QUARKONIA IN A HOT AND DENSE MEDIUM

David Blaschke

Institute for Theoretical Physics, University of Wroclaw, Poland

Bogoliubov Laboratory for Theoretical Physics, JINR Dubna, Russia

HISS “Heavy Quark Physics”, Dubna, 15.-28.07.2013

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Outline:

- Introduction: historical remarks on Mott effect in hadron physics
- Bound states in strongly correlated plasmas
- Quantum mechanical evolution of charmonium at the QCD transition
- Mott effect for D-mesons in a hot, dense medium

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HISS “Heavy Quark Physics”, Dubna, 15.-28.07.2013

INTRODUCTION: SOME HISTORICAL REMARKS ...

BI-TP 83/20
October 1983

COLOUR SCREENING IN SU(N) GAUGE THEORY

AT FINITE TEMPERATURE

Helmut Satz

Fakultät für Physik
Universität Bielefeld
Germany

Critical temperature values for Mott transitions in QCD

N_c	N_f	T_c [MeV]
3	0	120
	1	155
	2	170
	3	175
2	0	210

- 1983: Mott effect and color deconfinement
- 1984: Mott effect and hadron-to-quark matter transition
- 1986: Matsui-Satz; (Blaschke in N. P. Army)
- 1987: Mott dissociation; NA38 data
- 1989: Meeting H.S., J.H.; Wall breakup
- 1990: 1^{st} Visit at CERN - NA38
- ...

INTRODUCTION: SOME HISTORICAL REMARKS ...

Volume 151B, number 5,6 PHYSICS LETTERS 21 February 1985

THE MOTT MECHANISM AND THE HADRONIC-TO-QUARK MATTER PHASE TRANSITION

D. BLASCHKE, F. REINHOLZ [1]
Laboratory of Theoretical Physics, Joint Institute of Nuclear Research, Dubna, USSR

and

G. RÖPKE and D. KREMP
Department of Physics, Wilhelm-Pieck University, 2500 Rostock, GDR

Received 25 September 1984
Revised manuscript received 27 November 1984

Röpke & group (Ahrenshoop $\sim$ 1987)

- 1983: Mott effect and color deconfinement
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INTRODUCTION: SOME HISTORICAL REMARKS ...

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

- 1983: Mott effect and color deconfinement
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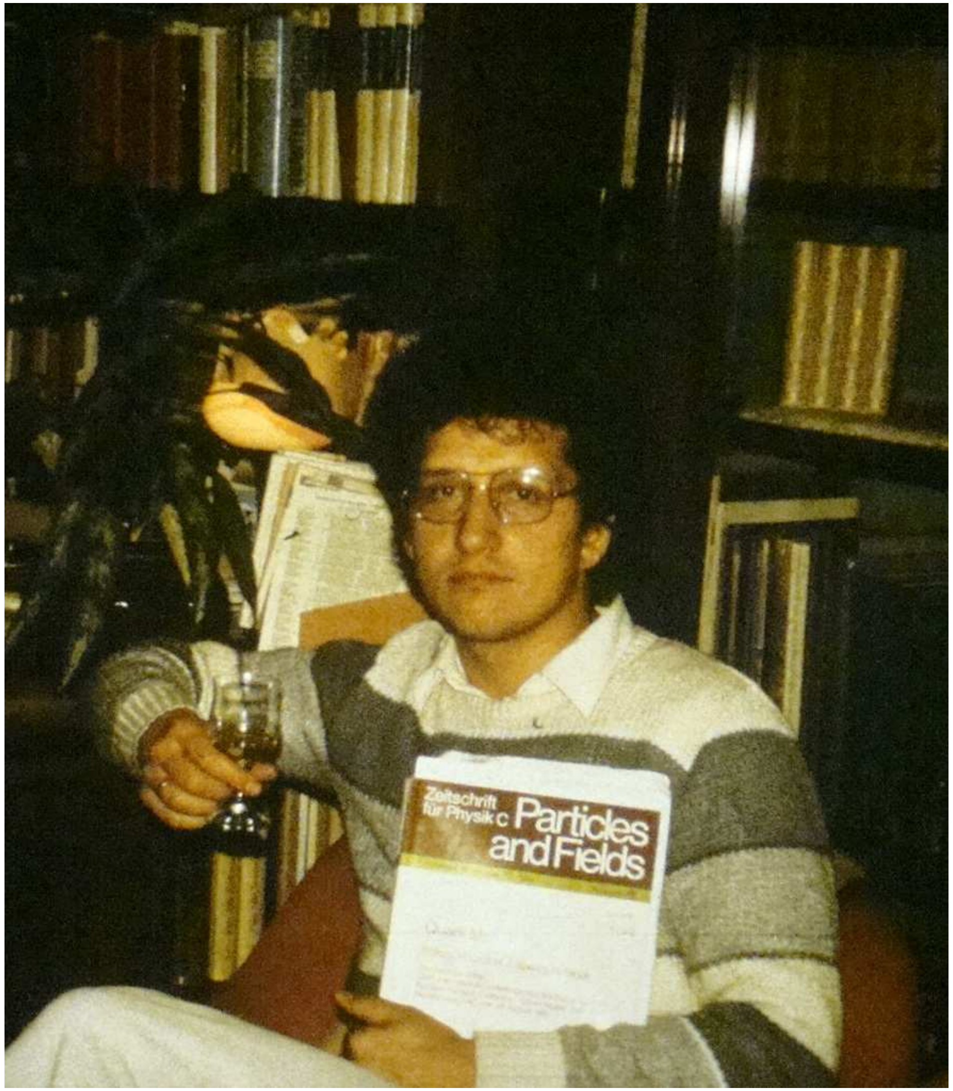
INTRODUCTION: SOME HISTORICAL REMARKS ...



D.B. (Rostock $\sim$ 1988)

- 1983: Mott effect and color deconfinement
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- ...

INTRODUCTION: SOME HISTORICAL REMARKS ...

Volume 202, number 4 PHYSICS LETTERS B 17 March 1988

HEAVY QUARK BOUND STATE SUPPRESSION BY MOTT DISSOCIATION AND THERMAL ACTIVATION

G. RÖPKE, D. BLASCHKE
Sektion Physik, Wilhelm-Pieck-Universität, DDR-2500 Rostock, GDR

and

H. SCHULZ
The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark and Central Institute for Nuclear Research, Rossendorf, DDR-8051 Dresden, GDR

Received 11 December 1987

D.B., Röpke, Schulz (Rathen 2006)

- 1983: Mott effect and color deconfinement
- 1984: Mott effect and hadron-to-quark matter transition
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INTRODUCTION: SOME HISTORICAL REMARKS ...

Hüfner, Aichelin, Werner (Heidelberg 1991)

- 1983: Mott effect and color deconfinement
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Introduction: Some historical remarks ...

The Berlin Wall at Potsdamer Platz (Dec. 1989)

- 1983: Mott effect and color deconfinement
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Introduction: Some historical remarks ...

Schulz, Knoll, Satz, Heinz (CERN 1990)

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Schulz, D.B., Knoll (CERN-NA38 1990)

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- 1987: Mott dissociation; NA38 data
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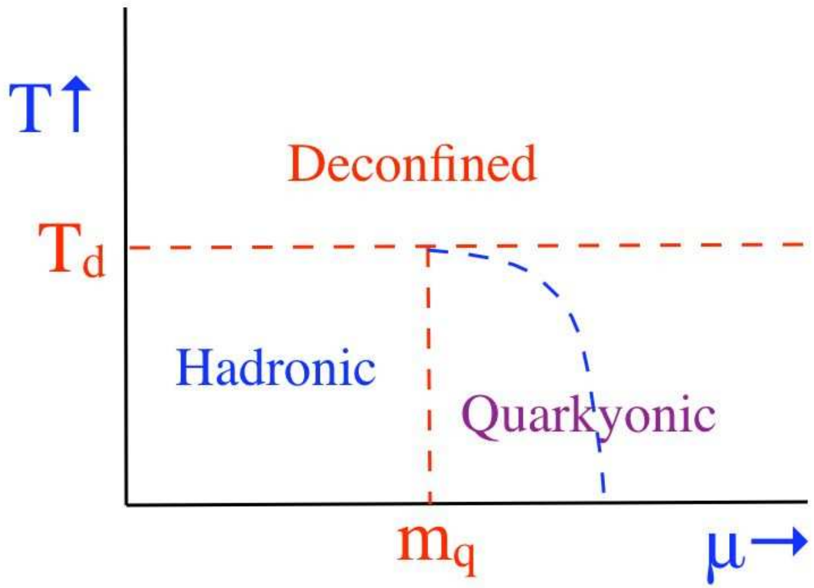
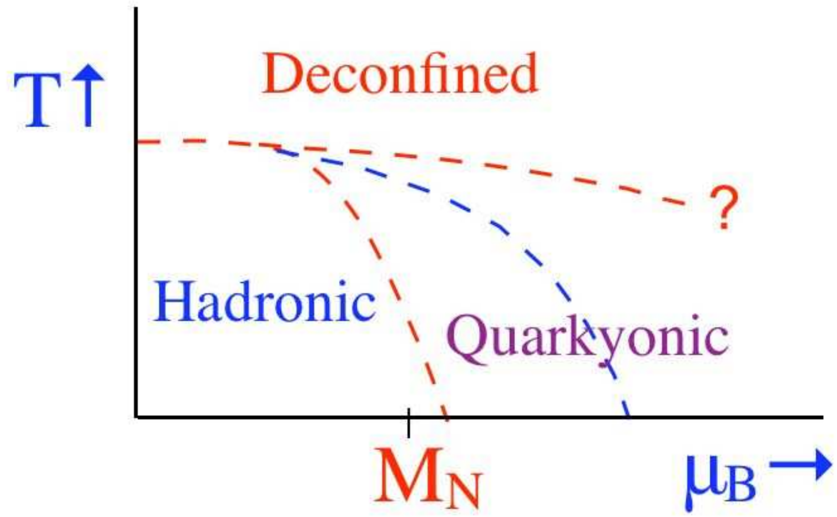
- ...

