Open heavy-flavour production in pp, p–Pb and Pb–Pb collisions in ALICE

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on behalf of the **ALICE Collaboration**

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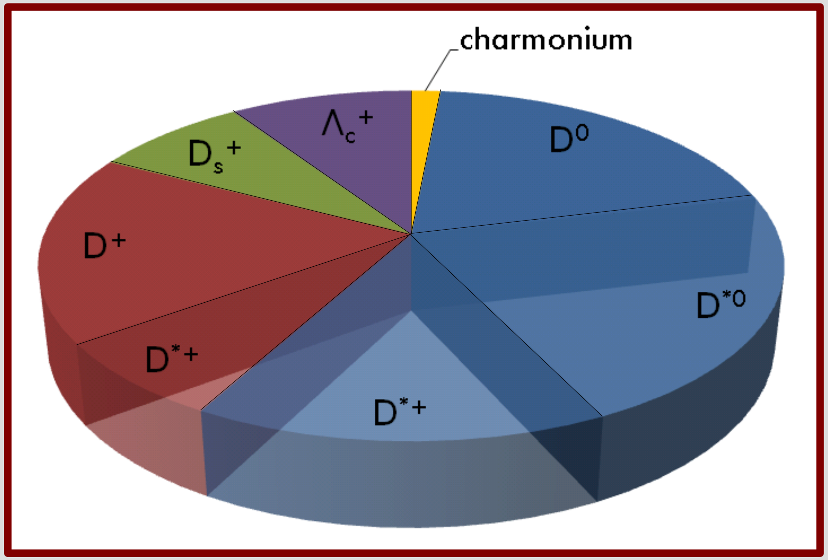
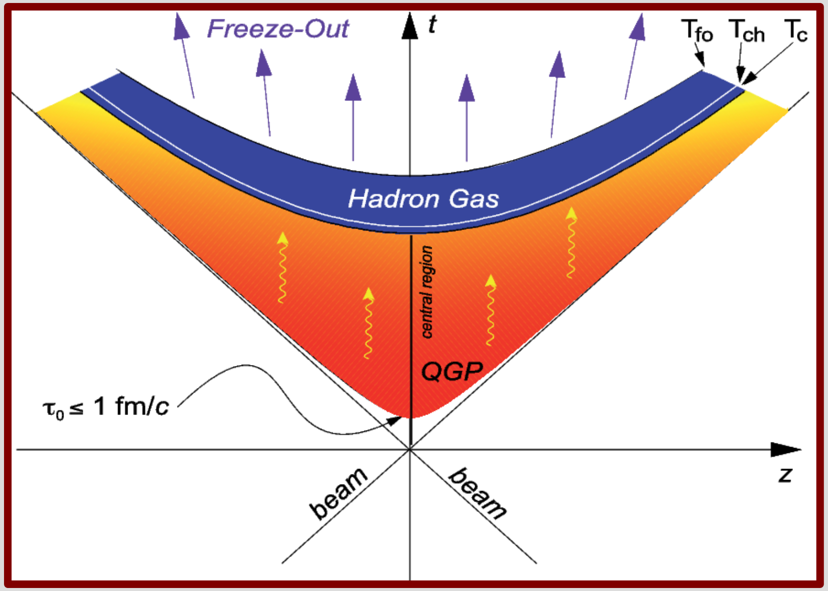
Why open heavy flavour in ALICE?

- Heavy-flavour (charm & beauty) production offers a unique probe into the properties of the **Quark-Gluon Plasma (QGP)** formed in heavy-ion collisions
- pp: cross section serves as test of pQCD calculations & important baseline for quarkonia
- p-Pb: moderate number of binary collisions ($\langle N_{\mathrm{coll}} \rangle \approx 7$); small system, medium effects expected to be small (if any)
  → Comparisons of results (such as nuclear modification factors) in p-Pb and Pb-Pb disentangle in-medium effects from cold nuclear matter effects
  → Study possible collectivity in small systems
- Pb–Pb: **study in-medium effects**
  → Due to large masses, charm and beauty quarks are produced in the **early stages** of the collision.
  → Expected hierarchy of energy loss due to dead cone and colour charge effects:
  $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$



Blue: D^0, Red: D^+; Solid: Direct production, Hollow: feed-down from resonant state)
Ratios: **Phys.Rev. D86, 010001 (2012)**

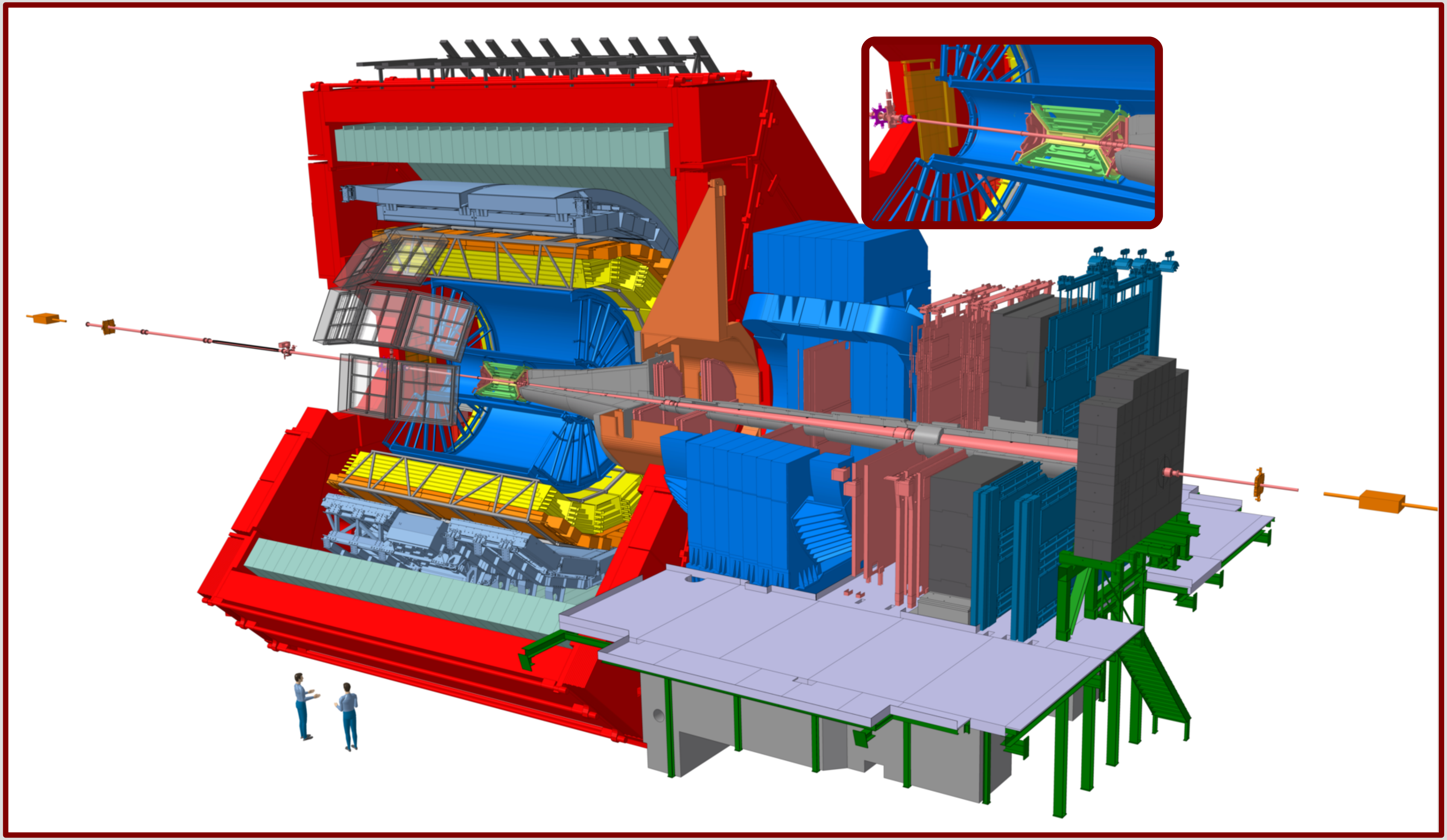


Measuring open charm production in ALICE

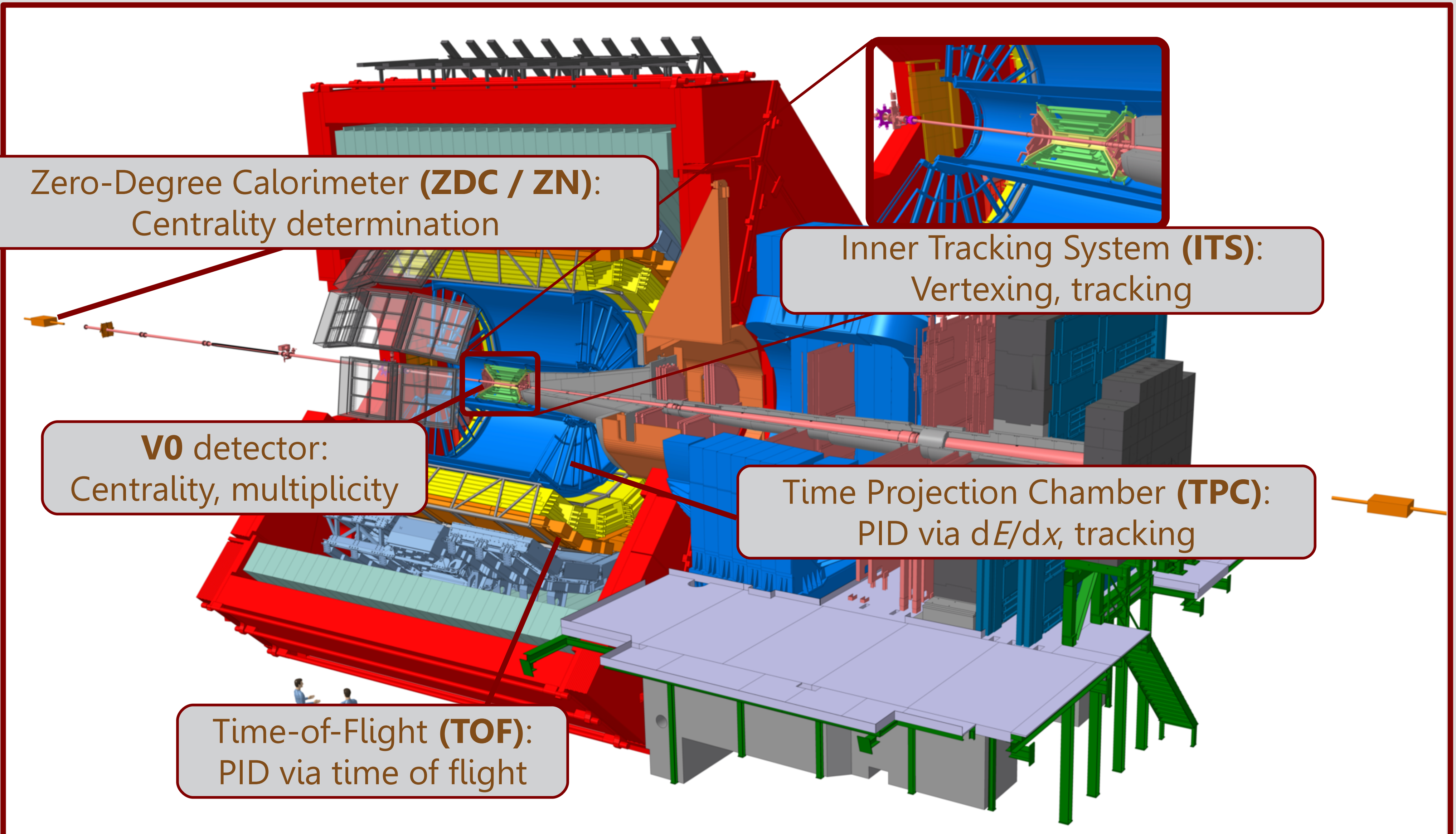
- Three main reconstruction methods:
  → **Hadronic decays of D mesons & Λ_c baryons:**
  $D^0 \rightarrow K^-\pi^+$ (BR = 3.93 ± 0.04%; $c\tau \approx 123$ μm)
  $D^+ \rightarrow K^-\pi^+\pi^+$ (BR = 9.46 ± 0.24%, $c\tau \approx 312$ μm)
  $D^{*+} \rightarrow D^0\pi^+$ (BR = 67.7 ± 0.5%)
  $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ (BR = 2.27 ± 0.08%, $c\tau \approx 150$ μm)
  $\Lambda_c^+ \rightarrow pK\pi$ (BR = 6.35%); $\Lambda_c^+ \rightarrow pK_S^0$ (BR = 1.58%)
  (and respective charge conjugates)
  → **Semileptonic decays to electrons:**
  $c \rightarrow e^\pm + X$ (BR ≈ 10%), $b \rightarrow e^\pm + X$ (BR ≈ 11%)
  $\Lambda_c^+ \rightarrow e^+\nu_e\Lambda$ (BR = 3.6%)
  $\Xi_c^0 \rightarrow e^+\nu_e\Xi^-$ (BR unknown)

