Open heavy flavour production in small systems with ALICE

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On behalf of the ALICE Collaboration

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Heavy flavour (HF) in pp collisions

- Charm and beauty (**HF**) **production** measurements in pp collisions represent a fundamental **test** of perturbative QCD (**pQCD**) **calculations**.

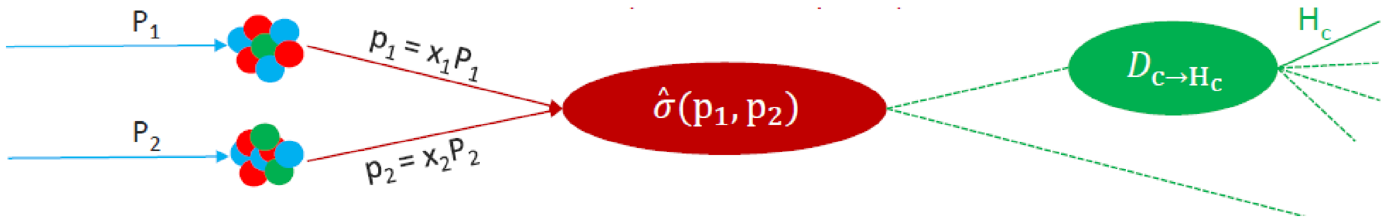
- The standard cross section description is based on **factorisation approach**:

$$\frac{d\sigma^{H_c}}{d\sigma^{H_c}_{p_T}}(p_T;\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F) \otimes \frac{d\sigma^c}{dp^c_T}(x_1,x_2;\mu_R,\mu_F) \otimes D_{c\to H_c}\left(z=\frac{p_{H_c}}{p_c},\mu_F\right)$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronisation)



- **Fragmentation fractions** are assumed **universal** among collision systems and constrained from e^+e^- and e^-p measurements

- **Ratios of particle species** → ratios of fragmentation fractions, sensitive to HF quark hadronisation

$$f(c\to H_c) = \sigma(H_c)/\sigma(c\bar{c})$$

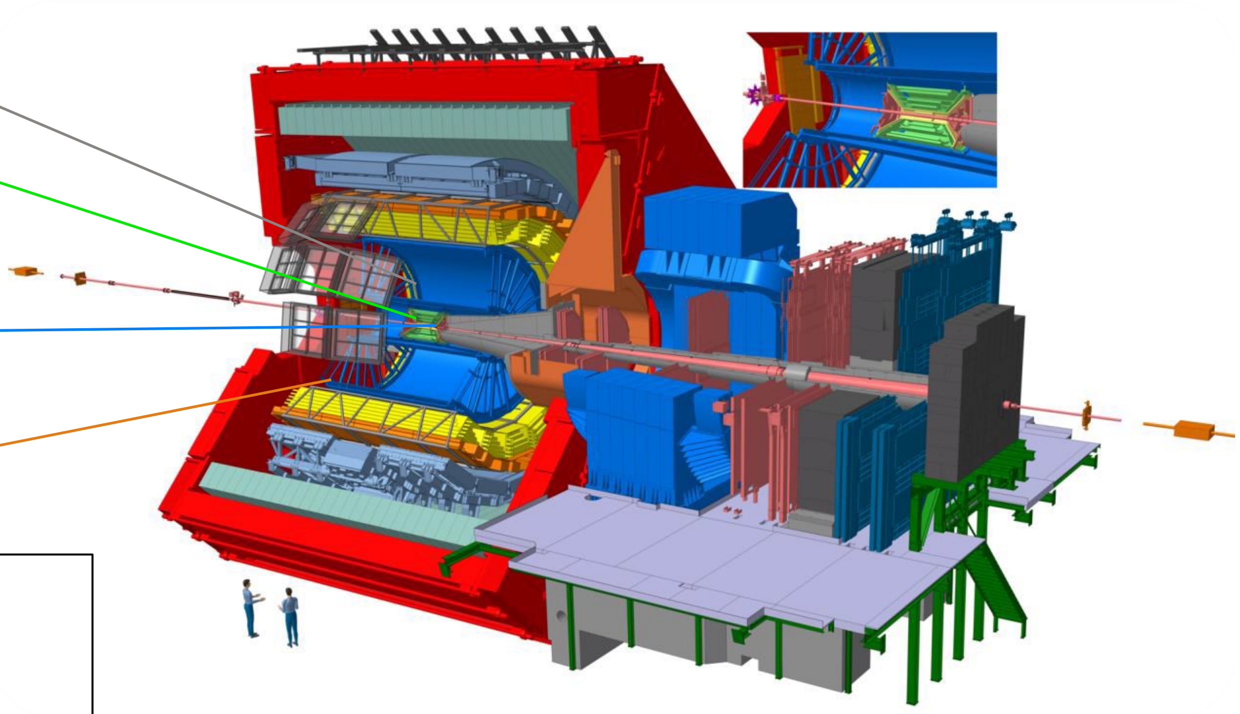
The ALICE experiment

V0: trigger, centrality

Inner Tracking System (ITS): tracking, vertexing (primary, secondary HF), PID via $\mathrm{d}E/\mathrm{d}x$, trigger

Time Projection Chamber(TPC): tracking, PID via $\mathrm{d}E/\mathrm{d}x$

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



Reconstructed decays (open heavy flavours):

- D mesons: $D^0(uc) \to K^-\pi^+$, $D^+(dc) \to K^-\pi^+\pi^+$
- $D_s^+(cs) \to \Phi\pi^+$
- $\Lambda_c^+(udc) \to pK^-\pi^+,\ pK_s^0 \to p\pi^+\pi^-$
- $\Sigma_c^{0,++}(ddc,\ uuc) \to \Lambda_c^+\pi^{-,+}$
- $\Xi_c^0(dsc) \to \Xi^- e^+ \nu_e, \Xi^-\pi^+$
- $\Xi_c^+(usc) \to \Xi^-\pi^+\pi^+$
- $\Omega_c^0(ssc) \to \Omega^-\pi^+$

Data samples:

- pp
  - $\sqrt{s} = 5.02$ TeV $\to$ $L_{\mathrm{int}} \approx 19\ \mathrm{nb}^{-1}$
  - $\sqrt{s} = 13$ TeV $\to$ $L_{\mathrm{int}} \approx 32\ \mathrm{nb}^{-1}$
- p-Pb
  - $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV $\to$ $L_{\mathrm{int}} \approx 287\ \mu\mathrm{b}^{-1}$

D meson production in pp collisions

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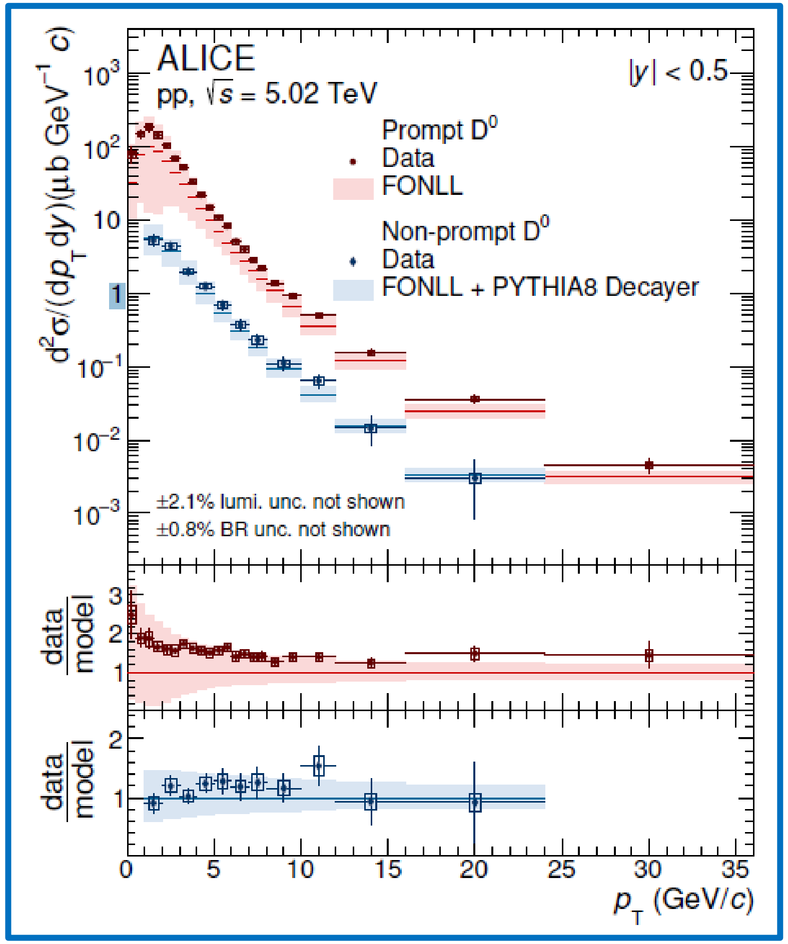
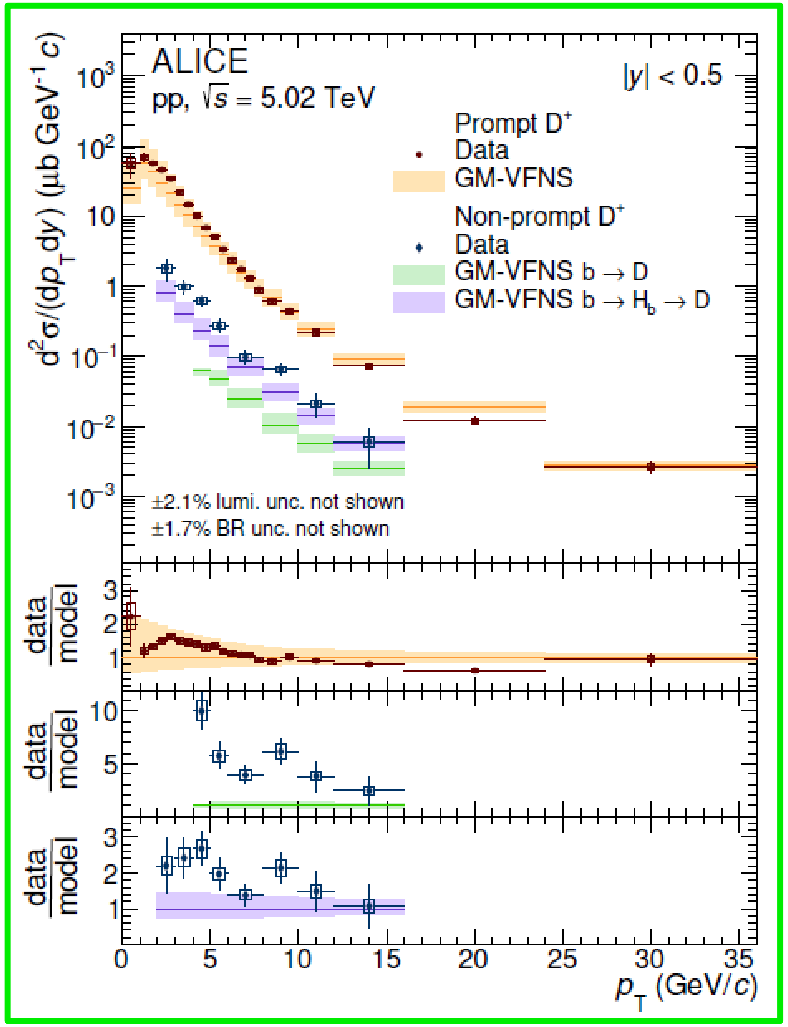
D^0



