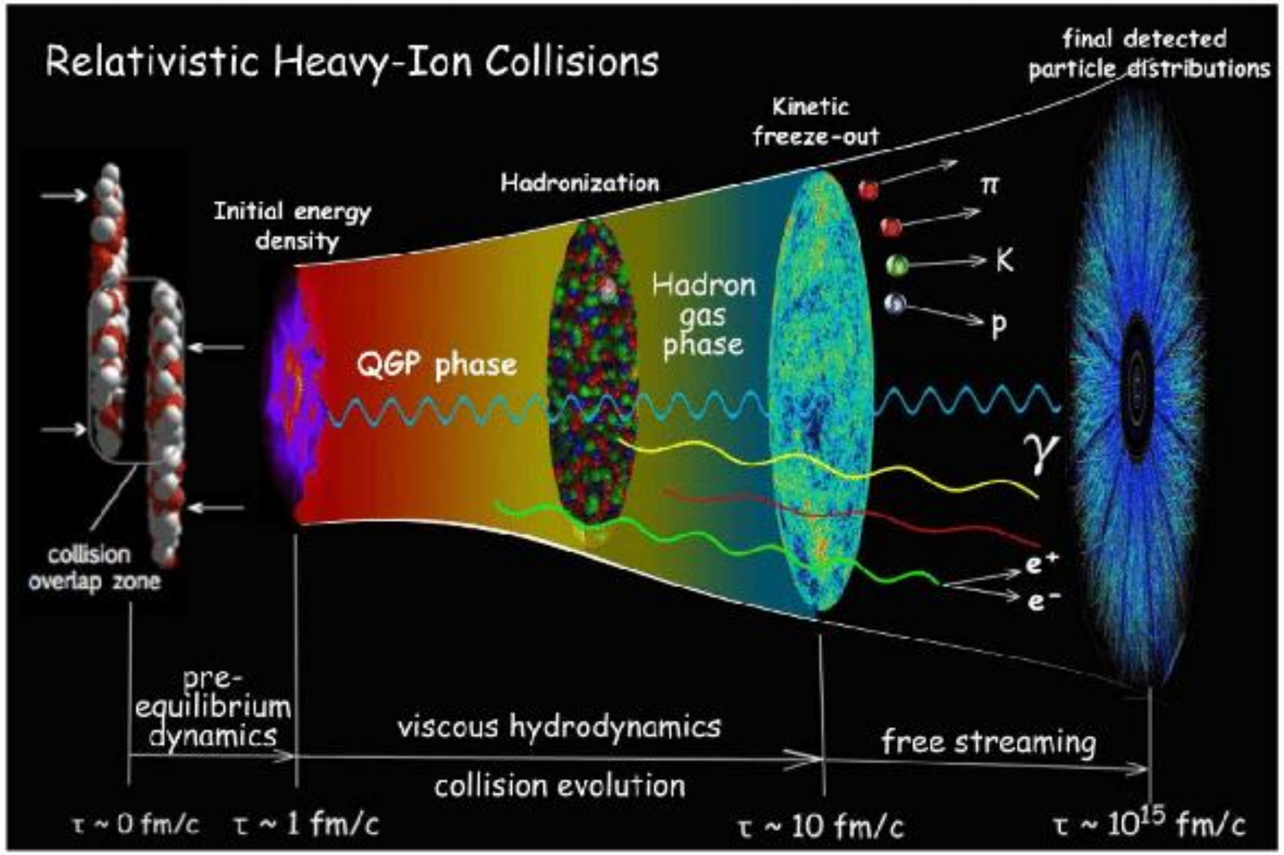
Hadronization of the QGP

Francesco Prino

INFN Sezione di Torino

Heavy-ion collision evolution



- 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
  - ⇨ The partonic degrees of freedom of the deconfined phase convert into hadrons, in which partons are confined
- No first-principle description of hadron formation
  - ⇨ Non-perturbative problem, not calculable with QCD

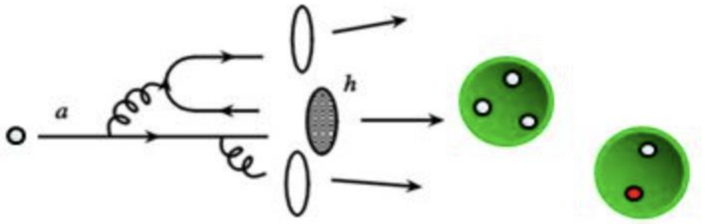
→ Hadronisation from a QGP may be different from other cases in which no bulk of thermalized partons is formed

Independent fragmentation

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

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

- Description of hadronisation effects (from quark to meson or baryon) must necessarily resort to models and make use of phenomenological parameters
- **Fragmentation functions** $D_{q\rightarrow h}$ are phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition*
  - ➪ z = fraction of the parton momentum taken by the hadron h
  - ➪ Do not specify the hadronization mechanism

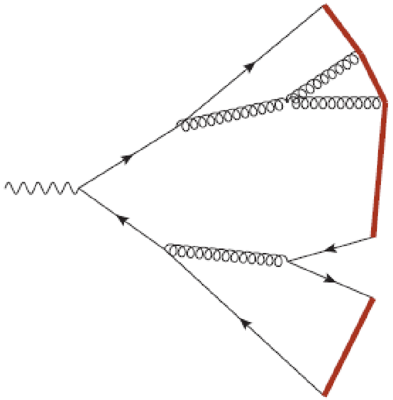


- Parameterized on data and assumed to be “universal”
- In A-A collisions:
  - ➪ Energy-loss of hard-scattered partons while traversing the QGP
  - ➪ Modified fragmentation function $D_{q\rightarrow h}(z)$ by ”rescaling” the variable z
    - ✓ Would affect all hadron species in the same way

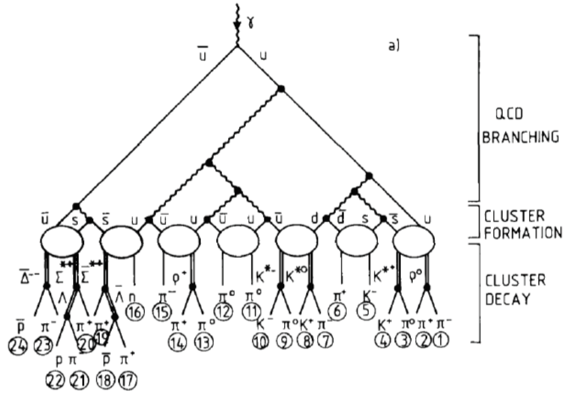
Hadronization of parton showers

- 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

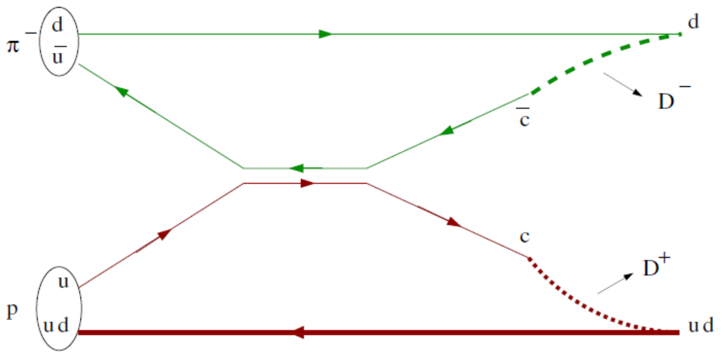


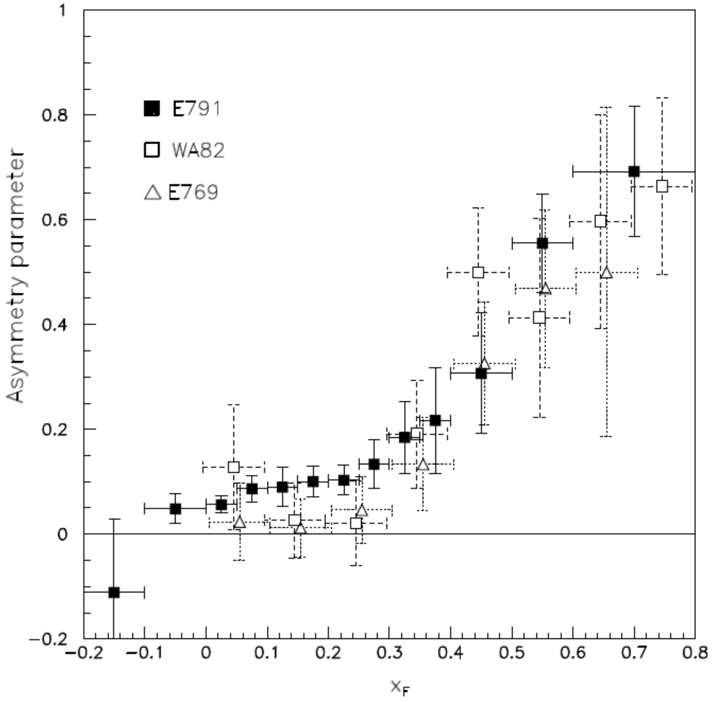
Leading particle effect

- 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

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

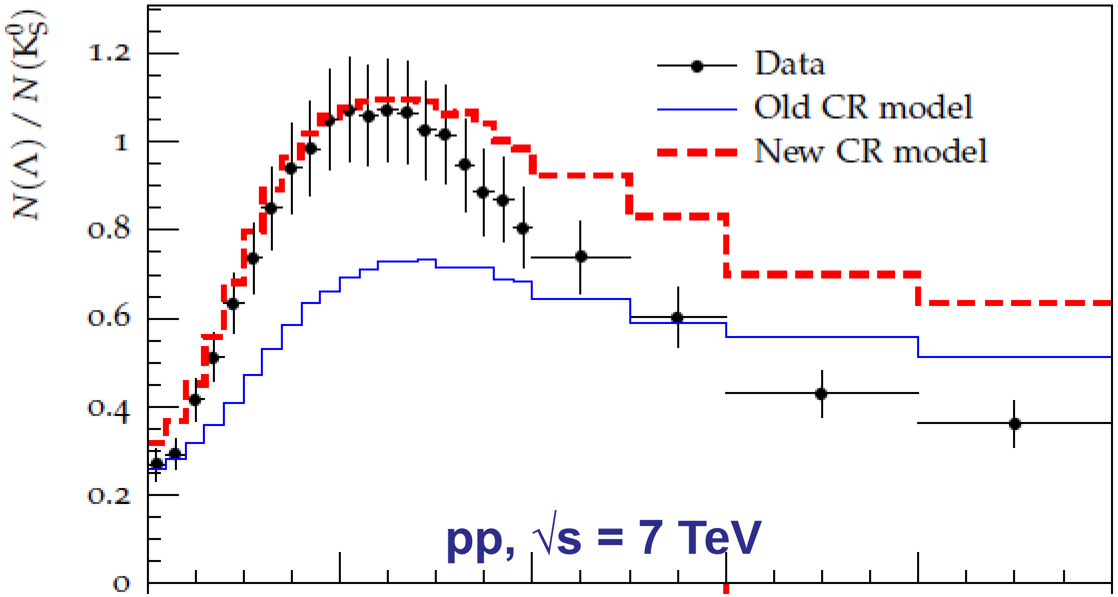




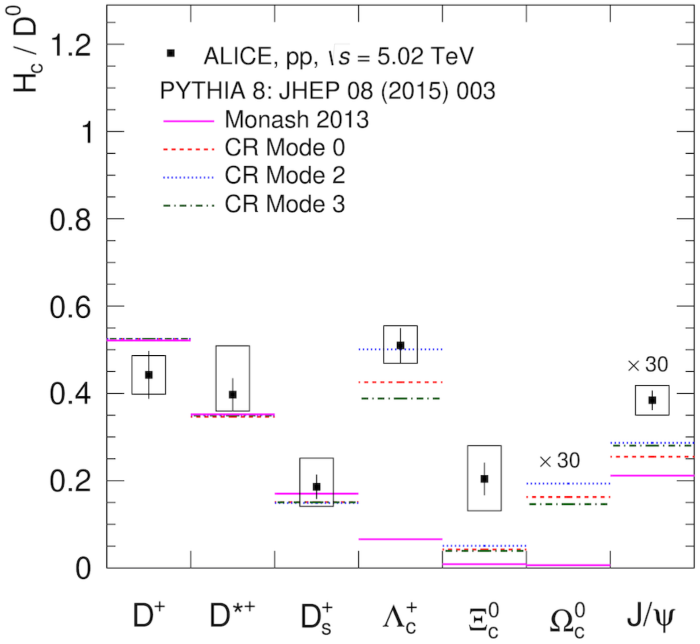
→ A reservoir of particles leads to significant changes in hadronisation

