Collective Flow, $R_{AA}$ and Heavy Flavor Rescattering

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Motivation

- Measured $p_T$ spectra and $v_2$ of non-photonic single electrons
- Coalescence model describes data under assumption of thermalized $c$ quarks, flowing with the bulk medium
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- What is the underlying microscopic mechanism for thermalization?
  - pQCD elastic HQ scattering: need unrealistically large $\alpha_s$ [Moore, Teaney '04]
  - Gluon-radiative energy loss: need to enhance transport coefficient $\hat{q}$ by large factor [Armesto et al '05]
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- Assumption: survival of $D$- and $B$-meson resonances in the sQGP
- Facilitates elastic heavy-quark rescattering
Chiral symmetry $SU_V(2) \otimes SU_A(2)$ in light-quark sector of QCD

$$\mathcal{L}_D^{(0)} = \sum_{i=1}^{2} \left[ (\partial_\mu \Phi_i^\dagger)(\partial^\mu \Phi_i) - m_D^2 \Phi_i^\dagger \Phi_i \right] + \text{massive (pseudo-)vectors } D^*$$

- $\Phi_i$: two doublets: pseudo-scalar $\sim (\begin{pmatrix} D_0^0 \\ D_-^0 \end{pmatrix})$ and scalar
- $\Phi_i^*$: two doublets: vector $\sim (\begin{pmatrix} D_0^{0*} \\ D_-^{0*} \end{pmatrix})$ and pseudo-vector

$$\mathcal{L}_{qc}^{(0)} = \bar{q} i \not{D} q + \bar{c} (i \not{D} - m_c) c$$

- $q$: light-quark doublet $\sim (u \ d)$
- $c$: singlet
Interactions determined by chiral symmetry

For transversality of vector mesons:
heavy-quark effective theory vertices

\[ \mathcal{L}_{\text{int}} = - G_S \left( \frac{1 + \gamma}{2} \Phi_1 c_v + \frac{1 + \gamma}{2} i \gamma^5 \Phi_2 c_v + h.c. \right) \]

\[ - G_V \left( \frac{1 + \gamma}{2} \gamma^\mu \Phi_{1\mu}^* c_v + \frac{1 + \gamma}{2} i \gamma^\mu \gamma^5 \Phi_{2\mu}^* c_v + h.c. \right) \]

\( \nu \): four velocity of heavy quark

in HQET: spin symmetry \( \Rightarrow G_S = G_V \)
Resonance Scattering

- **elastic heavy-light-(anti-)quark scattering**

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

- **parameters**
  - $m_D = 2 \text{ GeV}, \Gamma_D = 0.4 \ldots 0.75 \text{ GeV}$
  - $m_B = 5 \text{ GeV}, \Gamma_B = 0.4 \ldots 0.75 \text{ GeV}$
Contributions from pQCD

- Lowest-order matrix elements (Combridge '79)

\[ \mu_g = gT, \quad \alpha_s = 0.4 \]

- In-medium **Debye-screening mass** for \( t \)-channel gluon exchange:

\[ \mu_g = gT, \quad \alpha_s = 0.4 \]
total pQCD and resonance cross sections: comparable in size

BUT pQCD forward peaked $\leftrightarrow$ resonance isotropic

resonance scattering more effective for friction and diffusion
The Fokker-Planck Equation

- heavy particle (c,b quarks) in a heat bath of light particles (QGP)

\[ \frac{\partial f(t, \vec{p})}{\partial t} = \frac{\partial}{\partial p_i} \left[ p_i A(t, p) + \frac{\partial}{\partial p_j} B_{ij}(t, \vec{p}) \right] f(t, \vec{p}) \]

- Assumption: Relevant scattering processes are soft
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- \( A \) and \( B_{ij} \) given by averages with matrix elements (cross sections) from resonance model

- \( A(t, p) \) friction (drag) coefficient = \( 1/\tau_{eq} \)

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- to ensure correct equilibrium limit: \( B_1(t, p) = T(t) E_p A(t, p) \) (Einstein dissipation-fluctuation relation)
Drag and Diffusion: pQCD vs. resonance scattering

- 3-momentum dependence

- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

\begin{itemize}
  \item \text{resonance contributions factor}\end{itemize}
The Coefficients: pQCD vs. resonance scattering

- Temperature dependence

![Graphs showing temperature dependence of different coefficients and models, including pQCD and resonance scattering.]
Elliptic fire-ball parameterization fitted to hydrodynamical flow pattern [Kolb '00]

\[ V(t) = \pi(z_0 + v_z t)a(t)b(t), \quad a, b: \text{half-axes of ellipse}, \]

\[ v_{a,b} = v_\infty [1 - \exp(-\alpha t)] \mp \Delta v [1 - \exp(-\beta t)] \]
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Isentropic expansion: \( S = \text{const} \) (fixed from \( N_{\text{ch}} \))

QGP Equation of state:

\[
s = \frac{S}{V(t)} = \frac{4\pi^2}{90} T^3 (16 + 10.5n_f^*) \quad , \quad n_f^* = 2.5
\]

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
Initial conditions

- need initial $p_T$-spectra of charm and bottom quarks
- (modified) PYTHIA to describe exp. D meson spectra, assuming $\delta$-function fragmentation
- exp. non-photonic single-$e^\pm$ 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 parametrisation consistent with hydro