D^+

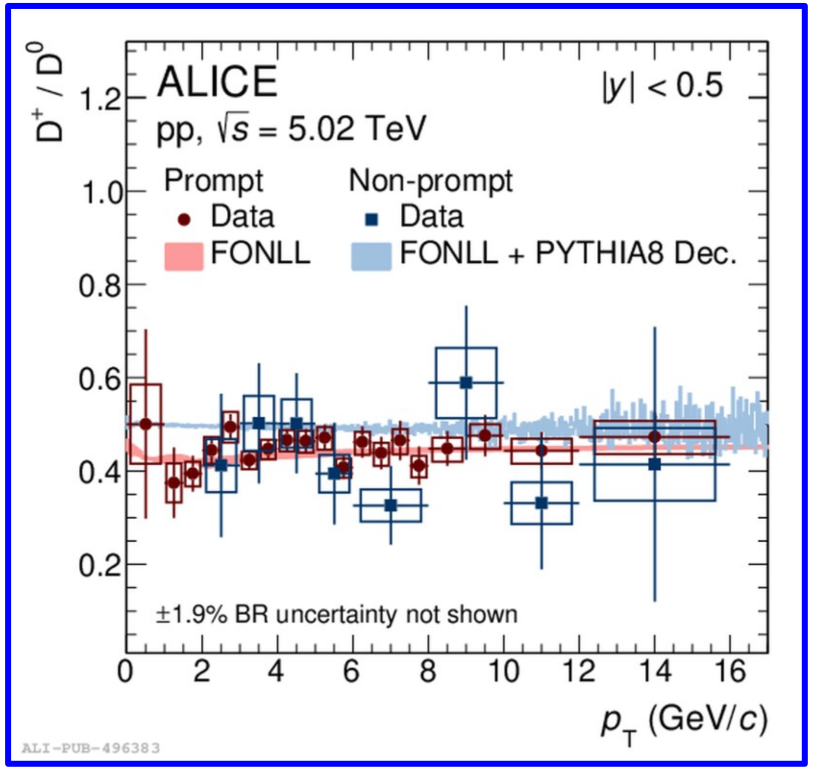


- $D^{0,+}$ measured **down to $p_T = 0$**
- p_T differential cross sections **described** within uncertainties **by pQCD models**
- **GM-VFNS** predictions **underestimate** non-prompt (from b quarks) D-meson cross sections
- Data provide **good constraints for models** (experimental uncertainties lower that theory ones)

FONLL JHEP 05 (1998) 007
JHEP 03 (2001) 006

GM-VFNS J.Phys. G 41 (2014) 075006
Nucl. Phys. B925(2017)