Colour reconnection

📖 Christiansen Skands, JHEP 08 (2015) 003



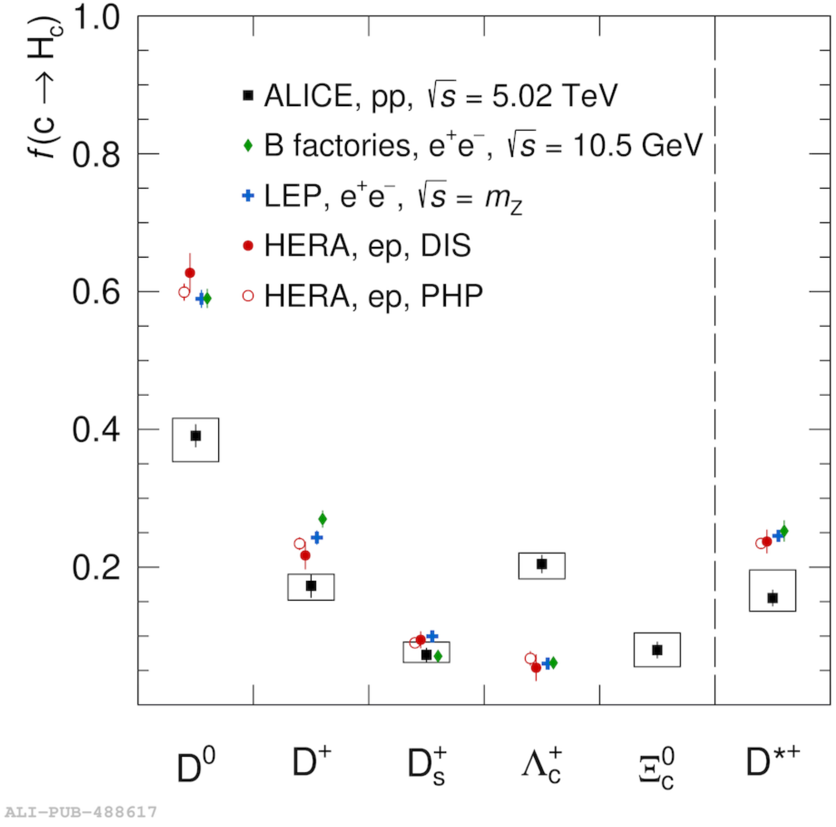
📖 ALICE, arXiv:2105.06335



- Baryon/meson ratios underestimated by PYTHIA tuned on e^+e^- (old CR model, Monash)
- Better description with Color Reconnection beyond the leading color (New CR model, CR mode 0,1,2)
  - ⇨ Suggests that single-particle independent-fragmentation picture is not valid in a hadronic (color-rich) environment

Fragmentation universality?

📖 ALICE, arXiv:2105.06335

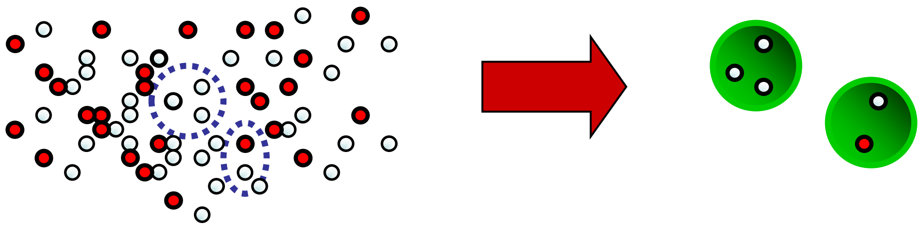


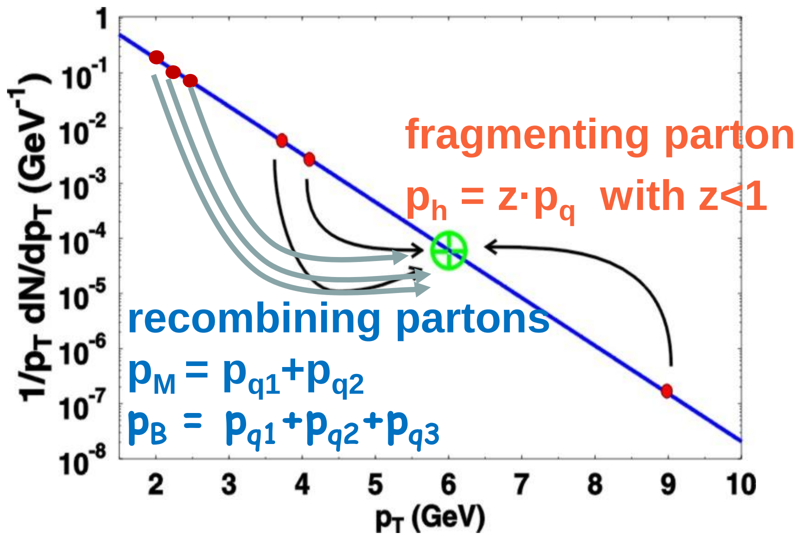
- Evidence of different fragmentation fractions in pp collisions at LHC and e^+e^- (ep) collisions at lower $\sqrt{s}$
  - ⇨ Indication that parton-to-hadron fragmentation depends on the collision system
  - ⇨ Assumption of their universality not supported by the measured cross sections

→ Independent fragmentation picture not valid in color-rich environment
→ Break-down of universality of fragmentation functions

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





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

Coalescence/recombination

- Back in 2003: hadronisation via **recombination** of quarks from a thermalized QGP provides a simple explanation of unexpected features 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

V. Greco,[1] C. M. Ko,[1] and P. Lévai[1,2]
[1]Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843-3366, USA
[2]KFKI Research Institute for Particle and Nuclear Physics, P.O. Box 49, Budapest 1525, Hungary
(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

Rudolph C. Hwa[1] and C. B. Yang[1,2]
[1]Institute of Theoretical Science and Department of Physics, University of Oregon, Eugene, Oregon 97403-5203
[2]Institute of Particle Physics, Hua-Zhong Normal University, Wuhan 430079, People's Republic of China
(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

R. J. Fries, B. Müller, and C. Nonaka
Department of Physics, Duke University, Durham, North Carolina 27708, USA
S. A. Bass
Department of Physics, Duke University, Durham, North Carolina 27708, USA
and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA
(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

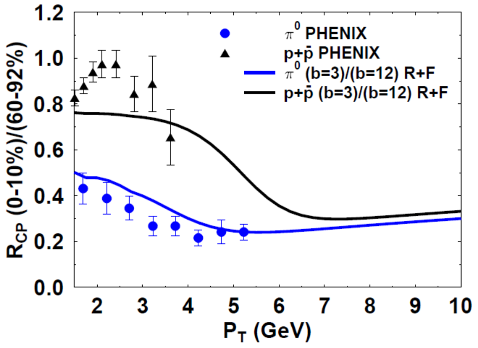
VOLUME 91, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2003

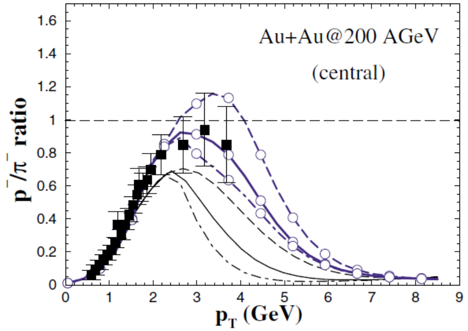
Elliptic Flow at Large Transverse Momenta from Quark Coalescence

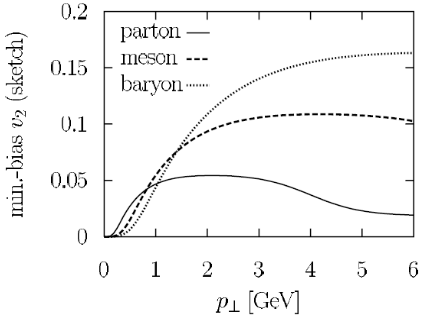
Dénes Molnár[1] and Sergei A. Voloshin[2]
[1]Department of Physics, Ohio State University, 174 West 18th Ave, Columbus, Ohio 43210, USA
[2]Department of Physics and Astronomy, Wayne State University, 666 W. Hancock, Detroit, Michigan 48201, USA
(Received 7 February 2003; published 27 August 2003)

