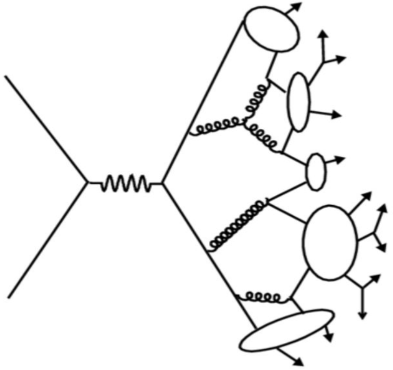
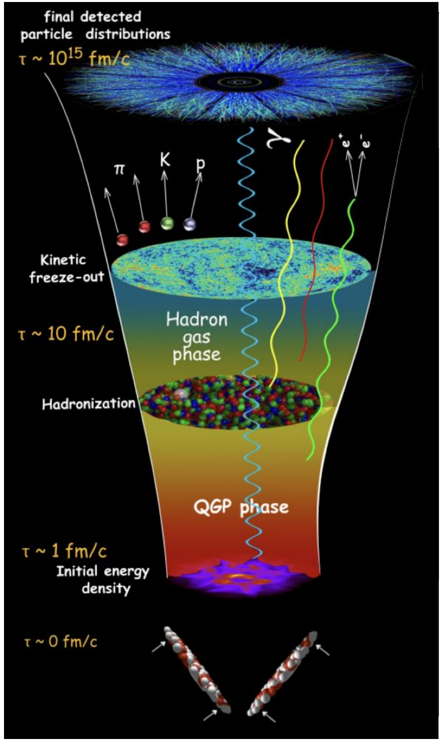
Hadronization of light and heavy flavour across collision systems

Andrea Dubla

Hadronisation





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

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

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

➢ Hadronization from a QGP: is it different from other cases in which no bulk of thermalized partons is formed?

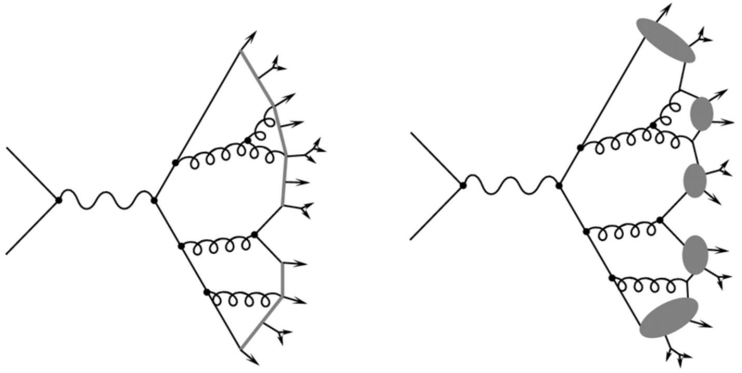
Independent fragmentation

- Inclusive hadron production from hard-scattering processes (large Q^2):
  - Factorization of: PDFs, partonic cross section (pQCD), fragmentation function

$$\sigma_{pp\to hx} = PDF(x_a,Q^2)PDF(x_b,Q^2)\otimes\sigma_{ab\to q\bar{q}}\otimes D_{q\to h}(z,Q^2)$$

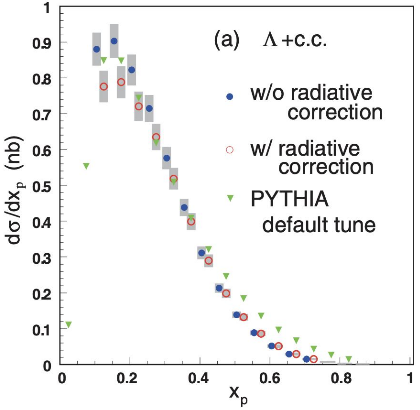
- **Fragmentation functions** $D_q{\to}h(z,Q^2)$:
  - Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition*
  - z is the fraction of the parton momentum taken by the hadron h
  - Parameterized on data (e^+e^-) and assumed to be “universal”

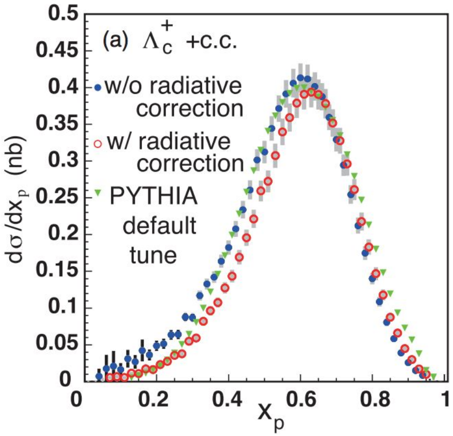
- In **event generators:** final stage of the parton shower interfaced to non-perturbative hadronisation models
  - (a) **String fragmentation** (e.g. Lund model in PYTHIA)
  - (b) **Cluster decay** in HERWIG

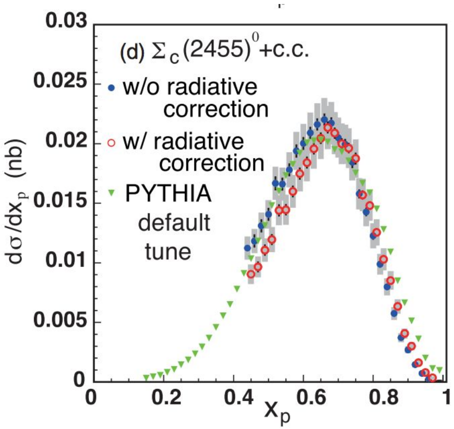


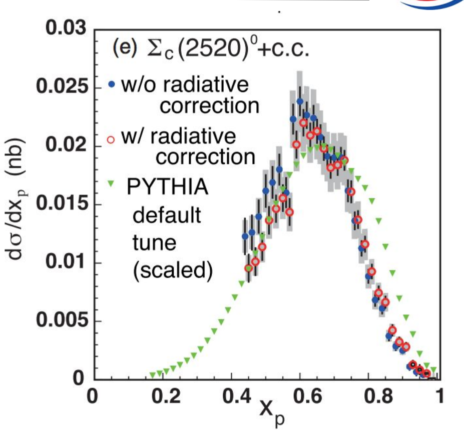
(a) String hadronization **(b)** Cluster hadronization

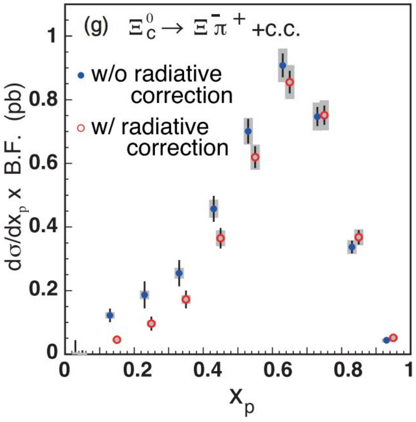
The smallest system - e^+e^-

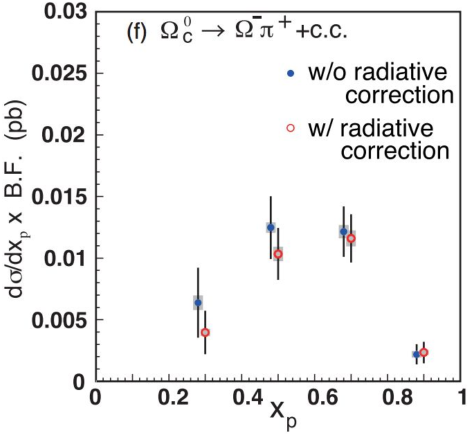












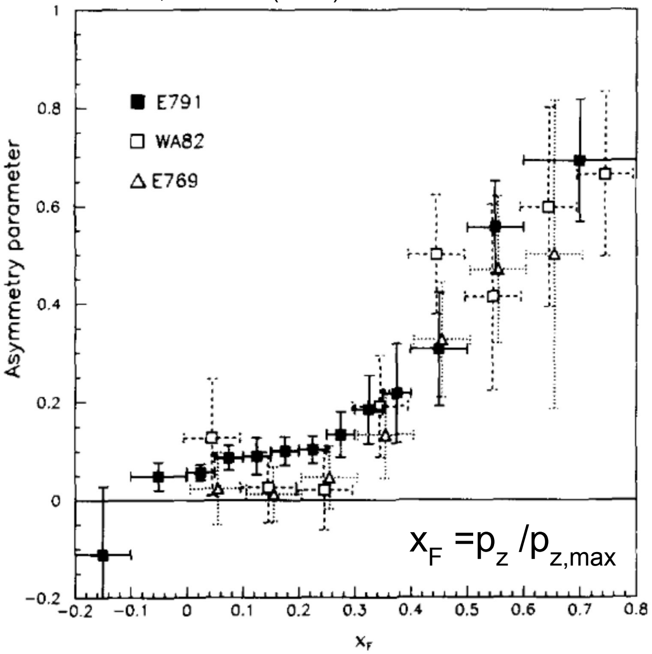
$$x_p = pc/\sqrt{s/4 - M^2c^4}$$

- ➢ Charm baryons vs PYTHIA in e^+e^-
  - Standard PYTHIA describe the data

Belle: PRD 97, 072005 (2018)

Leading particle effect

WA82, PLB 305 (1993) 402
E791, PLB 371 (1996) 157

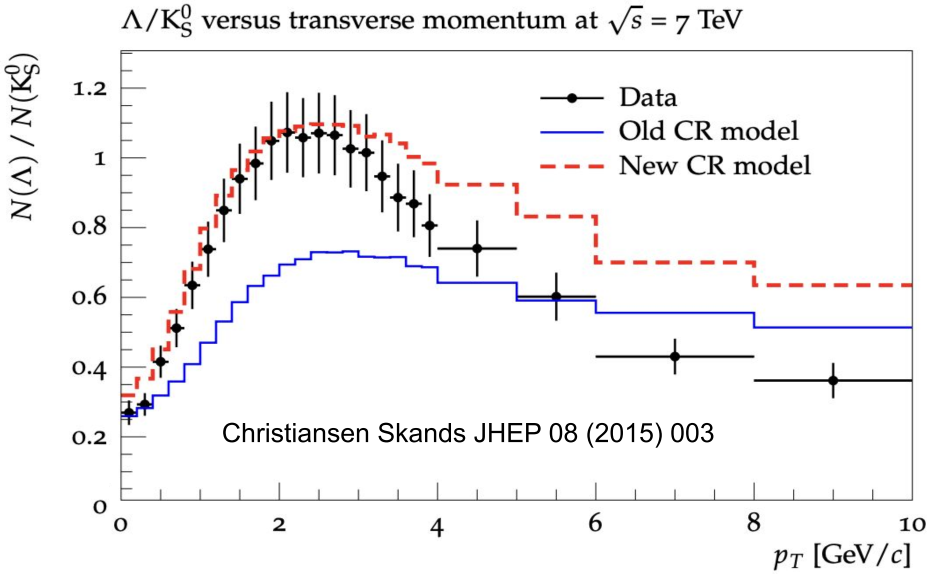


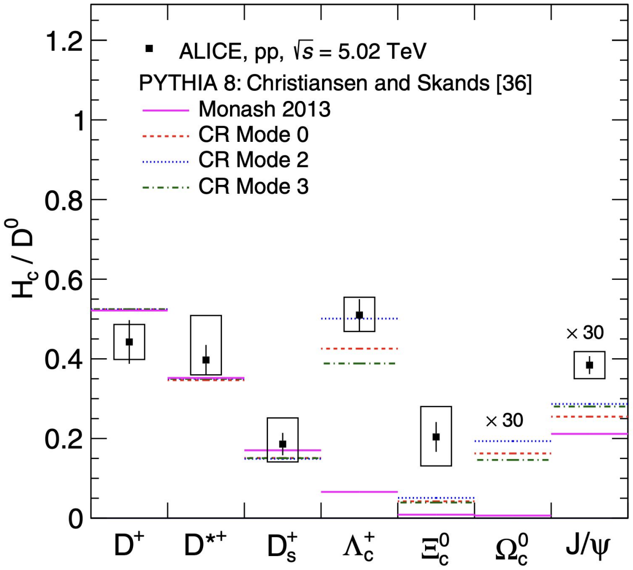
$$A(x_F) = \frac{\left(\frac{d\sigma}{dx_F}\right)^{D^-} - \left(\frac{d\sigma}{dx_F}\right)^{D^+}}{\left(\frac{d\sigma}{dx_F}\right)^{D^-} + \left(\frac{d\sigma}{dx_F}\right)^{D^+}}$$

- Measurements of charm production in pion-nucleon collisions
- At large x_F: favoured the production of hadrons sharing valence quarks with beam hadrons
  - D^- meson shares the d quark with the π^- projectile → favored over D^+
- **Break-up of independent fragmentation**

