Study of heavy-quark hadronisation from small to large systems with ALICE

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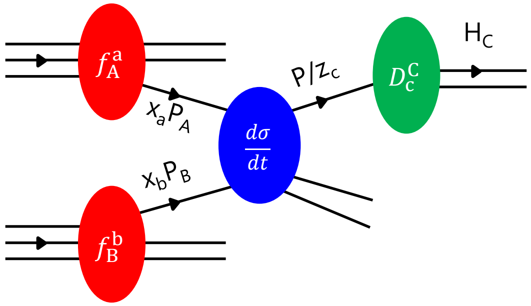
Exploring Quark-Gluon Plasma through soft and hard probes — Belgrade, 29-31/05/2023

PHYSICS MOTIVATIONS

Heavy quarks produced in **hard-scattering processes** in early stages of ultra-relativistic collisions

- Large Q^2 transfer → perturbative process → **test of pQCD** calculations
- Open heavy-flavour hadron production cross section calculated using the **factorisation approach**
  - **Fragmentation functions** assumed **universal** across different collision systems

$$E_{\mathrm{C}}\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{\mathrm{C}}^3}(\mathrm{AB}\to\mathrm{CX}) \propto \sum_{\mathrm{abcd}}\int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_{\mathrm{b}}\, \underbrace{f_{\mathrm{A}}^{\mathrm{a}}(x_{\mathrm{a}},Q^2) f_{\mathrm{B}}^{\mathrm{b}}(x_{\mathrm{b}},Q^2)}_{\text{PDF}}\, \underbrace{\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\mathrm{ab}\to\mathrm{cd})}_{\text{Partonic cross-section}}\, \underbrace{D_{\mathrm{c}}^{\mathrm{C}}(z_{\mathrm{c}},\mathrm{Q}^2)}_{\text{Fragmentation function}}$$

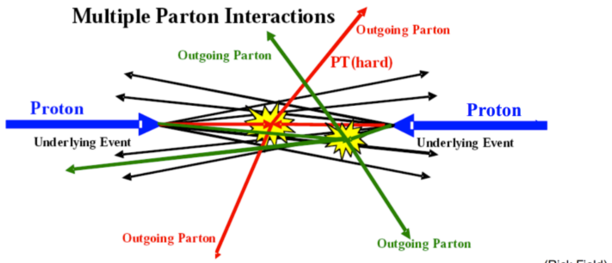


- Charm- and beauty-quark hadronisation investigated through measurements of **charm- and beauty-hadron production** in all collision systems.

PHYSICS MOTIVATIONS

Ratio of particle species (baryon-to-meson, strange-to-non-strange):

- Observables sensitive to **heavy-quark hadronisation**
- **FF universality questioned** by recent LHC measurements, several explanations proposed by theorists
  - More precise/additional data can discriminate among the different theoretical models



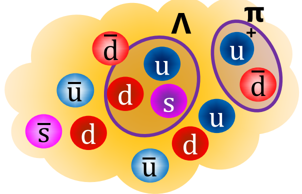
(Rick Field)

Measurements of HF as a function of event multiplicity:

- Investigate the role of **multiple-parton-interaction** (**MPI**) on heavy-flavour hadronisation

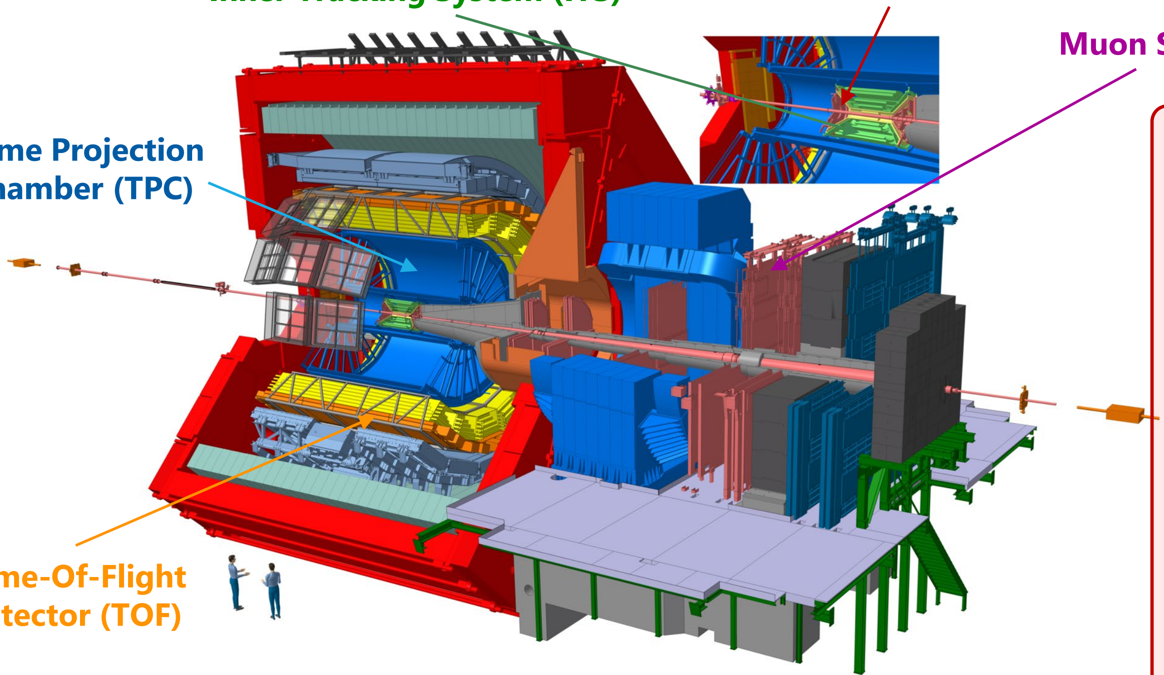
Studies in p-Pb and Pb-Pb probe hadronisation modifications in larger partonic-density environments

- In p-Pb collisions, sensitivity to cold (and possibly hot) nuclear matter effects
- What happens if a QGP medium is produced in the collisions?
  - Possible impact from hadronization via coalescence, radial flow, etc.



THE ALICE EXPERIMENT

A multi-purpose experiment at the LHC, with excellent PID capabilities and tracking down to ≈100 MeV/*c*
Main focus on heavy-ion studies, but rich physics programme also for small systems



HF mesons

$D^0 \to K^-\pi^+$

$D^+ \to K^-\pi^+\pi^+$

$D^{*+} \to D^0\pi^+$

$D_s^+ \to \phi\pi^+ \to K^-\pi^+\pi^+$

$J/\psi \to e^-e^+$

$J/\psi, \psi(2S) \to \mu^-\mu^+$

$\Upsilon(1S, 2S, 3S) \to \mu^-\mu^+$

$D \to e(\mu)X$

$B \to e(\mu)X$

HF baryons

$\Lambda_c^+ \to K_S^0 p$

$\Lambda_c^+ \to \pi^+K^-p$

$\Xi_c^0 \to \Xi^-e^+\nu_e$

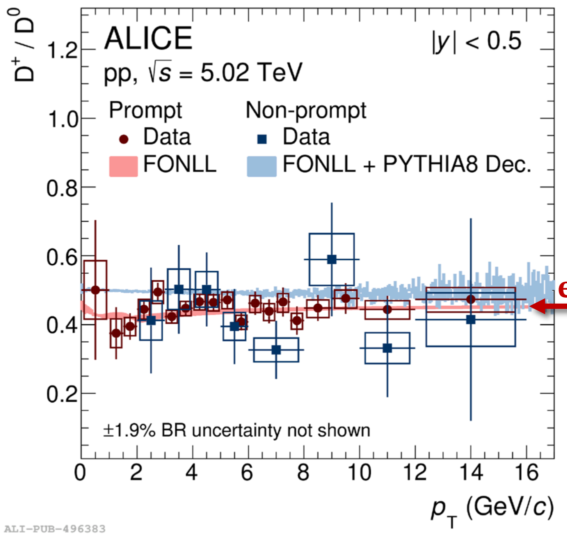
$\Xi_c^0 \to \Xi^-\pi^+$

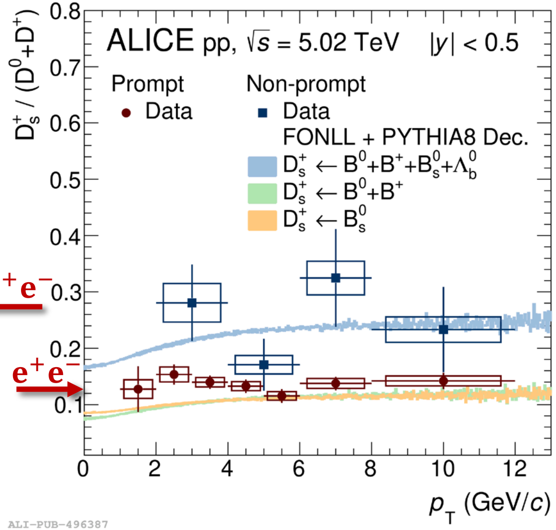
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$

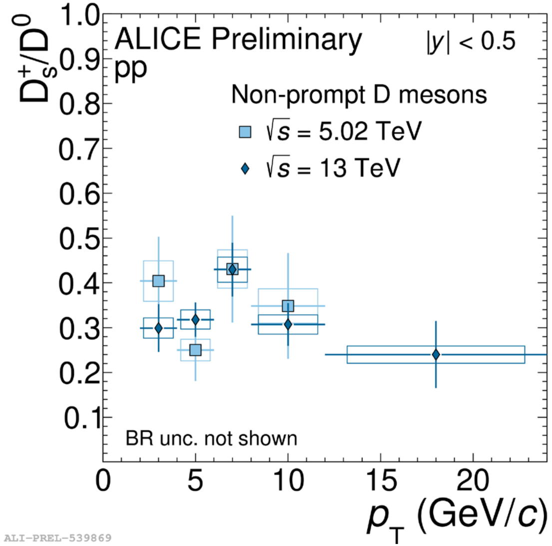
$\Omega_c^0 \to \Omega^-\pi^+$

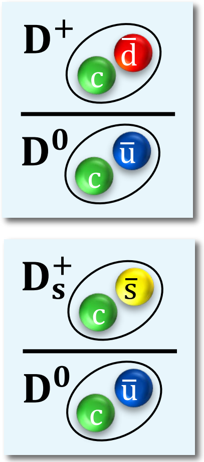
$\Sigma_c^{0,++} \to \Lambda_c^+\pi^{-,+}$

D-MESON YIELD RATIOS IN pp COLLISIONS









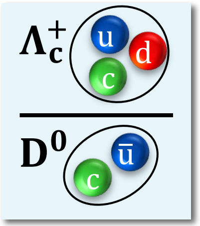
ALICE, JHEP 05 (2021) 220

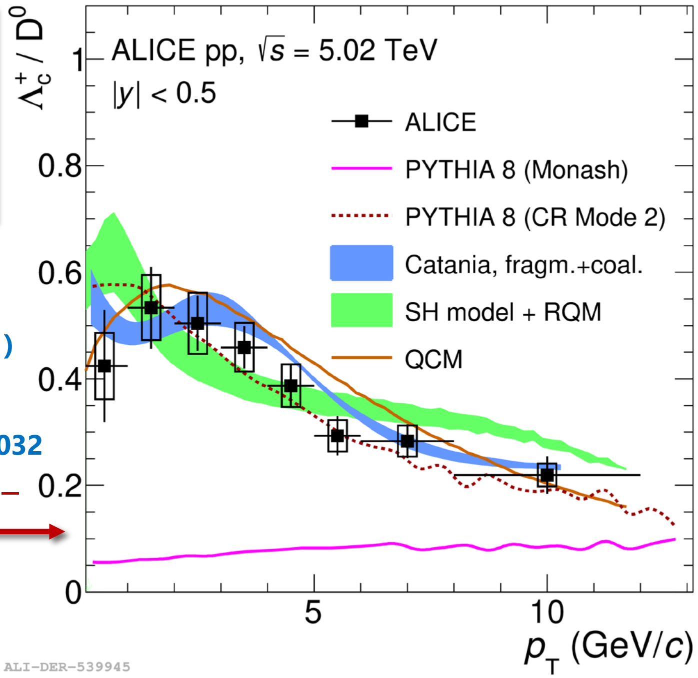
FONLL: M. Cacciari et al, JHEP 10 (2012) 137

