Hadronisation of the QGP

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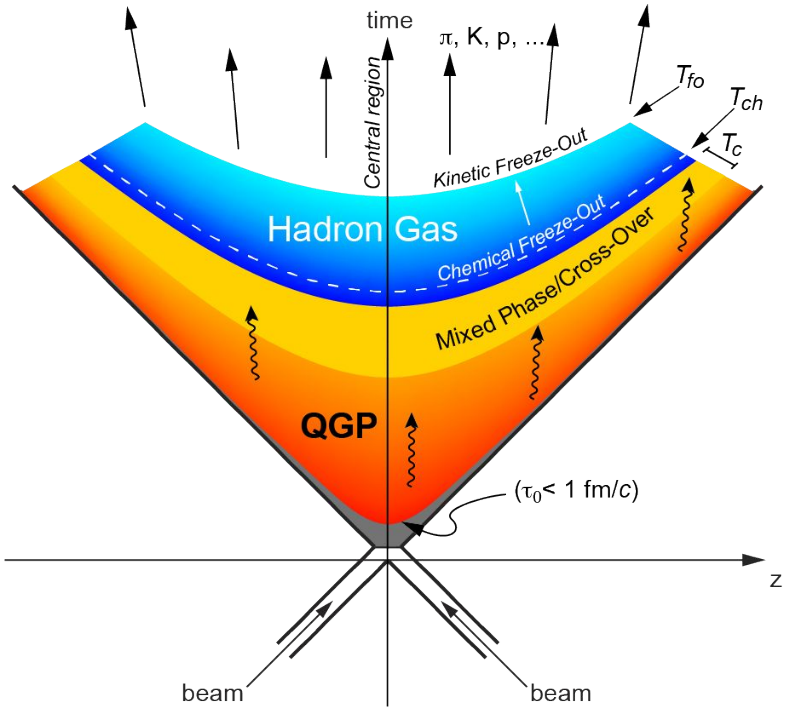


- Hadronization of the QGP medium at the pseudo-critical temperature
  - Transition from a deconfined medium composed of quarks, antiquarks and gluons to color-neutral hadronic matter
  - The partonic degrees of freedom of the deconfined phase convert into hadrons, in which partons are confined
- No first-principle description of hadron formation
  - Non-perturbative problem, not calculable with QCD

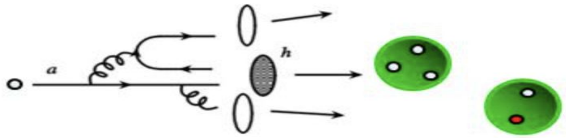
→ Hadronisation from a QGP may be different from other cases in which no bulk of thermalized partons is formed

Independent fragmentation

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

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

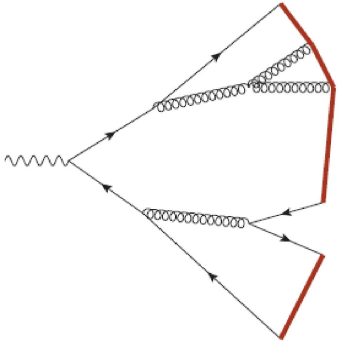
- Description of hadronisation effects (heavy quark to meson or baryon) must necessarily resort to models and make use of phenomenological parameters
- **Fragmentation functions** $D_{q\to h}$ are phenomenological functions to parameterise the *non-perturbative parton-to-hadron transition*
  - z = fraction of the parton momentum taken by the hadron h
  - Do not specify the “microscopic” hadronisation mechanism
  - Parametrised on data and assumed to be “universal”



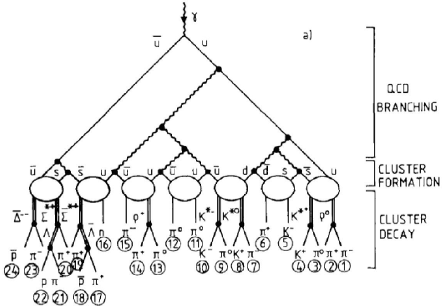
Hadrons from parton showers

- On a microscopic level hadronisation of jets modeled with:
  - Perturbative evolution of a parton shower with DGLAP down to a low-virtuality cut-off 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



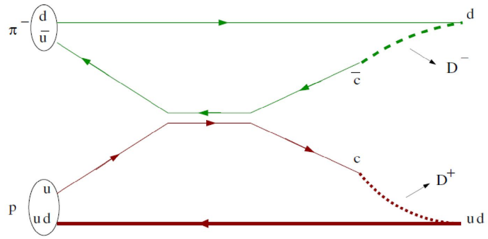
- **Cluster decay** in HERWIG
  - Shower evolved up to a softer scale
  - All gluons forced to split into $q\bar{q}$ pairs
  - Identify colour-singlet clusters of partons following color flow
  - Clusters decay into hadrons according to available phase space