QUARKYONIC PHASE = CHIRAL SYMMETRY + CONFINEMENT



Phase diagram for $N_c \to \infty$ and finite N_f

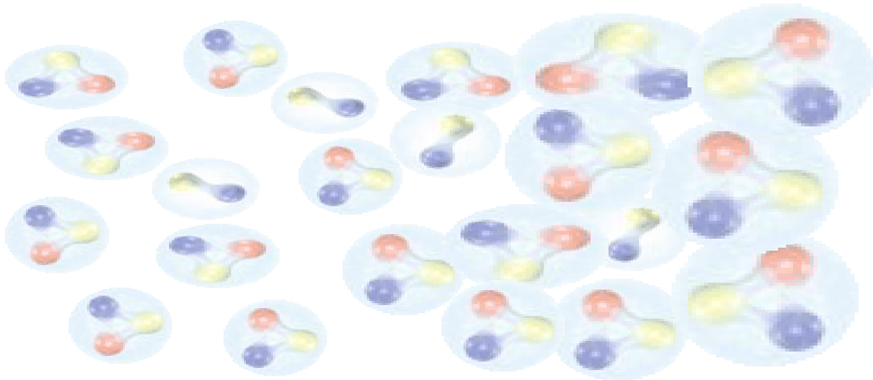


Phase diagram for $N_c \to \infty$ and small N_f/N_c

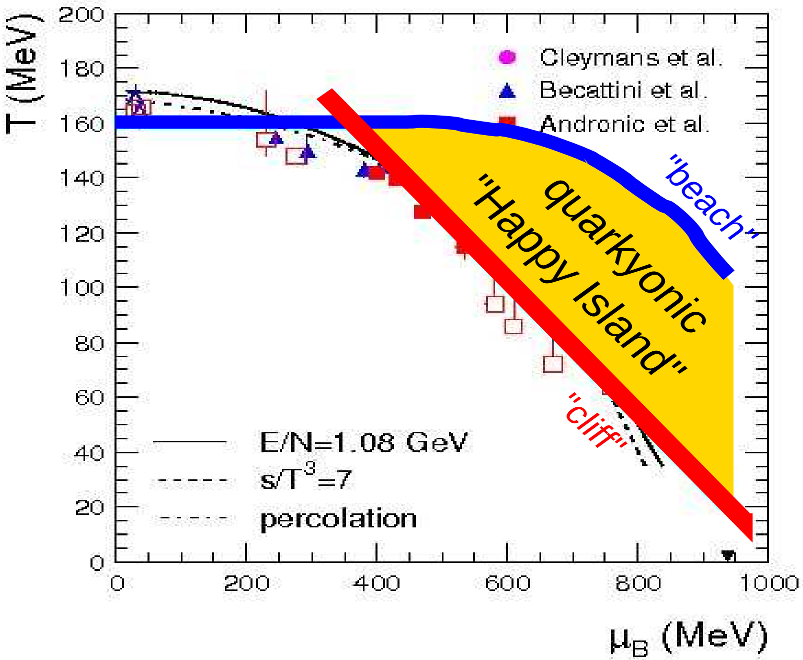
Hidaka, McLerran, Pisarski, Nucl. Phys. A 808 (2008) 117.
McLerran, Pisarski, Nucl. Phys. A 796 (2007) 83.

McLerran, Redlich, Sasaki, Nucl. Phys. A 824 (2009) 86; arXiv:0812.3585

WHAT HAPPENS ON "HAPPY ISLAND"?



Andronic et al., arxiv:0911.4806



"beach": hadron resonances ⟶ QGP

"cliff":

- (unmodified) vacuum bound state energies
- fast chemical equilibration

Explanation:

Strong medium dependence of rates for flavor (quark) exchange processes

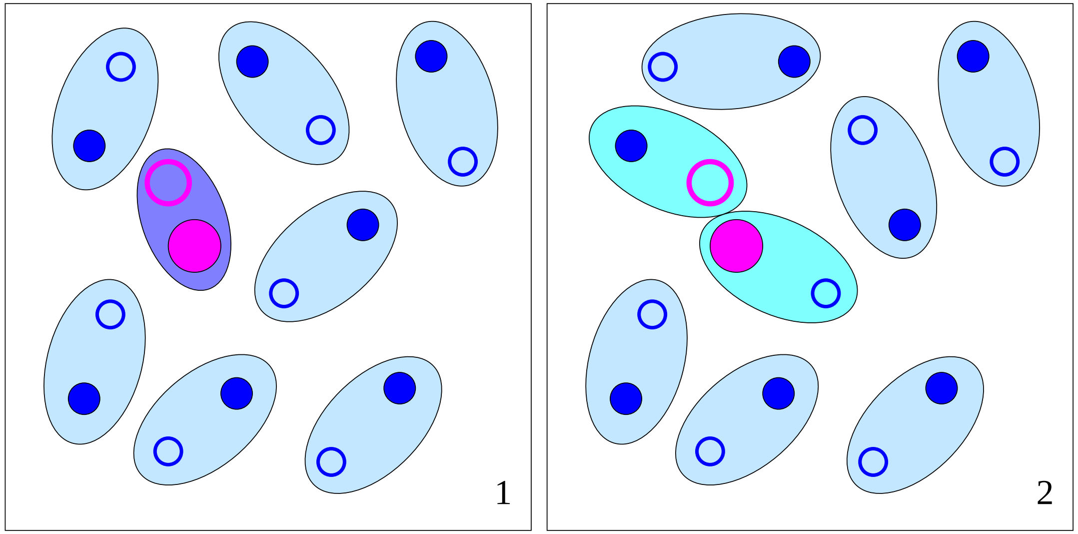
Reason:

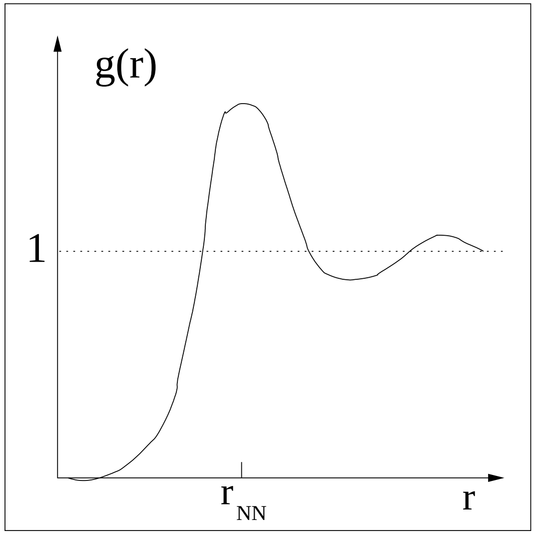
- lowering of thresholds
- increase of hadron size (Pauli principle) → geometrical overlap (percolation)

D.B., Berdermann, Cleymans, Redlich, Part. Nucl. Phys. Lett. (2011), arxiv:1102.2908; Few Body Syst. (2012) arxiv:1109.5391

A SNAPSHOP OF THE sQGP

The Picture: String-flip (Rearrangement) $\Longleftrightarrow$ Pair correlation





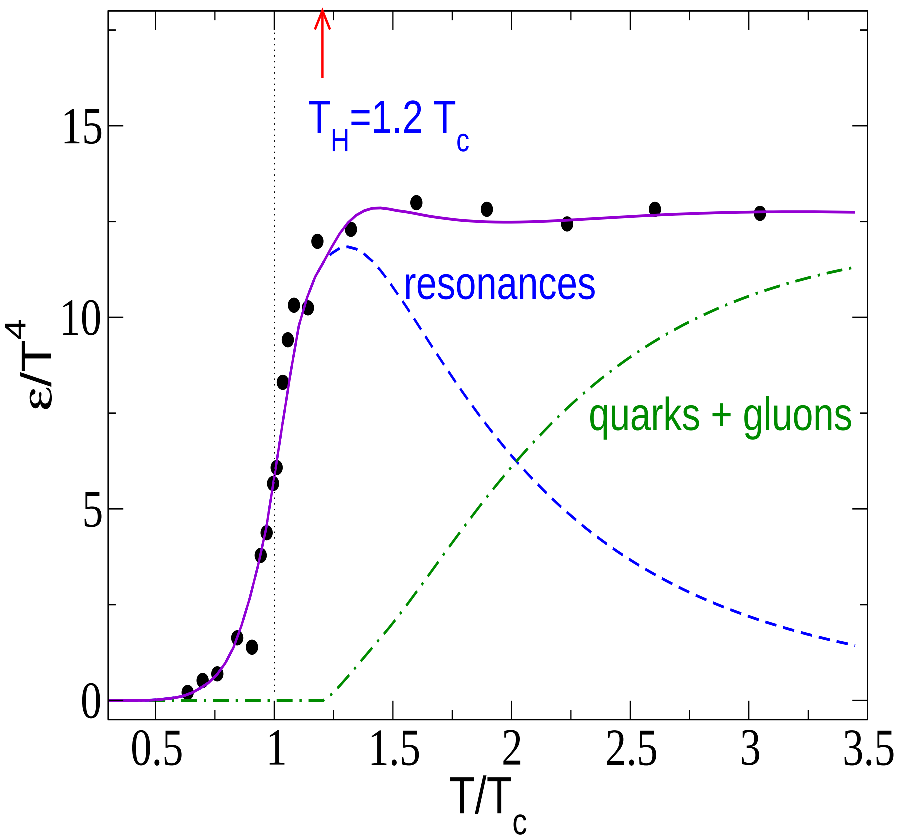
Horowitz et al. PRD (1985), D.B. et al. PLB (1985), Röpke, Blaschke, Schulz, PRD (1986)

