Hadronization of heavy-quarks: open questions and perspectives

Mainly based on the review: Altmann et. al arXiv:2405.19137

Andrea Dubla

04/09/2024

Relevance of hadronisation

Hadronization is relevant:

1) **In itself**: how hadron are produced? Is it a universal process in e^+e^-, e^-p, pp, pA and AA?

2) **HQ transport properties** → can affect estimates of $D_s(T)$: both $R_{AA}(p_T)$ & $v_n(p_T)$ affected

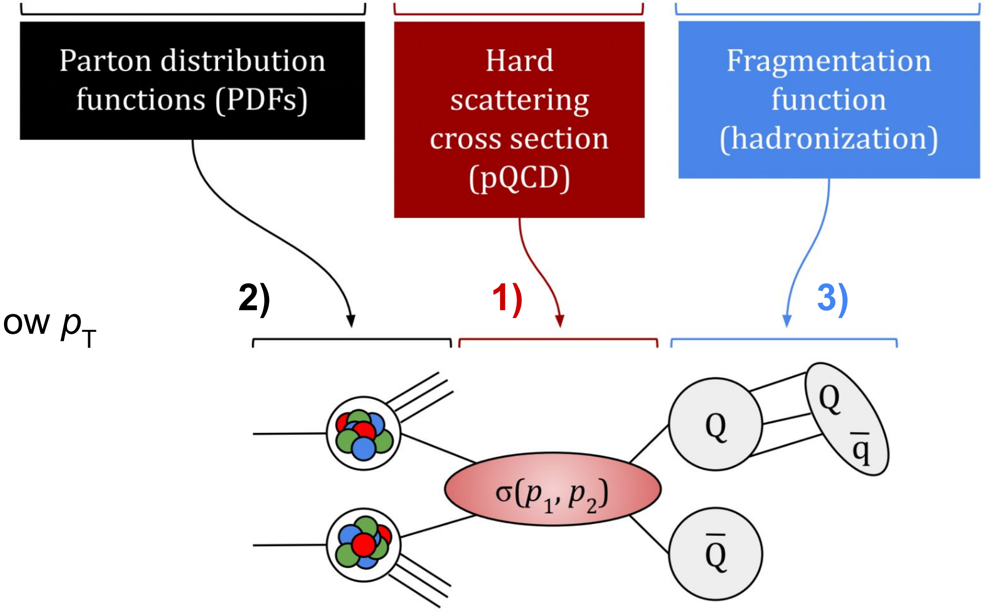
3) **QGP droplets**: infer properties of medium created in pp and/or pA

4) **Polarization**: underlying the interpretation for light hadrons, open HF and quarkonia

5) **Future physics program**: predictions for multi-charm production PbPb vs KrKr vs ArAr
Relevance of HF Hadronization

How to: one way among many

$$\frac{\mathrm{d}\sigma^{\mathrm{H_c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{H_c}}}(p_{\mathrm{T}};\mu_{\mathrm{F}},\mu_{\mathrm{R}}) = \mathrm{PDF}(x_1,\mu_{\mathrm{F}})\cdot\mathrm{PDF}(x_2,\mu_{\mathrm{F}})\otimes\frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(x_1,x_2,\mu_{\mathrm{F}},\mu_{\mathrm{R}})\otimes D_{\mathrm{c}\to\mathrm{H_c}}(z=p_{\mathrm{H_c}}/p_{\mathrm{c}},\mu_{\mathrm{F}})$$



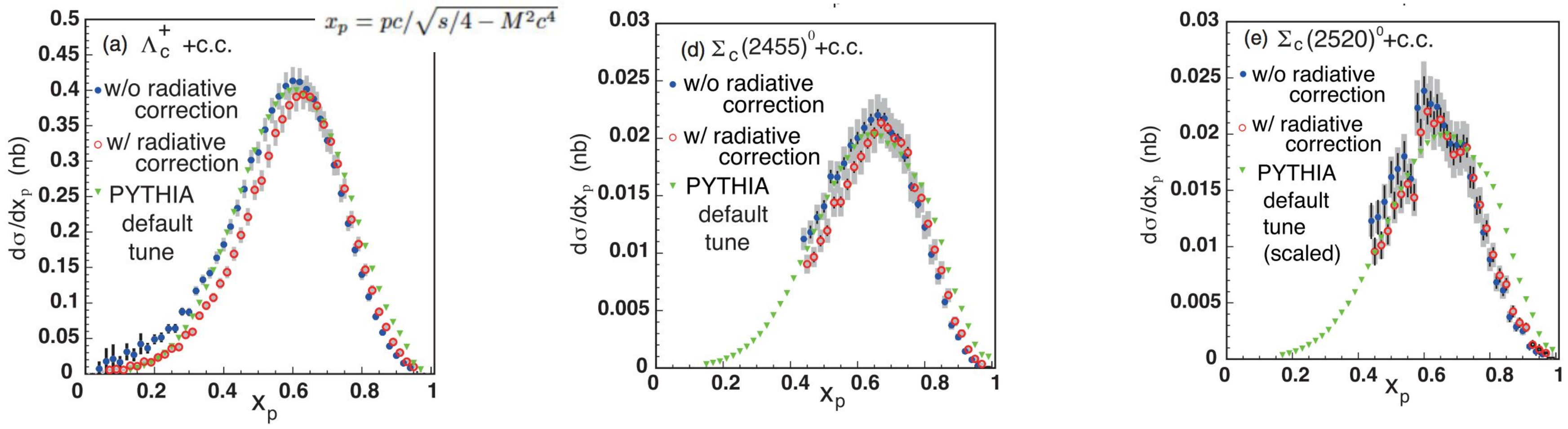
1) **Hard scattering:**
- large quark mass provides hard scale
- pQCD can calculate cross sections down to low p_T

2) **PDF** → from ep collisions

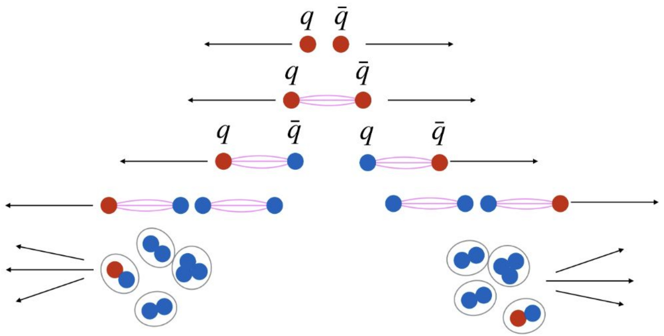
3) **FF** → from e^+e^- collisions

➢ **To isolate FF: hadron-to-hadron production ratios** are effective for probing hadronisation, PDFs and partonic cross sections cancel in the yield ratios

Charm baryons in e^+e^-



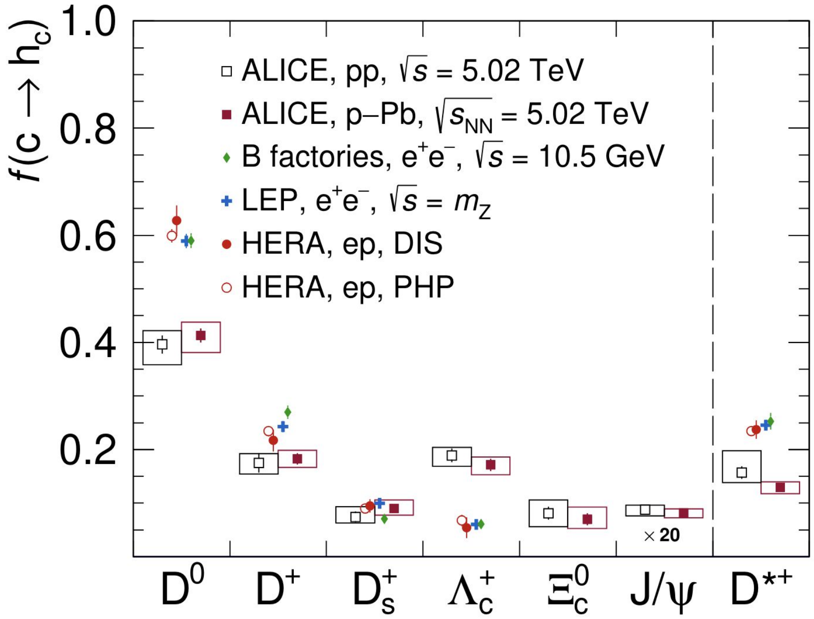
Belle: PRD 97, 072005 (2018)



- ➢ Charm baryons vs PYTHIA in e^+e^-
  - **Standard PYTHIA** with string fragmentation describe the experimental data

Hdronisation universality?

PRD 105 (2022) 1, L011103
arXiv:2405.14571

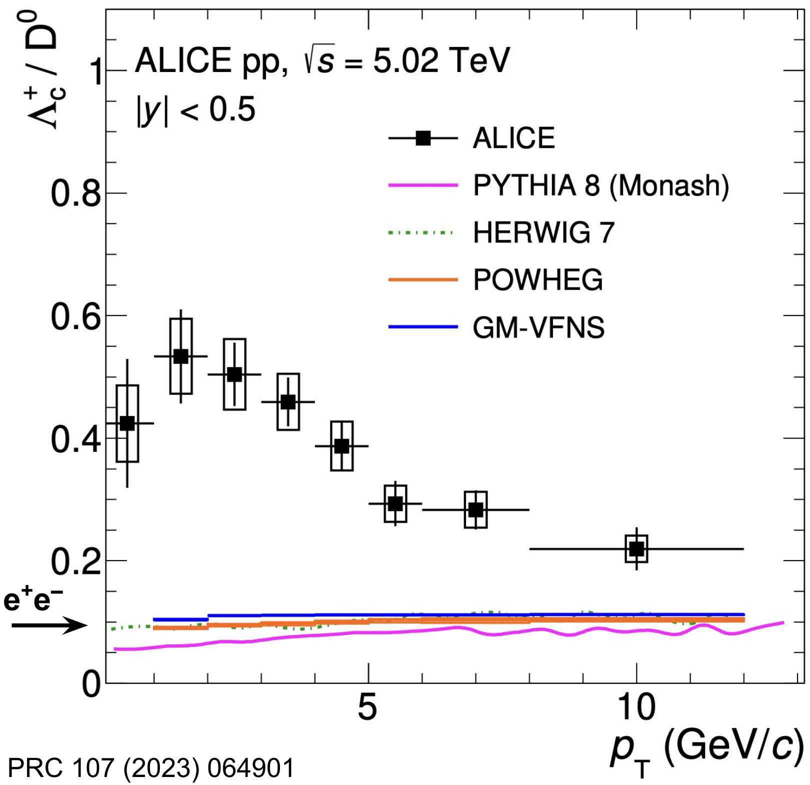


- Measurement of fragmentation fractions in pp collisions at LHC compared to e^+e^- (ep) collisions at lower √s
  - Indication that parton-to-hadron fragmentation depends on the collision system
  - Assumption of hadronisation universality not supported by the measured cross sections

→ Independent fragmentation picture not valid in partonic-color-rich environment

→ Break-down of hadronisation universality

How MC generators perform at LHC?



PRC 107 (2023) 064901

- **PYTHIA 8** with Monash tune and colour reconnection
  Eur. Phys. J. C74 no. 8, (2014) 3024
- **HERWIG 7** where hadronisation is implemented via clusters Eur. Phys. J. C58 (2008) 639–707
- **POWHEG** matched to PYTHIA 6 to generate the parton shower JHEP 09 (2007) 126
- **GM-VFNS** pQCD calculations → compute the ratios of the Λ_c and D^0 cross sections
  Phys. Rev. D 101 (2020) 114021

➢ Fragmentation processes tuned on charm production measurements in e^+e^- collisions, → Λ_c/D^0 ~ 0.1 mild p_T-dependence.

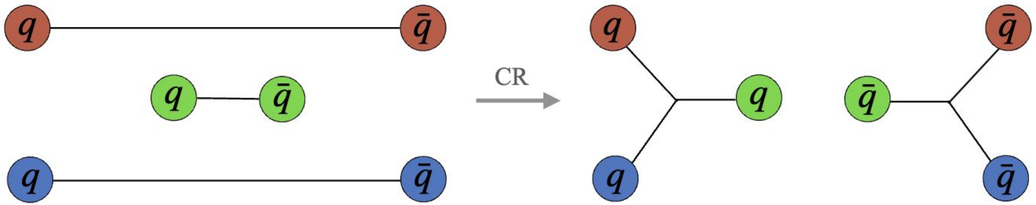
➢ Significantly underestimate the data at low p_T, while at high p_T the discrepancy is reduced

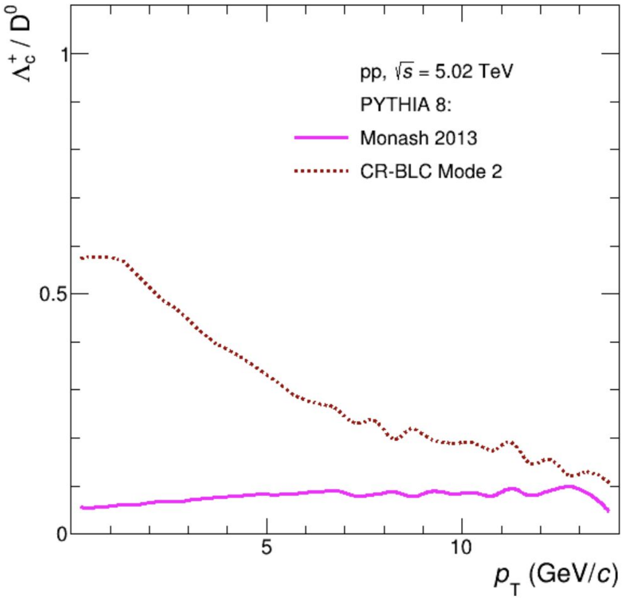
Can we explain the measured baryon enhancement?

