Recent (and older) progresses in heavy flavor physics in URHIC

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Sequential suppression in Stationary QGP…

Matsui & Satz (1986): QGP achieved in URHIC can lead to the deconfinement of Q-Qbar states and thus to an **anomalous** suppression of the (production of) quarkonia (as compared to the rescaled p-p production:

\[ \frac{T}{T_c} \]

\[ 2 \]

\[ 1.2 \]

\[ \leq T_c \]

\{ \gamma(1S), \chi_b(1P), J/\psi(1S), \gamma'(2S), \gamma''(3S), \chi_b'(2P), \chi_c(1P), \psi'(2S) \}

“robust” states

**However:** quarkonia production in pp is a complicated issue (see B.K. lecture), so that dealing with its alteration (dynamically) is (very/too) much complicated.
... a dream or a nightmare?
Main focus: « ...a direct extrapolation of anomalous suppression (of J/ψ) from the SPS energy range could be supplanted by a new formation mechanism fueled by the presence of multiple pairs of charm quarks in each nuclear collision at sufficiently high energy».

Recombination of exogenous quarks, spatially uncorrelated => quadratic dependence in $N_c$. Indeed, for a given c-quark, the probability $P$ to combine with a cbar quark to produce a J/ψ is:

$$P \propto \frac{N_{\bar{c}}}{N_{u,d,s}} \alpha \frac{N_{c\bar{c}}}{N_{ch}}.$$ 

True for each available c-quark ($N_c$ all together) => number of J/ψ’s through exogenous kinetic (re)combination » :

$$N_{J/\psi} \propto \frac{N_{c\bar{c}}^2}{N_{ch}}.$$ 

Precise $\alpha$-value: depends on the dynamics of the system

TRS: kinetic equation

$$\frac{dN_{J/\psi}(\tau)}{d\tau} = \frac{\lambda_F(\tau)}{V(\tau)} N_c N_{\bar{c}} - \lambda_D(\tau) \rho_{c}(\tau) N_{J/\psi}(\tau)$$
Even more interesting: momentum distribution could come with the Temperature at which those quarkonia are produced (beyond FO horizon)

Main caveat: as kinematic (re)combination is local in space-time and in momentum, the total number of produced J/ψ strongly depends on phase-space distribution of c-quarks (some assumptions used in TRS and then later in Thews and Mangano)
Ingredients of our calculation:

1. dissociation evaluated through $g + J/\psi \rightarrow c + c\bar{c}$ cross section (Bhanot-Peskin)

   \[
   \sigma(Q\overline{Q})g(\omega) = \frac{2}{34} \alpha_s \pi a_0^2 \left(\frac{\omega/\varepsilon(0) - 1}{\omega/\varepsilon(0)}\right)^{3/2} \Theta(\omega - \varepsilon(0))
   \]

2. (Re)combination evaluated through detailed balance mechanism.

3. Fokker Planck equation for heavy quark transport.

4. Transport coefficients evaluated according to Landau’s treatment (so-called “grazing approximation” (as in Svetitsky 87, Mustafa 97) + LO $qQ\rightarrow qQ$ and $gQ\rightarrow gQ$ elastic cross section evaluated in-vacuum with fixed $\alpha_s$ and some regulator $\mu$.

5. Some “soft” dissociation temperature above which no quarkonia formation is possible (following Matsui and Satz)

6. All of this implemented in a local transport approach.
(hard) production of heavy quarks in initial NN collisions + $k_T$ broad. (0.2 GeV$^2$/coll)

Bulk Evolution: non-viscous hydro (Heinz & Kolb) $\rightarrow T(M)$ & $v(M)$

Evolution of HQ in bulk: Fokker-Planck or reaction rate + Boltzmann (no hadronic phase)

Quarkonia formation in QGP through $c+c\rightarrow\Psi+g$ fusion process

D/B formation at the boundary of QGP (or MP) through coalescence of c/b and light quark (low $p_T$) or fragmentation (high $p_T$)
Results from the calculations (2004)

J/ψ production in Au-Au, b=0, RHIC, mid rapidity

\[ \frac{dN_{J/\psi}}{dy} (y = 0) \]

Heinz & Kolb’s hydro
No radial exp. hydro

- N<sub>c</sub> and T<sub>dissoc</sub>: key parameters to explain global numbers.
- Larger thermalisation of c-quarks (larger K) leads to moderate increase of J/ψ production.

