Istituto Nazionale di Fisica Nucleare

Charmed baryon production measured by ALICE at the LHC

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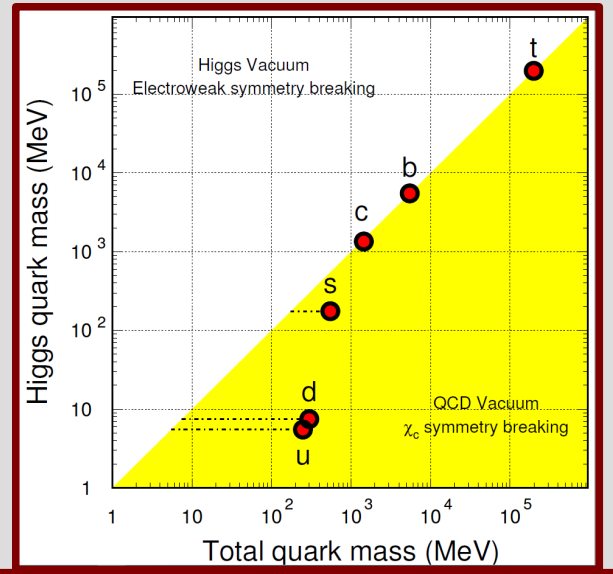
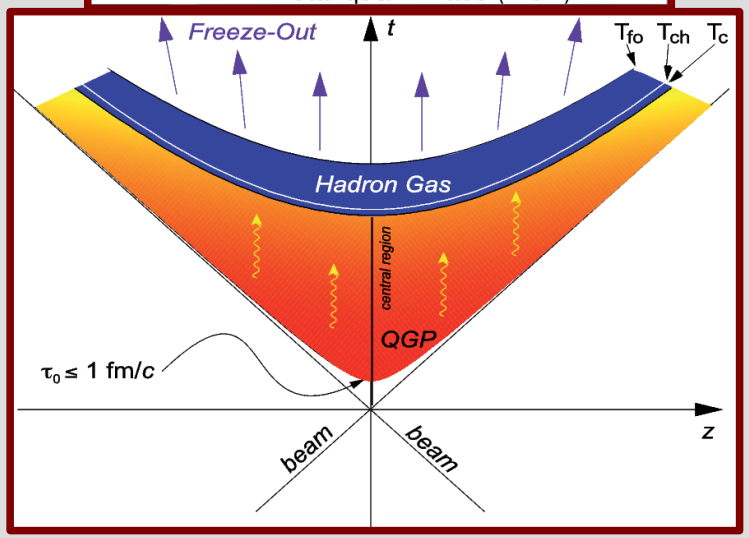
Why open heavy flavours in heavy-ion collisions?

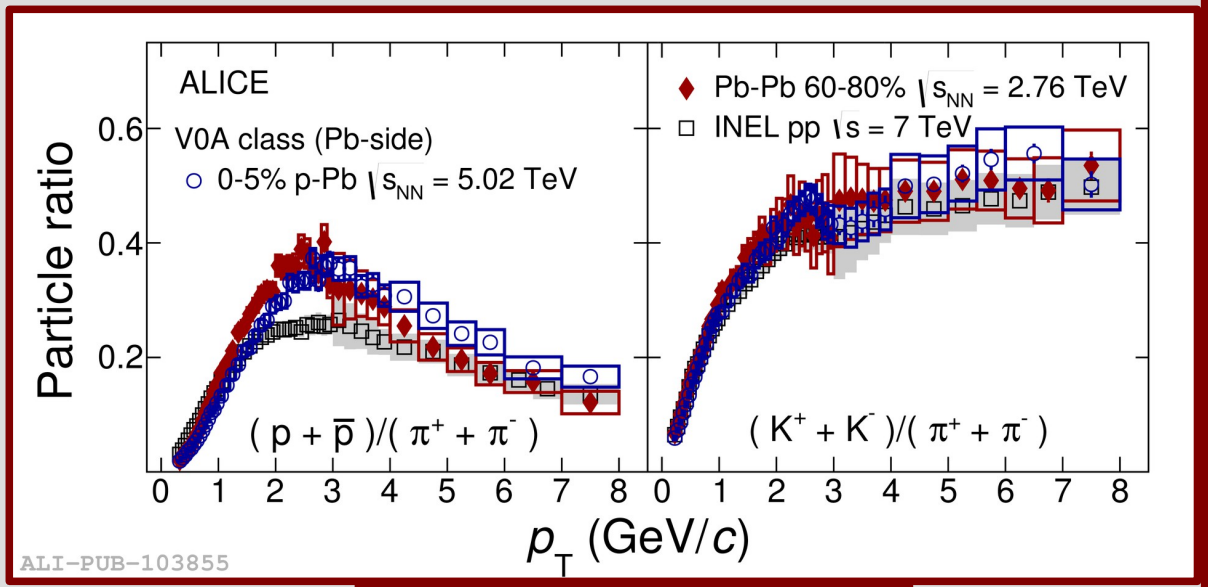
- Charm and beauty give a **unique probe of the QGP** formed in ultrarelativistic heavy-ion collisions
- Produced at **early times** in **hard partonic scatterings** (high-Q^2)
  - → $\tau_{c/b}$ (≈0.01–0.1 fm/c) < QGP formation time (≈0.1–1fm/c) → experience the full evolution of the system and interact with the medium
  - → $m_{c,b} \gg \Lambda_{QCD}$ → cross section calculable within perturbative QCD framework
- Study multiple different systems:
  - → **pp collisions**: Measure production cross sections, baseline for nuclear collisions, test for pQCD calculations.
  - → **p–Pb collisions**: Study cold nuclear matter effects to distinguish initial-state nuclear modifications from final-state in-medium effects
  - → **Pb–Pb collisions**: Study in-medium modifications in QGP

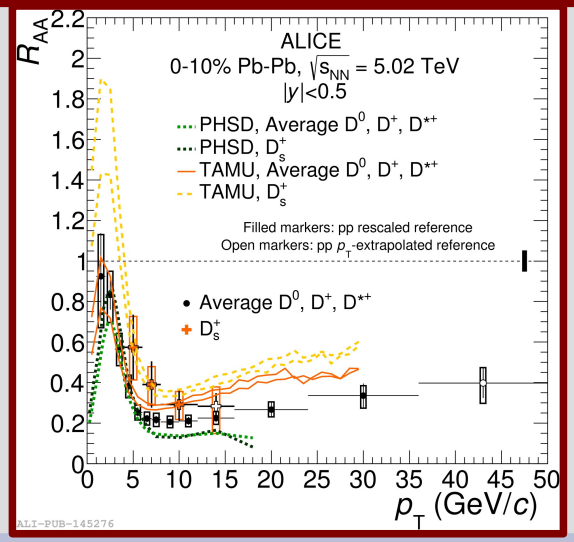




Why charmed baryons?

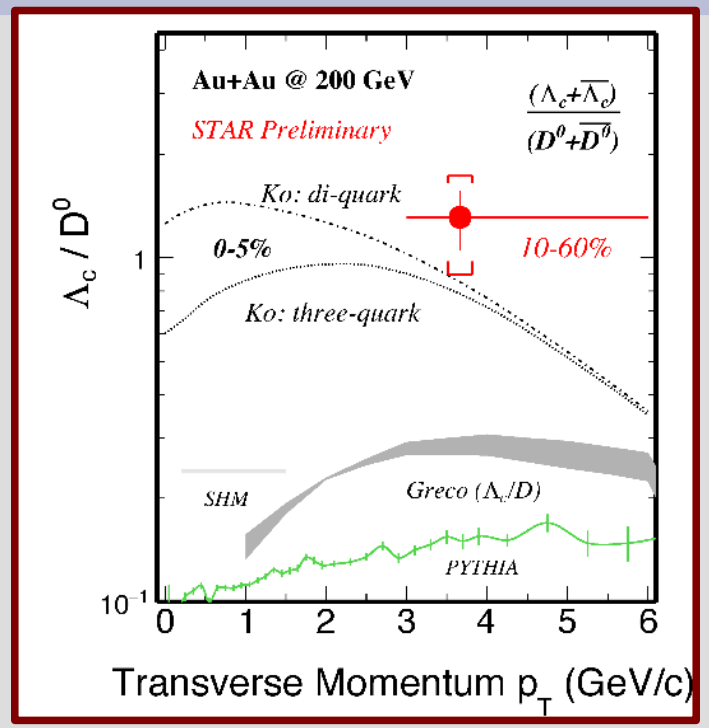
- Vital tool to test hadronisation mechanisms in-medium
- Light-flavour sector: enhancement of Λ/K^0 and p/π production ratios in Pb–Pb collisions compared to pp; possible effect of quark recombination/coalescence in medium? Is this effect present in the charm sector?
- How does this compare with strange D mesons (where recombination also plays a role)?





Why charmed baryons?

- Previous STAR measurement: enhancement of Λc+/D0 ratio in Au–Au collisions compared with expectations from models
  - → First sign of baryon anomaly effect in heavy-ion collisions in the charm sector
  - → Is this effect seen at the LHC?



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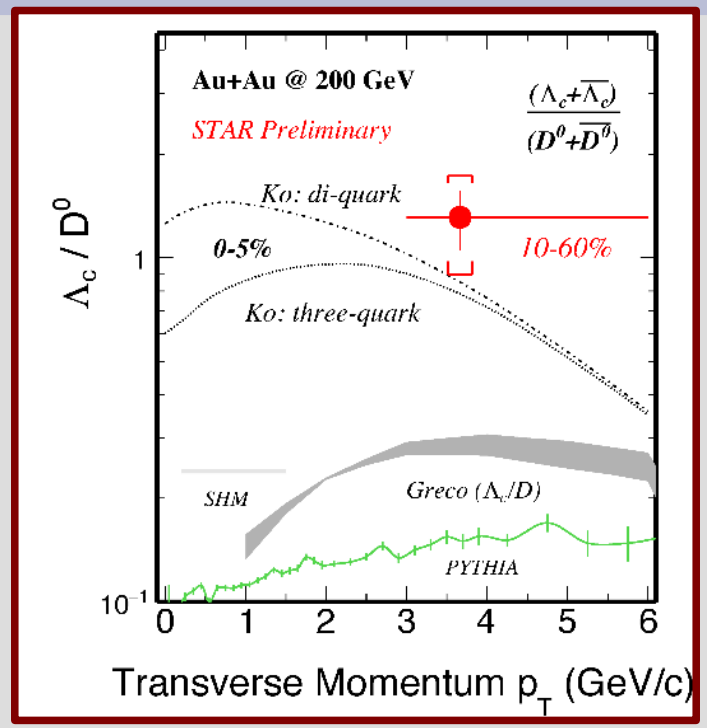
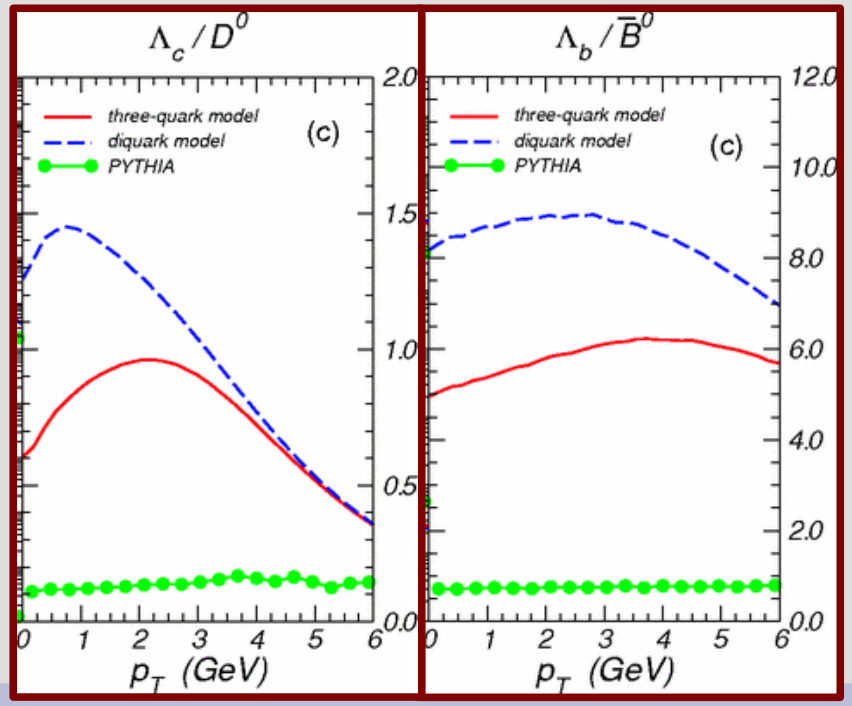
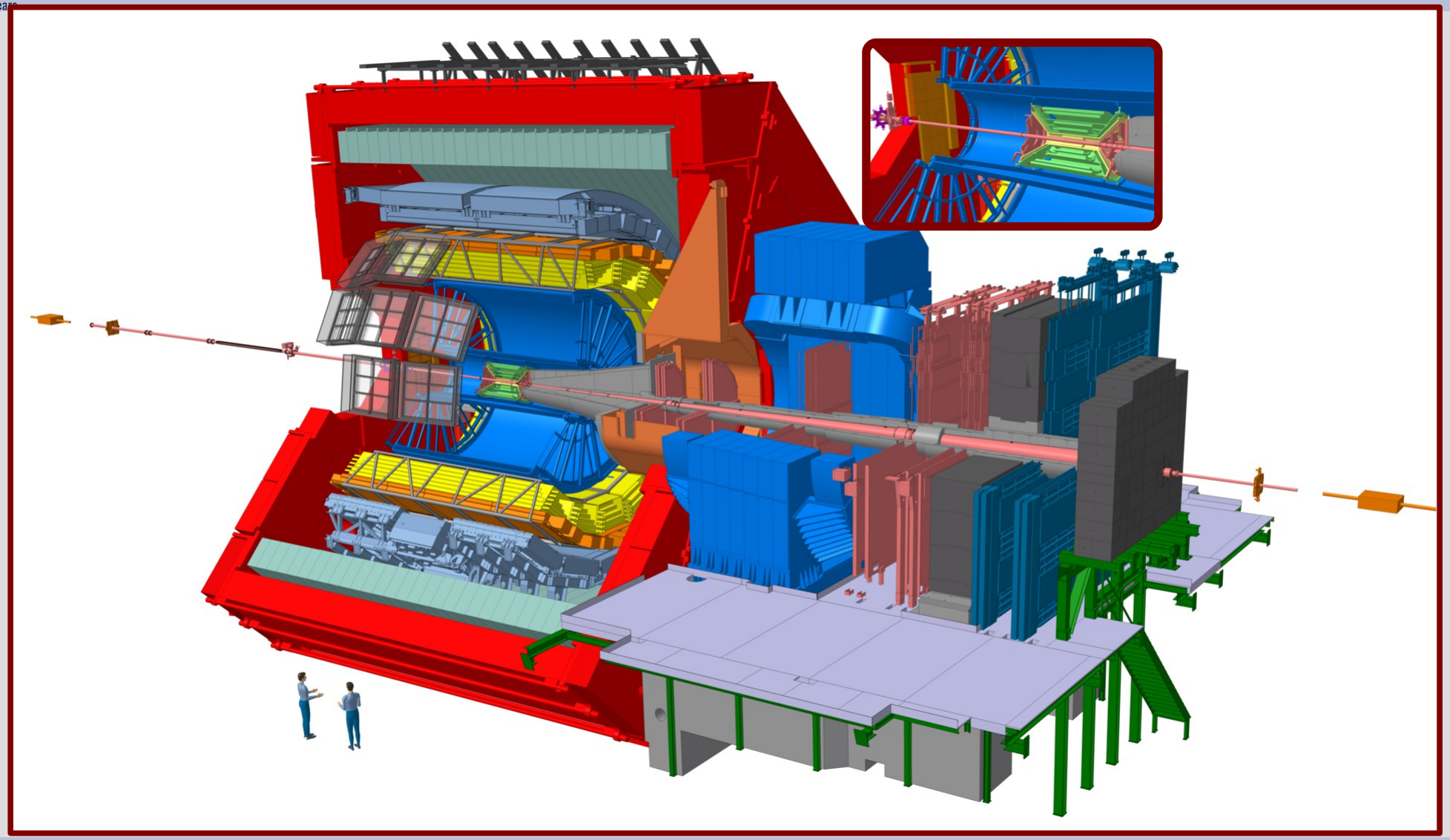




