Heavy-Quark Production in Heavy-Ion Collisions
Theory Summary

Hendrik van Hees

Goethe University Frankfurt and FIAS

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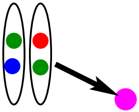
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

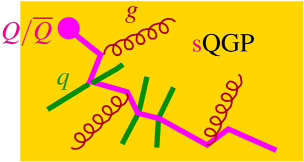
Outline

Introduction

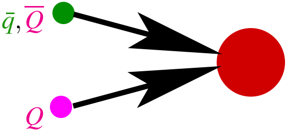


hard production of HQs
described by PDF's + pQCD

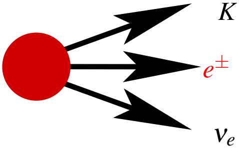
c,b quarks; D/B mesons,...; J/ψ, Υ,...



HQ rescattering in QGP: transport models
HQ transport coefficients
microscopic model for HQ interactions
(scattering, bound states) in the sQGP



Hadronization to D,B, quarkonia via
quark coalescence + fragmentation



(semi)leptonic decays $\Rightarrow$
"non-photonic" electron observables
$R_{AA}^{e^+e^-}(p_T)$, $v_2^{e^+e^-}(p_T)$
quarkonia (reg.+surv.) $\rightarrow \ell^+\ell^-$

Heavy-quarkonium observables

- Melting of heavy quarkonia considered a “classical” probe of QGP formation (Matsui/Satz 1986)
- probes properties of strong interaction in medium
- sequential melting of different states: thermometer for QGP?
- formation/dissociation of $Q\overline{Q}$ bound states in the medium
- static lattice potential F or U or combination?
- talks by M. Strickland, N. Brambilla: thermal NRQCD
- talk be E. Bratkovskaya: Use Hadron-strong dynamics transport simulation in hadronic kinetic approach
- $(Q\overline{Q})+B \leftrightarrow D_Q+\overline{D}_Q+X$

$Q\overline{Q}$-in-medium potential

Michael Strickland

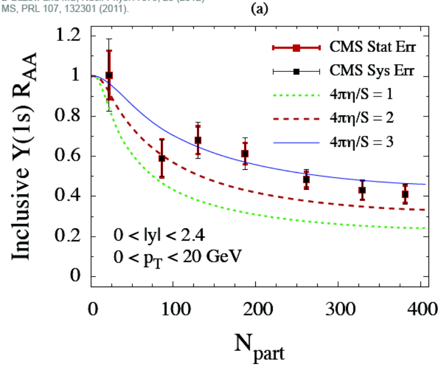
- thermal (real-time) QCD + HTL resummation: complex static potential from dressed gluon propagator
- real part: Debye-screening of “color-Coulomb potential”
- imaginary part: heavy quarkonia “decaying” due to Landau Damping
- pQCD short-range part supplemented by ansatz for long-range part; $\operatorname{Re} V$ Karsch-Mehr-Satz ansatz $\Rightarrow$ fit to U_{lat}
- results in sequential melting of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ states
- medium description: anisotropic hydro

$Q\overline{Q}$-in-medium potential

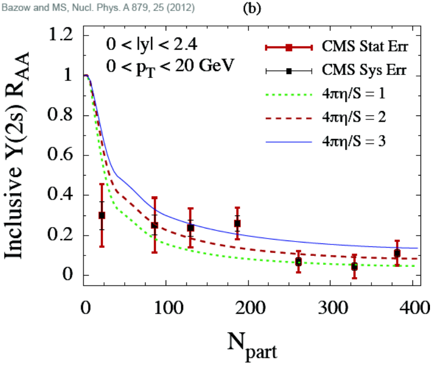
Michael Strickland

Comparison to CMS data on Υ-R_{AA}

D Bazow and MS, Nucl. Phys. A 879, 25 (2012)
MS, PRL 107, 132301 (2011).



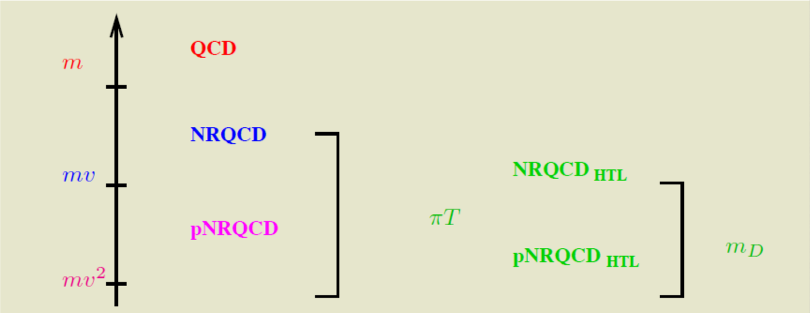
MS arXiv:1207.5327
D Bazow and MS, Nucl. Phys. A 879, 25 (2012)



$Q\overline{Q}$-in-medium potential

Nora Brambilla

Quarkonium at finite T: EFT treatment



We work under the conditions:

We assume that bound states exist for

- $T \ll m$
- $\langle 1/r \rangle \sim mv \gtrsim m_D$

We neglect smaller thermodynamical scales.

In the weak coupling regime:

- $v \sim \alpha_s \ll 1$; valid for tightly bound states: $\Upsilon(1S)$, J/ψ,
- $T \gg gT \sim m_D$.

Effects due to the scale $\Lambda_{\rm QCD}$ will not be considered.