Thoma,[hep-ph/0509154] Gelman et al., PRC 74 (2006)

- Strong correlations present: hadronic spectral functions above T_c (lattice QCD)
- Finite width due to rearrangement collisions (higher order correlations)
- Liquid-like pair correlation function (nearest neighbor peak)

Lattice QCD EoS and Mott-Hagedorn Gas

$$\varepsilon_{\rm R}(T,\{\mu_j\}) = \sum_{i=\pi,K,\dots} \varepsilon_i(T,\{\mu_i\}) + \sum_{r=M,B} g_r \int_{m_r} dm \int ds\, \rho(m) A(s,m;T) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+s}}{\exp\left(\frac{\sqrt{p^2+s}-\mu_r}{T}\right)+\delta_r}$$



Hagedorn mass spectrum: $\rho(m)$

Spectral function for heavy resonances:

$$A(s,m;T) = N_s \frac{m\Gamma(T)}{(s-m^2)^2 + m^2\Gamma^2(T)}$$

Ansatz with Mott effect at $T = T_H = 192$ MeV:

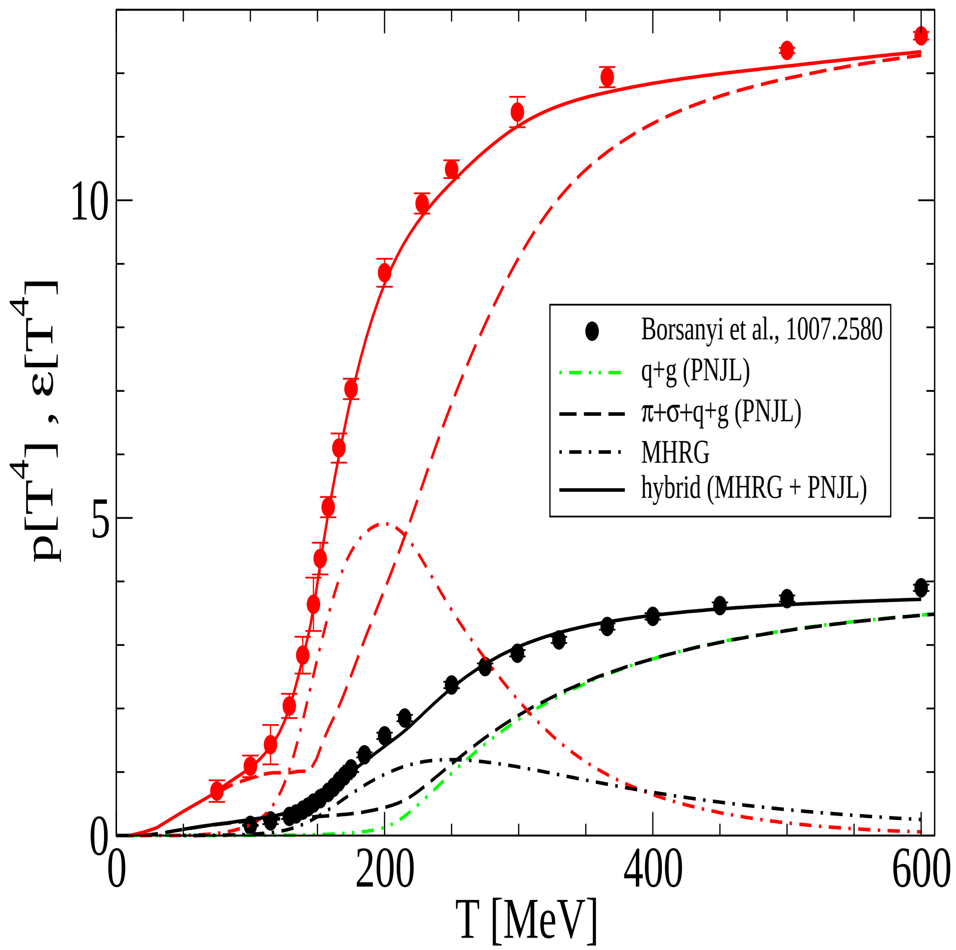
$$\Gamma(T) = B\Theta(T-T_H)\left(\frac{m}{T_H}\right)^{2.5}\left(\frac{T}{T_H}\right)^6 \exp\left(\frac{m}{T_H}\right)$$

No width below T_H: Hagedorn resonance gas
Apparent phase transition at $T_c \sim 160$ MeV

Blaschke & Bugaev, Fizika B13, 491 (2004)
Prog. Part. Nucl. Phys. 53, 197 (2004)
Blaschke & Yudichev (2006)

Hybrid appoach: PNJL & Mott-Hagedorn Resonance Gas

$$\varepsilon_{\rm hybrid}(T,\{\mu_j\}) = \varepsilon_{\rm PNJL}(T,\{\mu_i\}) + \sum_{r=M,B} g_r \int ds\, A(s,m_r;T) \int \frac{d^3p}{(2\pi)^3} \frac{\sqrt{p^2+s}}{\exp\left(\frac{\sqrt{p^2+s}-\mu_r}{T}\right)+\delta_r}$$



Spectral function for heavy resonances:

$$A(s,m;T) = N_s \frac{m\Gamma(T)}{(s-m^2)^2 + m^2\Gamma^2(T)}$$

Ansatz with Mott effect at $T = T_H = 198$ MeV:

$$\Gamma(T) = B\Theta(T-T_H)\left(\frac{m}{T_H}\right)^{2.5}\left(\frac{T}{T_H}\right)^{6}\exp\left(\frac{m}{T_H}\right)$$

Apparent phase transition at $T_c \sim 165$ MeV

Blaschke & Bugaev, Fizika B13, 491 (2004)

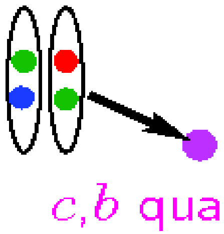
Prog. Part. Nucl. Phys. 53, 197 (2004)

Blaschke, Prorok & Turko, in preparation

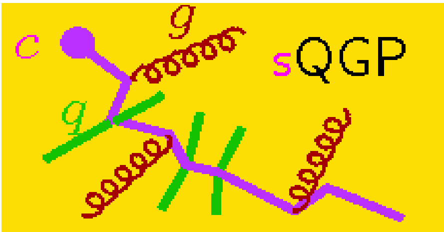
Motivation

- Fast equilibration of hot and dense matter in heavy-ion collisions: collective flow (nearly ideal hydrodynamics) $\Rightarrow$ sQGP
- Heavy quarks as calibrated probe of QGP properties
  - produced only in early hard collisions: well-defined initial conditions
  - not fully equilibrated due to large masses
  - heavy-quark diffusion $\Rightarrow$ probes for QGP-transport properties
- Langevin simulation
- drag and diffusion coefficients
  - T-matrix approach with static lattice-QCD heavy-quark potentials
  - resonance formation close to T_c
  - mechanism for non-perturbative strong interactions

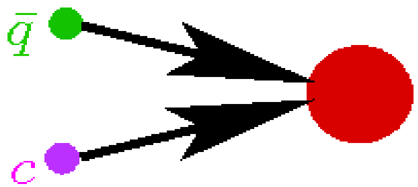
Heavy Quarks in Heavy-Ion Collisions



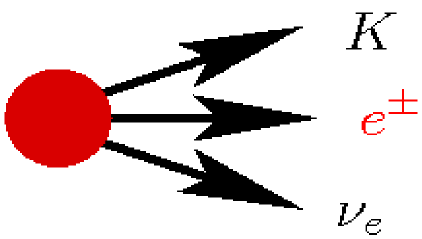
hard production of HQs
described by PDF's + pQCD (PYTHIA)



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



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

FOKKER-PLANCK EQUATION FOR HEAVY QUARKS

- Fokker-Planck equation

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

- transition rates

$$w(\vec{p},\vec{k}) = \gamma_q \int \frac{\mathrm{d}^3\vec{q}}{(2\pi)^3} f_q(\vec{q}) v_{\mathrm{rel}}(\vec{p},\vec{q} \rightarrow \vec{p}-\vec{k}, \vec{q}+\vec{k}) \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$$

- with drag and diffusion coefficients

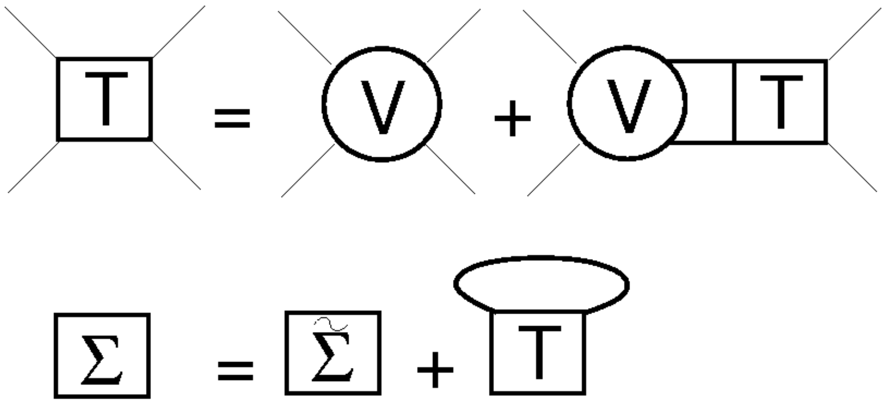
$$A_i(\vec{p}) = \int \mathrm{d}^3\vec{k}\; k_i w(\vec{p},\vec{k}), \quad B_{ij}(\vec{p}) = \frac{1}{2} \int \mathrm{d}^3\vec{k}\; k_i k_j w(\vec{p},\vec{k})$$

