Charm production and hadronisation in proton–proton, proton–Pb and Pb–Pb collisions with ALICE at the LHC

A. Rossi (Padua INFN)
on behalf of the ALICE Collaboration

5 - 10 September 2021

Physics motivation

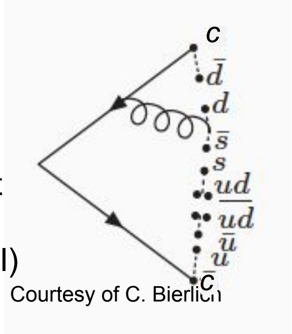
Heavy Quarks (charm and beauty) are produced only in hard-scattering processes with cross section calculable with pQCD

→ **"perturbative" probes of transition from quarks to hadrons in all collision systems**
→ measurement of cross sections and relative abundances of charm-hadron species provides a test for models incorporating (semi)dynamical description of hadronisation or based on a statistical approach

Main hadronisation model categories (in a simplified scheme)

Fragmentation "in vacuum"

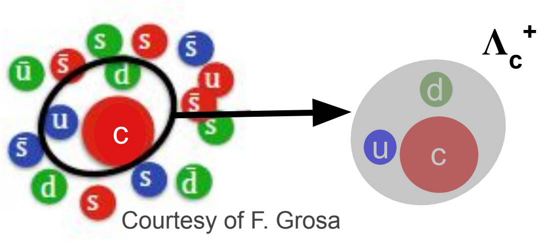
Light quark/diquark pairs popping out from QCD color-confinement potential (← strings in Lund model)



Reproduces phenomenological fragmentation functions used in pQCD-based calculations

Coalescence

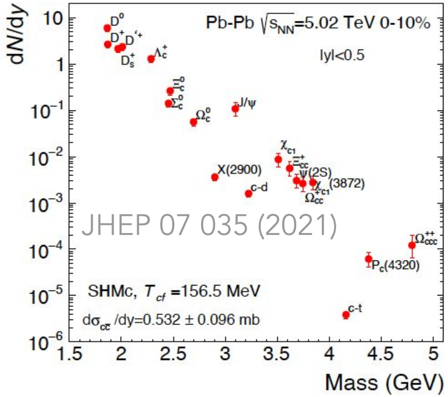
Combine already existing quarks



Originally introduced and thought to be suited for nucleus-nucleus collisions

Statistcal hadronisation

Yields defined only by hadron masses and system properties

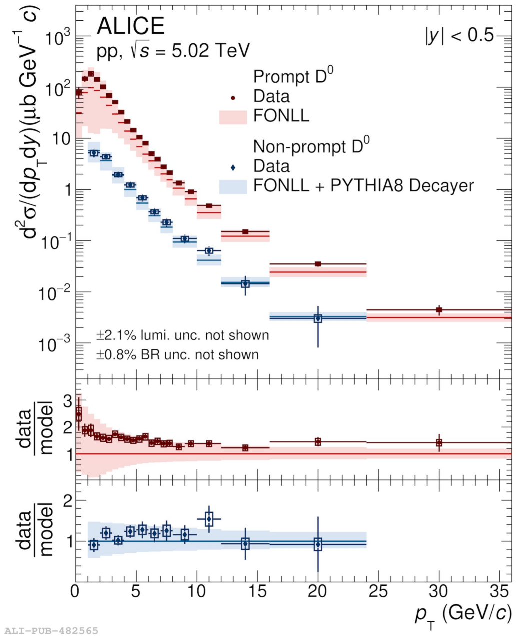


Factorisation: a very successful framework for HF mesons!

$$\frac{d\sigma^D}{dp_T}(p_T^D;\mu_F;\mu_R) = PDF(x_1,\mu_F)\,PDF(x_2,\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1,x_2;\mu_F;\mu_R) \otimes D_{c\to D}\left(z=\frac{p_D}{p_c};\mu_F\right)$$

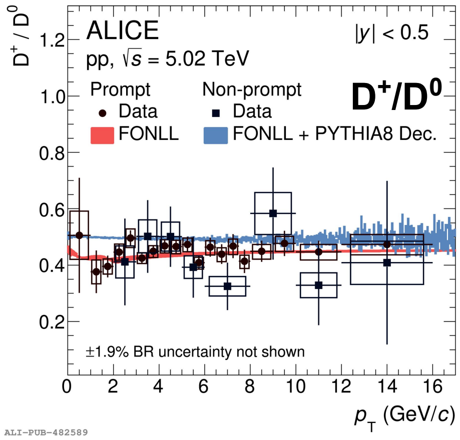
Fragmentation functions ($D_{c\to D}$) often **assumed** "**universal**": once constrained to e^+e^- and ep data they are used in different collision systems and energies.

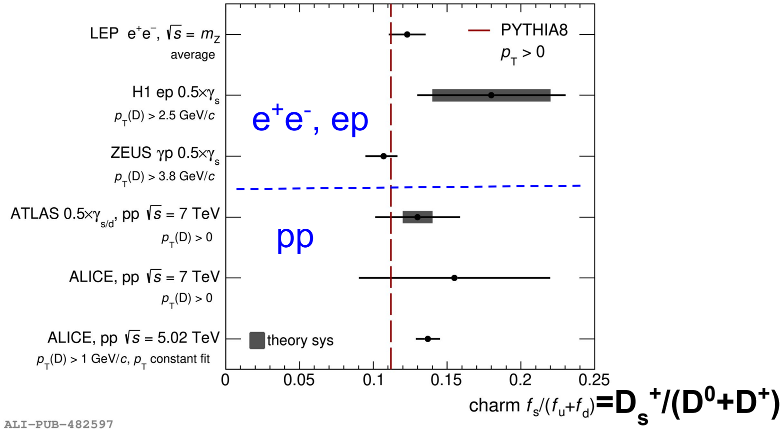
Naïve expectation: ratios of particle-species yields independent from collision system



JHEP 05 (2021) 220

FONLL: JHEP 10 (2012) 137





Prompt and non-prompt D mesons (including D_s^+) follow expectations… **does it hold for baryons?**

Up to what extent fragmentation functions tuned on e^+e^- can be effective in pp or heavy-ion collisions?

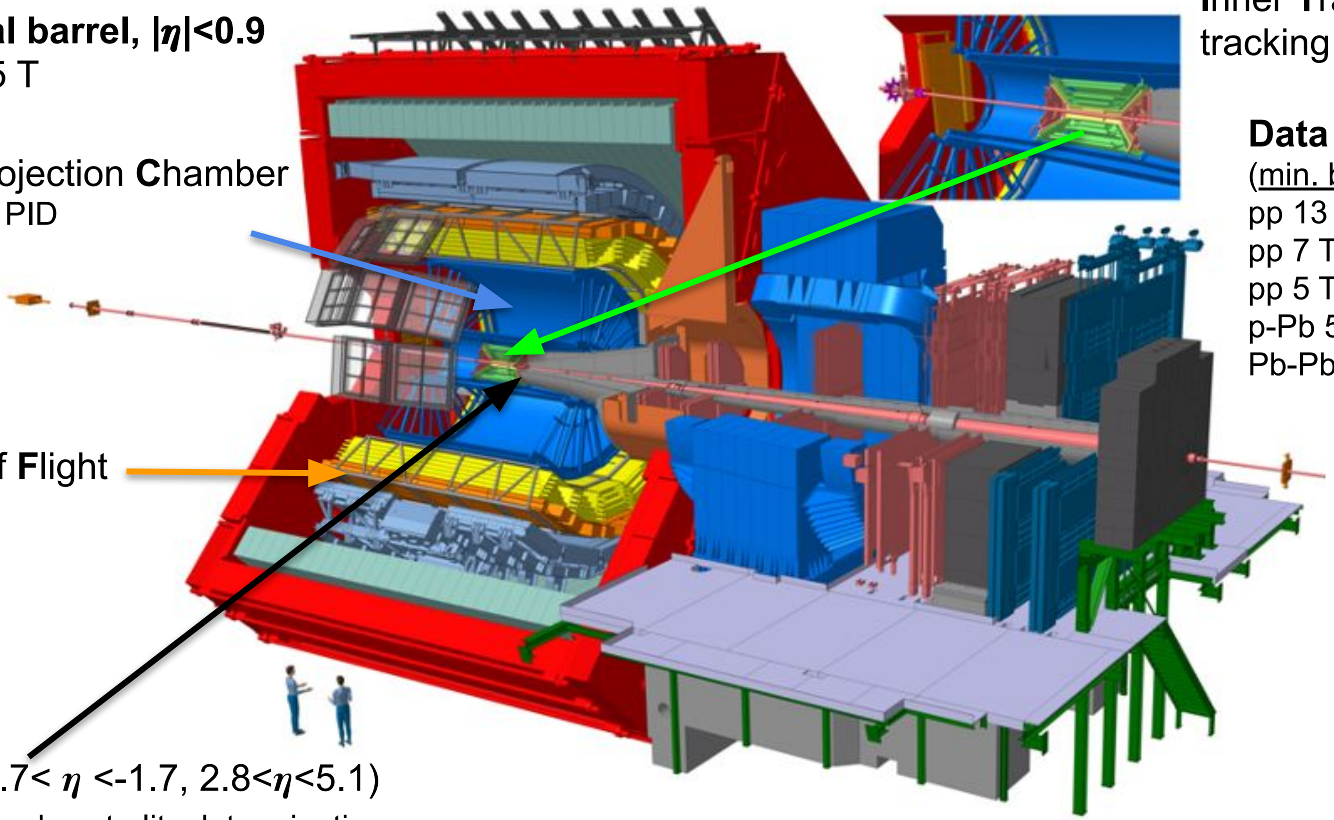
ALICE apparatus

Central barrel, |η|<0.9
B = 0.5 T

Time **P**rojection **C**hamber
Tracking, PID

Time **O**f **F**light
PID

V0 (-3.7< η <-1.7, 2.8<η<5.1)
trigger and centrality determination



Inner **T**racking **S**ystem
tracking and vertexing

Data samples
(min. bias trigger)