$Q\overline{Q}$-in-medium potential

Nora Brambilla

- (p)NRQCD potential at finite T is neither U nor F
- has a real Debye screened part and imaginary part (Landau damping)
- $\mathrm{Im}\, V \gg \mathrm{Re}\, V$ is responsible for melting
- $\Upsilon(1S)$ melting temperatures:

m_c (MeV)	$T_{\mathrm{dissociation}}$ (MeV)
∞	480
5000	480
2500	460
1200	440
0	420

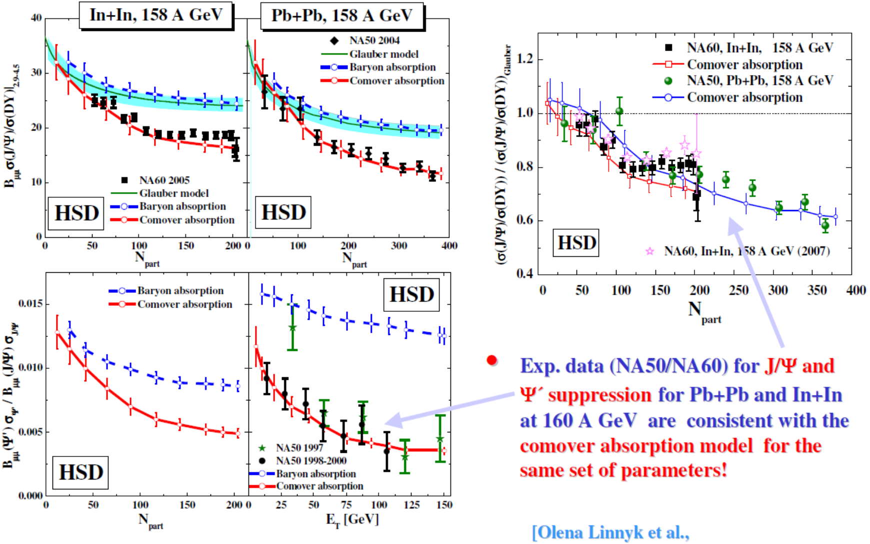
Transport models/simulations

Elena Bratkovskaya

- (partonic) Hadron String Dynamics (p)HSD
- generalized Boltzmann-Uehling-Uhlenbeck-Vlasov transport
- based on Kadanoff-Baym equations from neq-QFT $\Rightarrow$ off-shell transport
- HSD: follow heavy quarkonia from initial formation using measured NN, πN cross sections
- through whole evolution of the fireball
- charmonium dissociation cross sections fixed from pA data
- recombination cross section fixed by detailed balance

Transport models/simulations

Elena Bratkovskaya



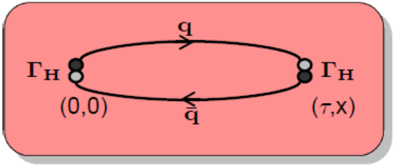
- Exp. data (NA50/NA60) for J/Ψ and Ψ' suppression for Pb+Pb and In+In at 160 A GeV are consistent with the comover absorption model for the same set of parameters!

[Olena Linnyk et al., nucl-th/0612049, NPA 786 (2007) 183]

Olaf Kaczmarek

$$G(\tau,\vec{p},T) = \int_0^\infty \frac{d\omega}{2\pi} \rho(\omega,\vec{p},T) K(\tau,\omega,T)$$

$$K(\tau,\omega,T) = \frac{\cosh\left(\omega(\tau - \frac{1}{2T})\right)}{\sinh\left(\frac{\omega}{2T}\right)}$$



Lattice observables:

$$G_{\mu\nu}(\tau,\vec{x}) = \langle J_\mu(\tau,\vec{x}) J_\nu^\dagger(0,\vec{0})\rangle$$

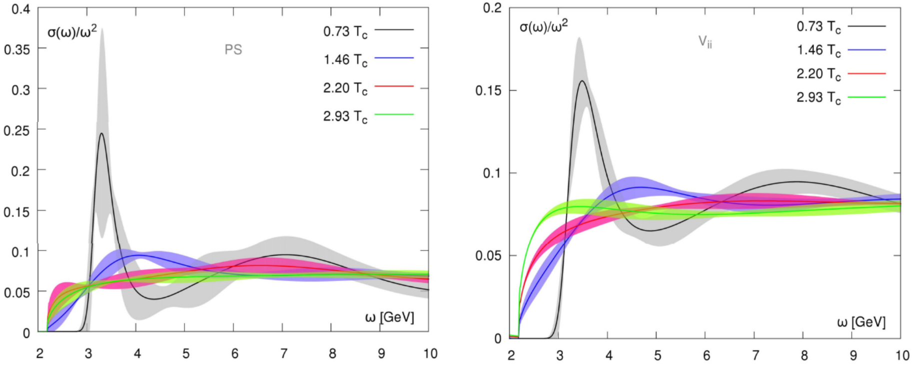
$$J_\mu(\tau,\vec{x}) = 2\kappa Z_V \bar{\psi}(\tau,\vec{x})\Gamma_\mu \psi(\tau,\vec{x})$$ ⟵ local, non-conserved current, needs to be renormalized

$$G_{\mu\nu}(\tau,\vec{p}) = \sum_{\vec{x}} G_{\mu\nu}(\tau,\vec{x}) e^{i\vec{p}\vec{x}}$$ ⟵ only $\vec{p}=0$ used here

Lattice QCD

Olaf Kaczmarek

Charmonium spectral functions from lattice correlators + MEM



now also $\vec{p}$ dependence available now!