PYTHIA 8 new Color Reconnection

➢ **PYTHIA8 with String Formation beyond Leading Colour (CR-BLC)**

Introduce new 'junction topologies for baryon enanchement'





JHEP 1508 (2015) 003

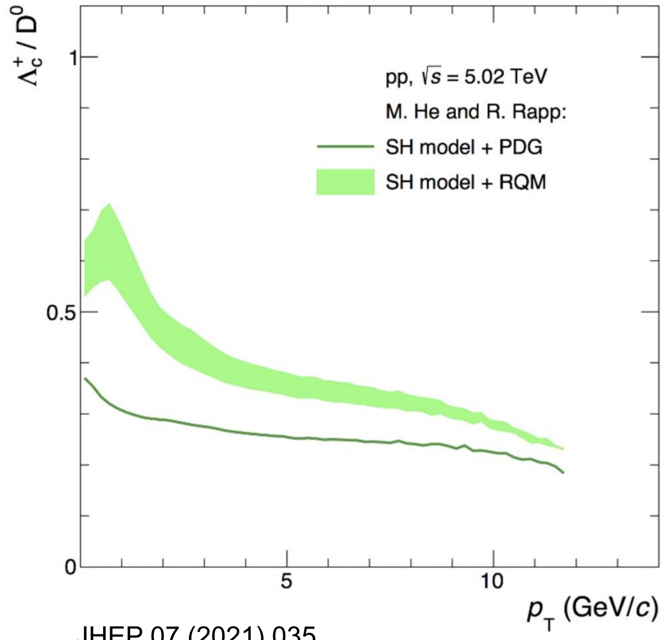
- ➢ CR allows to combine partons from different MPIs to minimize string length → used in Monash tune
- ➢ New CR-BLC
  - Minimization of the string length over all possible configurations
  - Include CR with MPIs and with beam remnants

SHM with additional baryon resonances

- ➢ **Statistical Hadronisation Model SHM+RQM**
  - production via statistical weights (scaling with mass)
  - Feed-down from augmented set of charm-baryon states based on Relativistic Quark Model

☐ PDG: 5 Λ_C (I=0) , 3 Σ_C (I=1), 8 Ξ_C (I=1/2), 2 Ω_C (I=0)➔ missing baryons?!
RQM: 18 extra Λ_C , 42 extra Σ_C, 62 extra Ξ_C, 34 extra Ω_C up to 3.5 GeV
➔ supported by lattice PRD 84 (2011) 014025; PoS LAT. 2014 (2015) 084; PLB 737 (2014) 210

n_i $(\cdot 10^{-4}$ fm$^{-3})$	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
PDG(160)	0.4996	0.2223	0.2113	0.1311	0.1201	0.0304	0.0021
RQM(170)	1.161	0.5098	0.5010	0.3165	0.6613	0.1173	0.0144
RQM(160)	0.4996	0.2223	0.2113	0.1311	0.2203	0.0391	0.0044



- ➢ Similar work performed for beauty hadrons and a similar effect is observed PRL 131 (2023) 1, 012301

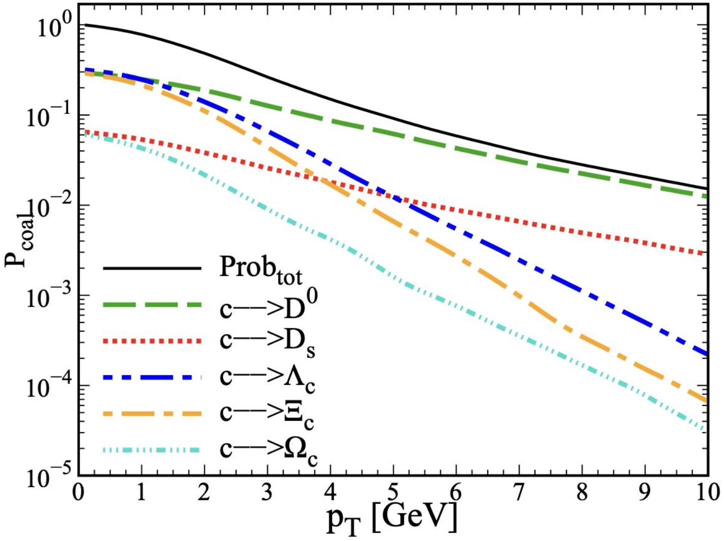
JHEP 07 (2021) 035
PLB 795 117-121 (2019)

Coalescence and its variations in pp

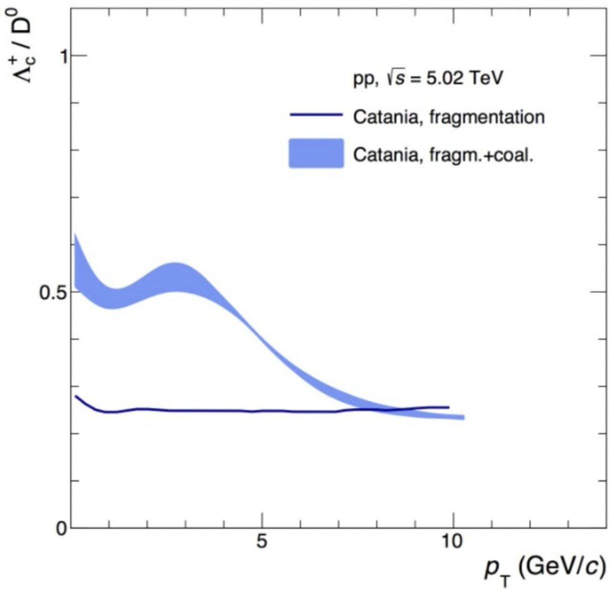
➢ Model with hadronization via coalescence+fragmentation

- **Catania**: Thermal spectra for light quark below 2 GeV/*c* and charm quark spectrum from FONLL
- **POWLANG**: Charm recombine locally with quarks & diquarks assumed thermally distributed + radial flow
- **EPOS4@HQ**: Similar to Catania but full realistic dynamics from ep, pp to AA

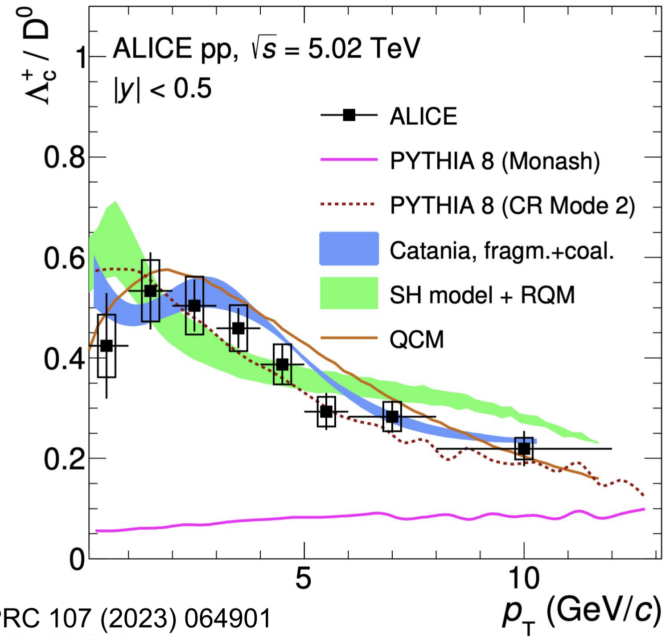
At $p_T \approx 0$, a charm quark only hadronize via coalescence, while at high p_T fragmentation becomes dominant



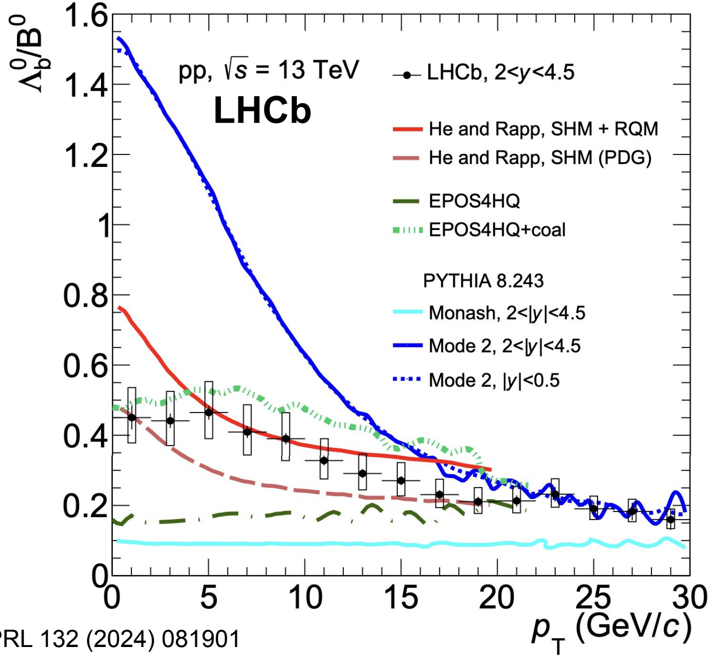
PLB 821 (2021) 136622
PRD 109 (2024) 5, 054011
PRD 109 (2024) 1, L011501



Baryon/meson ratio in pp



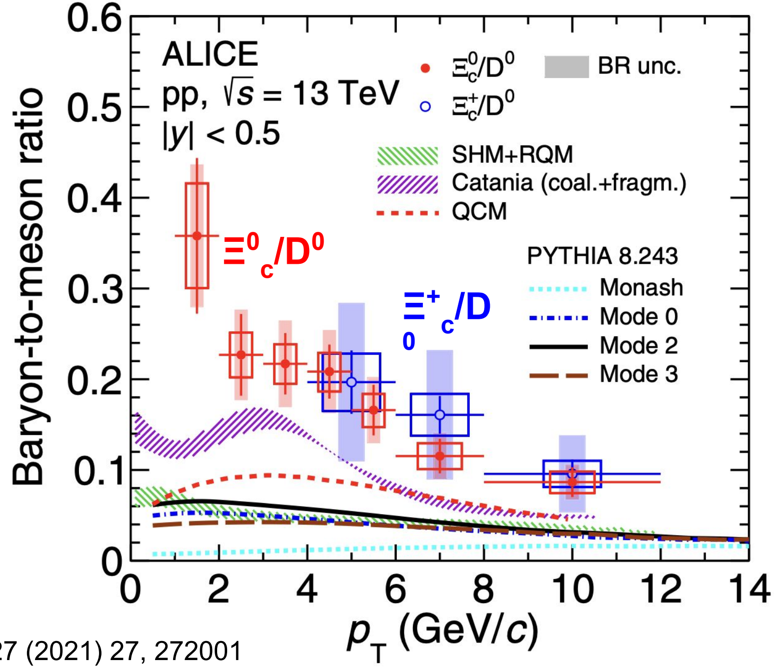
PRC 107 (2023) 064901



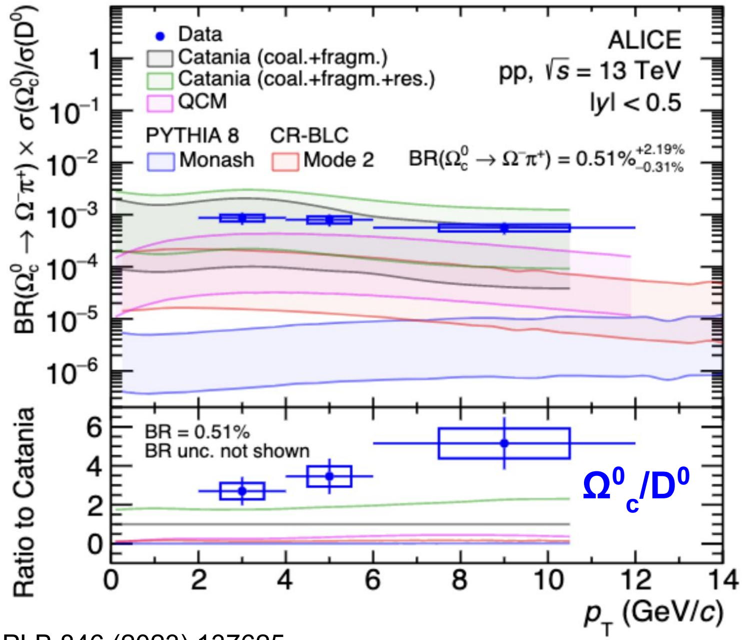
PRL 132 (2024) 081901

- CR Modes BLC in PYTHIA 8, SHM+RQM, Catania (and QCM) enhance the baryon yield and better describe the data
- **Do the model also describe measurements at forward rapidity?**
  - Is there any obvious difference (parton density, heavy-quark density)?

