Heavy-quark production and hadronisation as a function of event multiplicity with ALICE

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On behalf of ALICE Collaboration

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Istituto Nazionale di Fisica Nucleare

Introduction

Heavy quarks are formed in initial hard scatterings with cross sections that can be calculated with pQCD
→ "calibrated probes" of initial- and final-state effects in all collision systems
→ Test pQCD calculations and expectations of MC generators with different MPI, jet, hadronisation models

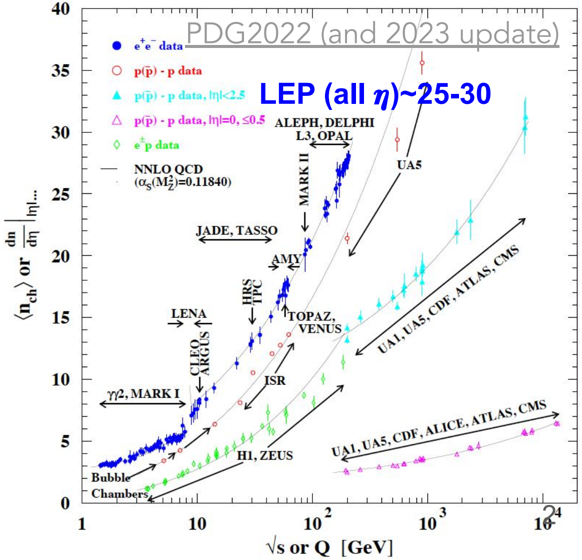
Experimentally:
- different hadron species
- event multiplicity, different collision systems

⇨ lever arm to investigate hadronisation mechanisms

LHC, CDF: heavy-flavour baryon formation not understood in proton-proton collisions → main topic of this talk

Typical charged particle multiplicities probed, <dN_{ch}/dη>(η=0):

	Low mult.	Min. bias	High mult.
pp (13 TeV)	~4.5	~7 (INEL>0)	~34 (~0.5% of events)
p–Pb (5.02 TeV)	~7	~17 (NSD)	~42 (~5% of events)
Pb–Pb (5.02 TeV)		~415 (30-50% centrality)	~1760 (0-10% centrality)



Multiplicities in e^+e^- at LEP not low (high-energy jets), overlap with pp ones
Intrinsic difference: MPI in pp, only 1 scattering in e^+e^-
→ comparison of min. bias pp vs. e^+e^- very sensitive to MPI

ALICE apparatus (Run 2)

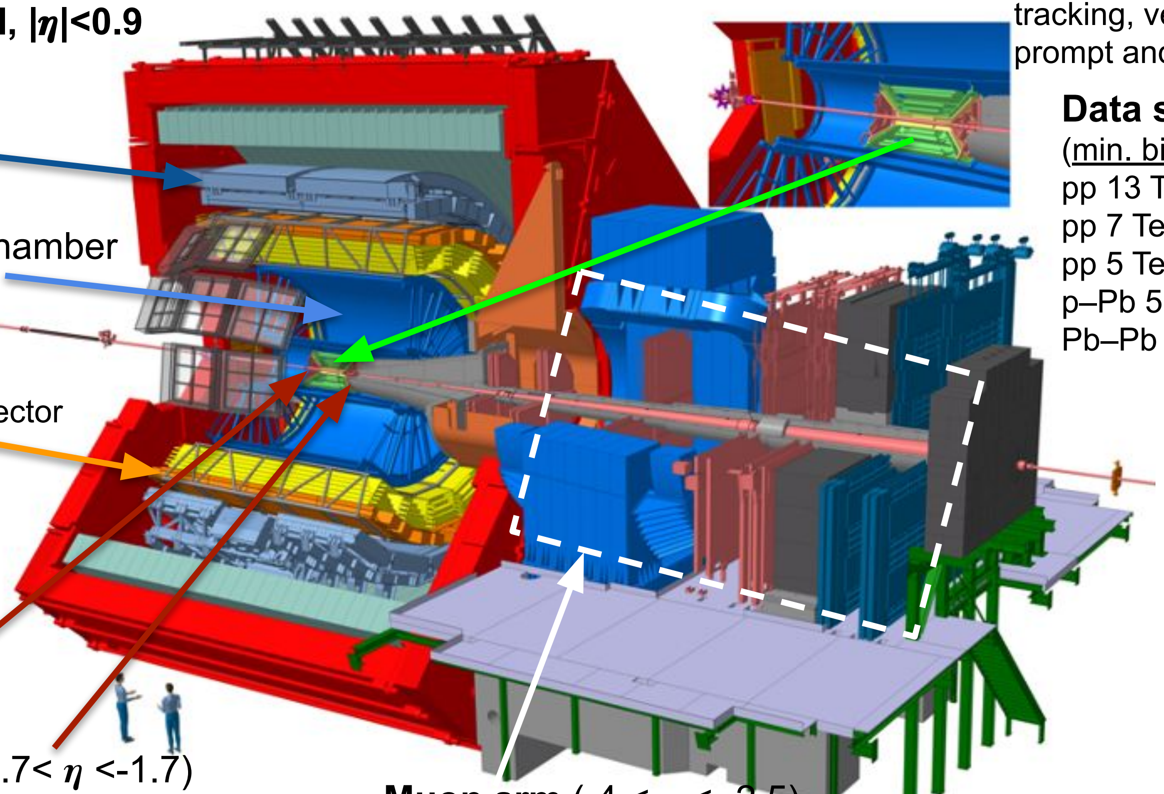
Central barrel, |η|<0.9
B = 0.5 T

EMCAL
Electron ID

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

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

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



Muon arm (-4 < η < -2.5)
Muon ID, tracking, and trigger

Inner **T**racking **S**ystem
tracking, vertexing, separation of prompt and non-prompt signals

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

$D^0 \rightarrow K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$
$D_s^+ \rightarrow \phi(\rightarrow K^-K^+)\pi^+$
$D^{*+} \rightarrow D^0\pi^+$
$\Lambda_c^+ \rightarrow pK^-\pi^+$, $\Lambda_c^+ \rightarrow pK_s^0$
$\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$
$\Xi_c^0 \rightarrow \Xi^-\pi^+$, $\Xi_c^0 \rightarrow \Xi^-e^+\nu_e$
$\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
$\Omega_c^0 \rightarrow \Omega^-\pi^+$
c,b $\rightarrow$ $e^\pm$ or $\mu^\pm$
$J/\psi \rightarrow e^+e^-$ or $\mu^+\mu^-$

Heavy-flavour meson production

D-meson cross sections and ratios

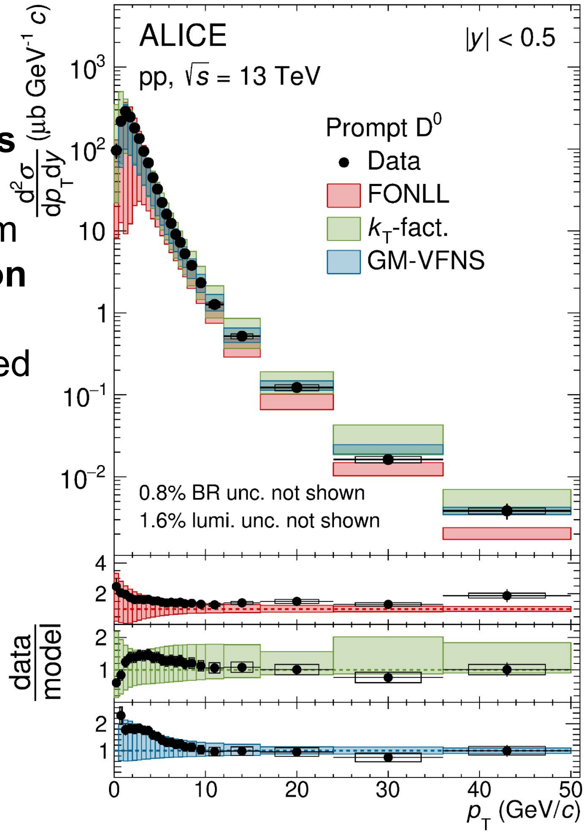
ALICE, arxiv 2308.04877

Precise measurements of **prompt D-meson cross sections**

Test pQCD calculations of charm production relying on **factorisation** approach and assumption that fragmentation functions determined in e^+e^- can be used in pp ("**universality**")

Yield-meson ratios compatible with e^+e^- values

Including D_s^+



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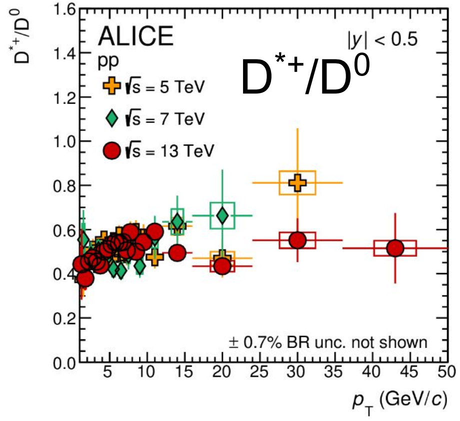

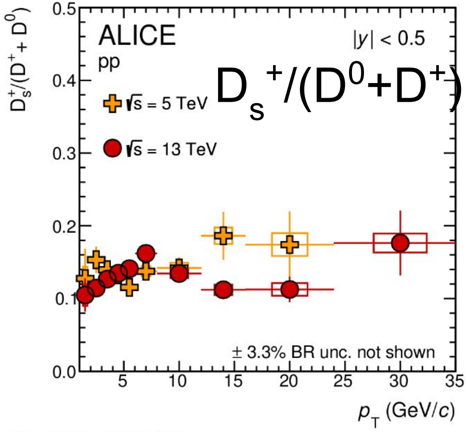

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FONLL: JHEP 05 (1998) 007
GM-VFNS: PRD 101 (2020) 114021
k_T-fact: PRD 104 (2021) 094038

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ALICE, arxiv 2308.04877

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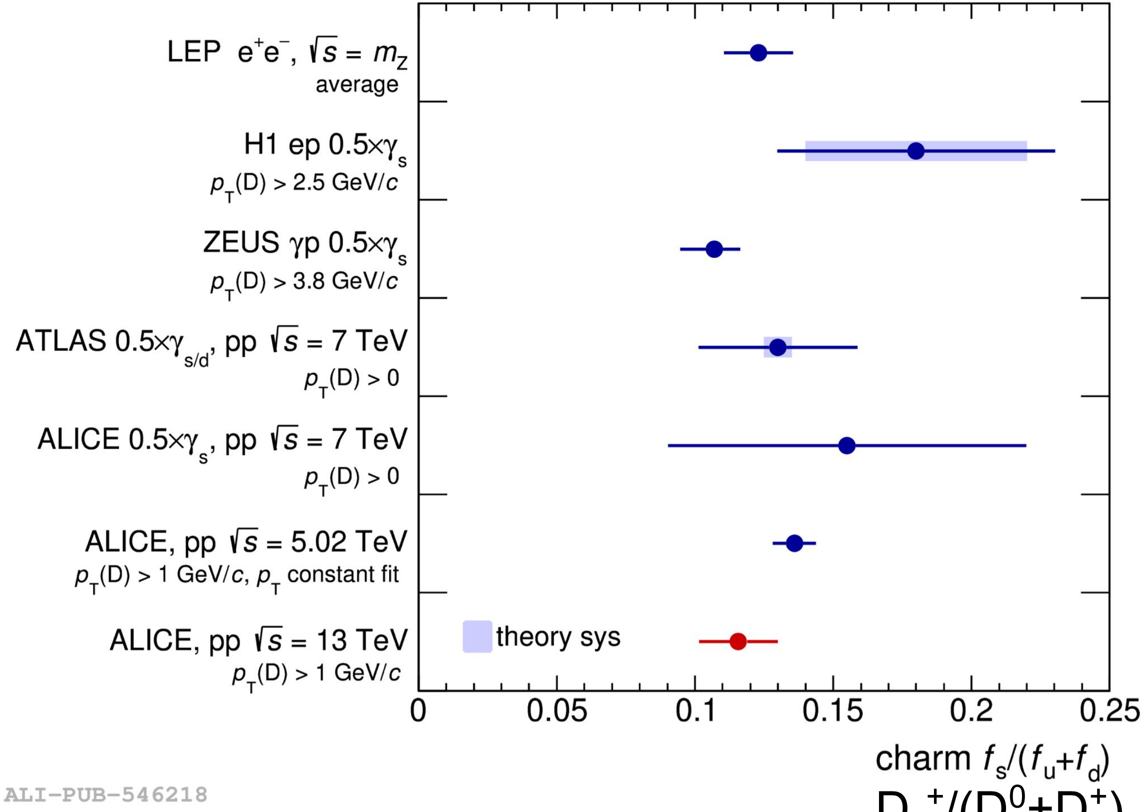
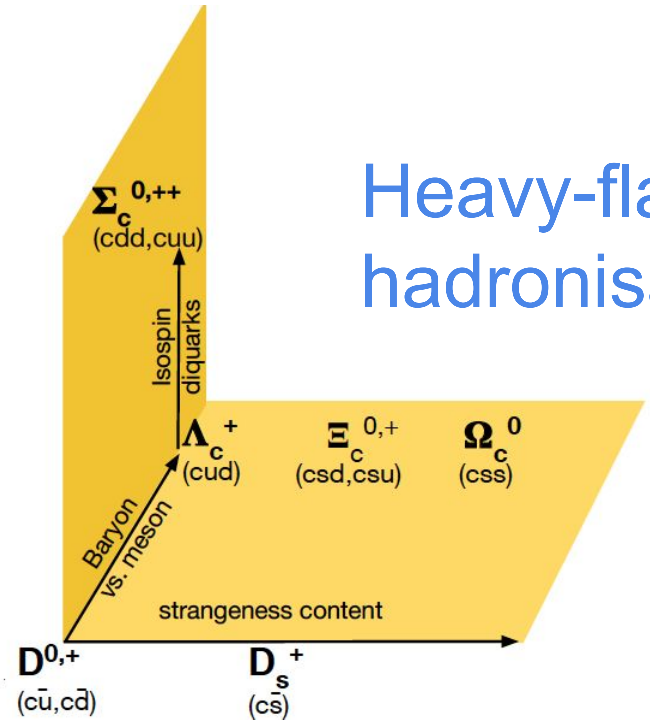


$D_s^+/(D^0+D^+)$

FONLL: JHEP 05 (1998) 007
GM-VFNS: PRD 101 (2020) 114021
k_T-fact: PRD 104 (2021) 094038



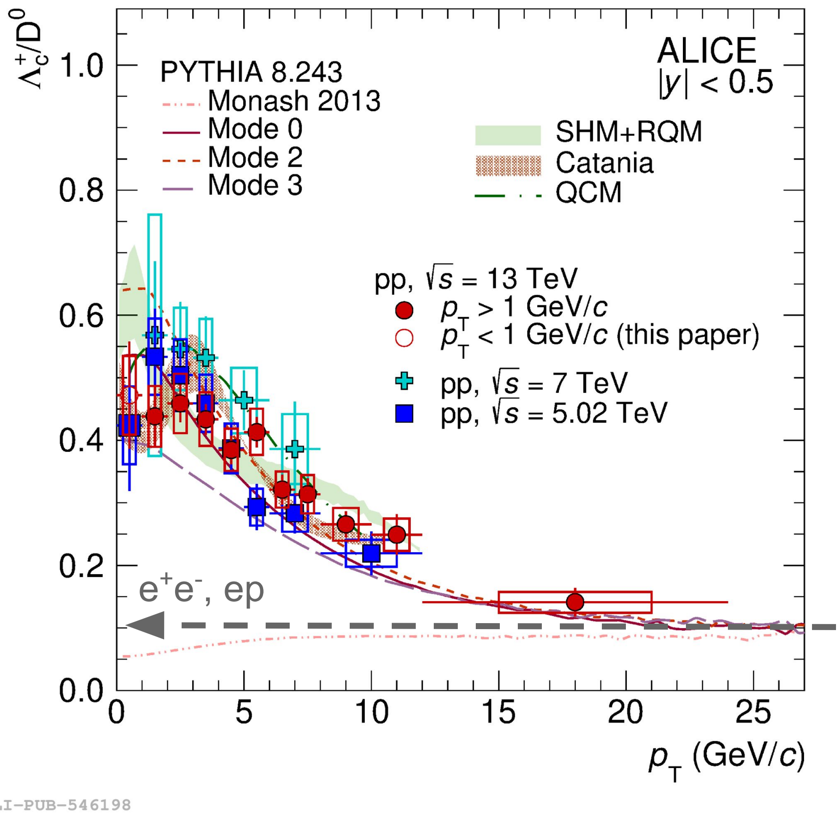
Heavy-flavour baryons and hadronisation

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^+/D^0 baryon-to-meson cross-section ratio

ALICE, arxiv 2308.04877

ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, PRC 107 (2023) 6, 064901



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

Significantly decreasing with p_T , approaching e^+e^- at high p_T

Recently extended down to p_T =0 at 5 and 13 TeV

No evidence of dependence on collision energy

	$\Lambda_c^+/D^0 \pm$ 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 baryon-to-meson cross-section ratio