- **A reservoir of particles leads to significant changes in hadronisation**

Color reconnection





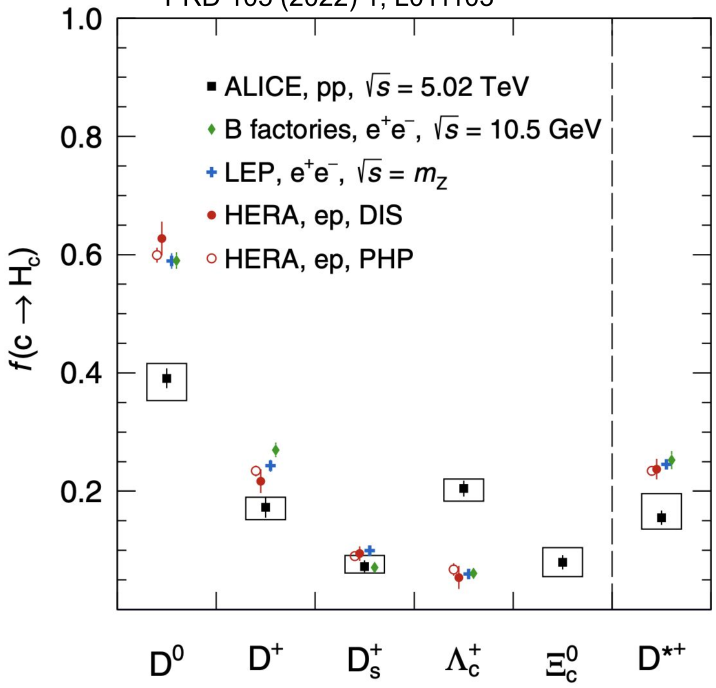
PRD 105 (2022) 1, L011103

- Baryon production and baryon/meson ratios:
  - Underestimated by PYTHIA tuned on e^+e^- (old CR model, Monash 2013)
  - Better description with Color Reconnection beyond leading color (New CR model, CR mode 0,2,3)

➢ **Independent fragmentation picture not valid in color-rich environment**

Fragmentation universality?

PRD 105 (2022) 1, L011103

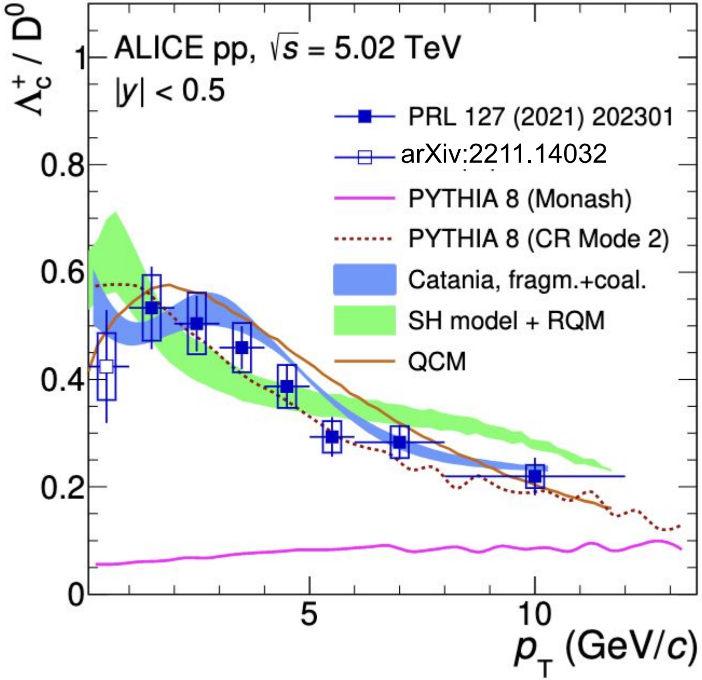


- Evidence of for different fragmentation fractions in pp collisions at LHC and e+e- (ep) collisions at lower √s
  - Indication that parton-to-hadron fragmentation depends on the collision system
  - Assumption of their universality not supported by the measured cross sections

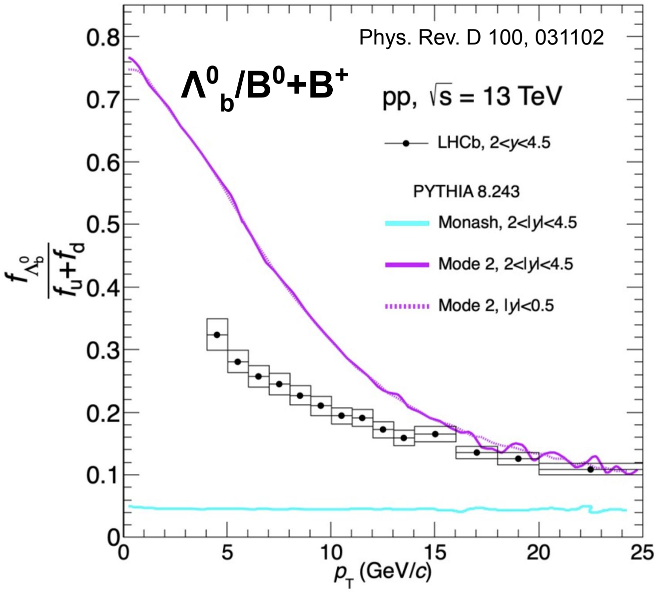
→ Independent fragmentation picture not valid in partonic-color-rich environment

→ Break-down of universality of fragmentation functions

Baryon/meson ratio in pp



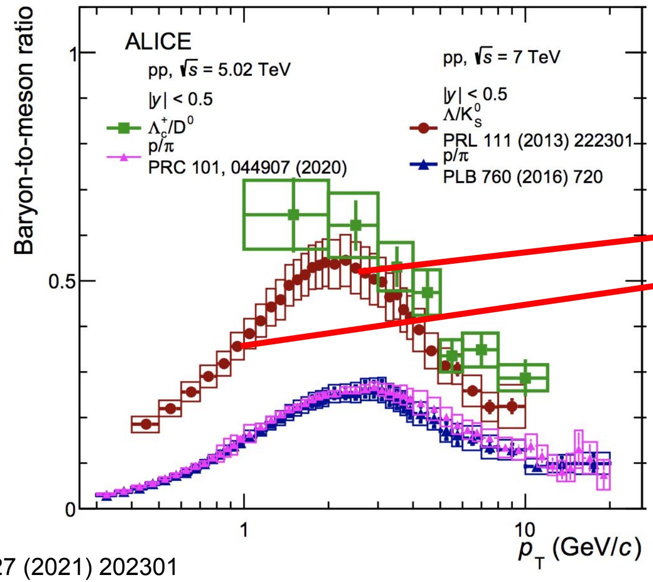
Similar observation in the beauty sector



- ➢ 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, charm density)?

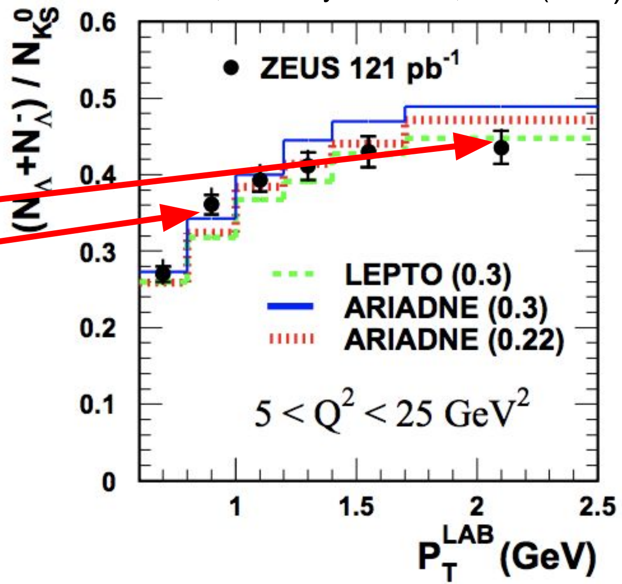
PYTHIA: JHEP 1508 (2015) 003
SHM+RQM: PLB 795 117-121 (2019)
Catania: PLB 821 (2021) 136622
QCM: EPJC 78 no. 4, (2018) 344

Similarities or accidentalities



Phys. Rev. Lett. 127 (2021) 202301
Phys. Rev. C 104 (2021) 054905

ZEUS, Eur. Phys. J. C 51, 1–23 (2007)



➢ **Note: in ep (DIS) for the LF sector this was apparently already there**
- larger values seen already at HERA in strange sector
- in ep baryon-to-meson measurements limited to p_T < 2 (2.5) GeV/c

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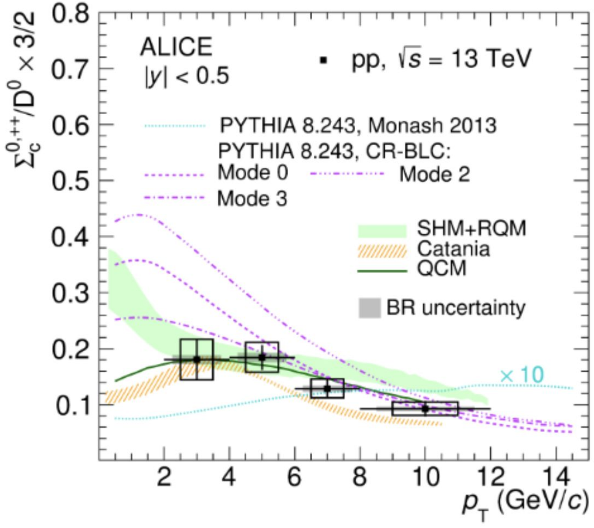
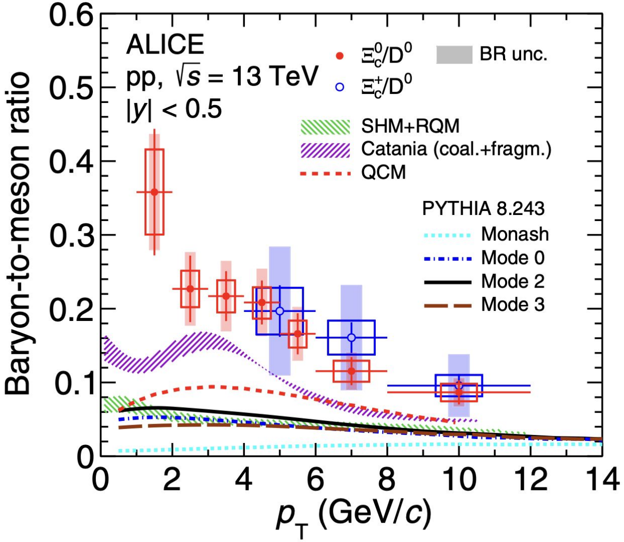
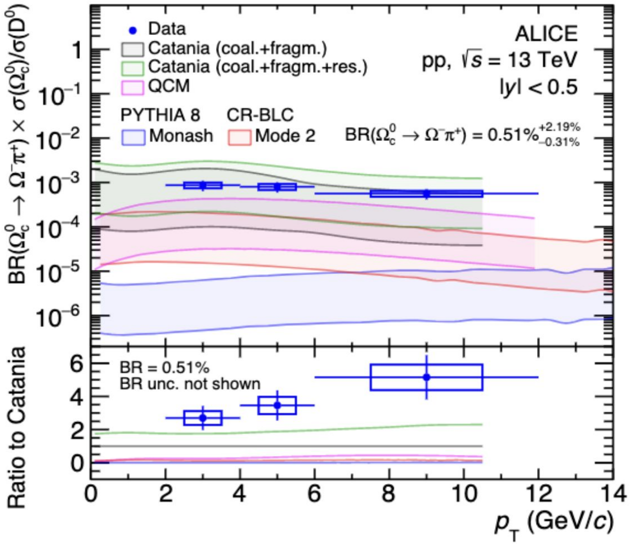
A common trend for charm baryons





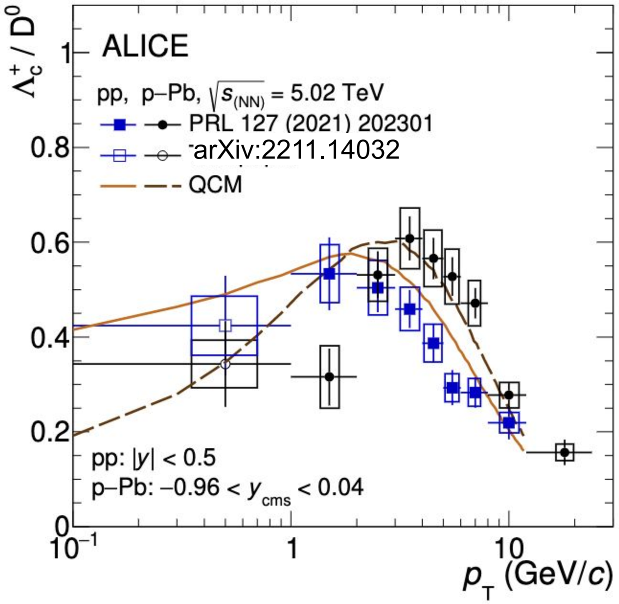


➢ **In the strangeness sector the enhancement is even larger!**

- Can we learn something on strangeness from HF measurements? D_s/D^0 does not significantly varies as a function of multiplicity
- What is the role of di-quark? Can we learn something about them?
- Coalescence is the model that gets consistently closer to data