A common trend for charm baryons



PRL 127 (2021) 27, 272001



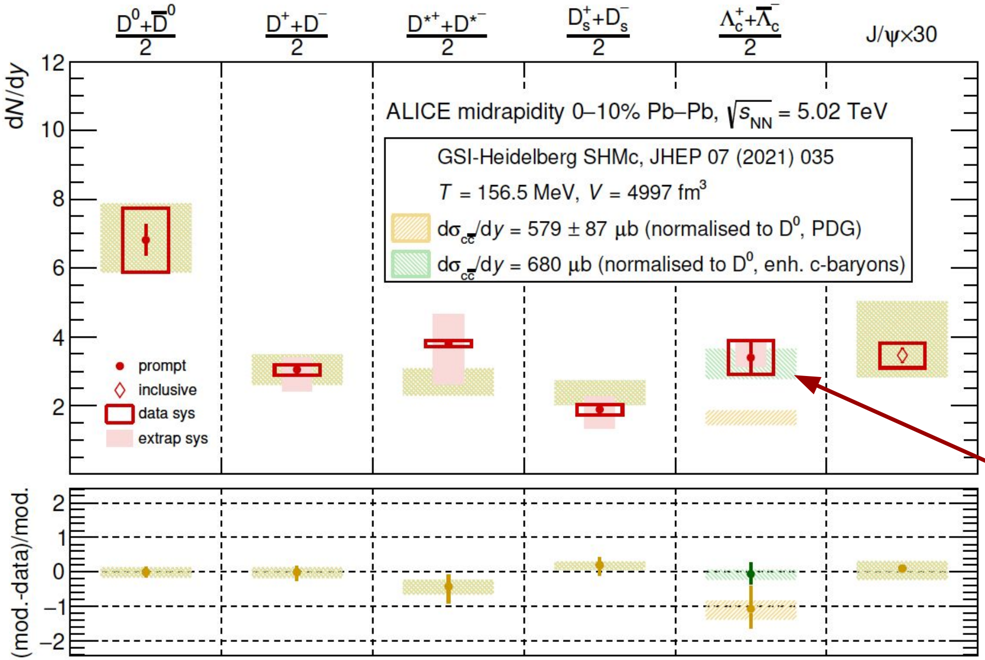
PLB 846 (2023) 137625

➢ **For charm baryons with strange content the enhancement is even larger!**

- Additional challenges from strange-quark production
- Coalescence is the model that gets consistently closer to data

Statistical hadronisation

Extremely good description of particle yield in the light flavour sector!

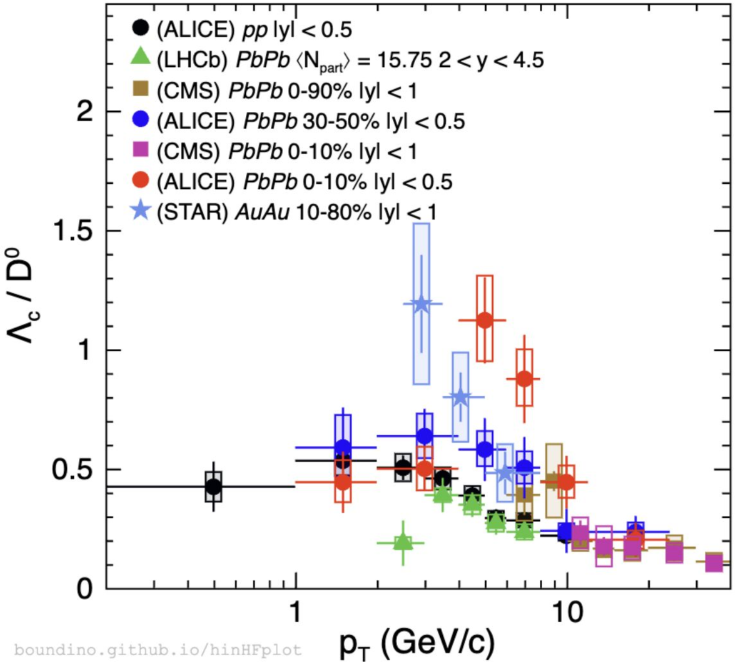


- ➢ Measured p_T-integrated yields of open charm mesons and J/Ψ midrapidity described by SHMc within uncertainties
  - Charm content determined by cross section and not by fireball temperature
  - Assume (full) charm quark thermalisation in the QGP
  - Charm quarks distributed to hadrons according to thermal weights

- ➢ **Yield of Λ_c baryons captured** assuming an enhanced production of charmed baryons

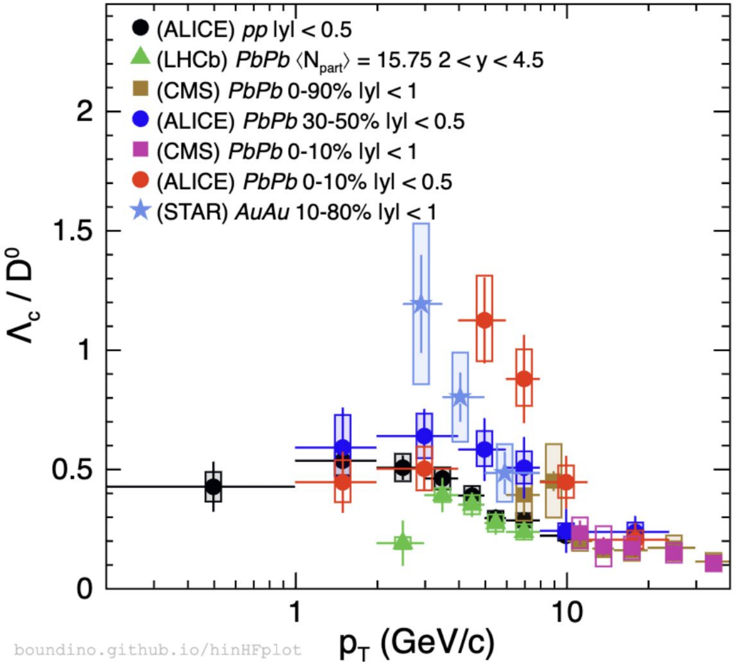
JHEP 07 (2021) 035
EPJC 84 (2024) 8, 813

Λ_c in Pb-Pb



- ➢ **Λ_c/D^0 in heavy-ion collision** is higher at intermediate p_T wrt e^+e^- and pp
  - Higher probability to hadronise via coalescence?
  - Radial flow?
  - An interplay of the two effect?

Λ_c in Pb-Pb



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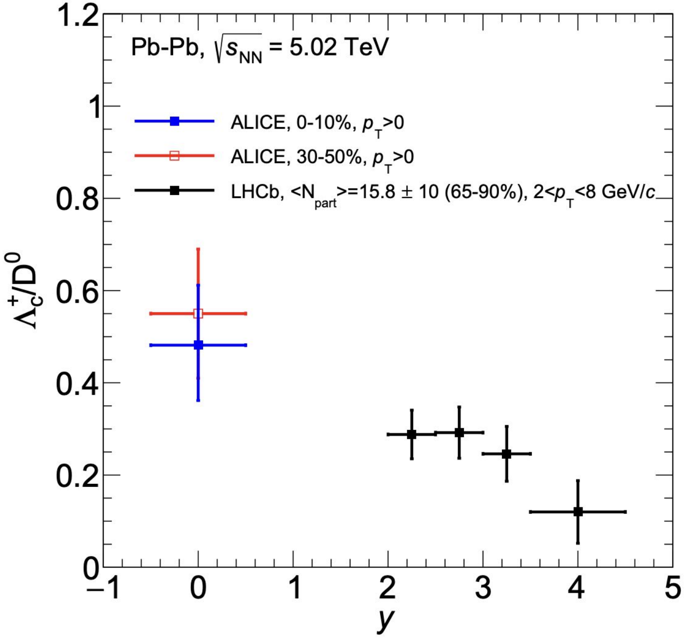
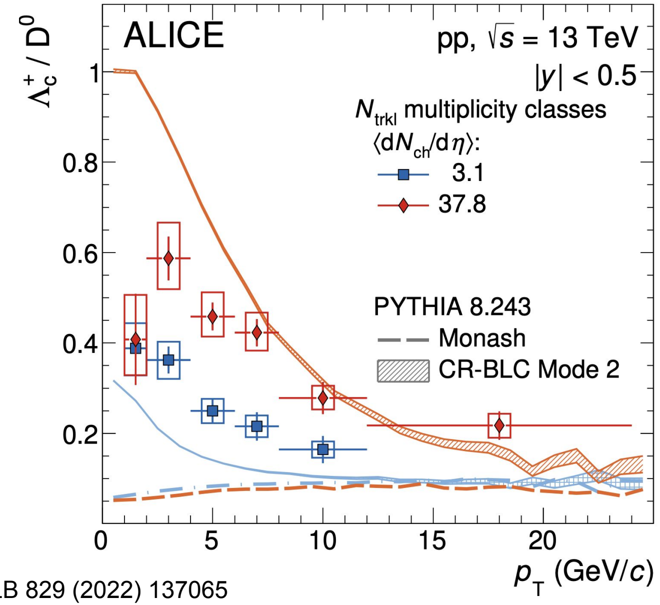
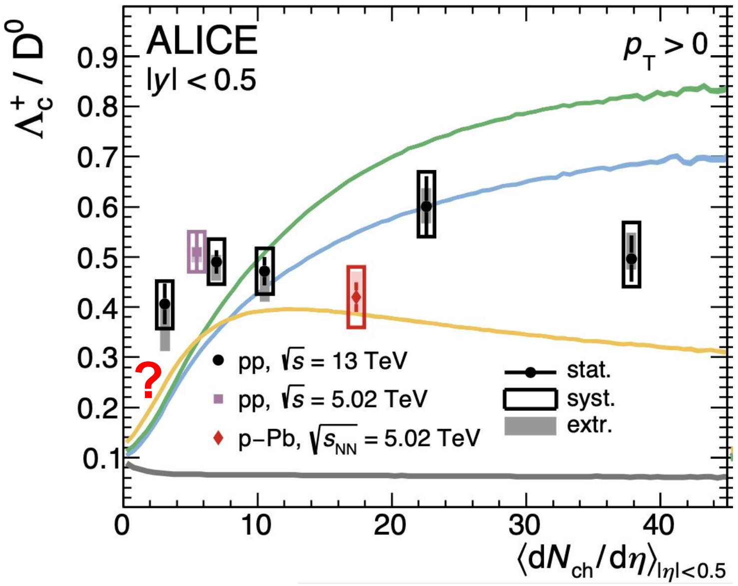


- Possible rapidity dependence need further investigation - what do models predict?

Baryon-to-meson ratio vs multiplicity

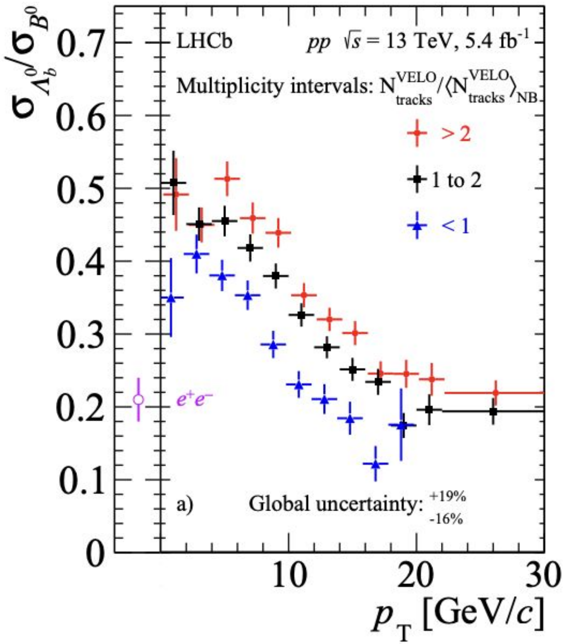


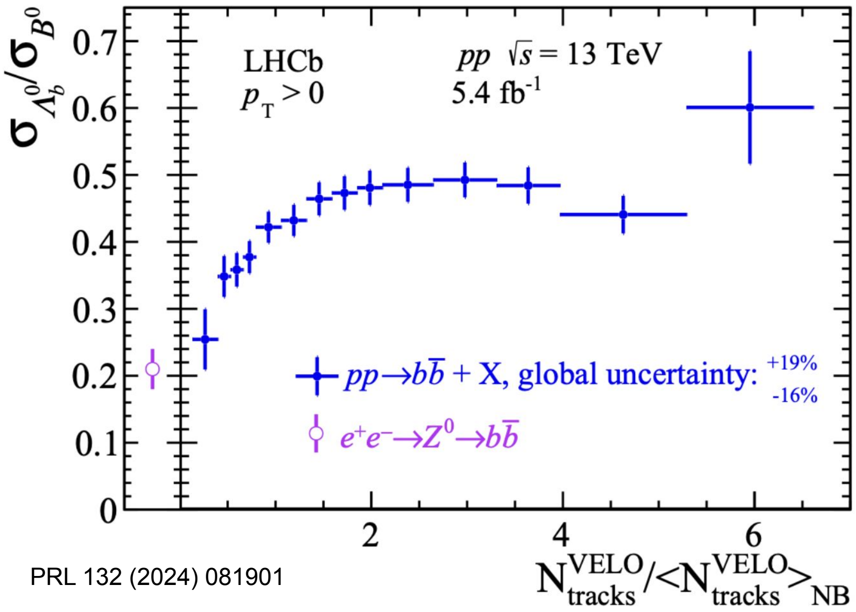
PLB 829 (2022) 137065



- ➢ Baryon/meson ratios in pp collisions: different p_T trend depending on multiplicity
  - Larger baryon production at intermediate p_T with increasing multiplicity
- ➢ No modification of p_T-integrated Λ_c/D^0 as a function of multiplicity
- ➢ **Towards very low multiplicity** - would it be possible to reach the e^+e^- limit?