K: overall cranking factor of the FP coeff. A & B

\[ \frac{\partial f}{\partial t} = \nabla_p \left[ A f + \nabla_p \left( B f \right) \right] \]

Larger K => larger thermalization => smaller effective T of the c-quark distribution.

Differential p<sub>T</sub> spectra reflects this effect (indeed seen later on by PHENIX)

T<sub>dissoc</sub>=180 MeV

(Heinz & Kolb)
2000 -> 2005: growing interest for the measurement of open heavy flavor

Motivations: QGP tomography with well-controlled probes (initial distribution in phase space) that do not completely thermalize.

\[ R_{AA} \text{ (Non photonic single electrons)} \]

Suppression of decay electron from c and b quarks at “large” \( p_T \) due to HQ energy loss (quenching)... A big surprise, in fact !!!

Shape ok, but at the price of a large cranking factor K !!!
The weak to strong axis for HQ

So-called “Failure of pQCD approach” aka “the non photonic single electron puzzle”

“Naive” pQCD (WHDG, ASW,...) \( \hat{q} \approx 1 \text{ GeV}^2/\text{fm} \)

“Optimized” pQCD (ok with pions)

ASW (pure rad. energy loss; extended BDMPS)


Conclude to rough agreement, subjected to b/c ratio in p-p

M Aggarwal et al, STAR, PRL 105 202301
**Motivations:**

1) Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$ => need for running coupling constant

2) From FP to Boltzmann transport => need for scattering amplitudes

**Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)**

- IR safe. $Q^2$ close to 0 does not contribute to Eloss
- Large values for intermediate momentum-transfer => larger cross section

\[
\frac{1}{Q_a} \int_{|Q^2| \leq Q_a^2} dQ \alpha_s(Q^2) \approx 0.5
\]

**Universality constrain** (Dokshitzer 02) helps reducing uncertainties:

\[
m_{D_{self}}^2(T) = (1 + n_f/6) \frac{4\pi \alpha_{eff}(m_{D_{self}}^2)}{\pi^2} T^2
\]

\[
\text{prop} \propto \frac{1}{q^2 - \kappa m_{D_{self}}^2(T)}
\]

One gluon exchange effective propagator, designed in order to guarantee maximal insensitivity of dE/dx in Braaten-Thomas scheme
Insufficient control on energy loss theory

Non perturbative « corrections » even at large HQ energy

In most models:

Lattice QCD :

Our force is close to the one extracted from the free energy as a potential

=> Still allow for some global rescaling of the interactions rates: “K” fixed on experiment
The weak to strong axis for HQ

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“Naive” pQCD (WHDG, ASW, …)

\[ \hat{q} \approx 1 \text{ GeV}^2/\text{fm} \]

“Optimized” pQCD

Collisional model with running $\alpha_s$ and optimized gluon propagator (Peshier, Gossiaux and Aichelin, BAMPS)
The weak to strong axis for HQ

So-called “Failure of pQCD approach” aka “the non photonic single electron puzzle”

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang 0904.0032v1 [hep-ph]
Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

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Running $\alpha_s$ (Peshier, Gossiaux & Aichelin, Uphoff & Greiner)

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Bound states diffusion or non-perturbative, lattice potential non-scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

ADS/CFT (akamatsu et al)
The weak to strong axis for HQ

“Naive” pQCD (WHDG, ASW, …)
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Non perturbative equivalent for g+Q ? No radiative!

Lesson n°1:
Several models containing either non-perturbative features or tunable parameters are able to reproduce the HQ data, but many questions remain… and how to reconcile them all stays a challenge

from Rapp & Van Hees 0903.1096
Elastic D mesons @ RHIC

(Allow for some global rescaling of the rates: “K” fixed on experiment)
Coalescence according to extended Dover framework

\[
N_\Phi = \int \frac{d^3 p_q}{(2\pi \hbar)^3} \frac{p_q \cdot \hat{d}\sigma}{E_q u_Q \cdot \hat{d}\sigma} f_q(x_Q, p_q)(\sqrt{2\pi R_c})^3 \times F_\Phi(p_Q, p_q),
\]

Rather little contribution from the light quark in our treatment… but conclusion may depend on the parameters (\(m_q\), wave function)
Elastic for leptons @ RHIC

