Charm production and fragmentation fractions at midrapidity in pp collisions at the LHC with ALICE

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Heavy flavour in pp collisions: motivation

Heavy quarks (charm and beauty) have large mass ($m_c \sim 1.3$ GeV/c^2 , $m_b \sim 4.2$ GeV/c^2).
$m_q >> \Lambda_{QCD} \Rightarrow$ production cross sections can be calculated using perturbative QCD

Cross section of hadron production can be factorised to parton distribution functions (PDFs), partonic cross sections and fragmentation functions (FF):

Fragmentation functions assumed universal among collision systems and constrained from measurements in e^+e^- and e^-p collisions

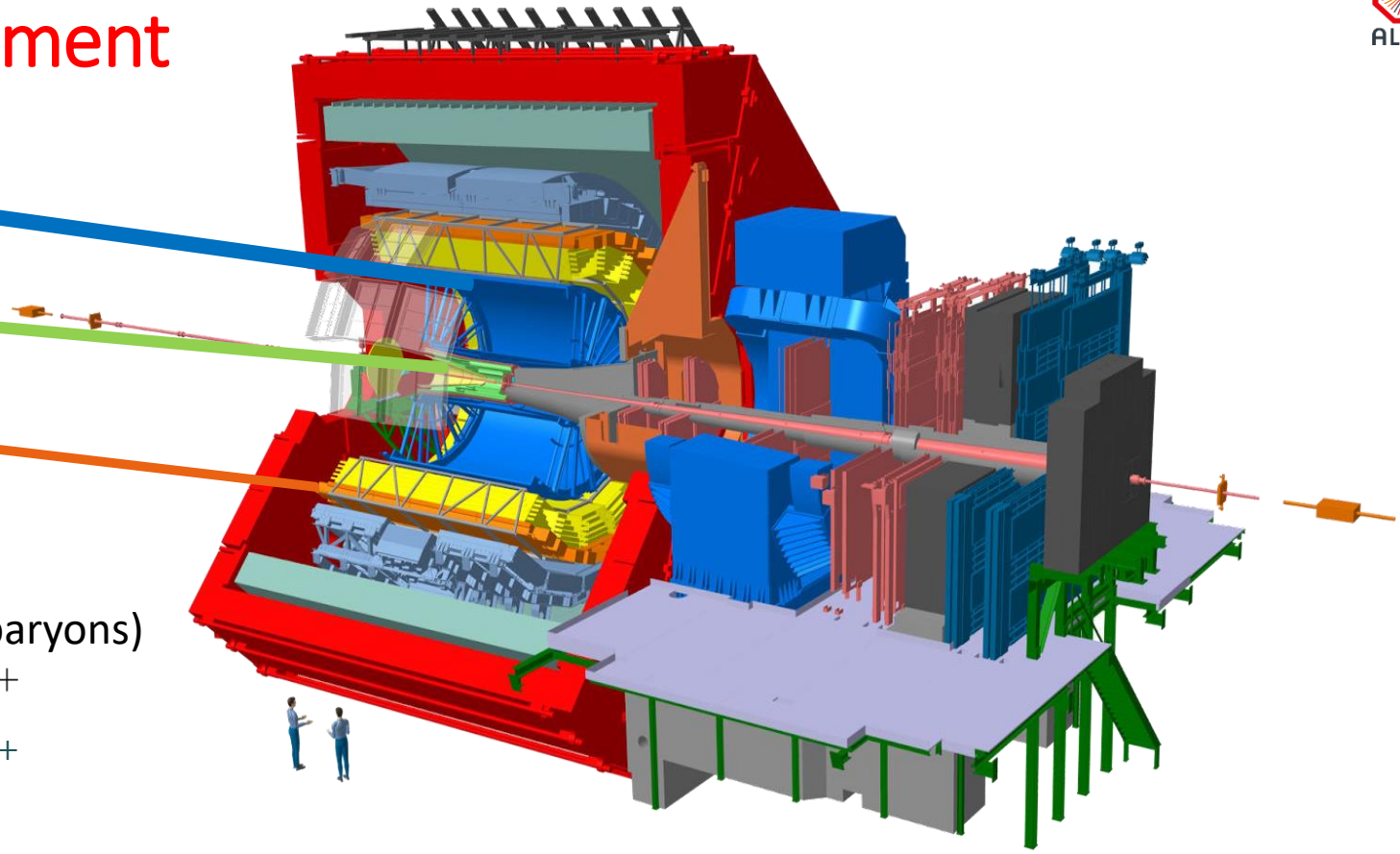
Ratios of particle species are sensitive to heavy-quark hadronization

ALICE Experiment

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

Inner Tracking System (ITS):
Tracking and vertexing

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



Reconstructed decays (open charm mesons and baryons)

D mesons : $\mathrm{D^0(uc)} \rightarrow \mathrm{K^-\pi^+}$, $\mathrm{D^+(dc)} \rightarrow \mathrm{K^-\pi^+\pi^+}$

$\mathrm{D^{*+}} \rightarrow \mathrm{D^0\pi^+}$, $\mathrm{D_s^+(cs)} \rightarrow \Phi\pi^+ \rightarrow \mathrm{K^-\pi^+\,\pi^+}$

$\Lambda_c^+(\mathrm{udc}) \rightarrow \mathrm{pK^-\pi^+}$, $\mathrm{pK_s^0} \rightarrow \mathrm{p\pi^+\pi^-}$

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

$\Xi_c^0(\mathrm{dsc}) \rightarrow \Xi^-\mathrm{e^+}\nu_\mathrm{e}, \Xi^-\pi^+$

$\Xi_c^+(\mathrm{usc}) \rightarrow \Xi^-\pi^+\pi^+$

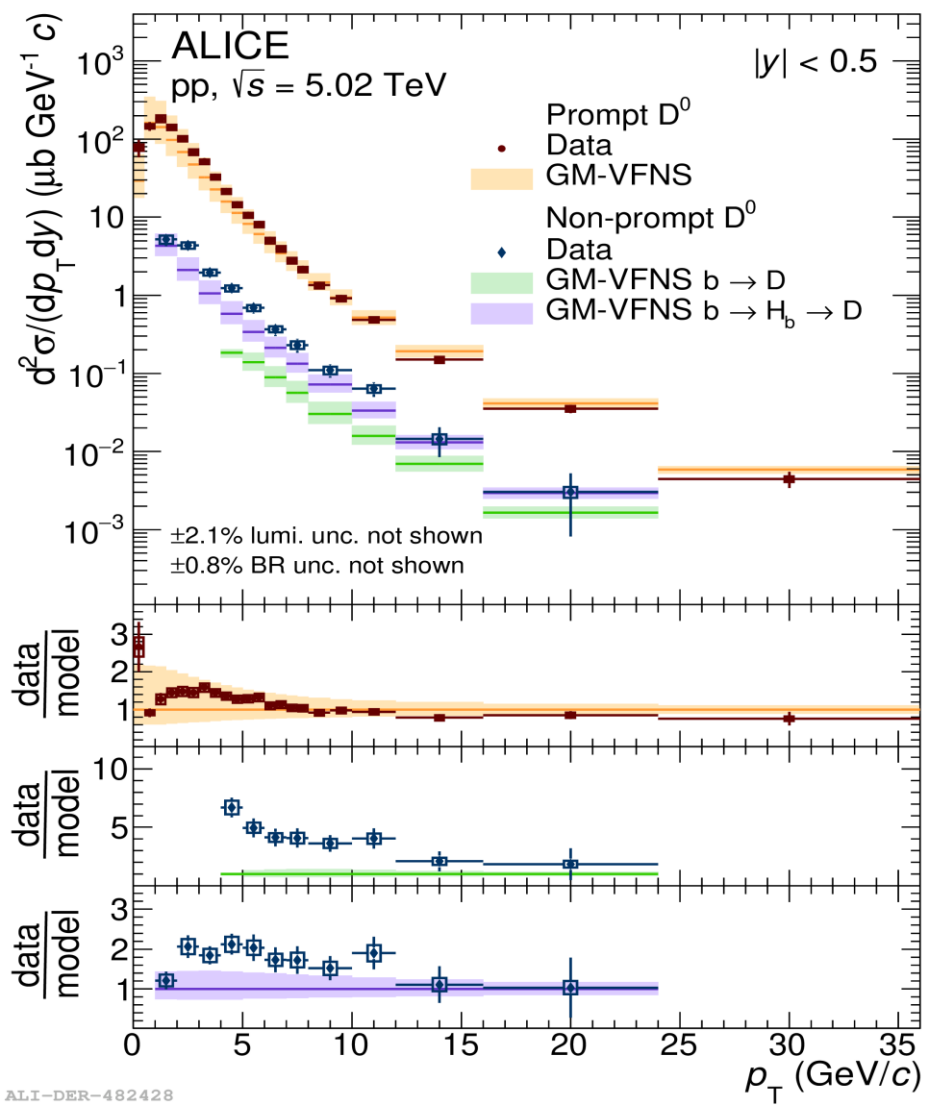
$\Omega_c^0(\mathrm{ssc}) \rightarrow \Omega^-\pi^+$