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

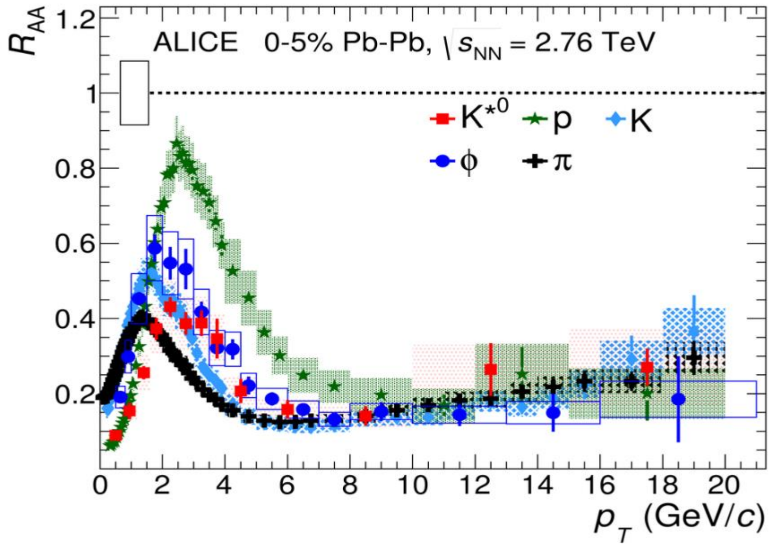




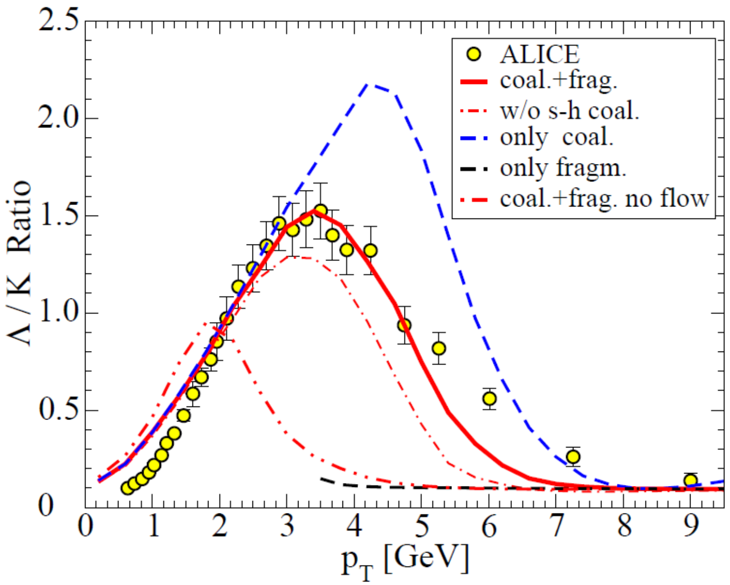


Light-flavour hadron yield and v_2 vs. p_T

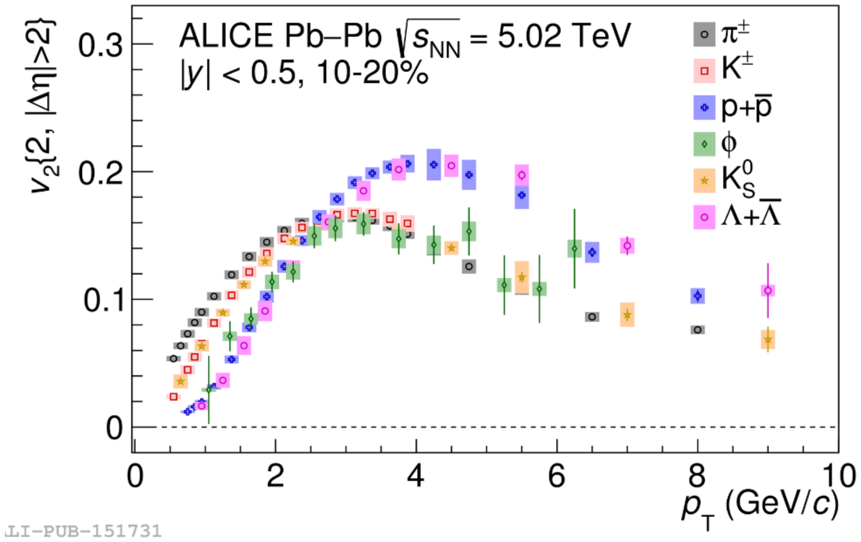
📖 ALICE, PRC 995 (2017) 064606



📖 Minissale et al., PRC92 (2015) 054904

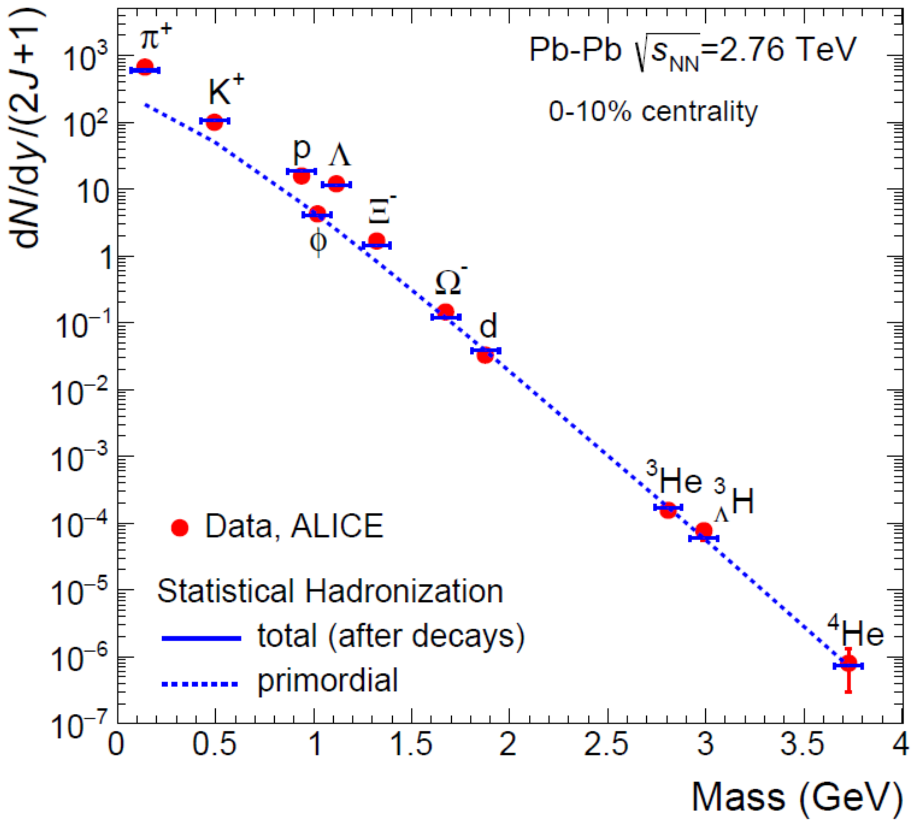


📖 ALICE, JEP09 (2018) 006



- Low p_T (<~2 GeV/c) :
  - ⇨ Thermal regime, hydrodynamic expansion driven by pressure gradients → mass ordering
- High p_T (>8-10 GeV/c):
  - ⇨ Partons from hard scatterings → energy loss in QGP → hadronisation via fragmentation → same R_{AA} and v_2 for all species
- Intermediate p_T (window sensitive to hadronization via recombination?):
  - ⇨ Kinetic regime, not described by hydro
  - ⇨ Different R_{AA} for different hadron species, baryon/meson enhancement, baryon / meson grouping of v_2

Statistical hadronization



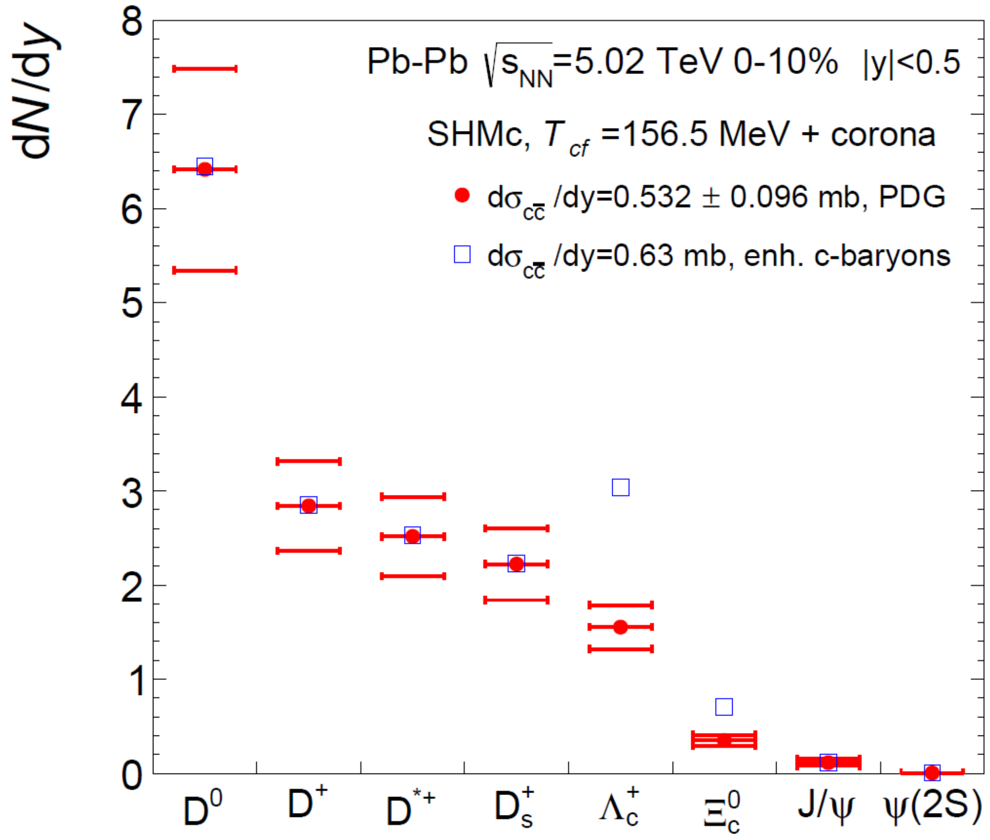
📖 **Andronic et al, Nature 561 (2018) 7723, 321**

- Abundances of light and strange hadrons (dominated by low-p_T particles) follow the equilibrium populations of a **hadron-resonance gas in chemical and thermal equilibrium** at a 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

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

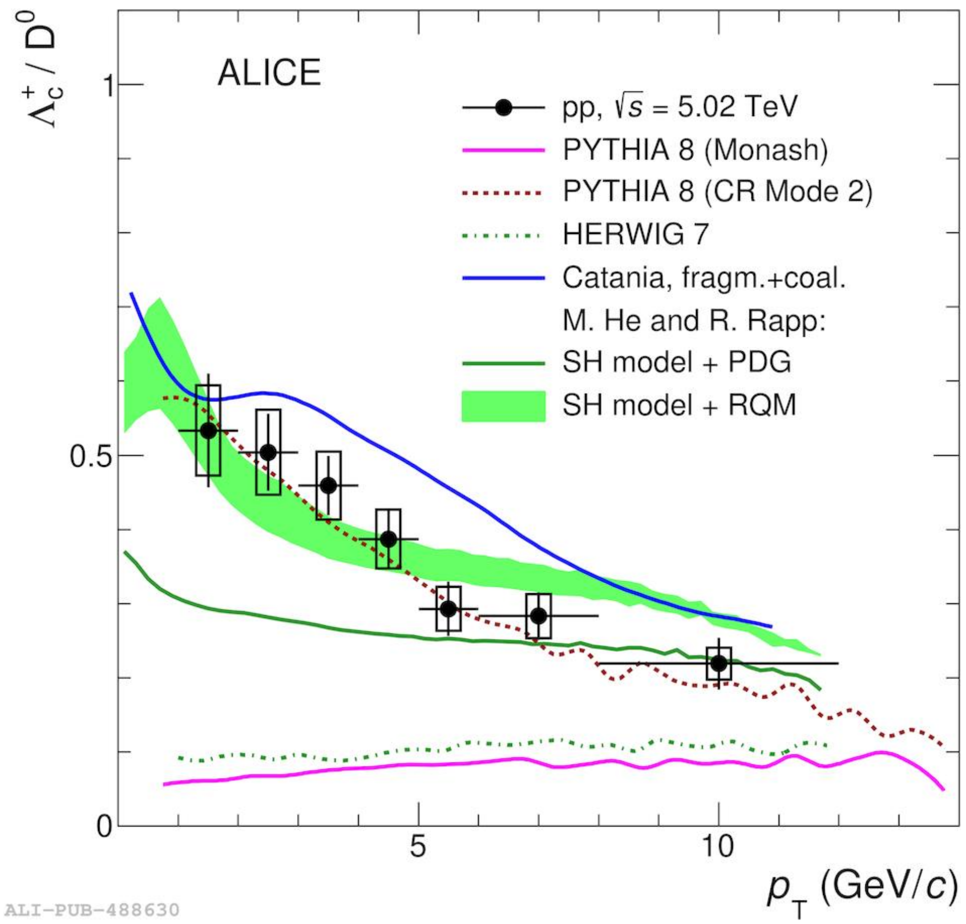
📖 **Andronic et al, JHEP 07 (2021) 035**



→ talk by A. Andronic

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

→ talk by M. Faggin
→ Talk by A. Rossi

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?

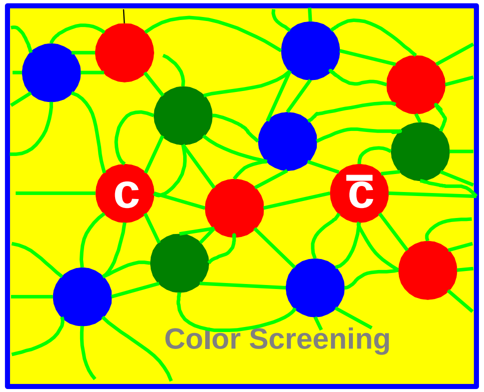
📖 **Fries et al., PRC 68 (2003) 044902**

