Modification of hadronization in heavy ion collisions

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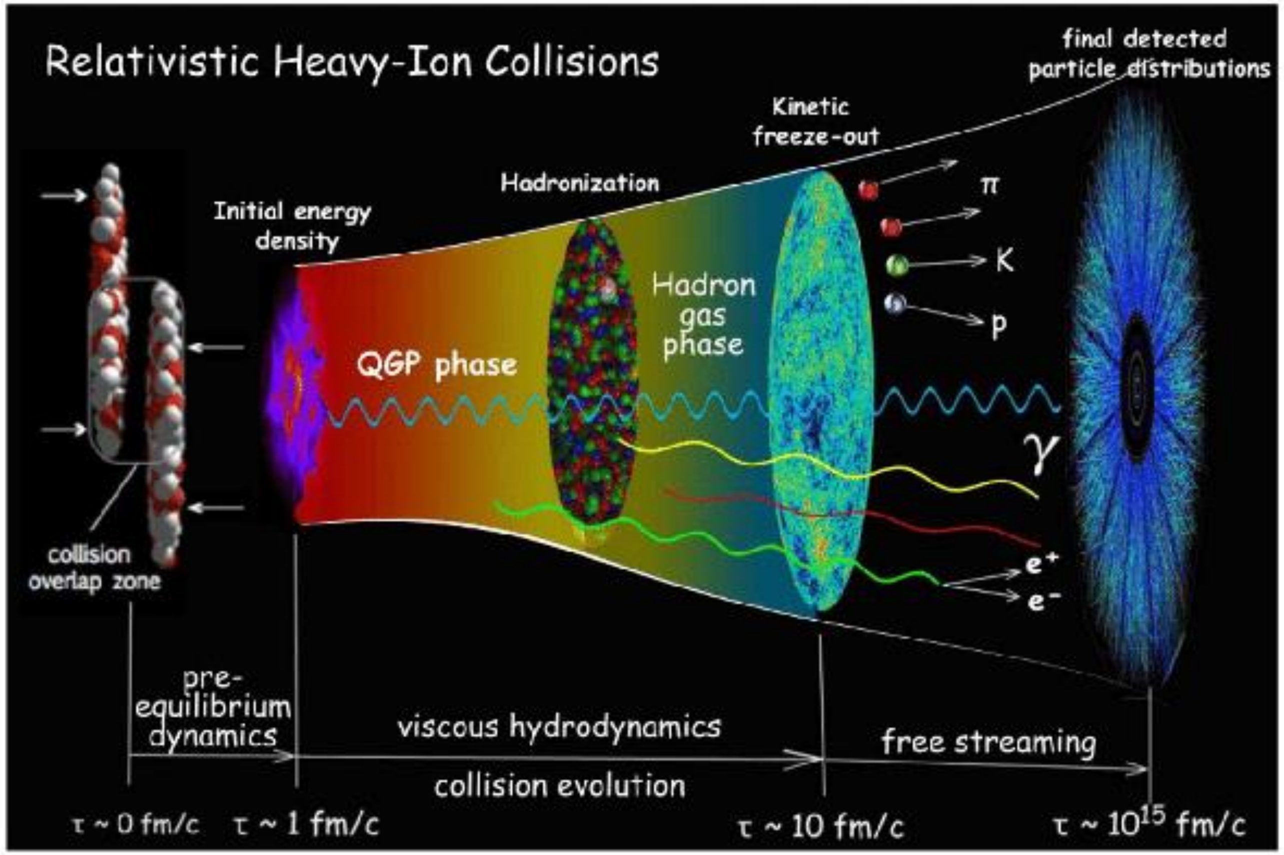
ALICE

ATLAS

CMS

LHCb

Hadronization of the QGP



- Hadronization 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
  - ⇨ Partonic degrees of freedom convert into hadrons, in which partons are confined
- 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

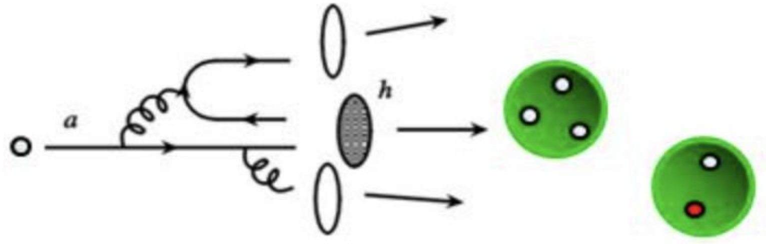
→ Hadronization from a QGP may be different from other cases in which no bulk of thermalized partons is formed

Independent fragmentation

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

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

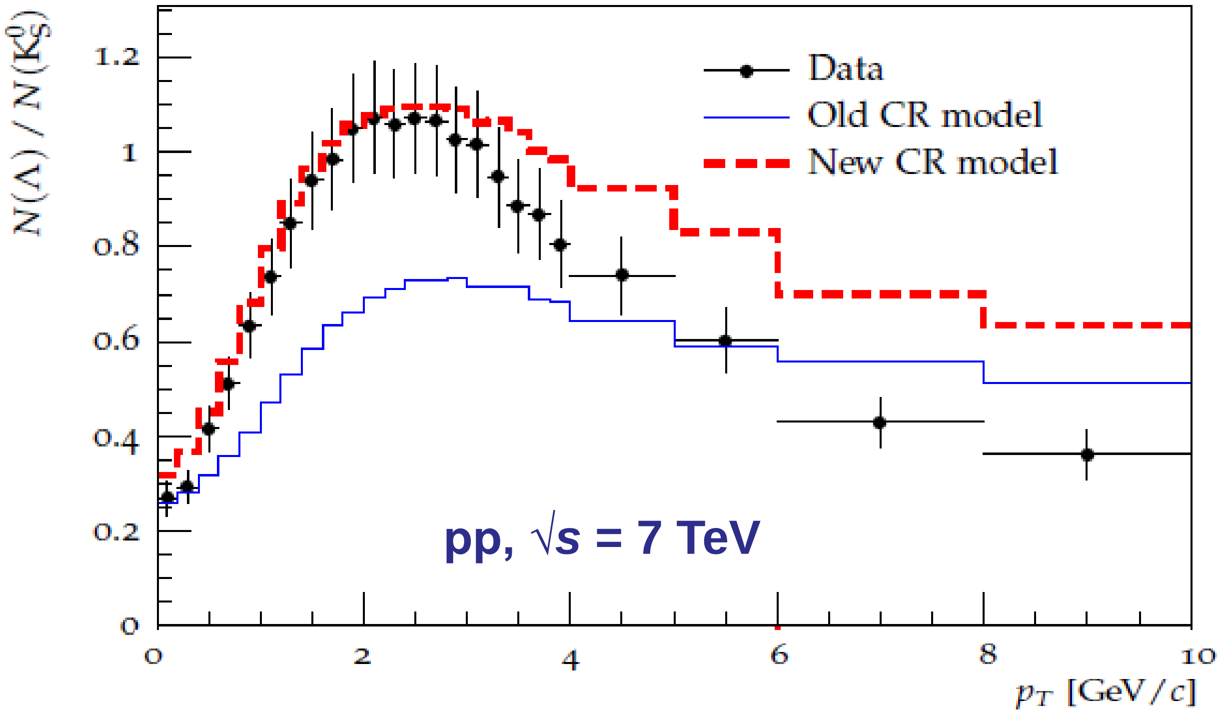
- **Fragmentation functions** $D_{q\to h}(z,Q^2)$:
  - ⇨ Phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition*
  - ⇨ z = fraction of the parton momentum taken by the hadron h
  - ⇨ Parameterized on data and assumed to be “universal”



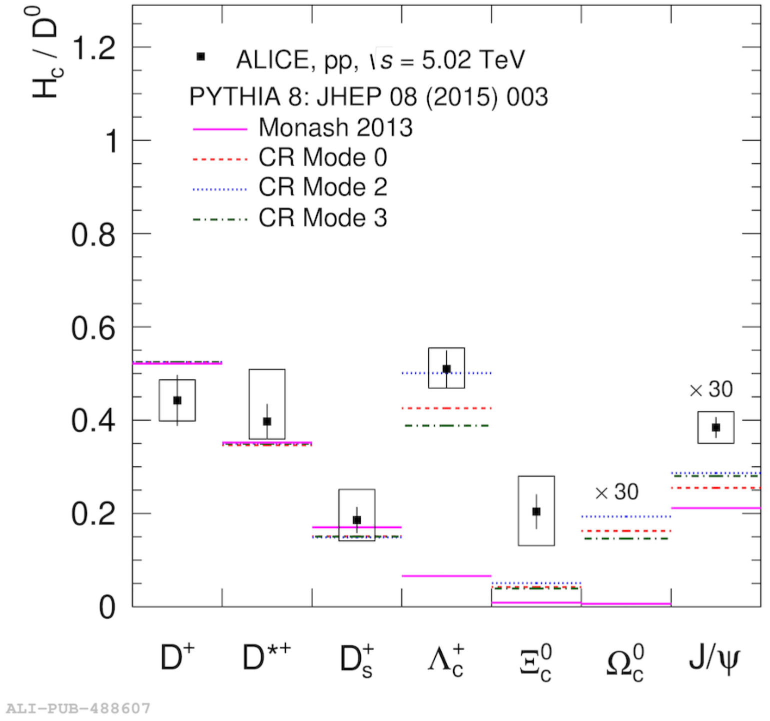
- In **event generators** hadronisation of jets modeled with:
  - ⇨ Perturbative evolution of **parton shower** down to a low-virtuality cut-off Q_0
  - ⇨ Final stage of parton shower interfaced to a non-perturbative hadronization model
    - ✓ **String fragmentation** (e.g. Lund model in PYTHIA)
    - ✓ **Cluster decay** in HERWIG

Colour reconnection

📖 Christiansen Skands, JHEP 08 (2015) 003



📖 ALICE, PRD 105 (2022) 1, L011103



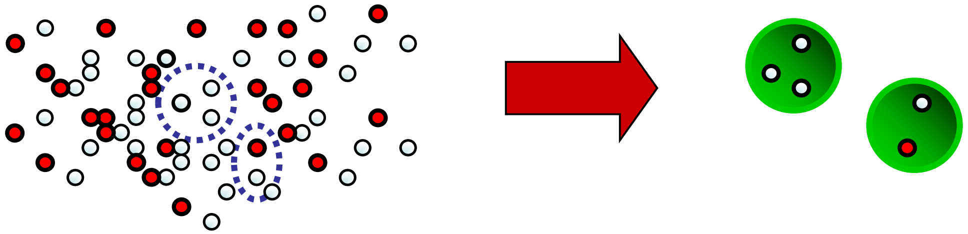
- Baryon production and baryon/meson ratios:
  - ⇨ Underestimated by PYTHIA tuned on e^+e^- (old CR model, Monash 2013)
  - ⇨ Better description with Color Reconnection beyond leading color (New CR model, CR mode 0,2,3)

→ Independent fragmentation picture not valid in color-rich environment

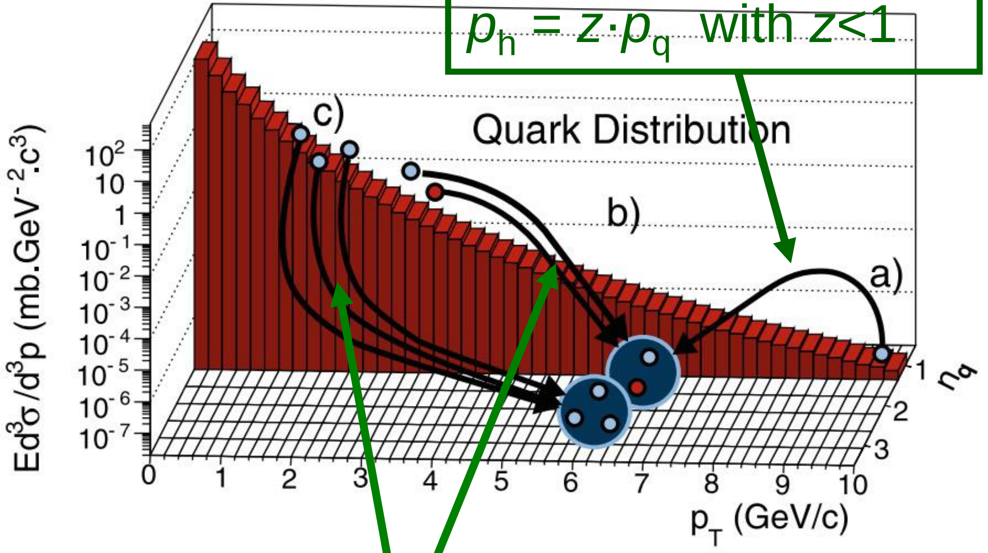
Quark recombination

- Phase space at the QGP hadronization is filled with (thermalized) partons
  - ⇨ Single parton description may not be valid anymore
  - ⇨ No need to create $q\bar{q}$ pairs via splitting / string breaking
  - ⇨ Partons that are *"close" to each other in phase space* (position and momentum) can **recombine** into hadrons
- 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**

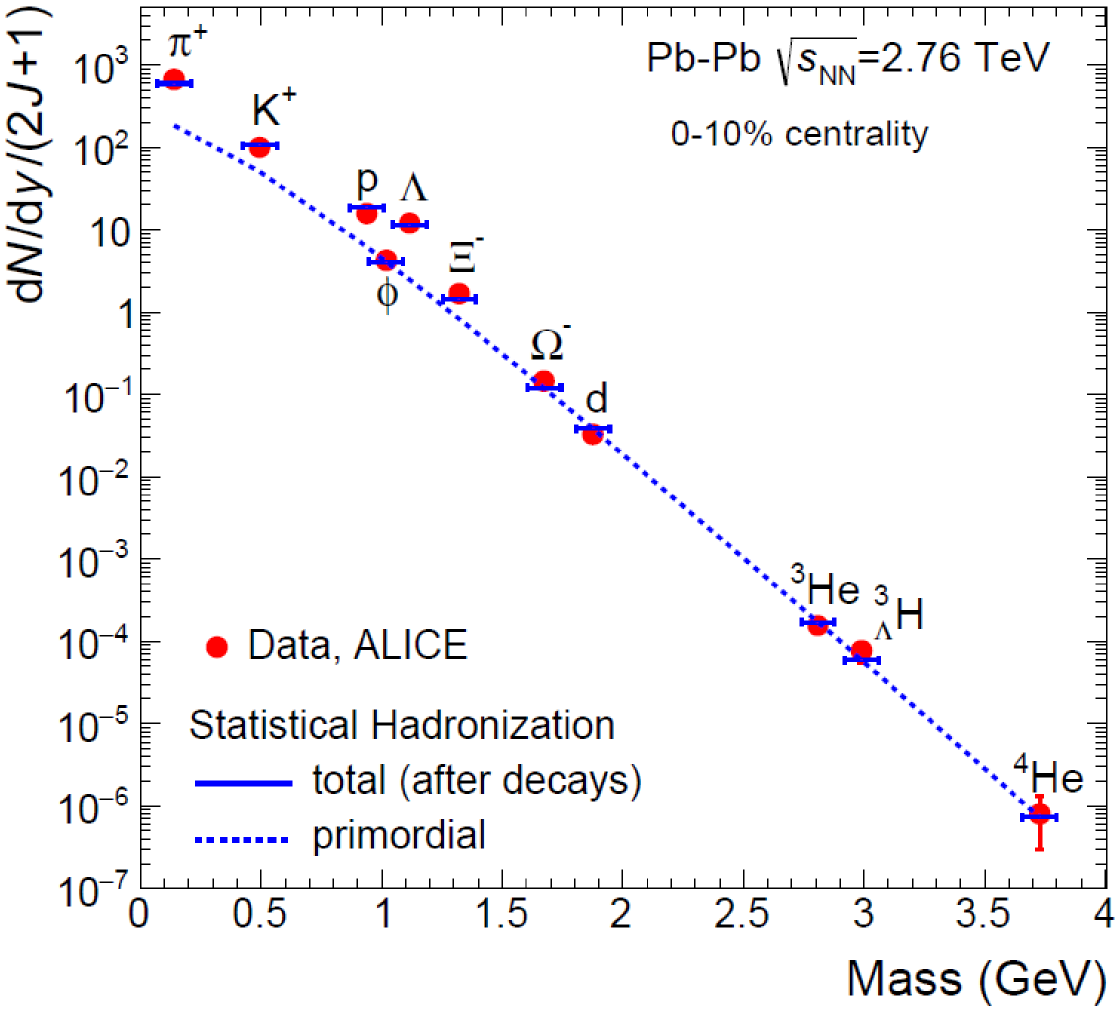


fragmenting parton: $p_h = z \cdot p_q$ with $z<1$



recombining quarks:
$p_{meson} = p_{q1}+p_{q2}$; $p_{baryon} = p_{q1}+p_{q2}+p_{q3}$

Statistical hadronization



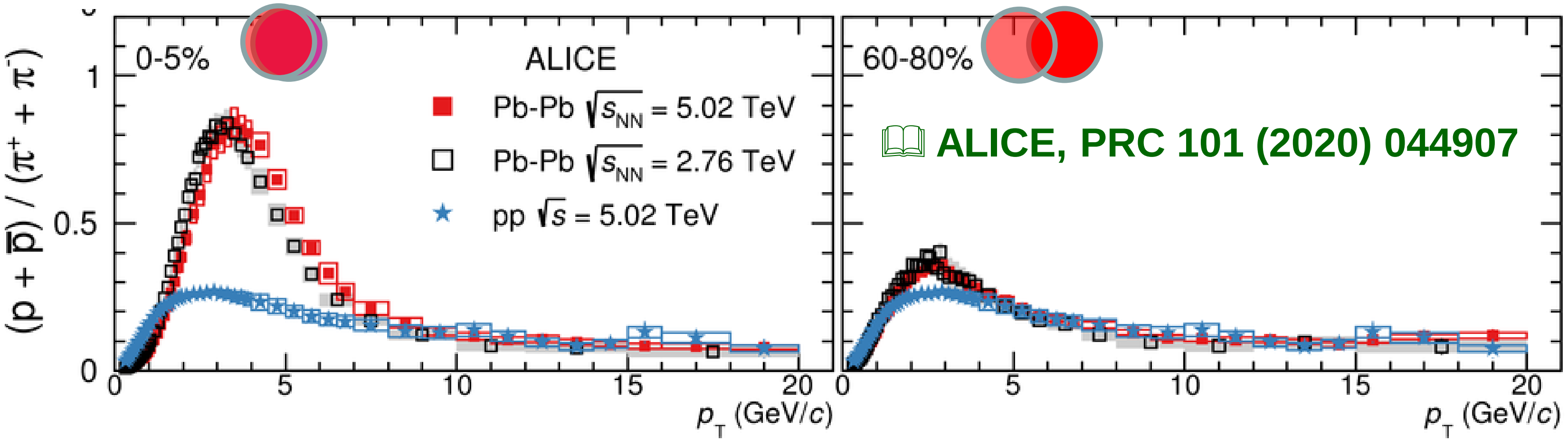
📖 **Andronic et al, Nature 561 (2018) 7723, 321**

- 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

Light flavours

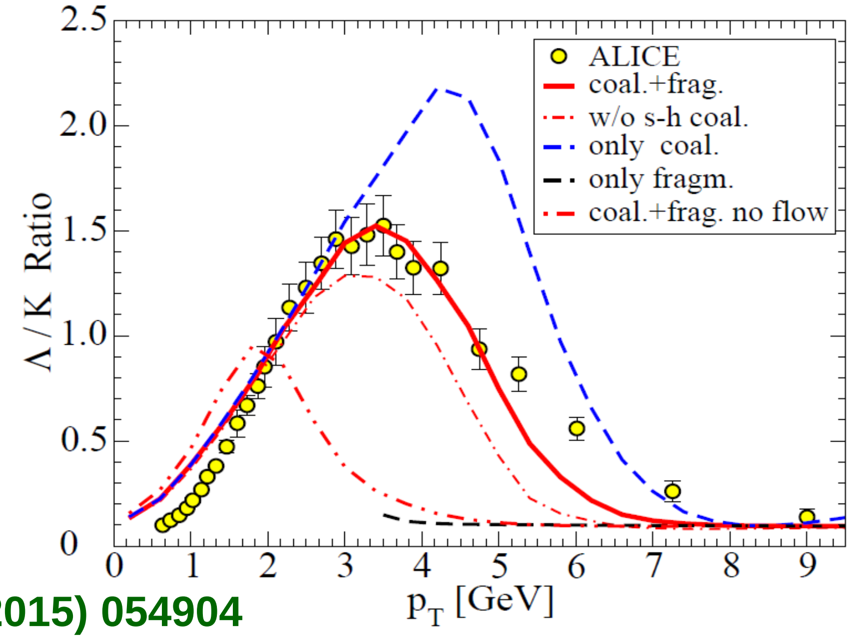
Baryon/meson ratios

- **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**



📖 ALICE, PRC 101 (2020) 044907

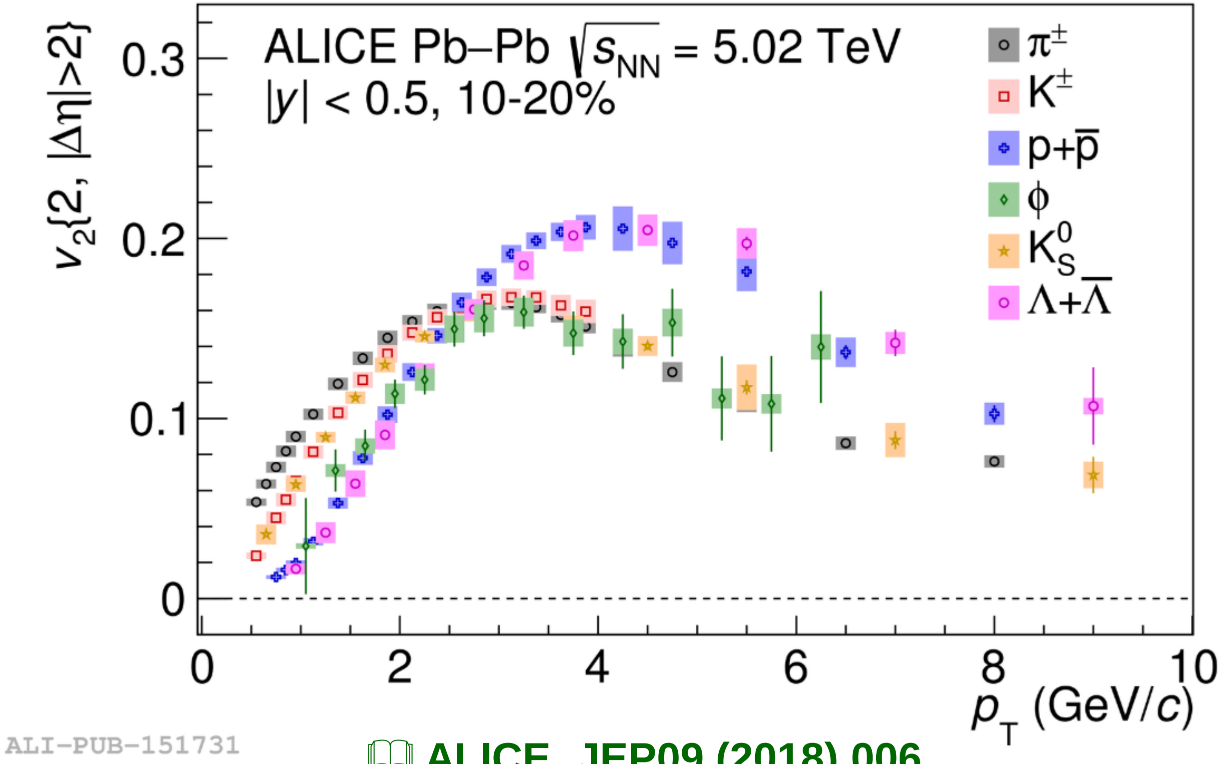
- Different model ingredients needed for a quantitative description of the data:
  - ➪ Radial flow of partons
  - ➪ Recombination+ fragmentation
    - ✓ Including recombination of soft partons with mini-jet partons
  - ➪ Resonance decays