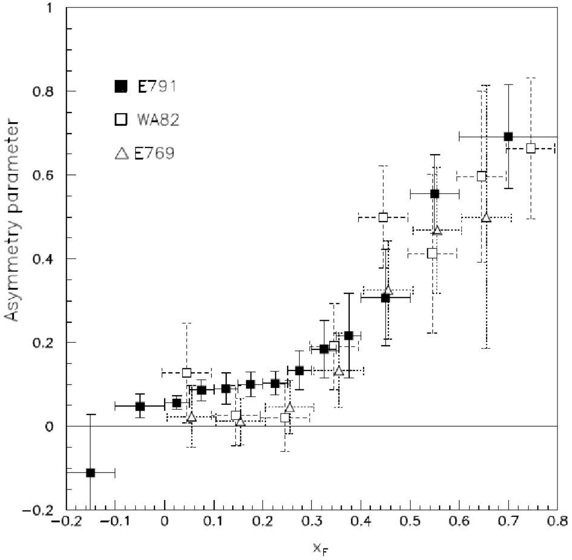


Leading particle effect

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

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



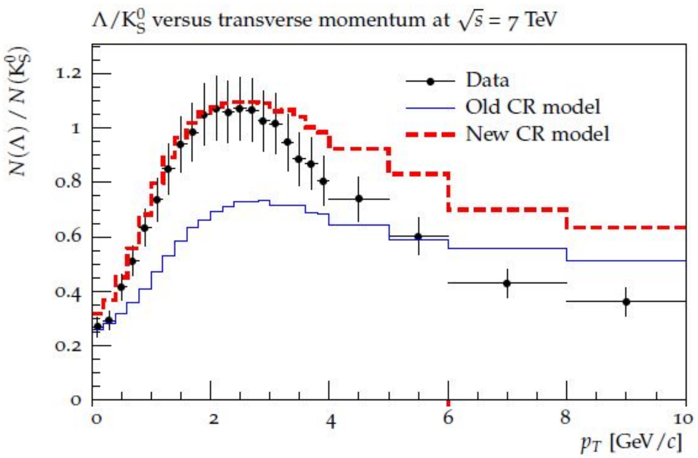


- Measurements of charm production in pion-nucleon collisions
- At **large x_F** : favoured production of hadrons sharing valence quarks with beam hadrons
  - D^- ([$\bar{c}d$], leading meson shares the d quark with the π^- projectile) favored over D^+ [$c\bar{d}$]
- Break-up of independent fragmentation

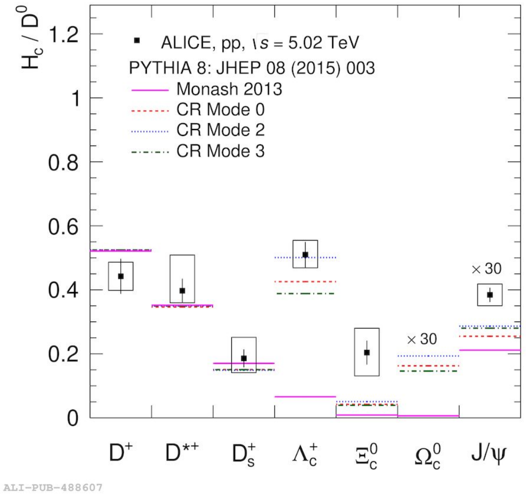
→ A reservoir of particles leads to significant changes in hadronisation

Color reconnection

📖 **Christiansen Skands, JHEP 08 (2015) 003**



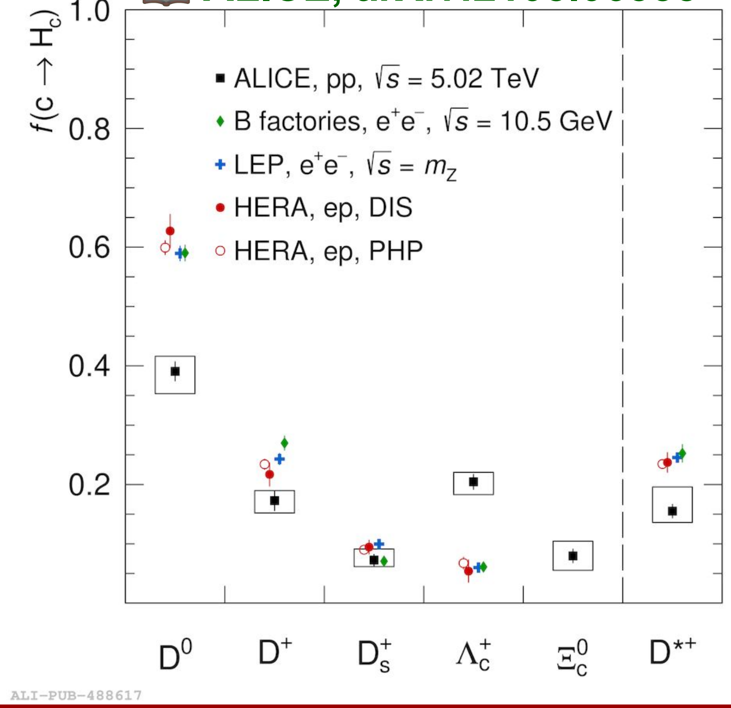
📖 **ALICE, arXiv:2105.06335**



- Baryon/meson ratios underestimated by PYTHIA tuned on e^+e^-
- Better description with Color Reconnection beyond the leading color
  - Suggests that single-particle independent-fragmentation picture is not valid in a hadronic (color-rich) environment

Fragmentation universality?

📖 ALICE, arXiv:2105.06335

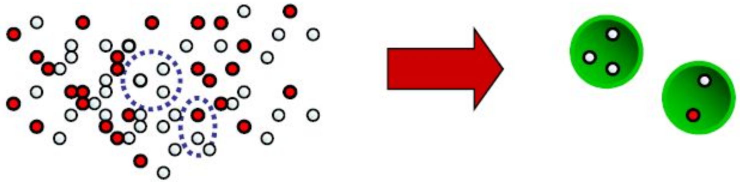


- Evidence of for different fragmentation fractions in pp collisions at LHC and e^+e^- (ep) collisions at lower √s
  - Indication that parton-to-hadron fragmentation depends on the collision system
  - Assumption of their universality not supported by the measured cross sections

