Heavy Probes in Heavy-Ion Collisions
Theory Part III

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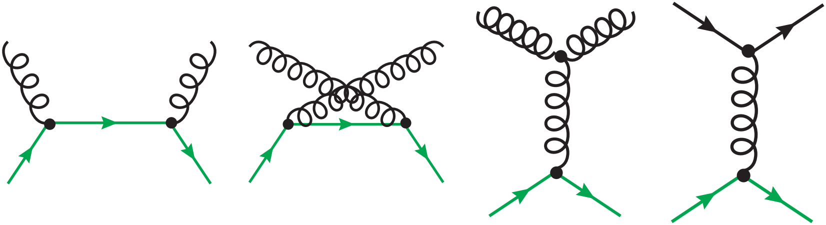
Outline

1. Elastic heavy-quark scattering in the sQGP with pQCD
   - Models based on pQCD
   - Hard-thermal loop (HTL) resummed pQCD interactions
   - HQ interactions with running coupling
   - Convergence of pQCD approach to transport coefficients
2. Nonperturbative approaches to elastic HQ scattering
   - Resonance-scattering model
   - Static heavy-quark potentials from lattice QCD + Brückner T-matrix
3. Radiative energy loss
   - Static-scattering-center models (BDMPS, ASW, DGLV)

Leading-order pQCD interactions

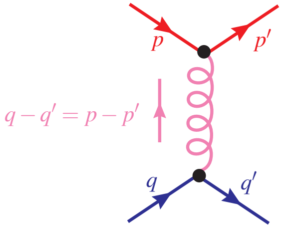
- leading-order diagrams for elastic scattering of heavy quarks with gluons and light quarks

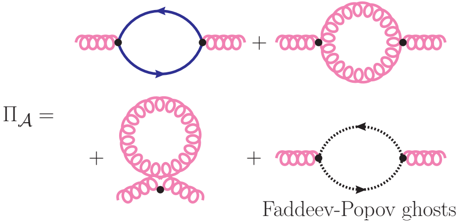


- last two diagrams with t-channel-gluon exchange most important
- lead to IR-divergent cross sections in naive perturbation theory!
- in the medium: Debye screening

Leading-order pQCD interactions

- kinematics: exchanged momentum $q - q' = p - p'$ in gluon propagator $\propto 1/t$ with $t = (q - q')^2$.
- leads to divergences when total cross section is evaluated
- comes from region of forward scattering $\Rightarrow$ IR divergence





- in the medium "tamed" by color-Debye screening
- color charges of medium particles screen each other
- generates gauge invariant thermal mass for gluons
- in hard-thermal loop approximation: $\mu_D \simeq gT$
- $G_{\text{gluon}}(t) \propto 1/(t - \mu_D{}^2)$

Hard-thermal loop resummed pQCD interactions

- more detailed calculation of gluon self-energy at finite temperature

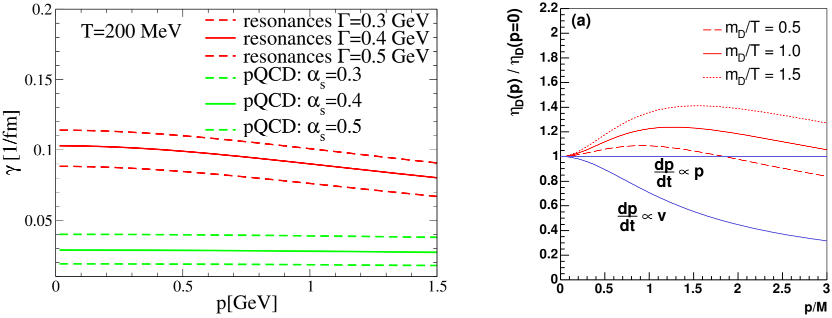
$$\Pi_T(\omega,\boldsymbol{q}) = \mu_D^2 \left\{ \frac{\omega^2}{2\boldsymbol{q}^2} + \frac{\omega(\boldsymbol{q}^2-\omega^2)}{4q^3} \left[\ln\left(\frac{q+\omega}{q-\omega}\right) - \mathrm{i}\pi \right] \right\} ,$$

$$\Pi_{00}(\omega,\boldsymbol{q}) = \mu_D^2 \left\{ 1 - \frac{\omega}{2q} \left[\ln\left(\frac{q+\omega}{q-\omega}\right) - \mathrm{i}\pi \right] \right\} .$$