📖 Minissale et al., PRC92 (2015) 054904

Identified hadron v_2

$$v_2 = \left\langle \cos\left[2\left(\varphi - \Psi_{RP}\right)\right]\right\rangle$$



📖 **ALICE, JEP09 (2018) 006**

- Low p_T (<2–3 GeV/c): mass ordering
  - ⇨ As predicted by hydrodynamics
- Mid p_T ($3<p_T<8$ 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**

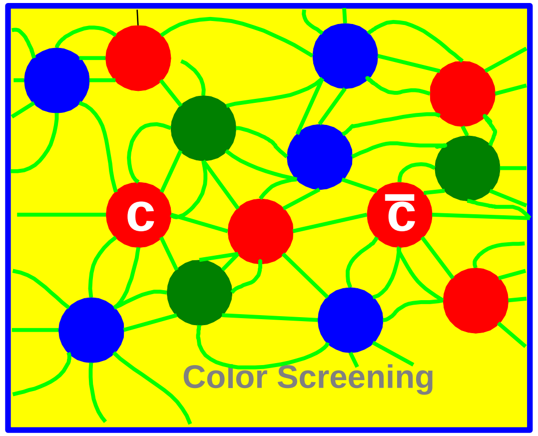
→ Baryon vs. meson grouping at intermediate p_T as expected from recombination

Heavy quarks

Quarkonium production

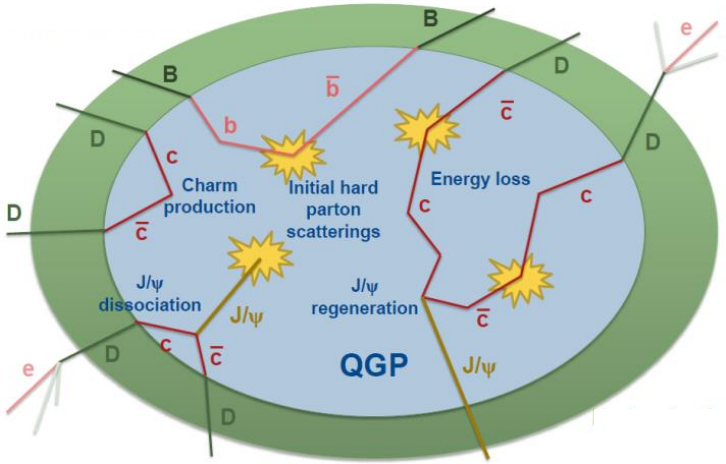
- Quarkonium **dissociation** in QGP
  - ⇨ Due to colour screening of $q\bar{q}$ potential
  - ⇨ Different quarkonium states melt at different temperatures depending on their binding energy → sequential suppression

    📖 **Matsui, Satz, PLB178 (1986) 416**
    📖 **Digal et al., PRD64 (2001) 094015**



- Quarkonium production can occur also via **quark (re)combination**
  - ⇨ In the QGP or at the phase boundary
  - ⇨ Charm and beauty yield increases with √s → larger recombination a larger √s
  - ⇨ Smaller recombination contribution for bottomomium than for charmonium

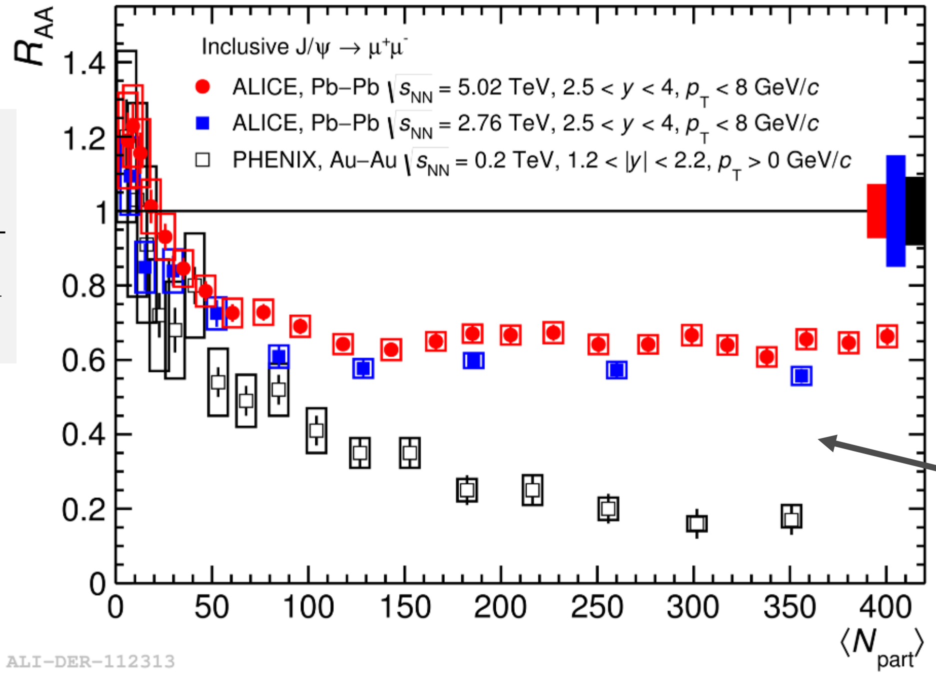
    📖 **Braun-Munzinger, Stachel, PLB 490 (2000) 196**
    📖 **Thews et al., PRC 63 (2001) 054905**



Quarkonium production

- Quarkonium **dissociation** in QGP
  - ⇨ Due to colour screening of $q\bar{q}$ potential

$$R_{AA} = \frac{\frac{dN_{AA}}{dy}}{\langle N_{coll} \rangle \frac{dN_{pp}}{dy}}$$



- Quarkonium production can occur also via **quark (re)combination**
  - ⇨ In the QGP or at the phase boundary

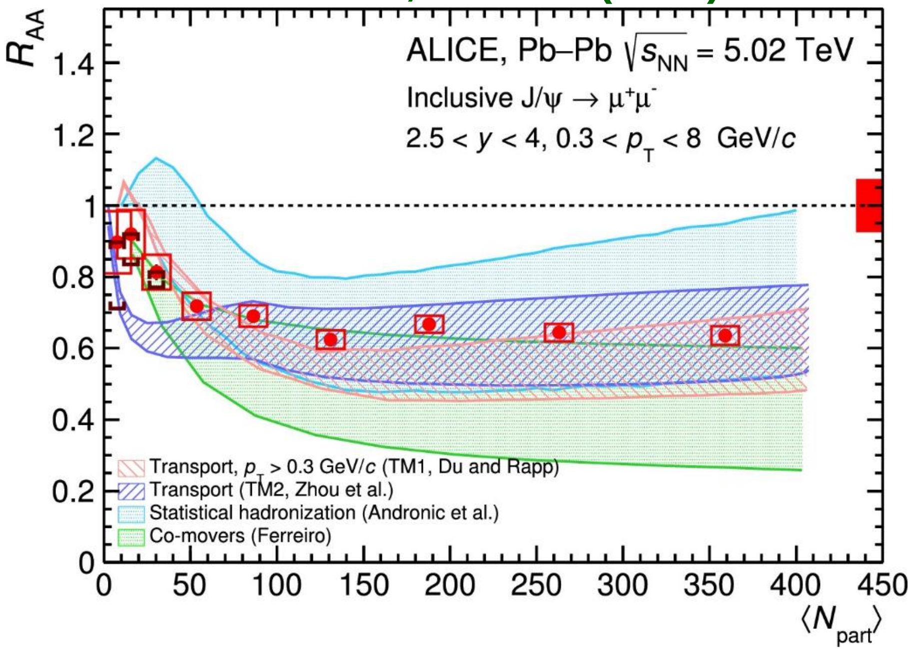
📖 **ALICE, PLB766 (2017) 212**
📖 **PHENIX, PRC84 (2011) 05912**

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)

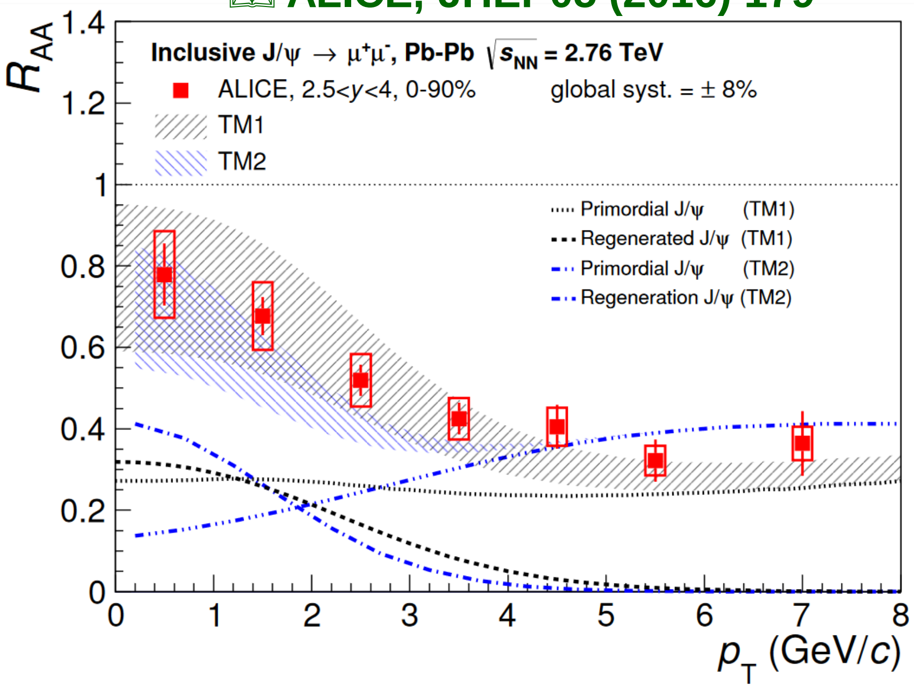
→ as expected in a scenario with dissociation + $c\bar{c}$ recombination

J/ψ yield in A-A collisions

ALICE, PLB766 (2017) 212



ALICE, JHEP05 (2016) 179

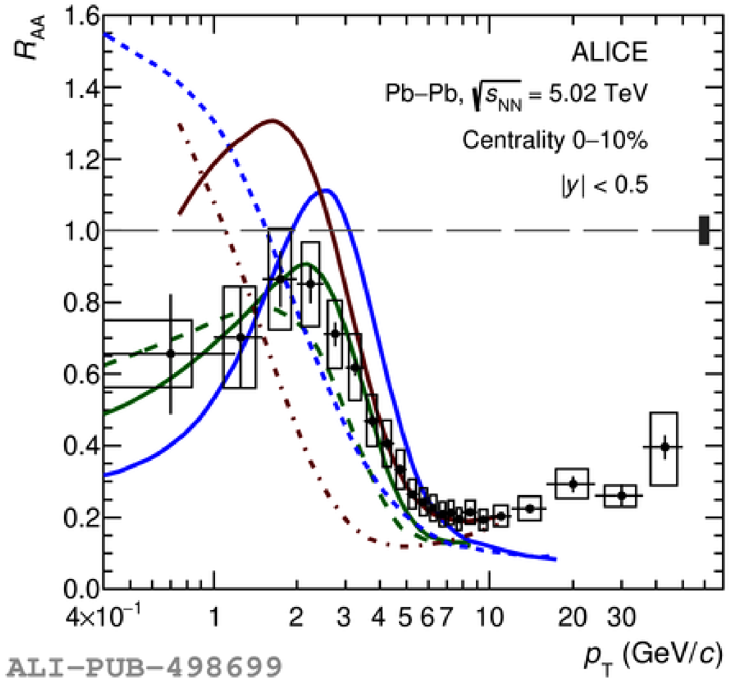


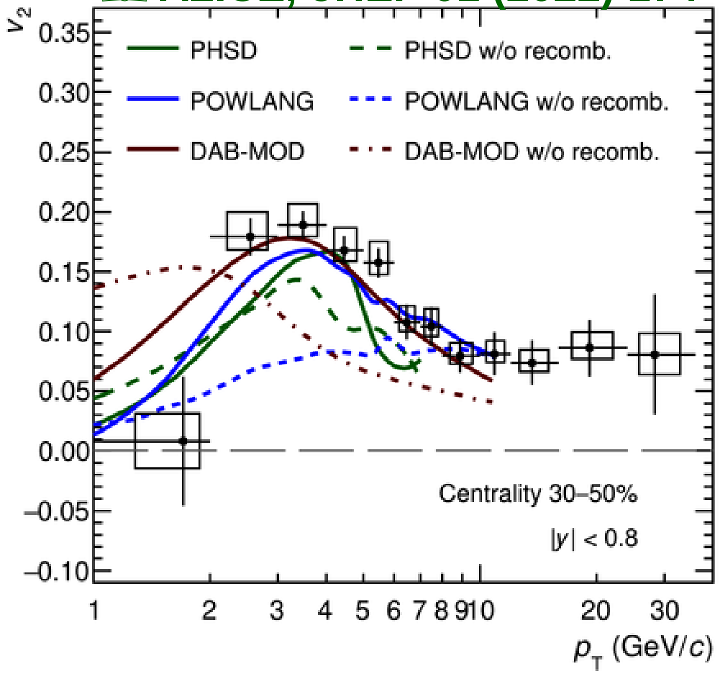
- Evidence from LHC results that charmonia are produced via **(re)combination of $c\bar{c}$ pairs originating from two independent hard scattering processes**
- Data described by:
  - ⇨ **SHM**: melting of initially produced $c\bar{c}$ pairs + combination at phase boundary
  - ⇨ **Transport models** with in-medium charmonium dissociation + recombination
    - ✓ **Recombination** relevant/dominant at **low p_T**

Charm R_{AA} and v_2 phenomenology

- **Recombination** 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
  - ⇨ Heavy-quark hadronization mechanism is an important ingredient to the phenomenology of heavy flavour R_{AA} and v_2

📖 ALICE, JHEP 01 (2022) 174

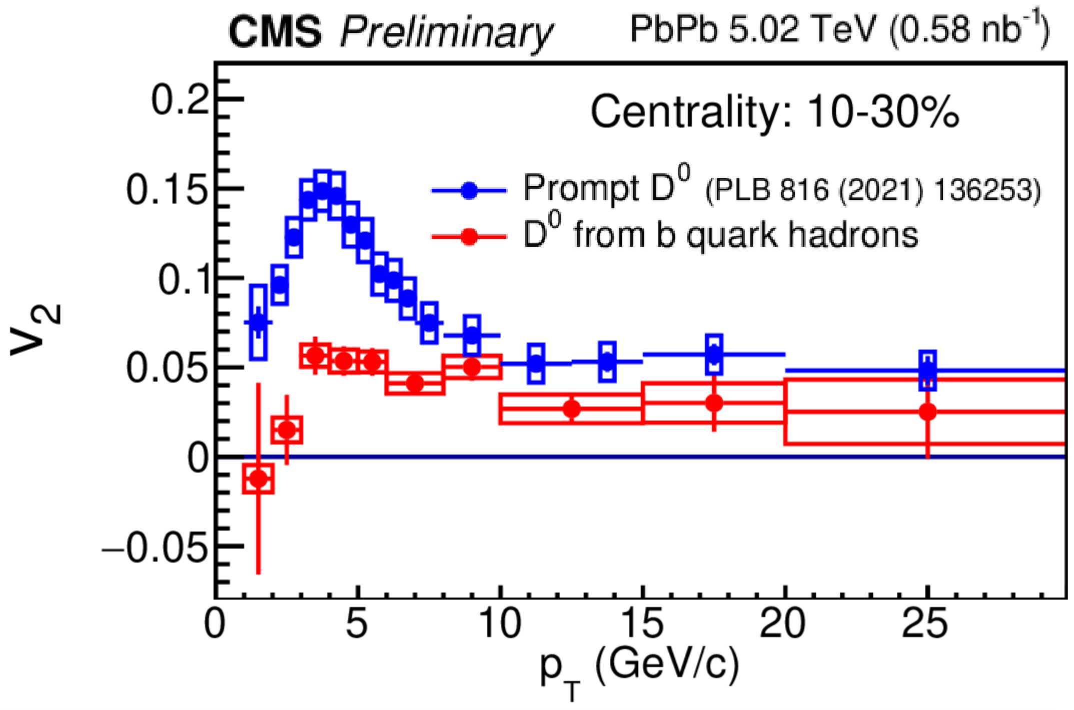


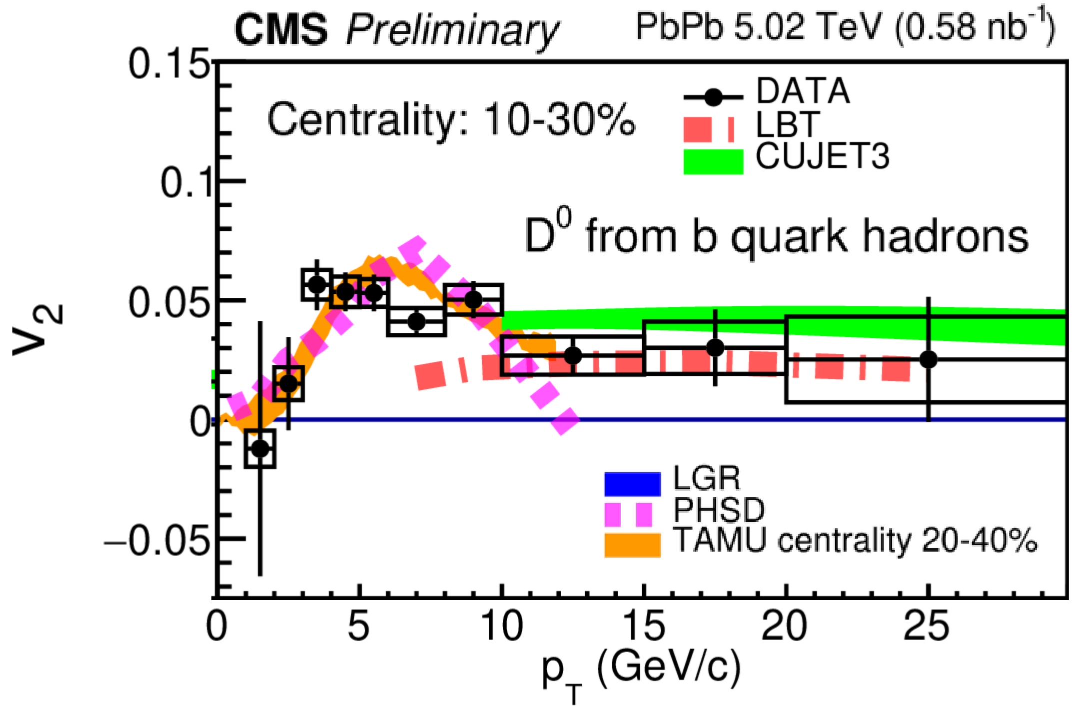


→ Recombination component crucial to describe the data at low/mid p_T

Charm vs beauty v_2

- **Recombination** 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
  - ➪ **Mass ordering** of v_2 magnitude captured by theory calculations

