Experimental results on heavy flavour baryons in pp and Pb-Pb

Mattia Faggin – University and INFN, Padova (Italy)

Terzo incontro sulla fisica con ioni pesanti alle alte energie

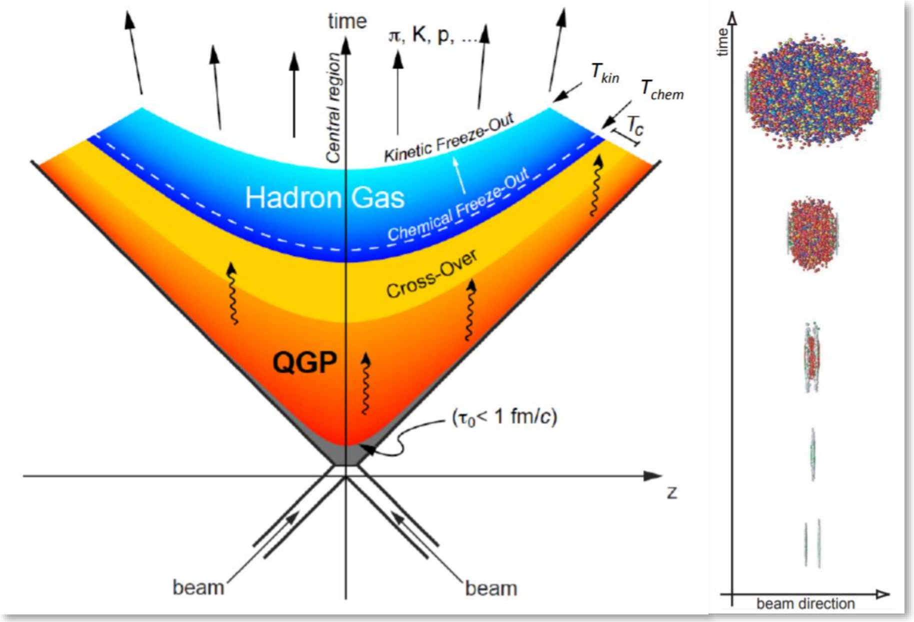
26th November 2021 – Padova (Italy)

Heavy quarks: a unique probe

- Mass of the order of $\sim$ GeV/c^2
  $\rightarrow$ charm and beauty quarks mainly produced in hard-scattering processes among partons

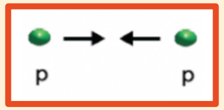
- Pb-Pb collisions: produced before the QGP formation
  $\tau_{\mathrm{QGP}} \sim 1$ fm/c (production timescale: $\Delta\tau \sim 1/Q \sim 1/2m$)

- <u>Full evolution</u> of the system experienced



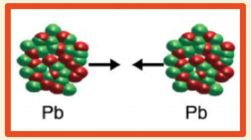
Measurement of charm and beauty hadrons: access to charm and beauty quarks dynamics

<u>pp collisions</u>



- Tests of pQCD calculations
- Reference for heavy-ion collisions

<u>Pb-Pb collisions</u>



- Hot nuclear matter effects
  $\rightarrow$ Energy loss in the QGP
  $\rightarrow$ Collective motion of the system
  $\rightarrow$ Modification of hadronization mechanisms

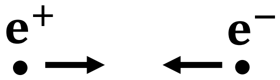
CHARM

- $m_{\mathrm{c}} \simeq 1.3$ GeV/c^2
- $\Delta\tau_{\mathrm{c}} \simeq 0.08$ fm/c

BEAUTY

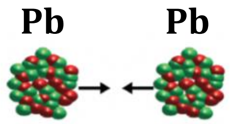
- $m_{\mathrm{b}} \simeq 4.2$ GeV/c^2
- $\Delta\tau_{\mathrm{b}} \simeq 0.03$ fm/c

Charm and beauty hadron formation in e^+e^- and Pb-Pb collisions

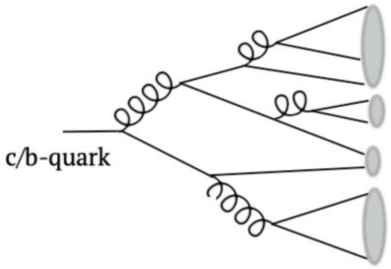


- "Point-like" object interaction
- Fragmentation

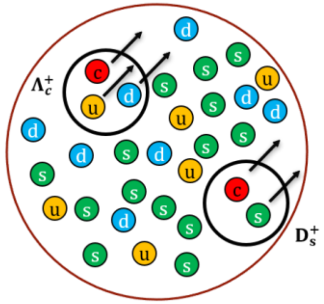
Increasing "point-like" object interactions



- QGP: complex large-size system
- Parton degrees of freedom
- Modification of hadronization mechanisms



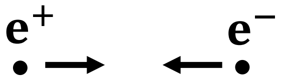
Fragmentation



Coalescence

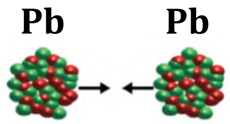
More on F. Bellini' talk "[Experimental overview: hadronization and coalescence in light and heavy flavour sector]"

Charm and beauty hadron formation in pp collisions



- "Point-like" object interaction
- Fragmentation

- Superimposition of many "e^+e^-" collisions?
- Colour charges from MPI enough to modify hadronization?



- QGP: complex large-size system
- Parton degrees of freedom
- Modification of hadronization mechanisms

Standard description of heavy-quark hadronization based on the factorization theorem

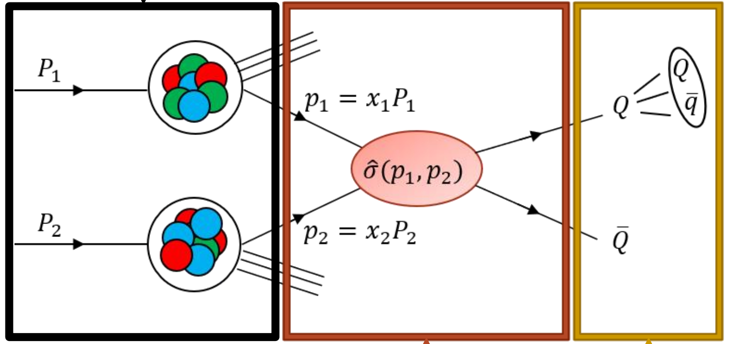
➢ Fragmentation functions assumed universal and constrained from e^+e^- and e^-p measurements

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

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)



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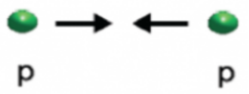
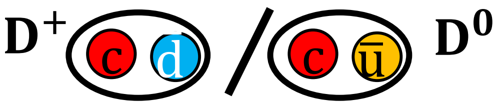
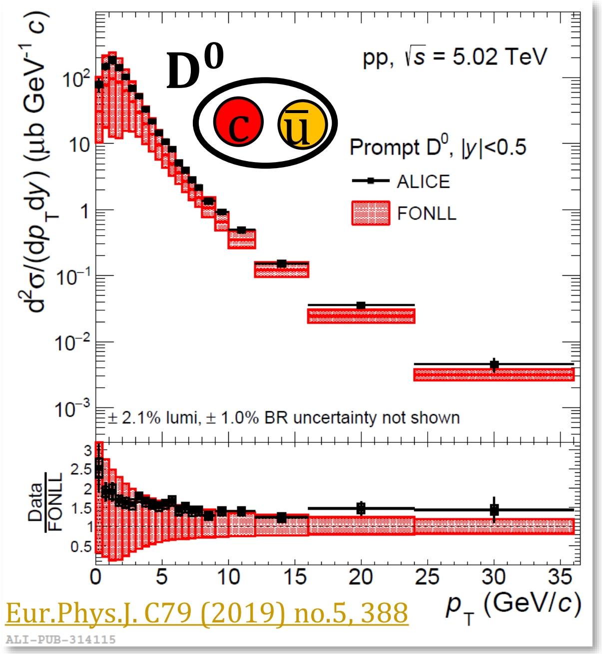
Heavy flavour (HF) production in pp collisions

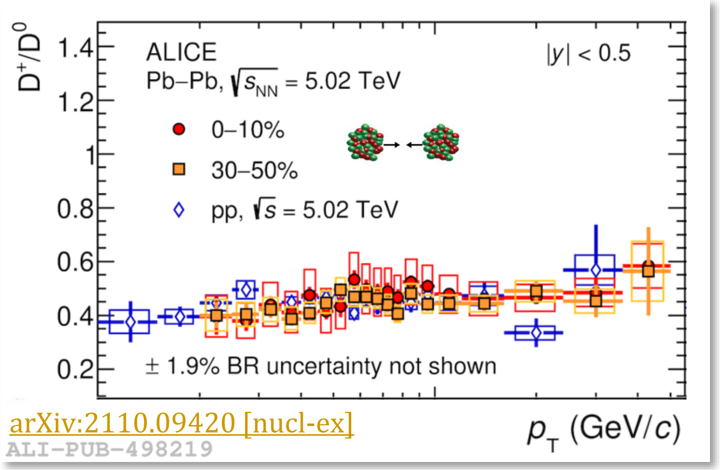


$\sqrt{s} = 5.02$ TeV





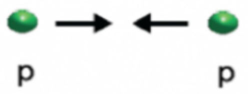
Eur.Phys.J. C79 (2019) no.5, 388



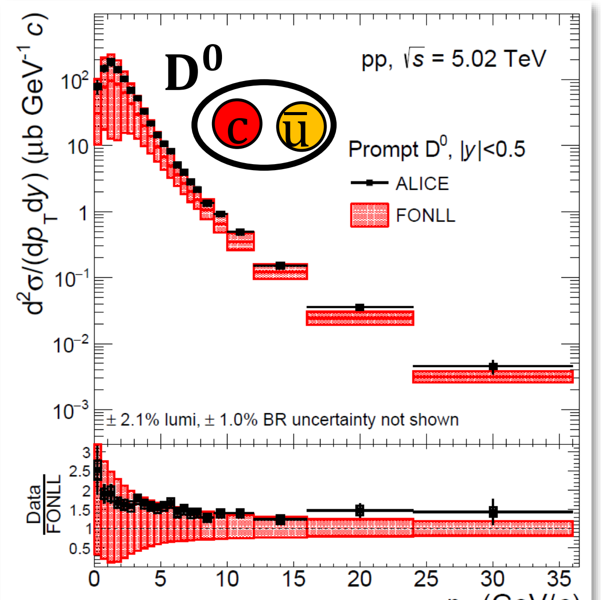
arXiv:2110.09420 [nucl-ex]