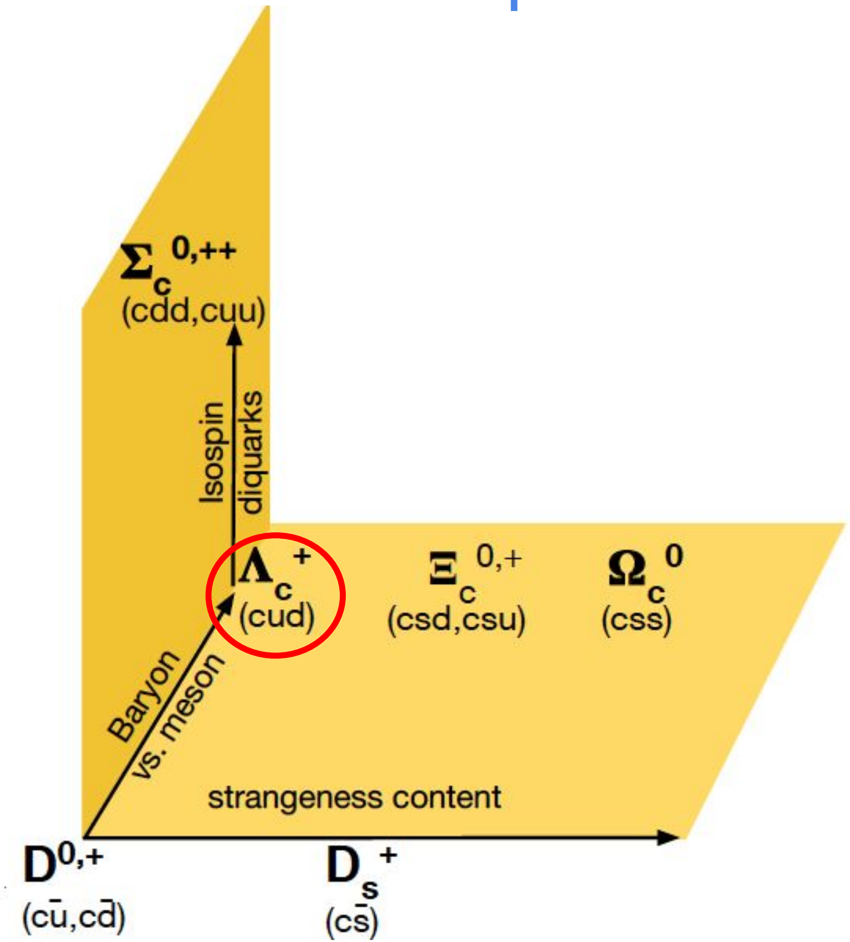
pp 13 TeV	~ 32 nb^{-1}
pp 7 TeV	~ 6 nb^{-1}
pp 5 TeV	~ 19 nb^{-1}
p-Pb 5.02 TeV	~ 292 μb^{-1}
Pb-Pb 5.02 TeV	~ 114 μb^{-1} (0-10%)

Decay channels

$D^0 \rightarrow K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$
$D_s^+ \rightarrow \phi(\rightarrow K^-K^+)\pi^+$
$D^{*+} \rightarrow D^0\pi^+$

$\Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c^+ \rightarrow pK_s^0$
$\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$
$\Xi_c^0 \rightarrow \Xi^-\pi^+$, $\Xi_c^0 \rightarrow \Xi^-e^+\nu_e$
$\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
$\Omega_c^0 \rightarrow \Omega^-\pi^+$

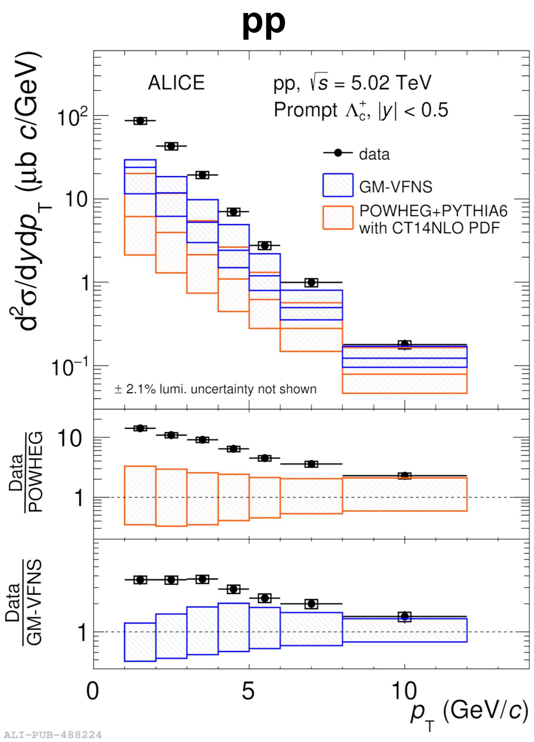
Several arrows in the quiver

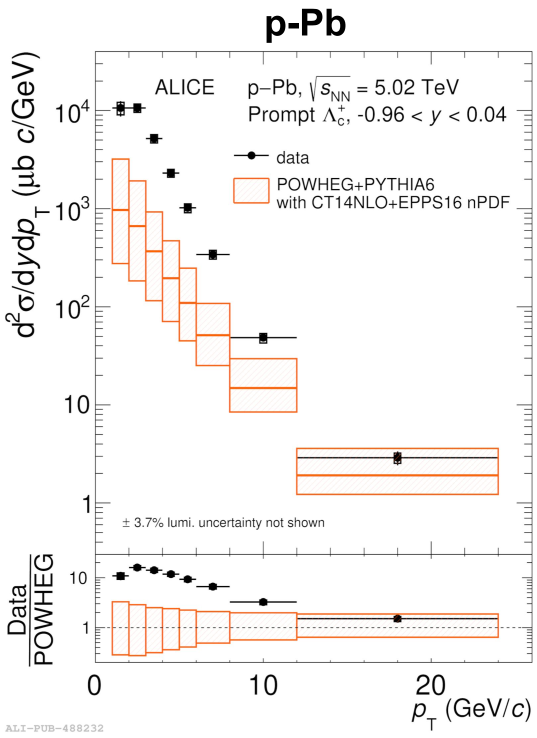


Particle	Mass (GeV/c^2)
D^0	1.865
D^+	1.870
D_s^+	1.968
Λ_c^+	2.286
$\Sigma_c^{0,++}$	2.454
Ξ_c^0	2.470
Ξ_c^+	2.468
Ω_c^0	2.695

Λ_c^+ cross section in pp and p-Pb collisions at $\sqrt{s_{NN}}$= 5 TeV

arXiv:2011.06079
arXiv:2011.06078

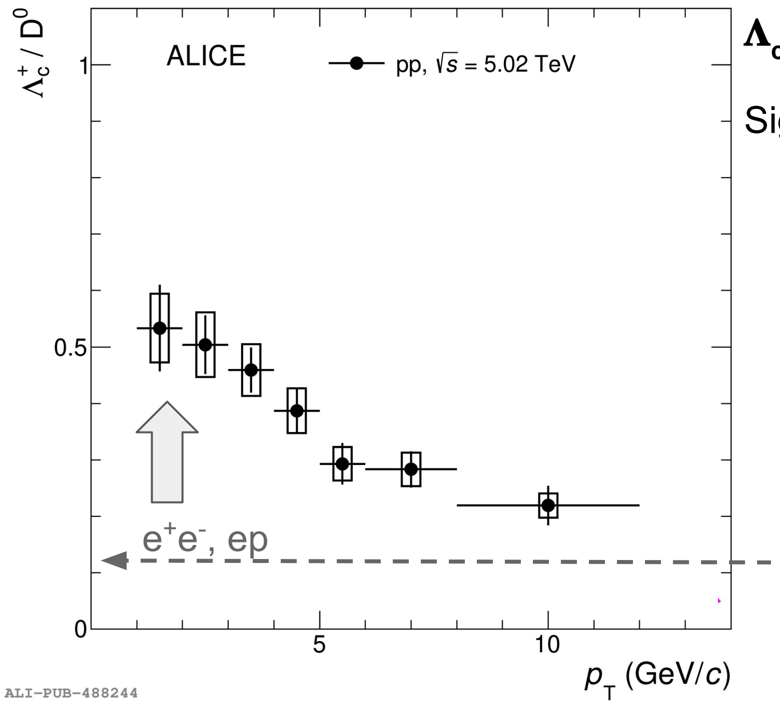




Λ_c^+ production significantly underestimated by pQCD-based models

GM-VFNS: PRD 101 (2020) 114021
POWHEG: JHEP 09 (2007) 126
PYTHIA6: JHEP 05 (2006) 026
CT14 NLO: Phys. Rev. D 93, 033006 (2016)

Λ_c^+/D^0 ratio in pp collisions at 5 TeV



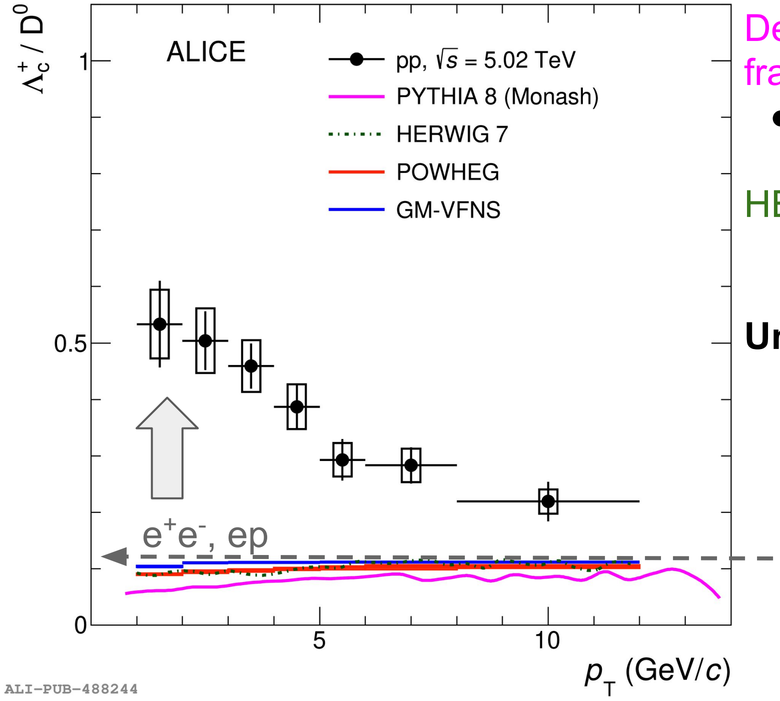
arXiv:2011.06079
arXiv:2011.06078

Λ_c^+/D^0 ratio higher (x4-5) values at low p_T than e^+e^-, ep

Significantly decreasing with p_T

	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)	Notes
ALICE	$0.51 \pm 0.04 \pm 0.04^{+0.01}_{-0.02}$	pp	5020	$p_T > 0, \lvert y \rvert < 0.5$
ALICE	$0.43 \pm 0.03 \pm 0.05^{+0.05}_{-0.03}$	p–Pb	5020	$p_T > 0, -0.96 < y < 0.04$
CLEO [16]	$0.119 \pm 0.021 \pm 0.019$	e^+e^-	10.55	
ARGUS [15, 17]	0.127 ± 0.031	e^+e^-	10.55	
LEP average [18]	$0.113 \pm 0.013 \pm 0.006$	e^+e^-	91.2	
ZEUS DIS [21]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	e^-p	320	$1 < Q^2 < 1000$ GeV^2, $0 < p_T < 10$ GeV/c, $0.02 < y < 0.7$
ZEUS γp, HERA I [19]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	e^-p	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert \eta \rvert < 1.6$
ZEUS γp, HERA II [20]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	e^-p	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert \eta \rvert < 1.6$

