Resonance Recombination model for Quarks in the Quark-Gluon Plasma

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Outline

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   - Fokker-Planck equation and Langevin simulations
   - Nonphotonic electrons at RHIC
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   - Constituent-quark number and KE_T scaling
   - Meson spectra
4. Conclusions

Motivation

- Strongly interacting medium in relativistic heavy-ion collisions (HICs)
  - (ideal) hydrodynamics describes low-p_T spectra of hadrons
  - collective radial and elliptic flow
  - medium close to local thermal equilibrium
  - very small viscosity $\Rightarrow$ strongly coupled Quark-Gluon Plasma (sQGP)
- Possible explanation for strong interactions in QGP close to T_c: formation of hadron-like resonances
- successful description of non-photonic $e^{\pm}$ data at RHIC
  - heavy-quark diffusion in QGP $\Leftrightarrow$ Fokker-Planck (FP) equation
  - non-perturbative elastic collisions close to T_c
  - facilitated by resonance formation
  - coalescence + fragmentation to D and B-mesons
  - simultaneous description of $e^{\pm}$-R_{AA} *und* v_2

[HvH, V. Greco, R. Rapp, Phys. Rev. C **73**, 034913 (2006)]
[HvH, M. Mannarelli, V. Greco, Phys. Rev. Lett. **100**, 192301 (2008)]

Motivation

- Success of quark-coalescence models
  - recombination of quarks to hadrons at the QGP phase transition
  - describes observed constituent-quark number scaling of elliptic flow:

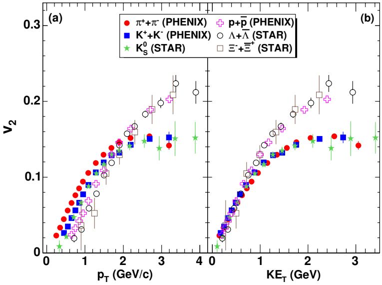
$$v_2^{\text{hadrons}}(p_T) \simeq n_q v_2^{(\text{quarks})}(p_T/n_q)$$

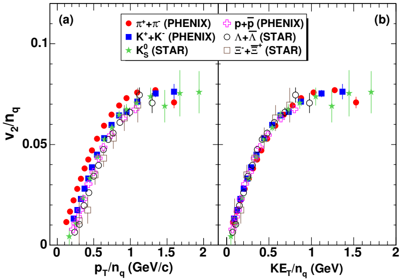
  $\Rightarrow$ recombination of comoving quarks to hadrons
  - describes large baryon/meson ratio in HICs compared to pp collisions
- Shortcomings
  - violates energy conservation
  - violates 2^{nd} Law of Thermodynamics
  - CQNS better with $\mathrm{KE}_T = m_T - m = \sqrt{p_T^2 + m^2} - m$ than with p_T
- Resonance-recombination model
  - based on kinetic theory: $q\bar{q} \leftrightarrow R$
  - detailed balance
  - fulfills energy-momentum conservation
  - obeys 2^{nd} law of thermodynamics

[L. Ravagli, HvH, Ralf Rapp, Phys. Rev. C **79**, 064902 (2009)]

Motivation

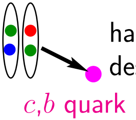
- Constituent-Quark Number Scaling: $v_2(p_T)$ vs. $v_2(\mathrm{KE}_T)$
  - $v_2^{(\mathrm{had})}(p_T) = n_q v_2^{(\mathrm{quark})}(p_T/n_q)$
  - vs. $v_2^{(\mathrm{had})}(\mathrm{KE}_T) = n_q v_2^{(\mathrm{quark})}(\mathrm{KE}_T/n_q)$



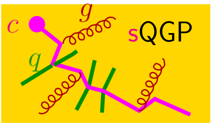


[Adare et al (PHENIX Collab.), Phys. Rev. Lett. **98**, 162301 (2007)]

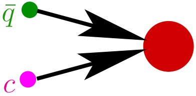
Heavy Quarks in Heavy-Ion collisions



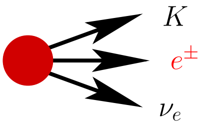
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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



