Heavy Flavor spectra in nucleus-nucleus collisions

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Outline

- Heavy quarks as a **hard probe** of the Quark Gluon Plasma
- Theoretical Framework
  - relativistic Langevin equation in an expanding medium
  - evaluation of the **transport coefficients**
- Numerical results of a full simulation:
  for RHIC (200 GeV) and LHC (2.6 and 5.5 TeV)
  from the initial $Q\bar{Q}$ spectrum to the final $D$, $B$, and $e$ spectra
  - Invariant yields $E(dN/d^3p)$: pp vs AA
  - Nuclear modification factor $R_{AA}(p_T)$
  - Elliptic flow coefficient $v_2(p_T)$
- Discussion of results:
  comparison with PHENIX data and predictions for LHC
Heavy quarks as probes of the QGP

- Heavy quarks are produced in hard pQCD processes at very early times of a heavy-ion collision. Then, when crossing the expanding fireball, heavy quarks loose their energy and perform multiple collisions with the medium.
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- Therefore $p_T$ spectra of D, B hadrons and of the electrons from their semi/leptonic decays are a good probe to perform QGP diagnostic, since they provide a measure of the energy dissipation (quenching) of heavy quarks while propagating in the hot QCD matter.
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- The energy lost by heavy quarks through soft-gluon radiation is expected to be less important than for light quarks. However RHIC spectra show a substantial suppression of heavy-flavor non-photonic electrons: collisions of HQ with plasma particles might be the explanation.
The relativistic Langevin equation

\[ \frac{\Delta p^i}{\Delta t} = -\eta_D(p)p^i + \xi^i(t), \]

with the properties of the noise encoded in

\[ \langle \xi^i(p_t)\xi^j(p_{t'}) \rangle = b^{ij}(p_t) \frac{\delta_{tt'}}{\Delta t} \]

\[ b^{ij}(p) \equiv \kappa_L(p)\hat{p}^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j) \]

**Transport coefficients** to calculate:

- **Momentum diffusion** \( \kappa_T \equiv \frac{1}{2} \frac{\langle \Delta p_T^2 \rangle}{\Delta t} \) and \( \kappa_L \equiv \frac{\langle \Delta p_L^2 \rangle}{\Delta t} \);
- **Friction term** (dependent on the discretization scheme!)

\[ \eta_D^{\text{Ito}}(p) = \frac{\kappa_L(p)}{2TE_p} - \frac{1}{E_p^2} \left[ (1 - v^2) \frac{\partial \kappa_L(p)}{\partial v^2} + \frac{d - 1}{2} \frac{\kappa_L(p) - \kappa_T(p)}{v^2} \right] \]

fixed in order to insure approach to equilibrium (Einstein relation):

Langevin \( \Leftrightarrow \) Fokker Planck with steady solution \( \exp(-E_p/T) \)
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The Langevin Equation

In a static medium...

For $t \gg 1/\eta_D$ one approaches a relativistic Maxwell-Jüttner distribution$^1$

$$f_{\text{MJ}}(p) \equiv \frac{e^{-E_p/T}}{4\pi M^2 T K_2(M/T)}, \quad \text{with} \quad \int d^3p \, f_{\text{MJ}}(p) = 1$$

(Test with a sample of $c$ quarks with $p_0 = 2$ GeV/c)

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$^1$A.B., A. De Pace, W.M. Alberico and A. Molinari, NPA 831, 59 (2009)
In an expanding fluid...

The fields $u^{\mu}(x)$ and $T(x)$ are taken from the output of two longitudinally boost-invariant ("Hubble-law" longitudinal expansion $v_z = z/t$)

\[
\begin{align*}
x^{\mu} &= (\tau \cosh \eta, r_\perp, \tau \sinh \eta) \quad \text{with} \quad \tau \equiv \sqrt{t^2 - z^2} \\
u^{\mu} &= \tilde{\gamma}_\perp (\cosh \eta, \bar{v}_\perp, \sinh \eta) \quad \text{with} \quad \tilde{\gamma} \equiv \frac{1}{\sqrt{1 - \bar{v}^2_\perp}}
\end{align*}
\]

hydro codes\textsuperscript{2}.

- $u^{\mu}(x)$ used to perform the update each time in the fluid rest-frame;
- $T(x)$ allows to fix at each step the value of the transport coefficients.

Evaluation of $\kappa_{T/L}(p)$

We account for the effect of binary collisions in the medium. The interaction rate must be weighted by the squared transverse/longitudinal exchanged momentum.

