UNIVERSITÄT HEIDELBERG
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ALICE

Charm production and hadronization in pp and p–Pb collisions at the LHC with ALICE

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ON BEHALF OF THE **ALICE COLLABORATION**

Heavy flavor production in pp collisions

$$\frac{d\sigma^{\mathrm{hh}\to H_{qx}}}{dp_{\mathrm{T}}} = f_i(x_1,\mu_f^2) f_j(x_2,\mu_f^2) \times \frac{d\sigma^q}{dp_{\mathrm{T}}} \times D_{q\to H_q}\left(z_q = \frac{p_{H_q}}{p_q}, \mu_f^2\right)$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)

Test pQCD-based calculations with heavy flavor (HF) hadron production measurements

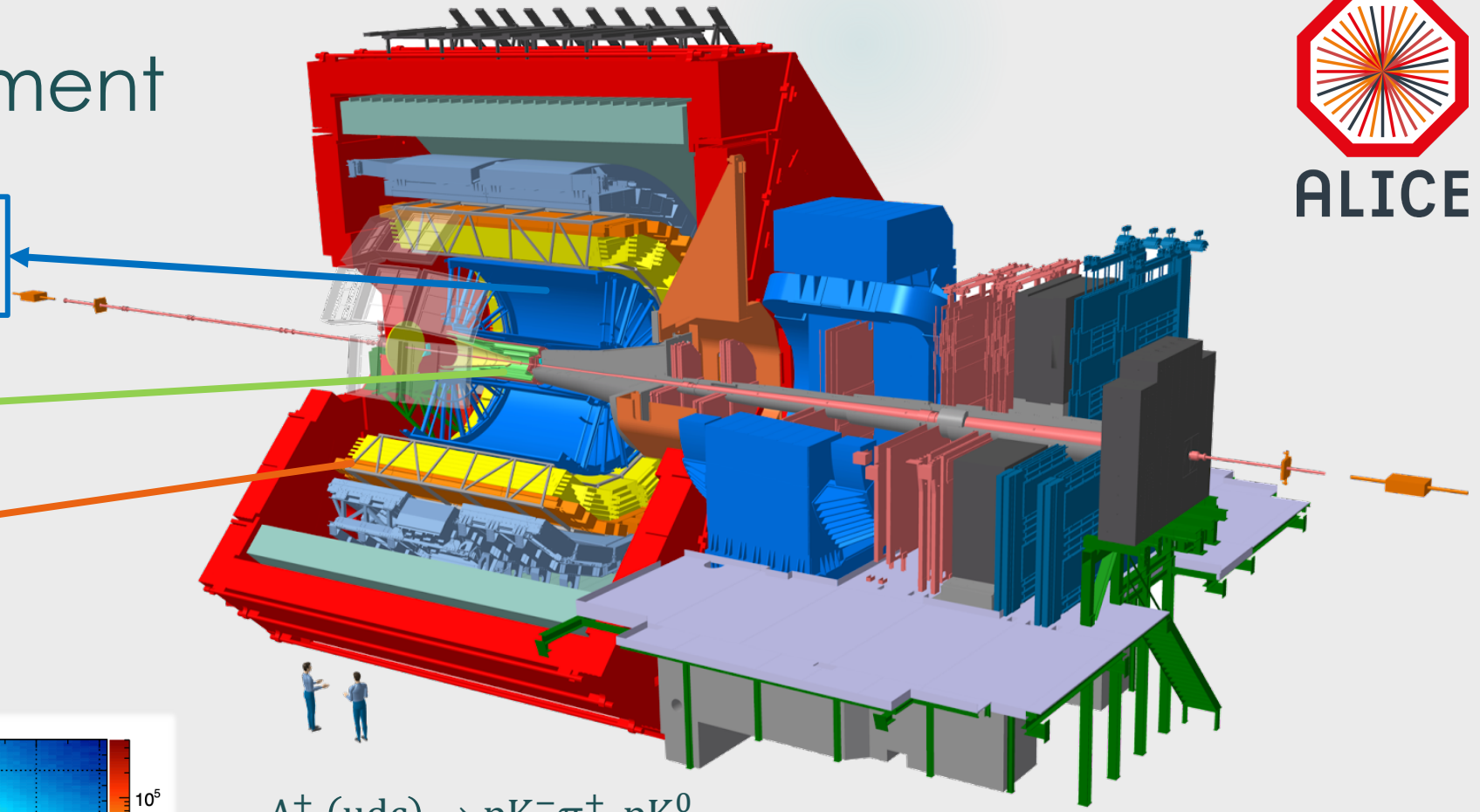
- Cross section of charm and beauty hadron production is typically calculated in a factorization approach
  - Fragmentation functions are constrained from e^+e^- and ep measurements
  - **Typical assumption: fragmentation functions apply universally across e^+e^-, pp and p–Pb collision systems**
- Yield ratios of hadrons are sensitive to heavy quark hadronization