Good agreement for NPSE as well

In principle: Need for radiative energy loss…
## Induced Energy Loss

**Generalized Gunion-Bertsch (NO COHERENCE) for finite HQ mass, dynamical light partons**

Eikonal limit (large $E$, moderate $q$)

\[ \omega \frac{d^3 \sigma_{\text{rad}}^{x \ll 1}}{d\omega d^2 k_\perp dq_\perp^2} = \frac{N_c \alpha_s}{\pi^2} (1 - x) \times \frac{J_{\text{QCD}}^2}{\omega^2} \times \frac{d\sigma_{\text{el}}}{dq_\perp^2} \]

with

\[ \frac{J_{\text{QCD}}^2}{\omega^2} = \left( \frac{\vec{k}_\perp}{k_\perp^2 + x^2 M^2 + (1 - x)m_g^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{\left(\vec{k}_\perp - \vec{q}_\perp\right)^2 + x^2 M^2 + (1 - x)m_g^2} \right)^2 \]

Gluon thermal mass $\sim 2T$ (phenomenological; not in BDMPS)

\[ \text{Quark mass} \]

Both cures the collinear divergences and influence the radiation spectra (dead cone effect)

Dominates as small $x$ as one "just" has to scatter off the virtual gluon $k'$
Incoherent Induced Energy Loss

... & finite energy!

Finite energy lead to strong reduction of the radiative energy loss at intermediate $p_T$
Incoherent Induced Energy Loss

Probability $P$ of energy loss $\omega$ per unit length ($T, M, \ldots$):

$$|\omega| \frac{dP(\omega)}{dz} \text{ [fm}^{-1}]$$

HUGE differences expected

Caveat: no detailed balance implemented yet
Allow for some global rescaling of the rates: “K” fixed on experiment.
No lack of elliptic flow wrt pure elastic processes

Coalescence according to extended Dover framework

\[ N_\Phi = \int \frac{d^3 p_q}{(2\pi \hbar)^3} \frac{p_q \cdot \hat{d}\sigma}{E_q u_Q \cdot \hat{d}\sigma} f_q(x_Q, p_q)(\sqrt{2\pi R_c})^3 \times F_\Phi(p_Q, p_q), \]
Good agreement for NPSE as well
Good agreement for NPSE as well
Conclusions from RHIC

- Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB) \( \Rightarrow \) Not sensitive to the large-\( \omega \) tail of the Energy-loss probability (thanks to initial HQ p_T-distribution)

- Good consistency between NPSE and D mesons (10% difference in K values)…

- … within a model with mass hierarchy

- \( \Delta E \) radiative \(<\) \( \Delta E \) elastic

- Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB)

“Fokker Planck” regime

“hard scattering” regime
Present RHIC experiments cannot resolve between those various trends.

Gathering all rescaled models (coll. and radiative) compatible with RHIC $R_{AA}$:

- The drag coefficient reflects the average momentum loss (per unit time) $\Rightarrow$ large weight on $x \sim 1$

- Present RHIC experiments cannot resolve between those various trends

Hope that LHC can do !!!

**Main message**

It is possible to reveal some fundamental property of QGP using HQ probes

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We extract it from data (starting from SQM 2008)

We compare with recent lattice results

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Going LHC: EPOS + Hydro as a background for MC@sHQ

EPOS + Hydro: state of the art framework that encompass pp, pA and AA collisions

EPOS (initial conditions):

- Model based on Gribov-Regge multiple pomeron interactions
- Particle production in cut (semi-hard) pomerons, seen as partons ladder
- Soft particles form a flux tube (string, with its own dynamics, incl. string breaking)… lots of them in A-A
- Slow string segments, far from the surface, are mapped to fluid dynamic fields (-→ hydro)
- Hard particles → jets

Going LHC: EPOS as a background for MC@sHQ

EPOS: state of the art framework that encompass pp, pA and AA collisions

Initial energy density

Kolb Heinz (used previously)  EPOS

More realistic hydro and initial conditions => original HQ studies such as:

1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)
2) correlations between HF and light hadrons

Beware: ≠ color scales
Large differences in the EOS!

