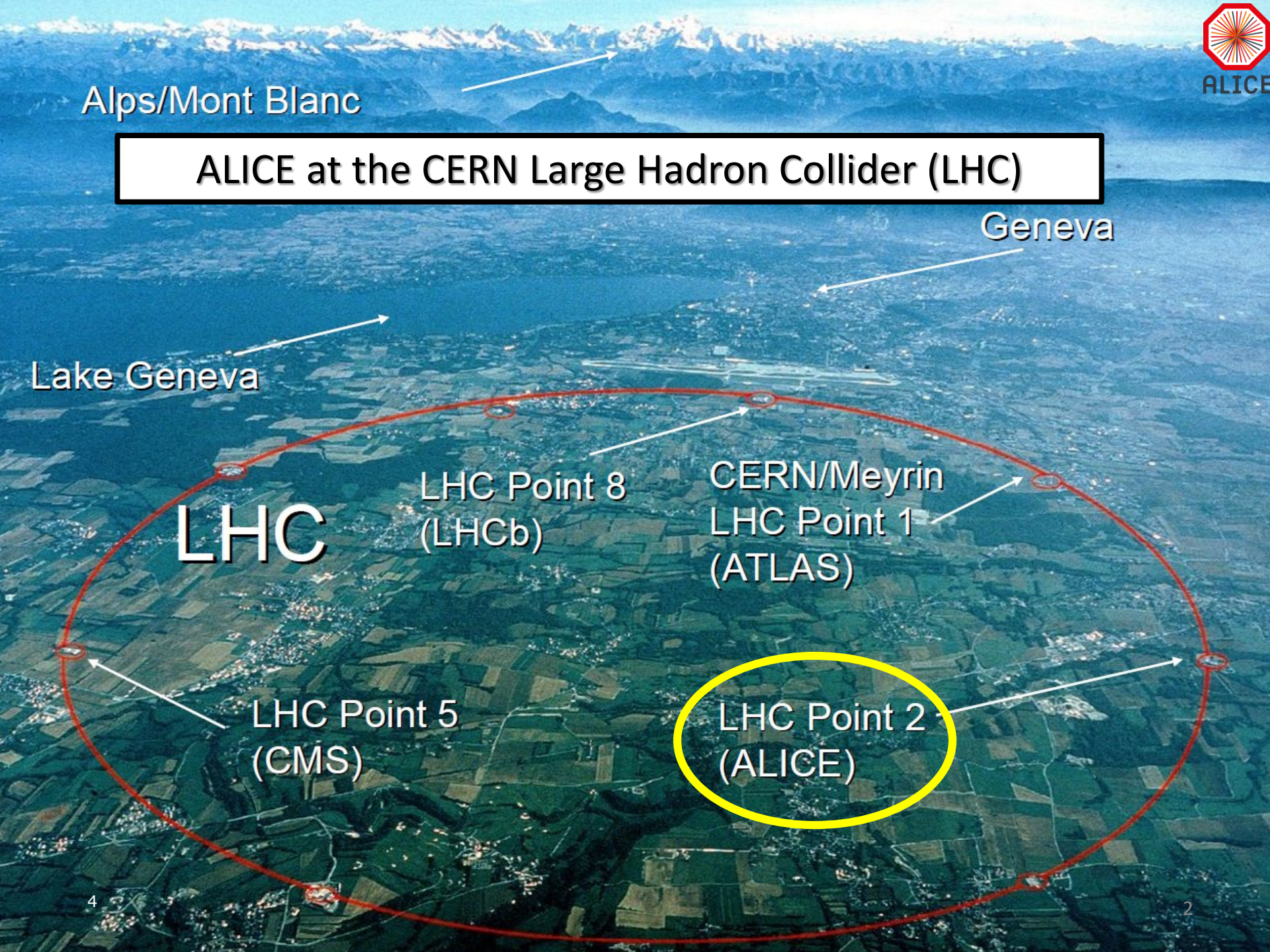
Edith Zinhle Buthelezi
For the ALICE Collaboration

ALICE

SAIP 2025, University of Witwatersrand
7-11 July 2025

ALICE at the CERN Large Hadron Collider (LHC)


Alps/Mont Blanc
ALICE at the CERN Large Hadron Collider (LHC)
Geneva
Lake Geneva
LHC
LHC Point 8
(LHCb)
CERN/Meyrin
LHC Point 1
(ATLAS)
LHC Point 5
(CMS)
LHC Point 2
(ALICE)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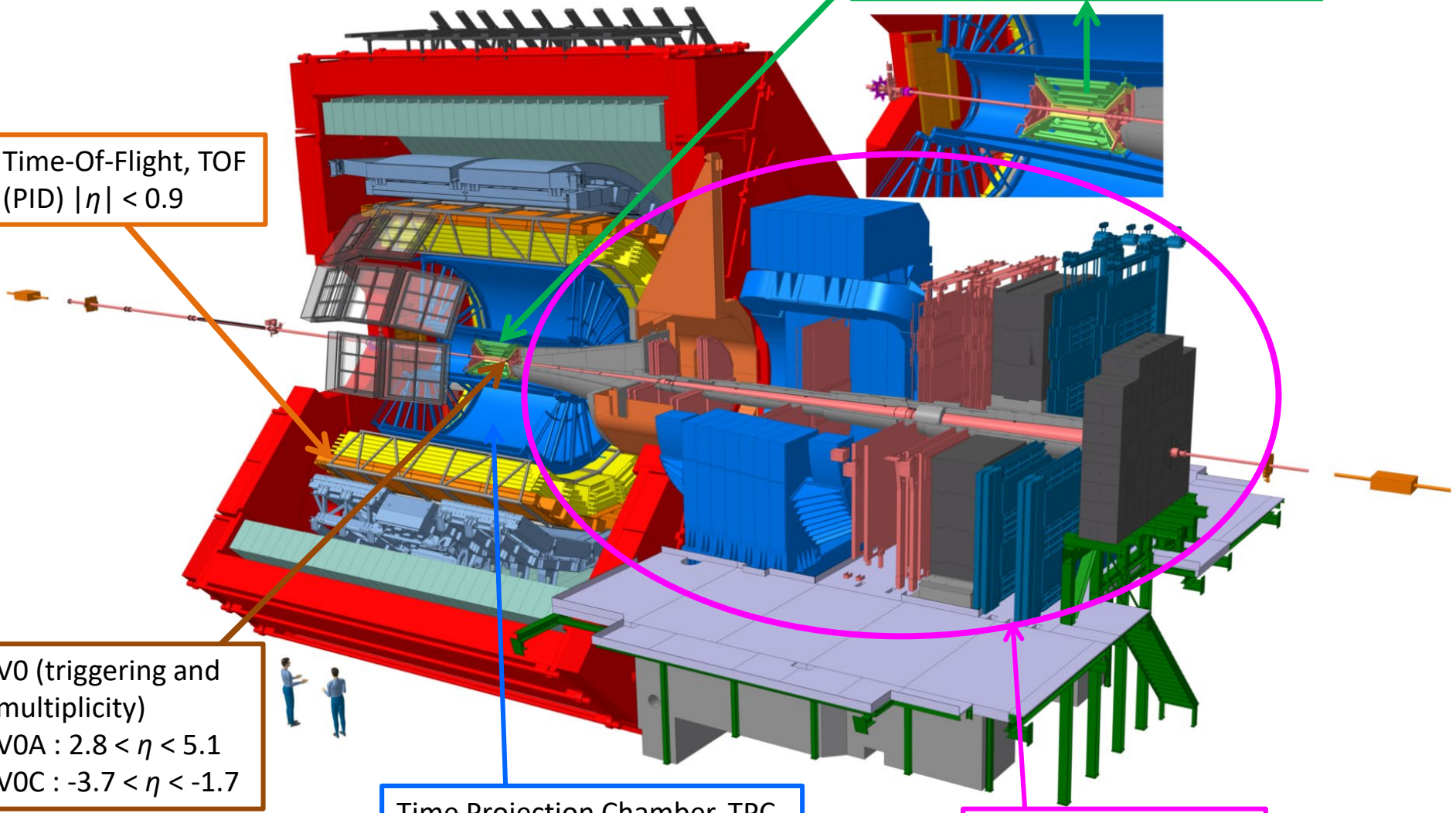
ALICE detector Run 1 and Run 2

Size: 16 x 16 x 26 meters
Weight: 10 000 tons



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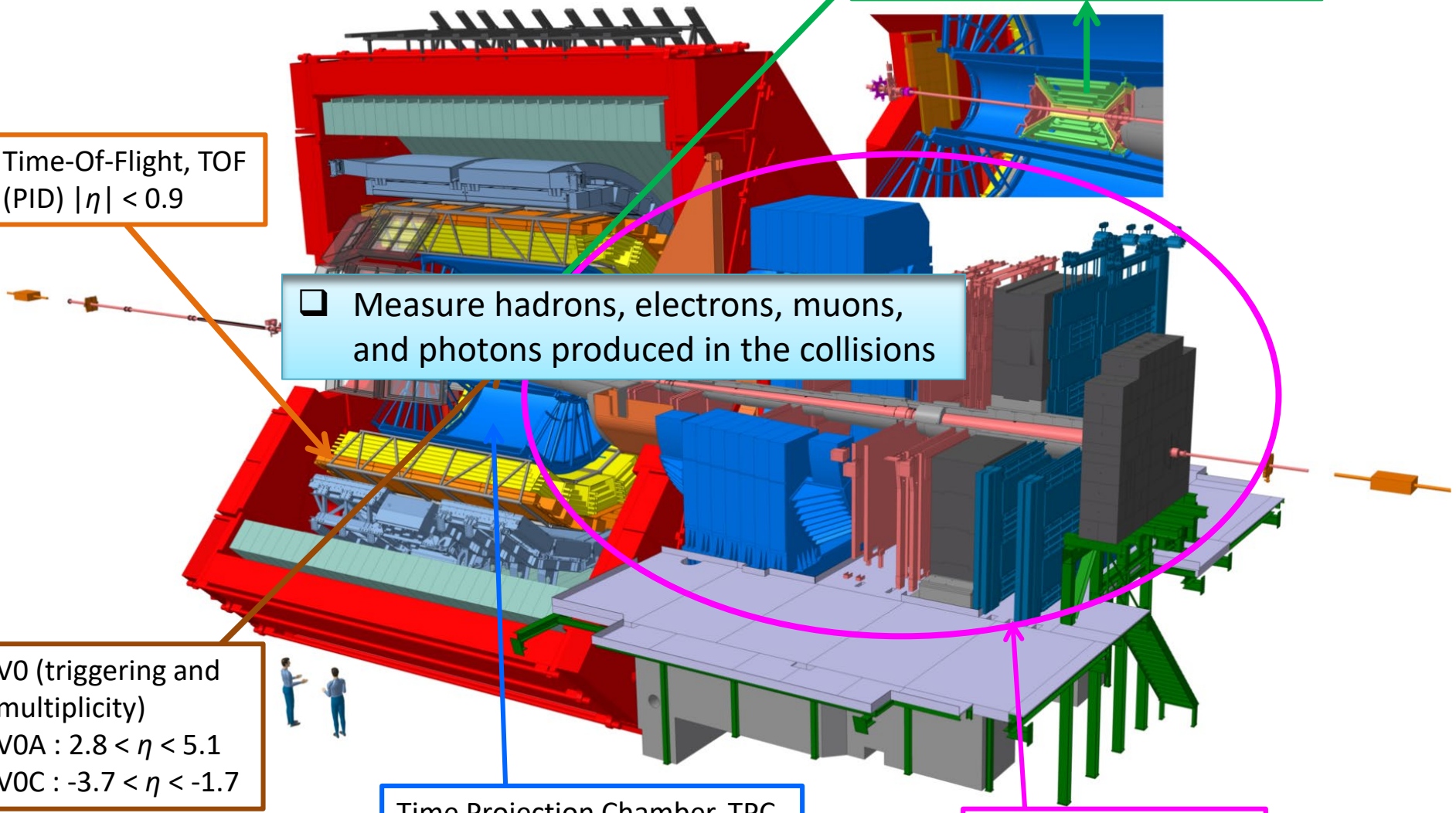


Inner Tracking System, ITS
(tracking, vertexing, PID) $|\eta| < 0.9$

Time-Of-Flight, TOF
(PID) $|\eta| < 0.9$

- Measure hadrons, electrons, muons, and photons produced in the collisions

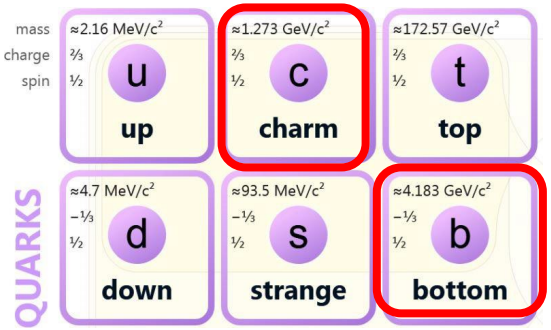
V0 (triggering and multiplicity)
V0A : $2.8 < \eta < 5.1$
V0C : $-3.7 < \eta < -1.7$

Time Projection Chamber, TPC
(tracking and PID) $|\eta| < 0.9$

Muon Spectrometer:
$-4.0 < \eta < -2.5$

Why heavy quarks?

- Heavy quarks are produced in initial hard-parton scatterings in hadronic collisions with high momentum transfer
- Formation time compared to the quark-gluon plasma (QGP) in ultra-relativistic lead-lead (Pb-Pb) collisions

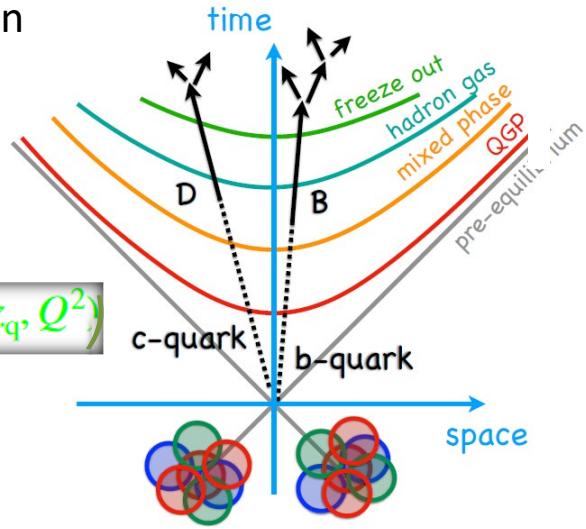


→ $\tau_{HF} \lesssim \hbar/m \approx 0.05\text{-}0.1$ fm/c (p_T dependent)

→ $\tau_{QGP\ formation}$ (LHC) ≈ 0.3 fm/c PRC89 (2014) 034906

- They experience the whole evolution of the QGP

→ "calibrated probes" of final-state effects, including **hadronisation,** in all collision systems: proton-proton (pp), proton-lead (p-Pb) and lead-lead (Pb-Pb)



- Cross sections described with a factorisation approach in quantum chromodynamics (QCD)

$$d\sigma_{AB\to H} = PDF(x_a, Q^2)PDF(x_b, Q^2) \otimes \sigma_{ab\to qq}(x_a, x_b, Q^2) \otimes P(\Delta E) \otimes D_{q\to H}(z_q, Q^2)$$

→ Parton distribution functions

→ Partonic cross section (perturbative)

→ Energy loss

→ Fragmentation functions (non-perturbative)

Until very recently, hadronisation of heavy quarks into mesons or baryons, which occurs on a long space-time scales was considered to be universal, i.e. independent of the colliding particle system, in particular the same in e^+e^- and pp collisions [ALICE, Phys. Rev. D 105, L011103 (2022)]

Heavy-quark production and hadronisation

Large data samples collected during LHC Run 2 (2015-2018) allowed ALICE to measure charm and beauty quarks produced in pp and Pb-Pb collisions by reconstructing the decays of several beauty and charm hadron species

- Investigate the hadronisation mechanism of charm quarks with Λ_c^+/D^0 baryon-to-meson cross section ratios

