Heavy Quarks in the QGP

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 THEORY OF STRONG INTERACTIONS: QUANTUM CHROMO DYNAMICS, QCD

AT HIGH ENOUGH DENSITIES/TEMPERATURES: HADROS DISSOLVE INTO A QUARK-GLUON PLASMA (QGP)

HOPE TO CREATE QGP IN HEAVY-ION COLLISIONS AT RHIC (AND LHC)

RHIC: COLLIDE GOLD NUCLEI WITH ENERGY OF 200 GeV PER NUCLEON:
Evidence for QGP from heavy-ion observables

- particle $p_T$ spectra show hydrodynamical behavior
- collective flow of matter in local thermal equilibrium
- nuclear modification factor $\Rightarrow$ degree of thermalization

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{coll}dN_{pp}/dp_T}$$

- no QGP $\Rightarrow R_{AA} = 1$; observed: $R_{AA} < 1$ (suppression) at high $p_T$
- in non-central collisions: anisotropic collective flow

- initially reaction zone of elliptic shape
- pressure gradients: $\langle |p_x| \rangle > \langle |p_y| \rangle$
- measure of flow anisotropy:

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos(2\phi_p) \rangle$$
Heavy Quarks in Heavy-Ion collisions

Hard production of HQs described by PDF’s + pQCD (PYTHIA)

Hadronization to $D, B$ mesons via quark coalescence + fragmentation

HQ rescattering in QGP: Langevin simulation
drag and diffusion coefficients from microscopic model for HQ interactions in the sQGP

Hadronization to $K$ mesons via quark coalescence + fragmentation

Semileptonic decay $\Rightarrow$ “non-photonic” electron observables
Relativistic Langevin process

- **Langevin process**: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

\[
d\vec{x} = \frac{\vec{p}}{E_p} dt,
\]

\[
d\vec{p} = -A \vec{p} dt + \sqrt{2} dt [\sqrt{B_0 P_\perp} + \sqrt{B_1 P_\parallel}] \vec{w}
\]

- \( \vec{w} \): normal-distributed random variable
- \( A \): friction (drag) coefficient
- \( B_{0,1} \): diffusion coefficients
- dependent on realization of stochastic process
- to guarantee correct equilibrium limit: Use Hänggi-Klimontovich calculus, i.e., use \( B_{0/1}(t, \vec{p} + d\vec{p}) \)
- Einstein dissipation-fluctuation relation \( B_0 = B_1 = E_p TA \).
- to implement flow of the medium
  - use Lorentz boost to change into local “heat-bath frame”
  - use update rule in heat-bath frame
  - boost back into “lab frame”
Elastic pQCD processes

- Lowest-order matrix elements [Combridge 79]

- Debye-screening mass for $t$-channel gluon exch. $\mu_g = gT$, $\alpha_s = 0.4$

- not sufficient to understand RHIC data on “non-photonic” electrons
Non-perturbative interactions: Resonance Scattering

- General idea: Survival of $D$- and $B$-meson like resonances above $T_c$
- elastic heavy-light-(anti-)quark scattering

\[
\begin{align*}
&\bar{q} \to c, D, D', D_s \\
&q \to c, D, D', D_s
\end{align*}
\]

- $D$- and $B$-meson like resonances in sQGP

\[
\begin{align*}
&D, D', D_s \\
k &\to c
\end{align*}
\]

- parameters
  - $m_D = 2$ GeV, $\Gamma_D = 0.4 \ldots 0.75$ GeV
  - $m_B = 5$ GeV, $\Gamma_B = 0.4 \ldots 0.75$ GeV
total pQCD and resonance cross sections: comparable in size

BUT pQCD forward peaked ↔ resonance isotropic

resonance scattering more effective for friction and diffusion
Transport coefficients: pQCD vs. resonance scattering

- three-momentum dependence

- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!
Transport coefficients: pQCD vs. resonance scattering

- Temperature dependence

![Graphs showing temperature dependence of transport coefficients](image)