- equilibrated light quarks and gluons: coefficients in heat-bath frame
- matter homogeneous and isotropic

$$A_i(\vec{p}) = A(p) p_i, \quad B_{ij}(\vec{p}) = B_0(p) P_{ij}^{\perp} + B_1(p) P_{ij}^{\parallel}$$

$$\text{with} \quad P_{ij}^{\parallel}(\vec{p}) = \frac{p_i p_j}{\vec{p}^2}, \quad P_{ij}^{\perp}(\vec{p}) = \delta_{ij} - \frac{p_i p_j}{\vec{p}^2}$$

T-MATRIX APPROACH TO QUARKONIA IN THE QGP

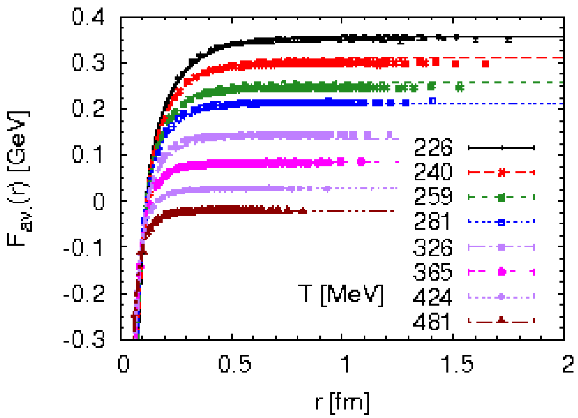


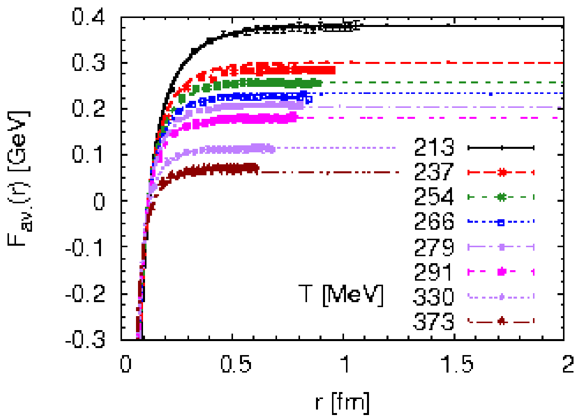
Riek & Rapp, PRC 82 (2010); arxiv:1005.0769

Open question: Wich potential to use?

$$U = F - T\frac{dF}{dT}$$
$$V(r;T) = F(r;T) - F(\infty,T) \text{ or } F \leftrightarrow U$$

Result: J/ψ good resonance below $1.5\,T_c$ for F, and $2.5\,T_c$ for U





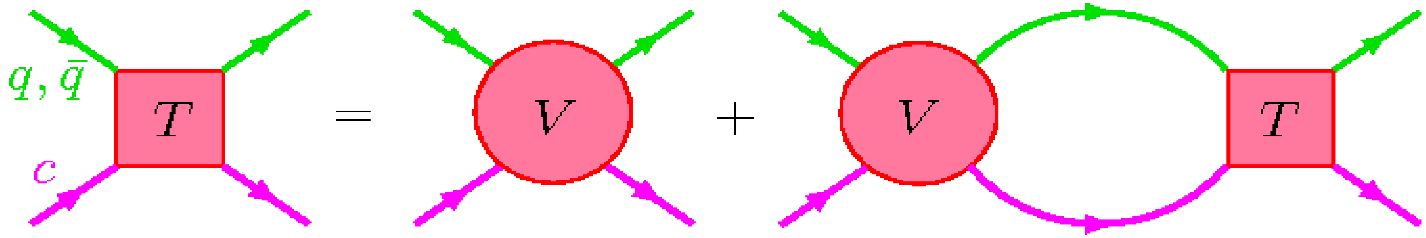
Field theoretic input:
Megias et al. JHEP (2006)

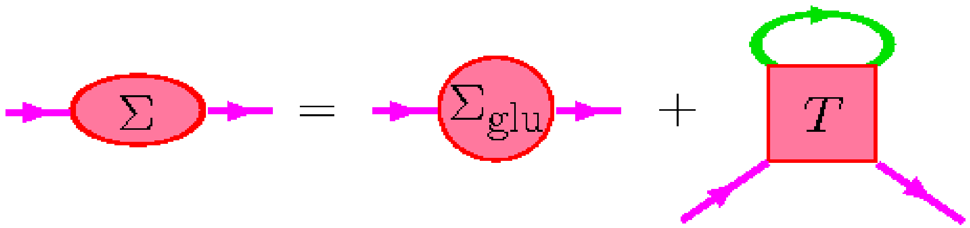
$$D_{00}(\vec{k}) = D^{P}_{00}(\vec{k}) + D^{NP}_{00}(\vec{k})$$
$$D^{P}_{00}(\vec{k}) = \frac{1}{\vec{k}^2 + m_D^2}$$
$$D^{NP}_{00}(\vec{k}) = \frac{m_G^2}{(\vec{k}^2 + \tilde{m}_D^2)^2}$$

Lattice:Kaczmarek et al. (left), Petreczky et al. (right)

T-MATRIX APPROACH

- T-matrix Brückner approach for heavy quarkonia as for HQ diffusion
- consistency between HQ diffusion and $\bar{Q}Q$ suppression!





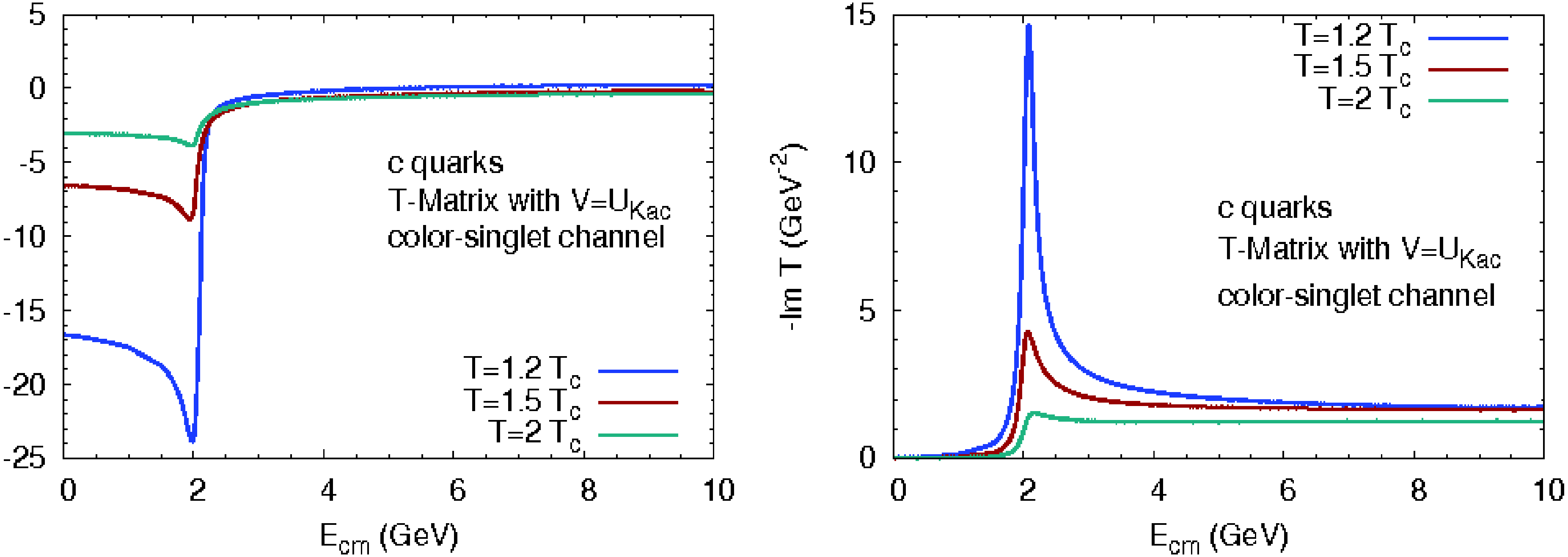
- 4D Bethe-Salpeter equation $\rightarrow$ 3D Lippmann-Schwinger equation
- relativistic interaction $\rightarrow$ static heavy-quark potential (lQCD)

$$T_\alpha(E; q', q) = V_\alpha(q', q) + \frac{2}{\pi} \int_0^\infty \mathrm{d}k\, k^2 V_\alpha(q', k) G_{Q\bar{Q}}(E; k) T_\alpha(E; k, q) \times \{1 - n_F[\omega_1(k)] - n_F[\omega_2(k)]\}$$

- q, q', k relative 3-momentum of initial, final, interm. qQ or $\bar{q}Q$ state

[F. Riek, R. Rapp, PRC 82, 035201 (2010)]

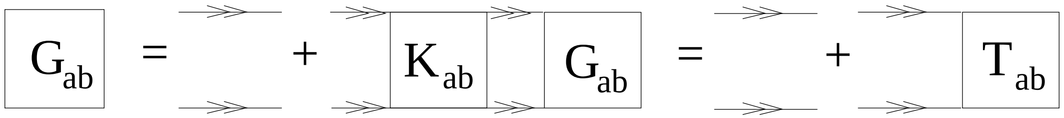
T-Matrix Results

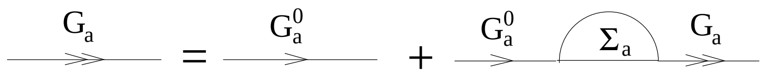


- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering!