Charm hadron formation in pp collisions

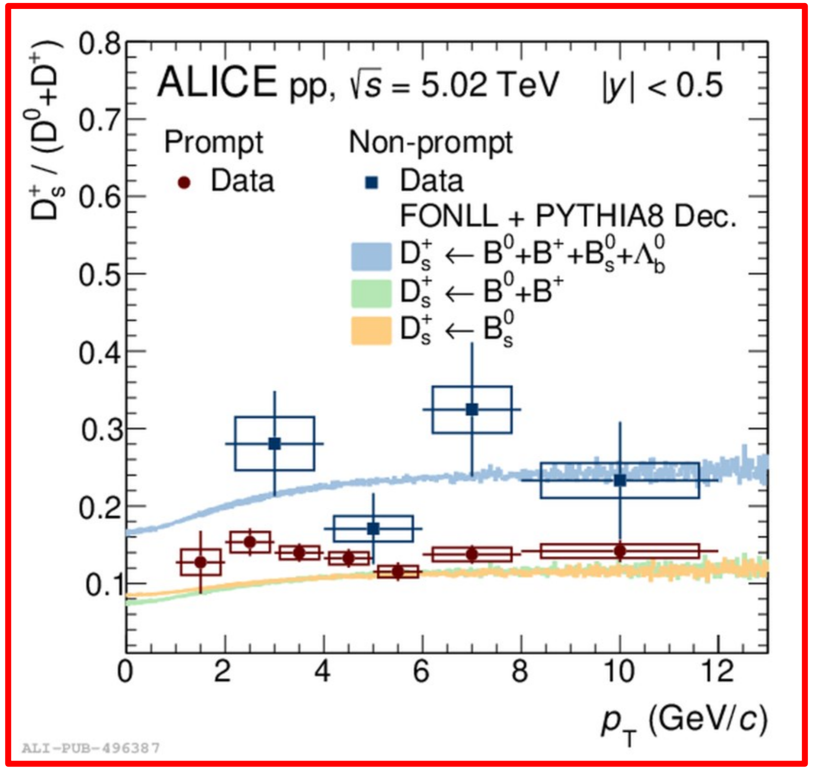


$\mathbf{D^+/D^0}$

$\mathbf{D_s^+/(D^0+D^+)}$

$e^+ e^-$ ←

$e^+ e^-$ →



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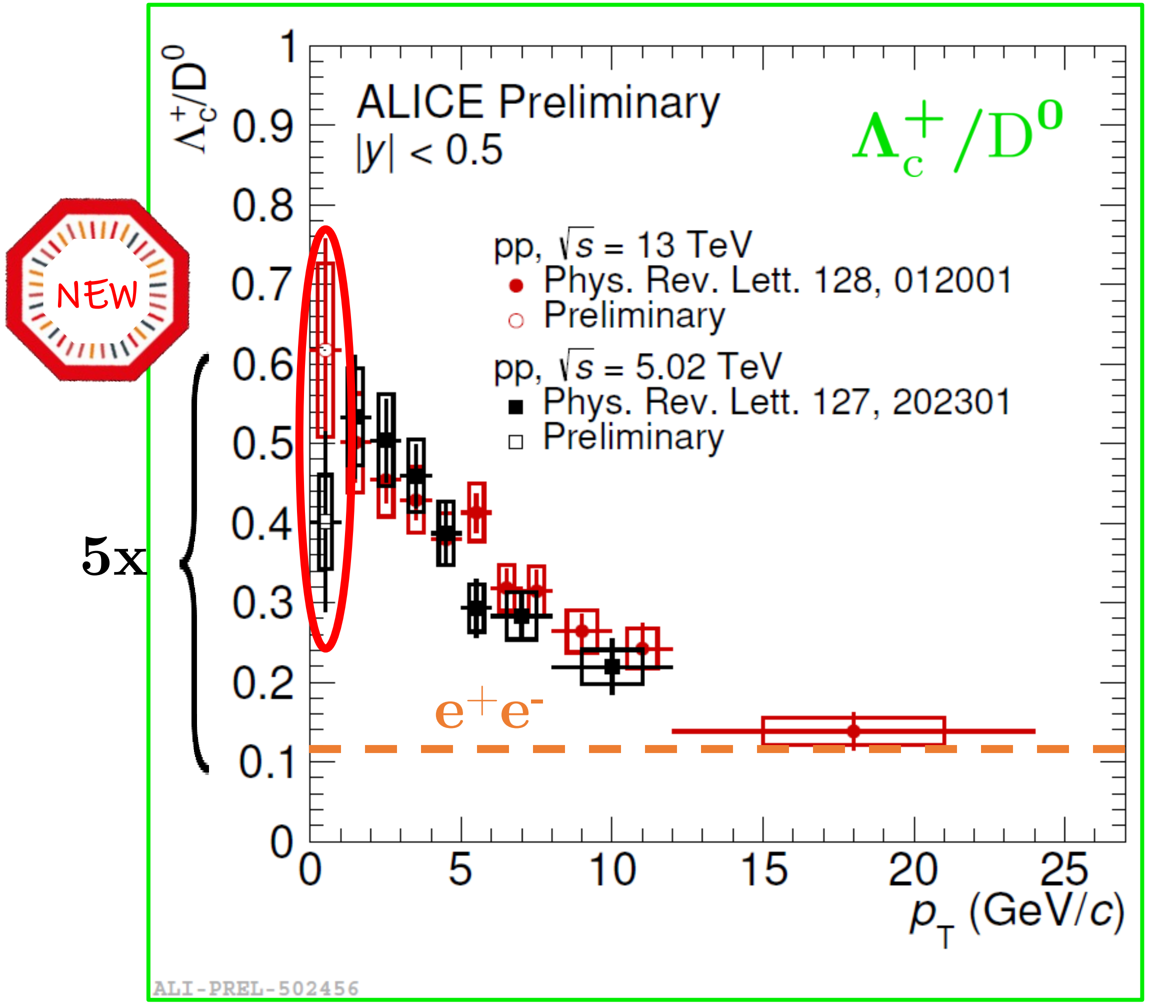
- **Meson-to-meson ratio** is p_T and collision system independent
- $\mathbf{D^+/D^0}$ prompt and non-prompt ratios are in **agreement** with:
  - **pQCD** model calculations (FONLL, JHEP 10 (2012) 137), based on factorisation approach and relying on universal fragmentation fractions (e^+e^-, e^-p measurements)
  - e^+e^- and e^-p **measurements**
- $\mathbf{D_s^+/(D^0+D^+)}$ **higher** for **non-prompt** mesons → substantial $\mathbf{B_s^0}$**-decay** contribution

Charm hadron formation in pp collisions



First Λ_c^+ measurement down to $p_T = 0$

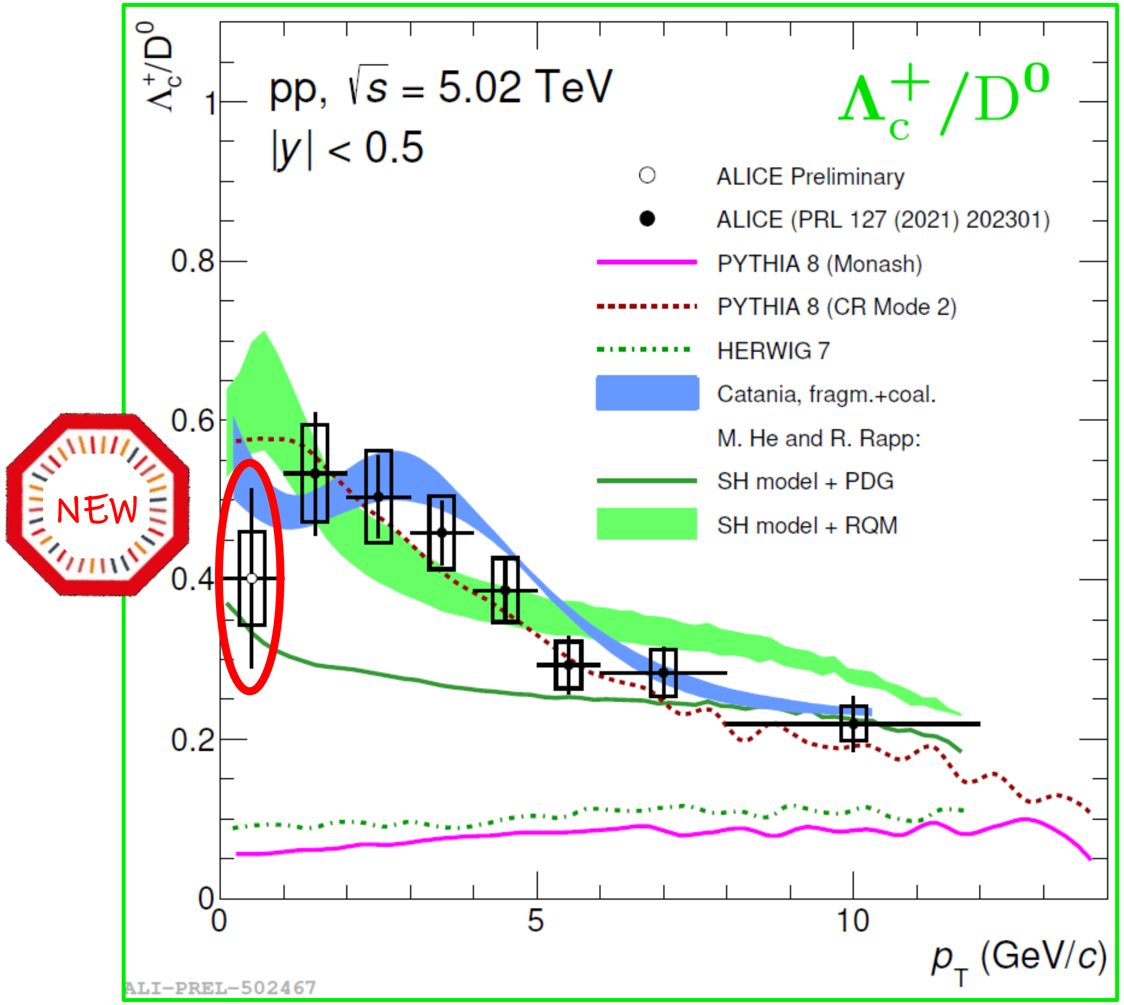
- **Charmed baryon-to-meson ratio** shows a strong p_T dependence
  - ratio significantly higher that in e^+e^- and e^-p collisions: factor 2x – 5x (at low p_T) enhancement
- Centre of mass energy independence within uncertainties ($\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV)

$0.113 \pm 0.013 \pm 0.006$
LEP average, EPJC 75, 19 (2015)

Phys. Rev. Lett. 127, 202301 (2021) Phys. Rev. Lett. 128, 012001 (2022)

Λ^+_c/D^0 in pp collisions - models

Phys. Rev. Lett. 127, 202301



- **Models** tuned to reproduce e^+e^- results, assuming universal fragmentation fractions (i.e. HERWIG7, GM-VFNS) **underestimate** Λ_c^+/D^0 measurements in pp collisions