Baryon-to-meson ratio vs multiplicity

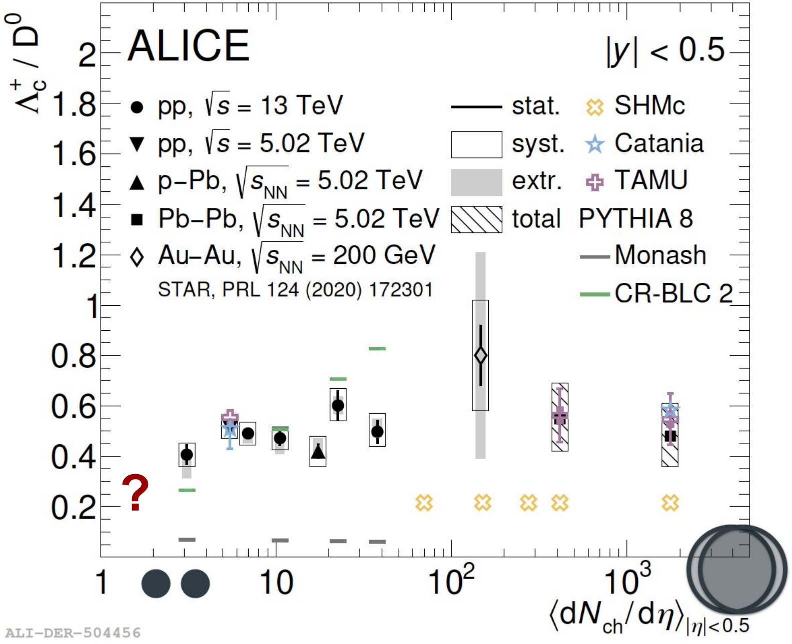




PRL 132 (2024) 081901

- Baryon/meson ratios in pp collisions: different p_T trend depending on multiplicity
  - Larger baryon production at intermediate p_T with increasing multiplicity
- **In the beauty sector the e^+e^- limit is reached**

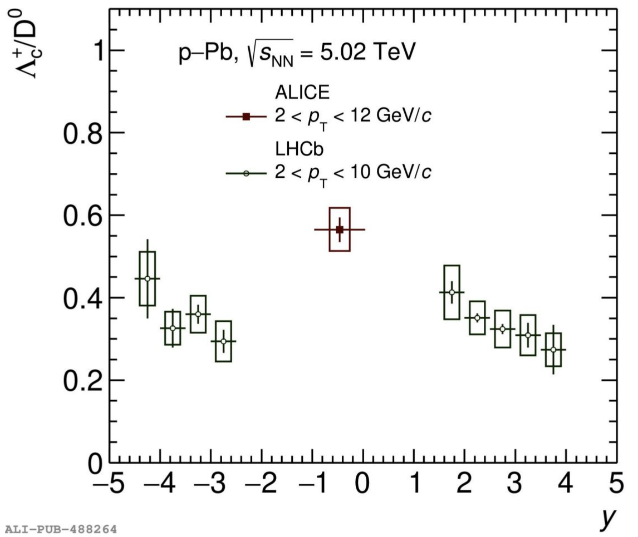
Baryon-to-meson ratio vs multiplicity

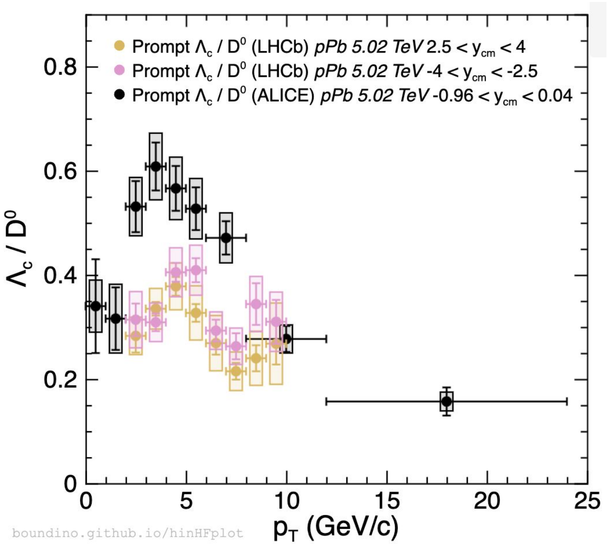


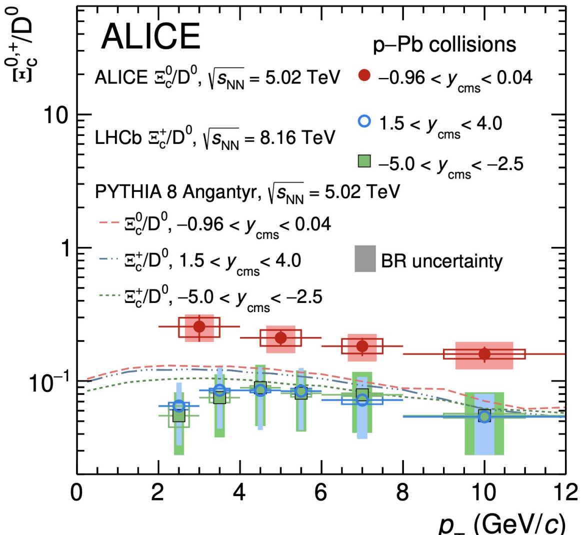
- ➢ No modification of p_T-integrated Λ_c/D^0 from pp to Pb-Pb
- ➢ **Towards very low multiplicity** - would it be possible to reach the e^+e^- limit?
- ➢ **Prospect:** measure Ξ_c and Ω_c baryons in heavy-ion collisions

Perspectives

The rapidity puzzle







arXiv:2405.14538 [nucl-ex]

- ➢ **Recurrent picture:** stronger enhancement at midrapidity than at forward rapidity
  → Possible trend to be revisited with Run 3 data (also in pp)

- ➢ What should we expect in coalescence models and SHMc? Flat in rapidity?

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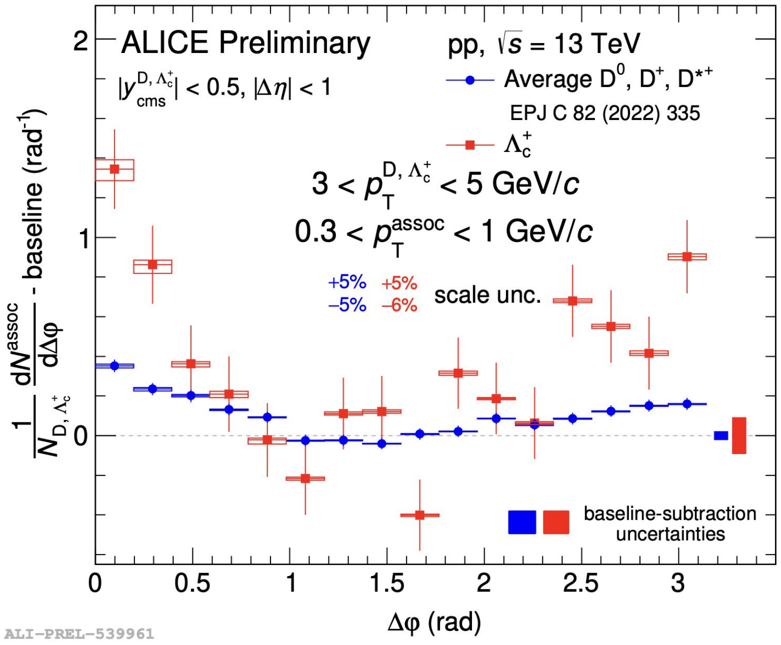
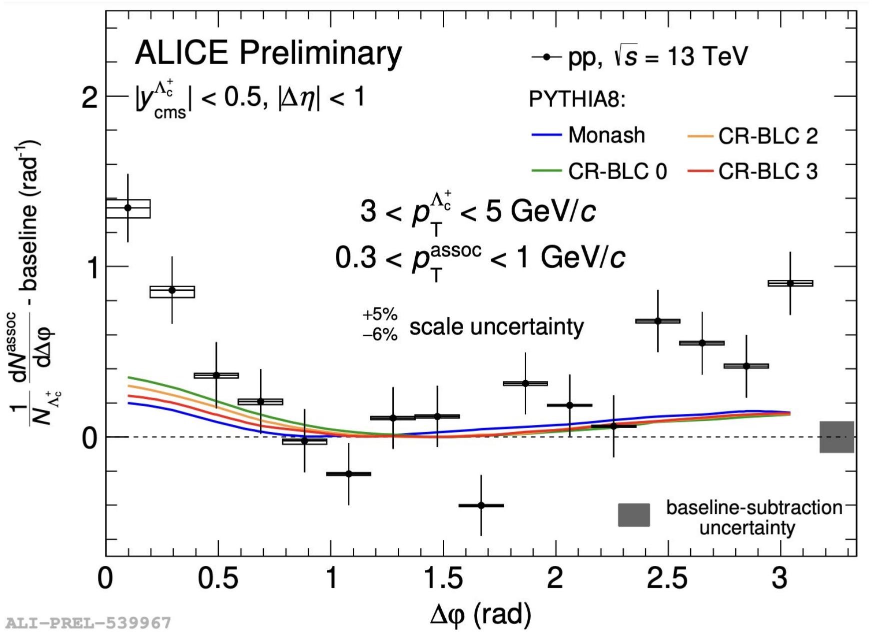
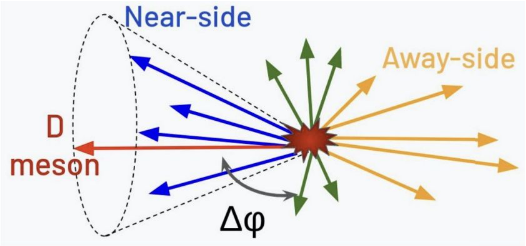
More differential - correlations and jets





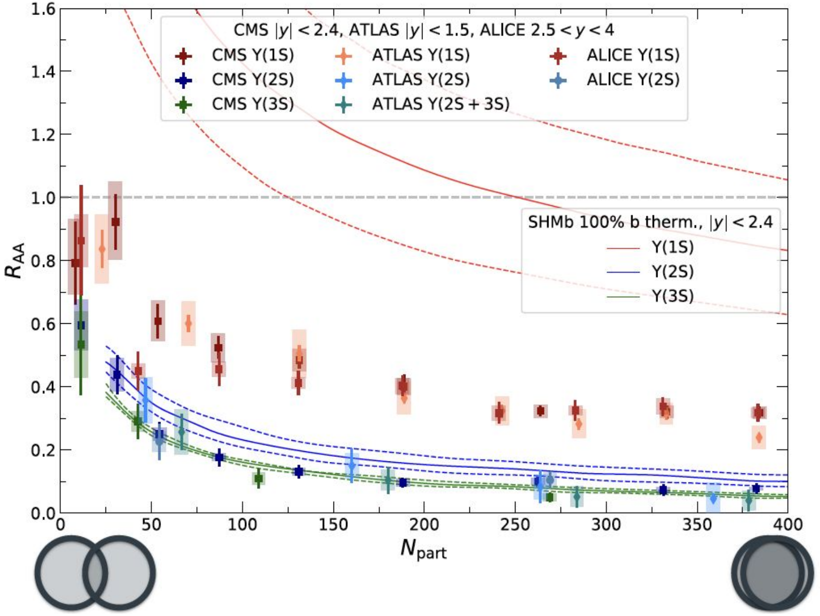


- ➢ Near-side and away-side peak yields larger for Λ_c–h than D–h
  → not described by PYTHIA
- ➢ Impact of softer Λ_c fragmentation?
  → hints from Λ_c-tagged jets analysis: arXiv:2301.13798

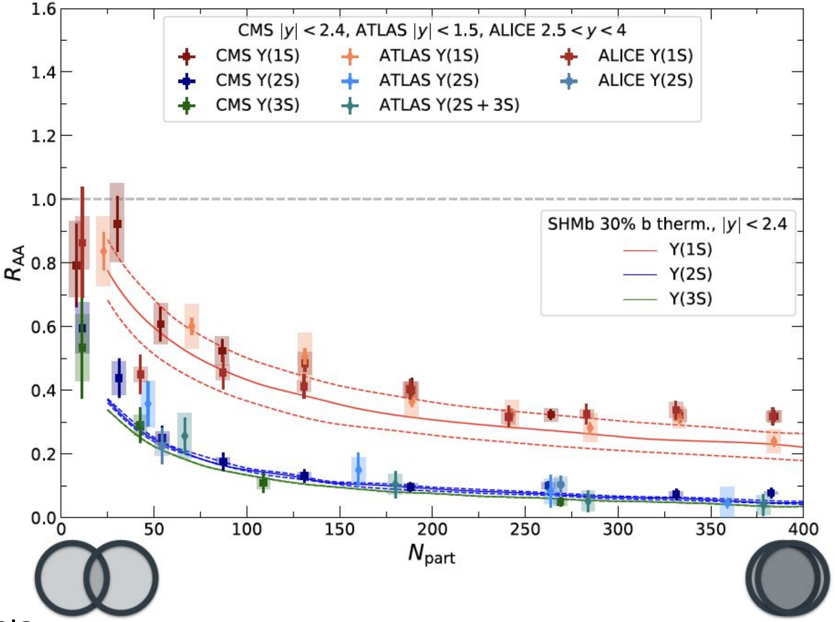
SHM with beauty

- Υ largely overestimated if 100% of beauty quarks assumed to be thermalized.
  - Does beauty quark reach thermal equilibrium
  - v_2 is compatible with zero