Open theory questions

- Which $Q\overline{Q}$ potential is to be used for in-medium heavy-quarkonia bound-state calculations?
- Using thermal QFT as a fundamental approach, one calculates properties of static $Q\overline{Q}$ pair in infinite equilibrated matter at given temperature and/or chemical potential!
- Is this applicable in description of matter created in heavy-ion collisions?
- in transport models to the other extreme free dissociation cross sections + detailed balance for recombination used
- both approaches describe $R_{AA}(J/\psi, \Upsilon, \ldots)$ data!?!
- can one discriminate these (and other) proposed theoretical mechanisms with measuring other observables?
- is there a first-principle generic non-equilibrium approach to calculate dissociation-regneration rates in the medium?
- if yes is it feasible in transport simulations "to get the numbers out" for comparison with experiment?

Open heavy-flavor observables

- R_{AA} and v_2 of open-heavy-flavor mesons and single electrons or muons from their semileptonic decay
  - generated in the early hard collisions and conserved ⇒
  - witness whole history of fireball evolution
  - heavy quarks ⇔ "less thermalized" than light quarks/gluons ⇒
  - probe transport properties of strongly interacting medium
- theoretical opportunities/challenges
  - can be described with Fokker-Planck-Langevin approach
  - can be used with any description of "bulk medium" like fireball parametrizations, hydro, transport
  - intuitive physical picture through drag and diffusion coefficients
  - direct relation to microscopic reaction rates

Fokker-Planck/Langevin approach

- approximates collision term in Boltzmann equation
- collision term in terms of local drag and diffusion coefficients
- $\rightarrow$ talk by Andrea Beraudo

Expanding the collision integral for *small momentum exchange*[1] (Landau)

$$C[f_Q] \approx \int d\mathbf{k} \left[k^i \frac{\partial}{\partial p^i} + \frac{1}{2} k^i k^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(\mathbf{p}, \mathbf{k}) f_Q(t, \mathbf{p})]$$

The Boltzmann equation reduces to the *Fokker-Planck equation*

$$\frac{\partial}{\partial t} f_Q(t, \mathbf{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\mathbf{p}) f_Q(t, \mathbf{p}) + \frac{\partial}{\partial p^j} [B^{ij}(\mathbf{p}) f_Q(t, \mathbf{p})] \right\}$$

where

$$A^i(\mathbf{p}) = \int d\mathbf{k}\, k^i w(\mathbf{p}, \mathbf{k}) \longrightarrow \underbrace{A^i(\mathbf{p}) = A(p)\, p^i}_{\text{friction}}$$

$$B^{ij}(\mathbf{p}) = \frac{1}{2} \int d\mathbf{k}\, k^i k^j w(\mathbf{p}, \mathbf{k}) \longrightarrow \underbrace{B^{ij}(\mathbf{p}) = \hat{p}^i \hat{p}^j B_0(p) + (\delta^{ij} - \hat{p}^i \hat{p}^j) B_1(p)}_{\text{momentum broadening}}$$

Fokker-Planck/Langevin approach

Andrea Beraudo

- equivalent to relativistic Langevin equation

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}} ,$$

with the properties of the noise encoded in

$$\langle \xi^i(\mathbf{p}_t)\xi^j(\mathbf{p}_{t'})\rangle = b^{ij}(\mathbf{p}_t)\frac{\delta_{tt'}}{\Delta t} \qquad b^{ij}(\mathbf{p}) \equiv \kappa_\parallel(p)\hat{p}^i\hat{p}^j + \kappa_\perp(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

Transport coefficients to calculate:

- *Momentum diffusion* $\kappa_\perp \equiv \frac{1}{2}\frac{\langle \Delta p_\perp^2 \rangle}{\Delta t}$ and $\kappa_\parallel \equiv \frac{\langle \Delta p_\parallel^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

$$\eta_D{}^{\text{Ito}}(p) = \frac{\kappa_\parallel(p)}{2TE_p} - \frac{1}{E_p^2}\left[(1-v^2)\frac{\partial \kappa_\parallel(p)}{\partial v^2} + \frac{d-1}{2}\frac{\kappa_\parallel(p) - \kappa_\perp(p)}{v^2}\right]$$

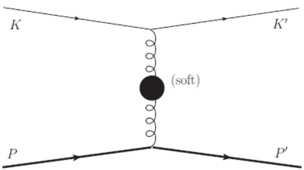
fixed in order to insure approach to equilibrium (Einstein relation):

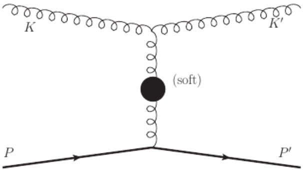
Overview over models discussed at this workshop

Speaker	Background medium	Interactions
A. Beraudo	hydro	el. pQCD HTL lQCD
S. Mazumder	hydro	el. + coll. pQCD (HTL)
S. Bass	hydro	el. (+coll.) pQCD
P. Gossiaux	hydro	el. (+coll.) pQCD (NANTES)
M. He	hydro	T-matrix lQCD pot. +hadr. interactions
M. Nahrgang	hydro/EPOS	el. (+coll.) pQCD (NANTES)
J. Uphoff	BAMPS for light & heavy	el. pQCD (NANTES)
E. Bratkowvskaya	HSD for light & heavy	hadr. interactions