- Resonances: $\Gamma = 0.4$ GeV
- pQCD: $\alpha_s = 0.4$
- Total

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Heavy Quarks in the QGP

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Time evolution of the fire ball

- Elliptic fire-ball parameterization
  fitted to hydrodynamical flow pattern [Kolb ’00]
  \[ V(t) = \pi(z_0 + v_z t)a(t)b(t), \quad a, b: \text{semi-axes of ellipse,} \]
  \[ v_{a,b} = v_\infty [1 - \exp(-\alpha t)] \pm \Delta v [1 - \exp(-\beta t)] \]

- Isentropic expansion: \( S = \text{const} \) (fixed from \( N_{\text{ch}} \))

- QGP Equation of state:
  \[ s = \frac{S}{V(t)} = \frac{4\pi^2}{90} T^3 (16 + 10.5n_f^\star) \]
  \[ n_f^\star = 2.5 \]

- obtain \( T(t) \Rightarrow A(t, p), B_0(t, p) \) and \( B_1 = TEA \)

- for semicentral collisions (\( b = 7 \) fm): \( T_0 = 340 \) MeV,
  QGP lifetime \( \simeq 5 \) fm/c.

- simulate FP equation as relativistic Langevin process
need initial $p_T$-spectra of charm and bottom quarks

(modified) PYTHIA to describe exp. D meson spectra, assuming δ-function fragmentation

exp. non-photonic single-$e^±$ spectra: Fix bottom/charm ratio
Spectra and elliptic flow for heavy quarks

- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances $\Rightarrow$ $c$-quark thermalization without upscaling of cross sections
- Fireball parametrization consistent with hydro

- $\mu_D = 1.5T$ fixed
- spatial diff. coefficient:
  \[ D = D_s = \frac{T}{m_A} \]
- $2\pi T D \approx \frac{3}{2\alpha_s^2}$
Spectra and elliptic flow for heavy quarks

\[ v_2 \text{ vs } p_T \]

- \( c, \text{ reso } (\Gamma = 0.4-0.75 \text{ GeV}) \)
- \( c, \text{ pQCD, } \alpha_s = 0.4 \)
- \( b, \text{ reso } (\Gamma = 0.4-0.75 \text{ GeV}) \)

Au-Au \( \sqrt{s} = 200 \text{ GeV (b=7 fm)} \)

LO QCD

[Moore, Teaney '04]
Observables: $p_T$-spectra ($R_{AA}$), $v_2$

- Hadronization: **Coalescence** with light quarks + fragmentation
  \[ \leftrightarrow c\bar{c}, b\bar{b} \text{ conserved} \]
- single electrons from decay of $D$- and $B$-mesons

![Graphs showing $R_{AA}$ and $v_2$ vs. $p_T$ for Au-Au collisions at $\sqrt{s}=200$ GeV (b=7 fm)]

- Without further adjustments: data quite well described
  
  [HvH, V. Greco, R. Rapp, Phys. Rev. C 73, 034913 (2006)]
Observables: $p_T$-spectra ($R_{AA}$), $v_2$

- Hadronization: Fragmentation only
- single electrons from decay of $D$- and $B$-mesons
Observables: $p_T$-spectra ($R_{AA}$), $v_2$

- Central Collisions
- single electrons from decay of $D$- and $B$-mesons

Coalescence + Fragmentation

Fragmentation only
Comparison to newer data

(a) $0^{-10\%}$ central

- Armesto et al. (I)
- van Hees et al. (II)
- $3/(2\pi T)$ Moore &
- $12/(2\pi T)$ Teaney (III)

(b) minimum bias

- $\pi^0 R_{AA}$, $p_T > 4$ GeV/c
- $\pi^0 v_2$, $p_T > 2$ GeV/c
- $e^\pm R_{AA}$, $e^\pm v_2^{HF}$

PHENIX Collaboration
PRL 98 172301 (2007)
color-singlet free energy from lattice
use internal energy

\[ U_1(r, T) = F_1(r, T) - T \frac{\partial F_1(r, T)}{\partial T}, \]
\[ V_1(r, T) = U_1(r, T) - U_1(r \rightarrow \infty, T) \]