- "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

Heavy quarks

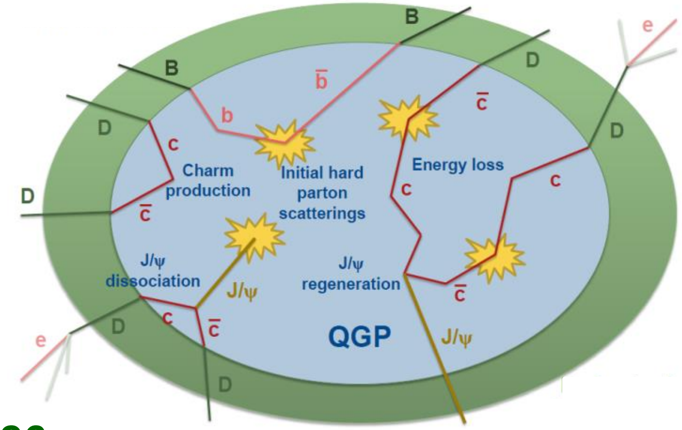
Quarkonium

- 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



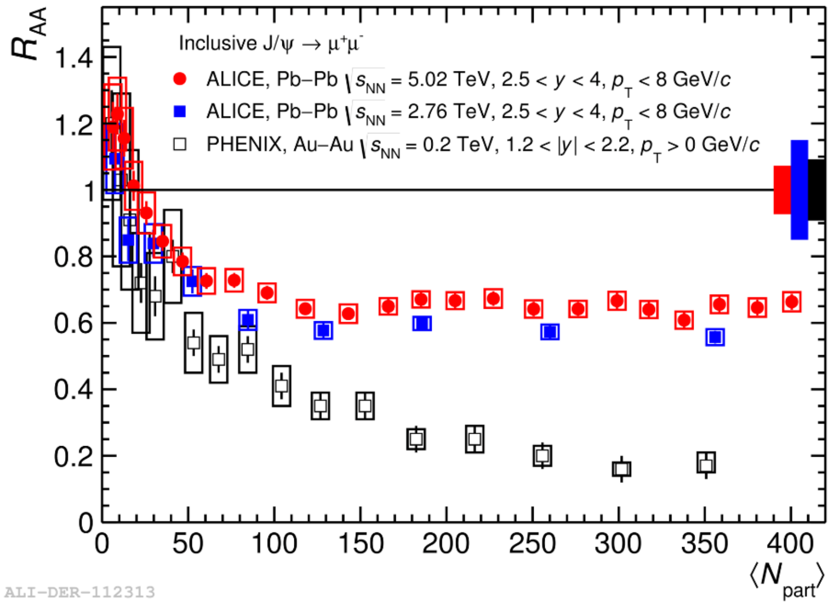
📖 **Matsui, Satz, PLB178 (1986) 416**
📖 **Digal et al., PRD64 (2001) 094015**

  - ⇨ 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



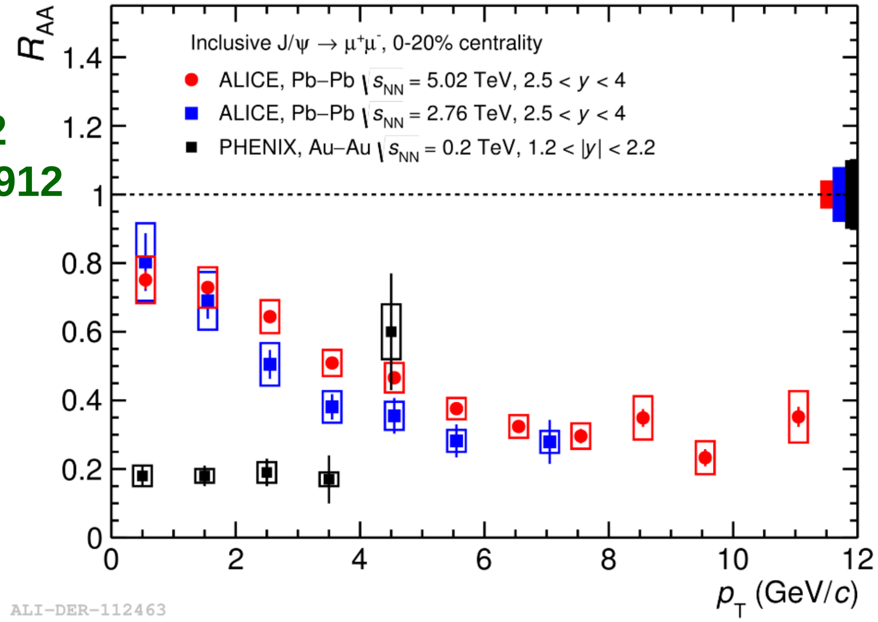
📖 **Braun-Munzinger, Stachel, PLB 490 (2000) 196**
📖 **Thews et al., PRC 63 (2001) 054905**

J/ψ yield in A-A collisions



📖 ALICE, PLB766 (2017) 212

📖 PHENIX, PRC84 (2011) 05912

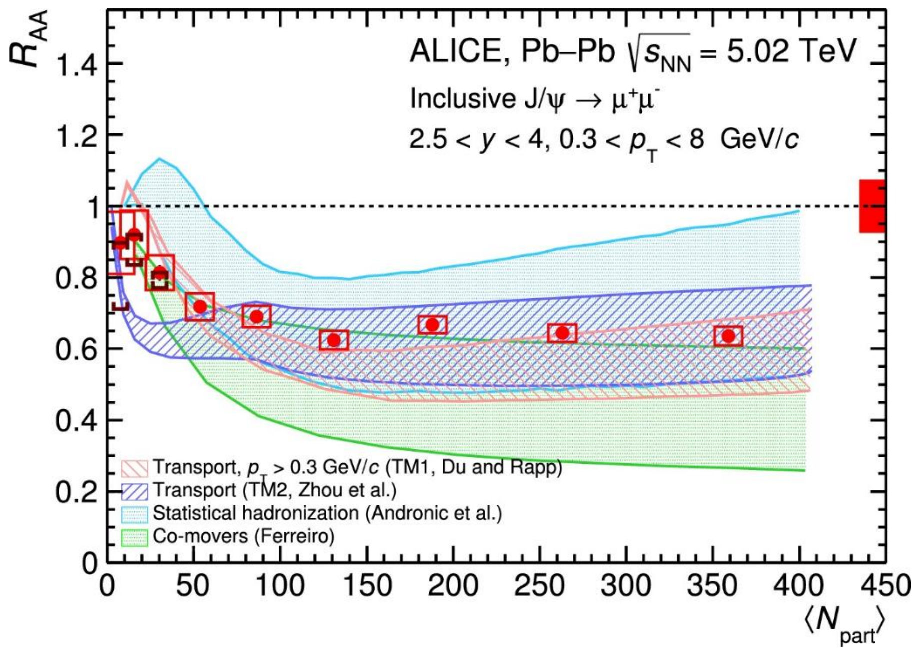


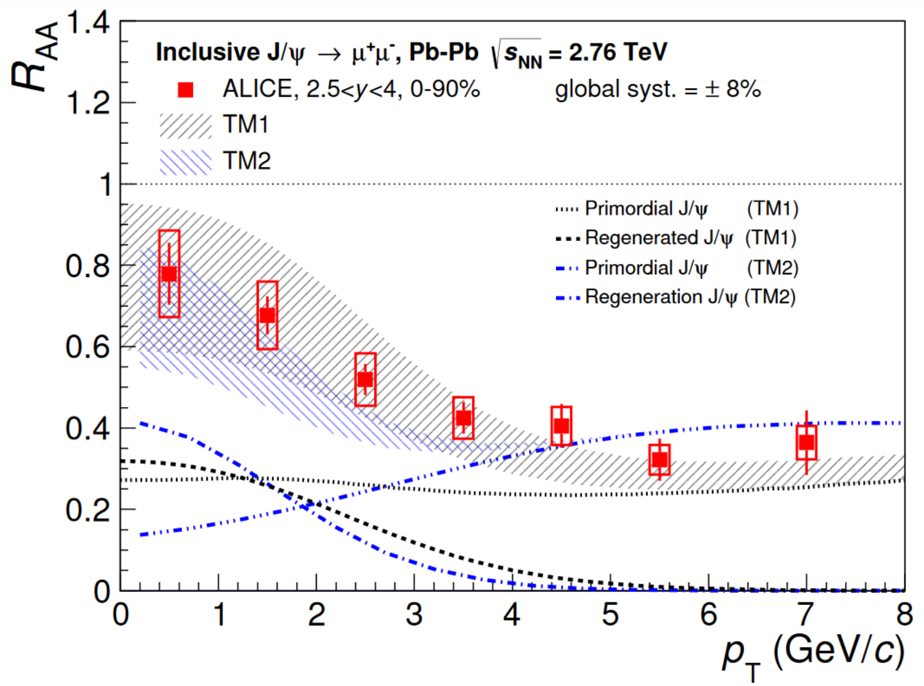
- Yield vs. centrality and $\sqrt{s_{NN}}$
  - ⇨ **Less suppression at LHC** ($\sqrt{s}$=**2.76**, **5.02** TeV) than at RHIC ($\sqrt{s}$=**200** GeV)
  - ⇨ Larger charm cross section with increasing $\sqrt{s}$ → larger regeneration contribution

- 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 + $\bar{c}c$ recombination

J/ψ yield in A-A collisions

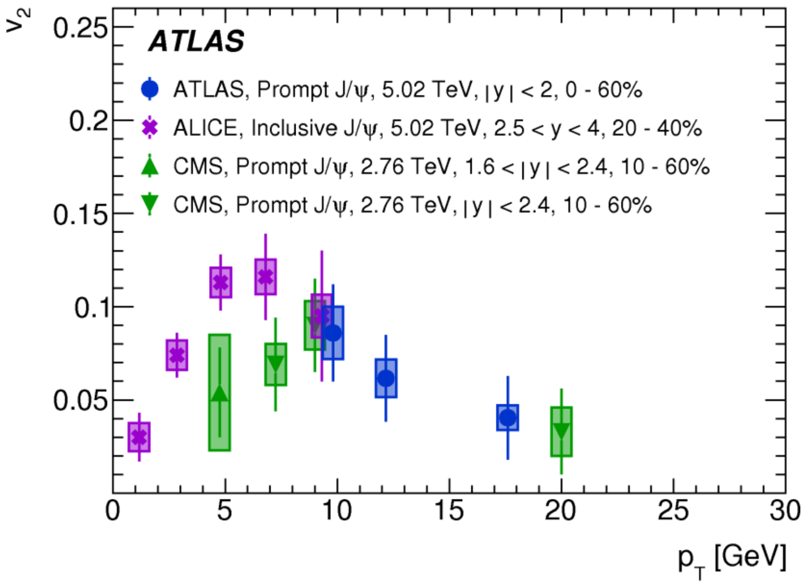




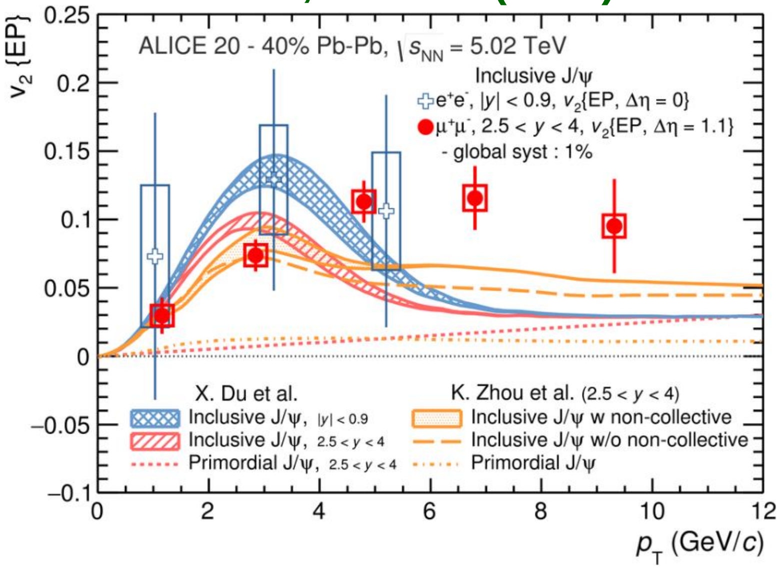
- Data described by:
  - ⇨**SHM**: melting of initially produced $c\bar{c}$ pairs + combination at phase boundary
  - ⇨**Transport models** with in-medium charmonium dissociation + regeneration

J/ψ elliptic flow in A-A collisions

📖 ATLAS, EPJC78 (2018) 784



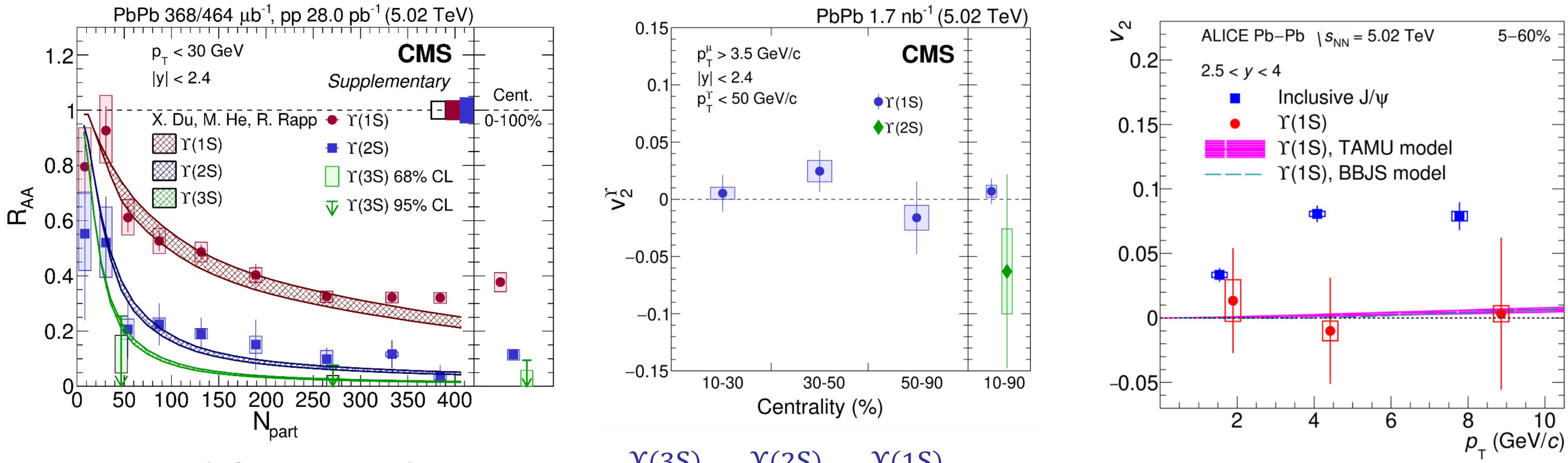
📖 ALICE, PRL119 (2017) 242301



- 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
- J/ψ v_2 at intermediate p_T (>6 GeV/c) not described by transport models
  - ⇨ Missing component in the models?