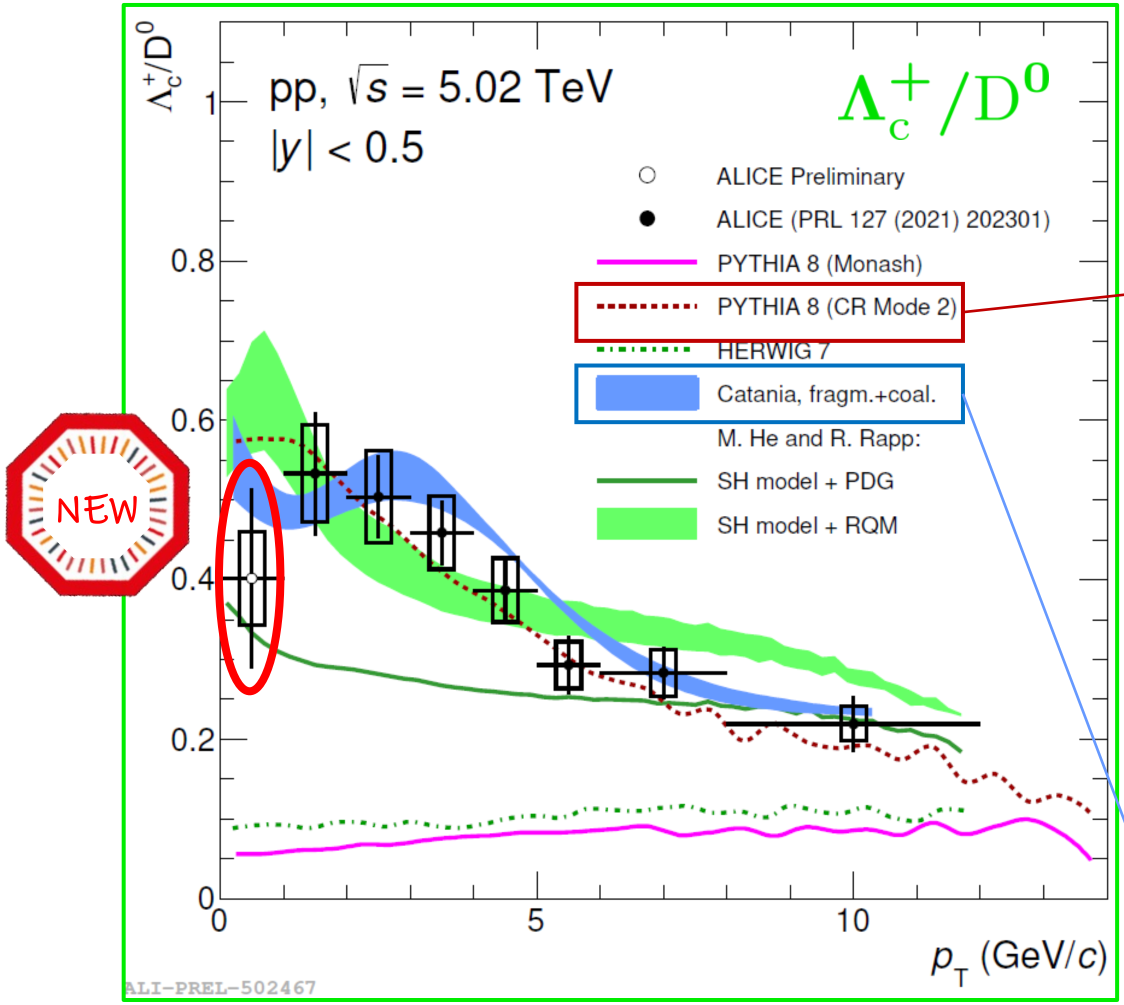
Further hadronisation mechanisms?

Non-universal fragmentation fractions?

- Models including enhanced HF hadronisation mechanisms better describe the results

Λ^+_c/D^0 in pp collisions - models

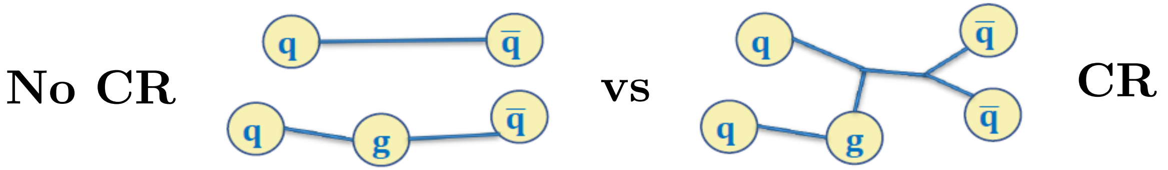
Phys. Rev. Lett. 127, 202301



PYTHIA 8 with enhanced Colour Reconnection (CR) modelling

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

- CR with SU(3) weights and string length minimisation
- «**junction**» topology recombination between quarks and gluons **enhances charm baryon production**



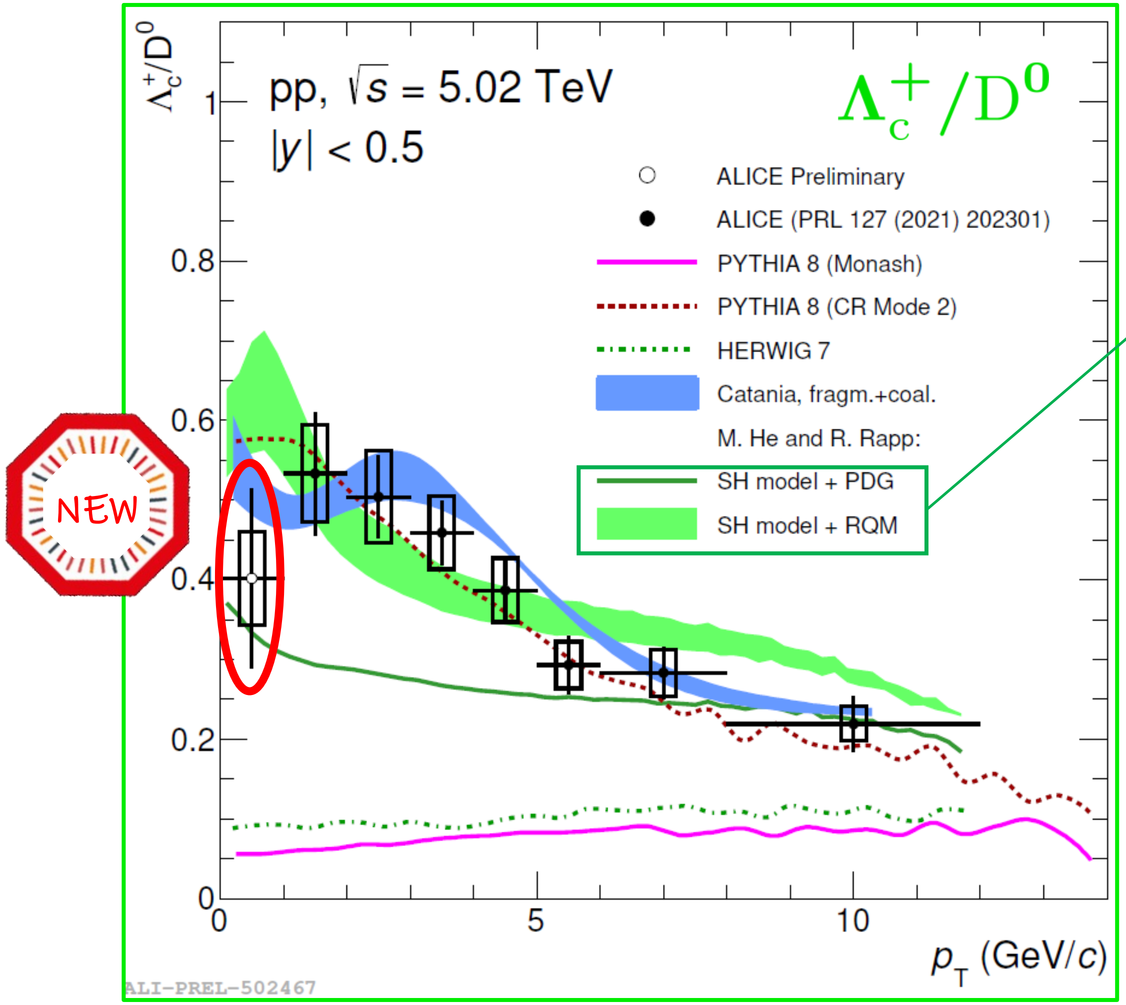
Catania model

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

- Light quarks (u,d,s) and gluons assumed as **thermalised system**
- Mixed hadron formation: **fragmentation** + **coalescence** (imposed as only mechanism at $p \to 0$)

Λ^+_c/D^0 in pp collisions - models

Phys. Rev. Lett. 127, 202301



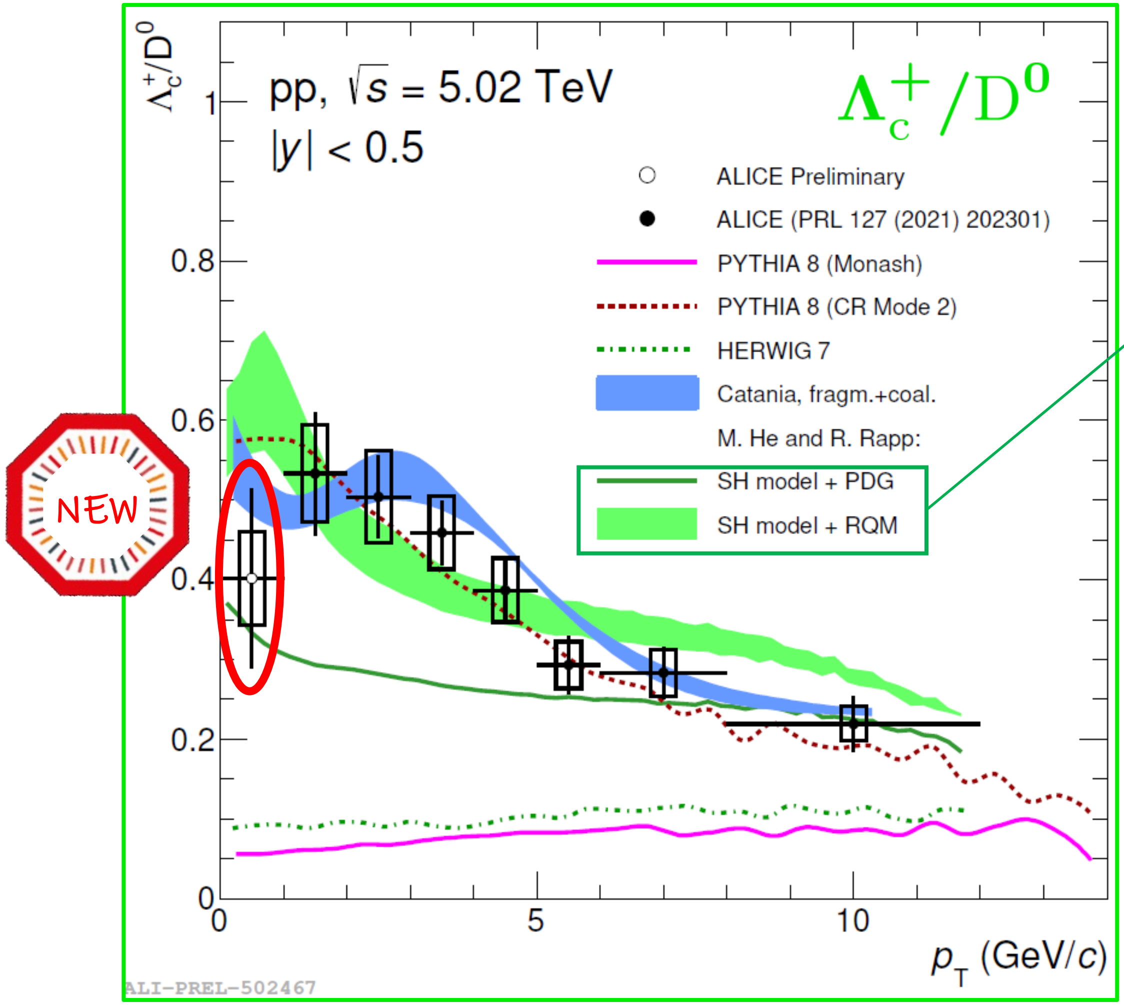
Statistical Hadronisation Model and Relativistic Quark Model (SHM + RQM)