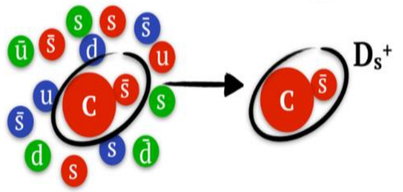




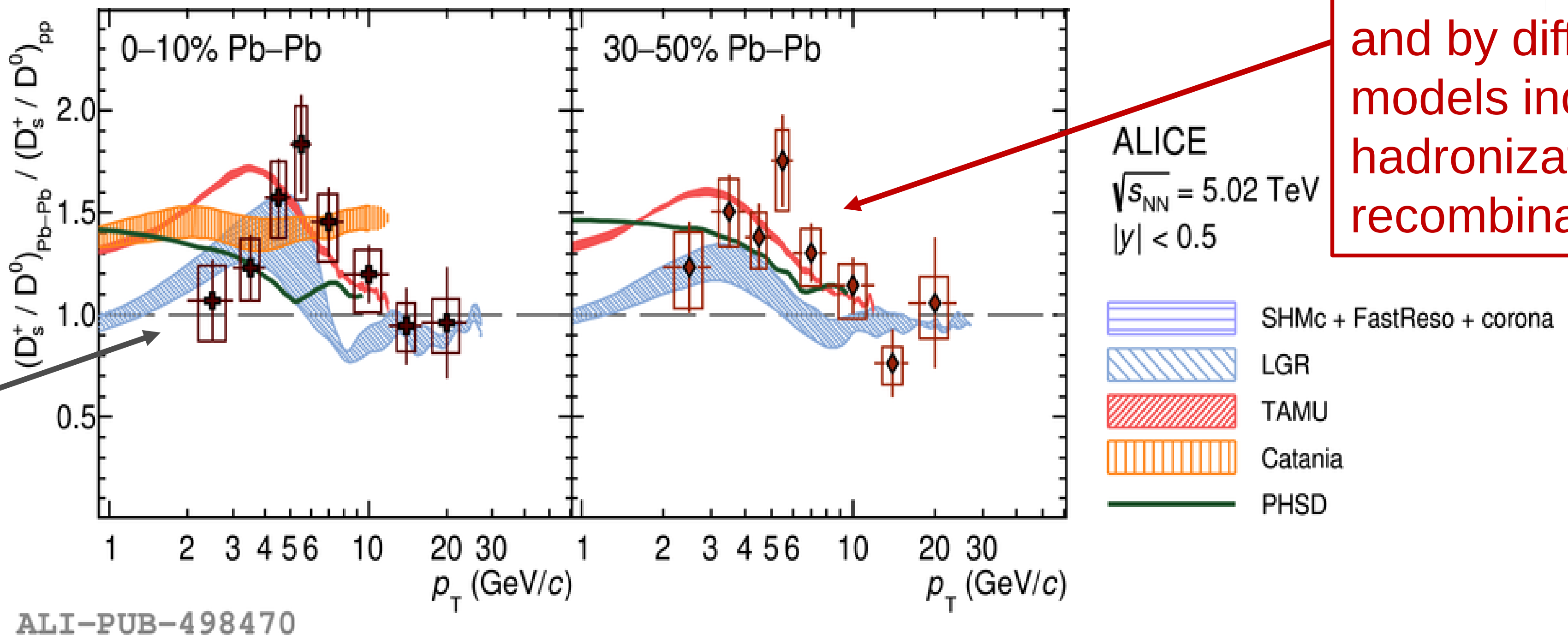
📖 CMS-PAS-HIN-21-003

Open charm hadrochemistry: D_s/D

- Recombination of heavy quarks with light quarks from the QGP affects **HF hadrochemistry** (i.e. relative abundances of meson and baryon species)
  - ⇨ **Enhanced D_s (B_s)** yield relative to non-strange mesons (strange quarks abundant in QGP)



📖 **ALICE, PLB 827 (2022) 136986**



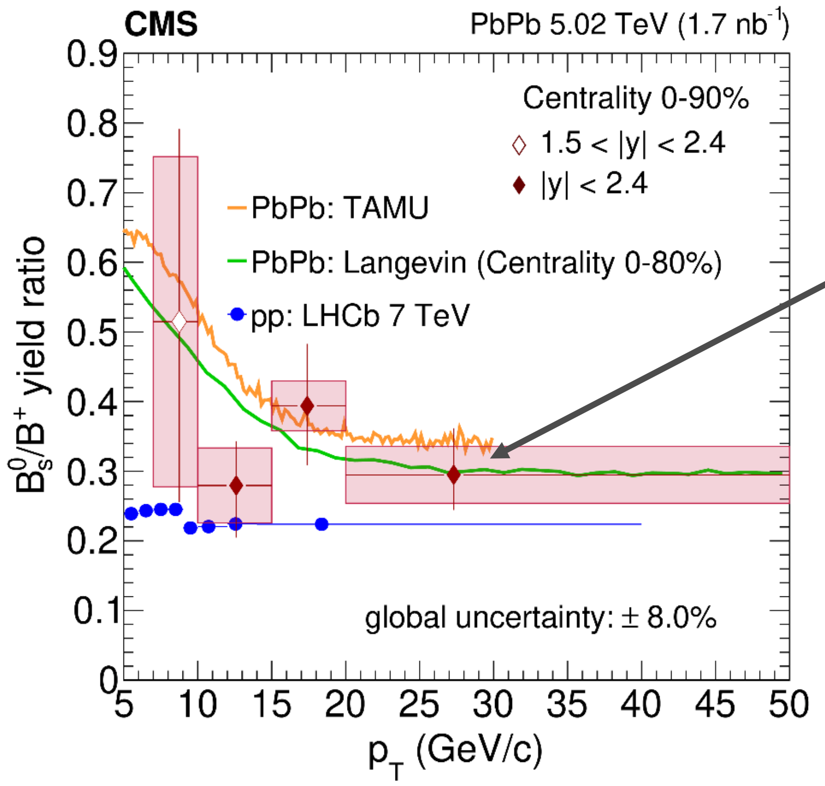
D_s/D^0 ratios in central and semicentral Pb–Pb hint at enhancement at mid p_T relative to pp

Described by SHM and by different models including hadronization via recombination

→ as expected in a scenario with hadronization via recombination

Open beauty hadrochemistry: B_s/B

- Recombination of heavy quarks with light quarks from the QGP affects **HF hadrochemistry** (i.e. relative abundances of meson and baryon species)
  - ⇨ **Enhanced D_s (B_s)** yield relative to non-strange mesons (strange quarks abundant in QGP)



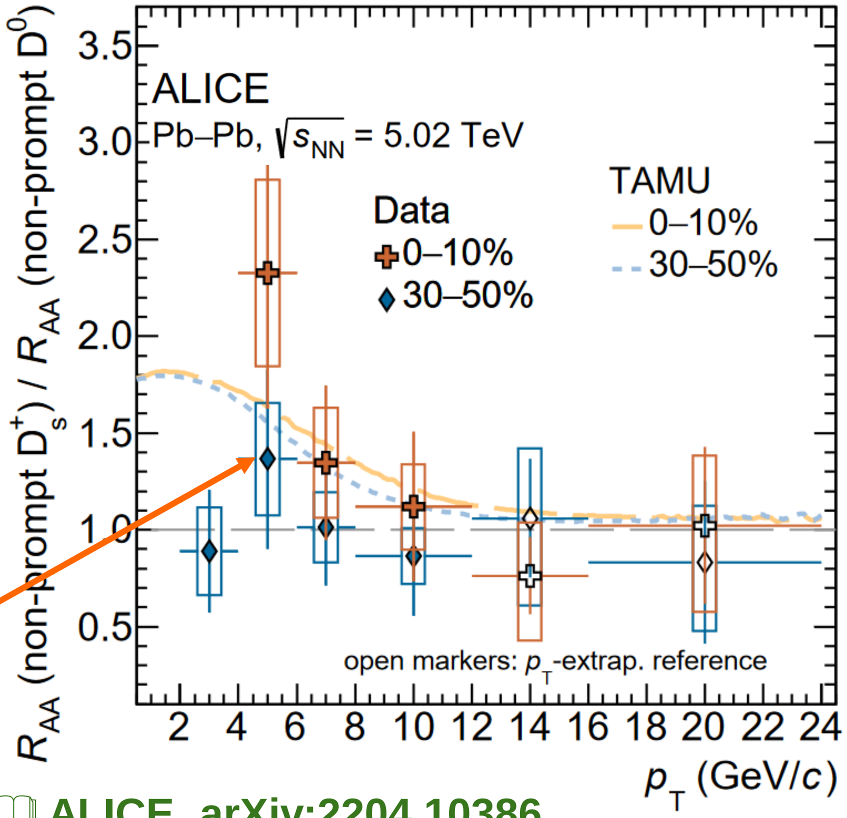
CMS, PLB 829 (2022) 137062

B_s / B^+ in Pb–Pb tend to lie systematically above the pp value

Hint for R_{AA} of non-prompt D_s larger than non-prompt D^0

Non-prompt D_s origin:

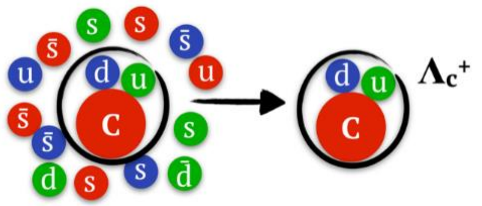
- 50% from B_s decays
- 50% from B^0, B^+ decays



ALICE, arXiv:2204.10386

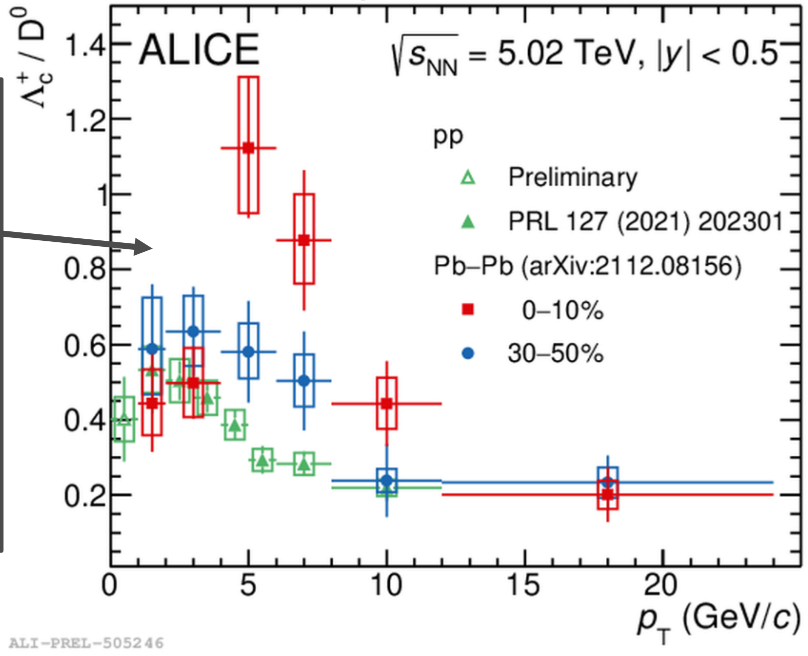
Open charm hadrochemistry: baryon/meson

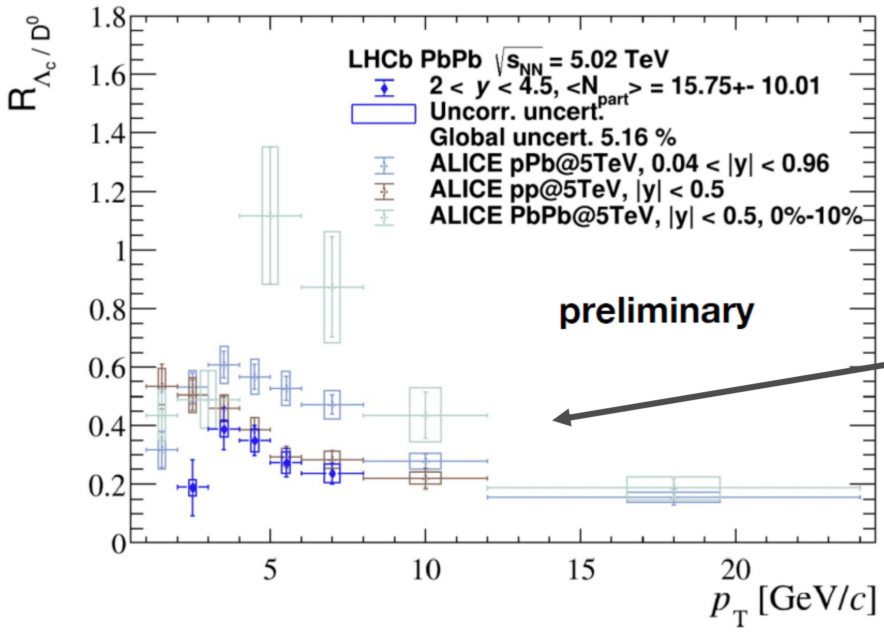
- Recombination of heavy quarks with light quarks from the QGP affects **HF hadrochemistry** (i.e. relative abundances of meson and baryon species)
  - ⇨ **Enhanced** production of **baryons** relative to mesons



📖 ALICE, arXiv:2112.08156

Λ_c/D^0 ratios in central and semicentral Pb–Pb hint at enhancement at mid p_T relative to pp





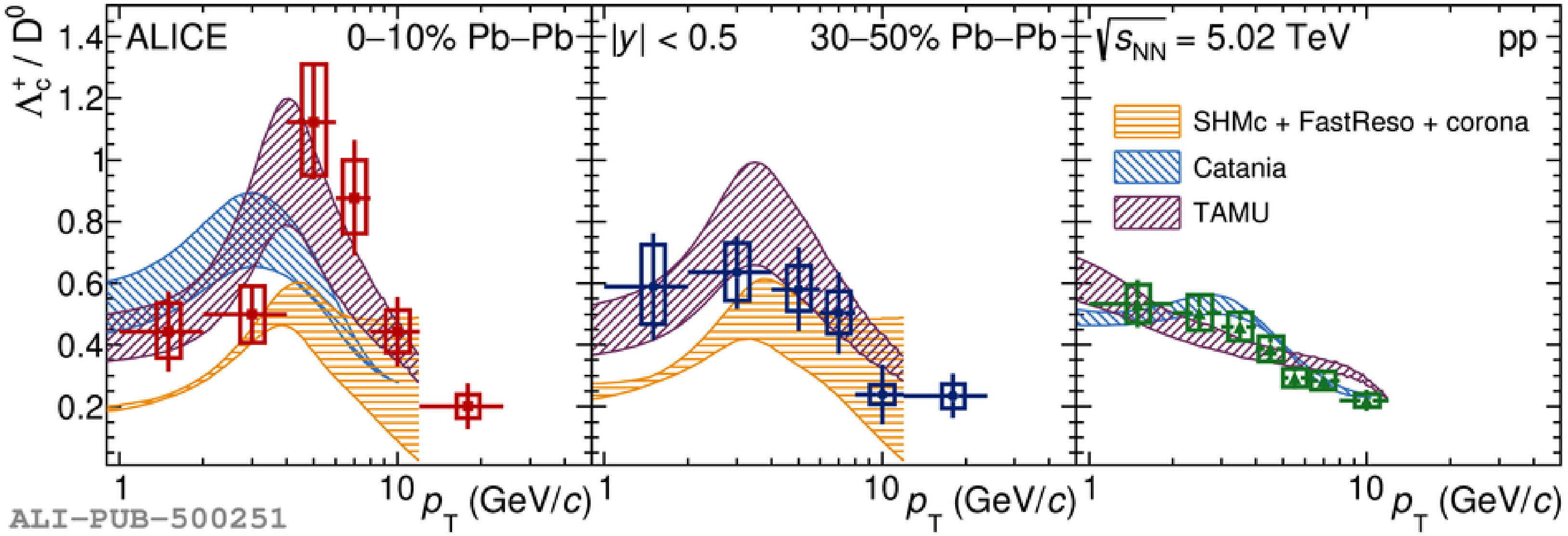
Λ_c/D^0 ratios in peripheral Pb–Pb at forward *y* similar to pp at mid *y*

→ as expected in a scenario with hadronization via recombination

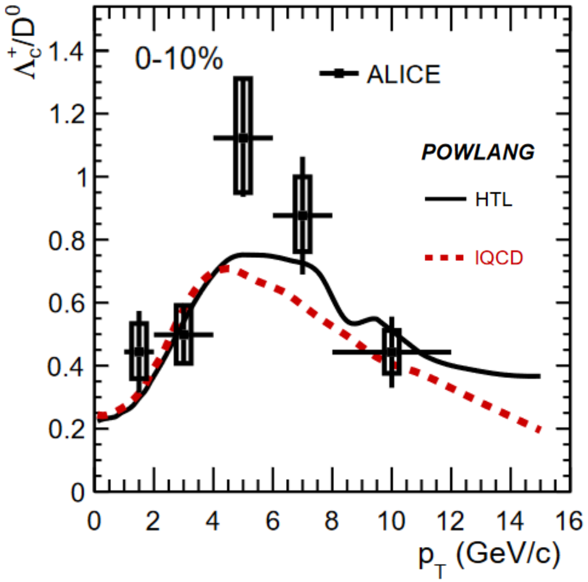
Open charm hadrochemistry: baryon/meson

- Recombination of heavy quarks with light quarks from the QGP affects **HF hadrochemistry** (i.e. relative abundances of meson and baryon species)
  - ⇨ **Enhanced** production of **baryons** relative to mesons

📖 ALICE, arXiv:2112.08156

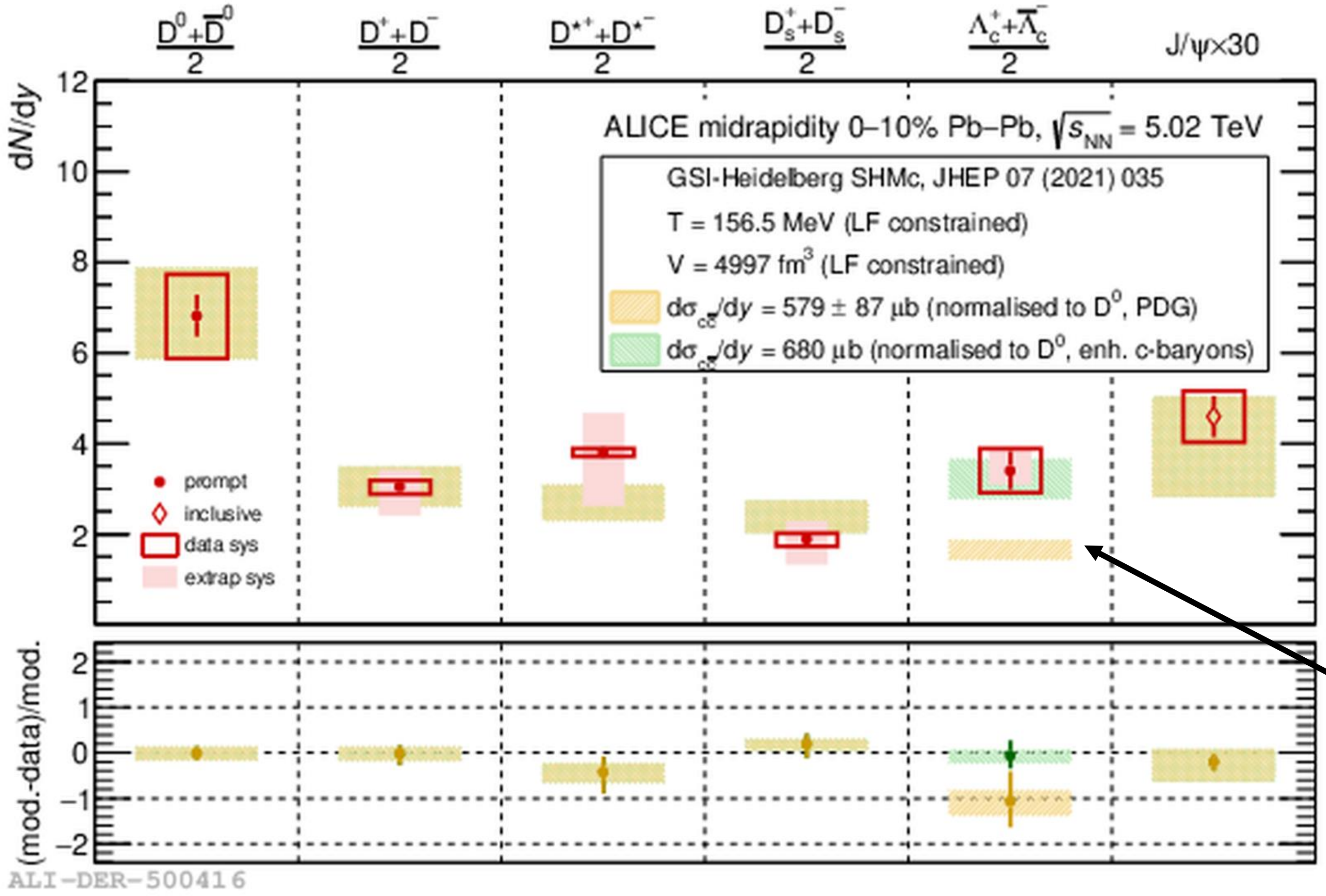


📖 Beraudo et al., arXiv:2202.08732



- Λ_c/D^0 ratios in central and semicentral Pb–Pb collisions described by different models including hadronization via recombination
  - ⇨ Crucial to understand the production in pp collisions!

