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

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December 12, 2005

## Abstract

### Open Charm and Bottom

We evaluate thermalization and collective flow of charm ($c$) and bottom ($b$) quarks in relativistic heavy-ion collisions. Motivated by recent lattice-QCD results, we assume the existence of $D$- and $B$-meson like resonance states in the strongly interacting quark-gluon plasma (sQGP) for temperatures $T \lesssim 2\,T_c$ to study heavy-quark thermalization via resonant elastic heavy-light quark scattering. We calculate drag and diffusion coefficients within a Fokker-Planck approach which we use in a Langevin simulation to compute transverse-momentum ($p_T$) spectra and elliptic flow ($v_2$) of $c$- and $b$-quarks in the quark-gluon plasma (QGP), while the flow profile of the expanding QGP is parameterized by an elliptic fireball model adapted to describe findings from hydrodynamic models. We find large suppression factors and $v_2$ for $c$-quarks without further upscaling of cross sections as is necessary in perturbative-QCD calculations for both elastic scattering and radiative energy loss. We use a combined heavy-light quark coalescence and fragmentation model for the hadronization of the heavy quarks to $D$- and $B$-mesons. We find that the $R_{AA}$ and $v_2$ of the associated decay electrons is in approximate agreement with recent experimental results from the Relativistic Heavy Ion Collider (RHIC) for non-photonic single electrons ($e^{\pm}$). Thus, the existence of resonances in the sQGP is a viable non-perturbative mechanism for early charm-quark thermalization as suggested by the $e^{\pm}$ data from RHIC.

### Bottomonia at RHIC

We investigate the properties of bottomonium states, $\Upsilon$, $\Upsilon'$, and $\chi_b$ ($Y$) in the QGP by evaluating dissociation rates, taking into account in-medium modifications of $b$-quarks and color screening. The latter renders bottomonia less bound in the QGP, and the usually applied dipole approximation for the gluo-dissociation process ($Y + g \rightarrow b + \bar{b}$) becomes inefficient. Therefore, we introduce quasi-free inelastic scattering, i.e., $g, q + Y \rightarrow g, q + b + \bar{b}$, as the most relevant breakup mechanism for bottomonia in the QGP. We apply corresponding dissociation rates in a rate equation to calculate the time evolution and centrality dependence of bottomonium yields under RHIC conditions. While in a similar approach for charmonia it was shown that a large fraction of the final $J/\psi$ yield at RHIC is due to secondary regeneration in the quark-gluon plasma, for the $\Upsilon$ we find a large suppression. This finding depends sensitively on the color-screening effects for the $\Upsilon$ in the QGP. If this scenario is valid, it may lead to a larger (net) suppression for bottomonia than for charmonia which would be an intriguing new signature for the formation of a strongly interacting QGP in heavy-ion collisions at collider energies.

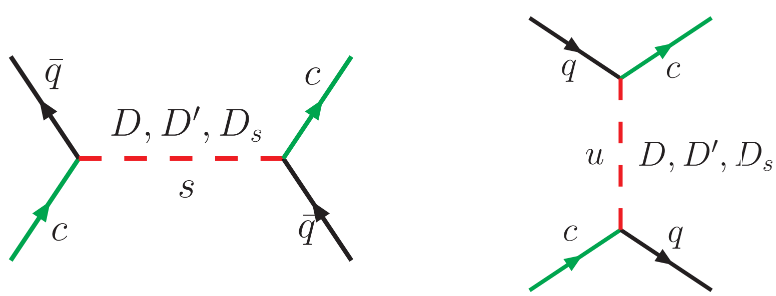
# I. Open Charm and Bottom

## Motivation

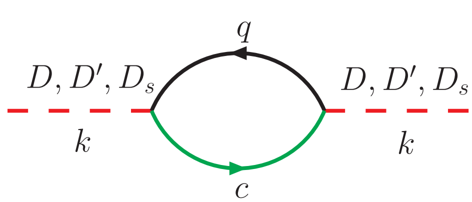
- Measured $p_T$ spectra and $v_2$ of non-photonic single electrons
- coalescence model describes data under assumption of thermalized c quarks, flowing with the bulk medium
- What is the underlying microscopic mechanism for thermalization?
  - pQCD elastic HQ scattering: need unrealistically large $\alpha_s$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