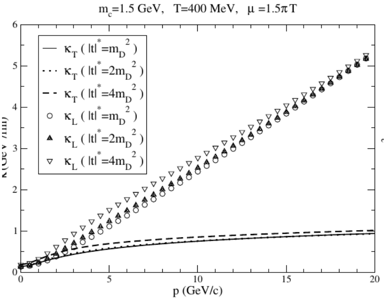
HQ interactions with the medium: pQCD/HTL resummed

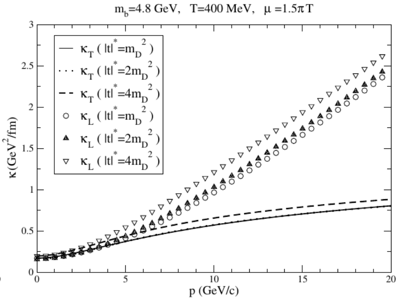
Andrea Beraudo





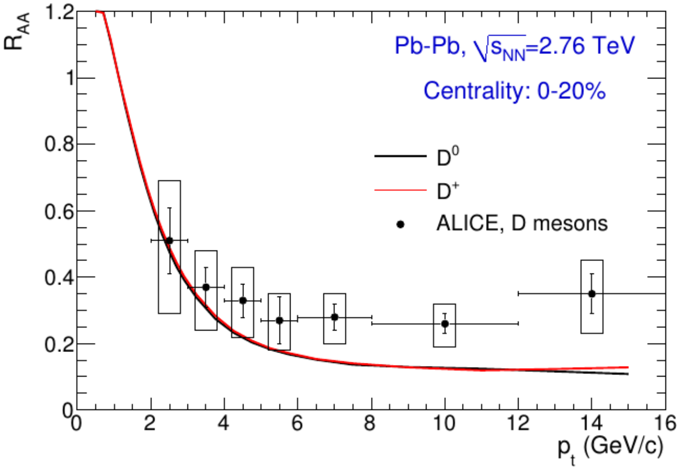
- soft ($|t| < t^*$): HTL-resummed gluon propagator; hard ($|t| > t^*$: pQCD)





HQ interactions with the medium: pQCD/HTL resummed

Andrea Beraudo: D-meson R_{AA} @LHC



HQ interactions with the medium: radiative processes

Surasree Mazumder

- radiative (gluon bremsstrahlung) contributions to drag and diffusion coefficients

ε → average energy per collision and is given by:

$$\varepsilon = \int d\eta d^2 k_\perp \frac{dn_g}{d\eta d^2 k_\perp} k_0 \times \Theta(\tau_{sc} - \tau_F) \times \Theta(E - k_0) \times F^2$$

LPM effect

Bound on energy

Dead Cone effect

$$\frac{C_A \alpha_s}{\pi^2} \frac{q_\perp^2}{k_\perp^2 [(\mathbf{q}_\perp - \mathbf{k}_\perp)^2 + m_D^2]}$$

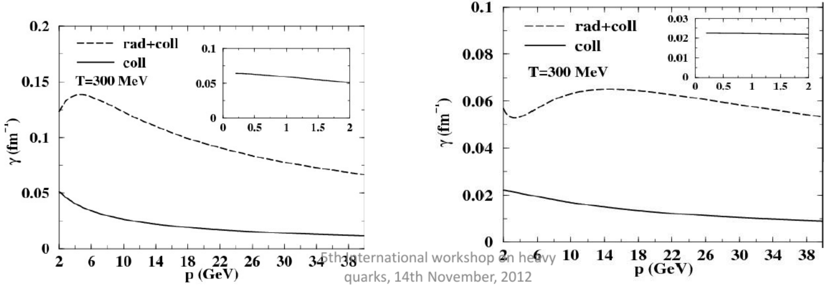
→ emitted gluon multiplicity distribution in Gunion-Bertsch approximation

$k_5 = (k_0, k_\perp, k_3)$ → four momentum and η → rapidity of emitted gluon.

$q = (q_0, q_\perp, q_3)$ → four momentum of the propagator gluon.

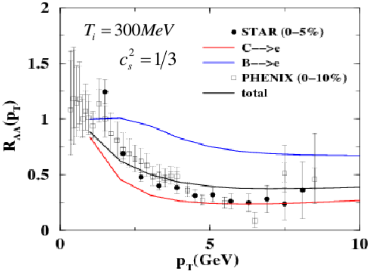
HQ interactions with the medium: radiative processes

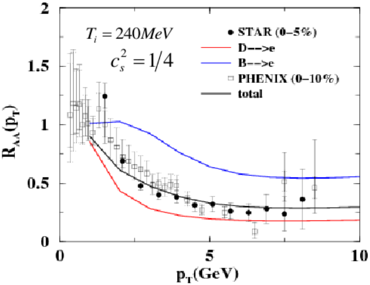
Surasree Mazumder

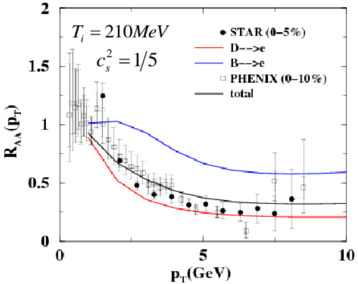


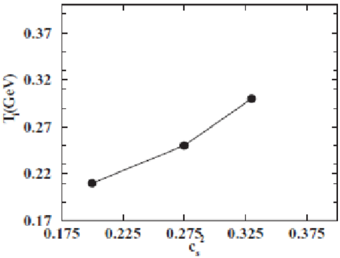
HQ interactions with the medium: radiative processes