  → **Semileptonic decays to muons:**
  $c \rightarrow \mu^\pm + X$ (BR ≈ 10%), $b \rightarrow \mu^\pm + X$ (BR ≈ 11%)

ALICE: A Large Ion Collider Experiment

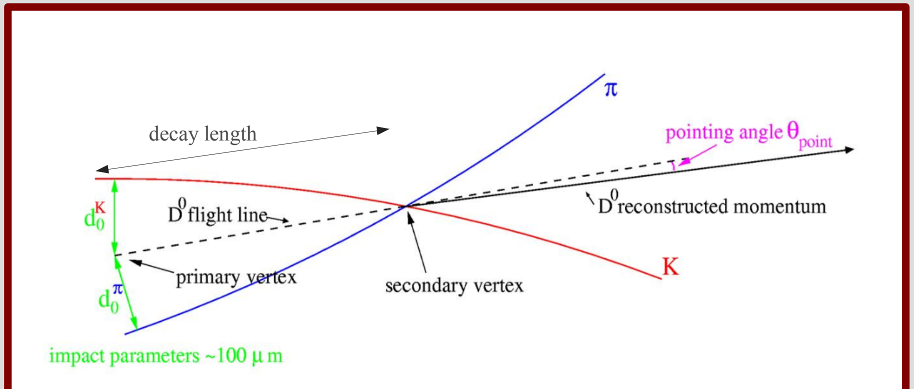


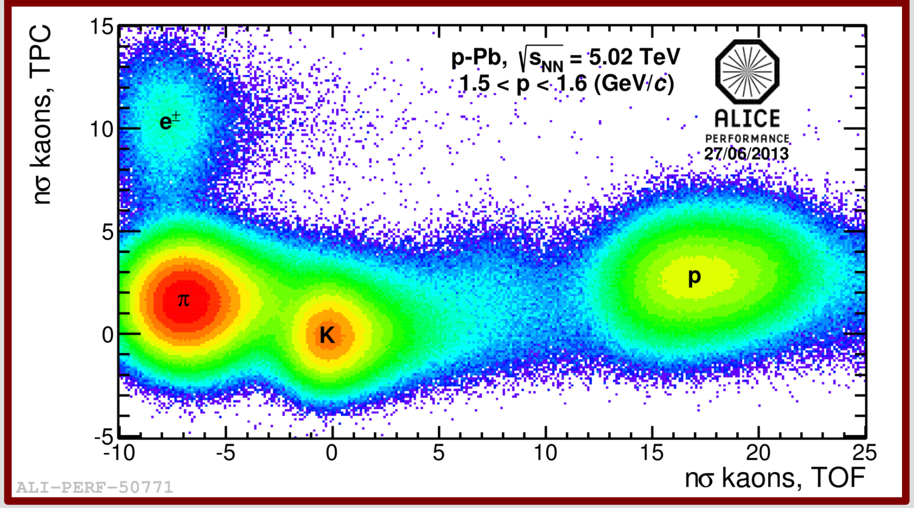
ALICE: A Large Ion Collider Experiment



Reconstruction of charmed hadrons

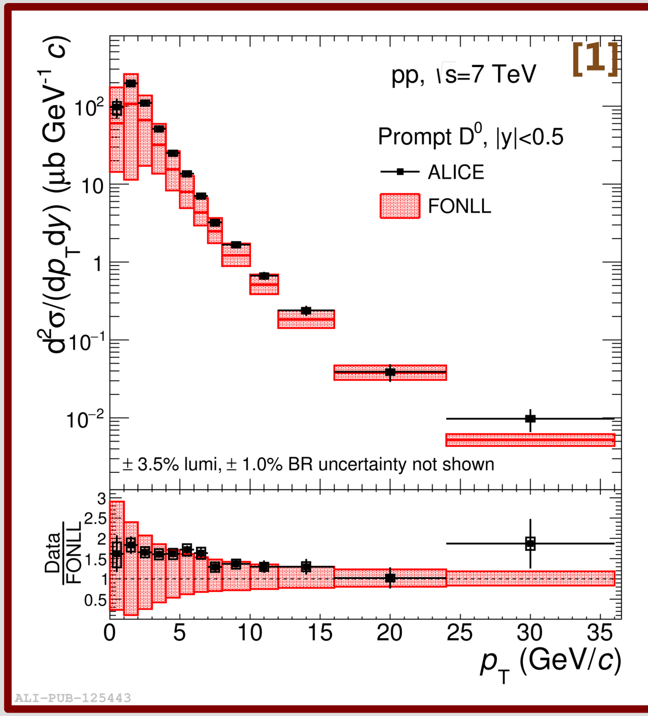
- Strategy: full reconstruction of hadronic decays of D mesons
  - → Retains full kinematic information of original particle
- Reconstruction relies on topological + PID selections to reduce combinatorial background

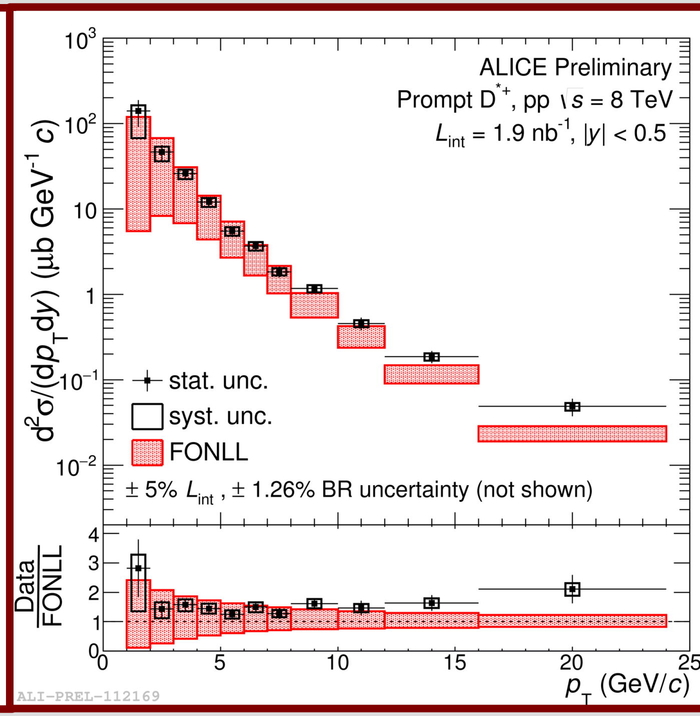


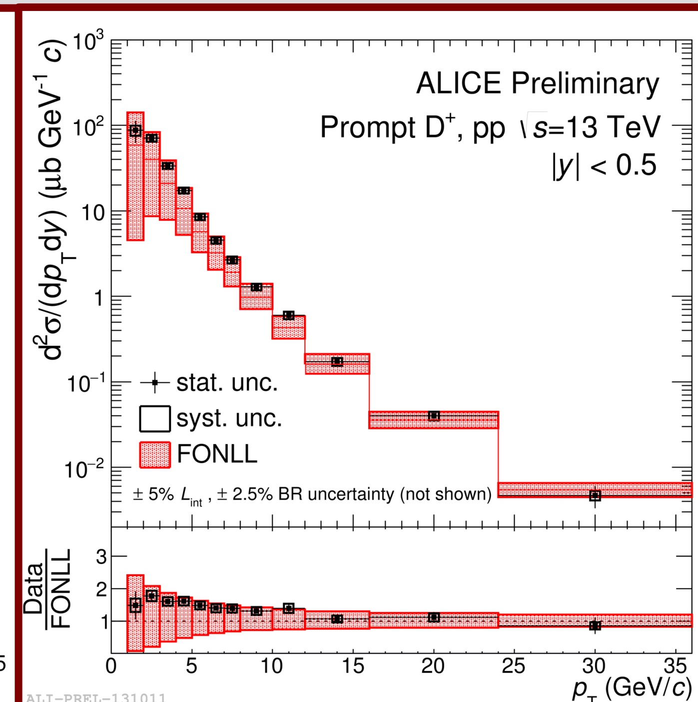


- Example: D^0 meson: non-zero lifetime; decay vertex displaced from interaction point (primary vertex)
  - → Decay length, impact parameter, pointing angle (for example) can be used to select candidates
- For D^{*+}, D^0 candidate paired with soft π^+ at primary vertex
- PID at mid-rapidity using TOF (where available) + TPC, with 'nσ' PID
  - → Strong separation of pions, kaons and protons in wide momentum range
- For Λ_c baryon: combination of direct reconstruction and machine learning techniques using Toolkit for Multivariate Analysis (TMVA) **[PoS ACAT:040,2007]**