- Theory prediction: Enhancement of charm and beauty baryon-to-meson ratios in coalescence models, further enhanced in presence of thermalised diquarks
- Small systems also a key contributor to understanding of hadronisation

ALICE: A Large Ion Collider Experiment



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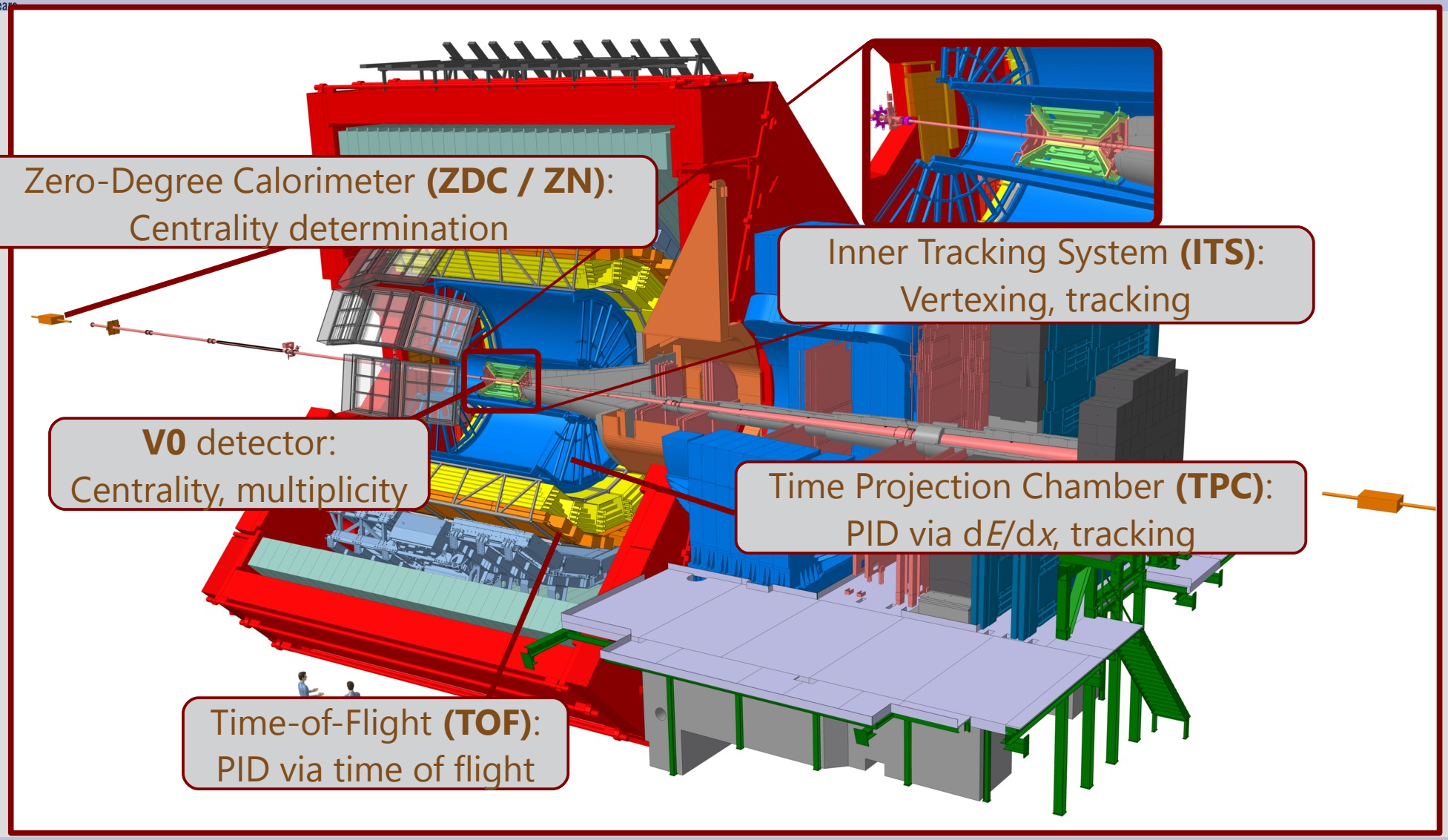
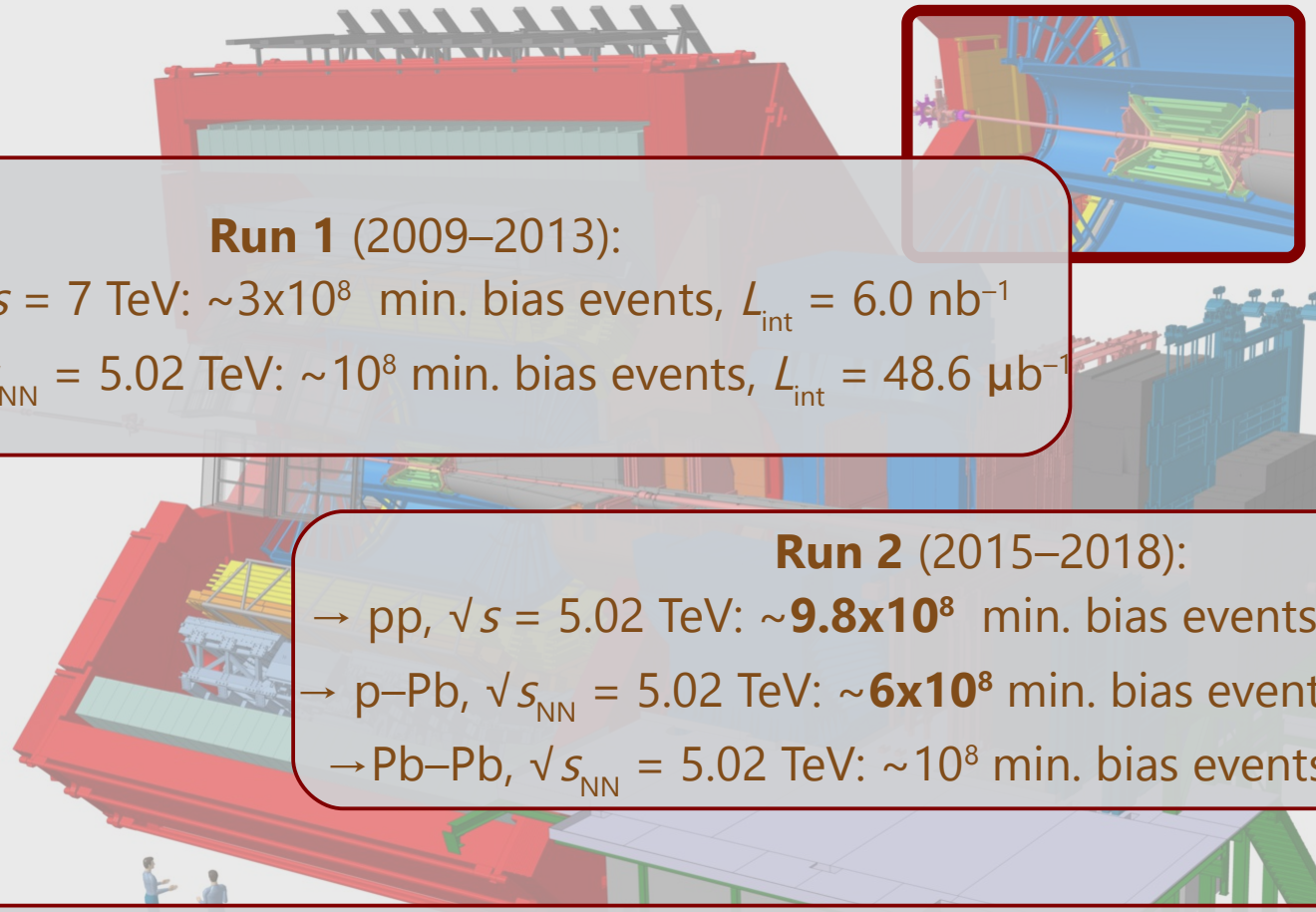


Data samples used



Run 1 (2009–2013):

→ pp, $\sqrt{s}$ = 7 TeV: ~3x10^{8} min. bias events, L_{int} = 6.0 nb^{-1}

→ p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV: ~10^{8} min. bias events, L_{int} = 48.6 µb^{-1}

Run 2 (2015–2018):

→ pp, $\sqrt{s}$ = 5.02 TeV: ~**9.8x10^{8}** min. bias events, L_{int} = **19.6 nb^{-1}**

→ p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV: ~**6x10^{8}** min. bias events, L_{int} = **292 µb^{-1}**

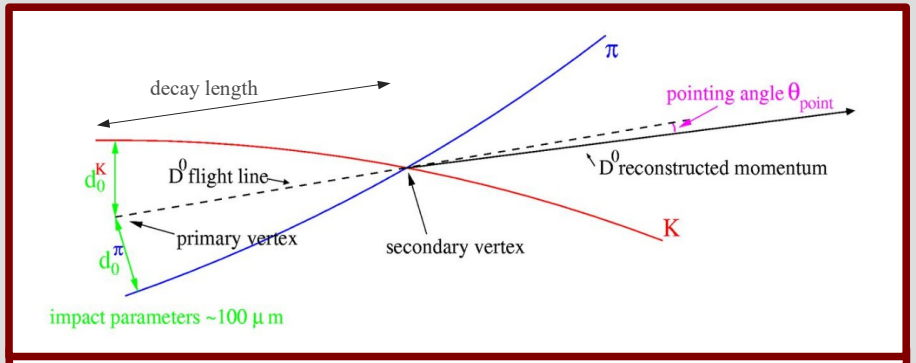
→ Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV: ~10^{8} min. bias events, L_{int} =13.4 µb^{-1}

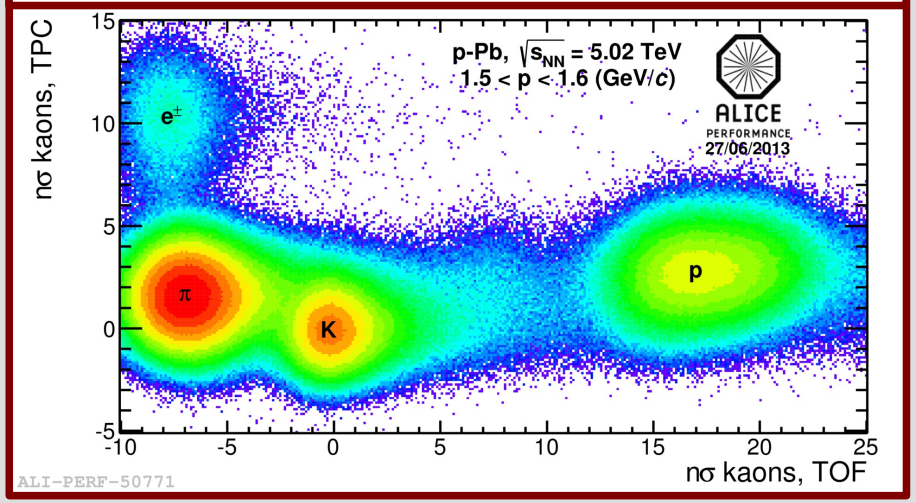
→ Run 2 dataset gives factor-3 increase in luminosity for pp, factor-6 for p–Pb

→ Vast improvement in statistical precision over previous results

Reconstruction of charmed hadrons in ALICE

- Strategy: full reconstruction of hadronic decays of charmed hadrons
  → Retains full kinematic information of original particle
- Reconstruction relies on topological + particle identification (PID) selections to reduce combinatorial background

