Strongly Interacting Matter in Heavy-Ion Collisions

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Outline

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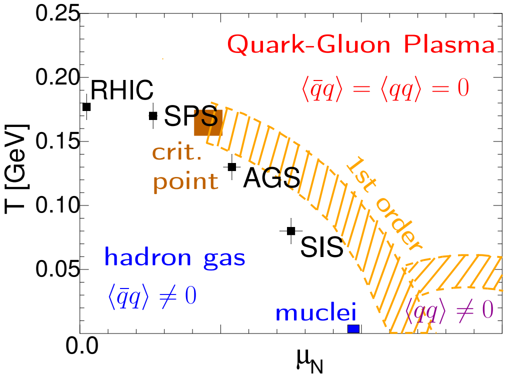
   - Heavy-quark diffusion: The Langevin Equation
   - Static heavy-quark potentials from lattice QCD
   - Non-photonic electrons at RHIC
   - Conclusions and Outlook II

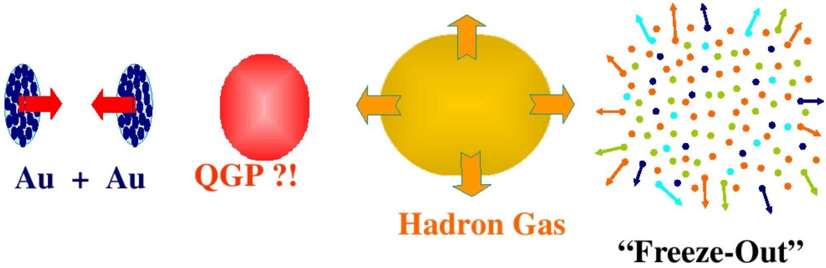
The phase diagram of strongly interacting matter

- hot and dense matter: quarks and gluons inside hadrons compressed
- highly energetic scatterings ⇒ deconfinement/chiral phase transition
- quarks and gluons relevant d.o.f. ⇒ Quark-Gluon Plasma
- still strongly couples: fast thermalization!
- @FAIR highest net-baryon density expected ⇒
  region in phase diagram not investigated yet!



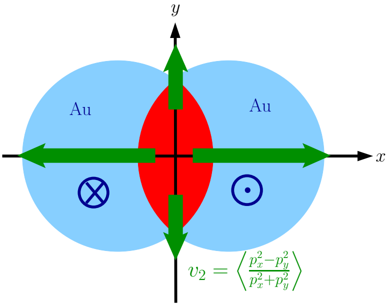
Ultra relativistic heavy-ion collisions

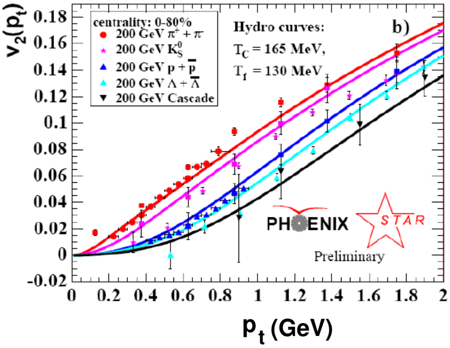
- highly energetic collisions of (heavy) nuclei
- many collisions of partons inside the nucleons
- creation of many particles ⇒ hot and dense fireball
- generation of the Quark-Gluon Plasma (QGP)?
- properties of QGP and/or compressed baryonic matter?
- signatures of 1st-order phase transition (critical end point)?



Hydrodynamical behavior

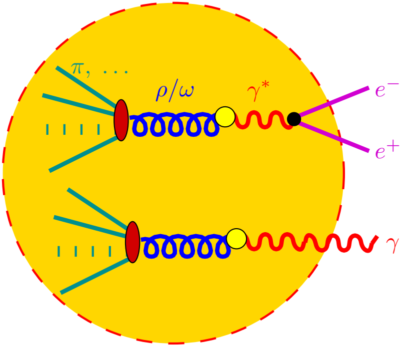
- particle spectra compatible with collective motion of an ideal fluid $\Rightarrow$ small viscosity
- Medium in local thermal equilibrium (after short formation time $\lesssim 1\ \text{fm}/c$)





Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^{\pm}$: no strong interactions
- reflect whole "history" of collision:
  - from pre-equilibrium phase
  - from thermalized medium QGP and hot hadron gas
  - from VM decays after thermal freezeout