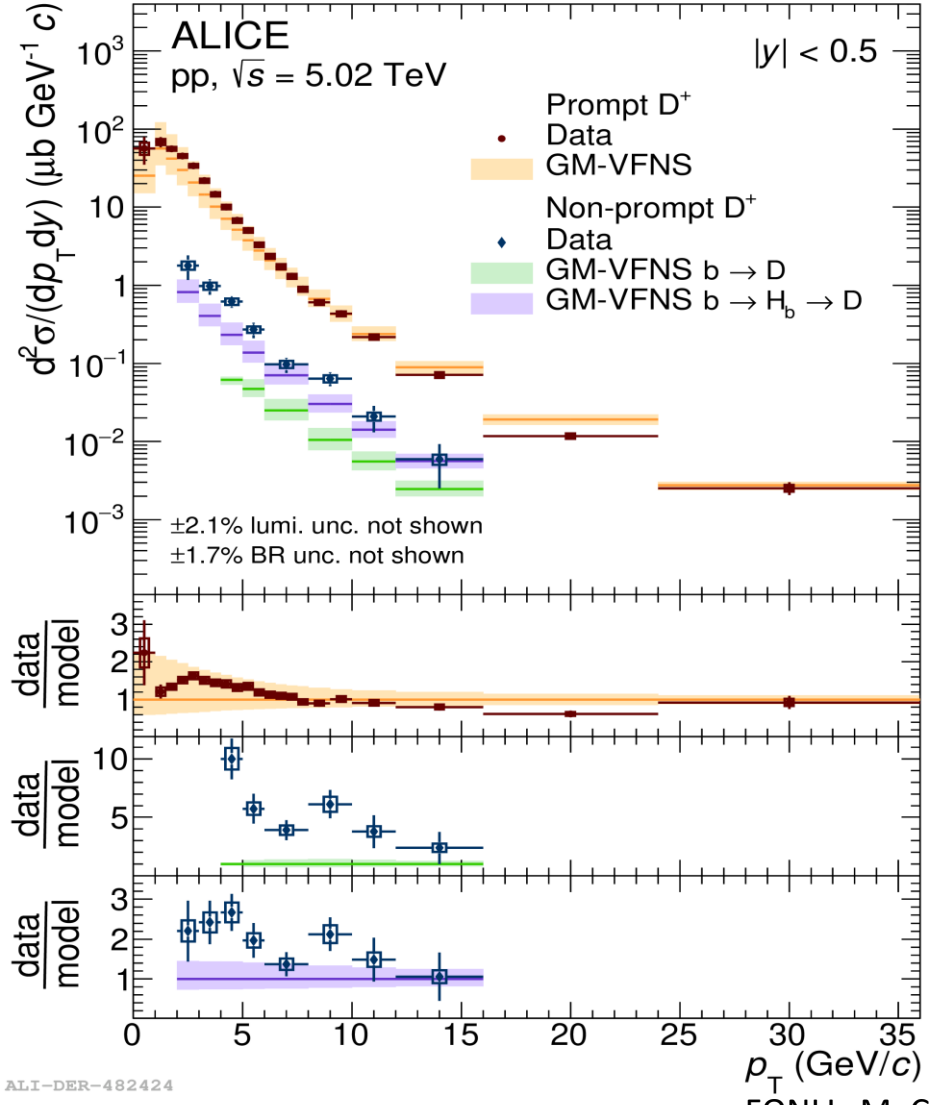
Data samples used for the analysis shown:

pp : $\sqrt{s} = 5.02$ TeV $\rightarrow$ $L_{\mathrm{int}} \approx 19\ \mathrm{nb}^{-1}$

$\sqrt{s} = 13$ TeV $\rightarrow$ $L_{\mathrm{int}} \approx 32\ \mathrm{nb}^{-1}$

Charm-meson production in pp collisions





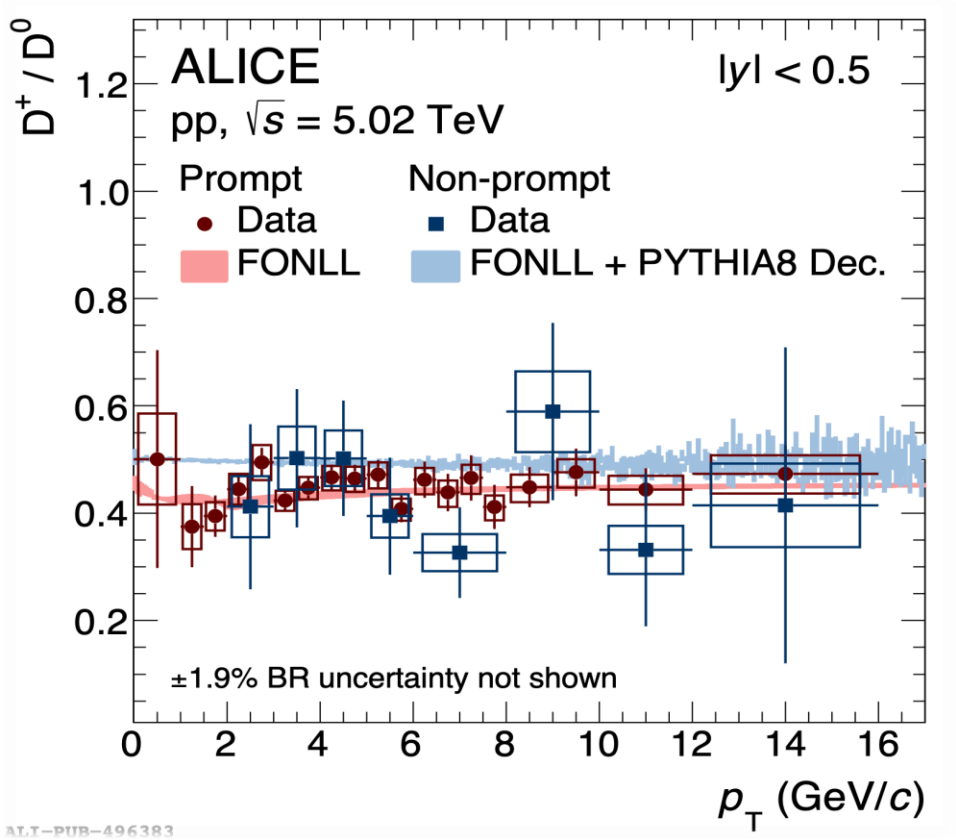
Precise measurements of prompt and non-prompt D-meson production cross sections over wide kinematic range