Λ_c^+/D^0 ratio in pp collisions at 5 TeV



arXiv:2011.06079
arXiv:2011.06078

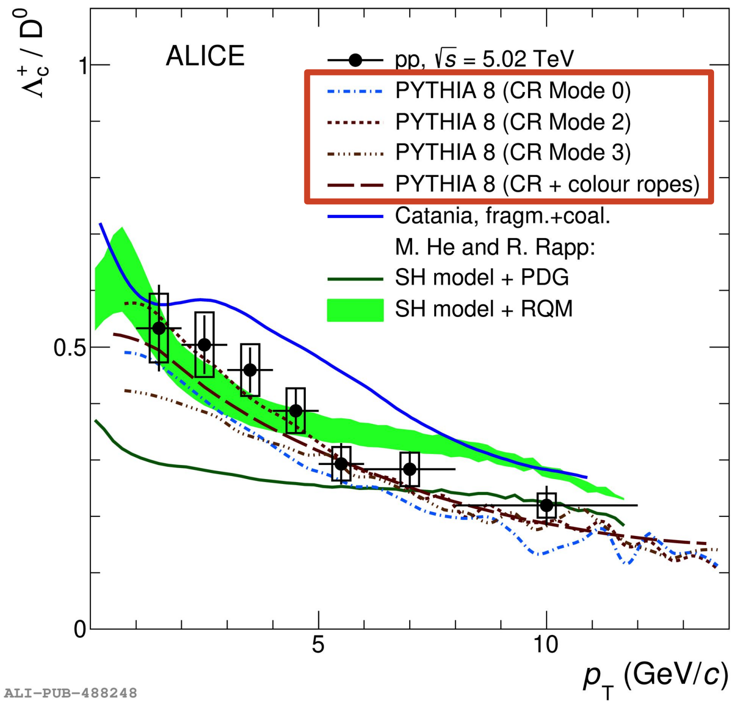
Default PYTHIA8 (Monash, EPJC 74 (2014) 3024), standard Lund string fragmentation

- Hadronisation of different MPI products largely independent

HERWIG7 (EPJC 58 (2008) 639-707), cluster hadronisation

Undershoot data by factor about 5 and do not catch p_T shape

Λ_c^+/D^0 ratio in pp collisions at 5 TeV

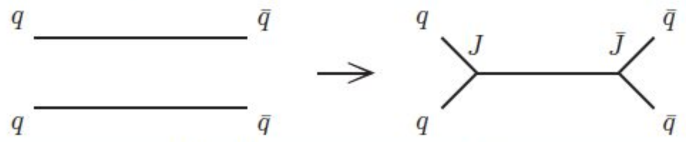


arXiv:2011.06079
arXiv:2011.06078

Data described by:

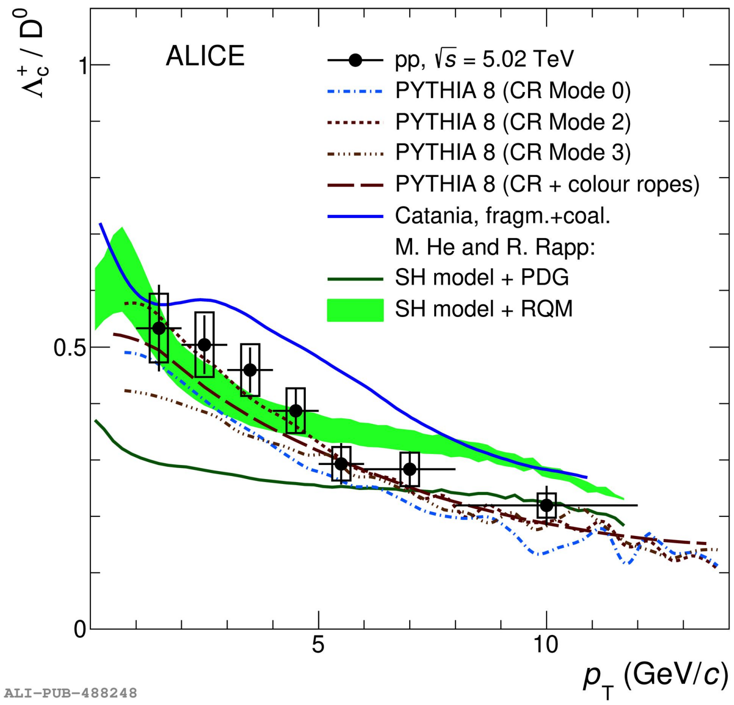
PYTHIA8 with String Formation beyond Leading Colour approximation (JHEP 1508 (2015) 003).
More complete and realistic (=closer to QCD) colour-reconnection (CR) scheme
- ***"...between which partons do confining potentials arise?"***

Junction reconnection topologies → enhance baryons.



(b) Type II: junction-style reconnection

Λ_c^+/D^0 ratio in pp collisions at 5 TeV



arXiv:2011.06079
arXiv:2011.06078

Data described by:

PYTHIA8 with String Formation beyond Leading Colour

Catania model: coalescence + "vacuum" fragmentation

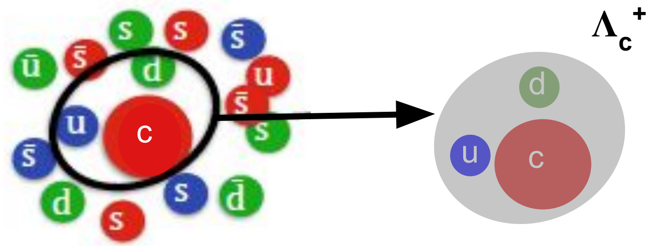
(arxiv.org 2012.12001)

Expanding system of thermalised light quarks and gluons

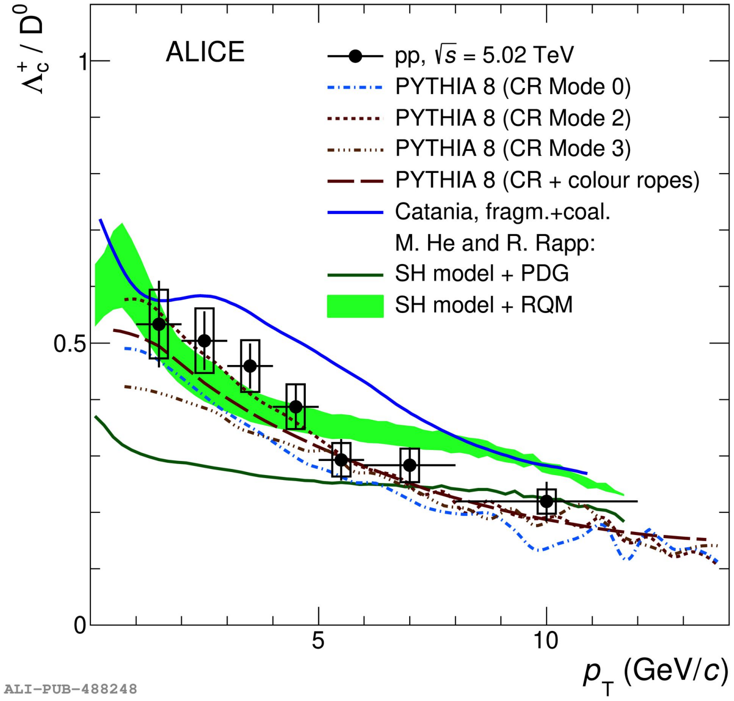
"Sudden" (fixed temperature) coalescence

Coalescence probability from Wigner formalism

Charm quarks that do not coalesce, fragment



Λ_c^+/D^0 ratio in pp collisions at 5 TeV



arXiv:2011.06079
arXiv:2011.06078

Data described by:

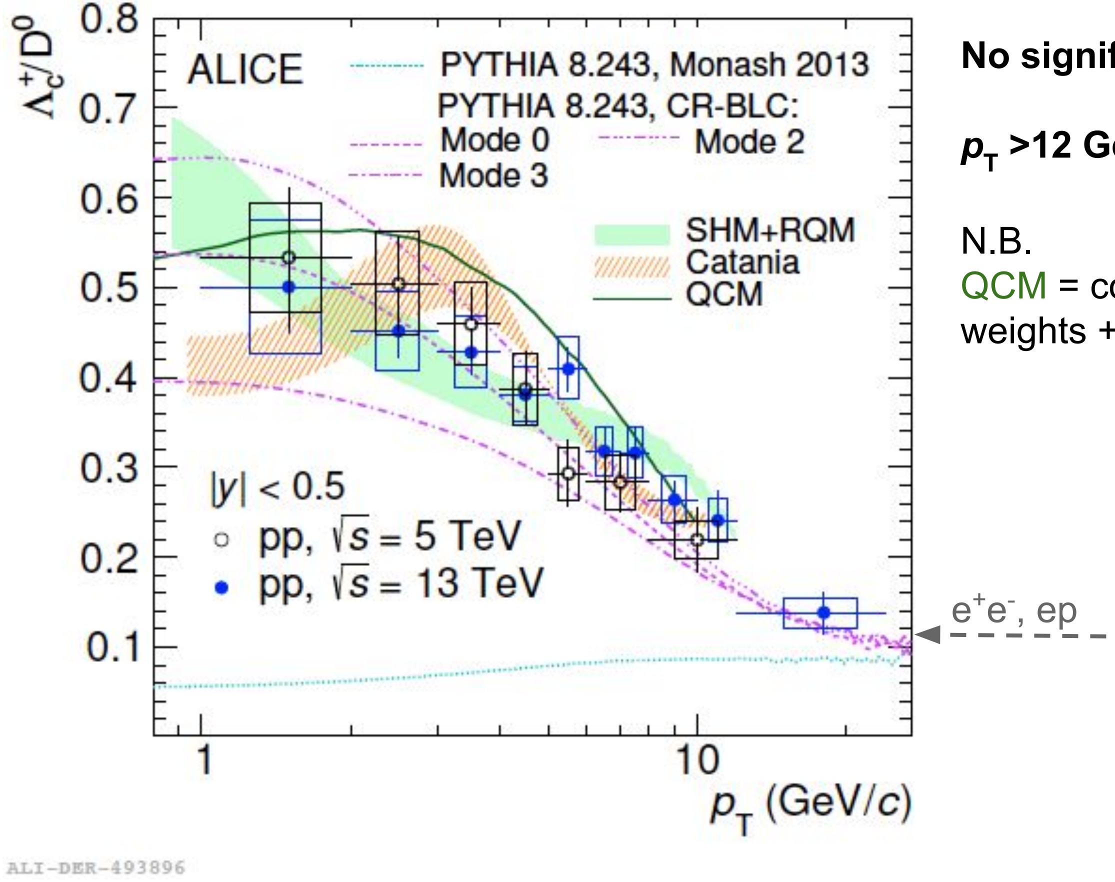
PYTHIA8 with String Formation beyond Leading Colour

Catania model: coalescence + "vacuum" fragmentation

SH+PDG/RQM, PLB 795 117-121 (2019):
Hadron abundances based on **statistical hadronisation model** + (RQM) large feed-down from **augmented set of charm-baryon states**

Λ_c^+/D^0 ratio in pp collisions at 5 TeV and 13 TeV

arxiv 2106.08278



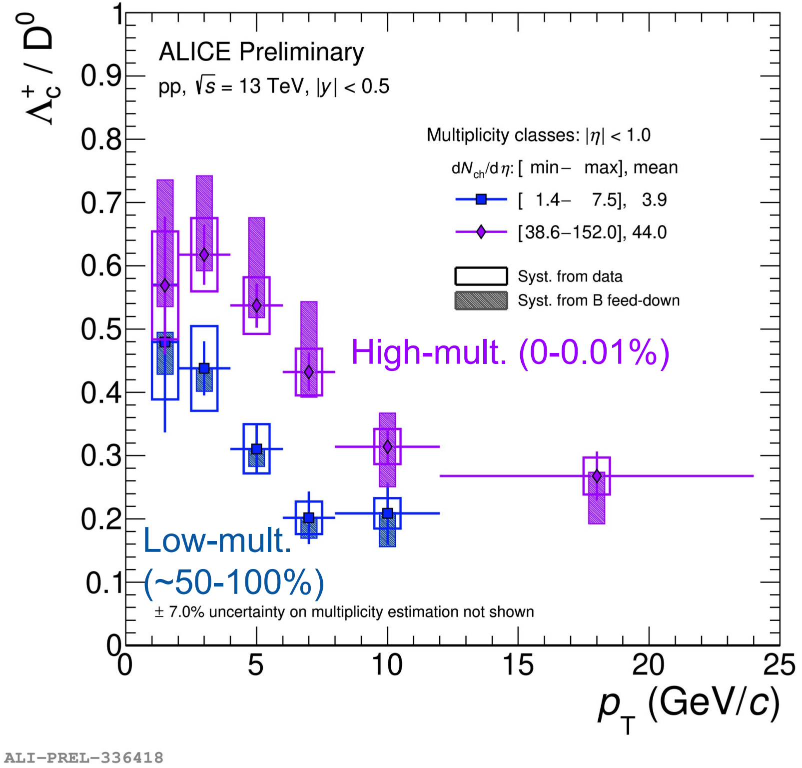
No significant dependence on collision energy

p_T >12 GeV/c: approaching e^+e^- values?