Bound states in strongly coupled plasmas (I)

Bethe-Salpeter Equation and Plasma Hamiltonan





$$G_{ab} = G^0_{ab} + G^0_{ab}\, K_{ab}\, G_{ab} = G^0_{ab} + G^0_{ab}\, T_{ab}\, G^0_{ab}$$

$$G_a = G^0_a + G^0_a \Sigma_a G_a$$

Equivalent Schrödinger equation [Zimmermann et al. (1978)]

$$\sum_q \{[\varepsilon_a(p_1) + \varepsilon_b(p_2) - z]\, \delta_{q,0} - V_{ab}(q)\}\, \psi_{ab}(p_1 + q, p_2 - q, z) = \sum_q H^{\mathrm{pl}}_{ab}(p_1, p_2, q, z) \psi_{ab}(p_1 + q, p_2 - q, z),$$

with Plasma Hamiltonian

$$H^{\mathrm{pl}}_{ab}(p_1, p_2, q, z) = \underbrace{V_{ab}(q)\, [N_{ab}(p_1, p_2) - 1]}_{\text{(i) Pauli blocking}} - \underbrace{\sum_{q'} V_{ab}(q')\, [N_{ab}(p_1 + q', p_2 - q') - 1]\, \delta_{q,0}}_{\text{(ii) Exchange self-energy}}$$
$$+ \underbrace{\Delta V_{ab}(p_1, p_2, q, z) N_{ab}(p_1, p_2)}_{\text{(iii) Dynamically screened potential}} - \underbrace{\sum_{q'} \Delta V_{ab}(p_1, p_2, q', z) N_{ab}(p_1 + q', p_2 - q')\, \delta_{q,0}}_{\text{(iv) Dynamical self-energy}}$$

In-medium modification of interaction: $\Delta V_{ab}(p_1, p_2, q, z) = K_{ab}(p_1, p_2, q, z) - V_{ab}(q)$

BOUND STATES IN STRONGLY COUPLED PLASMAS (II)

2-particle wave function ψ_{ab} and phase space occupation factor N_{ab}

- Uncorrelated fermionic medium: $N_{ab}(p_1, p_2) = 1 - f_a(p_1) - f_b(p_2)$
- Correlated medium with two-particle clusters ($\psi_{ab}(p_1, p_2, E_{nP})$)
  $f_a(p_1) \to \tilde{f}_a(p_1) = f_a(p_1) + \sum_{c,n,P} |\psi_{ac}(p_1, P - p_1, E_{nP})|^2 g_{ac}(E_{nP})$

Discussion of the plasma Hamiltonian:

- Bound states localized in x-space, therefore:
  over a finite range Λin q-space wave function q-independent:
  $\psi_{ab}(p_1 + q, p_2 - q, z = E_{nP}) \approx \psi_{ab}(p_1, p_2, z = E_{nP})$, for $q < \Lambda$, and vanishes for $q > \Lambda$.
- flat momentum dependence of the Pauli blocking factors:
  $N_{ab}(p_1 + q, p_2 - q) \approx N_{ab}(p_1, p_2)$
- approximate cancellations of:
  Pauli blocking term (i) by the exchange self-energy (ii), and
  dynamically screened potential (iii) by the dynamical self-energy (iv)
  result in **stability of bound states against medium effects !**
- Scattering states extended in x-space $\to$ no cancellations!,
  but **shift of the continuum threshold !**

SUMMARY: Mott effect for bound states possible due to cancellations of medium effects which do not apply for the continuum states.

Bound states in strongly coupled plasmas (III)

Application to heavy quarkonia in medium, where heavy quarks are rare

- $N_{ab} \approx 1$: Pauli blocking (i) and exchange selfenergy (ii) negligible
- medium effects due to dynamically screened potential (iii) and dynamical selfenergy (iv); from coupling of two-particle state to collective excitations (plasmons)

Screened potential (V_S) approximation to interaction kernel K

$$V_{ab}^S(p_1 p_2, q, z) = V_{ab}^S(q, z)\delta_{P,p_1+p_2}\delta_{2q,p_1-p_2}$$

$$V_{ab}^S(q, z) = V_{ab}(q) + V_{ab}(q)\Pi_{ab}(q, z)V_{ab}^S(q, z) = V_{ab}(q)[1 - \Pi_{ab}(q, z)V_{ab}(q)]^{-1}$$

Example: Heavy quarkonia in a relativistic quark plasma

$$\Pi_{ab}^{\mathrm{RPA}}(q, z) = 2\delta_{ab} \int \frac{d^3p}{(2\pi)^3} \frac{f_a(E_p^a) - f_a(E_{p-q}^a)}{E_p^a - E_{p-q}^a - z} .$$

Relativistic quark plasma described by a Polyakov-loop NJL model; evaluate the RPA polarization function for $N_c \times N_f$ massless quarks ($E_p^a = |p|$) in static ($\omega = 0$), long wavelength ($q \to 0$) case:

$$\Pi_{ab}^{\mathrm{RPA}}(q \to 0, 0) = 2\delta_{ab} \int \frac{d^3p}{(2\pi)^3} \frac{df_a(E_p^a)}{dE_p^a} = -2\delta_{ab} \int_0^\infty \frac{dp\, p}{\pi^2} f_\Phi(p) = -\frac{\delta_{ab}}{6\pi^2} I(\Phi)T^2 ,$$

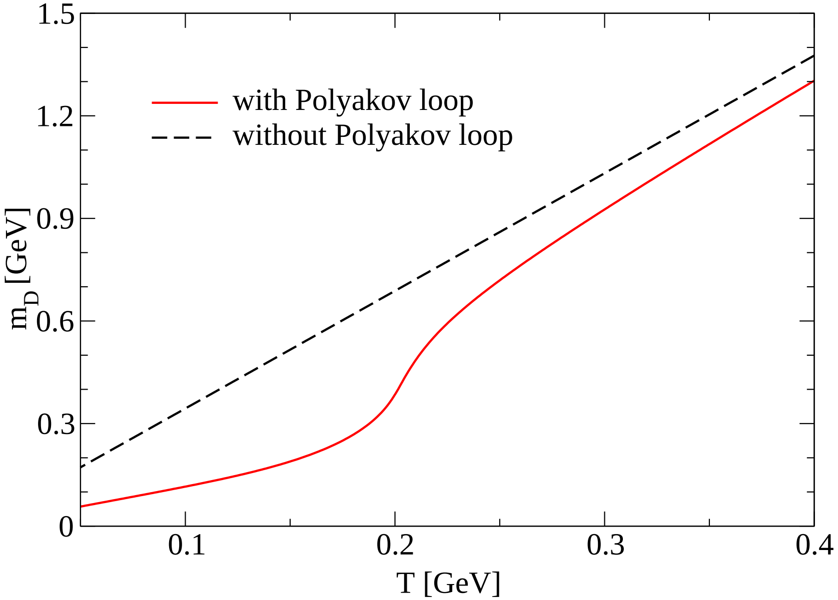
where $I(\Phi) = (12/\pi^2) \int_0^\infty dx x f_\Phi(x)$ and $f_\Phi(x) = [\Phi(1+2e^{-x})e^{-x} + e^{-3x}]/[1+3\Phi(1+e^{-x})e^{-x} + e^{-3x}]$ is the generalized quark distribution function (Hansen et al 2006).

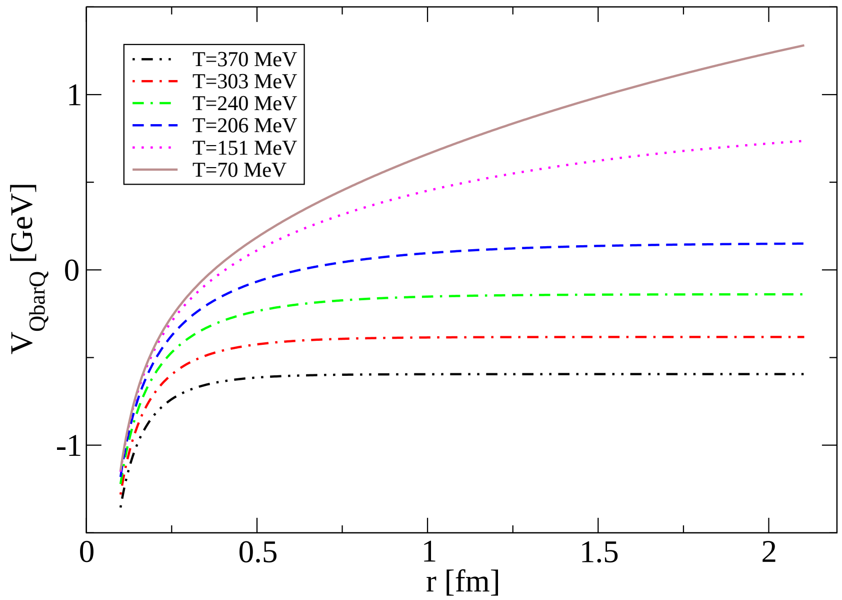
Bound states in strongly coupled plasmas (IV)