- Described within uncertainties by pQCD model calculations
- GM-VFNS predictions underestimate non-prompt D-meson (from b-quark) cross sections
- Data provides good constraints for models (experimental uncertainties are smaller than that of theoretical ones)

ALICE: JHEP 05 (2021) 220

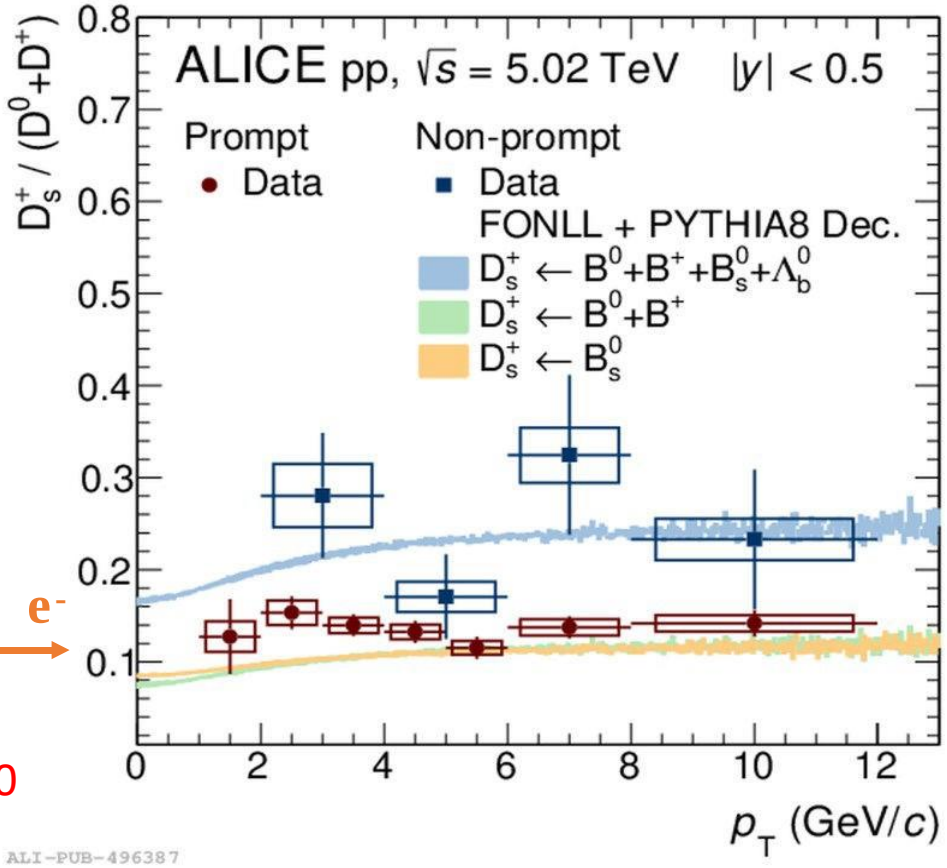
FONLL: M. Cacciari, et al., JHEP 10 (2012) 137
GM-VFNS: B. Kniehl, et al., EPJC 72 (2012) 2082

Charm meson ratio in pp collisions



e^+ e^-

e^+ e^-



ALICE: JHEP 05 (2021) 220

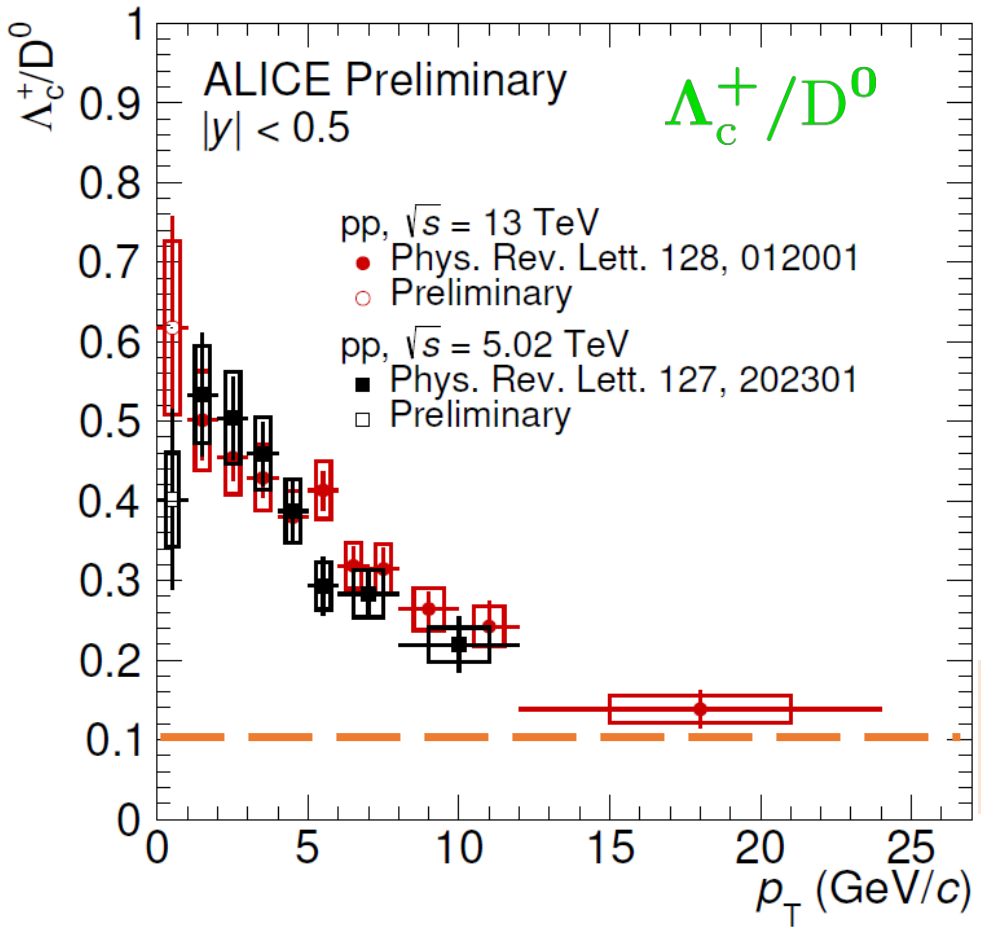
- Meson-to-meson ratios **independent of p_T** and collision system
- **FONLL calculations** (pQCD) correctly **describe** the data
  - Using fragmentation functions evaluated from e^+e^-, e^-p measurements

FONLL: M. Cacciari et al, JHEP 10 (2012) 137
PYTHIA 8 : P. Skands, et al., EPJC 74 (2014) 3024

- Higher $\mathrm{D_s^+/(D^0+D^+)}$ ratios for non-prompt mesons, due to relevant contribution to D_s^+ from B^0, B^+ decays