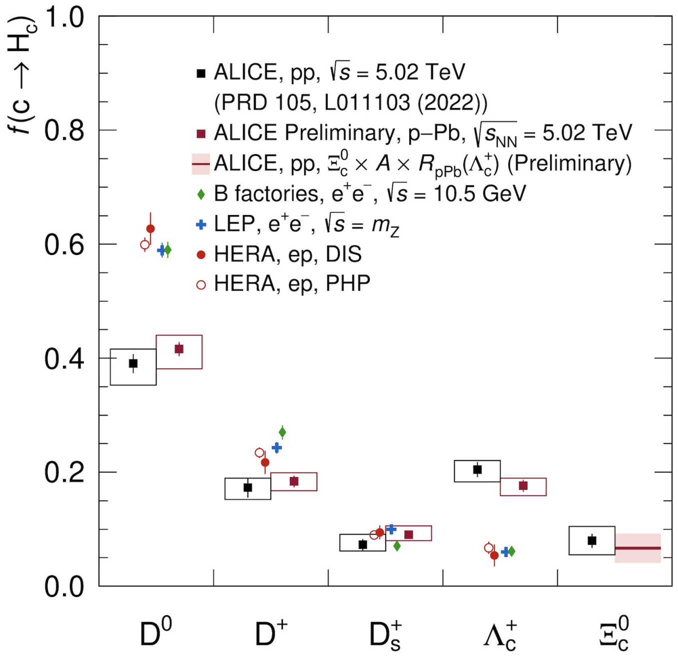
PYTHIA: JHEP 1508 (2015) 003
SHM+RQM: PLB 795 117-121 (2019)
Catania: PLB 821 (2021) 136622
QCM: EPJC 78 no. 4, (2018) 344

Baryon/meson ratio in p-Pb



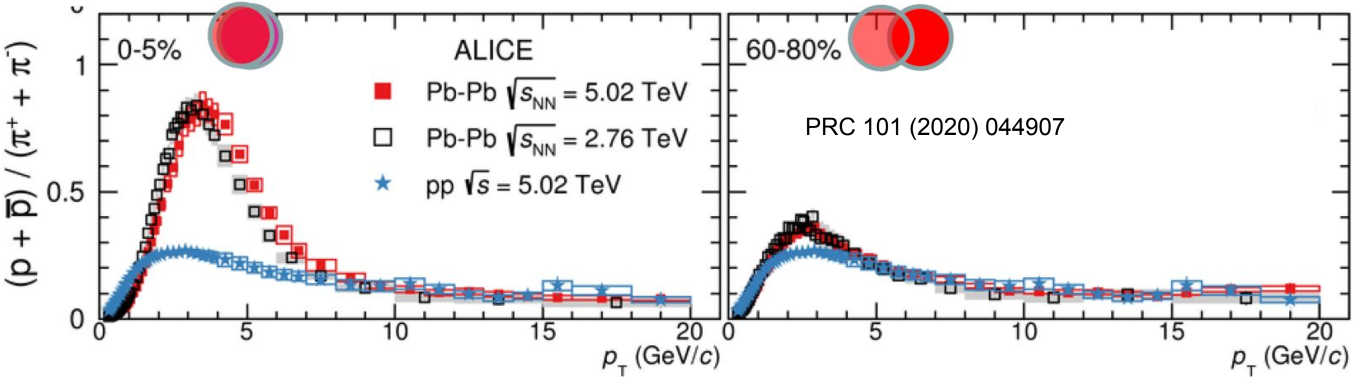
	Λ_c^+/D^0
pp	0.47 ± 0.04 (stat.) ± 0.04 (syst.)
p–Pb	0.42 ± 0.04 (stat.) ± 0.06 (syst.)

	$\langle p_T \rangle$ (GeV/c)	
	pp	p–Pb
D^0	2.06 ± 0.03 (stat.) ± 0.03 (syst.)	2.07 ± 0.02 (stat.) ± 0.04 (syst.)
Λ_c^+	1.86 ± 0.06 (stat.) ± 0.03 (syst.)	2.29 ± 0.06 (stat.) ± 0.06 (syst.)



- Do we see just radial flow in p-Pb collisions?
- **Can coalescence redistribute along p_T the same Λ_c baryon enhancement?**

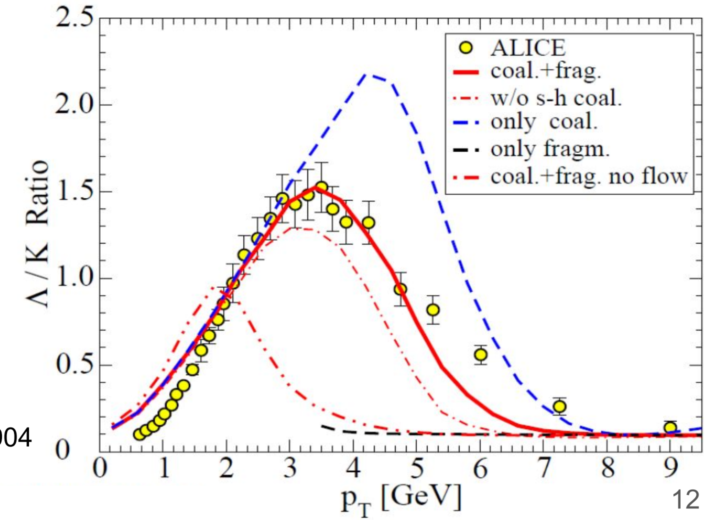
Baryon/meson ratios



PRC 101 (2020) 044907

- ➢ **Low / mid p_T**(< 8 GeV/c):
  - Ratios p/π(Λ/K^0_s) enhanced in Pb–Pb compared to pp
  - Interplay of **collective flow** and **recombination**
- ➢ **High p_T**(> 8-10 GeV/c):
  - Ratios compatible with those in pp
  - Independent **fragmentation**

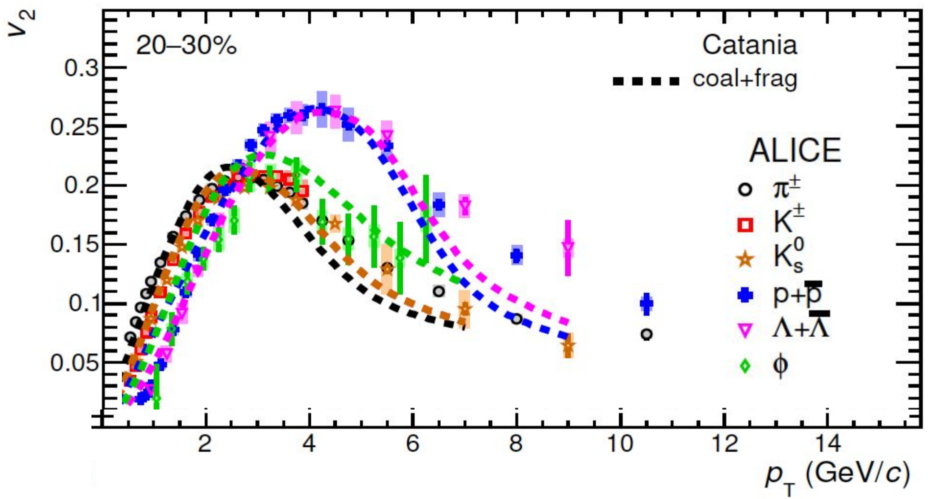
- ➢ **Different model ingredients needed:**
  - Radial flow of partons
  - Coalescence + fragmentation
  - Resonance decays



PRC 92 (2015) 054904

Identified hadron v_2

JHEP09(2018)006 Phys. Rev. C 92 (2015) 054904

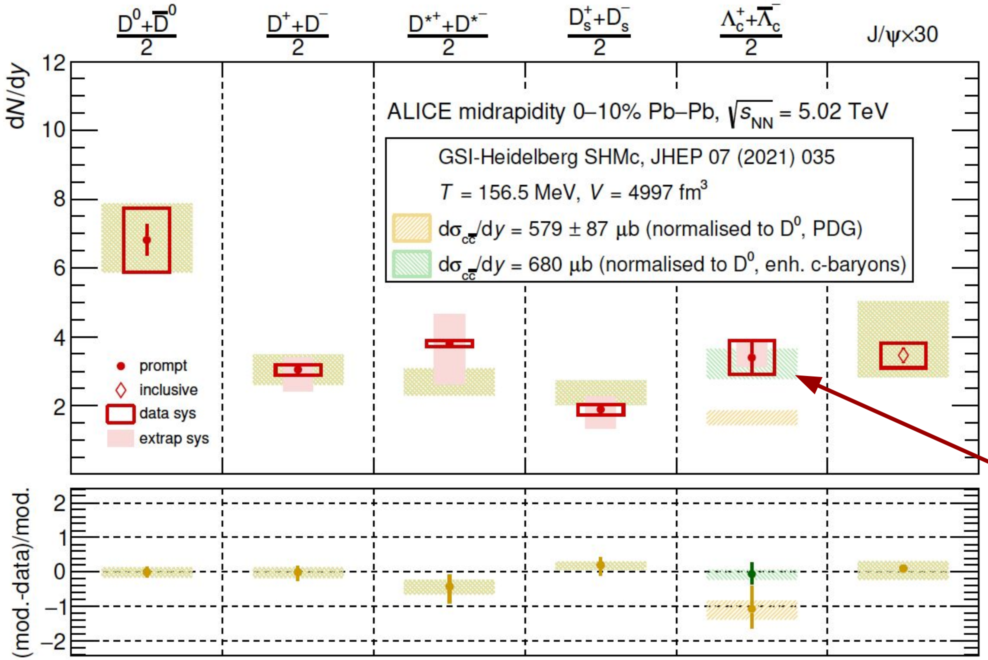


- **Baryon vs meson grouping at intermediate p_T as expected from coalescence**

- **Low p_T** (< 2-3 GeV/c): mass ordering
  - As predicted by hydrodynamics
- **Mid p_T** (3-8 GeV/c): grouping by number of constituent quarks
  - Supports hypothesis of hadron production via quark recombination
- **High p_T** (>10 GeV/c): similar v_2 for π and p
  - Path-length dependent energy loss + independent fragmentation
- **Φ meson v_2**: test mass ordering and particle type scaling
  - Follows proton v_2 (similar **mass**) at **low p_T** and meson v_2 (same number of **constituent quarks**) at **higher p_T**

SHM with charm

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

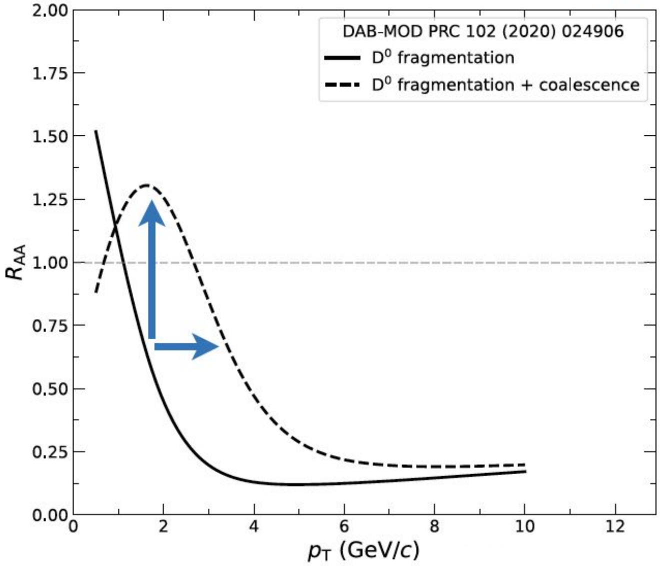


arXiv:2211.04384

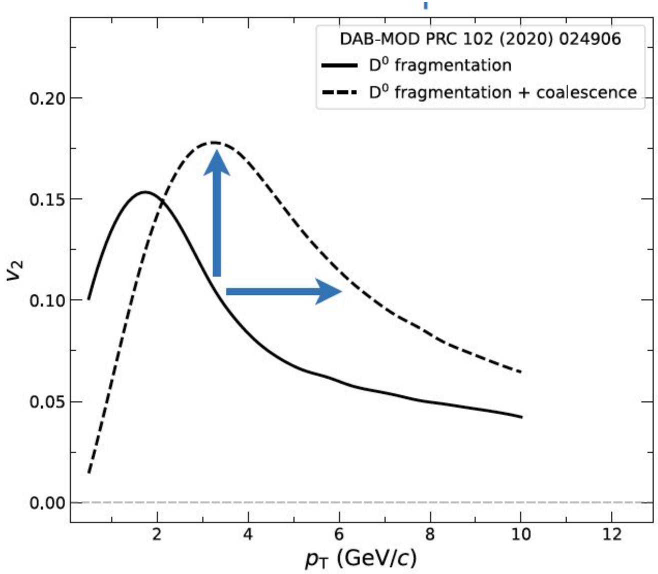
- ➢ Measured p_T-integrated yields of open charm mesons and J/Ψ midrapidity described by SHMc within uncertainties
  - Charm content determined by cross section and not by fireball temperature
  - Assume (full) charm quark thermalisation in the QGP
  - Charm quarks distributed to hadrons according to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