- Fragmentation functions constrained from e^+e^- measurements
- Theoretical models based on a factorisation approach describe the meson production within large uncertainties
- D-meson cross section on the upper edge of FONLL prediction
- D-meson ratios independent among collision systems and vs. p_T

Heavy flavour (HF) production in pp collisions



$\sqrt{s} = 5.02, 13$ TeV



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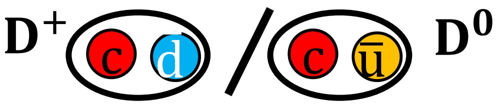
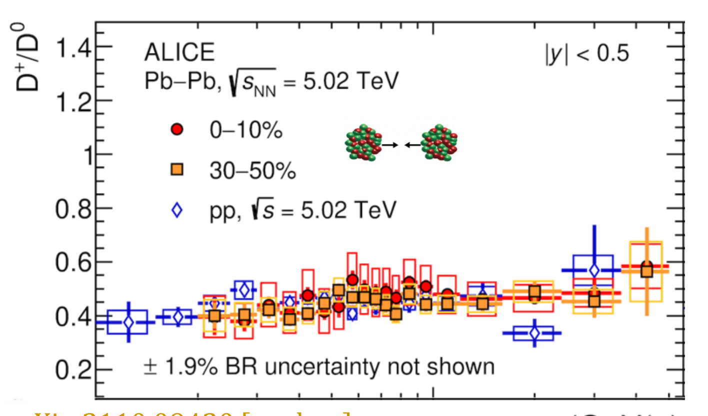
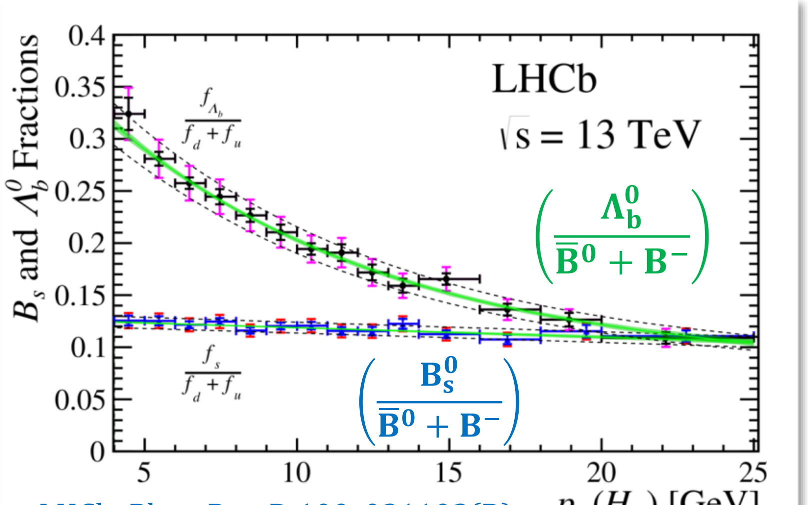
ALI-PUB-314115





arXiv:2110.09420 [nucl-ex]

ALI-PUB-498219

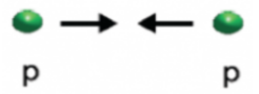


LHCb: Phys. Rev. D 100, 031102(R)

- Fragmentation functions constrained from e^+e^- measurements
- Theoretical models based on a factorisation approach describe the meson production within large uncertainties
- D-meson cross section on the upper edge of FONLL prediction
- D-meson ratios independent among collision systems and vs. p_T

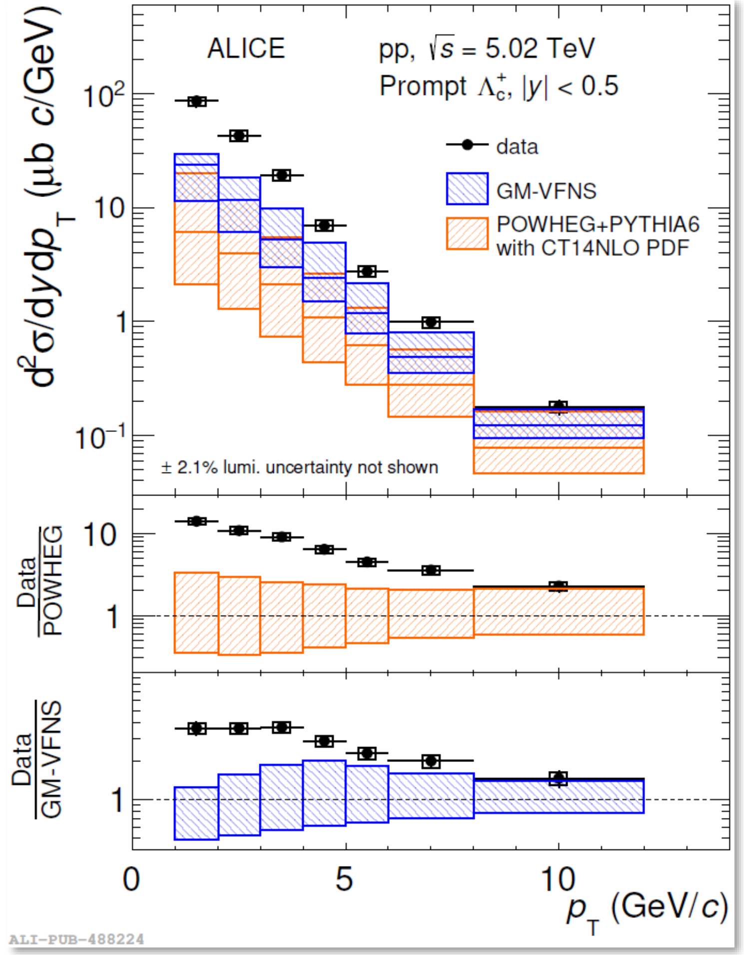
- Beauty baryon-to-meson:
  - ➢ Decreasing trend vs. p_T
  - ➢ Enhancement at low p_T with respect to $B_s^+/(\overline{B}^0 + B^-)$

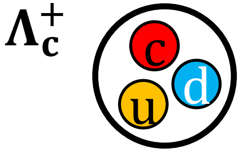
Heavy flavour (HF) production in pp collisions

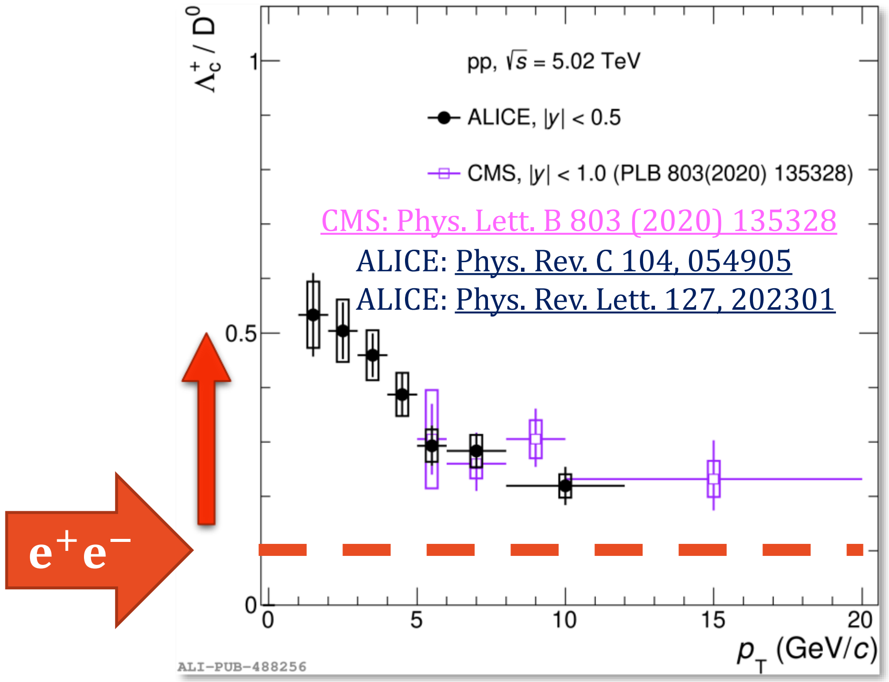


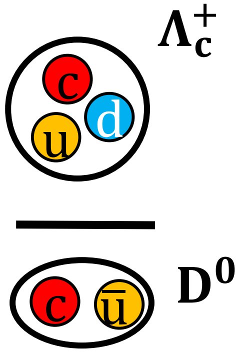
$\sqrt{s} = 5.02$ TeV

ALICE: Phys. Rev. C 104, 054905 ALICE: Phys. Rev. Lett. 127, 202301









- **Theoretical models** based on the same approach **significantly underestimate the baryon production**
- Λ_c^+/D^0 ratio:
  - → Significant decrease with p_T
  - → $\times\ 2.5-5$ enhancement in pp collisions compared to e^+e^-