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

- **Hadronisation** driven by statistical weights **governed by hadron masses** at hadronisation temperature T_H $(n_i \sim m_i^2 T_H K_2(m_i/T_H))$
- Strong **feed-down** from an **augmented set of excited charm baryons**
  - PDG/RQM define quantity of decaying additional baryons

Λ^+_c/D^0 in pp collisions - models

Phys. Rev. Lett. 127, 202301



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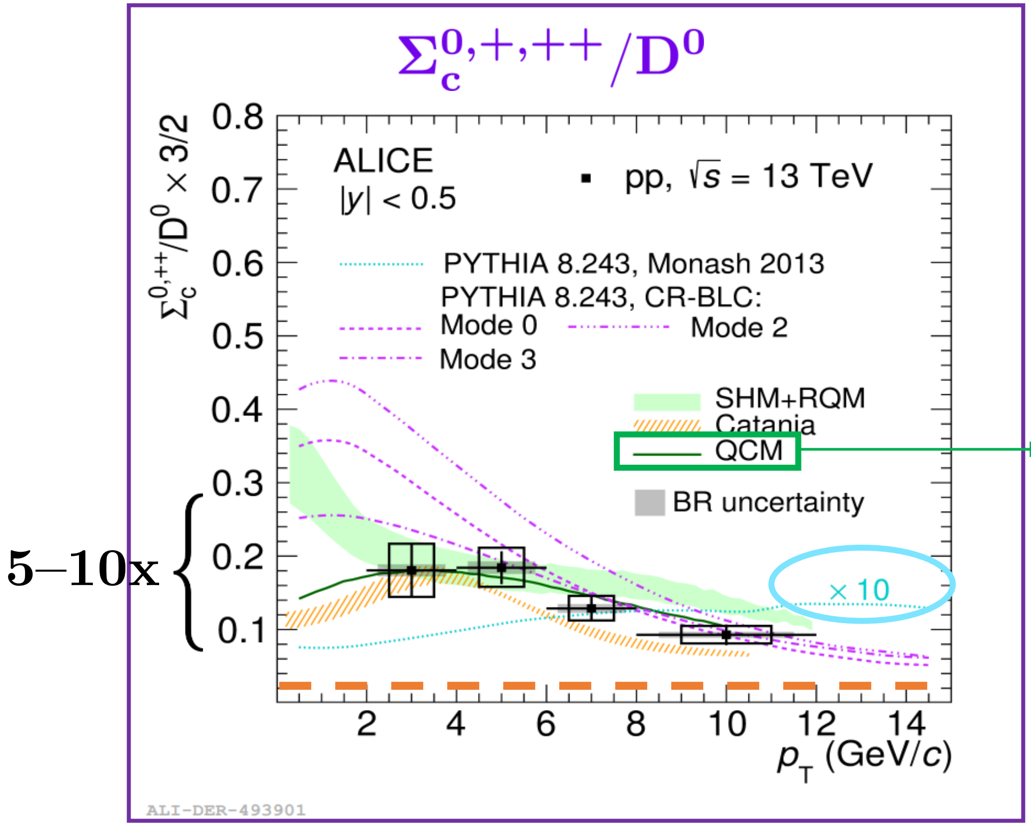
Further baryon measurements to understand the mechanisms that influence baryon enhancement

Heavier charmed baryons: $\Sigma_c^{0,+,++}(2455)$



Phys. Rev. Lett. 128, 012001

Eur.Phys.J. C 78, 344 (2018)

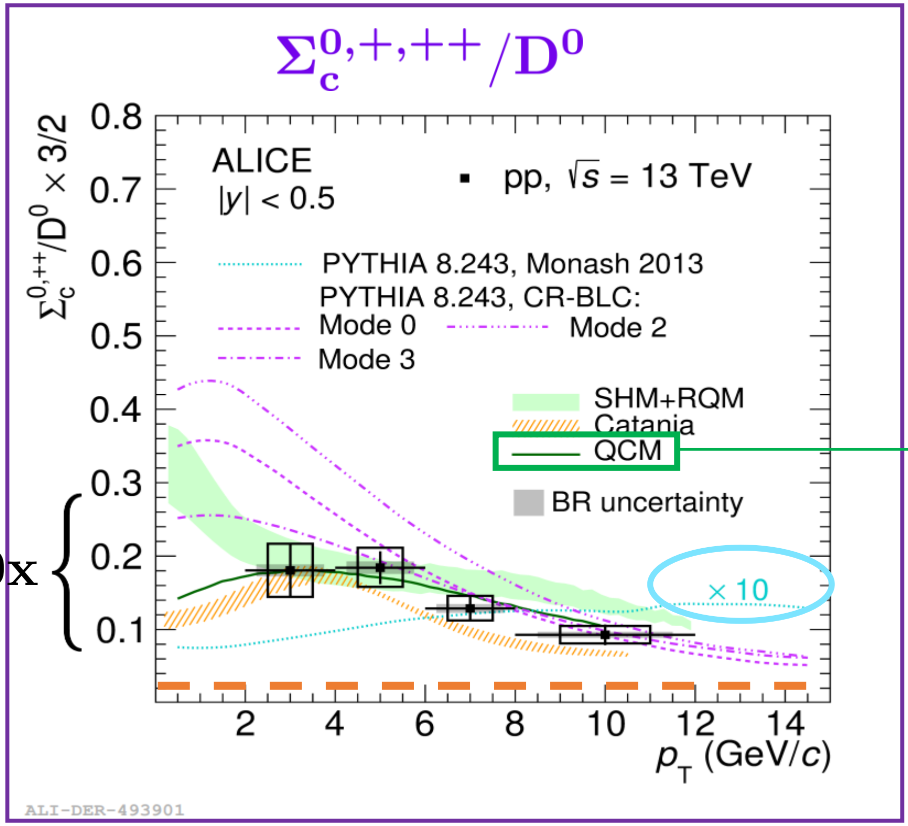
~0.02 (e^+e^-)

[Belle Collaboration, Phys. Rev. D 97 (2005) 07]

- Ratio **larger** than **e^+e^-** results and **PYTHIA Monash** (based on e^+e^-)
- $\Sigma^{0,+,++}/D^0$ well **described** by predictions from **SHM+RQM**, **Catania** and **QCM**