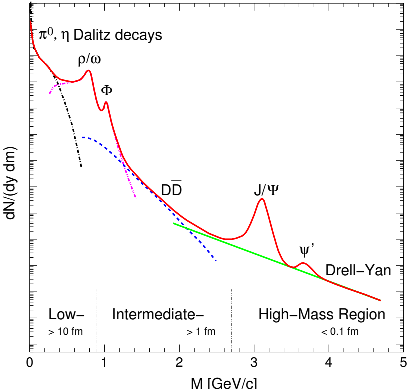


Fig. by A. Drees

Vector Mesons and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f$)

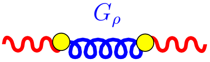
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 f_B(q_0) \,\mathrm{Im}\, \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

$$q_0 \frac{\mathrm{d}N_\gamma}{\mathrm{d}^4 x \mathrm{d}^3 \vec{q}} = \frac{\alpha}{2\pi^2} g^{\mu\nu} \,\mathrm{Im}\, \Pi^{(\mathrm{ret})}_{\mu\nu}(q) \Big|_{q_0 = |\vec{q}|} f_B(q_0)$$

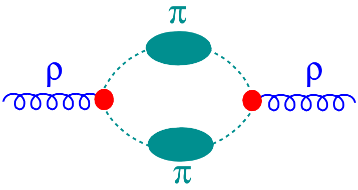
$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4 x \mathrm{d}^4 q} = -g^{\mu\nu} \frac{\alpha^2}{3q^2\pi^3} \,\mathrm{Im}\, \Pi^{(\mathrm{ret})}_{\mu\nu}(q) \Big|_{q^2 = M^2_{e^+e^-}} f_B(q_0)$$

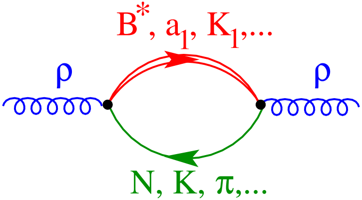
- to lowest order in α: $e^2 \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

$\Sigma^{\gamma}_{\mu\nu} =$ 

Hadronic many-body theory

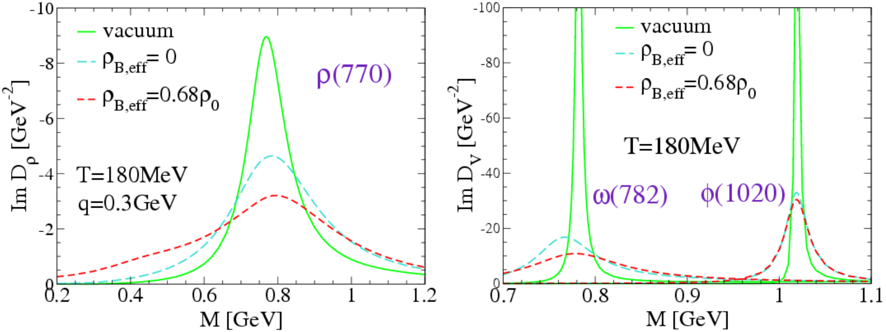
- HMBT for vector mesons [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, . . .]
- $\pi\pi$ interactions and baryonic excitations





- +corresponding vertex corrections ⇔ gauge invariance
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

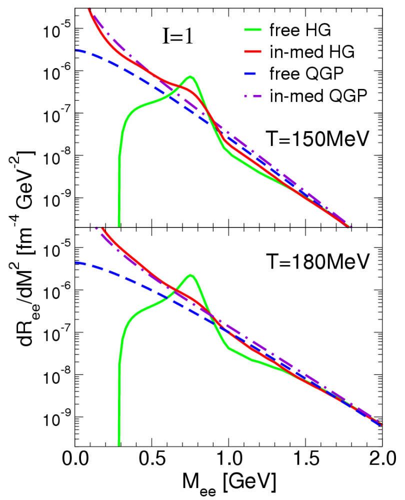
In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach 99]

- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

Dilepton rates: Hadron gas $\leftrightarrow$ QGP



- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"!?
- indirect evidence for chiral-symmetry restoration

Sources of dilepton emission in heavy-ion collisions

1. initial hard processes: Drell Yan
2. "core" ⇔ emission from thermal source [McLerran, Toimela 1985]

$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T}=\int \mathrm{d}^4 x \int \mathrm{d}y \int M \mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4 x \mathrm{d}^4 q}\text{Acc}(M,q_T,y)$$

3. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out ⇔ emission from "freeze-out" mesons

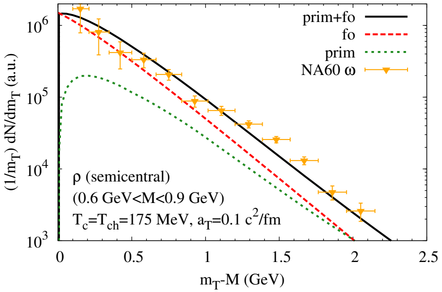
   [Cooper, Frye 1975]

$$N^{(\text{fo})}=\int \frac{\mathrm{d}^3 q}{q_0}\int q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu/T)\frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}}\text{Acc}$$

- additional factor $\gamma = q_0/M$ compared to thermal emission
- physical reason
  - thermal source rate $\propto \tau_{\text{med}} \frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\gamma}$
  - decay of mesons after fo: rate $\propto \frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}}$

NA60: Hadron spectra

- analysis of "cocktail": hadron-m_T spectra
- comparison to fireball evolution
- "sequential freeze-out" due to different coupling strength



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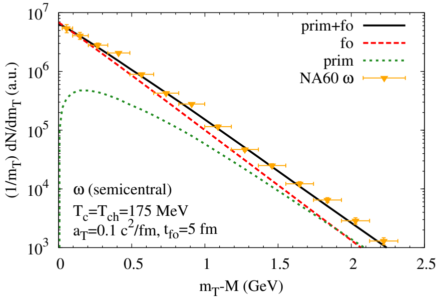
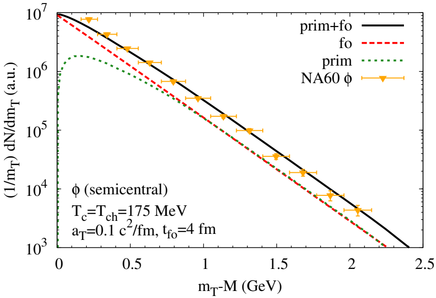
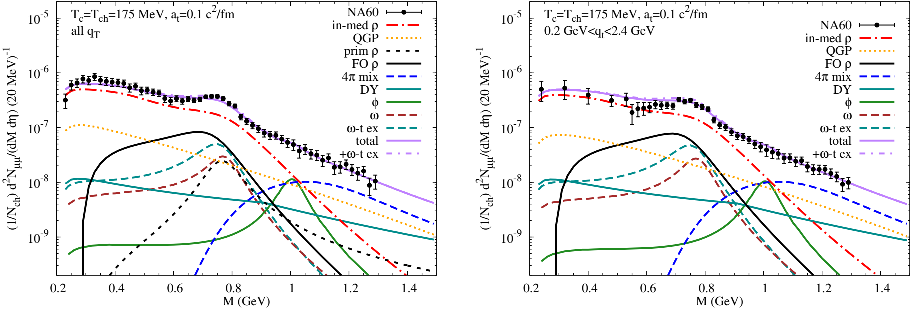




NA60: M spectra (in p_T slices)

- EoS-A: $T_c = T_{\text{ch}} = 175$ MeV
- transverse acceleration: $a_\perp = 0.1 c^2/\text{fm}$



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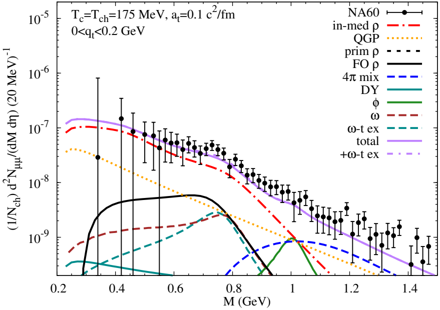