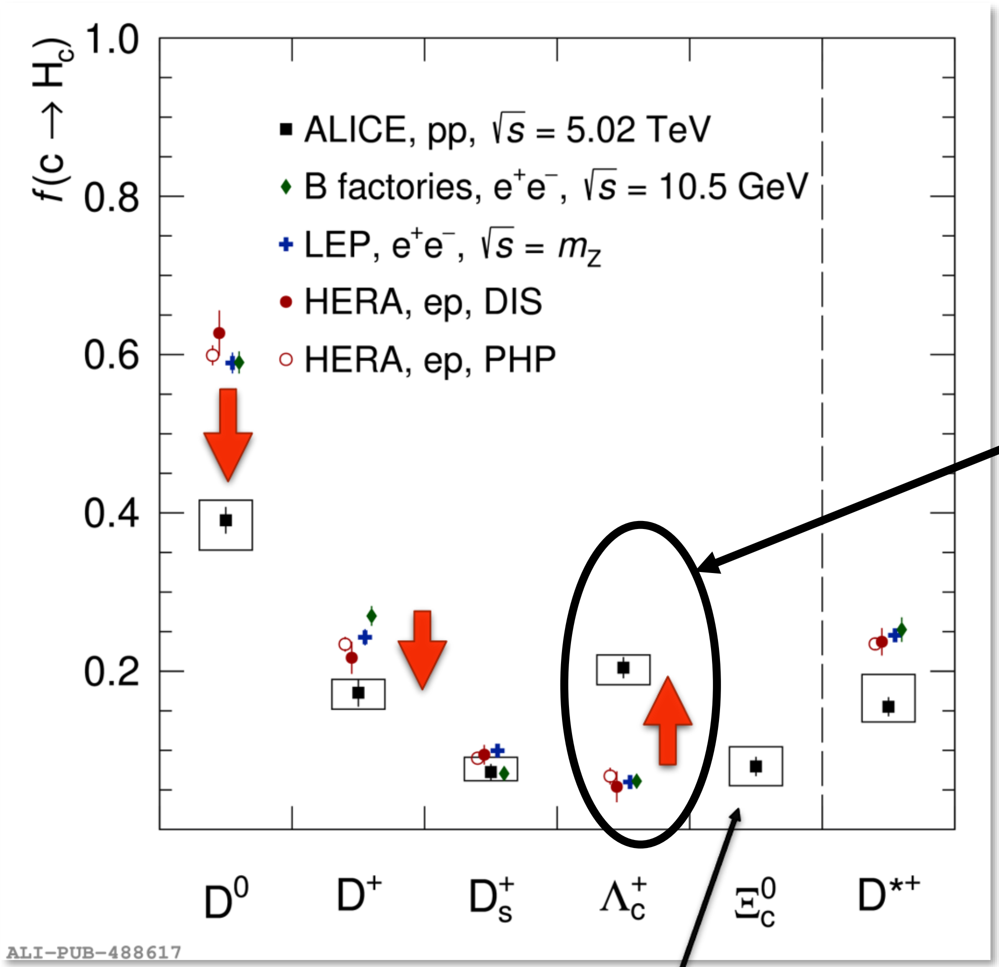
→ Further mechanisms playing a role? **→ Non-universality of fragmentation functions?**

Charm fragmentation fractions in pp collisions

$\sqrt{s} = 5.02$ TeV

p → ← p

ALICE: arXiv:2105.06335



Single species cross section normalised by the sum of all ground states charm hadrons

Fragmentation fractions $f(c \to H_c)$ not universal

→ significant baryon enhancement in pp collisions

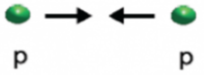
First measurement of $f(c \to \Xi_c)$

H_c	$f(c \to H_c)[\%]$
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

→ also for Ξ_c^+

Baryon enhancement – models

$\sqrt{s} = 5.02$ TeV



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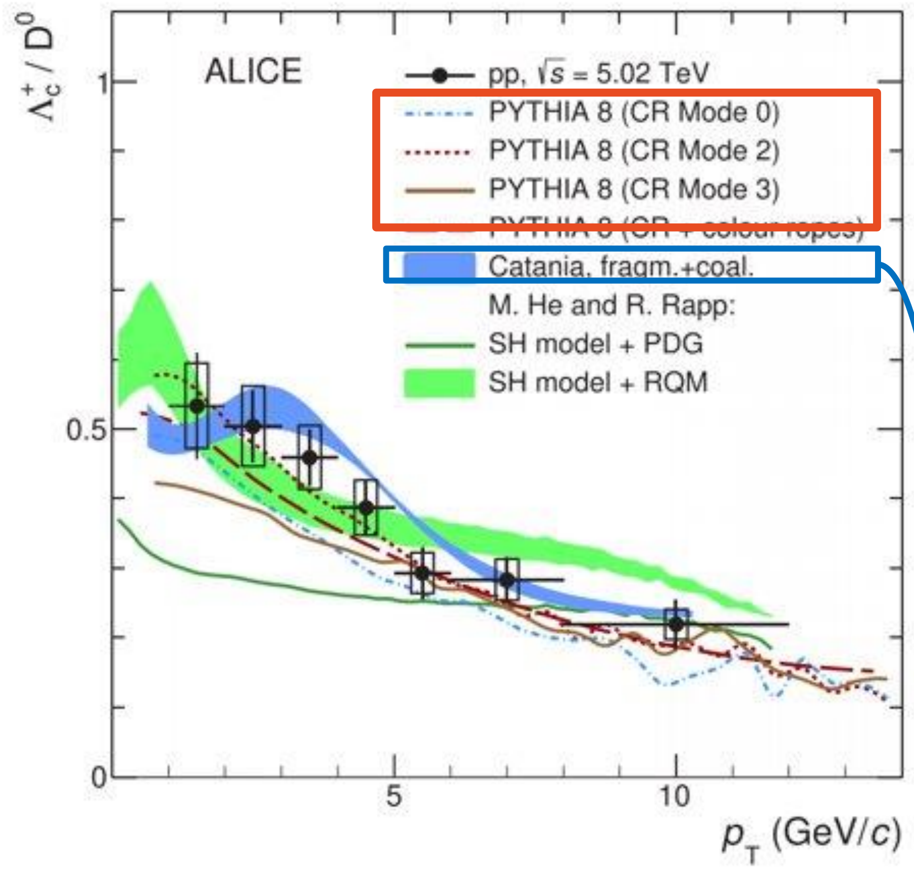
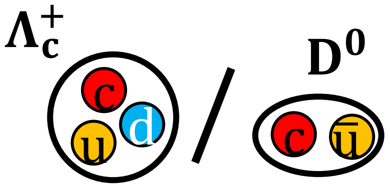
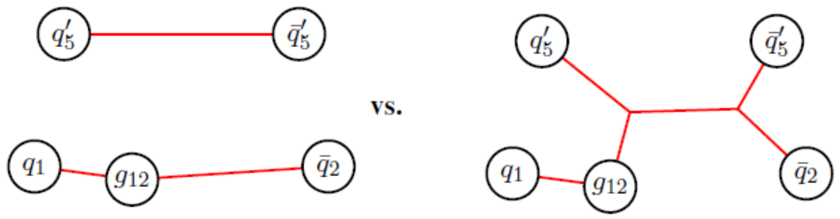




J.P. Christiansen, P. Z. Skands: JHEP 1508 (2015) 003

1. PYTHIA 8 with improved Colour Reconnection (CR)

   → **"junction"** topology **enhances charm baryon** production



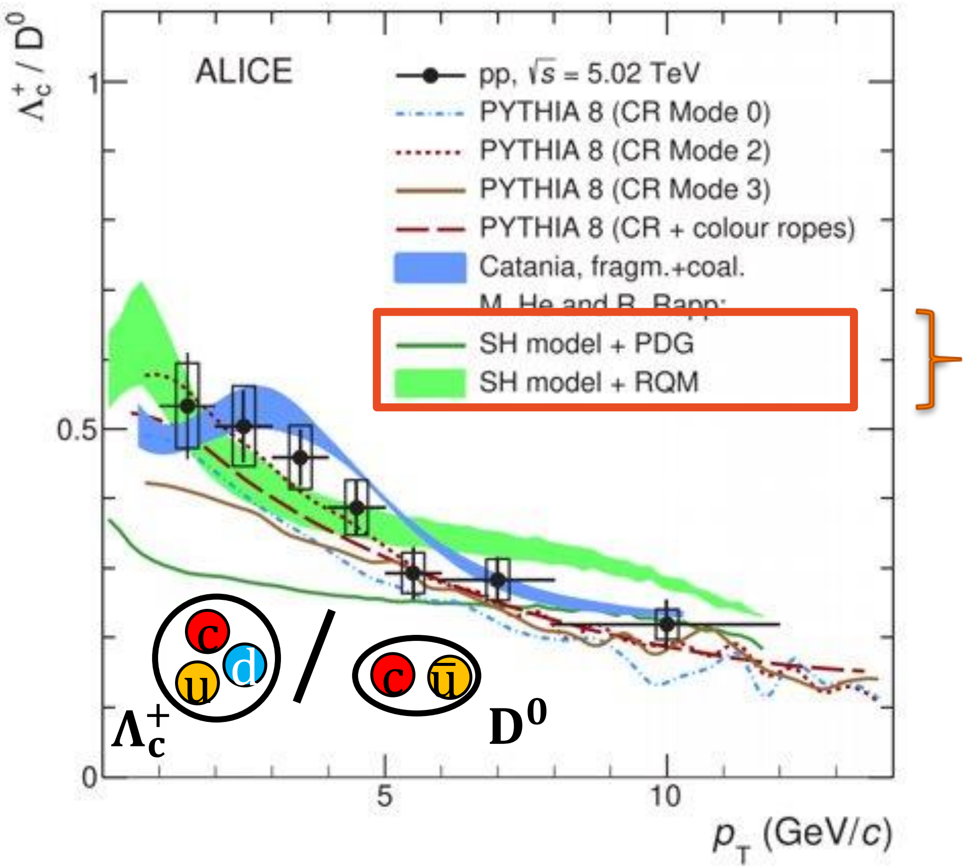
V. Minissale, S. Plumari, V. Greco: arXiv:2012.12001

2. Catania model
   - **Thermalised system** of u,d,s and gluons assumed
   - Mixed hadron formation
     a. **fragmentation**
     b. **coalescence**
        → imposed to be the only mechanism for $p \to 0$

Baryon enhancement – models

$\sqrt{s} = 5.02$ TeV

ALICE: Phys. Rev. C 104, 054905 ALICE: Phys. Rev. Lett. 127, 202301



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

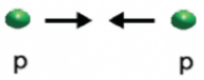
3. Statistical Hadronization Model and Relativistic Quark Model (SHM + RQM)
    - **Hadronization** ruled by thermo-statistical weights **governed by hadron masses** ($n_i \sim m_i^2 T_H K_2(m_i/T_H)$) at a universal hadronization temperature T_H
    - Strong **feed-down** from an **augmented set of excited charm baryons**
        - → 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

Can further baryon measurements help understanding the mechanisms underlying the baryon enhancement?