- leads to gluon propagator

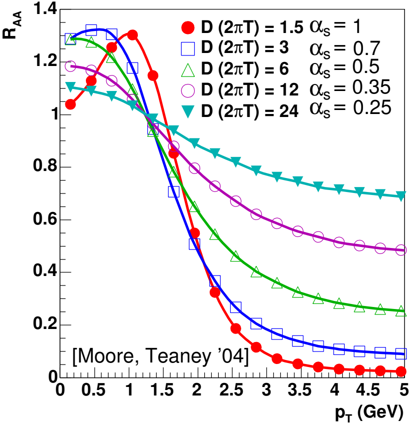
$$G_{\mu\nu}(\omega,q) = -\frac{\delta_{\mu 0}\delta_{\nu 0}}{q^2+\Pi_{00}} + \frac{\delta_{ij}-q_i q_j/q^2}{q^2-\omega^2+\Pi_T}$$

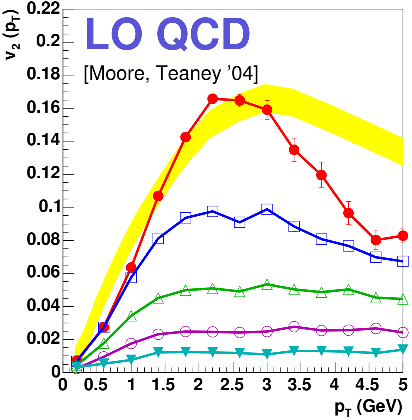
Drag coefficient



- drag coefficients for charm quarks in sQGP
  - left (green curves): LO pQCD with naive Debye-screening
    [HvH., R. Rapp, PRC **71**, 034907 (2005)]
  - right: LO hard-thermal-loop resummed pQCD
    [Moore, Teaney, PRC **71**, 064904 (2005)]

Langevin simulations with pQCD coefficients





- $\mu_D = 1.5T$ fixed!
- $2\pi T D_s \simeq 6(0.5/\alpha_s)^2$

[Moore, Teaney, PRC **71**, 064904 (2005)]

Interactions with running coupling

- with small $\alpha_s \lesssim 0.4$ + "naive Debye-screening" $\mu_D \simeq gT$
  not enough drag
- ansatz for effective Gluon propagator

$$G_r(t) \propto \frac{1}{t - r\mu_D^2}$$

- determining r such that the HQ energy loss in LO-pQCD matches with result where for $|t| < |t^*|$ the HTL propgator and for $|t| > |t^*|$ the perturbative propagator is used
- scale: $|t^*| \in [g^2 T^2, T^2]$
  - in QCD results depends on $|t^*|$ (not for QED)
  - solved by IR regulator mass in hard part of gluon-t-channel diagrams such that dependence on $|t^*| < T$ weak
  - leads to $r \simeq 0.1$-0.2
  - $r = 0.15$ enhances A only by factor of 2
  - reason: forward-scattering nature of pQCD (t-channel) scattering

[A. Peshier, arXiv: 0801.0595 [hep-ph]; P. B. Gossiaux, J. Aichelin, PRC 78, 014904 (2008)]

Interactions with running coupling

- self-consistent determination of m_D
  - start from running α_s:

$$\alpha_{\text{eff}}(Q^2) = \frac{4\pi}{\beta_0} \begin{cases} L_-^{-1} & \text{for } Q^2 \leq 0 \\ 1/2 - \pi^{-1} \arctan(L_+/\pi) & \text{for } Q^2 > 0, \end{cases}$$

with $\quad \beta_0 = 11 - 2N_f/3, \quad L_\pm = \ln(\pm Q^2/\Lambda^2)$

  - gluon propagator in t-channel diagrams

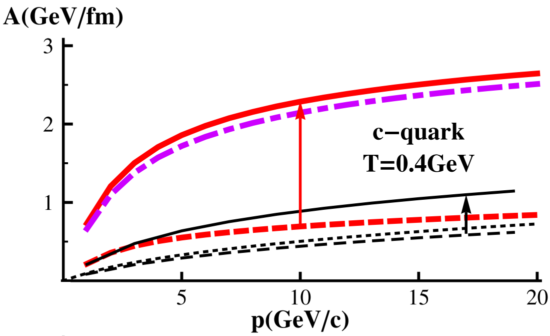
$$G_{\text{eff}}(t) \simeq \frac{\alpha_{\text{eff}}(t)}{t - \tilde{\mu}^2}$$