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

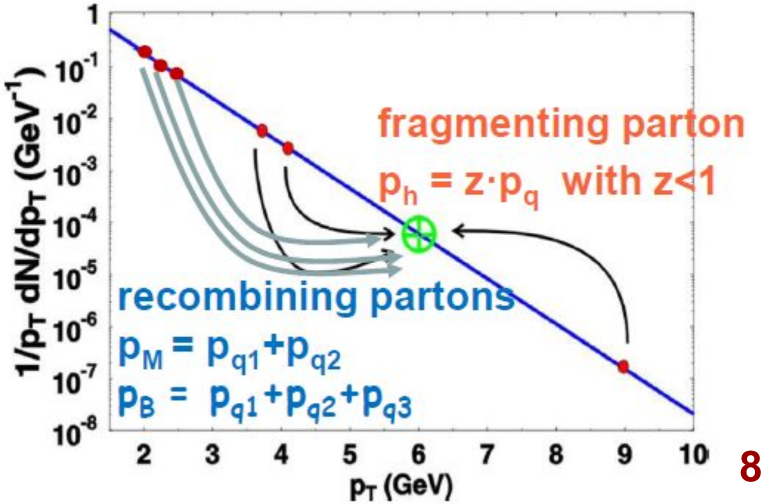
Quark recombination

- Phase space at the QGP hadronization is filled with 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



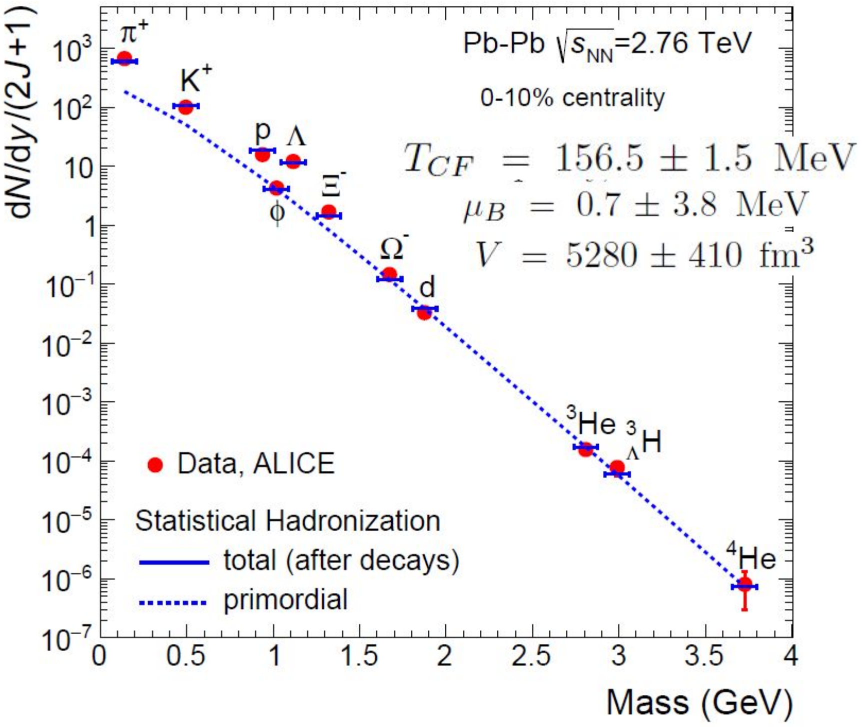
📖 Greco et al., PRL 90 (2003) 202302

📖 Fries et al., PRL 90 (2003) 202303



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

Statistical hadronisation

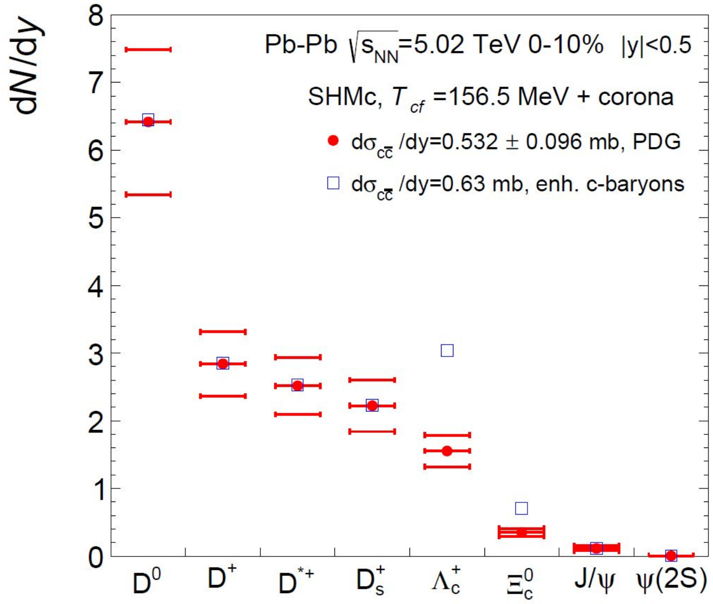


📖 **Andronic et al, Nature 561 (2018) 7723, 321**

- 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_c ~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