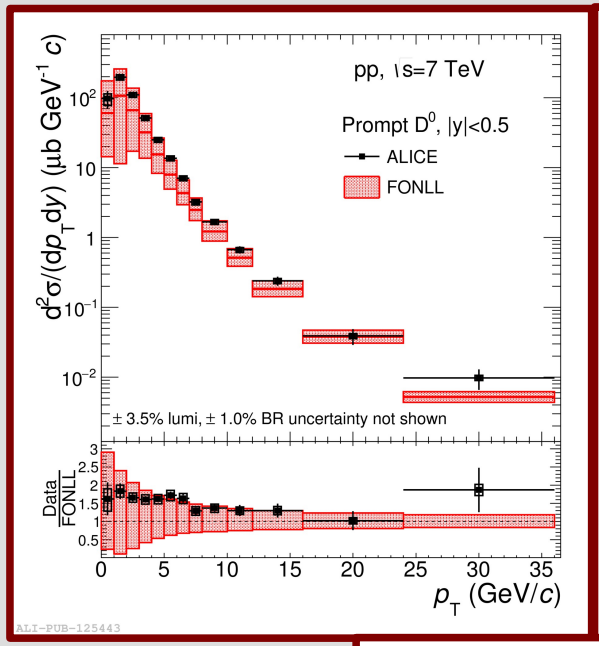


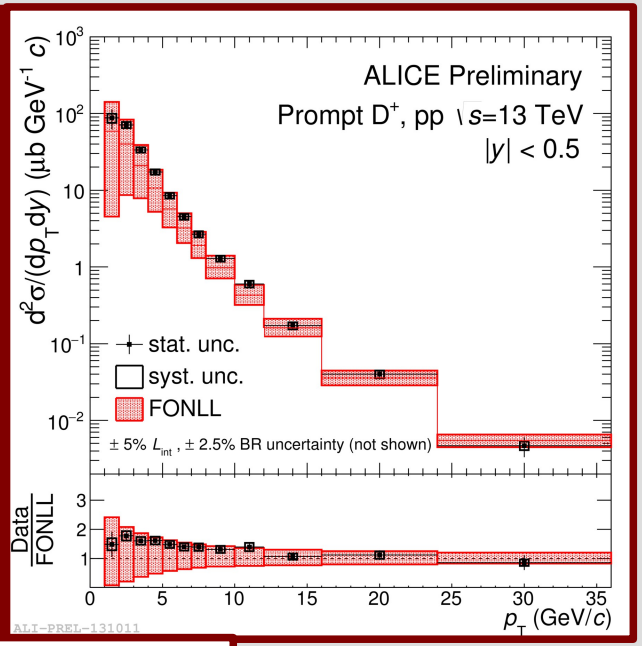


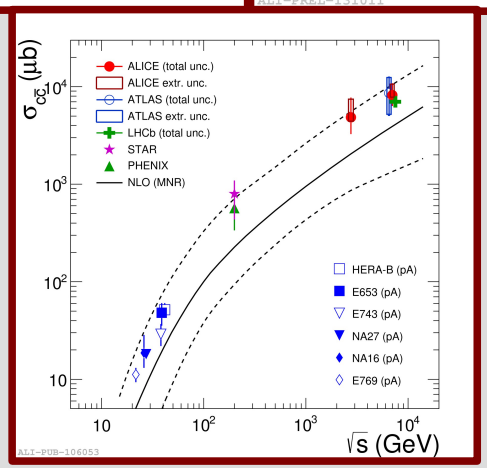
- Example: D^0 meson: non-zero lifetime; decay vertex displaced from interaction point (primary vertex)
  → Decay length, impact parameter, pointing angle (for example) can be used to select candidates
- PID at mid-rapidity using TOF (where available) + TPC, standard method with 'nσ' PID
  → Strong separation of pions, kaons and protons in wide momentum range

Measurements of Heavy-Flavour Production in ALICE

- D^0, D^+, D^{*+}, D_s^+ in pp collisions at multiple energies: strong test of perturbative QCD calculations
- D^0 measured down to p_T = 0 using non-topological analysis; allows measurement of full mid-rapidity D^0 cross-section without extrapolation
- Experimental results for production consistent with models (albeit in upper band of uncertainty)

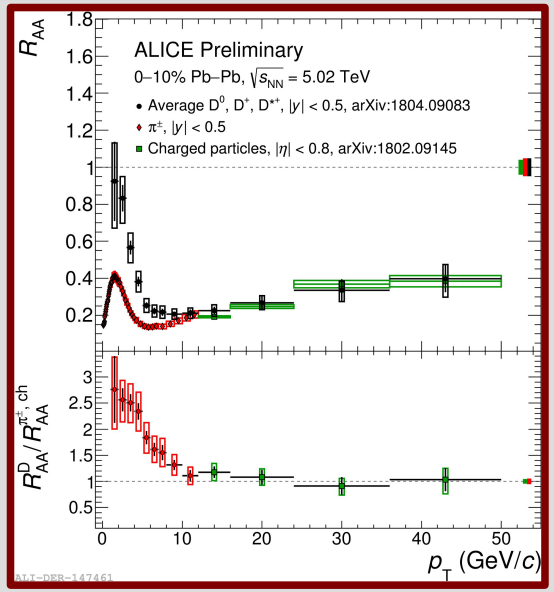


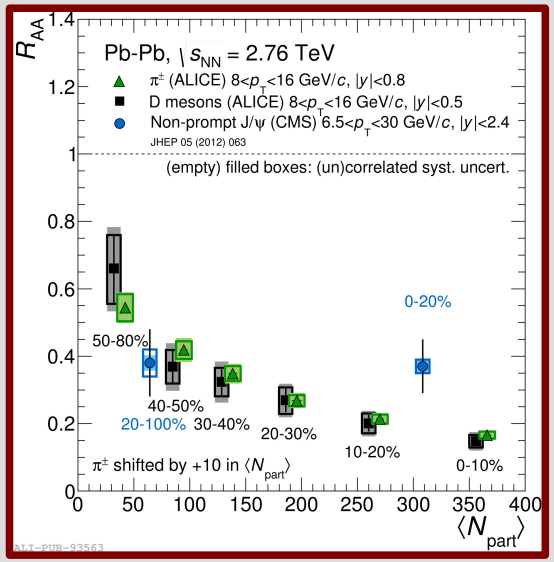


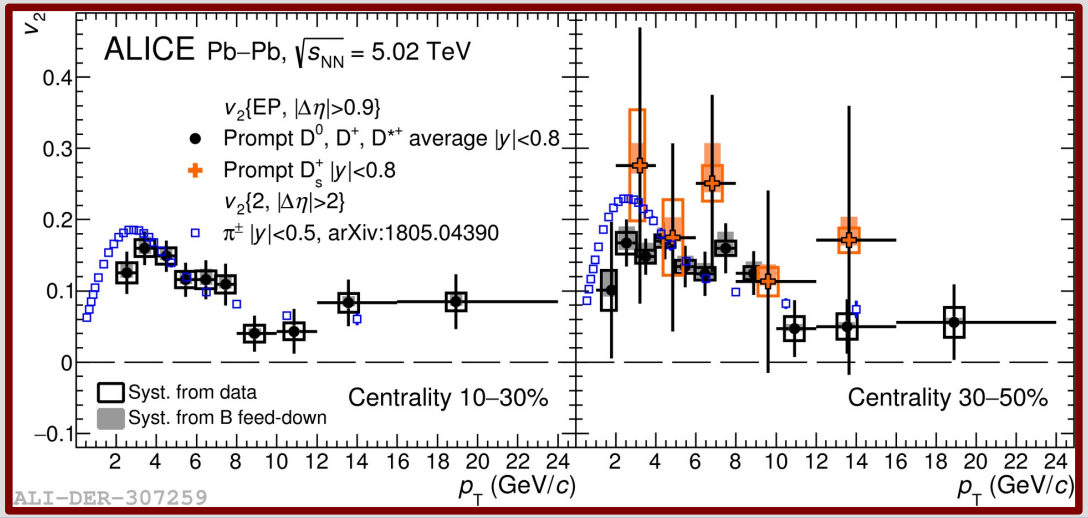


Measurements of Heavy-Flavour Production in ALICE

- Main observable: Nuclear modification factor (R_{AA}). Affected by energy loss of quarks in medium.
- Ratio of production in Pb–Pb to pp, scaled by number of binary collisions
- Expected hierarchy from "dead-cone" effect: ΔE (u,d,s) > ΔE (c) > ΔE (b) → R_{AA}(u,d,s) < R_{AA}(c) < R_{AA}(b)
- Significant suppression at intermediate-high p_T; R_{AA} decreases with increasing N_{part}
- Azimuthal anisotropy measured with v_2 - "elliptic flow" parameter
- Results for strange and non-strange D-mesons compatible with light charged hadrons → charm participates in collective expansion of medium

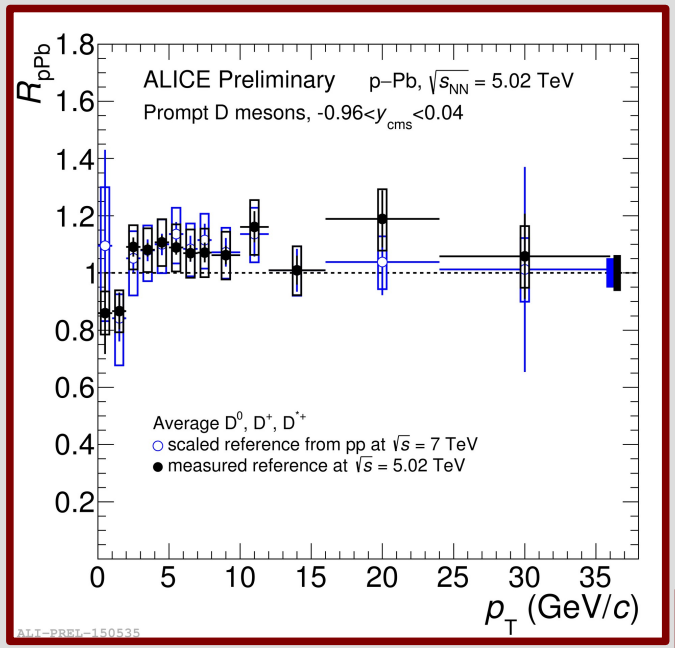


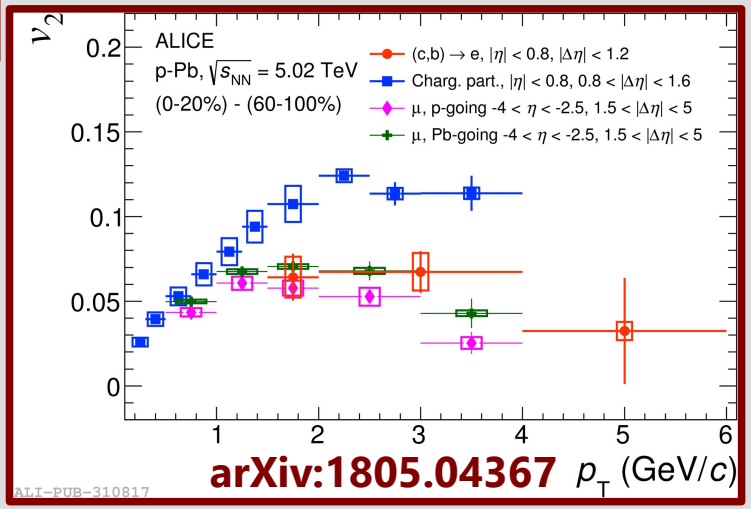




Measurements of Heavy-Flavour Production in ALICE

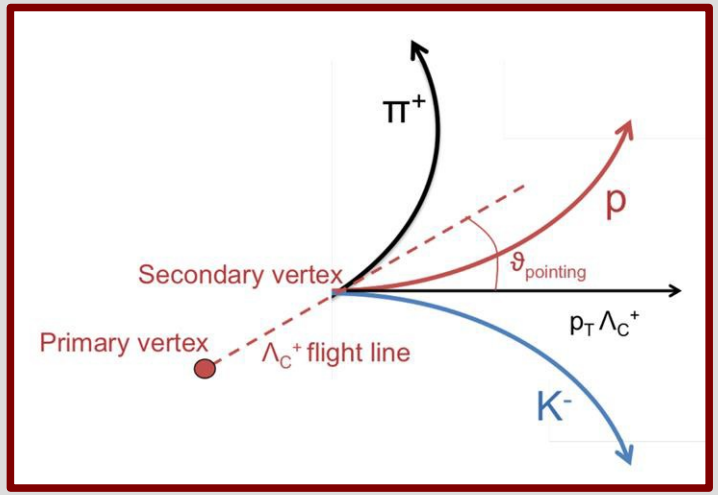
- p–Pb collisions: Disentangle hot in-medium effects in Pb–Pb collisions from initial-state "Cold Nuclear Matter" (CNM) effects such as nuclear (anti)shadowing, k_T broadening
- R_{pPb}: similar quantity to R_{AA}. Unity implies no modification → no significant CNM effect
- Access to run-2 pp data allows precise reference without energy rescaling, reducing systematic uncertainties
- Heavy-flavour decay electrons and muons show significant v_2 → flow-like effects in high-multiplicity p–Pb?