Heavier charmed baryons: $\Sigma_c^{0,+,++}(2455)$

5–10x



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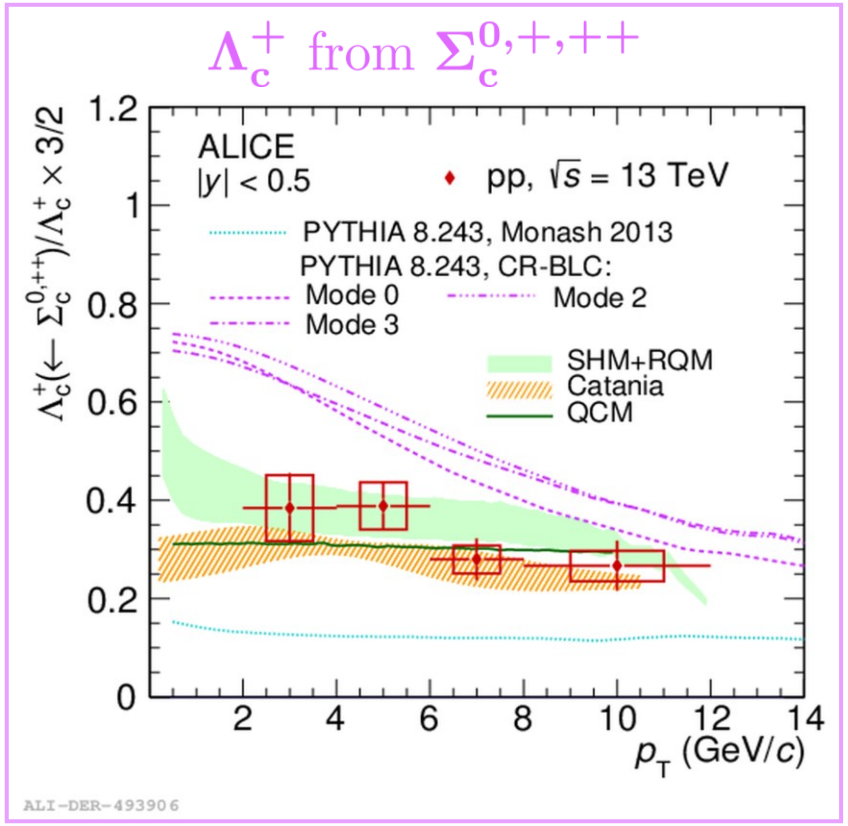
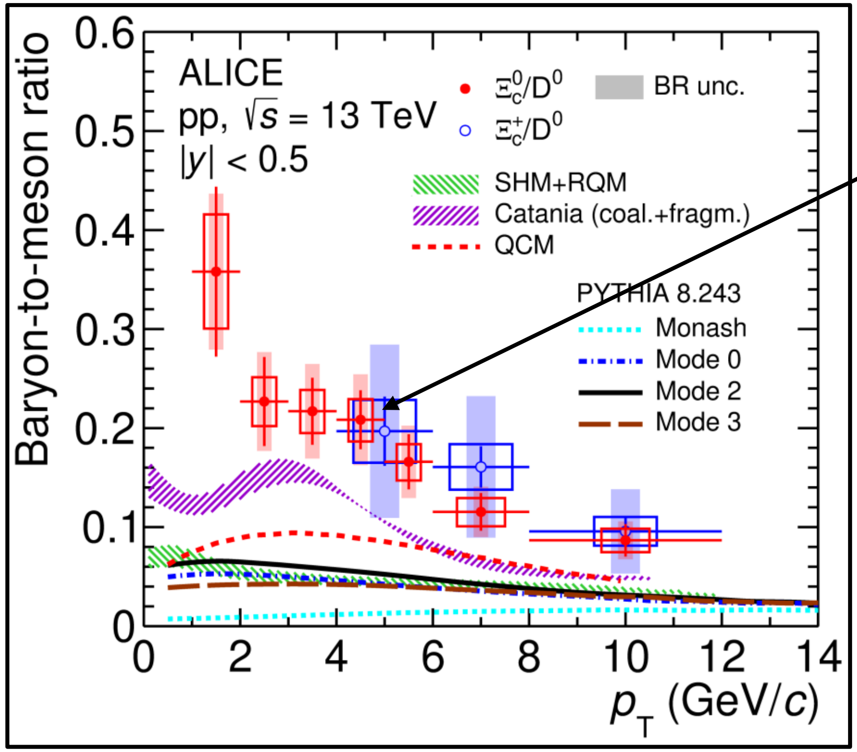


- Ratio **larger** than e^+e^- results and **PYTHIA Monash** (based on e^+e^-)
- $\Sigma^{0,+,++}/D^0$ well **described** by predictions from **SHM+RQM**, **Catania** and **QCM**
- The ratio enhancements partially accounts for larger Λ_c^+/D^0
- Measurement of $\boldsymbol{\Lambda_c}$ **feed-down from** $\boldsymbol{\Sigma_c}$: $\boldsymbol{\Lambda_c^+(\leftarrow \Sigma_c)/\Lambda_c^+ = 0.38 \pm 0.06\ (stat.) \pm 0.06\ (syst.)}$

Strange charmed baryons: $\Xi_c^{0,+}$

Phys. Rev. Lett. 127, 271001

JHEP 10 (2021) 159



$\Xi_c^{0,+}/D^0$

- Clear p_T **dependence**
- **Significantly underestimated** by models
  - factor ~30 at low p_T wrt PYTHIA Monash
  - Catania model (fragm. + coal.) closer to measurements than other theories

Strange charmed baryons: $\Xi_c^{0,+}$

Phys. Rev. Lett. 127, 271001

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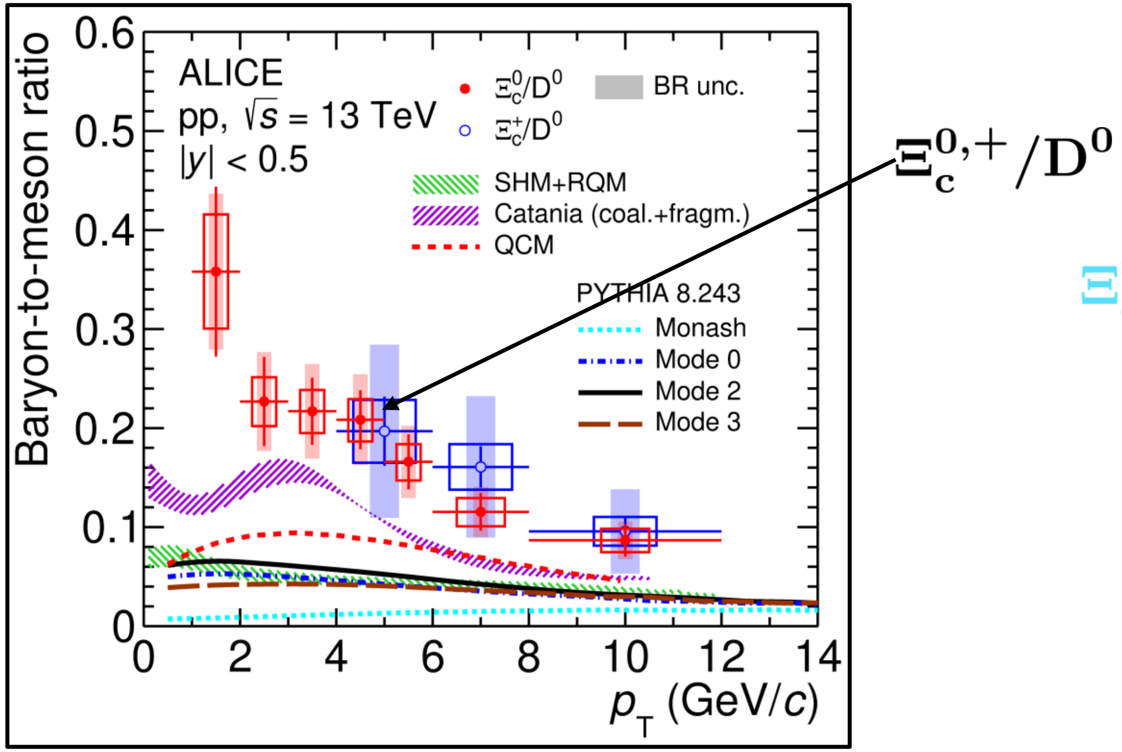