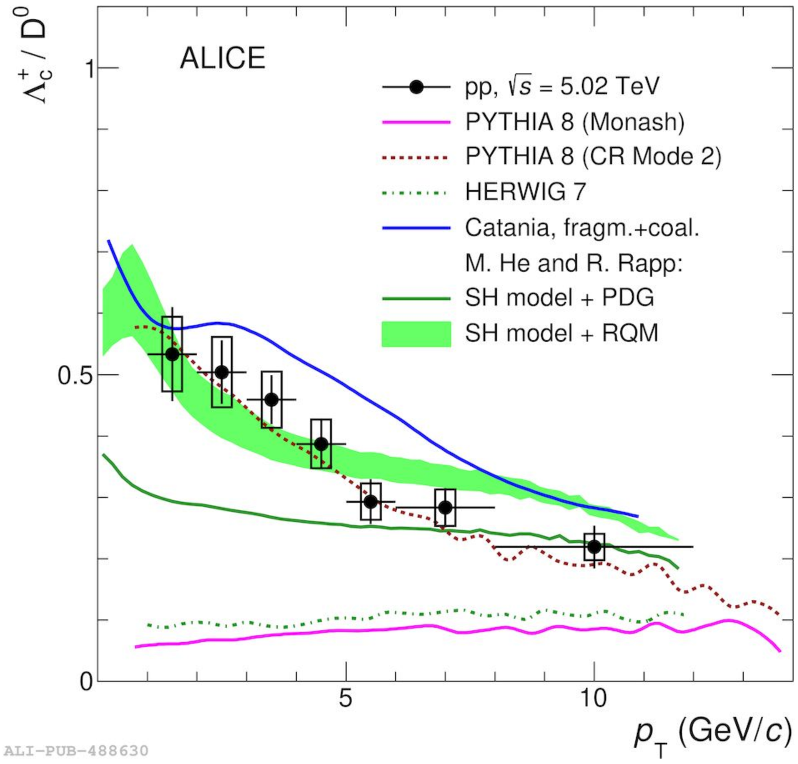
- Charm quarks produced in initial hard scatterings and conserved while traversing the QGP
  - Initial production from pQCD
  - Total yield determined by **charm cross section**, not by the fireball temperature.
  - Accounted for by **charm balance equation** leading to a *fugacity* g_c, which ensures 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**

Baryon/meson ratios in pp: models

📖 **ALICE, arXiv:2011.06078**



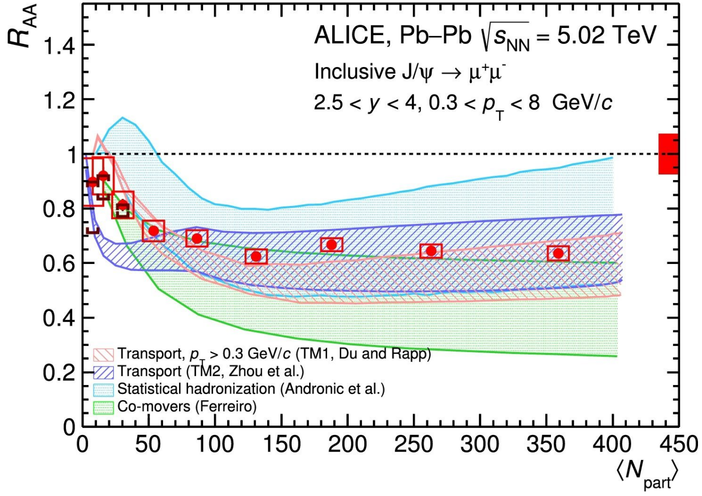
- Λ_c/D^0 ratio in pp captured by:
  - PYTHIA (pp paradigm) with CR beyond leading colour
    - i.e. including "interactions" among partons from different MPIs
  - Extensions of models typically used for A-A (QGP paradigm)
    - SHM (with additional baryonic states, important to describe the data)
    - Recombination
- More insight from: Ξ_c/D^0, Σ_c/D^0 (and Ω_c/D^0) 📖 **ALICE, arXiv:2106.08278**

Considerations

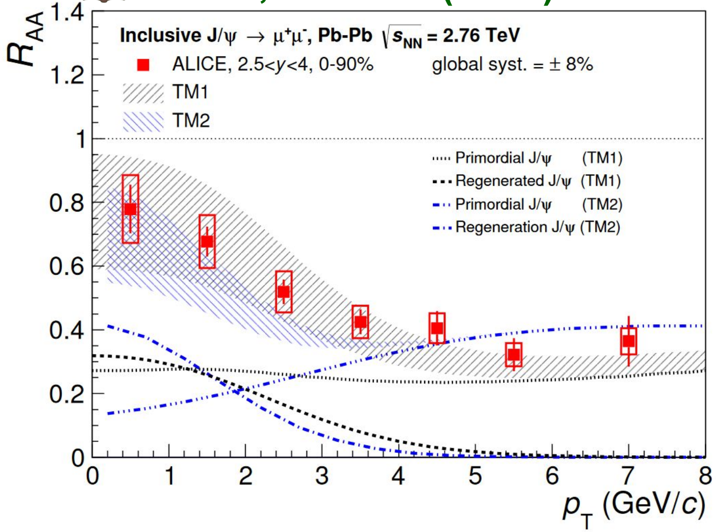
- **Color reconnection** beyond the leading colour are essentially an "interaction" between partons produced in different hard scatterings (**MPIs**)
  - Analogies with the coalescence mechanism
- Recombination has aspects in common with cluster hadronization model of HERWIG
- **Recombination/coalescence** can be seen as a *"dense" limit of hadronization*, as opposed to single parton fragmentation
- The coalescence 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 thermalisation of quarks in coalescence approach
    - Even though light quark spectra in the region where coalescence dominates are commonly taken from a thermal spectrum