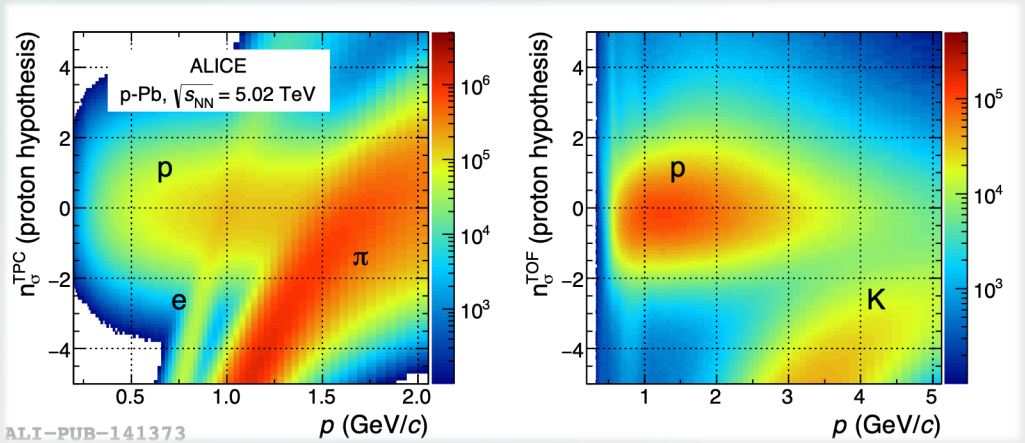
The ALICE experiment

Time Projection Chamber (TPC):
Tracking, PID via d*E*/d*x*

Inner Tracking System (ITS):
Tracking and vertexing

Time Of Flight (TOF):
PID via time of flight





Λ_c^+ (udc) $\rightarrow pK^-\pi^+, pK_S^0$

$\Sigma_c^{0,++}$ (ddc, uuc) $\rightarrow \Lambda_c^+\pi^{-,+}$

Ξ_c^0 (dsc) $\rightarrow \Xi^- e^+ \nu_e, \Xi^-\pi^+$

Ξ_c^+ (usc) $\rightarrow \Xi^-\pi^+\pi^+$

Ω_c^0 (ssc) $\rightarrow \Omega^-\pi^+$

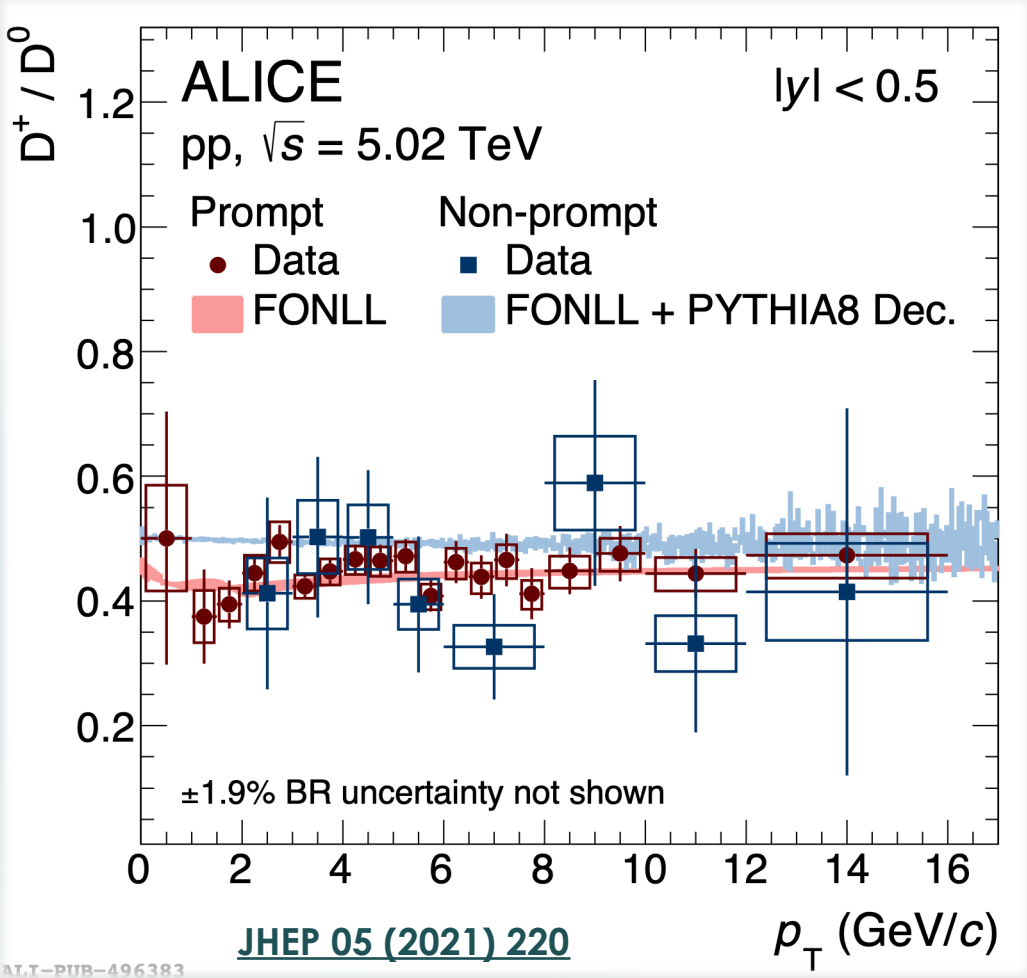
$D^0(\bar{u}c) \rightarrow K^-\pi^+$

$D^+(\bar{d}c) \rightarrow K^-\pi^+\pi^+$

$D_s^+(\bar{s}c) \rightarrow \Phi\pi^+ \rightarrow K^-\pi^+\pi^+$

Meson production in pp collisions

D^+/D^0



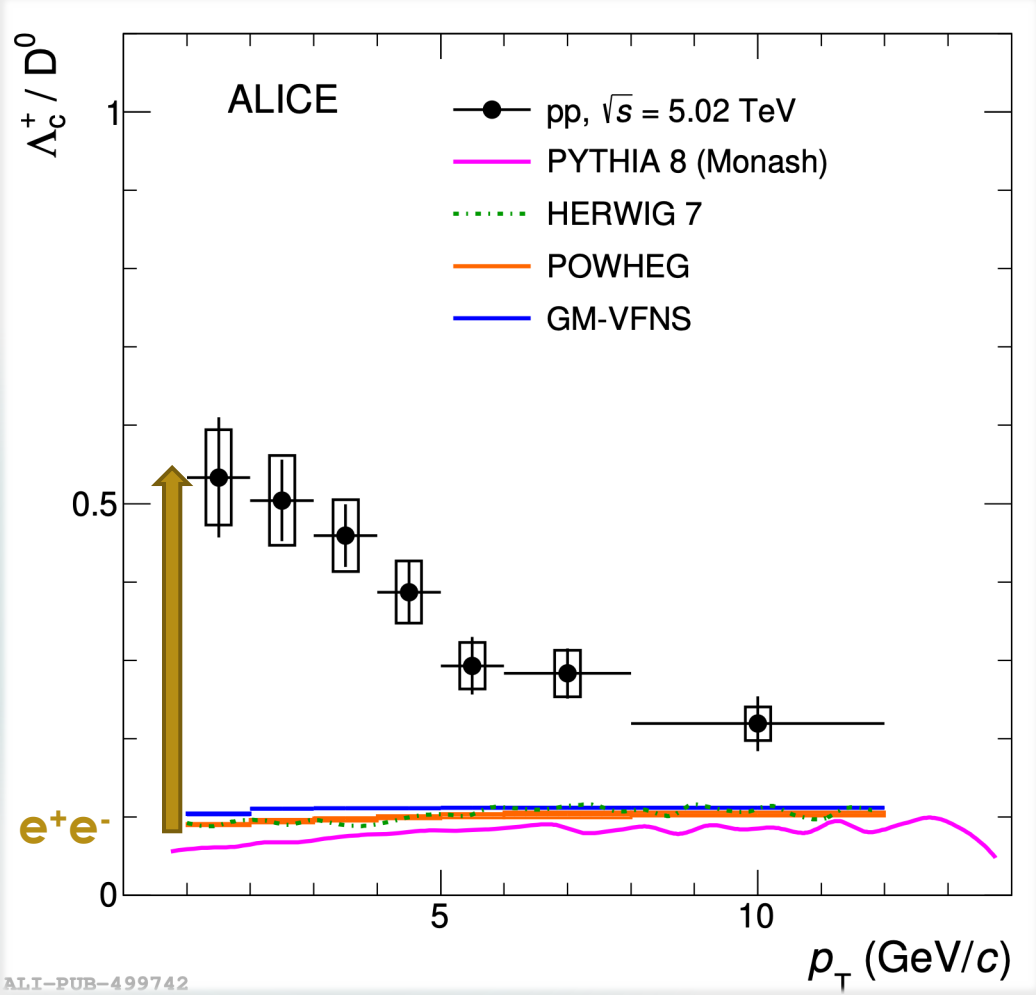
Meson-to-meson yield ratio:

- **D^+/D^0 yield ratios are independent of meson momentum** for prompt and non-prompt measurements (from decay of beauty hadrons). Charm and beauty meson-to-meson yield ratios are **well described by FONLL calculations**, based on the factorization approach assuming fragmentation functions from e^+e^- collisions

See talk by Pietro Antonioli (12:30) for non-prompt measurements and beauty studies.

Baryon production in pp collisions

Λ_c^+/D^0



Baryon-to-meson yield ratios:

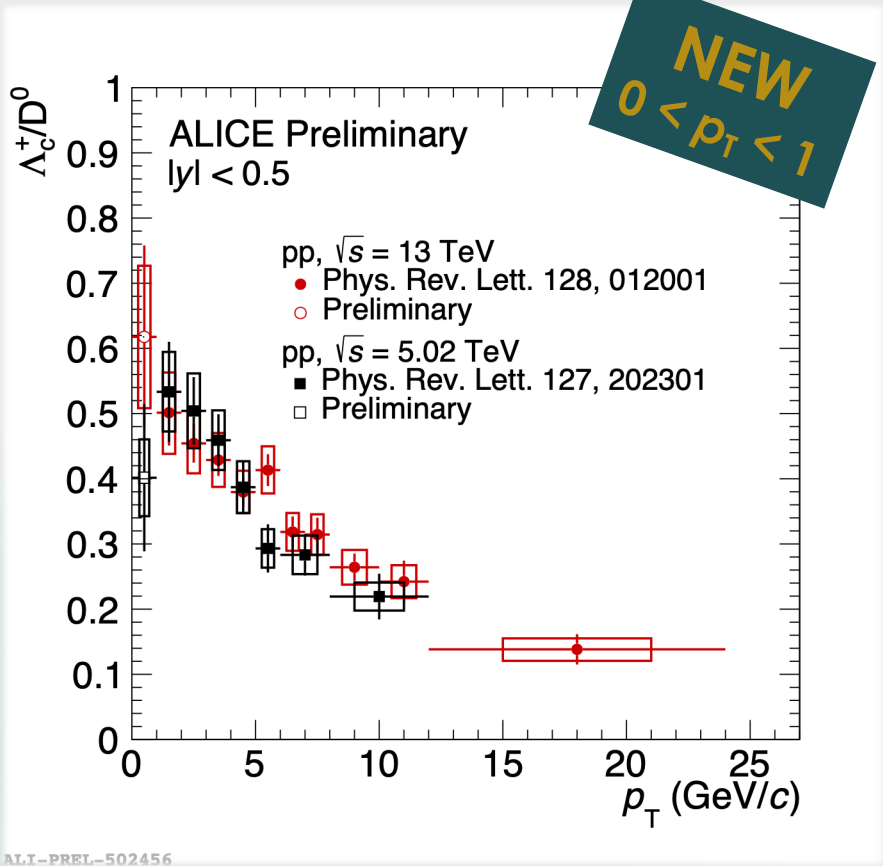
- Λ_c^+/D^0 **depends significantly on hadron momentum**
- Yield ratio is underestimated by models based on the factorization using charm fragmentation functions from e^+e^- collisions