CMS: PRL 120 (2018) 142301

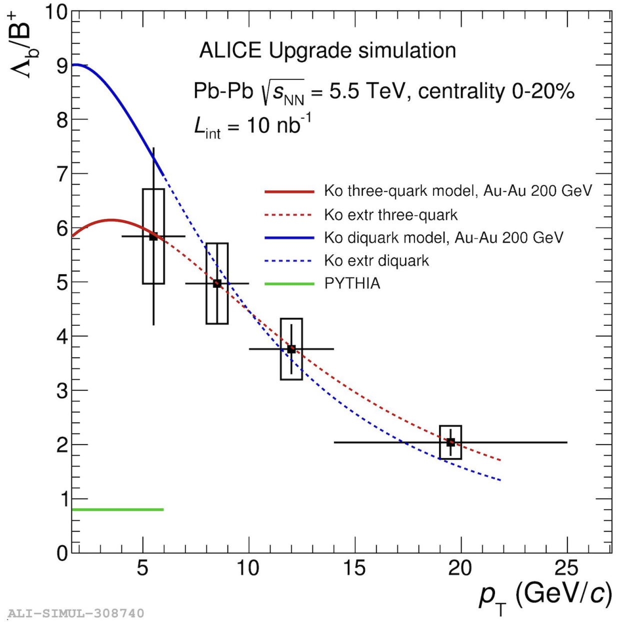


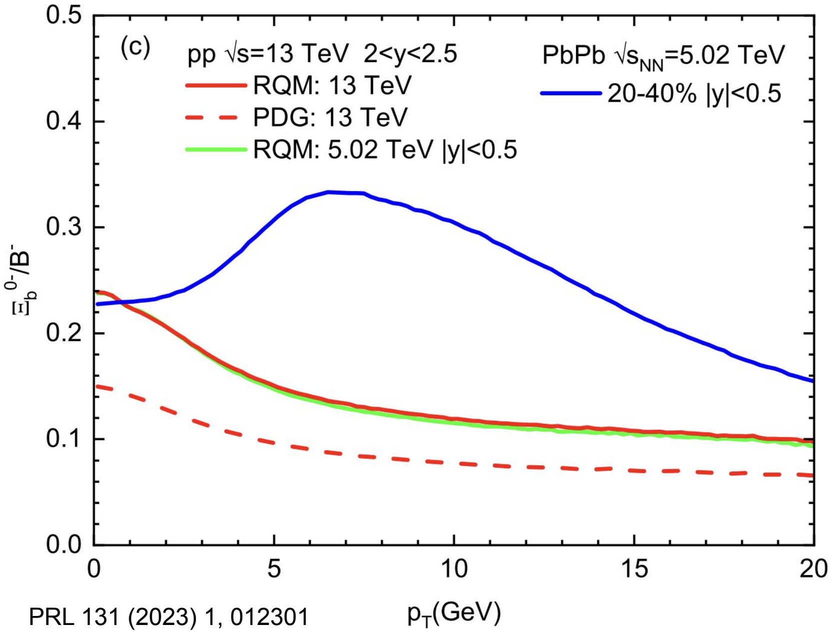
- **Υ described if 30% of beauty quarks assumed to thermalize.**
  - Reach partial equilibrium?
  - **Presence of currently unknown open beauty states will lead to a reduction of the bottomonia yields.**



SHMb: Acta Phys.Polon.Supp. 16 (2023) 1, 107

Beauty hadrons in Pb-Pb





PRL 131 (2023) 1, 012301

- **Full reconstruction of beauty hadrons will be at reach in Run 3-4**
  - Reconstruction of $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ (BR = 4.9 10^{-3})
    - Will be affected by large uncertainties and limited to p_T > 4-5 GeV/c in Run 3 and Run 4
  - Enhancement expected also for beauty-strange baryons

Loi: CERN-LHCC-2022-009

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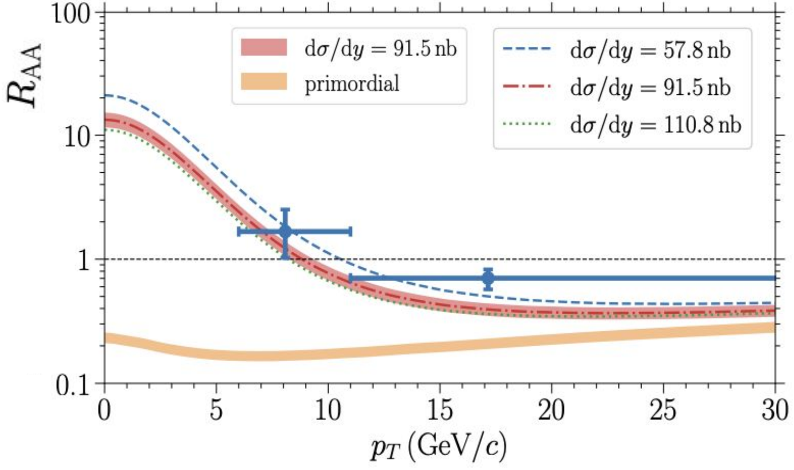
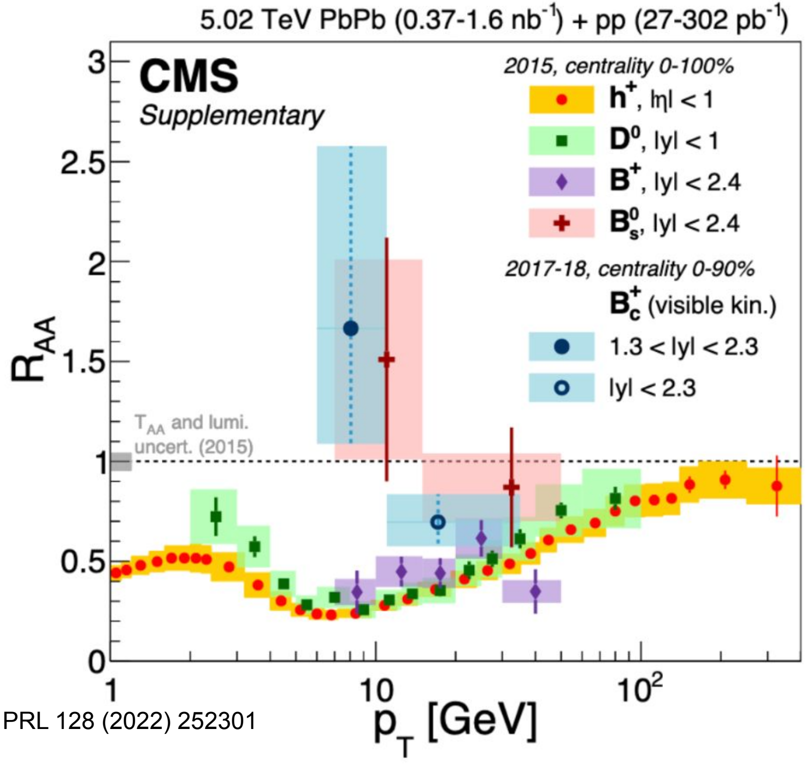
A new and challenging probe of QGP

- B_c^+ production in heavy-ion collisions is an ideal probe to be sensitive both to dead cone effect and statistical recombination
  - *CMS: used 2018 Pb-Pb data!*
  - *ALICE, LHCb: Possible first look with Run 3/4*
- **Largest contribution from recombination**

PRC 109 (2024) 1, 014906

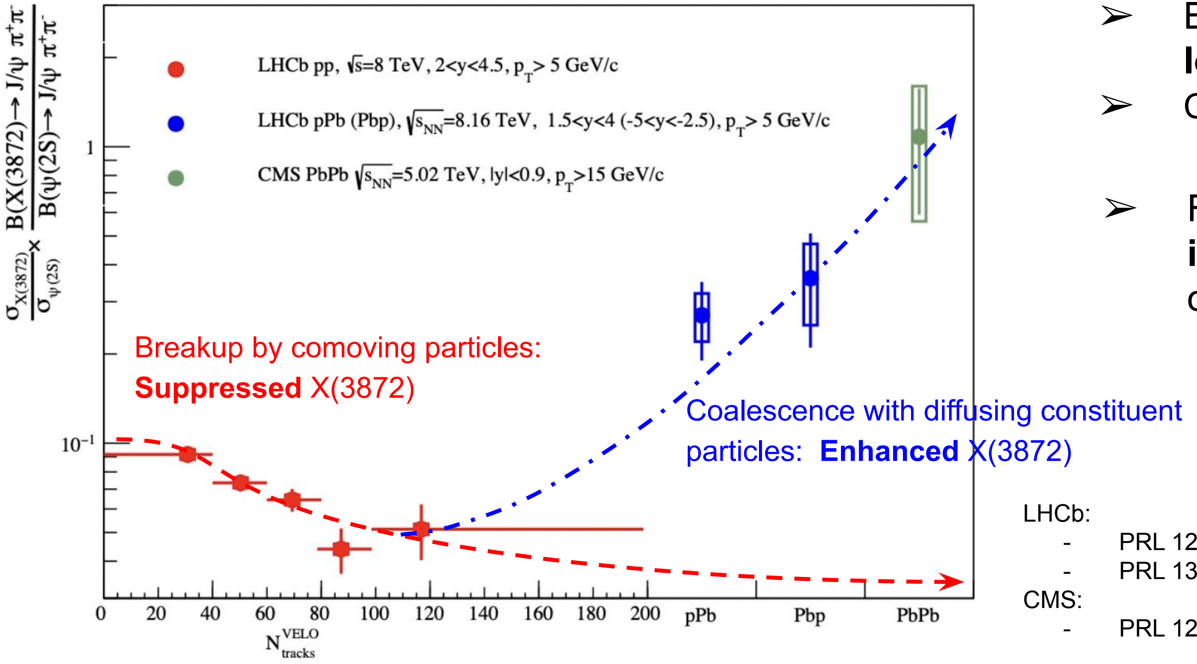




PRL 128 (2022) 252301

Another window on coalescence

- **Relevance of coalescence in large systems?**
  - X(3872) → form from suppression to enhancement?
  - Stress test with system size scan: *ep → eA → pp → pO → OO → pA → ArAr → XeXe → PbPb*



- Extension of measurements toward **low p_T is crucial**
- Centrality dependence

- Further studies might shed light on the **internal structure** of these exoctic objects

Loi: CERN-LHCC-2022-009
H. Zhang et al., PRL 126(2021) 012301
B. Wu et al., EPJA 57(2021) 122

LHCb:
- PRL 126 (2021) 092001
- PRL 132 (2024) 24, 242301

CMS:
- PRL 128 (2022) 3, 032001

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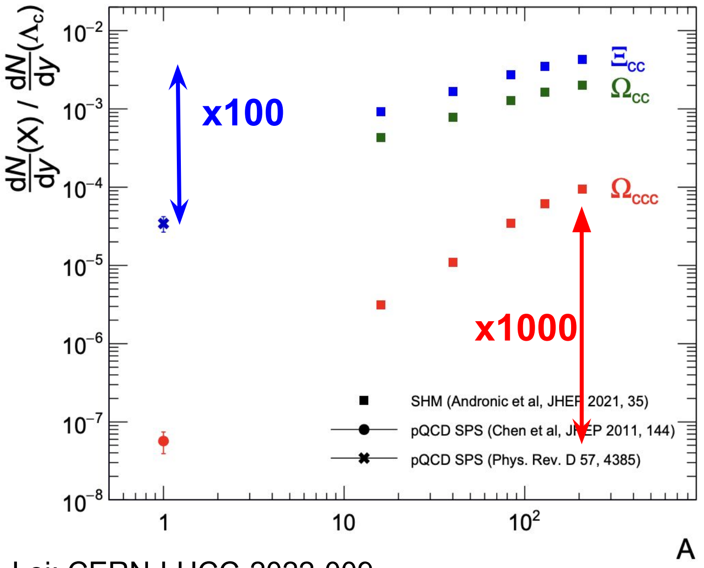
Multi-charm hadron states

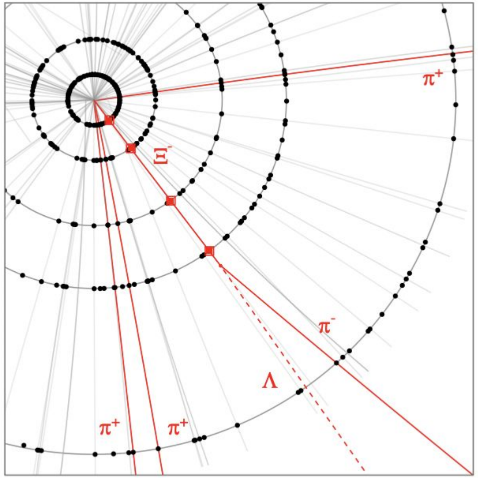
- Crucial new insight by measuring baryons containing multiple charm quarks (Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ω_{cc}^{+}, Ω_{ccc}^{++})
- Yields of multi-charm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models - production in single hard scattering disfavored

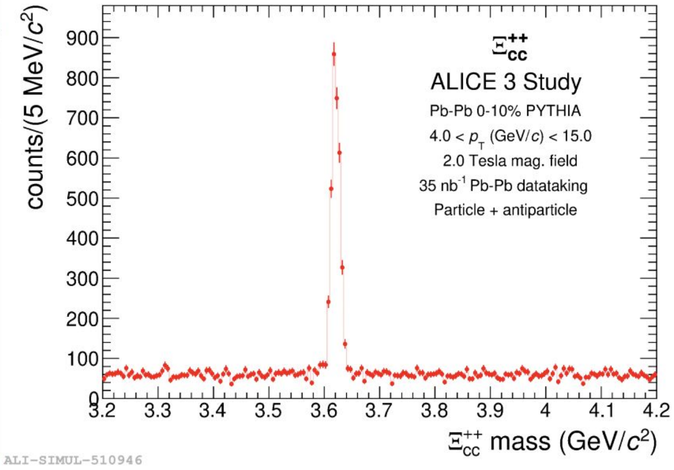
- **Direct window on hadron formation from QGP and unique testing ground for charm deconfinement and thermalisation**



Loi: CERN-LHCC-2022-009

strangeness tracking





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Conclusion

➢ **Hadronisation studied with heavy-flavour hadrons**

- LHC data challenge the universality of hadronisation
- Clear signs of coalescence in open charm measurements (and in J/Ψ - not shown today)
- Baryon enhancement present even at low mult. pp – e^+e^- limit in pp has been reached

Outlook:

➢ **Short term goal:** understanding the possible rapidity dependence, if any!