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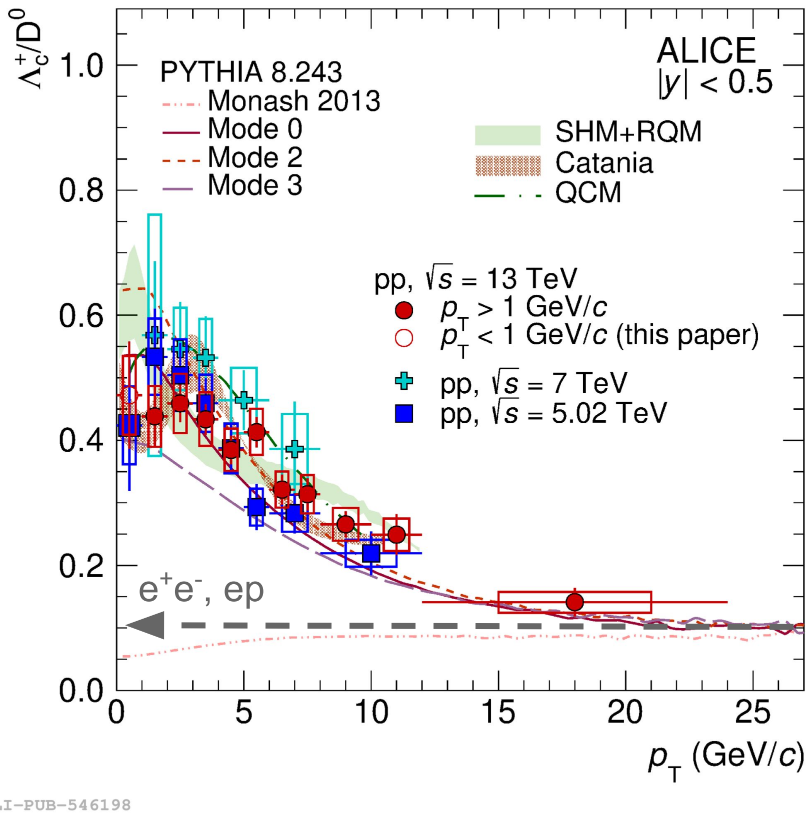

Not described by PYTHIA 8 Monash as well as by **pQCD-based calculations** relying on **factorisation** approach and **fragmentation function universality,** which work well for mesons

Universality of fragmentation function violated already in pp collisions

Λ_c^+/D^0 baryon-to-meson cross-section ratio

ALICE, arxiv 2308.04877

ALICE,PRC 104 054905 (2021)
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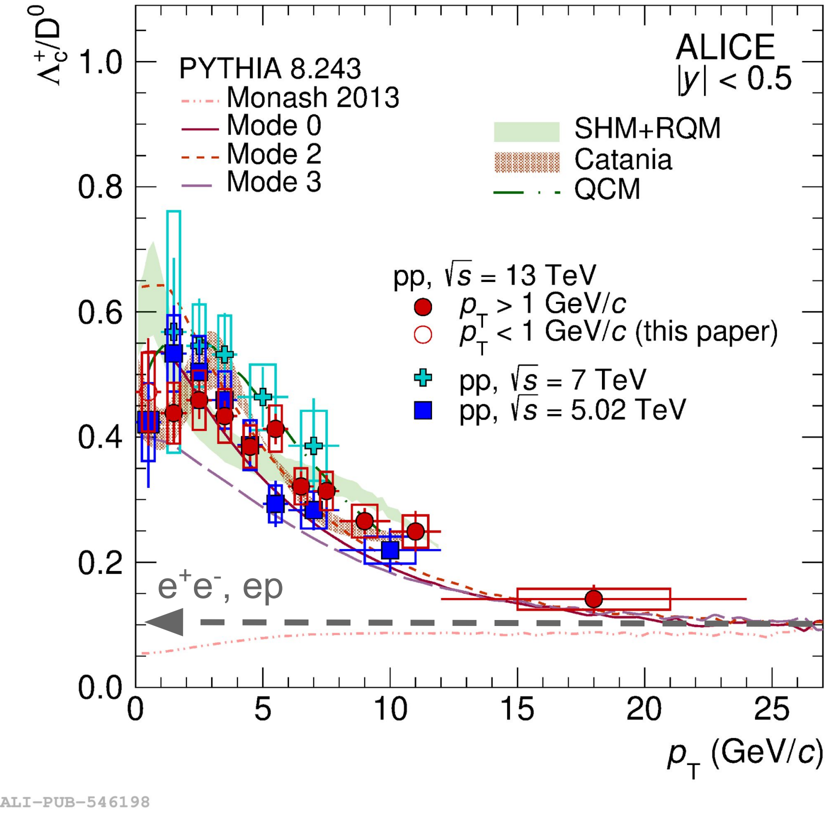
ALICE, PRC 107 (2023) 6, 064901



Data described by:

PYTHIA 8 with String Formation beyond Leading Colour

(JHEP 1508 (2015) 003) → more details in next talk

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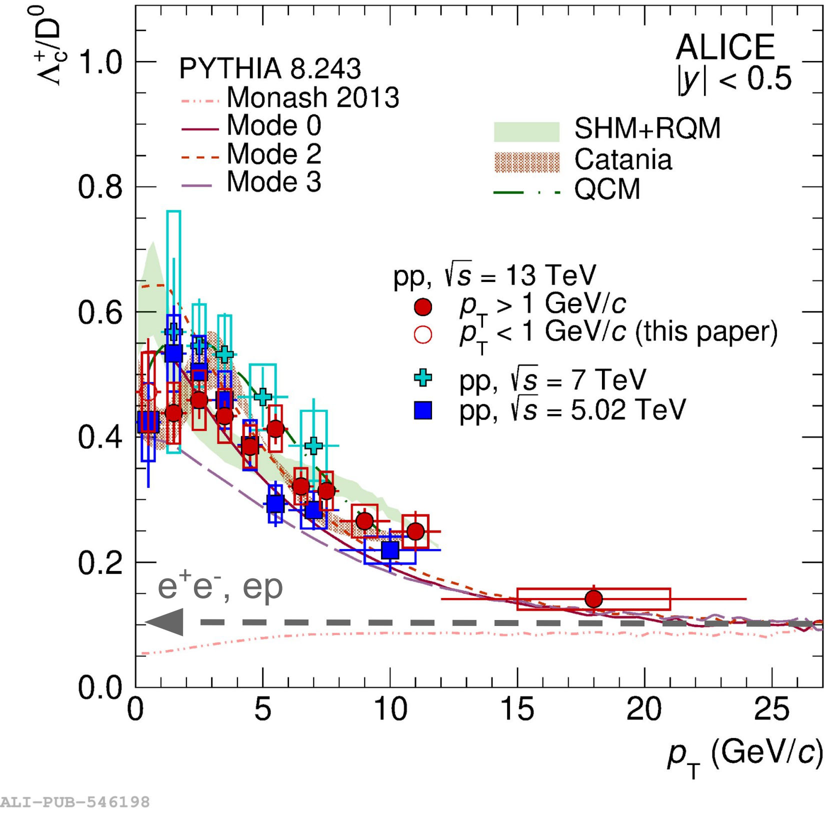

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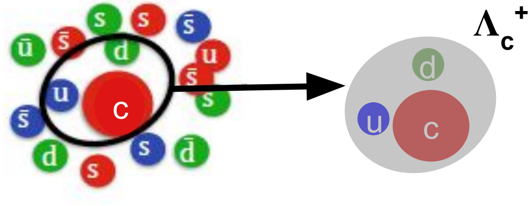
Catania model: "sudden" **coalescence** (Wigner function) + "vacuum" fragmentation (PLB 821 (2021) 136622)



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ALICE, arxiv 2308.04877

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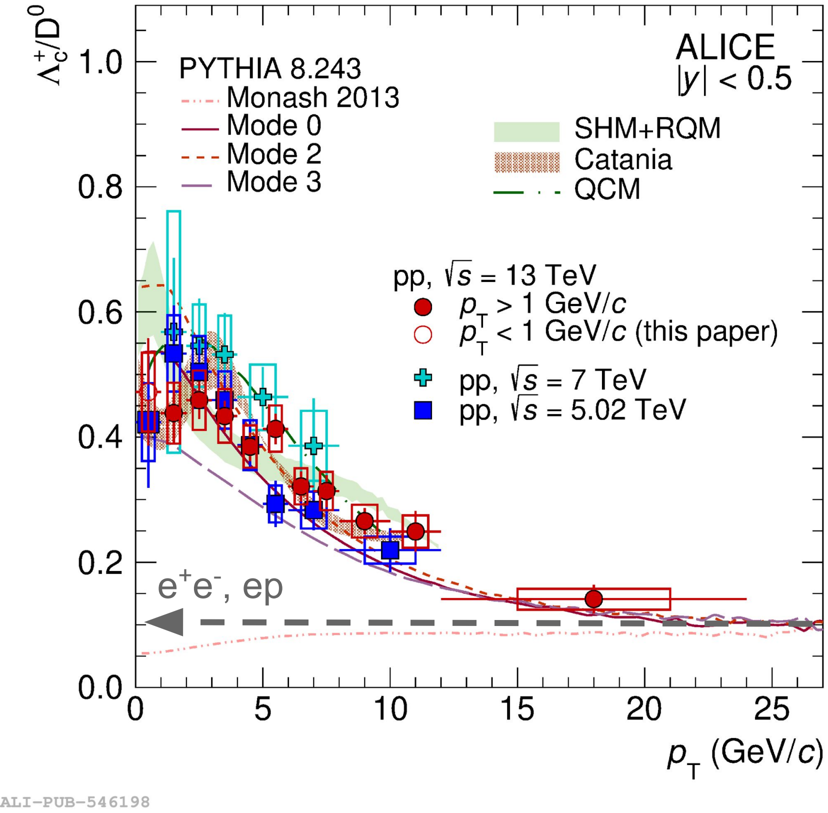

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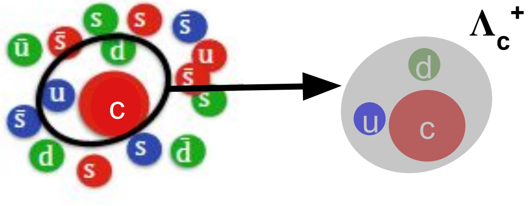
QCM: quark **recombination** model based on statistical weights + "equal quark-velocity" (EPJC 78, 2018 4, 344)



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ALICE, arxiv 2308.04877

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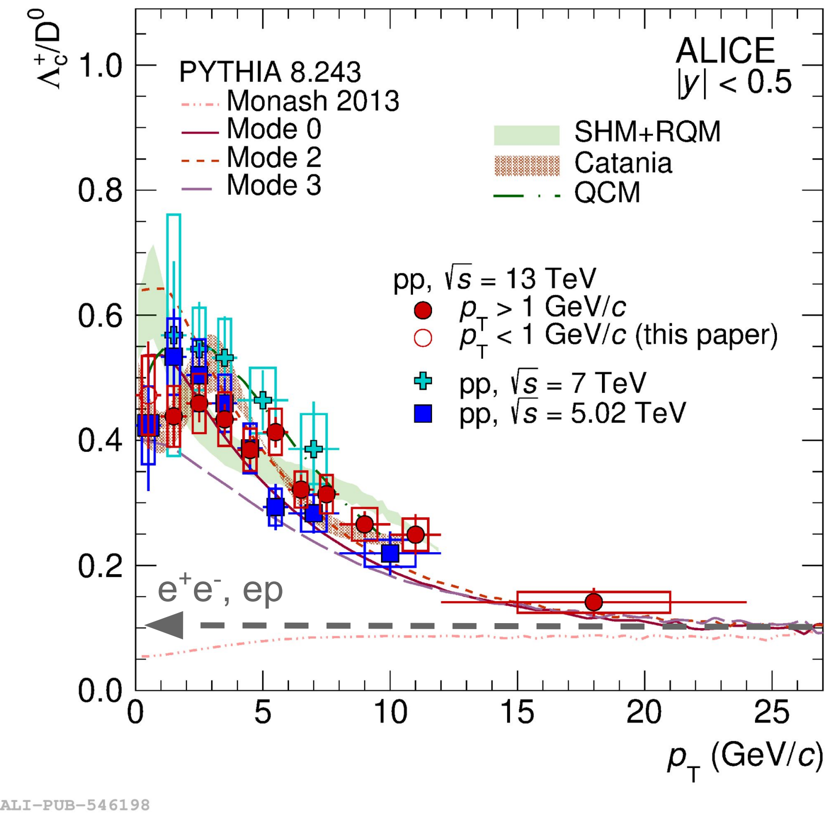

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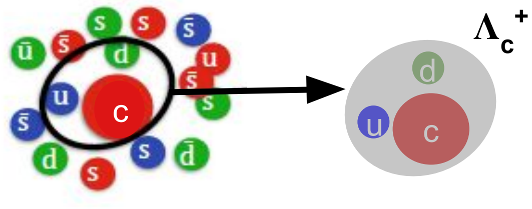
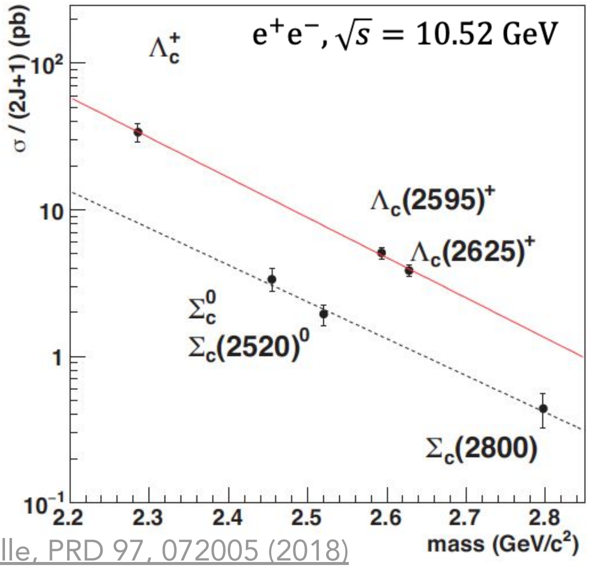
SHM+RQM, PLB 795 117-121 (2019): no info on partonic phase
Hadron abundances ← **Statistical Hadronisation Model** + feed-down from **augmented set of charm-baryon states** (from Relativistic Quark Model)

→ 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

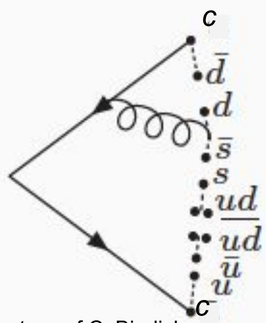


$\Sigma_c^{0,++}$ production and $\Lambda_c^+ \leftarrow \Sigma_c^{0,++}$ feedown

e^+e^- collisions

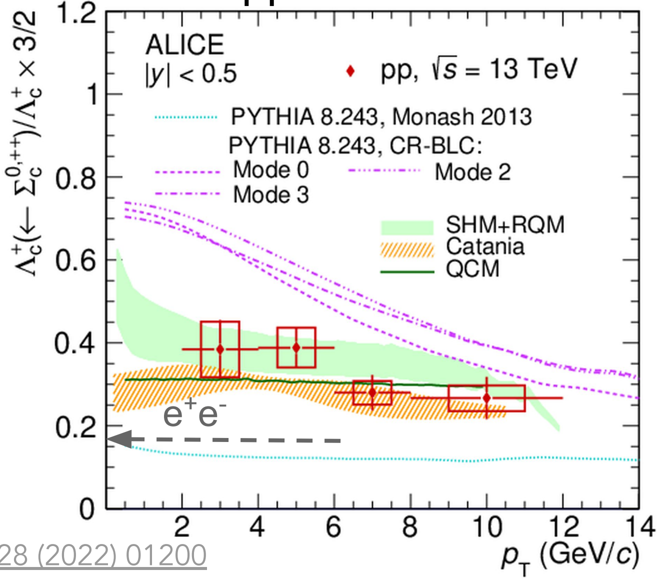


Belle, PRD 97, 072005 (2018)



Courtesy of C. Bierlich

pp collisions



PRL 128 (2022) 01200

Σ_c states suppressed w.r.t. Λ_c states

In string fragmentation: from heavier diquark-antidiquark pair from vacuum

Λ_c (isospin = 0) needs spin = 0 diquark $(ud)_0$

Σ_c (isospin = 1) needs spin = 1 diquark $(ud,dd,uu)_1$ which is heavier than $(ud)_0$

$\Lambda_c^+ \leftarrow \Sigma_c^{0,+,++}$ feed-down about twice larger than in e^+e^-

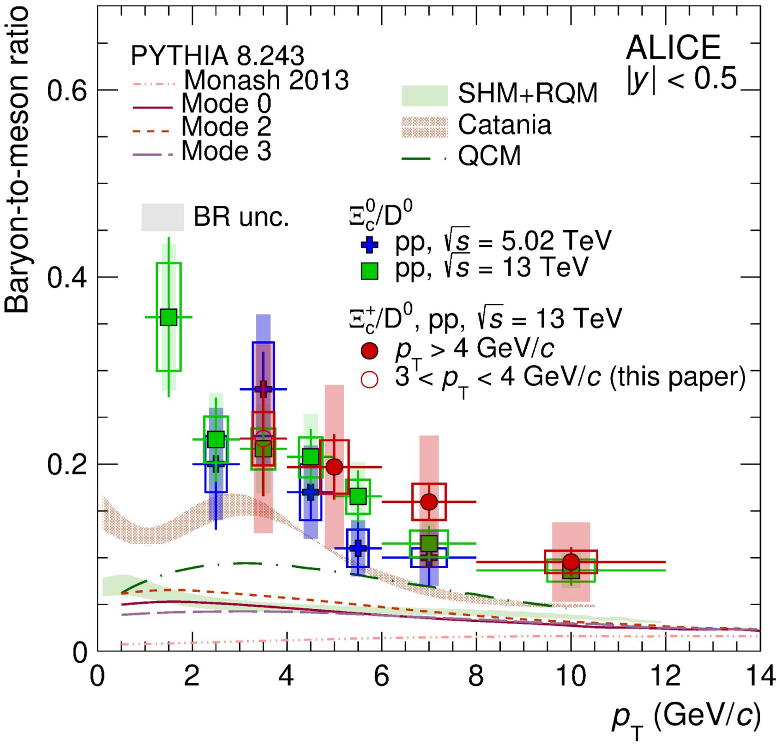
→ $\Sigma_c^{0,+,++}$ "enhancement" larger than Λ_c^+ one