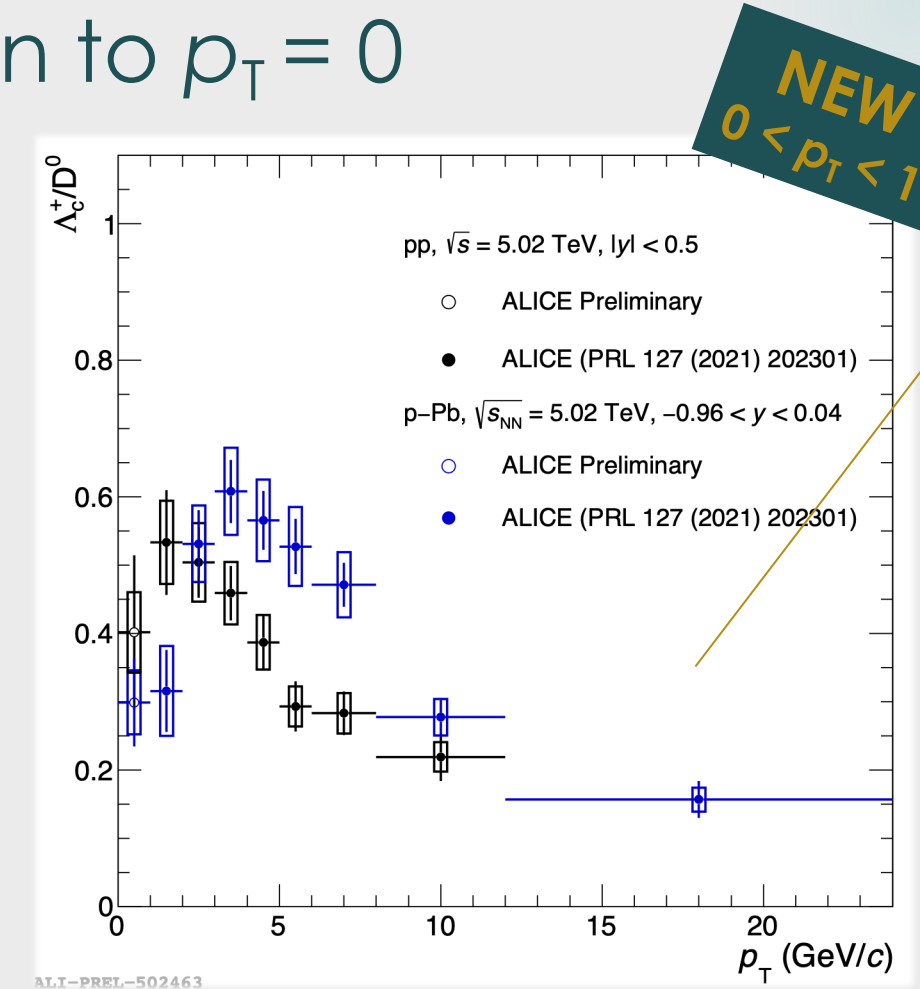
Non-universal hadronization via fragmentation with further hadronization mechanisms?

Phys. Rev. C 104 (2021) 054905

Λ_c^+ production down to $p_T = 0$

Λ_c^+/D^0





For p_T > 3 GeV/c Λ_c^+/D^0 larger in p–Pb collisions than in pp collisions

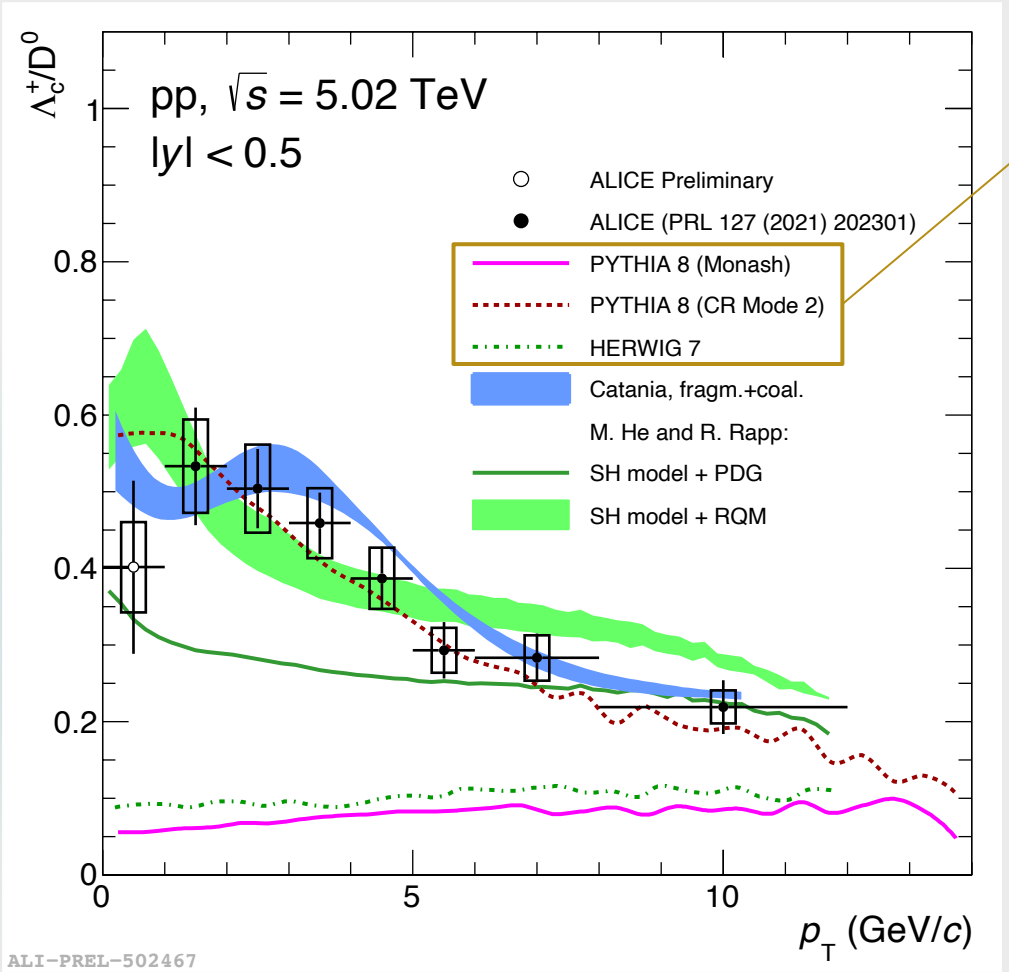
➢ Harder $p_T(\Lambda_c^+)$ spectrum

Collective expansion or multiplicity dependence?

