Heavy-flavor dynamics in nucleus–nucleus collisions: from RHIC to LHC

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work done in collaboration with:

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Ref: W. M. Alberico et al. “Heavy-flavour spectra in high-energy nucleus–nucleus collisions”, arXiv:1101.6008 [hep-ph], accepted for publication by EPJ C
Outline

- **Heavy quarks as** hard **probes of the Quark Gluon Plasma.**
- **Theoretical framework:**
  - the relativistic Langevin equation in an expanding medium
  - evaluation of the transport coefficients
- **Numerical results of a full simulation**
  for RHIC (200 GeV) and LHC (2.76 and 5.5 TeV):
  from the initial $Q\bar{Q}$ production 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 are produced in **hard pQCD processes** at **very early times** of a heavy-ion collision. Then, when crossing the expanding fireball, **heavy quarks lose their energy and perform multiple collisions with the medium.**

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Heavy quarks as hard probes of QGP

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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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- However, the energy lost by heavy quarks through soft gluon radiation is expected to be depleted. Because of the large quark-mass, the spectrum of radiated gluons was shown\(^1\) to be suppressed at large energy.

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Substantial suppression of heavy-flavor non-photonic electrons, on the same level as that one of light hadrons.
Heavy quark energy loss versus RHIC data

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Disagreement with the predictions of radiative energy loss models, with realistic values of gluon density.

Different approaches were proposed to explain RHIC results, taking into account also collisions of heavy quarks with plasma particles.
The relativistic Langevin equation

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

\( \text{determ.} \quad \text{stochastic} \)
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with the properties of the noise encoded in

\[ \langle \xi^i(p_t)\xi^j(p_{t'}) \rangle = b^{ij}(p_t)\frac{\delta_{tt'}}{\Delta t} \quad b^{ij}(p) \equiv \kappa_L(p)p^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j) \]
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**Transport coefficients** to calculate:

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

\[ \eta_D^{\text{Ito}}(p) = \frac{\kappa_L(p)}{2TE_p} - \frac{1}{E_p^2} \left[ (1 - v^2) \frac{\partial \kappa_L(p)}{\partial v^2} + \frac{d - 1}{2} \frac{\kappa_L(p) - \kappa_T(p)}{v^2} \right] \]
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fixed in order to insure the approach to equilibrium (**Einstein relation**): \( \text{Langevin eq.} \Leftrightarrow \text{Fokker Planck eq. with steady solution exp}(\frac{-E_p}{T}) \)
Evaluation of transport coefficients $\kappa_{T/L}(p)$

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- **soft collisions** ($|t| < |t|^*$): Hard Thermal Loop (HTL) approximation in a weak-coupling scenario, with the running coupling constant $g(\mu)$ taken at a scale $\mu \sim T$, the Debye screening mass $m_D$ preventing infrared divergencies.

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- **hard collisions** \(|t| > |t|^*\): kinetic pQCD calculation

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

\[ \mu \sim T \] , as for the soft component \((HTL1)\)

\[ \mu = |t| = -Q^2 \] \((HTL2)\)

---

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

$$\kappa_{T}^{g/q_{(\text{hard})}} = \frac{1}{2} \frac{1}{2E} \int_{k} \frac{n_{B/F}(k)}{2k} \int_{k'} \frac{1 \pm n_{B/F}(k')}{2k'} \int_{p'} \frac{1}{2E'} \theta(|t| - |t|^*) \times$$

$$\times (2\pi)^{4} \delta^{(4)}(P + K - P' - K') \left| \mathcal{M}_{g/q}(s, t) \right|^{2} q_{T}^{2}$$

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$$\times (2\pi)^{4} \delta^{(4)}(P + K - P' - K') \left| \mathcal{M}_{g/q}(s, t) \right|^{2} q_{L}^{2}$$

where: $|t| \equiv q^{2} - \omega^{2}$
Transport coefficients $\kappa_{T/L}(p)$: soft contribution

When the exchanged 4-momentum is soft the t-channel gluon feels the presence of the medium and requires resummation.
Transport coefficients $\kappa_{T/L}(p)$: soft contribution

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The blob represents the effective gluon propagator, which has a longitudinal and a transverse component:

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

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:

$$\kappa_{L/T}(p) \equiv \kappa_{L/T}^{\text{soft}} + \kappa_{L/T}^{\text{hard}}$$

- The dependence on the intermediate cutoff $|t|^*$ is very mild.
- Larger growth with $p$ of $\kappa_L$ with respect to $\kappa_T$.
- Slower increase with $p$ of $\kappa_L$ in the calculation HTL2 with respect to HTL1.
Implementation of a full simulation including Langevin evolution of heavy quarks in QGP

1. Initial generation of $Q\bar{Q}$ pairs with POWHEG (pQCD@NLO), and with EPS09 nuclear corrections to parton distributions (both at NLO accuracy); in addition, included Cronin effect ($k_T$ broadening).