*Intermediate cutoff $|t|^* \sim m_D^2$ introduced to separate*\(^3\) the contributions of

- **soft collisions** ($|t| < |t|^*$): Hard Thermal Loop approximation (*resummation of medium effects*)
- **hard collisions** ($|t| > |t|^*$): kinetic pQCD calculation

Two calculations, with $g(\mu)$ evaluated at:

1. $\mu \sim T$, as for the soft component (HTL1)
2. $\mu = |t| = -Q^2$ (HTL2)

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Transport coefficients $\kappa_{T/L}(p)$: hard contribution

\[
\kappa_{T}^{g/q(\text{hard})} = \frac{1}{2} \frac{1}{2E} \int \frac{n_{B/F}(k)}{2k} \int \frac{1 \pm n_{B/F}(k')}{2k'} \int \frac{1}{2E'} \theta(|t| - |t|^*) \times \\
(2\pi)^4 \delta^{(4)}(P + K - P' - K') |\overline{M}_{g/q}(s, t)|^2 q_T^2
\]

\[
\kappa_{L}^{g/q(\text{hard})} = \frac{1}{2E} \int \frac{n_{B/F}(k)}{2k} \int \frac{1 \pm n_{B/F}(k')}{2k'} \int \frac{1}{2E'} \theta(|t| - |t|^*) \times \\
(2\pi)^4 \delta^{(4)}(P + K - P' - K') |\overline{M}_{g/q}(s, t)|^2 q_L^2
\]

where: \(|t| \equiv q^2 - \omega^2\)
When the exchanged 4-momentum is soft the t-channel gluon feels the presence of the medium and requires resummation. The blob represents the dressed gluon propagator, which has longitudinal and transverse components:

\[
\Delta_L(z, q) = \frac{-1}{q^2 + \Pi_L(z, q)}, \quad \Delta_T(z, q) = \frac{-1}{z^2 - q^2 - \Pi_T(z, q)},
\]

where medium effects are embedded in the HTL gluon self-energy.
Transport coefficients $\kappa_{T/L}(p)$: numerical results

Combining together the hard and soft contributions:

- The dependence on the intermediate cutoff $|t|^\ast$ is very mild.
- Larger growth with $p$ of $\kappa_L$ with respect to $\kappa_T$.
- Slower increase with $p$ of $\kappa_L$ in the HTL2 case.
**Multi-step full simulation**

- **Initial generation of $Q\bar{Q}$ pairs:** in pQCD, with POWHEG + possible nuclear effects (corrections to nPDFs, $k_T$-broadening).

- **Langevin evolution in the QGP:** hydro codes provide a description of the background medium with $(T(x), u^\mu(x))$, used to evaluate the local value of the transport coefficients of the expanding fluid and to update position and 4-momentum of the HQ.

- **Hadronization:** at $T_c$ are made hadronize via fragmentation mechanism (not yet well under control, other mechanisms can be relevant, like coalescence)

- **Final decays:** heavy quark hadrons are made decay into electrons ($D \to X\nu e$, $B \to XJ/\psi...$), by using PYTHIA decayer with updated version of branching ratios table (PDG 2010)
Initial heavy-quark spectra

- Single inclusive HQ spectra $E(dN/d^3p)$ generated with POWHEG (pQCD @ NLO) using the PDF set CTEQ6M (+EPS09 in AA)

- HQ distributed in the transverse plane according to the nuclear overlap $dN/dx_\perp \sim T_{AB}(x, y) \equiv T_A(x + b/2, y) T_B(x - b/2, y)$, with

$$T_{A/B}(x_\perp) \equiv \int_{-\infty}^{+\infty} dz \, \rho_{A/B}(x_\perp, z)$$

- Each quark is given a random $k_\perp$ broadening extracted from a gaussian distribution, with $\langle k_\perp^2 \rangle = \langle k_\perp^2 \rangle_{pp} + \langle \delta k_\perp^2 \rangle_{AB}(\vec{b}, \vec{s})$. 
Some results: $pp \ @ \ \sqrt{s} = 200 \ GeV$

PHENIX heavy-flavor electrons vs POWHEG results\(^a\) with “default” parameters ($M_{c/b} = 1.5/4.8 \ GeV$, $\mu_R = \mu_F = m_T$):

- Nice agreement with a $k_T$-broadening $\langle k^2_T \rangle = 1$ GeV$^2$
- Underestimation of the data without $k_T$-broadening

\(^a\)W.M. Alberico et al., EPJC 71, 1666 (2011)
Heavy-flavor hadrons

Around $T_c$ HQs are made hadronize *like in the vacuum* with

- *momentum fractions* taken from a Peterson fragmentation function ($\epsilon = 0.04/0.005$ for $c/b$)

- *branching fractions* $f(c \to D, \Lambda_c)/f(b \to B, \Lambda_b)$ taken from the PDG ($D = D^0, D^+, D_s^+$ + anti-particles, the same for B), as measured in elementary collisions (e.g. at HERA)
Heavy-flavor electrons

- From charm: \( D \rightarrow X \nu e \)
- From beauty:
  
  \[
  B \rightarrow D \nu e \\
  B \rightarrow D \nu e \rightarrow X \nu e \nu e \\
  B \rightarrow D Y \rightarrow X \nu e Y
  \]

Non-prompt \( J/\psi \)

- Several exclusive channels
  
  \[
  B \rightarrow J/\psi X \\
  B \rightarrow \chi_c X \rightarrow J/\psi \gamma X \\
  B \rightarrow \psi' X \rightarrow J/\psi Y X \\
  B \rightarrow \psi' X \rightarrow \chi_c \gamma X \rightarrow J/\psi \gamma \gamma X
  \]
Heavy Flavor spectra in nucleus-nucleus collisions