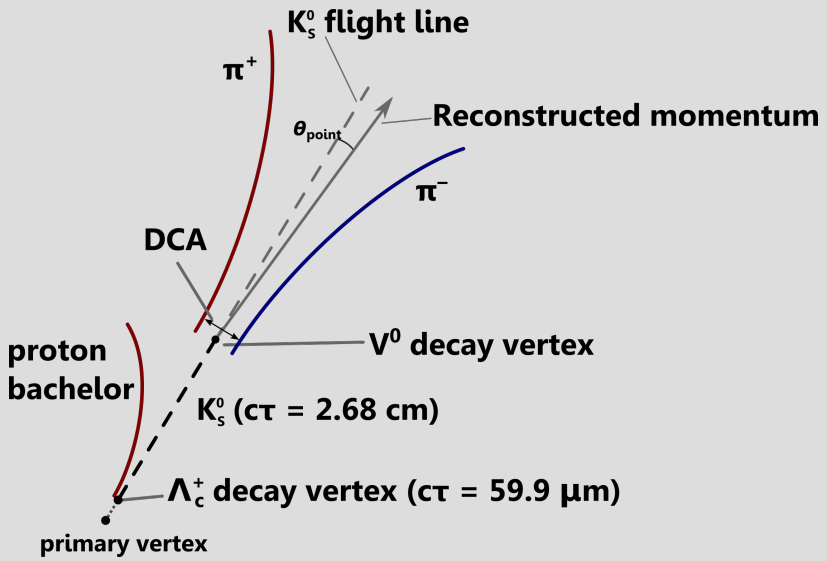




Λ_c baryon reconstruction in ALICE

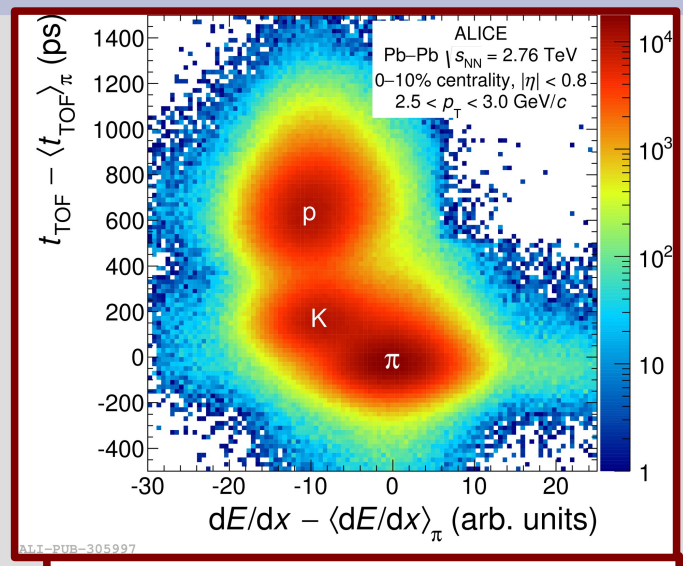
- Λ_c in hadronic decay channels: $\Lambda_c \rightarrow pK\pi$, $\Lambda_c \rightarrow pK^0_S$ and semileptonic ($\Lambda_c \rightarrow e^+\nu_e\Lambda$)
- $\Lambda_c \rightarrow pK\pi$: BR 6.23%; three-body decay via multiple resonant + nonresonant channels
- $\Lambda_c \rightarrow pK^0_S$: BR 1.58% (x 69.20% for $K^0_S \rightarrow \pi^+\pi^-$). Reconstructed using displaced K^0 vertex topology
- Typical selections include:
  - → PID of decay daughters
  - → Distance of closest approach & impact parameter of decay daughters
  - → Pointing angle of reconstructed momentum w.r.t. flight line
  - → Decay lengths of Λ_c and K^0_S
- Cross sections from each channel averaged together for final result

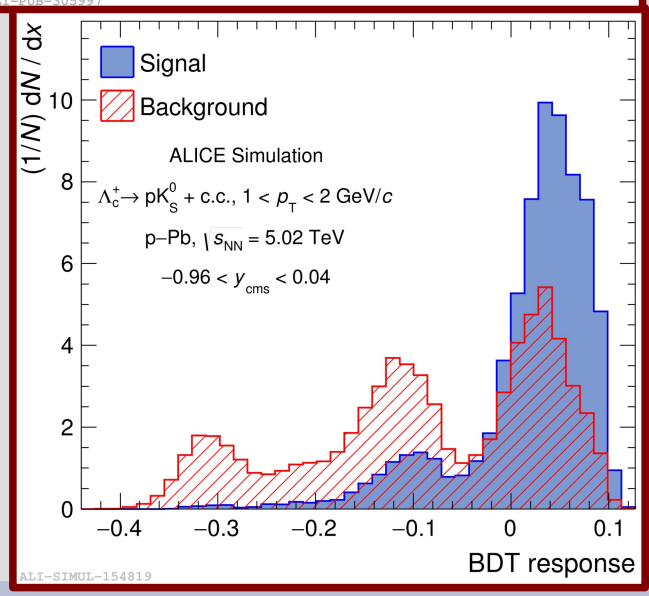




Analysis techniques for Λ_c baryons

- Very challenging measurement: rare probe with high level of combinatorial background
  - → Required development of novel identification techniques in ALICE
- **Bayesian Particle Identification [1]**:
  - → Probabilistic approach to combine signals from TPC and TOF in regions where species overlap; "most likely" species chosen as opposed to inclusive "n_σ" cut
  - → Prior probabilities for each species defined based on particle abundances in data
  - → Increases purity of selected sample
- **Toolkit for Multivariate Analysis [2]**:
  - → Machine learning method for signal classification with "Boosted Decision Trees" (BDT)
  - → Trained on kinematic variables and PID response from Monte Carlo candidates

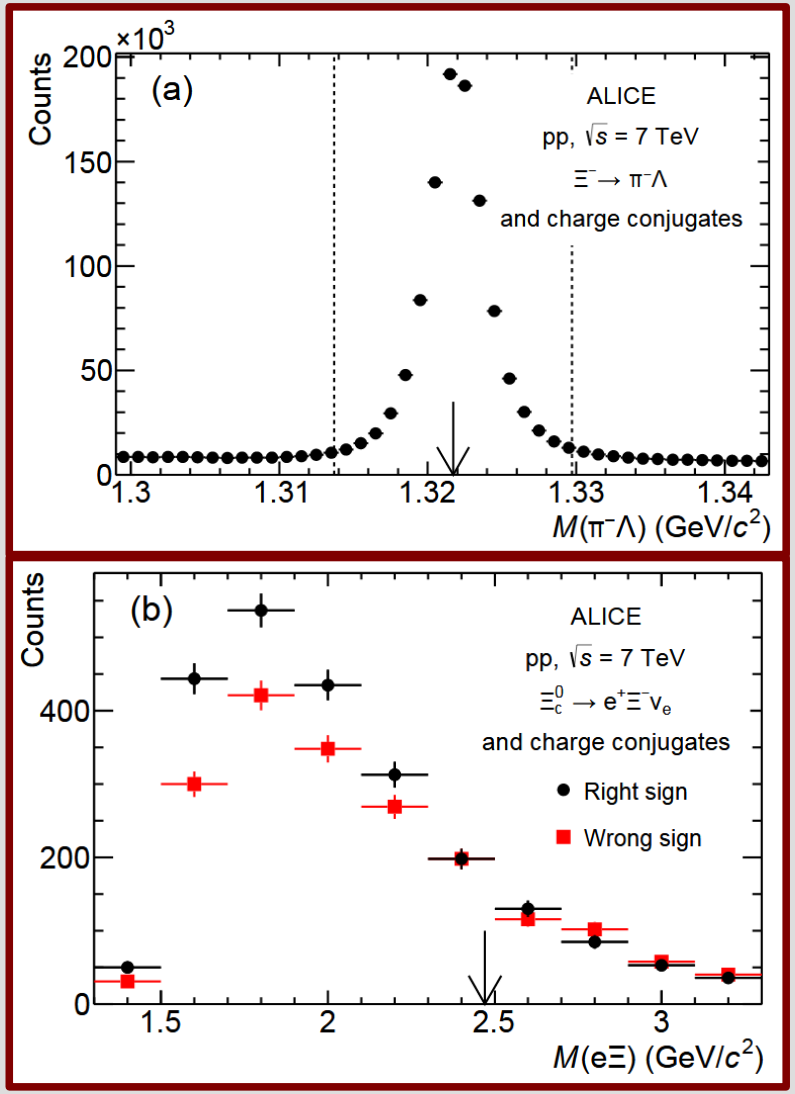




[1] Eur. Phys. J. Plus 131 (2016) no.5, 168
[2] PoS ACAT 040 (2007), arXiv:physics/0703039

Measurement of Ξ_c^0 baryon in ALICE

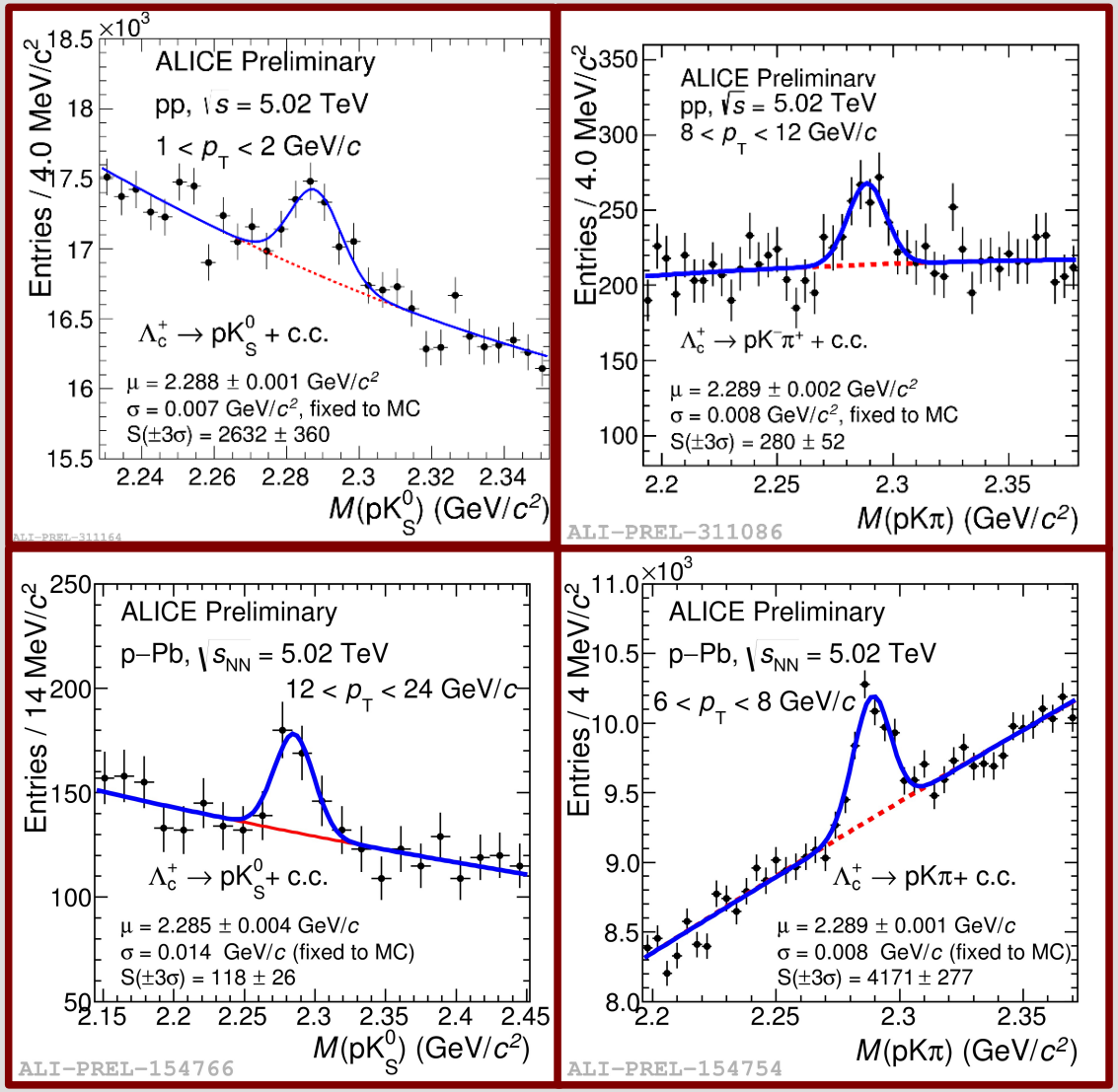
- First measurement of Ξ_c baryon at the LHC, recently published in Phys. Lett. B
- Lightest baryon with charm + strangeness → probe interplay of both flavours in recombination
- Measured in semileptonic channel ($\Xi_c \rightarrow e^+ \Xi \nu_e$)
- Ξ daughter reconstructed in $\Lambda\pi$ decay channel; background reduction via subtraction of wrong-sign candidates
- Absolute BR unknown; measurement presented as cross section times branching fraction



ALICE, Phys. Lett. B781(2018) 8-19

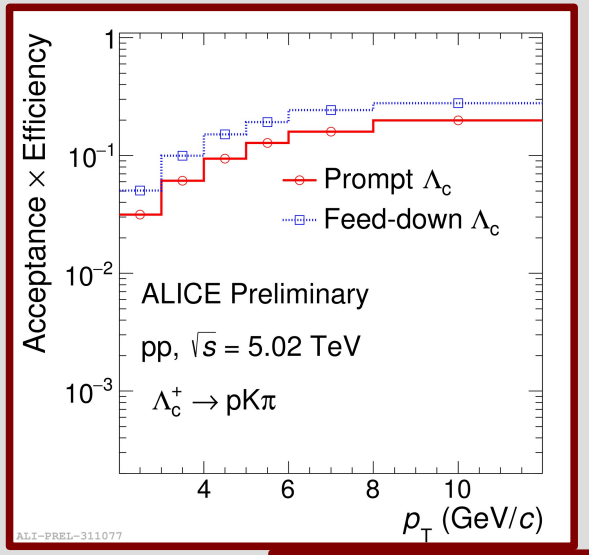
Invariant mass distributions for Λ_c baryons

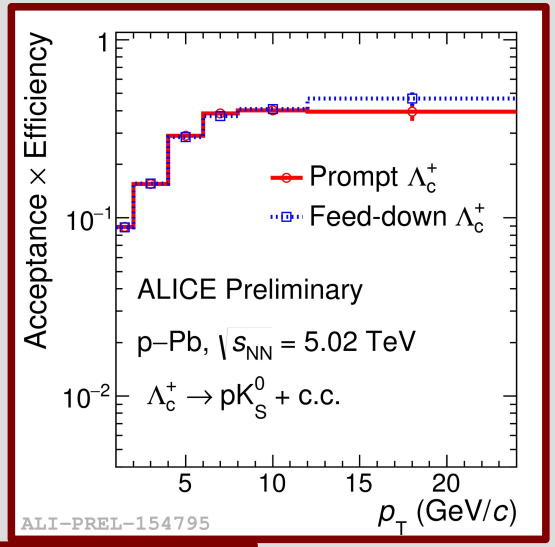
- Invariant mass distributions for both channels fitted with a Gaussian for the signal + exponential for background
- Examples shown: pK^0_S (left) and $pK\pi$ (right) decay channels in Run-2 pp (top) and p–Pb (bottom) collisions, in various p_T intervals
- Good statistical significance seen for wide range of p_T
- Systematic uncertainties estimated based on varying fit parameters: line shape of background; fixing Gaussian width vs. levaing free; range of fit; rebinning of mass histogram.