  - regulator mass $\tilde{\mu}^2 \in [1/2, 2]\tilde{\mu}_D^2$ determined by same matching procedure as for r-parameter approach
  - Debye-screening mass determined self-consistently

$$\tilde{\mu}_D^2 = \left(\frac{N_c}{3} + \frac{N_f}{6}\right) 4\pi\alpha(-\tilde{\mu}_D^2) T^2$$

[S. Peigné, A. Peshier, PRD **77**, 114017 (2008); A. Peshier, arXiv: 0801.0595 [hep-ph]; P. B. Gossiaux, J. Aichelin, PRC **78**, 014904 (2008)]

Interactions with running coupling

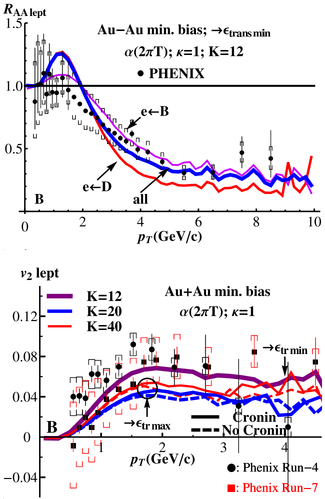


	α_S	μ^2	line form	figure color
A	0.3	m_D^2	dotted thin	black
B	$\alpha_S(2\pi T)$	m_D^2	dashed thin	black
C	$\alpha_S(2\pi T)$	$0.15 \times m_D^2$	full thin	black
D	running (Eq. (29))	$\tilde{m}_D^2$	dashed bold	red
E	running (Eq. (29))	$0.2 \times \tilde{m}_D^2$	full bold	red
F	running (Eq. (29))	$0.11 \times 6\pi\, \alpha_{\text{eff}}(t)\, T^2$	dashed dotted bold	purple

[P. B. Gossiaux, J. Aichelin, PRC 78, 014904 (2008)]

Interactions with running coupling

- Boltzmann-transport model and running-coupling model
- checked also with Fokker-Planck approach ⇒ good agreement!



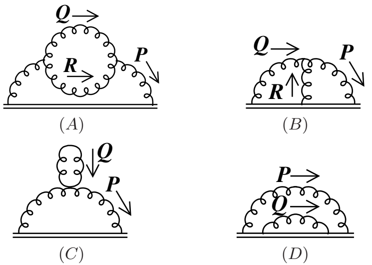
[P. B. Gossiaux, J. Aichelin, PRC 78, 014904 (2008)]

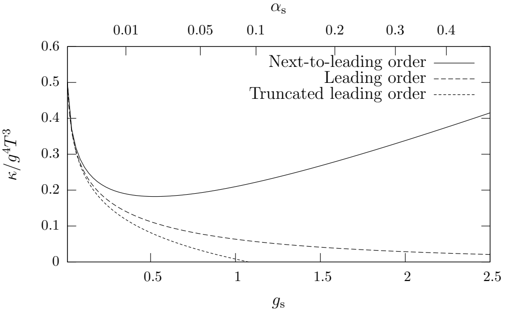
Convergence of pQCD for momentum-diffusion coefficient

- momentum-diffusion coefficient $\kappa = 2D$:
  Kubo-like formula for non-Abelian gauge theories

$$\kappa \simeq \frac{C_H g^2}{3} \int \frac{\mathrm{d}^3\vec{p}}{(2\pi)^3} \, \vec{p}^2 G^{>00}(\omega = 0^+, \vec{p}), \quad G^{>00}(t, \vec{x}) = \langle \mathbf{A}(x) \mathbf{A}(0) \rangle_T$$

- $C_H = 4/3$: Casimir operator of $\mathrm{SU}(3)_c$ representation of heavy quarks
- IR regulated by hard-thermal-loop corrections
- poor convergence ⇒ use effective models





[S. Caron-Huot, G. Moore PRL **100**, 052301 (2008)]

Resonance-scattering model

- lattice QCD: close to T_c strong correlations in sQGP
- hadron-like resonances survive above T_c (e.g., J/ψ)
- for elastic heavy-light-quark scattering: D/B-like resonances
- effective model based on heavy-quark-effective theory and chiral symmetry for light quarks