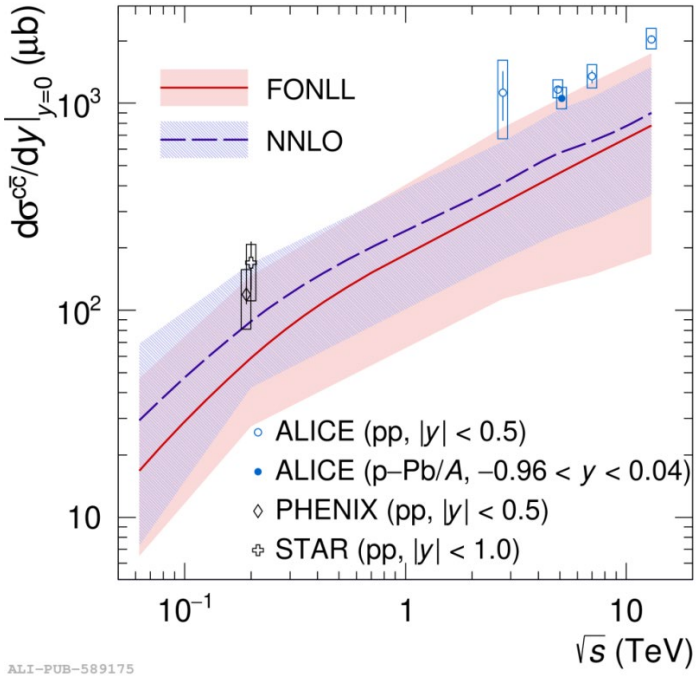
- Test of perturbative QCD (pQCD) calculations of charm and beauty production relying on the factorisation approach and the assumption that fragmentation functions, determined in collisions of small systems, e.g. e^+e^- collisions can be used in pp ("universality")

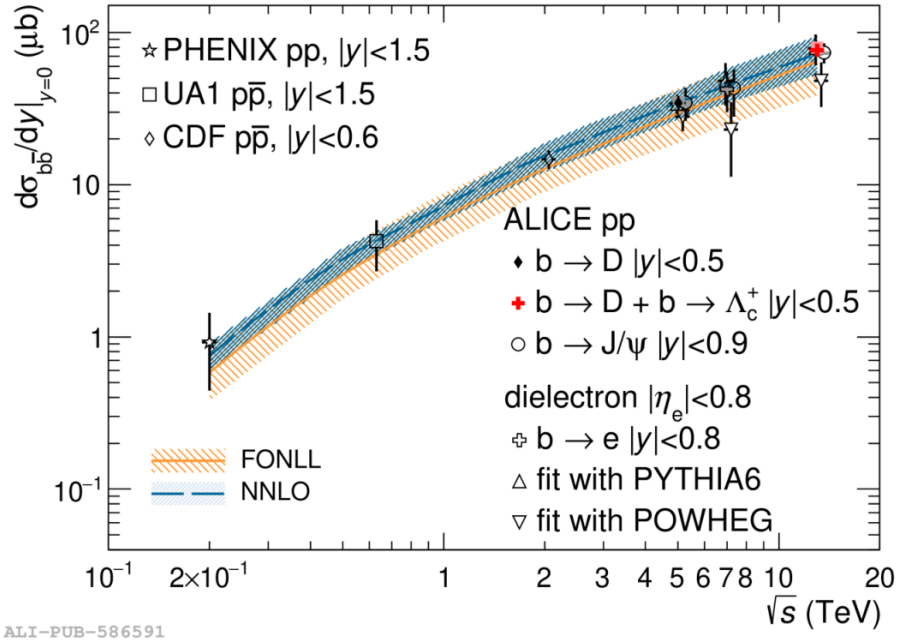
- How does hadronisation evolve across systems from collisions of small systems (e^+e^-) to heavy-ion collisions (AA)?

Charm and beauty production cross section vs. energy

ALICE, Eur. Phys. J. C (2024) 84:1286 ALICE, JHEP10(2024)110

- Total $c\bar{c}$ and $b\bar{b}$ cross sections in pp and pPb collisions at $\sqrt{s_{NN}}$ = 5.02 and 13 TeV, respectively at mid-rapidity
- $c\bar{c}$ cross sections: summing all prompt charm (D^0, D^+, D_s^+) and J/ψ mesons, and Λ_c^+ and Ξ_c^0 baryons
- $b\bar{b}$ cross sections: calculated from non-prompt D^0, D^+, D_s^+, and Λ_c^+





- Test of pQCD calculations: Experimental data lie on the upper edge of FONLL and NNLO uncertainty bands

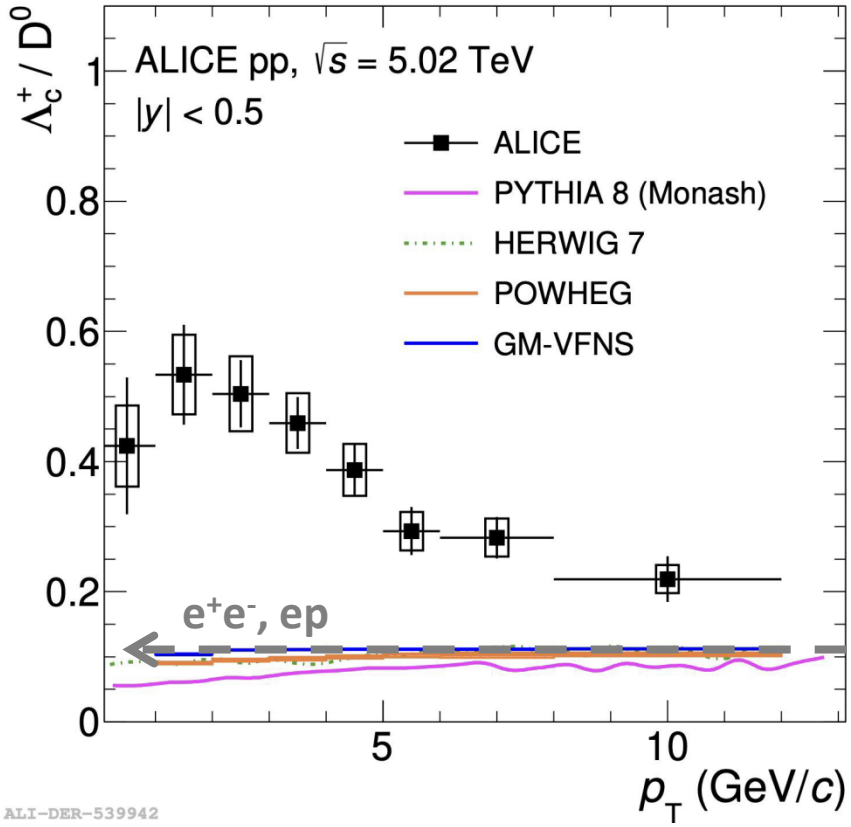
PHENIX, Phys.Rev. C 84, 044905 (2011), Phys. Rev.Lett. 103 (2009) 082002,
STAR, Phys. Rev. D 86, 072013 (2012),
FONLL, JHEP 05 (1998) 007, NNLO, JHEP 03 (2021) 029

UA1, [Phys. Rev. D 75 (2007) 012010],
CDF, Phys. Lett. B 256 (1991) 121

Charm baryon-to-meson cross-section ratio in pp collisions

ALICE, JHEP 12 (2023) 086

- Strong enhancement of Λ_c^+/D^0 baryon-to-meson cross section ratios in pp vs. e^+e^- collisions: ~4-5x higher at low p_T than in e^+e^-
- Data not described by PYTHIA 8 and pQCD models tuned on measurements performed in e^+e^- collision, which works well for mesons



ALICE: PRC 104 054905 (2021), PRL 127 202301 (2021), PRC 107 (2023) 6, 064901

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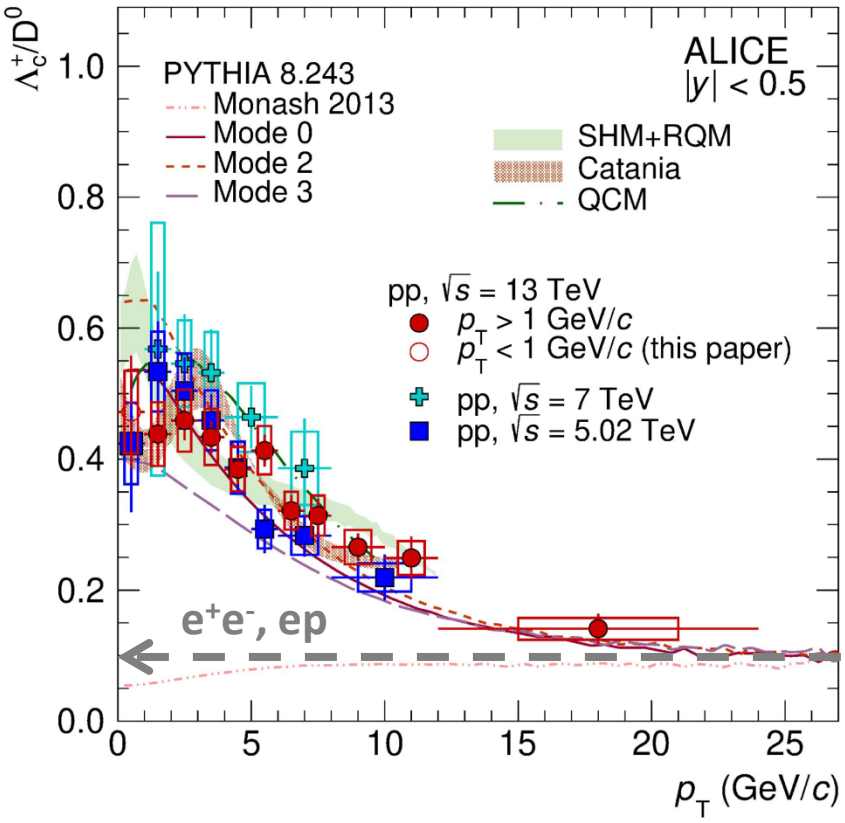

- No dependence on collision energy (compatible values at different collision energies)
- Approaching e^+e^- values at high p_T
- Good agreement with
  - PYTHIA 8 with colour reconnections beyond the leading colour
  - Quark coalescence (partons close in phase space can recombine)
  - Statistical hadronisation model (SHM) with an augmented set of charm-baryon excited states

ALI-PUB-546198

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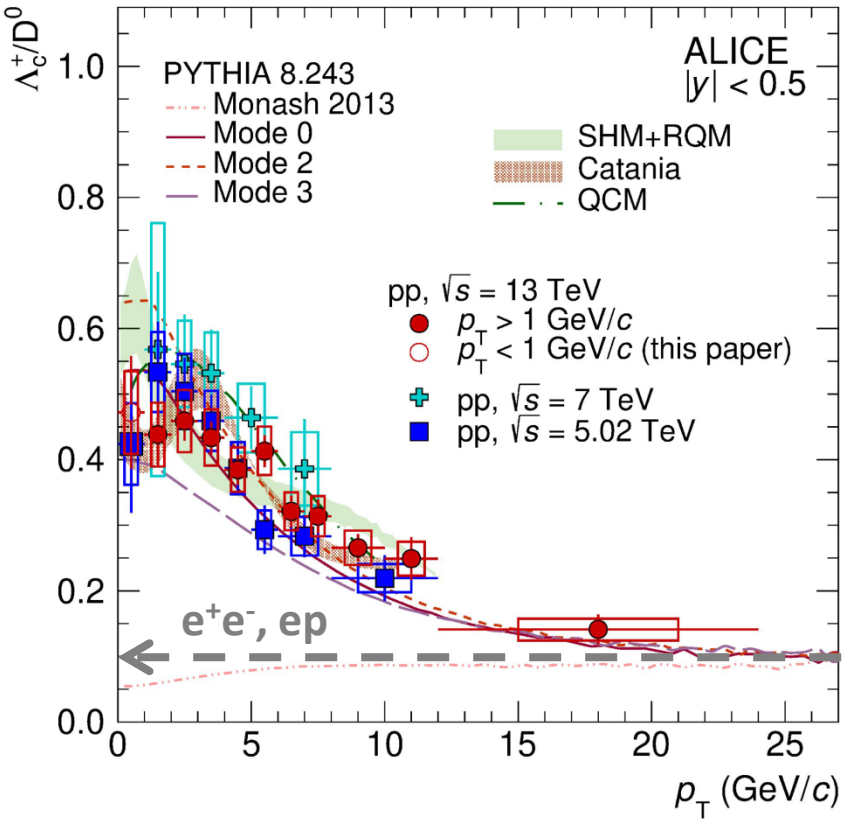

- No dependence on different collision energies
- Approaching e^+e^- values at high p_T
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  - PYTHIA 8 with colour reconnections beyond the leading colour
  - Quark-coalescence (partons close in phase space can recombine)
  - Statistical hadronisation model (SHM) with augmented set of charm-baryon excited states (compared to those listed in the PDG)

Hadronisation is not a universal process
Neither fragmentation (functions) are universal or sufficient; other mechanisms are needed

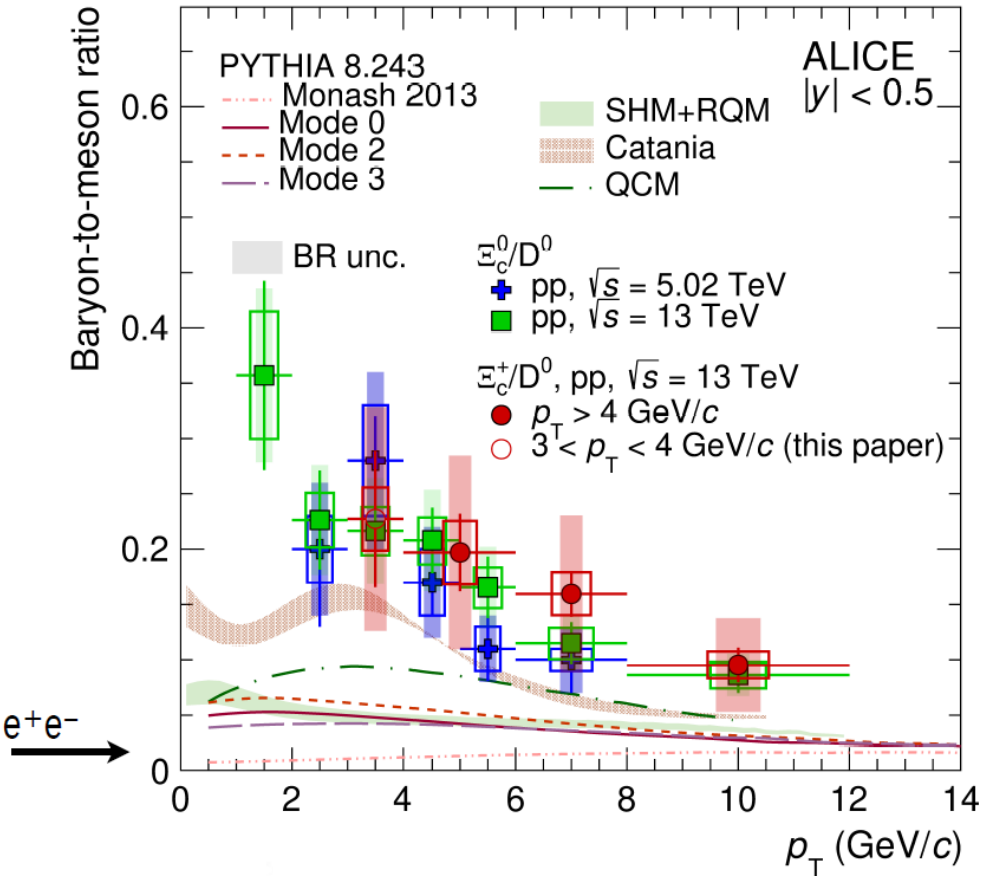
ALI-PUB-546198

ALICE: PRC 104 054905 (2021), PRL 127 202301 (2021), PRC 107 (2023) 6, 064901

Charm baryon-to-meson cross section ratio in pp collisions

ALICE, JHEP 12 (2023) 086

- $\Xi_c^{0,+}/D^0$ baryon-to-meson cross-section ratios at different pp collision energies