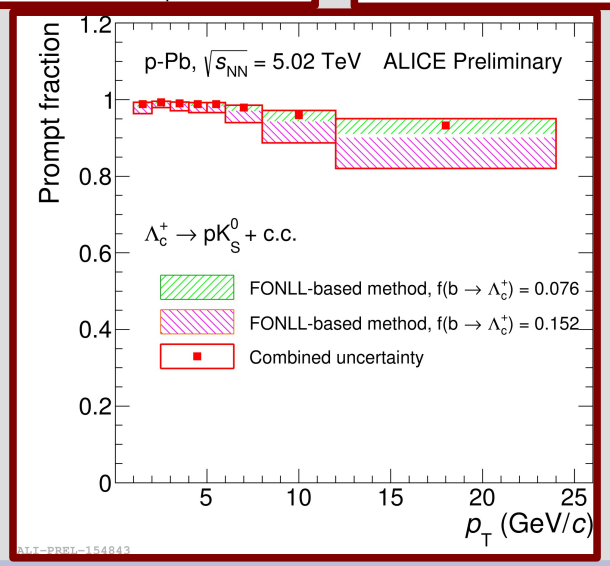


Correction factors

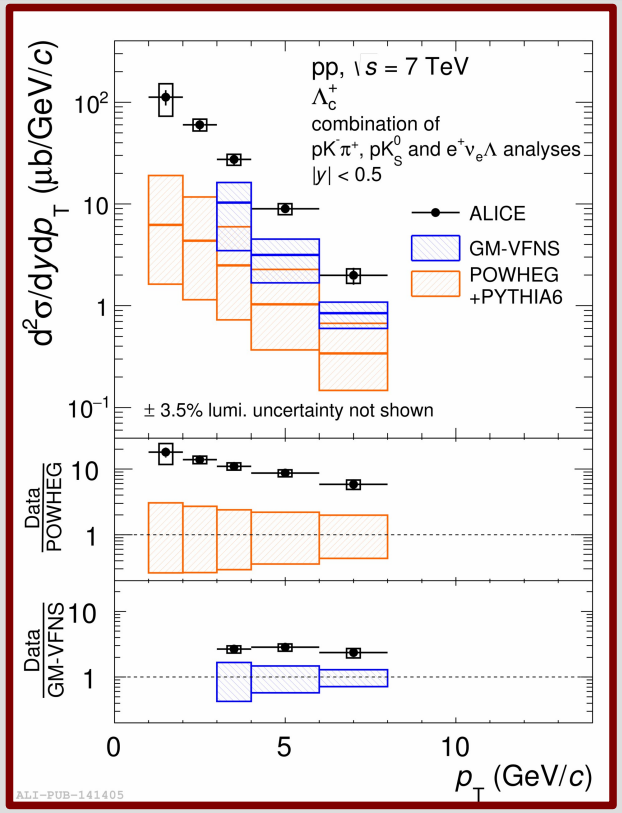
- Raw yield from invariant mass fit corrected for detector acceptance and reconstruction efficiency to obtain cross section
- Estimation made using simulated Λ_c from charm-enriched PYTHIA simulation (+HERWIG for heavy-ion collisions)
- Efficiency of feed-down from Λ_b baryons used along with FONLL pQCD calculations to estimate prompt fraction of Λ_c
- Further systematics estimated from p_T shape in MC, theory uncertainties on feed-down estimate, efficiency correction with different cuts

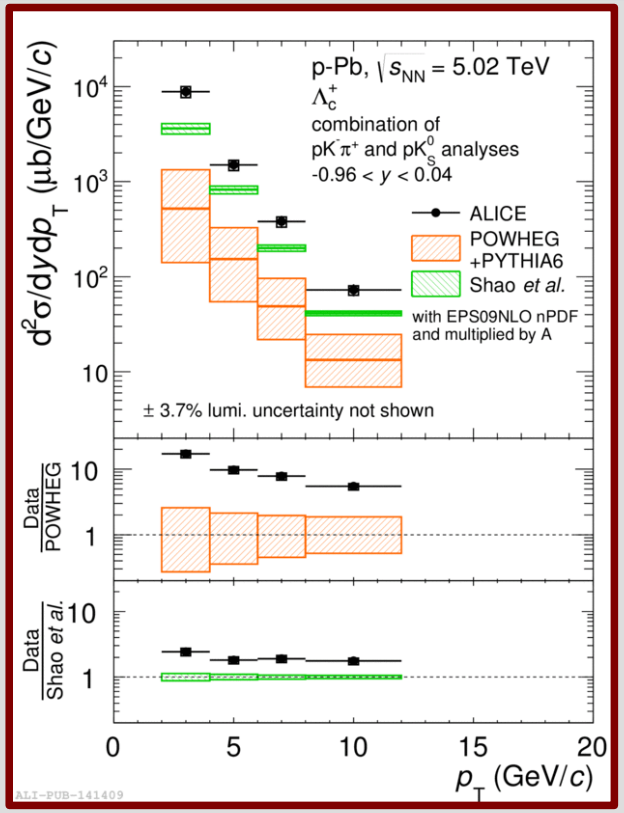






Cross sections of Λ_c baryons from run-1 data

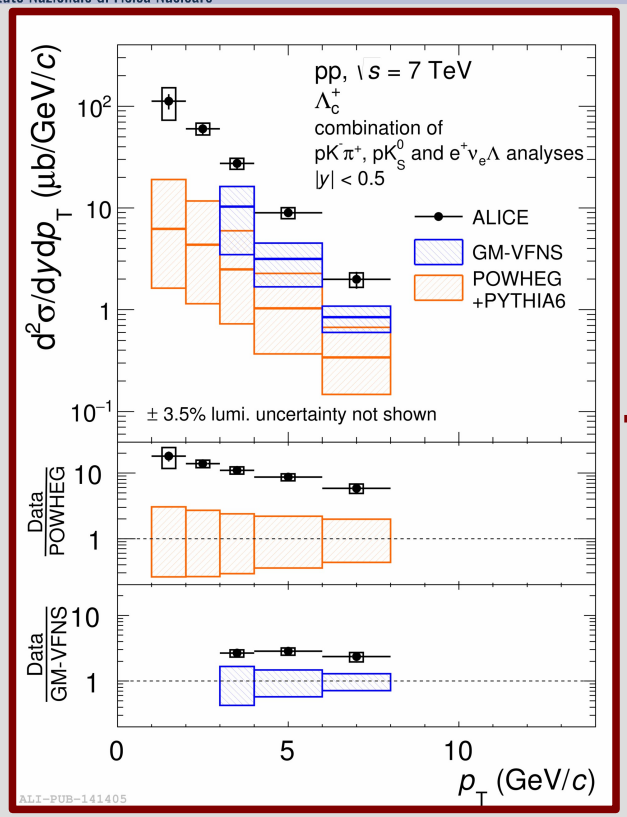


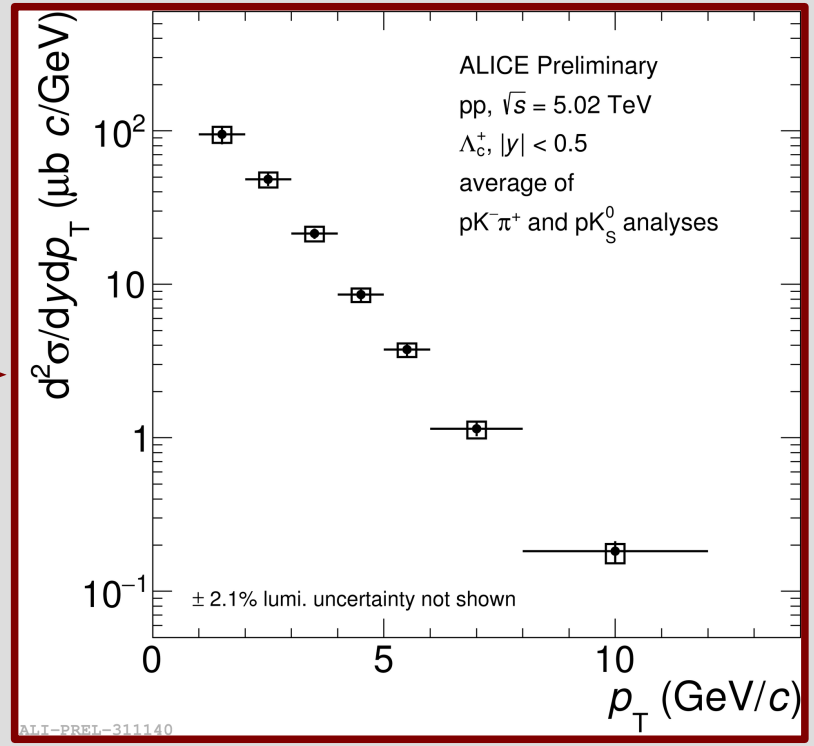


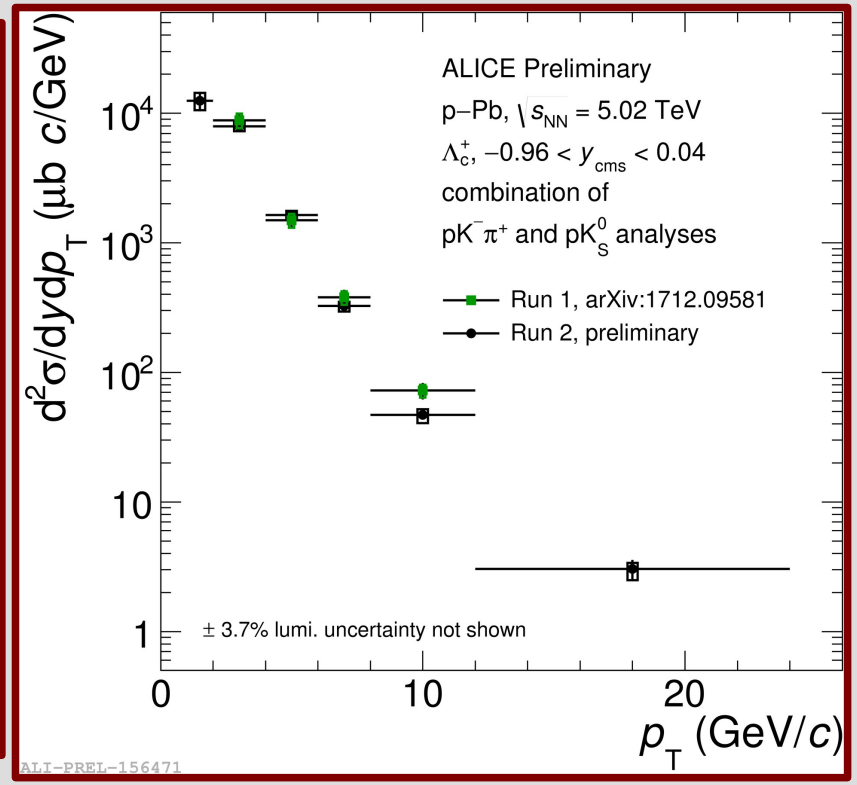
- Λ_c in pp collisions at 7 TeV and p–Pb collisions at 5.02 TeV: Production cross-sections significantly underestimated by MC models

ALICE, JHEP 1804 (2018) 108

Cross sections of Λ_c baryons from Run-1 and Run-2 data

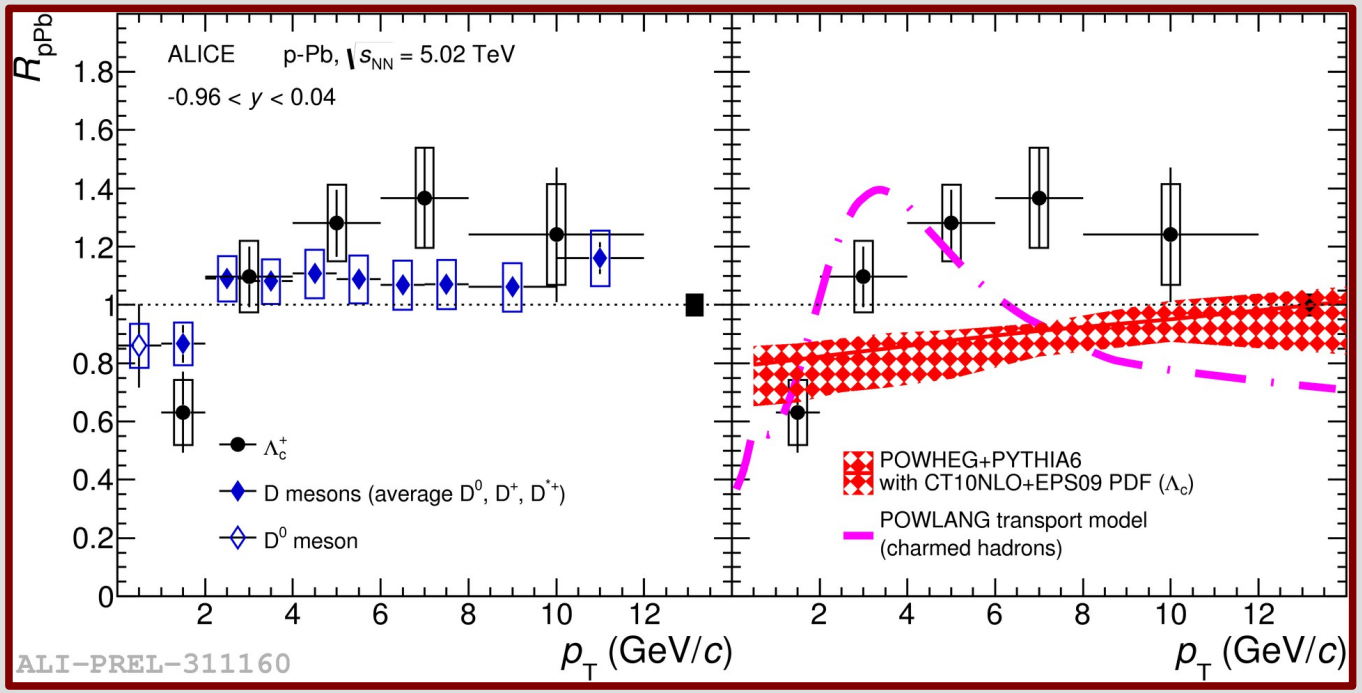






- New preliminary results extend p_T reach ([1,8]→ [1,12] GeV/c for pp, [2,12] → [1,24] GeV/c for p–Pb) and reduce statistical + systematic uncertainties; finer p_T binning achieved in pp collisions