- ➢ Significant fraction of charm cross section at low p_T: vital for a complete picture of hadronization
- ➢ New measurements in pp and p–Pb collisions are consistent between collision energies, $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV, and pp and p–Pb collision systems

Baryon-to-meson yield ratio - models

Λ_c^+/D^0



Phys. Rev. Lett. 127, 202301

J.P. Christiansen, P. Z. Skands: JHEP 1508 (2015) 003

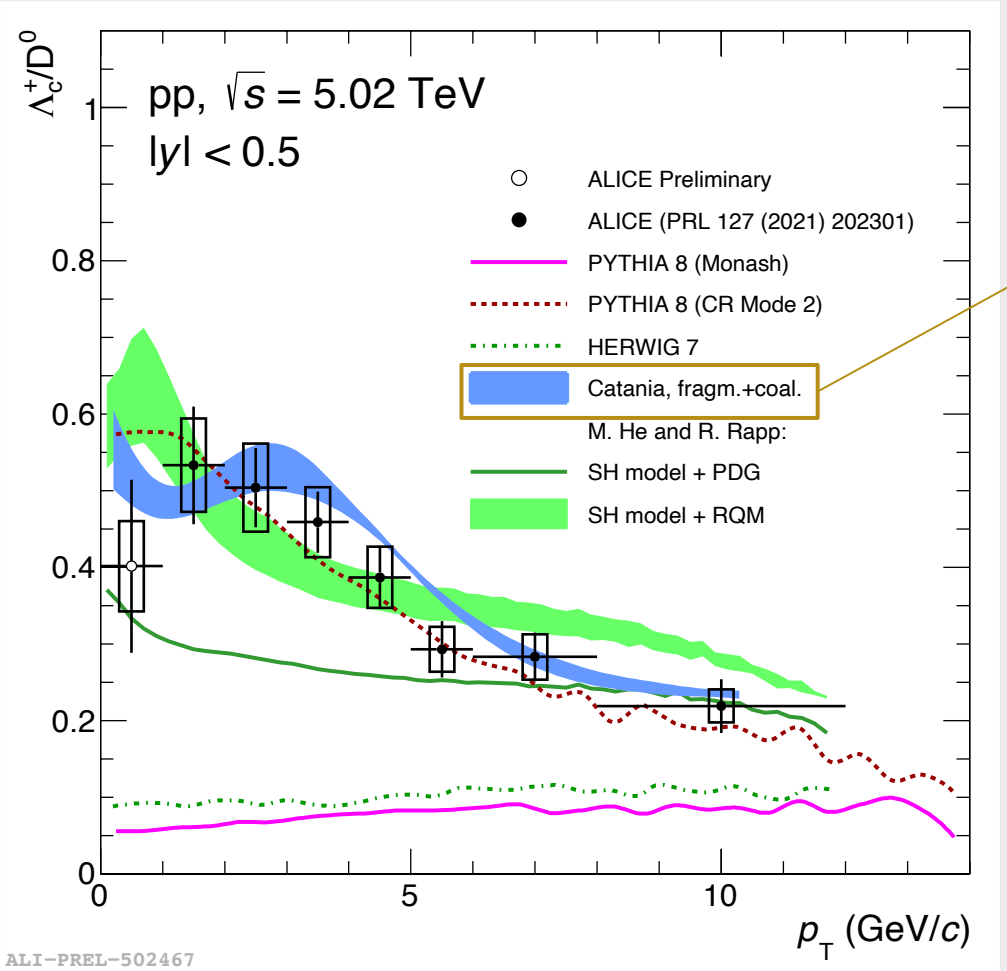
PYTHIA 8

- Models based on **fragmentation functions from e^+e^-** collisions underestimate the data (PYTHIA 8 Monash, HERWIG 7)
- Models including **color reconnection** beyond leading color describe the data (PYTHIA 8 CR Mode 2)

In multi-parton-interactions **"junction"** topologies enhance the charm baryon production

Baryon-to-meson yield ratio - models

Λ_c^+/D^0



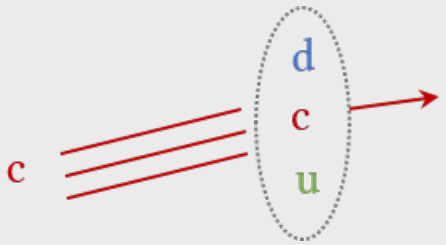
Phys. Rev. Lett. 127, 202301

PLB 821 (2021) 136622

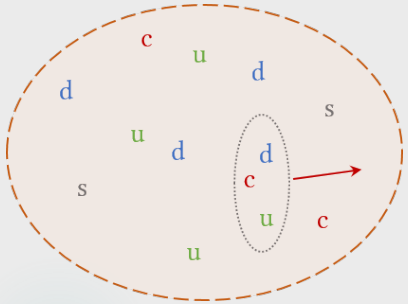
Catania

- Assumes a **thermalized system** of gluons, u,d,s quarks and anti-quarks (QGP)
- Hadronization via **coalescence and fragmentation**
  - at $p_T \approx 0$ charm quarks hadronize only via coalescence
  - at high p_T fragmentation is dominant