D mesons in pp collisions



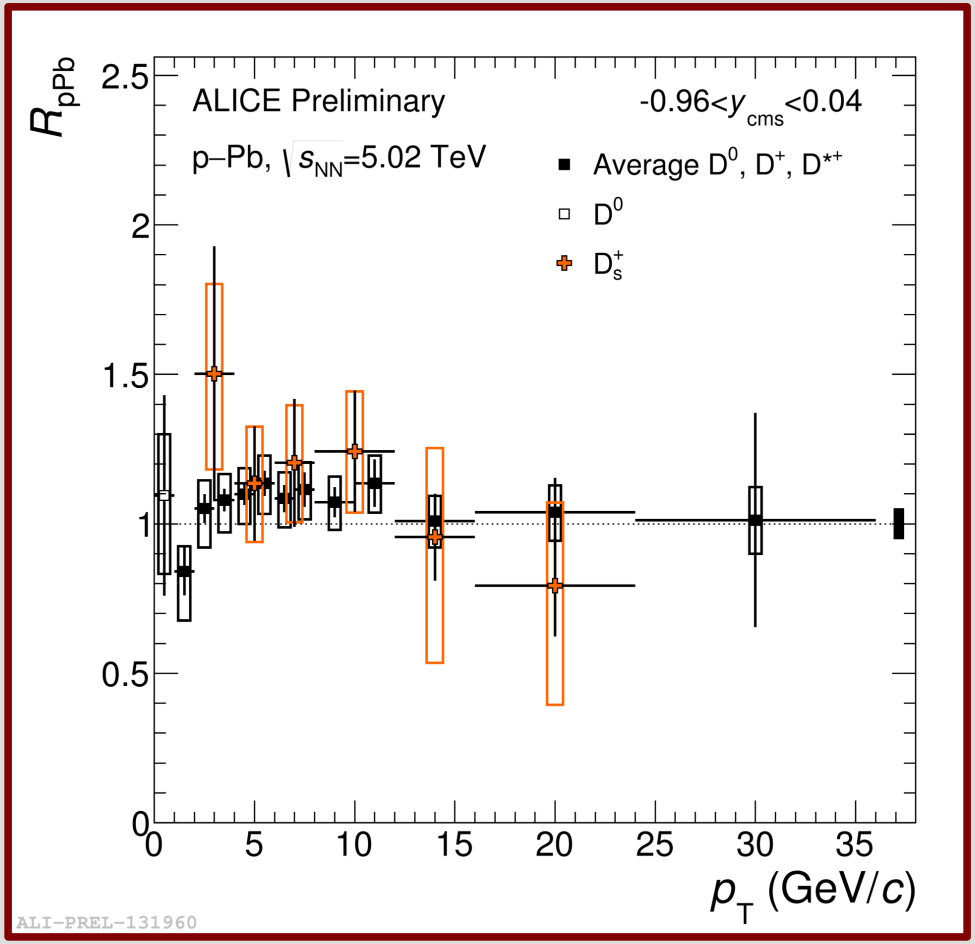


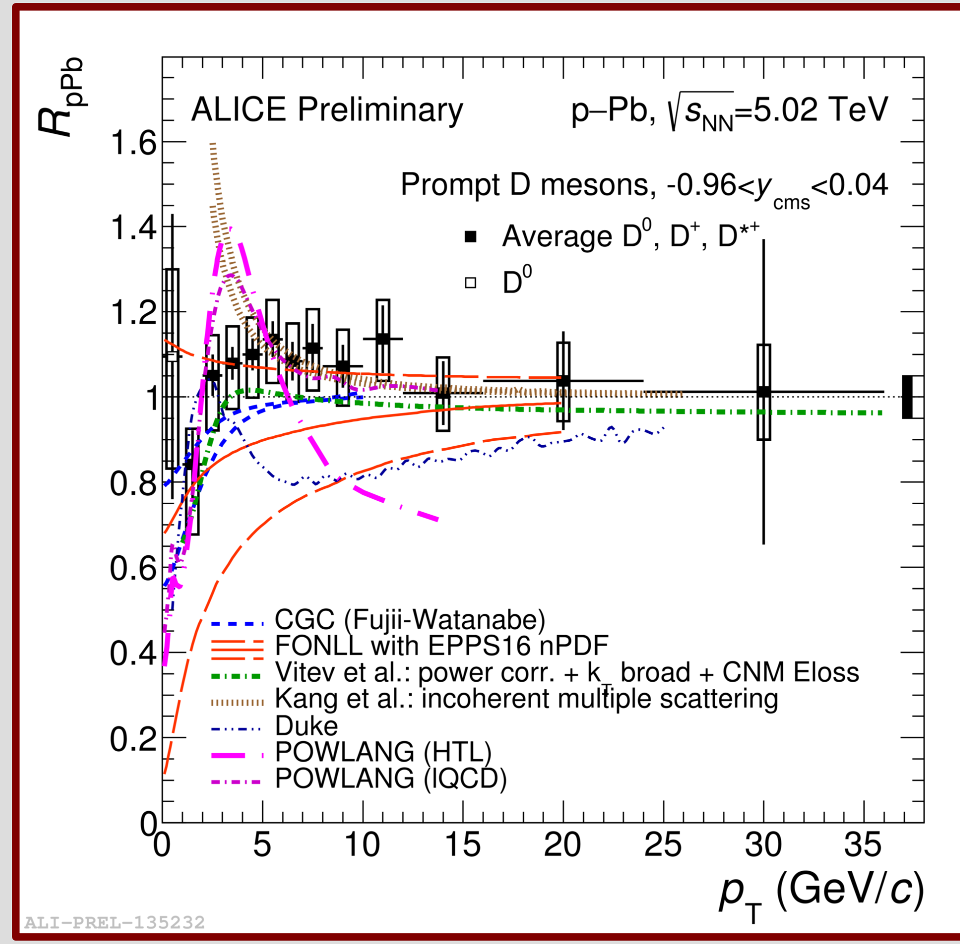


- D mesons measured in pp collisions at $\sqrt{s}$ = 7, 8 & 13 TeV
- D^0 mesons measured down to $p_T = 0$ using non-topological analysis; allows full mid-rapidity cross section to be measured without extrapolation
- Described within uncertainties by pQCD calculations at all energies

[1]: Eur. Phys. J. C77 (2017) 550

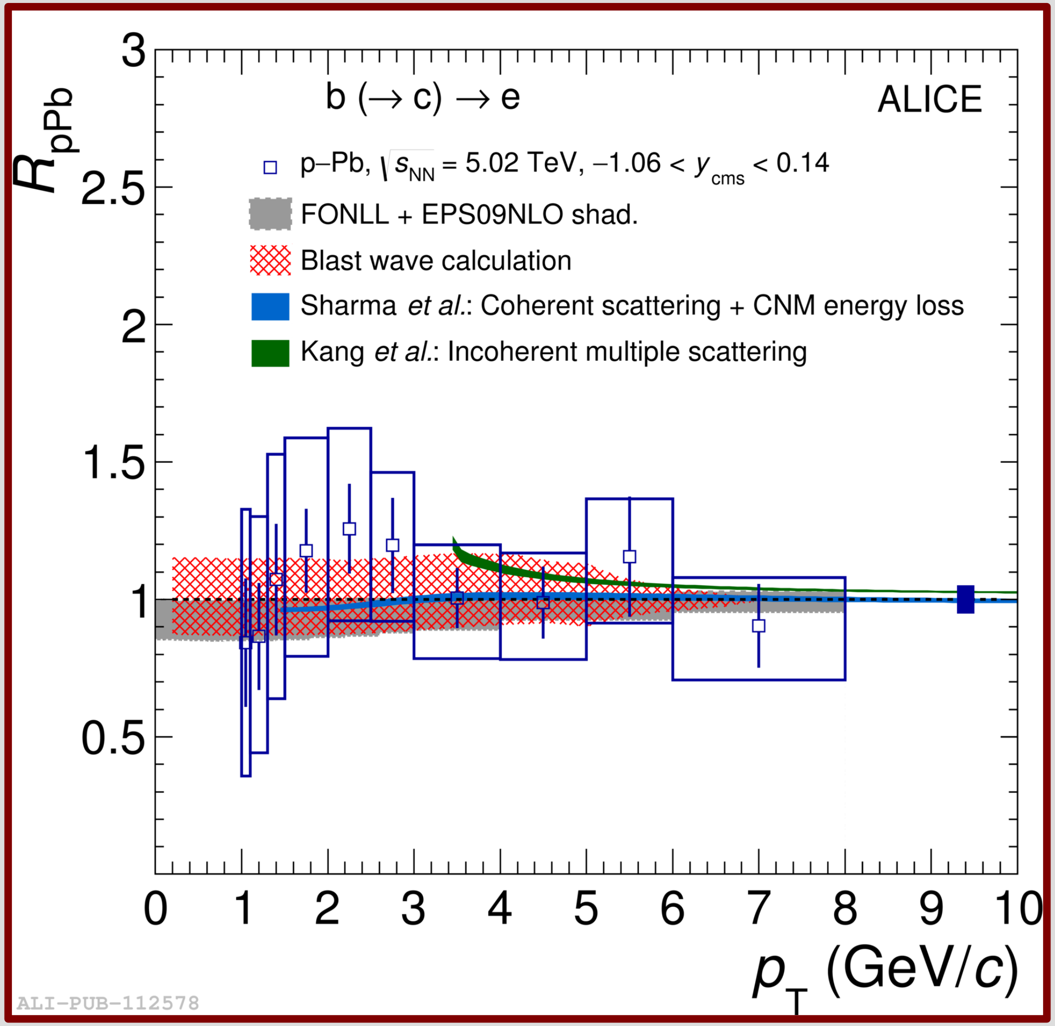
D mesons in p–Pb collisions





- Nuclear modification factor R_{pPb}: shows modification of spectrum compared to pp collisions (=1 in case of no initial-state nuclear effects)
- Run-2 data: factor ~2 improvement in statistics
- D-meson species consistent with unity (both strange and non-strange); described well by models including initial- and final-state effects

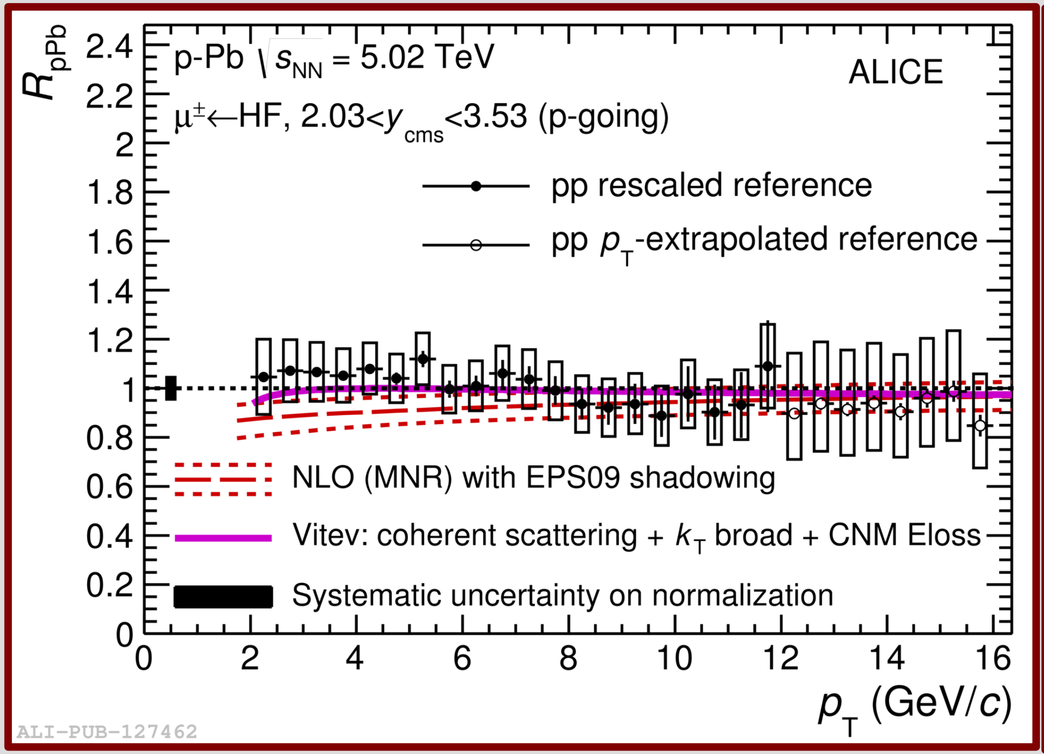
Heavy-flavour decay leptons in p-Pb collisions