📖 Du, Rapp NPA943 (2015) 147
📖 Zhou et al., PRC89 (2014) 054911

Bottomonium yield and v_2 in A-A collisions



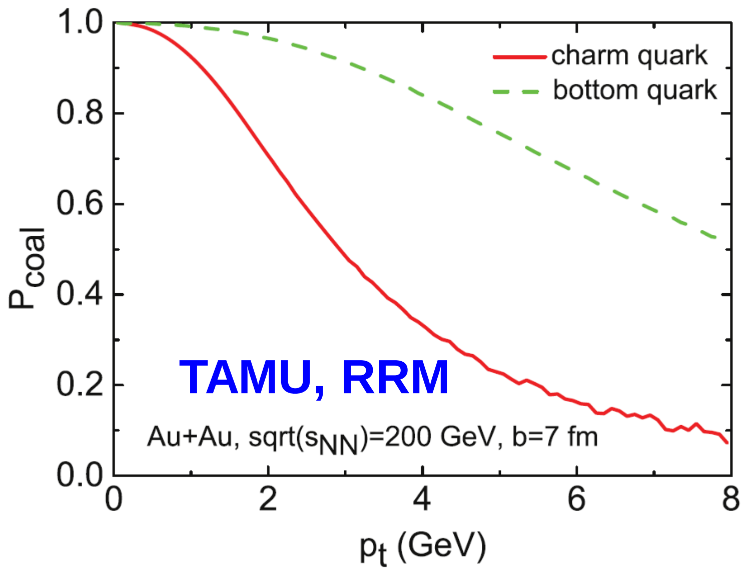
- Sequential suppression pattern: $R_{AA}^{\Upsilon(3S)}<R_{AA}^{\Upsilon(2S)}<R_{AA}^{\Upsilon(1S)}$
  - ⇨ Ordered by binding energy, as expected from sequential dissociation in QGP
- Elliptic flow of Υ compatible with zero and smaller than J/ψ v_2
- Described by transport models
  - ⇨ Small contribution from $b\bar{b}$ recombination
    - ✓ *Beauty quarks less abundant than charm quarks*

📖 **ALICE, PRL 123 (2019) 192301**
📖 **CMS, PLB790 (2019) 270**
📖 **CMS, PLB819 (2021) 136385**
📖 **Du et al., PRC96 (2017) 054901**

Open heavy flavours

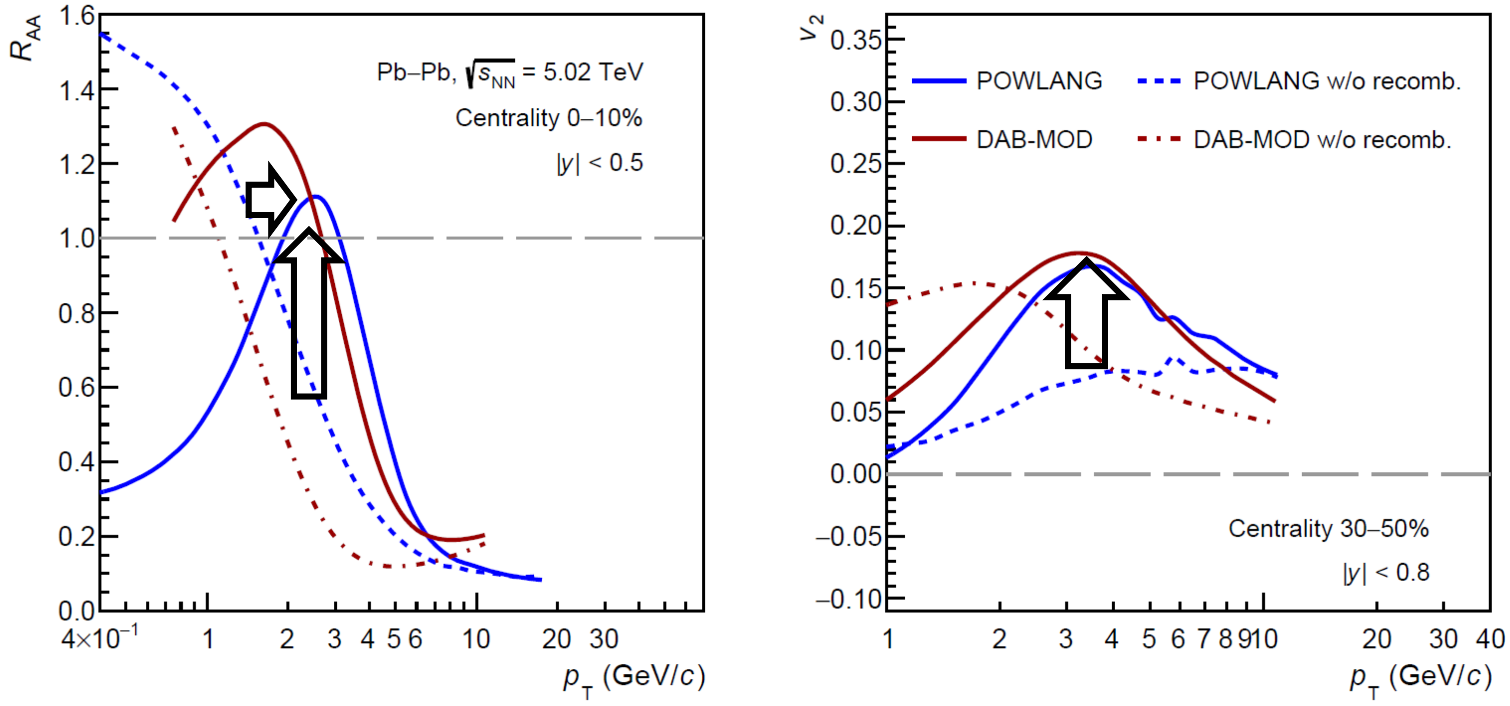
Recombination of heavy quarks with light quarks from the QGP affects:

- 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}



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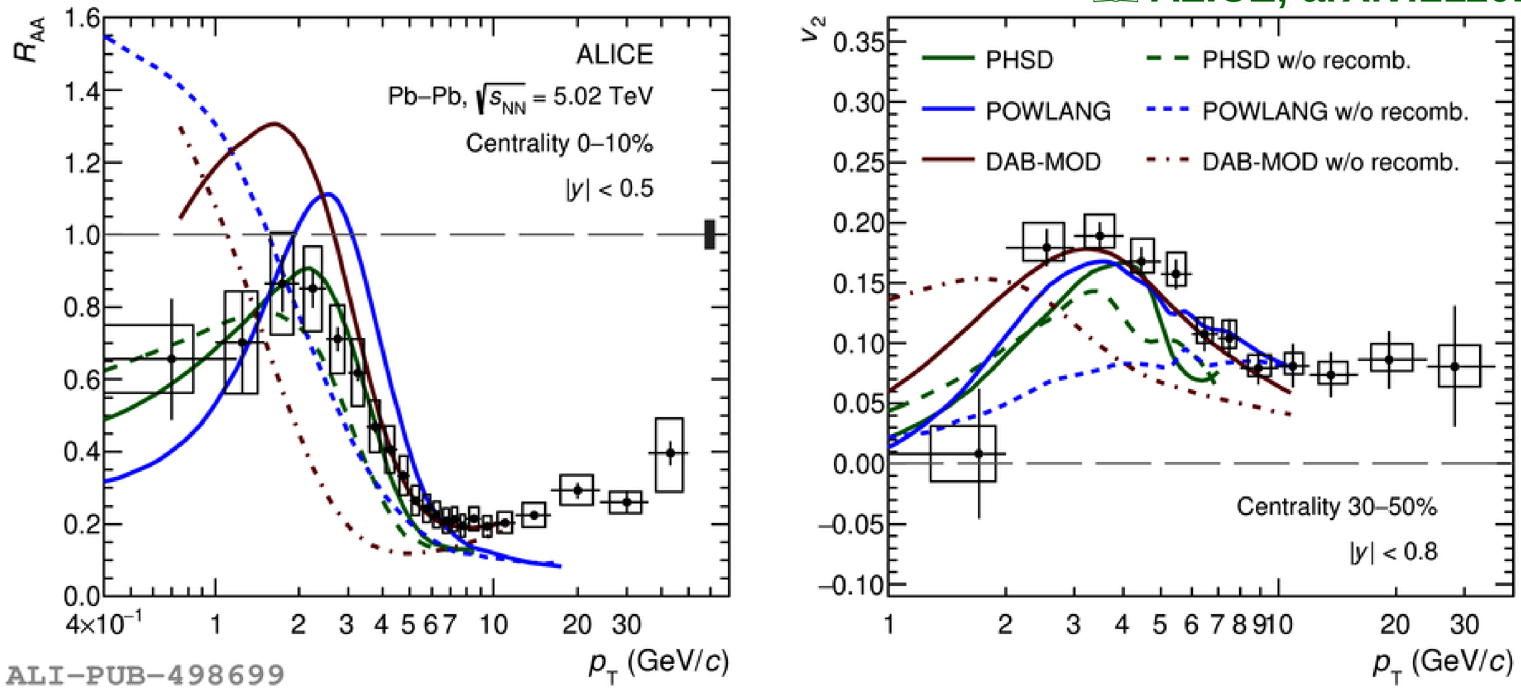
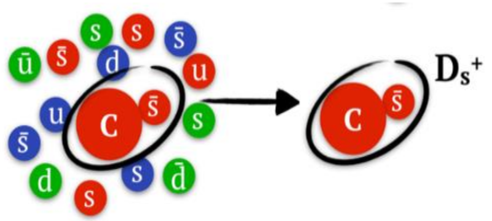
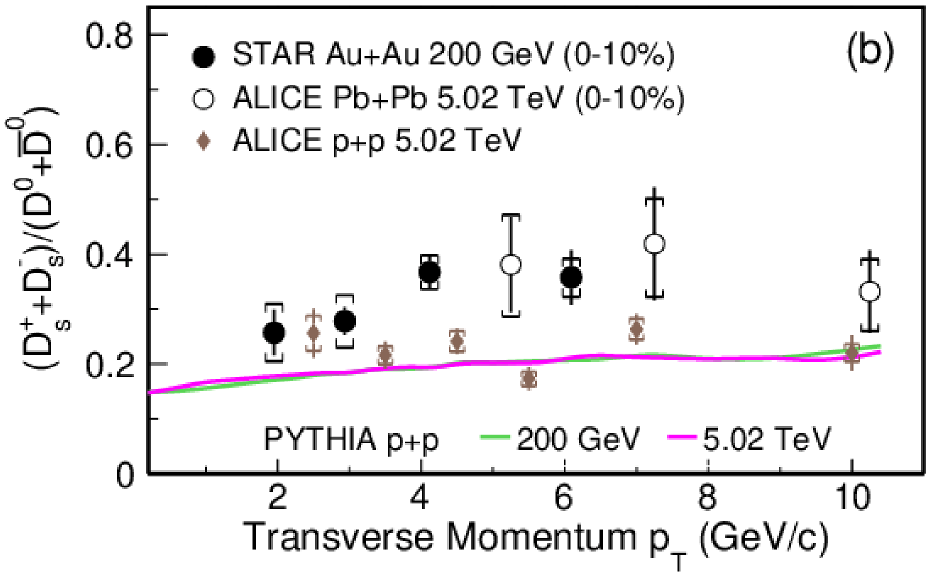
📖 **ALICE, arXiv:2110.09420**