# Elastic Resonance Scattering

- elastic heavy-light-(anti-)quark scattering: Dress propagators with

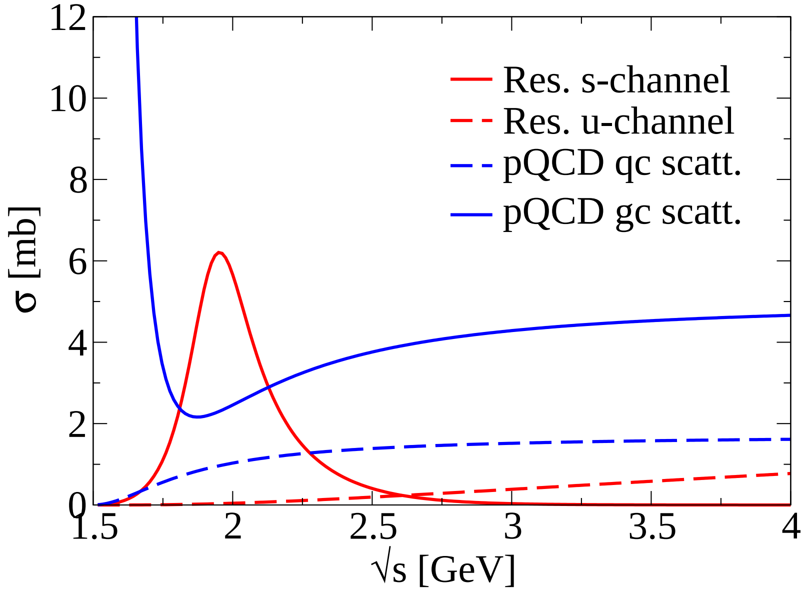



- $D$- and $B$-meson like resonances in sQGP




- 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

## Cross sections




Use LO pQCD with Debye-screened $t$-channel gluons ($\mu_D = gT$)

total pQCD and resonance cross sections: comparable in size

BUT pQCD forward peaked ↔ resonance isotropic

resonance scattering more effective for friction and diffusion

## Heavy-quark rescattering in QGP

Calculate drag and diffusion coefficients in Fokker-Planck approach from elastic resonance scattering cross sections

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

$B_{ij}$: time scale for momentum fluctuations

to ensure correct equilibrium limit: $B_1(t,p) = T(t)E_p A(t,p)$ (Einstein dissipation-fluctuation relation)

Resonance scattering $\Rightarrow$ enhancing FP coefficients by factor $\sim 4$ compared to pQCD

describe bulk QGP medium by elliptic fire-ball parameterization fitted to hydrodynamical flow pattern [Kolb '00]

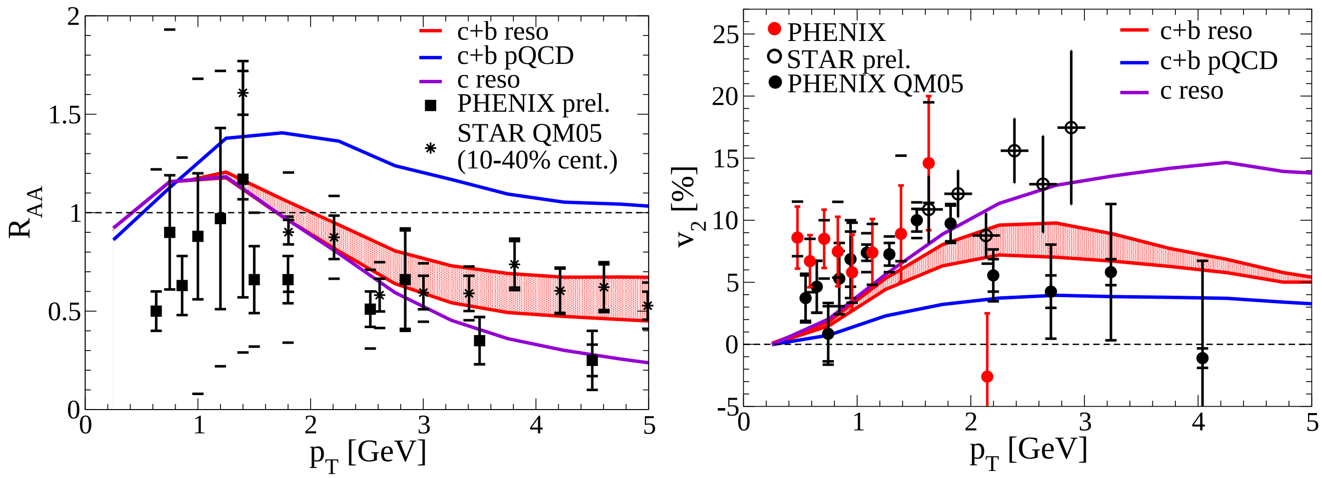
Isentropic expansion: $S = \text{const}$ (fixed from $N_{\text{ch}}$) $\Rightarrow T(t)$