Surasree Mazumder



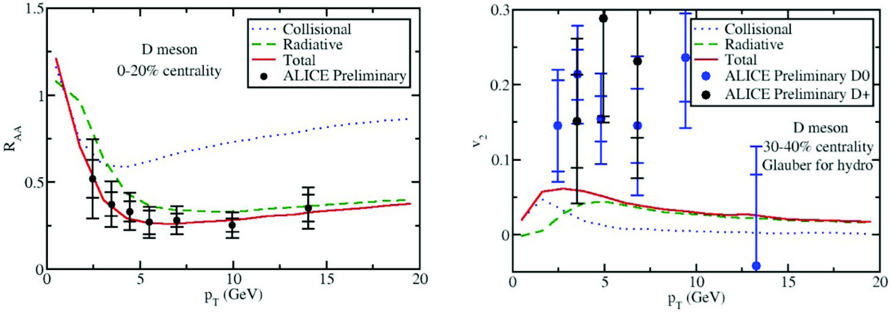






Steffen Bass

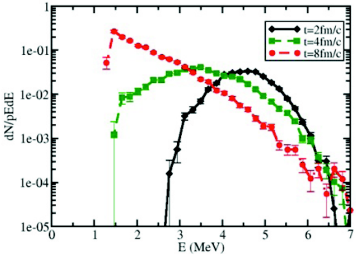
- HQ radiative scattering implemented as drag force only
- may violate Einstein relations/equilibrium limit

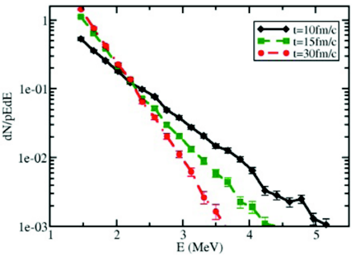


HQ degree of thermalization

Steffen Bass

- "box calculation"@$T = 400$MeV, fixed $D_p(2\pi T) = 6$
- start with fixed momentum
- note: low-p_T part of initial distibution usually closer to "equilibrium shape" than this extreme initialization!

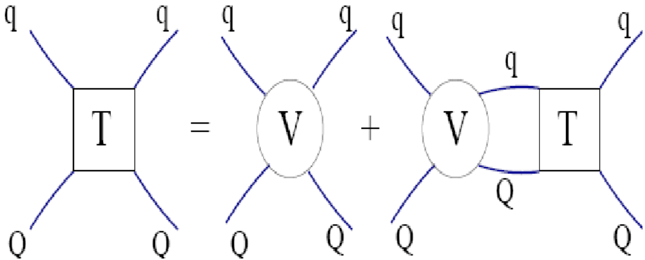




Non-perturbative QCD interactions

Min He

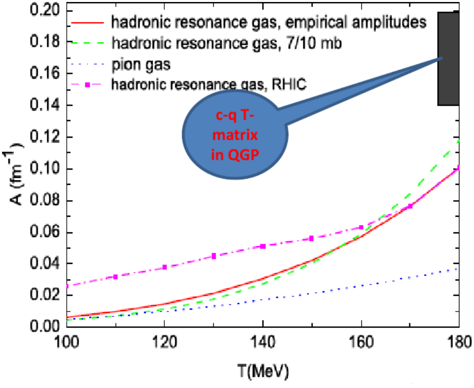
- many-body-T-matrix calculation with kernel, $V = F$ or $V = U$
  static $q\bar{q}$ potential from lQCD

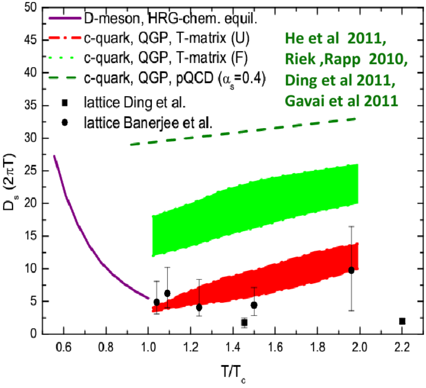


- D/B-like resonance formation close to T_c
- + same T-matrix approach for gQ scattering
  (using the same Casimir scaled kernels!?!)
- + hadron-resonance gas cross sections in hadronic phase!

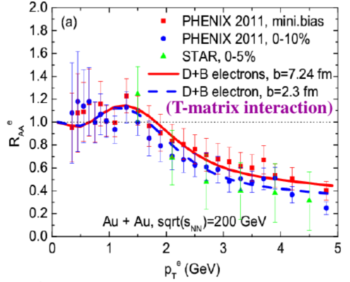
Min He

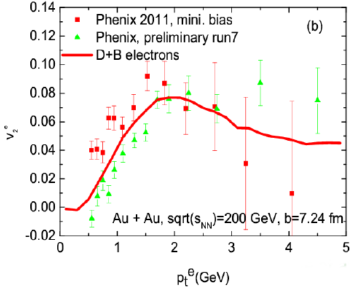
- smooth transition of transport coefficients at T_c “hadron-parton duality”
- shows typical behavior of transport coefficients close to phase transitions (η/s minimal @ T_c)