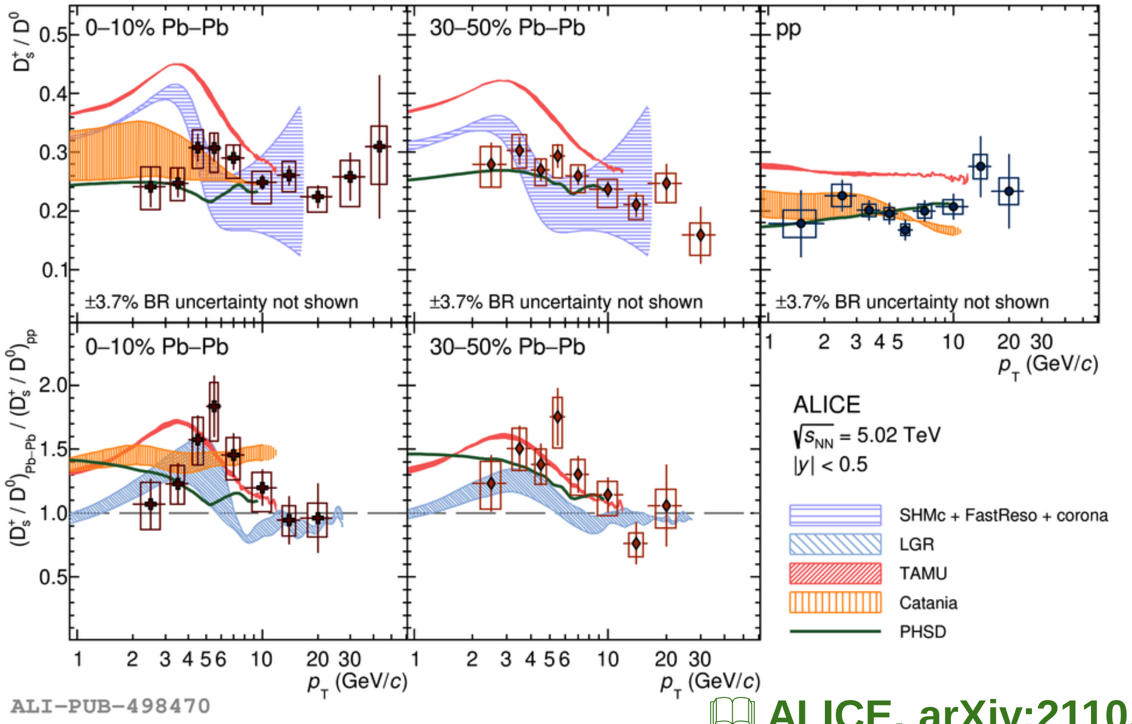


Open charm hadrochemistry: D_s/D

- Strange/non-strange meson (D_s/D^0) ratios in A-A collisions at LHC and RHIC hint at an enhancement at low/mid p_T relative to pp
  - ⇨ **Consistent with the recombination picture**
  - ⇨ Strange quarks abundant in QGP, D_s yield relative to non-strange D enhanced by recombination
    - 🕮 **Kuznetsova, Rafelski, EPJ C51 (2007) 113**
    - 🕮 **Andronic et al., PLB659 (2008) 149**





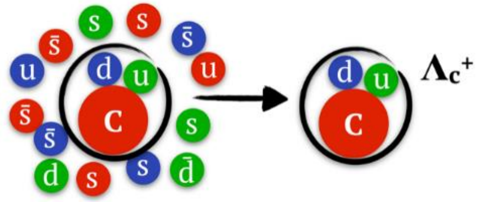


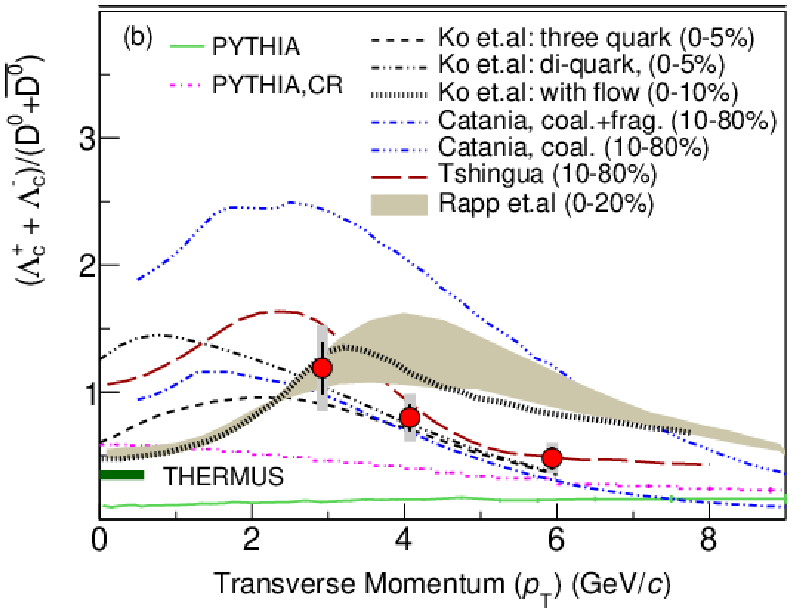
🕮 **STAR, PRL 127 (2021) 092301**

🕮 **ALICE, arXiv:2110.10006**

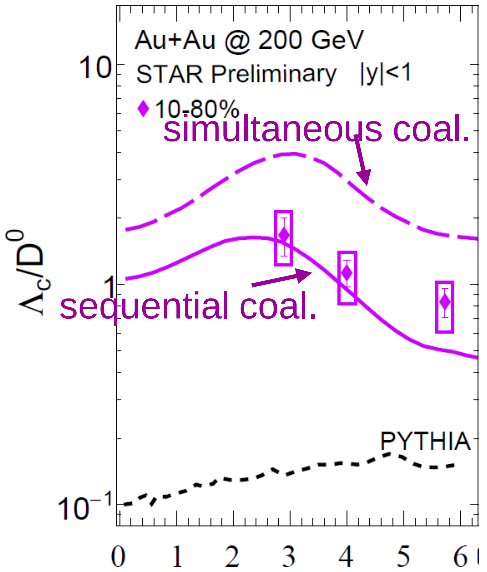
Open charm hadrochemistry: baryon/meson

- Baryon/meson (Λ_c/D^0) ratios in A-A collisions at LHC and RHIC hint at an enhancement at low/mid p_T relative to pp
  - ⇨ **Consistent with the recombination picture**
  - ⇨ Described by different models including hadronization via recombination
    - ✓ Role of diquarks and sequential vs instantaneous coalescence
  - ⇨ Crucial to understand production in pp collisions!

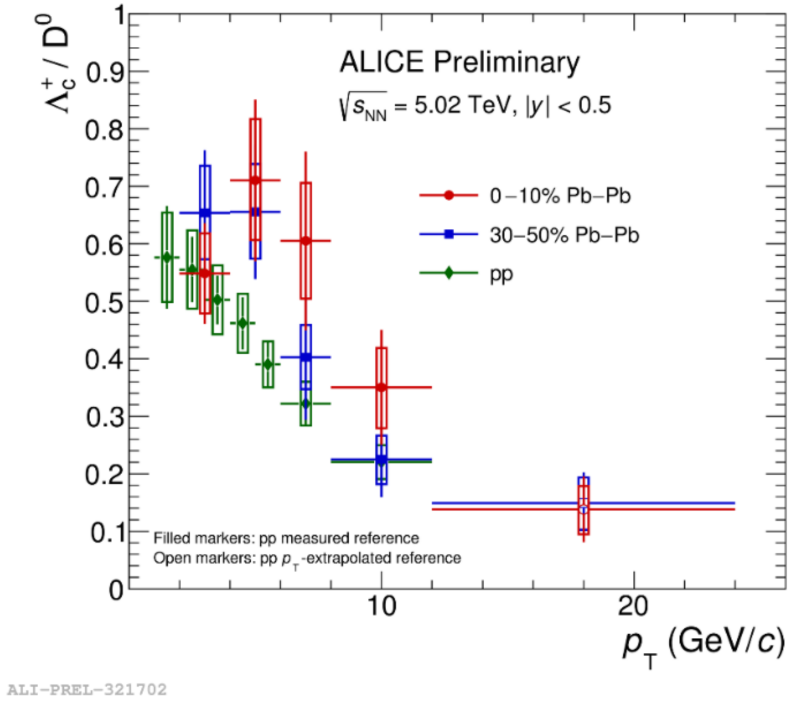




📖 STAR, PRL 124 (2020) 172301

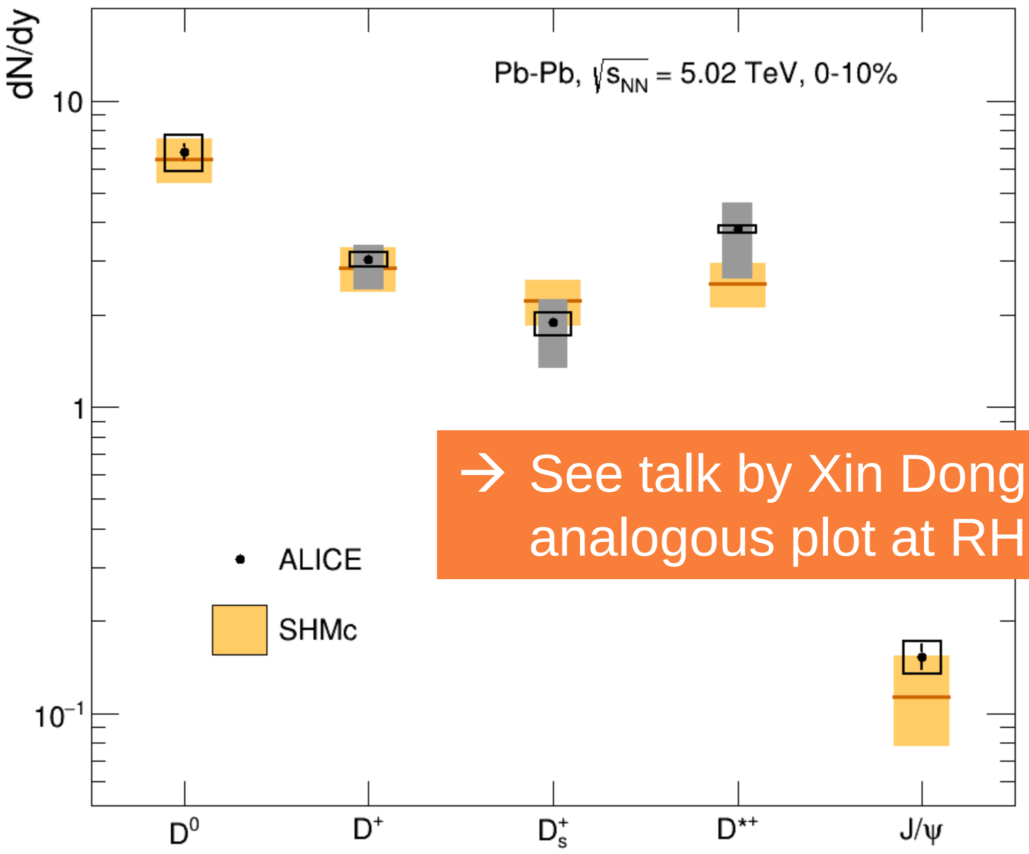


📖 Zhao et al.: arXiv:1805.10858



Charm hadron yields vs SHM

- Yield of D-meson and J/ψ at midrapidity integrated over p_T published by ALICE
  - ⇨ No extrapolation to p_T=0 needed for D^0 and J/ψ
  - ⇨ For D^+, D_s and D^{*+} the extrapolation was based on the ratios to D^0 in the measured p_T intervals
- SHMc describes the data within uncertainties
  - ⇨ Under the hypothesis of charm quark thermalisation in the fireball
  - ⇨ NOTE: SHMc predictions used $(d\sigma_{cc}/dy)_{PbPb}$=0.532±0.096 mb to calculate the charm content of the fireball
    - ✓ Based on measured charm cross section in pp collisions and parameterization of nPDFs
    - ✓ The pp measurements used as input did not include (yet) the information on enhanced baryon production in pp at LHC as compared to e^+e^-
    - ✓ The SHMc yields would increase if the recent measurement of $d\sigma_{cc}/dy$ in pp were used as input