Charm baryons in pp collisions

$$\Lambda_c^+(\mathrm{udc}) \rightarrow \mathrm{pK}^-\pi^+,\ \mathrm{pK}_\mathrm{s}^0 \rightarrow \mathrm{p}\pi^+\pi^-$$



Charmed baryon-to-meson ratio shows a strong p_T dependence

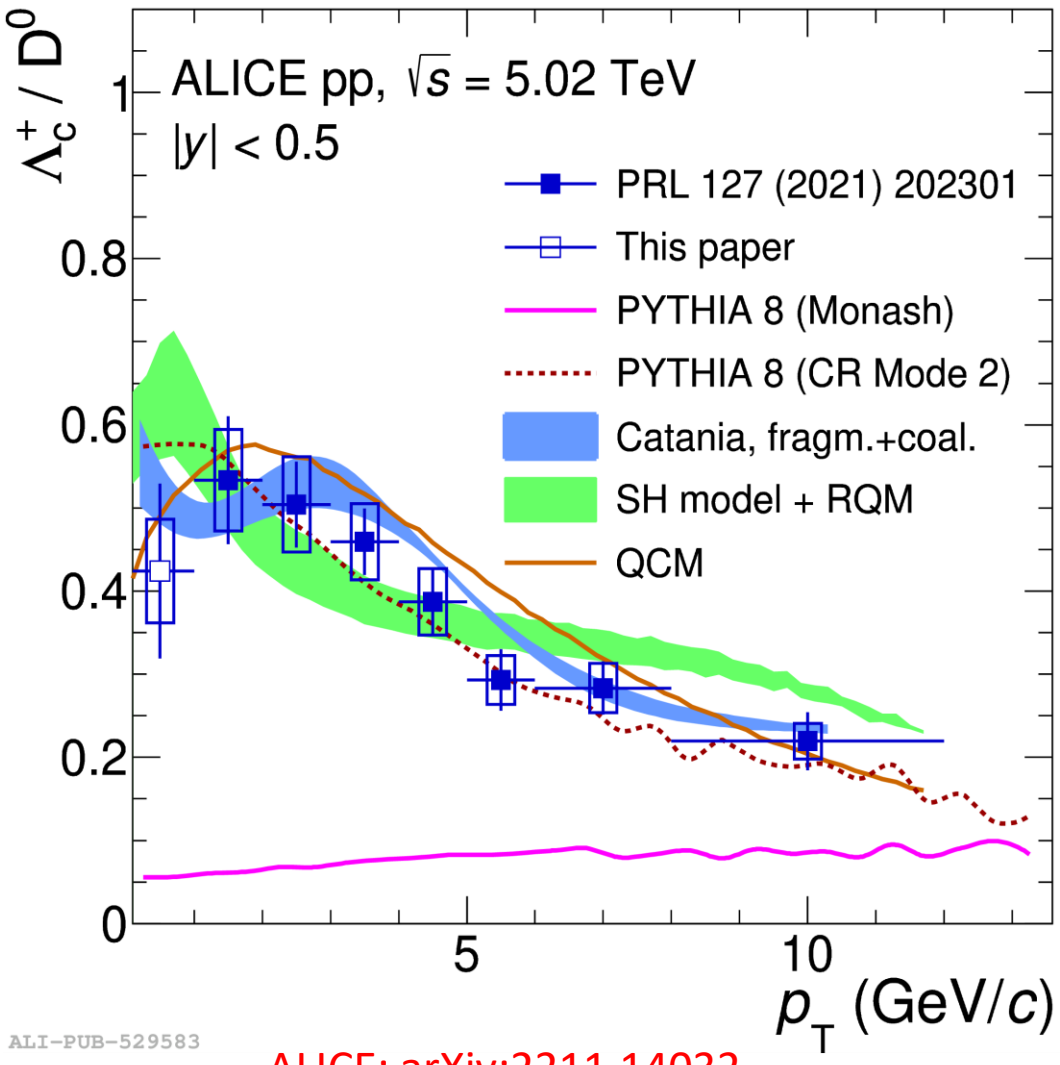
- Ratio significantly higher than in e^+e^- and e^-p collisions : factor of 5x enhancement at low p_T

Centre of mass energy independence within uncertainties

$$(\sqrt{s} = 5.02\ \mathrm{TeV}\ \ \text{and}\ \sqrt{s} = 13\ \mathrm{TeV})$$

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

Charm baryons in pp collisions: comparison with models



ALICE: arXiv:2211.14032

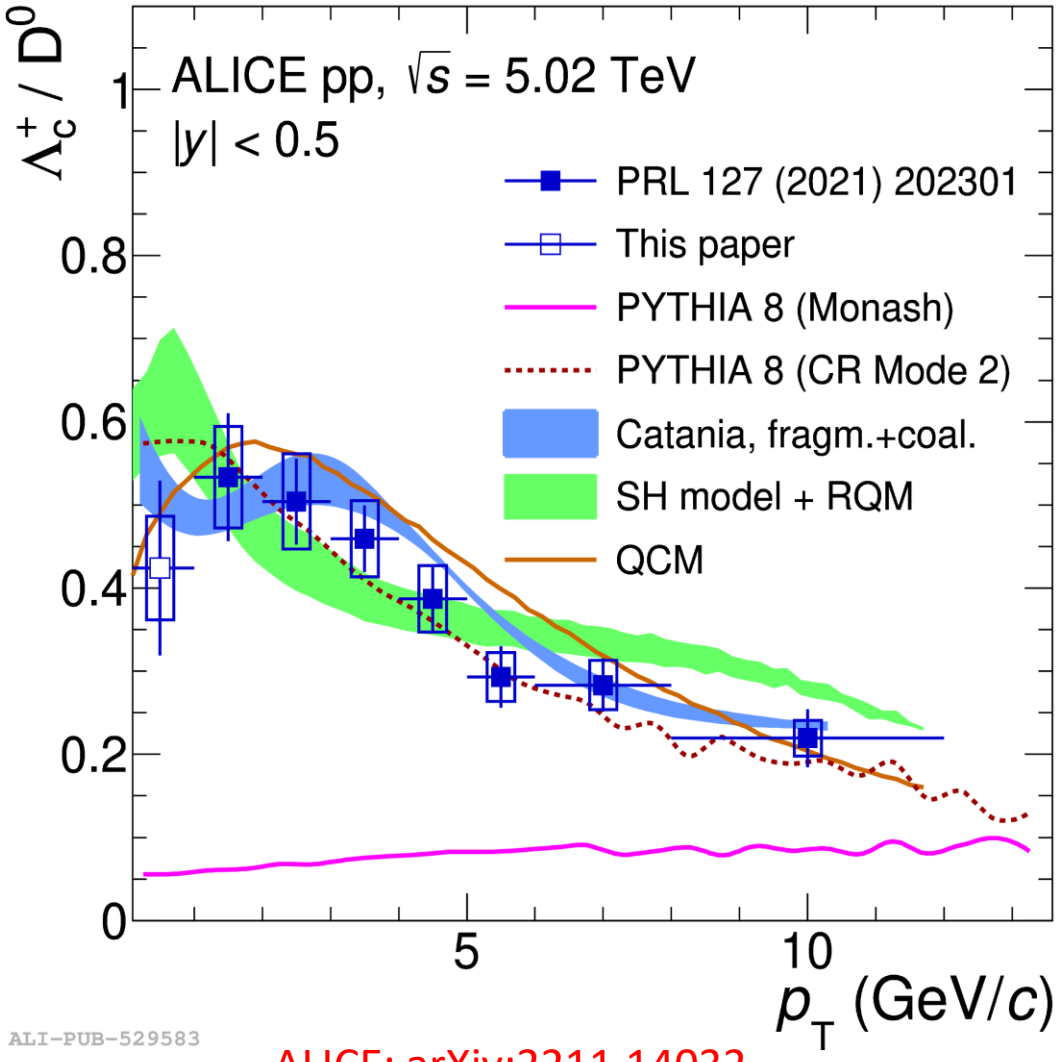
PYTHIA 8

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

Catania

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

Charm baryons in pp collisions: comparison with models



ALICE: arXiv:2211.14032

Statistical Hadronization Model + Relativistic Quark Model (SHM+RQM)