Kolb Heinz: bag model
(1rst order transition btwn hadronic phase and massless partons)

EPOS2: fitted on the lattice data from the Wuppertal-Budapest collaboration: cross-over
Coupling EPOS and MC@sHQ

Two main (physical) issues:

1) Generating initial HQ consistently with the multi-partonic approach in EPOS (done in EPOS3; B. Guiot)

2) Dealing properly with the underlying degrees of freedom in a crossover evolution between hadronic phase and QGP.
Going LHC: EPOS2 as a background for MC@sHQ

Same microscopic ingredients as for RHIC ($\Delta E \propto L$);

N.B.: K values: slightly smaller than what obtained from RHIC

Data at large $p_T$ seems to favor « Collisional only »-like average momentum loss
Further comparison with model calculations at LHC

Sapore Gravis report (arxiv 1506.03981)

Elastic

(Elastic +) Radiative

Other
Moving forward…

Central question (to better understand the probe):

How to distinguish between

**Typical - Collisional**

- Large cross-section,
- moderate E-loss per collision
- large angular deflection
- Mass comes as a scale in a log

**Typical - Radiative**

- Small cross-section,
- large E-loss per collision
- small angular deflection
- Mass regularizes collinear divergence
=> stronger mass-influence
Distinguishing between the models: mass dependence

\[ R_{AA} \text{ (NP J/\(\psi\))} \]

CMS preliminary for non prompt J/\(\psi\)

PbPb @ 2.76 TeV

0–100% centrality

El., K=1.5

El. + Rad LPM, K=0.8

Ratio of \(\langle p \rangle\)-loss

\[ \frac{d\langle p\rangle}{d\langle p\rangle(c)} \]

\( m_c/m_b \)

Interm. Mass hierarchy

\[ R_{AA} \]

CMS

Collisional, K=1.5

ALICE

EPOS2 + MC@HQV508

\( \langle N_{\text{part}} \text{ weighted by } N_{\text{col}} \rangle \)

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Distinguishing between the models: mass dependence

Predictions:
(moderate but finite difference… to be seen)
Distinguishing between the models: angular correlations…

Large cross-section, 
moderate E-loss per collision 
large angular deflection, 

Small cross-section, 
large E-loss per collision 
small angular deflection,

Transverse plane

Transverse broadening ./. Initial direction

Initial correlation ; back to back at leading order

Effect of hadronization on angular correlation ?

Heavy quarks azimuthal correlations: Back-to-back

Pb-Pb at LHC, HQ initialized back-to-back, no background from uncorrelated pairs, eff.deg=1; decoupling at T=155 MeV

- Stronger broadening in a purely collisional than in a collisional+radiative interaction mechanism
- At low pT, initial correlations are almost washed out. Some collectivity seen in the purely collisional scenario
- Variances in the intermediate pT range (4 GeV-10 GeV): 0.18 vs 0.094 (charm) and 0.28 vs 0.12 (bottom)
- At higher pT, initial correlations survive the propagation in the medium

Next-to-leading order QCD matrix elements coupled to parton shower (HERWIG) evolution: MC@NLO


- Gluon splitting processes lead to an initial enhancement of the correlations at $\Delta\phi \approx 0$.
- For intermediate $p_T$: increase of the variances from 0.43 (initial NLO) to 0.51 ($\approx 20\%$) for the purely collisional mechanisms and to 0.47 ($\approx 10\%$) for the interaction including radiative corrections (no additivity with initial width).
- At larger $p_T$, the deviations from back to back correlations are mostly due to initial NLO corrections.
- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production!
Consequences on the observables: $p_T(c)-p_T(c\bar{c})$ correlations

Toy study: back to back $c$-$c\bar{c}$ (LO). Pb-Pb @ 2.76 TeV; 40-60%.

Residual correlation after evolution through QGP (similar path length for most of HQ produced in the core of the reaction)
Consequences on the observables: $p_t$-$p_{t\bar{b}}$ correlations

Toy study: back to back $c$-$c\bar{b}$ (LO). Pb-Pb @ 2.76 TeV; 40-60%.

- Significant residual correlation for the case of Elastic energy loss (or LPM radiative + gluon damping)
  
  - $p_t(c\bar{b})\in[20,22]$

- No significant residual correlation for the case of radiative GB or LPM radiative

Background at small $p_T$
More recent observables: Higher HQ flow components

Fluctuations in the Initial energy-density profile => odd components of the flow: $v_3, v_5, \ldots$ (seen indeed in the light particle spectra)

As heavy quarks couple to the expending QGP, same trend should be observed
More recent observables: Higher HQ flow components

Indeed finite v3 observed at all centralities, both at RHIC and LHC

Nahrgang et al, Phys. Rev. C 91 (2015), 014904
More recent observables: Higher HQ flow components

In 1\textsuperscript{st} approximation: $v_n \propto \text{excentricity } \varepsilon_n$ \implies look at the ratio for less trivial effects

More detailed analysis reveals that HQ benefit less and less from the flow of the bulk at large centrality, especially for higher harmonics.

