

# T-Matrix approach to heavy quarks in the Quark-Gluon Plasma

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with

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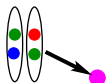


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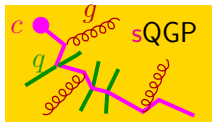
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# Heavy Quarks in Heavy-Ion collisions



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

$c, b$  quark

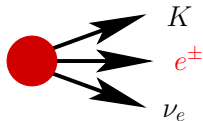


HQ rescattering in QGP: Langevin simulation  
drag and diffusion coefficients from  
microscopic model for HQ interactions in the sQGP



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

V. Greco, C. M. Ko, R. Rapp, PLB **595**, 202 (2004)



semileptonic decay  $\Rightarrow$   
“non-photonic” electron observables

# Heavy-Quark diffusion

- Fokker Planck Equation

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

- drag (friction) and diffusion coefficients

$$p_i A(t, \vec{p}) = \langle p_i - p'_i \rangle$$

$$\begin{aligned} B_{ij}(t, \vec{p}) &= \frac{1}{2} \langle (p_i - p'_i)(p_j - p'_j) \rangle \\ &= B_0(t, p) \left( \delta_{ij} - \frac{p_i p_j}{p^2} \right) + B_1(t, p) \frac{p_i p_j}{p^2} \end{aligned}$$

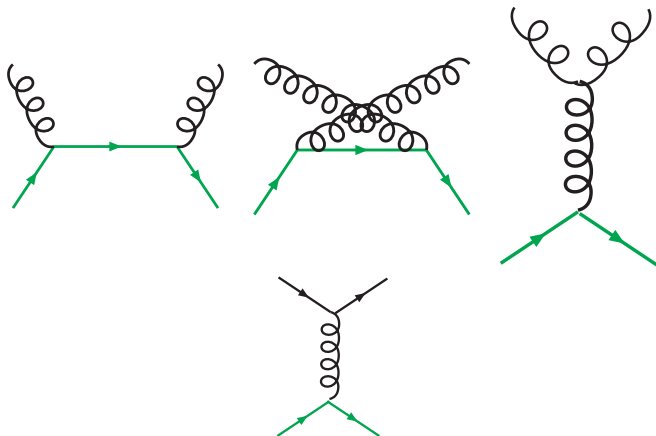
- transport coefficients defined via  $\mathcal{M}$

$$\begin{aligned} \langle X(\vec{p}') \rangle &= \frac{1}{\gamma_c} \frac{1}{2E_p} \int \frac{d^3 \vec{q}}{(2\pi)^3 2E_q} \int \frac{d^3 \vec{q}'}{(2\pi)^3 2E_{q'}} \int \frac{d^3 \vec{p}'}{(2\pi)^3 2E_{p'}} \\ &\quad \sum |\mathcal{M}|^2 (2\pi)^4 \delta^{(4)}(p + q - p' - q') \hat{f}(\vec{q}) X(\vec{p}') \end{aligned}$$

- correct equil. lim.  $\Rightarrow$  Einstein relation:  $B_1(t, p) = T(t) E_p A(t, p)$

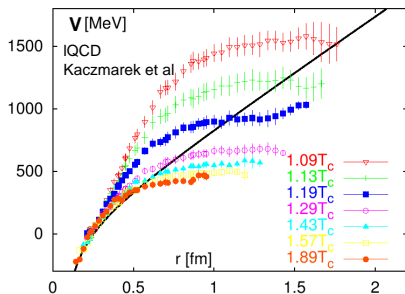
# Elastic pQCD processes

- Lowest-order matrix elements [Cambridge 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

# Static potentials from lattice QCD



- color-singlet free energy from lattice
- use **internal energy**

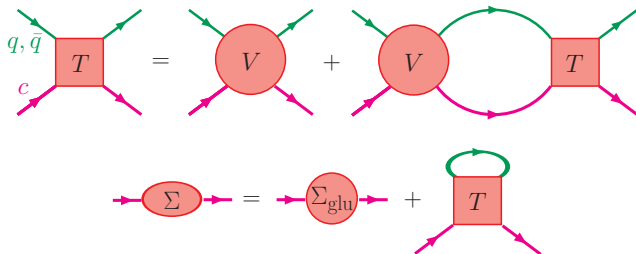
$$U_1(r, T) = F_1(r, T) - T \frac{\partial F_1(r, T)}{\partial T},$$

$$V_1(r, T) = U_1(r, T) - U_1(r \rightarrow \infty, T)$$

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

$$V_{\bar{3}} = \frac{1}{2}V_1, \quad V_6 = -\frac{1}{4}V_1, \quad V_8 = -\frac{1}{8}V_1$$

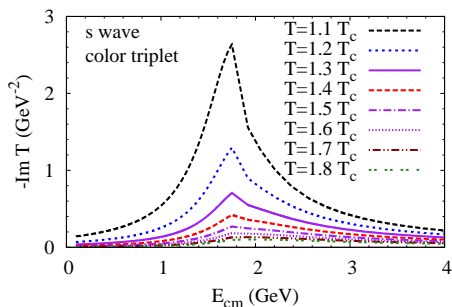
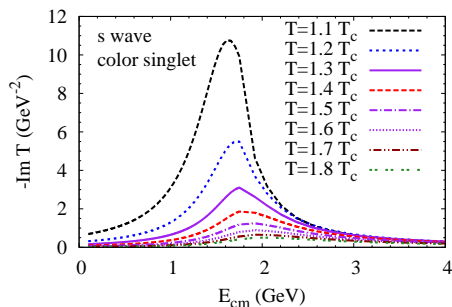
- Brueckner many-body approach for elastic  $Qq, Q\bar{q}$  scattering