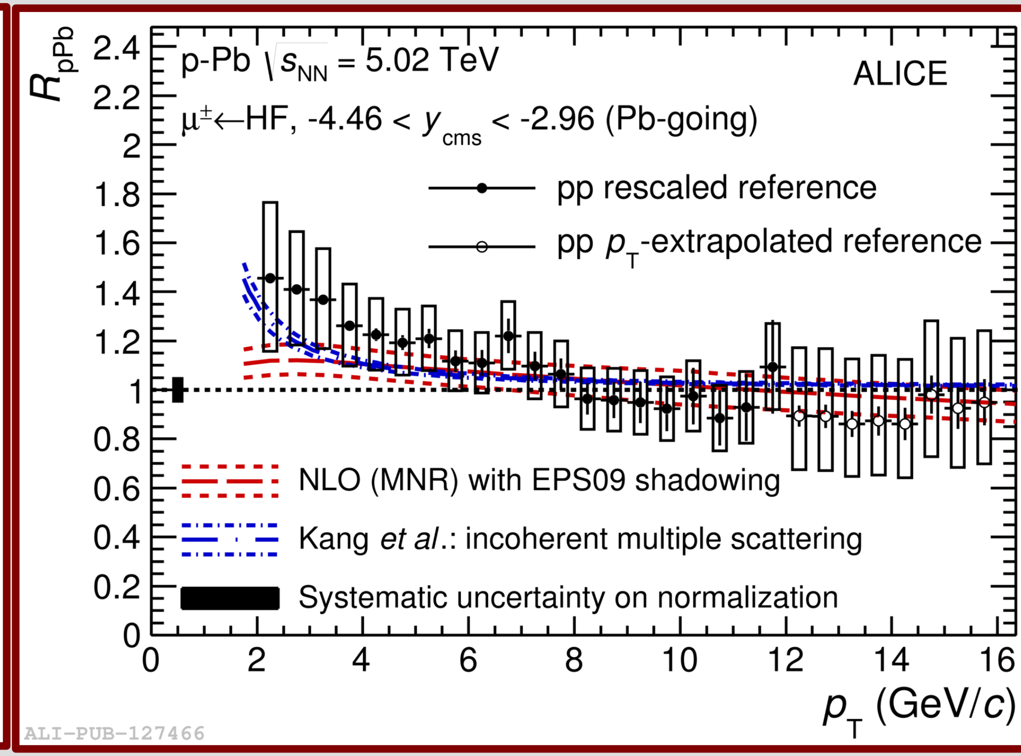


- Electrons from beauty decays: R_{pPb} consistent with unity and models
  - → No significant cold nuclear matter effects seen for either charm or beauty

[JHEP 07 (2017) 052]

Heavy-flavour decay leptons in p-Pb collisions

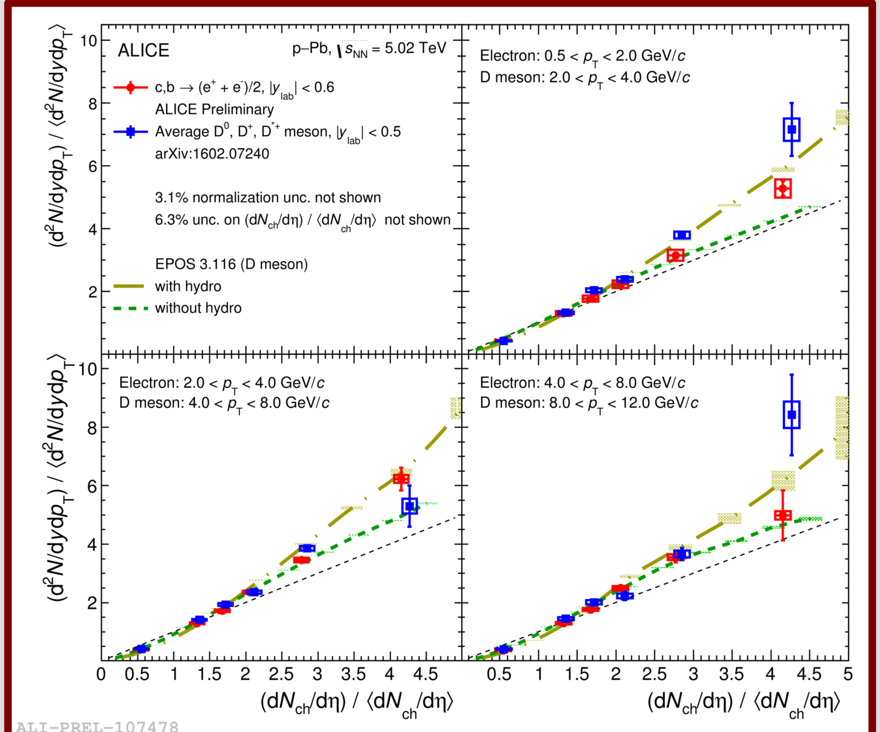


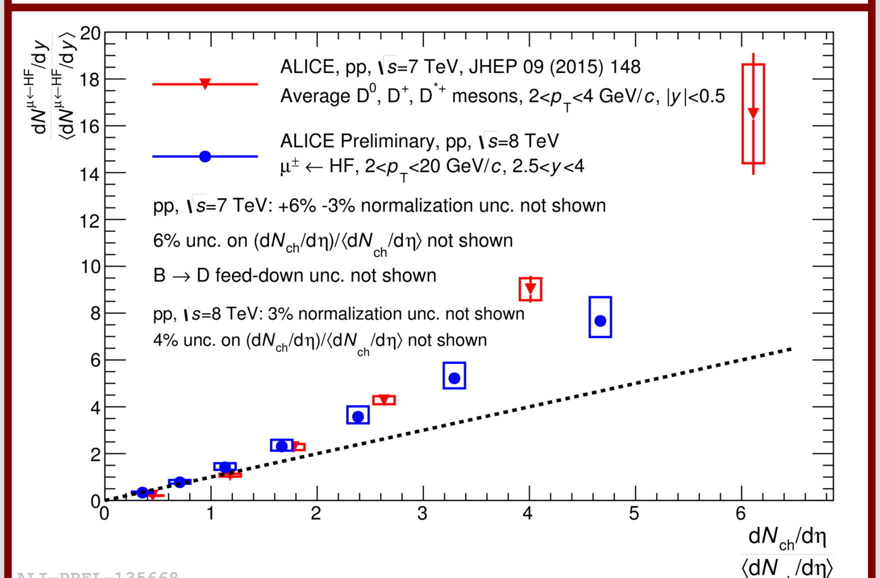


- Muons from heavy-flavour decays measured at forward (p-going) and backward (Pb-going) direction
  - → Probes lower and higher Bjorken-*x* in Pb nucleus
- Forward rapidity: R_{pPb} consistent with unity for all p_T
- Backward: R_{pPb} tends above unity at low p_T (2-sigma effect); consistent with unity at higher p_T
  - → Suppression at high p_T in Pb-Pb collisions is due to final-state effects

[Phys. Lett. B 770 (2017) 459-472]

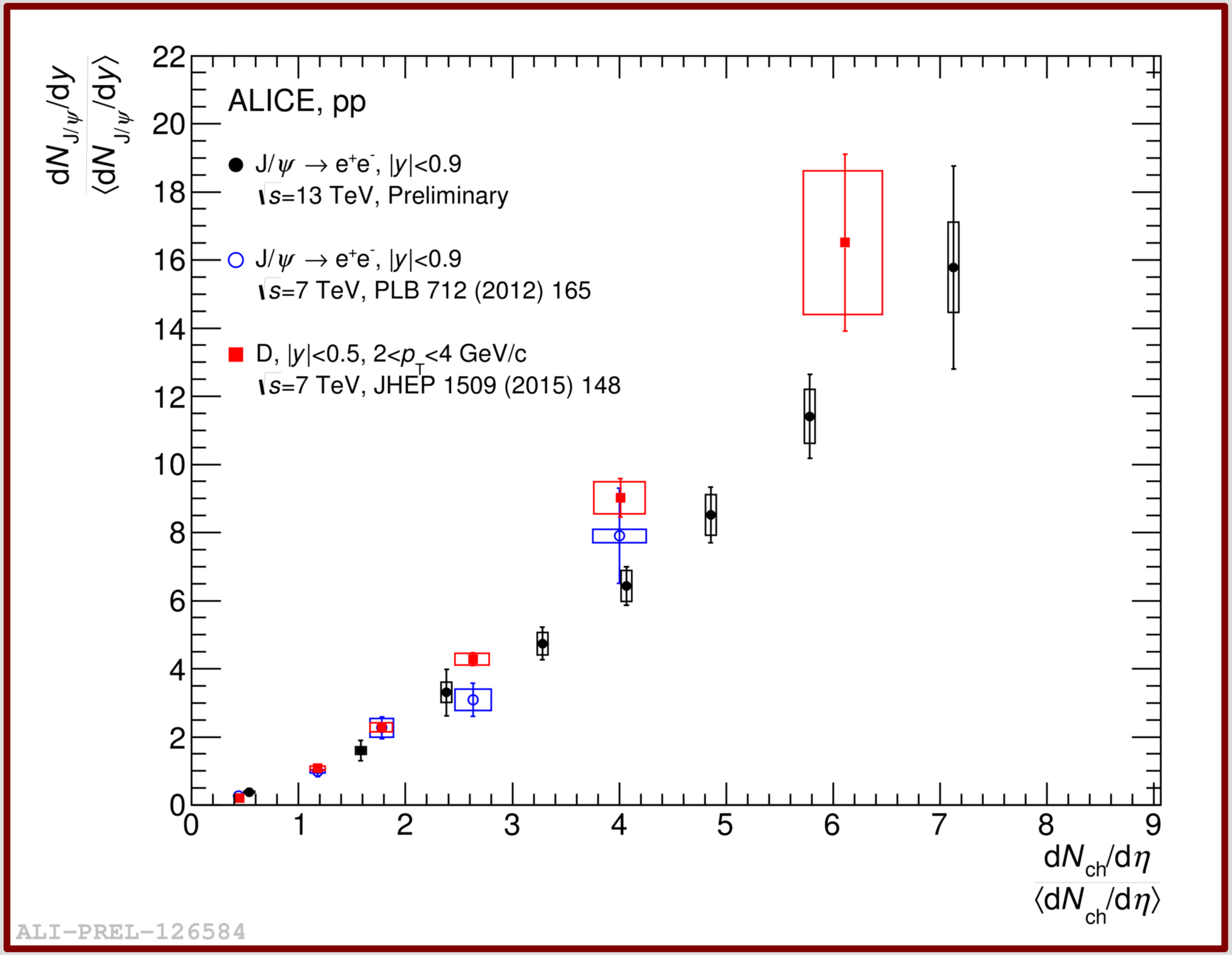
Heavy flavours vs multiplicity in small systems





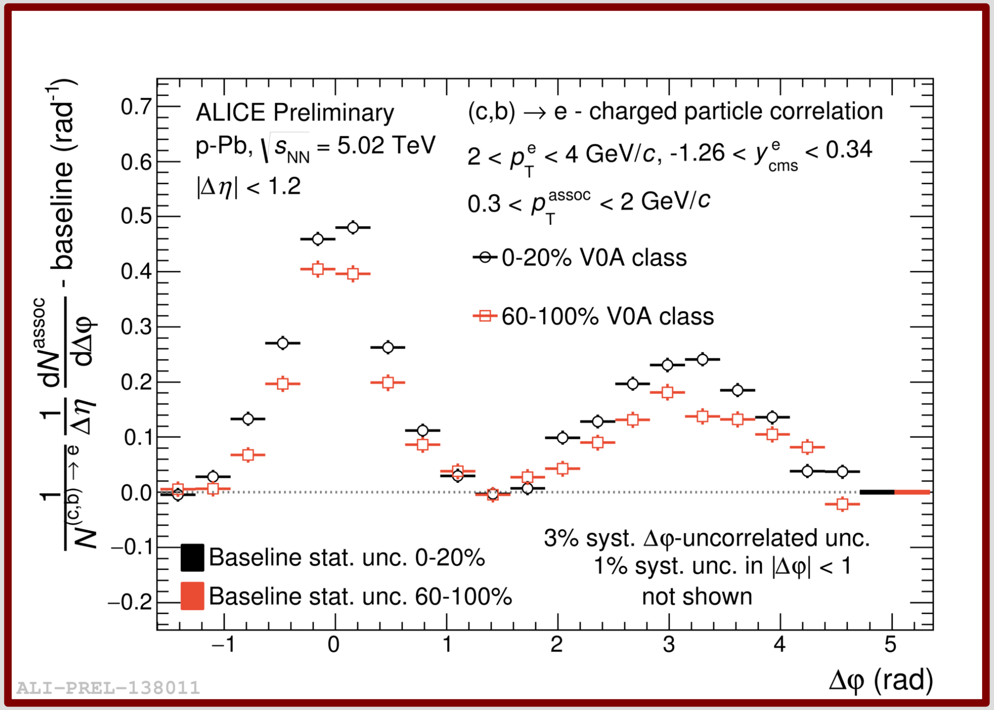
- Multiplicity dependence: examine correlation between heavy-flavour production & overall charged particle production
- "Self-normalised yield": a $y = x$ trend (dashed line) would mean same degree of scaling between heavy quarks and light quarks
- Faster than linear increase is seen for D mesons and beauty hadrons (which dominate semileptonic decays at high p_T) in both pp and p-Pb collisions
  - → Increased rate of HF production in high-multiplicity events, where multi-parton interactions play essential role
- Data described better by EPOS generator when hydrodynamic effects are considered.