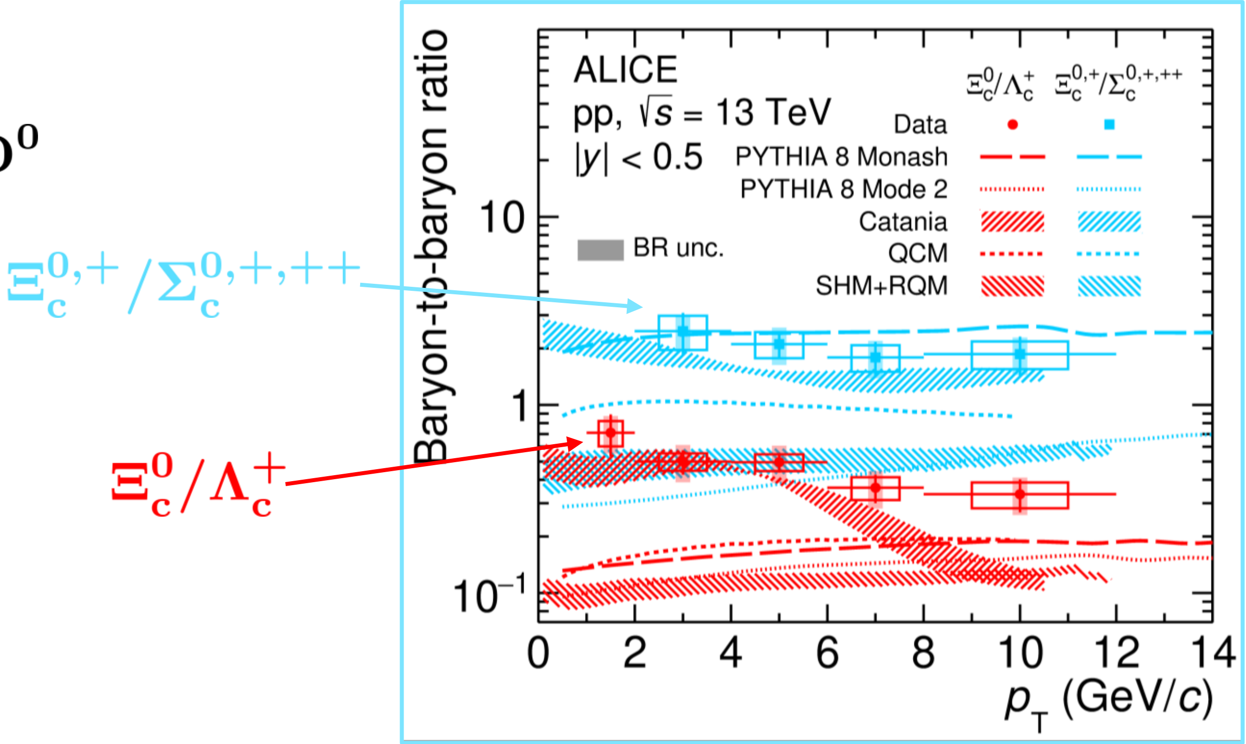

- Clear p_T **dependence**
- **Significantly underestimated** by models
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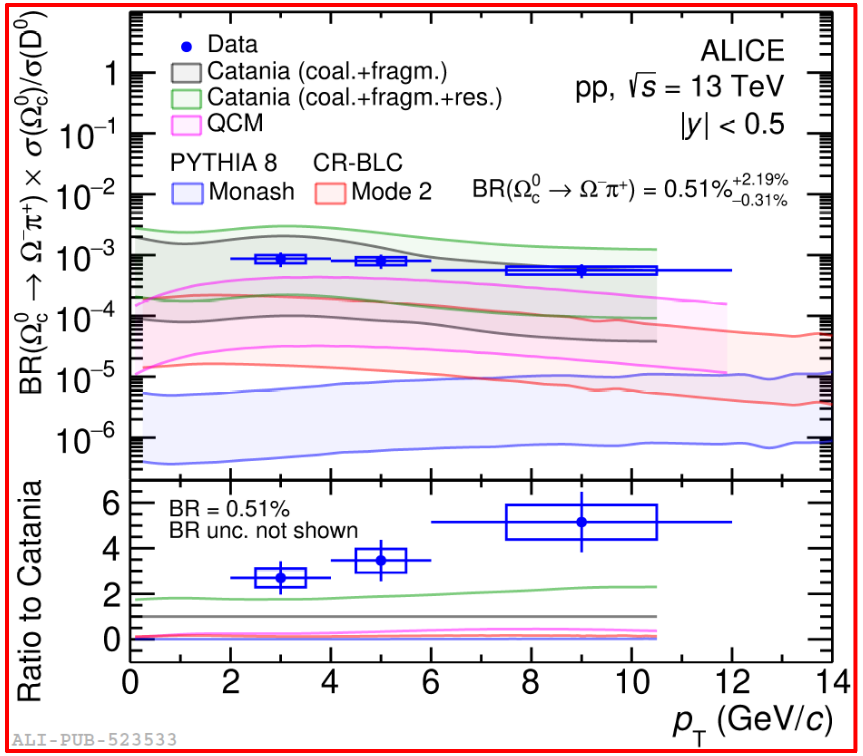
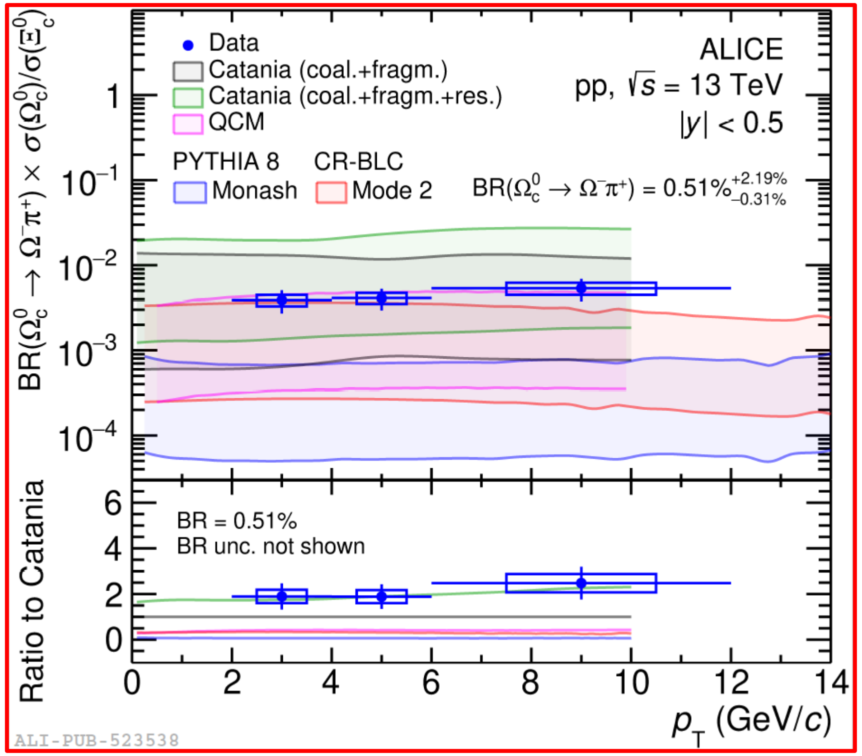
- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ in **agreement with PYTHIA Monash**
  - similar suppression in e+e- for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$