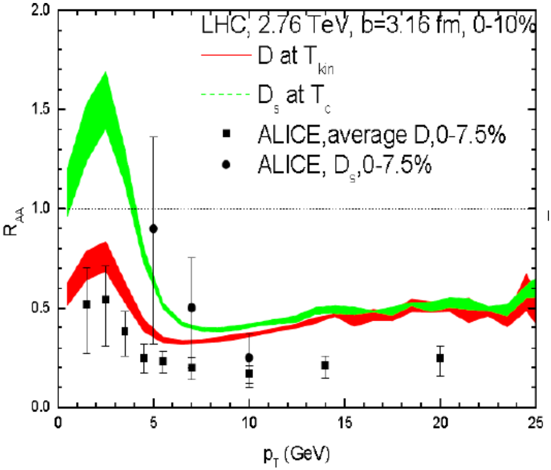


Min He



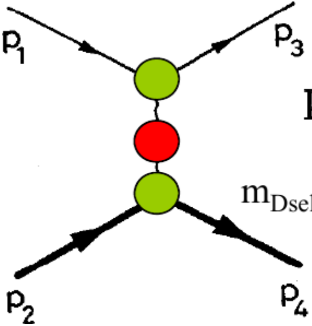


- hydro: R_{AA} and v_2 of light hadrons
- multi-strange hadrons freeze out at $\sim T_c$



Pol Gossiaux

- collisional: self-consistently determined Debye mass from running of α_s



$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{\text{Dself}}(T)}$$

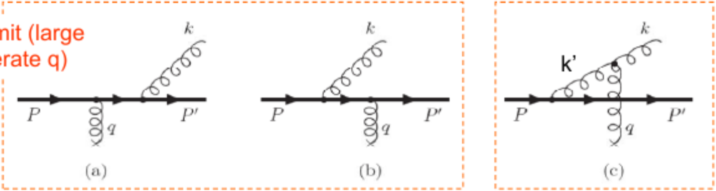
$$m_{\text{Dself}}^2\,(T) = (1+n_f/6)\;4\pi\alpha_{\text{eff}}(m_{\text{Dself}}^2)\;T^2$$

Pol Gossiaux

- radiative:

Radiation α deflection of current (semi-classical picture)

Eikonal limit (large E, moderate q)



Dominates as small x as one “just” has to scatter off the virtual gluon k’

$$\omega \frac{d^3\sigma_{\rm rad}^{x\ll 1}}{d\omega d^2 k_\perp dq_\perp^2} = \frac{N_c \alpha_s}{\pi^2}(1-x) \times \frac{J_{\rm QCD}^2}{\omega^2} \times \frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}$$

with

$$\frac{J_{\rm QCD}^2}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2 + x^2 M^2 + (1-x) m_g^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{\left(\vec{k}_\perp - \vec{q}_\perp\right)^2 + x^2 M^2 + (1-x) m_g^2} \right)^2$$

m_g: Gluon thermal mass ~2T (phenomenological; not in BDMPS)

M: Quark mass

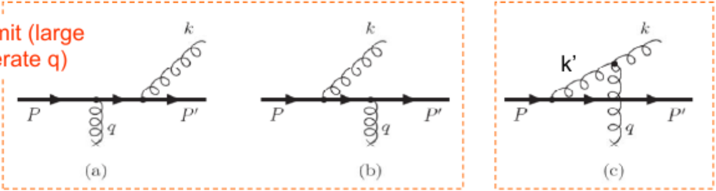
QCD interactions with running coupling

Pol Gossiaux

- radiative:

Radiation α deflection of current (semi-classical picture)

Eikonal limit (large E, moderate q)



Dominates as small x as one "just" has to scatter off the virtual gluon k'

$$\omega \frac{d^3\sigma_{\text{rad}}^{x\ll 1}}{d\omega d^2k_\perp dq_\perp^2} = \frac{N_c \alpha_s}{\pi^2}(1-x) \times \frac{J_{\text{QCD}}^2}{\omega^2} \times \frac{d\sigma_{\text{el}}^{Qq}}{dq_\perp^2}$$

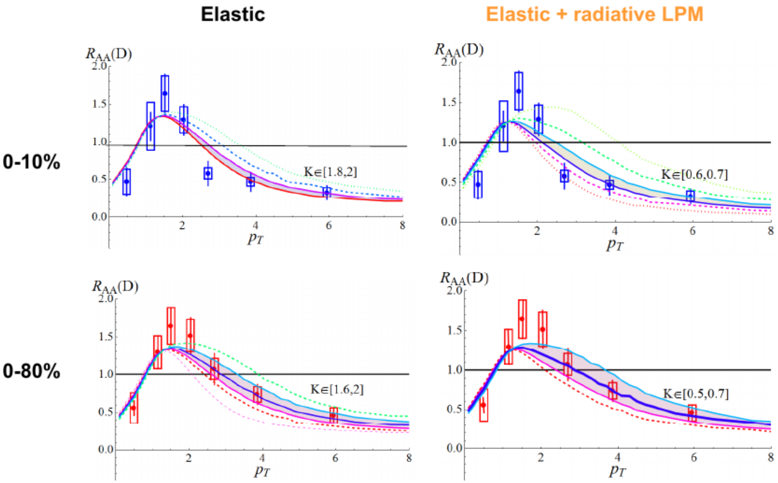
with
$$\frac{J_{\text{QCD}}^2}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2 + x^2 M^2 + (1-x) m_g^2} - \frac{\vec{k}_\perp - \vec{q}_\perp}{\left(\vec{k}_\perp - \vec{q}_\perp\right)^2 + x^2 M^2 + (1-x) m_g^2} \right)^2$$

Gluon thermal mass ~2T (phenomenological; not in BDMPS)

Quark mass

QCD interactions with running coupling

Pol Gossiaux



NB: with radiative HQ interactions: $K \in [0.6, 0.7]$!