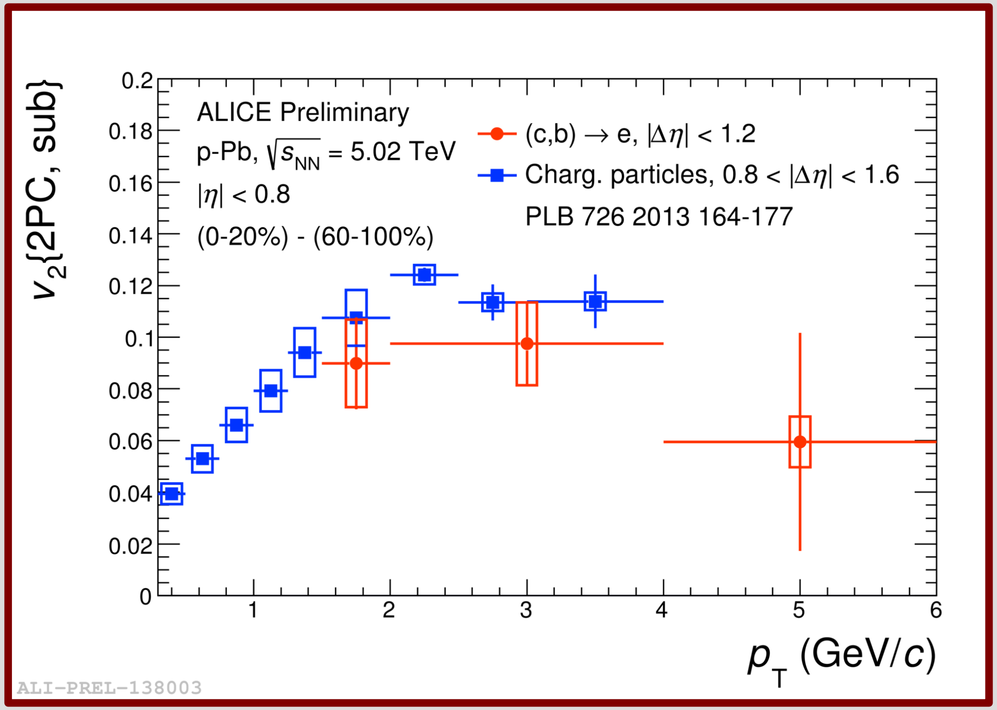
Heavy flavours as a function of multiplicity



- Multiplicity dependence also studied for J/ψ in pp collisions at $\sqrt{s}$ = 13 TeV; similar trend seen as for D mesons

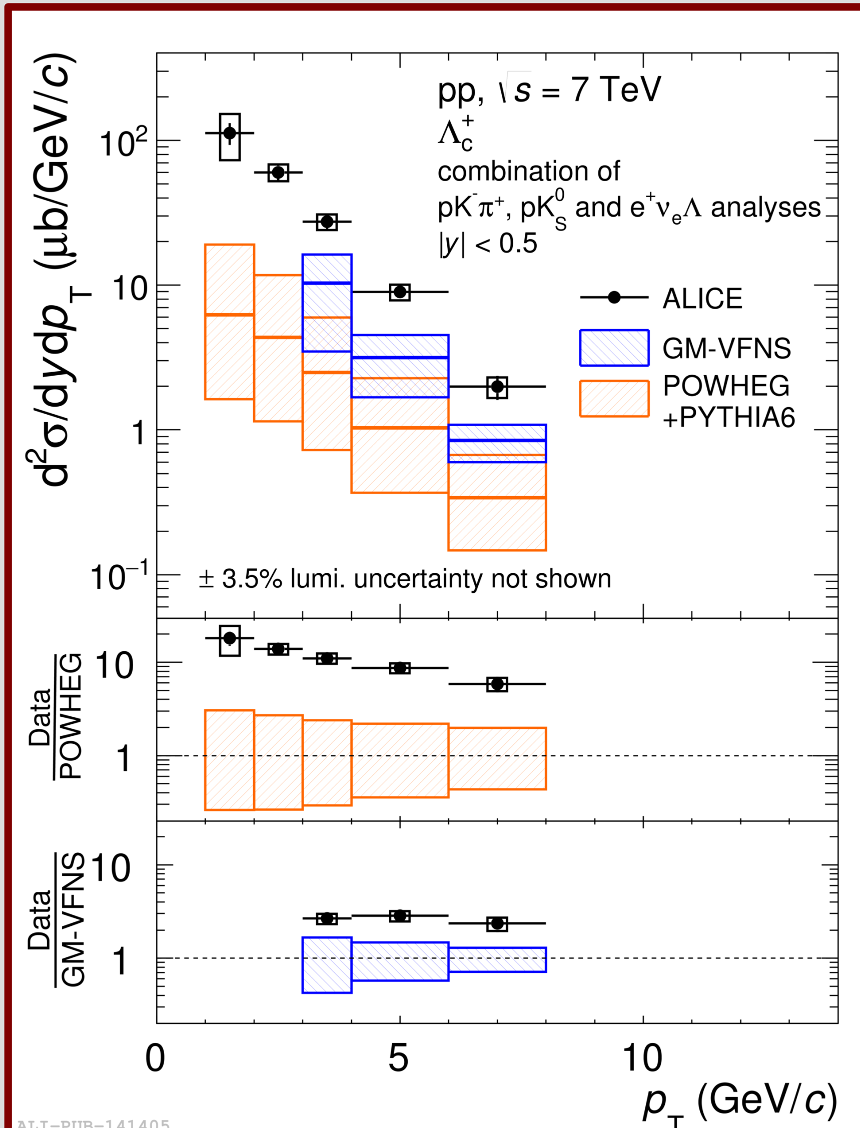
Azimuthal correlations in p-Pb collisions

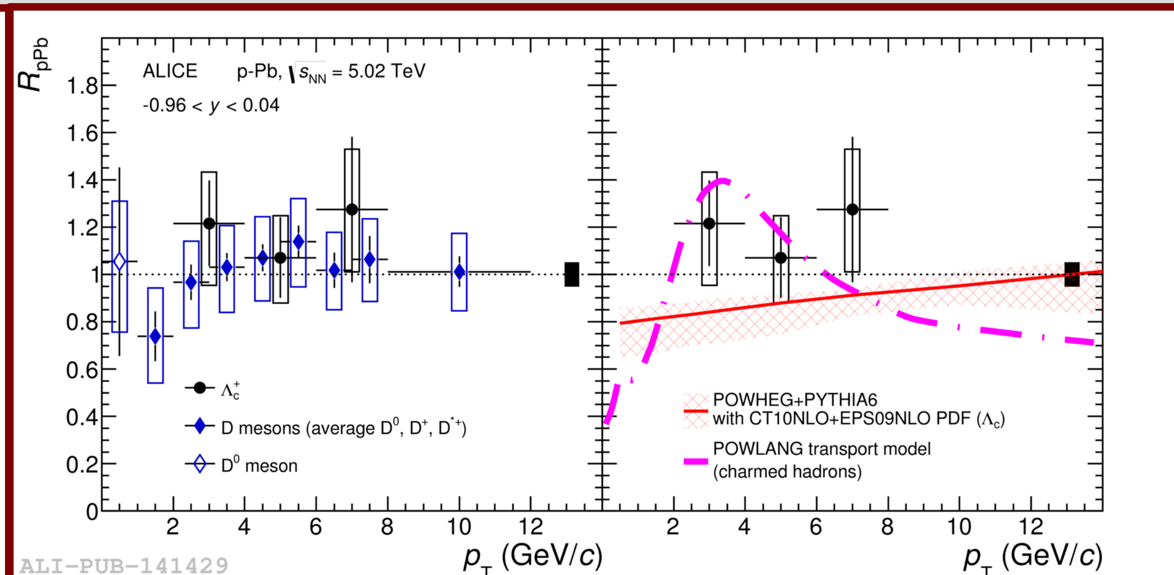




- Baseline-subtracted per-trigger azimuthal correlation of heavy-flavour decay electrons with charged particles measured from low- to high-multiplicity events
- v_2: “elliptic flow” coefficient; measures degree of anisotropy in collision
- Positive v_2\{2,sub\}, similar to charged particles
  - → Initial-state effects, possible collective effects in small systems?

Charmed baryons in pp & p–Pb collisions

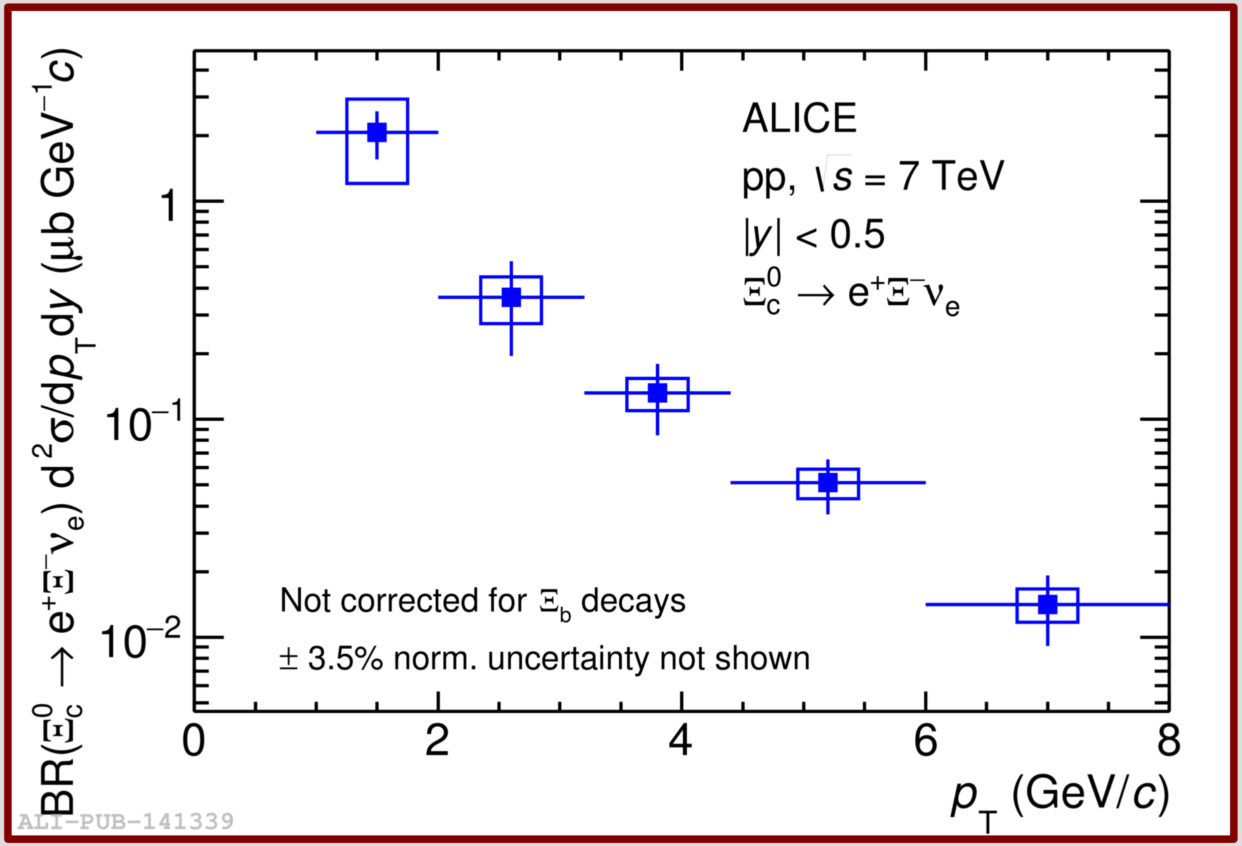




- First mid-rapidity measurement of Λ_c production at LHC
- Cross section underestimated by pQCD (GM-VFNS) & Monte Carlo (POWHEG+PYTHIA) models
- R_{pPb} of Λ_c^+ baryons consistent with D mesons & unity within uncertainties; also consistent with models

arXiv:1712.09581 [nucl-ex]