PYTHIA 8 :P. Skands, et al., EPJC 74 (2014) 3024

- **FONLL calculations** (pQCD) correctly **describe** the data
  - ➢ Using fragmentation functions evaluated from e^+e^-, e^-p measurements
- Meson-to-meson ratios **independent of p_T** and collision energy
- Higher $D_s^+/(D^0+D^+)$ ratios for non-prompt mesons, due to relevant contribution to D_s^+ from B^0, B^+ decays

PROMPT Λ_c^+/D^0 YIELD RATIOS IN pp COLLISIONS





ALICE, PRL 127 (2021) 202301
ALICE, arXiv:2211.14032

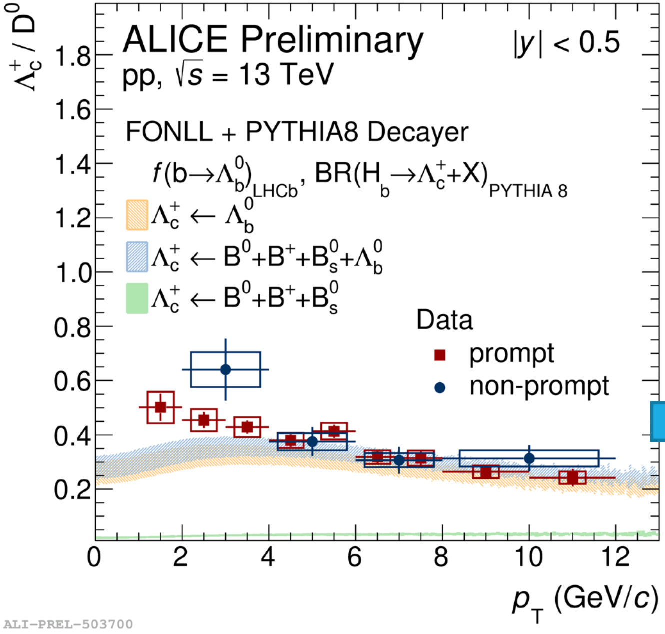
- Λ_c^+ measurement now available down to $p_T = 0$
- Ratio **significantly higher** than in e⁺e⁻ and e⁻p collisions

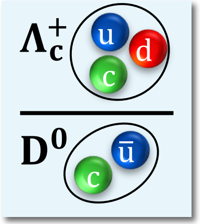
LEP average value: **0.113 ± 0.013 ± 0.006**
(L. Gladilin, EPJC 75 (2015) 19)

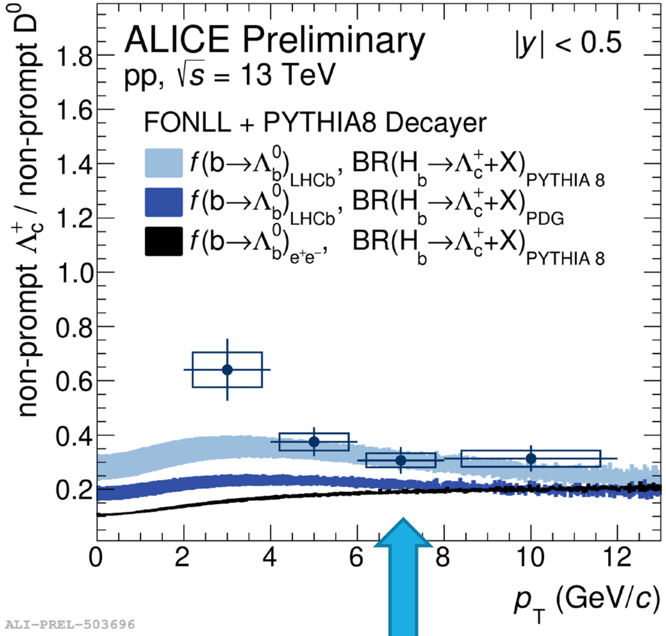
- **Strong p_T dependence**, as for baryon-over-meson ratios in light-flavour sector
- Ratio **underestimated** by models with **FF tuned on e⁺e⁻, e⁻p** collisions (**PYTHIA 8 Monash**, **Herwig 7**)
- Proper description by models with modified fragmentation or augmented feeddown from higher-mass states:
  - **PYTHIA 8 with updated CR modelling** → "Junction" topologies enhance charm-baryon production
  - **Catania model** → Thermalised system of light quarks and gluons, hadronization via coalescence+fragmentation
  - **Statistical Hadronization Model + Relativistic Quark Model** → large feed-down contribution from augmented set of excited charm baryons, not yet observed

PYTHIA 8 Monash: P. Skands, et al., EPJC 74 (2014) 3024
PYTHIA 8 CR Tunes: J. Christiansen, et al., JHEP 08 (2015) 003
Herwig: Eur.Phys.J. C76 (2016) no.4, 196
SHM: M. He and R. Rapp, PLB 795 (2019) 117-121
RQM: D. Ebert, et al., PRD 84:014025, 2011
Catania: V. Minissale, et al., PLB 821 (2021) 136622

NON-PROMPT Λ_c^+/D^0 YIELD RATIOS IN pp COLLISIONS



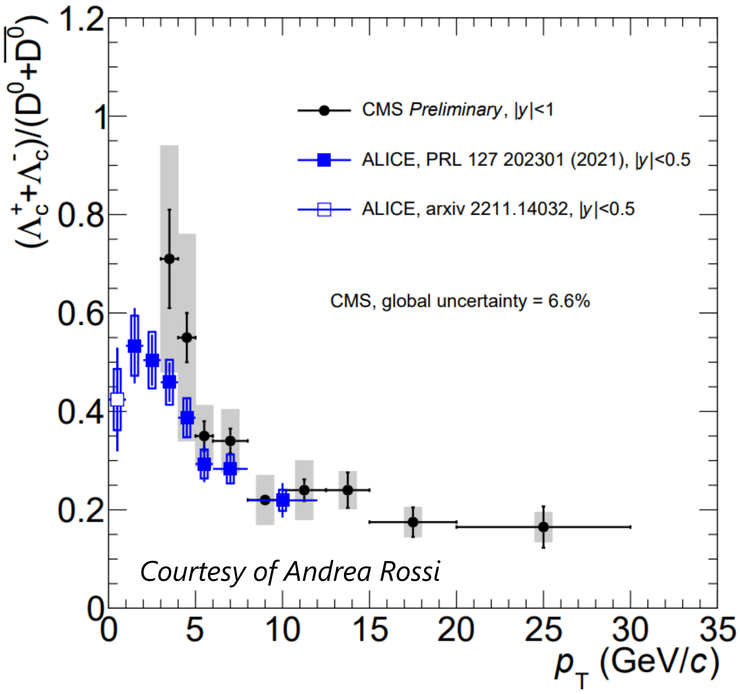




Dominant contribution to non-prompt Λ_c^+ from Λ_b^0 decays

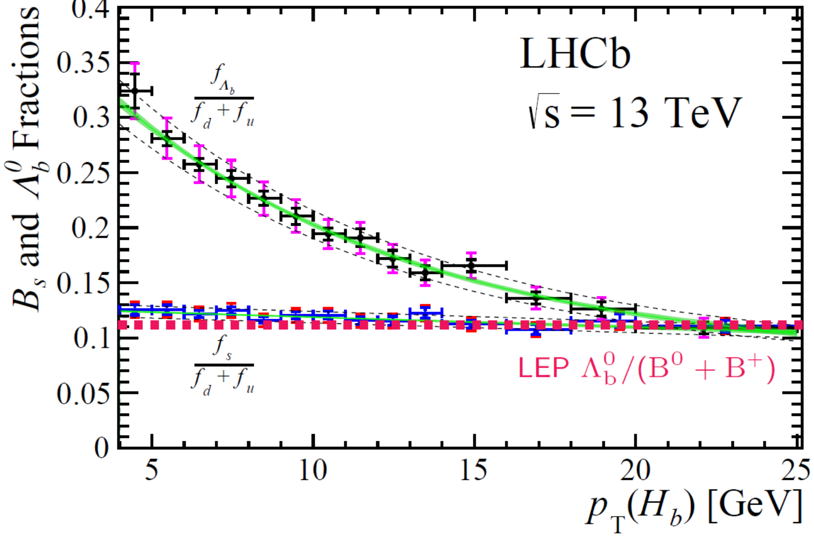
- Provides access to the fragmentation of beauty quarks
- **Enhanced beauty-baryon production** w.r.t. e+e- collisions → **suggests non-universality also of $f(b \to H_b)$**
  - Ratio well described by FONLL using LHCb FF and PYTHIA8 decay table for p_T > 4 GeV/c
- Similar p_T dependence for prompt and non-prompt Λ_c^+/D^0 ratios

COMPARISON WITH OTHER LHC EXPERIMENTS



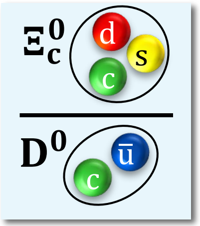
ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv:2211.14032
CMS, PAS-HIN-21-004

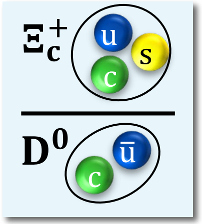
LHCb: PRD 100 (2019) 031102

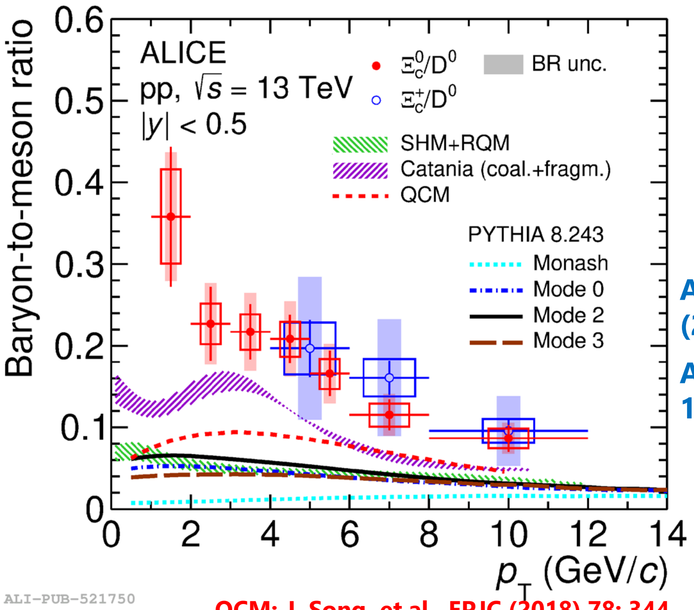


- Prompt Λ_c^+ results released by CMS **compatible with ALICE results** in the common p_T range
- Direct measurement of beauty mesons and baryons by LHCb supports findings **of baryon-to-meson enhancement** in pp collisions also in the **beauty sector**