Heavy quark hadronisation in Pb-Pb

📖 ALICE, PLB 766 (2017) 212



📖 ALICE, JHEP05 (2016) 179



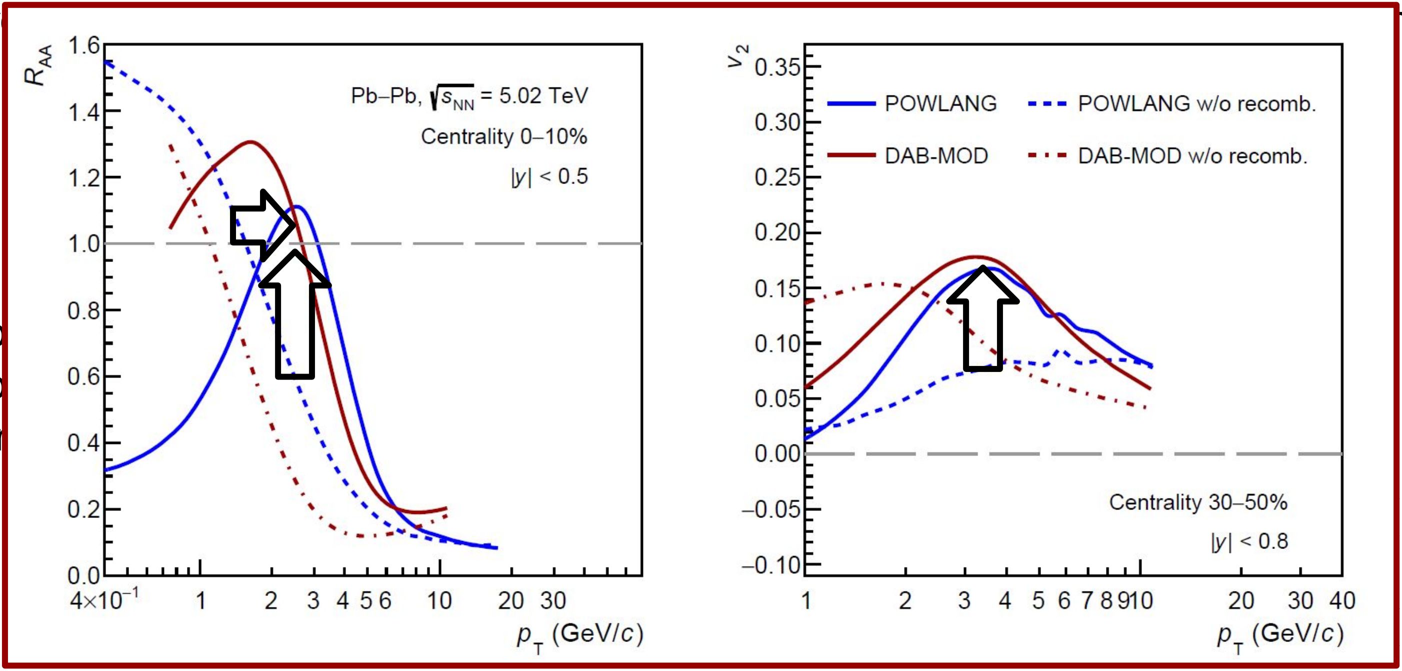
- Evidence from LHC results that charmonia are produced via **(re)combination of $c\bar{c}$ pairs originating from two independent hard scattering processes**
- Data described by:
  - SHM: melting of initially produced $c\bar{c}$ + combination at phase boundary
  - Transport models with in-medium charmonium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

Heavy quark hadronisation in Pb-Pb

- Hadronization of heavy quarks via recombination with light quarks from the QGP modifies:
  - **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 $\mathbf{D_s}$ $\mathbf{(B_s)}$ yield relative to non-strange mesons
- 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
- Different implementations in different transport models:
  - **Instantaneous coalescence** at the phase boundary based on Wigner function — 📖 **Scheibl, 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**

Heavy quark hadronisation in Pb-Pb

- Hadr... modifies:
  -
  -



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  - ... 1999) 1585
  - ... 2007) 126
  - **In-medium string formation** between heavy ... 121

→ Crucial to have hadronisation under control to estimate QGP transport coefficients from HF data-to-model comparison

Heavy quark hadronisation in Pb-Pb

- Hadronization of he ... m the QGP modifies:
  - **Momentum d**
    - HF hadr ... uark
  - **Hadrochemis** ... species)
    - Enhance
    - Enhance
- Recombination for ... nt flavours
- Recombination for ... r
- Different implemen
  - **Instantaneou** boundary bas ... nz, PRC 59 (1999) 1585
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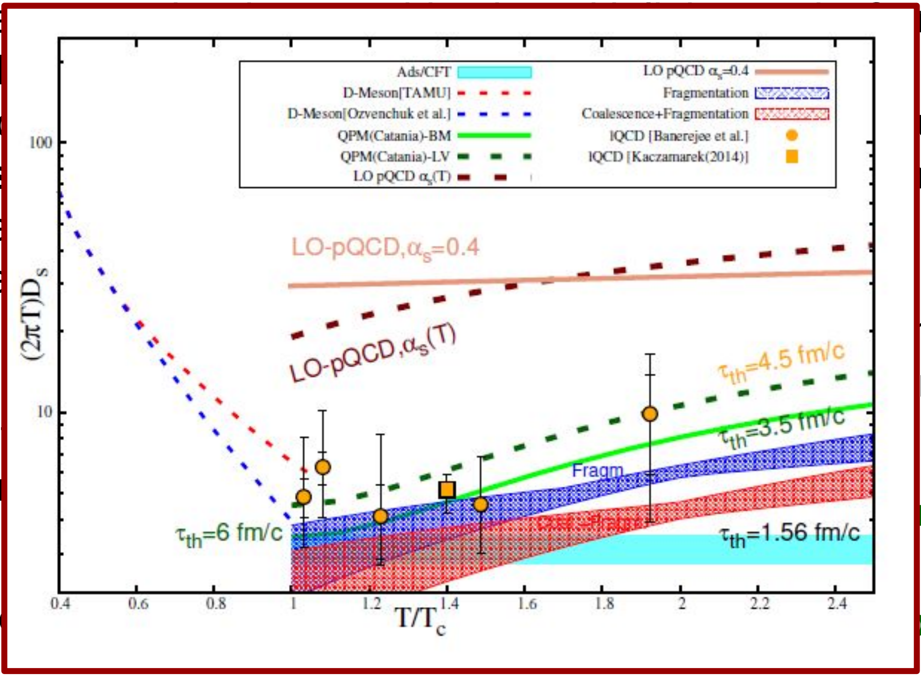
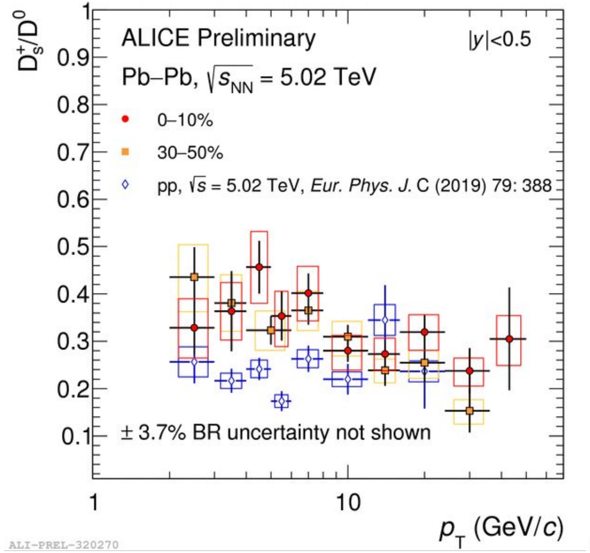