N.B.

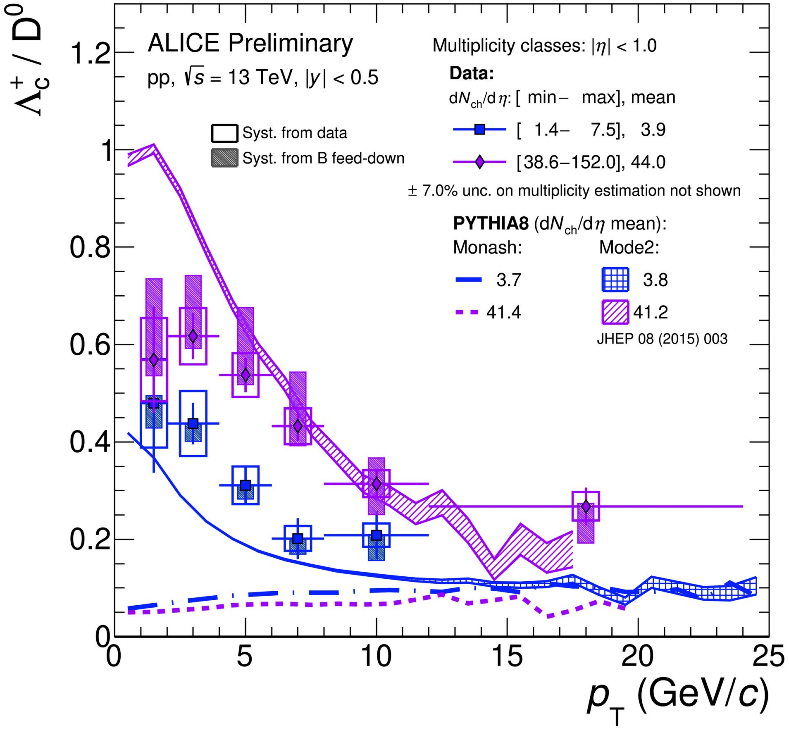
QCM = coalescence model based on statistical weights + “equal quark-velocity” (EPJC 78, 2018 4, 344)

Λ_c^+/D^0 evolution with event activity: pp



Λ_c^+/D^0 increases with particle multiplicity at midrapidity

Λ_c^+/D^0 evolution with event activity: pp



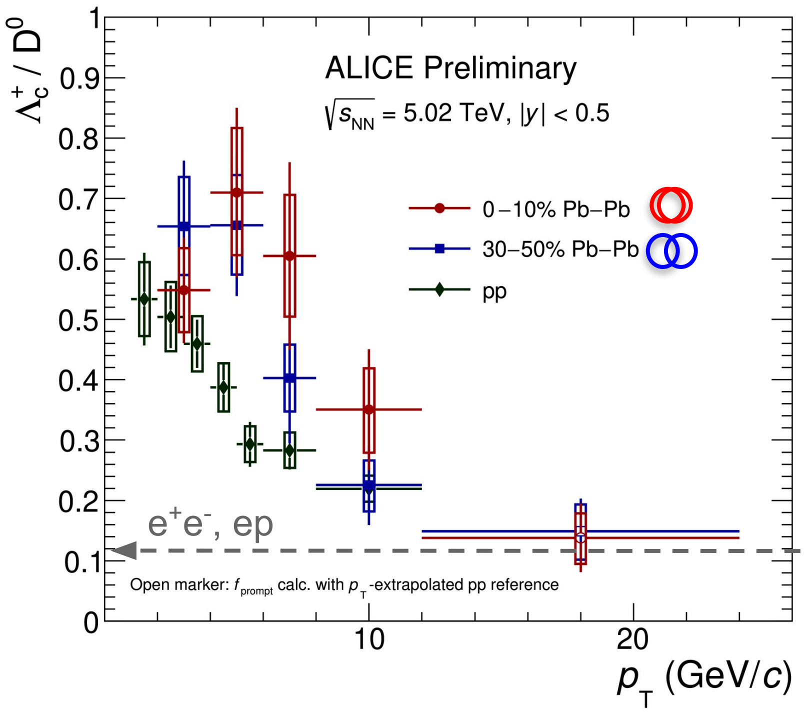
ALI-PREL-336442

Λ_c^+/D^0 increases with particle multiplicity at midrapidity

Trend expected by **PYTHIA8 with String Formation beyond Leading Colour (Mode 2)**
→ confirms importance of Colour Reconnection in rich partonic environments
→ **interplay of Color Reconnection (CR) and Multiple Parton Interactions**

Do we have a smooth evolution with multiplicity from (e^+e^- to) pp to AA?

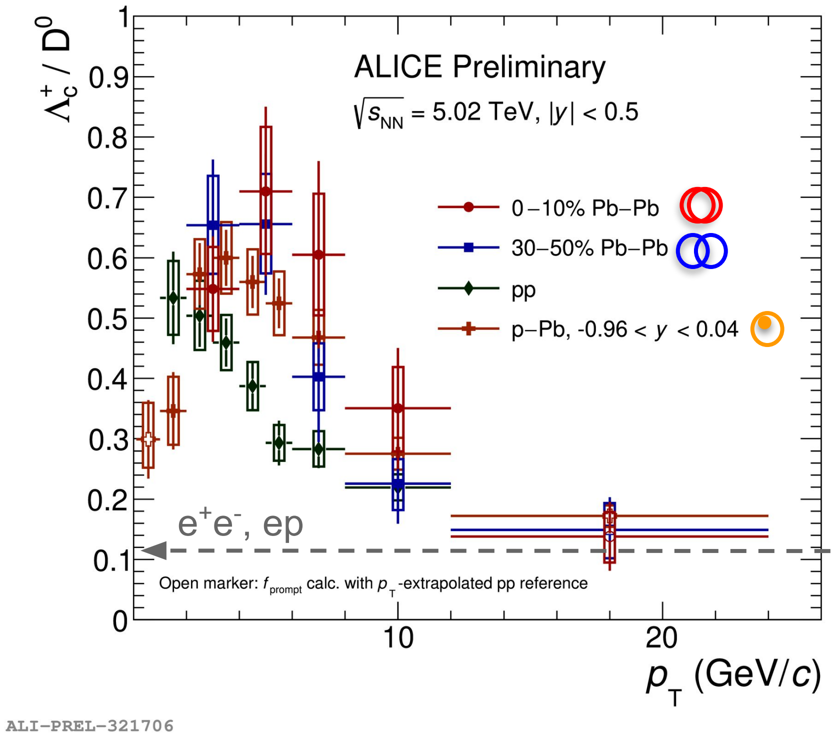
Λ_c^+/D^0 evolution with event activity: from pp to Pb-Pb



ALI-PREL-321702

- Λ_c^+/D^0 in Pb-Pb collisions higher than in pp collisions at intermediate p_T
- Similar in 0-10% and 30-50% centrality
- Close to high-multiplicity pp collisions
- Larger "jump" from e^+e^- to pp than from pp to Pb-Pb

Λ_c^+/D^0 evolution with event activity: from pp to Pb-Pb



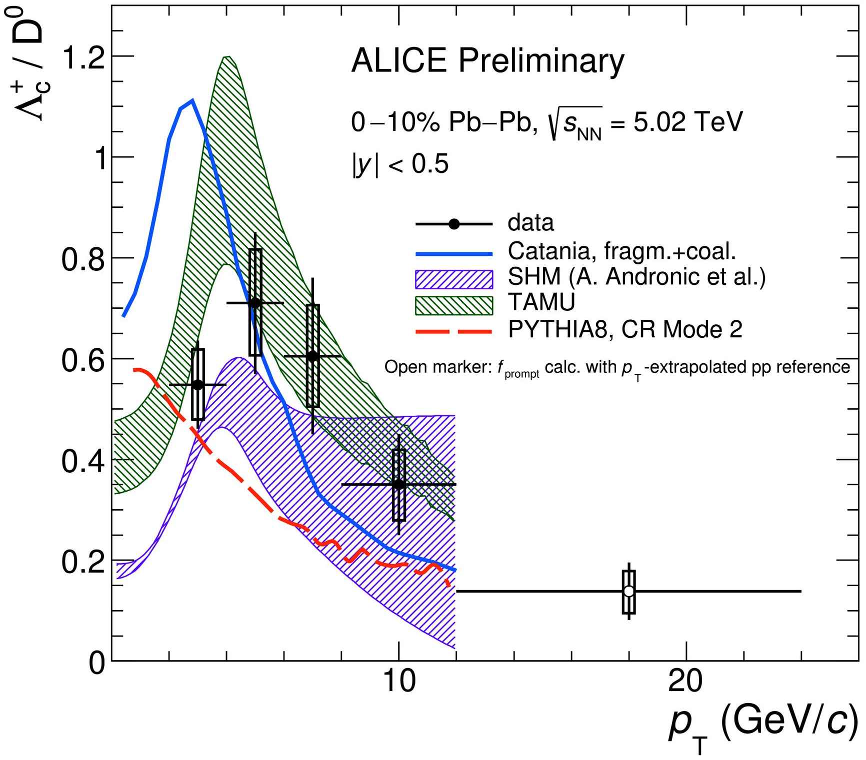
- Λ_c^+/D^0 in Pb-Pb collisions higher than in pp collisions at intermediate p_T
- Similar in 0-10% and 30-50% centrality
- Close to high-multiplicity pp collisions
- Larger "jump" from e^+e^- to pp than from pp to Pb-Pb
- p-Pb in-between pp and Pb-Pb
  - Measured down to $p_T \approx 0$ → Highlights importance to study evolution of p_T-integrated yield with multiplicity

Λ_c^+/D^0 in Pb-Pb collisions vs. models

Models

- Including hadronisation via coalescence (Catania, TAMU)
- based on Statistical Hadronisation (SHM)