HEAVIER BARION YIELD RATIOS TO D^0 IN pp COLLISIONS



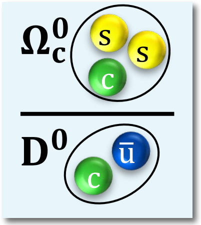




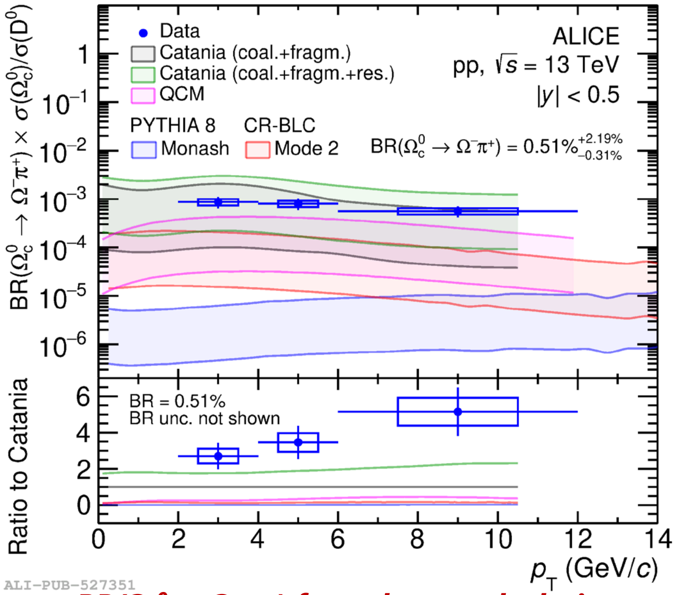
QCM: J. Song, et al., EPJC (2018) 78: 344

ALICE, PRL 127 (2021) 271001

ALICE, JHEP 10 (2021) 159



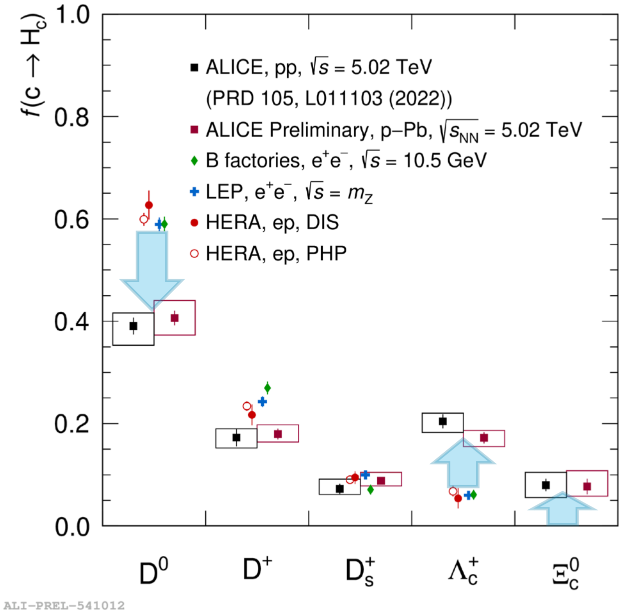
ALICE, arXiv:2205.13993

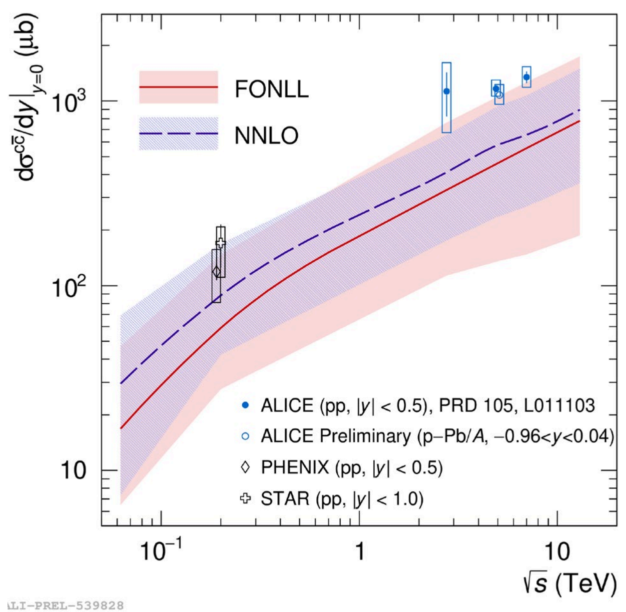


BR($\Omega_c^0 \to \Omega^-\pi^+$) from theory calculations

- Heavier baryon-to-meson ratios **underestimated by PYTHIA8 Monash** by several orders of magnitude
- **PYTHIA 8 with CR-BLC** modes and **SHM+RQM** models also not able to correctly reproduce the data
- Coalescence-based models get closer to measurements: **Catania** qualitatively describe the data, **QCM** underestimates them but by a lesser extent

CHARM PRODUCTION AND FF IN pp (AND p-Pb) COLLISIONS





Charm fragmentation fractions:

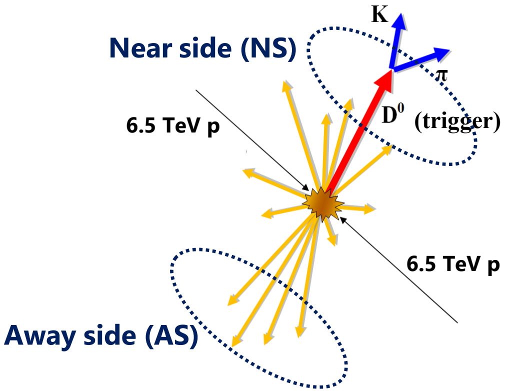
- pp collisions at $\sqrt{s}$ = 5.02 TeV:
  - Published in PRD 105 (2022) 1, L011103
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV:
  - **D^0**, **Λ_c^+**: measured from p_T = 0
  - **D^+**, **D_s^+**, **Ξ^0_c**: extrapolated to p_T = 0 using POWHEG+PYTHIA (D^+, D_s^+) or QCM (Ξ^0_c)

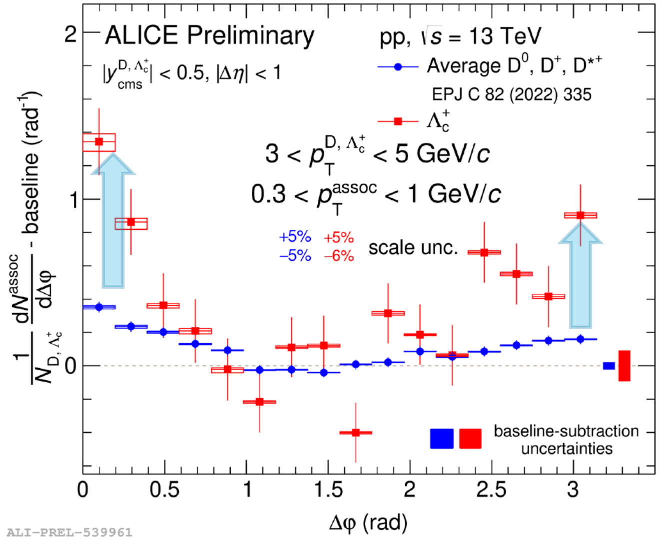
→ *More on p-Pb later on!*

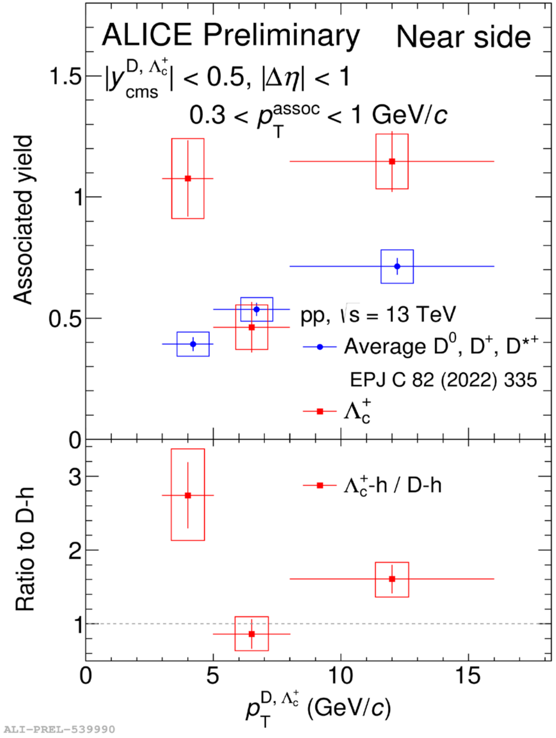
- **Compatibility** between **pp and p-Pb** fragmentation fractions at $\sqrt{s_{NN}}$ = 5.02 TeV (→ more on p-Pb later!)
  - Significant baryon enhancement w.r.t. e^+e^- and e^-p: **charm fragmentation functions are not universal!**
- **$c\bar{c}$ production cross section** in $|y|$ < 0.5 in pp at $\sqrt{s}$ = 5.02 TeV measured by summing all charm ground states
  - Updated results at $\sqrt{s}$ = 2.76 TeV, 7 TeV, all points on **upper edge of pQCD calculations**

MORE DIFFERENTIAL HADRONISATION PROBES

Azimuthal correlations between Λ_c^+ baryon and charged particles in pp collisions at 13 TeV



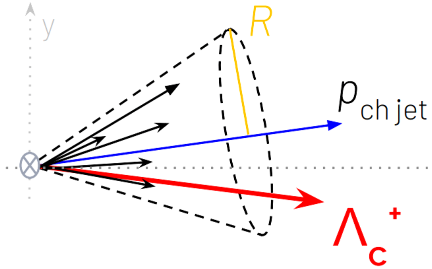




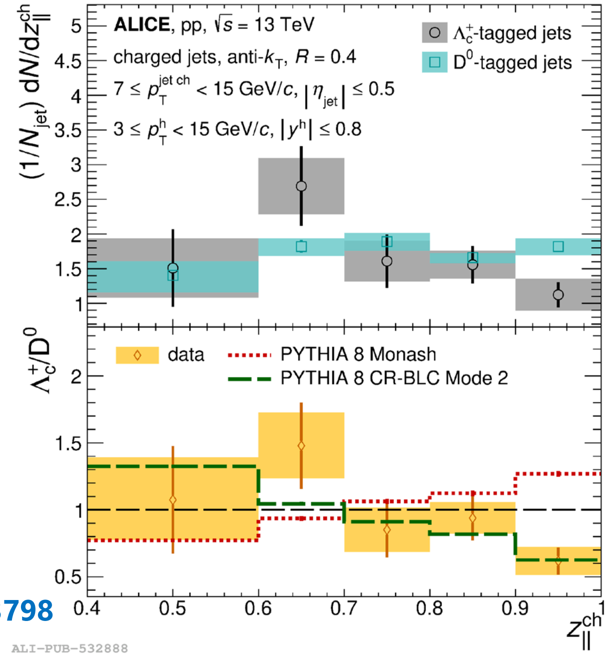
- Probe **parton shower** and **hadronisation of charm** (into baryons) and characterise charm-induced jets
- **Higher NS and AS yields** in Λ_c^+-h than D-h at low p_T
  - Different energy of the charm quark owing to a **softer Λ_c^+ fragmentation**?
  - Decay of **higher-mass charm states**, whose daughters enter the NS peak region?