- Enhanced production of Ξ_c relative to D^0 in pp vs. e^+e^- collisions
- Similar trend to that of Λ_c^+/D^0

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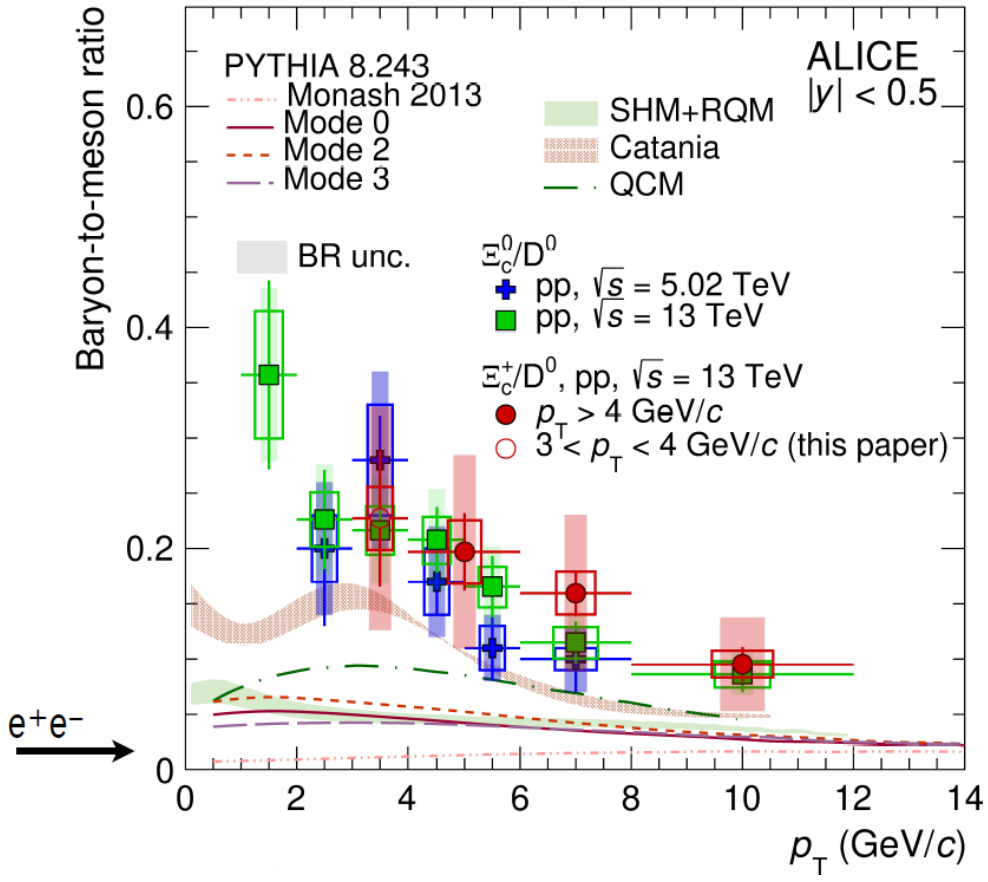

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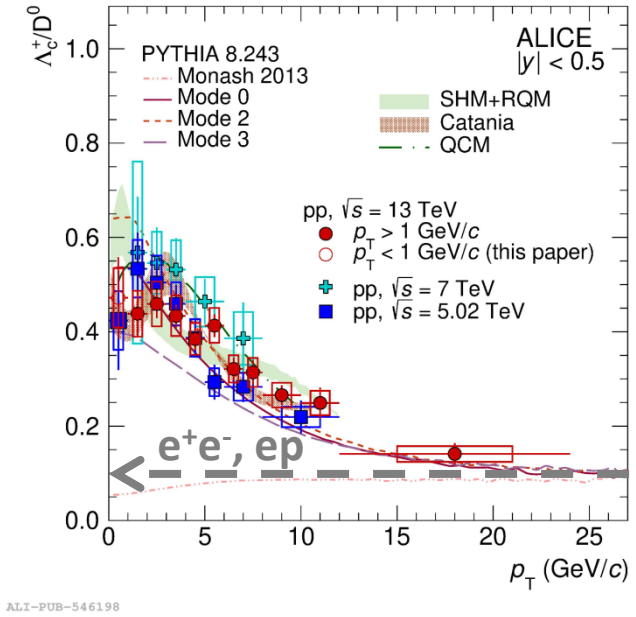

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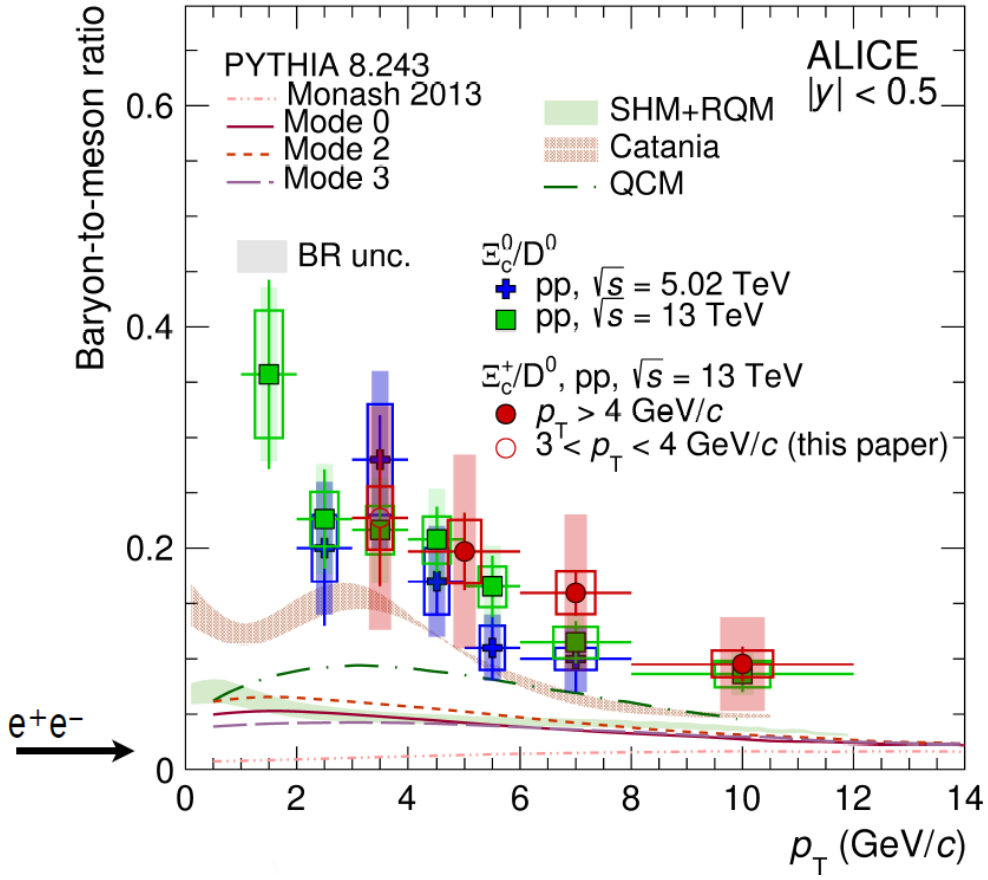

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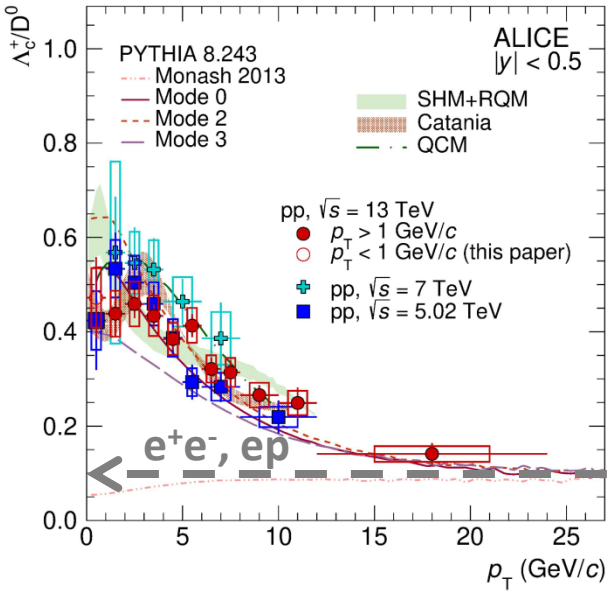
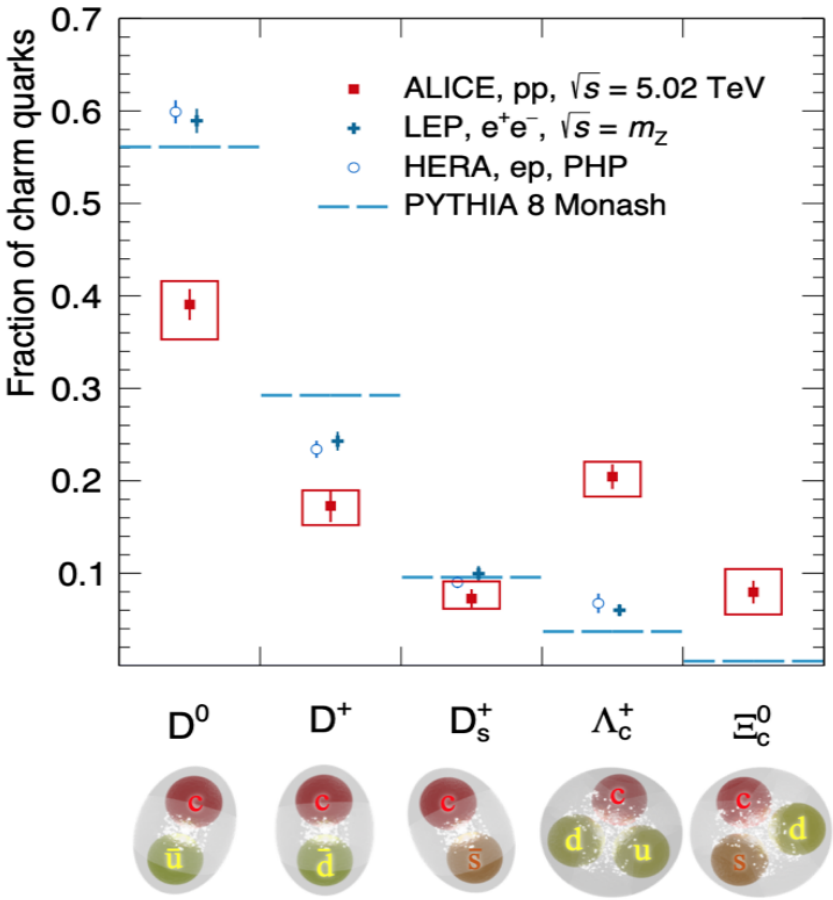


- Tension with predictions that describe Λ_c^+ production
  - Due to the strangeness content?
  - Difficult to conclude due to the large branching ratio uncertainties of different channels

Charm–quark fragmentation fractions in pp vs. e^+e^-

ALICE, Phys. Rev. D 105, L011103 (2022), JHEP 12 (2023) 086

- Fractions of charm-quark fragmentation into charm hadron species, pp collisions at √s = 5.02 and 13 TeV
- Obtained from direct measurement of ground-state meson and baryon cross sections



- Values for mesons significantly lower than in e^+e^- [1]

[1]Eur. Phys. J. C 76 no. 7, (2016) 397

Charm–quark fragmentation function in pp vs. e⁺e-

ALICE, Phys. Rev. D 105, L011103 (2022), JHEP 12 (2023) 086

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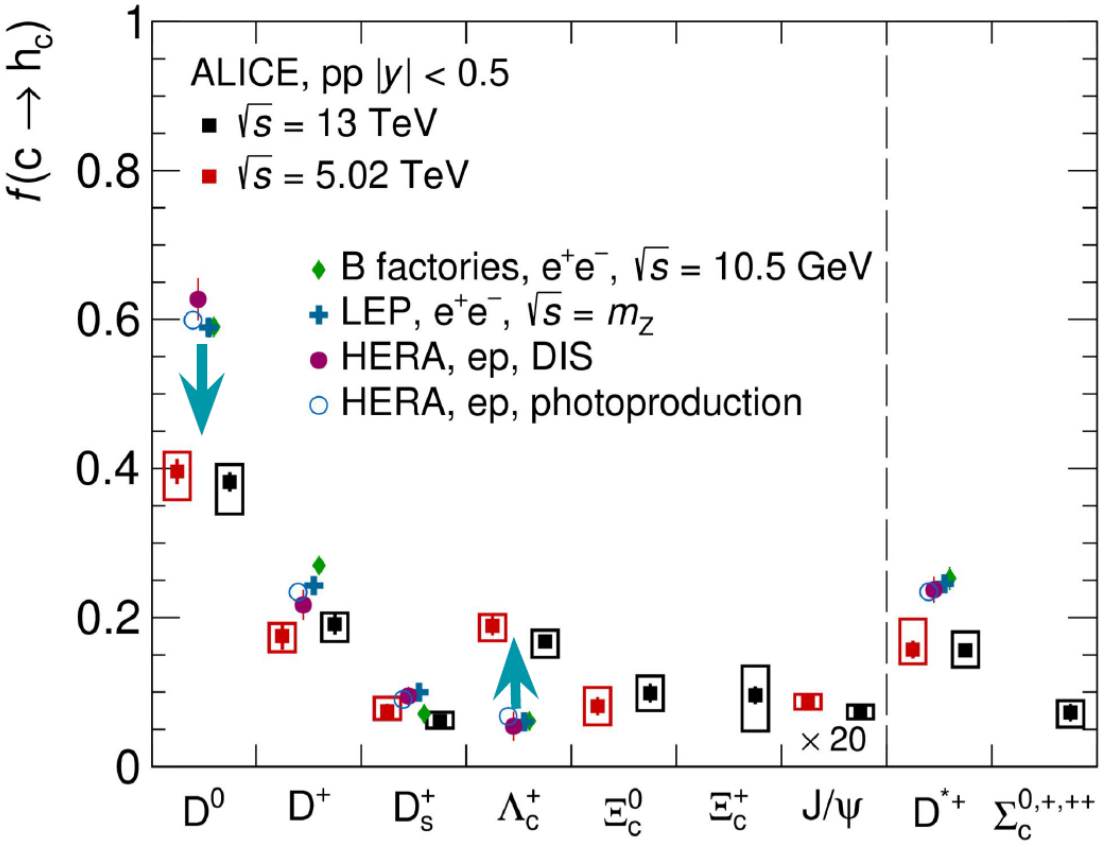