simulate FP equation as relativistic Langevin process

initial conditions from exp. $p_T$-spectra for $D$-mesons and non-phot. electrons $\Rightarrow$ initial $b$, $c$ spectra

## Observables: $p_T$-spectra ($R_{AA}$), $v_2$

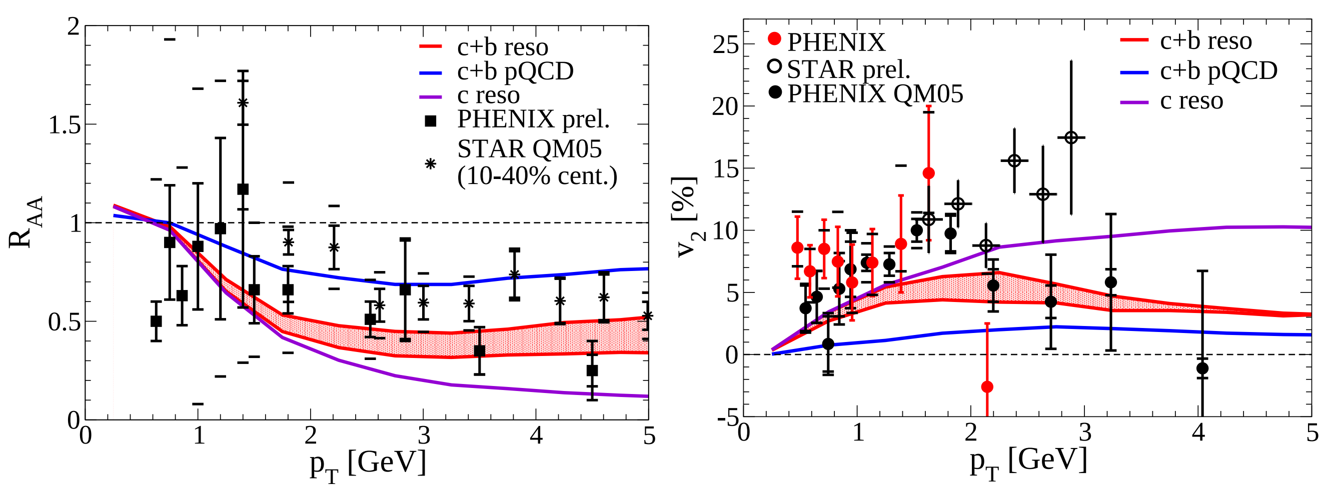
Hadronization: Coalescence with light quarks
(fixed before [Greco et al 03]) + fragmentation ($c\bar{c}$, $b\bar{b}$ conserved)
input for $c$- and $b$-quarks from Langevin simulation
single electrons from decay of $D$- and $B$-mesons




Rough agreement with data from elastic resonance scattering without further upscaling of cross sections!

## Observables: $p_T$-spectra ($R_{AA}$), $v_2$

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




need to readdress question of coalescence to fragmentation ratio!