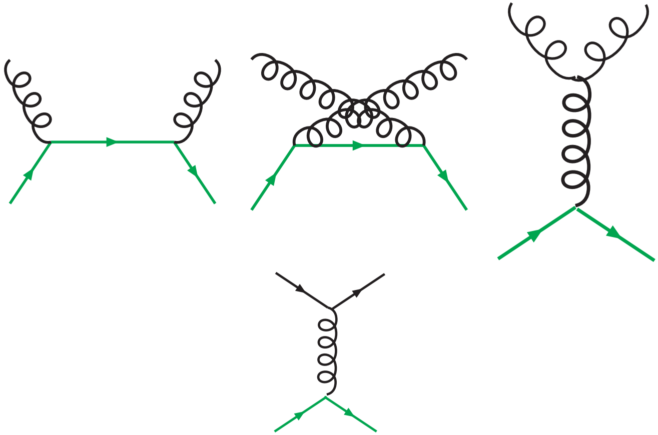
Hadronization to D,B mesons via
quark coalescence + fragmentation
V. Greco, C. M. Ko, R. Rapp, PLB **595**, 202 (2004)



semileptonic decay ⇒
"non-photonic" electron observables
$R_{AA}^{\mathrm{e}^+e^-}(p_T)$, $v_2^{e^+e^-}(p_T)$

Elastic pQCD processes

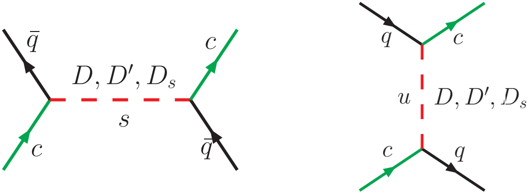
- Lowest-order matrix elements [Combridge 79]



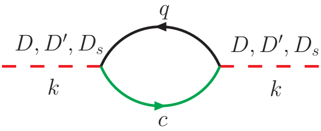
- Debye-screening mass for t-channel gluon exch. $\mu_g = gT$, $\alpha_s = 0.4$
- not sufficient to understand RHIC data on "non-photonic" electrons

Non-perturbative interactions: Resonance Scattering

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

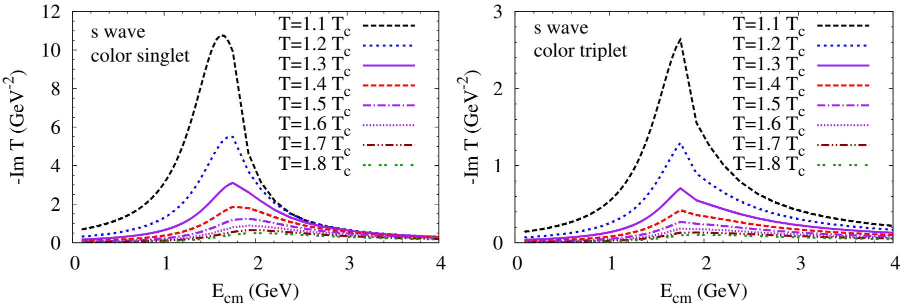


- D- and B-meson like resonances in sQGP



- 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

T-matrix



- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T! $\Rightarrow$ sQGP
- P wave smaller
- resonances near T_c: natural connection to quark coalescence

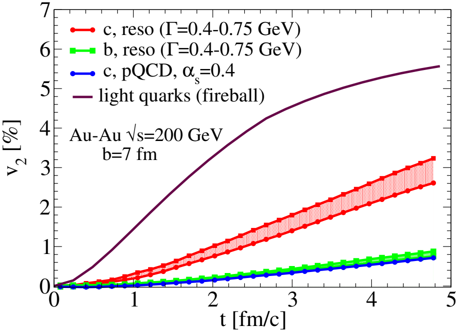
  [Ravagli, Rapp 07; Ravagli, HvH, Rapp 08]
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering
- problems: uncertainties in extracting potential from lQCD in-medium potential V vs. F?

Relativistic Langevin process

- FP equation equivalent to stochastic Langevin process
- Langevin process: friction force + Gaussian random force
- From models for heavy-light-quark scattering:
  - A: friction (drag) coefficient
  - $B_{0,1}$: diffusion coefficients
- 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"

Time evolution of the fire ball

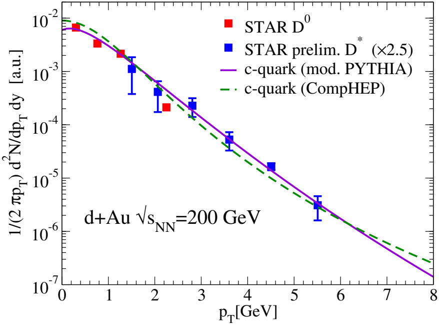
- Elliptic fire-ball parameterization
  fitted to hydrodynamical flow pattern [Kolb '00]