ALI-PUB-546222

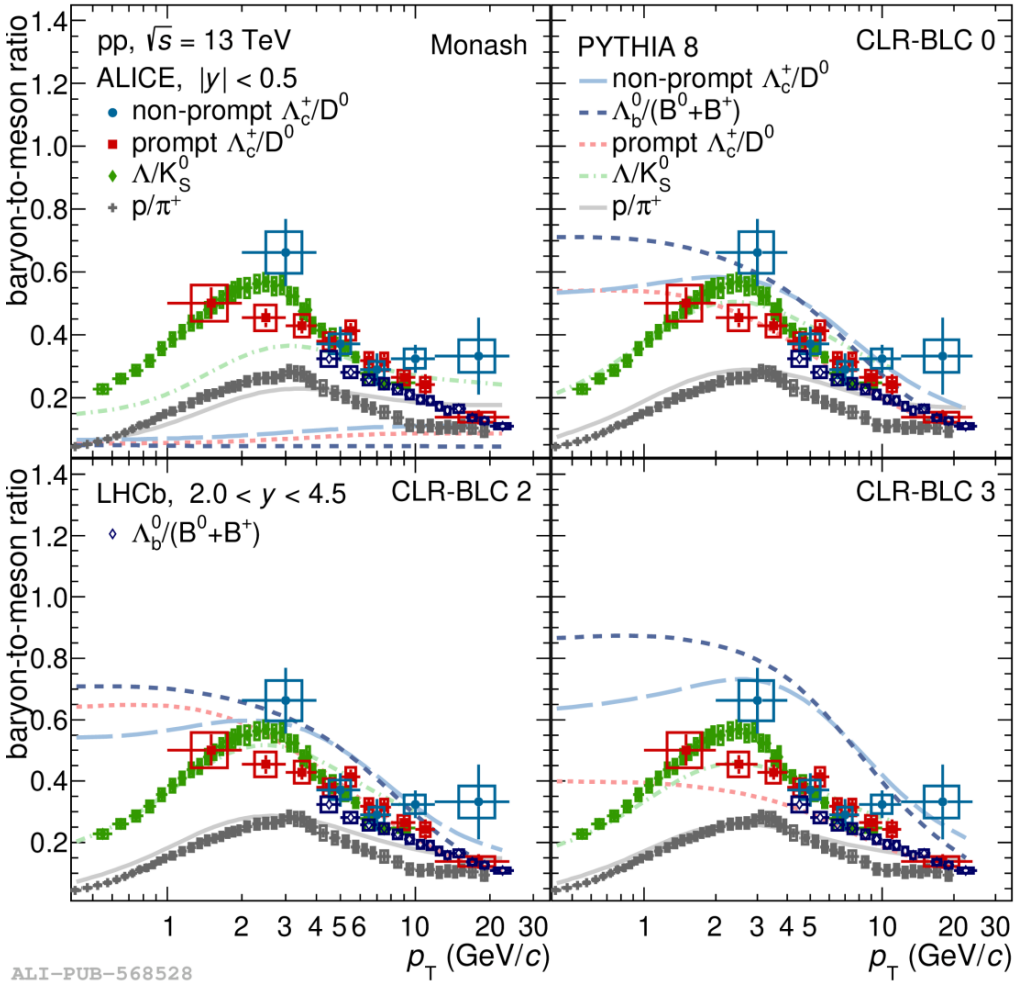
- Values for mesons significantly lower than in e^+e^- [1]
- A larger fraction of charm quarks form baryons, almost 40% of the time
  → 4x more than expectations based on e^+e^- and ep
- No evidence of energy dependence
- Lower p_T reach expected with Run 3 data will allow further reduction of extrapolation uncertainties

[1]Eur. Phys. J. C 76 no. 7, (2016) 397

Baryon-to-meson cross section ratios: beauty vs. charm and light flavour

PHYSICAL REVIEW D 108, 112003 (2023)

- Investigate the hadronisation mechanism of beauty quarks
- ALICE measurements at mid-rapidity vs. LHCb $\Lambda^0_b/(B^0+B^+)$ at forward rapidity ($2.5 < y < 4$) [1]



- Similar patterns of baryon-to-meson ratio for all flavours: light, strange, charm and beauty
  - ➢ suggest a similar baryon-formation mechanism for all flavours
- All ratios are significantly higher than in e^+e^- collisions, except for p/π^+
- All flavours needed to constrain MC and model parameters

Hadronisation is not a universal process already in pp, with large and not understood differences vs. e^+e^-

[1] LHCb, Phys. Rev. D 100,031102 (2019)
[2] PYTHIA, Comput. Phys. Commun. 191, 159 (2015
[3] TAMU, Phys. Lett. B 795, 117 (2019)

Heavy-quark hadronisation

- **Hadronisation is not a universal process: already in pp, with large and not understood differences w.r.t. e^+e^-**

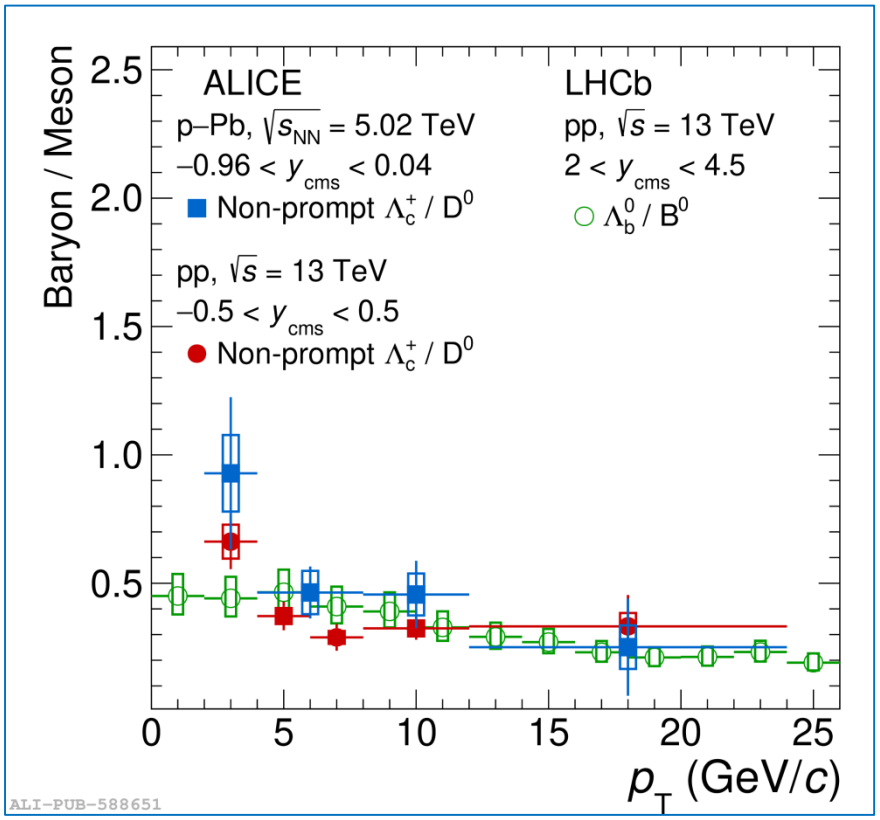
→ How does it evolve across systems from e^+e^- to AA?

- ✓ What regulates its modification?
- ✓ In which regimes does fragmentation dominate?
- ✓ Which models/mechanisms can better describe the data?

Baryon-to-meson cross section ratios in p-Pb: beauty vs. charm

Phys. Rev. C 107 (2023) 064901

- Non-prompt Λ_c^+/D^0 ratios to investigate hadronisation mechanisms of beauty quarks into mesons and baryons in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



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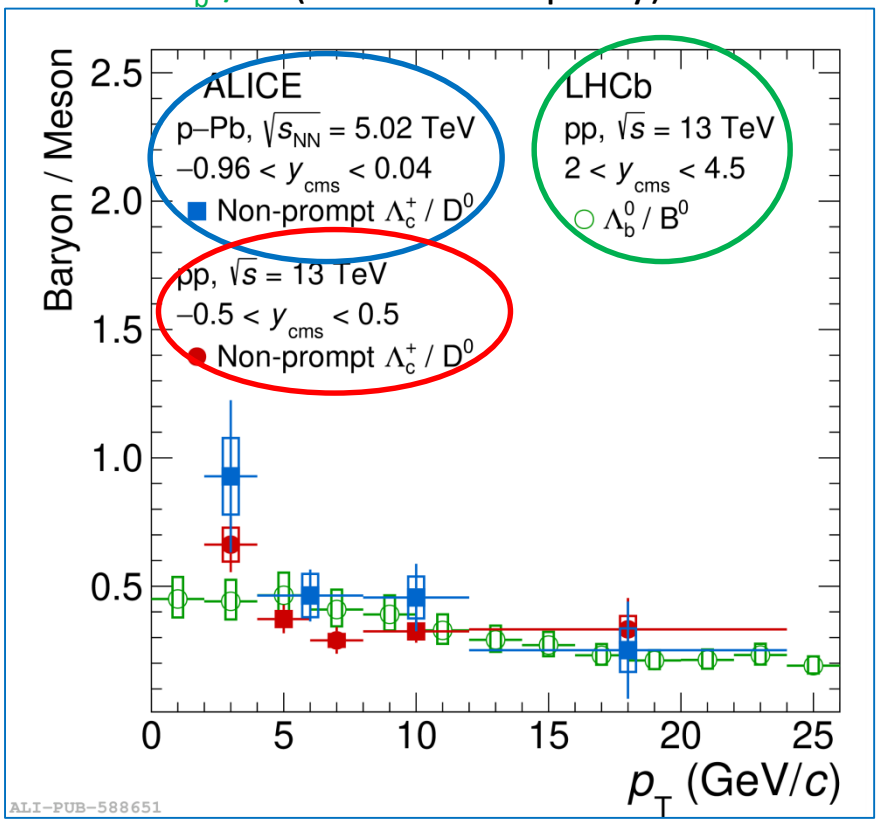
✓ pp collisions at 13 TeV non-prompt Λ_c^+/D^0 (mid rapidity)

✓ LHCb Λ_b^+/B^0 (at forward rapidity)



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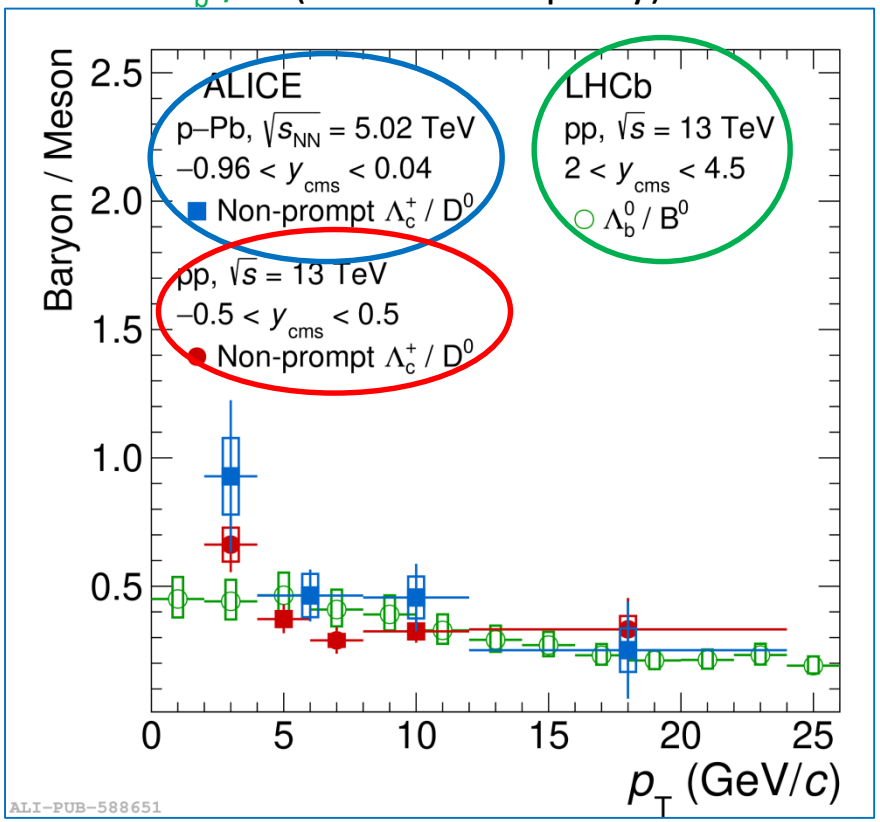
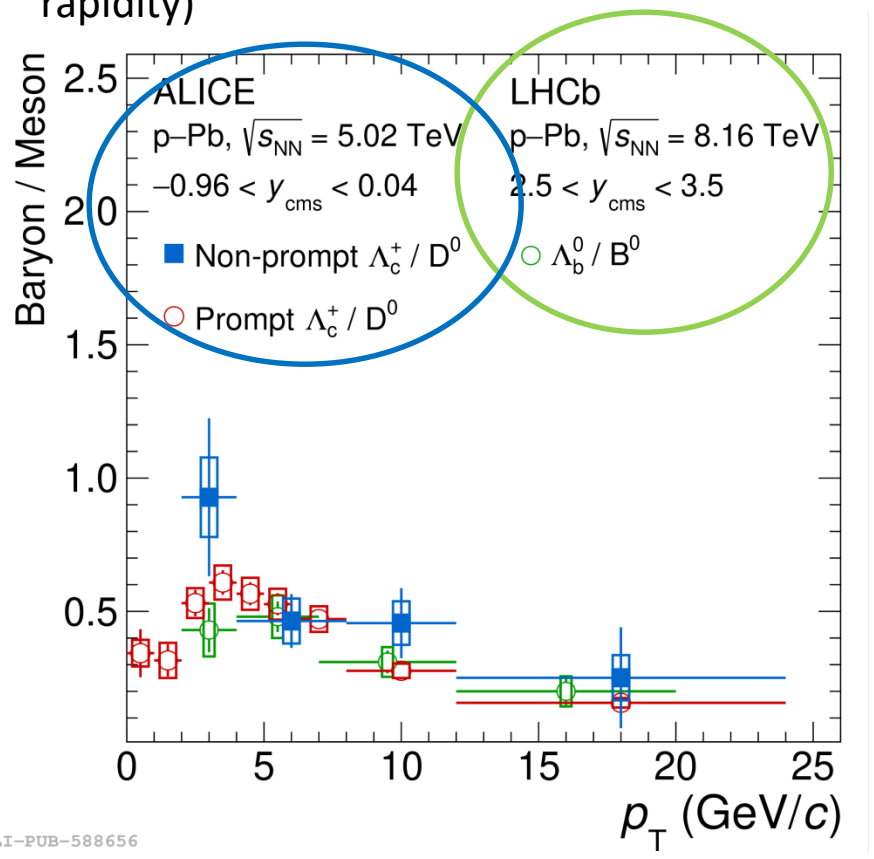
- ✓ LHCb Λ_b^+/B^0 (at forward rapidity)



- ✓ prompt and non-prompt Λ_c^+/D^0, p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
- ✓ p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV: Λ_b^+/B^0 (forward rapidity)

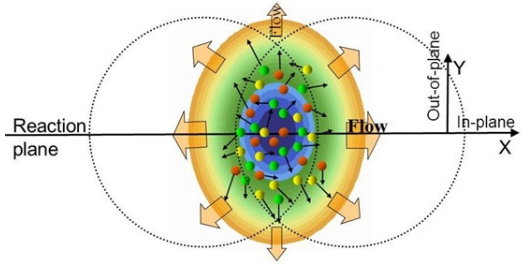


- Similar trend for charm and beauty hadrons in the same collision system

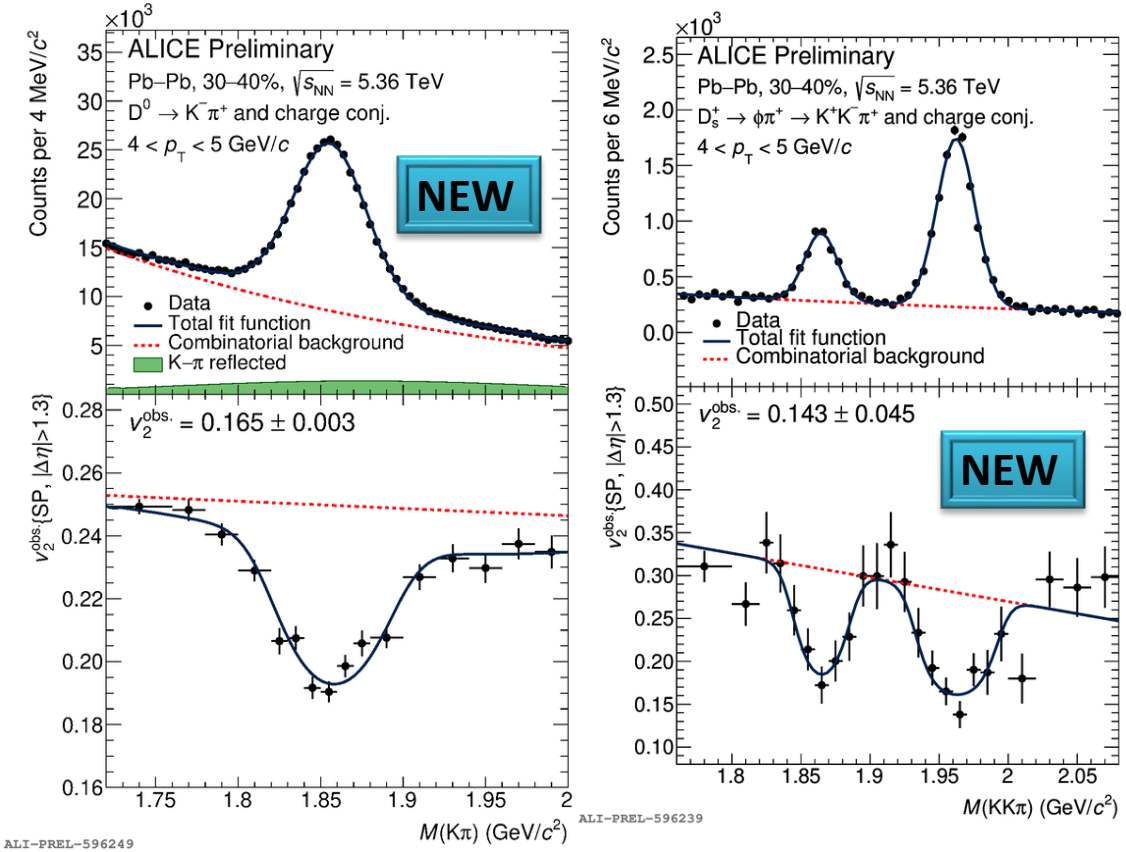
Charm meson elliptic flow (v_2) in Run 3