Charm hadron yields vs SHM

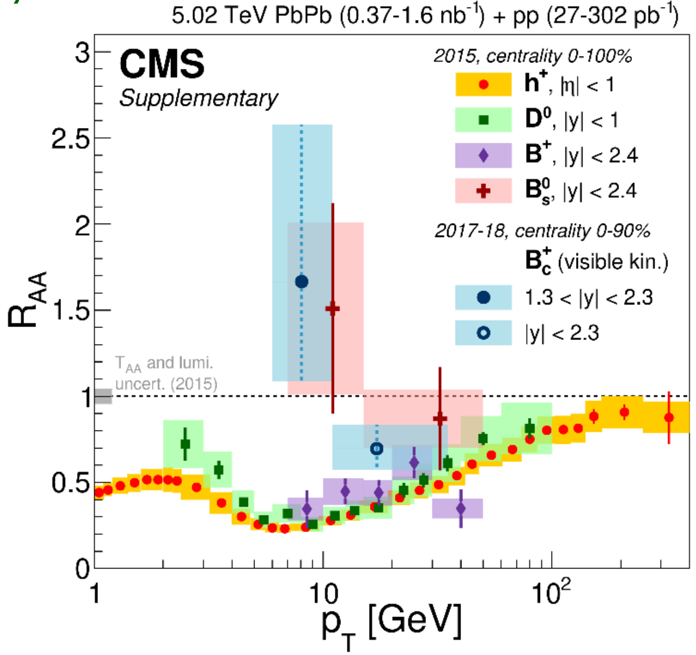


📖 **Andronic et al, JHEP 07 (2021) 035**

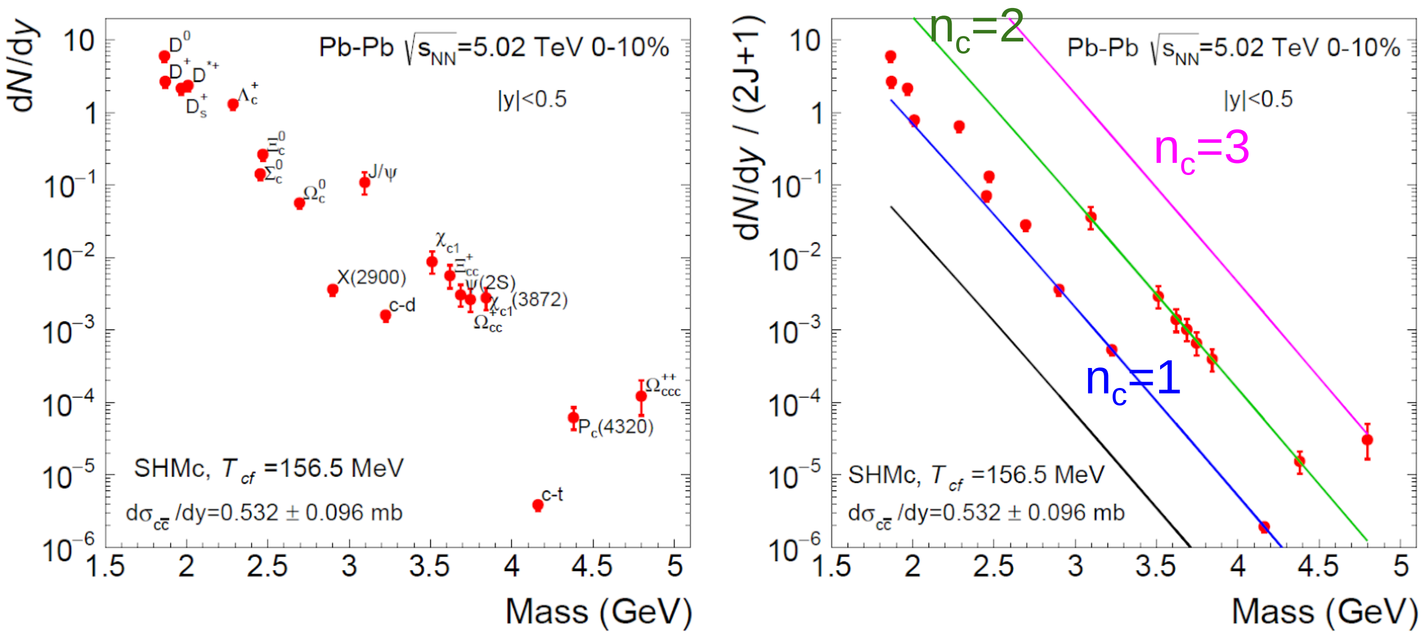
- Measured p_T-integrated yields of open charm mesons and J/ψ at midrapidity described by SHM within uncertainties
  - ⇨ Charm content of the fireball fixed by initial production
  - ⇨ Assume (full) charm quark thermalisation in the QGP
  - ⇨ Charm quarks distributed to hadrons according to thermal weights
- Yield of Λ_c baryons underestimated
  - ⇨ Captured assuming an enhanced production of charmed baryons

Outlook: multi heavy-flavours

📖 CMS, arXiv:2201.02659



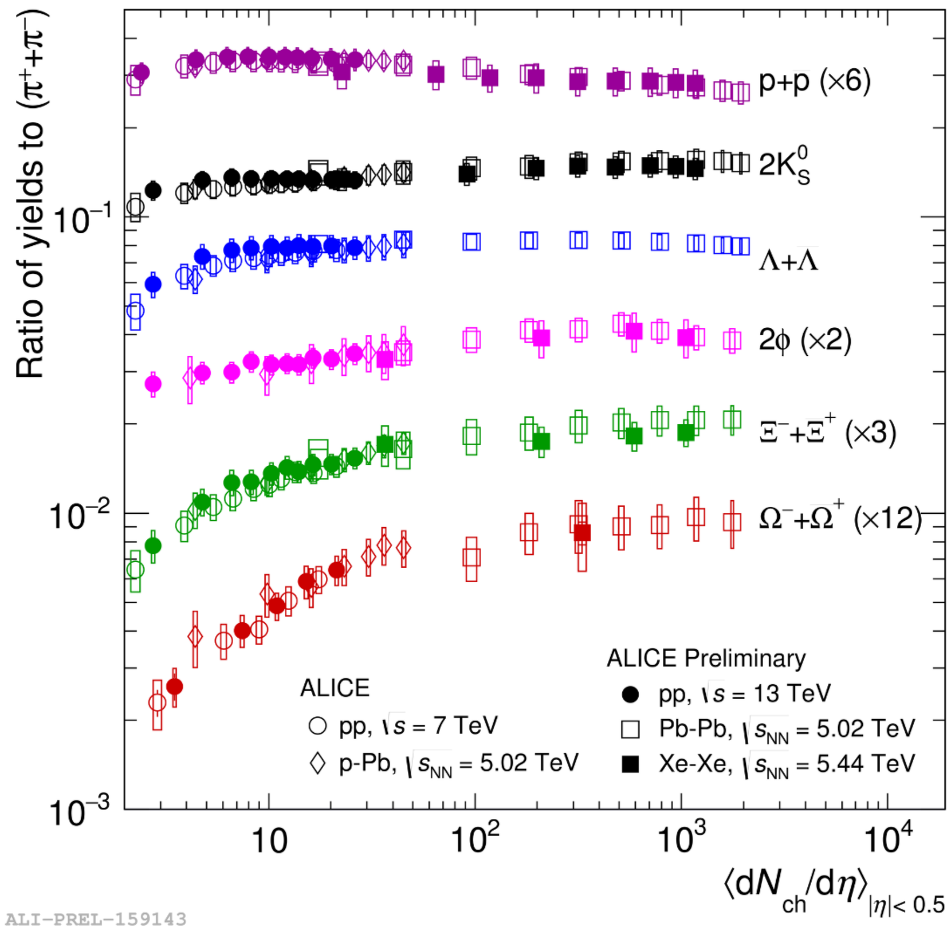
📖 Andronic et al, JHEP 07 (2021) 035



- B_c and baryons containing multiple charm quarks (Ξ_{cc}^+, Ξ_{cc}^{++}, Ω_{cc}^+, Ω_{ccc}^{++}, and T_{cc}^+)
  - ⇨ Large enhancement in A–A collisions predicted by SHM and recombination models (x100 for Ξ_{cc})
- Multi-charm baryons in SHM:
  - ⇨ Emergence of unique pattern due to dependence on fugacity and mass hierarchy
  - ⇨ Unique testing ground for **charm deconfinement, thermalisation and hadronization**
- Accessible with future large data samples at the LHC

Evolution with multiplicity / particle density

Strangeness production vs. multiplicity



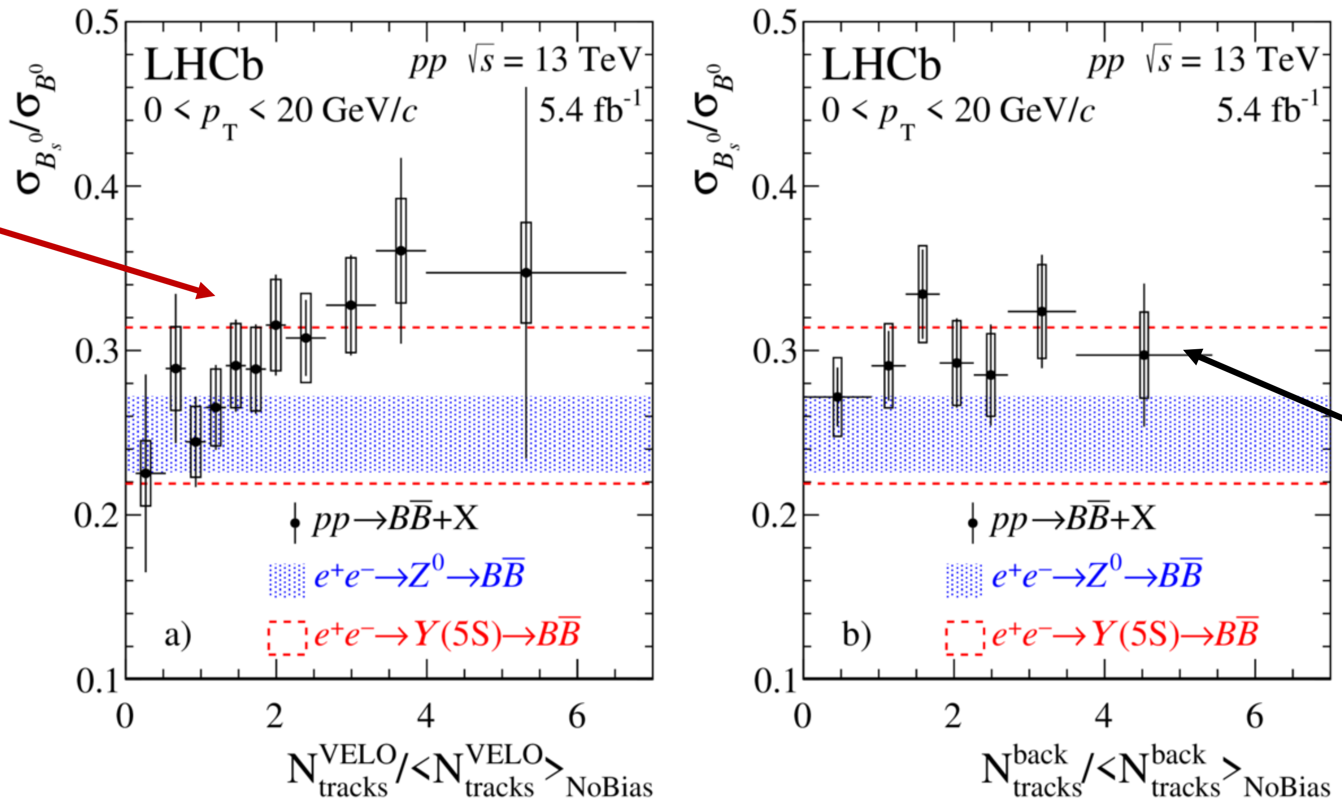
📖 **ALICE, Nature Physics 13 (2017) 535**

- 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

Charm and beauty hadronization vs. multiplicity

- Charm and beauty quark production dominated by hard parton-parton scatterings
- Increase of strangeness production with increasing multiplicity
- Hadronization via recombination may enhance D_s/D^0 , B_s/B^0 with increasing multiplicity

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



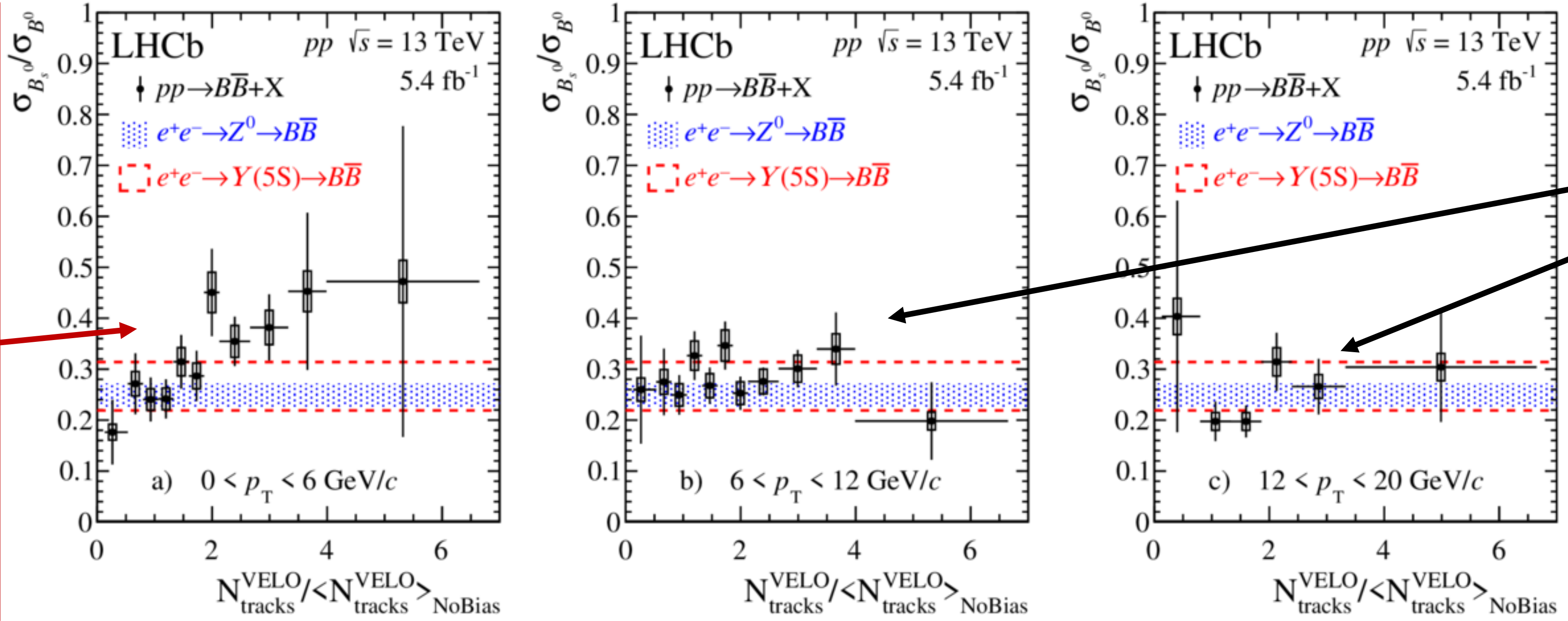
No significant dependence of B_s/B^0 on multiplicity at backward rapidity

LHCb, arXiv:2204.13042

Charm and beauty hadronization vs. multiplicity

- Charm and beauty quark production dominated by hard parton-parton scatterings
- Increase of strangeness production with increasing multiplicity
- Hadronization via recombination may enhance D_s/D^0 , B_s/B^0 with increasing multiplicity

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



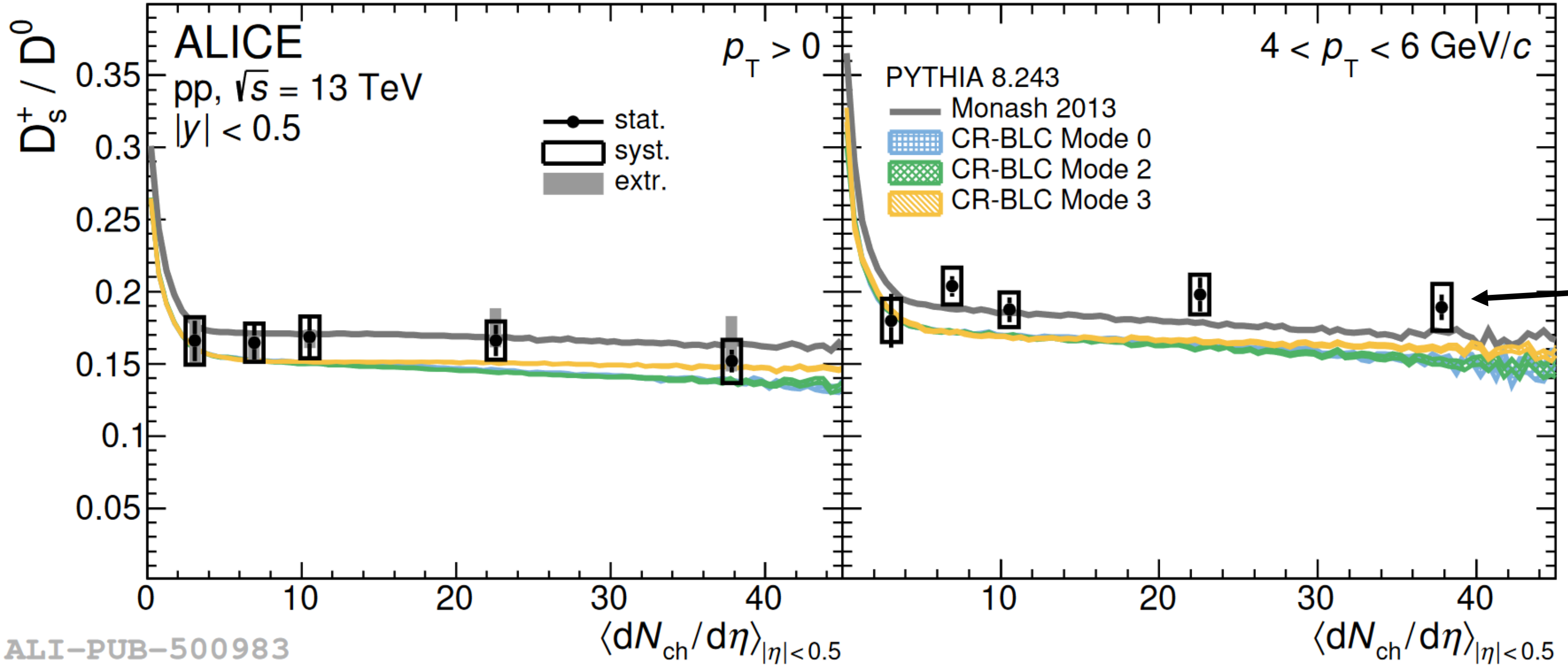
No significant dependence of B_s/B^0 on multiplicity at higher p_T

→ B_s/B^0 at low p_T increases with local particle density
→ Qualitatively as expected in a recombination scenario

LHCb, arXiv:2204.13042

Charm and beauty hadronization vs. multiplicity

- Charm and beauty quark production dominated by hard parton-parton scatterings
- Increase of strangeness production with increasing multiplicity
- Hadronization via recombination may enhance D_s/D^0 , B_s/B^0 with increasing multiplicity

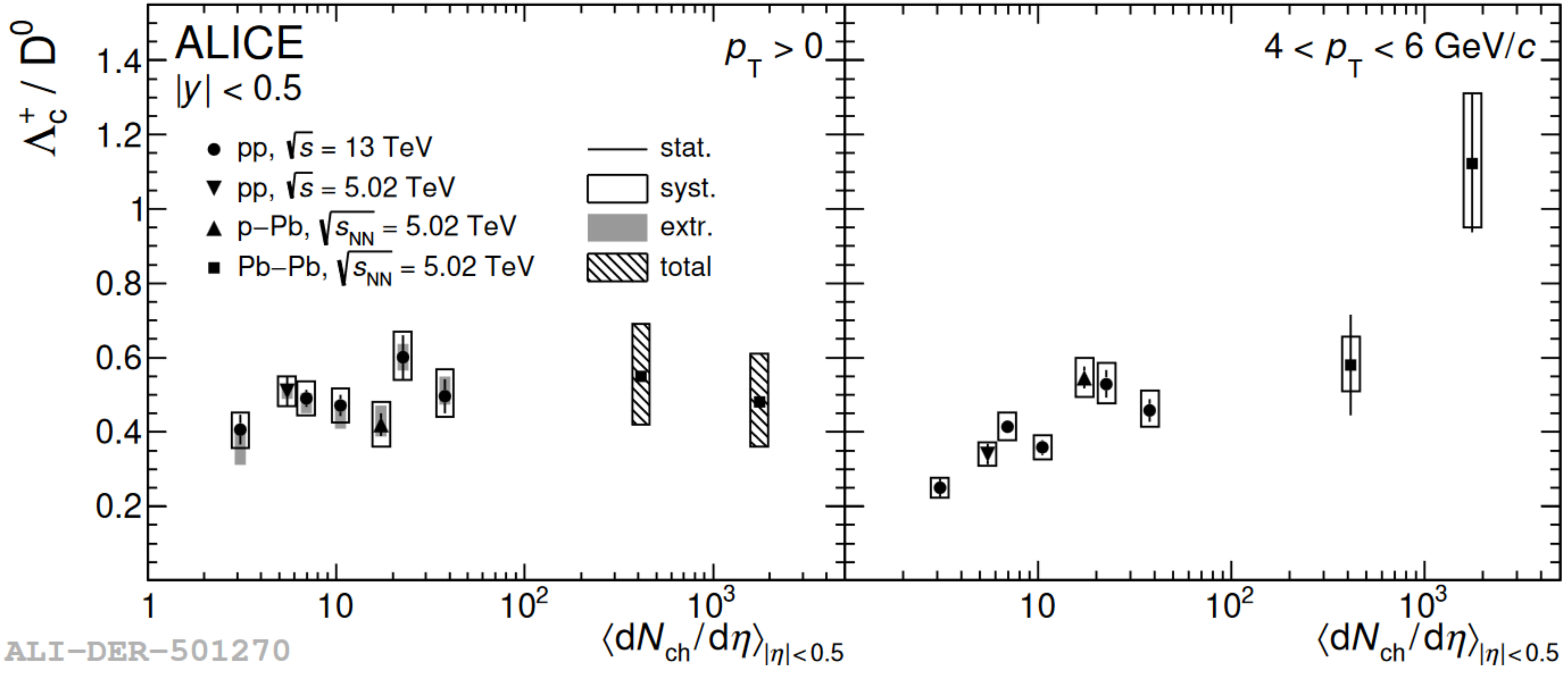


No significant dependence of D_s/D^0 on multiplicity within current uncertainties