Modification of p_T distributions

Nuclear modification factor



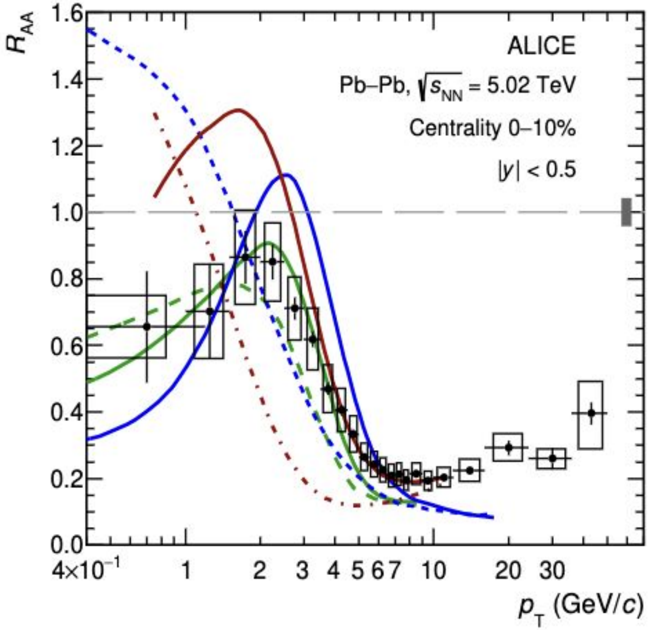
Elliptic flow



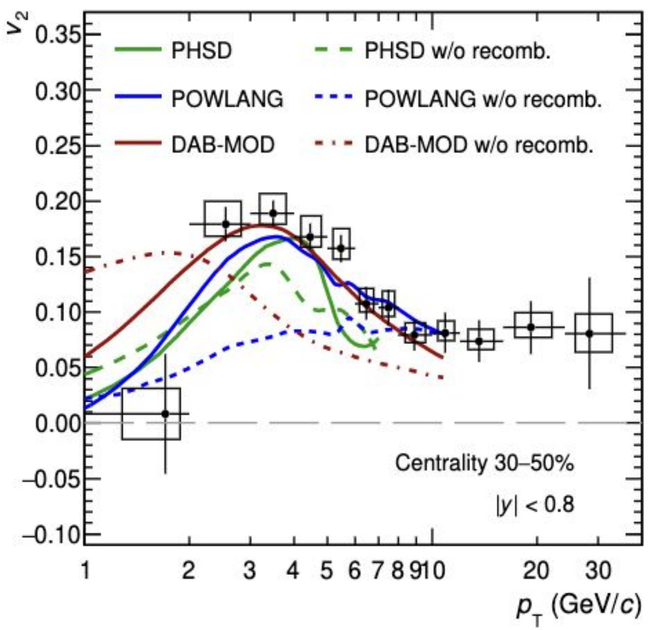
- **Coalescence** of heavy quarks with light quarks from the QGP affects **HF hadron momentum distributions**
  - HF hadrons pick-up the radial and elliptic flow of the light quark

Modification of p_T distributions

Nuclear modification factor

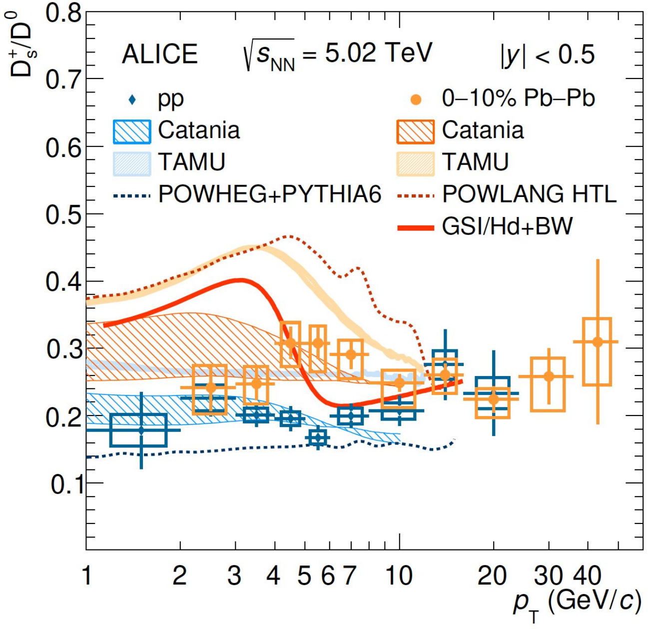


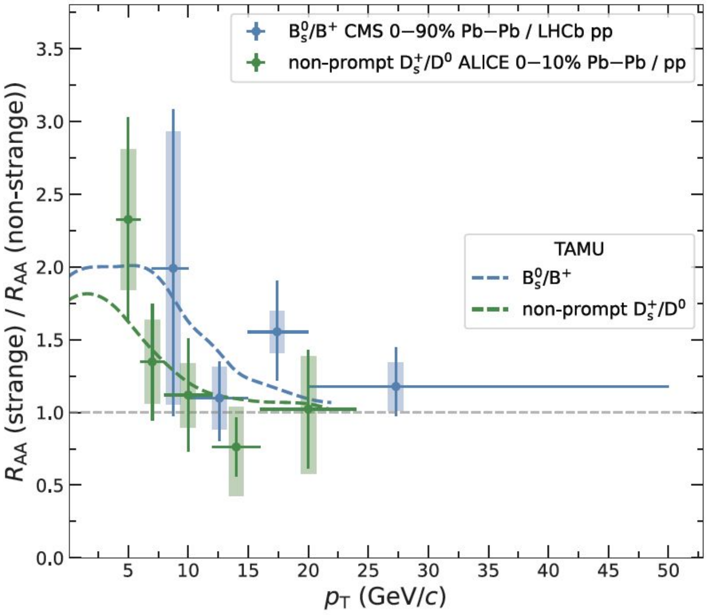
Elliptic flow



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

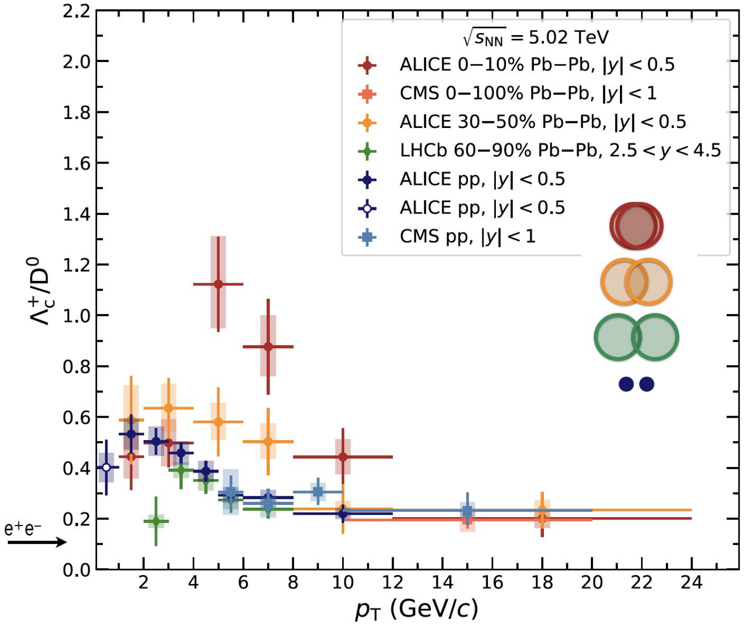
Open charm and beauty hadrochemestry





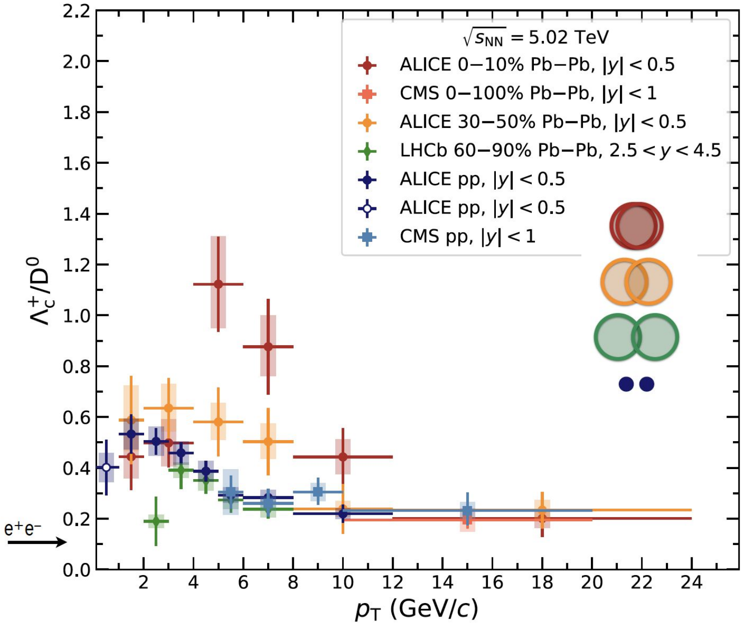
- Coalescence of heavy quarks with light quarks from the QGP affects **HF hadrochemestry**
  - **Enhanced D_s(B_s)** yield relative to non-strange mesons (strange quarks abundant in QGP)
  - D_s/D^0 ratios in central Pb-Pb hint at enhancement at mid-p_T relative to pp
  - Similar indication observed in the strange-beauty sector (B_s and non-prompt D_s)

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 hadronize via coalescence?
  - Radial flow?
  - An interplay of the two effect?

Λ_c in Pb-Pb



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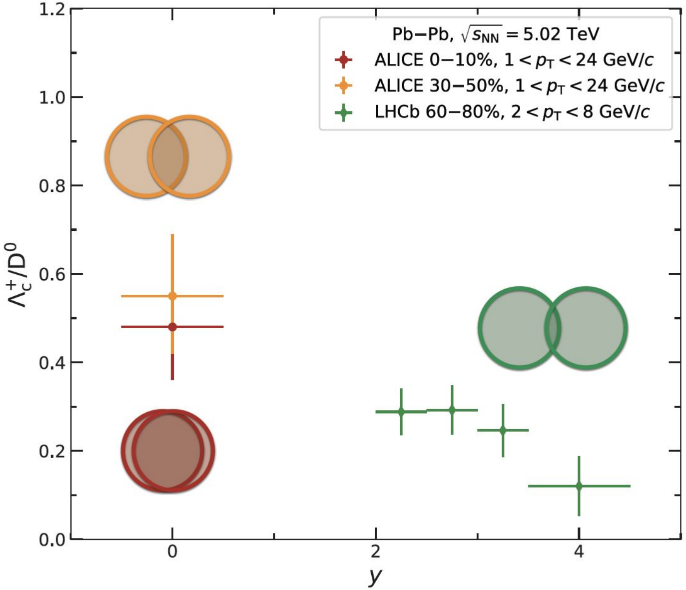

- Possible rapidity dependence need further investigation - what do models (coalescence) predict?
- Other baryons with strange component?