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

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

$\Xi_c^{0,+}/D^0$ baryon-to-meson cross-section ratio

ALICE, arxiv 2308.04877



ALI-PUB-546202

Similar trend than Λ_c^+/D^0

Even **larger increase** w.r.t. PYTHIA 8 Monash and e^+e^-

Catania and QCM expectation close to data

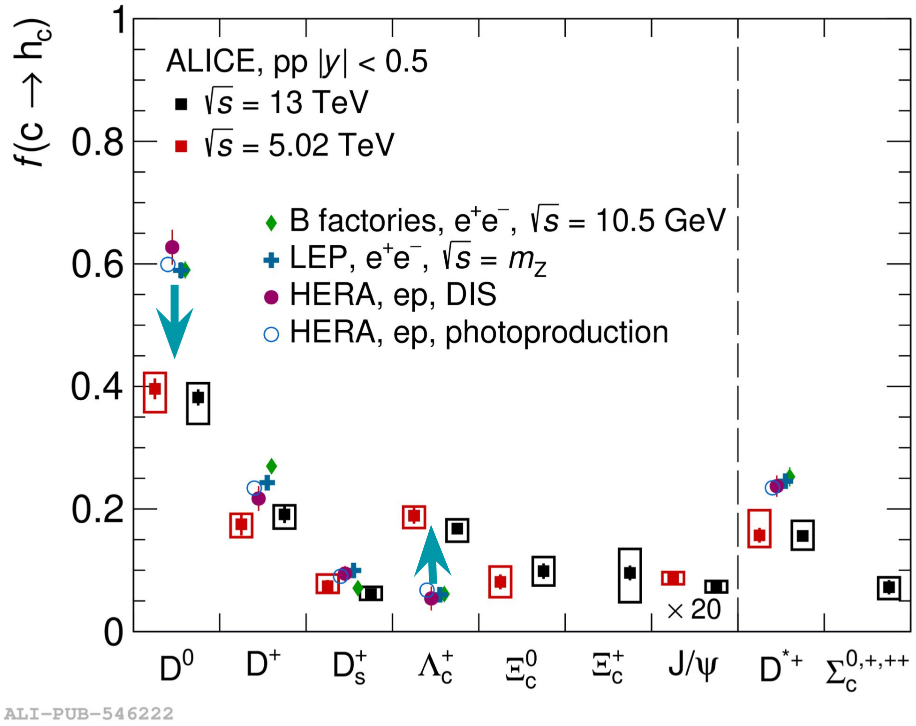
PYTHIA 8 with CR-BLC and SHM+RQM expect significant larger values than e^+e^- but underestimate the data

Large branching ratio (BR) uncertainty

Run 3 data will allow to reduce experimental uncertainty

Fragmentation fractions: pp vs. e^+e^- collisions

ALICE, arxiv 2308.04877



Calculated from sum of cross sections of weakly decaying hadrons

Values for mesons significantly lower than in e^+e^-

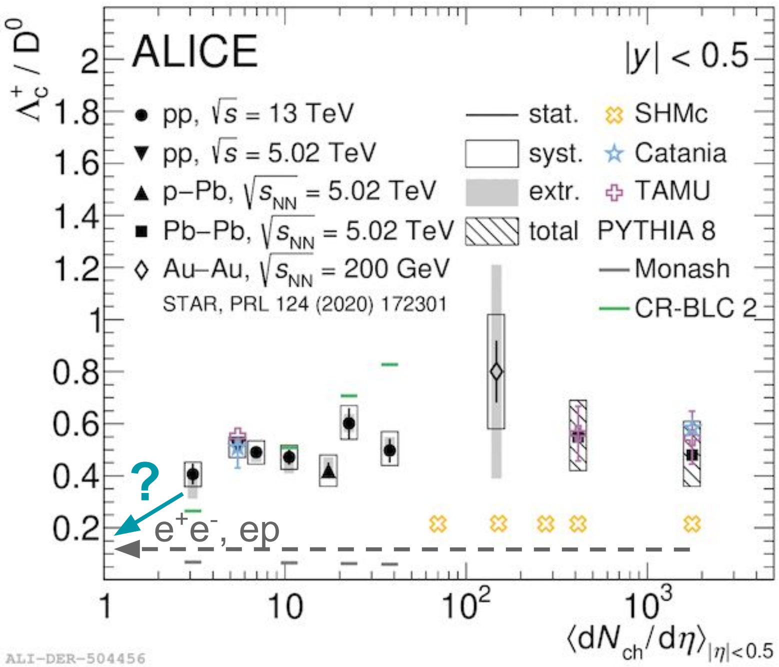
About 30-40% of charm quarks hadronise to baryons

No evidence of energy dependence

Lower p_T reach expected with Run 3 data will allow to further reduce extrapolation uncertainties

Λ_c^+/D^0 from pp to central AA: p_T-integrated

ALICE, PRC 104 054905 (2021) , PRL 127 202301 (2021), PLB 829 (2022) 137065, PLB 839 (2023) 137796



No evidence of evolution of p_T-integrated Λ_c^+/D^0 ratio despite strong modification of p_T-differential trend (see later).

Data uncertainty large

Significantly higher values than e^+e^-

STAR Au-Au data compatible with ALICE

PYTHIA 8 CR-BLC expects increase with multiplicity

SHMc (Pb–Pb): flat trend **below data** SHMc, JHEP 07 035 (2021)

Note: no additional RQM high-mass baryons

TAMU, Catania: similar values in pp and Pb–Pb

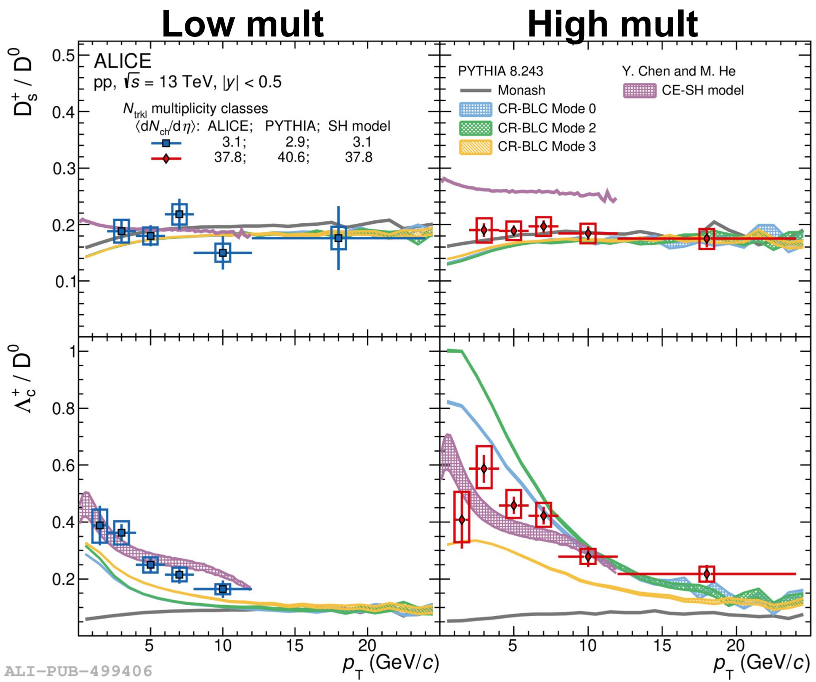
TAMU, PRL 124, 4 (2020) 042301; Catania, EPJC 78 4 (2018) 348

Lowest multiplicity still to be covered: will recover e^+e^- ?

→ more precise measurements from LHC new runs awaited

Seems so in beauty sector (see LHCb result in backup)

Evolution with event activity: Λ_c^+/D^0 and D_s^+/D^0 vs. p_T in pp



D_s^+/D^0 independent on charged-particle multiplicity

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

Trends qualitatively reproduced by **PYTHIA 8 with CR-BLC**
→ interplay of Color Reconnection (CR) and MPI

Canonical Ensemble-SH (+ RQM baryons) catches Λ_c^+/D^0 but not D_s^+/D^0 : ratios decrease at low multiplicity from baryon and strangeness number conservation in smaller volume

ALICE, PLB 829 (2022) 137065
PYTHIA8: Monash, EPJ C74 (2014) 3024,
CR-BLC JHEP 1508 (2015) 003
CE-SH, PLB 815 (2021) 136144

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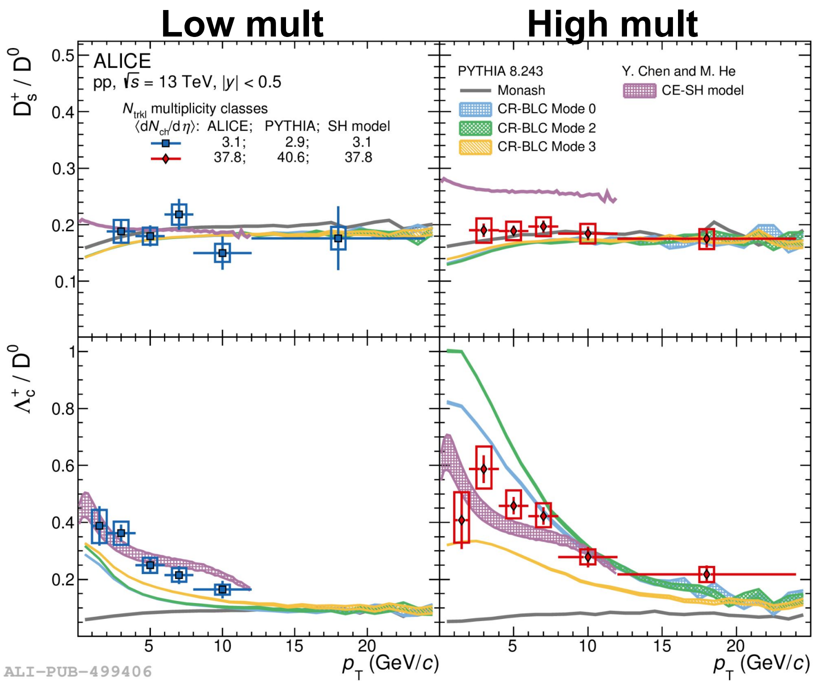

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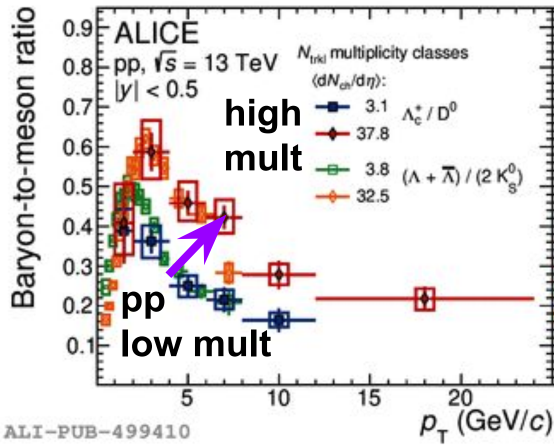
Similar trend than Λ/K_s^0



ALICE, PLB 829 (2022) 137065
PYTHIA8: Monash, EPJ C74 (2014) 3024,
CR-BLC JHEP 1508 (2015) 003
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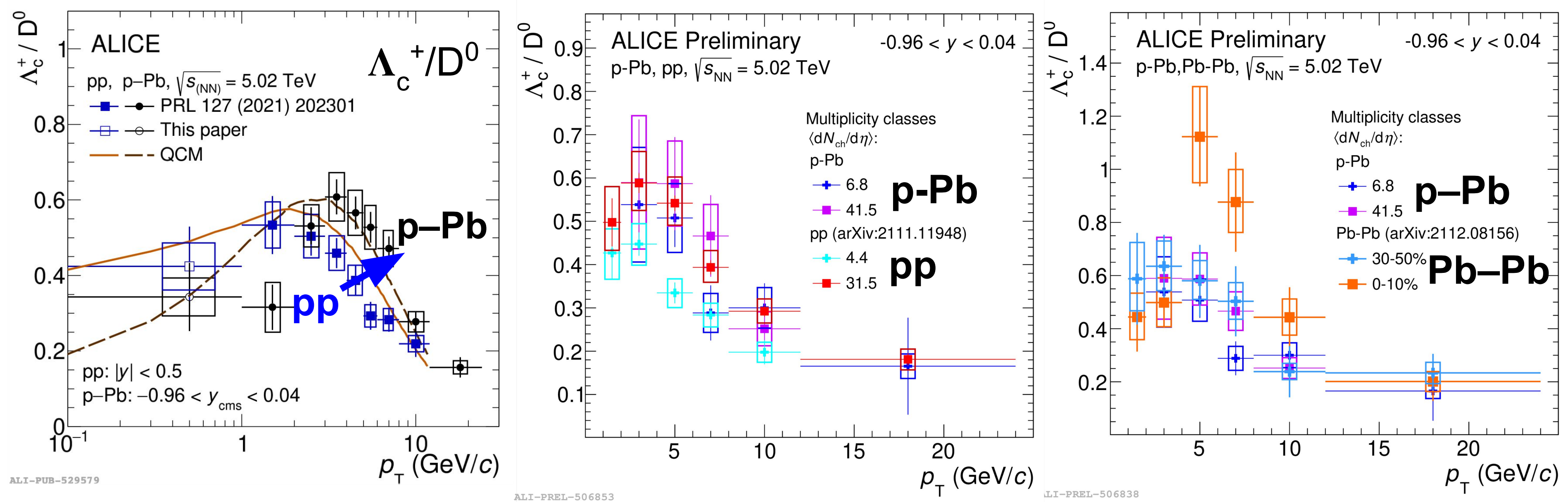
Λ_c^+/D^0 vs. p_T in pp, p–Pb, Pb–Pb

ALICE, PRC 104 054905 (2021) , PRL 127 202301 (2021), PRC 107 (2023) 064901

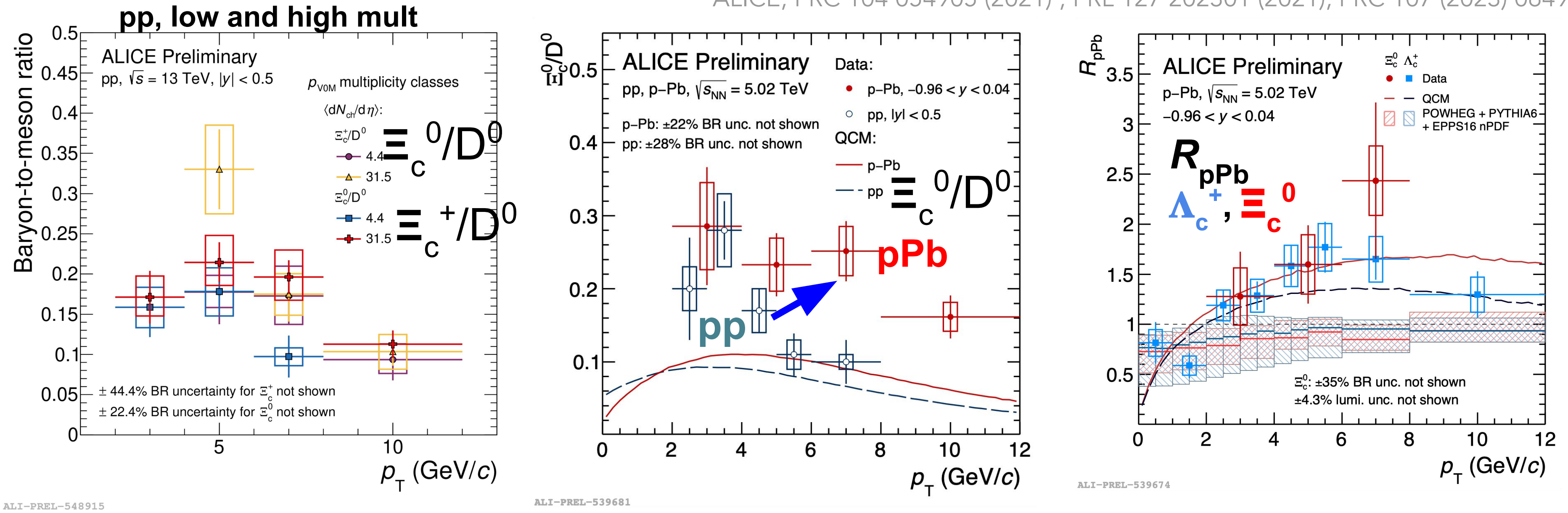
More about Pb–Pb results: M. Faggin talk



- **Push (flow?) towards higher p_T of Λ_c^+/D^0** from (min bias) pp to p–Pb, described by QCM PRC 97 064915 (2018)
- Similar values in high-mult. pp, low- and high-mult p–Pb, and semicentral Pb–Pb
  → **very low multiplicity pp "isolated", ~threshold effect?**
- **Central Pb–Pb: "radial-flow"-like peak** appearing at intermediate p_T, which could be caused by recombination of charm with flowing light quarks