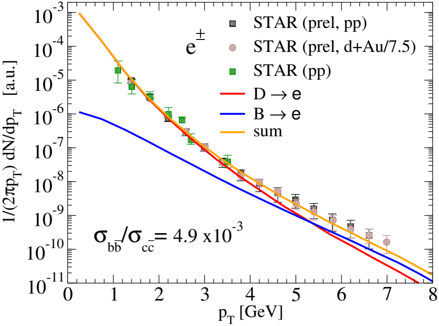


- Isentropic expansion: $S = \text{const}$ (fixed from N_{ch})
- QGP Equation of state:
- for semicentral collisions ($b = 7$ fm): $T_0 = 340$ MeV,
  QGP + mixed phase lifetime $\simeq 5$ fm/c.
- flow field $\vec{v}_\perp(\vec{r}_\perp) \propto r_\perp$; $\perp$ isobars (confocal ellipses)

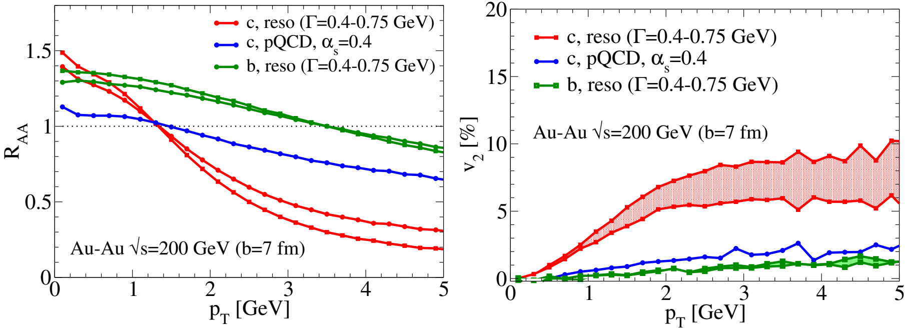
Initial conditions

- 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-$e^{\pm}$ spectra: Fix bottom/charm ratio



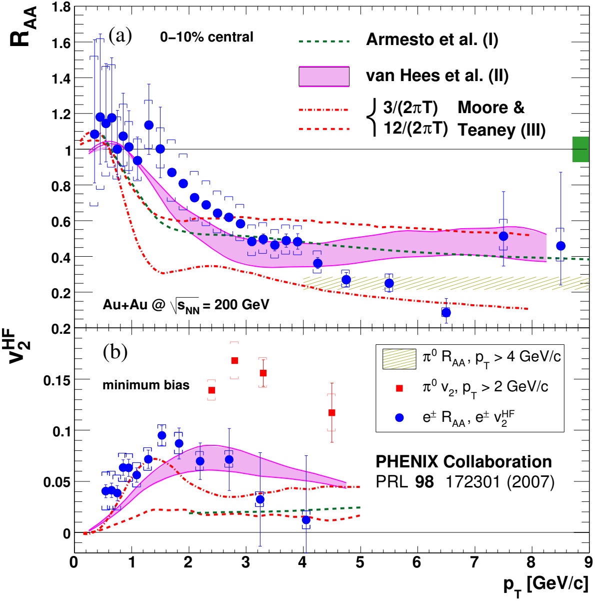


Spectra and elliptic flow for heavy quarks



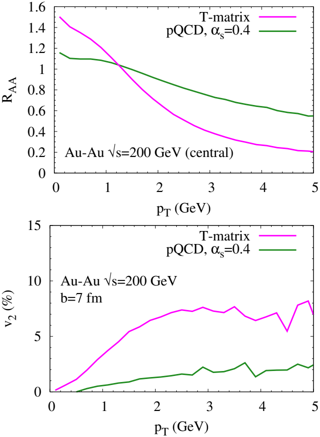
- $\mu_D = gT$, $\alpha_s = g^2/(4\pi) = 0.4$
- resonances ⇒ c-quark thermalization
  without upscaling of cross sections
- Fireball parametrization consistent with hydro