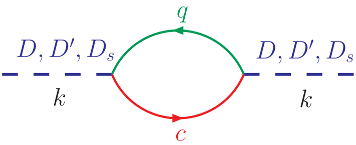
$$\begin{aligned}
\mathscr{L}_{Dcq} =& \mathscr{L}_D^0 + \mathscr{L}_{c,q}^0 - \mathrm{i} G_S \left(\bar{q} \Phi_0^* \frac{1+\not{v}}{2} c - \bar{q} \gamma^5 \Phi \frac{1+\not{v}}{2} c + h.c. \right) \\
& - G_V \left(\bar{q} \gamma^\mu \Phi_\mu^* \frac{1+\not{v}}{2} c - \bar{q} \gamma^5 \gamma^\mu \Phi_{1\mu} \frac{1+\not{v}}{2} c + h.c. \right) \ , \\
\mathscr{L}_{c,q}^0 =& \bar{c}(\mathrm{i}\not{\partial} - m_c) c + \bar{q}\, \mathrm{i}\not{\partial} q, \\
\mathscr{L}_D^0 =& (\partial_\mu \Phi^\dagger)(\partial^\mu \Phi) + (\partial_\mu {\Phi_0}^{*\dagger})(\partial^\mu \Phi_0^*) - m_S^2 (\Phi^\dagger \Phi + \Phi_0^{*\dagger} \Phi_0^*) \\
& - \frac{1}{2} (\Phi_{\mu\nu}^{*\dagger} \Phi^{*\mu\nu} + \Phi_{1\mu\nu}^\dagger \Phi_1^{\mu\nu}) + m_V^2 (\Phi_\mu^{*\dagger} \Phi^{*\mu} + \Phi_{1\mu}^\dagger \Phi_1^\mu) \ .
\end{aligned}$$

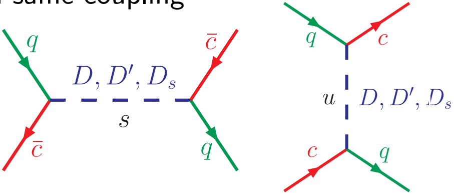
- scalar+pseudoscalar (D/B), vector+axialvector (D^*/B^*) resonances
- leading order HQET: $G_S = G_V$

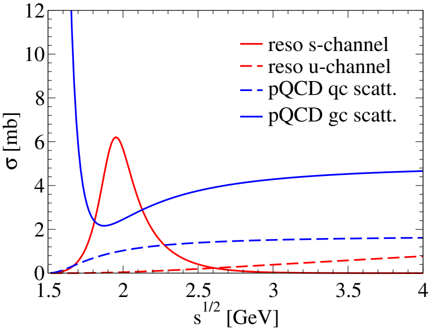
[HvH, R. Rapp, PRC **71**, 034907 (2005)]

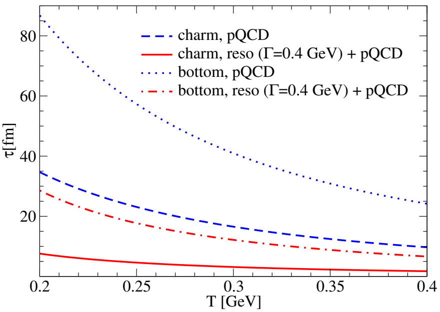
Resonance-scattering model

- width of D/B-like resonances via one-loop self energy
- heavy-light-quark scattering with same coupling

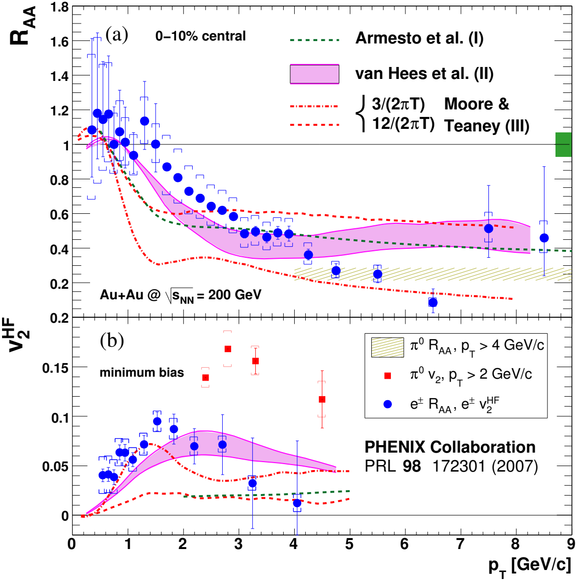






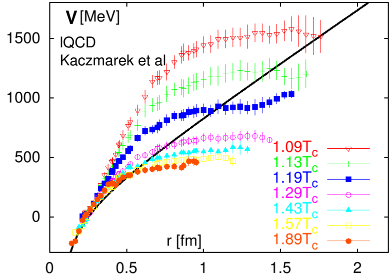


[HvH, R. Rapp, PRC **71**, 034907 (2005)]