Pol Gossiaux & Thierry Gousset

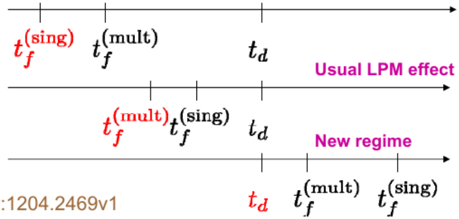
Consequences of radiation damping on energy loss

Basic question: Implications of a finite lifetime of the radiated gluon ?

Concepts

- In QED or pQCD, damping is a NLO process (damping time $t_d >> \lambda$); neglected up to now.
- However: formation time of radiation t_f increases with boost factor γ of the charge
- Expected effects when $t_f \approx t_d$ or $t_f > t_d$: in this regime, t_d should become the relevant scale (gluons absorbed being formed)

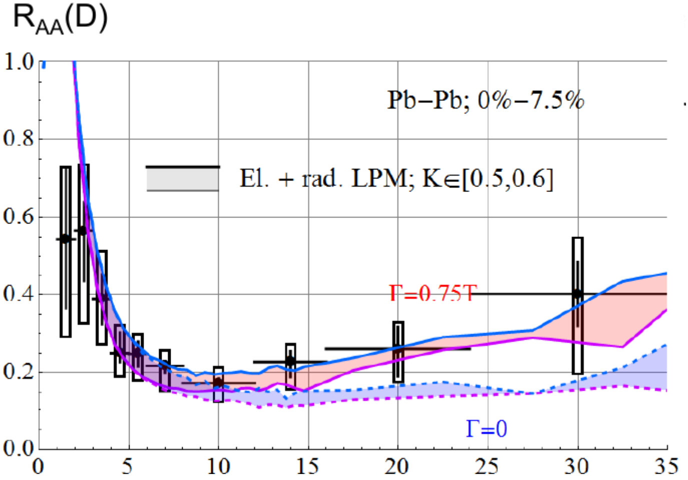
γ - hierarchy:



M. Bluhm, PBG & J. Aichelin, arXiv:1204.2469v1

Effects of radiation damping

Pol Gossiaux

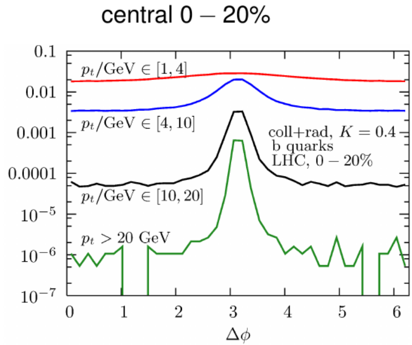


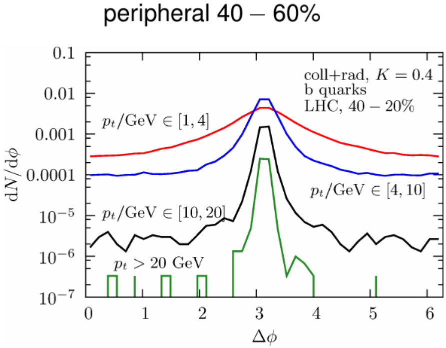
- radiation damping reduces HQ quenching at high p_T
- still K factor $K \in [0.5, 0.6]$ needed!

Angular Correlations of $Q\overline{Q}$ pairs

Marlene Nahrgang

- elastic and radiative energy loss (NANTES model)



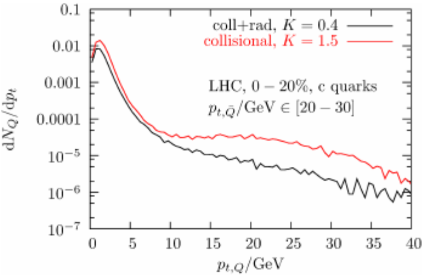


p_T correlations of $Q\overline{Q}$ pairs

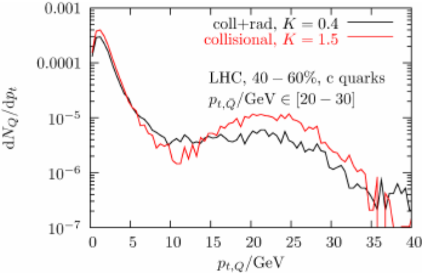
Marlene Nahrgang

- elastic and radiative energy loss (NANTES model)

central 0 – 20%



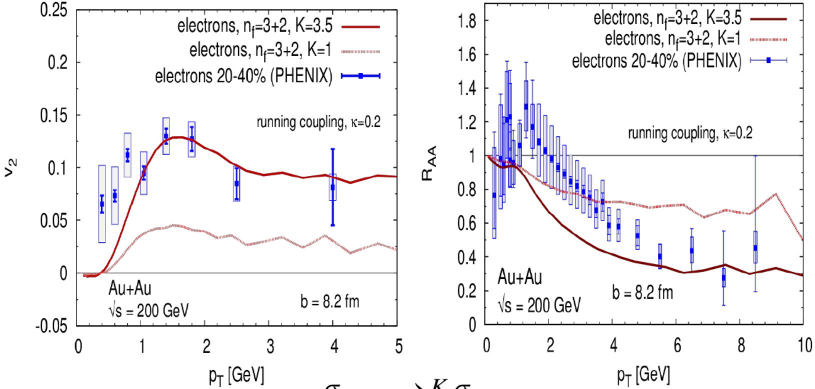
peripheral 40 – 60%



Full transport simulations (BAMPS)