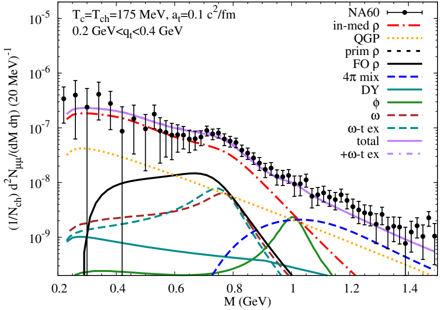

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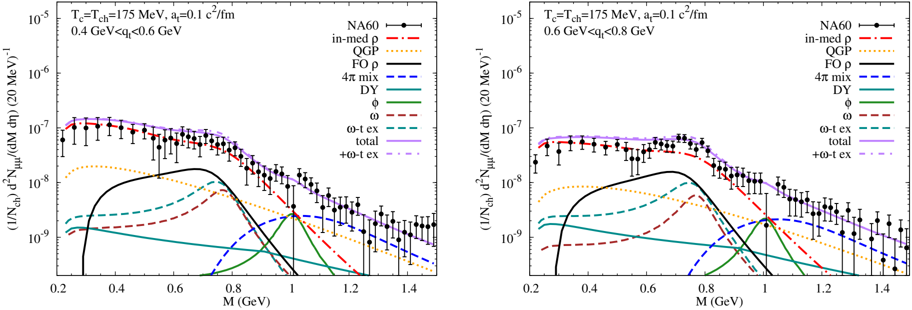

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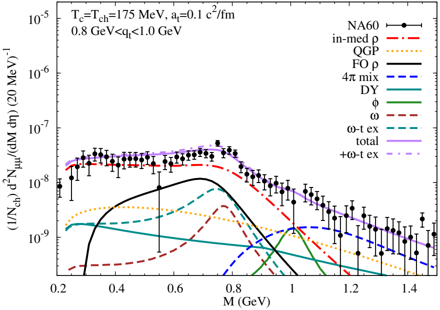

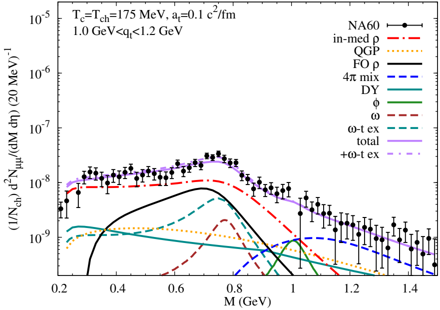

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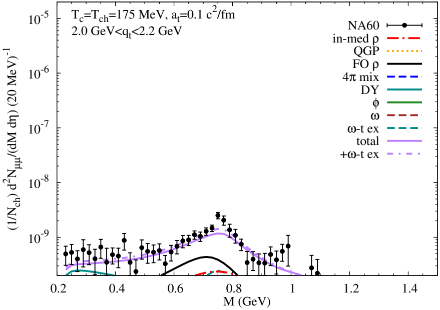
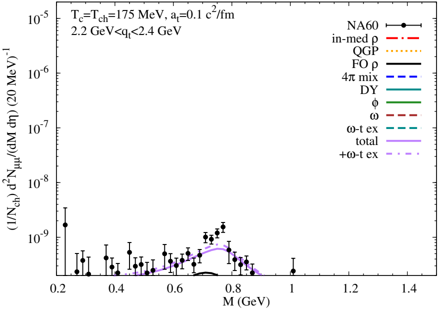




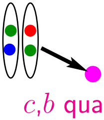
Conclusions and Outlook I

- dilepton spectra $\Leftrightarrow$ in-medium em. current correlator
- model for dilepton sources
  - radiation from thermal sources: QGP, ρ, ω, ϕ, multi-pion processes
  - ρ-decay after thermal freeze-out
  - decays of non-thermalized primordial ρ's
  - Drell-Yan annihilation, correlated $D\bar{D}$ decays
- invariant-mass spectra and medium effects
  - excess yield dominated by radiation from thermal sources
  - baryons essential for in-medium properties of vector mesons
  - melting ρ with little mass shift
  - dileptons in In-In (NA60), Pb-Au (CERES/NA45), γ in Pb-Pb (WA98)

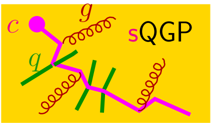
Conclusions and Outlook I

- Further developments
  - understand recent PHENIX results (large dilepton excess in LMR)
  - understand "DLS puzzle" (exp. confirmed by HADES)
    NN (np!) bremsstrahlung!
  - vector- should be complemented with axial-vector-spectral functions (a_1 as chiral partner of ρ)
  - constrained with lQCD via in-medium Weinberg chiral sum rules
  - direct connection to chiral phase transition!
  - making predictions for CBM@FAIR

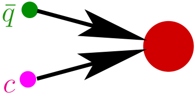
Heavy Quarks in Heavy-Ion collisions



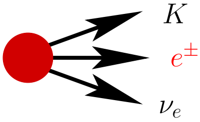
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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
$R_{AA}^{\mathrm{e}^{+}e^{-}}(p_T)$, $v_2^{e^{+}e^{-}}(p_T)$