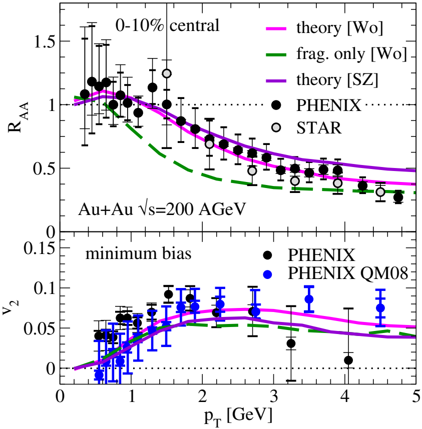
Nonphotonic electrons at RHIC



Non-photonic electrons at RHIC

- T-matrix model for charm and 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]

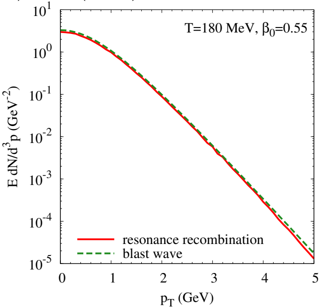
Resonance-Recombination Model

- transport approach for hadronization by $q + \bar{q} \leftrightarrows$ meson resonance

$$\frac{\partial}{\partial t} f_M(t,p) = -\frac{\Gamma}{\gamma_p} f_M(t,p) + g(p) \Rightarrow f_M^{(\text{eq})}(p) = \frac{\gamma_p}{\Gamma} g(p)$$

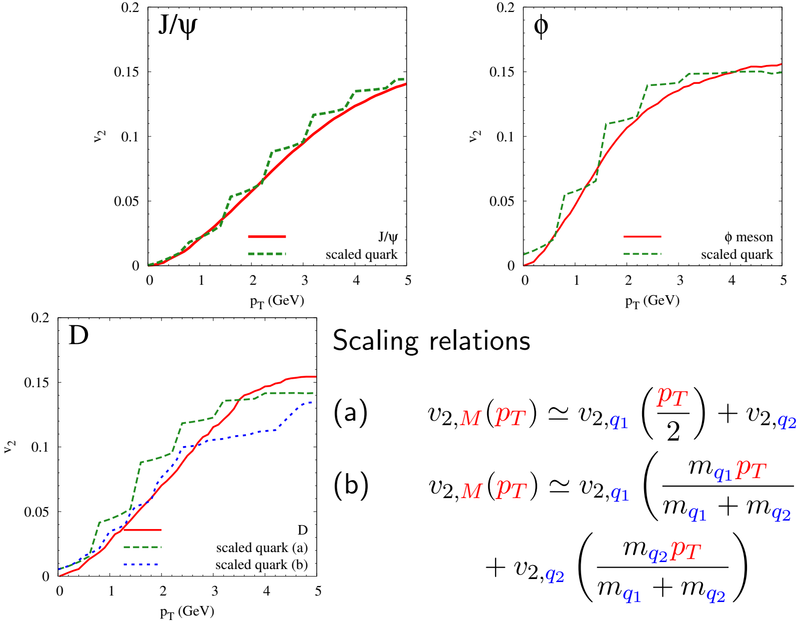
$$g(p) = \int \frac{\mathrm{d}^3 p_1 \mathrm{d}^3 p_2}{(2\pi)^6} \int \mathrm{d}^3 x f_q(x,p_1) f_{\bar{q}}(x,p_2) \sigma(s) v_{\text{rel}} \delta^{(3)}(p - p_1 - p_2)$$

$$\sigma(s) = g_\sigma \frac{4\pi}{k_{\text{cm}}^2} \frac{(\Gamma m)^2}{(s-m^2)^2 + (\Gamma m)^2}$$



[L. Ravagli, R. Rapp, Phys. Lett. B **655**, 126, (2007); L. Ravagli, HvH, R. Rapp arXiv:0806.2055 [hep-ph]]

Constituent-quark number scaling (p_T)



Scaling relations

(a) $$v_{2,M}(p_T) \simeq v_{2,q_1}\left(\frac{p_T}{2}\right) + v_{2,q_2}\left(\frac{p_T}{2}\right)$$

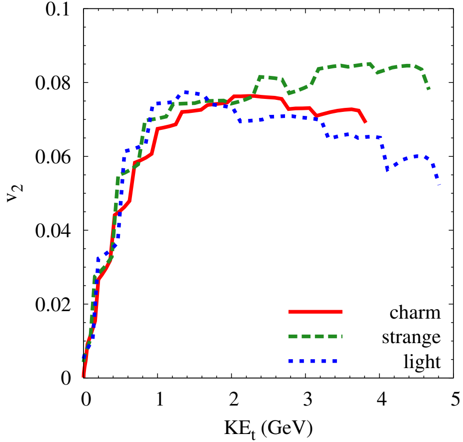
(b) $$v_{2,M}(p_T) \simeq v_{2,q_1}\left(\frac{m_{q_1} p_T}{m_{q_1}+m_{q_2}}\right) + v_{2,q_2}\left(\frac{m_{q_2} p_T}{m_{q_1}+m_{q_2}}\right)$$