Casimir scaling for other color channels [Nakamura et al 05; Döring et al 07]

\[ V_3 = \frac{1}{2} V_1, \quad V_6 = -\frac{1}{4} V_1, \quad V_8 = -\frac{1}{8} V_1 \]
T-matrix

- Brueckner many-body approach for elastic $Qq$, $Q\bar{q}$ scattering

\[
T(q, \bar{q}) = V + T \Sigma + VT
\]

- Reduction scheme: 4D Bethe-Salpeter $\rightarrow$ 3D Lipmann-Schwinger

- $S$- and $P$ waves

- Same scheme for light quarks (self consistent!)

- Relation to invariant matrix elements

\[
\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left( |T_{a,l=0}(s)|^2 + 3 |T_{a,l=1}(s)|^2 \cos \theta_{cm} \right)
\]
- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher $T! \Rightarrow \text{sQGP}$
- $P$ wave smaller
- resonances near $T_c$: natural connection to quark coalescence

[Ravagli, Rapp 07; Ravagli, HvH, Rapp 08]

- model-independent assessment of elastic $Qq, Q\bar{q}$ scattering
- problems: uncertainties in extracting potential from IQCD in-medium potential $V$ vs. $F$?
from non-pert. interactions reach \( A_{\text{non-pert}} \approx 1/(7 \text{ fm}/c) \approx 4A_{\text{pQCD}} \)

- \( A \) decreases with higher temperature
- higher density (over)compensated by melting of resonances!
- spatial diffusion coefficient

\[
D_s = \frac{T}{mA}
\]

increases with temperature
Non-photonic electrons at RHIC

- same model for bottom
- quark coalescence + fragmentation $\rightarrow D/B \rightarrow e + X$

- coalescence crucial for description of data
- increases both, $R_{AA}$ and $v_2 \Leftrightarrow$ “momentum kick” from light quarks!
- “resonance formation” towards $T_c \Rightarrow$ coalescence natural [Ravagli, Rapp 07]
pQCD with running coupling

- Ansatz for screen gluon propagator
  \[ G_g(t) \propto \frac{1}{t - \kappa \mu_D^2} \]

- requiring \( \frac{dE}{dx} \) to match calculation with HTL-gluon propagator for \(|t| < |t^*|\) and pert. gluon propagator for \(|t| > |t^*|\), where \(|t^*| \in (g^2T^2, T^2)\)

- in QED result independent of \(|t^*|\), in QCD IR regulator in hard part \( \Rightarrow \kappa \simeq 0.15-0.2 \)

- Running coupling
  \[ \frac{\alpha}{t} \to \frac{\alpha_{\text{eff}}(t)}{t - \lambda \tilde{\mu}_D^2}, \quad \tilde{\mu}_D^2 = \frac{N_c}{3} \left( 1 + \frac{N_f}{6} \right) 4\pi \alpha (-\tilde{\mu}_D^2) T^2 \]

- IR regulator mass \( \lambda \): similar strategy as for \( \kappa \)

[Peigné, Peshier 2008, Gossiaux, Aichelin 2008]
Boltzmann-transport model with fixed and running-coupling model

\[ R_{AA, lept} \]

\[ \text{Au–Au min. bias; } \rightarrow \epsilon_{\text{transmin}} \]

\[ \alpha(2\pi T); \kappa=1; K=12 \]

\[ \bullet \text{ PHENIX} \]

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

\[ \text{B} \]

\[ e \rightarrow B \]

\[ e \rightarrow D \]

\[ \text{all} \]

\[ R_{AA, lept} \]

\[ \text{Au–Au min. bias; } \rightarrow \epsilon_{\text{transmin}} \]

\[ \alpha_{\text{eff}}(t); \kappa=0.2; K=1.5–2 \]

\[ \bullet \text{ PHENIX} \]