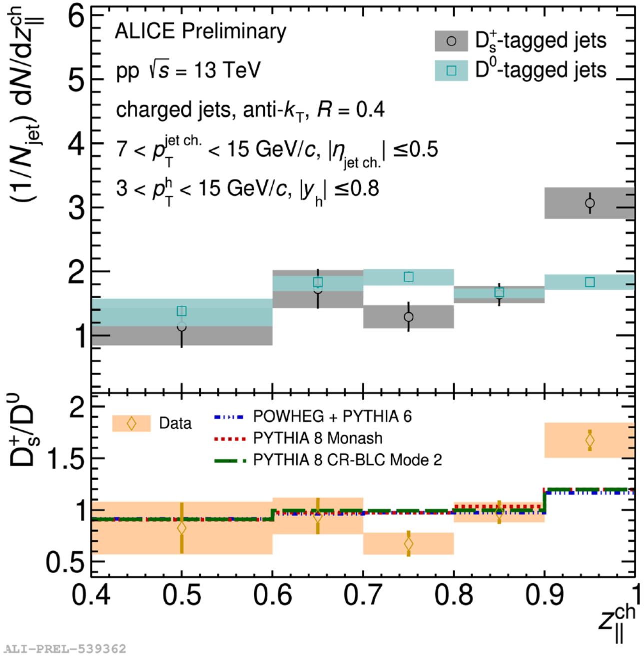
MORE DIFFERENTIAL HADRONISATION PROBES

- Complementary information from **jet longitudinal momentum fraction** taken by **HF hadrons**
- Here $\mathbf{\Lambda_c^+}$ (and $\mathbf{D_s^+}$) vs $\mathbf{D^0}$



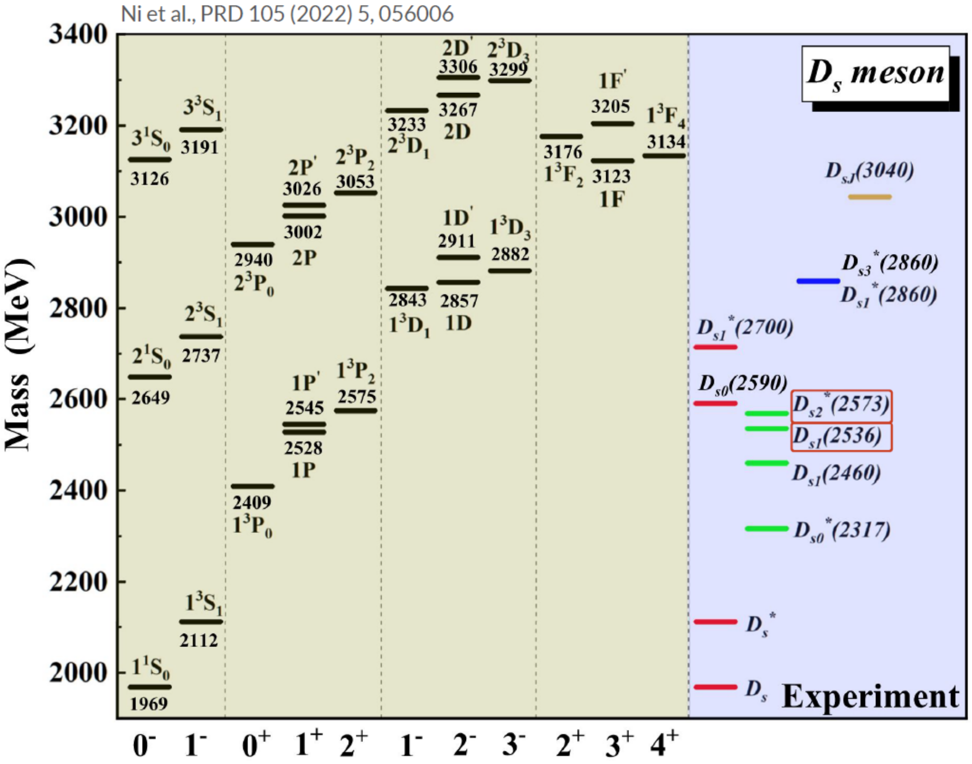
ALICE, arxiv:2301.13798





- Tendency for a **softer fragmentation** observed for $\mathbf{\Lambda_c^+}$ **baryon** compared to D^0 meson
  - ➢ PYTHIA8 describes better the $z_{//}$ shape if **CR-BLC modes** are considered
- A hint of **harder fragmentation** ($z_{//}$ peaked at 1) found instead for $\mathbf{D_s^+}$ **meson** (charm-strange)

CHARM-RESONANCE HADRONISATION STUDIES

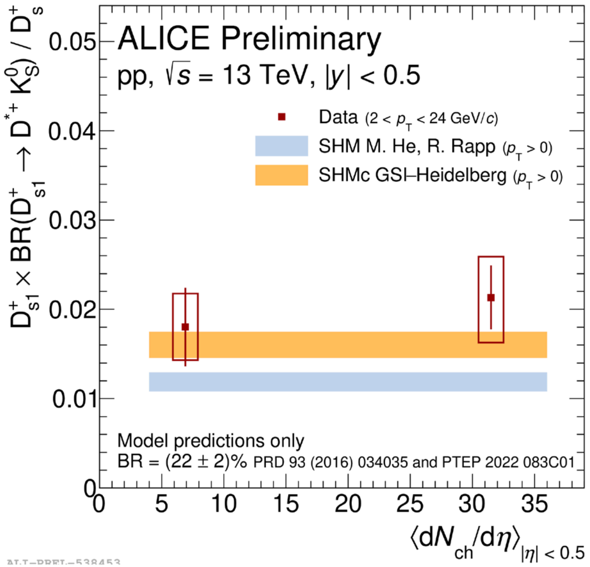


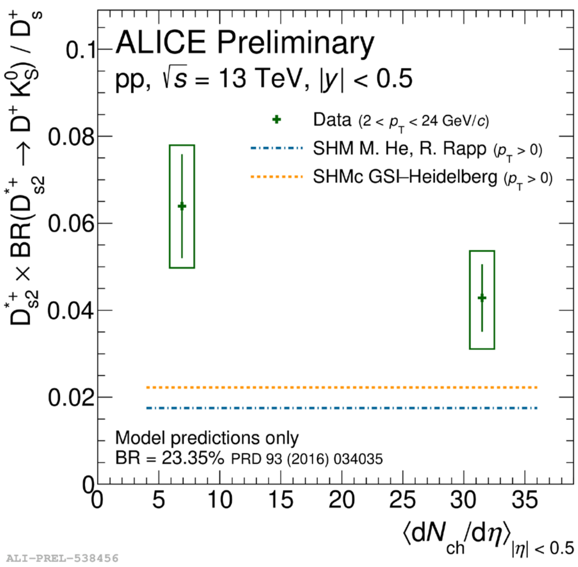
- Measurements of charm hadronisation extended to **meson resonances**
  - Is charm hadronisation into mesons similar to e^+e^- collisions also for resonances?
  - Test recombination/SHM/CR scenarios
  - Measurement as a function of multiplicity allows probing **hadronic rescattering** phase

- Studied production yield ratios of $\mathbf{D_{s1}^+/D_s^+}$ and $\mathbf{D_{s2}^{*+}/D_s^+}$ in pp collisions at 13 TeV (MB and HM)

CHARM-RESONANCE HADRONISATION STUDIES

- p_T-integrated yield ratios to ground state cancel out s- and c-dependencies for predictions
- **No multiplicity dependence** explicitly expected from SHM/SHMc





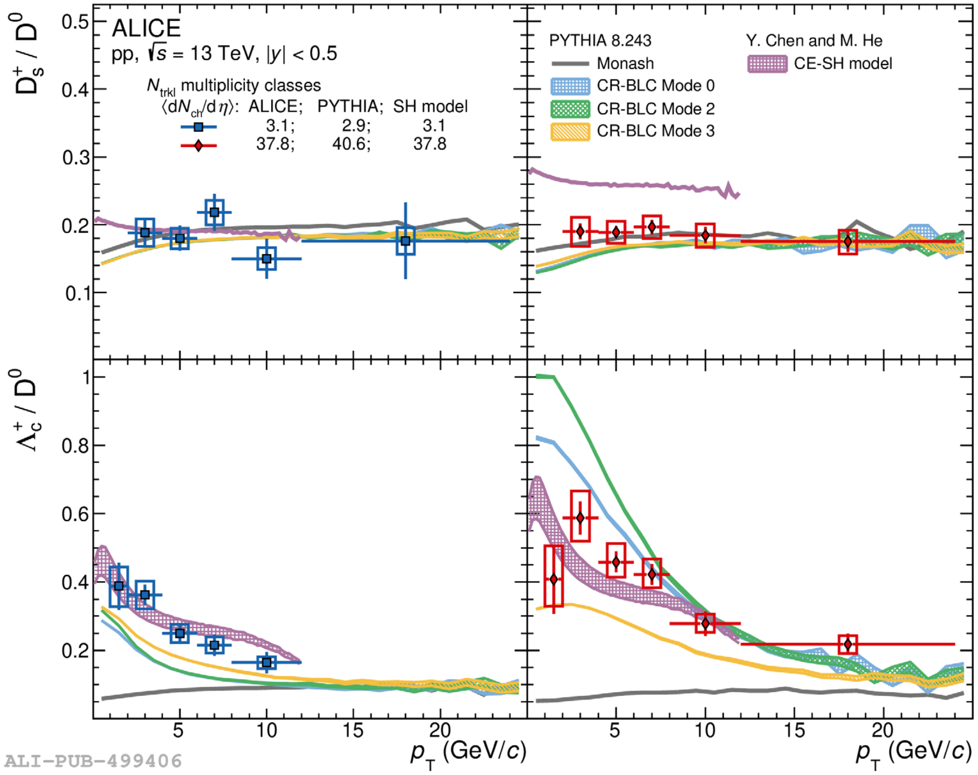
D_{s1}^+/D_s^+

- No observed multiplicity evolution
- Model predictions compatible to data

D_{s2}^{*+}/D_s^+

- **Hint of enhancement in MB collisions**, possibly from hadronic rescattering due to D_{s2}^{*+} shorter lifetime
  - $\tau(D_{s2}^{*+}) \sim 11.61$ fm/c; $\tau(D_{s1}^+) \sim 219$ fm/c
  - Similar behaviour found in LF sector (Φ/K vs Λ(1520)/Λ)
- Some **tension with predictions**, about 2.5σ (1.5σ) for MB (HM) collisions

PROMPT Λ_c^+/D^0 YIELD RATIOS VS MULTIPLICITY



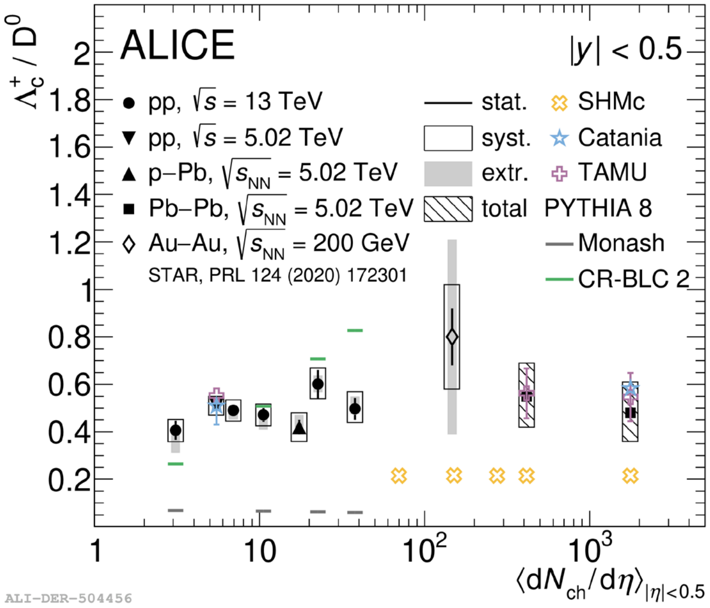
ALICE, PLB 829 (2022) 137065

Does HF-baryon enhancement evolve with event multiplicity?