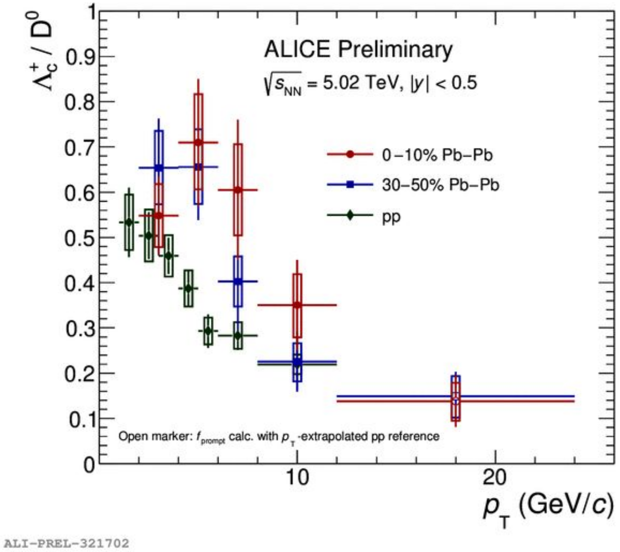
see talk by S. Bass

→ Crucial to have hadronisation under control to estimate QGP transport coefficients from HF data-to-model comparison

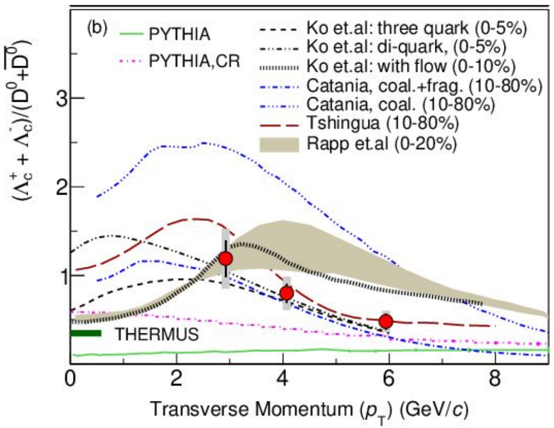
Charm hadrochemistry

- Baryon/meson and D_s/D ratios in Pb-Pb collisions from LHC Run-2 (and RHIC) hint at an enhancement at low/mid p_T, **consistent with the recombination picture**
- Precise measurements of charmed hadrons in Run-3 and Run-4 crucial to:
  - Assess the role of recombination
  - Improve phenomenological extraction of QGP transport properties (e.g. spatial diffusion coefficient D_s)





📖 STAR, PRL 124 (2020) 172301

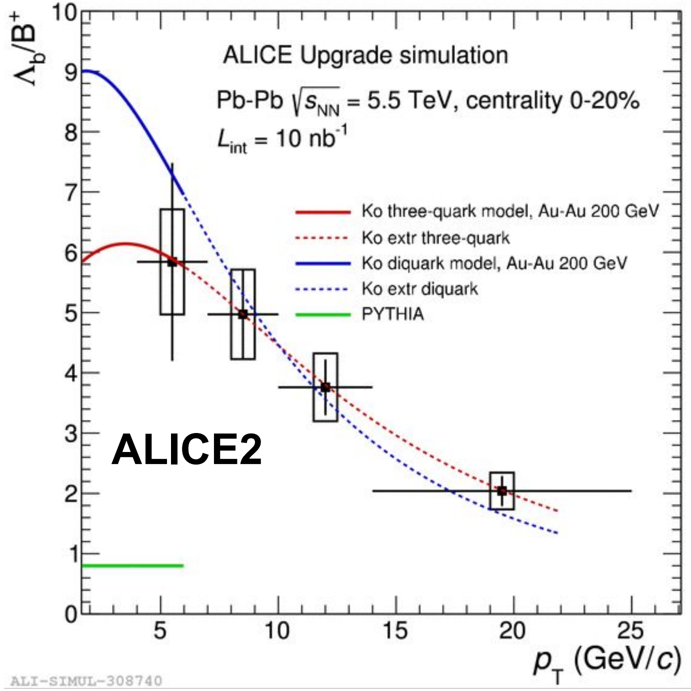


Beauty hadronisation in Pb-Pb

- More sensitive extraction of the spatial diffusion coefficient D_s via **data-to-model comparison** of **beauty** hadrons as compared to charm
  - Better controlled theoretical calculation of the transport coefficient
  - More robust modelling of their transport (Boltzmann/Langevin) in the QGP
  - Larger mass (~3x charm quark mass) -> longer relaxation time ($>\tau_{QGP}$)
    - Preserve stronger memory of the thermalisation process providing enhanced sensitivity on their coupling strength
- Need to have under control b quark hadronisation
  - Crucial to measure beauty-hadrons down to low p_T (<5-10 GeV/c)
- Combined measurement of **beauty-hadron $\mathbf{R_{AA}}$** and $\mathbf{v_n}$ and the relative abundances of different beauty-hadron species (in particular **baryon-to-meson** ratios) down to low p_T crucial to simultaneously constrain the **heavy-quark diffusion coefficient** and the **hadronisation mechanism** in the beauty sector