ALICE, PLB 829 (2022) 137065

Baryon/meson ratios vs. multiplicity

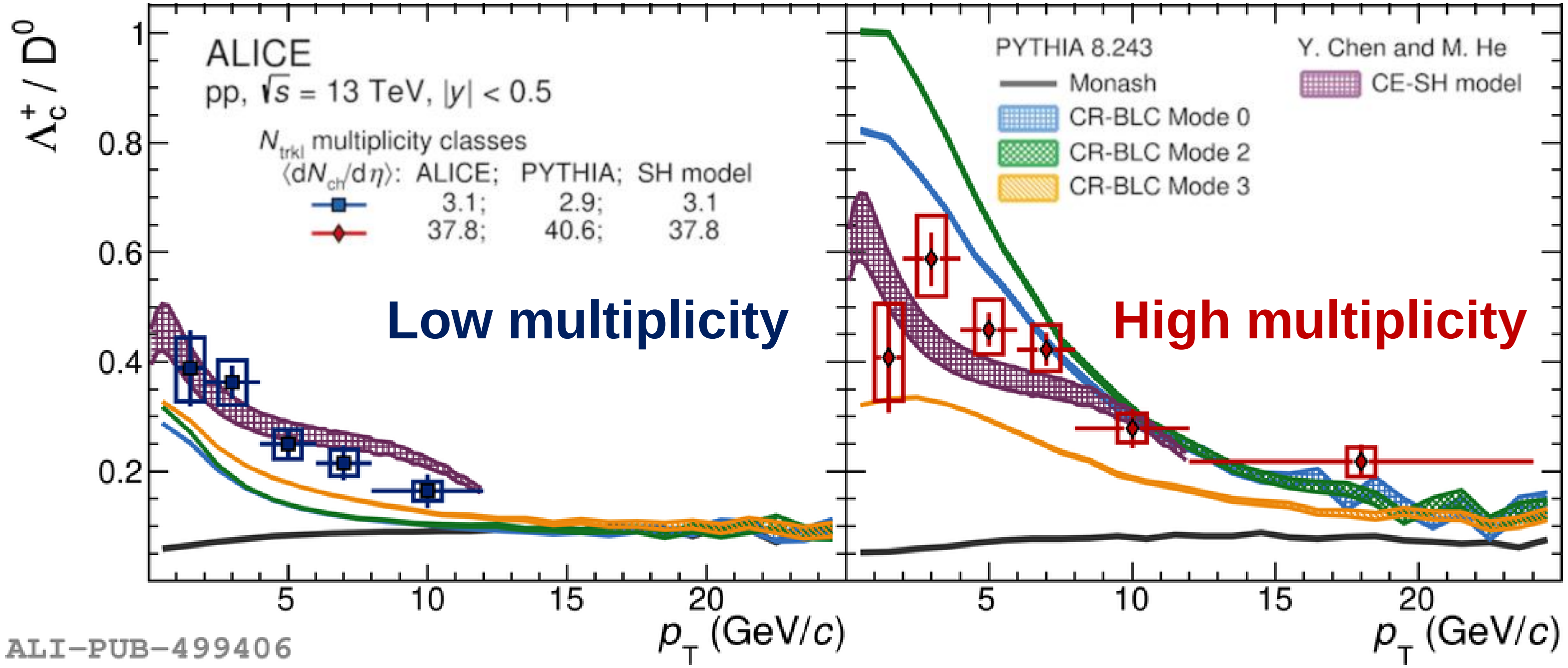
- Baryon/meson ratios at intermediate p_T increase with increasing multiplicity
- p_T-integrated ratios do not depend on multiplicity



ALICE, PLB 829 (2022) 137065
ALICE, arXiv:2112.08156

Baryon/meson ratios 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
- Dense particle environment affecting hadronization
  - ⇨ Qualitatively as expected from recombination
  - ⇨ Captured by PYTHIA with colour reconnection beyond leading-colour and SHM

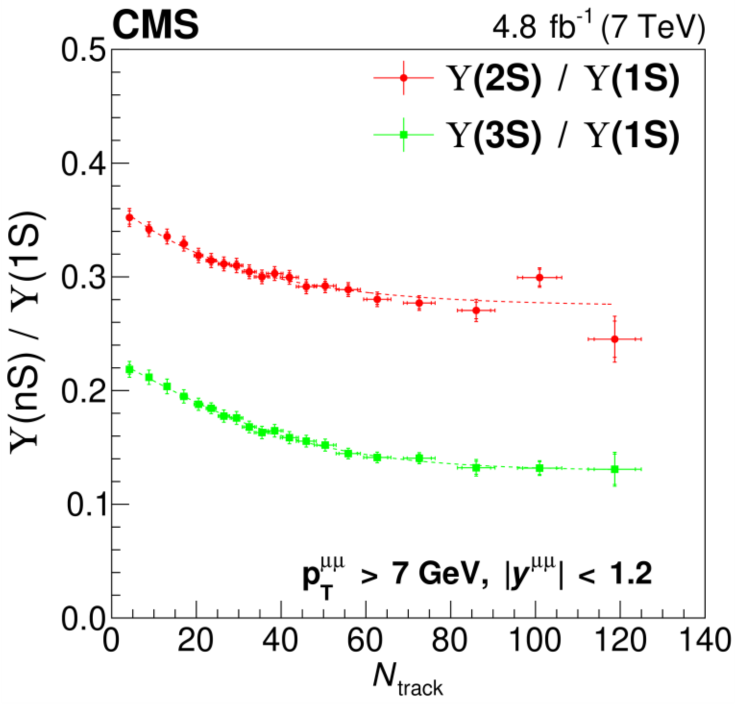


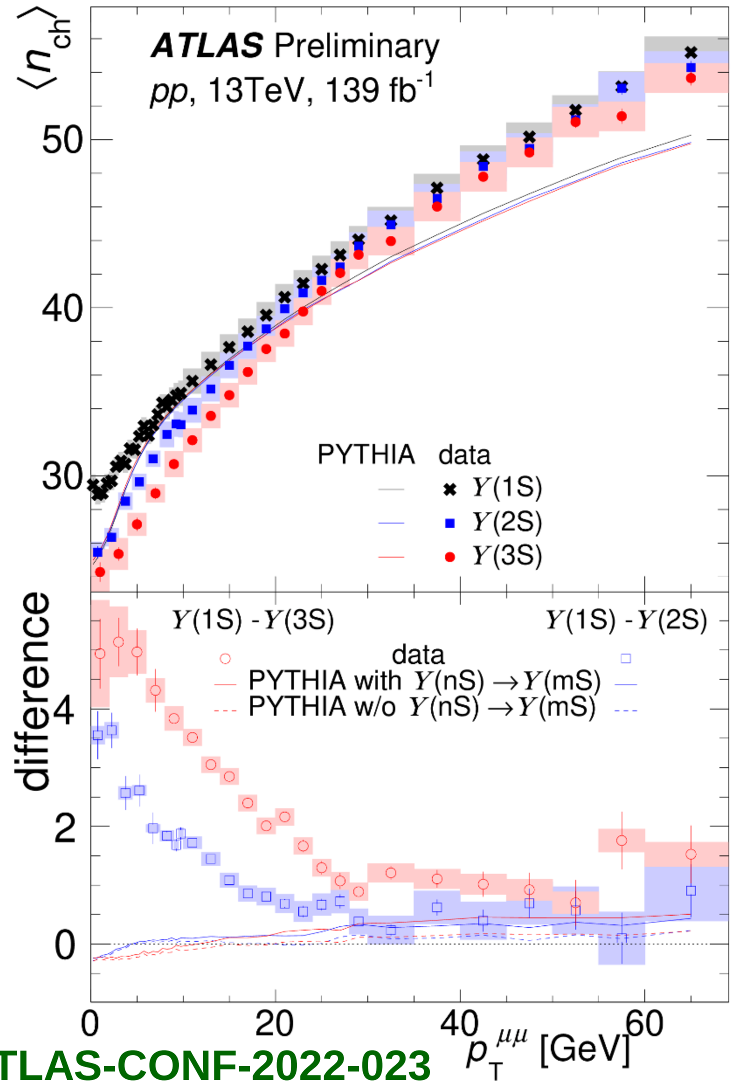
ALICE, PLB 829 (2022) 137065

Bottomonia vs. multiplicity

- Significant difference in the multiplicity of the underlying event for different ϒ(nS) states
  - ⇨ Not described by PYTHIA

- Consistent with different multiplicity dependence of ϒ(nS) yields in pp collisions
  - ⇨ Excited states more easily dissociated by interactions with other particles?
  - ⇨ Reminiscent of sequential melting scenario for quarkonium states in QGP?





📖 CMS, JHEP 11 (2020) 001 📖 ATLAS-CONF-2022-023

Summary and prospects

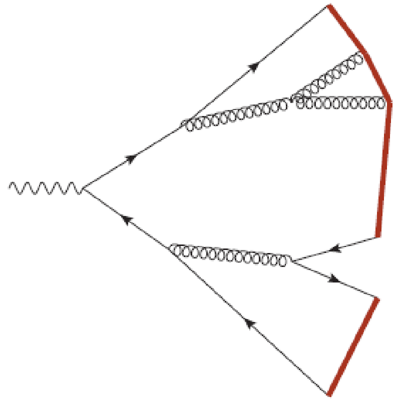
- Light flavour production at intermediate p_T
  - ⇨ Transition from thermal (hydro) to kinetic regime -> window on hadronization mechanism?
  - ⇨ Quark coalescence captures many features of the data
    - ✓ Modelling of several aspects needed for a quantitative description
- Heavy flavours
  - ⇨ Clear signs of recombination in J/ψ and open charm results
    - ✓ R_{AA}, v_2, strange meson yield, baryon/meson ratios
  - ⇨ Charm-hadron yields vs SHM provide complementary information on charm quark thermalization
- Outlook:
  - ⇨ Beauty mesons, Λ_b , B_c and multi-charm hadrons can provide further insight into QGP hadronization
    - ✓ Accessible with precision with future large Pb–Pb data sets
  - ⇨ Hadronisation in (high-multiplicity) pp and p–A collisions
    - ✓ Link between color-reconnection in string models and recombination?

Backup

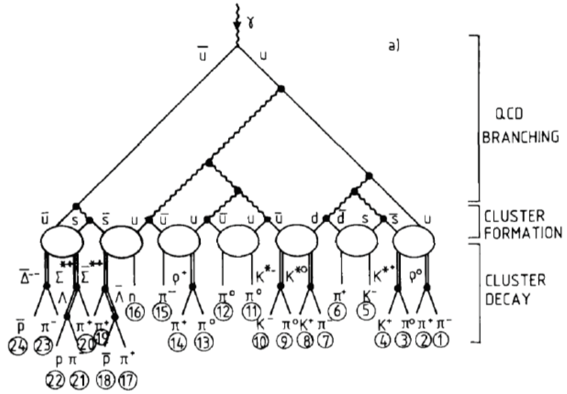
Hadronization of parton showers

- On a microscopic level hadronisation of jets modeled with:
  - ⇨ Perturbative evolution of a **parton shower** with DGLAP down to a low-virtuality cut-off Q_0
  - ⇨ Final stage of parton shower interfaced to a non perturbative hadronization 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

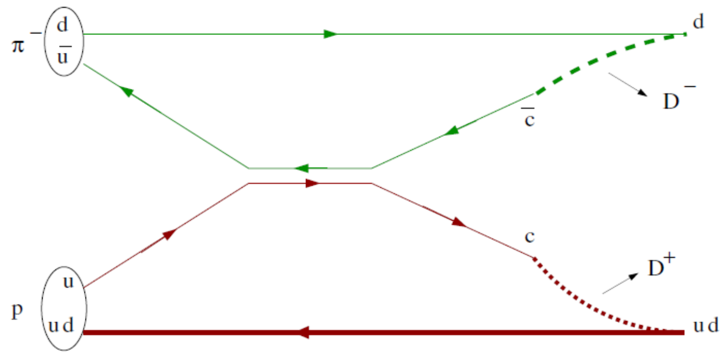


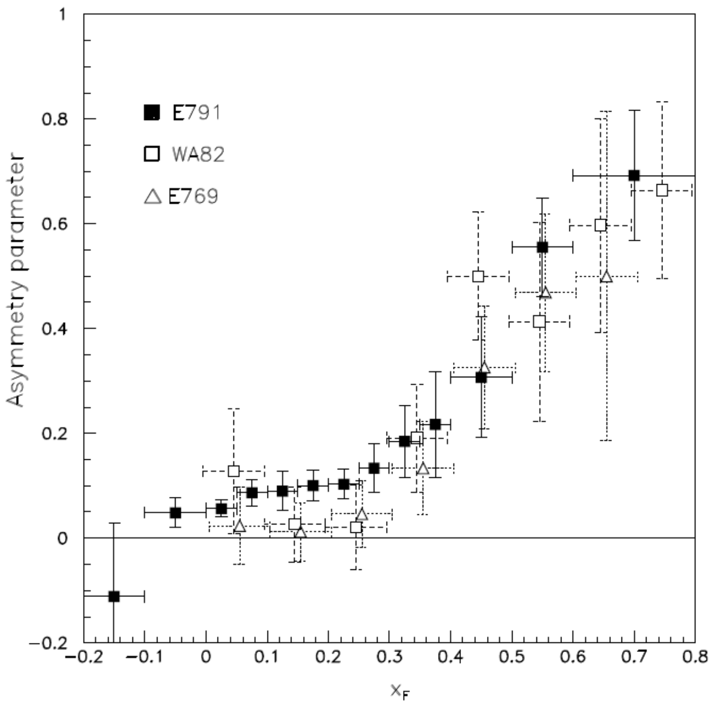
Leading particle effect

- Measurements of charm production in pion-nucleon collisions
- At **large x_F** : favoured production of hadrons sharing valence quarks with beam hadrons
  - ⇨ D^- ([$\bar{c}$d], leading meson shares the d quark with the π^- projectile) favored over D^+ [c$\bar{d}$]
  - ⇨ Break-down of independent fragmentation

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

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

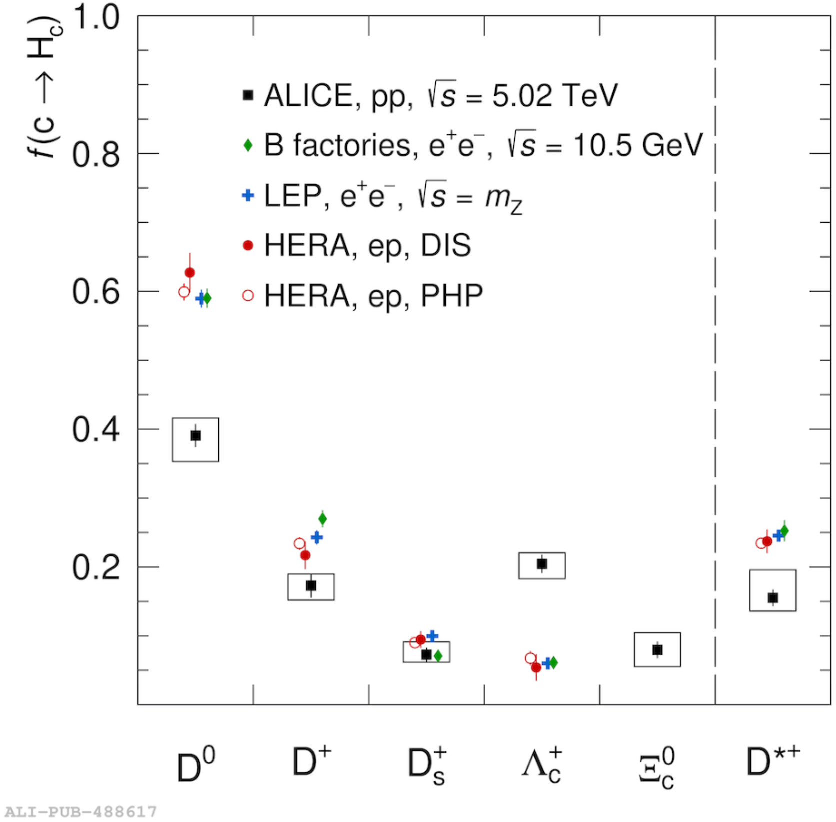




→ A reservoir of particles leads to significant changes in hadronisation

Fragmentation universality?

📖 ALICE, arXiv:2105.06335

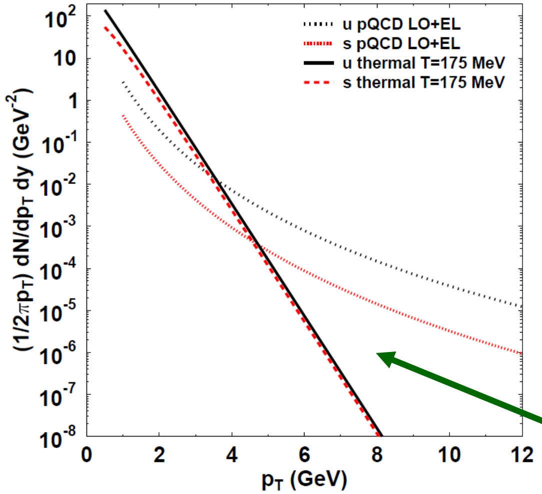


- Evidence of different fragmentation fractions in pp collisions at LHC and e^+e^- (ep) collisions at lower $\sqrt{s}$
  - ⇨ Indication that parton-to-hadron fragmentation depends on the collision system
  - ⇨ Assumption of their universality not supported by the measured cross sections

→ Break-down of universality of fragmentation functions

Hadronisation via quark coalescence

- **Instantaneous coalescence** approach:
  - ⇨ Formalism originally developed for light-nuclei production from coalescence of nucleons on a freeze-out hypersurface
    📖 **Scheibl and Heinz, PRC 59 (1999) 1585**
  - ⇨ Extended to describe meson and baryon formation from the quarks of a hadronising a QGP through 2→1 and 3→1 recombination processes



- Projection of parton states into hadron states:
  - ⇨ Phase space at hadronisation filled with partons
  - ⇨ Very rapid freeze-out → instantaneous recombination on infinitely thin hypersurface
  - ⇨ Quarks are dressed (constituent quarks)
  - ⇨ Gluons are split into quark-antiquark pairs (no dynamical gluons)
  - ⇨ Coalescence probability via Wigner function

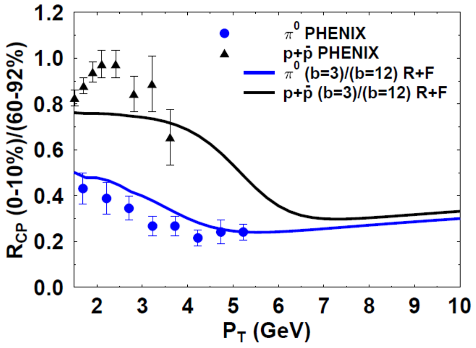
parton distributions

Hadron Wigner function

$$\frac{dN_{meson}}{dp_T} \propto \int f_q(x_q, p_q) f_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \boxed{f_W(x_a, x_{\bar{q}}; p_q, p_{\bar{q}})}$$

Coalescence/recombination

- Back in 2003: hadronisation via **recombination** of quarks from a thermalized QGP provides a <u>simple explanation of unexpected features</u> of RHIC data:
  - ⇨ Different R_{AA} of π and p
  - ⇨ Apparent scaling of identified particle v_2 with number of constituent quarks



VOLUME 90, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 23 MAY 2003

Parton Coalescence and the Antiproton/Pion Anomaly at RHIC

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(Received 28 January 2003; published 22 May 2003)

Coalescence of minijet partons with partons from the quark-gluon plasma formed in relativistic heavy ion collisions is suggested as the mechanism for production of hadrons with intermediate transverse momentum. The resulting enhanced antiproton and pion yields at intermediate transverse momenta give a plausible explanation for the observed large antiproton to pion ratio. With further increasing momentum, the ratio is predicted to decrease and approach the small value given by independent fragmentations of minijet partons after their energy loss in the quark-gluon plasma.

DOI: 10.1103/PhysRevLett.90.202302 PACS numbers: 25.75.Dw, 12.38.Bx, 25.75.Nq

PHYSICAL REVIEW C **67**, 034902 (2003)

Scaling behavior at high p_T and the p/π ratio

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(Received 7 November 2002; published 10 March 2003)

We first show that the pions produced at high p_T in heavy-ion collisions over a wide range of high energies exhibit a scaling behavior when the distributions are plotted in terms of a scaling variable. We then use the recombination model to calculate the scaling quark distribution just before hadronization. From the quark distribution, it is then possible to calculate the proton distribution at high p_T, also in the framework of the recombination model. The resultant p/π ratio exceeds one in the intermediate-p_T region where data exist, but the scaling result for the proton distribution is not reliable unless p_T is high enough to be insensitive to the scale-breaking mass effects.

DOI: 10.1103/PhysRevC.67.034902 PACS number(s): 25.75.Dw, 24.85.+p

VOLUME 90, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 23 MAY 2003

Hadronization in Heavy-Ion Collisions: Recombination and Fragmentation of Partons

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(Received 28 January 2003; published 22 May 2003)

We argue that the emission of hadrons with transverse momentum up to about 5 GeV/c in central relativistic heavy ion collisions is dominated by recombination, rather than fragmentation of partons. This mechanism provides a natural explanation for the observed constant baryon-to-meson ratio of about one and the apparent lack of a nuclear suppression of the baryon yield in this momentum range. Fragmentation becomes dominant at higher transverse momentum, but the transition point is delayed by the energy loss of fast partons in dense matter.

DOI: 10.1103/PhysRevLett.90.202303 PACS numbers: 25.75.Dw, 24.85.+p

VOLUME 91, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2003

Elliptic Flow at Large Transverse Momenta from Quark Coalescence

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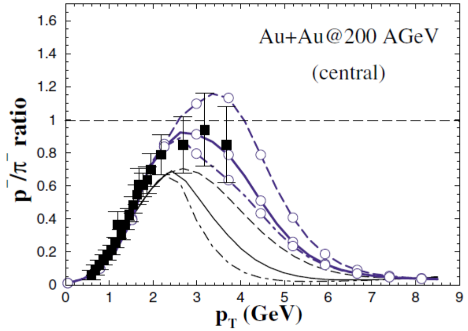
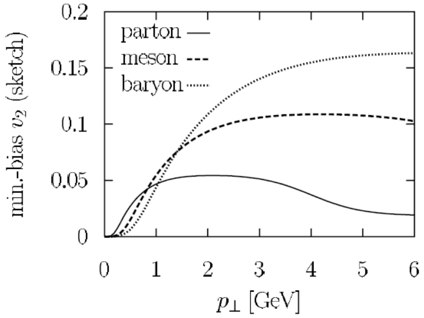
(Received 7 February 2003; published 27 August 2003)

We show that hadronization via quark coalescence enhances hadron elliptic flow at large $p_\perp$ relative to that of partons at the same transverse momentum. Therefore, compared to earlier results based on covariant parton transport theory, more moderate initial parton densities $dN/d\eta(b=0) \sim 1500$–3000 can explain the differential elliptic flow $v_2(p_\perp)$ data for Au + Au reactions at $\sqrt{s} = 130$ and $200A$ GeV from BNL RHIC. In addition, $v_2(p_\perp)$ could saturate at about 50% higher values for baryons than for mesons. If strange quarks have weaker flow than light quarks, hadron v_2 at high $p_\perp$ decreases with relative strangeness content.