- Λ_c^+/D^0 ratios at intermediate p_T larger for highest multiplicity than for lowest multiplicity
  - **5.3σ significance** for $1 < p_T < 12$ GeV/c
- p_T and multiplicity dependence qualitatively described by:
  - **PYTHIA with colour reconnection** beyond leading-colour approximation (CR-BLC)
  - **CE-SH,** a statistical hadronization model with particle set from RQM
- No multiplicity dependence for D_s^+/D^0 ratios

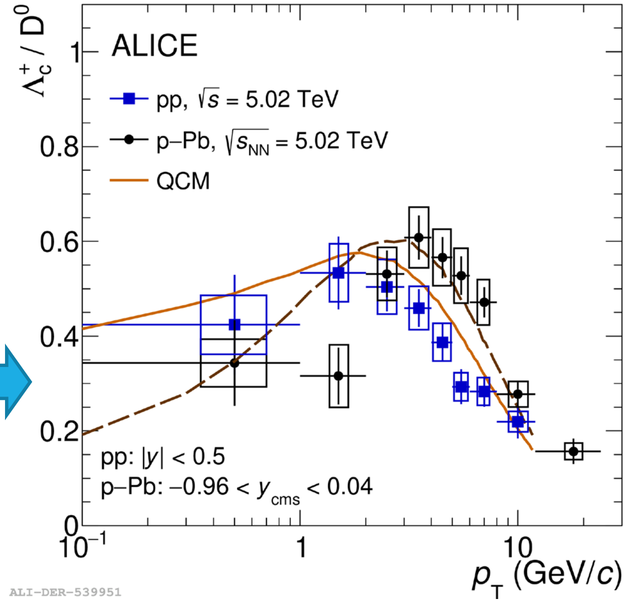
PYTHIA 8 Monash: P. Skands, et al., EPJC 74 (2014) 3024
PYTHIA 8 CR Tunes: J. Christiansen, et al., JHEP 08 (2015) 003
CE-SH: Phys. Lett. B 815 (2021) 136144

PROMPT Λ_c^+/D^0 YIELD RATIOS IN DIFFERENT SYSTEMS



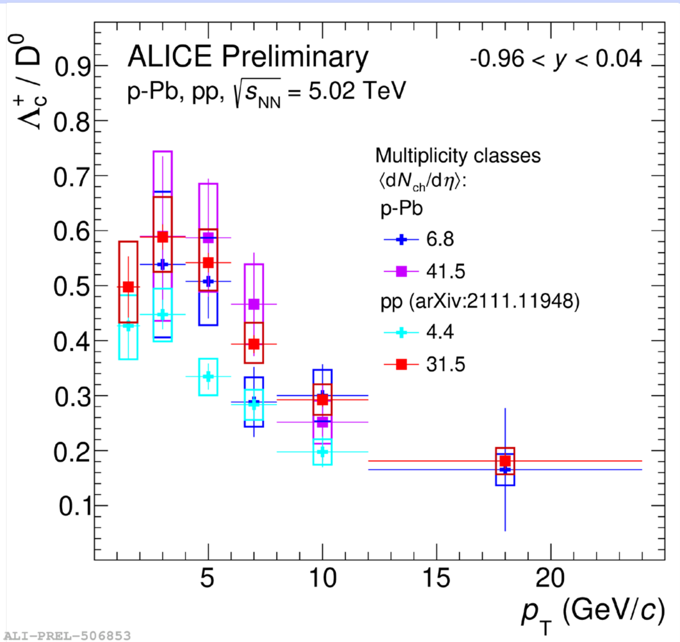
ALICE, PLB 829 (2022) 137065
ALICE, PRC 104 (2021) 054905
ALICE, arXiv:2112.08156

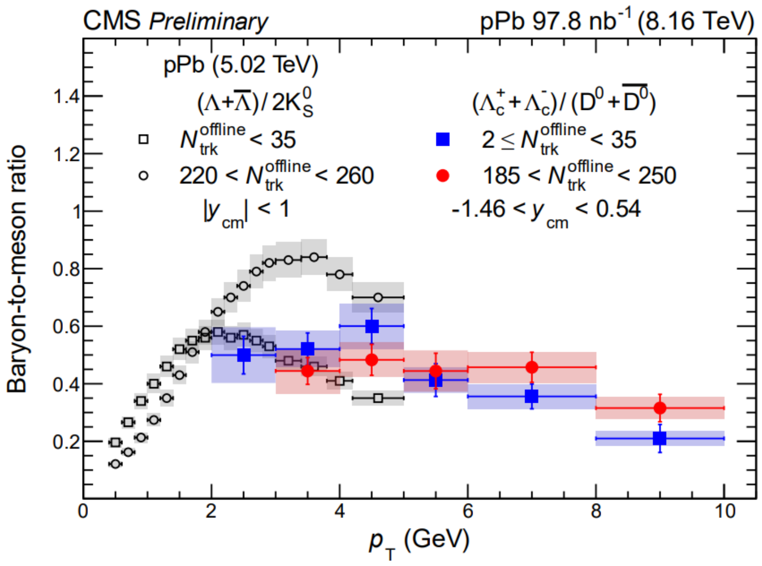
PRC 104 (2021) 054905
PRL 127 (2021) 202301
arXiv:2211.14032



- p_T-integrated Λ_c^+/D^0 ratios **independent of multiplicity** across the hadronic collision systems
  - Different p_T redistribution between baryons and mesons rather than overall baryon yield enhancement
- In p-Pb collisions, **larger Λ_c^+/D^0 ratios** for **p_T > 3 GeV/c** (different p_T spectrum)
  - Possible contribution from collective-like effects (as radial flow)?

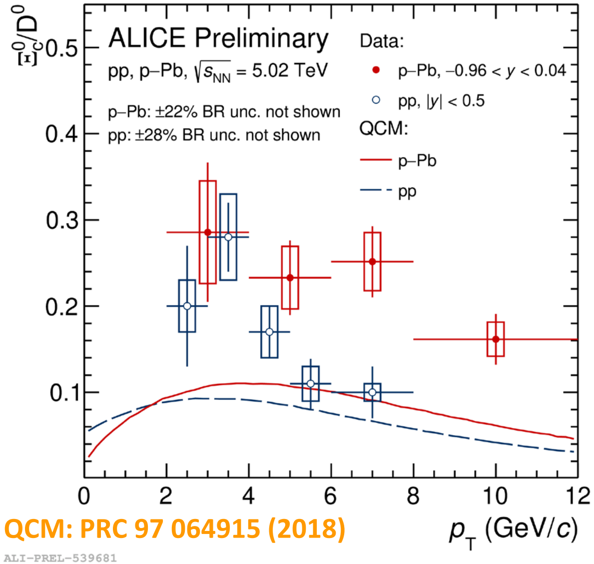
PROMPT Λ_c^+/D^0 YIELD RATIOS IN DIFFERENT SYSTEMS

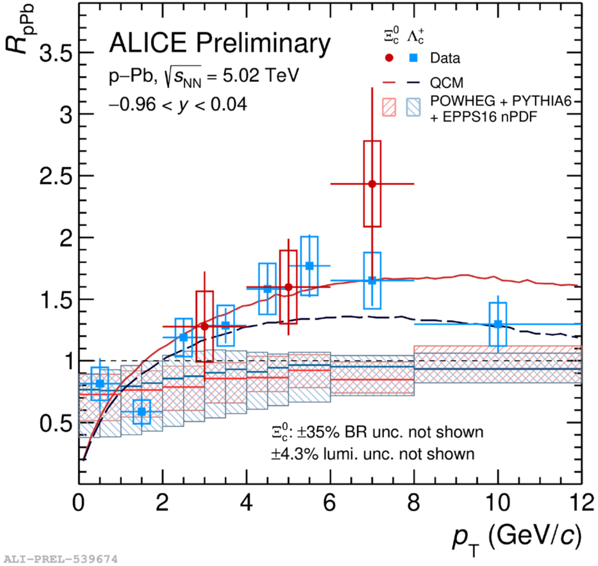


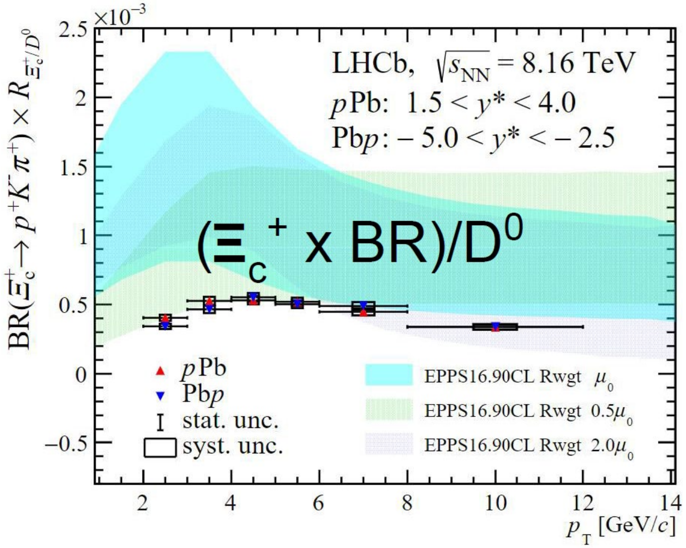


- Differently from pp**, no significant Λ_c^+/D^0 multiplicity dependence** is observed in p-Pb collisions
  - Comparing across collision systems, smaller values in LM pp, then similar values from HM pp through p-Pb
- Similar findings found by CMS (at larger √s = 5.02 TeV)
  - **Different trend** with respect to **light-flavour hadrons**, where a hierarchy similar to pp was observed

PROMPT Ξ_c^0/D^0 YIELD RATIOS IN p-Pb COLLISIONS







- Ξ_c^0/D^0 ratio **shifted toward larger p_T** in p-Pb compared to pp, as observed for Λ_c^+
- **Consistent R_{pPb}** for both baryons, described by QCM within uncertainties
- **Comparison with new Ξ_c^+ LHCb results** at forward rapidity interesting, but limited by large BR uncertainties
  - $BR(\Xi_c^+ \to pK^-\pi^+) = (6.2 \pm 3.0) \times 10^{-3}$

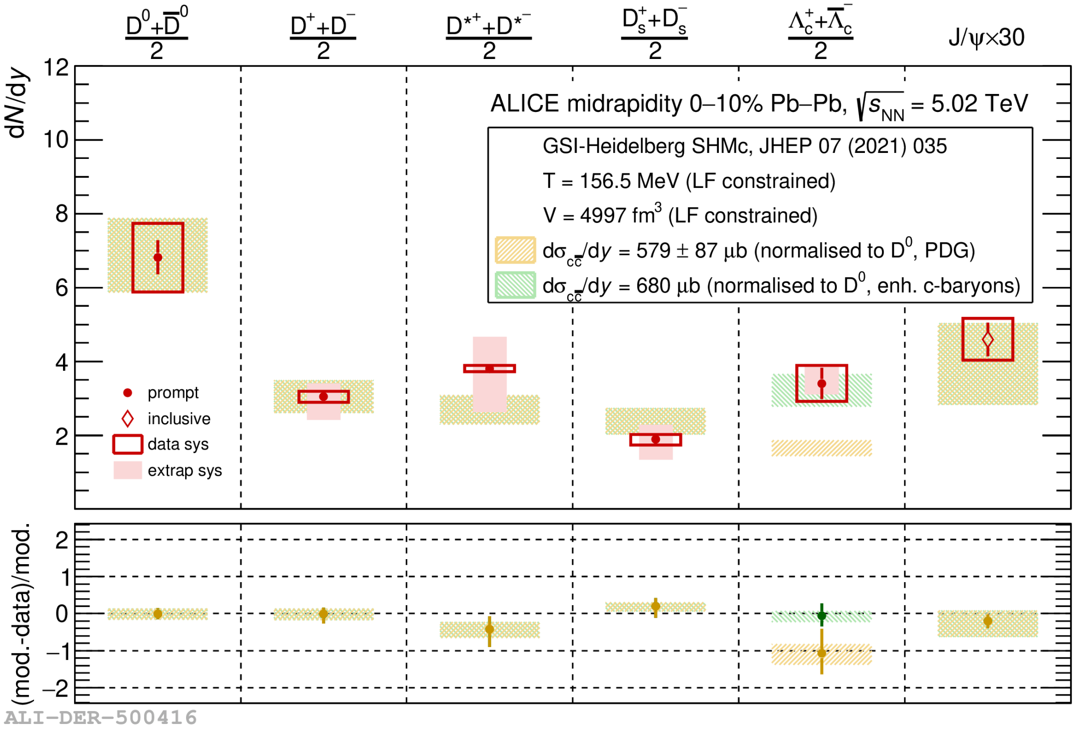
CHARM HADRONISATION IN HEAVY-ION COLLISIONS