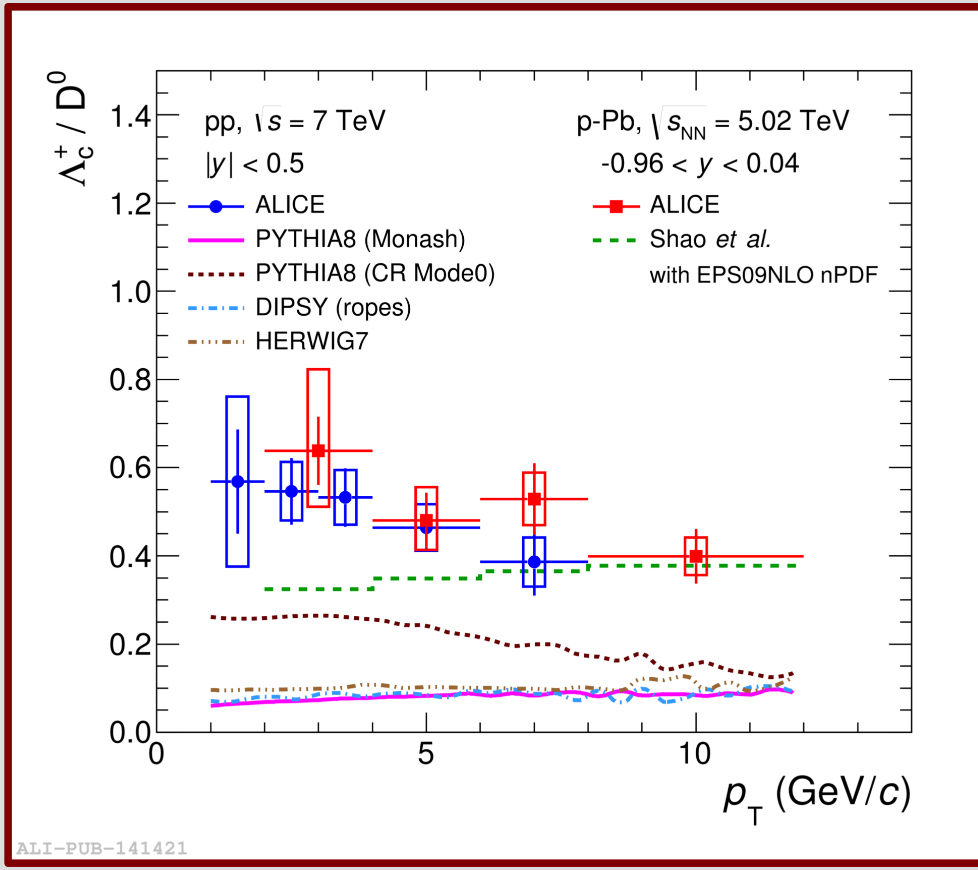
Charmed baryons in pp & p–Pb collisions

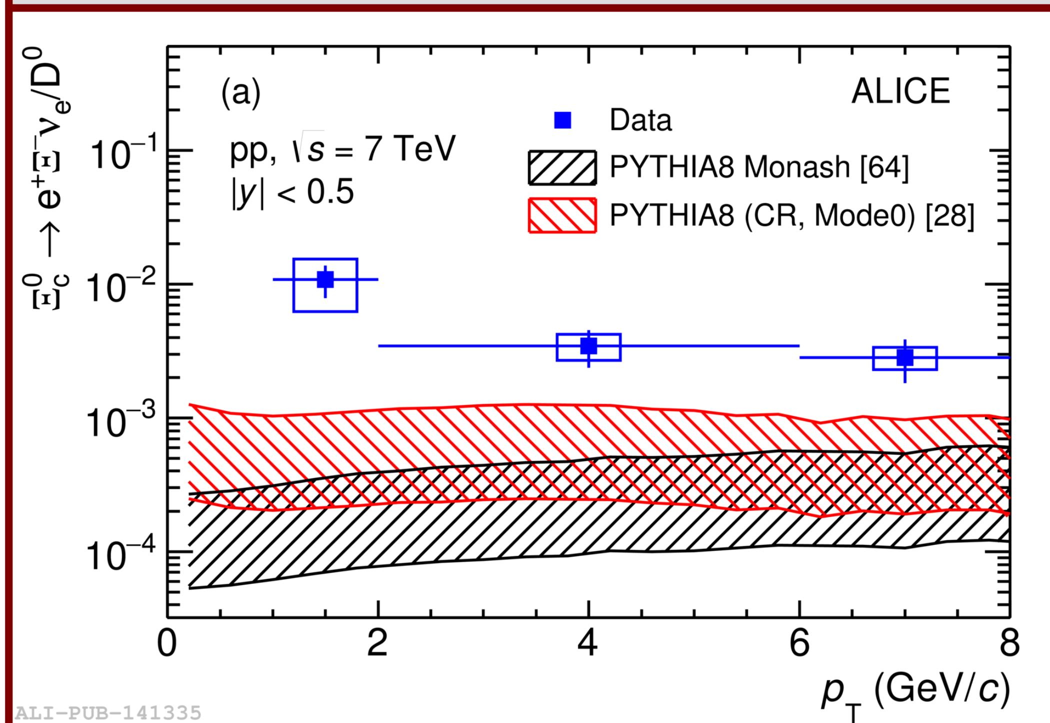


- Ξ_c^0 baryon in pp collisions at $\sqrt{s}$ = 7 TeV, using semileptonic decay channel ($\Xi_c^0 \to e^+\Xi^-\nu_e$)
- First measurement of Ξ_c^0 baryon production at LHC

arXiv:1712.04242 [hep-ex]

Charmed baryons in pp & p–Pb collisions

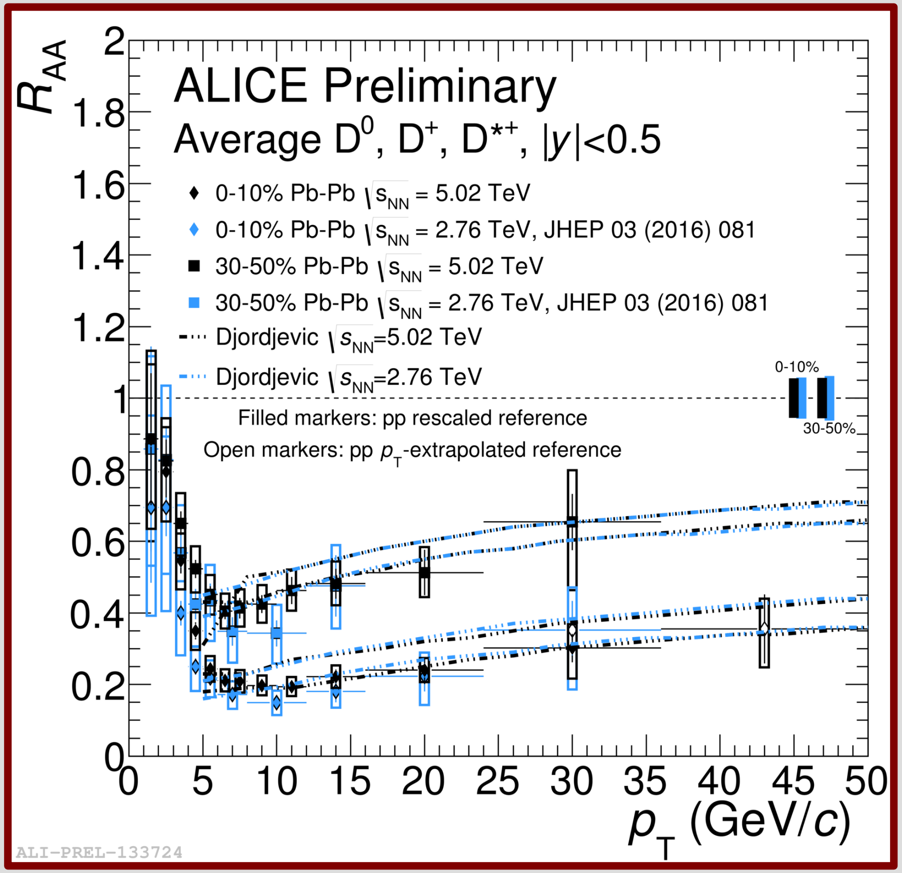




- Baryon-to-meson ratio sensitive to hadronisation mechanisms
- Λ_c/D^0 ratio consistent in pp & p–Pb collisions; no significant evidence of p_T dependence with current uncertainties
- Both baryons in both systems underestimated by model calculations

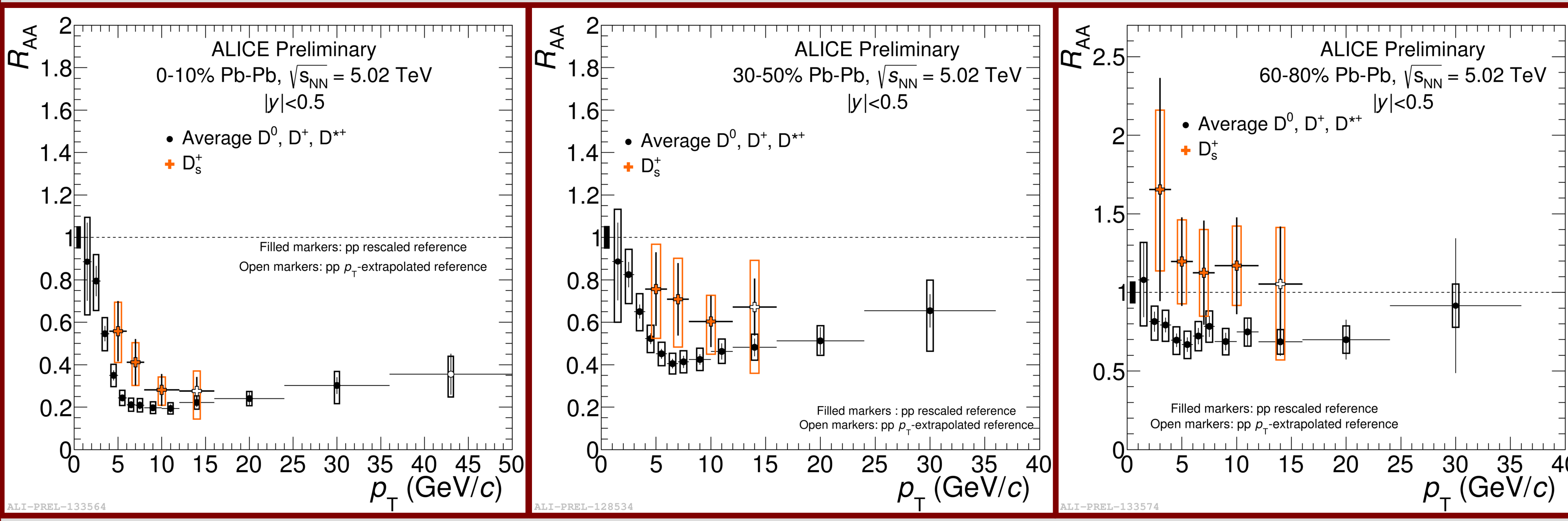
arXiv:1712.04242 [hep-ex], arXiv:1712.09581 [nucl-ex]