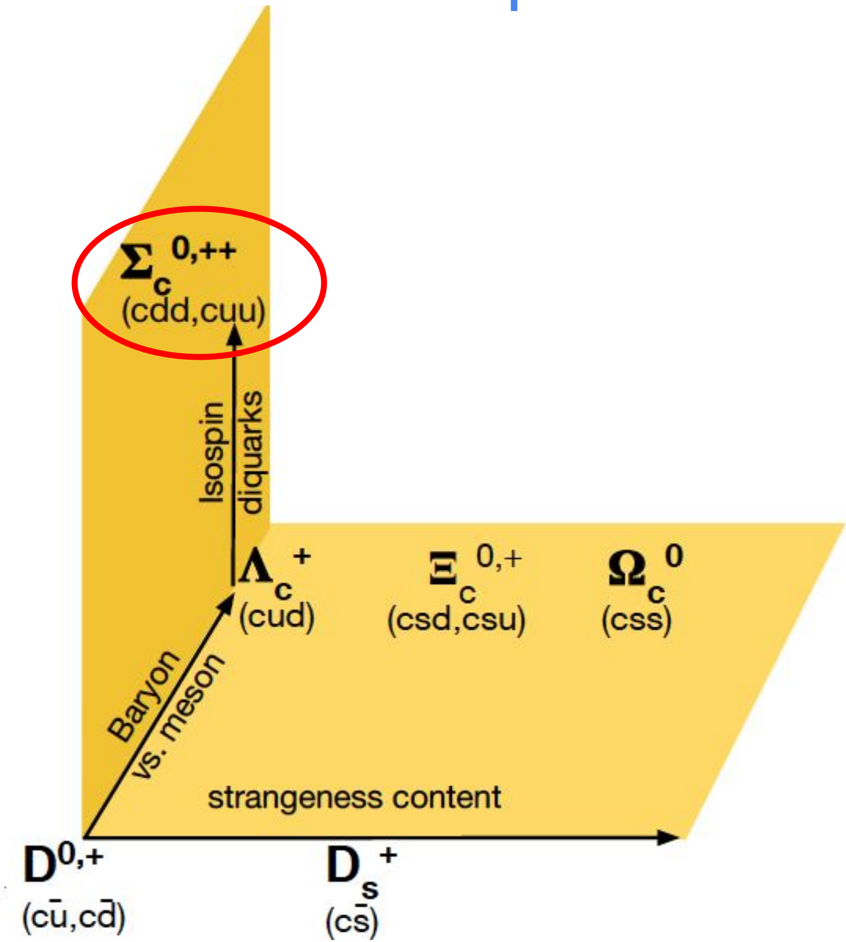
describe the data within uncertainties



ALI-PREL-325749

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

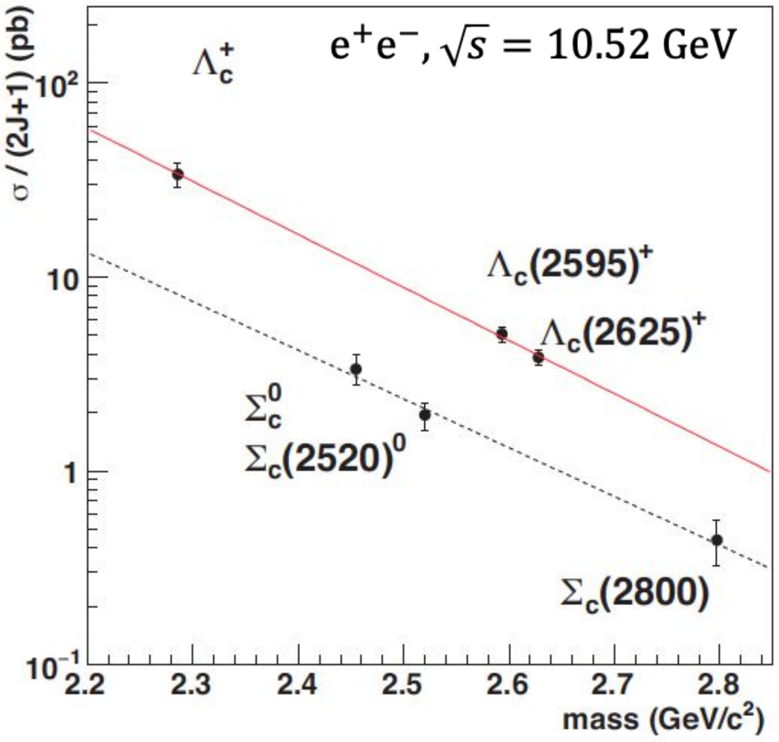
Several arrows in the quiver



Particle	Mass (GeV/c^2)
D^0	1.865
D^+	1.870
D_s^+	1.968
Λ_c^+	2.286
$\Sigma_c^{0,++}$	2.454
Ξ_c^0	2.470
Ξ_c^+	2.468
Ω_c^0	2.695

$\Sigma_c^{0,++}$ production and $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$ feedown

Belle, PRD 97, 072005 (2018)



e^+e^- collisions: production of $\boldsymbol{\Sigma}_c$ states suppressed w.r.t. $\boldsymbol{\Lambda}_c$ states

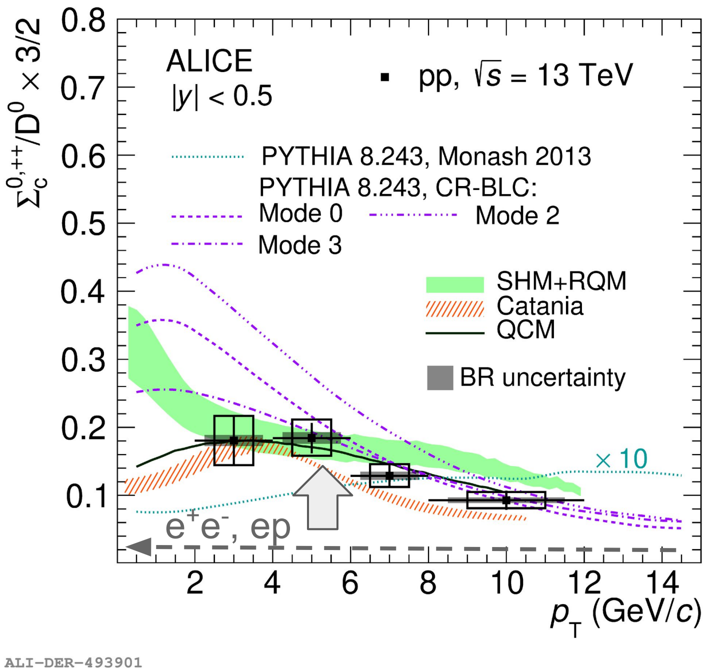
In string fragmentation models charm baryons formed by combining initially produced c quarks with light-quark diquarks, produced in pair in string breaking

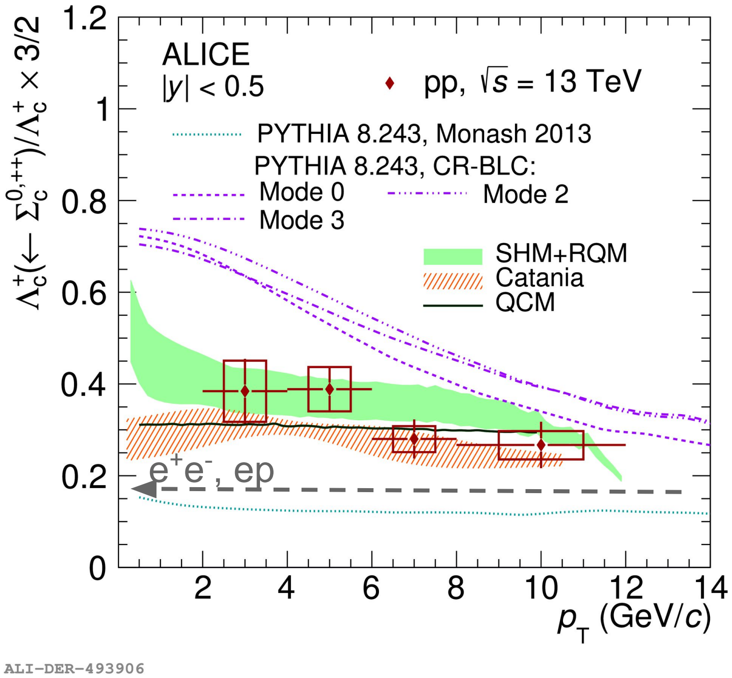
$\boldsymbol{\Lambda}_c$ (isospin = 0) needs diquark with spin = 0 $(ud)_0$
$\boldsymbol{\Sigma}_c$ (isospin = 1) needs diquark with spin = 1 $(ud,dd,uu)_1$

$(ud,dd,uu)_1$ larger mass than $(ud)_0$ mass → suppression

$\Sigma_c^{0,++}$/D^0 and $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feedown in pp at 13 TeV

arxiv 2106.08278





$\Sigma_c^{0,+,++}$/D^0 ratio significantly larger than in e$^+$e$^-$ collisions

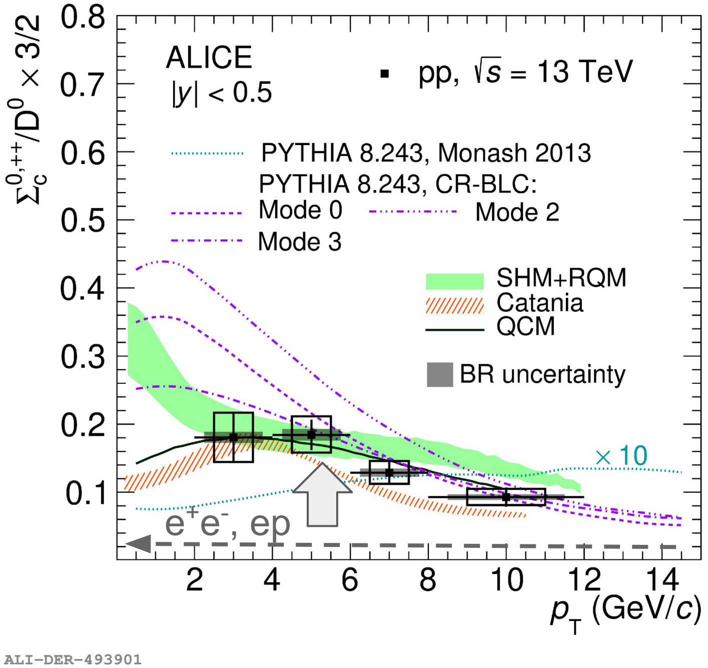
About x2 increase of $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feed-down → $\Sigma_c^{0,+,++}$ "enhancement" larger than Λ_c^+ one