Evolution with event activity in pp and p–Pb: $\Xi_c^{0,+}$

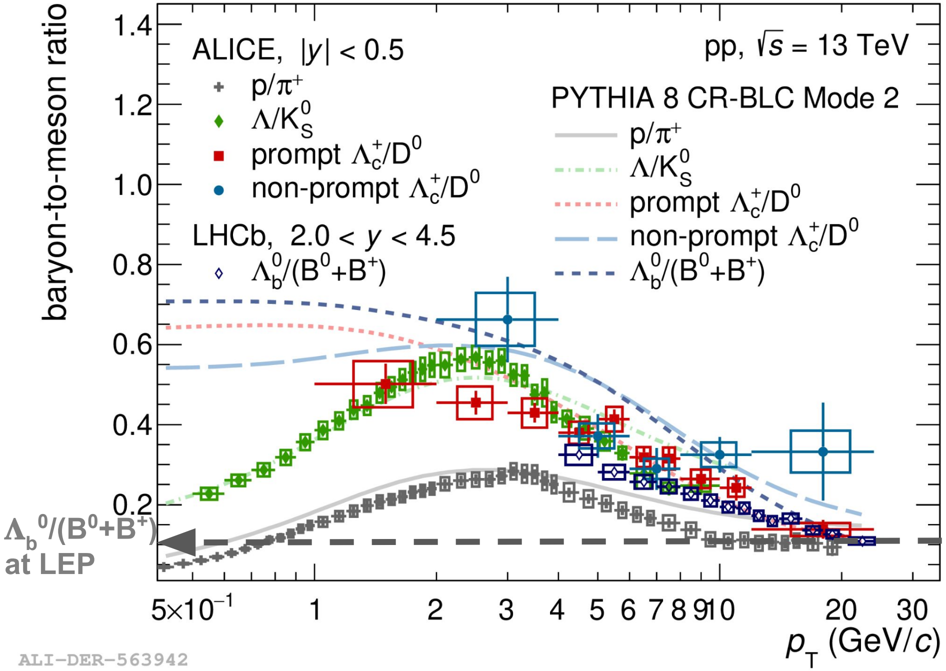
ALICE, PRC 104 054905 (2021) , PRL 127 202301 (2021), PRC 107 (2023) 064901



- Precision not enough to conclude about multiplicity trend of $\Xi_c^{0,+}/D^0$ in pp → Run 3 data needed
- **p–Pb: similar push towards higher p_T observed for Λ_c^+/D^0 and $\Xi_c^{0,+}/D^0$ ratios**
  - Similar nuclear modification factor (R_{pPb})
  - Described by QCM within uncertainties QCM: PRC 97 064915 (2018)

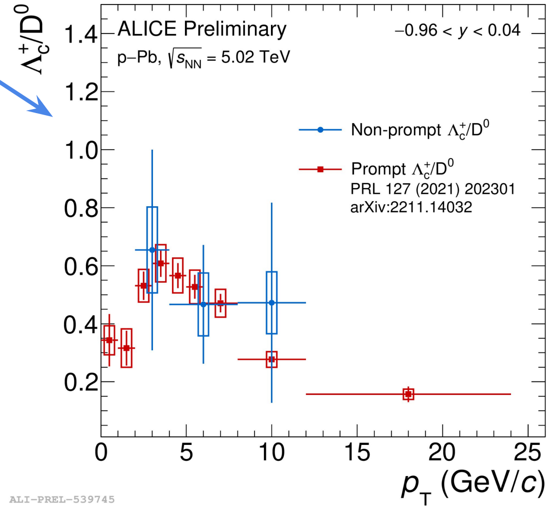
Beauty vs. charm (and light flavour)

ALICE, arxiv 2308.04873
LHCb, PRD100 (2019) no.3, 031102



Non-prompt Λ_c^+ / non-prompt D^0 similar to Λ_c^+/D^0

- also in p–Pb collisions (large uncertainties)

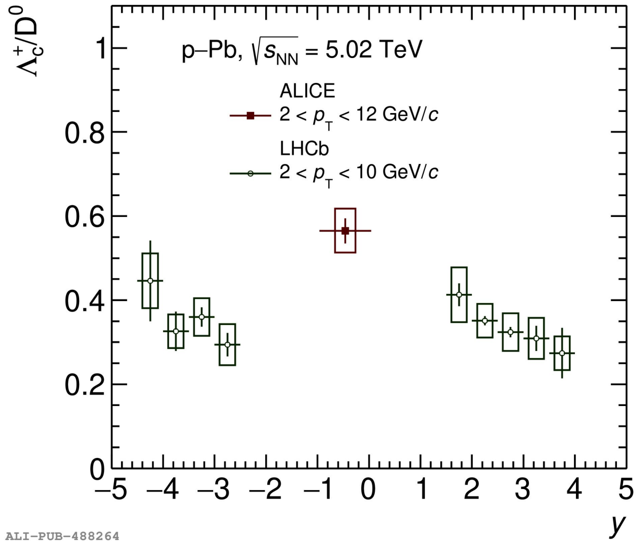


Similar p_T trend for charm, beauty, and light-flavour baryon-to-meson ratios for p_T>2 GeV/c

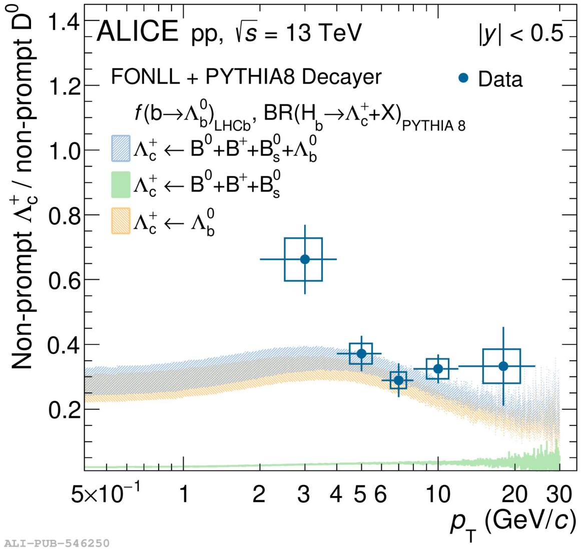
PYTHIA8 CR-BLC JHEP 1508 (2015) 003

Rapidity dependence

charm, p–Pb



beauty, pp



Possible non-flat rapidity trend of Λ_c^+/D^0? To be revisited with run 3 data (also in pp)

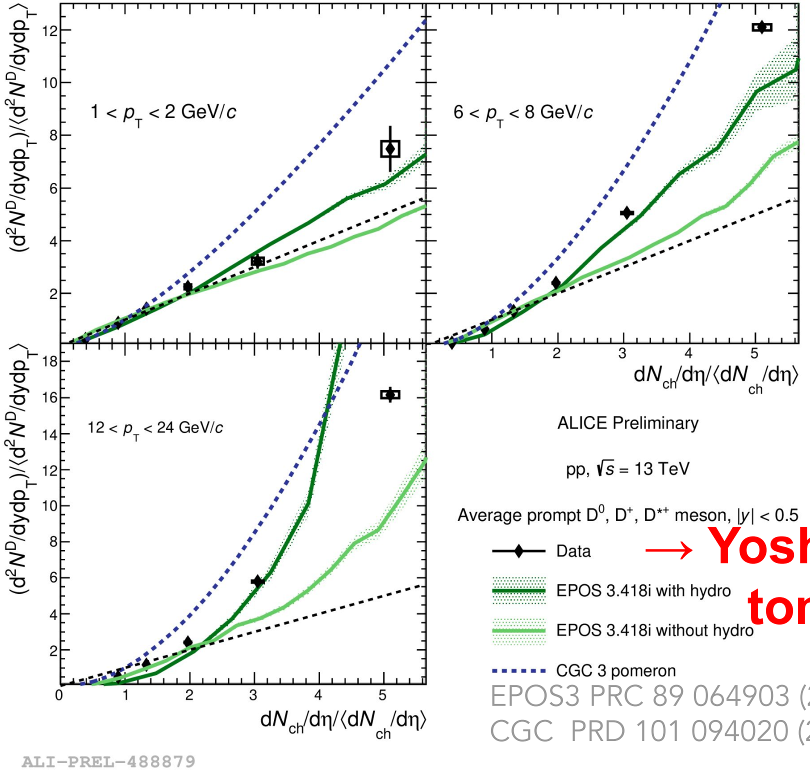
- May apply also to $\Xi_c^{0,+}/D^0$

Beauty: non-prompt Λ_c^+ ALICE data consistent with LHCb Λ_b^0 data
→ low p_T region to be explored with run 3 data

What should we expect in coalescence models and SHM?

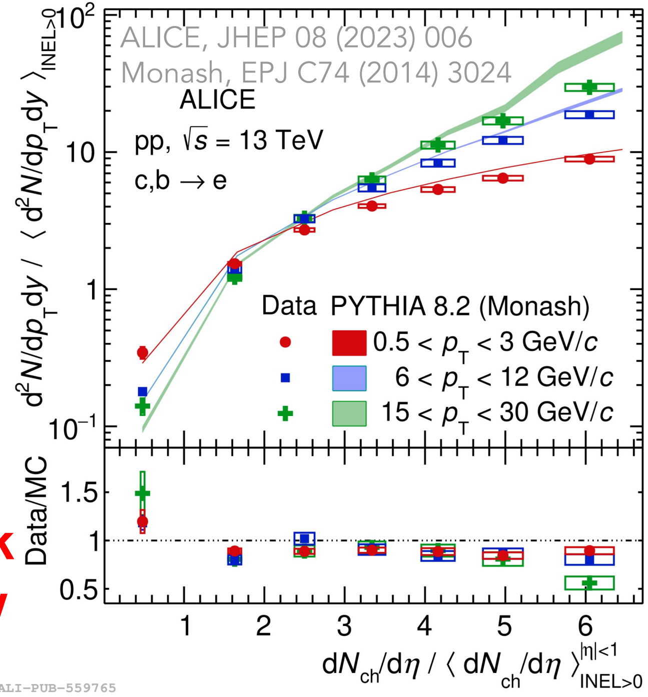
ALICE, JHEP 04 (2018) 108
ALICE, PRC 104 054905 (2021)
LHCb (p-Pb), JHEP 02 102 (2019)
ALICE, beauty: arxiv 2308.04873
LHCb, beauty: PRD100 (2019) no.3, 031102

Production yield evolution with multiplicity



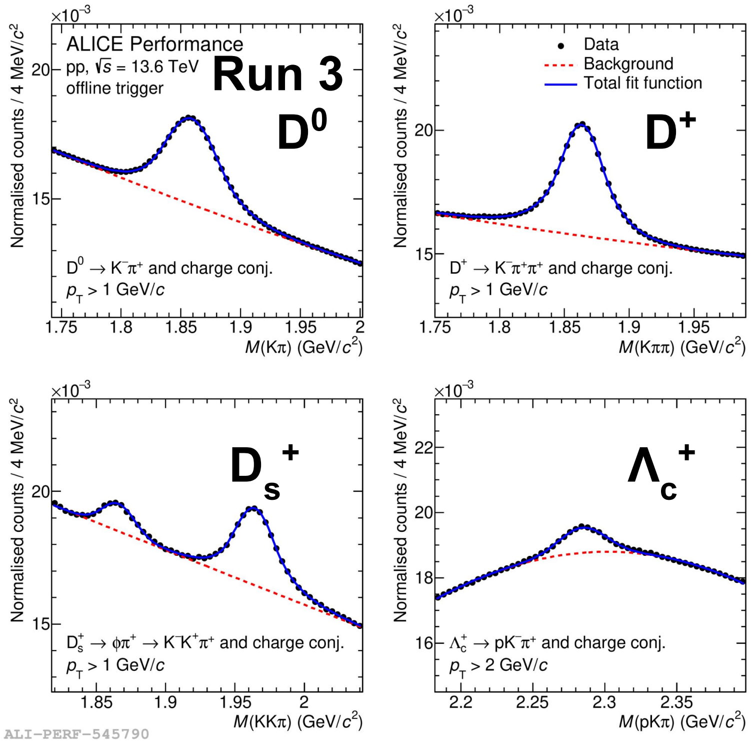
→ Yoshini talk tomorrow

EPOS3 PRC 89 064903 (2014)
CGC PRD 101 094020 (2020)



Useful constraints to models though physical “biases” on the steeply falling event-multiplicity distribution make it difficult to decouple role of different effects
→ simultaneous description of event multiplicity and jet constituents is a prerequisite

Outlook



ALICE apparatus upgraded before Run 3

New Inner Tracking System

New readout for most subsystems
→ allows triggerless (online) data collection at higher interaction rates (**more than x100 in pp**)

→ boost in available statistics and performance for heavy-flavour physics

→ more differential studies + new observables
From “surprise” to precision era

- **Low p_T, rapidity and multiplicity dependence**
- **Strangeness, diquarks**
- **Jets and correlations**

Summary: HF hadronisation in our QCD laboratories

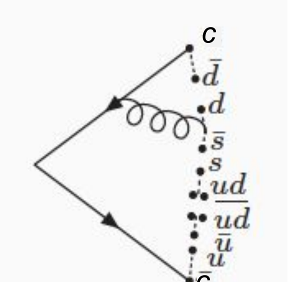
Fragmentation functions universality violated already in pp collisions
Multiple parton interactions in pp build a system rich of quarks or gluons, dense enough to alter hadronisation w.r.t. e^+e^-

e^+e^- = “vacuum”

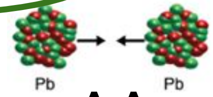
pp
~~not far from vacuum ~ many independent scatterings~~
(for HF at least)

MPI, system size

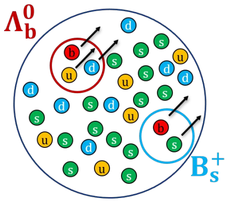
Dynamical model
“Local” dynamical constraints
(e.g. Lund string fragmentation, quarks and diquarks popping out from QCD potential)



Courtesy of C. Bierlich



A-A
Dense, extended-size system
Equilibrium
Flow

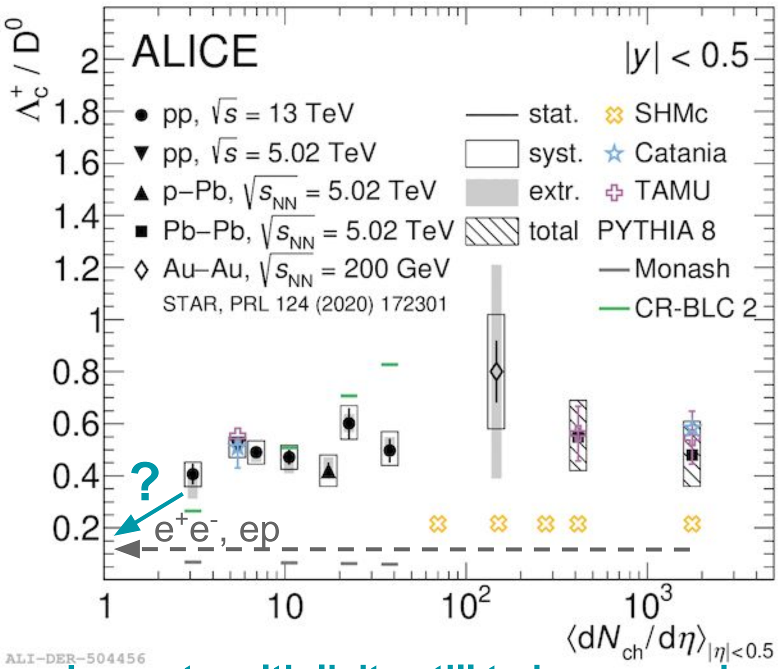


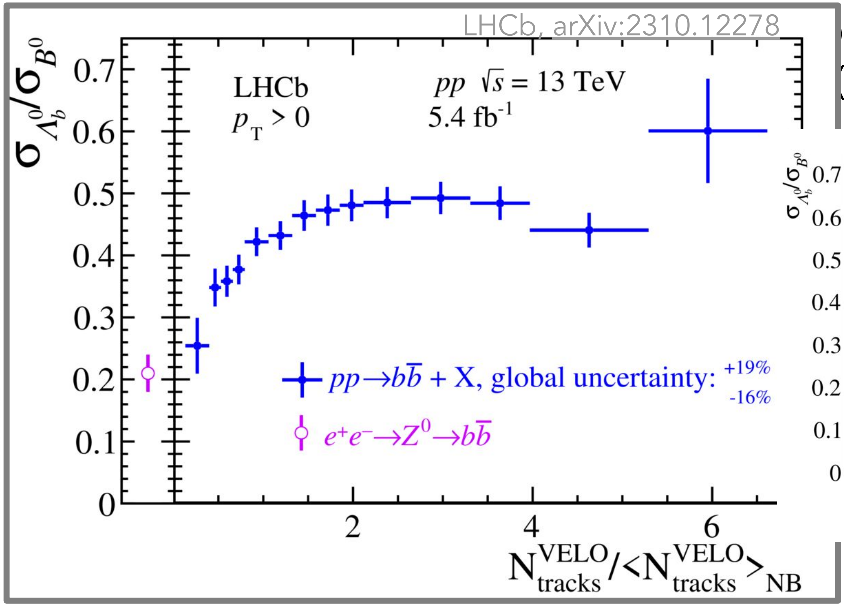
(Semi)phenomenological models sufficient to describe relative particle abundances *once ingredients are tuned*?

Extra

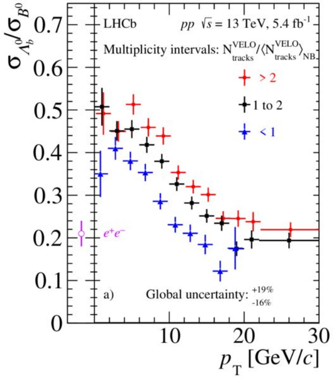
Λ_c^+/D^0 from pp to central AA: p_T-integrated

PRC 104 054905 (2021) , PRL 127 202301 (2021), PLB 829 (2022) 137065, arxiv 2112.08156





⁰ ratio
(see later).