D mesons in Pb–Pb collisions



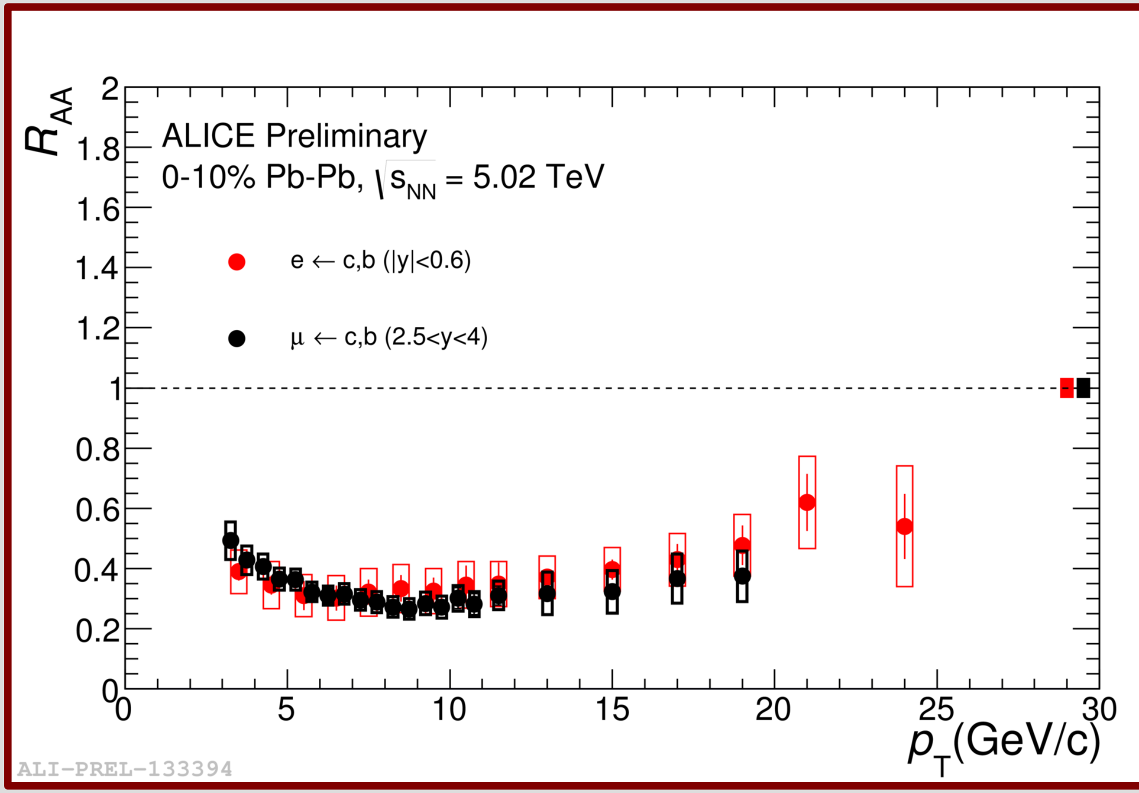
- D mesons measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 & 5.02 TeV
- Nuclear modification factor (R_{AA}) shows strong suppression of D mesons in Pb–Pb collisions w.r.t. pp collisions
- Suppression independent of energy, but increases for more central collisions
- Described by model calculations

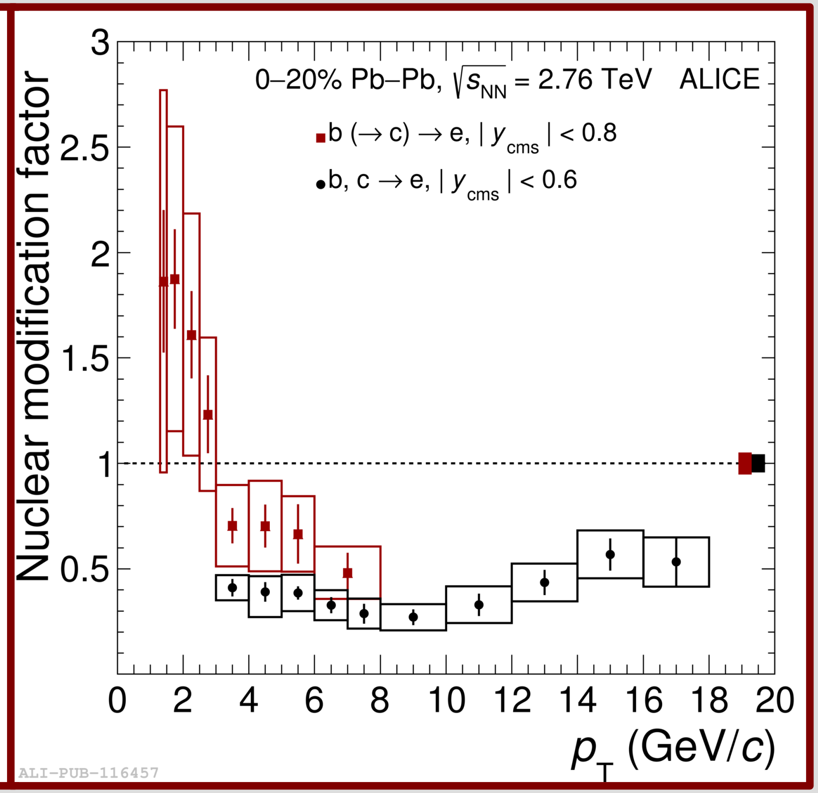
Strange D mesons in Pb–Pb collisions



- D_s^+ mesons measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- Hint towards lower level of suppression for strange than non-strange D mesons at intermediate p_T
  - → Indicates possible role of recombination in charm hadronisation

Heavy-flavour decay leptons in Pb-Pb collisions

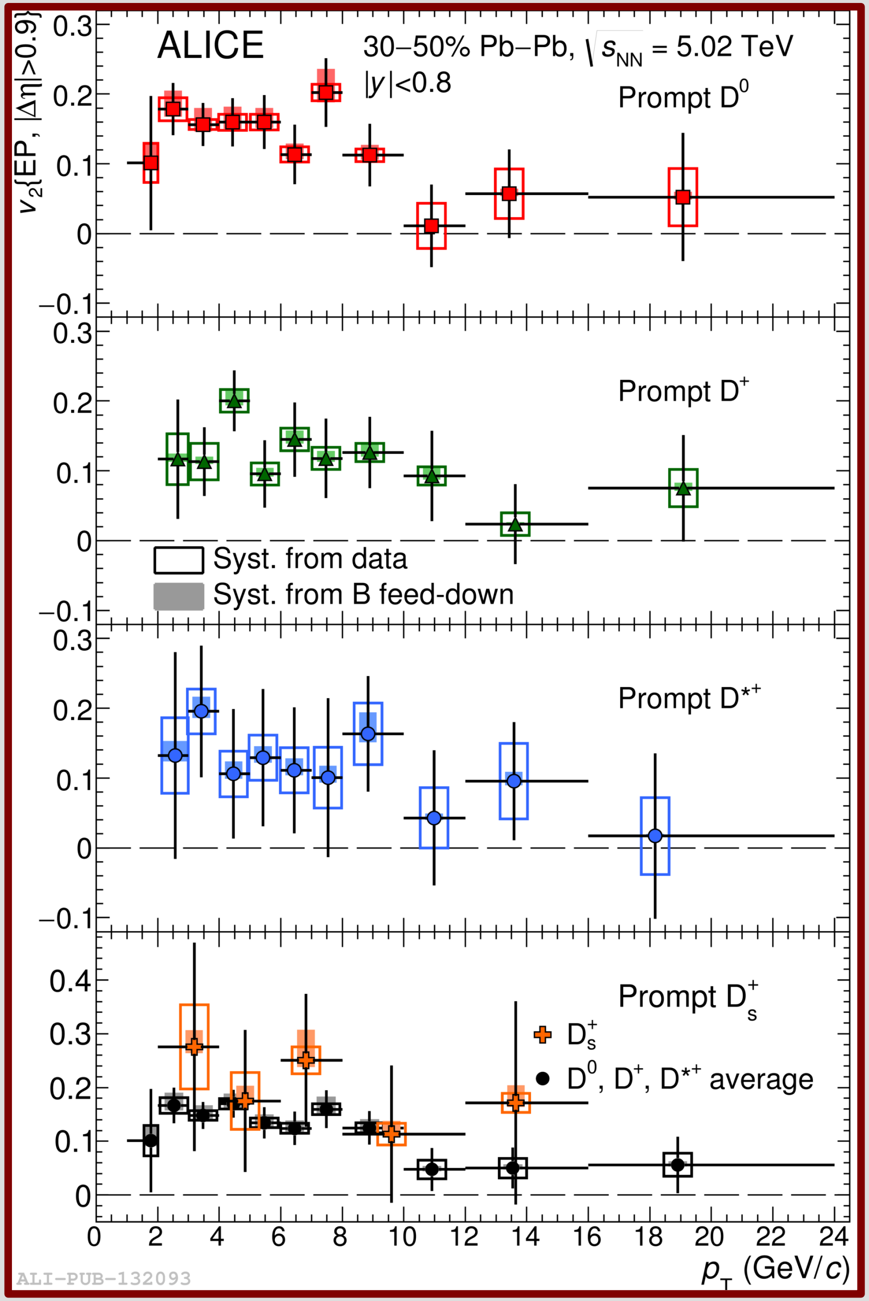


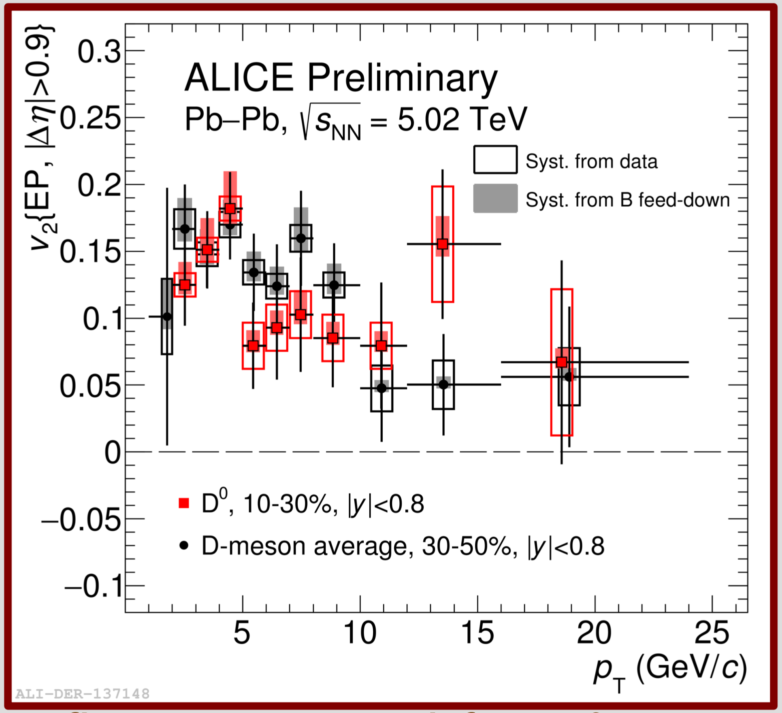


- Heavy suppression of electrons (muons) from charm and beauty decays at mid- (forward) rapidity in central collisions
- Beauty decay electrons separated from charm using fits to impact parameter distributions at 2.76 TeV; hint of higher R_{AA} for beauty than charm
  - → consistent with expectation from mass dependence of energy loss