[HvH, V. Greco, R. Rapp, Phys. Rev. C **73**, 034913 (2006)]

Microscopic model: Static potentials from lattice QCD



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

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

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

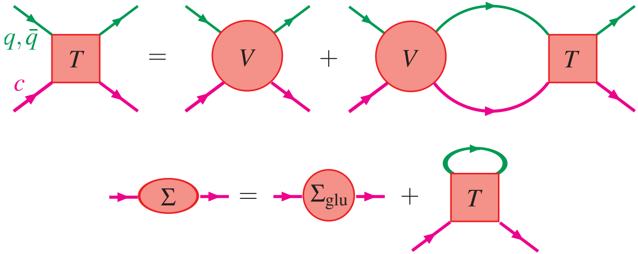
- Casimir scaling for other color channels [Nakamura et al 05; Döring et al 07]

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

[HvH, M. Mannarelli, V. Greco, R. Rapp, PRL **100**, 192301 (2008); HvH, M. Mannarelli, R. Rapp, EJC **61**, 799 (2009)]

T-matrix

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

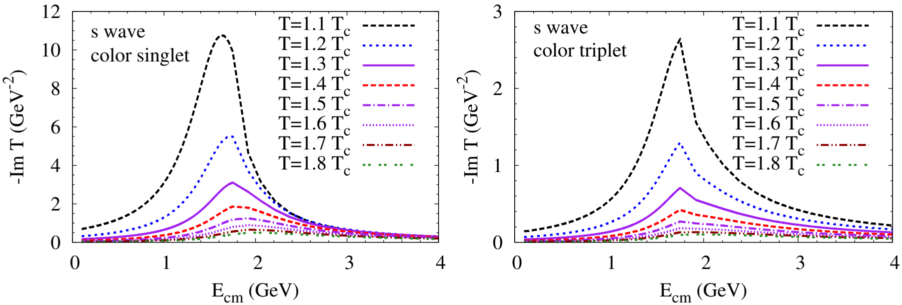


- reduction scheme: 4D Bethe-Salpeter $\rightarrow$ 3D Lipmann-Schwinger
- S- and P waves
- same scheme for light quarks (self consistent!)
- Relation to invariant matrix elements

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

[HvH, M. Mannarelli, V. Greco, R. Rapp, PRL **100**, 192301 (2008); HvH, M. Mannarelli, R. Rapp, EJC **61**, 799 (2009)]

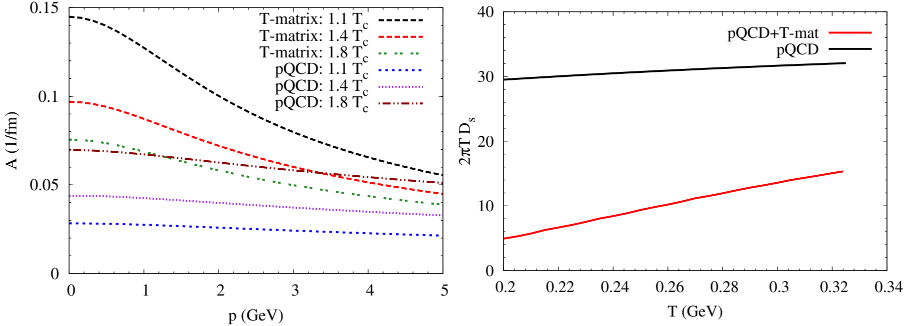
T-matrix



- 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 U vs. F?