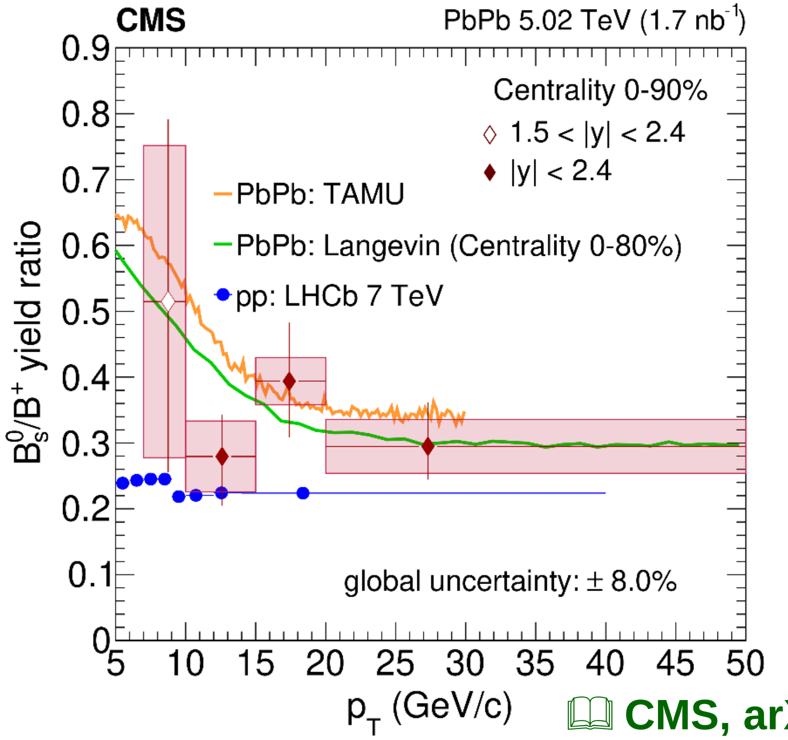


→ See talk by Xin Dong for analogous plot at RHIC

📖 ALICE, arXiv:2110.09420
📖 ALICE, arXiv:2110.10006
📖 ALICE, PLB 805 (2020) 135434
📖 Andronic et al, JHEP 07 (2021) 035

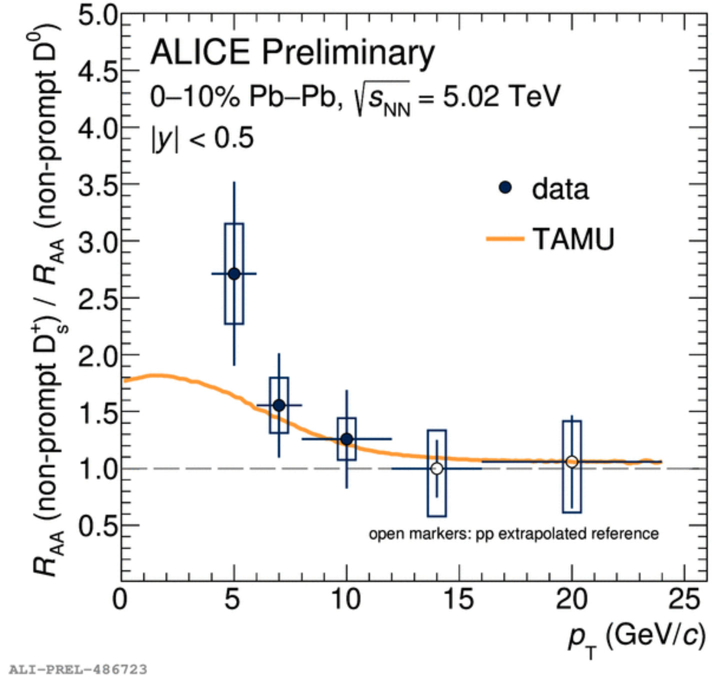
Open beauty hadrochemistry

- B_s and B^+ mesons measured in Pb-Pb collisions at the LHC
  - ⇨ B_s / B^+ in Pb-Pb tend to lie systematically above the pp value, but uncertainties prevent from concluding on the enhancement expected from b-quark recombination



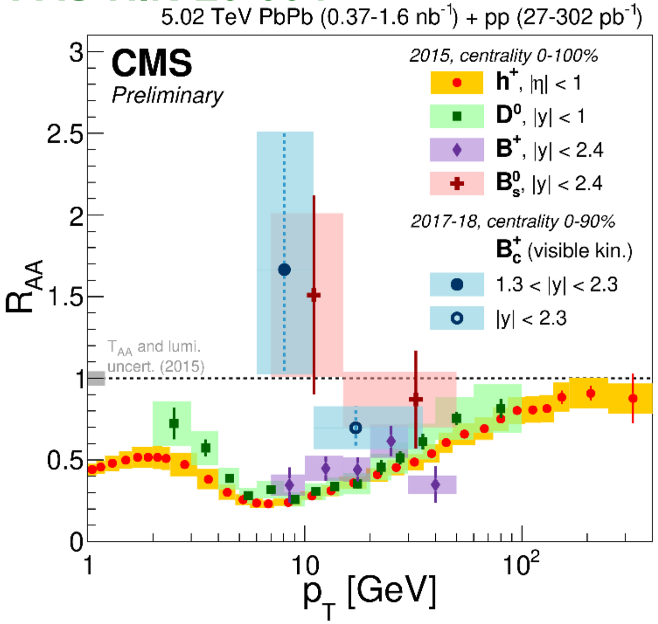
📖 **CMS, arXiv:2109.01908**

- Non-prompt D^0 and non-prompt D_s in Pb-Pb collisions at the LHC
  - ⇨ Hint for increased non-prompt D_s yield relative to non-prompt D^0
  - ⇨ Non-prompt D_s originating 50% from B_s decays and 50% from B^0 and B^+ decays

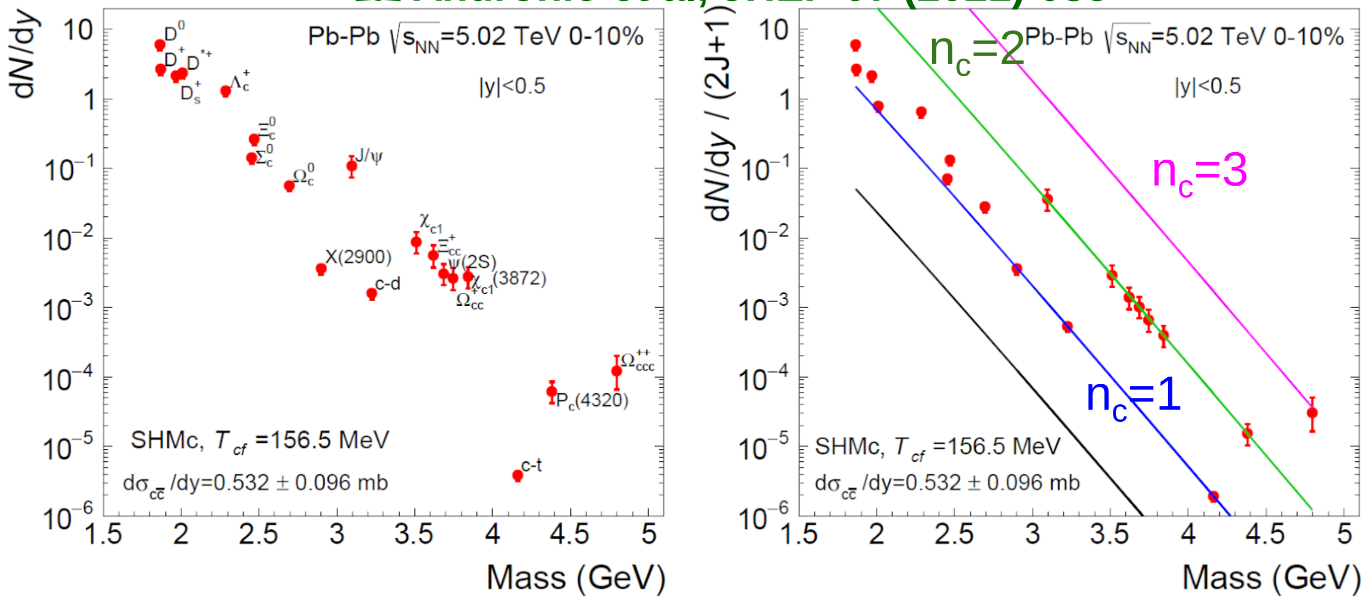


Outlook: multi heavy-flavours

📖 CMS-PAS-HIN-20-004



📖 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}^{+})
  - ⇨ Production in single-parton scattering strongly disfavoured
  - ⇨ Large enhancement in A-A collisions predicted by SHM and recombination models (x100 for Ξ_{cc})
- Multi-charm baryons in SHMc:
  - ⇨ Emergence of unique pattern due to dependence on fugacity and mass hierarchy
  - ⇨ Unique testing ground for **charm deconfinement, thermalisation and hadronization**
- Accessible with future data samples at the LHC

→ talk by G.M. Innocenti

Summary and prospects

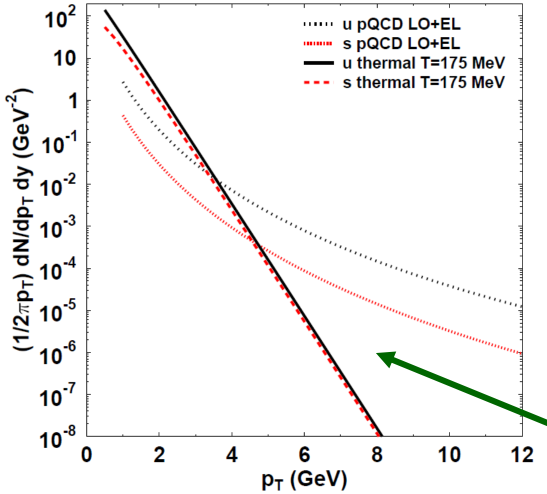
- Lot of progress from experiment and phenomenology with latest RHIC and LHC results
- Light flavour production at intermediate p_T
  - ⇨ Transition from thermal (hydro) to kinetic regime -> window on hadronization mechanism?
  - ⇨ Quark coalescence captures many features of the data
    - ✓ Modelling of several aspects needed for a quantitative description
- Heavy flavours
  - ⇨ Clear signs of recombination in J/ψ and open charm results
  - ⇨ Assessing the role of recombination in hadronization relevant for:
    - ✓ Proper comparison of the B, D and π R_{AA} to get insight into the colour charge and quark mass dependence of parton in-medium energy loss
    - ✓ Extraction of medium transport coefficients via data-to-model comparison
  - ⇨ Charm-hadron yields vs SHMc provide complementary information on charm quark thermialization
- Outlook:
  - ⇨ Beauty mesons, Λ_b , B_c and multi-charm hadrons can provide further insight into QGP hadronization
    - ✓ Accessible with precision with future large A-A data sets
  - ⇨ Hadronisation in (high-multiplicity) p-A (d-A) and pp collisions
    - ✓ Link between color-reconnection in string models and recombination?