JHEP 07 (2017) 052

Heavy-flavour v_2 in Pb–Pb collisions





- Elliptic flow measured for D^0, D^+, D^{*+}, D_s^+ (left): compatible between all species, significantly above unity
- v_2 also consistent between 10-30% and 30-50% centrality classes for D^0 mesons
  → implies strong interaction between charm quarks and medium

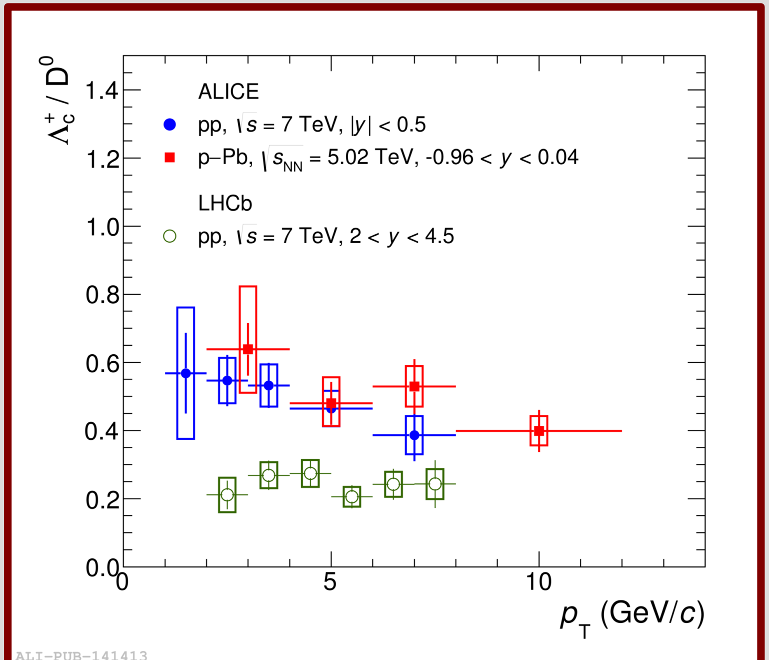
arXiv:1707.01005 [nucl-ex]

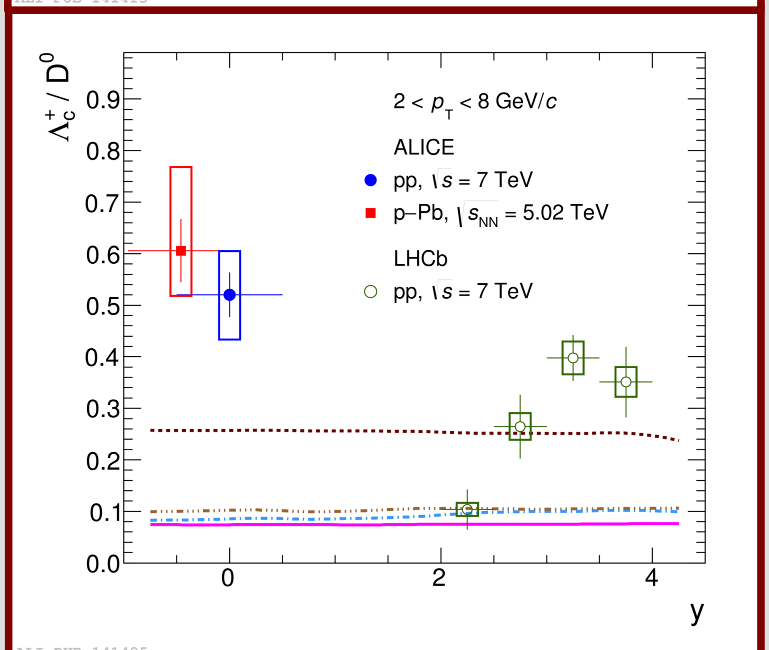
Summary & Outlook

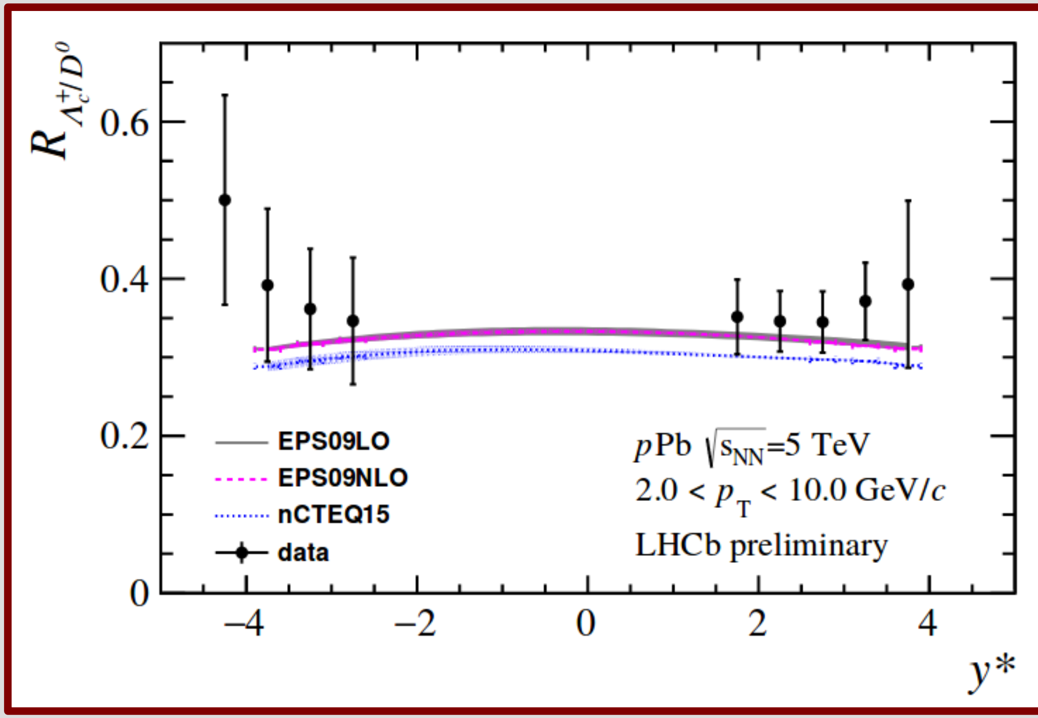
- Open heavy flavour production in pp collisions described by perturbative QCD
- First measurement of Λ_c (at mid-rapidity) and Ξ_c in LHC: baryon-to-meson ratio underpredicted by models
- p–Pb: nuclear modification factor consistent with unity; suppression in Pb–Pb collisions due to final-state effects
- Strong suppression of D-meson yields in Pb–Pb collisions, but with hint of smaller suppression for strange D mesons → possible recombination effects
- Outlook:
  - → Improved pp reference at 5.02 TeV will allow refinements to R_{pPb} and R_{AA} to better understand nuclear effects
  - → New measurements of Λ_c production in pp collisions at 5 and 13 TeV, p-Pb collisions (run 2, x6 more statistics), and Pb-Pb collisions
  - → Measurements of charm and beauty jet properties in pp, p-Pb and Pb-Pb (ongoing)
  - → Towards Run 3: ITS and TPC upgrades will allow direct reconstruction of B mesons

– Backup –

Comparison of Λ_c with LHCb

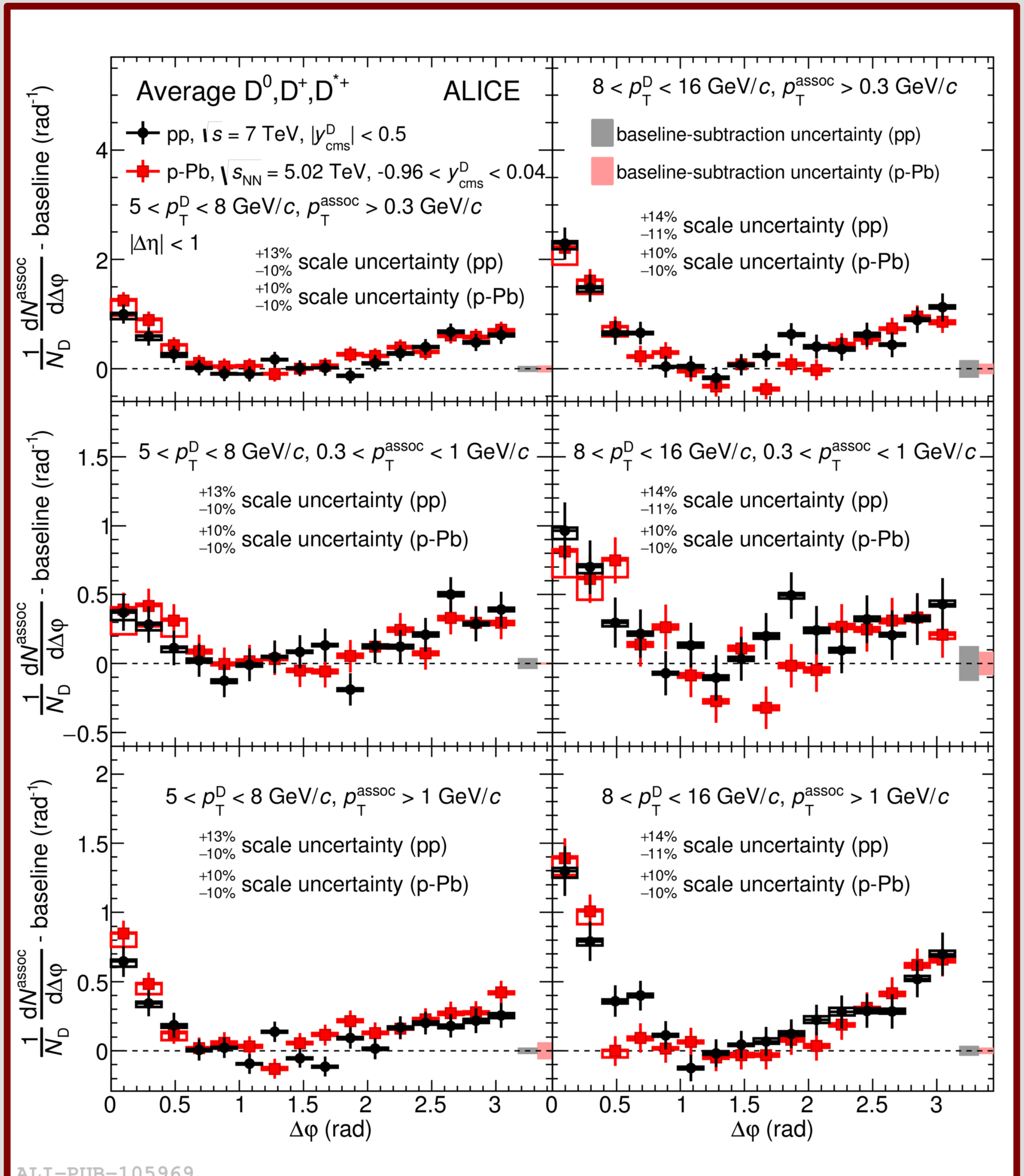






- LHCb pp results: lower baryon-to-meson ratio than ALICE; significant difference seen in rapidity trend
- Effect not seen in preliminary p–Pb results from LHCb; ratio more consistent with ALICE results

D-hadron azimuthal correlations in p–Pb collisions



- Azimuthal correlation of D mesons with charged hadrons - studies modification of jet fragmentation
- Near-side studies modification of parton fragmentation
- Away-side: check for yield suppression; probes path-length dependence of energy loss
- No modification seen in p–Pb collisions with respect to pp baseline

[Eur. Phys. J. C 77 (2017) 245]

D-tagged jets

- Ongoing analysis of D^0 and D^{*+}-tagged jets in pp collisions to study charm-quark fragmentation
- Anti-k_T algorithm for jet finding
- Jet cross section consistent with predictions within uncertainties