Beauty hadronisation in Pb-Pb

- ALICE3 in Run-5: ideal setup for full reconstruction of beauty baryons from their hadronic decays
  - Low production rate, very small branching ratios, and several particles in the final state



- For instance: reconstruction of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ (BR=4.9 10^{-3})
  - Will be affected by large uncertainties and limited to p_T>4-5 GeV/c in Run3 and Run4
  - With ALICE3 it will greatly benefit from the large improvement in $\Lambda_c^+ \rightarrow pK\pi$ purity

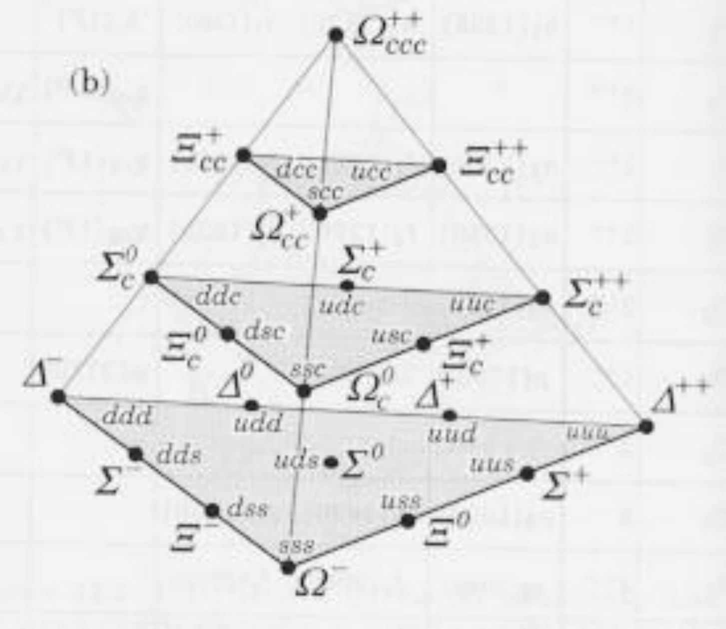
see talk by G.M. Innocenti

📖 **Citron et al., CERN Yellow Rep. 7 (2019) 1159**

Multi-charm hadron yields

- Crucial new insight by measuring **baryons** containing **multiple charm quarks** (Ξ_{cc}^{+}, Ξ_{cc}^{++}, Ω_{cc}^{+}, Ω_{ccc}^{++}, and T_{cc}^{+})
  - Production in single-parton scattering strongly disfavoured as compared to single-charm Λ_c^+ baryons
  - Yields of multicharm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models

📖 **Becattini, PRL 95 (2005) 022301**
📖 **He et al., PLB 746 (2015) 59**
📖 **Yao, Muller, PRD 97 (2018) 074003**
📖 **Cho, Lee, PRC 101 (2020) 024902**
📖 **Andronic et al, JHEP 07 (2021) 035**