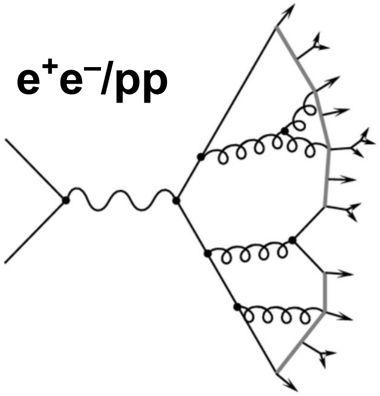
➢ **Beauty**: need of precise measurements of hadrochemistry, p_T spectra for different hadrons
- Accessible with precision with future large pp and Pb-Pb data samples

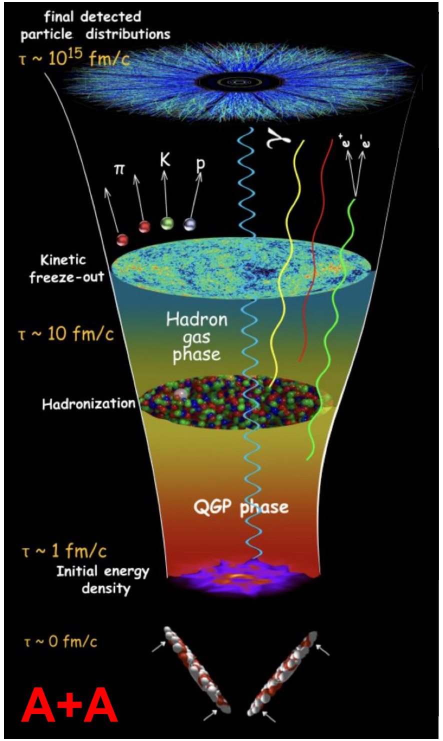
➢ **Multi-charm hadron**, B_c, and exotica will 'soon' be at reach
- They can open a new window for further testing coalescence and statistical hadronization

Thank you all for the attention

Hadronisation

e^+e^-/pp





- **Hadronisation in elementary reactions:** the mechanism by which quarks and gluons produced in hard partonic scattering processes form hadrons

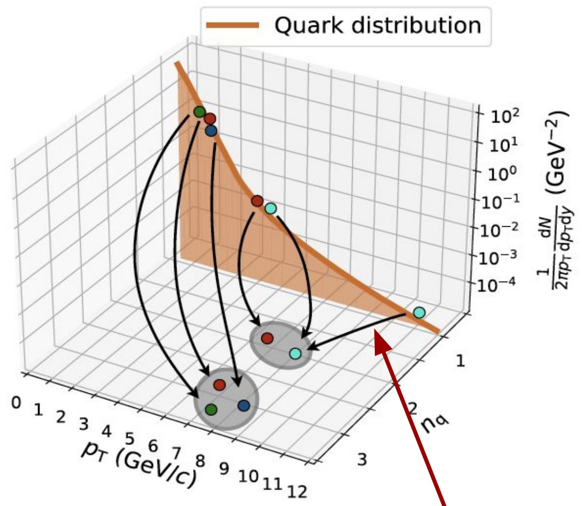
- **No first-principle description of hadron formation**
  - Non-perturbative problem, not calculable with pQCD
  - Necessary to resort to models and make use of phenomenological parameters

- **Hadronisation of the QGP medium**
  - Transition from a deconfined medium composed of quarks, antiquarks and gluons to color-neutral hadronic matter

- Hadronization of QGP: is it different from e^+e^-/pp in which no thermalized partons are formed?

Fragmentation and coalescence

- **Independent fragmentation**:
  - Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition* $D_{q \to h}(z)$
  - z is the fraction of the parton momentum taken by the hadron h
  - Parameterized on data (e^+e^-) and assumed to be **"universal"**
  - Event generators: string fragmentation



Fragmenting parton:
$p_h = z \cdot p_q$ with $z<1$

Fragmentation and coalescence

➢ **Independent fragmentation**:

- Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition* $D_{q \to h}(z)$
- z is the fraction of the parton momentum taken by the hadron h
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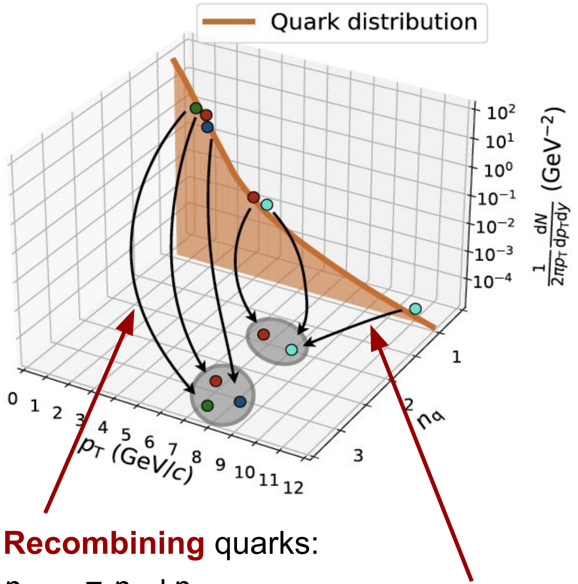
➢ **Coalescence/recombination**:

- Single parton description is not be valid anymore
- No need to create $q\bar{q}$ pairs via string fragmentation
- Partons that are *“close” to each other in phase space* (position and velocity) can **recombine** into hadrons



Recombining quarks:

$p_{meson} = p_{q1} + p_{q2}$

$p_{baryon} = p_{q1} + p_{q2} + p_{q3}$

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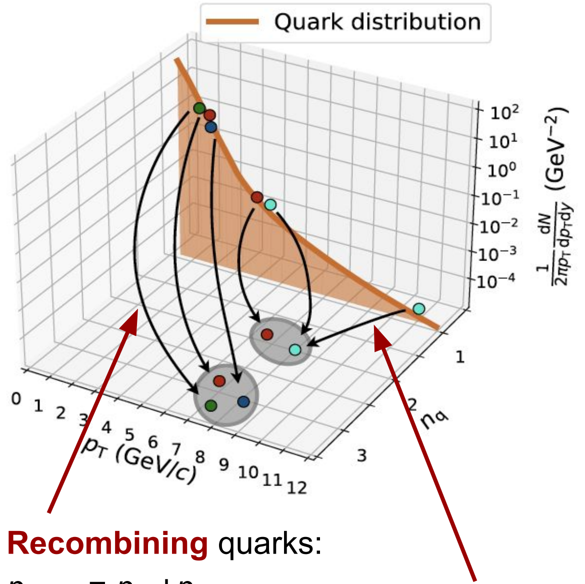
➢ **Coalescence vs. fragmentation:**
- Competing mechanisms, dominant in different p_T regions
- **Recombination depends on "environment"**, i.e. density and momentum distribution of surrounding (anti)quarks



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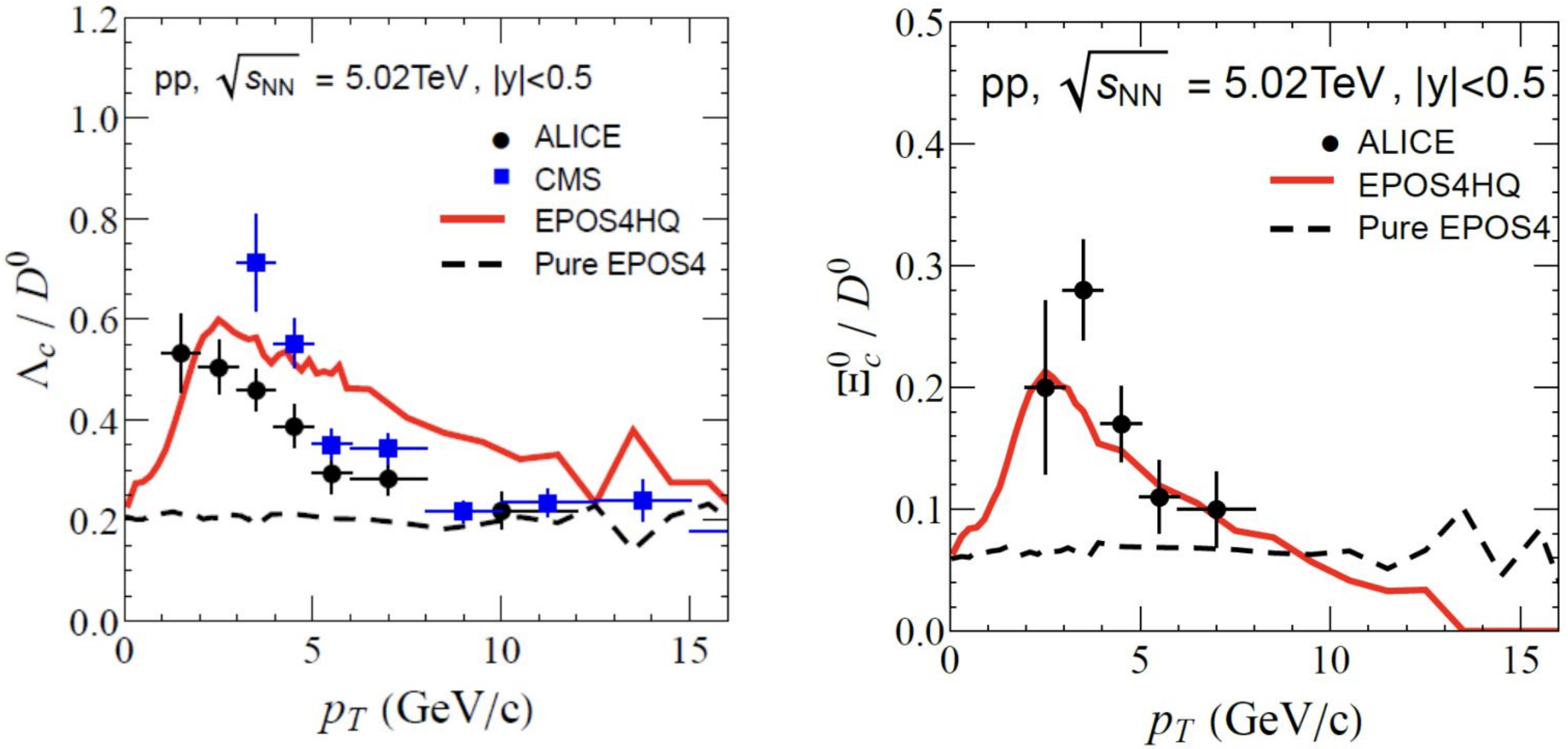
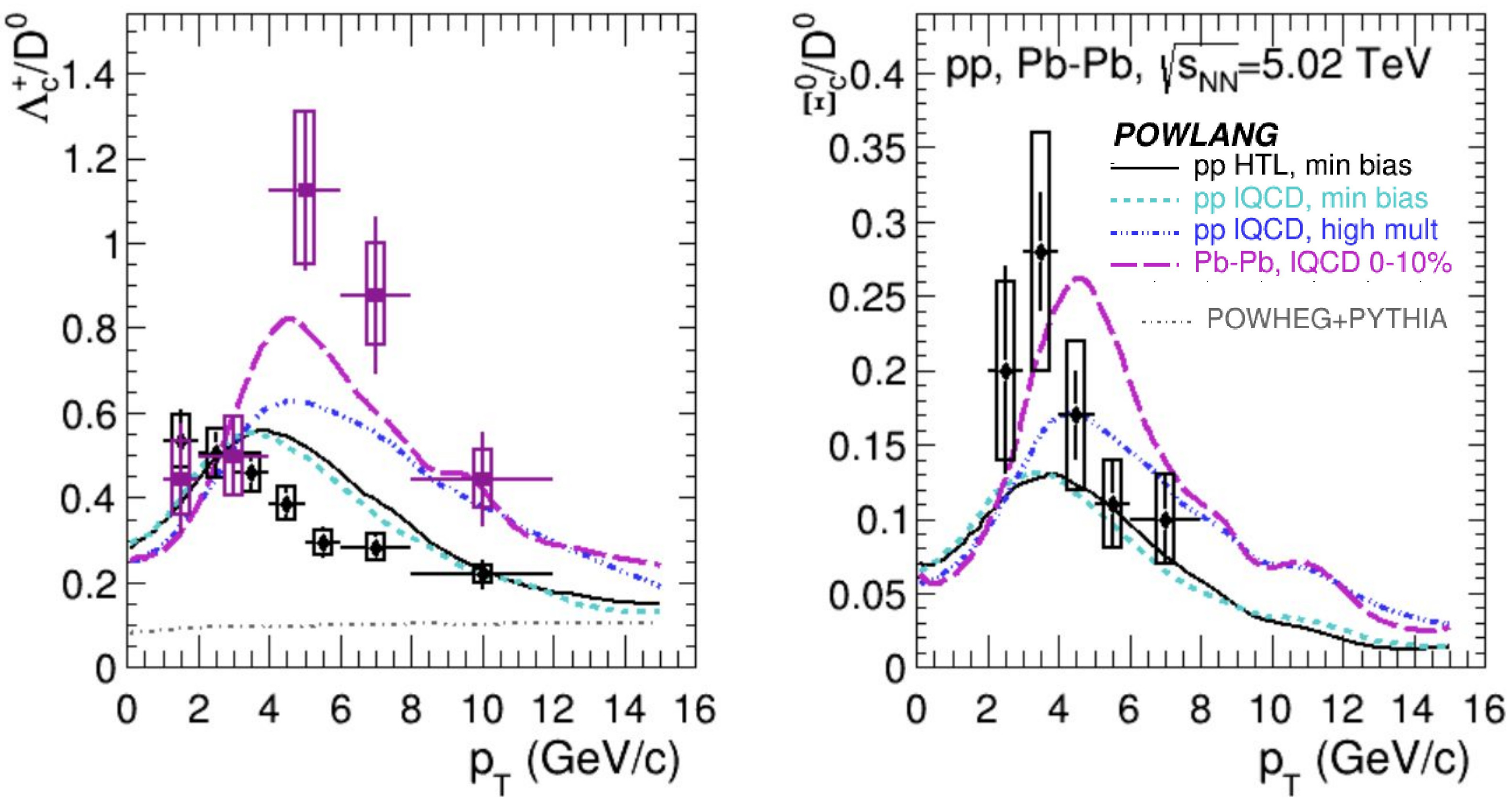
Baryon/meson ratio in pp