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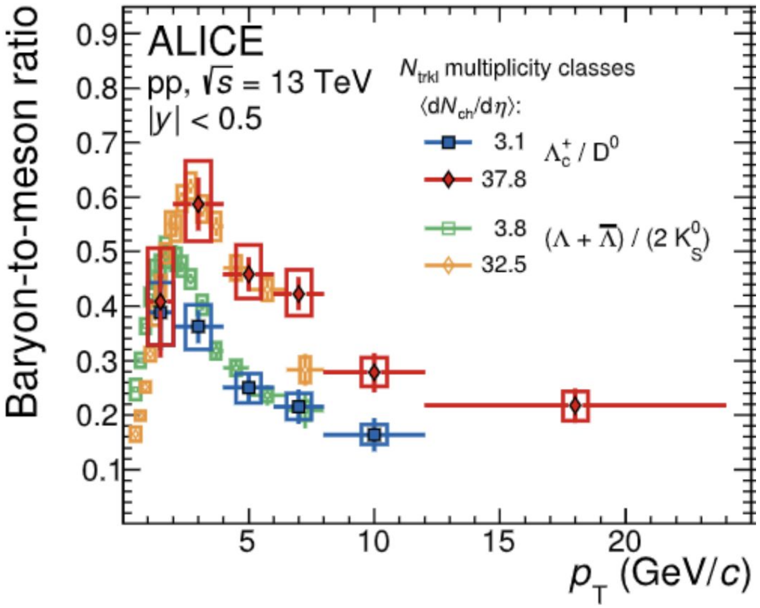
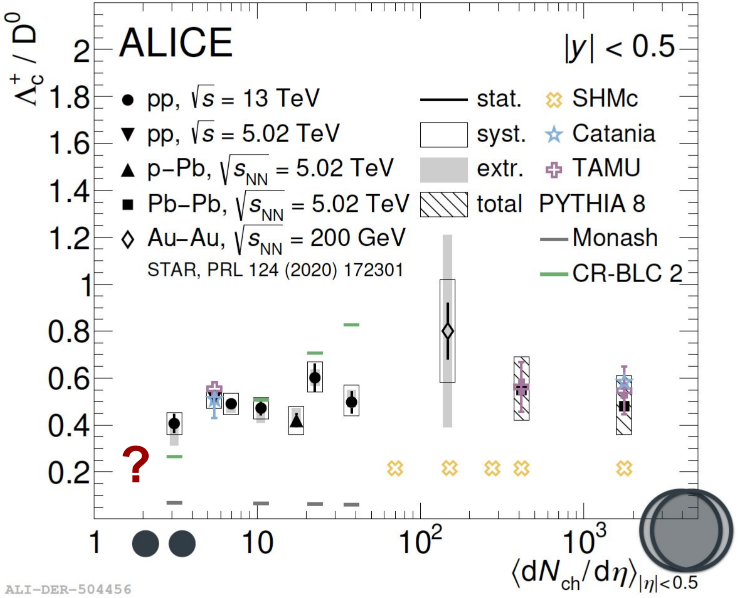
Baryon-to-meson ratio vs multiplicity





- ➢ 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 from pp to Pb-Pb
- ➢ **Towards very low multiplicity** - would it be possible to reach the e^+e^- limit?

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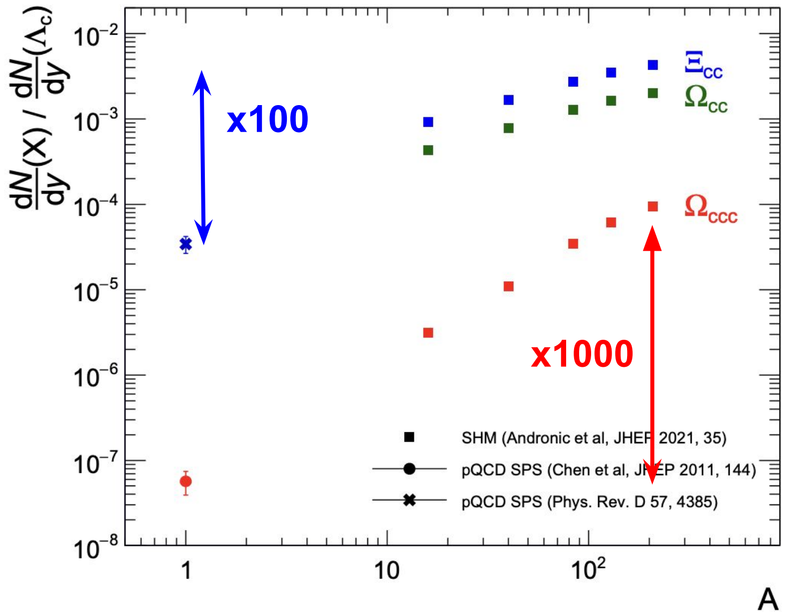
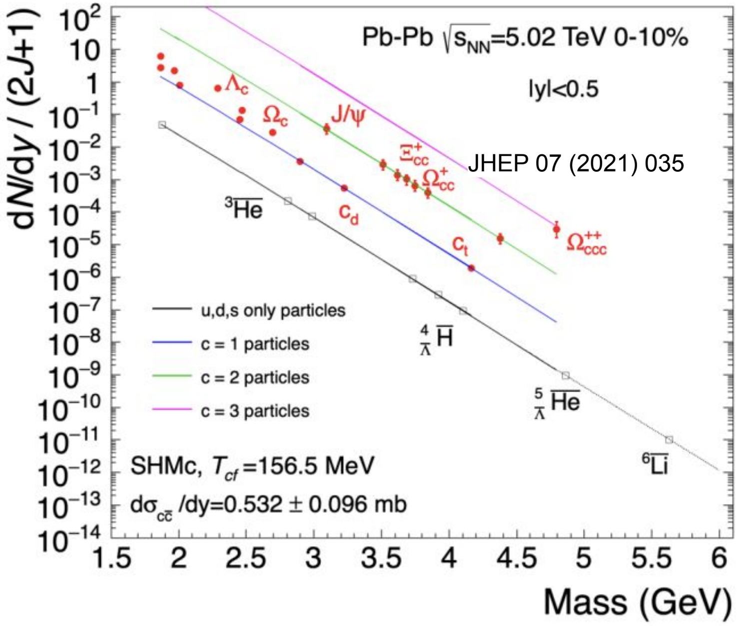
Multi-charm hadron states

- 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**





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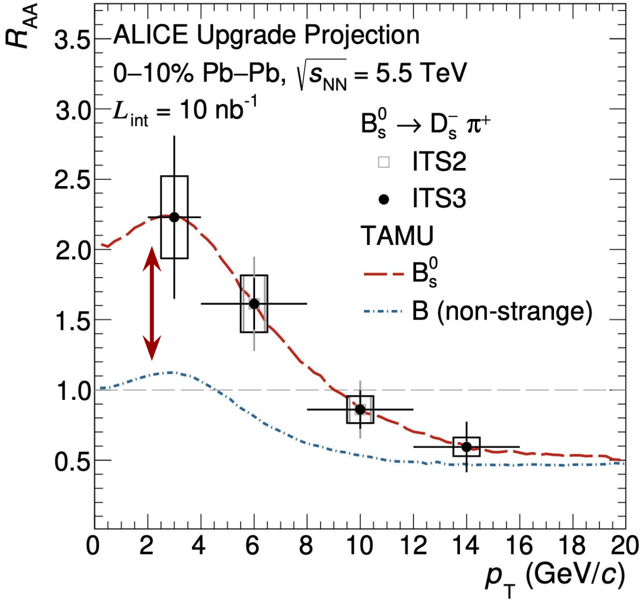
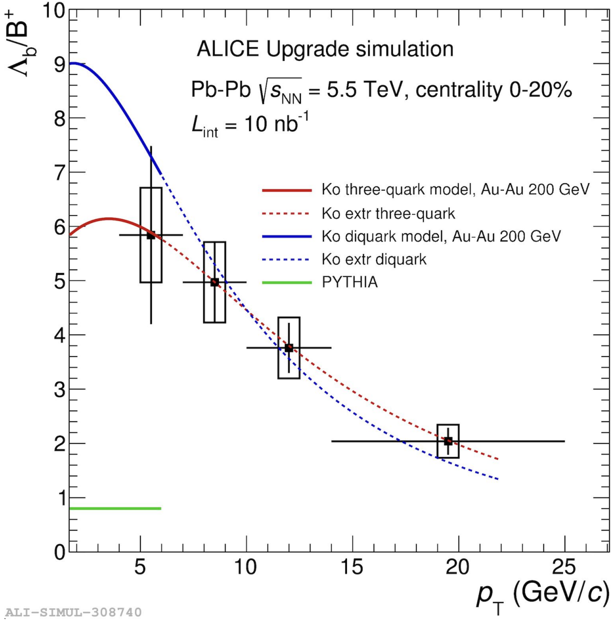
Beauty hadrons in Pb-Pb

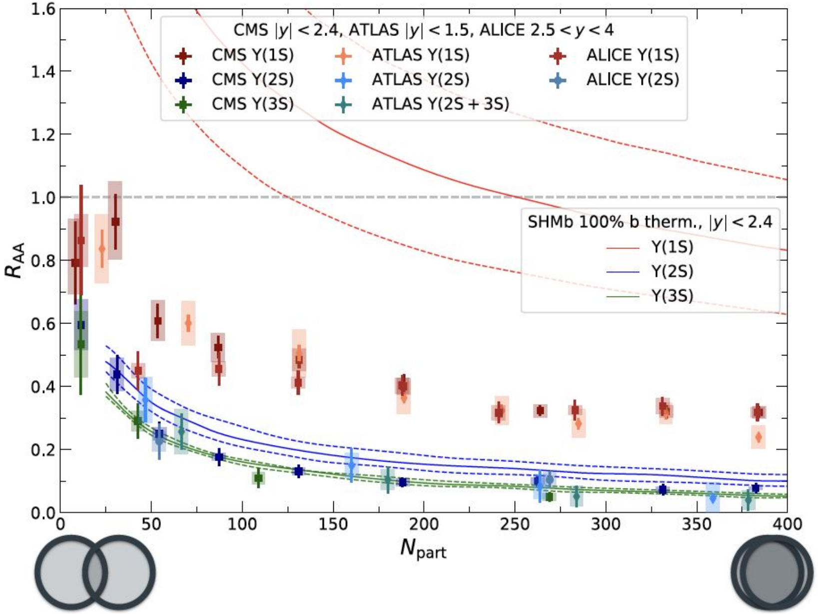


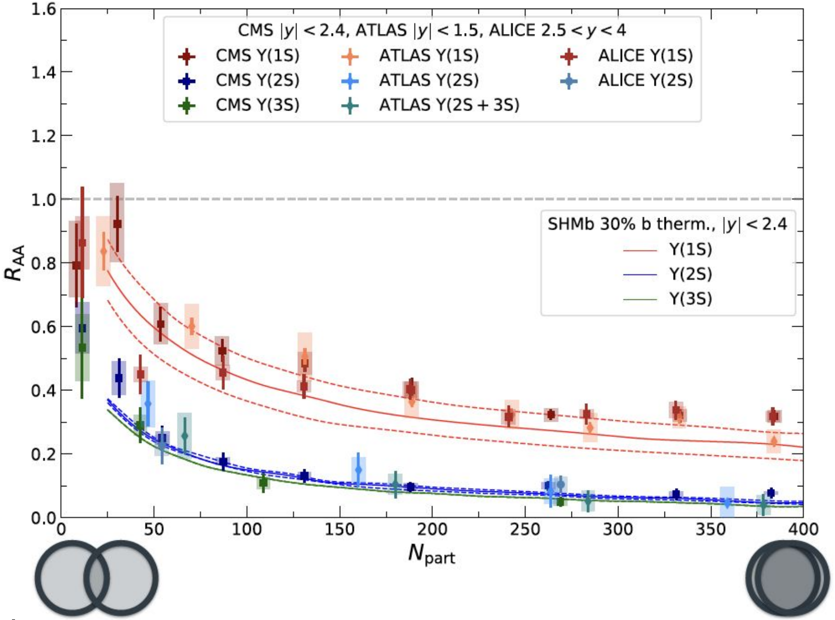


- **Full reconstruction of beauty hadrons will be at reach in Run 3-4**
  - Expected enhancement in B^0_s in Pb-Pb collisions will be quantifiable for the first time
  - Reconstruction of $\Lambda^0_b \to \Lambda^+_c \pi^-$ (BR = 4.9 10-3)
    - Will be affected by large uncertainties and limited to p_T > 4-5 GeV/c in Run 3 and Run 4

Bottomonia states

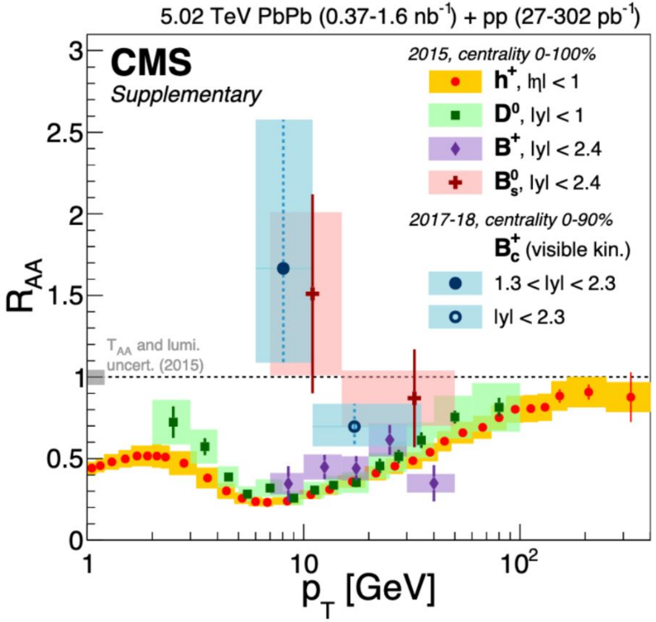
- ➢ Υ largely overestimated if 100% of beauty quarks assumed to be thermalized.
  - Does beauty quark reach thermal equilibrium
  - v_2 is compatible with zero
- ➢ **Υ described if 30% of beauty quarks assumed to thermalize.**
  - Reach partial equilibrium?
  - **Presence of currently unknown open beauty states will lead to a reduction of the bottomonia yields.**