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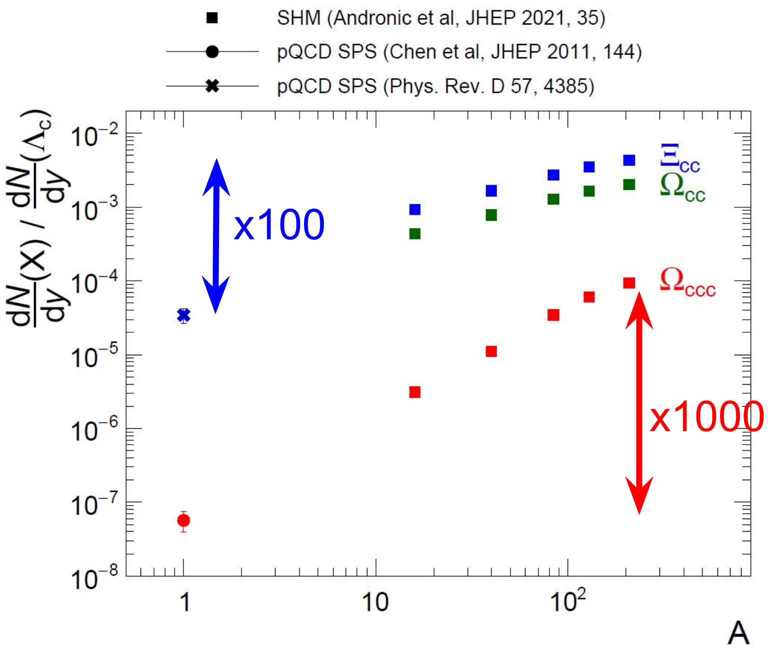
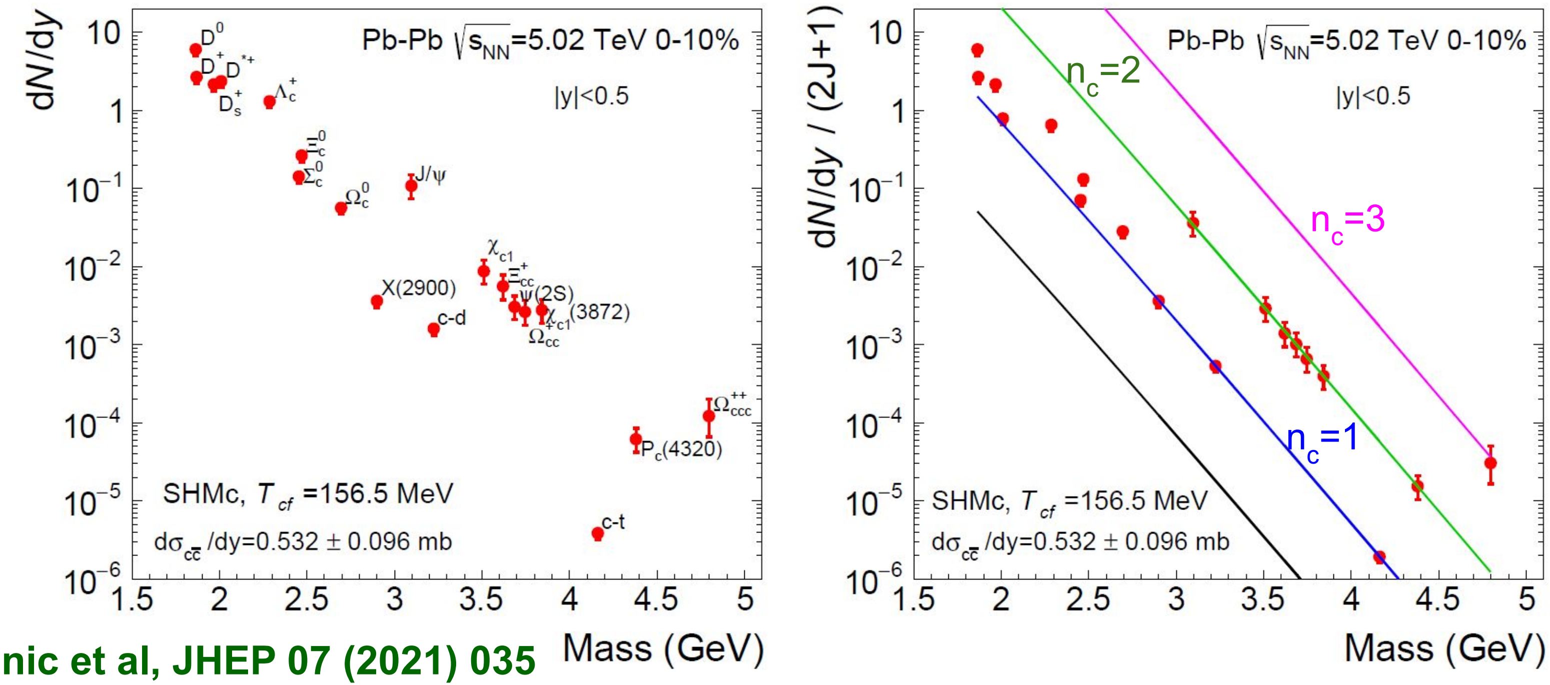
  - Production in single-parton scattering strongly disfavoured as compared to single-charm Λ_c^+ baryons
  - Yields of multicharm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models
  - Factor of about 100 for Ξ_{cc} and up to about 1000 for the yet undiscovered Ω_{ccc}
- **Direct window on hadron formation from QGP**



more details in talk by D. Chinellato

Multi-charm baryons in SHMc

- Emergence of unique pattern, due to g_c^n and mass hierarchy
- Unique testing ground for **charm deconfinement and thermalisation**
  - Enhanced sensitivity to deviations from full equilibrium due to g_c^n dependence



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

Multi-charm in recombination models

- Models including hadronisation via quark coalescence predict large yields of multi-charm baryons in A-A collisions at LHC energies
  - Large abundance of charm quarks -> finite probability that two or three charm quarks from different hard scatterings coalesce into a multi-charm baryon
- In general, in the recombination approach hadron yields depend on:
  - Quark phase-space density (from transport / hydro)
  - Characteristics of hadron (radius and binding energy) usually encoded in Wigner function

$$\frac{dN_{\Xi_{cc}}}{dp_{\mathrm{T}}} \propto \int f_l(x_l, p_l) f_c(x_c, p_c) f_c(x_c, p_c) W_{\Xi_{cc}}(x_1, x_2, x_3, p_1, p_2, p_3)$$

- Different approaches for multi charm hadrons in different models:
  - *Instantaneous* or "*sequential*" quark coalescence at hadronisation assuming either that charm quarks are *fully* or *partially* kinetically equilibrated in the QGP
    - 📖 **He et al., PLB 746 (2015) 59**
    - 📖 **Zhao et al, PLB 771 (2017) 349**
    - 📖 **Cho, Lee, PRC 101 (2020) 024902**
  - *In-medium dynamical evolution* in which bound *heavy diquarks* and formed and dissociated in the QGP 📖 **Yao, Muller, PRD 97 (2018) 074003**

Conclusions

- Measurements of the production of several **heavy-flavour hadron species** can provide crucial progress in the understanding of the *QGP transport properties* and the *QGP hadronisation*
  - Characterize the common microscopic dynamics underlying the interactions of heavy quarks with the QGP and their hadronisation
- **Beauty**: precise measurements of hadrochemistry, p_T spectra and v_n for different meson and baryon species down to low p_T
  - Precise determination of the QGP diffusion coefficient
- **Baryons with multiple charm quarks**
  - Direct window on hadron formation from the QGP
  - Enhanced sensitivity to the degree of equilibration of charm quarks in the medium
- ALICE3 has **unique capabilities** to perform precise measurements of these probes in LHC Run-5 and beyond