- ALICE Preliminary results from 2023 Pb-Pb data at $\sqrt{s_{NN}}$ = 5.36 TeV (1.5 nb^{-1})
- Initial geometrical anisotropy translates to the momentum anisotropy of the final hadron in off-central collisions

$$\frac{d^2N}{dp_T d\varphi} \approx \frac{1}{2\pi}\frac{dN}{dp_T}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos\left[n\left(\varphi - \psi_R\right)\right]\right)$$



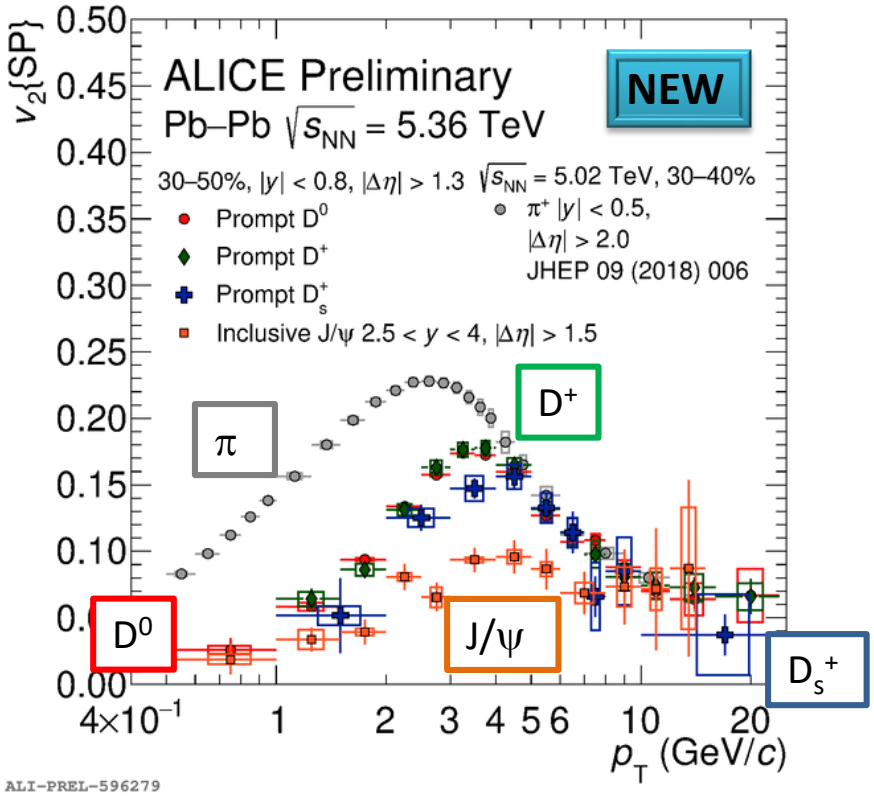
- Fourier series: second (2nd) harmonic, **elliptic flow (v_2)**



- Elliptic flow (v_2) of D^0 and D_s^+ in Pb-Pb collisions in 30-40% centrality in the interval $4 < p_T < 5$ GeV/c
- Charm v_2 extracted using the Scalar Product technique:
  - Simultaneous fit to invariant mass distribution and inclusive v_2 vs. invariant mass

Charm meson elliptic flow (v_2) production in Run 3

- Charm mesons production (D^0, D^+, D_s^+) at midrapidity vs. inclusive J/ψ at forward rapidity in Run 3 vs. light (π) hadrons at midrapidity in Run 2



- A positive v_2 is observed for charm mesons
  - Charm thermalisation (partial)

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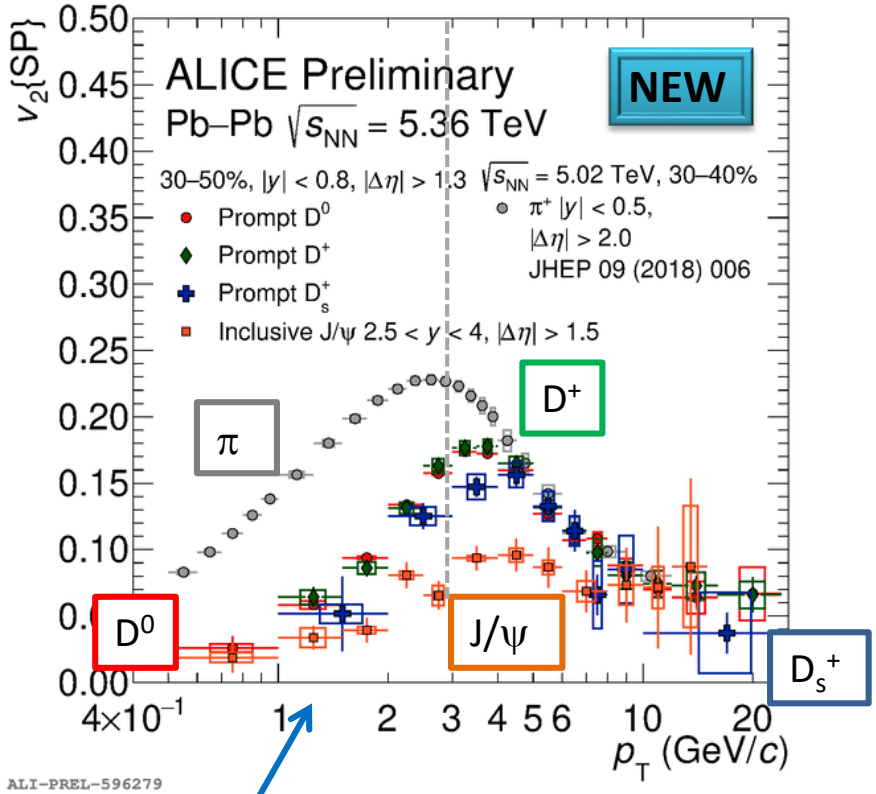

$v_2(J/\psi) < v_2(D) < v_2(\pi)$

- A positive v_2 is observed for charm mesons
  - Charm thermalisation (partial)
- Apparent mass ordering at $p_T < 3$ GeV/c
  - Meson v_2 hydrodynamic description

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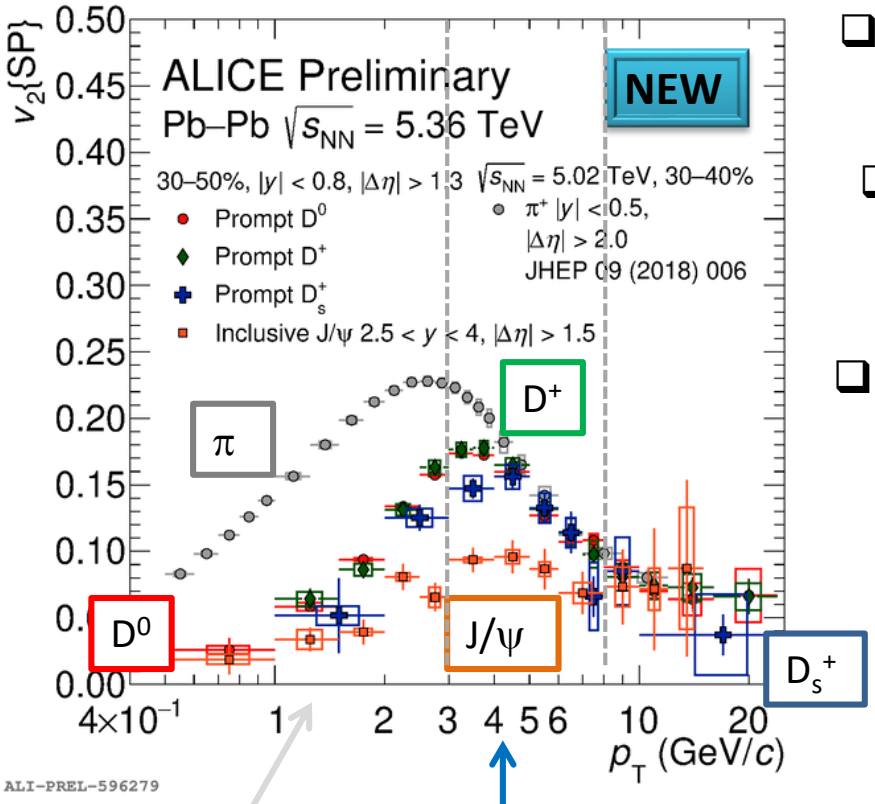

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- A positive v_2 is observed for charm mesons
  - Charm thermalisation (partial)
- Apparent mass ordering at p_T < 3 GeV/c
  - Meson v_2 hydrodynamic description
- 3 < p_T < 8 GeV/c: large v_2 observed for open charm (D^0, D^+, D_s^+) compared to hidden charm (J/ψ)
  - Contribution from the bulk and coalescence

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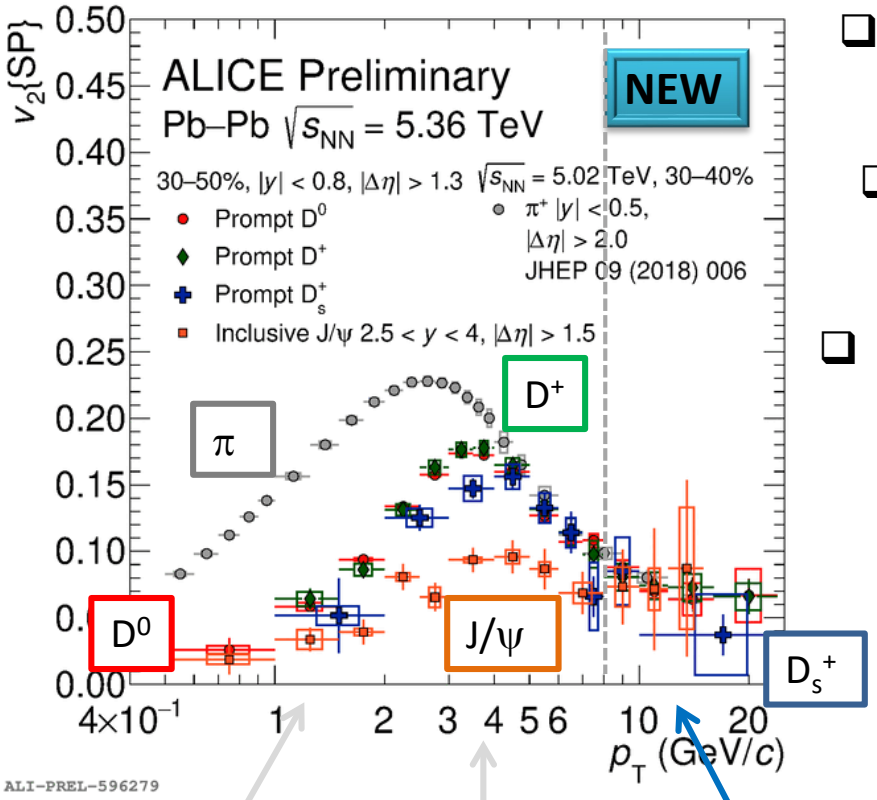


- A positive v_2 is observed for charm mesons
  - Charm thermalisation (partial)
- Apparent mass ordering at $p_T < 3$ GeV/c
  - Meson v_2 hydrodynamic description
- $3 < p_T < 8$ GeV/c: large v_2 observed for open charm (D^0, D^+, D_s^+) compared to hidden charm (J/ψ)
  - Contribution from the bulk and coalescence
- $p_T > 8$ GeV/c: a similar v_2 greater than 0 for charm and light mesons
  - In-medium energy loss
  - Fragmentation dominates coalescence

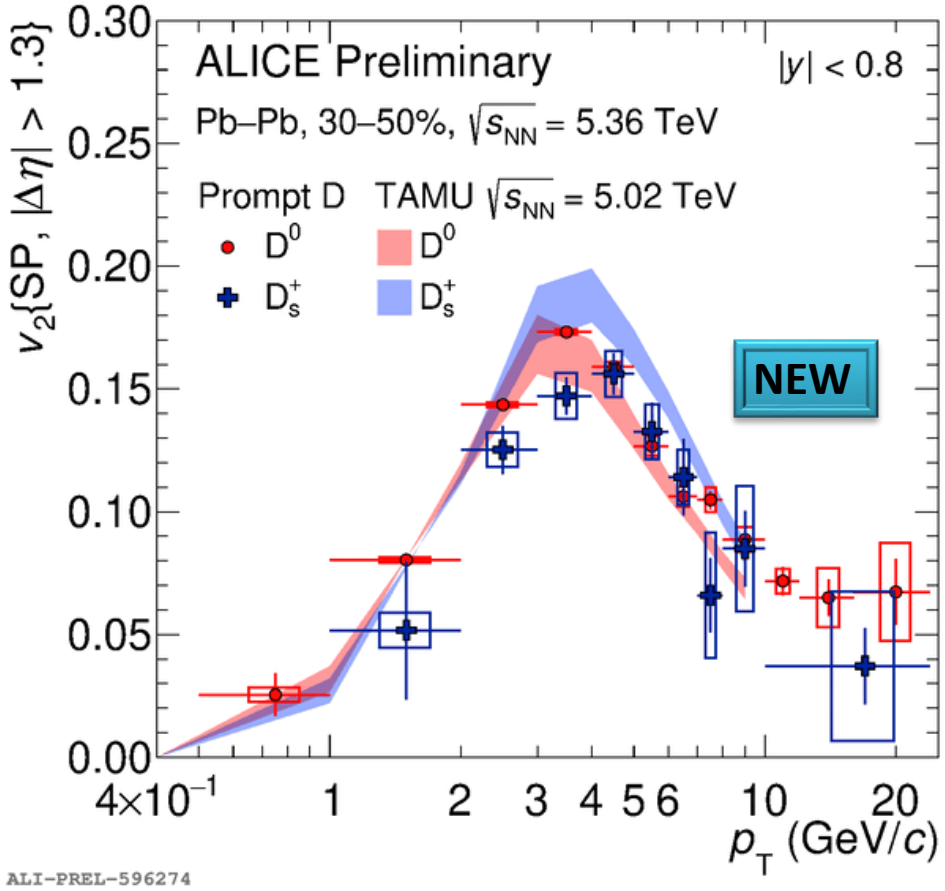
$v_2(J/\psi) < v_2(D) < v_2(\pi)$

$v_2(J/\psi) < v_2(D) < v_2(\pi)$

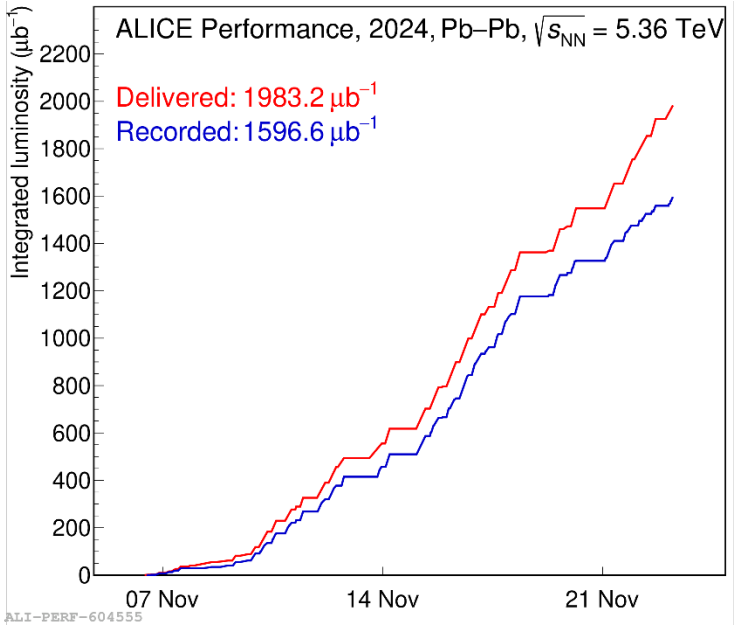
$v_2(J/\psi) \sim v_2(D) \sim v_2(\pi) > 0$