If bare potential a color singlet one-gluon exchange $V(q) = -4\pi\alpha/q^2$, $\alpha = g^2/(3\pi)$,
then Fourier transform of screened potential is a Debye potential $V^S(r) = -\alpha\exp(-m_D(T)r)/r$
with Debye mass $m_D(T) = 4\pi\alpha I(\Phi)T^2$.
Add a screened confinement potential $V^S_{\rm conf}(r) = (\sigma/\tilde{m}_D)(1-\exp(-\tilde{m}_D r))$, calculate Hartree selfenergies [Rapp, DB, Crochet, arxiv:0807.2470] and solve the effective Schrödinger equation for

$$V_{Q\bar{Q}}(r;T) = -\frac{\alpha}{r}\exp(-m_D(T)r) - \alpha m_D + \frac{\sigma}{\tilde{m}_D}\left[1-\exp(-\tilde{m}_D r)\right]$$

Here σ =const, $\tilde{m}_D = m_D$; see Riek/Rapp, PRC 82, 035201 (2010) for $\sigma = \sigma(T)$ and $\tilde{m}_D \neq m_D$





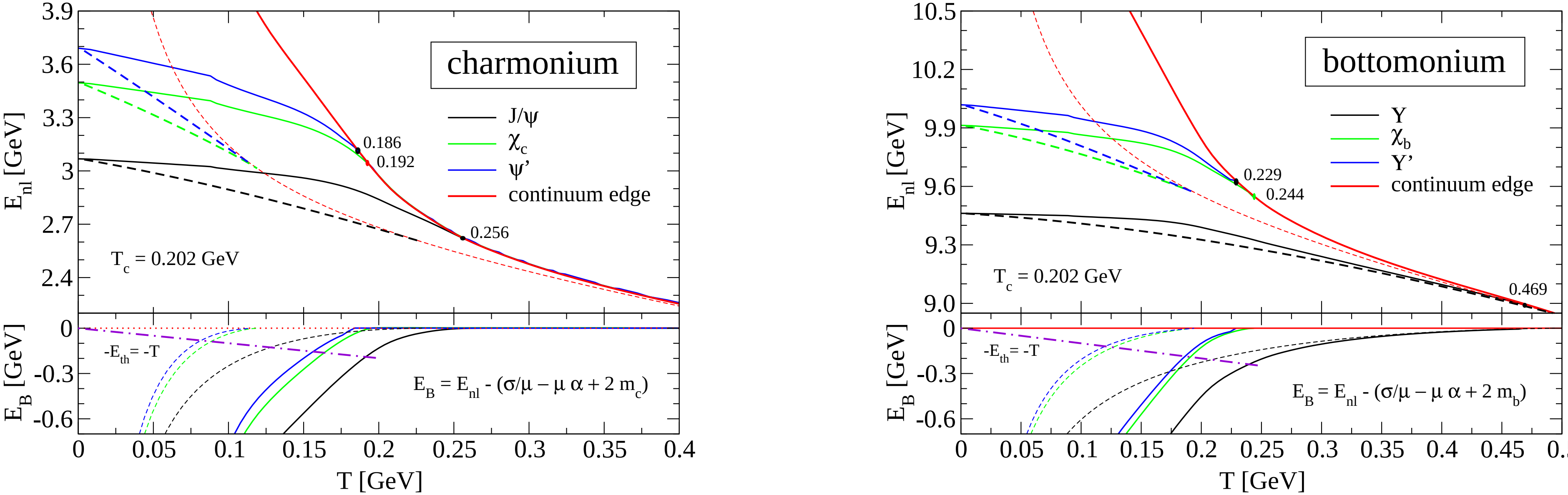
Temperature dependent Debye mass (left) with PL-suppressed screening and corresponding statically screened Cornell potential (right) [Jankowski, DB, Proceedings CPOD-2010].

Bound states in strongly coupled plasmas (V)

If bare potential a color singlet one-gluon exchange $V(q) = -4\pi\alpha/q^2$, $\alpha = g^2/(3\pi)$, then Fourier transform of screened potential is a Debye potential $V^S(r) = -\alpha\exp(-\mu_D(T)r)/r$ with Debye mass $\mu_D(T) = 4\pi\alpha I(\Phi)T^2$.
Add a screened confinement potential $V^S_{\rm conf}(r) = (\sigma/\mu_D)(1-\exp(-\mu_D r))$, calculate Hartree self-energies [Rapp, DB, Crochet, arxiv:0807.2470] and solve the effective Schrödinger equation

$$H^{\rm pl}(r;T)\phi_{nl}(r;T) = E_{nl}(T)\phi_{nl}(r;T)$$

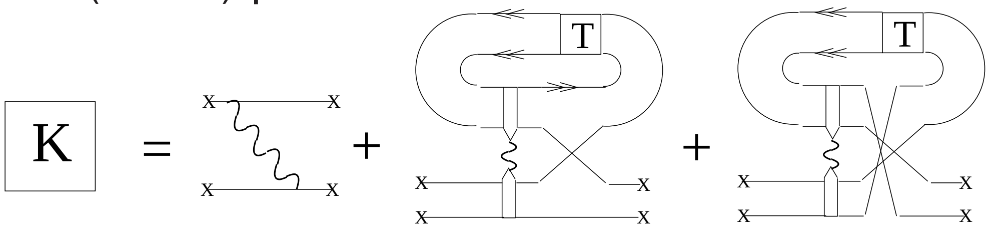
for the plasma Hamiltonian $H^{\rm pl}(r;T) = 2m_Q - \alpha\mu_D(T) - \vec{\nabla}^2/m_Q + V_{Q\bar{Q}}(r;T)$

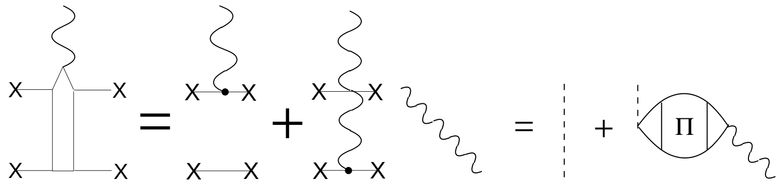


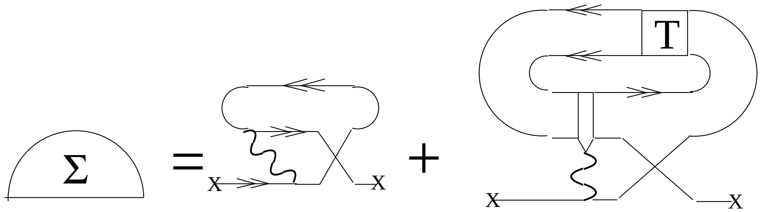
Two-particle energies of charmonia (left) and bottomonia (right) in a statically screened Cornell potential, [Jankowski, DB, Grigorian, Acta Phys. Pol. B (PS) 3, 747 (2010)].

BOUND STATES IN STRONGLY COUPLED PLASMAS (VI)

Two(three-)-particle states in the medium: cluster expansion







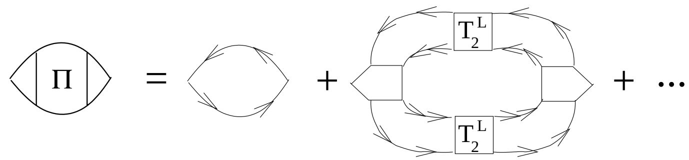
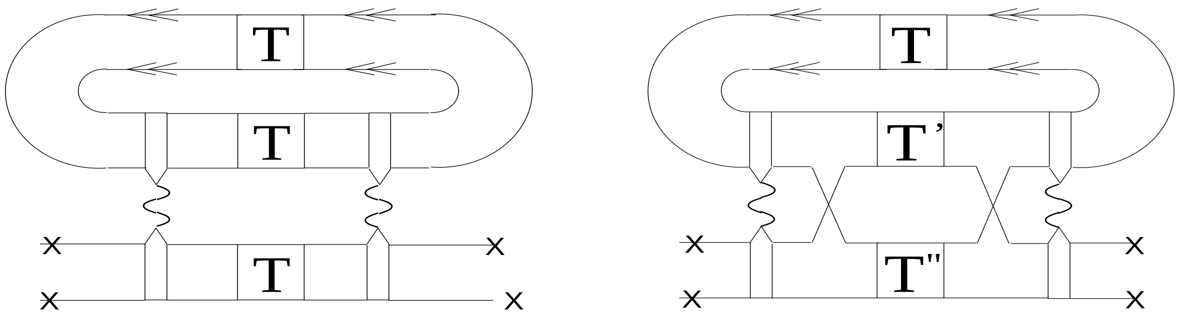


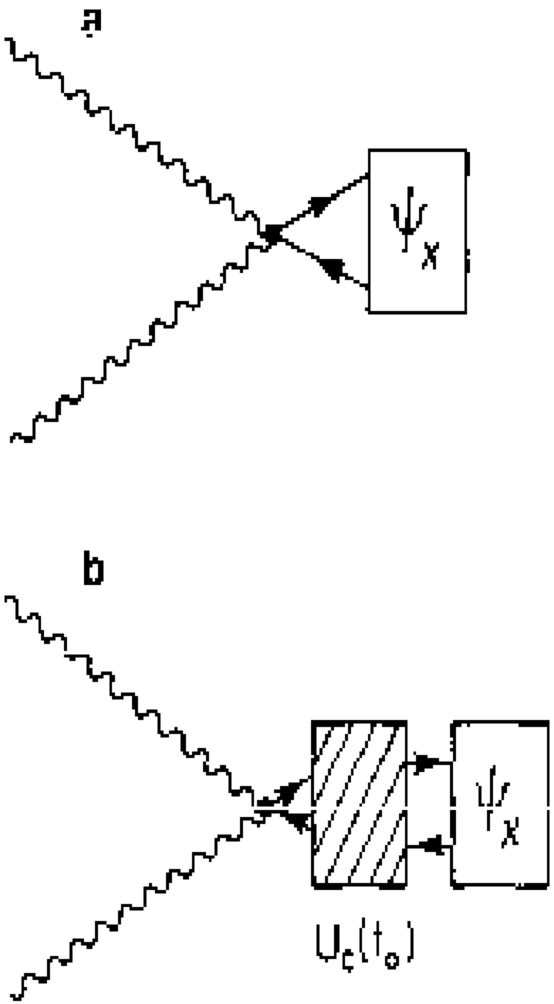
Diagram expansion for 1st and 2nd Born order cluster-cluster interactions