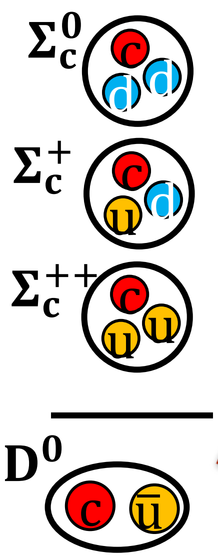
$n_i[\cdot 10^{-4}\ \mathrm{fm}^{-3}](T_H\ [\mathrm{MeV}])$	D^0	D^+	D^{*+}	D_s^+	Λ_c^+	$\Xi_c^{0,+}$	Ω_c^0
PDG (170)	1.161	0.5098	0.5010	0.3165	0.3310	0.0874	0.0064
RQM (170)	1.161	0.5098	0.5010	0.3165	0.6613	0.1173	0.0144

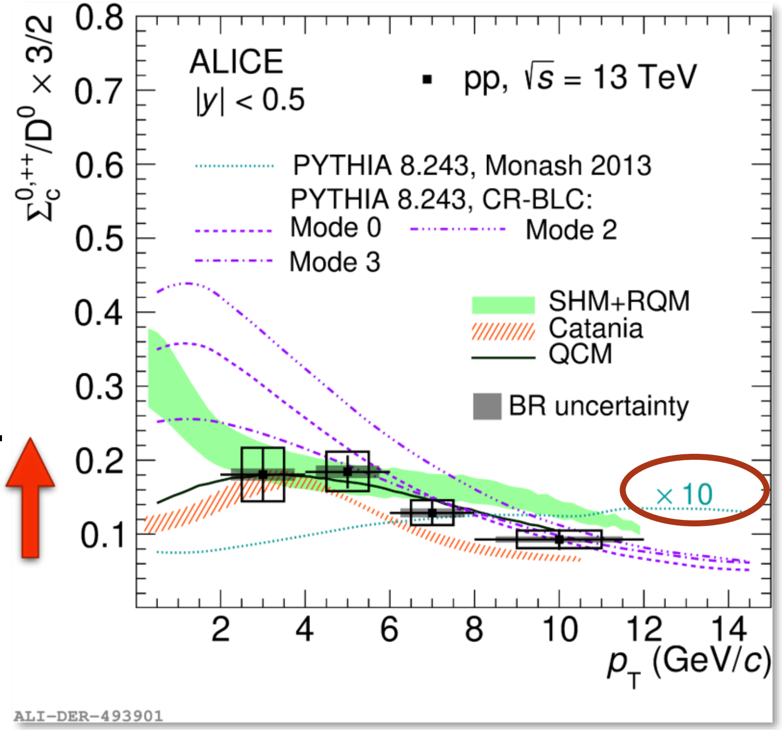
Heavier charmed baryons: $\Sigma_c^{0,+,++}$

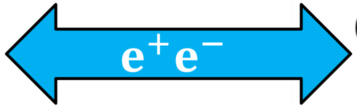
$\sqrt{s}$ = 13 TeV

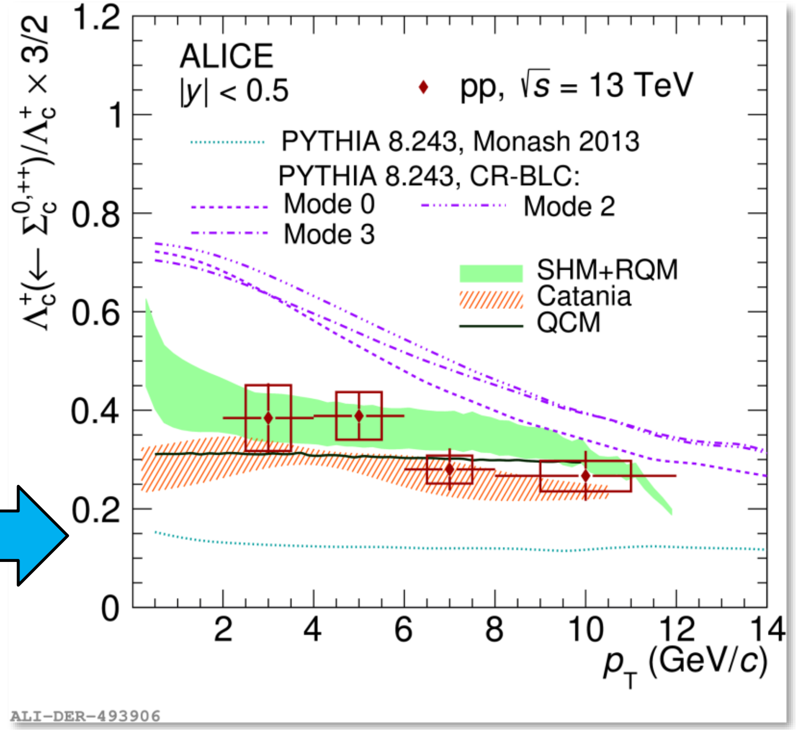


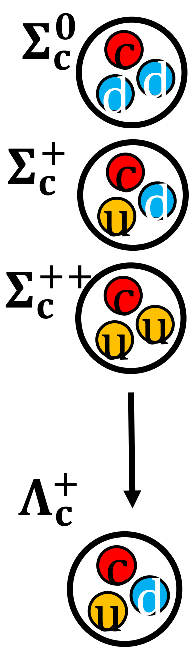
ALICE: arXiv:2106.08278 [hep-ex]











- **Larger** than $\mathbf{e^+e^-}$ results (↔ Monash)
  → **larger relative enhancement than Λ_c/D^0**

- $\Sigma_c^{0,+,++}/D^0$ partially accounts for larger Λ_c^+/D^0
- Well **described** by **SHM + RQM** and **QCM** (c coalescence with equal-velocity light quarks, thermal weights for abundances) predictions

- Measurement of **Λ_c feed-down from Σ_c**

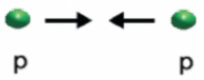
$$\Lambda_c^+ \leftarrow \Sigma_c/\Lambda_c^+ = 0.38 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})$$

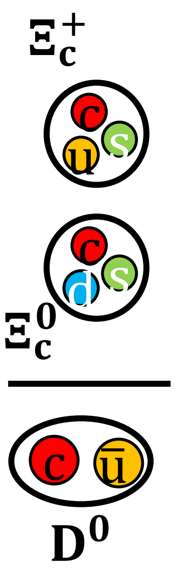
- **Overestimated** by **CR modes**
  → some parameter to be tuned to describe the direct Λ_c production?

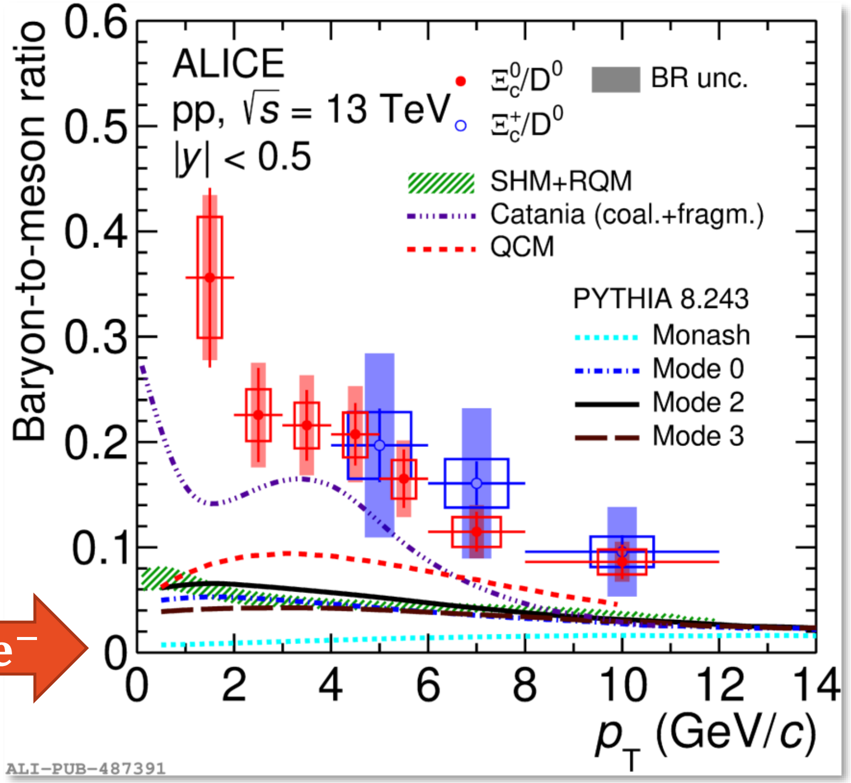
QCM: J. Song, H. Li, F. Shao: Eur. Phys. J. C (2018) 78: 344