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

\[ E \]

\[ e \rightarrow B(K=2) \]

\[ e \rightarrow D(K=2) \]

\[ \text{all}(K=2) \]

\[ \nu_2 \text{ lept} \]

\[ K=12 \]

\[ K=20 \]

\[ K=40 \]

\[ \text{Au+Au min. bias} \]

\[ \alpha(2\pi T); \kappa=1 \]

\[ \rightarrow \epsilon_{\text{r min}} \]

\[ \rightarrow \epsilon_{\text{r max}} \]

\[ \rightarrow \epsilon_{\text{r max}} \]

\[ \text{Cronin} \]

\[ \text{No Cronin} \]

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

\[ \bullet \text{ Phenix Run–4} \]

\[ \bullet \text{ Phenix Run–7} \]

\[ \nu_2 \text{ lept} \]

\[ \rightarrow \epsilon_{\text{r min}} \]

\[ \rightarrow \epsilon_{\text{r max}} \]

\[ \rightarrow \epsilon_{\text{r max}} \]

\[ \text{K=1.5–2} \]

\[ \text{K=2–3} \]

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

\[ \bullet \text{ Phenix Run–4} \]

\[ \bullet \text{ Phenix Run–7} \]

[Gotusiaux, Aichelin 2008]
Radiative energy loss

- Gluo-bremsstrahlung energy-loss calculations
  - medium modelled by static scattering centers
  - energy loss through *gluo bremsstrahlung*: \( \Delta E = \frac{\alpha_s}{2} \hat{q} L^2 \)
  - perturbative estimate for RHIC conditions: \( \hat{q} \simeq 1 \text{ GeV}^2/\text{fm} \)

\[ \begin{array}{c}
\text{Mass and scale uncertainties} \\
\text{PHENIX} \\
\text{STAR (Prelim)} \\
\hat{q} = 14 \text{ GeV}/\text{fm} \\
\end{array} \]

- Need \( \hat{q} = 14 \text{ GeV}^2/\text{fm} \); \( v_2 \): only through almond-shape geometry
- without *drag* ⇒ no heavy-quark collective flow:
  no consistent description of \( R_{AA} \) and \( v_2 \)!

[Armento, Cacciari et al. (2006)]
Collisional dissociation/fragmentation in the QGP

- **in-medium dissociation of** $D/B$ mesons $\leftrightarrow$ **in-medium fragmentation of** $c/b$ quarks
  - medium modification of quark-wave functions in QGP
  - dissociation by collision with QGP particles
  - **in-medium fragmentation** $c/b \rightarrow D/B$

[Adil, Vitev (2007)]

- **$B$ mesons stronger bound than** $D$ mesons
- smaller **$B$ formation times** $\iff$ **stronger suppression for** $B$ **than for** $D$!
- could be distinguished from HQ elastic-scattering processes by separate measurement of $D$ and $B$ only!
Transport properties of the sQGP

- spatial diffusion coefficient: Fokker-Planck \[ D_s = \frac{T}{m_A} = \frac{T^2}{D} \]
- measure for coupling strength in plasma: \( \frac{\eta}{s} \)

\[ \frac{\eta}{s} \approx \frac{1}{2} TD_s \quad \text{(AdS/CFT)}, \quad \frac{\eta}{s} \approx \frac{1}{5} TD_s \quad \text{(wQGP)} \]

![Graph showing \( \eta/s \) vs. \( T \) for different models and data points.](image)

[Hendrik van Hees (JLU Gießen)]

[Heavy Quarks in the QGP]
Summary

- **Heavy quarks in the sQGP**
- **non-perturbative interactions**
  - mechanism for strong coupling: resonance formation at $T \gtrsim T_c$
  - IQCD potentials parameter free
  - res. melt at higher temperatures $\Leftrightarrow$ consistency betw. $R_{AA}$ and $v_2$!
- also provides “natural” mechanism for quark coalescence
- **resonance-recombination model**
- problems
  - extraction of $V$ from lattice data
  - potential approach at finite $T$: $F$, $V$ or combination?

Outlook

- include **inelastic heavy-quark processes** (gluo-radiative processes)
- other **heavy-quark observables** like charmonium suppression/regeneration