Resulting plasma Hamiltonian [Ebeling, DB, et al., arxiv:0810.3336 [physics.plasm-ph]]:

$$H^{\mathrm{pl}} = H^{\mathrm{Hartree}} + H^{\mathrm{Fock}} + H^{\mathrm{Pauli}} + H^{\mathrm{MW}} + H^{\mathrm{Debye}} + H^{\mathrm{pp}} + H^{\mathrm{vdW}} + \dots,$$

Quantum evolution of the $c\bar{c}$ state: Matsui's model



Harmonic oscillator Hamiltonian

$$H_{c\bar{c}} = 2m_c + \frac{p^2}{m_c} + \frac{m_c}{4}\omega^2 x^2$$

Time evolution operator

$$U_c(r, t_0) = \left(\frac{m_c \omega}{4\pi i \sin(\omega t_0)} \exp\left[\frac{i m_c \omega}{4} r^2 \cot(\omega t_0) \right] \right)$$

Supression ratio (survival probability)

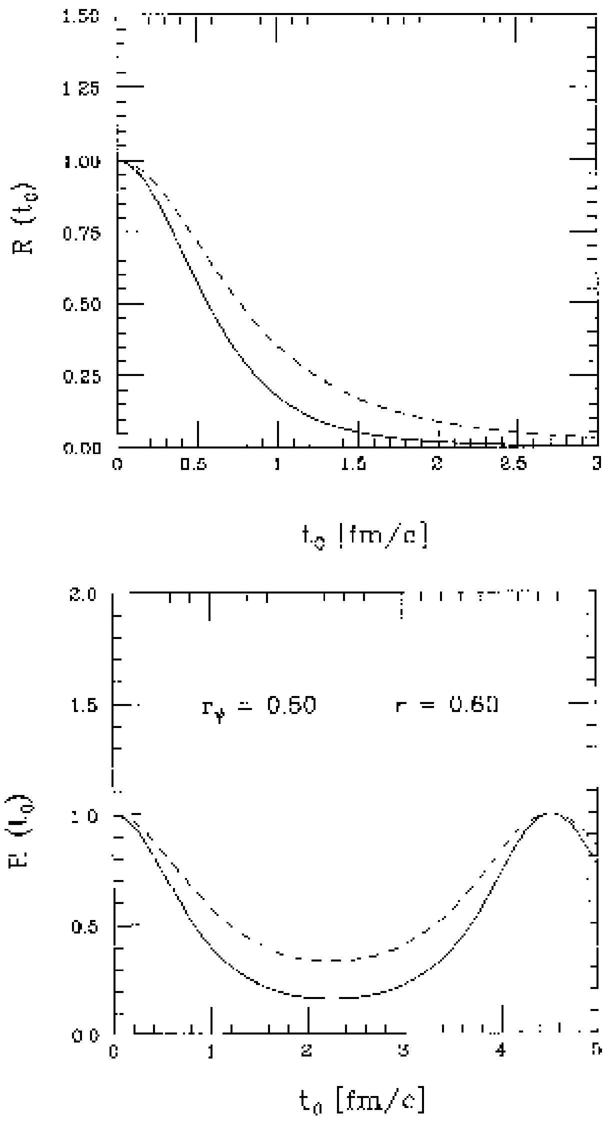
$$R_\psi(t_0) = \frac{|\langle c\bar{c}, \psi | U_c(t_0) H_{2g \to c\bar{c}} | 2g, k_0 \rangle|^2}{|\langle c\bar{c}, \psi | H_{2g \to c\bar{c}} | 2g, k_0 \rangle|^2}$$

Result for pseudoscalar state

$$\begin{aligned} R_{\eta_c}(t_0, \omega) &= \left[\cos^2(\omega t_0) + (\omega/\omega_\psi)^2 \sin^2(\omega t_0)\right]^{-3/2} \\ &\to (\omega_\psi^2 t_0^2)^{-3/2} \ ; \quad \omega = 0, \text{complete deconfinement} \end{aligned}$$

T. Matsui, Ann. Phys. 196 (1989) 182

QUANTUM EVOLUTION OF THE $c\bar{c}$ STATE: MATSUI'S MODEL



Harmonic oscillator Hamiltonian

$$H_{c\bar{c}} = 2m_c + \frac{p^2}{m_c} + \frac{m_c}{4}\omega^2 x^2$$

Time evolution operator in coordinate representation

$$U_c(r,t_0) = \left(\frac{m_c\omega}{4\pi i \sin(\omega t_0)}\right)^{3/2} \exp\left[\frac{i m_c \omega}{4} r^2 \cot(\omega t_0)\right]$$

Supression ratio (survival probability)

$$R_\psi(t_0) = \frac{|\langle c\bar{c},\psi|U_c(t_0)H_{2g\to c\bar{c}}|2g,k_0\rangle|^2}{|\langle c\bar{c},\psi|H_{2g\to c\bar{c}}|2g,k_0\rangle|^2}$$

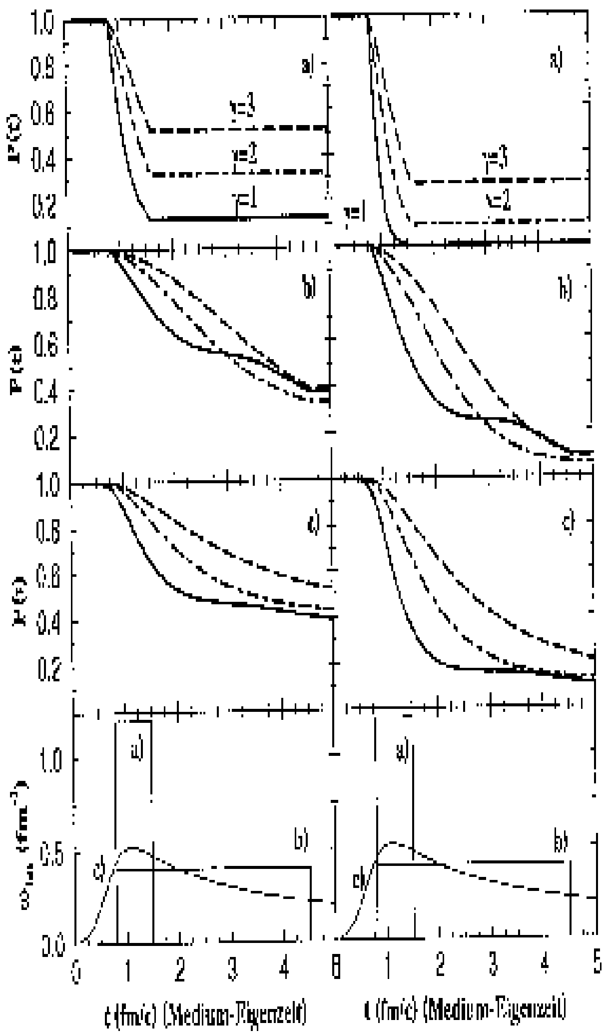
Result for pseudoscalar state

$$\begin{aligned} R_{\eta_c}(t_0,\omega) &= \left[\cos^2(\omega t_0) + (\omega/\omega_\psi)^2 \sin^2(\omega t_0)\right]^{-3/2} \\ &\to (\omega_\psi^2 t_0^2)^{-3/2} \ ; \quad \omega = 0, \text{complete deconfinement} \end{aligned}$$

Lower Fig.: $\omega \neq 0$, $r = \sqrt{2/(m_c\omega)} = 0.6$ fm

T. Matsui, Ann. Phys. 196 (1989) 182

EXTENDING THE $c\bar{c}$ OSCILLATOR MODEL TO COMPLEX FREQUENCIES



Imaginary part in the potential (optical potential = dissociation) studied by

Cugnon/Gossiaux, ZPC 58 (1993) 77, 94

Koudela/Volpe, PRC 69 (2004) 054904

Harmonic oscillator with complex frequency $\omega^2 = \omega_R^2 + i\omega_I^2$

$$H_{c\bar{c}} = 2m_c + \frac{p^2}{m_c} + \frac{m_c}{4}\omega^2 x^2$$

Time evolution operator in coordinate representation is

$$U_c(r, \Delta t) = \left(\frac{m_c \omega}{4\pi i \sin(\omega \Delta t)}\right)^{3/2} \exp\left[\frac{i m_c \omega}{4} r^2 \cot(\omega \Delta t)\right]$$

Supression ratio (survival probability) can oscillate ...