Relativistic Langevin process

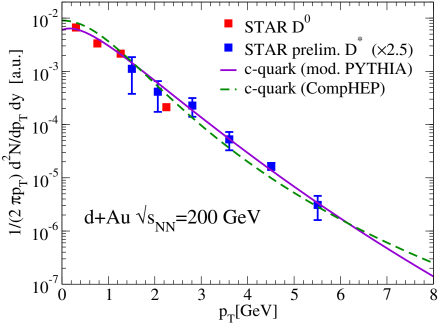
- Langevin process: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

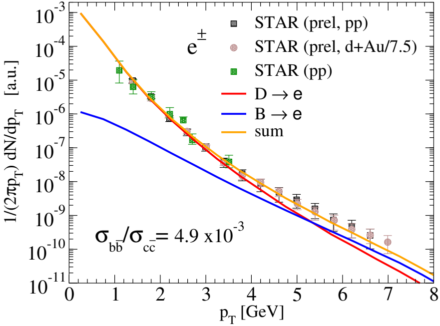
$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E_p}\mathrm{d}t,$$
$$\mathrm{d}\vec{p} = -A\,\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t}[\sqrt{B_0}P_\perp + \sqrt{B_1}P_\parallel]\vec{w}$$

- $\vec{w}$: normal-distributed random variable
- A: friction (drag) coefficient
- $B_{0,1}$: diffusion coefficients
- background medium: elliptic thermal QGP fireball cylinder

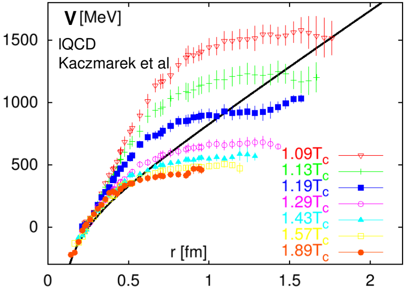
Initial conditions

- 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





Static potentials from lattice QCD



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

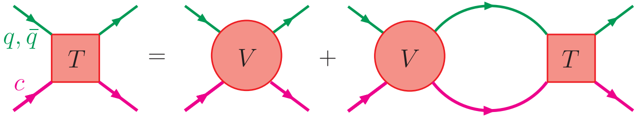
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$

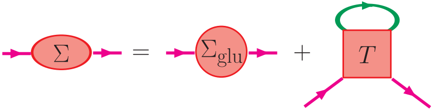
$$V_1(r,T) = U_1(r,T) - U_1(r \to \infty, T)$$

- 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

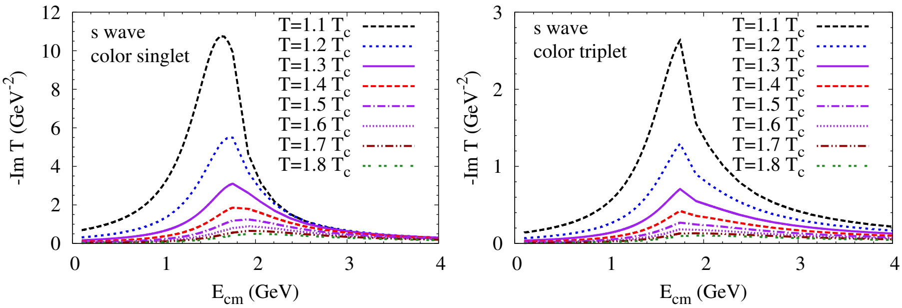




- reduction scheme: 4D Bethe-Salpeter → 3D Lipmann-Schwinger
- S- and P waves
- same scheme for light quarks (self consistent!)
- Relation to invariant matrix elements

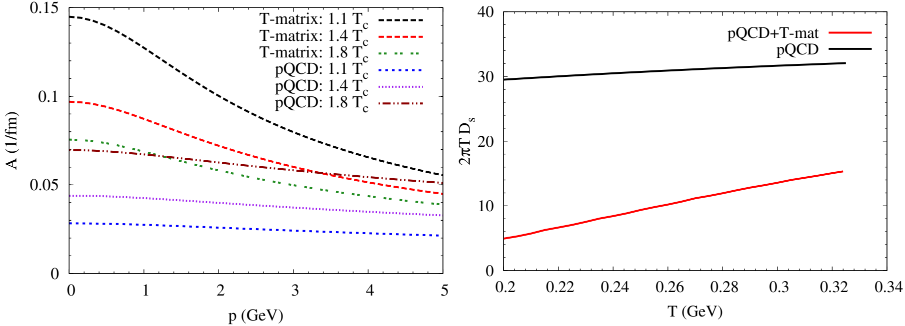
$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}}\right)$$

T-matrix calculation



- use static heavy-quark potentials from lQCD
- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T! $\Rightarrow$ sQGP
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering
- problems: uncertainties in extracting potential from lQCD
  in-medium potential V vs. F?