Fragmentation



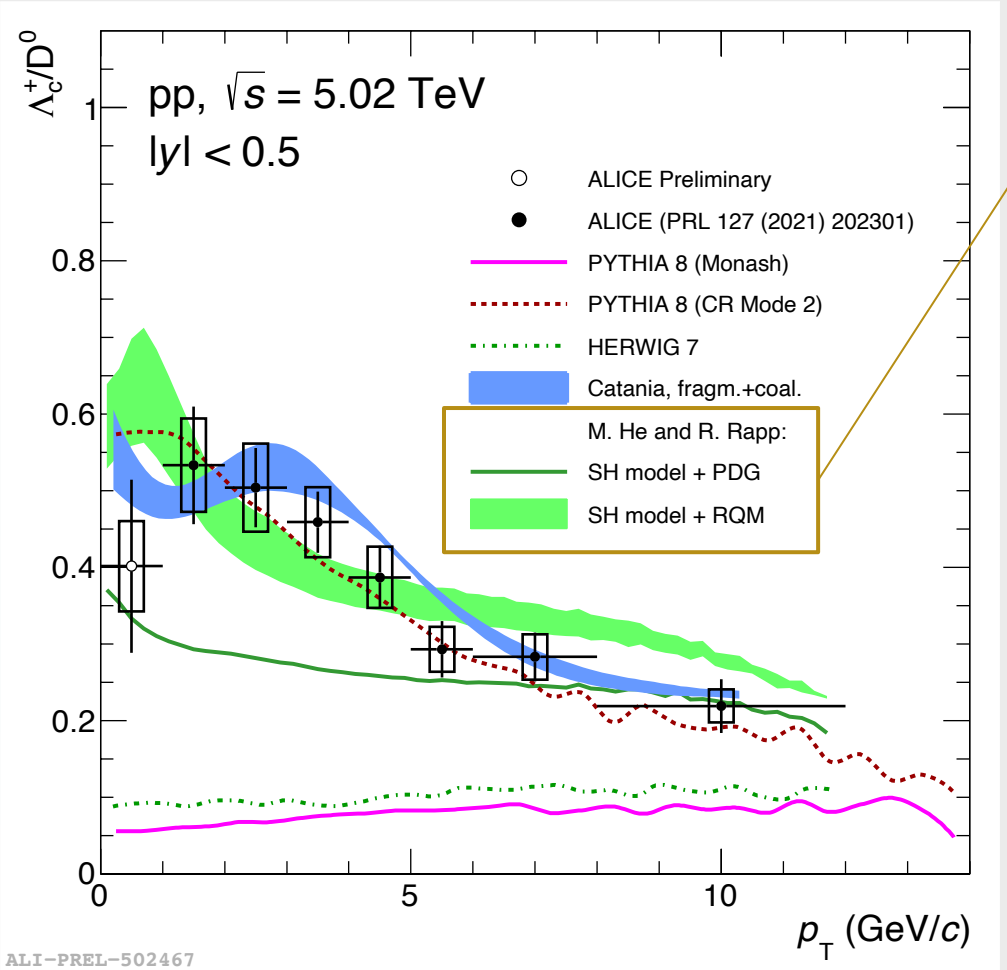
Coalescence



Baryon-to-meson yield ratio - models

Λ_c^+/D^0

M. He, R. Rapp: PLB 795 (2019) 117-121



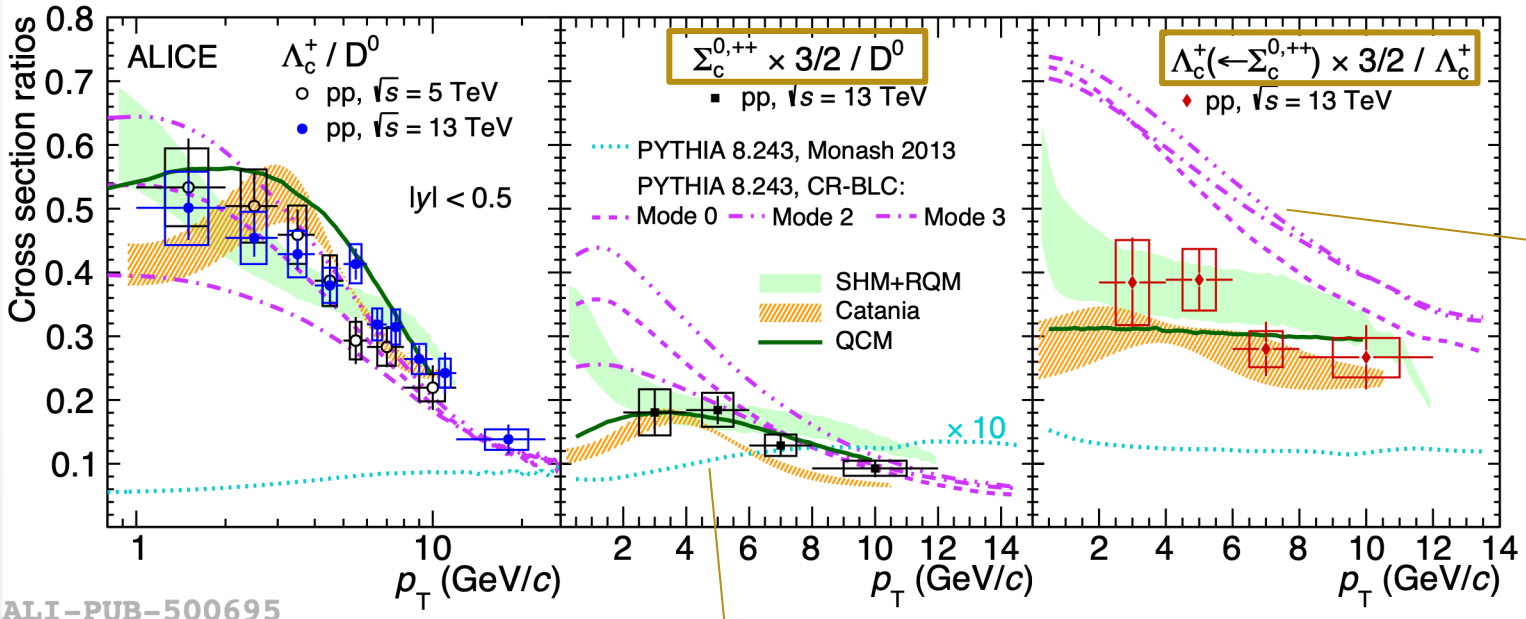
Statistical Hadronization Model

- Replaces the complexity of hadronization by **thermo-statistical weights** governed by the masses of available hadron states at a universal hadronization "temperature"
- Feed-down from an augmented set of excited charm baryons necessary to describe Λ_c^+/D^0
  - PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
  - RQM: additional 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

Phys. Rev. Lett. 127, 202301

Resonant charmed baryon states

$\Sigma_c^{0,+,++}$



[Phys. Rev. Lett. 128 (2022) 012001](#)
[QCM: J. Song, H. Li, F. Shao: Eur. Phys. J. C (2018) 78: 344](#)

Larger Σ_c/D^0 wrt. e^+e^- partially accounts for enhanced Λ_c^+/D^0 yield ratio

- Feed-down from Σ_c to Λ_c^+:

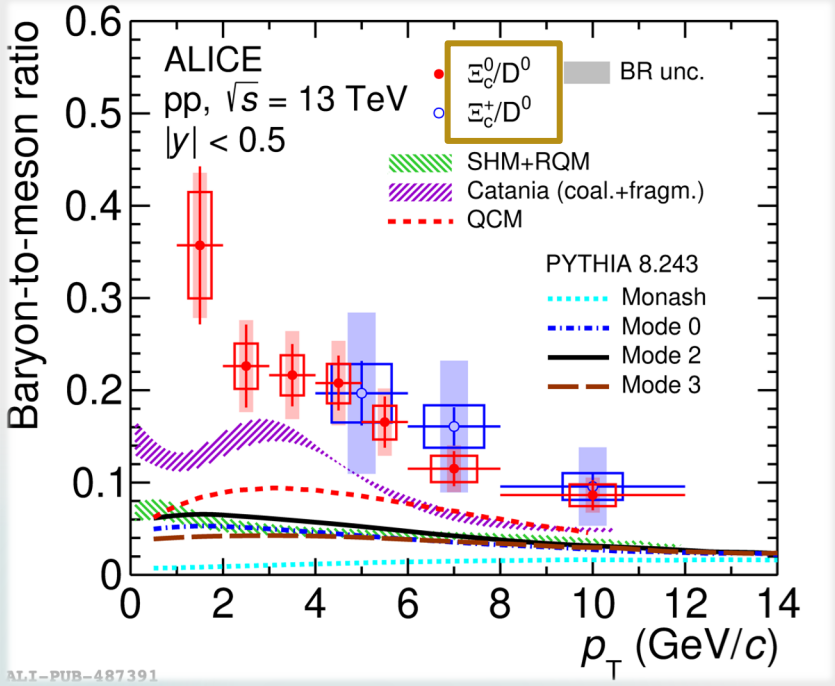
$$\frac{\Lambda_c^+(\leftarrow\Sigma_c)}{\Lambda_c^+} = 0.38 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})$$

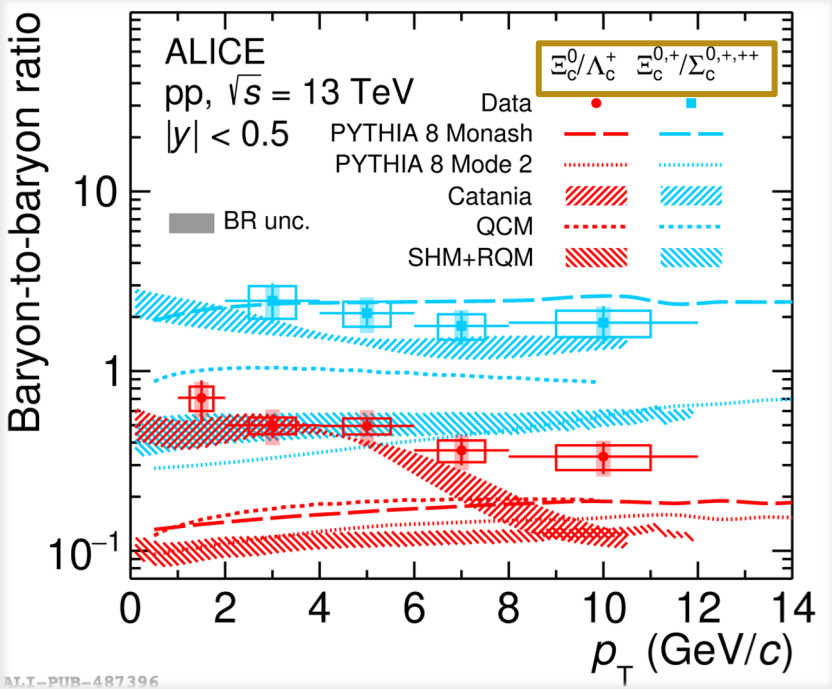
- Overestimated by models with color reconnection

- Significant enhancement of Σ_c/D^0 yield ratio in pp collisions wrt. e^+e^- collisions (PYTHIA 8 Monash)
- Σ_c is well described by SHM+RQM, Catania (fragmentation + coalescence), QCM (coalescence)

