Hadronisation of the QGP

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Hadronisation 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
  - 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
  \[
  \sigma_{pp\to hx} = \text{PDF}(x_a, Q^2) \times \text{PDF}(x_b, Q^2) \times \sigma_{ab\to q\bar{q}} \times D_{q\to h}(z, Q^2)
  \]
- 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 $Q_0$
  - 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

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

→ A reservoir of particles leads to significant changes in hadronisation

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

- 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

References:
- Greco et al., PRL 90 (2003) 202302
- Fries et al., PRL 90 (2003) 202303
Statistical hadronisation

- 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 \(T_c \sim 155\) 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 $\mu_B$
- **NOTE**: significant impact of possible yet-undiscovered excited charm baryon states

![Graph showing charm particle yields](image)
Baryon/meson ratios in pp: models

- $\Lambda_c^+/D^0$ 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: $\Xi_c^+/D^0$, $\Sigma_c^+/D^0$ (and $\Omega_c^+/D^0$)


(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)

- “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

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Fries et al., PRC 68 (2003) 044902
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 $D_s (B_s)$ 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
  - **Resonance recombination** model
  - **In-medium string formation** between heavy quark and a thermal light quark from the bulk

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📖 Beraudo et al., EPJ C75 (2015) 121
📖 Scheibl, Heinz, PRC 59 (1999) 1585
📖 Ravagli, Rapp, PLB655 (2007) 126
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→ Crucial to have hadronisation under control to estimate QGP transport coefficients from HF data-to-model comparison
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See talk by S. Bass

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Ravagli, Rapp, PLB655 (2007) 126
Scheibl, Heinz, PRC 59 (1999) 1585
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 $D_s$)

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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 ($\sim 3\times$ charm quark mass) $\rightarrow$ longer relaxation time ($>\tau_{\text{QGP}}$)
    - 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 $p_T$ ($<5\text{-}10 \text{ GeV}/c$)
- Combined measurement of **beauty-hadron** $R_{AA}$ and $v_n$ 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
Crucial new insight by measuring baryons containing multiple charm quarks \((\Xi_{cc}^+, \Xi^{++}_{ccc}, \Omega^+_c, \Omega^{++}_{ccc}, \text{and } T^+_c)\)

- Production in single-parton scattering strongly disfavoured as compared to single-charm \(\Lambda^+_c\) baryons
- Yields of multicharm/single-charm hadrons predicted to be largely enhanced in \(\text{A-A}\) compared to \(\text{pp}\) 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
Multi-charm baryon yields

- Crucial new insight by measuring baryons containing multiple charm quarks ($\Xi_{cc}^+, \Xi_{cc}^{++}, \Omega_{cc}^+, \Omega_{ccc}^{++},$ and $T_{cc}^+$)
  - Production in single-parton scattering strongly disfavoured as compared to single-charm $\Lambda_c^+$ 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 $\Xi_{cc}$ and up to about 1000 for the yet undiscovered $\Omega_{ccc}$

- 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

\[
\frac{dN_{\Xi_{cc}}}{dp_T} \propto \int f_1(x_1, p_1) f_c(x_c, p_c) f_c(x_c, p_c) W_{\Xi_{cc}}(x_1, x_2, x_3, p_1, p_2, p_3)
\]

- 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