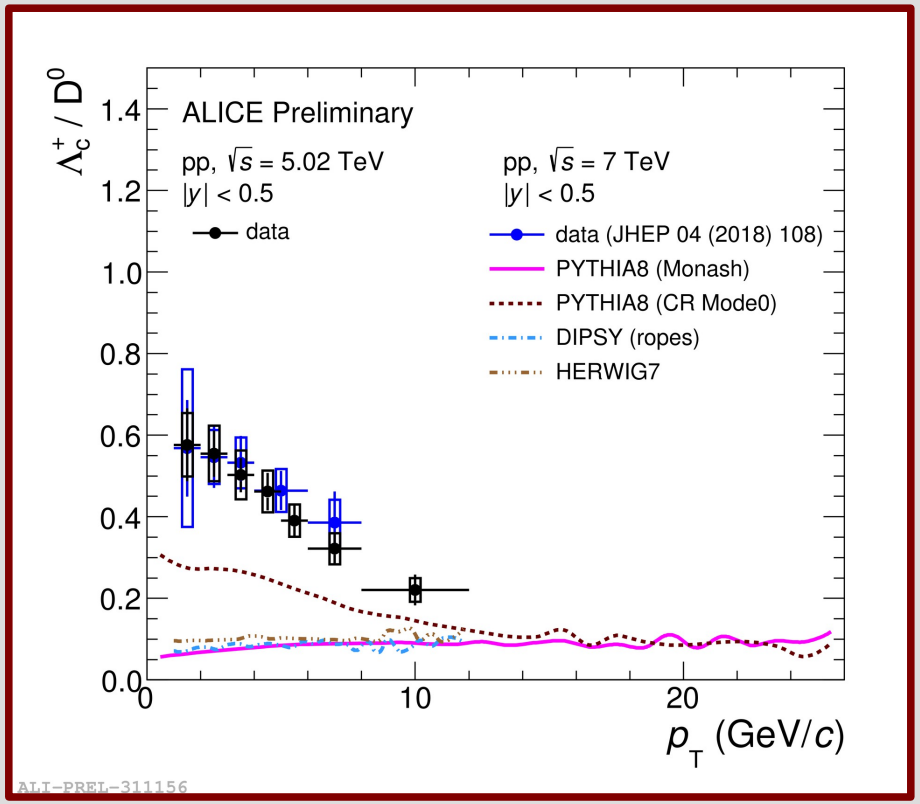
Λ_c R_{pPb}



- POWLANG: includes small QGP formation
- POWHEG+PYTHIA6: only considers CNM effects

- R_{pPb} of Λ_c baryons in p–Pb
- Cross section in p–Pb collisions divided by pp cross section, scaled by mass number of Pb nucleus
- Value of unity consistent with no initial-state "cold nuclear matter" effects in collision
- Results consistent between charmed baryons and mesons, no significant CNM effects
- Λ_c R_{pPb} described reasonably well by PYTHIA/POWLANG models within uncertainties

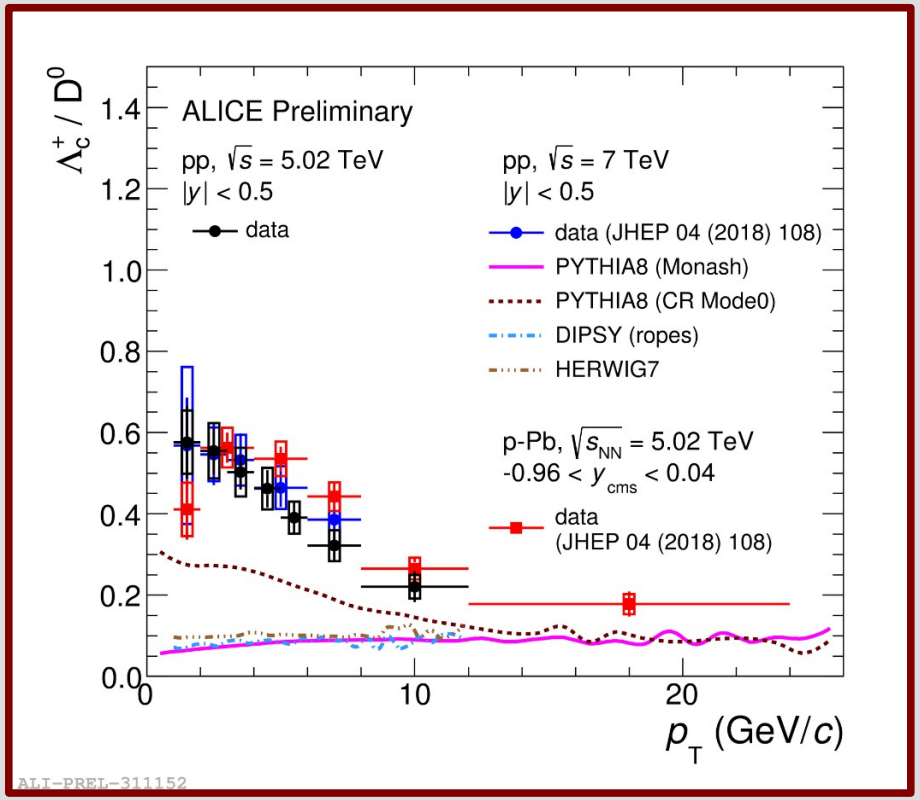
Baryon-to-meson ratio in small systems



- Λ_c/D^0 baryon-to-meson ratio as function of p_T at mid-rapidity in pp collisions at both energies
- No significant difference with collision energy between the sets of results
- Improved precision & p_T reach reveals significant downward trend towards higher p_T
- Models with e^+e^- fragmentation not able to predict magnitude or shape of ratio
- PYTHIA8 including enhanced colour reconnection comes closer to data

PYTHIA8 Monash: P. Skands et al., Eur. Phys. J. C (2014) 74:3024
Colour reconnection (CR): J. R. Christiansen and P. Skands, JHEP 08 (2015) 003
DIPSY: JHEP 08 (2011) 103
HERWIG7: Eur. Phys. J. C58 (2008) 639-707

Baryon-to-meson ratio in small systems



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- Models with e^+e^- fragmentation not able to predict magnitude or shape of ratio
- PYTHIA8 including enhanced colour reconnection comes closer to data
- p–Pb results consistent

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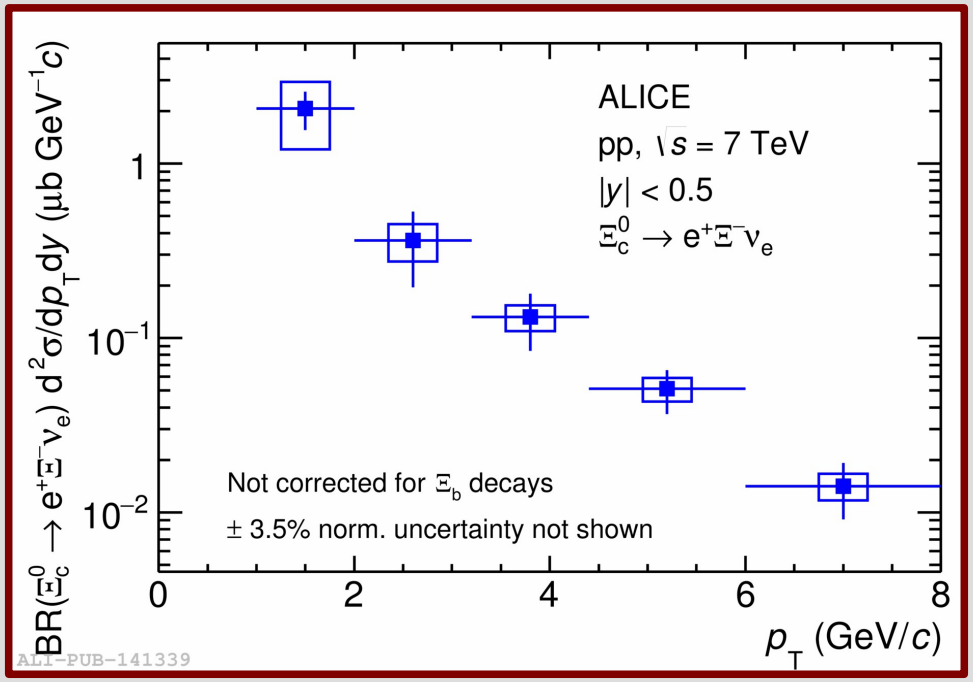
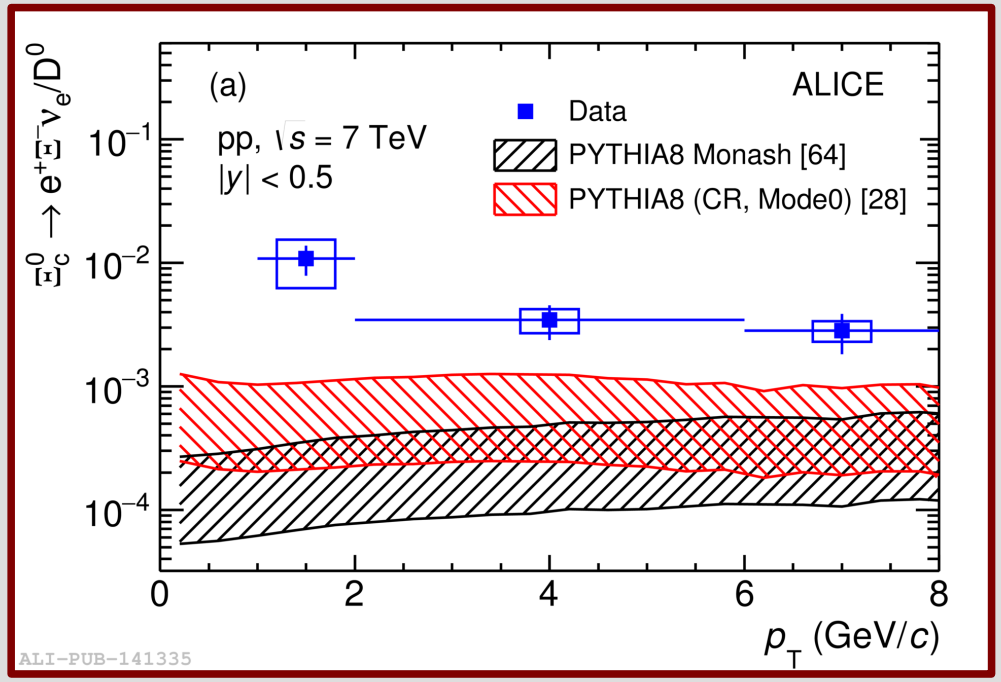
Ξ_c / D^0 production in pp collisions