KE_T scaling of quarks

- usual coalescence models: factorization ansatz

$$f_q(p, x, \varphi) = f_q(p, x)[1 + 2v_2^q(p_T)\cos(2\varphi)]$$

- CQNS usually not robust with more realistic parametrizations of v_2
- here: q input from relativistic Fokker-Planck-Langevin simulation



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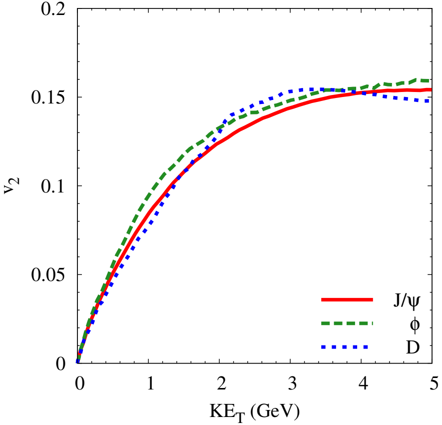
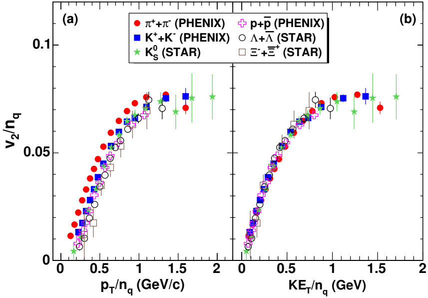
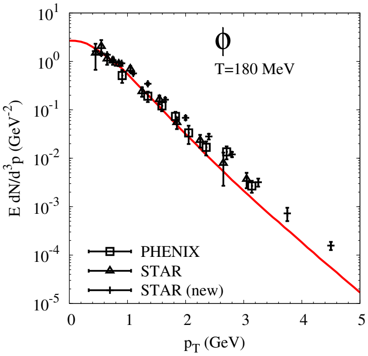
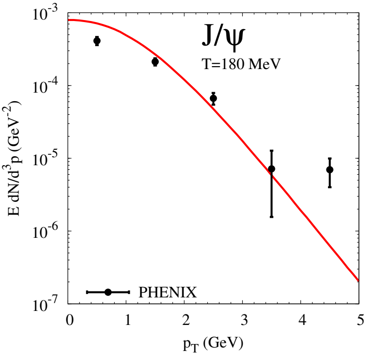




Meson spectra

- q-$\bar{q}$ input: Fokker-Planck-Langevin
- meson output: resonance-recombination model





Data from [A. Adare et al. (PHENIX) PRL **98**, 232301 (2007); S. S. Adler et al. (PHENIX) PRC **72**, 014903 (2005); J. Adams et al. (STAR) PLB **612**, 181 (2005) B. I. Abelev et al. (STAR) PRL **99**, 112301 (2007)]

Conclusions

- Heavy-quark diffusion in the QGP
  - strongly interacting QGP ⇔ "hadron"-resonance formation close to T_c
  - resonance-scattering model
    (confirmed with T-matrix approach with lQCD potentials)
  - Fokker-Planck (FP) simulation of heavy quarks
  - + coalescence + fragmentation ⇒ good description of non-photonic electron flow data
- Kinetic Resonance-Recombination model
  - quark recombination into meson-resonance states in the QGP at T_c
    (consistent with resonance-scattering approach in HQ diffusion!)
  - based on Boltzmann transport approach
  - energy-momentum conservation
  - detailed balance
  - 2^{nd} Law of Thermodynamics
  - realistic space-momentum correlations (v_2) from FP simulation
  - results in CQNS and KET scaling of meson spectra

Problems and Outlook

- include inelastic (gluo-radiative) processes in heavy-quark interaction
- T-matrix approach: which potential is the correct one?
- FP approach for light (and strange?) quarks problematic (self-consistency problem between "bulk medium" in FP simulation and quark distributions used in recombination)
- Resonance recombination should be combined with fragmentation (particularly at higher p_T)
- analogous treatment of baryons (quark-diquark recombination!?)