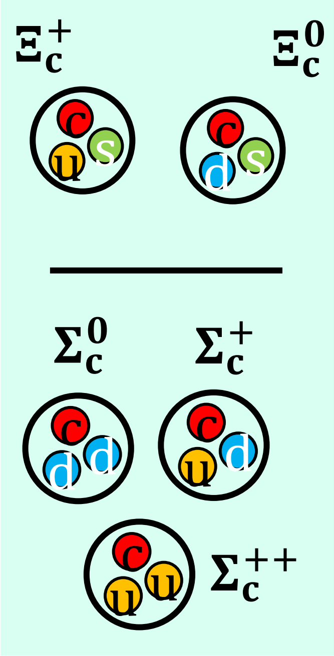
Heavier charmed baryons: $\Xi_c^{0,+}$

$\sqrt{s}$ = 13 TeV

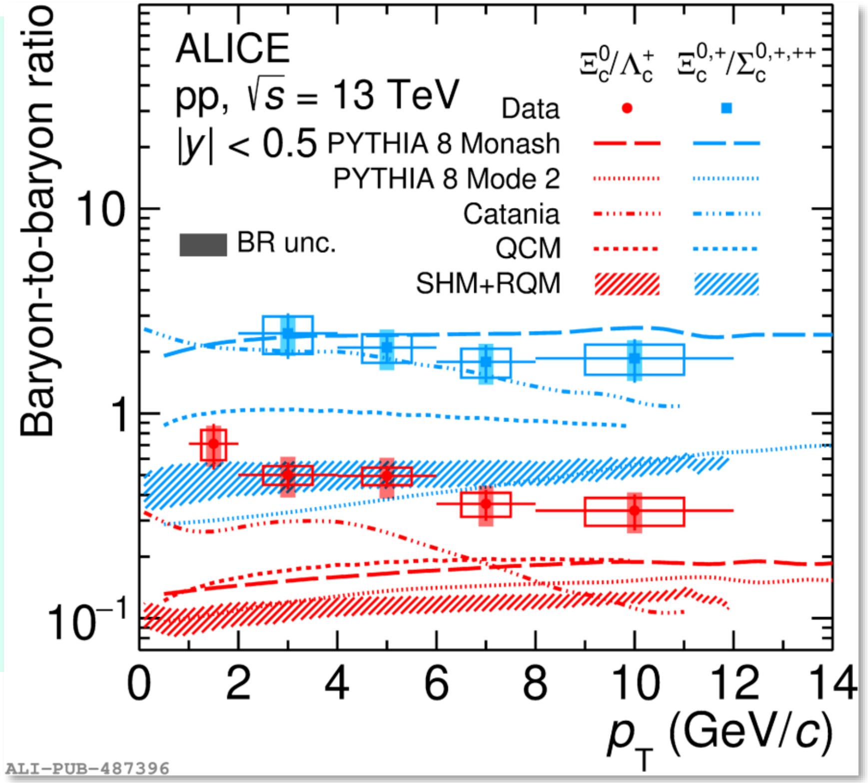








ALICE: arXiv:2105.05187
ALICE: arXiv:2105.05616

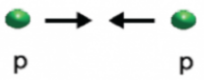


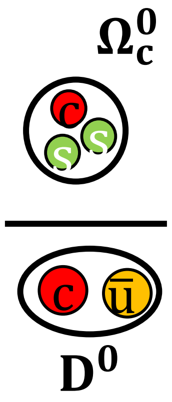
- $\Xi_c^{0,+}/D^0$ shows clear p_T dependence and is **larger** than e^+e^-
- Significantly **underestimated** by models
  - Something anomalous with strange quarks?
  - $D_s^+/(D^0 + D^+)$ compatible with expectations from e^+e^- ⟶ baryons are 'strange'
- Catania (fragm. + coal.) works better

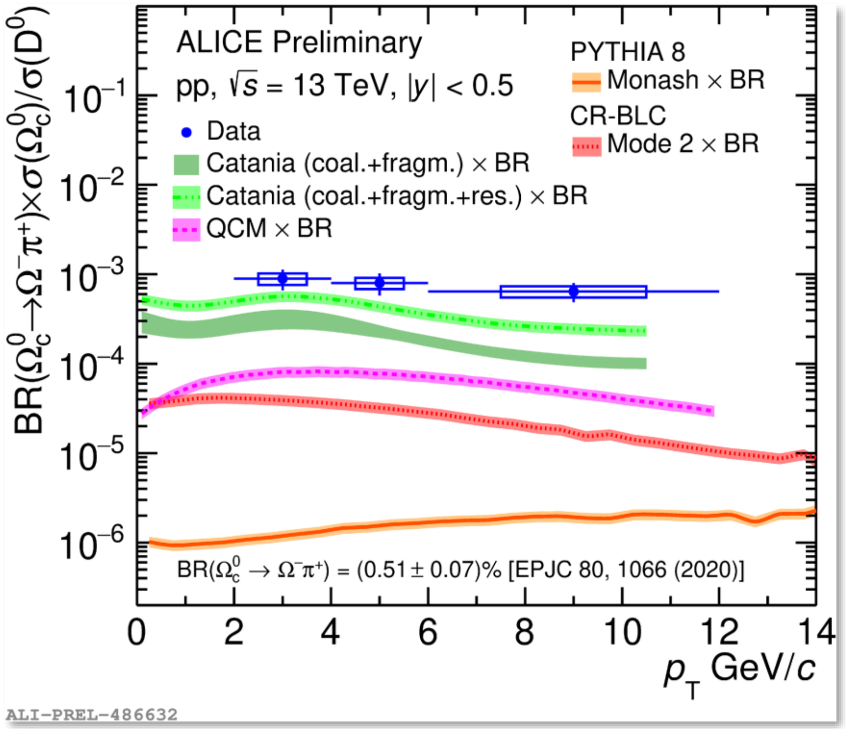
- $\Xi_c^0/\Sigma_c^{0,+,++}$ in **agreement** with **Monash**
  → similar enhancement for the two baryons w.r.t e^+e^- collisions?

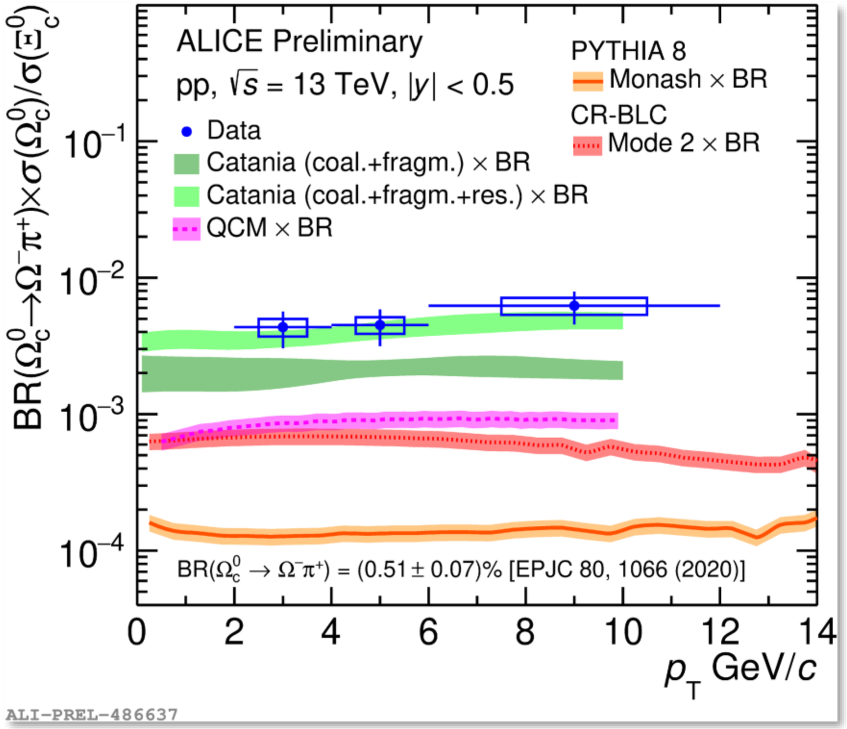
Heavier charmed baryons: Ω_c^0

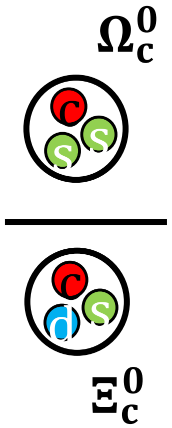
$\sqrt{s} = 13$ TeV











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

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

- **Pythia 8** with **CR underestimates** data
- **Coalescence models** get **closer** to Ω_c^0/D^0, but still not enough (higher-mass resonance decays included)

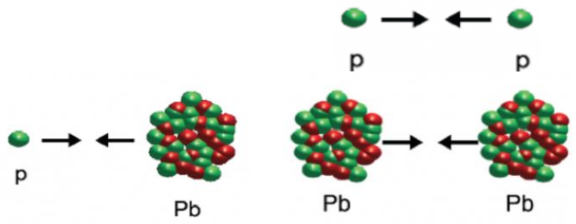
$BR(\Omega_c^0 \to \Omega^-\pi^+) = (0.51 \pm 0.07)\%$