Numerical Results

Analysis strategy

3 energies, 5 centrality intervals + Minimum Bias

- RHIC 200 GeV pp, Au-Au
- LHC 5.5 TeV pp, Pb-Pb
- LHC 2.76 TeV pp, Pb-Pb, only 1 central bin (0-10%) + MB

Analyzed cases for different choices of input parameters and hydro code

- $\mu$ scale in HTL calculation of $\kappa_{soft}$: $\mu = \pi T / 2\pi T$
- QGP thermalization time $\tau_0$
- Viscous/ideal hydrodynamics code
- $\mu$ scale in pQCD calculation of $\kappa_{hard}$: HTL1 or HTL2 (only for LHC)
Systematics on $R_{AA}$: role of hydrodynamics

charm thin lines, bottom thick lines

- very small influence from the hydrodynamics (viscous or ideal)
- Some sensitivity to the initial $\tau_0$
Systematics on $R_{AA}$: role of the coupling

- **Strong** dependence upon the scale $\mu$ at which the coupling $\alpha_s$ is evaluated;

- **NB**: at $T = 200$ MeV $\alpha_s(\pi T) \approx 0.34$, $\alpha_s(2\pi T) \approx 0.63$
Systematics on $R_{AA}$: effect of fragmentation and decays

charm thin lines, bottom thick lines

Fragmentation and semi-leptonic decays lead to a quenching of $R_{AA}$
Heavy-flavor electrons: invariant spectra at RHIC

- Continuous curves: after Langevin evolution;
- Dashed curves: $pp$ result scaled by $\langle N_{\text{coll}} \rangle$
Heavy Flavor spectra in nucleus-nucleus collisions

Numerical Results

Heavy-flavor electrons: $R_{AA}$

- Left panel: $R_{AA}(p_T)$ in central events;
- Right panel: integrated $R_{AA}$ vs centrality
- Viscous hydro, $\tau_0 = 1$
Flow at low-$p_T$ results underestimated;

With a very small $\tau_0 \sim 0.1$ fm discrepancy reduced, but still present.

$v_2$ would be increased by coalescence (not included here).
LHC: D mesons vs ALICE results

High-$p_T$ D-meson suppression nicely reproduced$^4$

$^4$Data points from Dainese, plenary talk @QM2011
Charm has a much larger elliptic flow with respect to RHIC

Modest elliptic flow of bottom

HTL2 calculation displays a lower $v_2$. 

Elliptic flow (hadrons vs electrons)
Summary

- Relativistic Langevin equation is a powerful tool to study the HQ dynamics in the QGP.
- The required transport coefficients $\kappa_L/T$ have been evaluated considering only $2 \rightarrow 2$ collisions and distinguishing soft and hard scatterings, with the aim of delivering a benchmark weak-coupling calculation.
- For large $p_T$ it is possible to accommodate RHIC data for the single electrons spectra: the actual values of $\kappa_L/T$ should be realistic.
- Preliminary results for the LHC were presented both for electrons and D/B meson yields: comparison with the fresh data from experiments is in progress.
- The results of our study support the relevance of collisional energy loss in describing heavy-quark propagation in the medium.
- Further efforts required, e.g., for hadronization mechanisms (coalescence...).
Back-up slides
Heavy-flavor electrons: invariant spectra at LHC
Transport coefficients: numerical results

Combining together the hard and soft contributions...

...the dependence on the intermediate cutoff $|t|^*$ is very mild!
Initial $Q\bar{Q}$ production (from POWHEG)

<table>
<thead>
<tr>
<th>$\sqrt{s}_{NN}$</th>
<th>$\sigma_{pp}^{cc\bar{c}}$ (mb)</th>
<th>$\sigma_{pp}^{cc\bar{c}}$ (mb)</th>
<th>$\sigma_{pp}^{bb}$ (mb)</th>
<th>$\sigma_{pp}^{bb}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 GeV</td>
<td>0.254</td>
<td>0.236</td>
<td>1.77 × 10^{-3}</td>
<td>2.03 × 10^{-3}</td>
</tr>
<tr>
<td>2.76 TeV</td>
<td>1.947</td>
<td>1.513</td>
<td>0.091</td>
<td>0.085</td>
</tr>
</tbody>
</table>

Important shadowing effects (EPS09-NLO) for $c\bar{c}$ production in Pb-Pb @ LHC!
To model the effects of an expanding fluid the fields $u^\mu(x)$ and $T(x)$ are taken from the output of two longitudinally boost-invariant hydro codes\textsuperscript{5}.

- $u^\mu(x)$ used to perform the update each time in the fluid rest-frame;
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<table>
<thead>
<tr>
<th></th>
<th>$\eta/s = 0$</th>
<th>$\eta/s = 0.08$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_0$ (fm)</td>
<td>$s_0$ (fm$^{-3}$)</td>
</tr>
<tr>
<td>RHIC 200 GeV</td>
<td>0.6</td>
<td>110</td>
</tr>
<tr>
<td>LHC 2.76 TeV</td>
<td>0.6</td>
<td>278</td>
</tr>
</tbody>
</table>


\textsuperscript{6}Hirano, Huovinen and Nara, PRC 83 021902