- 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 (predicted by RQM) necessary to describe Λ_c^+ / D^0

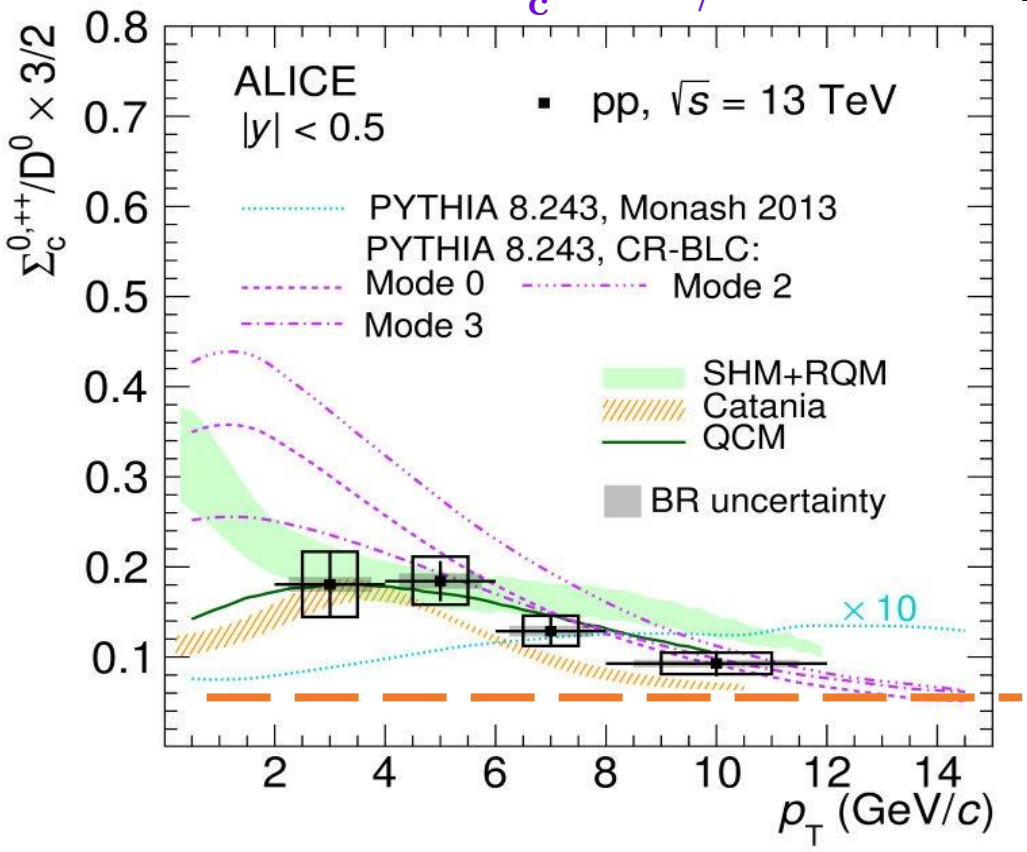
PDG: 5 Λ_c , 3 Σ_c , 8 Ξ_c , 2 Ω_c

RQM: additional 18 Λ_c , 42 Σ_c , 62 Ξ_c , 34 Ω_c

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

Resonant Charmed baryons in pp collisions $\Sigma_c^{0,+,++}$

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

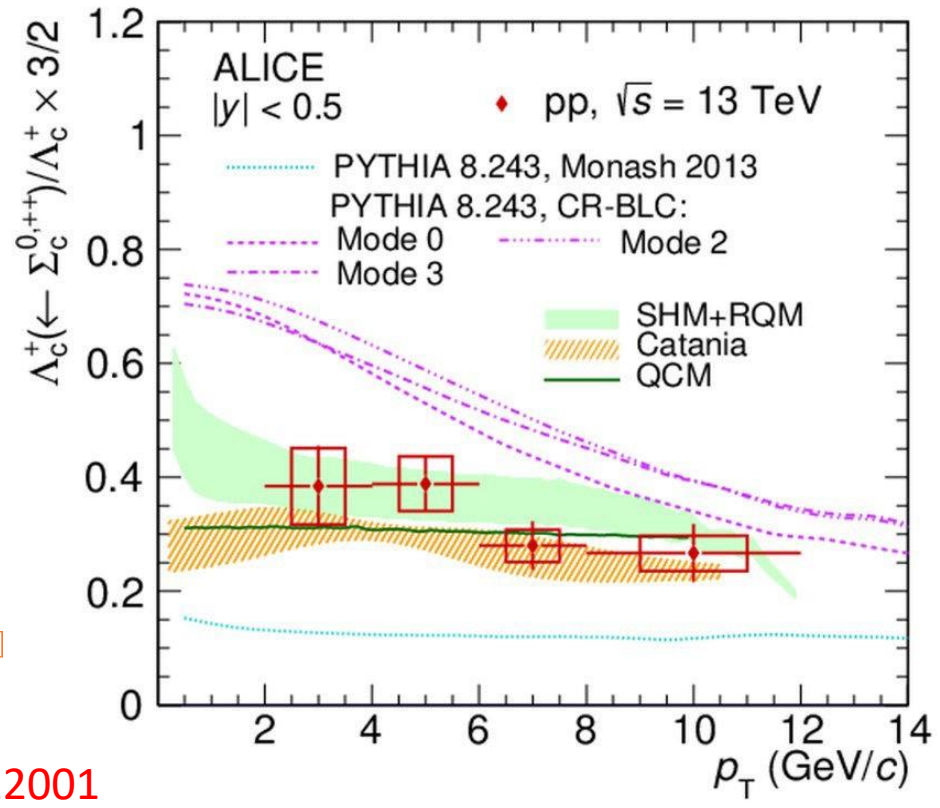


ALI-DER-493901

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

~ 0.02 ($e^+ e^-$)
[Belle Collaboration, Phys. Rev. D 97 (2005) 07]