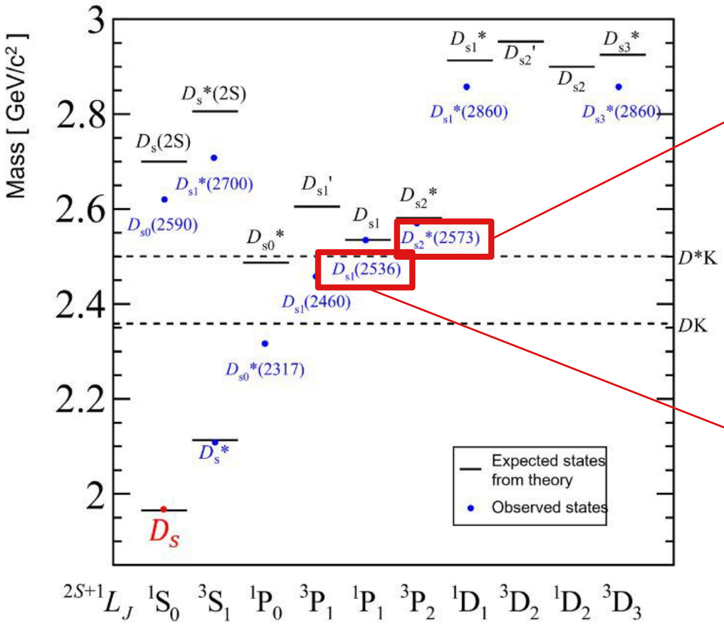


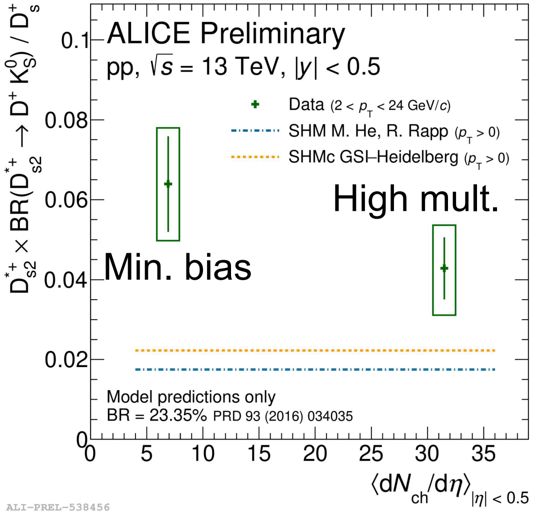
Lowest multiplicity still to be covered: will recover e^+e^- ?

→ more precise measurements from LHC new runs awaited

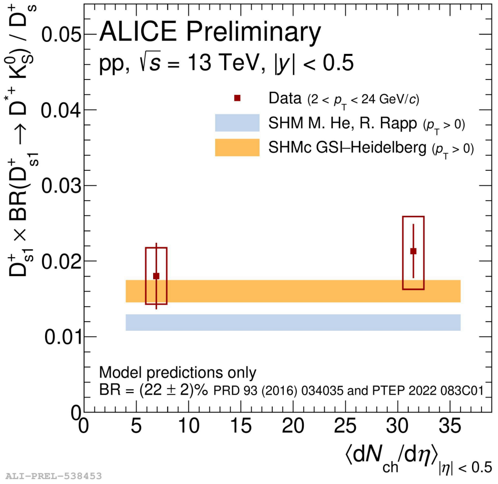
Seems so in beauty sector (see backup)

Excited D_s mesons





Γ~16.9 MeV
τ ~ 11.6 fm/c

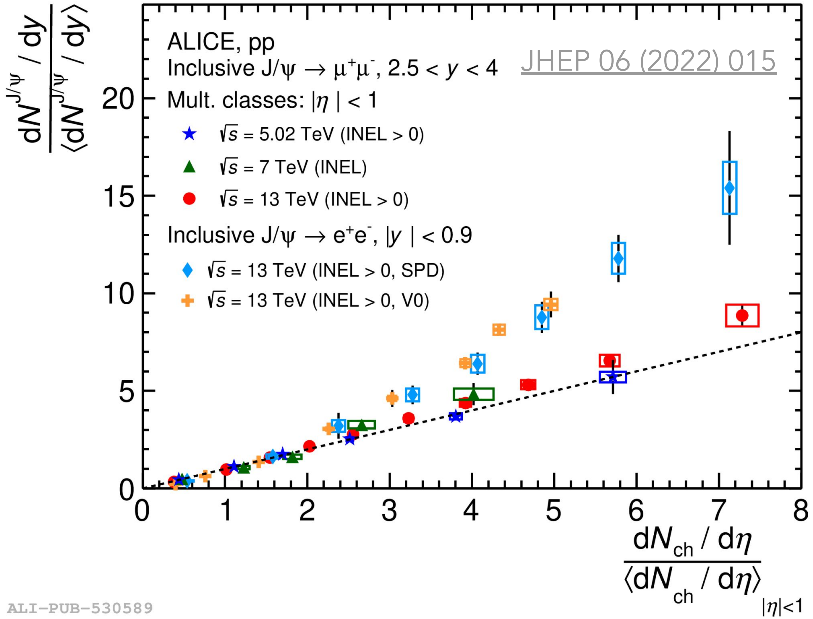


Γ~0.92 MeV
τ ~ 219 fm/c

Important to test SHM expectations

(More precise) studies of multiplicity dependence of states with different widths may reveal possible role of hadronic rescattering.

J/ψ self-normalised yield



→ **Chi Zhang**

Inclusive J/ψ self-normalised yield at midrapidity **increasing more than linearly with multiplicity** even when multiplicity is sampled at forward *y* (V0 detector)

Contribution from recombination? Could rise with N_{MPI}^2 from colour-reconnection expected in PYTHIA 8

S.G. Weber et al., EPJC 79 36 (2019)

Assessment of non-prompt fraction evolution with multiplicity is needed

Non-prompt D meson fraction vs. multiplicity

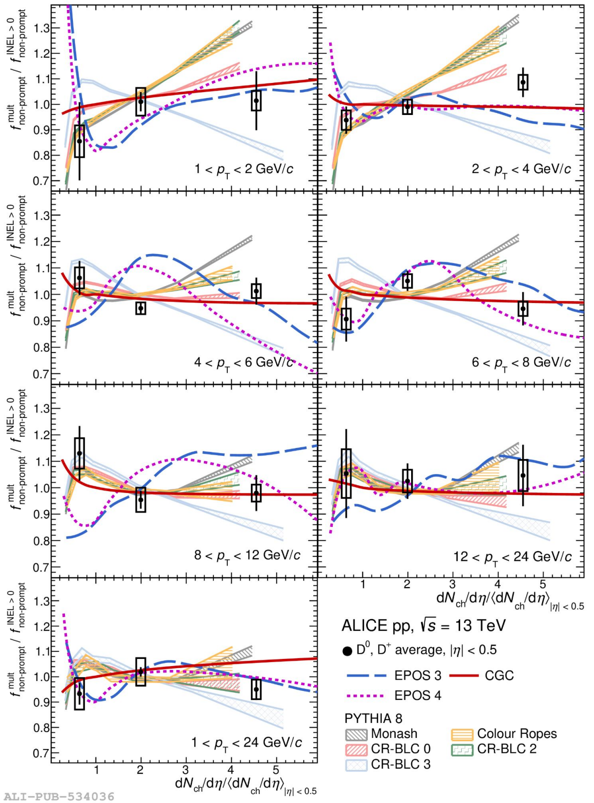
JHEP 10 (2023) 092

***y* axis:** Non-prompt D-meson fraction (mult) / Non-prompt D-meson fraction (INEL>0)
***x* axis:** mult / mult(INEL>0)

None or mild dependence of prompt D-meson fraction on multiplicity at all p_T

Comparison to models also depends on evolution of baryon/meson ratio with p_T and multiplicity

EPOS3 PRC 89 064903 (2014)
EPOS 4, arxiv 2301.12517
CGC PRD 101 094020 (2020)
PYTHIA8: Monash, EPJ C74 (2014) 3024, CR-BLC JHEP 1508 (2015) 003, ROPES, arxiv 2203.11601



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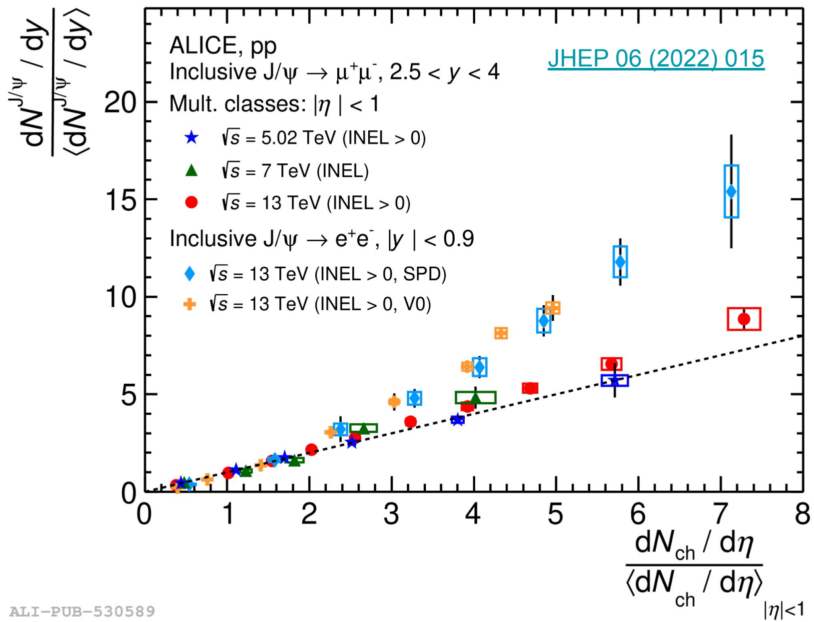
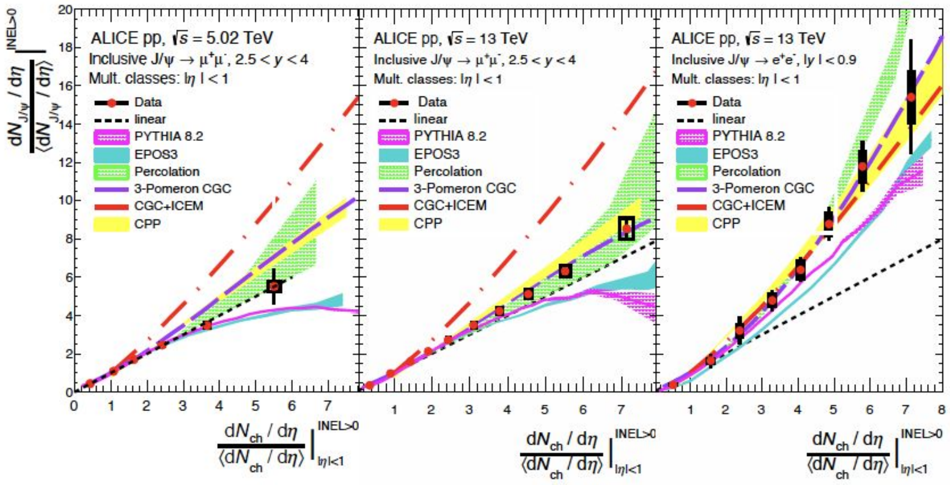
→ simultaneous description of event multiplicity and jet constituents is a prerequisite

J/ψ self-normalised yield





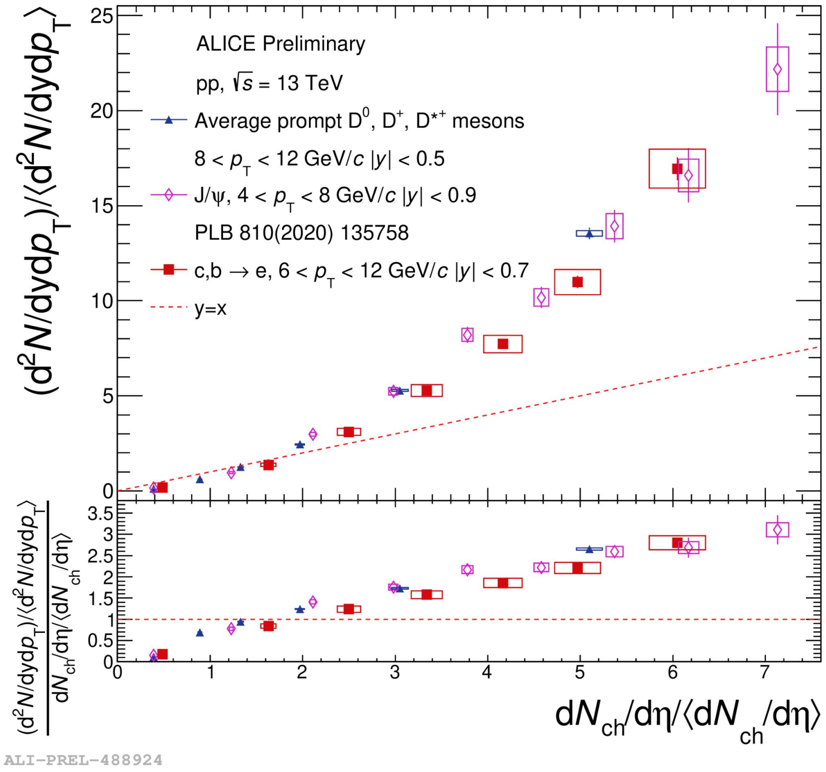
Inclusive J/ψ self-normalised yield at midrapidity increasing with multiplicity even when multiplicity is sampled at forward y (V0 detector)

Contribution from recombination? It would rise with N_{MPI}^2 from colour-reconnection expected in PYTHIA8

S.G. Weber et al., EPJC 79 36 (2019)

Assessment of non-prompt fraction evolution with multiplicity is needed

Production yield evolution with multiplicity



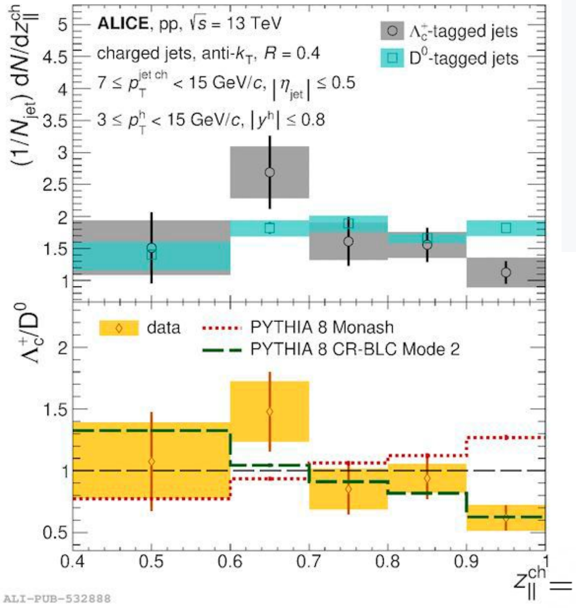
Similar multiplicity-increasing trends for

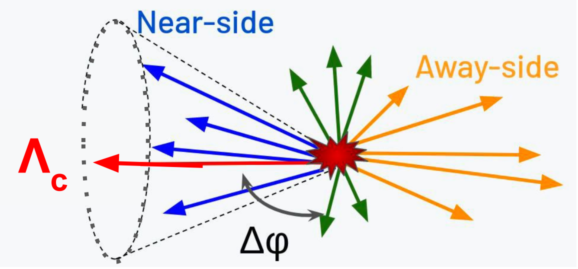
- D mesons
- HF electrons
- Inclusive J/ψ