Heavy quark position distributed in the transverse plane according to nuclear geometry, in a Glauber framework.

Langevin evolution in the QGP: at each step $u_\mu(x)$ and $T(x)$ are given by hydro codes, and used to evaluate transport coefficients of the expanding fluid and to update position and 4-momentum of the heavy quark.

At $T_c$ HQs are made hadronize. Fragmentation is performed by sampling hadron species from experimental branching-fractions, and by sampling momentum from a Peterson parametrization of fragmentation function;

Finally, heavy quark hadrons are made decay into electrons, by using the PYTHIA decayer with an updated version of branching-ratios table based on 2010 PDG review.
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### Analysis strategy

3 energies; 5 centrality intervals + Minimum Bias

- **RHIC** 200 GeV pp, Au-Au ⇒ comparison to PHENIX $R_{AA}^e$ and $v_2^e$
- **LHC** 5.5 TeV pp, Pb-Pb
- **LHC** 2.76 TeV pp, Pb-Pb only 1 central bin (0-10%) + Min.Bias (0-80%)
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Analyzed cases for different choices of input parameters and hydro code

- $\mu$ scale in HTL calculation of $\kappa_{soft}$: $\mu = \frac{1}{2} \pi T$
- QGP thermalization time $\tau_0$
- viscous/ideal hydrodynamics code
- $\mu$ scale in pQCD calculation of $\kappa_{hard}$; HTL1 or HTL2 (only for LHC at 2.76 TeV)
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Analyzed cases for different choices of input parameters and hydro code

- $\mu$ scale in HTL calculation of $\kappa_{soft}$: $\mu = \frac{1}{\pi} T \div 2 \pi T$
- QGP thermalization time $\tau_0$
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Results: contributions from c, b and from their weighted combination (c+b)

- Invariant $p_T$ spectra (in pp and AA)
- $R_{AA}^e$ and $R_{AA}^{D,B}$ for D,B hadrons
- $v_2^e$ and $v_2^{D,B}$ for D,B hadrons

Acceptance cuts: $|\eta| < 0.35/0.9$ (PHENIX/ALICE)
Some systematics on $R_{AA}$

Heavy-quark $R_{AA}$ (at RHIC): role of the coupling
charm: thin lines, bottom: thick lines

Strong dependence on the scale $\mu$ at which the coupling $\alpha_s(\mu)$ is evaluated ($\mu = 1\pi \, T \div 2\pi \, T$): at $T = 200$ MeV $\alpha_s \approx 0.34$ and 0.63.

In the following we will focus on $\mu = 1.5\pi \, T$. 
Some systematics on $R_{AA}$

Heavy-quark $R_{AA}$ (at RHIC): role of hydrodynamics
charm: thin lines, bottom: thick lines

The dependence on the selected hydrodynamical scenario \(^3\) appears very mild.

Some systematics on $R_{AA}$

Effects of fragmentation and decays: $h_{c/b}$ and $e_{c/b}$

charm: thin lines, bottom: thick lines

Fragmentation and semileptonic decays lead to a quenching of $R_{AA}$
PHENIX data on the invariant differential cross section of electrons from heavy-flavour decay in *pp* collisions at $\sqrt{s} = 200$ GeV are nicely reproduced by POWHEG, both in shape and in absolute magnitude.

(default POWHEG values $\mu_R/F = m_T$, $m_{c/b}=1.5/4.8$ GeV; CTEQ6M(NLO) PDFs)
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The discrepancy between data and theory decreases, at the level of 12\%, when we include transverse momentum broadening.

(default POWHEG values $\mu_{R/F}=m_T$, $m_{c/b}=1.5/4.8$ GeV; CTEQ6M(NLO) PDFs)
HQ single-electron spectra: AuAu results at RHIC

Dashed curves: pp result scaled by $\langle N_{\text{coll}} \rangle$;
Continuous curves: AA result after Langevin (viscous hydro, $\tau_0=1$ fm).
Fair description of PHENIX data over many orders of magnitude!
Viscous hydro, $\tau_0=1$ fm, $\mu = 1.5\pi T$. 
Viscous hydro, \( \tau_0 = 1 \text{ fm}, \mu = 1.5\pi T \).