Λ_c^+ from $\Sigma_c^{0,+,++}$



ALI-DER-493906

ALICE: PRL 128(2022)1,012001

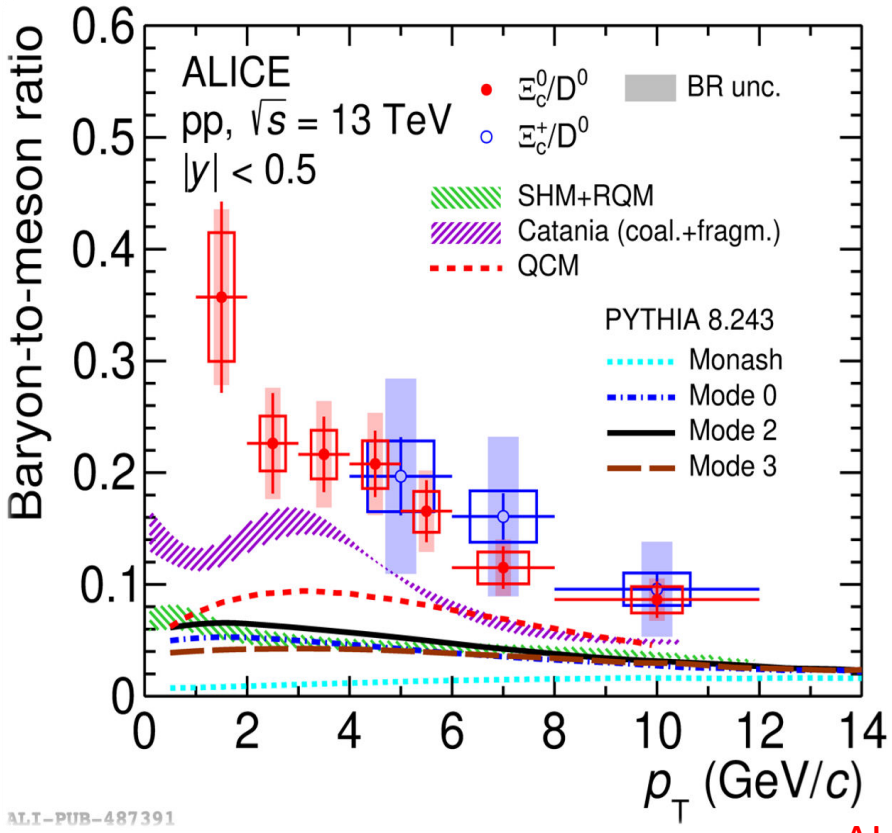
- Ratio to D^0 larger than e^+e^- results and PYTHIA Monash (based on e^+e^- fragmentation function)
- $\Sigma^{0,+,++}/D^0$ well **described** by predictions from **SHM+RQM**, **Catania** and **QCM**

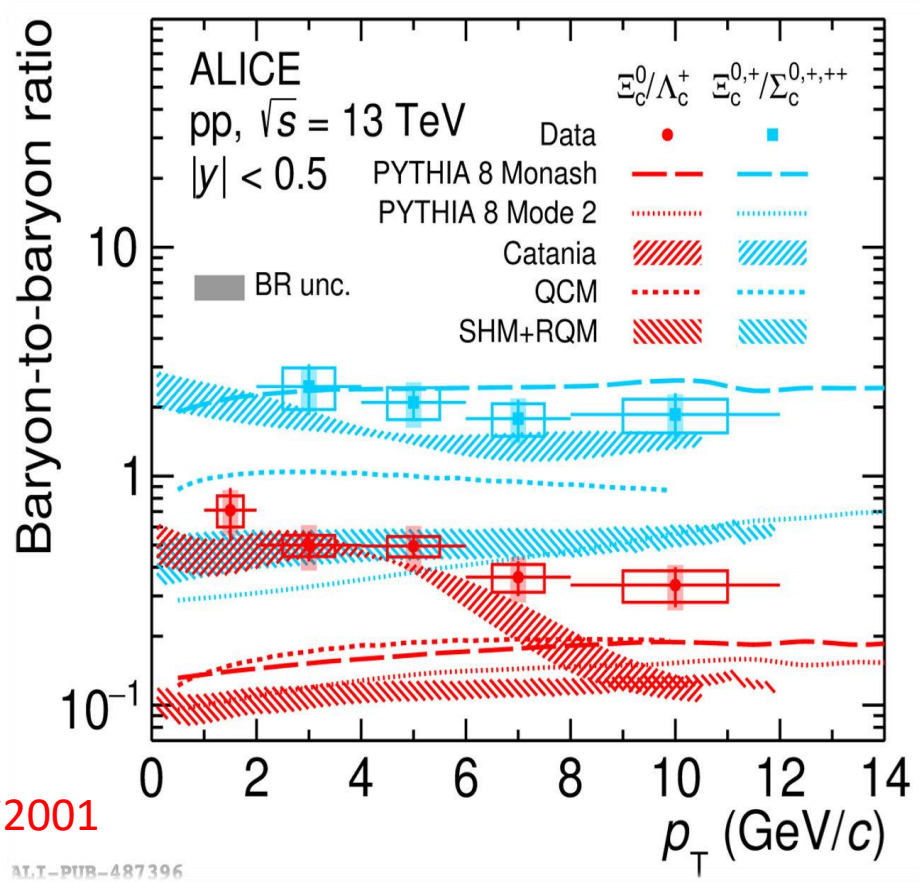
- The ratio enhancements partially accounts for larger Λ_c^+/D^0
- Measurement of **Λ_c feed-down from Σ_c ($2<p_T<12$ GeV/c)**:

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

Strange Charmed baryons in pp collisions Ξ_c^{0+}

$\Xi_c^0(\mathrm{dsc}) \rightarrow \Xi^- e^+ \nu_e, \Xi^- \pi^+$



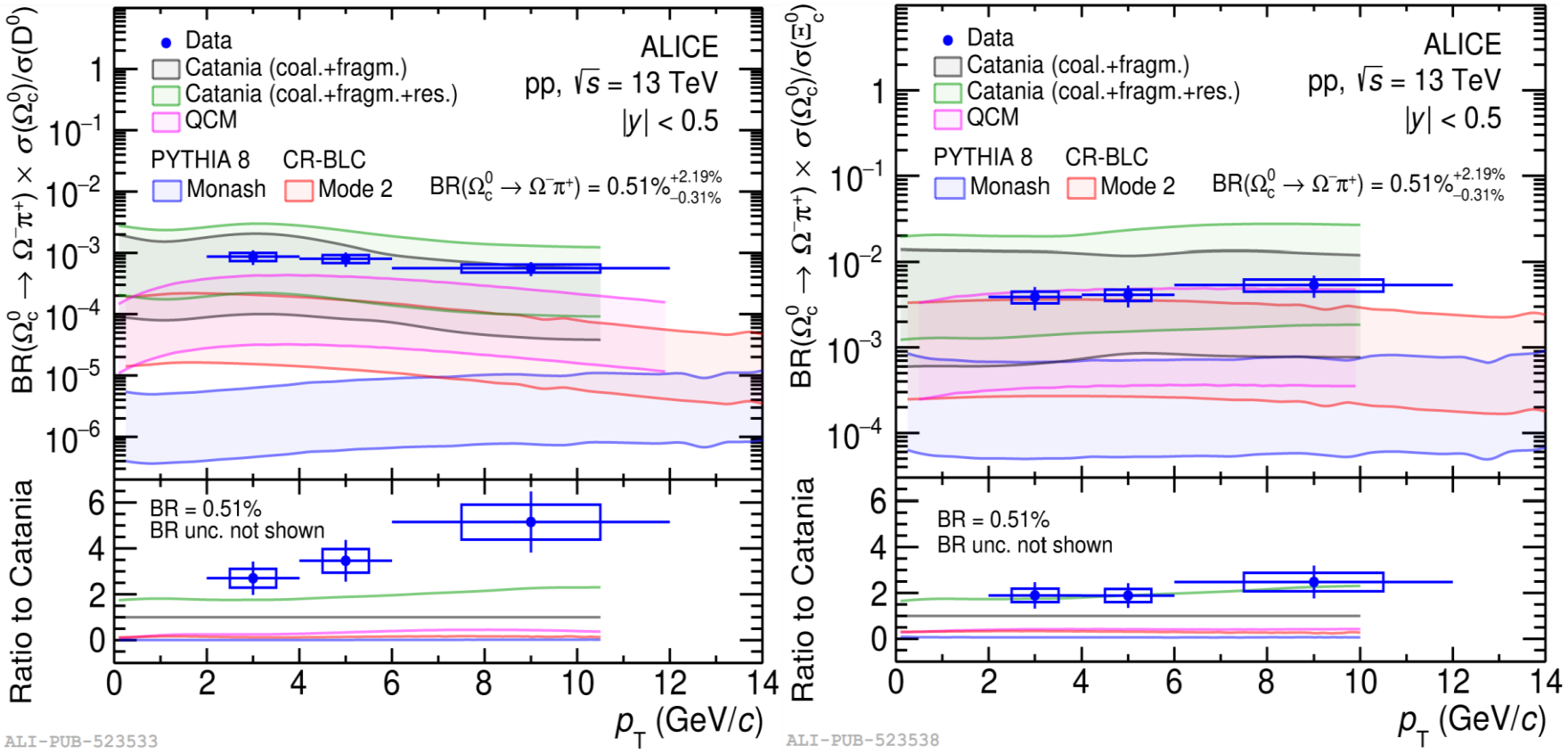


ALICE: PRL 127(2021)27, 272001

- Ratio to D^0 shows 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 models

- Ratio $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ in agreement with PYTHIA Monash
- Similar suppression in e^+e^- for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$

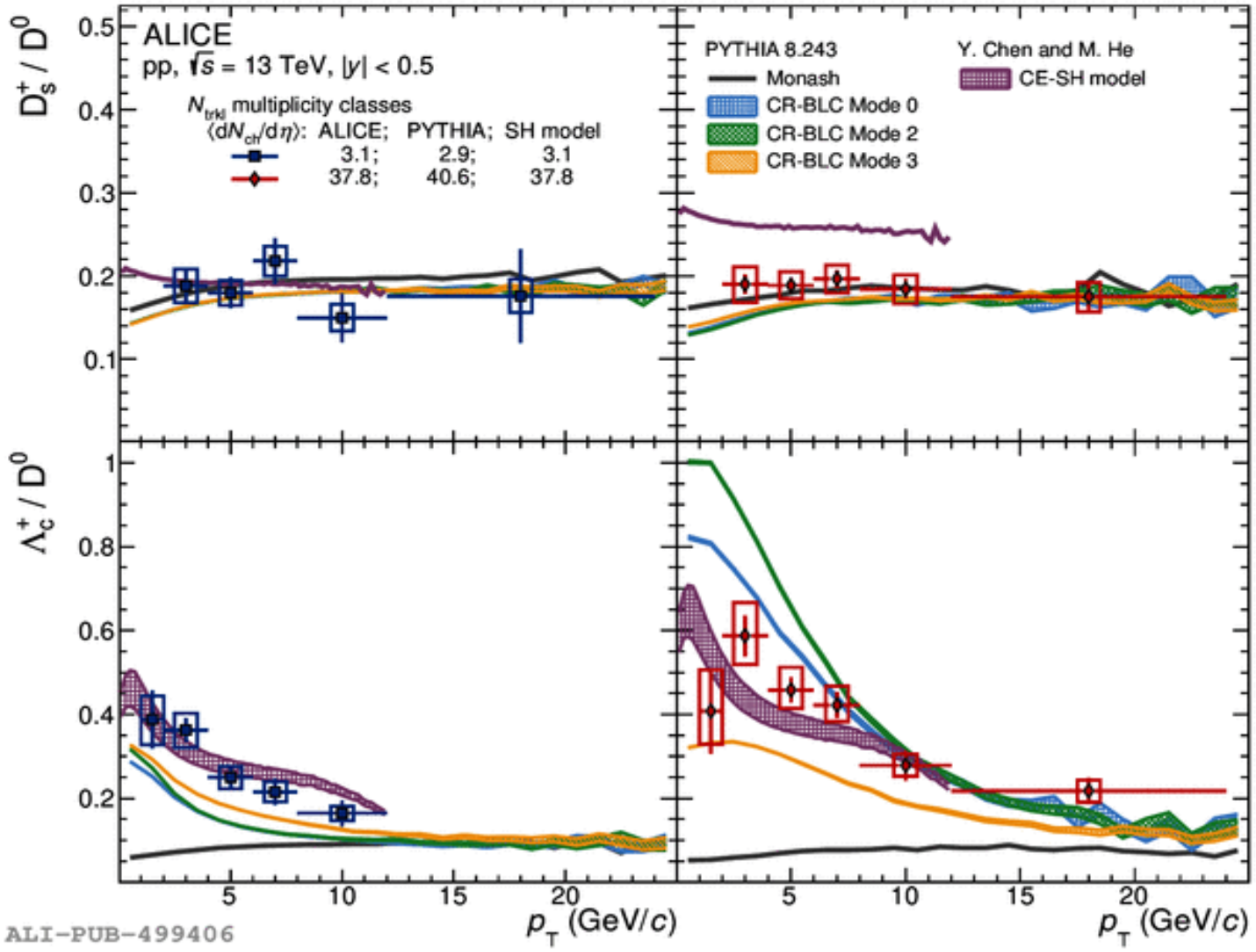
Doubly strange charmed baryon in pp collisions Ω_c^0 $\Omega_c^0(\mathrm{ssc}) \to \Omega^-\pi^+$



ALICE: arXiv:2205.13993

- Model predictions rescaled by branching ratio obtained from theoretical models (Hsiao et.al EPJC80, 1066 (2020))
- PYTHIA 8 +CR-BLC effects underestimate the data
- Better agreement with Catania and Quark-recombination model (QCM)
- $\Omega_c^0/\Xi_c^0 \approx 1 \implies$ important contribution to charm production at LHC energies by Ω_c^0?