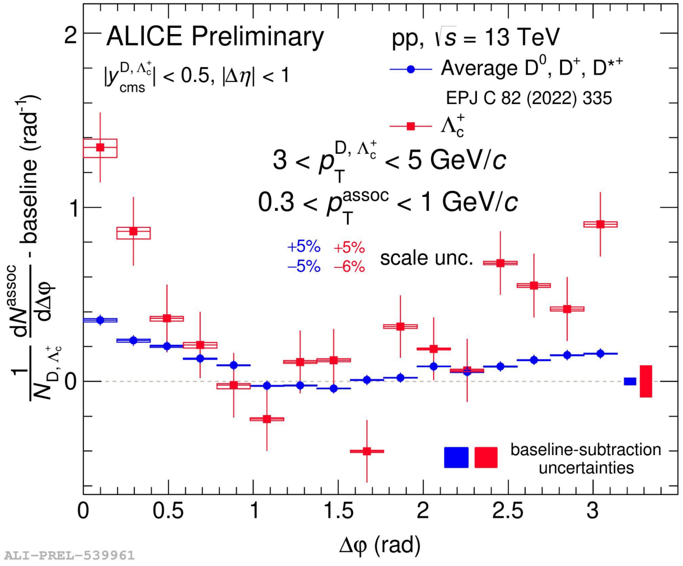
at intermediate p_T

Jets and correlations

ALICE, arXiv:2301.13798





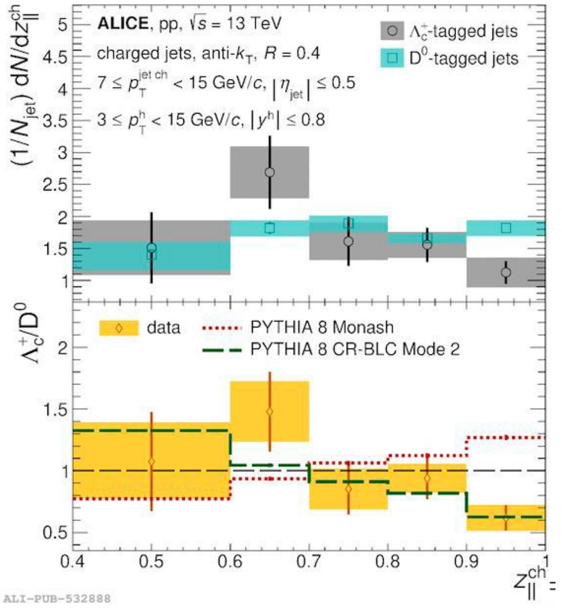


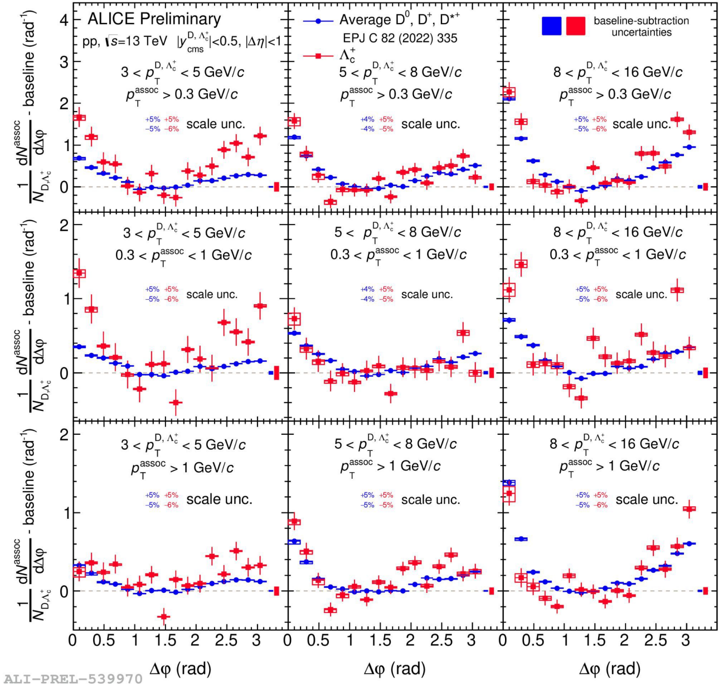
$$z_{\parallel}^{\text{ch}} = \frac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$$

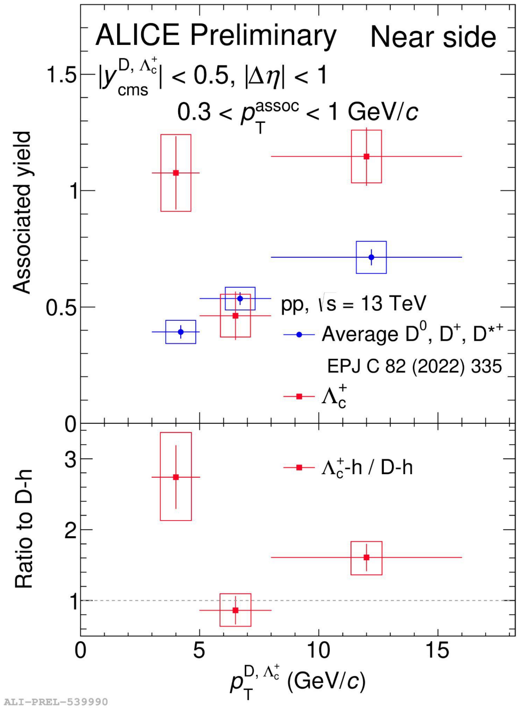
- Jets: indication of **softer fragmentation c→Λ_c than c→D**
- Coherent with higher associated yield in the nearside of Λ_c^+ - hadron azimuthal correlations w.r.t. D-hadron
  … away side surprisingly high!!! No straightforward explanation
  Higher-mass states + decay kinematics? Production process?

Jets and correlations

ALICE, arXiv:2301.13798





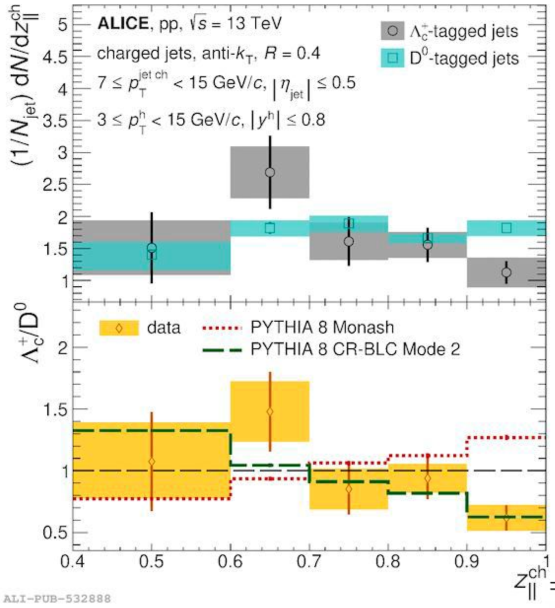


The large AS suggests that the $z_{//}$ distribution (and the NS) are not altered because of some local effect coming with hadronisation

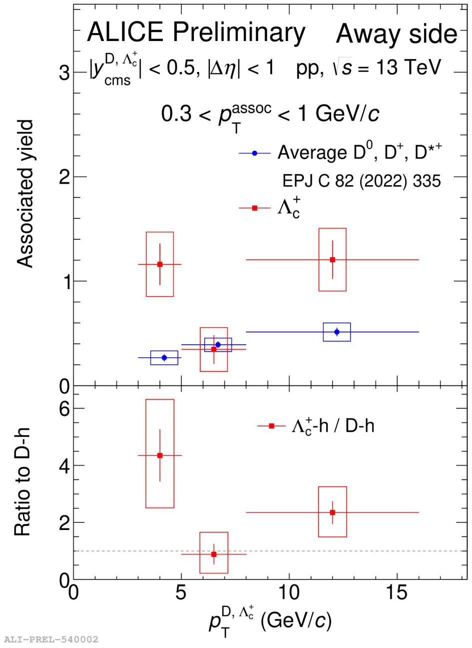
→ The most natural, straightforward conclusion we have is that a large fraction of low-pt Λ_c^+ comes from moderate-high-p_T jets!

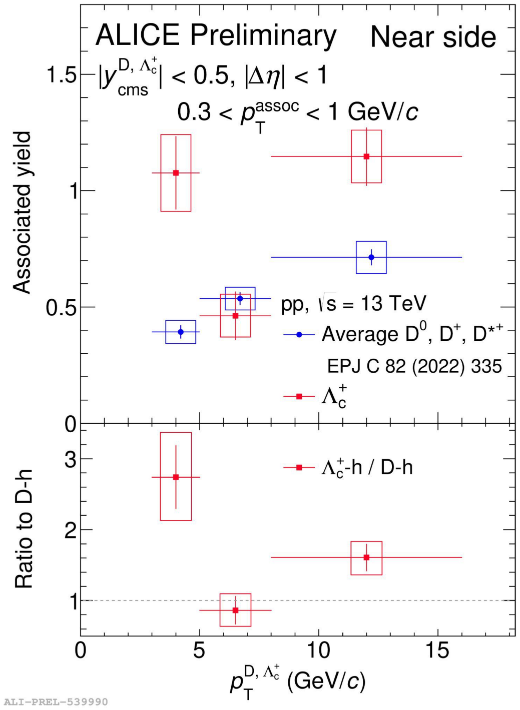
Jets and correlations

ALICE, arXiv:2301.13798



$$z_{||}^{ch} = \frac{\vec{p}_{\rm ch\ jet} \cdot \vec{p}_{\rm HF}}{\vec{p}_{\rm ch\ jet} \cdot \vec{p}_{\rm ch\ jet}}$$





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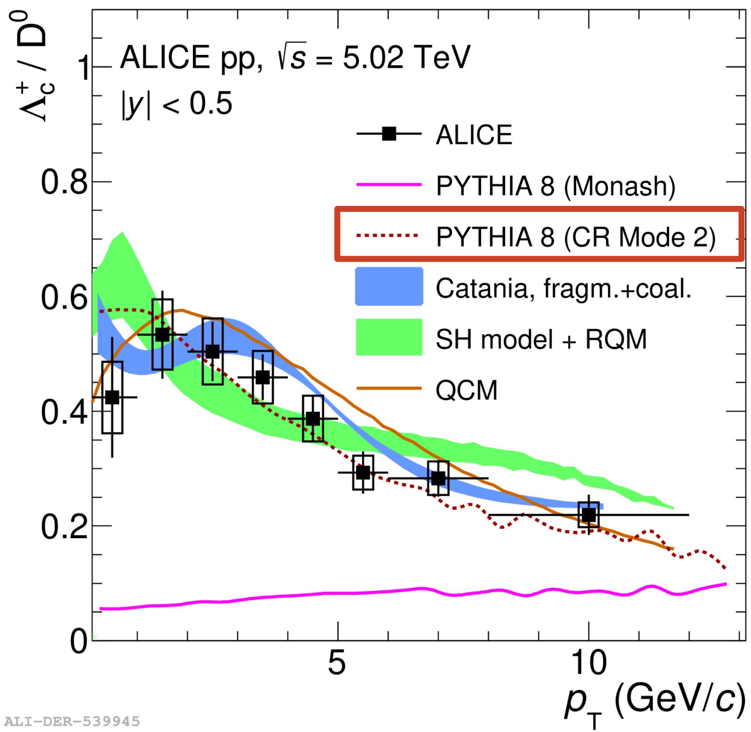
→ The most natural, straightforward conclusion we have is that a large fraction of low-pt Λ_c^+ comes from moderate-high-p_T jets!

Λ_c^+/D^0 ratio in pp collisions vs. models (3)



ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

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.

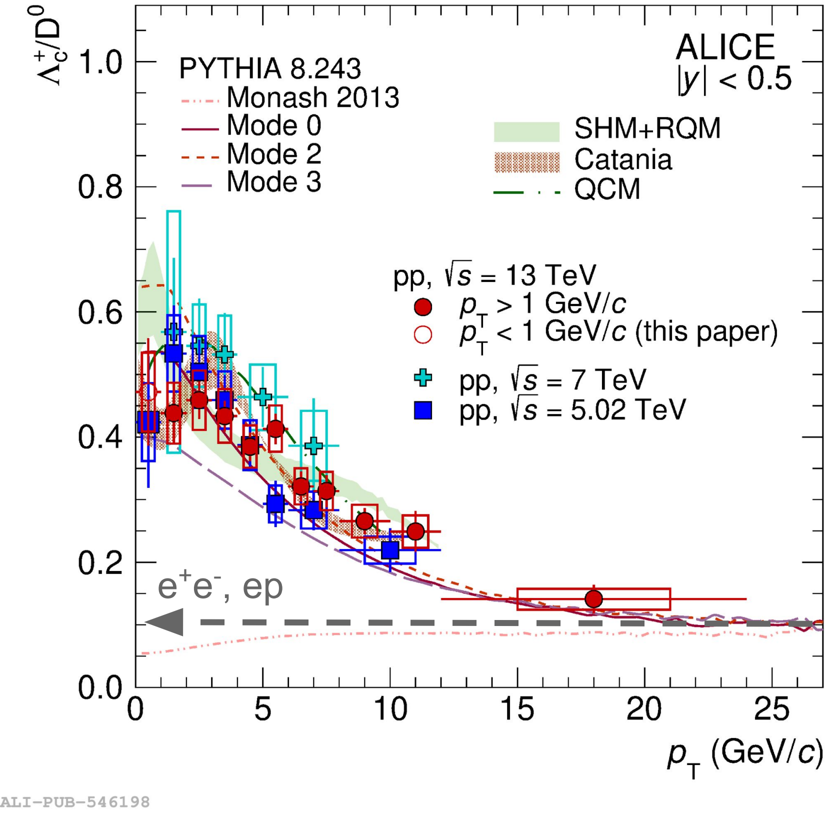
(b) Type II: junction-style reconnection

Support need of abandoning independent hadronisation of different MPI
A hadronic environment matters

Λ_c^+/D^0 baryon-to-meson cross-section ratio

ALICE, arxiv 2308.04877

ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, PRC 107 (2023) 6, 064901



Data described by:

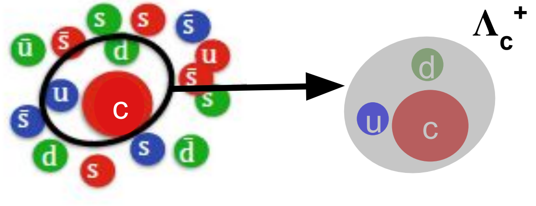
PYTHIA 8 with String Formation beyond Leading Colour (JHEP 1508 (2015) 003) → more details in next talk

Catania model: "sudden" **coalescence** (Wigner function) + "vacuum" fragmentation (PLB 821 (2021) 136622)

$$\frac{dN_H}{dy d^2 P_T} = g_H \int \prod_{i=1}^{N_q} \frac{d^3 p_i}{(2\pi)^3 E_i} p_i \cdot d\sigma_i \; f_{q_i}(x_i, p_i) \times f_H(x_1 ... x_{N_q}, p_1 ... p_{N_q}) \, \delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right)$$

f_q = phase-space distributions of quarks in the system

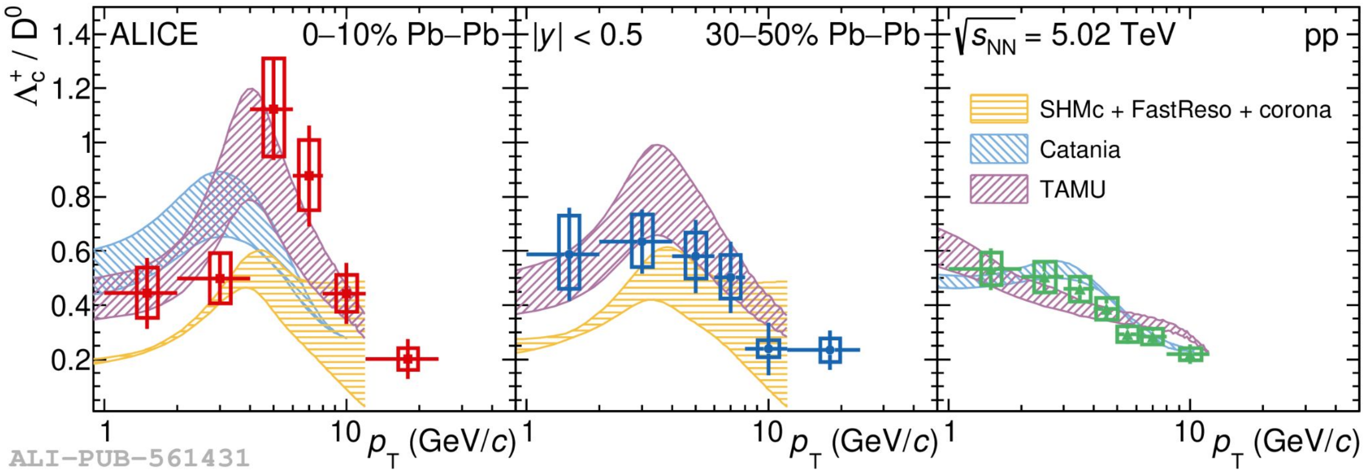
f_H = phase-space distributions of quarks within hadron



Λ_c^+/D^0 in Pb-Pb vs. models

PLB 839 (2023) 137796

Discussed in M. Faggin talk



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

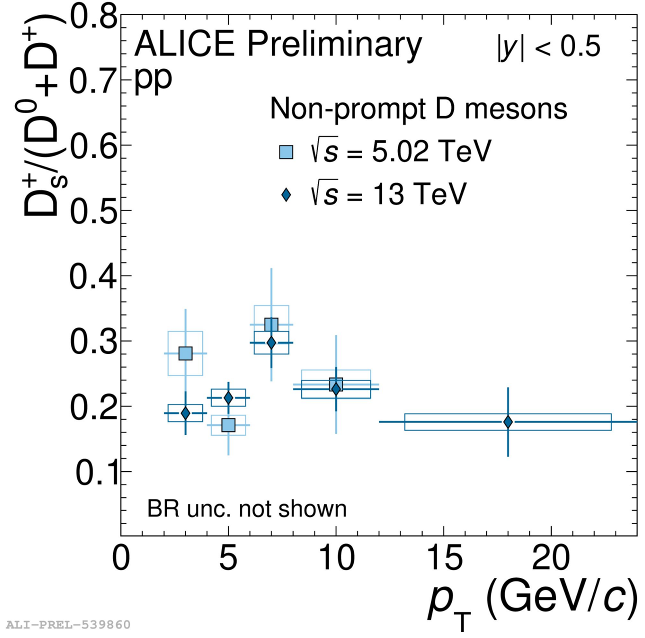
TAMU (hadronisation via Relativistic Resonant Scattering model + RQM states) and **Catania** (sudden coalescence + fragmentation) describe data within uncertainties