Baryon/meson ratio in pp

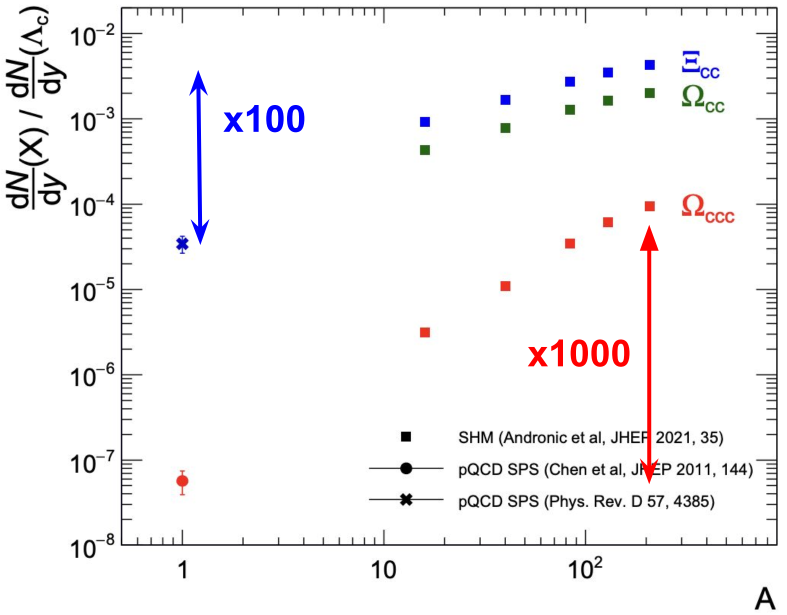


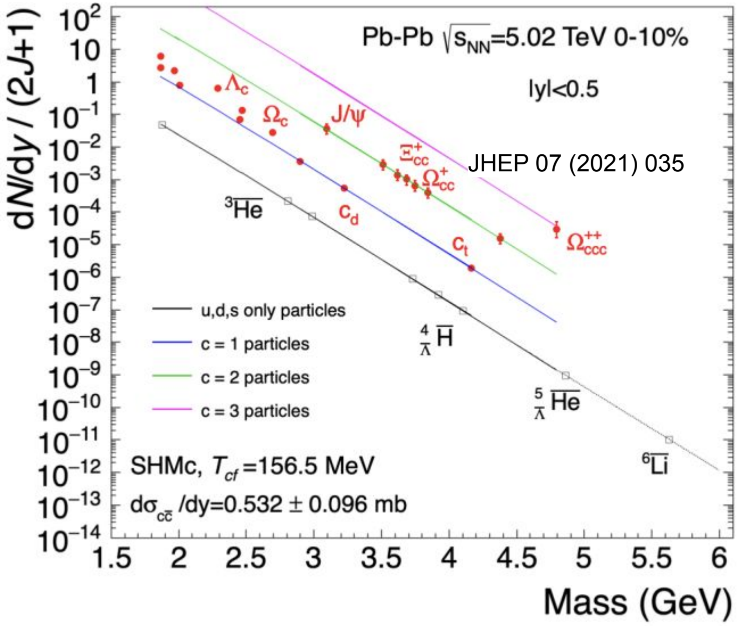
Andrea Dubla

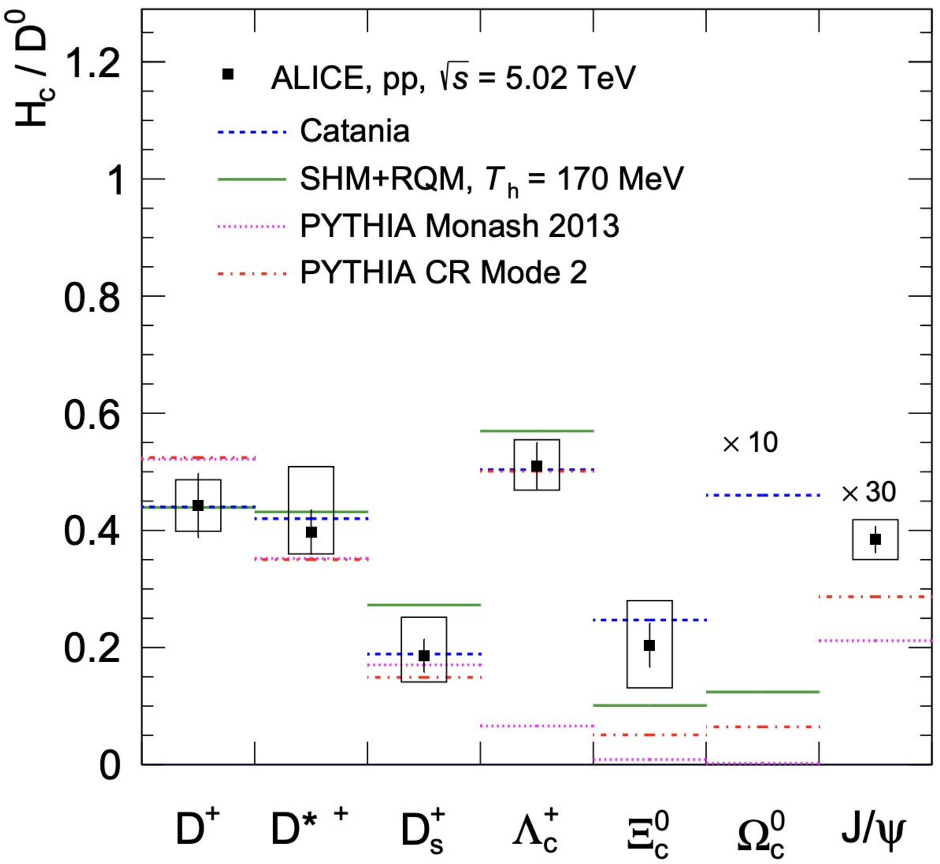
Multi-charm hadron states

- ➢ Crucial new insight by measuring baryons containing multiple charm quarks (Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ω_{cc}^{+}, Ω_{ccc}^{++})
- ➢ Yields of multi-charm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models - production in single hard scattering disfavored

➢ Direct window on hadron formation from QGP and unique testing ground for charm deconfinement and thermalisation

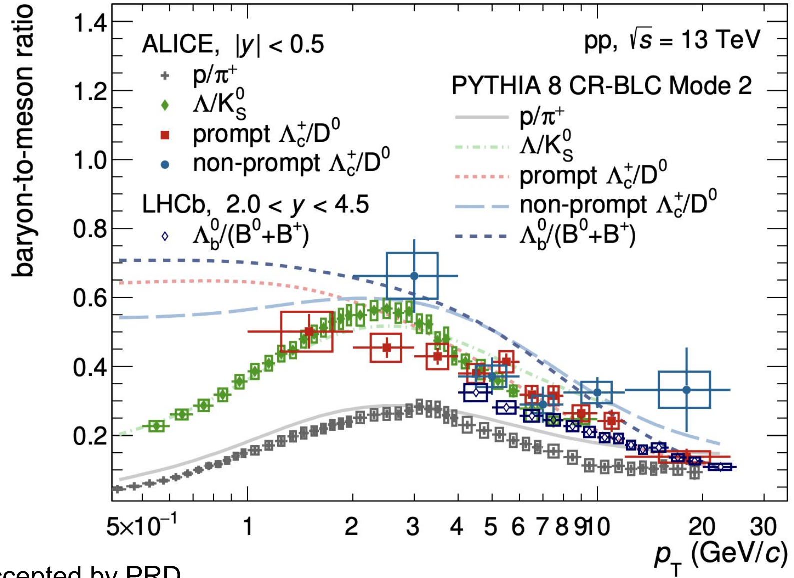




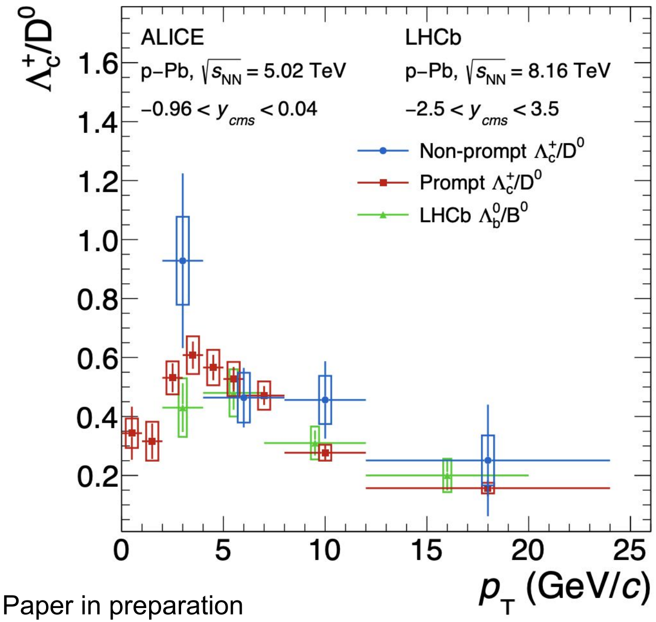


H_c / D^0
1.2
1
0.8
0.6
0.4
0.2
0
ALICE, pp, $\sqrt{s}$ = 5.02 TeV
Catania
SHM+RQM, T_h = 170 MeV
PYTHIA Monash 2013
PYTHIA CR Mode 2
× 10
× 30
D^+
D^{*+}
D_s^+
Λ_c^+
Ξ_c^0
Ω_c^0
J/ψ

Baryon-to-meson ratio – beauty



Accepted by PRD



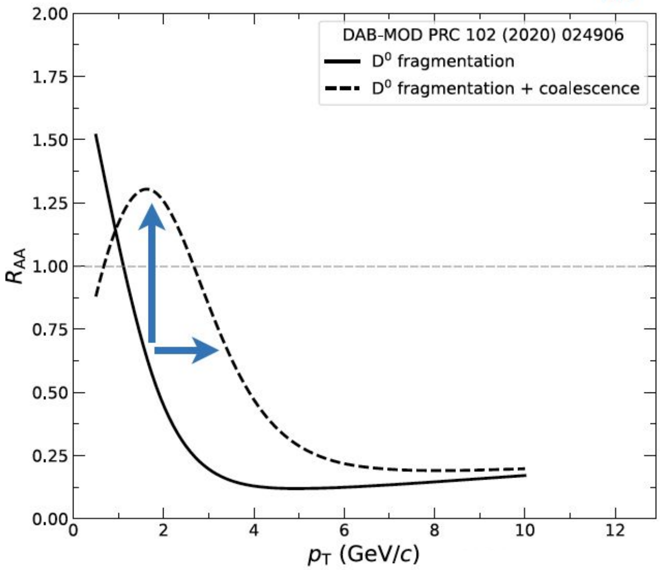
Paper in preparation

- ➢ First measurement of non-prompt charm-baryon production (|y| < 0.5) in pp and p-Pb collisions
- ➢ Prompt and non-prompt Λ_c^+ /D^0 ratio similar in both pp and p-Pb collisions
  - similar baryon-to-meson enhancement compared to e$^+$e$^-$