Doubly strange charmed baryons: Ω_c^0

arXiv:2205.13993

First measurement in pp collisions at $\sqrt{s} = 13$ TeV

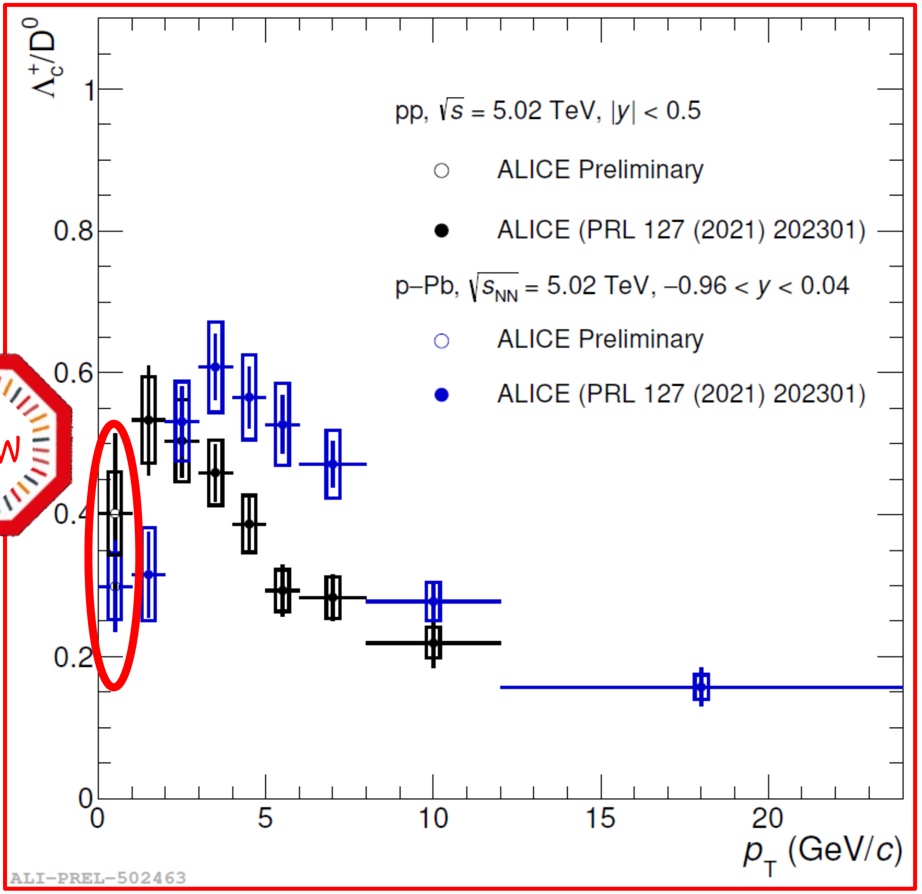


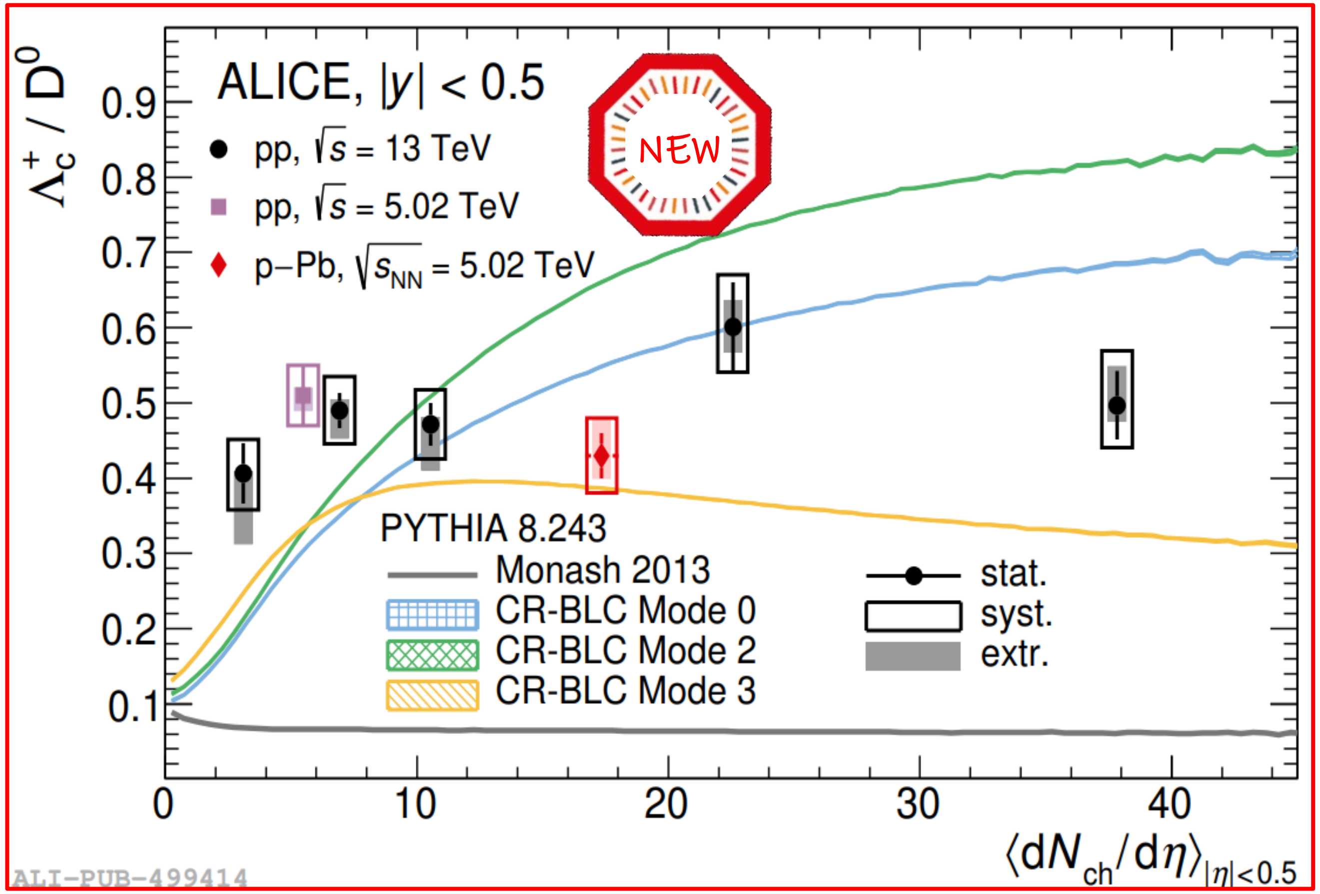


- Branching ratio $BR(\Omega_c^0 \to \Omega_c^- \pi^+) = (0.51 \pm 0.07)\%$ from Y. Hsiao et al., EPJC 80, 1066 (2020)
- **PYTHIA 8 + CR-BLC** effects **underestimates** the data
- Better **agreement with coalescence** models
- Ω_c^0/Ξ_c^0 described by Catania (fragm. + coal.) including **higher-mass resonance** decays
- $\Omega_c^0/\Xi_c^0 \approx 1 \implies$ **important contribution to charm production** at LHC energies by Ω_c^0?

Λ^+/D^0 in pp and in p–Pb

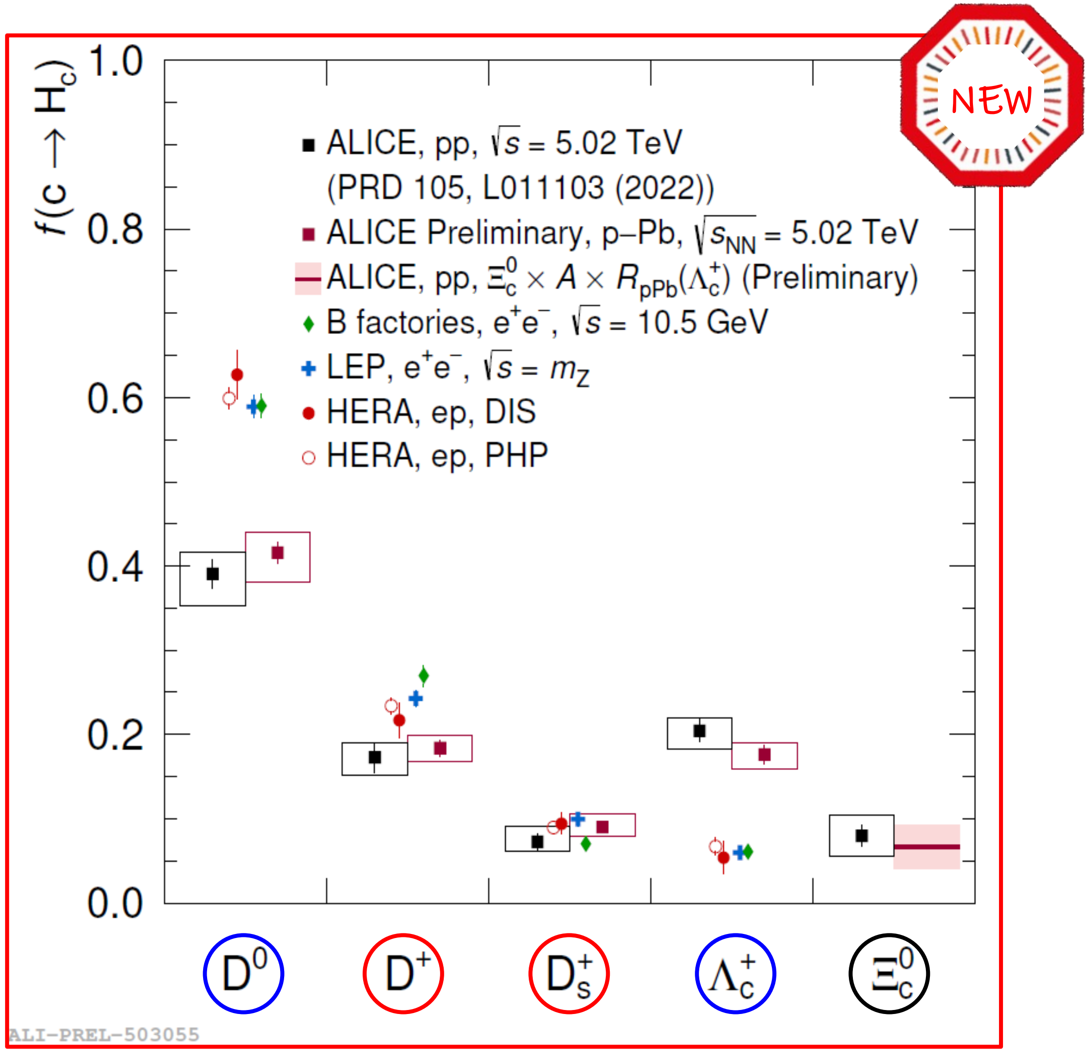
[Phys. Rev. D 105, L011103 (2022)]





- Λ_c^+/D^0 in **p–Pb** collisions **larger** than in pp collisions **for p_T > 3 GeV/c** (harder $p_T(\Lambda_c^+)$ spectrum)
- **Compatible p_T-integrated** Λ_c^+/D^0 ratio in **pp** and **p–Pb** collisions within uncertainties

Charm fragmentation in pp and in p–Pb



Charm fragmentation fractions in hadronic collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- pp: Phys. Rev. D 105, L011103 (2022)
- p–Pb:
  - D^0 and Λ_c: measured
  - D^+ and D_s^*: extrapolated to $p_T = 0$ with PYTHIA+POWEG
  - Ξ_c^0: not measured $\to \sigma_{pp}(\Xi_c^0) \times 208 \times R_{pPb}(\Lambda_c^+)$

- pp and p–Pb results compatible
- Significant baryon enhancement with respect to e^+e^- and e^-p

Summary

- **pQCD calcuations** based on **factorisation approach** and assuming **universal fragmentation fractions** among different collision systems **do not describe charm baryon production** in hadronic collisions at the LHC:
  - **baryon-to-meson ratios** and **fragmentation fractions** significantly **differ** among different collision systems

  → **charm parton-to-hadron fragmentation** is **not universal** across different collision systems

- **Additional charm hadronisation mechanisms** could happen in pp compared to e^+e^- and e^-p

  → models including enhanced baryon production better describe the ALICE data

  → more studies are needed to discriminate among different theoretical descriptions

- **New measurements** will open **new physics horizons**, thanks to:
  - Run 3 and Run 4 larger statistics and improved tracking resolution
  - a new heavy-ion experiment at LHC for Run 5 and 6