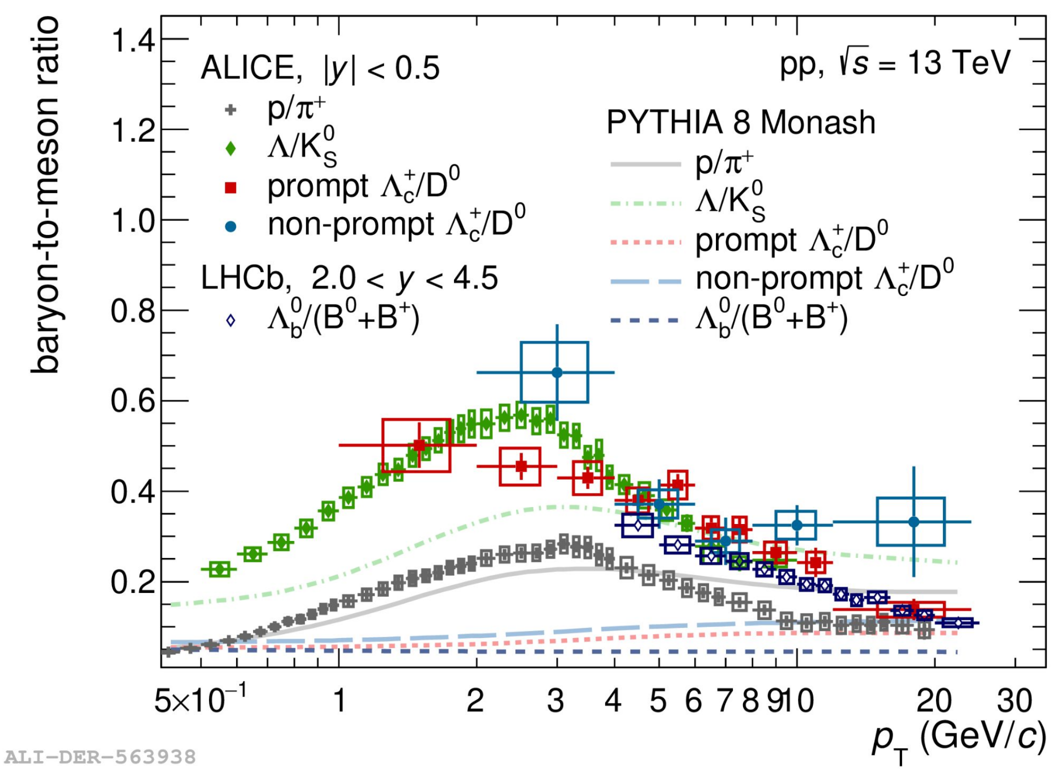
SHMc + FastReso + corona tends to underestimate data

Important specific constraints to model features (hadronisation, space-momentum correlations) needed to describe D meson flow and R_{AA}

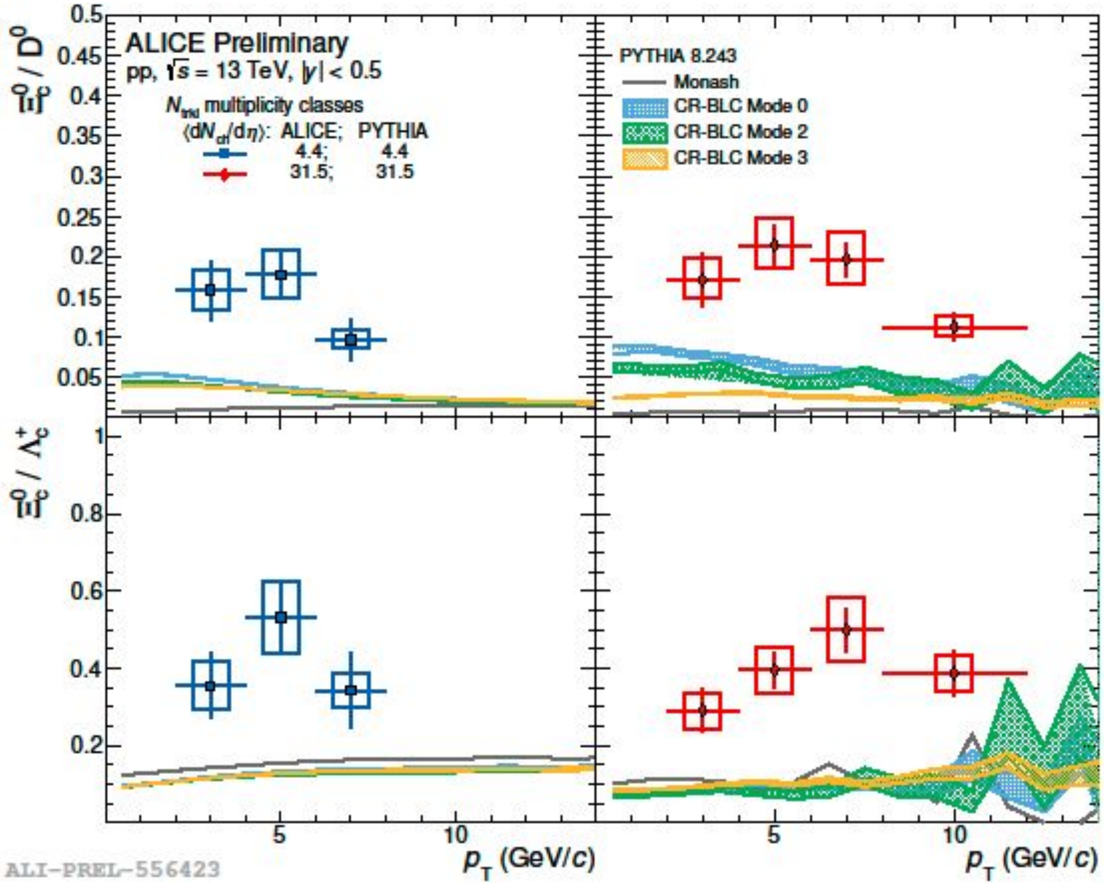
Beauty vs. charm

arxiv 2308.04873



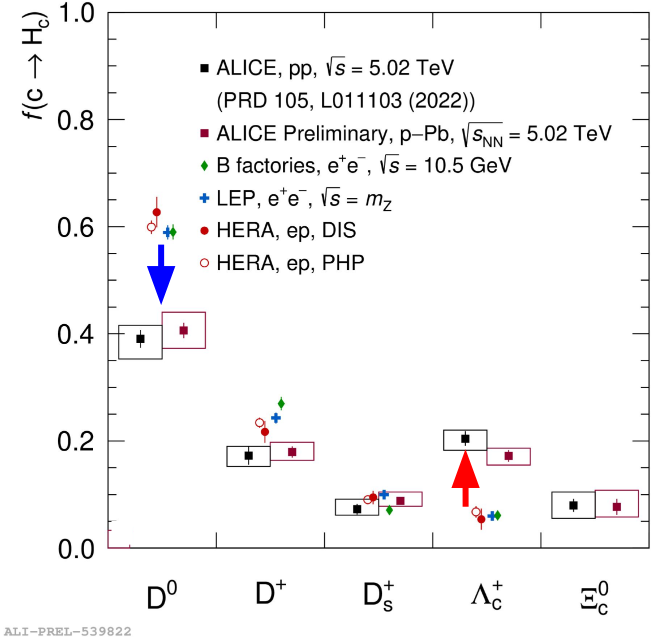


Evolution with event activity in pp and p–Pb: $\Xi_c^{0,+}$



Fragmentation fractions from all ground-state baryons

PRD 105 (2022) 1, L011103, arxiv 2211.14032



Direct measurement of all ground-state baryons (Ξ_c^+ similar to Ξ_c^0, checked at 13 TeV)

→ new Fragmentation Fractions

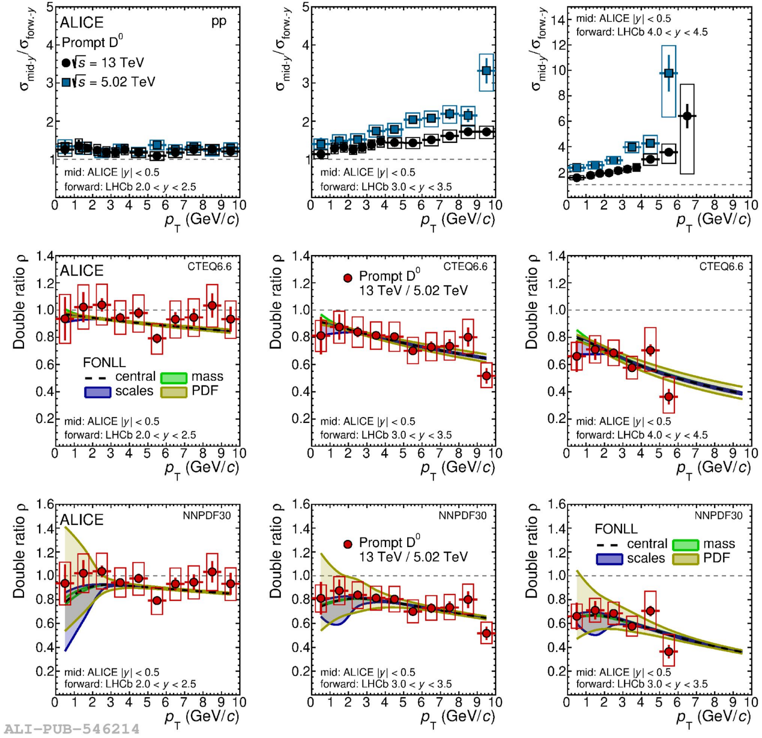
Large increase for $c \to \Lambda_c^+$ and $c \to \Xi_c^0$ w.r.t e^+e^-

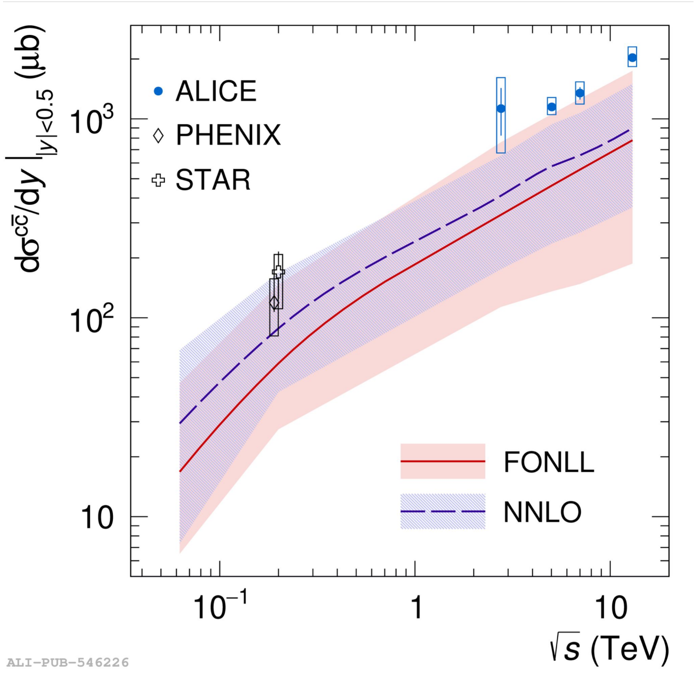
More than 1/3 of charm quarks go to baryons!

No significant modification of p_T-integrated yield ratios from pp to p-Pb

Charm production cross section and rapidity dependence

arxiv 2308.04877



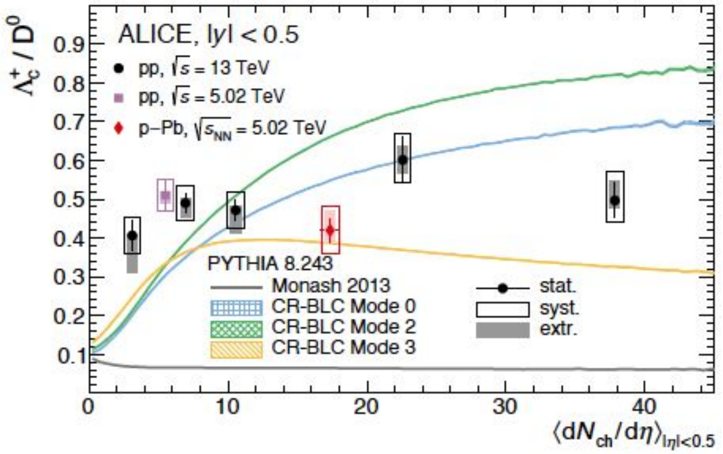


Forward/mid-rapidity ratio and its collision energy evolution reproduced by FONLL

- Sensitivity to PDF

Total ccbar crossection at midrapidity at the edge of FONLL and NNLO calculation uncertainty band

Evolution with event activity in pp: Λ_c^+/D^0 p_T integrated

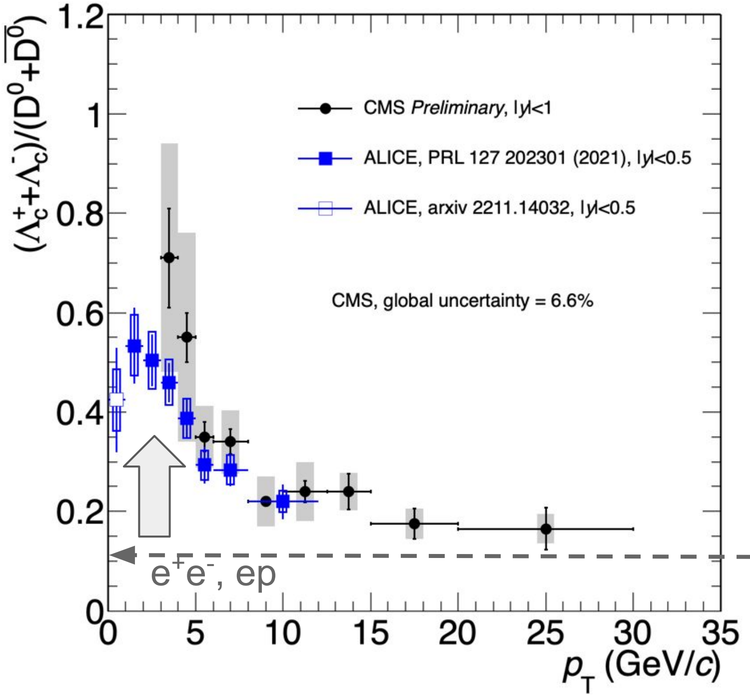


p_T-integrated ratio: no evidence of multiplicity dependence

Contrary to expectations from PYTHIA8 with CR-BLC

PLB 829 (2022) 137065, https://arxiv.org/abs/2111.11948

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



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

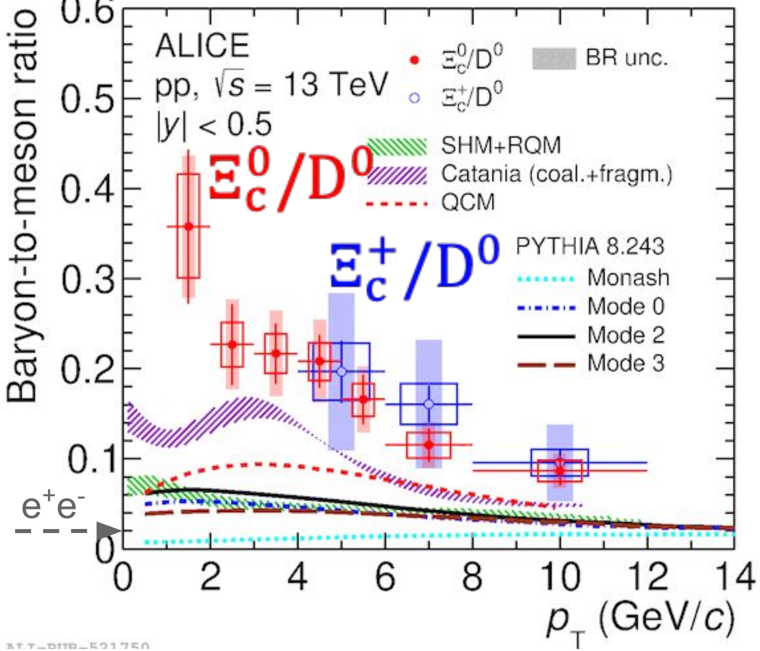
Significantly decreasing with p_T , approaching e^+e^- at high p_T

	$\Lambda_c^+/D^0 \pm$ 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, $\lvert\eta\rvert < 1.6$

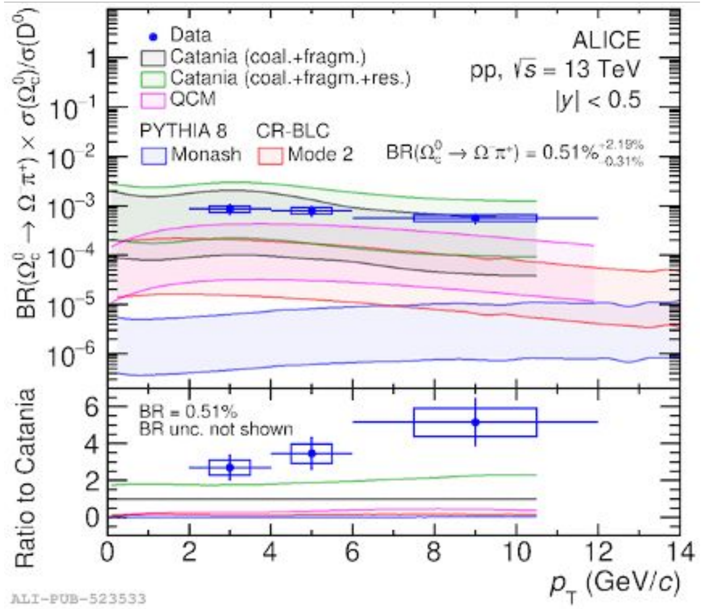
ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032
CMS, PAS-HIN-21-004