$\mu_D = 1.5T \text{ fixed}$
$2\pi T D \sim \frac{3}{2\alpha_s^2}$
Spectra and elliptic flow for heavy quarks

\[ v_2 \text{ vs. } p_T \text{ for } \text{Au-Au } \sqrt{s}=200 \text{ GeV (b=7 fm)} \]

- Red: c, reso (\(\Gamma=0.4\)-0.75 GeV)
- Blue: c, pQCD, \(\alpha_s=0.4\)
- Green: b, reso (\(\Gamma=0.4\)-0.75 GeV)

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

- **Hadronization**: Coalescence with light quarks
  (fixed before [Greco et al 03])
  + fragmentation ($c\bar{c}$, $b\bar{b}$ conserved)

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

- Hadronization: Fragmentation only
- single electrons from decay of $D$- and $B$-mesons
Conclusions and Outlook I

- Assumption: survival of resonances in the (s)QGP
- nonperturbative re-interactions of heavy quarks in QGP
- Observables via Langevin approach and coalescence+fragmentation
  - Elastic resonance scattering ⇒ $R_{AA}^{(c)} \approx 0.2$, $v_2^{(c)} \approx 0.1$
    - without upscaling of cross sections
  - small effects on bottom quarks
  - Heavy-light quark coalescence enhances $v_2^{(e)}$ and $R_{AA}$ for $p_T \approx 2$ GeV
    - bottom dominates for $p_T > 3.5$ GeV ⇒ reduced suppression, $v_2^{(e)}$
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Further investigations
- improved (softer) fragmentation
- better control of coalescence/fragmentation ratio
- implementation of gluon-radiation processes
- quantitative consequences for quarkonia
Motivation

- Matsui & Satz (1986): Quarkonia suppression due to colour screening as signature of QGP in heavy-ion collisions
- sQGP: from lQCD $Q\bar{Q}$ resonances survive at $T > T_c$
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  - $J/\psi$ and $\eta_c$ “melt” at $T_{\text{diss}}(J/\psi) \approx 2T_c$
  - $\Upsilon$: $T_{\text{diss}}(\Upsilon) \approx 4T_c$
- Resonances facilitate secondary regeneration of quarkonia in QGP
Bottomonia at RHIC

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  - $J/\psi$ and $\eta_c$ “melt” at $T_{\text{diss}}^{(J/\psi)} \approx 2T_c$
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- $c\bar{c}$ recombination substantial part of final $J/\psi$ yield at RHIC
  [Braun-Munzinger et al 01, Thews et al 01, Grandchamp, Rapp 01]

- $J/\psi$ suppression dominant at SPS

- Bottomonium at RHIC? similar to Charmonium at SPS?
Dissociation Cross Sections

- Need **Dissociation Cross Sections** to evaluate $\Upsilon$ yield
- Usual mechanism: **Gluo dissociation** (in dipole approximation)
- Problem: becomes inefficient for loosely bound states

\[ \Gamma_Y = \tau_Y^{-1} = \int \frac{d^3k}{(2\pi)^3} f_{q,g}(\omega_k, T)v_{rel}\sigma_{diss}^{g}(s) \]

\[ m_Y = 2m_b(T) - \epsilon_Y(T) = \text{const} \]

- $\epsilon_Y(T)$ from Schrödinger eq. with **screened** Cornell potential
  
  [Karsch, Mehr, Satz 88]
Dissociation Cross Sections

- breakup mechanism for loosely bound states: quasifree dissociation

- use LO pQCD cross sections for elastic scattering [Combridge 79]

\[ \tau_\Upsilon \text{ [fm/c]} \]

- Color screening reduces $\Upsilon$ lifetime by factor of 10!
Rate Equation (detailed balance!)

\[
\frac{d N_Y}{dt} = -\Gamma_Y \left[ N_Y - N_Y^{(eq)} \right]
\]

Fugacities for $b\bar{b}$-pair number conservation

\[
N_{b\bar{b}} = \frac{1}{2} \gamma_b N_{\text{open}} \frac{I_1(\gamma_b N_{\text{open}})}{I_0(\gamma_b N_{\text{open}})} + \gamma_b^2 N_{\text{hidden}}
\]

Initial conditions from hard production only ($m_b \gg T_0$)
Suppression prevalent effect
- color screening in QGP
- suppression of higher bottomonia and feeddown to $\Upsilon$
- with vacuum $\Upsilon$: thermal suppression for $\Upsilon$ negligible magnitude of suppression sensitive to color screening
- $J/\psi$: yield dominated by regeneration

Grandchamp et al 03
Conclusions and Outlook II

- **rate-equation approach** to evaluate $\Upsilon$ abundances
- **Suppression** predominant effect at RHIC (and LHC)
- At LHC: substantial fraction of total $\Upsilon$ yield due to **regeneration**
- **Color screening** main microscopic mechanism for **suppression**
- For details see: L. Grandchamp, S. Lumpkins, D. Sun, HvH., R. Rapp [ hep-ph/0507314]
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Suppression predominant effect at RHIC (and LHC)
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Color screening main microscopic mechanism for suppression

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Future work

- more microscopic approach for dissociation-regeneration processes
- $p_T$ spectra ($v_2$) for bottomonia
Central Collisions

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

Hadronization:
Coalescence + fragmentation

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Fragmentation only
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At both LHC and RHIC: Suppression prevalent effect

mostly due to Debye screening of color potential