- Extension of **statistical hadronisation model** for LF hadron production to **charm-hadron species** (SHMc)

- Charm quarks produced via **hard-parton scatterings** in early collision stages
  - ➢ Accounted for by **fugacity factor g_c**, whose value depends on measured σ_{ccbar}

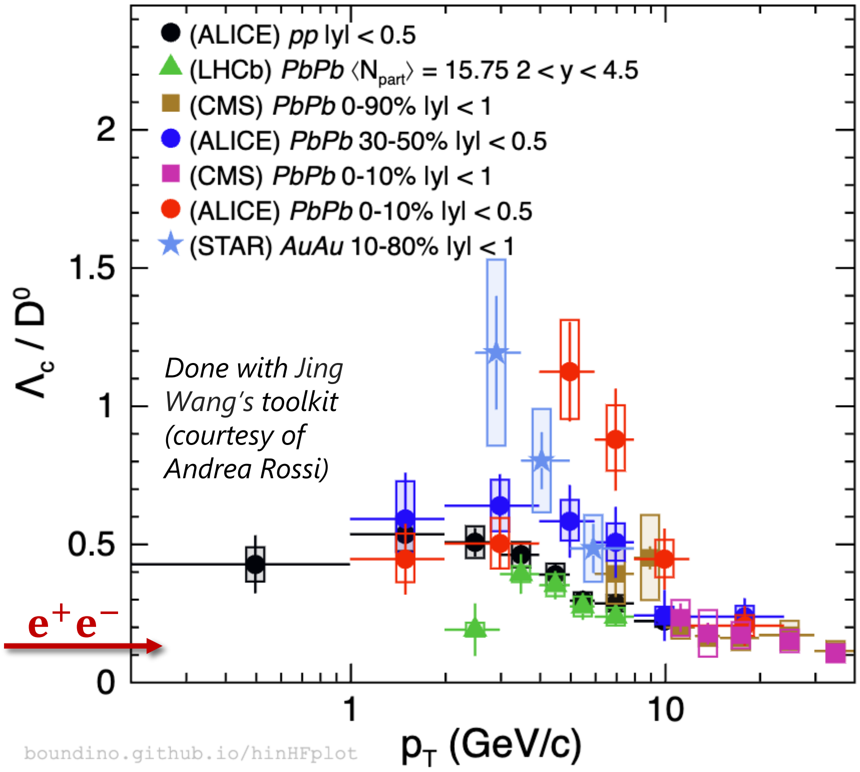
- SHMc predictions of ALICE **p_T-integrated** charm hadron yields, fixing T_{chem}, V, and $\sigma_{c\bar{c}}$, **reproduces well** the data

- Charm-quark produced out of equilibrium, but relative charm-hadron abundancies at chemical freeze-out follow **thermal weights**
  - ➢ Supports **thermalization of charm** in QGP medium



CHARM HADRONISATION IN HEAVY-ION COLLISIONS

Going p_T-differentially



- Significant evolution of Λ_c^+/D^0 ***p_T*-differential** yields
- Largest increase from e^+e^- to pp collisions
- Further baryon enhancement in central Pb-Pb collisions at intermediate p_T
  - **Coalescence** contribution? (only in Pb-Pb, or increased w.r.t. pp)
  - Higher-p_T push from **radial flow**?
  - Influence of rescattering in the hadronic phase?
- LHCb Pb-Pb results consistent with ALICE pp (different rapidity, peripheral vs central collisions)
- Large ratio observed also at STAR, shifted towards lower p_T compared to LHC measurements

ALICE pp: PRL 127 (2021) 202301
LHCb Pb-Pb: arXiv:2210.06939
CMS Pb-Pb: CMS-PAS-HIN-21-004
ALICE Pb-Pb: arXiv:2112.08156
STAR Au-Au: PRL 124 (2020) 172301

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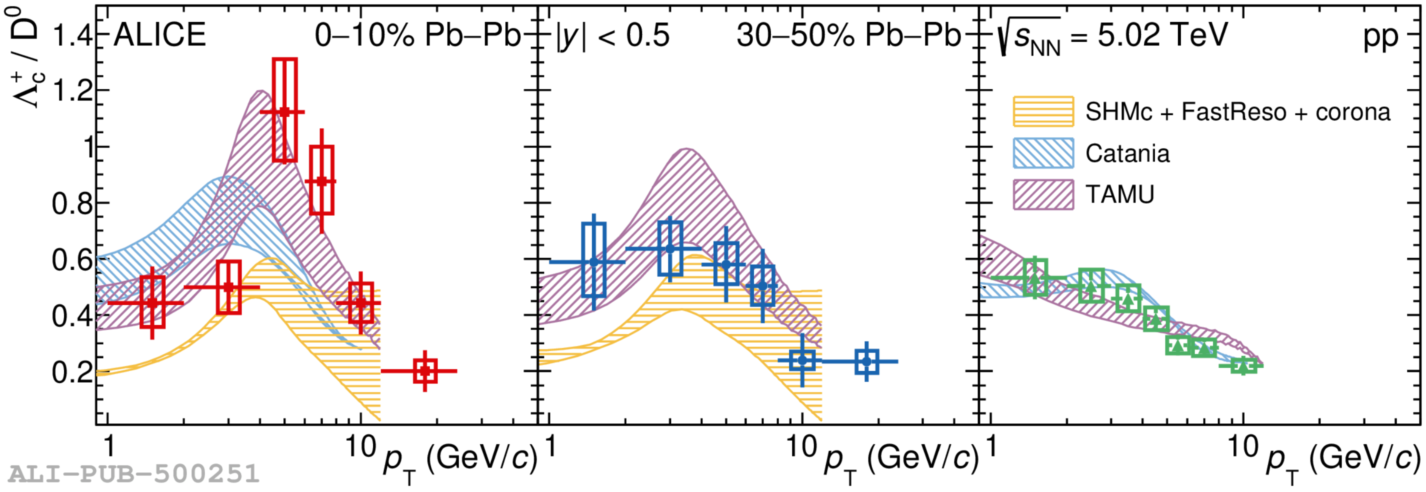


Catania, EPJC 78 4 (2018) 348
TAMU, PRL 124, 4 (2020) 042301
SHM, JHEP 07 035 (2021)
ALICE, arxiv:2112.08156

- Both **TAMU** and **Catania** models, including a coalescence contribution for hadronisation, able to describe data within uncertainties
- **SHMc + FastReso + corona** reproduces the trend of measurements, but tends to underestimate their values in central collisions
- Semi-central Pb-Pb collision results consistent with pp measurement within uncertainties

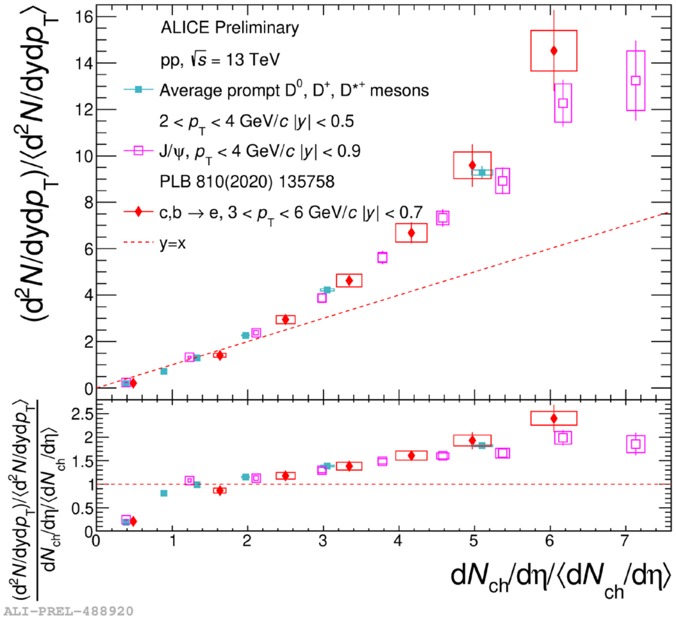
SUMMARY AND PERSPECTIVES

- Wealth of results released by the ALICE Collaboration exploiting **Run 2** data, providing relevant findings on heavy-flavour hadronisation from small to large hadronic collision systems
  - **Meson production** and meson-to-meson ratios **well described** by pQCD predictions tuned on e^+e^- collisions
    - Studies being extended to charm meson resonances, to test hadronisation models
  - **Baryon-to-meson ratios** and baryon fragmentation fractions in pp collisions **significantly larger** than in e^+e^-, e^-p collisions
    - **Charm fragmentation fractions are not universal** across the collision systems
  - No modification of p_T-integrated yields moving to heavy-ion systems, but higher-p_T push in p-Pb and **further intermediate-p_T enhancement** in central Pb-Pb for baryon-to-meson ratios
  - Further insights (and surprising observations) on fragmentation/hadronisation from more differential measurements involving **Λ_c^+ jets and correlations**

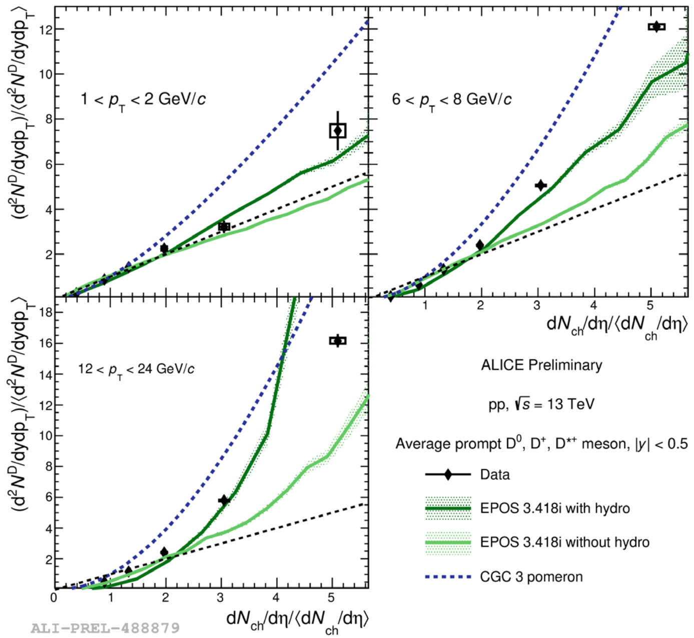
- ALICE Collaboration **already analysing Run 3 data** to shed light on hadronisation open questions