Transport coefficients



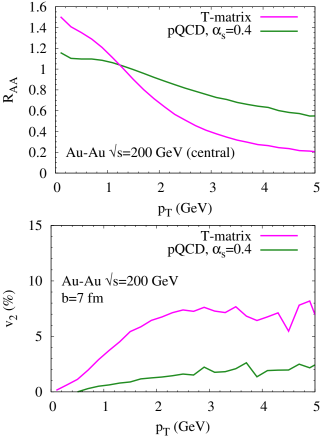
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7\ \text{fm}/c) \simeq 4 A_{\text{pQCD}}$
- A decreases with higher temperature
- higher density (over)compensated by melting of resonances!
- spatial diffusion coefficient

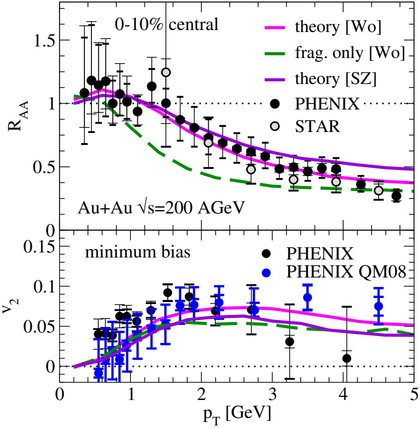
$$D_s = \frac{T}{mA}$$

increases with temperature

Non-photonic electrons at RHIC

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

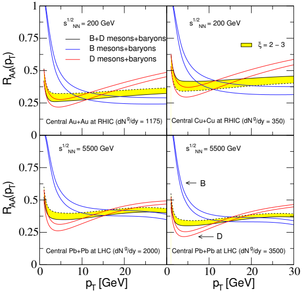


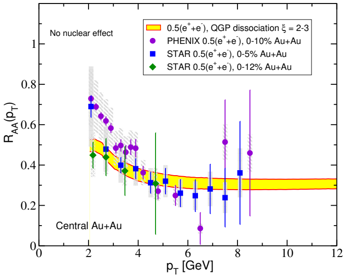


- coalescence crucial for description of data
- increases both, R_{AA} and $v_2 \Leftrightarrow$ "momentum kick" from light quarks!
- "resonance formation" towards $T_c \Rightarrow$ coalescence natural [Ravagli, Rapp 07]

Collisional dissociation/fragmentation in the QGP

- in-medium dissociation of D/B mesons $\leftrightarrow$ in-medium fragmentation of c/b quarks
  - medium modification of quark-wave functions in QGP
  - dissociation by collision with QGP particles
  - in-medium fragmentation $c/b \rightarrow D/B$





[Adil, Vitev (2007)]

- B mesons stronger bound than D mesons
- smaller B formation times $\Leftrightarrow$ stronger suppression for B than for D!
- could be distinguished from HQ elastic-scattering processes by separate measurement of D and B only!

Radiative energy loss (BDMPZ, ASW)

- medium modelled as set of static scattering centers
- center at position $\vec{x}_i$ (Debye-screened static color potential):

$$V_i(\vec{q}) = \frac{g}{\vec{q}^2 + \mu_D^2} \exp(-\mathrm{i}\vec{q}\vec{x}_i)$$

- mean free path of high-energy quarks, $\lambda \gg r_D = 1/\mu_D \Rightarrow$ scatterings independent
- Fokker-Planck like approach possible

  [R. Baier, Y. L. Dokshitzer, S. Peigne, D. Schiff, NPB **483**, 29 (1997); NPB **483**, 291 (1997)]
- equivalent approach via path integrals

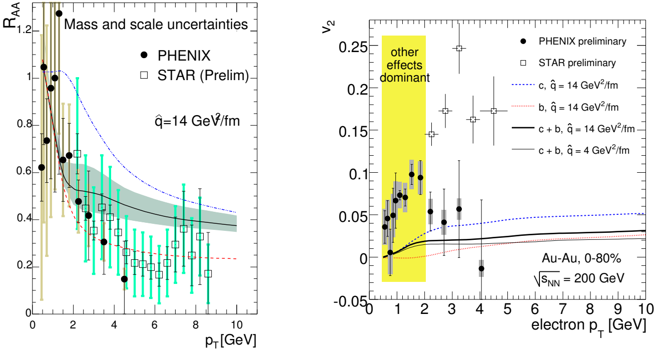
  [N. Armesto, C. A. Salgado, U. A. Wiedemann, PRD **69**, 114003 (2004)]
- in scattering bremsstrahlung gluons radiated
- coherent resummation (Landau-Pomeranchuk-Migdal effect)
- energy loss characterized by diffusion coefficient for transverse-momentum broadening, $\hat{q}$

$$\Delta E = \frac{\alpha_s}{2} \hat{q} L^2$$

- L: mean path length of the medium

Radiative energy loss (BDMPS, ASW)