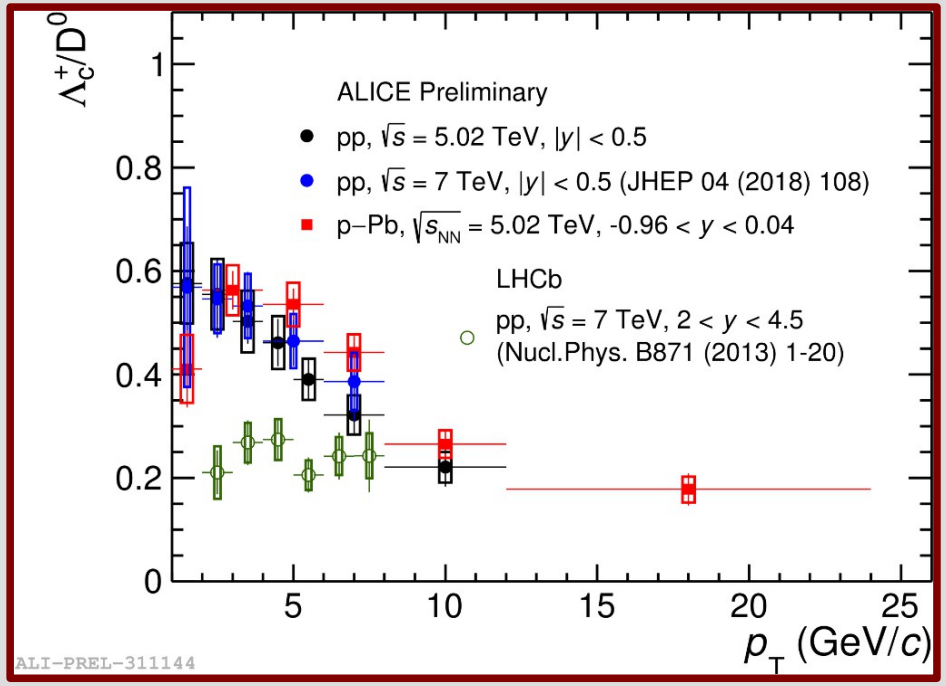


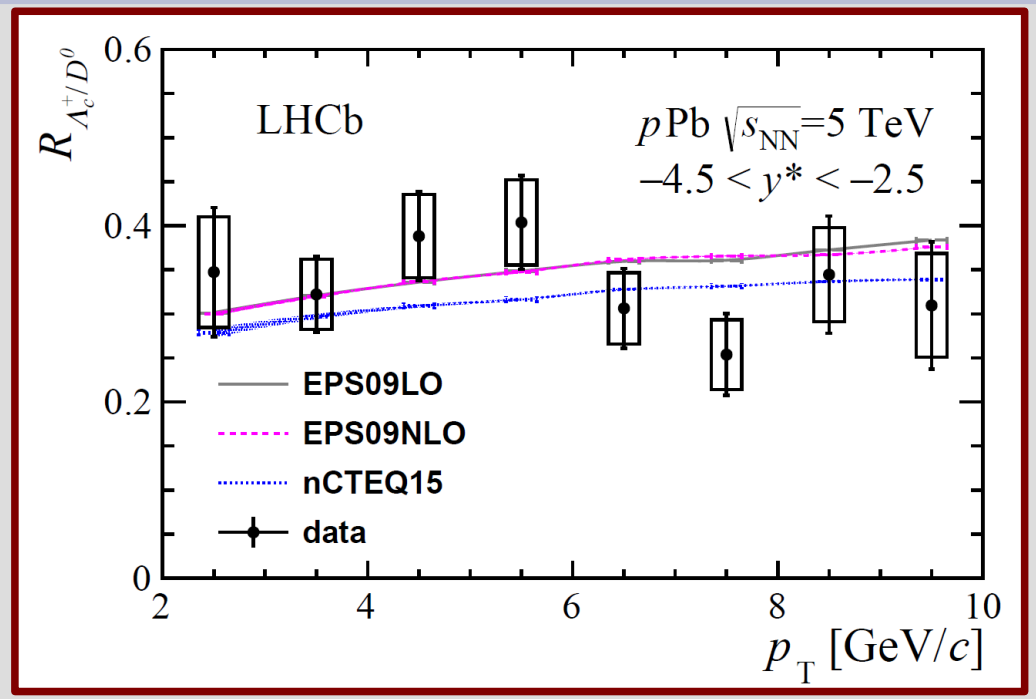


- Baryon-to-meson ratio for strange charmed baryons in $1 < p_T < 8$ GeV/c
- Compared with PYTHIA8 Monash tune & colour reconnection models
- Factor ~10 discrepancy between results and models; → further work needed on theory side to understand charm baryon hadronisation

[1] ALICE Collaboration, Phys.Lett. B781 (2018) 8-19

Baryon-to-meson ratios: Comparison with LHCb

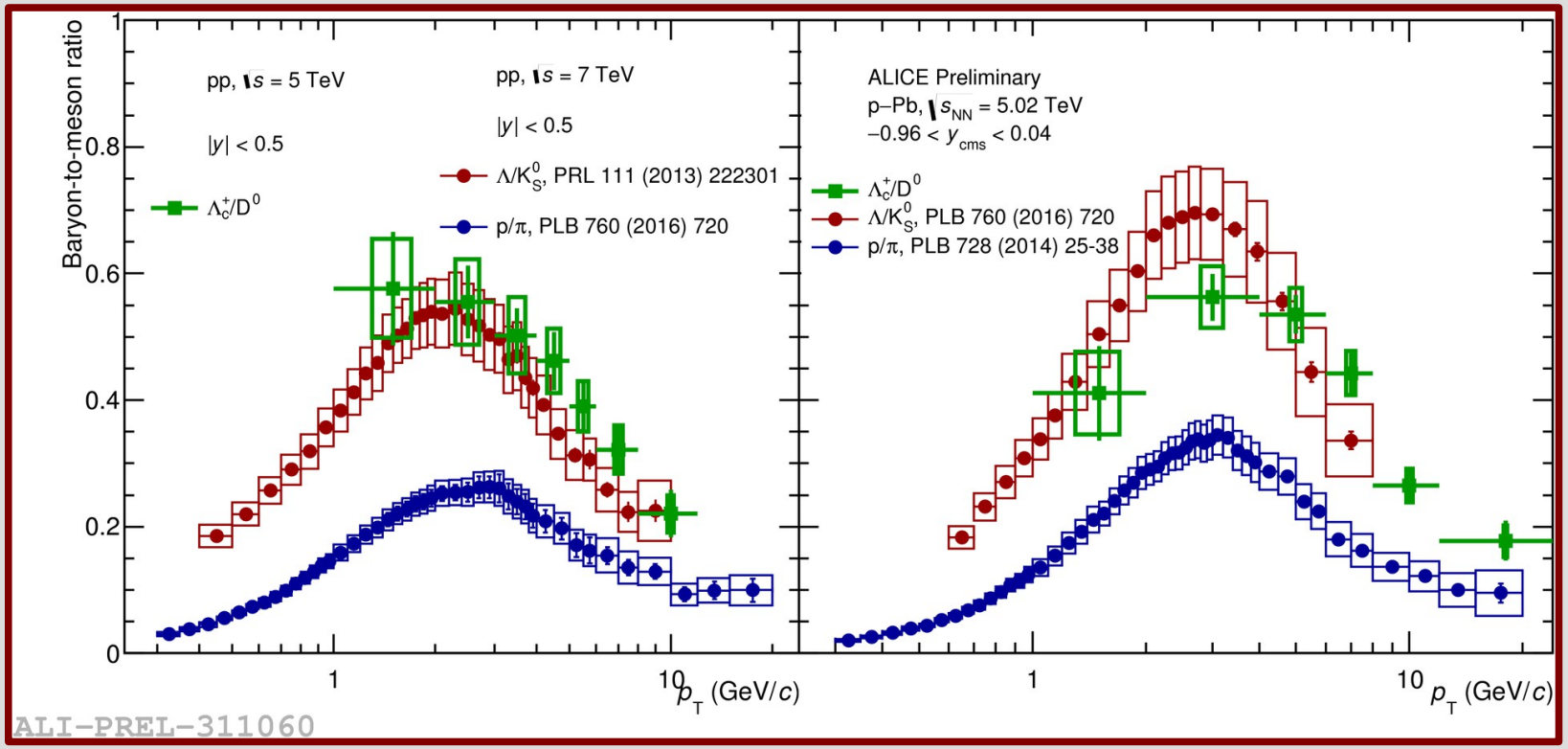




- pp collisions: LHCb results (forward rapidity) significantly below ALICE results (mid-rapidity). Possible rapidity dependence of hadronisation processes?
- p–Pb collisions: Results closer than in pp collisions but still higher for ALICE at low p_T
- EPS09 calculations (including tuning to LHCb pp results) describe LHCb data well at forward rapidity

LHCb: arXiv:1809.01404

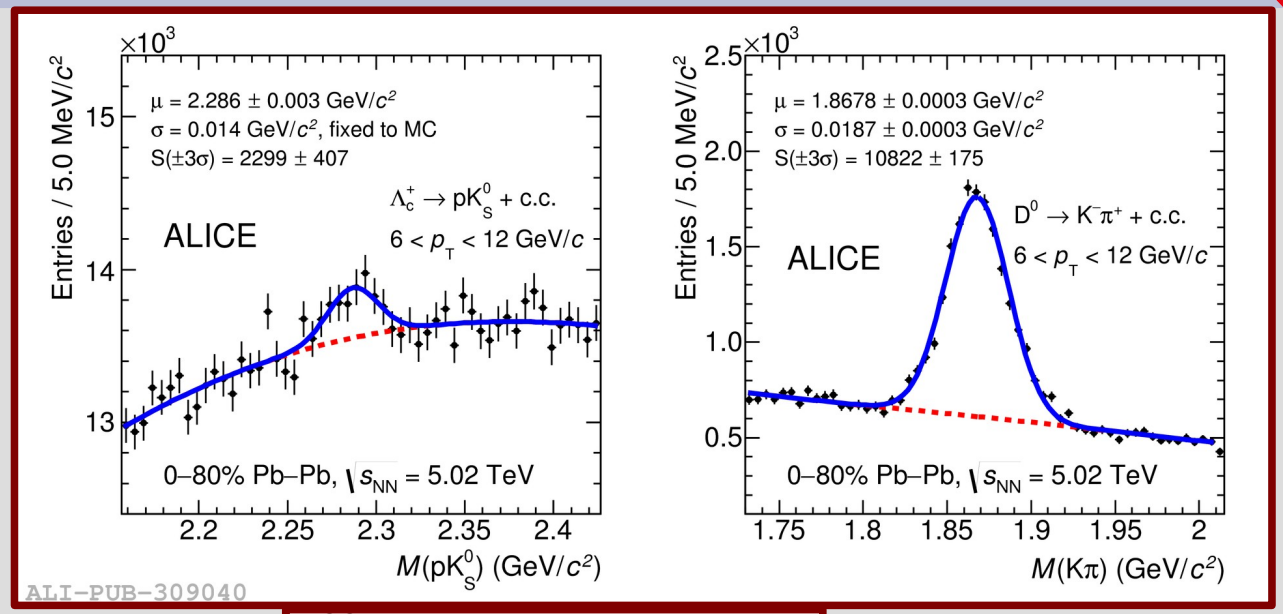
Baryon-to-meson ratios: Comparison with light flavours

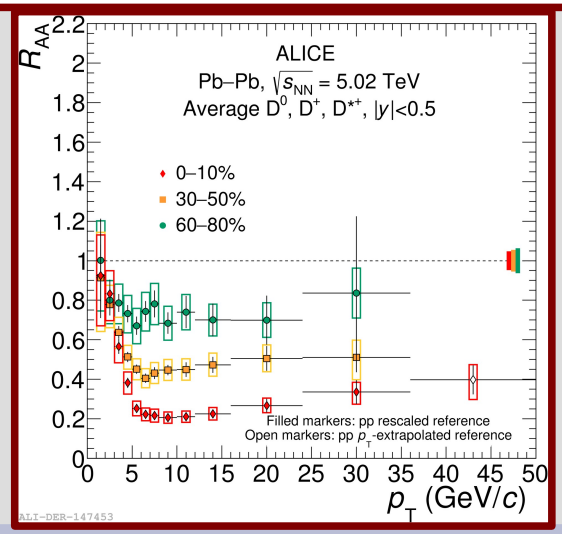


- Baryon-to-meson ratio compared between charm & light flavours
- Striking similarity between Λ_c/D^0 and Λ/K^0_S for both collision systems; p_T shape similar to p/π ratio
- Future goal: finer p_T binning in p–Pb to better compare flavour dependence

Λ_c in Pb–Pb collisions

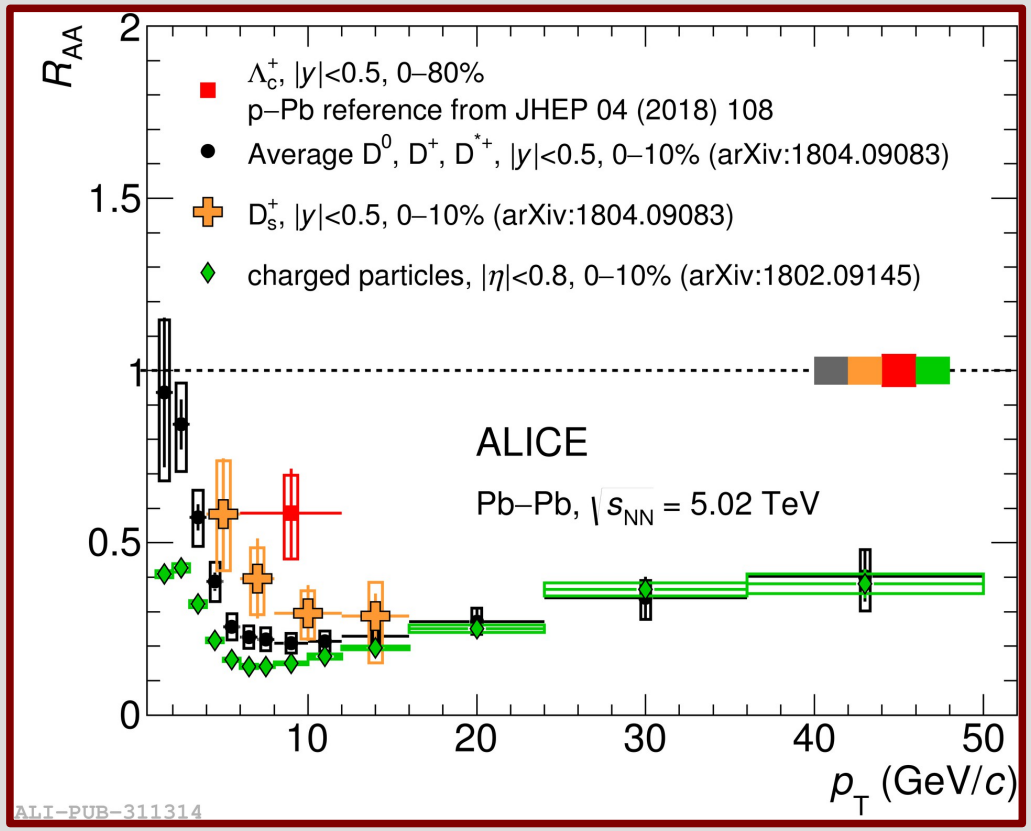
- First measurement in Pb–Pb collisions at the LHC
- With current data sample, currently one pT interval analysed in minimum-bias (0–80% centrality) Pb–Pb collisions
- D^0 meson re-analysed in same pT / centrality for consistent reference
- Major observable: R_{AA}: particle yield in Pb–Pb collision divided by yield in pp, scaled by number of binary collisions
- Existing D-meson results from run-2 show significant suppression in central–midcentral collisions