A new and challenging QGP probe

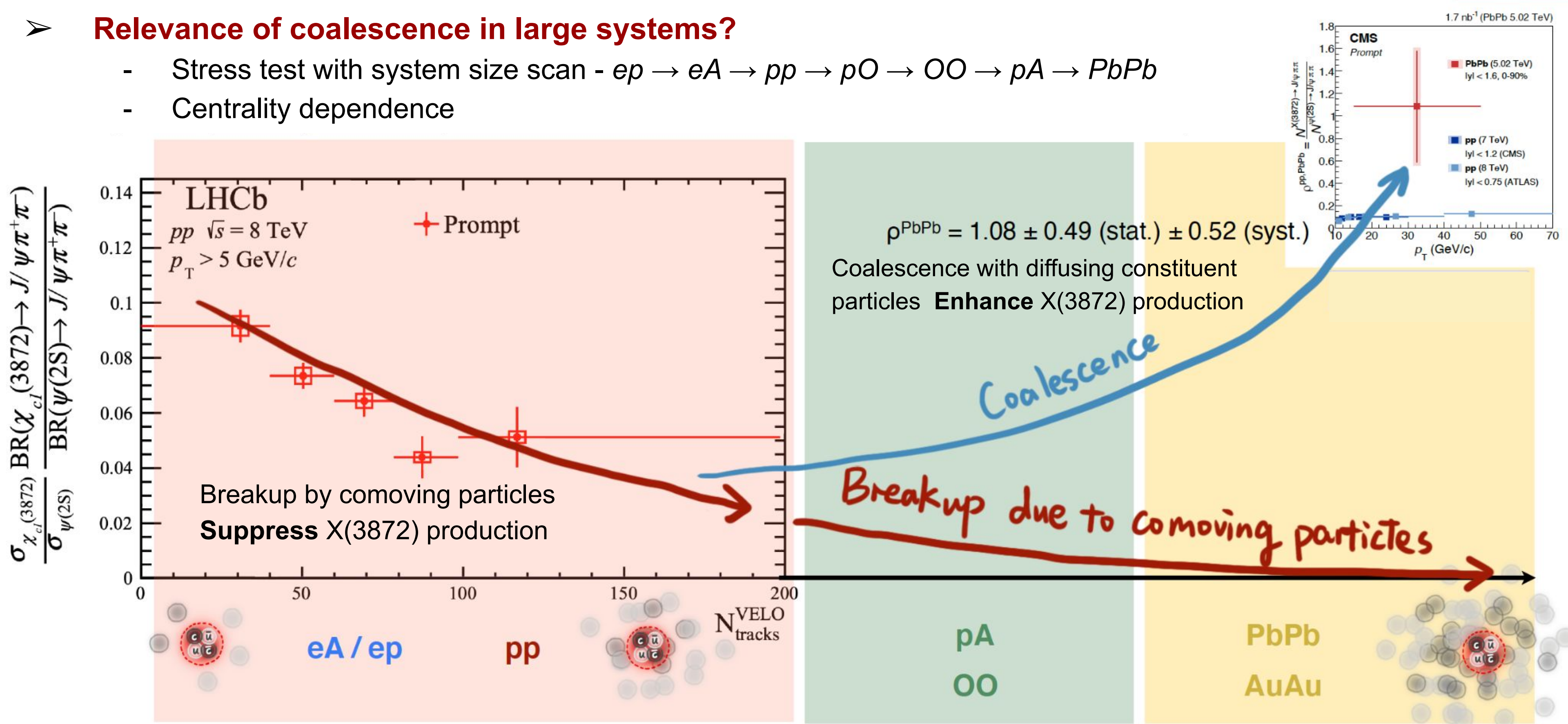
- B_c^+ production in heavy-ion collisions is an ideal probe to be sensitive both to dead cone effect and statistical recombination
  - *CMS: used 2018 Pb-Pb data!*
  - *ALICE, LHCb: aim for Run 3*



Another window on coalescence

➢ **Relevance of coalescence in large systems?**

- Stress test with system size scan - *ep → eA → pp → pO → OO → pA → PbPb*
- Centrality dependence



Slide from Jin Wang

Conclusion

➢ **Light flavour production at intermediate p_T**
- Transition from thermal (hydro) to kinetic regime -> window on hadronization mechanism?
- Quark coalescence captures many features of the data

➢ **Heavy flavours**
- Clear signs of coalescence in open charm measurements (and in J/Ψ - not shown today)
- Charm-hadron yields vs SHM provide complementary information on charm quark thermalization
- Baryon enhancement present even at low mult. pp – can we reach an e^+e^- limit in pp?

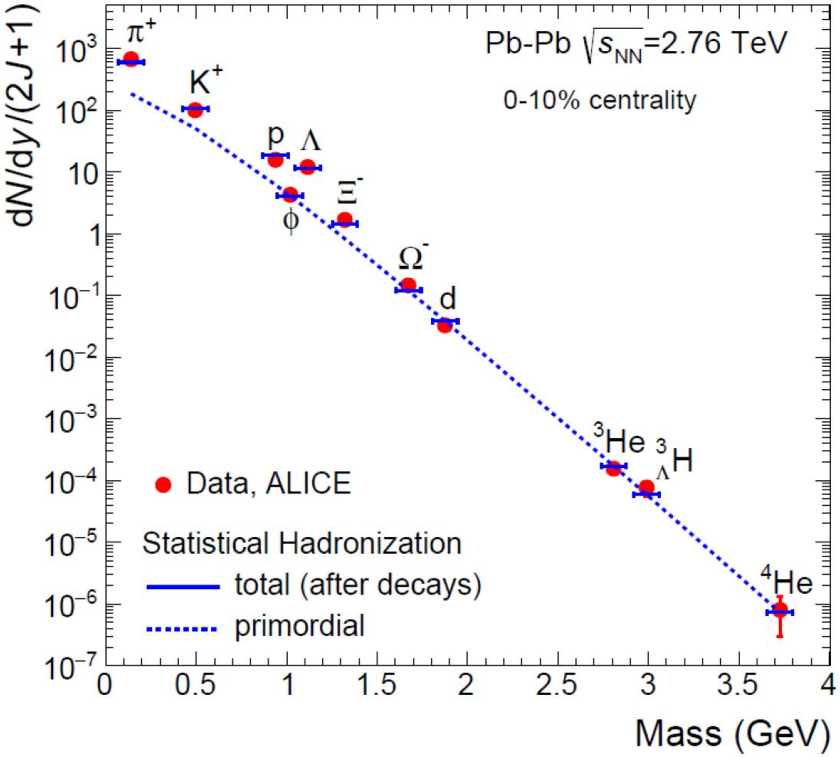
Outlook:

➢ Beauty: need of precise measurements of hadrochemistry, p_T spectra and v_n 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 (at least in pp collisions)
- They can open a new window for further testing coalescence and statistical hadronization

Backup

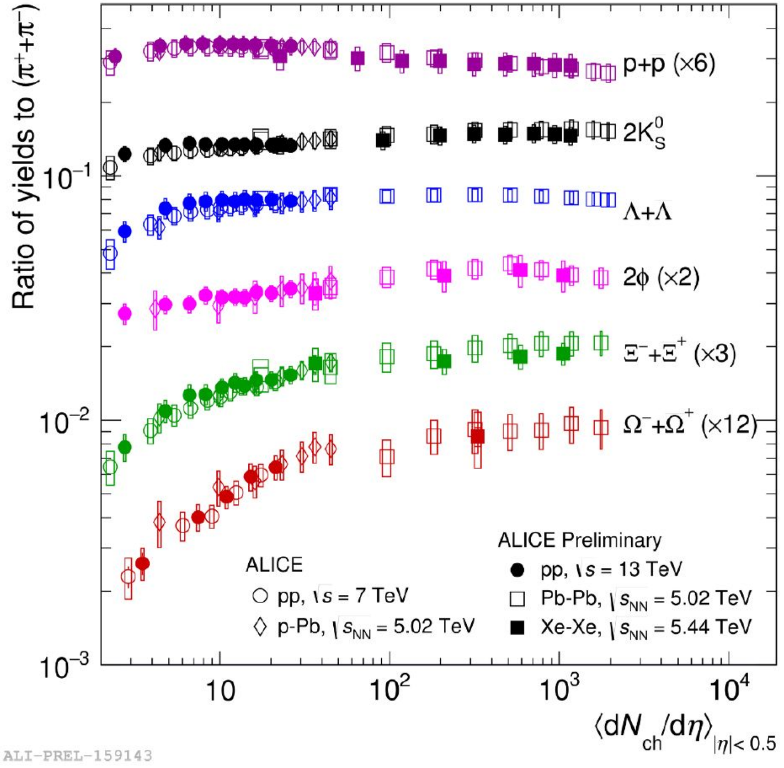
Statistical hadronization



- Abundances of light and strange hadrons and nuclei:
  - Follow equilibrium populations of a **hadron-resonance gas in chemical and thermal equilibrium**
  - Freeze-out temperature T_{ch} ~ 155 MeV
- Thermal origin of particle production
  - Macroscopic description of the hadron gas in terms of thermodynamic variables
- **Statistical hadronisation models** (SHM)
  - Yields depend on:
    - Hadron masses (and spins)
    - Chemical potentials
    - Temperature and volume of the fireball

Andronic et al, Nature 561 (2018) 7723, 321

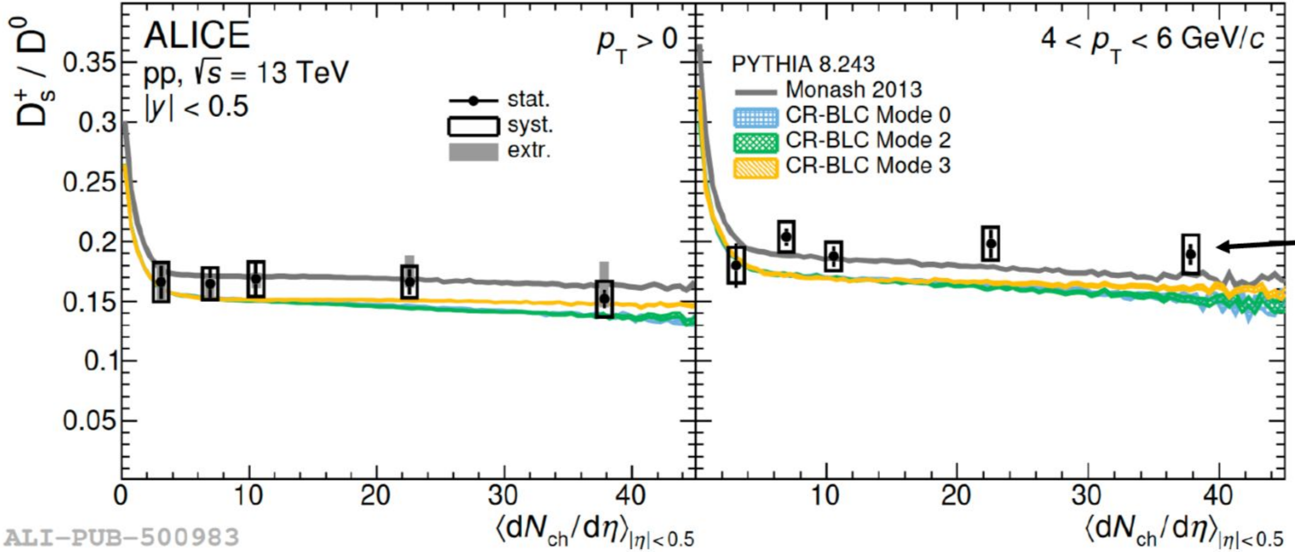
Strangeness vs mult



- Particle ratios measured in pp collisions show a smooth evolution with multiplicity from small to large collision systems

- Increasing strangeness relative to pion yield with increasing multiplicity
  - Challenge for pp event generators