Backup slides

D-MESON PRODUCTION VS MULTIPLICITY



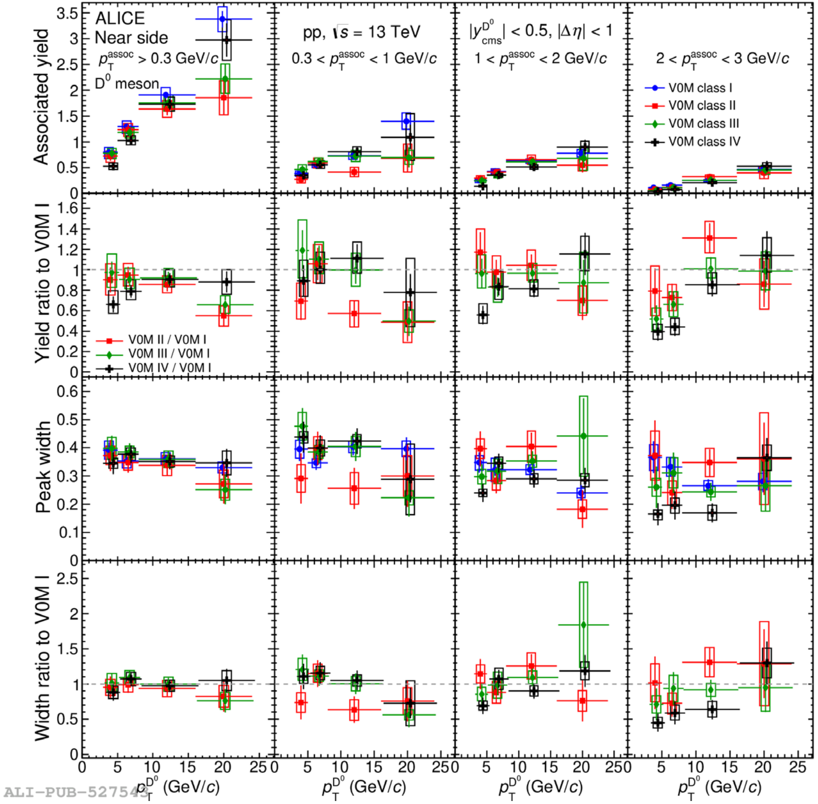
- **Prompt D-meson** self-normalized yields at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV
- **Faster-than-linear** increase with increasing multiplicity
  - Consistent with other ALICE **open and hidden** HF measurements at y≈0
  - Points towards a feature of **charm production**, rather than hadronisation



- **EPOS 3** predictions **with hydrodynamic component** reproduce the data trend better than EPOS 3 without hydrodynamics, and Colour Glass Condensate (CGC) with the 3 pomeron mechanism
  - None of the above models provides an optimal description of the measurement

EPOS 3: Phys. Rev. C 89 no. 6, (2014) 064903
CGC: , Eur. Phys. J. C 80 no. 6, (2020) 560

D-h CORRELATIONS VS MULTIPLICITY

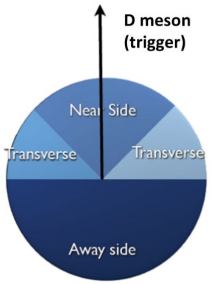


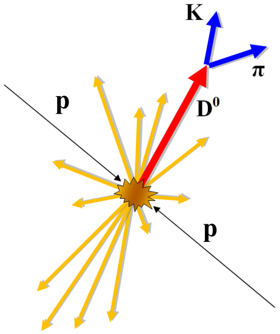
V0M classes, I-II-III-IV: higher to lower multiplicities

- What about possible **modifications of charm fragmentation** with multiplicity?

- Measurement of **angular correlations** of prompt D^0 mesons with charged particles in pp collisions at $\sqrt{s}$ = 13 TeV
  - Evaluated near-side peak yields and widths in different forward-rapidity multiplicity ranges
  - **No significant dependence** of peak features with multiplicity observed

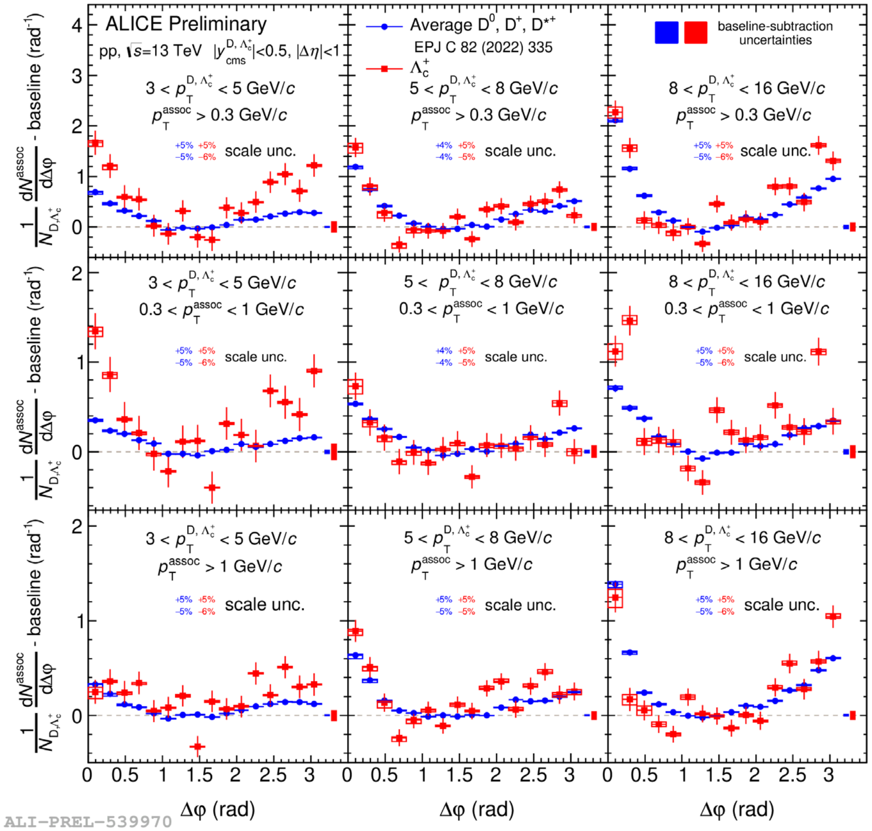
- Suggests **similar fragmentation** of charm into hadrons at different event multiplicities, at least when it hadronises to D^0 mesons