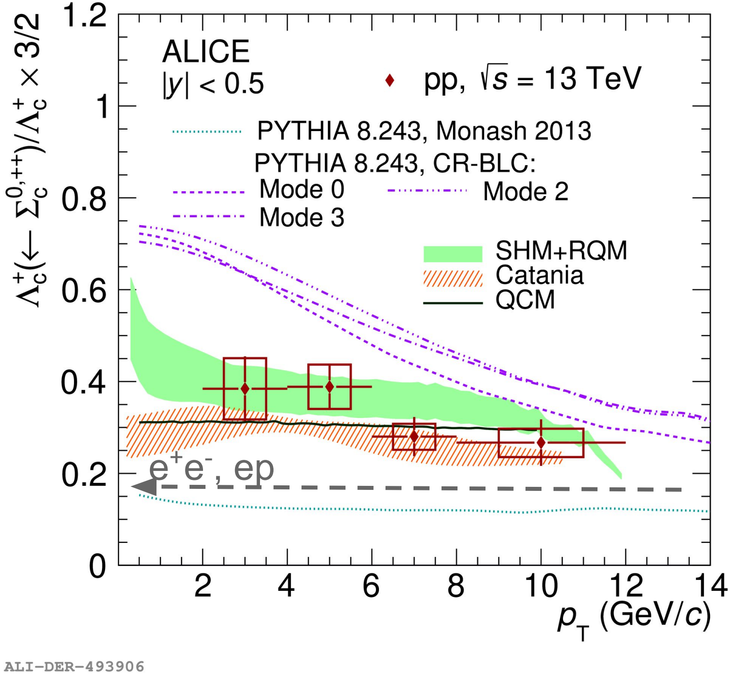
→ $\Sigma_c^{0,+,++}$produced differently in pp than e$^+$e$^-$ collisions

→ suppression from $(ud,dd,uu)_1$ diquark creation absent or reduced, as comparison to models suggests

$\Sigma_c^{0,++}$/D^0 and $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feedown in pp at 13 TeV

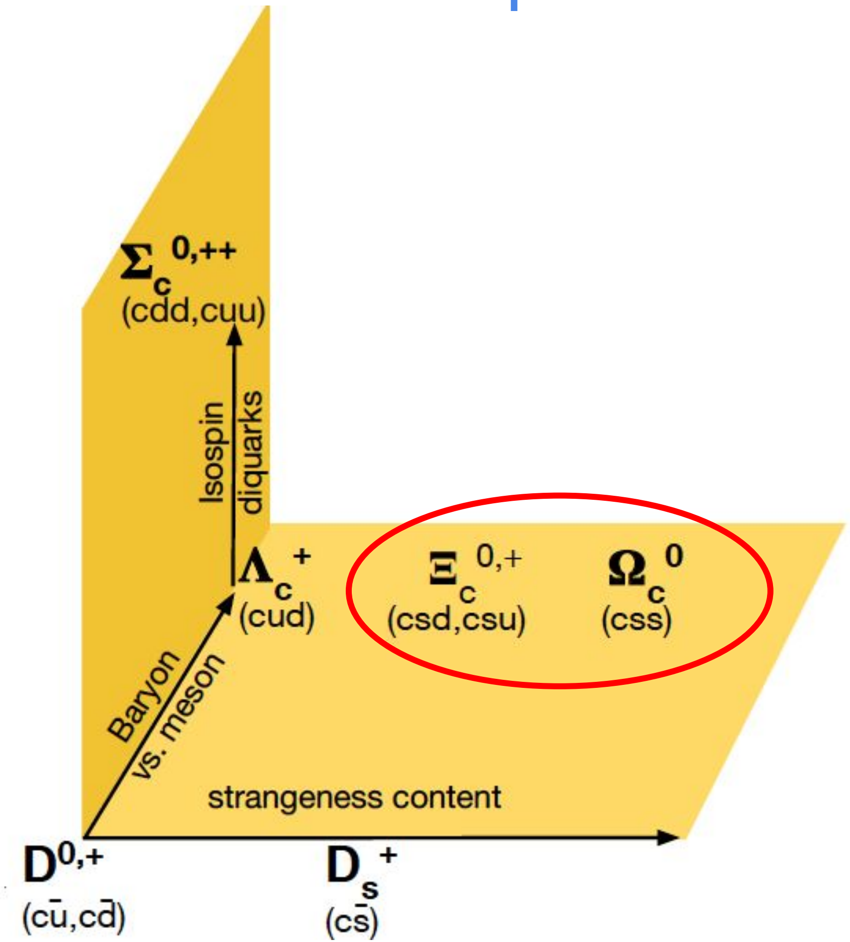
arxiv 2106.08278





- Default PYTHIA8 (Monash 2013): significantly underestimates data
- PYTHIA8 with CR beyond Leading Colour: Σ_c enhanced by junction CR topologies
  - describes $\Sigma_c^{0,+,++}$/D^0 but overestimates $\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$/D^0
- Catania, QCM and SHM+RQM models describe both ratios

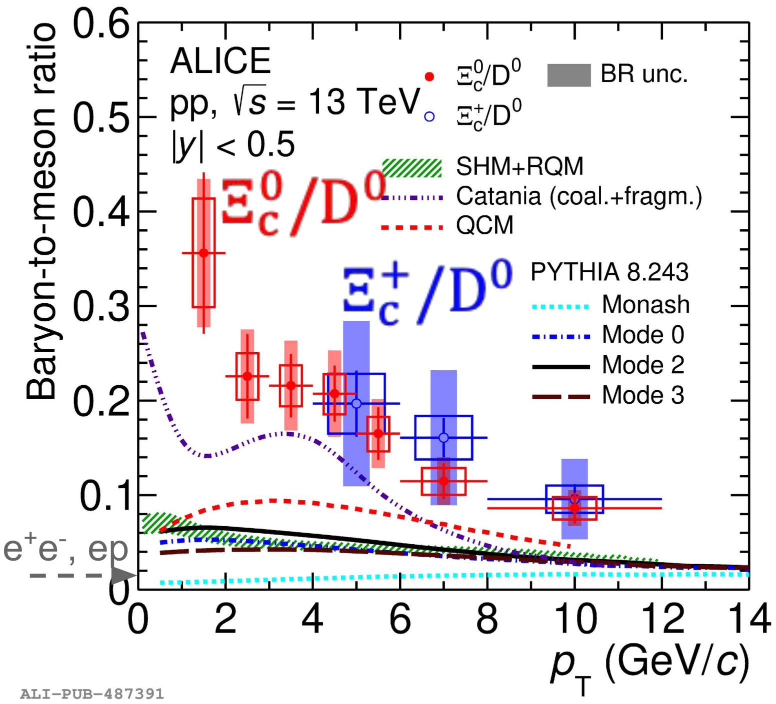
Several arrows in the quiver



Particle	Mass (GeV/c^2)
D^0	1.865
D^+	1.870
D_s^+	1.968
Λ_c^+	2.286
$\Sigma_c^{0,++}$	2.454
Ξ_c^0	2.470
Ξ_c^+	2.468
Ω_c^0	2.695

Charm-strange baryons: $\Xi_c^{0,+}$

arxiv 2105.05187



$\Xi_c^{0,+}/D^0$ ratio significantly larger than in e^+e^- collisions

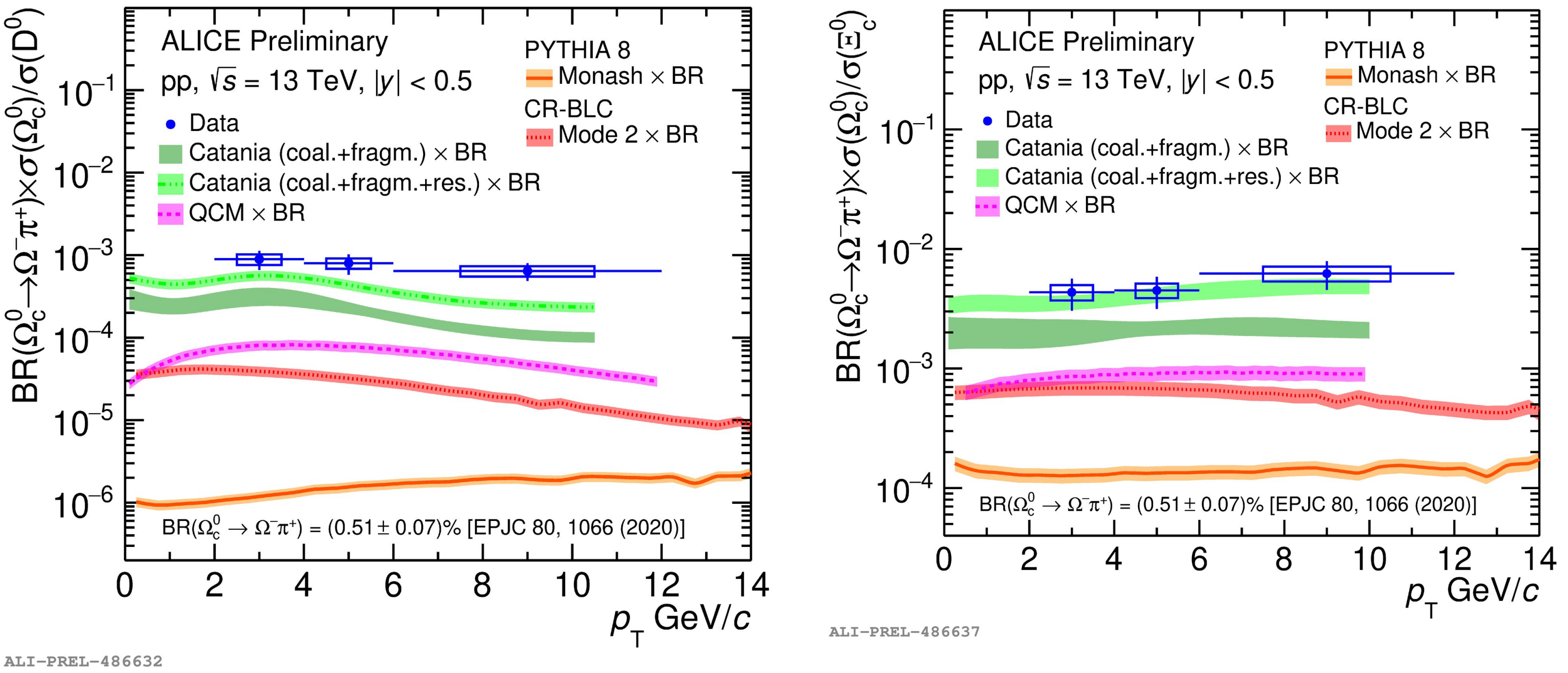
Default PYTHIA8 (Monash) largely underestimates the data

PYTHIA8 with CR-BLC (**Mode0,2,3**) and **SHM+RQM** predict ratios significantly larger than in e^+e^- but significantly underestimate the data

QCM underestimates the ratios

Catania closer to the data

Ω_c^0/D^0 and Ω_c^0/Ξ_c^0 ratios in pp collisions at 13 TeV

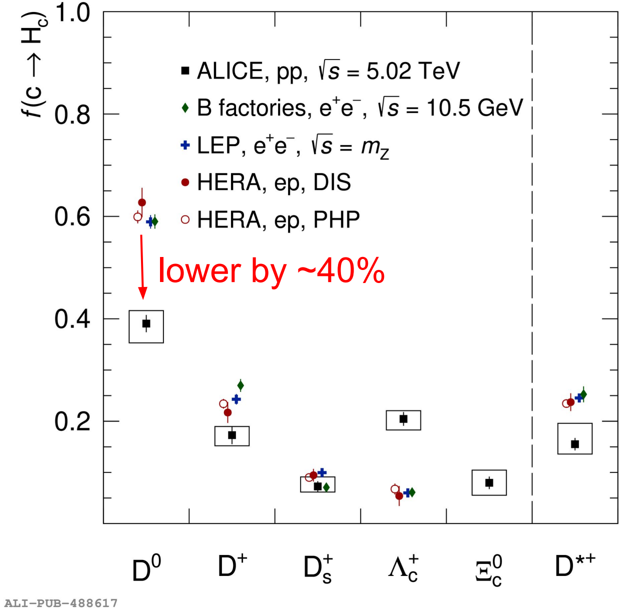


BR of $\Omega_c^0 \rightarrow \Omega^-\pi^+$: only theoretical estimate exists. Assuming this value for comparing models to data:

- Only Catania reproduce both ratios when including contribution from higher-mass resonance decays
- QCM, PYTHIA8 CR-BLC (Mode 2), and especially Monash lower by order(s) of magnitude

Impact on branching fractions and cross sections

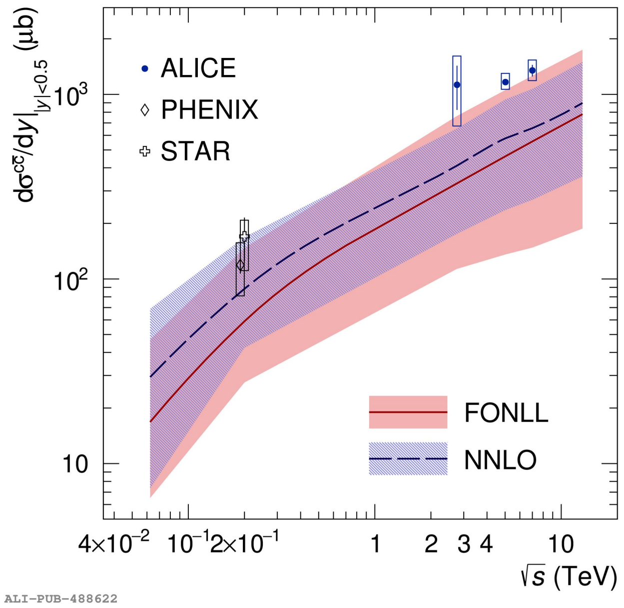
arxiv 2105.06335



Measured baryon-to-meson ratios imply **violation of universality of fragmentation fractions (FF) already in pp collisions**:

→ cannot rely on e^+e^- FF to calculate charm cross section from D meson data

→ new FF estimated in pp collisions at 5 TeV from all measured hadron-species cross sections



Total $c\bar{c}$ cross section at $|y|<0.5$ estimated at 5 TeV from all measured particle-species cross sections

Re-evaluated at 2.76 and 7 TeV using new D^0 FF

40% higher values w.r.t. using e^+e^- FF

On upper edge of FONLL and NNLO

Summary

Charm-hadron particle species production and relative abundances powerful probe of hadronisation process in all systems

Overall: large enhancement of charm baryon production relative to charm meson in pp, p-Pb and Pb-Pb collisions with respect to e^+e^- and ep collisions

→ **Charm hadronisation involves different processes in hadronic collisions than in e^+e^- and ep collisions**

- **Coalescence** of charm quarks with light quarks from a thermalised and expanding bulk?
- Stronger effects from **Colour Reconnection** in an environment enriched of coloured partons from MPI

Far from a full understanding:

- most of theoretical models do not provide a complete and satisfactory description
- "Catania" model with coalescence in pp closer to the data

New data from incoming **run 3 and run 4 at the LHC** will improve and extend experimental results

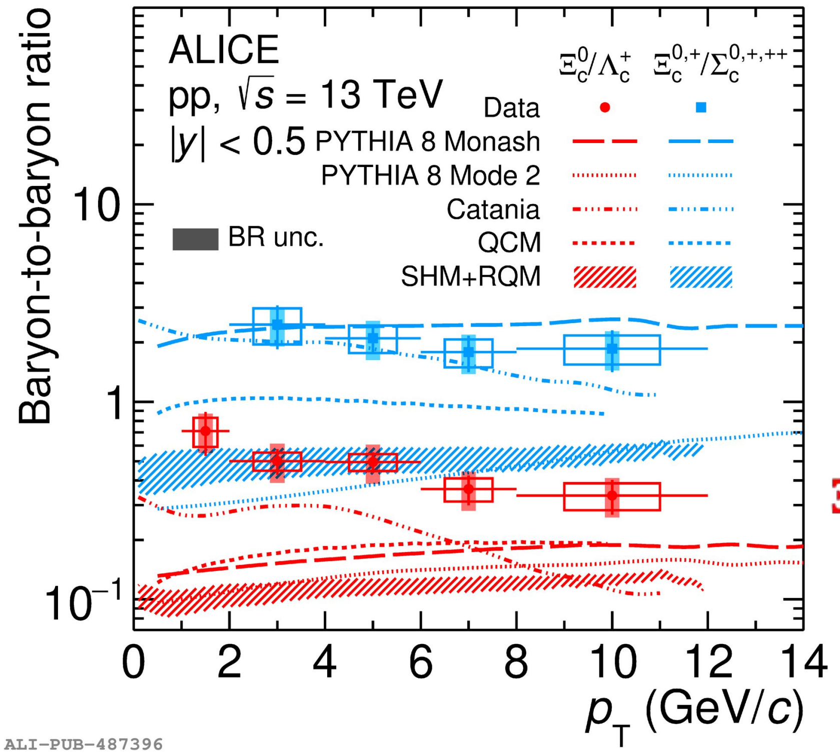
- ALICE upgrade: higher statistics (more than factor 100 for min. bias pp collisions) + new ITS

Other related results:
A. Isakov, ALICE measurements of inclusive untagged and heavy flavor-tagged jets in pp, p-Pb and Pb-Pb collisions

Extra

Baryon-to-baryon ratios

arxiv 2105.05187



ALI-PUB-487396

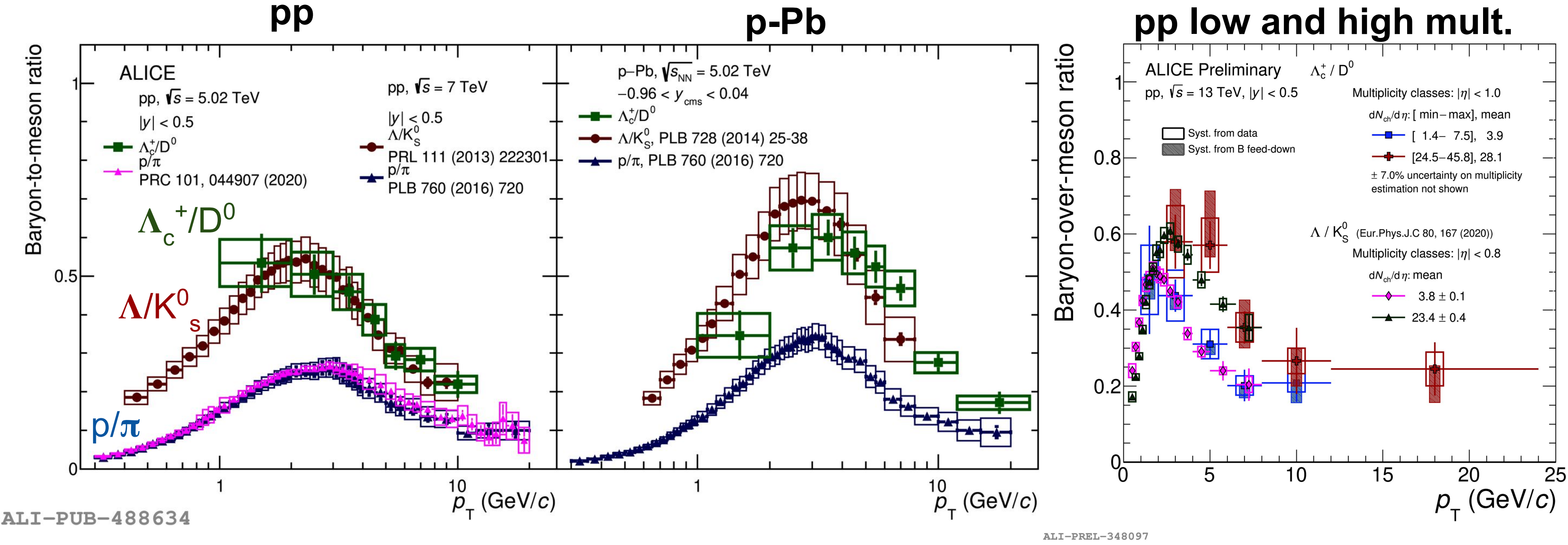
$\Xi_c^{0,+}/\Sigma_c^{0,++}$ ratio described by default PYTHIA8 (Monash)!

By Catania as well

$\Xi_c^{0,+}/\Lambda_c^{+}$ ratio underestimated by all models

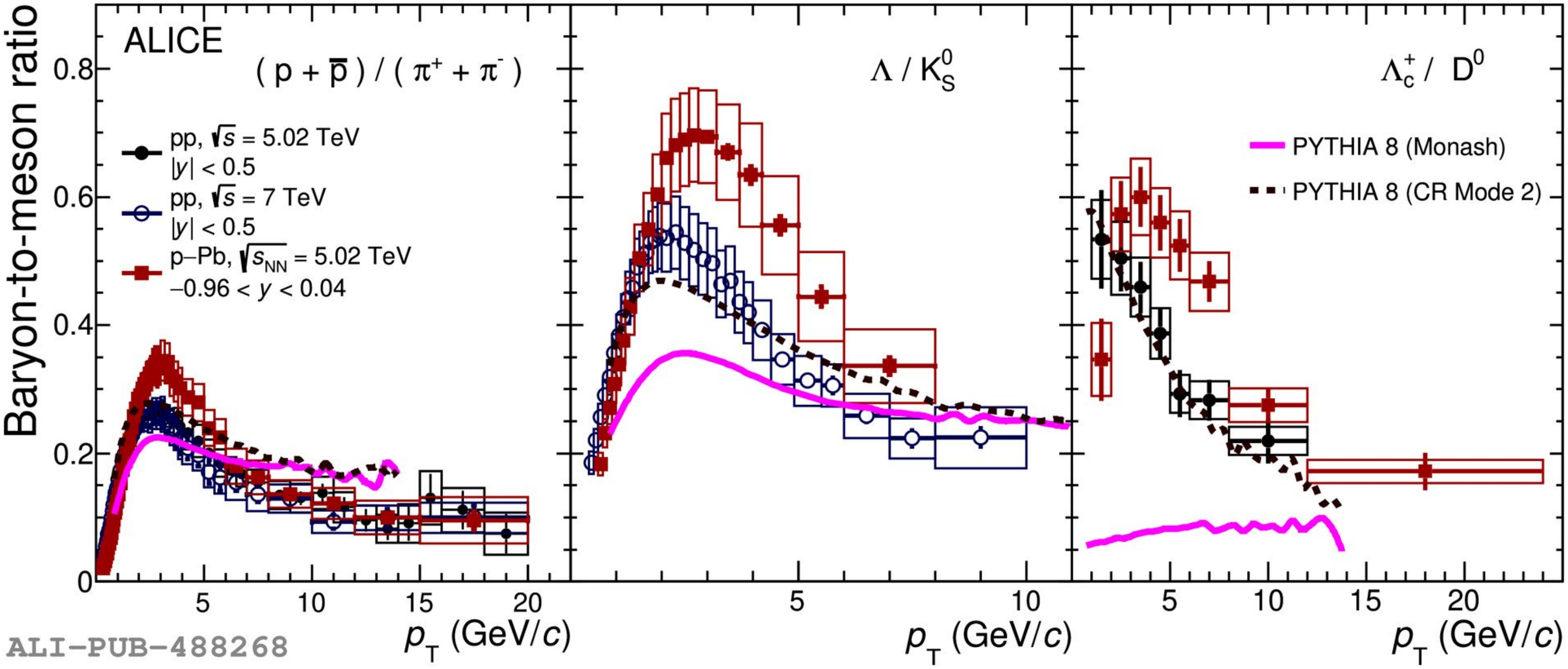
Λ_c^+/D^0 compared with Λ/K_S^0 and p/π^+