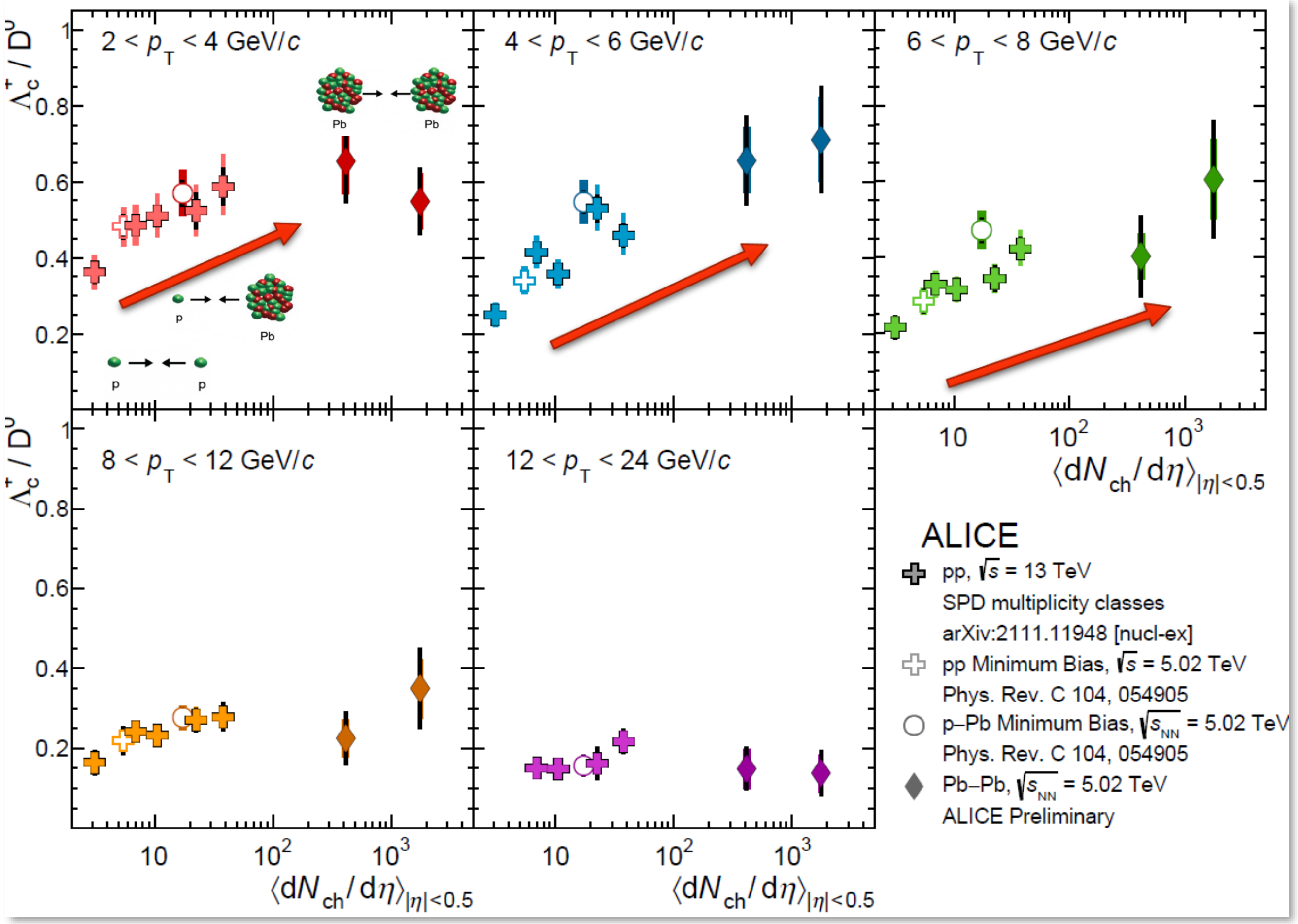
(Y. Hsiao et al. EPJC 80, 1066 (2020)) used to scale model predictions → not measured

Ω_c^0 : sizeable contribution to charm production at LHC energies?

Charm production vs. multiplicity

$\sqrt{s_{NN}} = 5.02, 13$ TeV

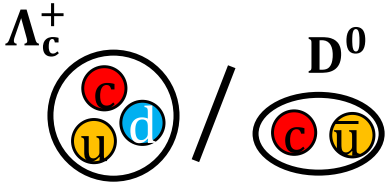




Increasing event multiplicity

- pp, p-Pb, Pb-Pb colliding **systems** compared through **common multiplicity estimators**
- Λ_c^+/D^0 ratio smoothly **increasing** at intermediate p_T from pp to Pb-Pb

- **Same underlying processes ruling the HF production in different colliding systems?**

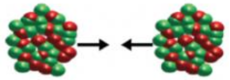


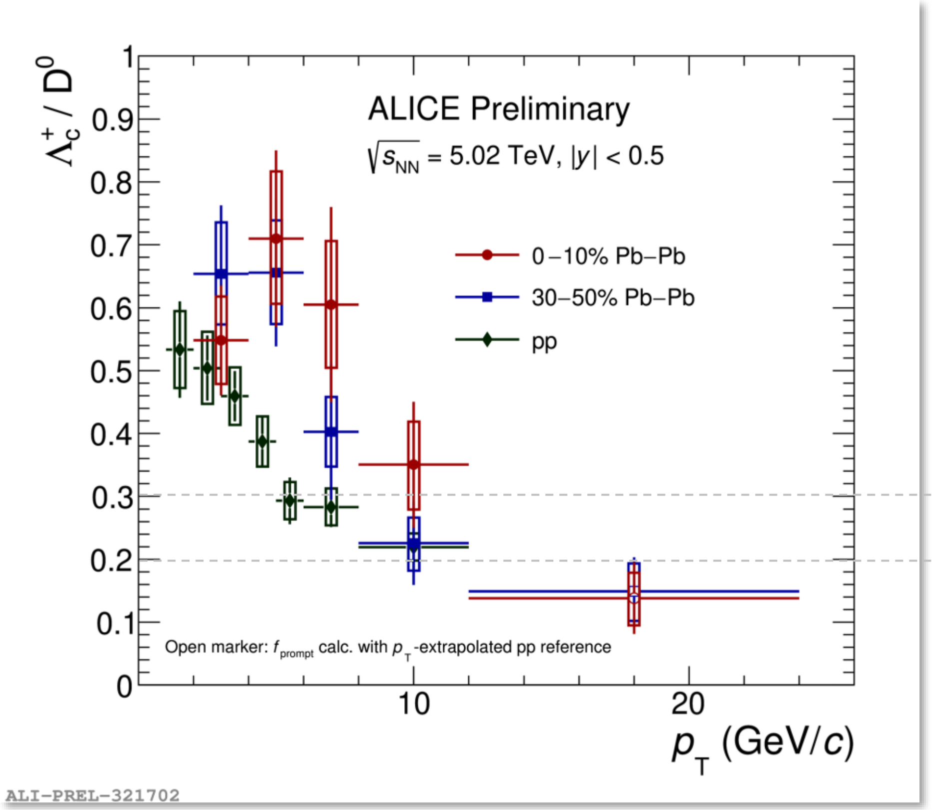
More on C. Terrevoli's talk: "Experimental results on open heavy flavour vs. multiplicity"

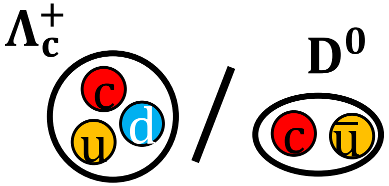
Λ_c^+/D^0 ratio in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

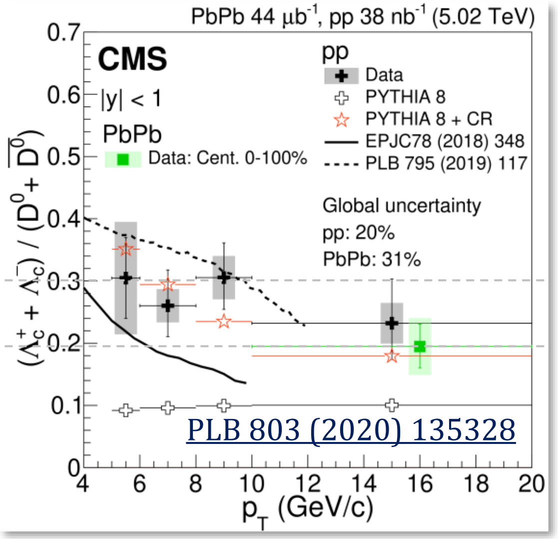
- Hint of higher Λ_c^+/D^0 ratio at intermediate p_T in Pb-Pb collisions than in pp

- Radial-flow push in Pb-Pb?
- Modification of hadronization?









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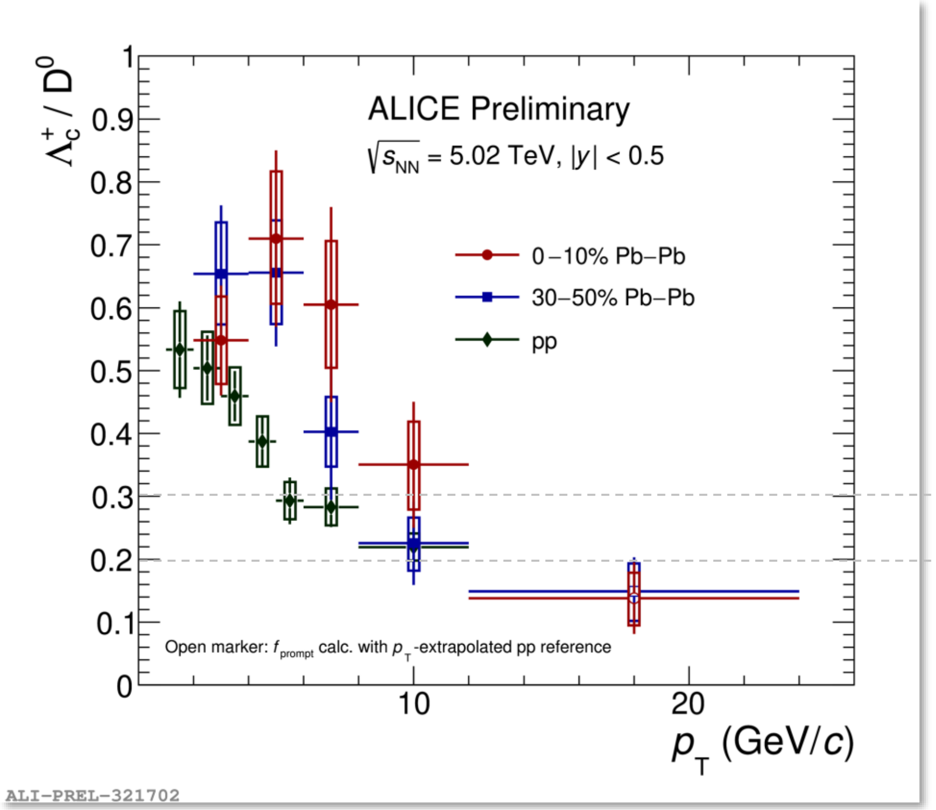