## 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 $\Rightarrow R_{AA}^{(c)} \simeq 0.2$, $v_2^{(c)} \simeq 0.1$
- without upscaling of cross sections
- small effects on bottom quarks
- Heavy-light quark coalescence enhances $v_2^{(e)}$ and $R_{AA}$ for $p_T \simeq 2$ GeV
- bottom dominates for $p_T > 3.5$ GeV $\Rightarrow$ reduced suppression, $v_2^{(e)}$

For details, see: HvH, R. Rapp, Phys. Rev. C 71, 034907 (2005) [nucl-th/0412015],
HvH, V. Greco, R. Rapp [nucl-th/0508055,hep-ph/0510050]

Further investigations

- improved (softer) fragmentation
- better control of coalescence/fragmentation ratio
- implementation of gluon-radiation processes
- quantitative consequences for quarkonia

## Bottomonia at RHIC

### Motivation

Matsui & Satz (1986):
Quarkonia suppression due to color screening as signature of QGP in heavy-ion collisions

sQGP: from lQCD $Q\bar{Q}$ resonances survive at $T > T_c$

- $J/\psi$ and $\eta_c$ "melt" at $T_{\text{diss}}^{(J/\psi)} \simeq 2T_c$
- $\Upsilon$: $T_{\text{diss}}^{\Upsilon} \simeq 4T_c$

Resonances facilitate secondary regeneration of quarkonia in QGP

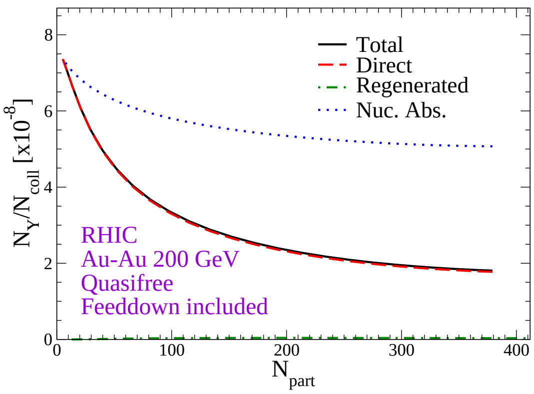
$c\bar{c}$ recombination substantial part of final $J/\psi$ yield at RHIC [Braun-Munzinger et al 01, Thews et al 01, Grandchamp, Rapp 01]

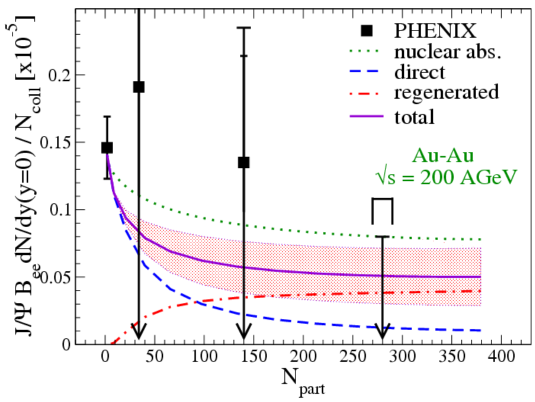
$J/\psi$ suppression dominant at SPS

Bottomonium at RHIC?
similar to Charmonium at SPS?

## $\Upsilon$ vs. $J/\psi$ at RHIC

gluo-dissociation becomes inefficient for loosely bound states
$\Rightarrow$ destruction by quasifree scattering of bound $c$(or $\bar{c}$) with $q$ and $g$




[Grandchamp et al 03]

Suppression prevalent effect

- color screening in QGP [Karsch, Mehr, Satz 88]
- suppression of higher bottomonia and feeddown to $\Upsilon$

with vacuum $\Upsilon$ masses: thermal suppression for $\Upsilon$ negligible
magnitude of suppression sensitive to color screening
$J/\psi$: yield dominated by regeneration

## Conclusions and Outlook II

rate-equation approach to evaluate $\Upsilon$ abundances

Dissociation rates from quasi-free destruction process

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

$\Upsilon$ may be more suppressed than $J/\psi$

intriguing new signature for QGP formation in ultra-relativistic heavy-ion collisions!

For details see: L. Grandchamp, , S. Lumpkins, D. Sun, HvH., R. Rapp [ hep-ph/0507314]

Future work

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