Multiplicity dependence of charm-hadron production

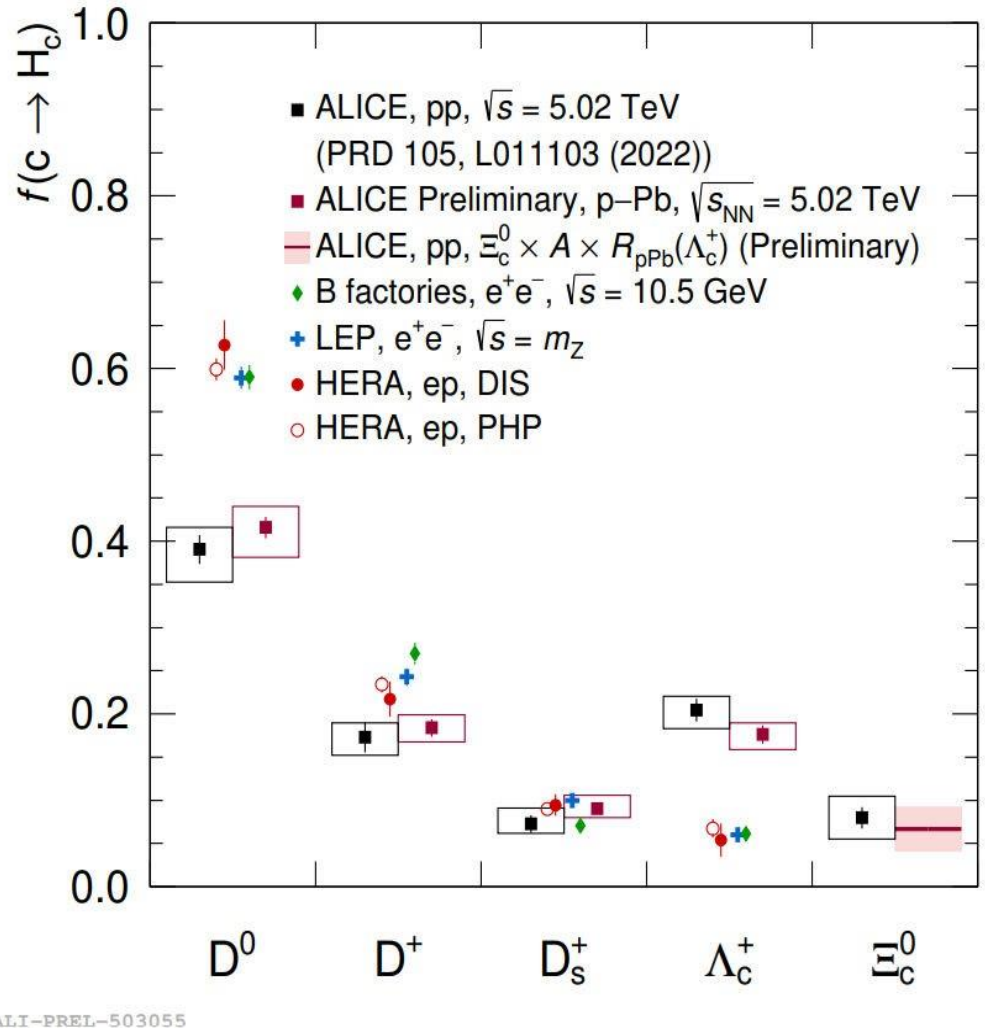


ALICE:PLB 829 (2022) 137065

- No multiplicity dependence for D^+_s /D^0 ratios
- 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

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

Charm fragmentation fractions in small systems



- Charm fragmentation fractions in hadronic collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV
  - pp: published in PRD 105 (2022), L011103
  - p–Pb:

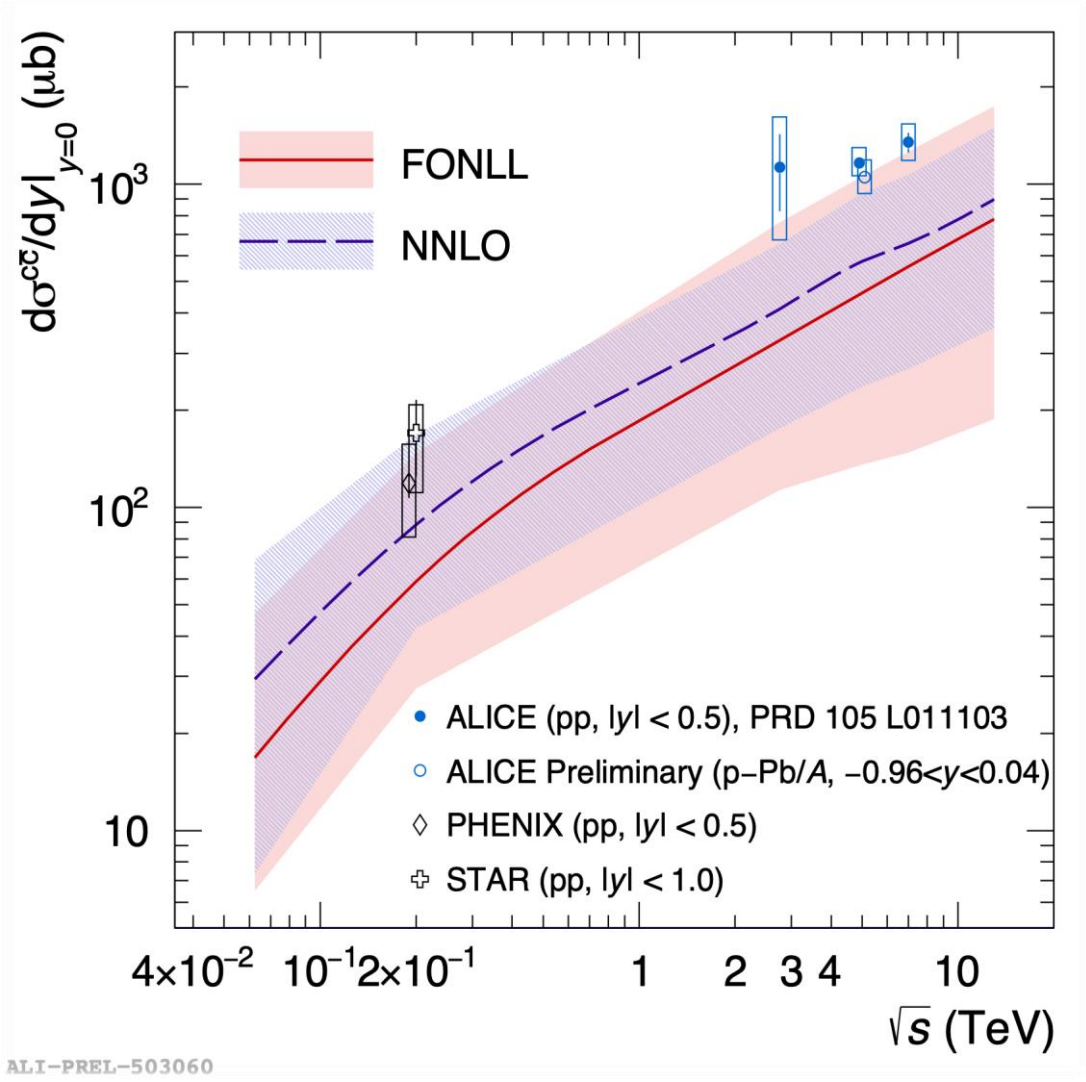
    D^0 and Λ_c : measured down to p_T=0

    D^+ and D_s^+ extrapolated to p_T= 0 with POWHEG+PYTHIA

    Ξ_c^0: not measured $\rightarrow$ $\sigma_{\rm pp}(\Xi_c^0) \times 208 \times R_{\rm pPb}(\Lambda_c^+)$

- Charm fragmentation fractions are compatible in pp and p-Pb collisions, but differ significantly from those in e^+e^- and e-p
  - **charm fragmentation fractions are not universal!**

Total charm production cross-section



Total charm production cross section measured at midrapidity in pp and p-Pb collisions at $\sqrt{s}$ = 5 TeV by summing all charm ground states

$$(d\sigma^{c\bar{c}}/dy)_{|y|<0.5} = 1165 \pm 44(stat.)^{+134}_{-101}(syst)\ \mu b$$

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

STAR: PRD 86 (2012) 072013
PHENIX: PRC 84 (2011) 044905
FONLL: JHEP 10 (2012) 137
NNLO: PRL 118 (2017) 122001

Summary and Outlook

- Precise measurements of charm-meson production described by pQCD predictions with large theoretical uncertainties

- pQCD calculations based on factorization approach and assuming universal fragmentation fractions among different collision systems do not describe charm-baryon production in hadronic collisions

  - Baryon-to-meson ratios and fragmentation fractions significantly differ among different collision systems
    ⇨ charm fragmentation not universal across different collision systems

- Additional hadronization mechanism could take place in pp compared to e^+e^- and e^-p
  - Models including enhanced production of baryons or coalescence better describe the measurements
  - More studies are needed to discriminate among different theoretical descriptions

- New measurement will be performed opening new physics horizons, thanks to
  - Larger data samples and improved tracking resolution in Run 3 & Run 4 with the upgraded ALICE detector

Thank you for your kind attention!!!