Strange charm (D_s) vs. non-strange charm (D^0) v_2 in Run 3

- v_2 of D^0 and D_s^+ is compared with TAMU predictions [1]
- A different v_2 for D_s^+ is observed compared to D^0?
- Different mass, different rescattering, different hadronisation [2]



- Hint of lower D_s v_2 is consistent within uncertainties below 4 GeV/c
  - Analysis of 2024 and 2025 data samples may allow us to set tighter constraints needed to draw conclusions



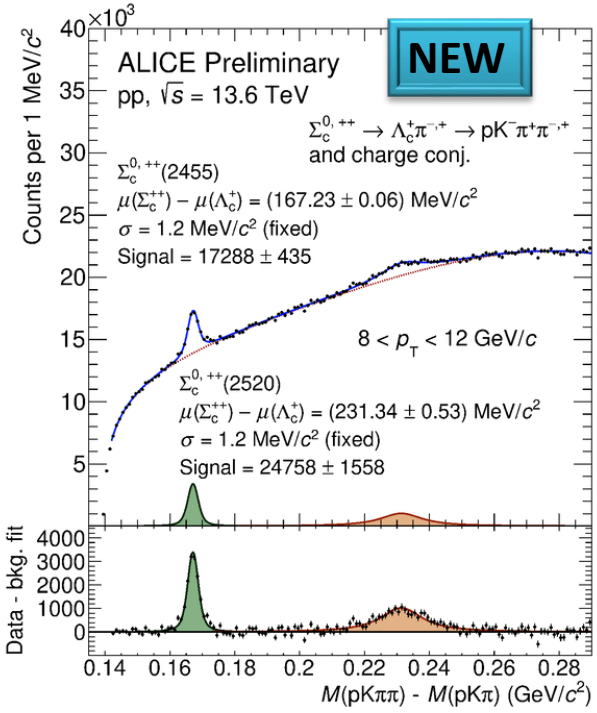
[1] TAMU: PRL 124 (4) (2020)
[2] M He. Et all, PRL 110 (2013) 112301

Summary

- Heavy-quark hadronisation in our QCD laboratory in the last decade:
  - e^+e^- ~ "vacuum"
  - pp collisions far from vacuum ~ many (independent) scatterings correlated by colour reconnection at hadronisation?
  - Pb-Pb collisions: dense extended system, equilibrium, flow
- Violation of hadronisation universality already in pp collisions
- Multiple parton interactions enable quark and gluon-rich environment, dense enough to influence/change hadronisation relative to e^+e^- collisions
- From the measurements shown, a clear picture emerges, allowing for a general trend to be established

- Ongoing in Run 3:
  - Lower p_T reach expected with Run 3 data, allowing further reduction of extrapolation uncertainties
  - Spectroscopy: measuring higher mass states of heavy quarks: charm baryons, e.g. ground and excited $\Sigma_c^{0,++}$ in pp collisions at √s = 13.6 TeV

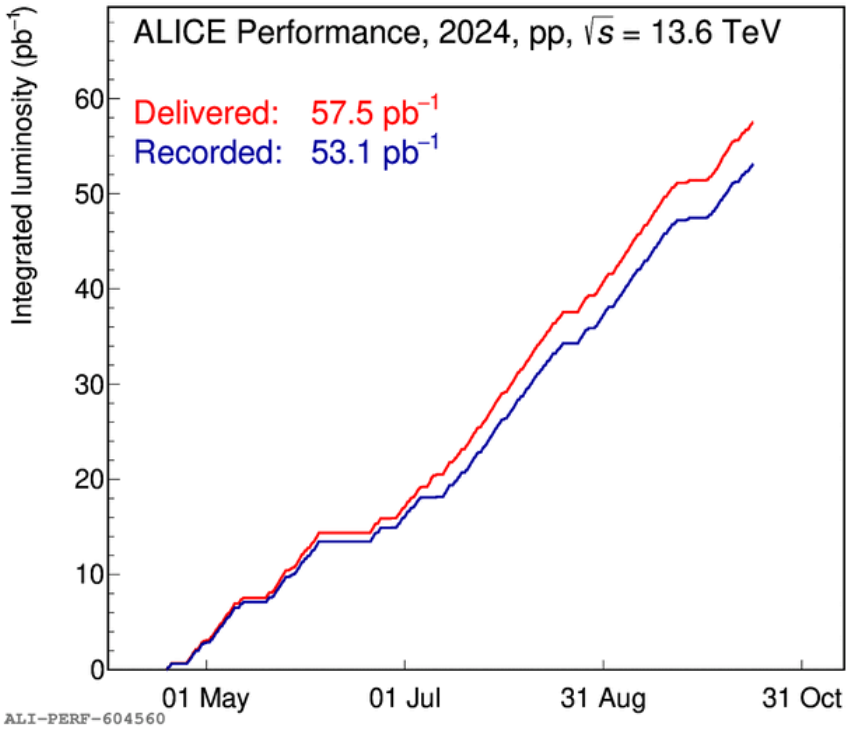
→ large improvements expected for $\Sigma_c^{0,++}(2520)$, which is measured for the first time

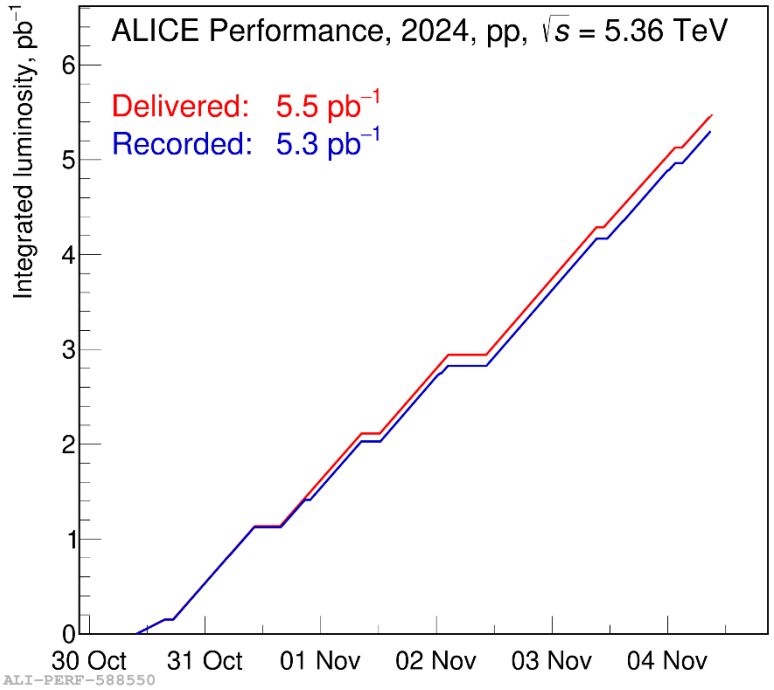


ALI-PREL-571534

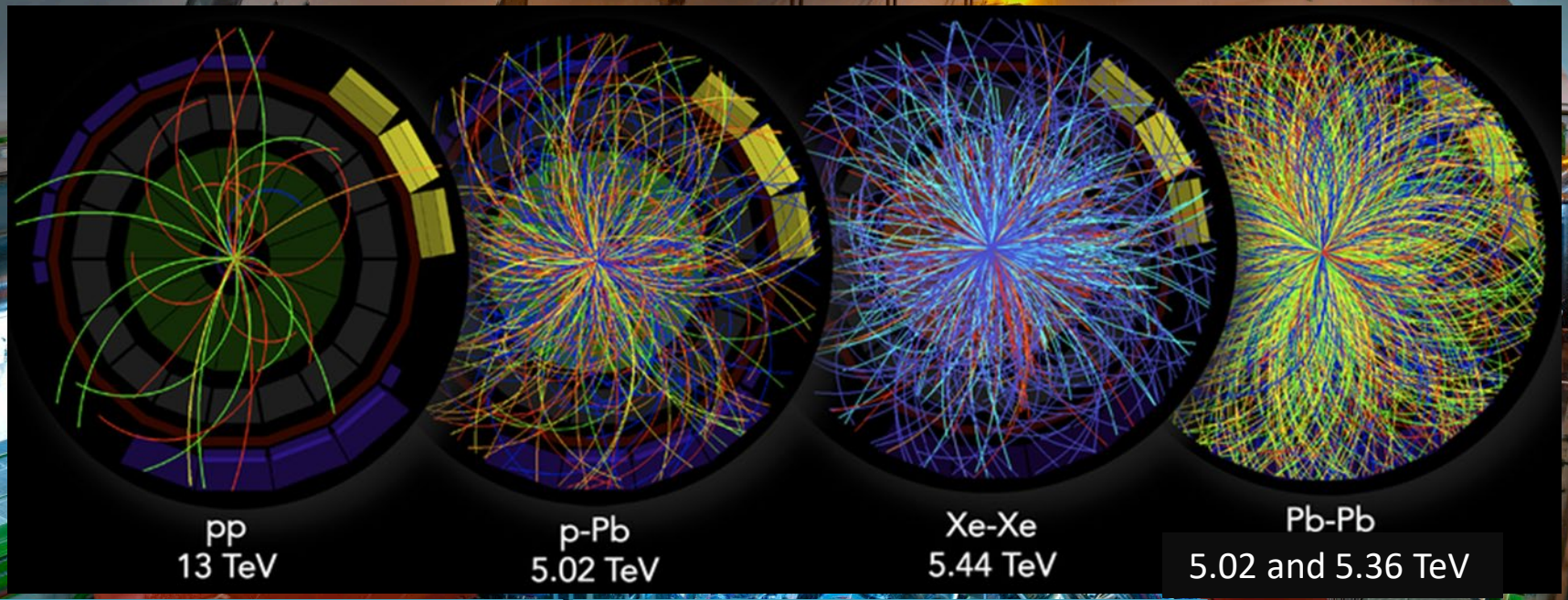
Thanks for listening

ALICE Integrated Luminosity in Run 3 pp collisions

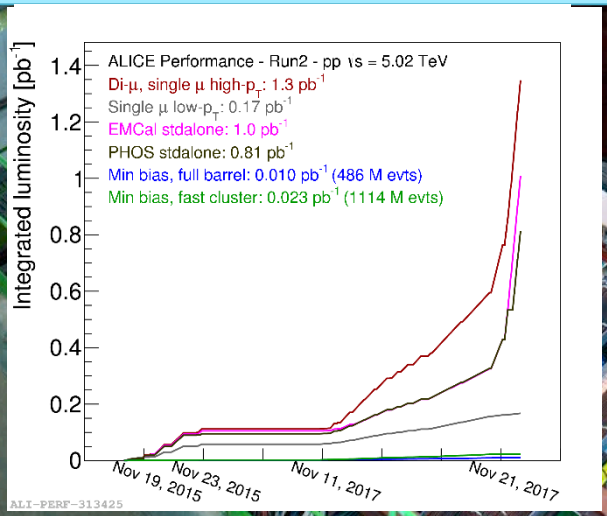


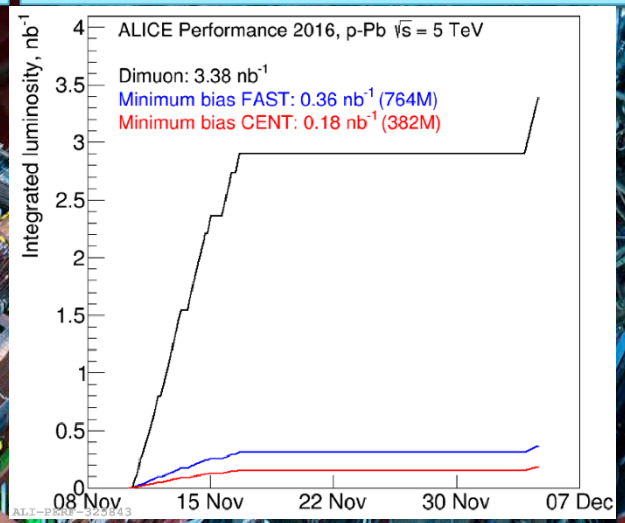


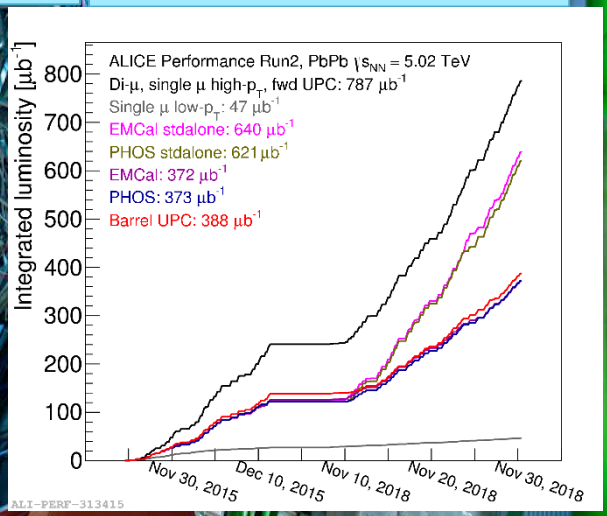
ALICE measurements in Run 2



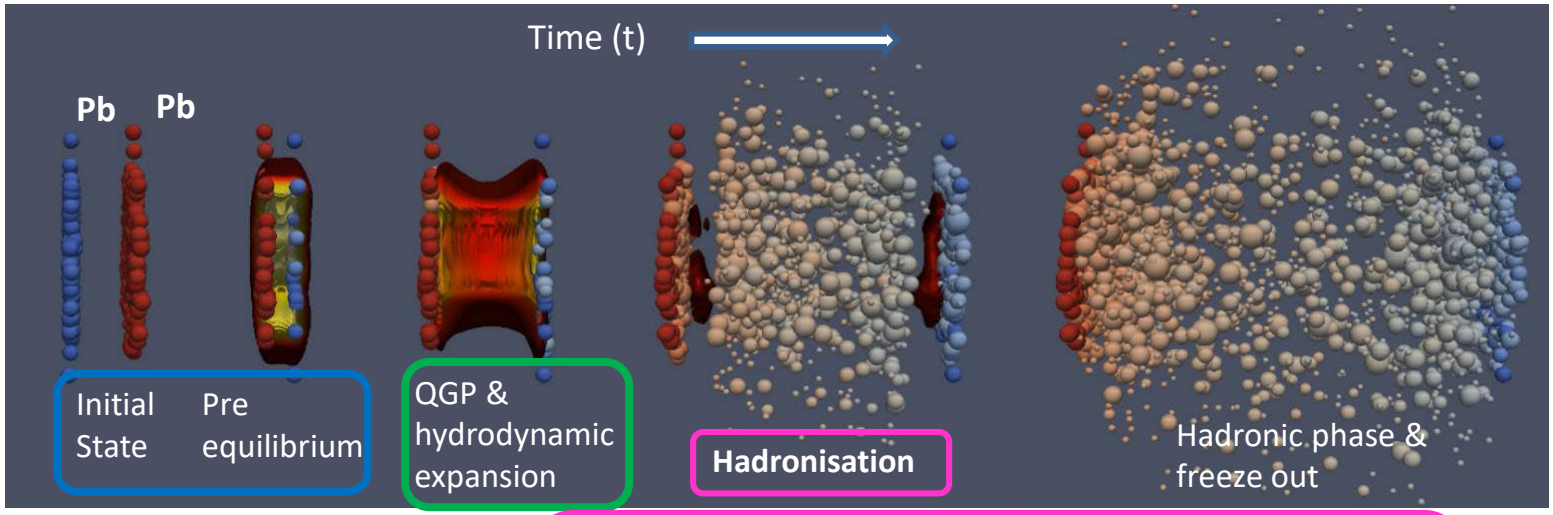
- ❑ Test QCD-driven models
  - Reference for p-Pb & Pb-Pb
- ❑ disentangle initial & final state effects
- ❑ QGP properties and characterisation