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

PRL. 127 (2021) 272001



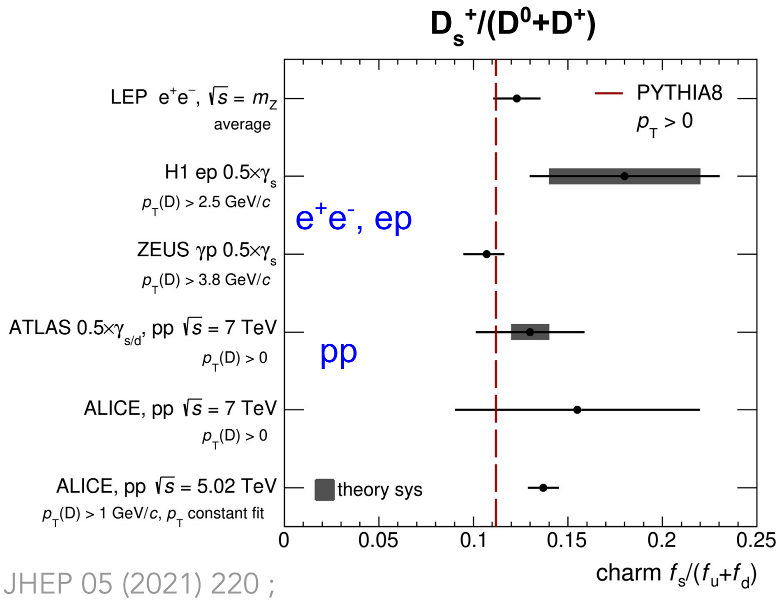
arXiv:2205.13993



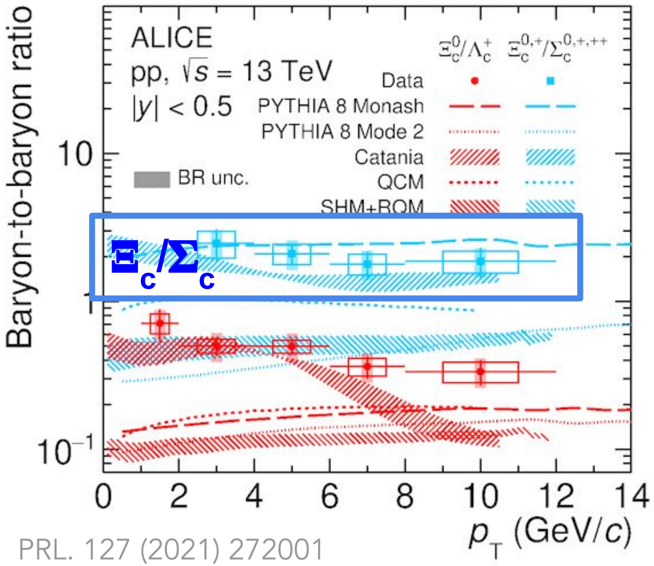
- Both $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0x BR($\Omega_c^0 \to \Omega^-\pi^+$) ratios significantly larger than in e^+e^- collisions
- Only **Catania** model (coalescence) close to the data.

→ Additional challenges from strange-quark production?

Baryon-to-baryon: $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$



JHEP 05 (2021) 220 ;
EPJC 79 (2019) 5, 388

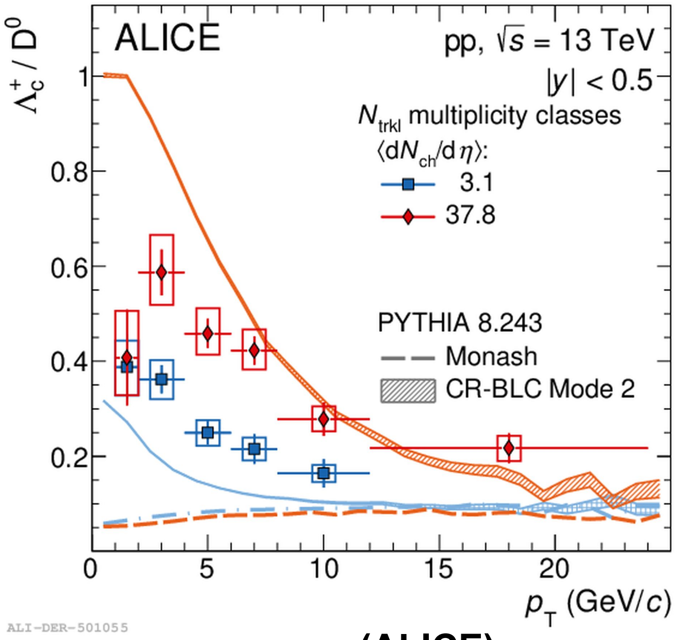


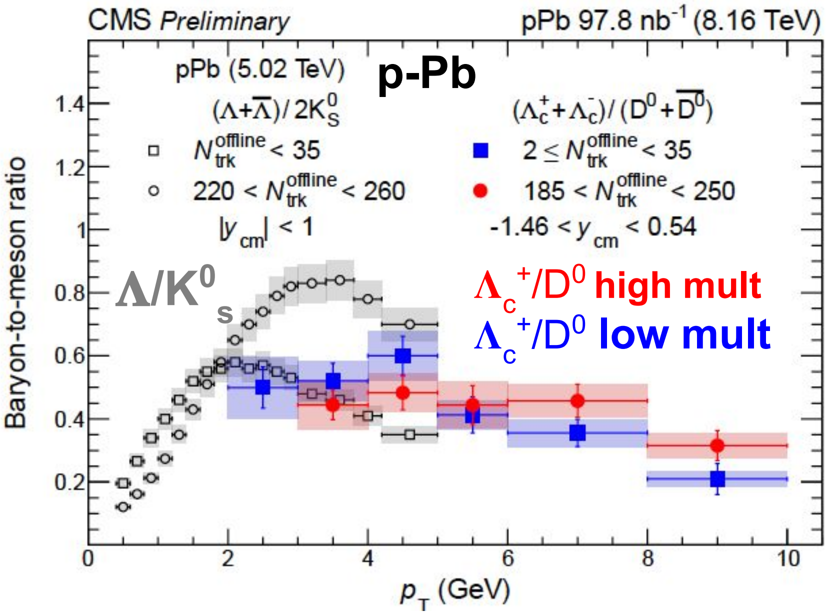
PRL. 127 (2021) 272001

- **$D_s^+/(D^0+D^+)$ (prompt and non-prompt) compatible with expectations from e^+e^-**
- **$\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio close to default PYTHIA8, which strongly underestimates their production! (described by Catania as well)**
  → similar suppression in e^+e^-? Related to diquark rather than quarks?
  (note mass of spin-1 $(dd,ud,uu)_1$ diquarks might be similar to spin-0 $(us,ds)_0$ diquarks)

Evolution with event activity in pp and p-Pb: Λ_c^+/D^0

PLB 829 (2022) 137065





pp (ALICE):

Λ_c^+/D^0 increases with multiplicity from p_T>2 GeV/c

Qualitatively reproduced by **PYTHIA8 with CR-BLC**
→ interplay of CR and MPI

p-Pb (CMS):

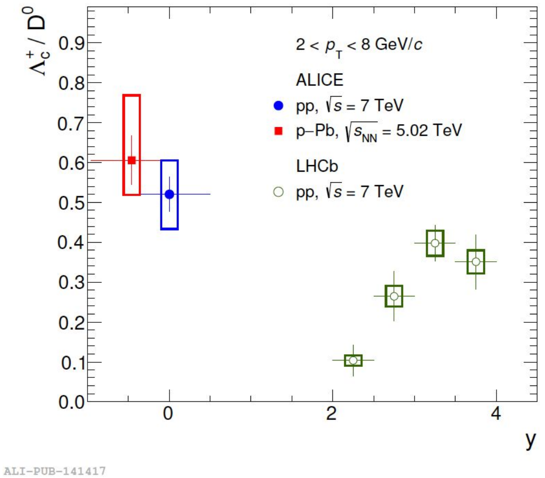
Λ_c^+/D^0 does not evolve significantly with multiplicity

Close to ALICE pp high-multiplicity data

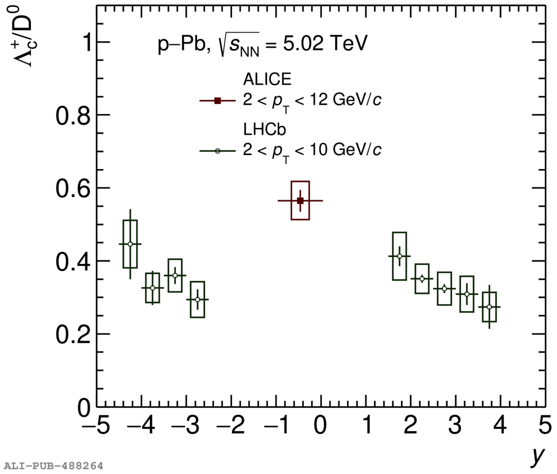
Breaking the similarity with Λ/K^0_s observed in pp (see backup)

Rapidity dependence

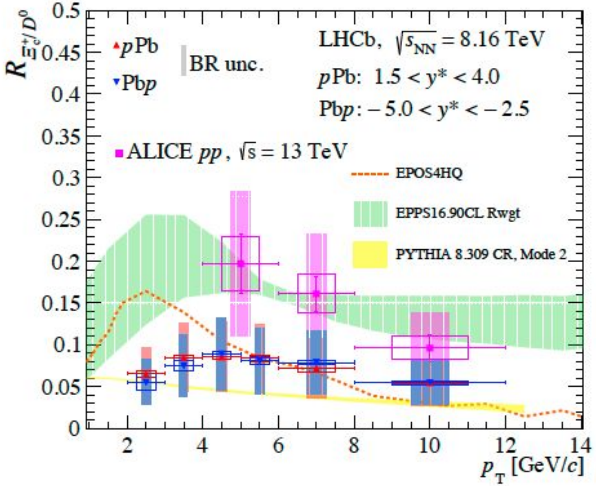
charm, pp



charm, p-Pb



LHCb, arxiv 2305.06711

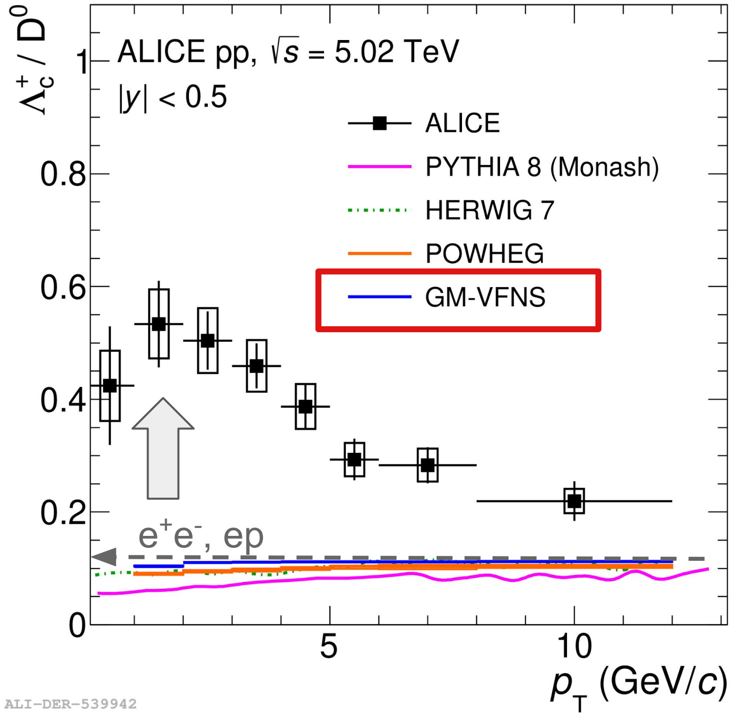


Not clear for charm (especially in pp), to be revisited with run 3 data?

Beauty: non-prompt Λ_c^+ ALICE data consistent with LHCb Λ_b^0 data
→ low p_T region to be explored with run 3 data

ALICE, JHEP 04 (2018) 108
ALICE, PRC 104 054905 (2021)
LHCb (pp), Nucl.Phys.B 871 (2013)
LHCb (p-Pb), JHEP 02 102 (2019)

Λ_c^+/D^0 ratio in pp collisions vs. models (1)



Data far from **pQCD-based calculations** based on **factorisation** approach**,** which works well for mesons (plethora of results at RHIC, Fermilab, LHC,...)

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

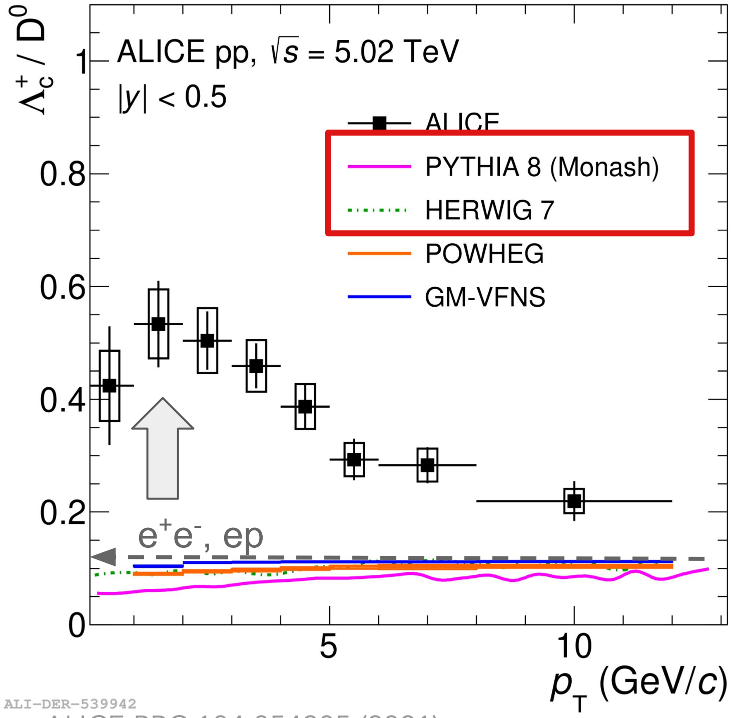
Naïve expectation: ratios of particle-species yields independent from collision system

→ **Universality of fragmentation function does not hold already in pp collisions**

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

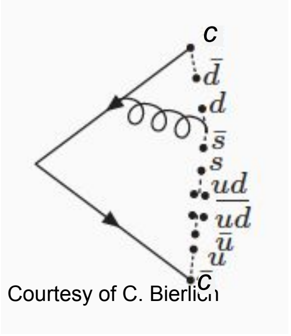
fragmentation function

Λ_c^+/D^0 ratio in pp collisions vs. models (2)

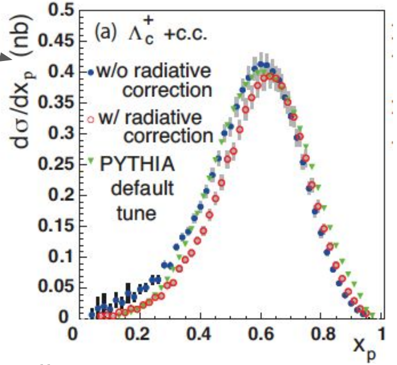


ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

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



- Light quark/diquark pairs popping out from QCD color-confinement potential (← strings)
  - **Diquarks ↔ baryons**
- Hadronisation of different MPI products largely independent
- Reproduces e^+e^- data ~ fragmentation functions used in pQCD-based calculations

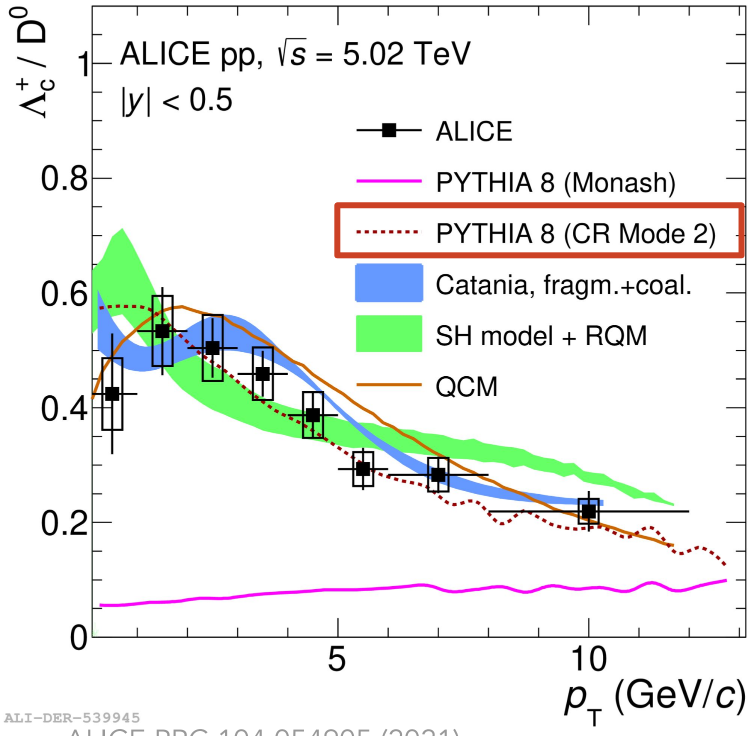


Belle, PRD 97, 072005 (2018)

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

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

Λ_c^+/D^0 ratio in pp collisions vs. models (3)

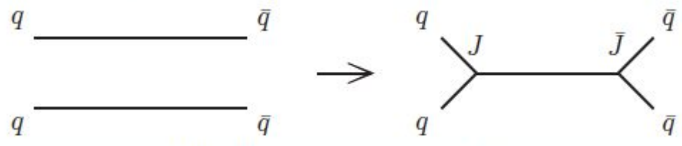


ALICE,PRC 104 054905 (2021)
ALICE, PRL 127 202301 (2021)
ALICE, arxiv 2211.14032

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

Support importance of interplay of CR and MPI for hadronisation
A hadronic environment matters