For large \( p_T (p_T \gtrsim 3 \text{ GeV/c}) \) our results turn out to be on the whole in agreement with the pattern of the data from PHENIX, with an evident contribution from the bottom.
Results on $R_{AA}(\text{elec})$ at RHIC/PHENIX

- **Viscous hydro, $\tau_0=1$ fm, $\mu = 1.5\pi T$.**
- For large $p_T$ ($p_T \gtrsim 3$ GeV/c) our results turn out to be on the whole in agreement with the pattern of the data from PHENIX, with an evident contribution from the bottom.
- At low $p_T$ ($p_T \lesssim 3$ GeV/c) the data are underestimated. That could be a consequence of the adopted hadronization scheme (parameterization of pure fragmentation, with no contribution from coalescence).
plots done using the *integrated yields*;

- parameter set: $\mu = 3\pi T/2$ and viscous hydro with $\tau_0 = 1$ fm;

- similar general trend (medium softens the spectrum conserving $N_e^{\text{tot}}$)
  - $p_T > 0.3$ GeV/c: flat $R_{AA} \sim 1$ ($R_{AA} \neq 1$ at LHC due to nPDFs!)
Elliptic flow of heavy-flavor electrons at RHIC

RHIC 0-92 %

\[ v_2 \text{ with hot-QCD + fragmentation results a bit underestimated; } \]

\[ \text{slightly better agreement with } \tau_0 = 0.1 \text{ fm; } \]

\[ v_2 \text{ could be increased by coalescence (not included here). } \]
Results on $R_{AA}(\text{elec})$ at LHC(2.76 TeV)

- General features of $R_{AA}$ appear similar to those at RHIC.
- Both charm and bottom are more suppressed.
General features of $R_{AA}$ appear similar to those at RHIC.

Both charm and bottom are more suppressed.

For the centrality interval 0-80 % (an approximation of a minimum bias sample) results obtained in the scenario HTL2 display a flattening and a higher value of $R_{AA}$ (less quenching) above $p_T > 2 \div 4$ GeV/c.
Results on $R_{AA}(D,B)$ at LHC(2.76 TeV)

\[ R_{AA} \]

\[ p_T \text{ (GeV/c)} \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \]

\[ D \quad B \]

\[ 0-10\% \quad 0-80\% \]

\[ \{ \text{HTL1} \} \]

Marco Monteno (INFN Torino)
Results on $R_{AA}(D,B)$ at LHC(2.76 TeV)

![Graph showing $R_{AA}$ vs. $p_T$ for different centrality classes and flavors.]
Elliptic flow of electrons and D,B hadrons at LHC (2.76 TeV)

hadrons (left panel) vs electrons (right panel)

Charm has a much larger elliptic flow with respect to RHIC

Modest elliptic flow of bottom
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Modest elliptic flow of bottom

Calculation HTL2 displays a lower saturation value of $v_2$, especially for electrons.
The relativistic Langevin equation is a powerful tool to study the HQ dynamics in the QGP.
Summary and outlook

- The relativistic Langevin equation is a powerful tool to study the HQ dynamics in the QGP.
- The required transport coefficients $\kappa_{T/L}(p)$ 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. However....
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• Preliminary results for the LHC were presented, both for electrons and D/B mesons yields. Comparison with fresh data from the experiments is welcome!
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Results of our study are in support of reconsidering the relevance of collisional energy loss in describing heavy-quark propagation in-medium.
Back-up slides
**initial $Q\bar{Q}$ production (from POWHEG)**

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\sigma_{c\bar{c}}^{pp}$ (mb)</th>
<th>$\sigma_{c\bar{c}}^{AA}$ (mb)</th>
<th>$\sigma_{b\bar{b}}^{pp}$ (mb)</th>
<th>$\sigma_{b\bar{b}}^{AA}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.254</td>
<td>0.236</td>
<td>$1.77 \times 10^{-3}$</td>
<td>$2.03 \times 10^{-3}$</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>
<tr>
<td>5.5 TeV</td>
<td>3.015</td>
<td>2.288</td>
<td>0.187</td>
<td>0.169</td>
</tr>
</tbody>
</table>