Possible inertia effect: HQ need a longer time to develop their flow \implies earlier freeze out at larger centrality prevents the $v_n$ to develop fully.

This may offer a different perspective on the probing of the system evolution.
HQ collectivity in “small” systems: the pp case at LHC.

Even in p-p collisions: several ($\nu$) pomerons exchange, up to $\nu = 10$

$$\left. \frac{dN_{ch}}{dy} \right|_{y=0} \approx 29$$

Similar to Cu-Cu (RHIC)

Test whether HQ quenching in p-p

Some (10%) quenching seen indeed in the model

HQ collectivity in “small” systems: the pp case at LHC.

As a function of “centrality”

\[ R(z) = \left. \frac{dN/dp_T(N_{ch})}{dN/dp_T(MB)} \right|_{p_T>10 GeV} \times \frac{N_{MB}}{N_{ch}}, \]

\[ z = \frac{dN_{ch}}{dy} / \left( \frac{dN_{ch}}{dy} \right)_{MB} \]

(Self-normalizing)

Opposite trend seen in data…

(Working hypothesis: \( N_{ch} \) a \( \nu \), but hydro created in pp leads to a strong reduction.)

ALICE (arxiv 1505.00664)

\[ \equiv R(z) = 1 \]

(b) D meson with \( 8 < p_T < 12 \text{ GeV}/c \)
2015: HQ collectivity in p-Pb at LHC.

Shadowing implemented in EPOS3

Vitalii Ozvenchuk, 2nd Conference on HIC in the LHC Era and Beyond (Quy Nhon, Vietnam)

Very preliminary

D mesons

Radial flow from hadronisation

|y| < 1

N of pomeron > 30

|y| < 1

c-quark cooling

Initial spectra

$|y| < 1$

$p_T$ [GeV]

$1/N_{coll} \frac{d^2N}{dp_T dp_T dy}$ [GeV$^2$]

$s^{1/2} = 5$ TeV

c quarks

$|y| < 1$

$p_T$ [GeV]

$R_{pA}$

$|y| < 1$

$|y| < 1$

$N_{coll} \frac{d^2N}{dp_T dp_T dy}$ [GeV$^2$]

$s^{1/2} = 5$ TeV

$|y| < 1$

$c$ quarks

$c$ quark cooling
2015: HQ collectivity in p-Pb at LHC.

Shadowing implemented in EPOS3

Vitalii Ozvenchuk 2nd Conference on HIC in d (Quy Nhon, Vietnam)
Despite all progresses made in the field of URHIC probing the “quark gluon soup” with heavy flavour and assessing unambiguously its physical properties is still a delicate task.

This is partially due to the abundance of models and the lack of constrains from the fundamental theory.
Conclusion: Antique view of QGP probing with HQ

The blind

The paralytic

... but they go forward together!
Elastic Eloss @ RHIC

We “explain” it all provided we allow for a multiplication of our pQCD (inspired) cross section by a factor 2…

Deur et al. (PLB 2008)

Our choice

$\alpha_{\text{eff}}$

S–L

T–L

$\alpha_f = 3$

$\alpha_f = 2$

$g_{I}/\pi$

$\alpha_{s,gl}/\pi$

$\alpha_{s,F3}/\pi$

GDH limit

$pQCD$ evol. eq.

$\alpha_{s,\pi}/\pi$

JLab CLAS

JLab PLB 650 4 244

$\alpha_f/\pi$ world data

Our choice
Running $\alpha_s$ : some Energy-Loss values

$$dE_{\text{coll}}(c / b) \frac{dx}{dx}$$

<table>
<thead>
<tr>
<th>$T$(MeV)</th>
<th>$p$(GeV/c)</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1 / 0.65</td>
<td>1.2 / 0.9</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>2.1 / 1.4</td>
<td>2.4 / 2</td>
<td></td>
</tr>
</tbody>
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$\approx 10\%$ of HQ energy

Drag coefficient (inverse relax. time)

Transport Coefficient

… of expected magnitude to reproduce the data (we “explain” the transp. coeff. in a rather parameter free approach).