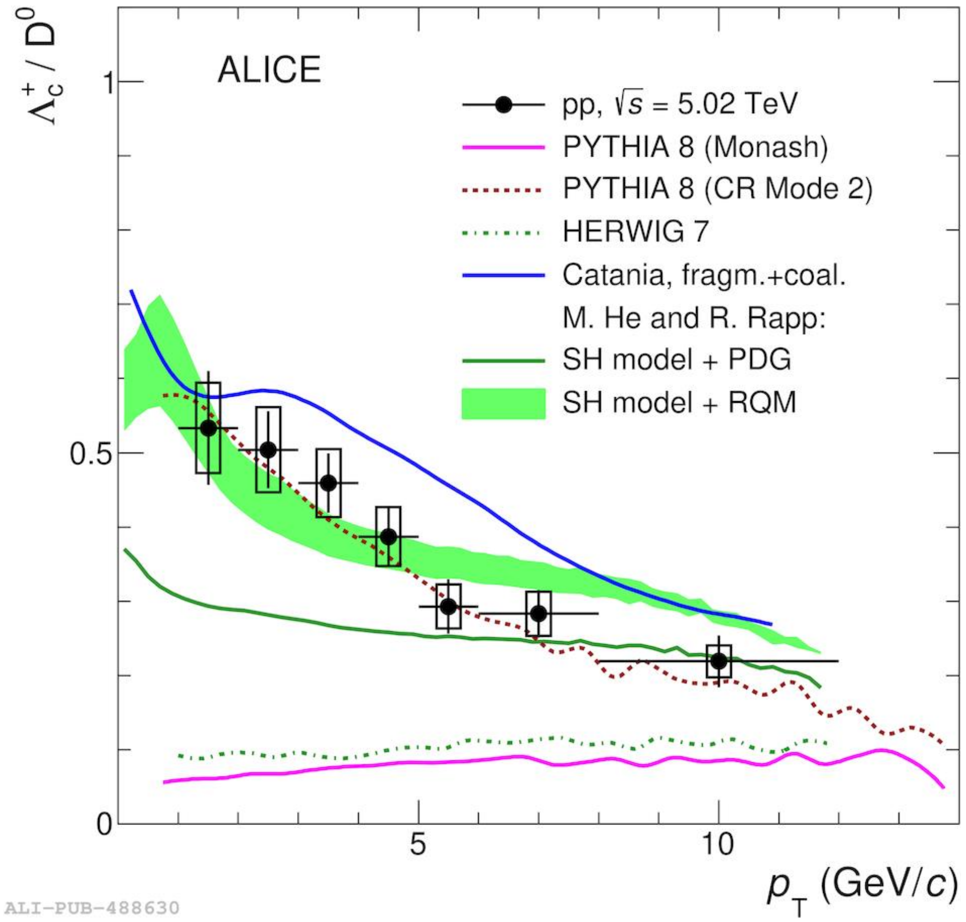
DOI: 10.1103/PhysRevLett.91.092301 PACS numbers: 12.38.Mh, 24.85.+p, 25.75.Ld





Baryon/meson ratio in pp vs. models

📖 ALICE, arXiv:2011.06078



- Λ_c/D^0 ratio in pp captured by:
  - ⇨ PYTHIA (pp paradigm) with CR beyond leading colour
    - ✓ i.e. including "interactions" among partons from different partonic scatterings (MPIs)
  - ⇨ Extensions of models typically used for A-A (QGP paradigm)
    - ✓ SHM (with additional baryonic states, important to describe the data)
    - ✓ Recombination
- More insight from: Ξ_c/D^0, Σ_c/D^0 and Ω_c/D^0

📖 ALICE, arXiv:2106.08278

Considerations and "links"

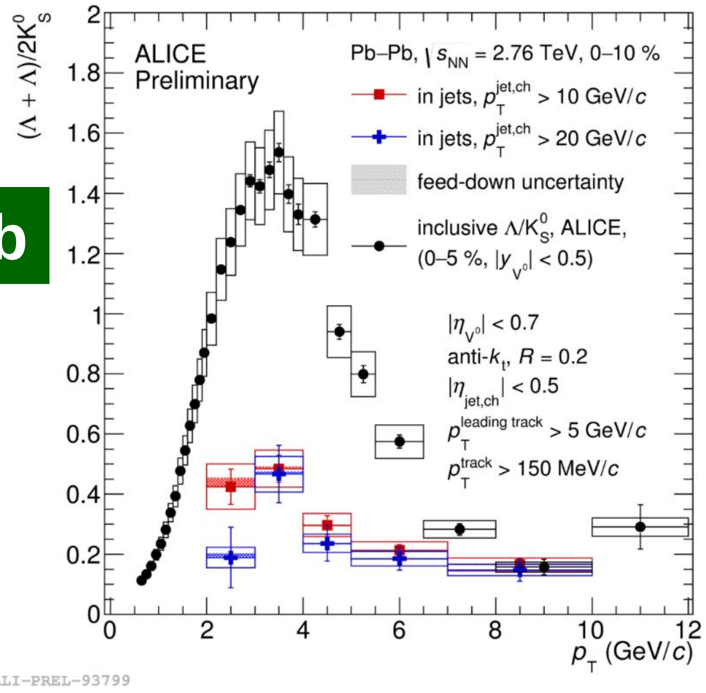
- **Color reconnections** beyond the leading colour are essentially an "interaction" between partons produced in different hard scatterings (**MPIs**)
  - ⇨ Analogy with the recombination/coalescence mechanism
- **Recombination** has aspects in common with **cluster hadronization** model of HERWIG
- **Recombination**/coalescence can be seen as a *"dense" limit of hadronization*, as opposed to single parton fragmentation
- The **recombination** models are essentially a *statistical combination of quarks at the phase boundary*
  - ⇨ Microscopic realisation of the statistical limit for hadron production?
  - ⇨ Recombination mechanism connecting a thermal parton phase with the observed thermal hadron phase?

📖 **Fries et al., PRC 68 (2003) 044902**

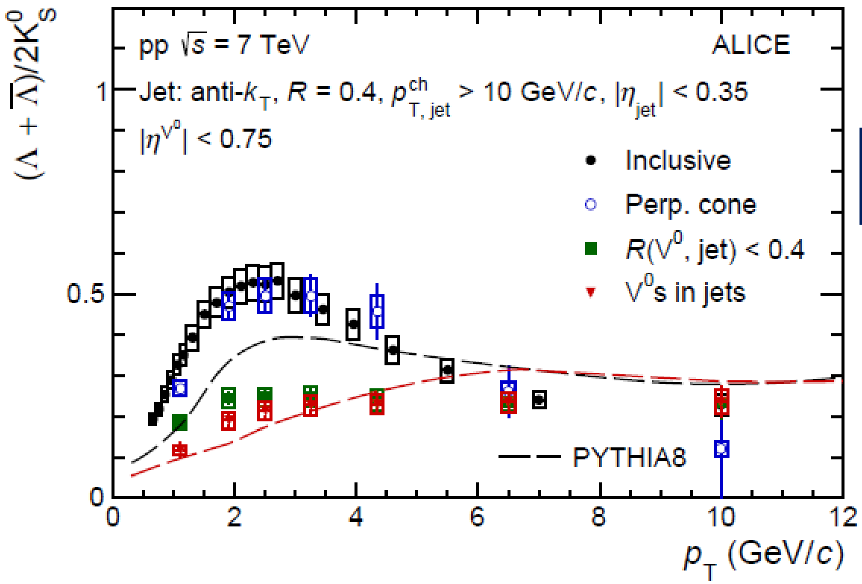
- "Statistical" approach in common between coalescence and SHM but:
  - ⇨ Degrees of freedom are different: hadrons in SHM vs. quarks in coalescence
  - ⇨ No assumption of full thermalization of quarks in coalescence approach
    - ✓ Even though light-quark spectra in the region where coalescence dominates are commonly taken from a thermal spectrum

Λ/K^0 in jets and bulk

Pb-Pb

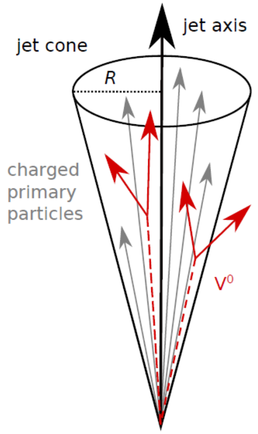


📖 ALICE, PLB 827 (2022) 136984



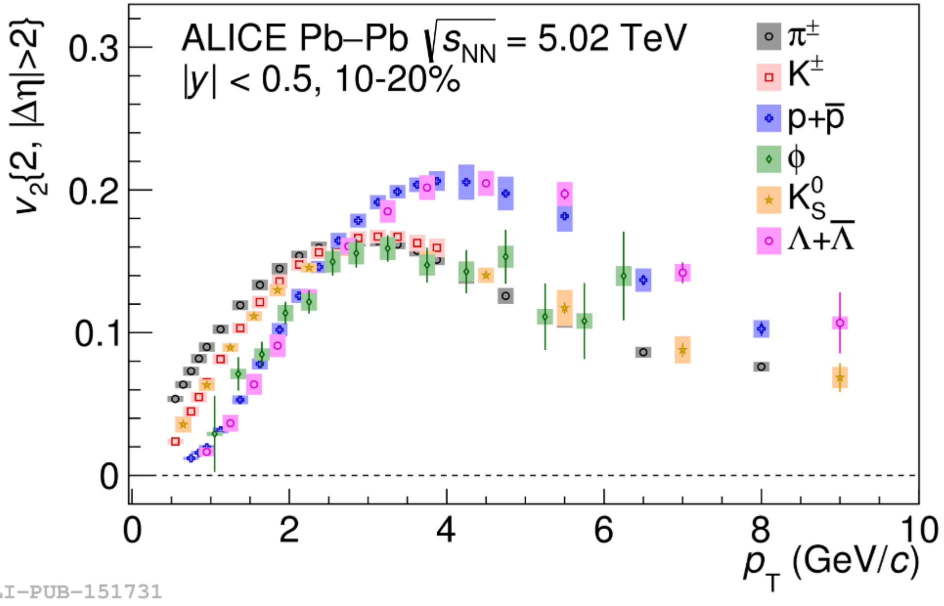
pp

- 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/K^0 in-jet is similar in pp and Pb-Pb
    - ✓ Fragmentation of the jet not modified by the medium

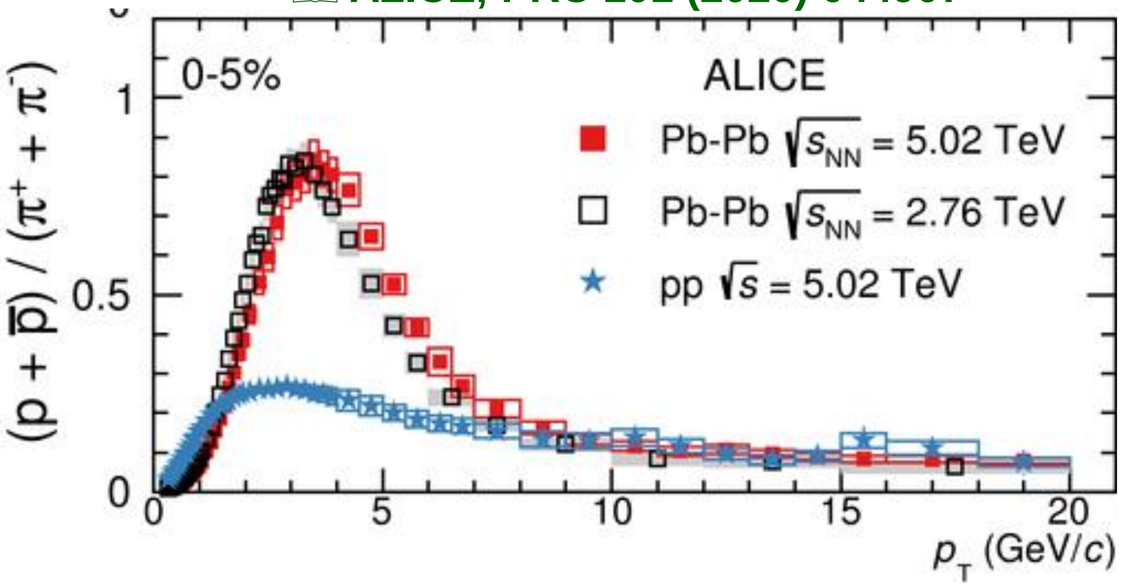


Light-flavour hadron yield and v_2 vs. p_T

📖 ALICE, JEP09 (2018) 006



📖 ALICE, PRC 101 (2020) 044907



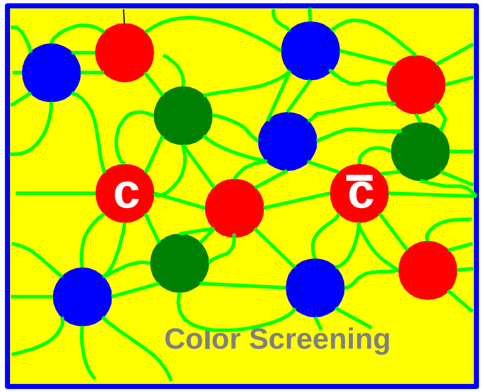
Low p_T (<~2 GeV/c):
- ⇨ Thermal regime
- ⇨ Hydrodynamic expansion driven by pressure gradients
- ⇨ Mass ordering

Intermediate p_T :
- ⇨ Baryon/meson enhancement
- ⇨ Baryon vs. meson grouping of v_2
- ⇨ Kinetic regime, not described by hydro
- ⇨ Window sensitive to recombination?

High p_T (>8–10 GeV/c):
- ⇨ Partons from hard scatterings
- ⇨ Energy loss in QGP
- ⇨ Hadronization via fragmentation
- ⇨ Same v_2 for all species
- ⇨ Relative abundances as in pp

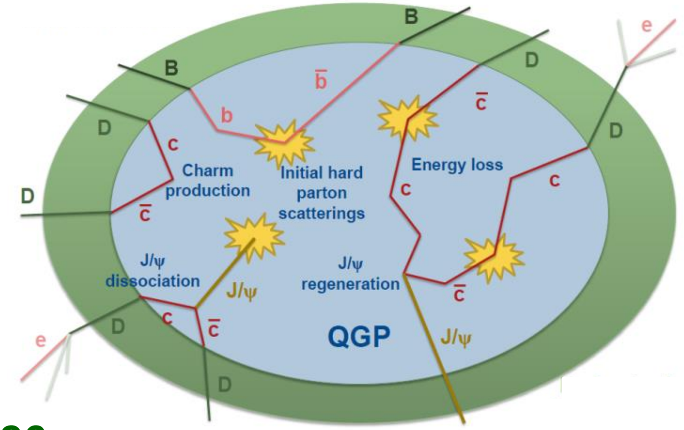
Quarkonium

- Quarkonium production in A-A collisions:
  - ⇨ Quarkonium **dissociation** in the QGP due to colour screening of the $q\bar{q}$ potential
    - ✓ Different quarkonium states melt at different temperatures, depending on their binding energy → sequential suppression



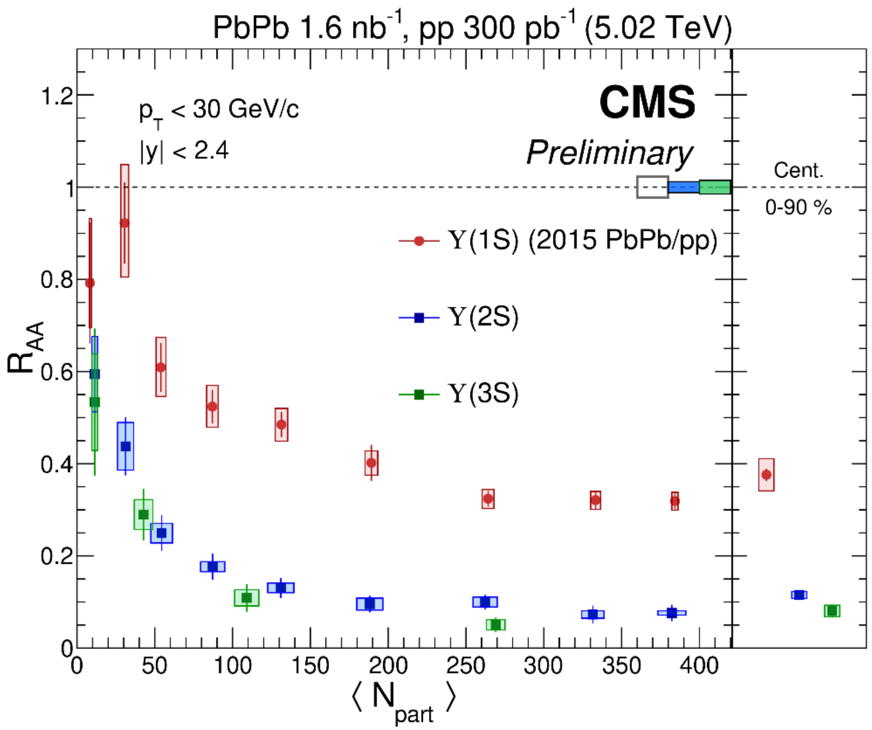
📖 Matsui, Satz, PLB178 (1986) 416
📖 Digal et al., PRD64 (2001) 094015

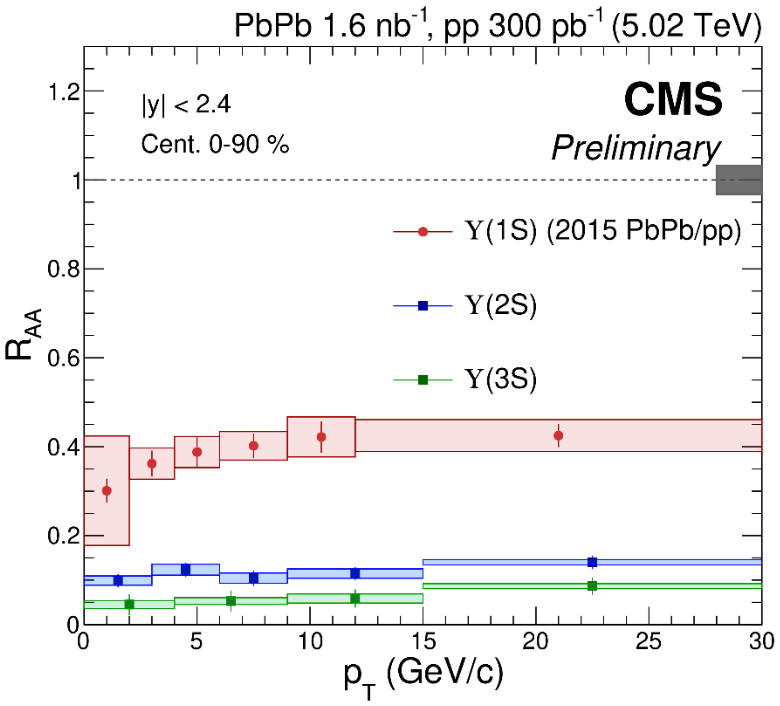
  - ⇨ Quarkonium production can occur also via **quark (re)combination** in the QGP or at the phase boundary
    - ✓ Charm and beauty production cross section increase with √s → higher recombination contribution with increasing √s
    - ✓ Smaller recombination contribution for bottomomium than for charmonium



📖 Braun-Munzinger, Stachel, PLB 490 (2000) 196
📖 Thews et al., PRC 63 (2001) 054905