arXiv:2011.06079 , arXiv:2011.06078



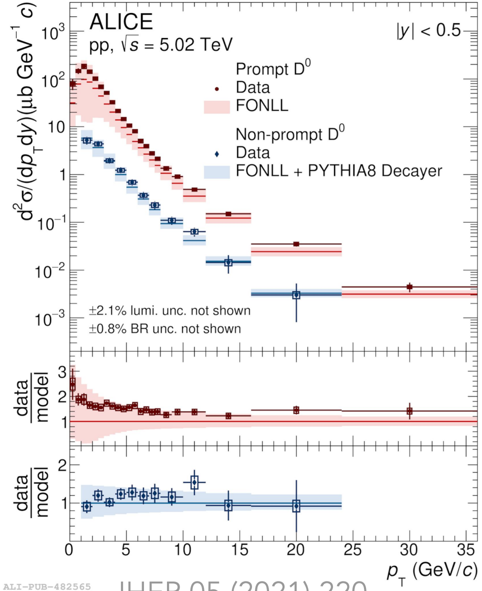
Similar p_T trend and evolution with multiplicity of baryon-to-meson ratios in light and heavy-flavour sector

Λ_c^+/D^0 compared with Λ/K_s^0 and p/π^+



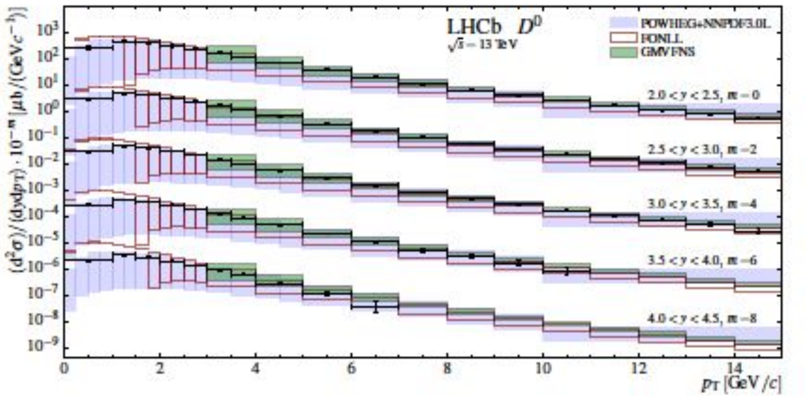
Open heavy-flavour production vs. pQCD

Prompt and non prompt D^0
pp 5 TeV, |y|<0.5



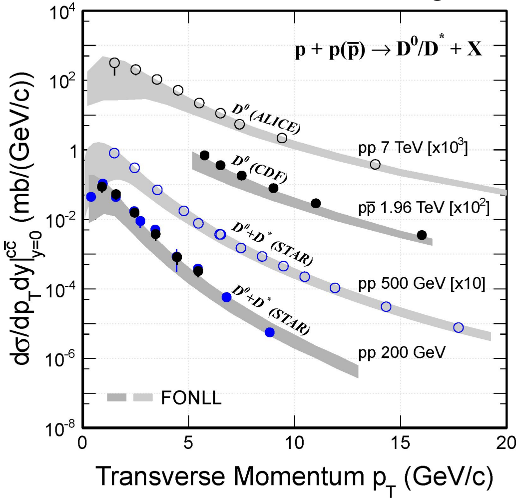
JHEP 05 (2021) 220

Prompt D^0 at forward *y*
pp 13 TeV



JHEP 03 (2016) 159

Prompt D^0 at mid *y*
RHIC, Tevatron, LHC energies



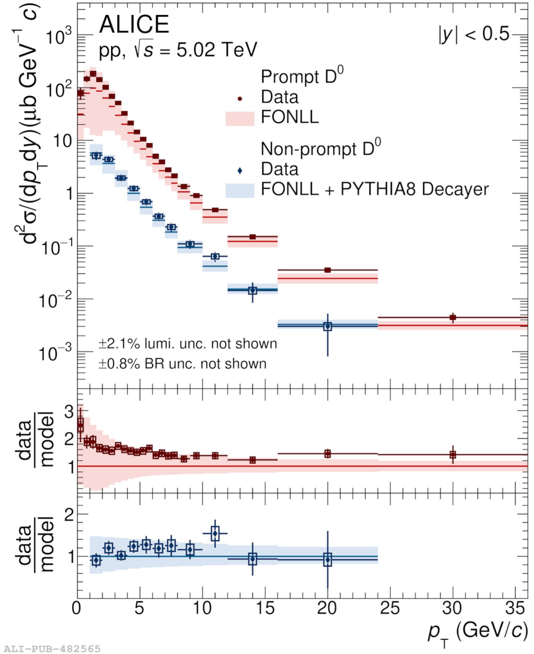
X. Luo et al., JHEP 1909 (2019) 008

Plethora of data indicating that **open-charm and open-beauty meson** production

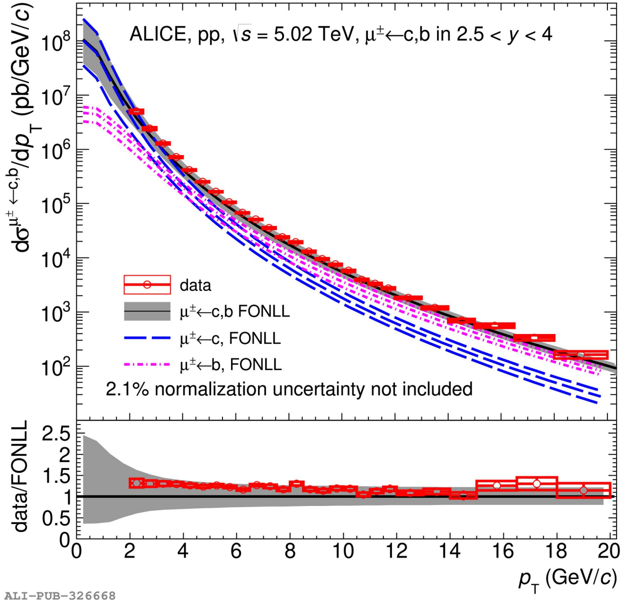
- vs. p_T and *y* (wide range covered)
- at very different collision energies
- charm meson species relative abundances

is **described by pQCD calculations relying on factorisation**

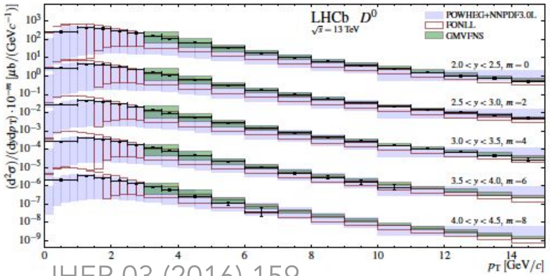
Open heavy-flavour production vs. pQCD



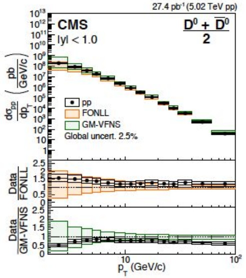
JHEP 05 (2021) 220

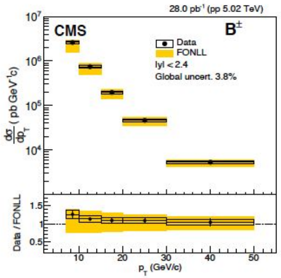


JHEP 1909 (2019) 008



JHEP 03 (2016) 159





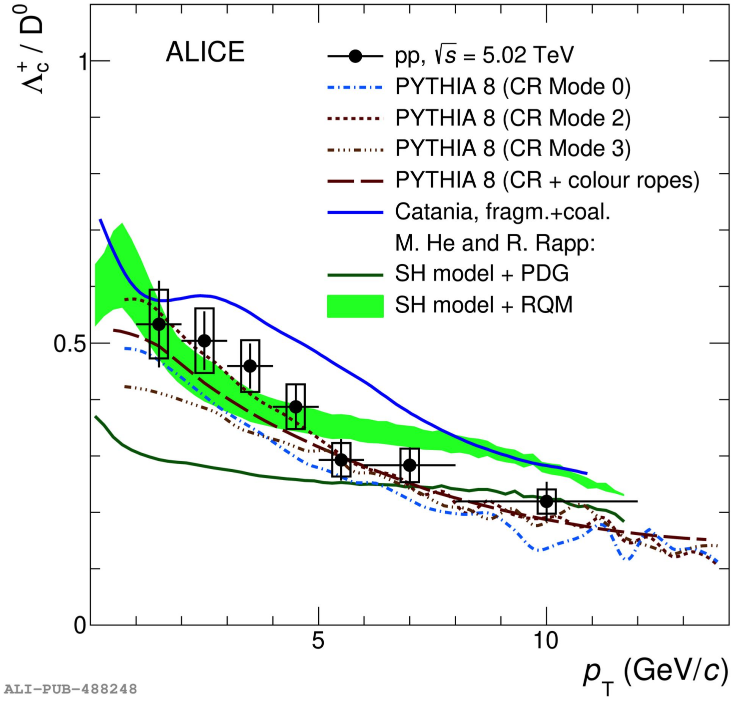
PRL 119, 152301 (2017) PLB 782 (2018) 474

Plethora of data indicating that **open-charm and open-beauty** production

- vs. p_T and y (wide range covered)
- at very different collision energies
- charm meson species relative abundances

is **described by pQCD calculations relying on factorisation**

Λ_c^+/D^0 ratio in pp collisions at 5 TeV



arXiv:2011.06079
arXiv:2011.06078

Data described by:

PYTHIA8 with String Formation beyond Leading Colour

Catania model: coalescence + "vacuum" fragmentation

(arxiv.org 2012.12001)

Expanding system of thermalised light quarks and gluons

"Sudden" (fixed temperature) coalescence

f_q = phase-space distributions of quarks in the system

$$\frac{dN_H}{dyd^2P_T} = g_H \int \prod_{i=1}^{N_q} \frac{d^3p_i}{(2\pi)^3 E_i} p_i \cdot d\sigma_i \; f_{q_i}(x_i, p_i)$$

$$\times f_H(x_1 ... x_{N_q}, p_1 ... p_{N_q})\, \delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right)$$

f_H= Wigner function, phase-space distributions of quarks within hadron