Strange charmed baryon production

$\Xi_c^{0,+}$





[PRL 127(2021)127, 272001]

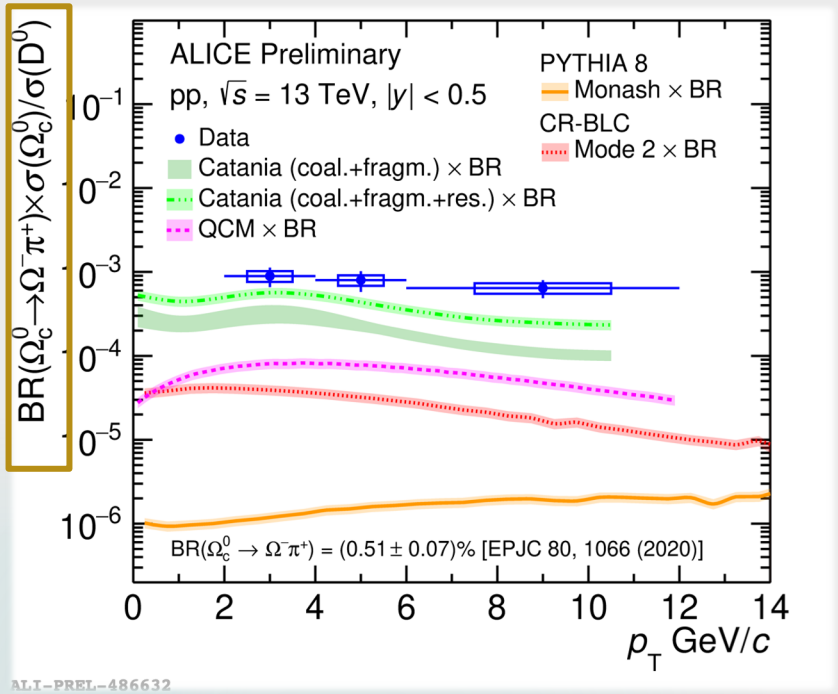
$\Xi_c^0/\Sigma_c^{0,+,++}$ in pp in agreement with PYTHIA Monash tune

- Similar suppression of $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$ in e^+e^- collisions?

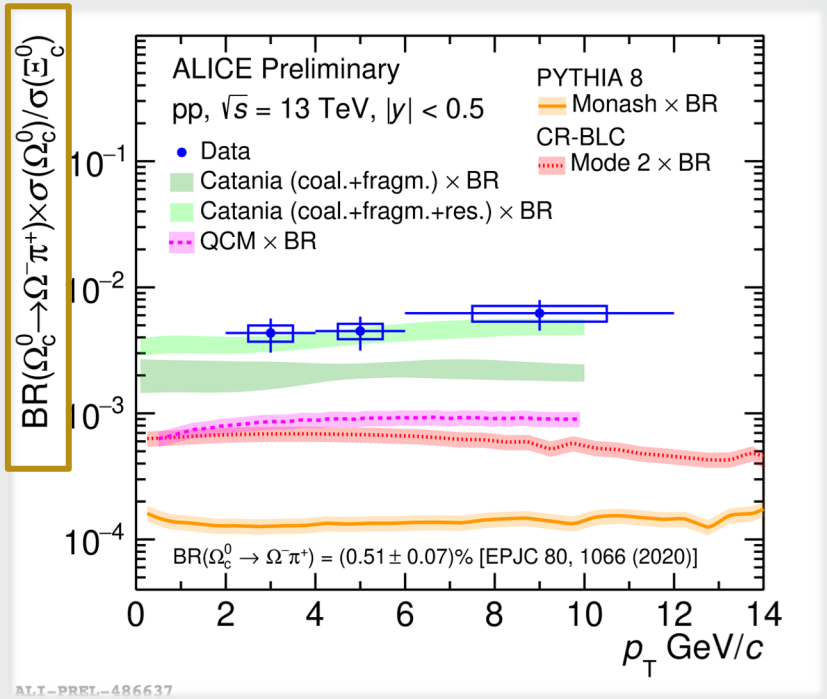
- Enhancement of Ξ_c/D^0 yield ratio by factor ~30 in pp collisions wrt. e^+e^- collisions (PYTHIA 8 Monash)
- PYTHIA with CR-BLC and the SHM+RQM also underestimate Ξ_c/D^0 yield ratio
- Catania describes the shape down to $p_T \approx 2$ GeV/c and is close to the data

Doubly strange charmed baryon production

Ω_c^0



$\mathbf{BR(\Omega_c^0 \to \Omega^-\pi^+) \times \Omega_c^0/D^0}$



$\mathbf{BR(\Omega_c^0 \to \Omega^-\pi^+) \times \Omega_c^0/\Xi_c^0}$

Belle: $\frac{\Omega_c^0}{\Xi_c^0} \approx 0.1$ ALICE*: $\frac{\Omega_c^0}{\Xi_c^0} \approx 1$

fragmentation fraction ~7%

Belle: PRD 97, 072005 (2018)

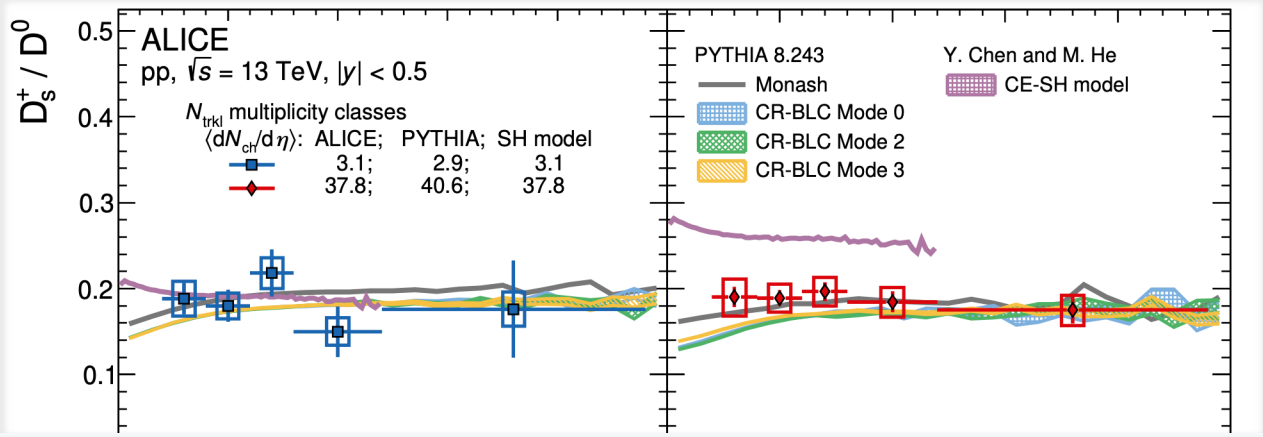
Sizable Ω_c^0 contribution to charm production at LHC energies?