→ talk by G.M. Innocenti
→ talk by Z. Conesa

Backup

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

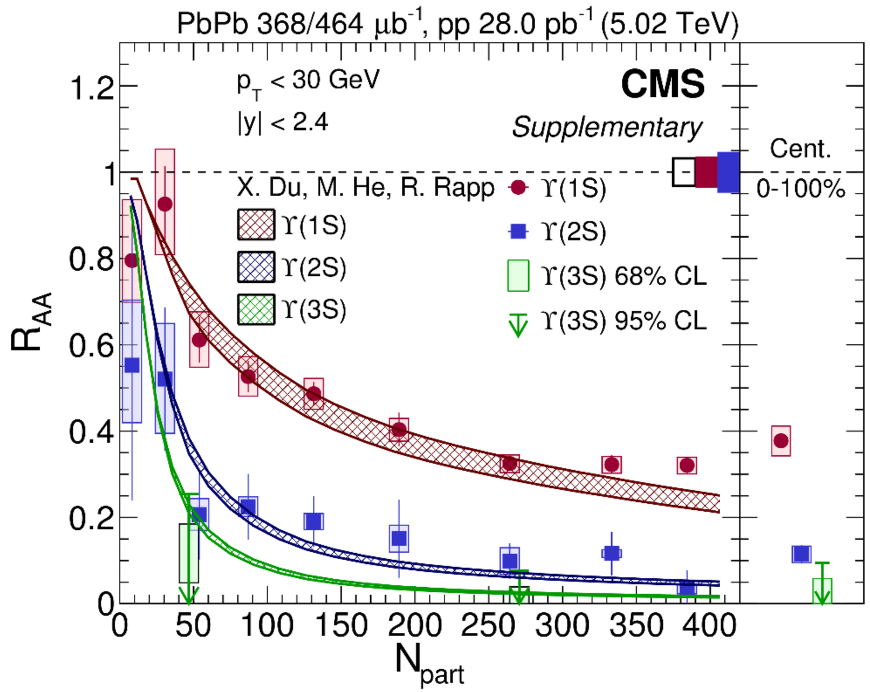


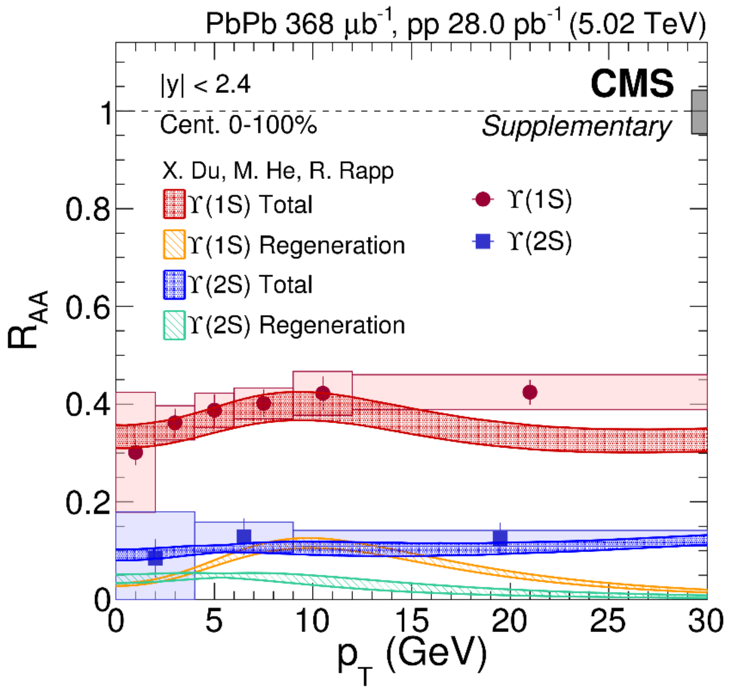
- Projection of parton states into hadron states:
  - ⇨ Phase space at hadronisation filled with partons
  - ⇨ Very rapid freeze-out → instantaneous recombination on infinitely thin hypersurface
  - ⇨ Quarks are dressed (constituent quarks)
  - ⇨ Gluons are split into quark-antiquark pairs (no dynamical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

parton distributions **Hadron Wigner function**

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

Bottomonium R_{AA}





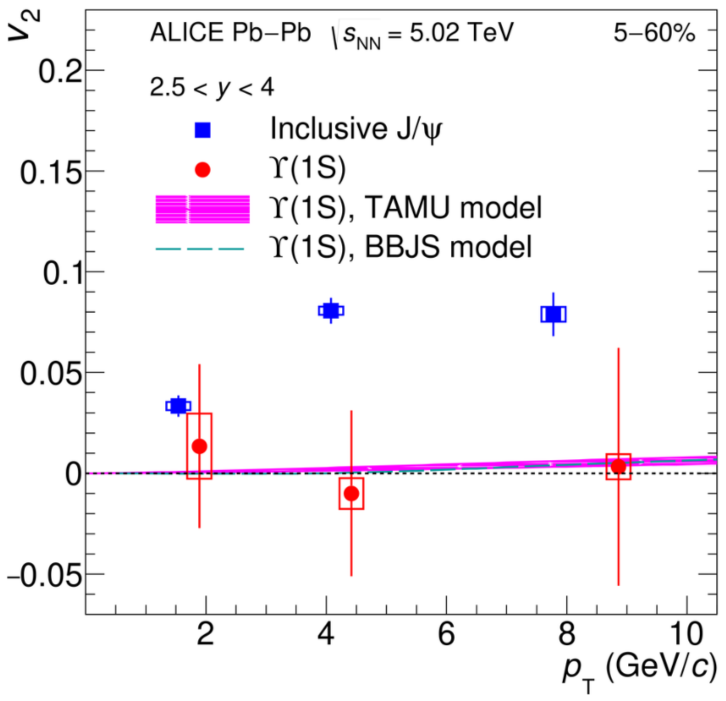
- Sequential suppression pattern: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
  - ⇨Ordered by binding energy, as expected from dissociation in QGP
- Described by transport models
  - ⇨Small contribution from $b\bar{b}$ recombination
    - ✓ *Beauty quarks less abundant than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

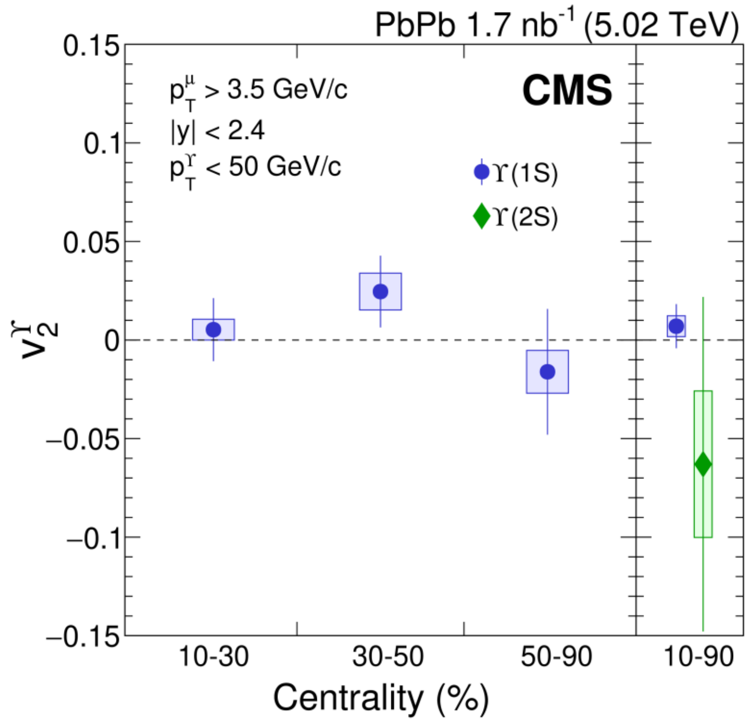
CMS, PLB790 (2019) 270

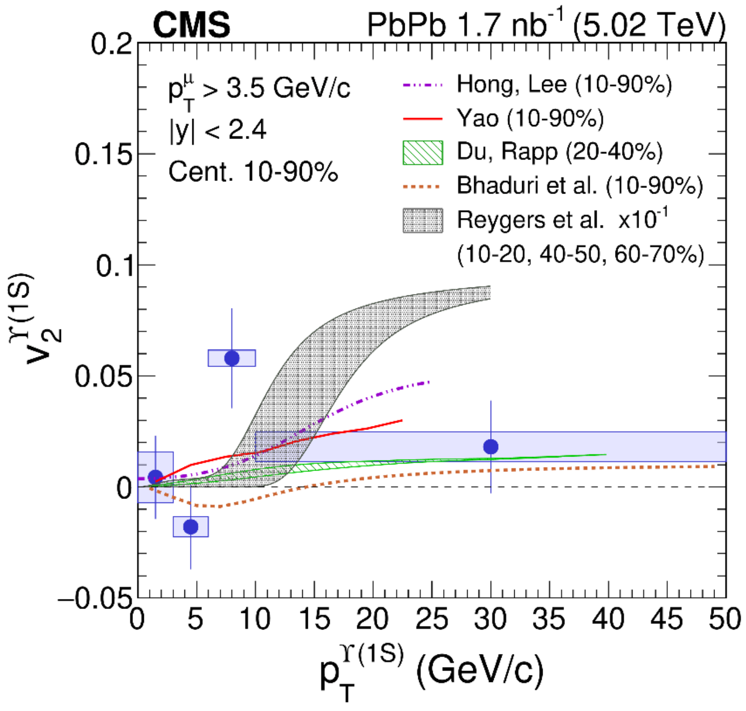
Du et al., PRC96 (2017) 054901

Bottomonium v_2 in A-A collisions

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





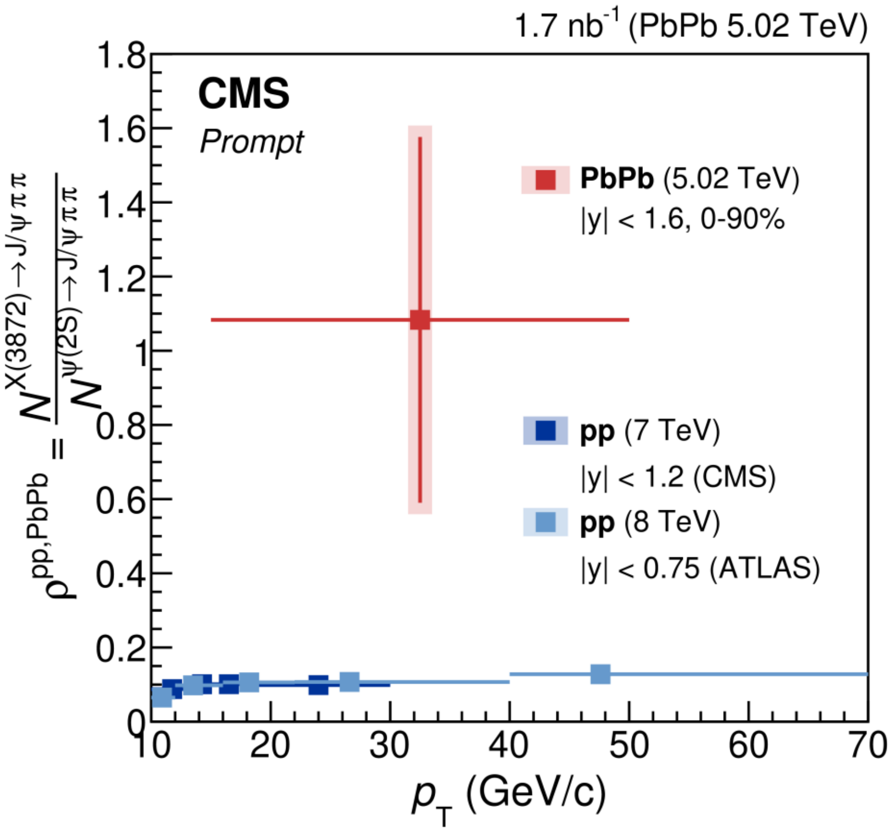


📖 **ALICE, PRL 123 (2019) 192301**

📖 **CMS, PLB819 (2021) 136385**

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, arXiv:2102.13048**