- Gluo-bremsstrahlung energy-loss calculations
  - perturbative estimate for RHIC conditions: $\hat{q} \simeq 1\ \mathrm{GeV}^2/\mathrm{fm}$
  - for light partons main energy-loss mechanism (jet quenching!)
  - dead-cone effect: $\Theta < m_Q/E$ radiation suppressed



[N. Armesto, M. Cacciari, A. Dainese, C. A. Salgado, U. A. Wiedemann, PLB **637**, 362 (2006)]

- Need $\hat{q} = 14\ \mathrm{GeV}^2/\mathrm{fm}$; v_2: only through almond-shape geometry
- without drag $\Rightarrow$ no heavy-quark collective flow:
  no consistent description of R_{AA} and v_2!

Radiative energy loss (DGLV)

- another approach with static scattering centers: reaction-operator approach
- opacity of the medium $\bar{n} = L/\lambda$ (L: path length of jet in medium, λ: mean free path)
- hard parton emits soft bremsstrahlung gluons $\Rightarrow$ soft-gluon emission distribution calculated in pQCD (in leading order $\mathcal{O}(\bar{n})$)
- multiple gluon emissions Poisson distributed $\Leftrightarrow$ each emission independent within coherence region
- probability for energy-loss fraction ϵ by radiating n gluons

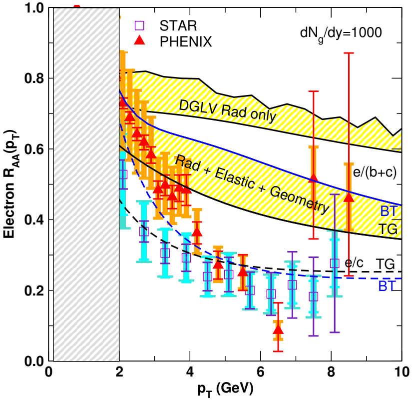
$$P_n(\epsilon, P^+) = \frac{\exp(-\langle N_h \rangle)}{n!} \prod_{i=1}^{n} \int \mathrm{d}x_i \frac{\mathrm{d}N_g}{\mathrm{d}x_i} \delta\left(\epsilon - \sum_{i=1}^{n} x_i\right)$$

- medium-modified fragmentation function

$$\tilde{D}(z, Q^2) = \int_0^1 \mathrm{d}\epsilon P(\epsilon) \frac{D[z/(1-\epsilon), Q^2]}{1-\epsilon}$$

- for heavy quarks dead-cone effect implemented
  [M. Gylassi, P. Levai, I. Vitev, NPB **594**, 371 (2004); M. Djordjevic, M. Gyulassi, NPA **733**, 265 (2004)]

Radiative energy loss (DGLV)



- with radiative energy loss only: suppression too low by a factor of 3
- dead-cone effekt ⇒ need for elastic scattering for heavy quarks
- still underestimates suppression
- need non-perturbative effects for heavy-quark diffusion in sQGP!

[S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, NPA **784**, 426 (2007)]

Instead of a summary: Questions

- Which pQCD models for elastic heavy-quark rescattering in the sQGP have been used?
- Why are non-perturbative approaches addressed?
- What's the basic idea behind the elastic resonance-scattering approach?
- Why is elastic resonance scattering more efficient for drag/diffusion than pQCD-cross sections?
- Why is radiative energy loss less important for heavy quarks than for light quarks?

Summary

- elastic heavy-quark scattering (pQCD)
  - "naive" pQCD with simple Debye screening for t-channel
  - hard-thermal-loop resummed pQCD
  - implementing running coupling $+$ self-consistent determination of Debye mass
  - convergence for diff. coeff. slow $\Rightarrow$ non-perturbative approaches
  - in-medium D/B-meson dissciation $\leftrightarrow$ fragmentation approach
- non-perturbative approaches
  - survival of D/B-like resonances above T_c
  - elastic s-channel scattering more efficient (isotropic cross section)
  - Brückner T-matrix approach with static potentials from lQCD
  - fundamental open question:
    which potential to use (F, U, "combination")?

Summary

- radiative vs. collisional energy loss (DGLW, BDMPS, ASW)
  - gluo bremsstrahlung most important energy-loss mechanism for light high-enegetic partons/jets
  - for heavy quarks dead-cone effect: gluon emission suppressed for $\Theta < m_Q/E$
  - models successful in describing jet quenching cannot account for non-photonic electron data
  - collisional energy loss important