Bottomonium R_{AA}

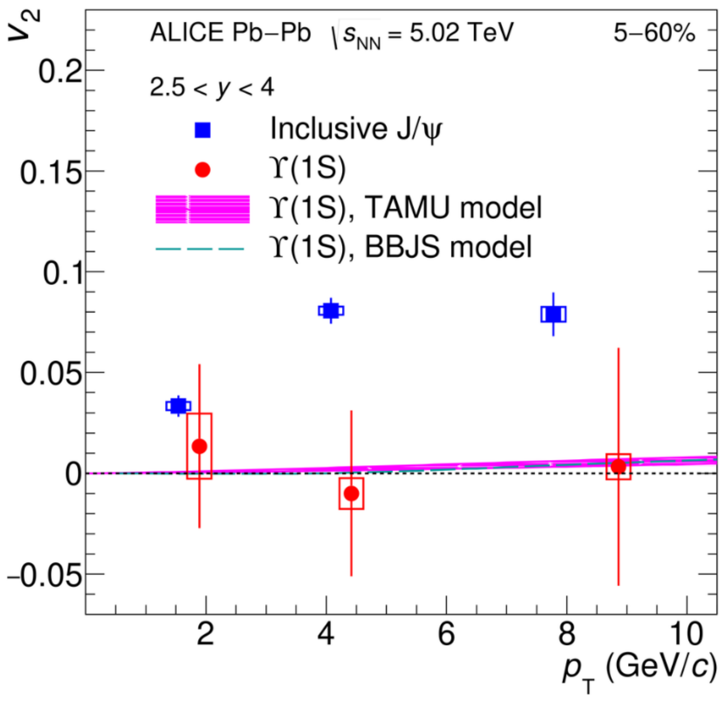


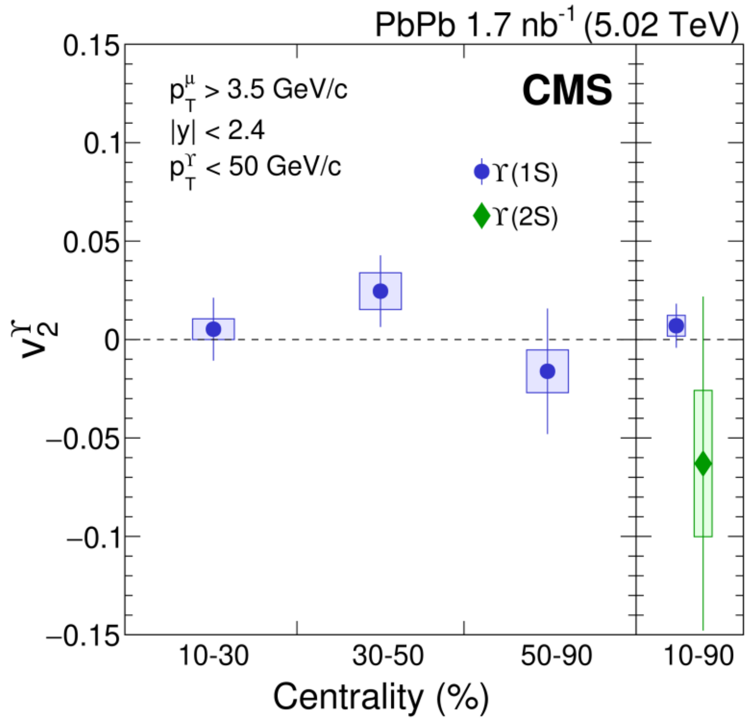


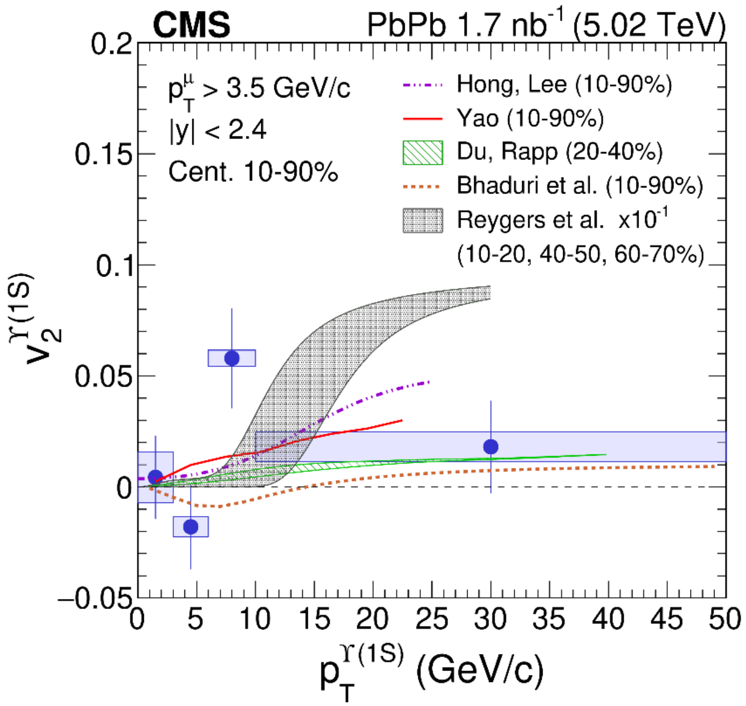
- Sequential suppression pattern: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
  - ⇨ Ordered by binding energy, as expected from dissociation in QGP
  - ⇨ Small contribution from $b\bar{b}$ recombination
    - ✓ *Beauty quarks less abundant than charm quarks*

Bottomonium v_2 in A-A collisions

- Elliptic flow of ϒ compatible with zero and smaller than J/ψ v_2



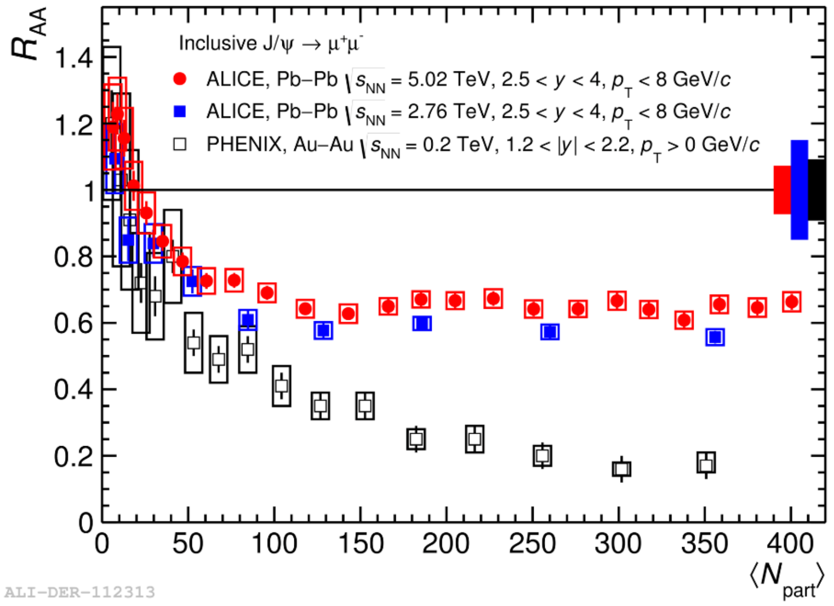




📖 **ALICE, PRL 123 (2019) 192301**

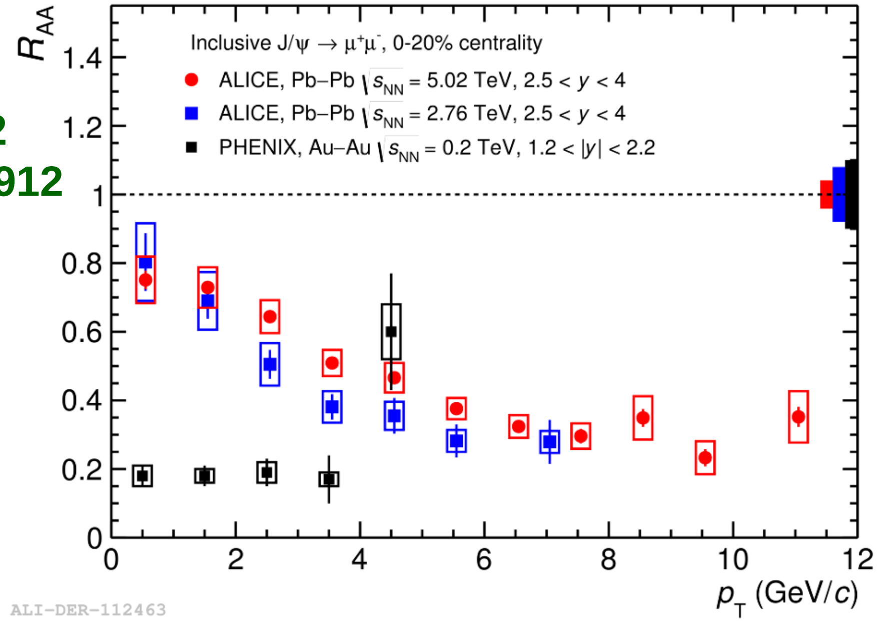
📖 **CMS, PLB819 (2021) 136385**

J/ψ yield in A-A collisions



📖 **ALICE, PLB766 (2017) 212**

📖 **PHENIX, PRC84 (2011) 05912**

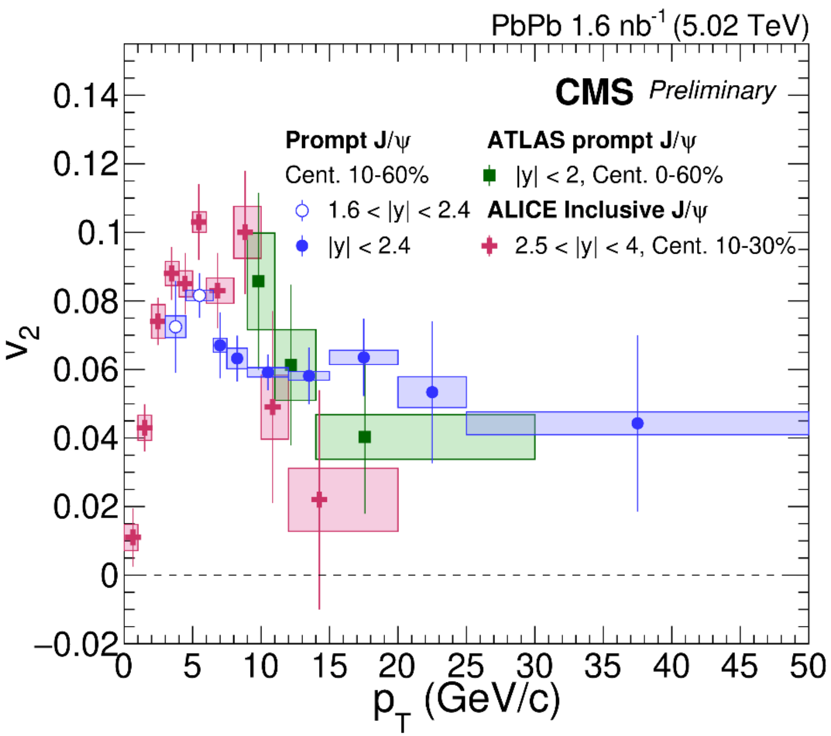


- Yield vs. centrality and $\sqrt{s_{NN}}$
  - ⇨ **Less suppression at LHC** ($\sqrt{s}$=**2.76**, **5.02** TeV) than at RHIC ($\sqrt{s}$=**200** GeV)
  - ⇨ Larger charm cross section with increasing $\sqrt{s}$ → larger regeneration contribution

- Yield vs. p_T and $\sqrt{s_{NN}}$
  - ⇨ **Less suppression at low p_T** than at high p_T
  - ⇨ Different p_T dependence of J/ψ R_{AA} at RHIC and LHC

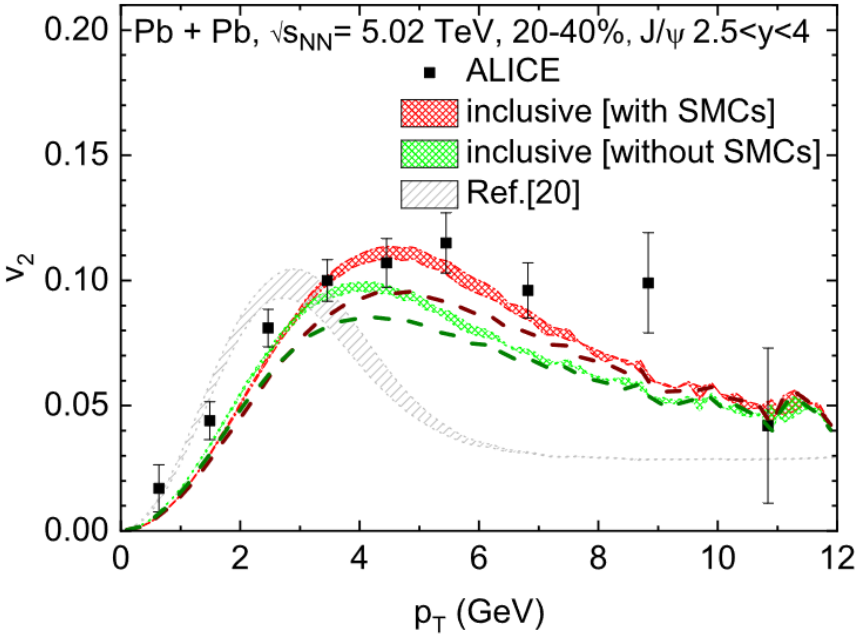
→ as expected in a scenario with dissociation + $c\bar{c}$ recombination

J/ψ elliptic flow in A-A collisions



📖 ALICE, PRL119 (2017) 242301

📖 He, Wu, Rapp PRL 128 (2022) 162301

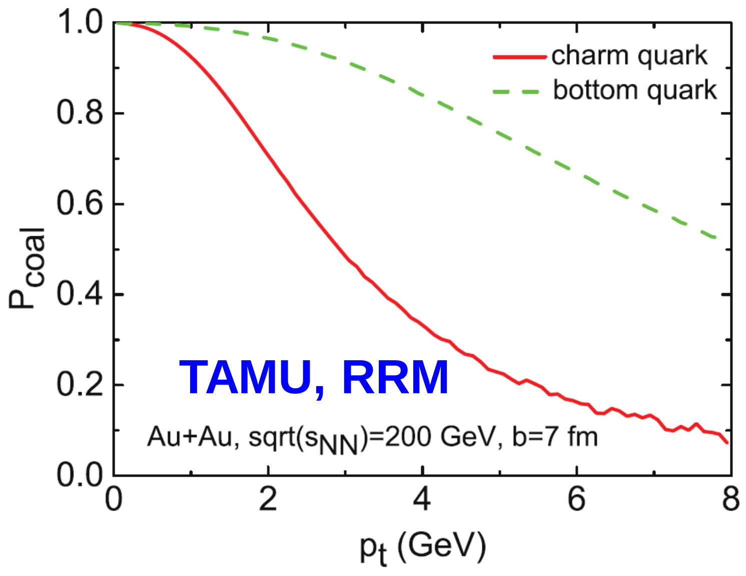


- Significant J/ψ elliptic flow observed at the LHC
  - ⇨ Confirms the contribution of J/ψ production from recombination
  - ⇨ Low p_T charm quarks thermalize in the QGP and flow with the medium before recombining into J/ψ
- Described by transport models when including space momentum correlations

Open heavy flavours

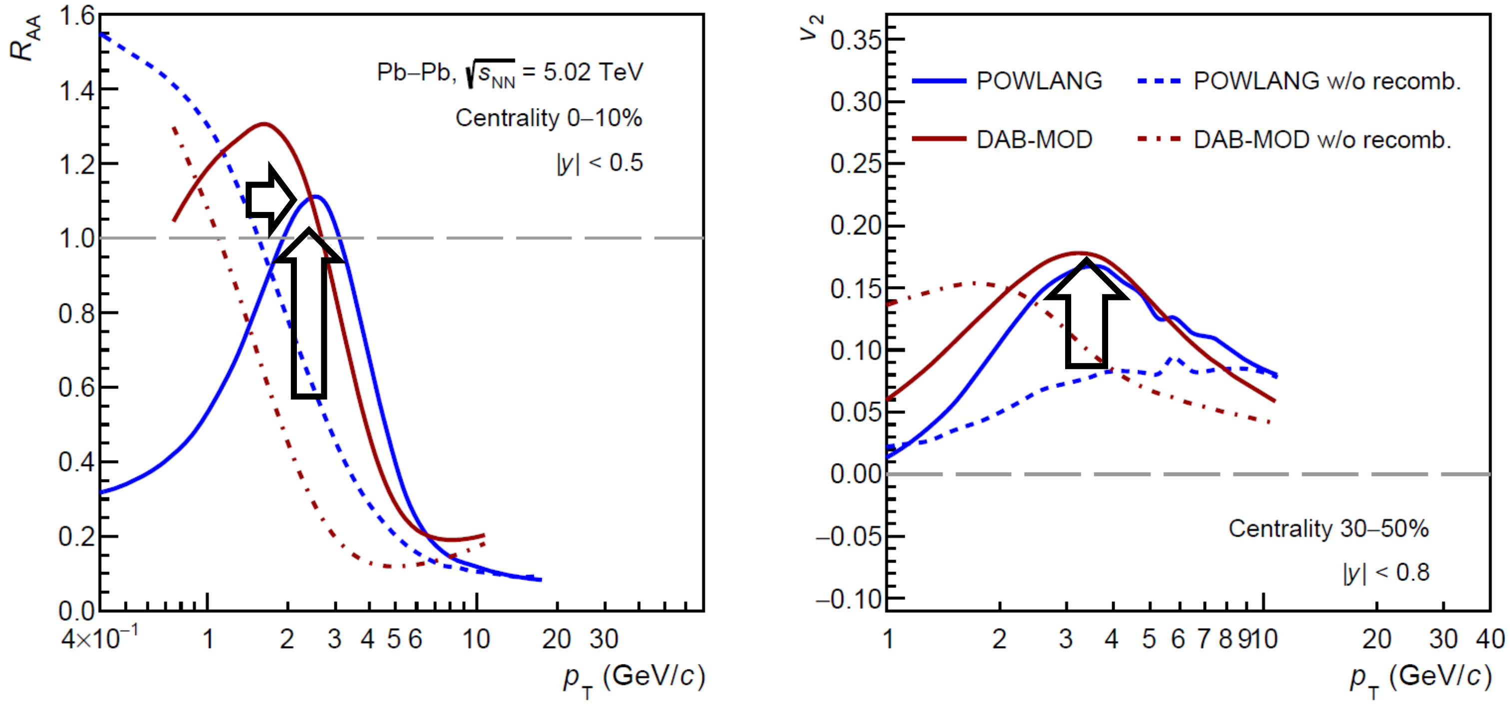
Recombination of heavy quarks with light quarks from the QGP affects:

- Momentum distributions
  - ⇨ HF hadrons pick-up the radial and elliptic flow of the light quark
- Hadrochemistry (i.e. relative abundances of meson and baryon species)
  - ⇨ **Enhanced** production of **baryons** relative to mesons
  - ⇨ **Enhanced D_s (B_s)** yield relative to non-strange mesons
- Different implementations in different transport models:
  - ⇨ Instantaneous coalescence at phase boundary based on Wigner function 📖 **Scheibl and Heinz, PRC 59 (1999) 1585**
  - ⇨ Resonance recombination model 📖 **Ravagli. Rapp, PLB655 (2007) 126**
  - ⇨ In-medium string formation between heavy quark and a thermal light quark from the bulk 📖 **Beraudo et al., EPJ C75 (2015) 121**
- Features:
  - ⇨ Recombination for heavy flavours relevant up to higher p_T than for light flavours
  - ⇨ Recombination for beauty extends up to higher p_T with respect to charm



Charm R_{AA} and v_2 phenomenology

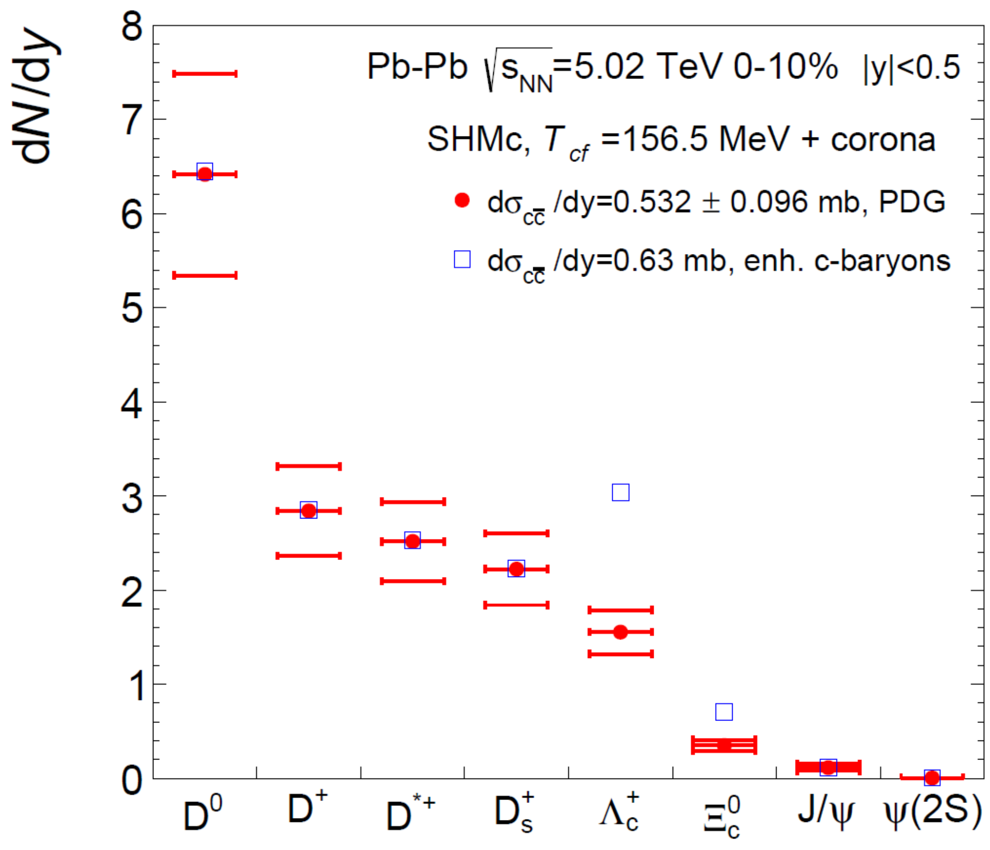
- Heavy-quark hadronization mechanism is an important ingredient to the phenomenology of heavy flavour R_{AA} and v_2 📖 **Van Hees et al., PRC73 (2006) 034907**
- Recombination with light quarks enhances R_{AA} and v_2 at intermediate p_T
  - ⇨ Needed to describe the data at low and intermediate p_T
  - ⇨ D-meson v_2 and radial flow peak in R_{AA}