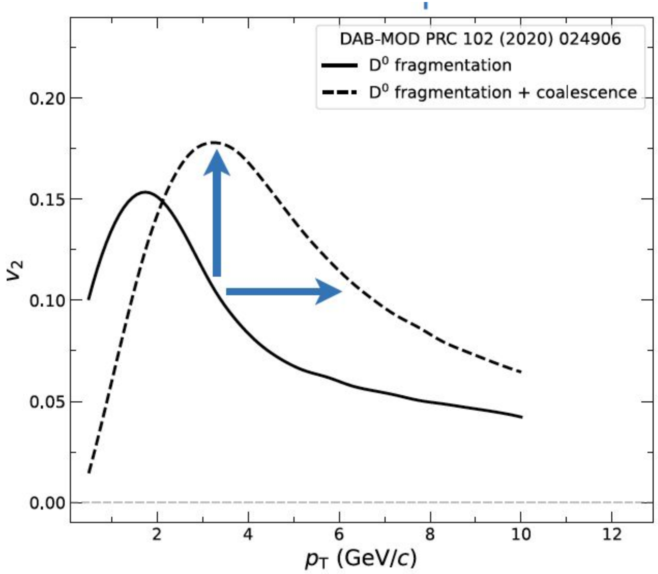
Andrea Dubla

Modification of p_T distributions

Nuclear modification factor



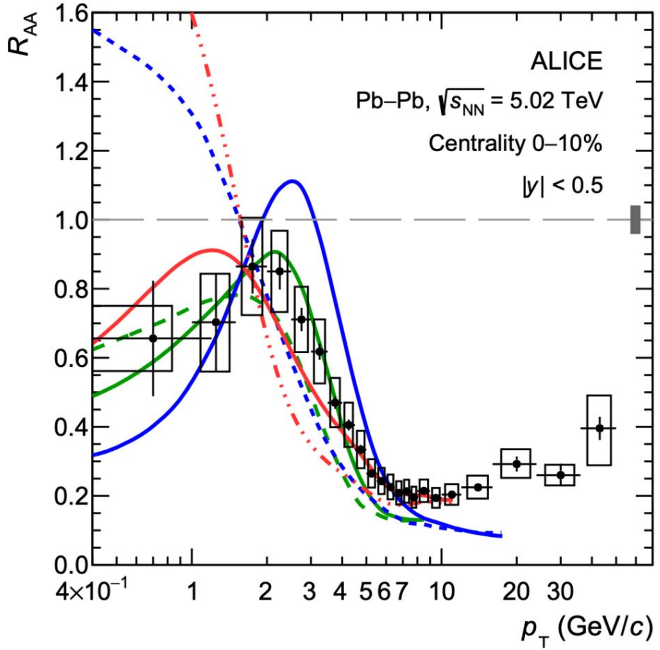
Elliptic flow



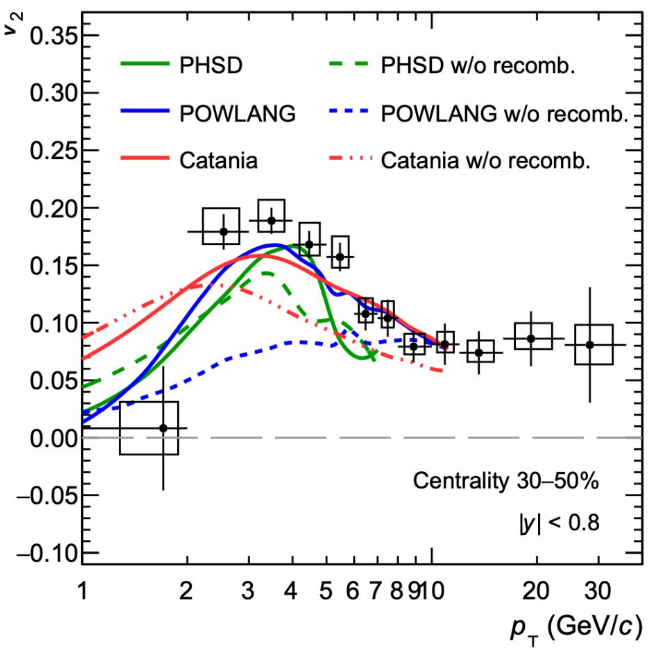
- **Coalescence** of heavy quarks with light quarks from the QGP affects **HF hadron momentum distributions**
  - HF hadrons pick-up the radial and elliptic flow of the light quark

Modification of p_T distributions

Nuclear modification factor

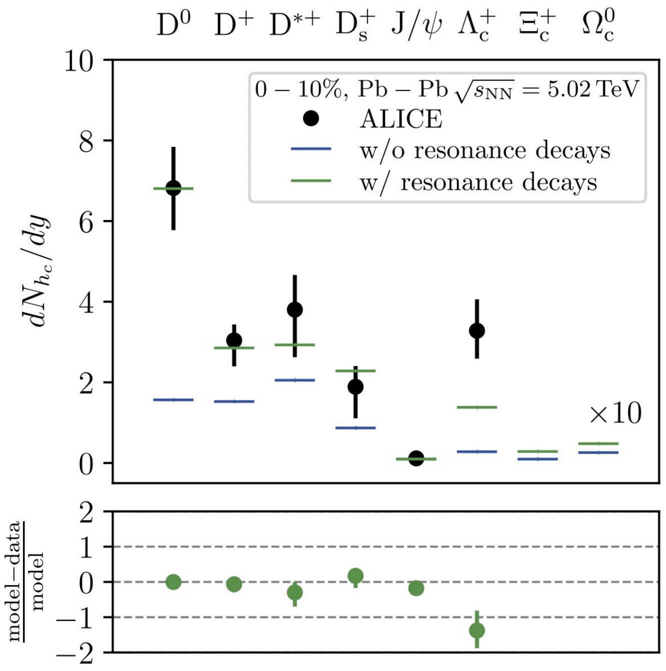


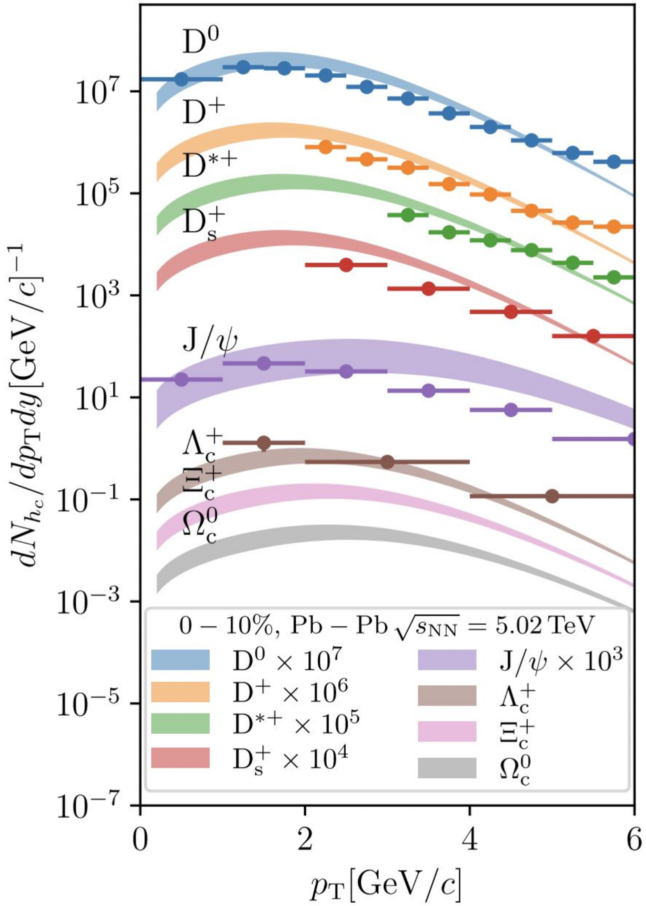
Elliptic flow



➢ **Coalescence component is crucial to describe the data at low/mid p_T**

Charm hadron yields - hydro approach





- ➢ Cooper-Frye prescription + resonance decays at T_{fo}= 156.5 MeV
- ➢ Expected deviation for Λ_c as in SHM w/o additional resonances
- ➢ Deviation for J/ψ : primordial J/ψ at high p_T?

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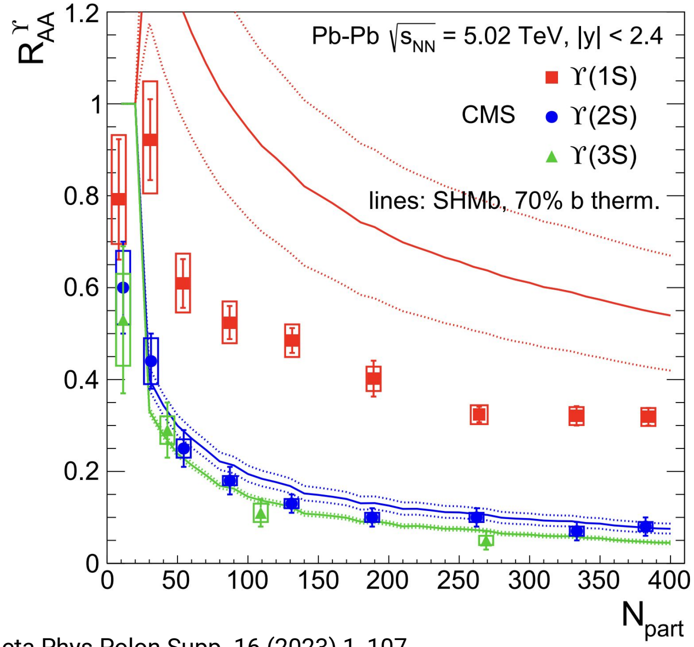
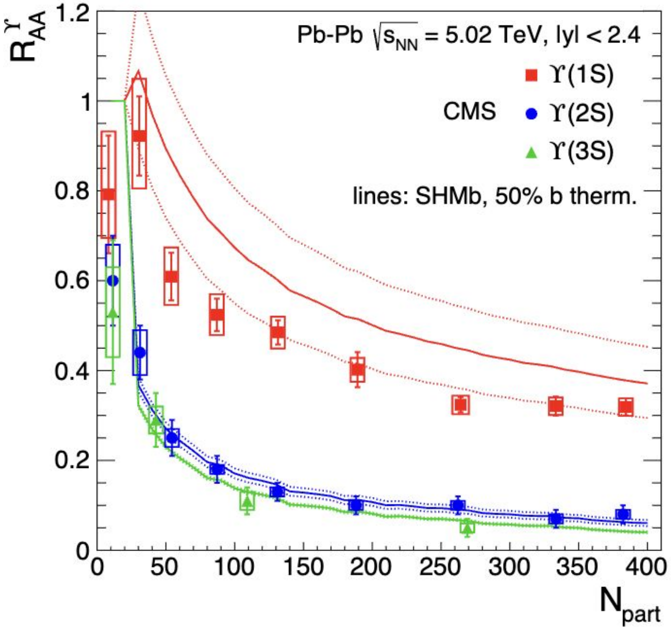
Bottomonia states

- Υ largely overestimated if 100% of beauty quarks assumed to be thermalized.
  - Does beauty quark reach thermal equilibrium
  - v_2 is compatible with zero

- **Υ described if 30% of beauty quarks assumed to thermalize.**
  - Reach partial equilibrium?
  - **Presence of currently unknown open beauty states will lead to a reduction of the bottomonia yields.**

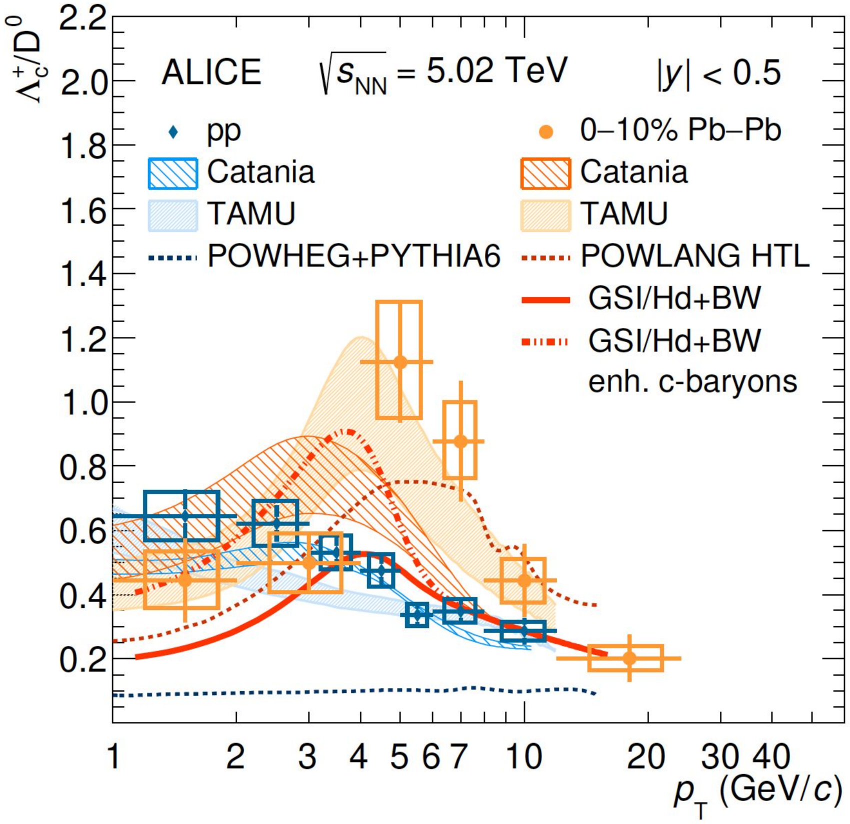
CMS: PRL 120 (2018) 142301





SHMb: Acta Phys.Polon.Supp. 16 (2023) 1, 107

Λ_c in Pb-Pb



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