Transport coefficients



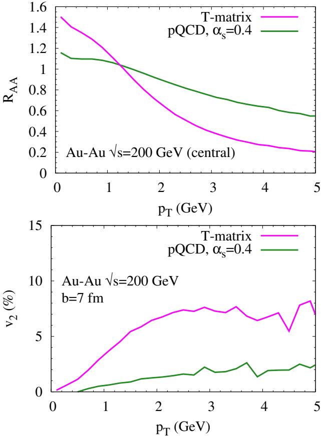
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7 \text{ fm}/c) \simeq 4 A_{\text{pQCD}}$
- A decreases with higher temperature
- higher density (over)compensated by melting of resonances!
- spatial diffusion coefficient

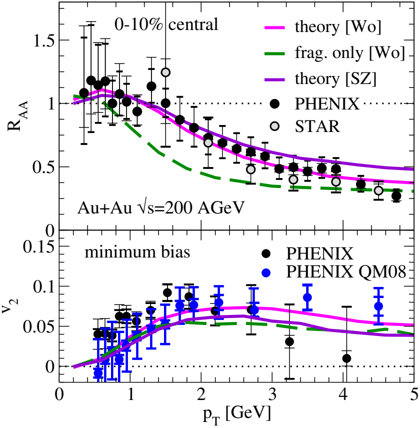
$$D_s = \frac{T}{mA}$$

increases with temperature

Non-photonic electrons at RHIC

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



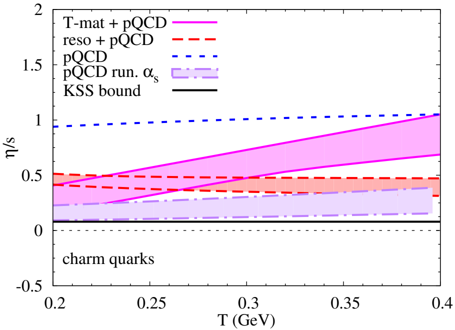


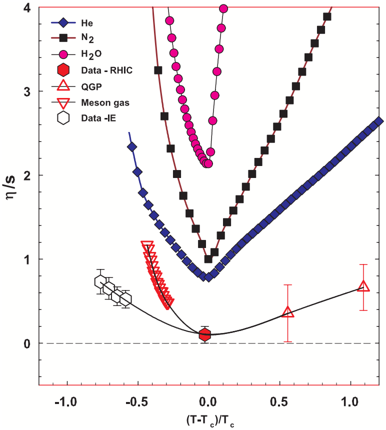
- coalescence crucial for description of data
- increases both, R_{AA} and $v_2 \Leftrightarrow$ "momentum kick" from light quarks!
- "resonance formation" towards $T_c \Rightarrow$ coalescence natural [Ravagli, Rapp 07]

Transport properties of the sQGP

- spatial diffusion coefficient: Fokker-Planck $\Rightarrow D_s = \frac{T}{mA} = \frac{T^2}{D}$
- measure for coupling strength in plasma: η/s

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





[Lacey, Taranenko (2006)]

Conclusions and Outlook II

- Summary
  - Heavy quarks in the sQGP
  - non-perturbative interactions
    - mechanism for strong coupling: resonance formation at $T \gtrsim T_c$
    - lQCD potentials parameter free
    - res. melt at higher temperatures ⇔ consistency betw. R_{AA} and v_2!
  - also provides "natural" mechanism for quark coalescence
  - resonance-recombination model [L. Ravagli, HvH, R. Rapp, Phys. Rev. C **79**, 064902 (2009)]
  - 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
  - include D/B-meson interactions in hadronic phase
  - CBM@FAIR: D vs. $\bar{D}$ ⇔ check dominance of quark vs. gluon interactions via resonances ($\bar{q}Q$ vs. $q\bar{Q}$!)