Heavy-flavour meson and baryon production in high-energy nucleus-nucleus collisions

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Heavy-particle diffusion: physics motivation

**Goal:** getting access to the **microscopic properties of the background medium** in which the Brownian particle propagates

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- Perrin (1909): proving the granular structure of matter and providing an estimate of the Avogadro number

\[ N_A = \frac{\mathcal{R} T}{6\pi a \eta D_s} \approx 5.5 - 7.2 \cdot 10^{23} \]
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- Perrin (1909): proving the **granular structure of matter** and providing an estimate of the **Avogadro number**

\[ N_A = \frac{RT}{6\pi a \eta D_s} \approx 5.5 - 7.2 \cdot 10^{23} \]

- 100 years later: getting an estimate of similar accuracy of some transport coefficients, like e.g. the **momentum broadening**

\[ \kappa = \frac{2T^2}{D_s} \]
A crucial difference

In HF studies in nuclear collisions the nature of the Brownian particle changes during its propagation through the medium:

- possible thermal mass-shift (here neglected)
- hadronization (impossible to neglect)
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- hadronization (impossible to neglect)
  - source of systematic uncertainty in extracting transport coefficients;
  - an issue of interest in itself: how quark → hadron transition changes in the presence of a medium (the topic of this talk)
HF hadronization: experimental findings

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- baryon enhancement observed also in $pp$ collisions: is a dense medium formed also there? Breaking of factorization description in $pp$ collisions

$$d\sigma_h \neq \sum_{a,b,X} f_a(x_1) f_b(x_2) \otimes d\hat{\sigma}_{ab \rightarrow c\bar{c}X} \otimes D_{c \rightarrow h_c}(z)$$
Grouping colored partons into color-singlet structures: strings (PYTHIA), clusters (HERWIG), hadrons (coalescence).
Hadronization models: common features

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Grouping colored partons into color-singlet structures: strings (PYTHIA), clusters (HERWIG), hadrons (coalescence). Partons taken in “elementary collisions”: from the hard process, shower stage, underlying event and beam remnants;

in heavy-ion collisions: from the hot medium produced in the collision. NB Involved partons closer in space in this case and this has deep consequence!
Our new hadronization model

Once a $c$ quark reaches a fluid cell at $T_H = 155$ MeV it is recombined with a light antiquark or diquark, assumed to be thermally distributed (for more details see A.B. et al., 2202.08732 [hep-ph]).

1. Extract the medium particle species according to its thermal weight

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2. Extract its thermal three-momentum in the LRF of the fluid;

3. Boost the thermal particle to the LAB frame and recombine it with the HQ, constructing the cluster $C$;

4. Evaluate cluster mass $M_C$. If $M_C$ is smaller than lightest charmed hadron in that channel go back to point 1, otherwise go to point 5;

5. Introduce intermediate cutoff $M_{\text{max}} \approx 4$ GeV (as in HERWIG) and simulate cluster decay, depending on its invariant mass:

   - Light clusters ($M_C < M_{\text{max}}$) undergo isotropic two-body decay in their own rest frame, as in HERWIG;
   - Heavier clusters ($M_C > M_{\text{max}}$) undergo string fragmentation into $N$ hadrons, as in PYTHIA.
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Cluster mass distribution