* $\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) = (0.51 \pm 0.07)\%$ is not measured → use calculation for scaling Y. Hsiao et al. EPJC 80, 1066 (2020)

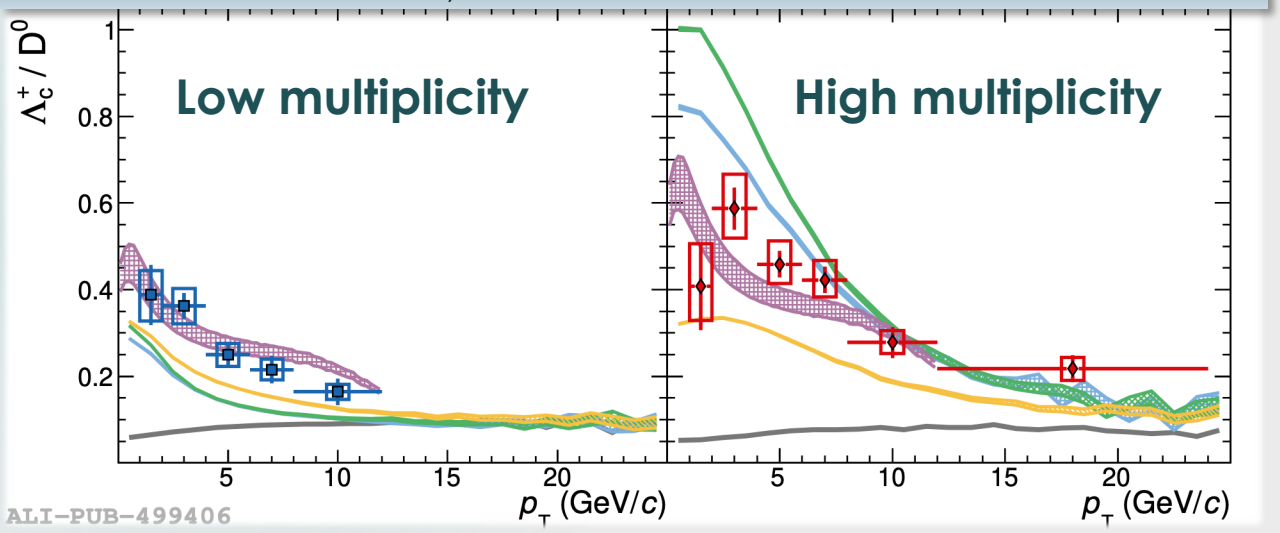
- Baryon-to-baryon and baryon-to-meson yield ratios show a **significant increase over all models**
- **Catania comes closest to data** and describes baryon-to-baryon yield ratio when including higher mass resonance decays

Multiplicity dependence of charm production

Λ_c^+/D^0
D_s^+/D^0



Flat as a function of p_T, no multiplicity dependence



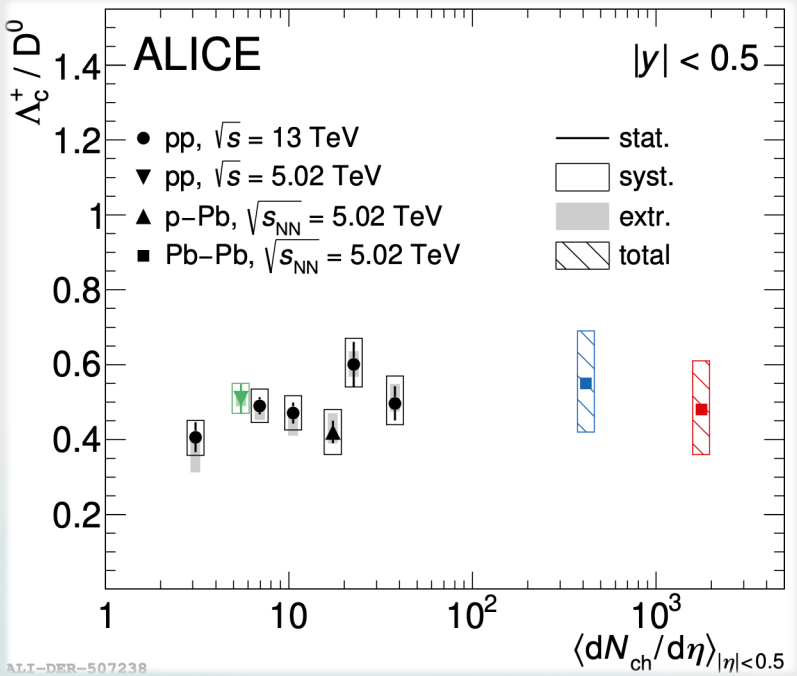
Significant modification of p_T spectrum with multiplicity

Models:

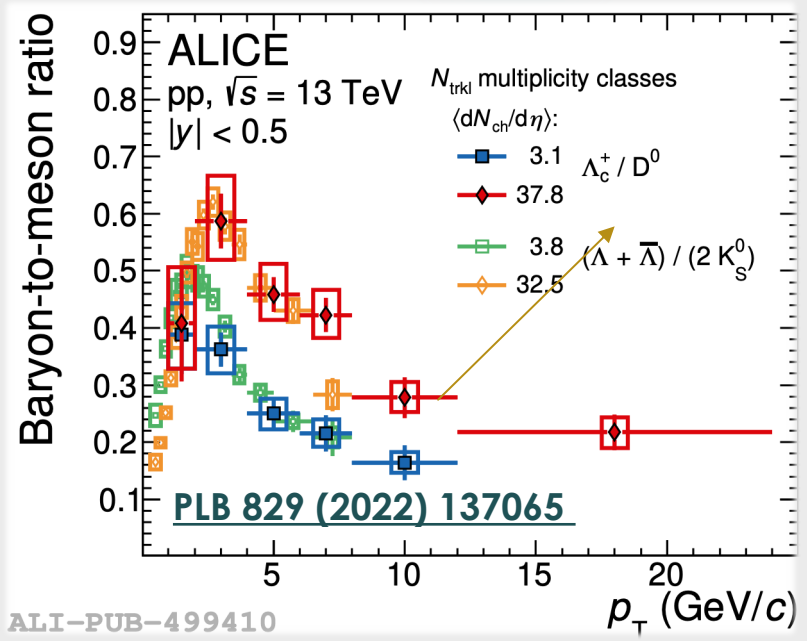
- PYTHIA Monash describes D_s^+/D^0 but fails to reproduce Λ_c^+/D^0
- PYTHIA with CR-BLC qualitatively describes both yield ratios
- Canonical Ensemble (CE) statistical hadronization (SH) model describes Λ_c^+/D^0 but does not describe the multiplicity (in)dependence of D_s^+/D^0

PLB 829 (2022) 137065

Multiplicity dependence of charm production Λ_c^+/D^0



p_T integrated



p_T differential

p_T-integrated Λ_c^+/D^0 :

No significant variation as a function of multiplicity or collision system within the uncertainties

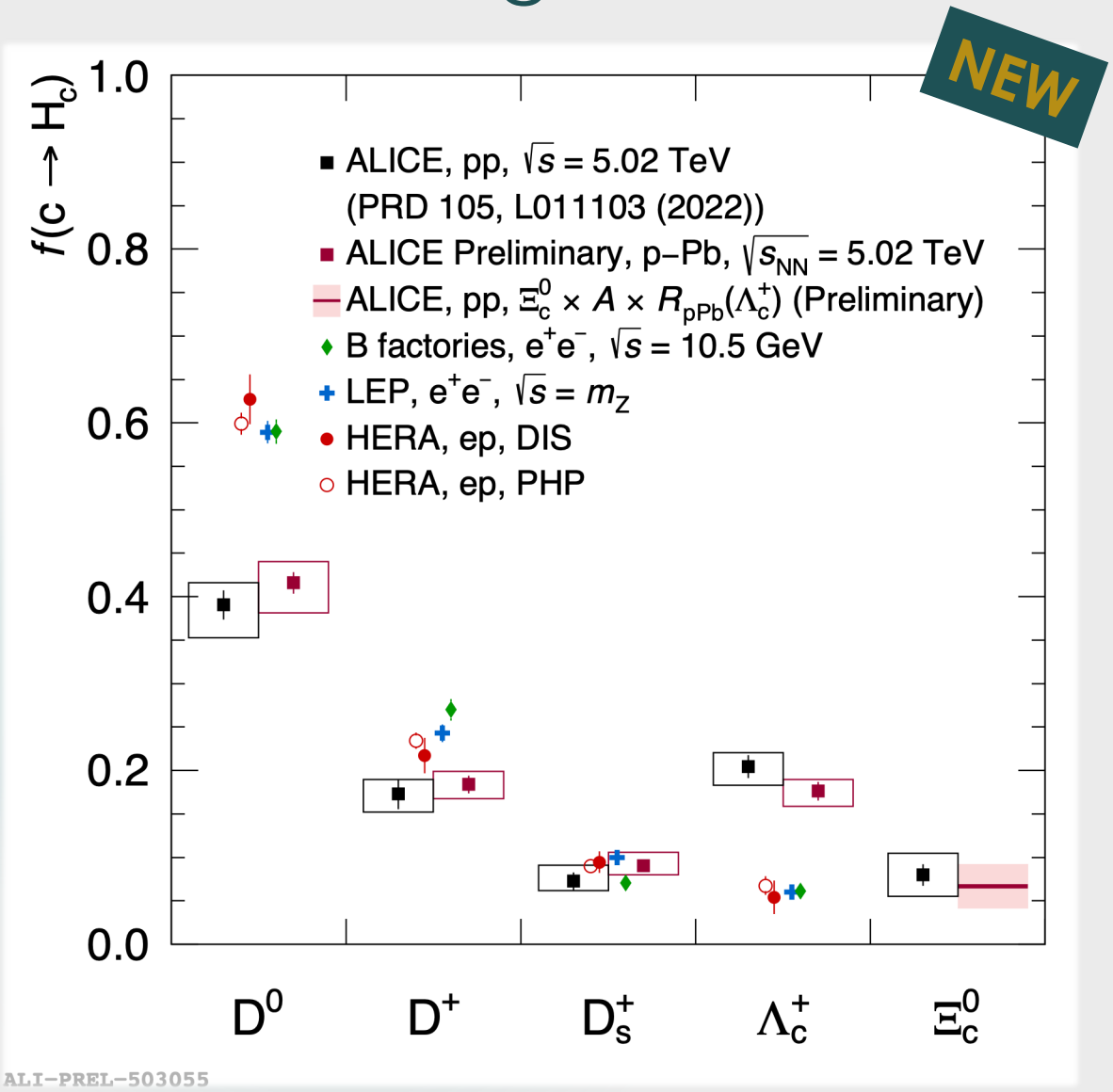
Comparison with strangeness sector:

Similarity between Λ_c^+/D^0 and Λ/K_S^0 yield ratios versus multiplicity

Multiplicity dependence due to momentum redistribution, no modification of overall yield

Possible common mechanisms for light- and heavy-flavor baryon production

Charm fragmentation fractions



p–Pb:

- D^0, Λ_c^+ (new): measured down to $p_T = 0$
- D^+, D_s^+: extrapolated to $p_T = 0$ using POWHEG+PYTHIA
- Ξ_c^0 in p–Pb not yet measured: $\sigma_{pp}(\Xi_c^0) \times 208 \times R_{pPb}(\Lambda_c^+)$

$$\frac{f(c \to \Xi_c^0)}{f(c \to \Lambda_c^+)} = 0.39 \pm 0.07\ (\text{stat})\ ^{+0.08}_{-0.07}\ (\text{syst})\ \ (\text{pp})$$

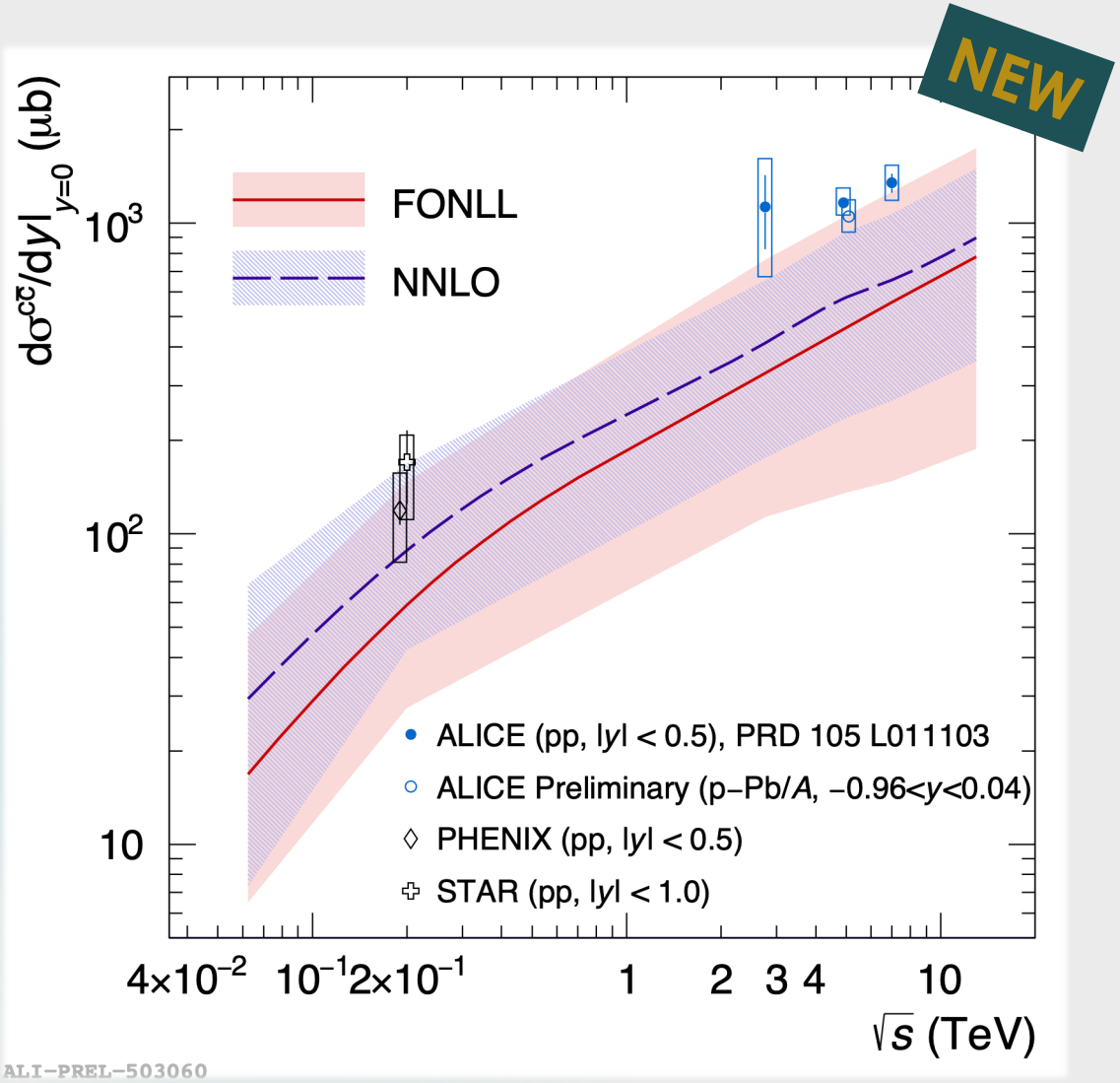
$$\frac{f(c \to \Xi_c^+)}{f(c \to \Lambda_c^+)} = \frac{f(s \to \Xi^-)}{f(s \to \Lambda^0)} \sim 0.004\ \ (e^+e^-)$$

Eur. Phys. J. C75 (2015) 19
PRD 105, L011103 (2022)

pp and p–Pb results are compatible

Significant baryon enhancement with respect to e^+e^- and e^-p collisions

Total charm cross section



Total charm cross section:

Measured at midrapidity in pp and p–Pb (new) collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV as a sum of ground state hadron cross sections

- Cross sections in pp and p–Pb collisions are compatible within the uncertainties
- Results are on the **upper edge of FONLL and NNLO** calculations

Summary and outlook

Heavy-flavor baryon production gives unique insights into hadronization mechanisms in hadronic collisions

- **Additional hadronization mechanisms could be needed to describe the measurements**
- Models including quark coalescence / recombination, or including feed-down from unmeasured resonance states, successfully reproduce most measured species

Detectors in ALICE Run 3

Larger data sample and upgraded apparatus (ITS 2): Closer to interaction point, lower material budget, faster readout, improved granularity and spatial resolution

Physics with ITS 3:

Full beauty reconstruction and reconstruction of multiple charmed baryons

Backup

Nuclear modification factor

Nuclear modification factor:

- Charm nuclear modification factor is slightly lower than unity but consistent within the systematic uncertainties
- No significant difference in overall charm production between pp and p–Pb collision systems