- 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**

$$\sum |\mathcal{M}(s)|^2 \propto \sum_a d_a (|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos^2 \theta_{\text{cm}})$$

# T-matrix

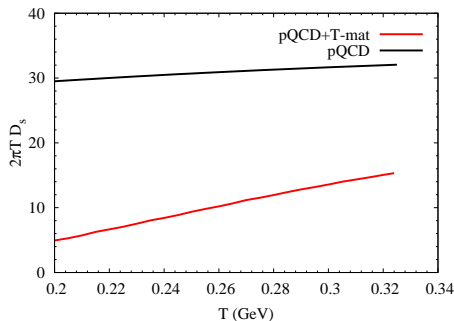
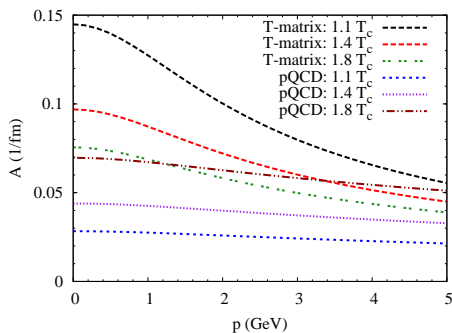


- resonance formation at lower temperatures  $T \simeq T_c$
- melting of resonances at higher  $T$ !  $\Rightarrow$  sQGP
- $P$  wave smaller
- resonances near  $T_c$ : natural connection to quark coalescence

[Ravagli, Rapp 07]

- model-independent assessment of elastic  $Qq$ ,  $Q\bar{q}$  scattering
- problems: uncertainties in extracting potential from IQCD  
in-medium potential  $V$  vs.  $F$ ?

# Transport coefficients



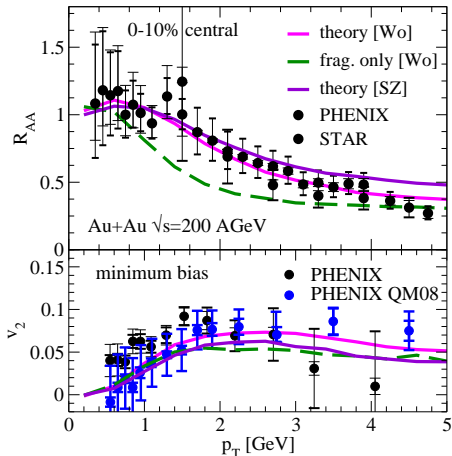
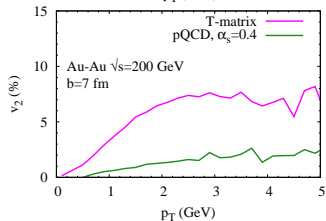
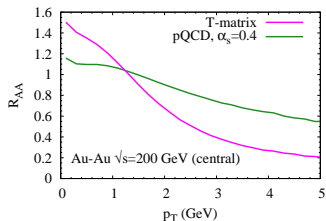
- from **non-pert.** interactions reach  $A_{\text{non-pert}} \simeq 1/(7 \text{ fm}/c) \simeq 4A_{\text{pQCD}}$
- **A decreases with higher temperature**
- higher density (over)compensated by **melting of resonances!**
- spatial diffusion coefficient

$$D_s = \frac{T}{mA}$$

**increases** with temperature

# Non-photonic electrons at RHIC

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

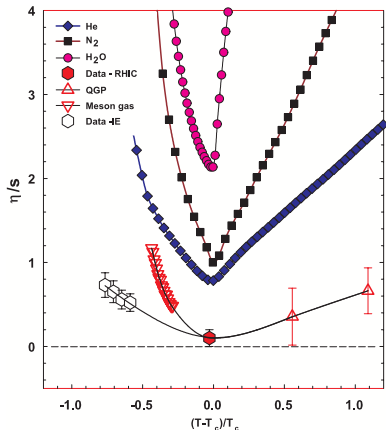
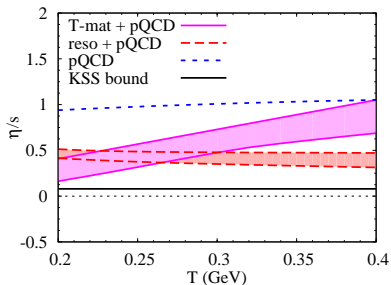


- **coalescence crucial for explanation of data**
- increases **both**,  $R_{AA}$  and  $v_2 \Leftrightarrow$  “momentum kick” from light quarks!

# Transport properties of the sQGP

- measure for coupling strength in plasma:  $\eta/s$
- relation to spatial diffusion coefficient

$$\frac{\eta}{s} \simeq \frac{1}{2} T D_s \quad (\text{AdS/CFT}), \quad \frac{\eta}{s} \simeq \frac{1}{5} T D_s \quad (\text{wQGP})$$



[Lacey 06]

## • Summary

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

## • Outlook

- include inelastic heavy-quark processes (gluon-radiation processes)
- other heavy-quark observables like charmonium (and bottomonium) suppression/regeneration