SHM with charm

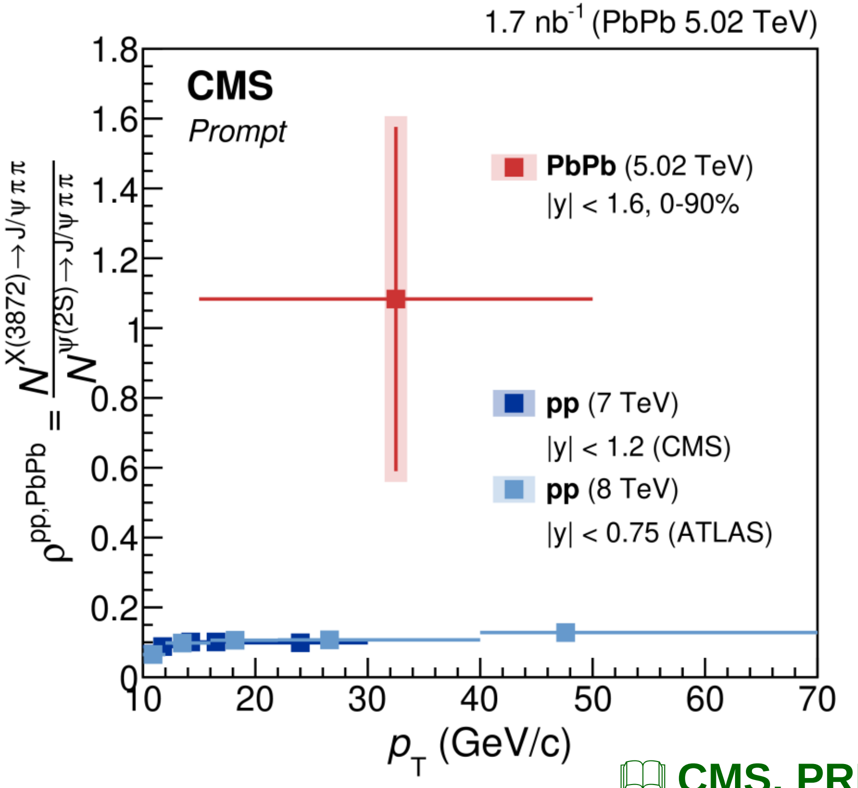
- Charm quarks produced in initial hard scatterings and conserved while traversing the QGP
  - ⇨ Initial production from pQCD
  - ⇨ Total yield determined by **charm cross section**, not by the fireball temperature.
  - ⇨ Accounted for by **charm balance equation** leading to a fugacity g_c, which ensures that all initially produced charm quarks are distributed into hadrons at the phase boundary
- Charm quarks **thermalize** in the QGP
  - ⇨ Charm hadrons formed at phase boundary according to thermal weights
  - ⇨ Relative yields depend on: hadron mass, temperature, and μ_B
- NOTE: significant impact of possible yet-undiscovered excited charm baryon states

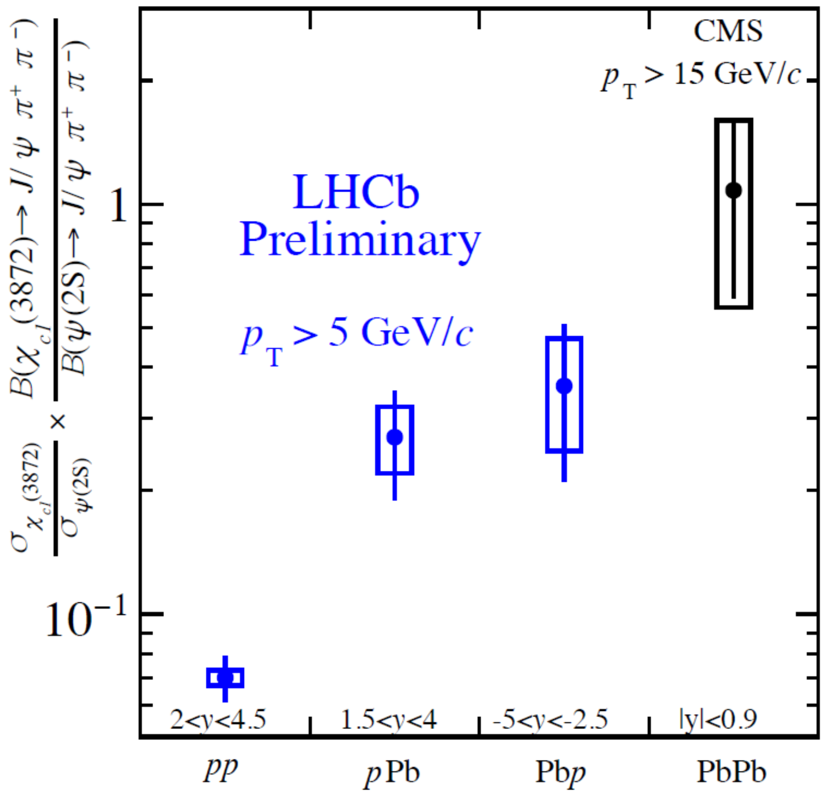
📖 Andronic et al, JHEP 07 (2021) 035



X(3872)

- X(3872) yield expected to be enhanced by hadronization via recombination
  - ⇨ Formation and dissociation rates depend on the spatial configuration of the exotic state
    - ✓ Tetraquark vs molecular state

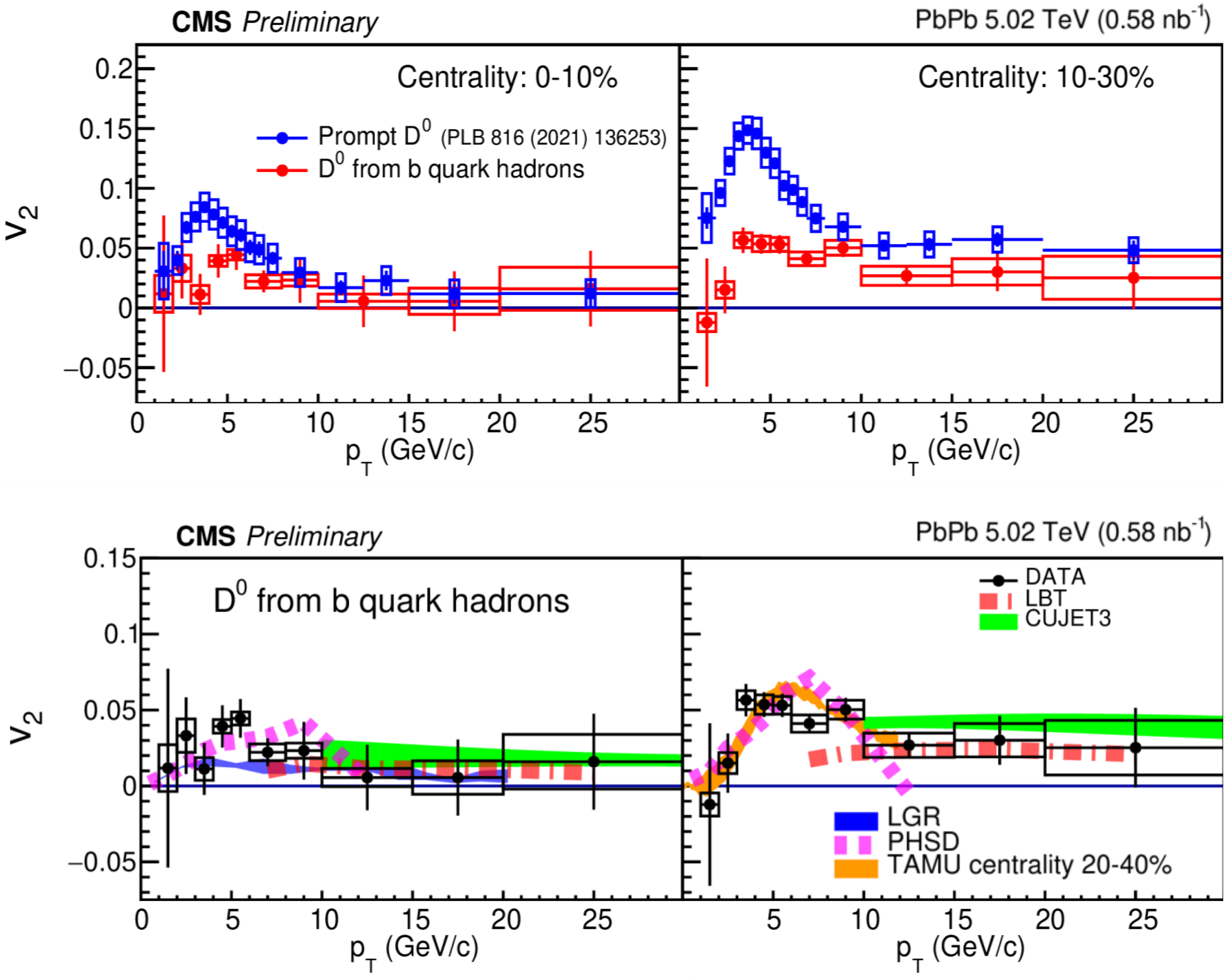




📖 CMS, PRL 128 (2022) 032001

Charm vs beauty v_2

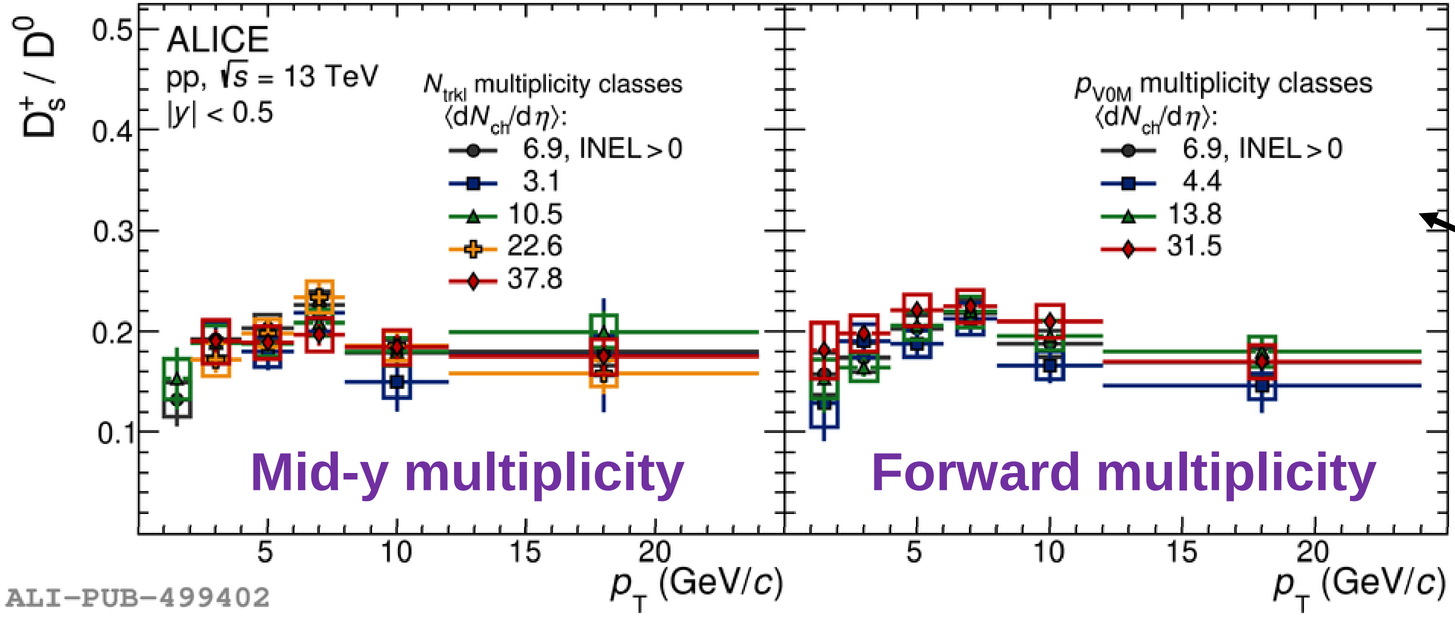
- **Recombination** of heavy quarks with light quarks from the QGP affects **HF hadron momentum distributions**
  - ⇨ HF hadrons pick-up the radial and elliptic flow of the light quark
- Heavy-quark flow mechanism:
  - ⇨ low p_T: collisions with (hydrodynamically expanding) QGP constituents (diffusion)
  - ⇨ high p_T : path-length dependent (radiative) energy loss
  - ⇨ all p_T : hadronization via recombination
- Mass ordering of elliptic flow magnitudes
  - ⇨ Qualitatively captured by theory calculations



📖 CMS-PAS-HIN-21-003

Charm and beauty hadronization vs. multiplicity

- Charm and beauty quark production dominated by hard parton-parton scatterings
- Increase of strangeness production with increasing multiplicity
- Hadronization via recombination may enhance D_s/D^0 , B_s/B^0 with increasing multiplicity

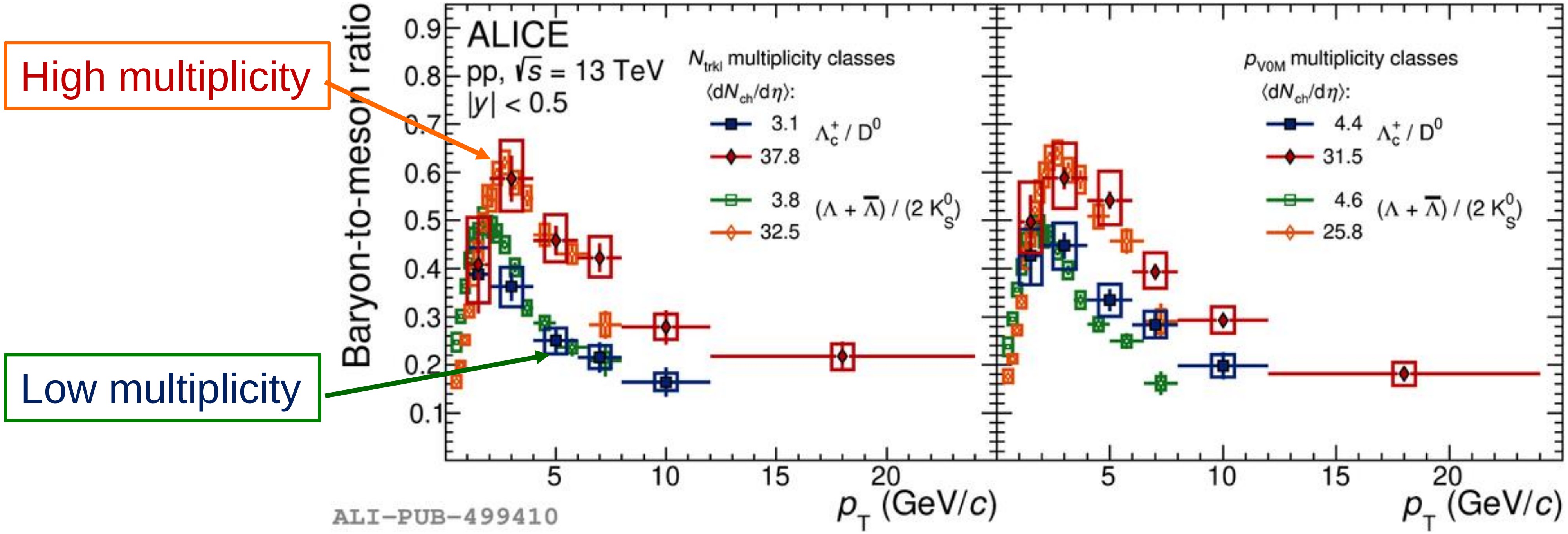


No significant dependence of D_s/D^0 on multiplicity within current uncertainties

ALICE, PLB 829 (2022) 137065

Baryon/meson ratios vs. multiplicity

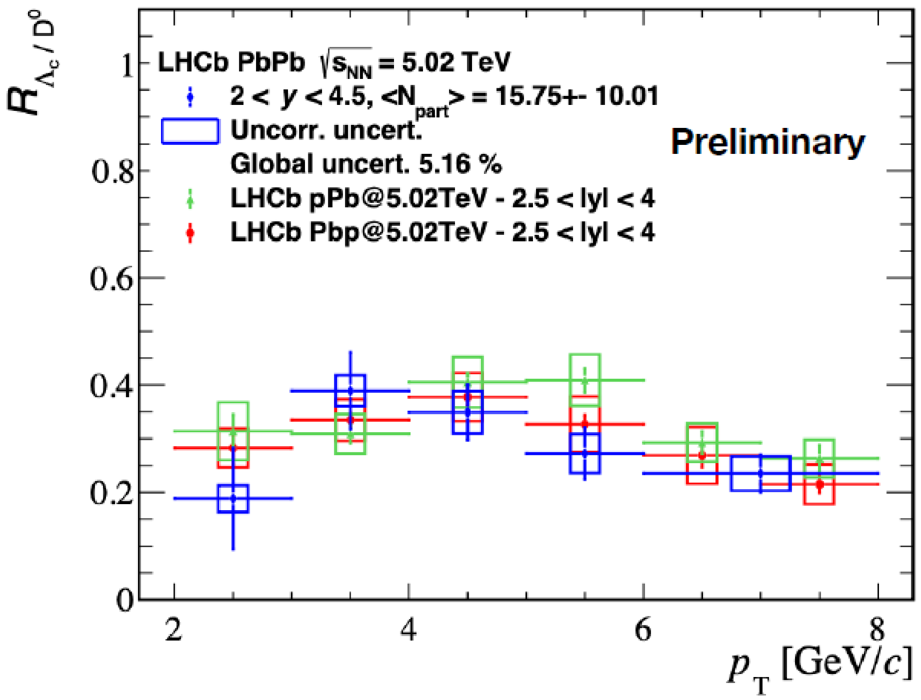
- Baryon/meson ratios in pp collisions: different p_T trend depending on multiplicity
  - ⇨ Larger baryon production at intermediate p_T with increasing multiplicity
  - ⇨ Similar effect an magnitude for charm (Λ_c/D^0) and strange (Λ/K^0_s) hadrons
- Dense particle environment affecting hadronization
  - ⇨ Qualitatively as expected from recombination
  - ⇨ Captured by PYTHIA with colour reconnection beyond leading-colour and SHM

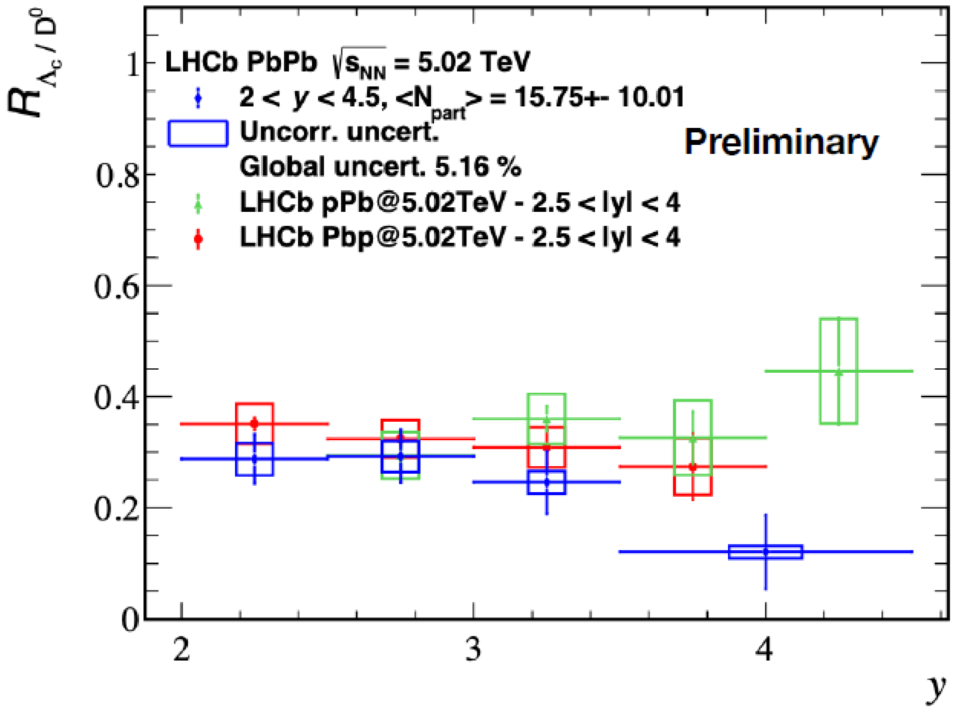


📖 **ALICE, PLB 829 (2022) 137065**

Λ_c/D^0 at forward y

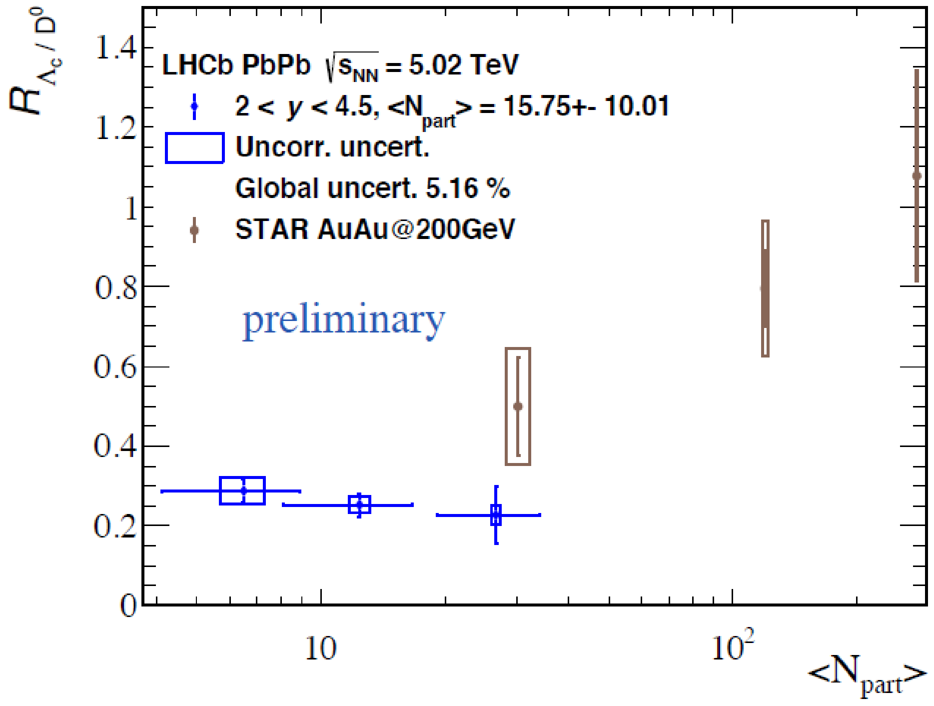
- New measurement in peripheral Pb-Pb collisions compatible with previous measurements in p-Pb and Pb-p collisions (forward and backward rapidity)





Λ_c/D^0 at forward y

- New measurement in peripheral Pb-Pb collisions compatible with STAR (Au-Au at RHIC energies) results for similar centrality / N_{part}



- New measurement in peripheral Pb-Pb collisions at forward rapidity: hint of lower Λ_c/D^0 than in p-Pb data at midrapidity