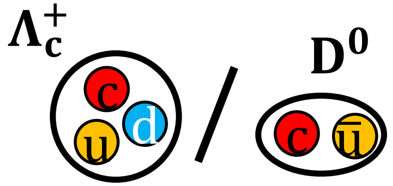

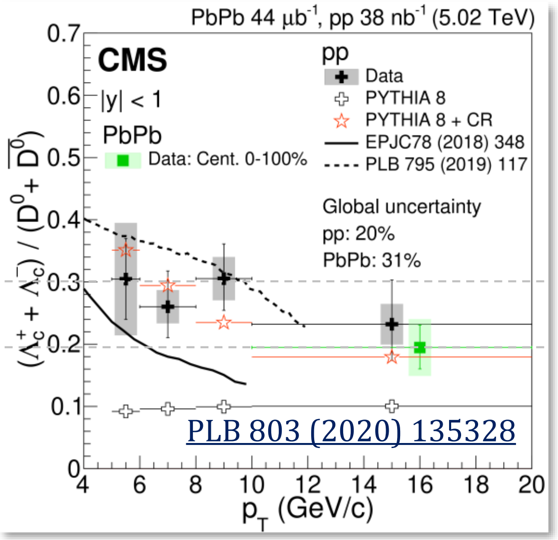

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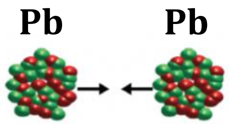
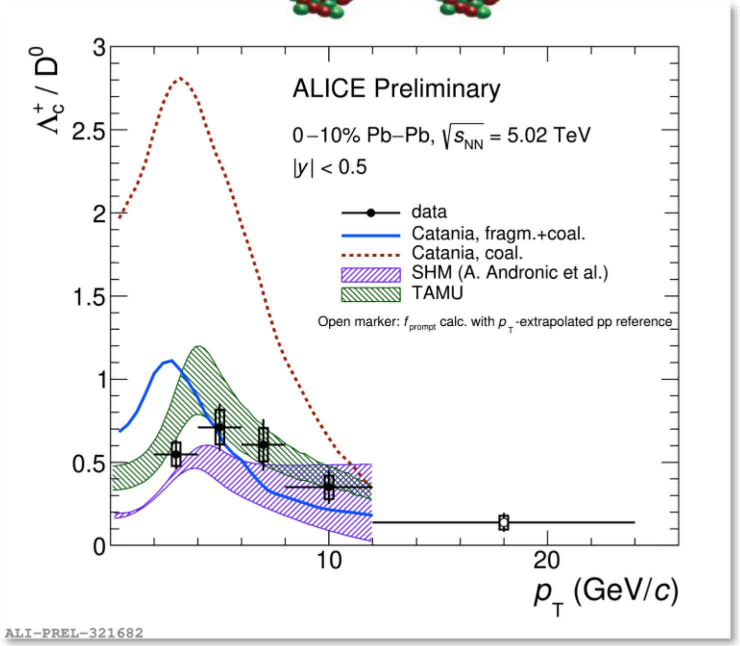


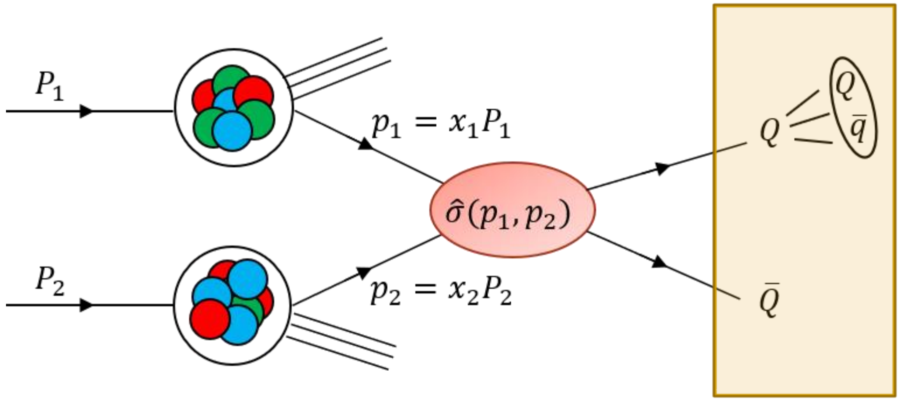


- Measurement described by:
  1. statistical hadronization models
  2. models implementing the heavy-quark hadronization via fragmentation + coalescence
- A pure coalescence picture fails

Summary

LHCb: CHIN. PHYS. C44 (2020) 022001
LHCb: PRL 124, 082002 (2020)
CMS: arXiv:2001.06533 [hep-ex]

- Standard picture for the **heavy flavour production** in pp collisions based on the factorization approach, assuming **universal fragmentation functions**
- Recent results from LHC show that this **assumption** is **no more valid** in **hadronic collisions** at LHC



- New mechanisms in place?
- Hidden relationship among collision systems?

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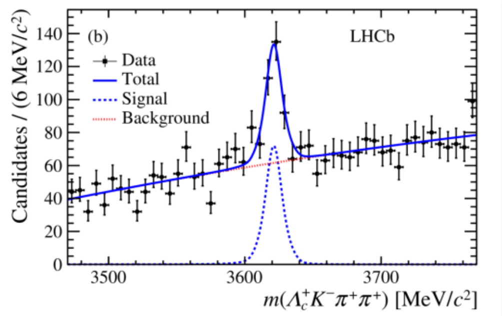
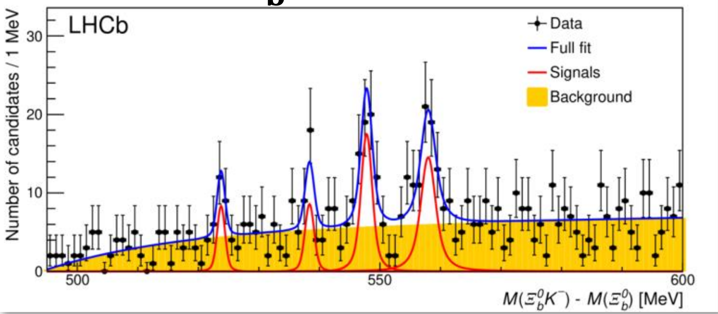
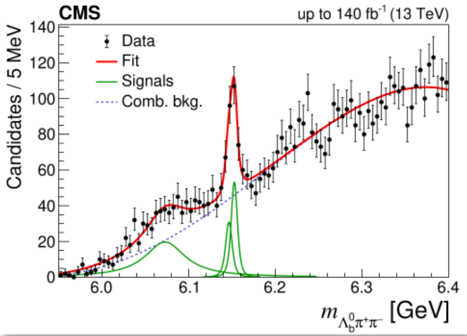
Ξ_{cc}^{++}



Excited Ω_b^- states





Excited Λ_b^0 states

- Further inputs on hadron structure from multi-HF production and spectroscopy measurements
- Joint effort between theory and experiments to investigate the baryon enhancement is necessary!

Thank you very much for your attention!

Backup

The role of Λ_c^+ and $\Sigma_c^{0,+,++}$

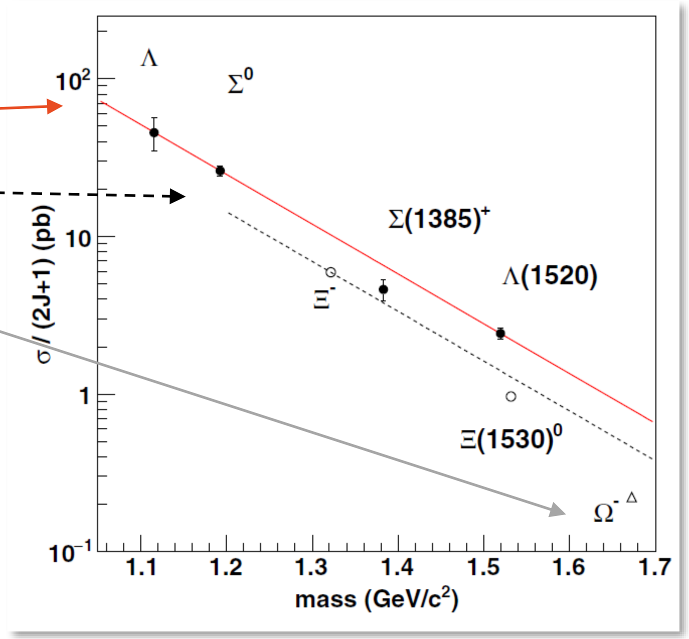
(PYTHIA 8)
$m(\mathrm{ud})_0 = 579$ MeV/c^2
$m(\mathrm{ud})_1 = 771$ MeV/c^2

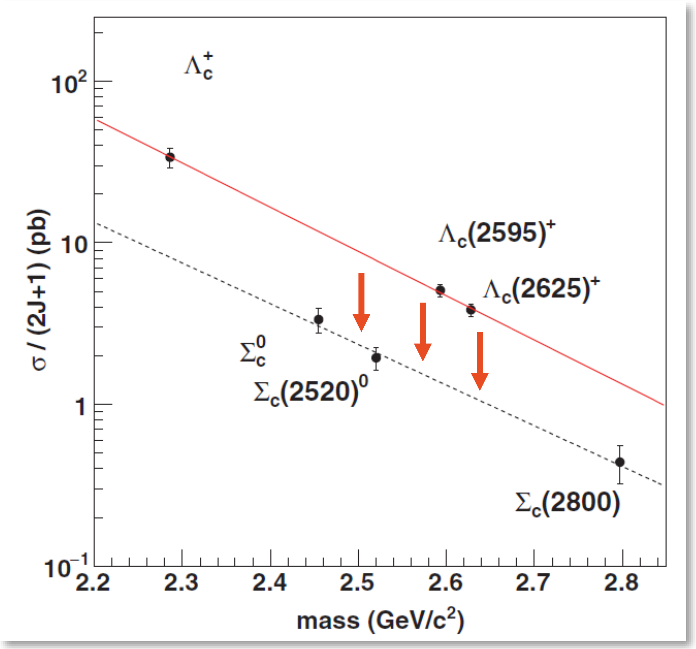
Belle, e^+e^- $\sqrt{s} = 10.52$ GeV
(Phys. Rev. D 97, 072005)

$f(m) = a_0 \exp(a_1 m)$

S = -1
S = -2
S = -3

Hierarchy driven by $s\bar{s}$ pair creation





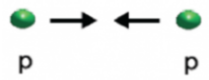
- In conventional fragmentation:
  - charm picks up a spin-0 $(\mathrm{ud})_0$ diquark $\rightarrow$ Λ_c^+ $(I = 0)$
  - charm picks up a spin-1 $(\mathrm{ud})_1$ diquark $\rightarrow$ Σ_c^+ $(I = 1)$