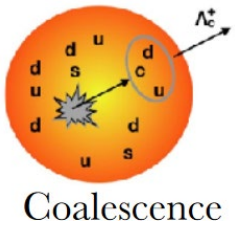


Heavy-quark in heavy ion-collisions



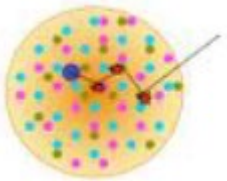
Initial state effects:
- Gluon saturation
- Modification of PDFs

Coalescence;
Partons close in phase space recombine into higher p_T hadrons (dominant at low p_T)
→ Modification of the hadronisation mechanism



In-medium effects:

Energy loss: interaction of heavy quarks with the medium

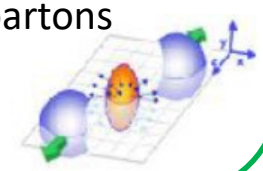


$$R_{AA} = \frac{Y_{AA}}{N_{coll} \times Y_{pp}}$$

$R_{AA}(p\mathrm{T}, y) = 1$, No nuclear effects
$\neq 1$ Nuclear effects

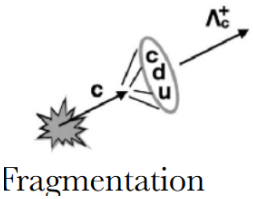
Collectivity: mean free path of outgoing partons

$$\frac{d^2N}{dp_T d\varphi} \approx \frac{1}{2\pi}\frac{dN}{dp_T}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos\left[n\left(\varphi - \psi_R\right)\right]\right)$$



Fragmentation:
- ✓ Parton shares a fraction of its momentum with the hadron (dominant at high p_T)

→ Modification of hadronisation mechanisms

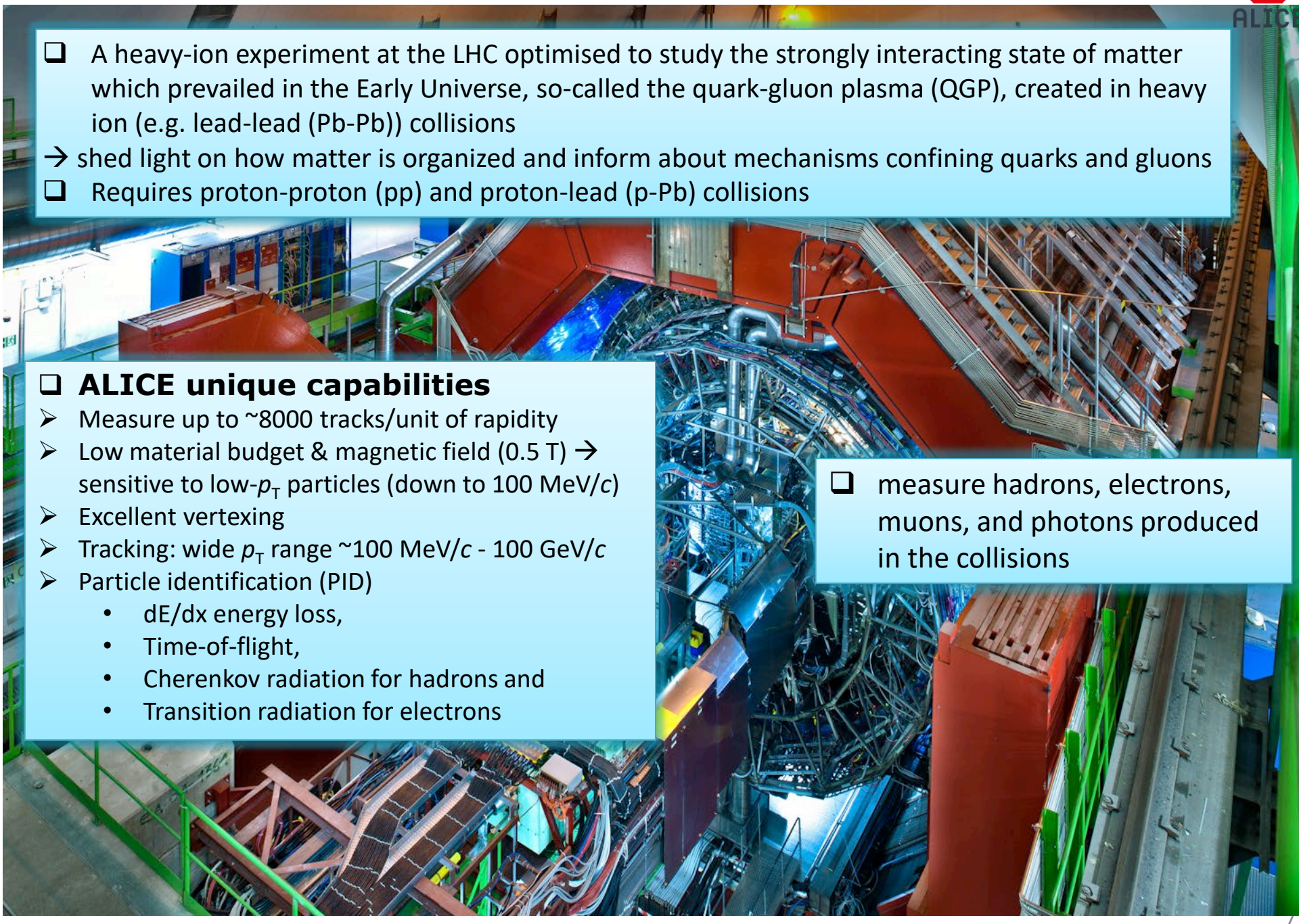


A Large Ion Collider Experiment (**ALICE**)

- A heavy-ion experiment at the LHC optimised to study the strongly interacting state of matter which prevailed in the Early Universe, so-called the quark-gluon plasma (QGP), created in heavy ion (e.g. lead-lead (Pb-Pb)) collisions

→ shed light on how matter is organized and inform about mechanisms confining quarks and gluons

- Requires proton-proton (pp) and proton-lead (p-Pb) collisions

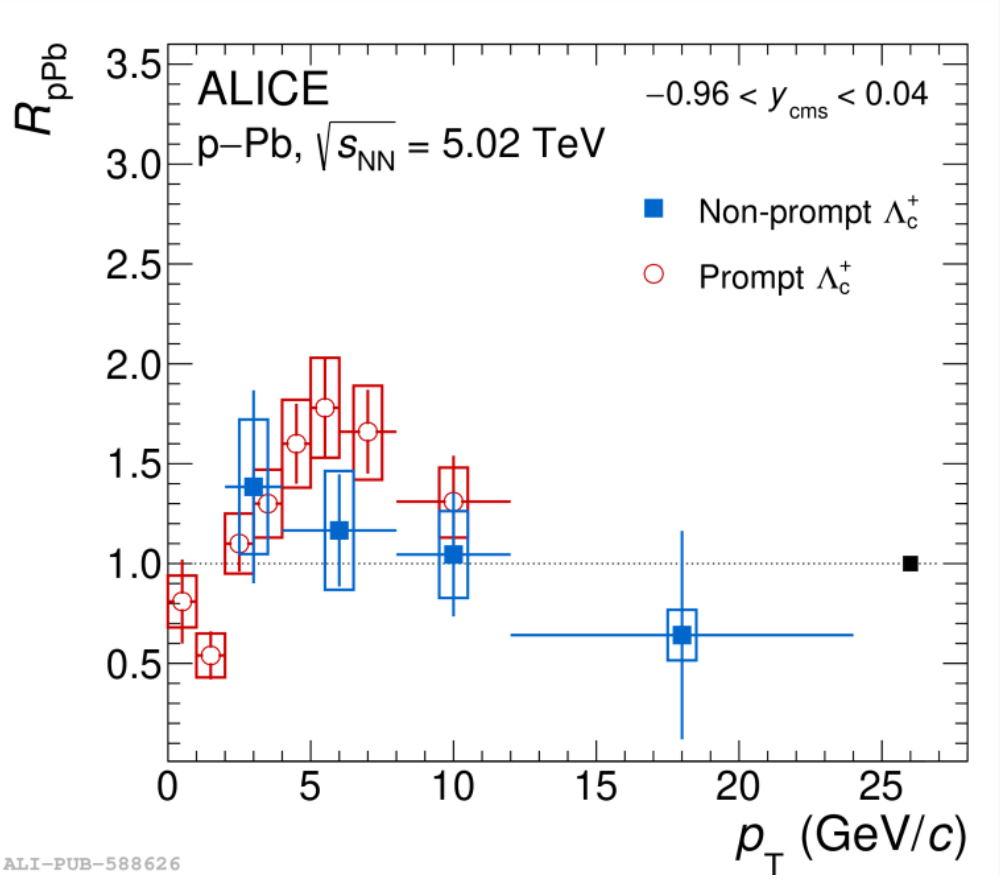


- **ALICE unique capabilities**
  - Measure up to ~8000 tracks/unit of rapidity
  - Low material budget & magnetic field (0.5 T) → sensitive to low-p_T particles (down to 100 MeV/c)
  - Excellent vertexing
  - Tracking: wide p_T range ~100 MeV/c - 100 GeV/c
  - Particle identification (PID)
    - dE/dx energy loss,
    - Time-of-flight,
    - Cherenkov radiation for hadrons and
    - Transition radiation for electrons

- measure hadrons, electrons, muons, and photons produced in the collisions

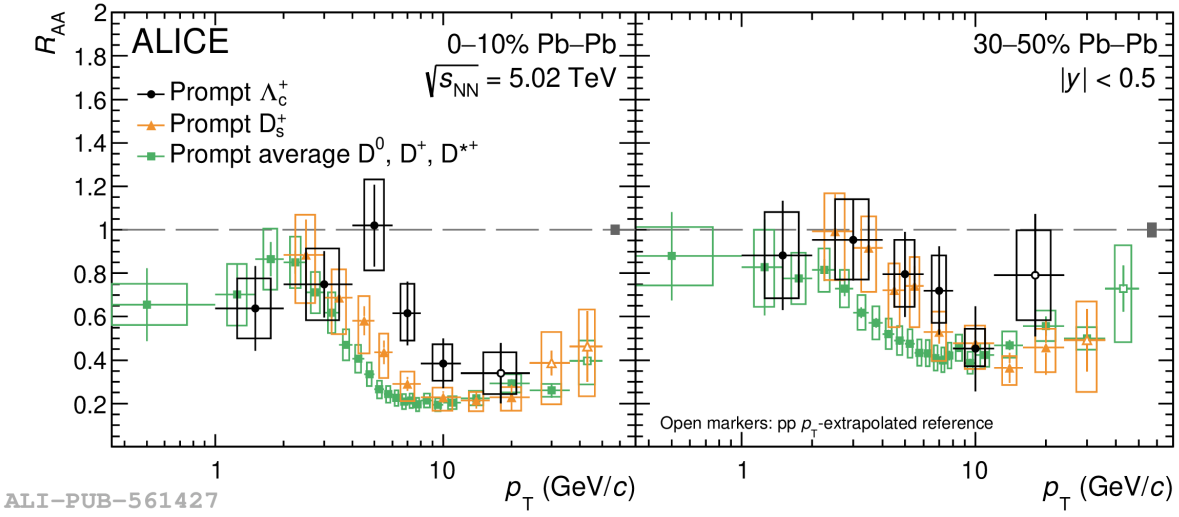
Constraining hadronization mechanisms with Λ_c^+ / D^0 production ratios in Pb-Pb collisions at $\sqrt{s_{NN}}$ =5.02 TeV

- Λ_c^+/D^0 in 0−10% (left) and 30−50% (middle) Pb−Pb and pp (right) compared with different theoretical model predictions

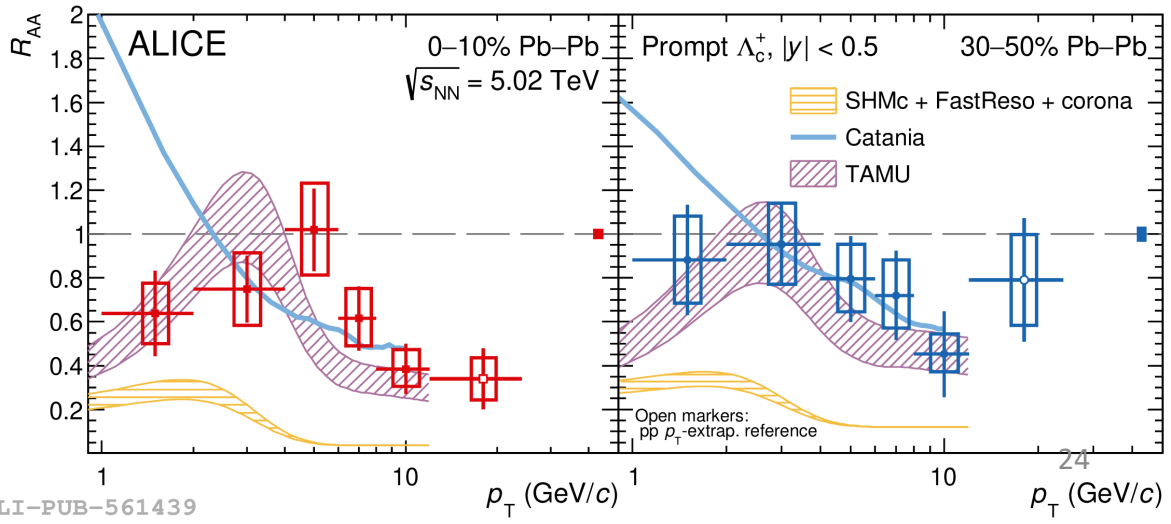


Constraining hadronization mechanisms with Λc+/D0 production ratios in Pb-Pb collisions at √ s_{NN} =5.02 TeV

R_{AA} of prompt Λc+ baryons in central (0−10%; left) and mid-central (30−50%; right), compared with the R_{AA} of prompt Ds+ and the average of prompt non-strange D mesons.