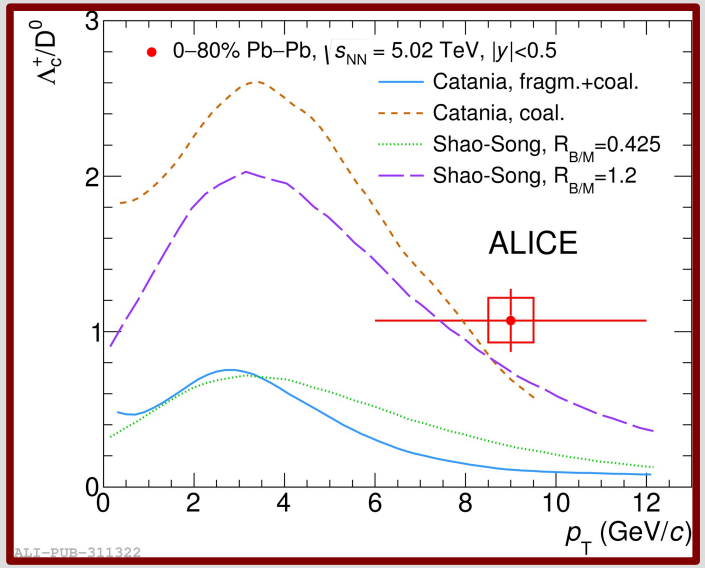


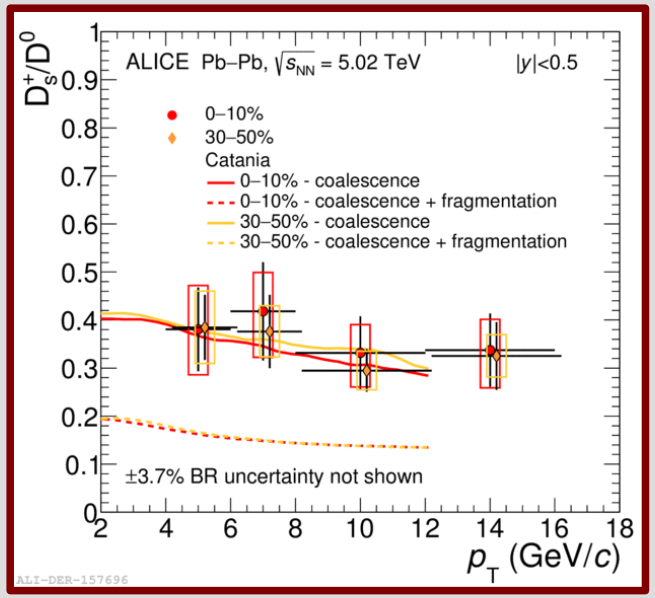
Λ_c and D_s^+ in heavy-ion collisions

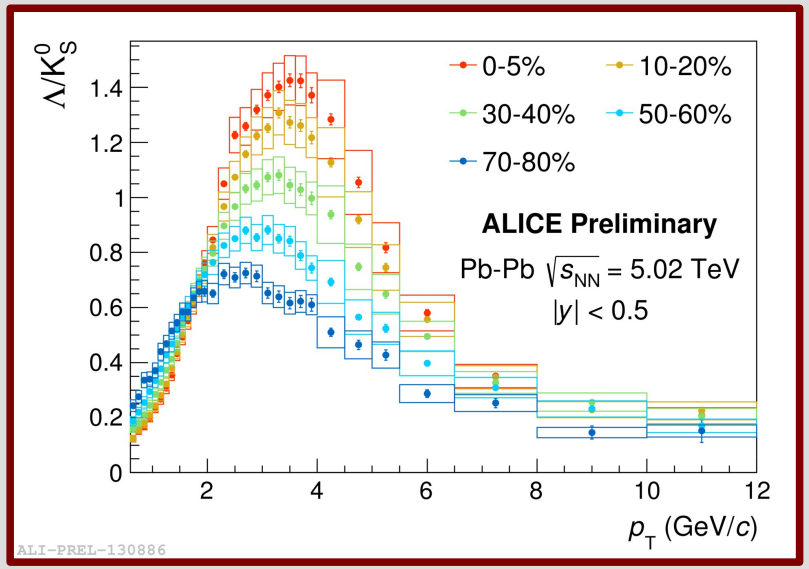
- Λ_c R_{AA} measured using p–Pb result as reference
- Compared with R_{AA} of pions, charged particles, nonstrange D mesons and strange D mesons.
  - → Λ_c production significantly higher than D mesons
  - → Hierarchy at intermediate p_T implies ΔE (u,d,s) > ΔE (c) (expected from dead cone effect)
  - → D_s^+ production increased over non-strange D mesons; further increase for Λ_c. Stronger recombination effect for baryons?



Λ_c and D_s^+ in heavy-ion collisions



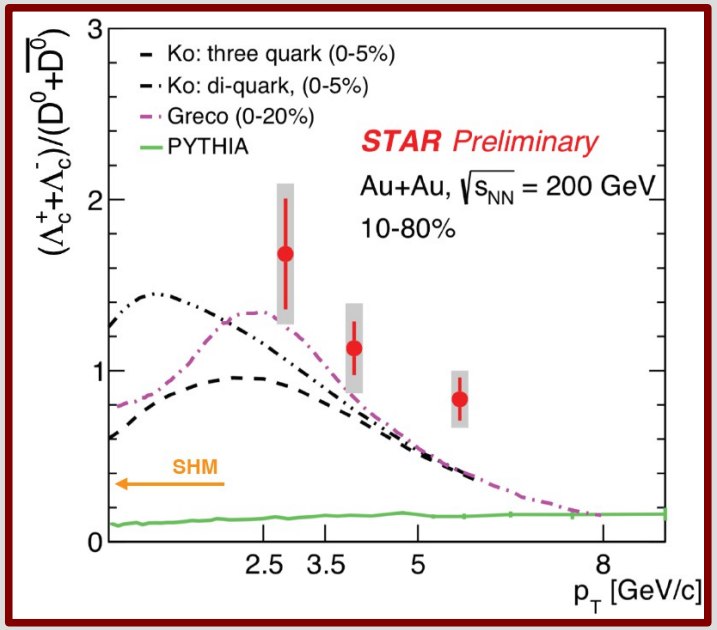


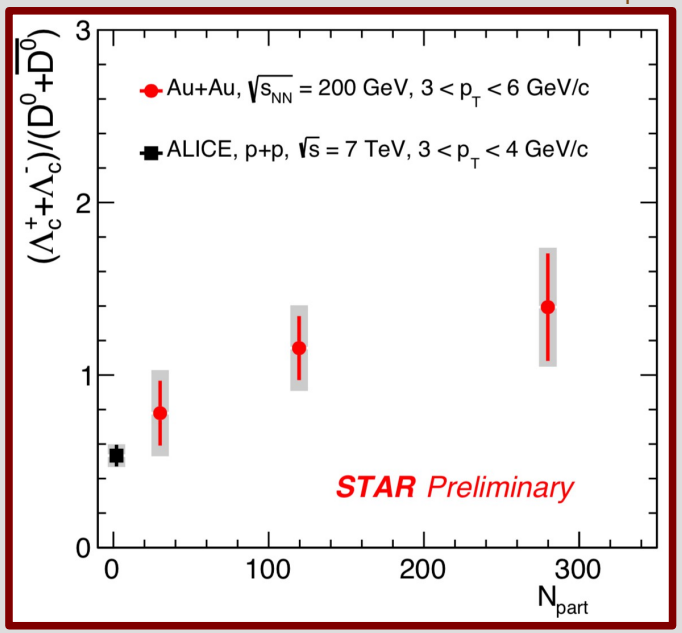


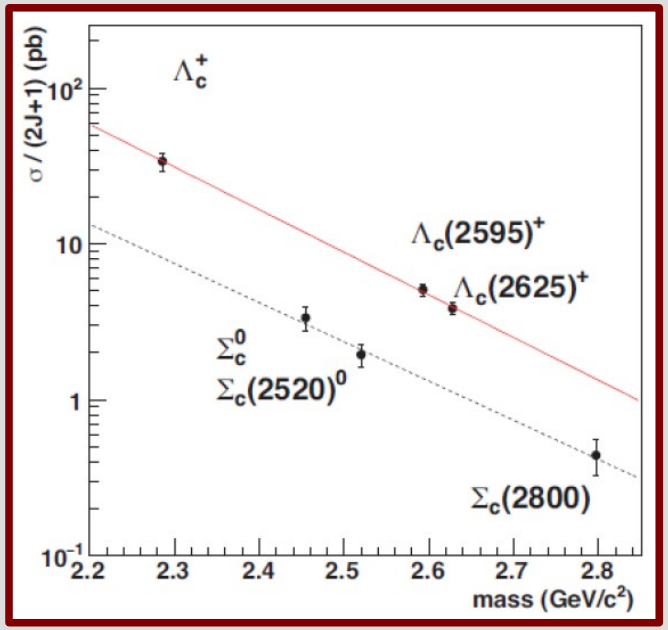
- Λ_c / D^0 ratio: Enhancement over unity in Pb–Pb collisions, significantly higher than pp and p–Pb collisions. Result underestimated by most existing models.
- D_s^+ production modelled better with pure coalescence model than coalescence + fragmentation. No centrality dependence seen.
- Λ_c/D^0 appears higher than Λ/K^0_S in Pb–Pb at same p_T, despite being similar in small systems → needs further statistics to better study flavour dependence

Comparison with other experiments

- Recent updated measurement by STAR in Au–Au collisions:
  - → Enhancement of Λ_c/D^0 ratio increases going to lower p_T; similar shape to pp/p–Pb from ALICE
  - → Λ_c/D^0 increases going towards higher centrality; recombination stronger in larger medium?
  - → Diquark coalescence slightly favoured over three-quark model; supported also by Belle result for Λ_c and Σ_c production
  - → Look to 2018 Pb–Pb campaign for improved statistics for p_T / centrality studies

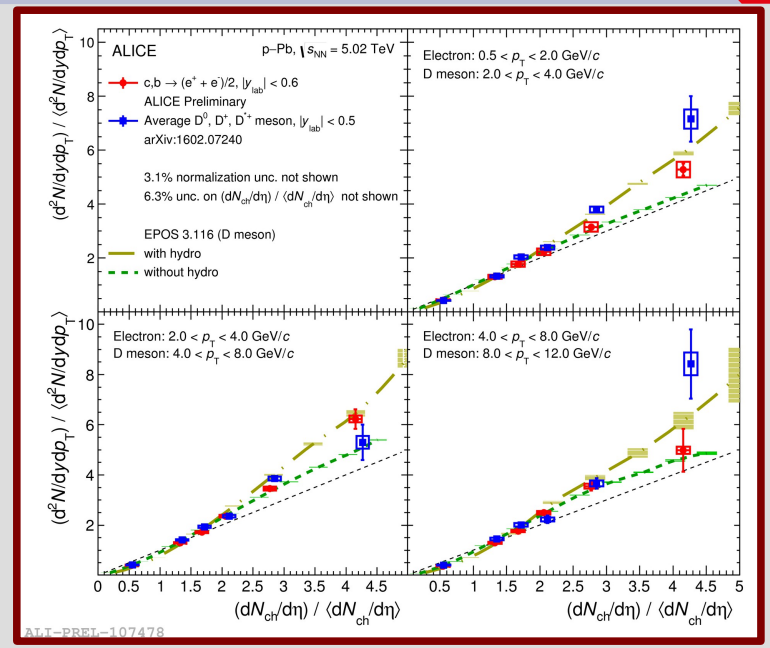


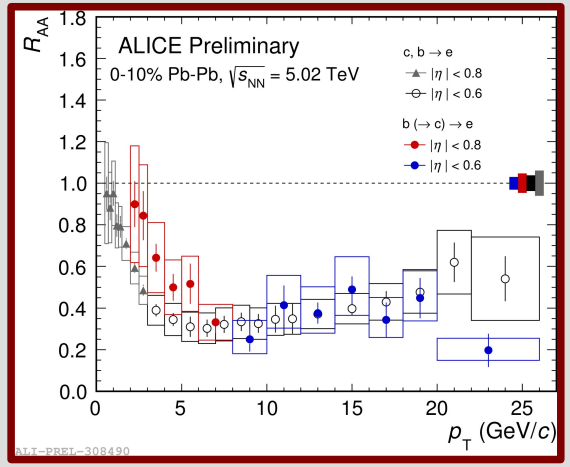


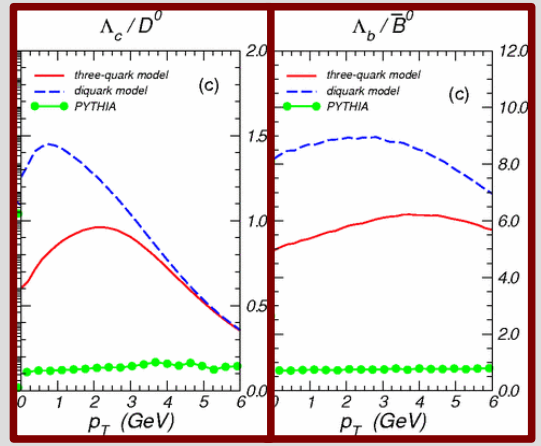


Prospects for future measurements

- **Multiplicity dependence in small systems:**
- Heavy-flavour yields as function of multiplicity probe role of multi-parton interactions (MPI) in particle production
- D mesons, heavy-flavour decay electrons: Moderate faster-than-linear trend seen; results better described by models that include hydrodynamics than without
- Possible modification of Λ_c measurement vs multiplicity will determine if this plays a role in baryon formation
- **Λ_b/B^0 measurement**
- Beauty found to be less suppressed than charm; models predict higher Λ_b/B^0
- Further test flavour dependence of hadronisation processes







Conclusions / outlook

- Λ_c and Ξ_c baryons successfully studied in pp, p–Pb and Pb–Pb collisions with ALICE
- Baryon-to-meson ratio in charm sector shows similar behaviour to light flavours in small systems
- Significant enhancement of Λ_c/D^0 production ratio in Pb–Pb compared to pp and p–Pb collisions → confirms observation made by STAR. Larger system size seems to lead to higher production ratio
- Models (esp. including e^+e^- fragmentation) unable to adequately describe observed production; needs further work to understand baryon hadronisation in hadronic collisions
- Outlook: 2018 Pb–Pb campaign will be crucial for improved statistics to allow p_T and centrality dependence
- Run 3, 4: Access to Λ_b, Σ_c to further study flavour and spin dependence