Jan Uphoff

- elastic heavy-quark scattering (model by Peshier/Peigne, Gossiaux/Aichelin)$\times K = 3.5$
- bulk medium (gluons) and HQ diffusion within one full transport (hadron cascade BAMPS)



$$\sigma_{gQ\to gQ} \to K\,\sigma_{gQ\to gQ}$$

Full transport simulations (BAMPS)

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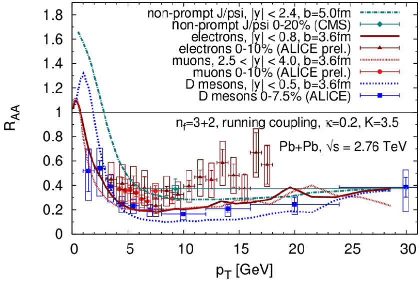
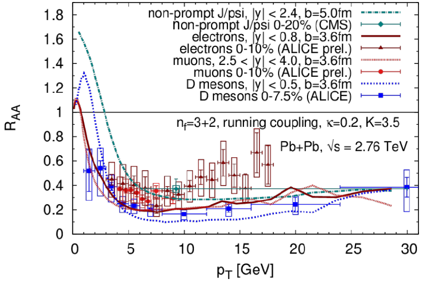
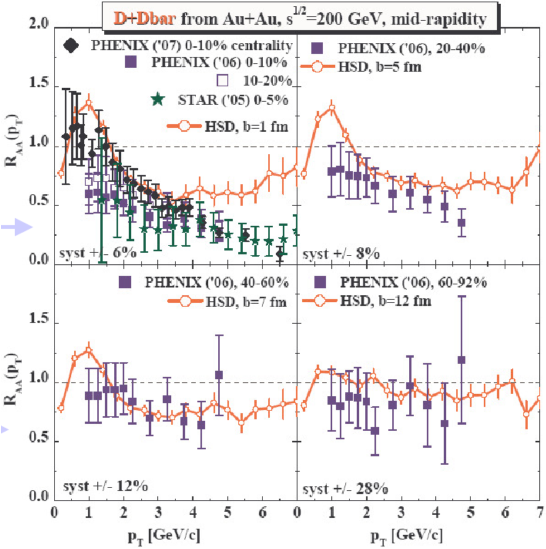




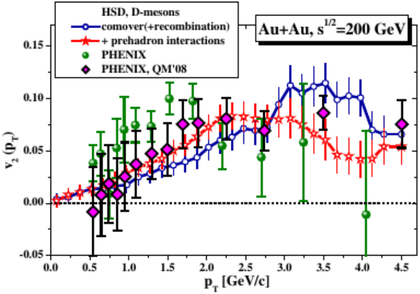
Full transport simulations (HSD)

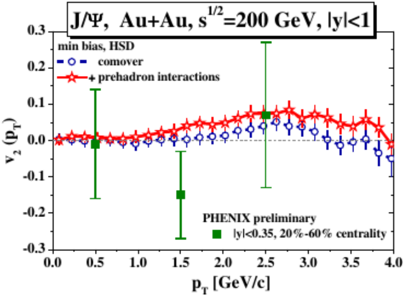
Elena Bratkovskaya



Full transport simulations (HSD)

Elena Bratkovskaya





Open Theory Questions

- plethora of models on in-medium HQ interactions!
- what's a realistic quantitative relation between collisional and radiative scattering?
- is pQCD applicable?
- are F/U static HQ potentials applicable (T-matrix approach)?
- is D/B-meson diffusion in hadronic phase important?
- can one experimentally quantify role of hadronization mechanism (coalescence/resonance recombination vs. fragmentation) by CQNS of v_2 or other (more sensitive observables)?
- can the bulk-medium evolution be contrained better?
- p_T and angular $Q\overline{Q}$ correlations measurable?
  NB also important for dilepton analysis in $m_\phi \lesssim M \lesssim m_{J/\psi}$ (competition between correlated $D\overline{D}$ decay and QGP radiation!)

Apologies to speakers not covered in the review

Many important issues discussed but not covered in summary!

- HQ production in pp, pA, decay to leptons:
  - Production of two $c\bar{c}$ pairs and two identical D mesons - evidence for double parton scattering mechanism (Antoni Szczurek)
  - Heavy-quarkonium suppression in p-A collisions from parton energy loss (Stephane Peigne)
  - Exclusive coherent production of heavy vector mesons in nucleus-nucleus collisions (Wolfgang Schäfer)
  - Open charmed mesons at LHC (including $\mathrm{D}\overline{\mathrm{D}}$ angular correlations) (Rafal Maciula)
  - QCD factorization theorems for production of heavy quarkonia (Jianwei Qiu)
  - Gauge/gravity, thermalization and energy loss (Wilke van der Schee)
- more lattice results
  - dilepton rates from lQCD (Olaf Kaczmarek)
  - The chiral transition and equation of state (Szabolcs Borsanyi)