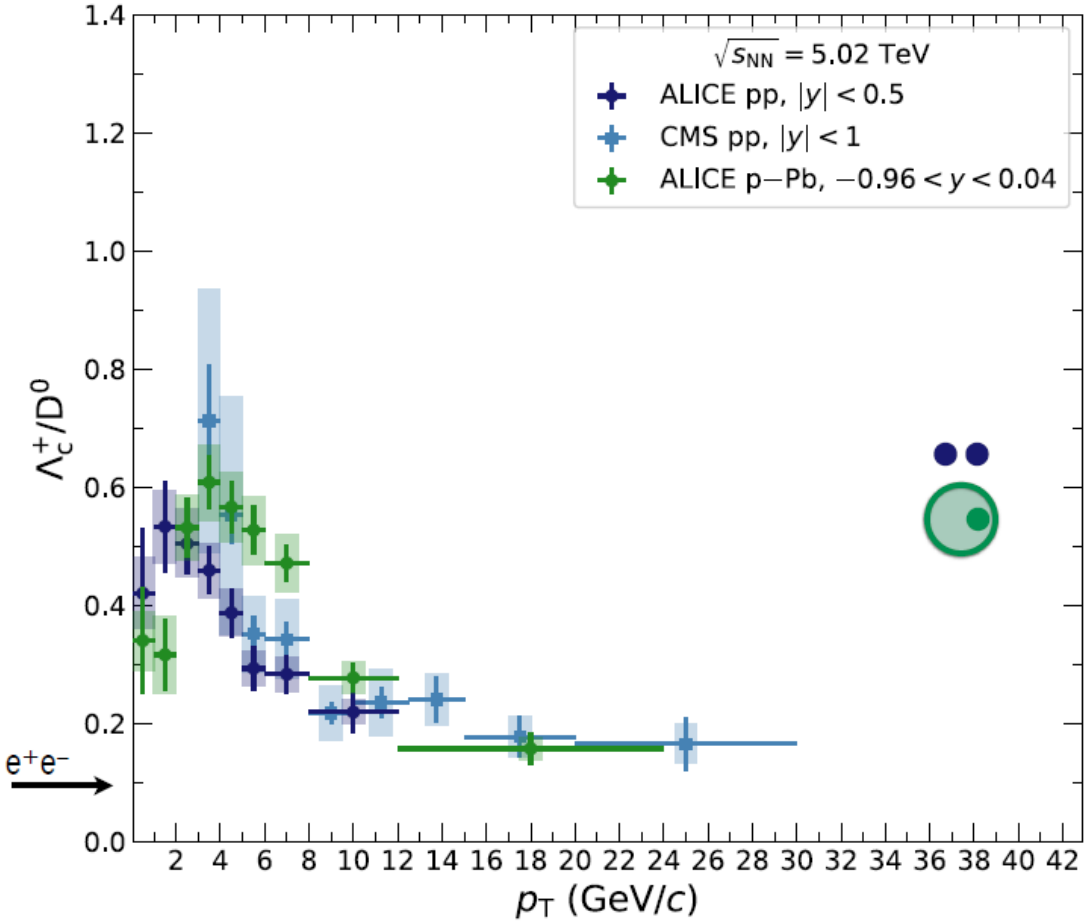


RAA compared with model predictions.



Charm Baryon-to-meson ratios in pp, p-Pb and Pb-Pb collisions

- Good agreement between ALICE and CMS in pp collisions
- Comparison with p-Pb: modification of the Λ_c^+/D^0 ratio in p-Pb collisions
  - Radial-flow like effects or quark recombination



ALICE, Phys. Rev. C 107 (2023) 064901
CMS, JHEP 01 (2024) 128

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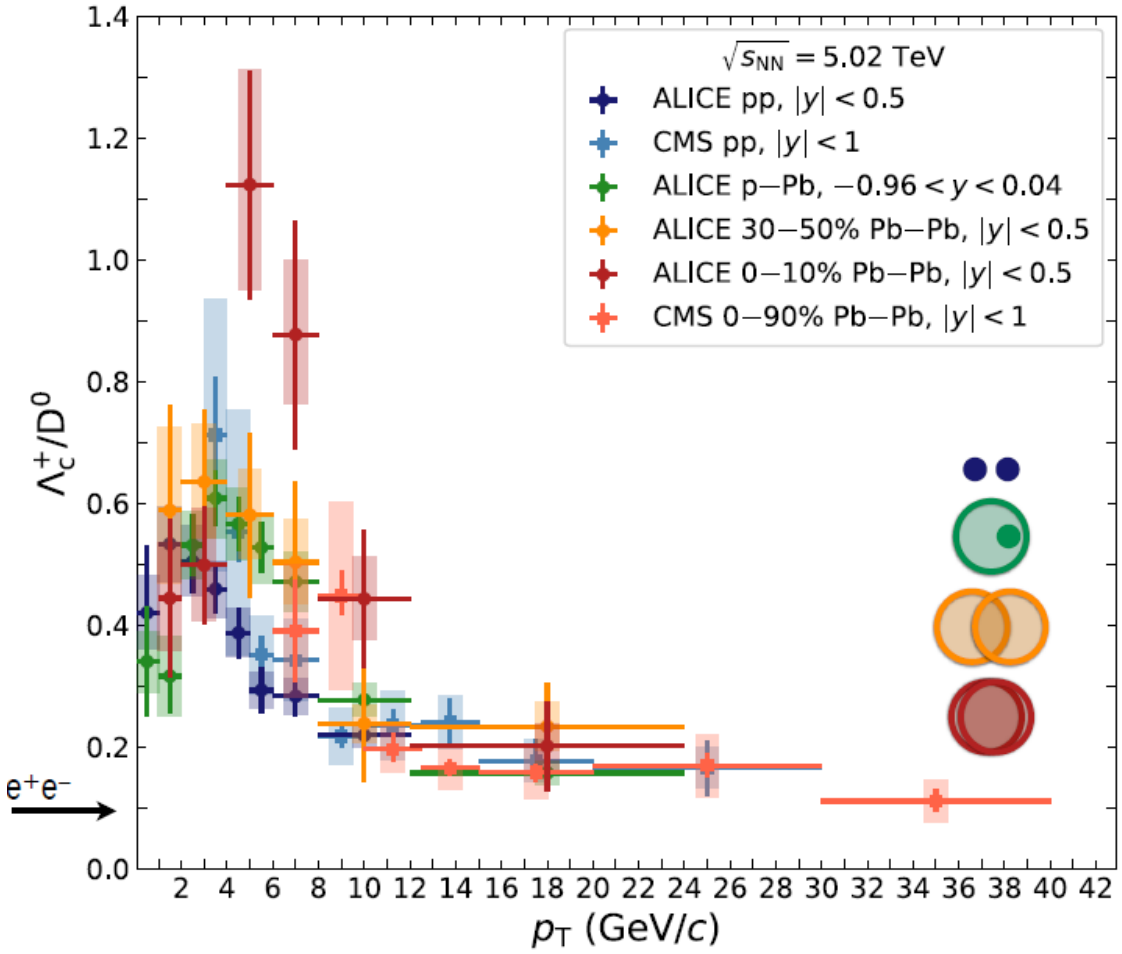

- Similar modification in Pb-Pb collisions, enhancement observed with centrality at intermediate p_T

ALICE, Phys. Rev. C 107 (2023) 064901
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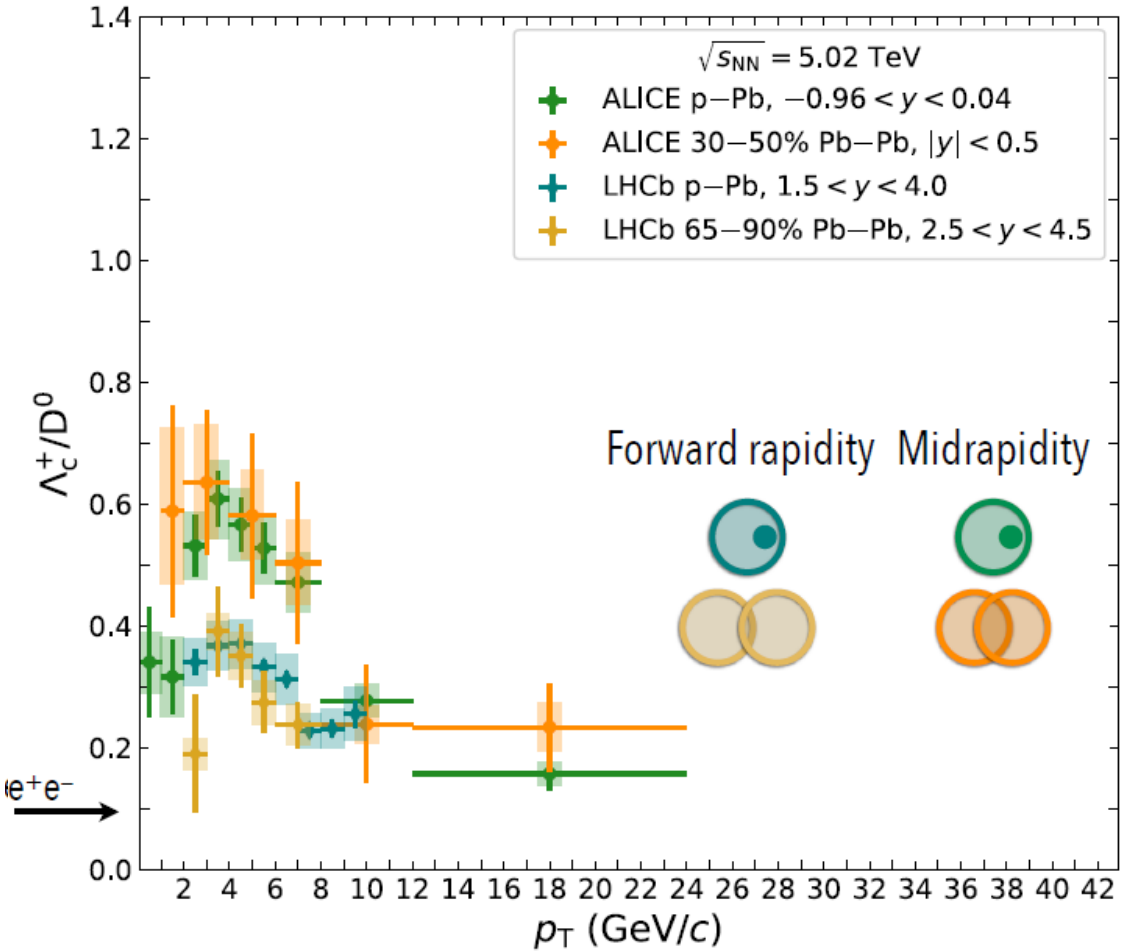
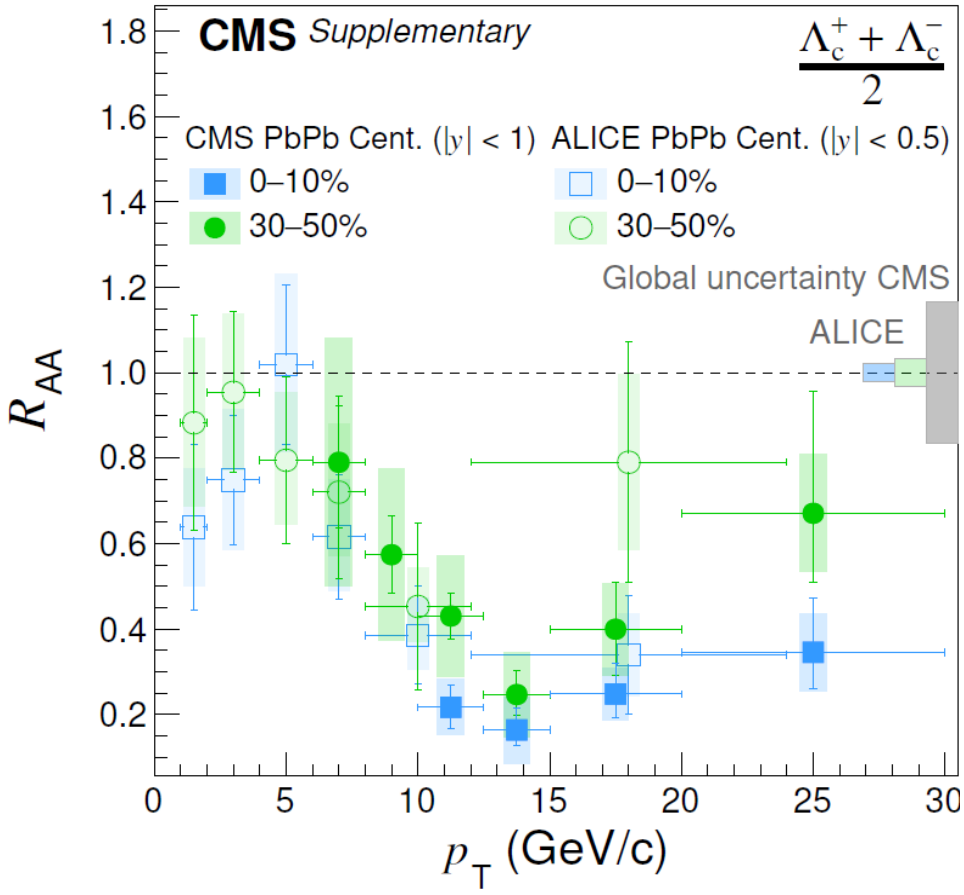
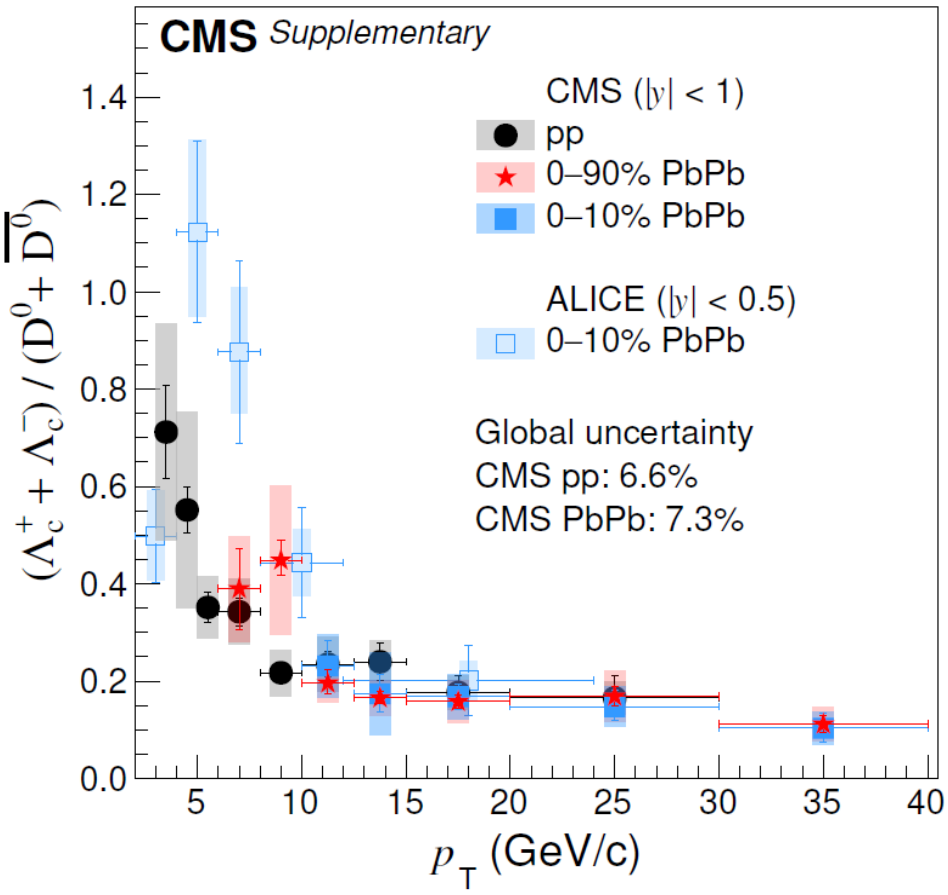


- Similar modification in Pb-Pb collisions, enhancement observed with centrality at intermediate p_T
- Similar trend at forward rapidity (LHCb) but lower in absolute value
  - Rapidity dependence?

ALICE, Phys. Rev. C 107 (2023) 064901
CMS, JHEP 01 (2024) 128
LHCB, JHEP06(2023)132, JHEP 02 (2019) 102


CMS Supplementary
$\frac{\Lambda_c^+ + \Lambda_c^-}{2}$
CMS PbPb Cent. (|y| < 1)
0–10%
30–50%
ALICE PbPb Cent. (|y| < 0.5)
0–10%
30–50%
Global uncertainty CMS
ALICE
R_{AA}
p_T (GeV/c)


CMS Supplementary
CMS (|y| < 1)
pp
0–90% PbPb
0–10% PbPb
ALICE (|y| < 0.5)
0–10% PbPb
Global uncertainty
CMS pp: 6.6%
CMS PbPb: 7.3%
$(\Lambda_c^+ + \Lambda_c^-) / (D^0 + \overline{D^0})$
p_T (GeV/c)