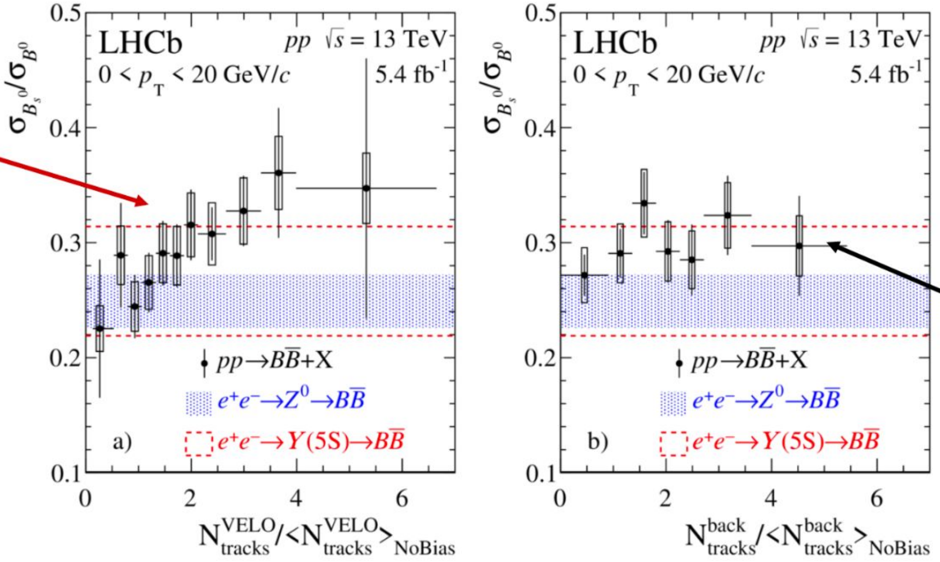
Strangeness vs mult in HF



No significant dependence of D_s/D^0 on multiplicity within current uncertainties

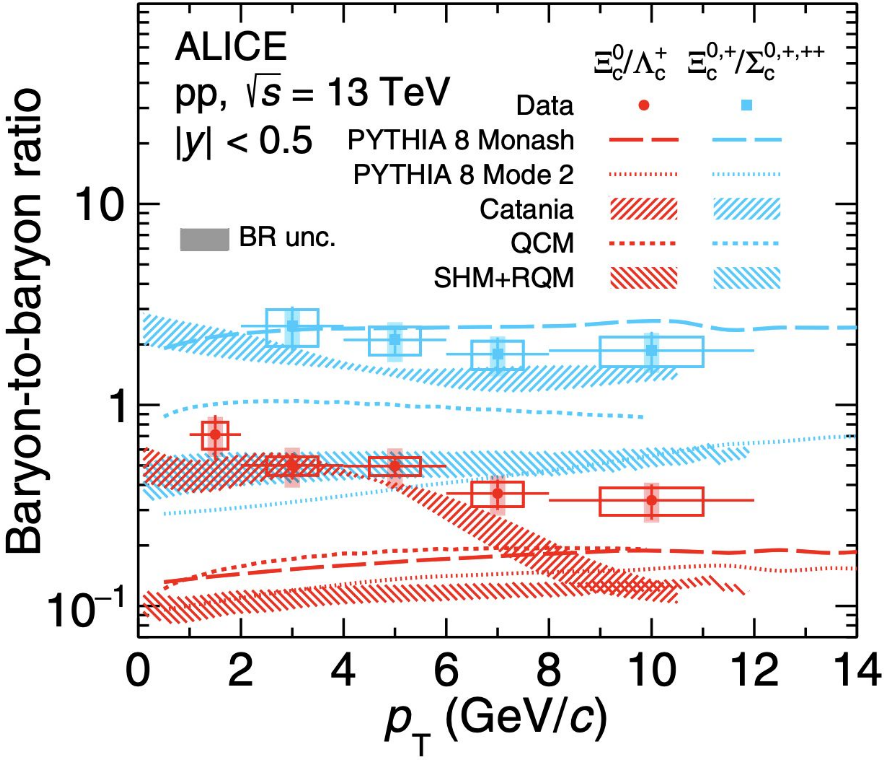
Strangeness vs mult in HF

Increasing trend of B_s/B^0 ratios vs. multiplicity in the VELO (same rapidity region of B mesons)



No significant dependence of B_s/B^0 on multiplicity at backward rapidity

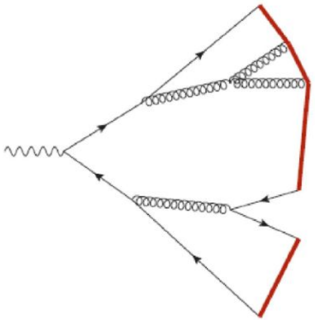
Di-quark – do they play a role?



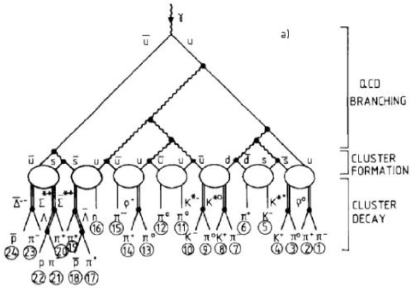
➢ Ξ_c/Σ_c described by Monash
- Does it tells us something?
- Do diquarks play any role?

- On a microscopic level hadronisation of jets modeled with:
  - Perturbative evolution of a parton shower with DGLAP down to a low-virtuality cut-off Q0
  - Final stage of parton shower interfaced to a non perturbative hadronisation model

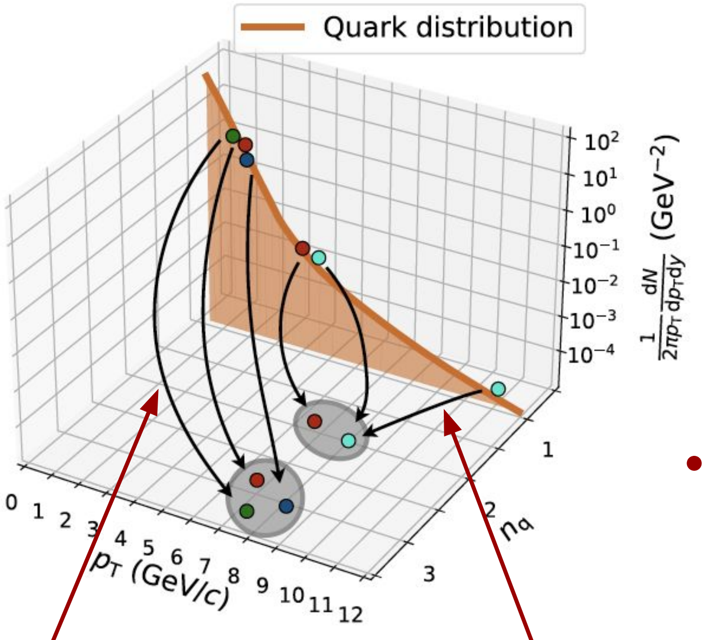
- **String fragmentation** (e.g. Lund model in PYTHIA)
  - Strings = colour-flux tubes between q and $\bar{q}$ end-points
  - Gluons represent kinks along the string
  - Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs



- **Cluster decay** in HERWIG
  - Shower evolved up to a softer scale
  - All gluons forced to split into $q\bar{q}$ pairs
  - Identify colour-singlet clusters of partons following color flow
  - Clusters decay into hadrons according to available phase space



Quark coalescence/recombinaton



Recombining quarks:

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

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

Fragmenting parton:

$p_h = z \cdot p_q$ with $z<1$

- Single parton description may not be valid anymore
- No need to create qq pairs via splitting/string breaking
- Partons that are *"close" to each other in phase space* (position and momentum) can **recombine** into hadrons
- Initially thought to happen only in heavy-ion collisions

- **Recombination vs. fragmentation:**
  - Competing mechanisms, dominant in different p_T regions
  - **Recombination depends on "environment"**, i.e. density and momentum distribution of surrounding (anti)quarks
  - Recombination naturally enhances baryon/meson ratios at intermediate p_T

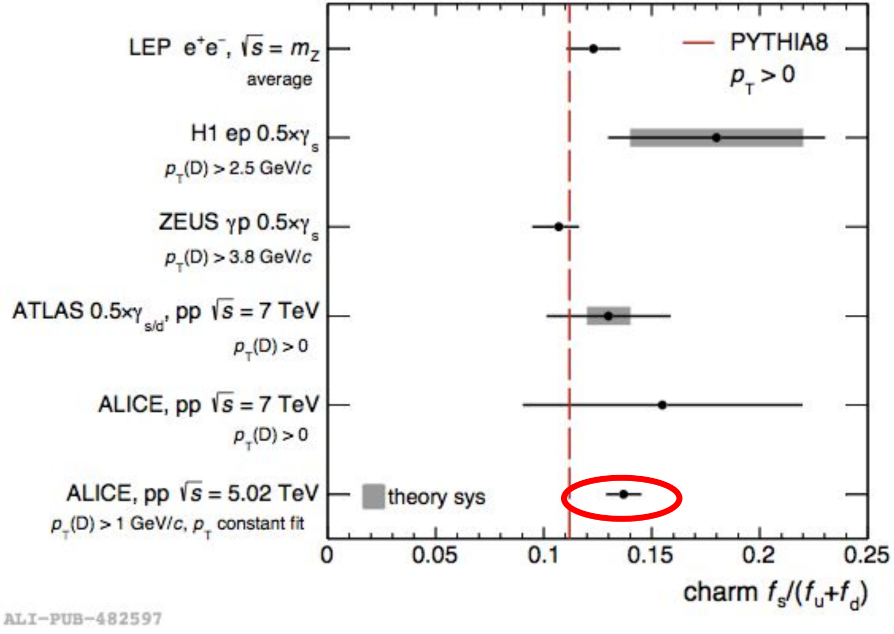
Greco et al., PRL 90 (2003) 202302
Fries et al., PRL 90 (2003) 202303
Hwa, Yang, PRC 67 (2003) 034902

Charm and beauty fragmentation to meson

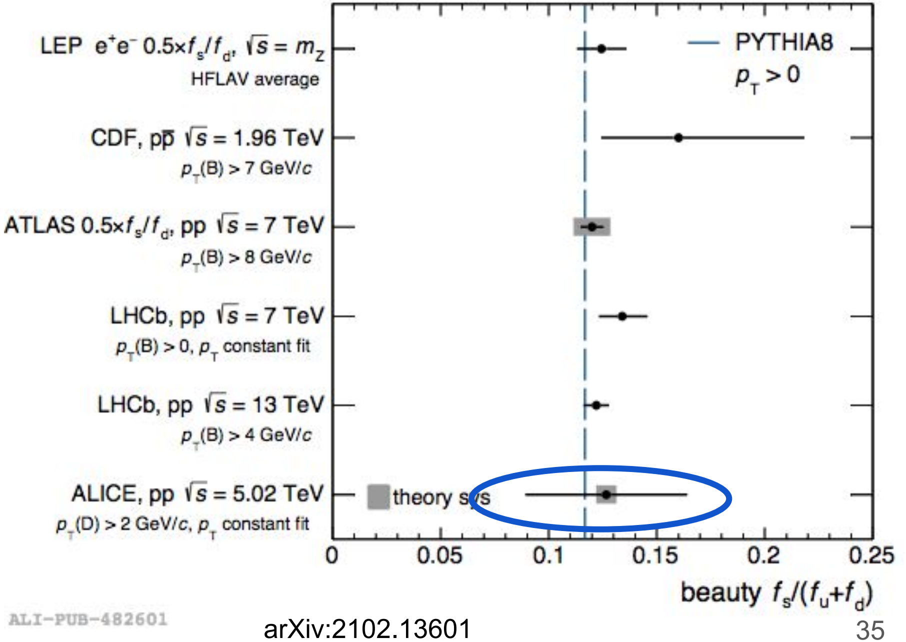
- Ratio fragmentation fraction (FF) to meson with and w/o strange quark content similar for charm and beauty
- No significant dependence on energy and collision system