Huge *shadowing effects* (EPS09-NLO) for $c\bar{c}$ production in Pb-Pb @ LHC!
Glauber and $k_{\perp}$ broadening

Each HQ is given a $k_{\perp}$-kick extracted from a gaussian distribution with

$$\langle k^2 \rangle_{AB}(\vec{b}, \vec{s}) = \langle k^2 \rangle_{pp} + \frac{a_{gN}}{2} \left[ \int dz_A \rho_A(\vec{s}, z_A) l_A(\vec{s}, z_A) \right]$$

$$+ \int dz_B \rho_B(\vec{s} - \vec{b}, z_B) l_B(\vec{s} - \vec{b}, z_B)$$

due to the length crossed by the incoming partons in nucleus A/B before the hard event:

$$l_A(\vec{s}, z_A) \equiv \int_{-\infty}^{z_A} dz \rho_A(\vec{s}, z)/\rho_0$$

and

$$l_B(\vec{s} - \vec{b}, z_b) \equiv \int_{z_b}^{+\infty} dz \rho_B(\vec{s} - \vec{b}, z)/\rho_0$$

We choose

<table>
<thead>
<tr>
<th>$a_{gN}$ (GeV$^2$/fm)</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC (5.5 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>0.072</td>
<td>0.10</td>
<td>0.17</td>
</tr>
<tr>
<td>$b$</td>
<td>0.197</td>
<td>0.27</td>
<td>0.47</td>
</tr>
</tbody>
</table>
Hydrodynamic codes

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\(^3\).

- $u^\mu(x)$ 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.

<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) (s_0) (fm(^{-3})) (T_0) (MeV)</td>
<td>(\tau_0) (fm) (s_0) (fm(^{-3})) (T_0) (MeV)</td>
</tr>
<tr>
<td>RHIC 200 GeV</td>
<td>0.6 110 357</td>
<td>0.1 8.4 666</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6 140 387</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 84 333</td>
</tr>
<tr>
<td>LHC 2.76 TeV</td>
<td></td>
<td>0.6 278 475</td>
</tr>
<tr>
<td>LHC 5.5 TeV</td>
<td>0.1 2438 1000</td>
<td>0.1 1840 854</td>
</tr>
<tr>
<td></td>
<td>0.45 271 482</td>
<td>1 184 420</td>
</tr>
</tbody>
</table>


\(^4\)Hirano, Huovinen and Nara, PRC 83 021902
The easiest Langevin evolution algorithm

Going to the fluid rest-frame:

\[ \Delta \vec{p}_n = -\eta_D(\vec{p}_n)\vec{p}_n \Delta \bar{t} + \xi^i(\bar{t}_n)\Delta \bar{t} \equiv -\eta_D(\vec{p}_n)\vec{p}_n \Delta \bar{t} + g^{ij}(\vec{p}_n)\zeta^i(\bar{t}_n)\sqrt{\Delta \bar{t}}, \]

\[ \Delta \vec{x}_n = \vec{p}_n / \bar{E}_n \Delta \bar{t} \]

with \( \Delta \bar{t} = 0.02 \text{ fm/c (in the fluid rest-frame!)} \) and

\[ g^{ij}(p) \equiv \sqrt{\kappa_{\|}(p)\hat{p}^i \hat{p}^j + \sqrt{\kappa_{\perp}(p)}(\delta^{ij} - \hat{p}^i \hat{p}^j)} \quad \text{and} \quad \langle \zeta^i_n \zeta^j_{n'} \rangle = \delta^{ij} \delta_{nn'} \]

Hence one needs simply to:

- extract three independent random numbers \( \zeta^i \) from a gaussian distribution with \( \sigma = 1 \);
- update the momentum and position of the heavy quark;
- go back to the Lab-frame: \( x_{n+1} \) and \( p_{n+1} \).
Effects of fragmentation

Fragmentation function:

\[ \text{Delta } = 0.04 \varepsilon_{\text{Peterson}} \]

\[ \text{charm } b = 8.44 \text{ fm} \]

\[ \mu = 2\pi \]

\[ \text{bottom } b = 8.44 \text{ fm} \]

\[ \mu = 2\pi \]

Fragmentation performed with Peterson FF tends to slightly suppress \( R_{AA} \)

- Mild dependence on the parameter \( \epsilon \)
- \( \epsilon = 0.04 \) and 0.005 (for \( c \) and \( b \)) fixed in order to reproduce HQET FFs\(^5\)

Fragmentation fractions taken from DESY results and PDG 2009