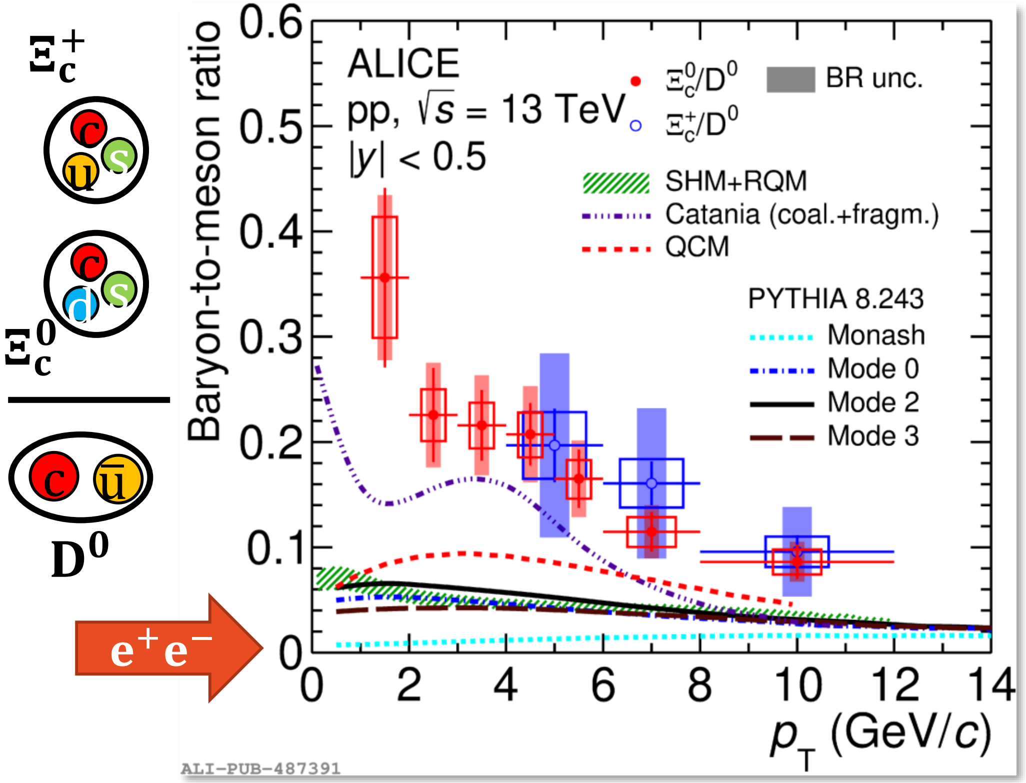
- $(\mathrm{ud})_1$ mass much larger than $(\mathrm{ud})_0$
  $\Rightarrow$ production of Σ_c states expected to be suppressed compared to Λ_c^+

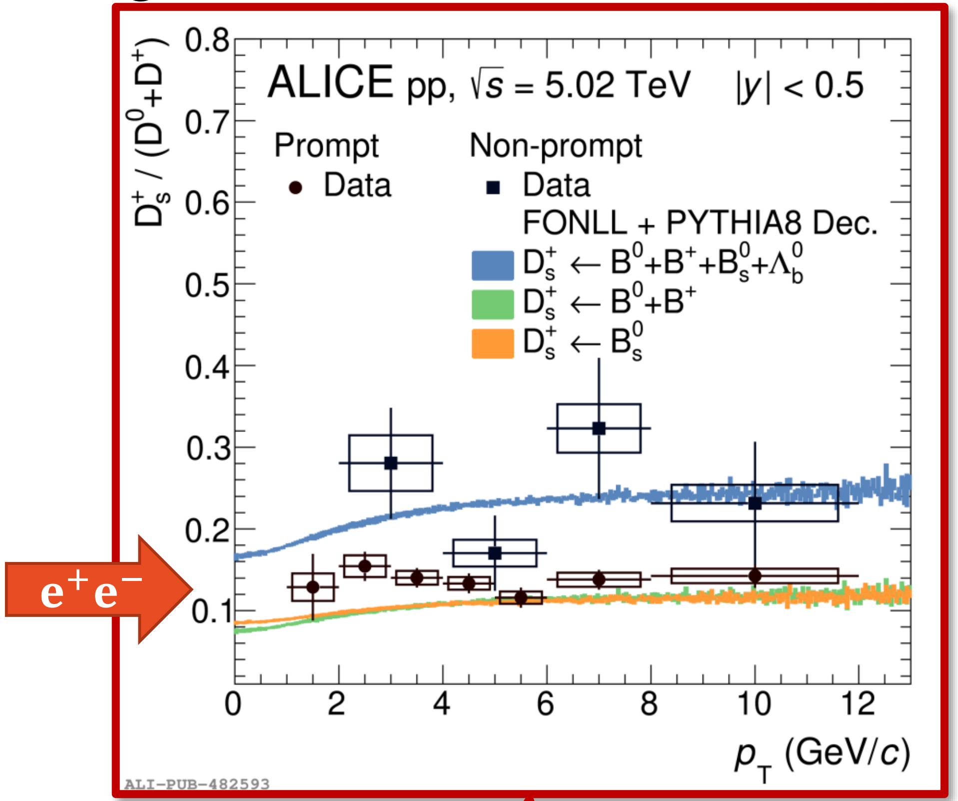
- Σ_c-state production suppressed by ~3-4 times that of excited Λ_c^+ states in e^+e^- collisions at $\sqrt{s} = 10.52$ GeV

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

$\sqrt{s} = 13$ TeV







- $\Xi_c^{0,+}/D^0$ shows clear p_T dependence and is **larger** than e^+e^-
- Significantly **underestimated** by models
  - Something anomalous with strange quarks?
  - $D_s^+/(D^0 + D^+)$ compatible with expectations from e^+e^- $\longrightarrow$ baryons are 'strange'
- Catania (fragm. + coal.) works better

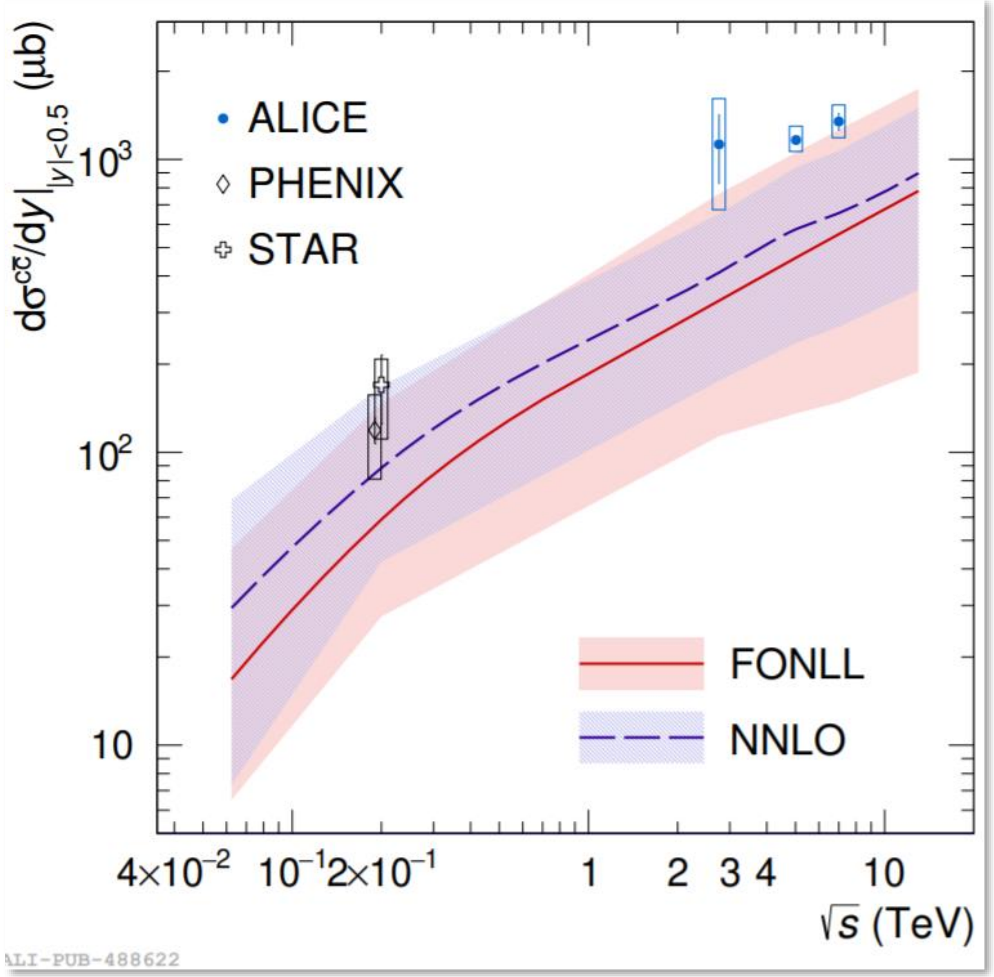
$c\bar{c}$ cross section in pp collisions

$\sqrt{s} = 5.02$ TeV

p p

NEW

ALICE: arXiv:2105.06335



FONLL: JHEP 1210 (2012) 137
NNLO: PRL 118 (2017) 122001, JHEP 03 (2021) 029
PHENIX: Phys. Rev. C 84 (2011) 044905
STAR: Phys. Rev. D 86 (2012) 072013

- **$c\bar{c}$ production cross section** at midrapidity in **pp collisions at $\sqrt{s} = 5.02$ TeV** measured as sum of ground state hadron cross sections

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

- **Results previously published** at $\sqrt{s} = 2.76$ and 7 TeV from D mesons **updated** with fragmentation fractions from $\sqrt{s} = 5.02$ TeV analysis
  → **40% increase**
- **Higher** values driven by the observed **baryon enhancement** in pp collisions
- Results on **upper edge of FONLL and NNLO** calculations