<table>
<thead>
<tr>
<th>Species</th>
<th>$g_s$</th>
<th>$g_I$</th>
<th>$M$ (GeV)</th>
<th>$h_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$</td>
<td>2</td>
<td>2</td>
<td>0.33000</td>
<td>$D^0, D^+$</td>
</tr>
<tr>
<td>$s$</td>
<td>2</td>
<td>1</td>
<td>0.50000</td>
<td>$D_s^+$</td>
</tr>
<tr>
<td>$(ud)_0$</td>
<td>1</td>
<td>1</td>
<td>0.57933</td>
<td>$\Lambda_c^+$</td>
</tr>
<tr>
<td>$(ll)_1$</td>
<td>3</td>
<td>3</td>
<td>0.77133</td>
<td>$\Lambda_c^+$</td>
</tr>
<tr>
<td>$(sl)_0$</td>
<td>1</td>
<td>2</td>
<td>0.80473</td>
<td>$\Xi_c^0, \Xi_c^+$</td>
</tr>
<tr>
<td>$(sl)_1$</td>
<td>3</td>
<td>2</td>
<td>0.92953</td>
<td>$\Xi_c^0, \Xi_c^+$</td>
</tr>
<tr>
<td>$(ss)_1$</td>
<td>3</td>
<td>1</td>
<td>1.09361</td>
<td>$\Omega_c^0, \Xi_c^+$</td>
</tr>
</tbody>
</table>

(masses taken from PYTHIA 6.4)

- Cluster mass distribution is steeply falling, most clusters are light and undergo a two-body decay $C \rightarrow h_c + \pi/\gamma$;
- This arises from **Space-Momentum Correlation**: charm momentum usually parallel to fluid velocity $\rightarrow$ recombination occurs between quite collinear partons;
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Cross-check: remove SMC by randomly selecting light parton from a different point on the FO hypersurface $\rightarrow$ long high-$M_C$ tail

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On the suppression of high-mass clusters

Both in our model and in QCD event generators like e.g. HERWIG (B.R. Webber, NPB 238 (1984) 492) one gets a steeply falling $M_C$ distribution due to preferential cluster formation between collinear partons.
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- In our model this is due to the SMC arising from recombining nearby partons;
- In Herwig this is due to the angular ordered parton shower (pre-confinement)
Charmed hadron $p_T$-spectra normalized to integrated $D^0$-yield per event. At high $p_T$ better agreement with experimental data for curves including momentum dependence of the transport coefficients (HTL curves)
Qualitative agreement with STAR results;
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Overprediction of the $D_s^+/D^0$ ratio measured by ALICE;
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NB We have not attempted a tuning of the parameters to fit the data, e.g. quark and diquark masses taken from default values in PYTHIA
Results: fragmentation fractions

FF’s in AA collisions pretty independent from the centrality, leading simply to a reshuffling of the $p_T$-distribution (stronger radial flow of charmed baryons in central events);

- Strong enhancement of charmed baryon production wrt theoretical predictions by default tunings of QCD generators in pp collisions
How much flow acquired at hadronization?

Big enhancement of charmed hadron production at intermediate $p_T$

- **SMC** efficient mechanism to transfer flow from the fireball to the charmed hadrons;
- stronger signal for heaviest charmed baryons due to the larger radial flow of the heaviest diquarks
Two different bands for charmed mesons and baryons arising in our model from the higher mass of diquarks involved in the recombination process (mass scaling rather than quark-number scaling)
Explore the role of SMC’s combining the HQ with a thermal particle chosen from a different point on the FO hypersurface → recombining partons no longer collinear, hence:
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- No big enhancement of the charmed hadron $v_2$
- Larger invariant mass of the formed cluster → fragmentation into a larger number of hadrons as a standard Lund string, with no modified HF hadrochemistry
Some comments

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![Diagram](image_url)

Second endpoint boosts the string along the direction of the beam-remnant (beam-drag effect), leading to an asymmetry in the rapidity distribution of $D^+/D^-$ mesons

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NB Small invariant-mass string can collapse into a single hadron: non-universal flavor composition (E. Norrbin and T. Sjostrand, EPJC 17 (2000) 137)
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In summary

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- Rather than attempting a precision fit of the data through a fine tuning of the parameters we were interested in displaying very general features of the proposed mechanism and its connection with well known hadronization models employed in the literature;

- Strong implications for the extraction of transport coefficients (same flow can be reproduced with a milder in-medium interaction);

- The generalization of the results to the \( pp \) and \( pA \) case is currently in progress.
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