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

Charm



Beauty

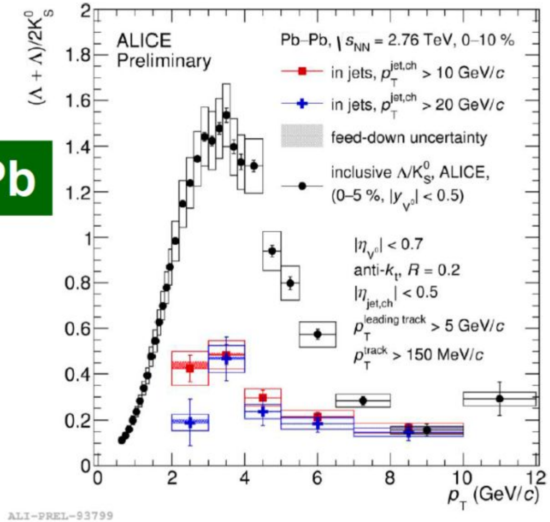


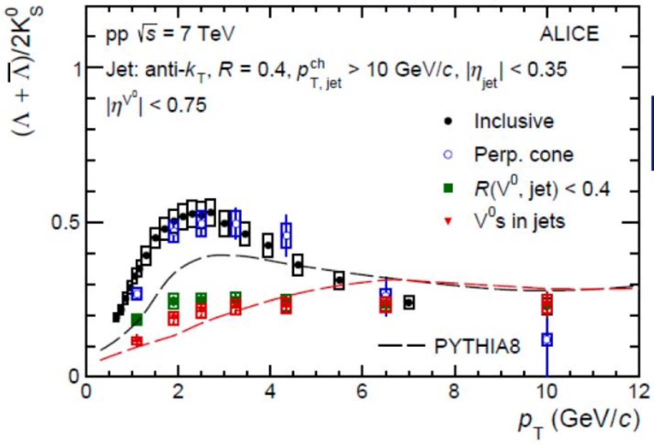
arXiv:2102.13601

Andrea Dubla

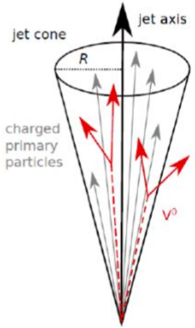
In jet and in bulk

Pb-Pb



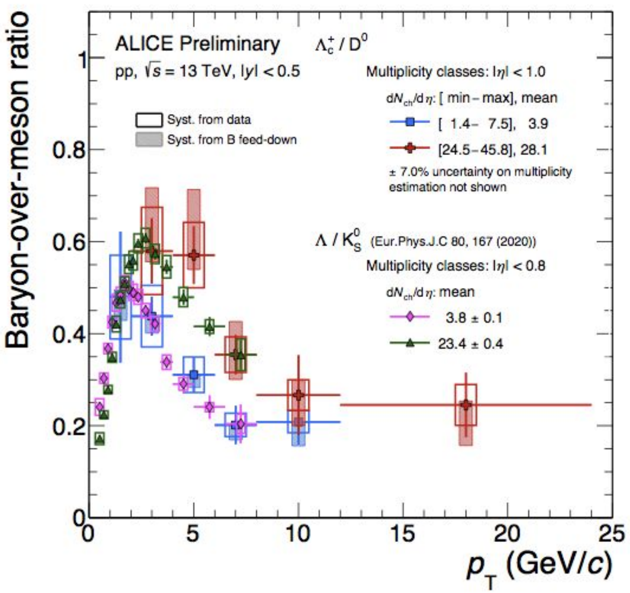


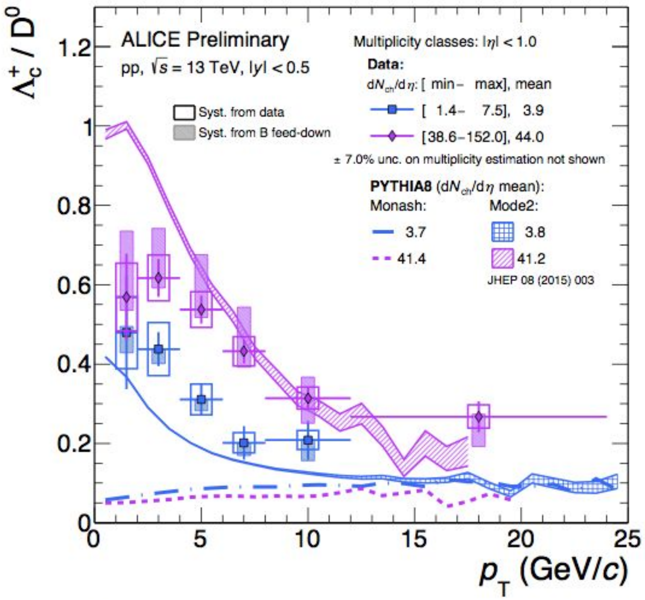
pp



- ➢ Baryon/meson ratios different in-jet and out-of-jet
  - Baryon enhancement mostly from the bulk
  - Connected to collective expansion and hadronisation of bulk
- ➢ Ratio of Λ/K0in-jet is similar in pp and Pb-Pb
- ➢ Fragmentation of the jet not modified by the medium

More differential: low multiplicity



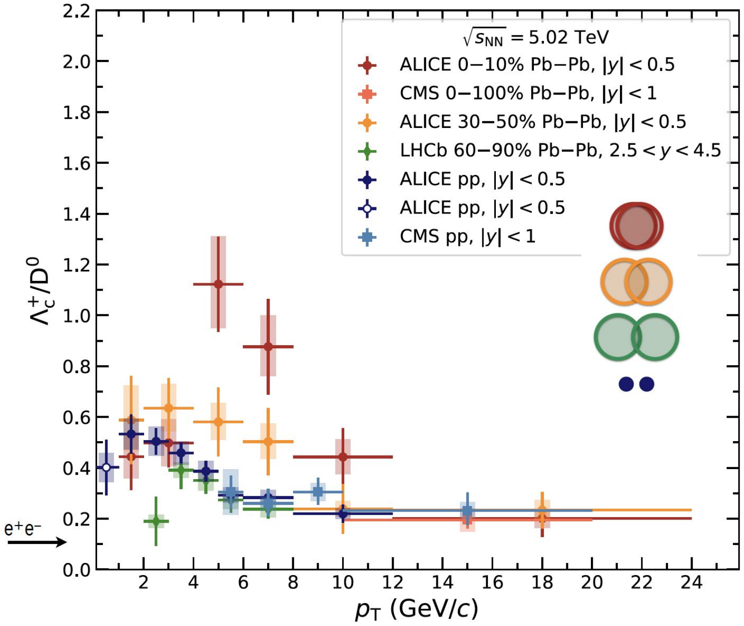


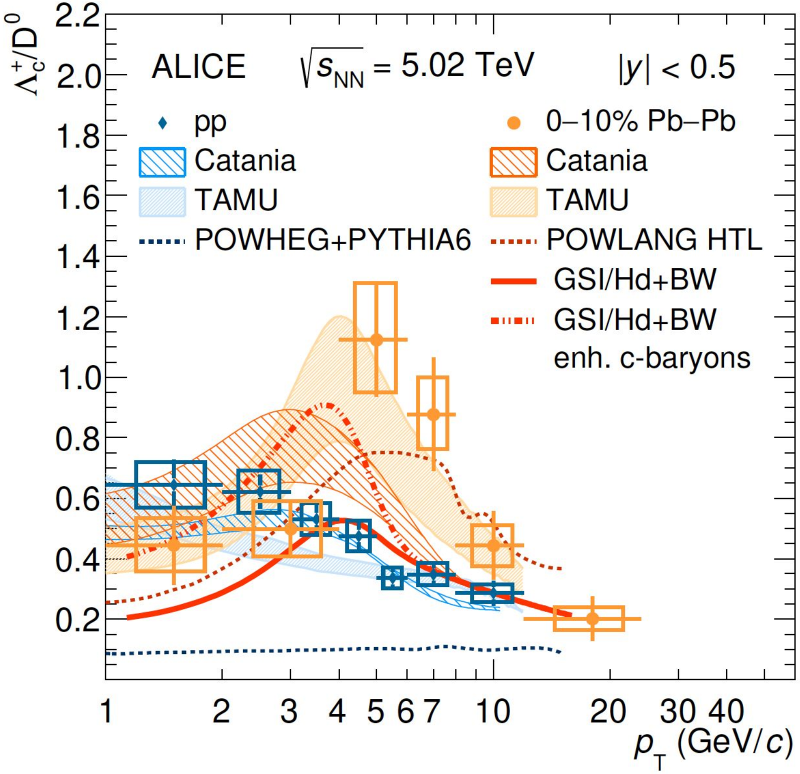
- Enhancement observed for Λ_c/D^0 from low to high multiplicity

The question is low mult vs ee collisions

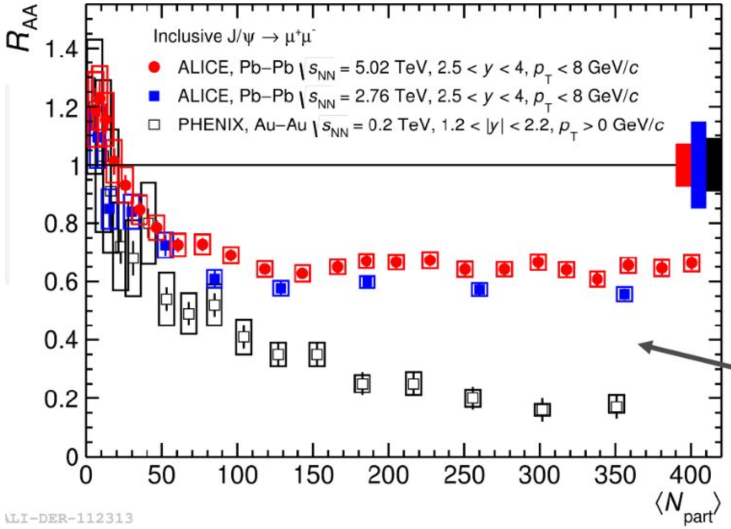
- Pythia Mode2: Multiplicity trend qualitatively in line with data
- no variation with mult in default PYTHIA8 (Monash)

Λ_c in Pb-Pb





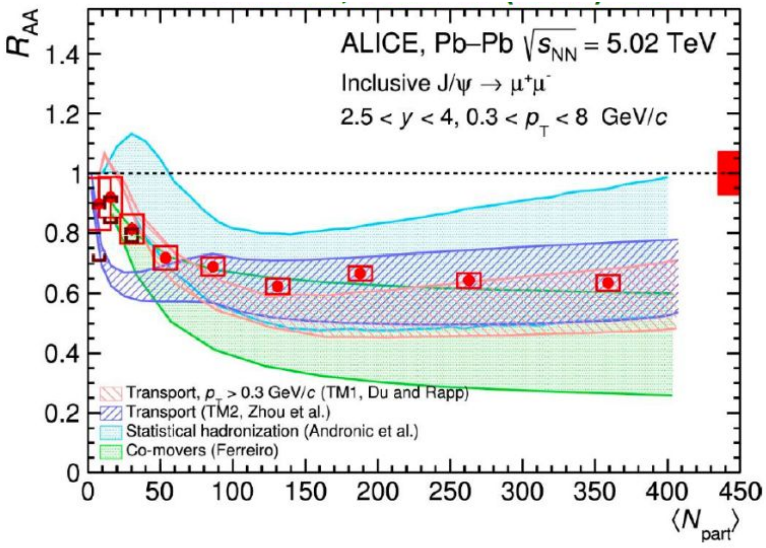
Quarkonia



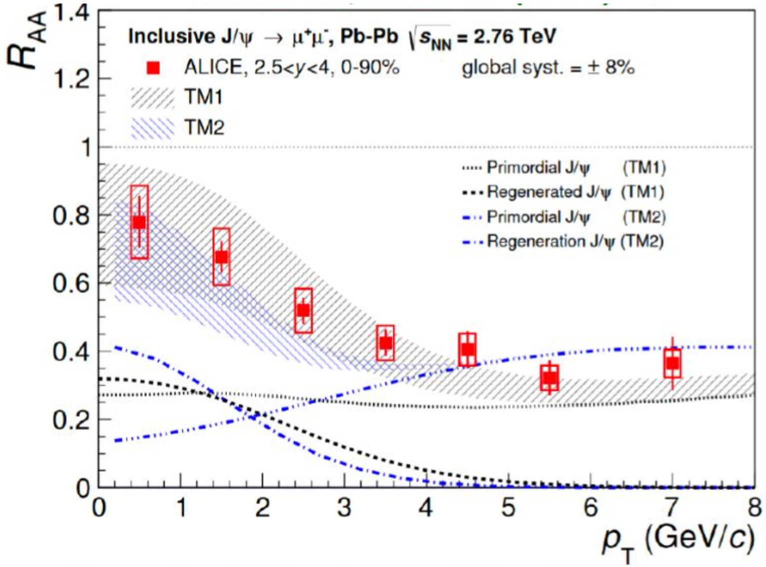
J/ψ Yield vs. centrality and $\sqrt{s_{NN}}$

- Less suppression at LHC ($\sqrt{s_{NN}}$=**2.76**, **5.02** TeV) than at RHIC ($\sqrt{s_{NN}}$=**200** GeV)

Quarkonia



ALICE, Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Inclusive J/ψ → μ⁺μ⁻
2.5 < y < 4, 0.3 < p_T < 8 GeV/c
Transport, p_T > 0.3 GeV/c (TM1, Du and Rapp)
Transport (TM2, Zhou et al.)
Statistical hadronization (Andronic et al.)
Co-movers (Ferreiro)
R_{AA}
⟨N_{part}⟩



Inclusive J/ψ → μ⁺μ⁻, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
ALICE, 2.5<y<4, 0-90%
global syst. = ± 8%
TM1
TM2
Primordial J/ψ (TM1)
Regenerated J/ψ (TM1)
Primordial J/ψ (TM2)
Regeneration J/ψ (TM2)
R_{AA}
p_T (GeV/c)