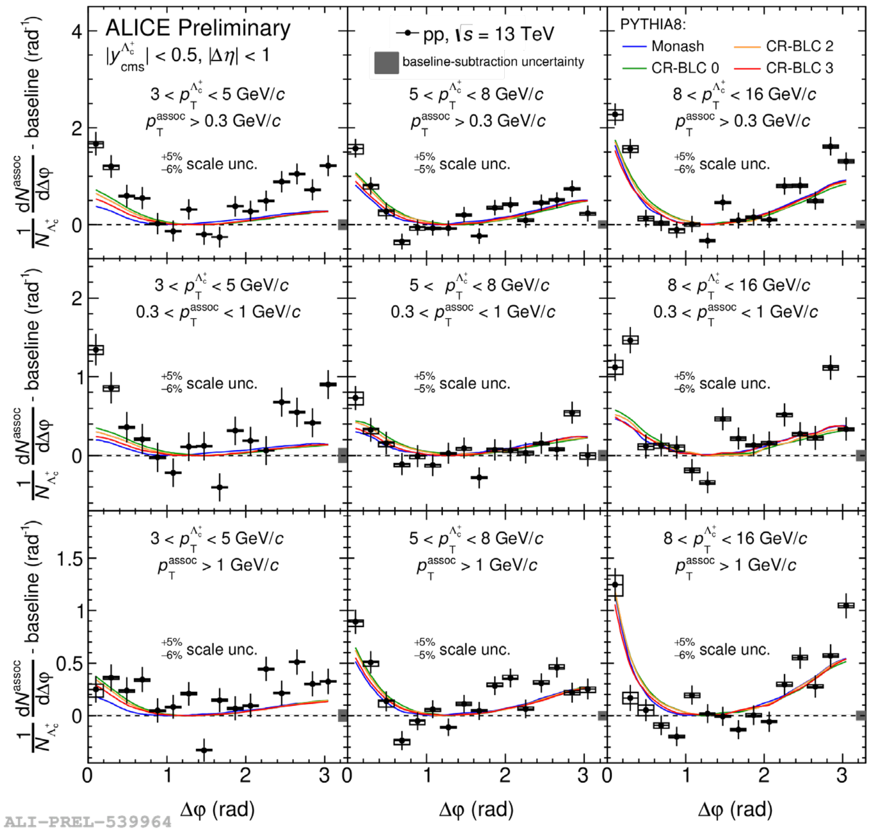




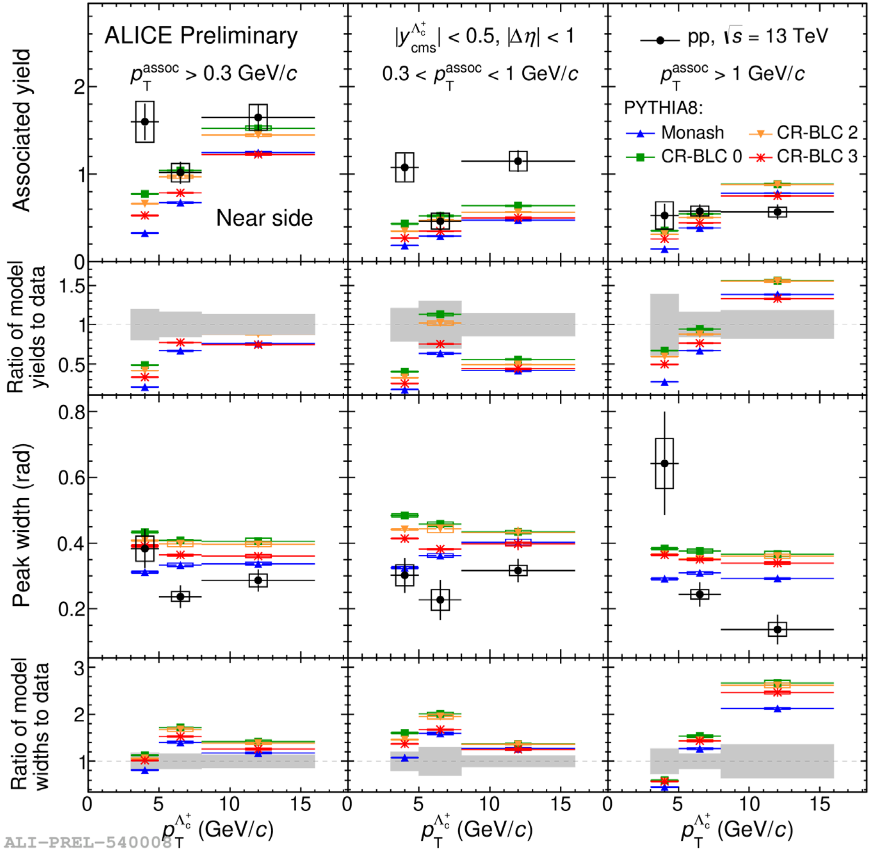
ALICE, Eur. Phys. J. C (2022) 82:335

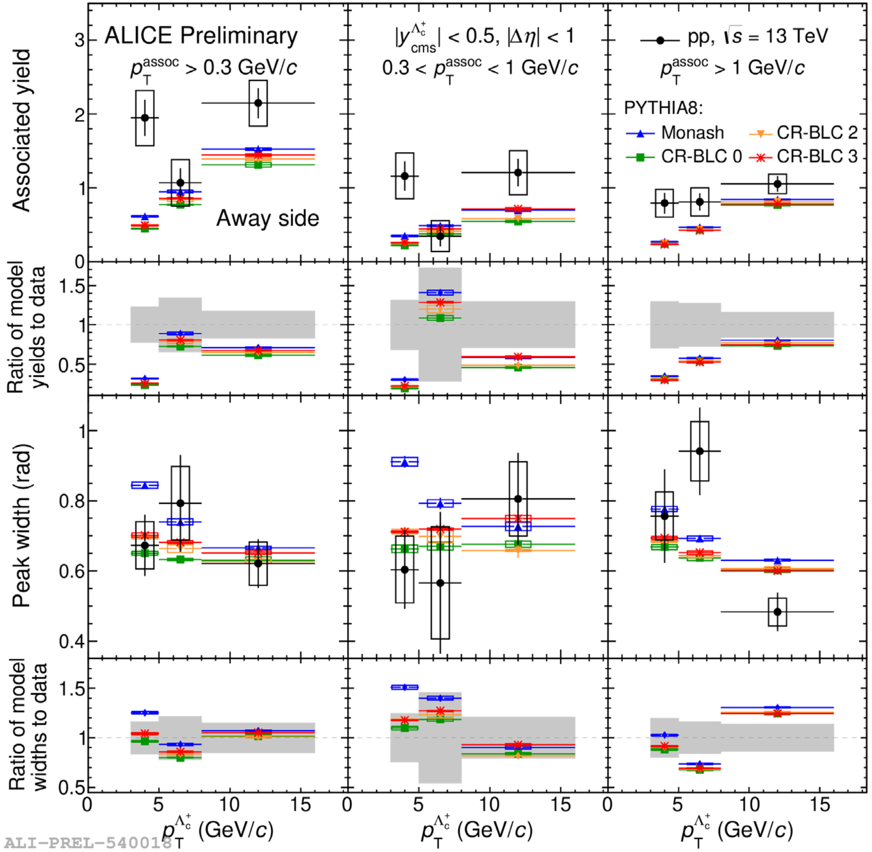
Λ_c^+-h CORRELATIONS



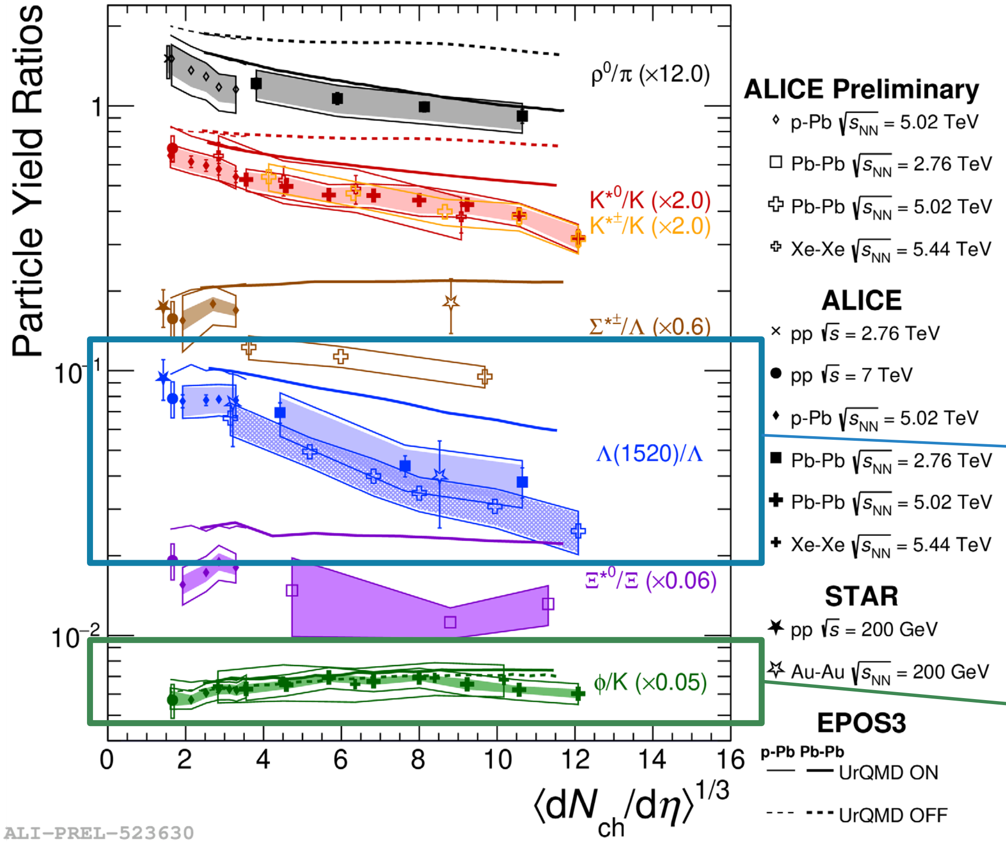


Λ_c^+-h CORRELATIONS





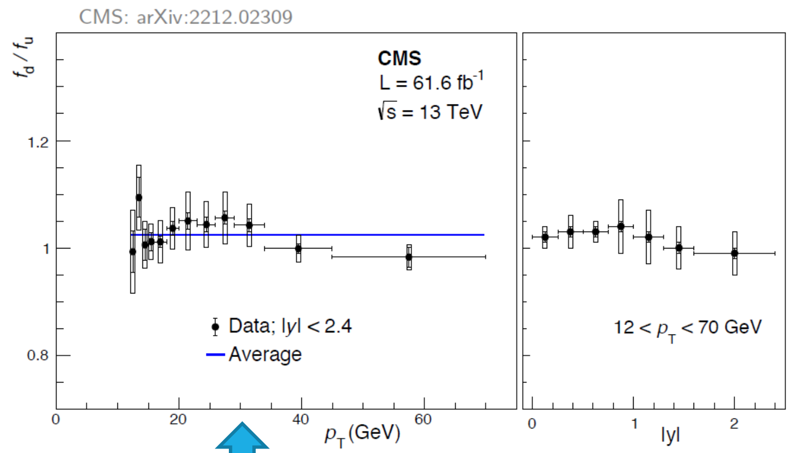
D_s^+ RESONANCES VS LF RESONANCES

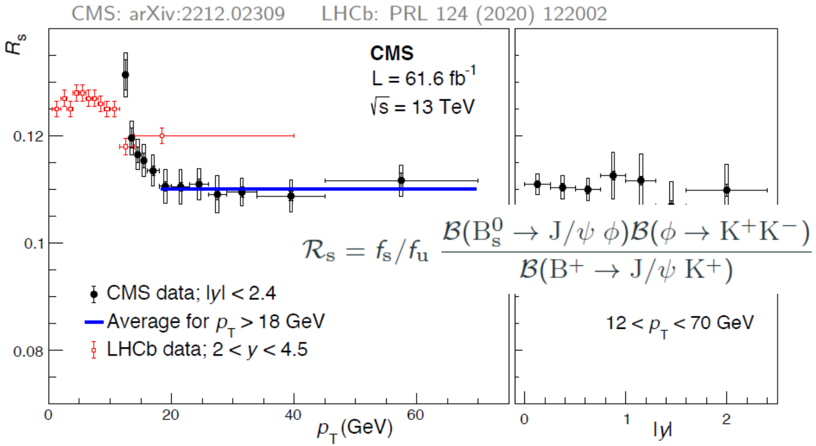


Almost same lifetime as D_{s2}^{*+}

D_{s1}^+ lifetime x5 larger

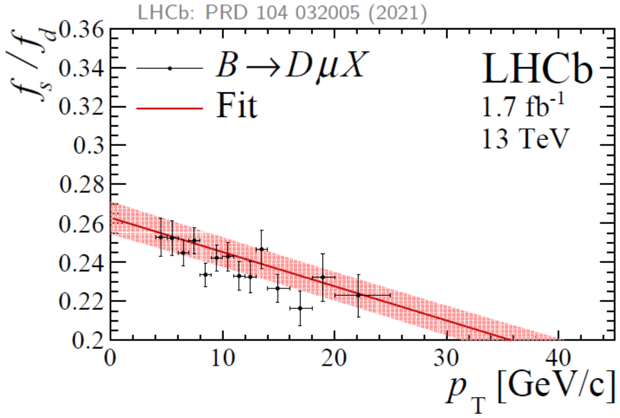
CMS RESULTS FOR B MESONS





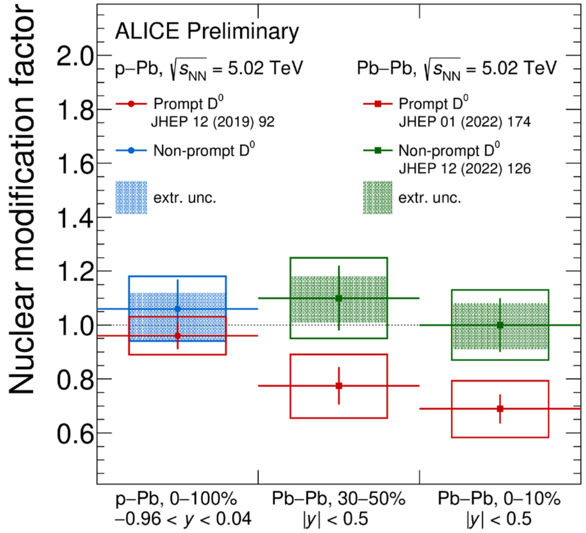
No p_T and y dependence of B^0/B^+ ratio

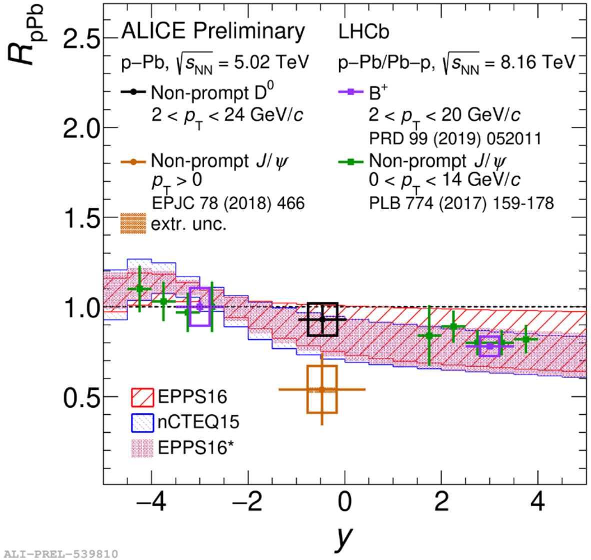
At low p_T, decrease of B^0_s/B^+ ratio, then flattens out

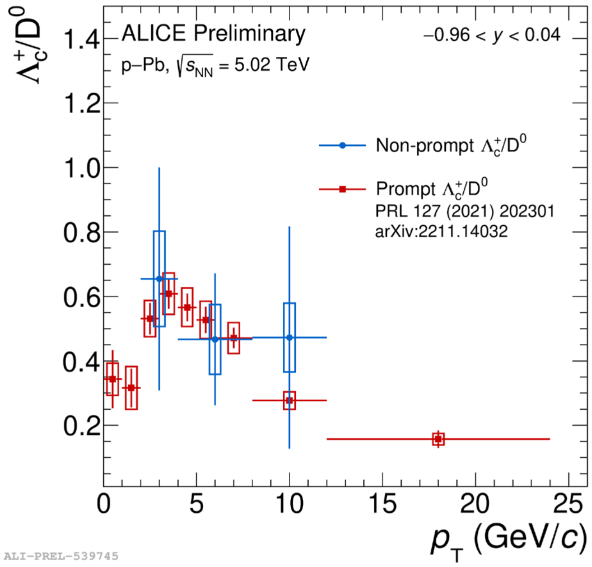


Significant p_T dependence of B^0_s/B^0 ratio

NON-PROMPT CHARM HADRONS IN p-Pb







NON-PROMPT CHARM HADRONS IN p-Pb