Reasonable assumptions for time dependencies:

$t \leq t_0: \quad \omega_R = \omega_\psi; \ \omega_I = 0$

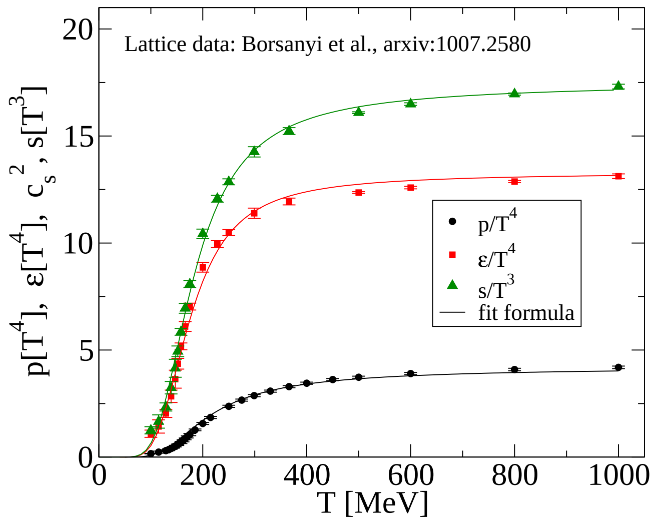
$t > t_0: \quad \omega_R = \omega_R(t) : \ \omega_I = \omega_I(t)$

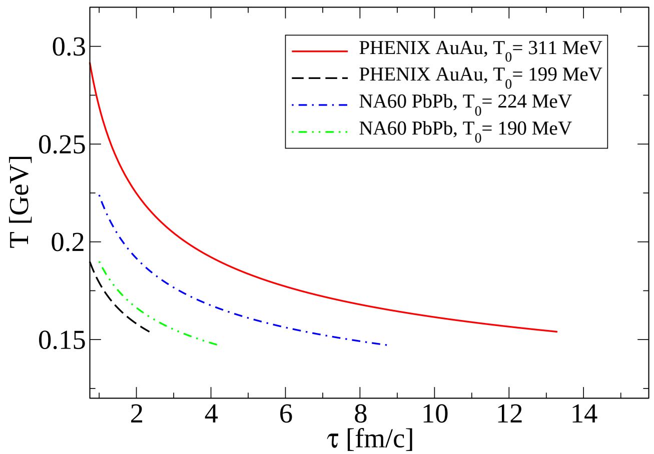
$\rightarrow$ results for the survival probability $P(t)$, see Figure

$\omega_I^2 = (\omega_I^0)^2 \gamma$, $\gamma = 1/\sqrt{1 - v_{\rm rel}^2}$ (Lorentz factor)

K. Martins, PhD Thesis (1996), unpublished.

TIME-DEPENDENCE OF COMPLEX FREQUENCY: T-EVOLUTION





$S = \text{const} = s(T(t))V(t)$

$T(t)$ from $V(t)$ - Bjorken scaling

Harmonic oscillator with time-dependent complex frequency $\omega(t)$

$$H(t) = 4\mu + \frac{p^2}{2\mu} + \frac{\mu}{2}\omega^2(t)r^2$$

Linear combination of two solutions

$$r(t) = \rho(t)\exp(\pm i\phi(t)) \ , \quad \phi(t) = \int_{t_i}^{t} \frac{dt'}{\rho^2(t')} \ .$$

$\rho(t)$ fulfills Ermakov equation (exact solutions exist)

$$\ddot{\rho}(t) + \omega^2(t)\ \rho(t) - \frac{1}{\rho^3(t)} = 0\ .$$

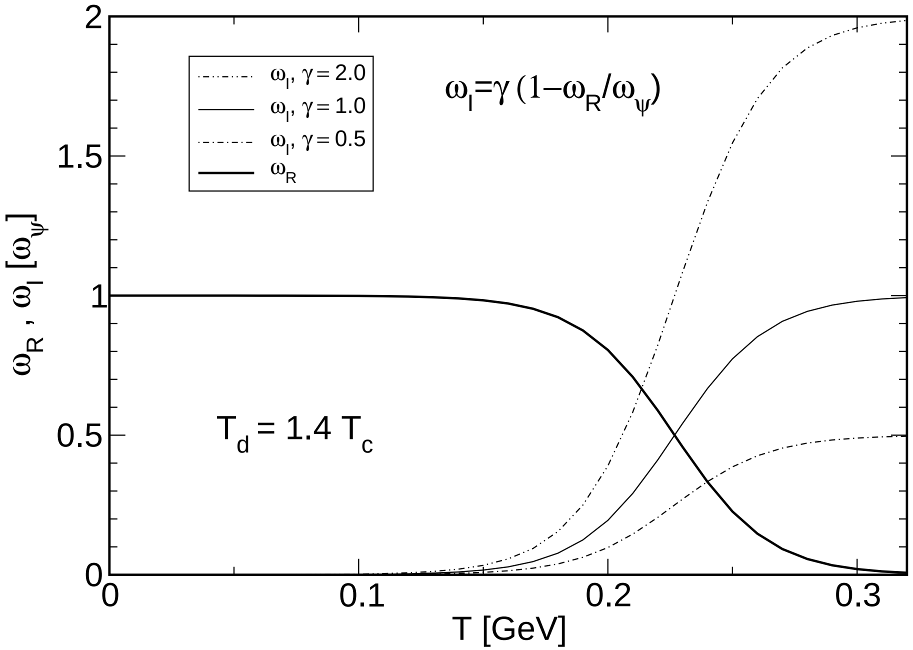
Time evolution operator in coordinate space

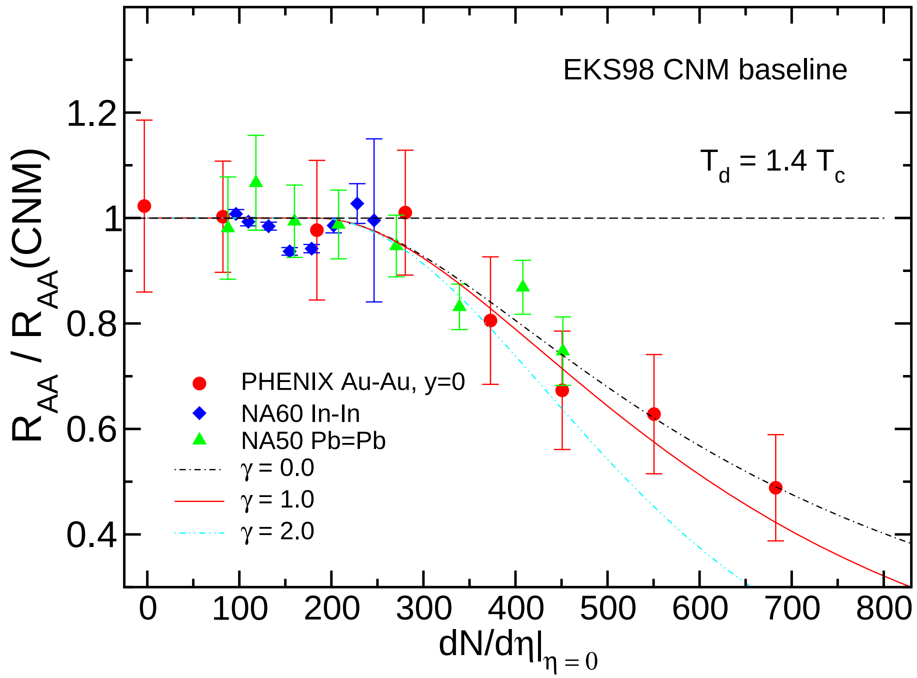
$$U(r;t_f,t_i) = \left[\frac{\mu\ \rho_f\ \rho_i^{-1}\dot{\phi}_f}{2\pi i\sin(\phi_f - \phi_i)}\right]^{3/2} \mathrm{e}^{iS_{\mathrm{cl}}} \ ,$$

Supression ratio (survival probability)

$$\frac{R_{\mathrm{AA}}}{R_{\mathrm{AA}}^{\mathrm{CNM}}} = \left|\frac{\rho_f/\rho_i}{\cos(\phi_f) + \left(\frac{\dot{\rho}_f}{\rho_f\dot{\phi}_f} + i\ \frac{\omega_\psi}{\dot{\phi}_f}\right)\ \sin(\phi_f)}\right|^3$$

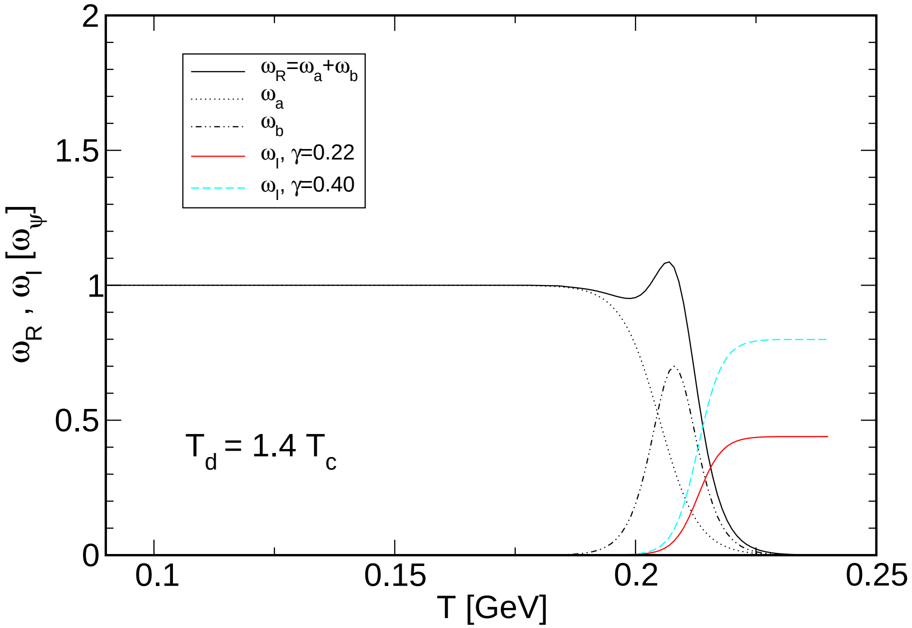
Combined description of RHIC and SPS centrality dependence

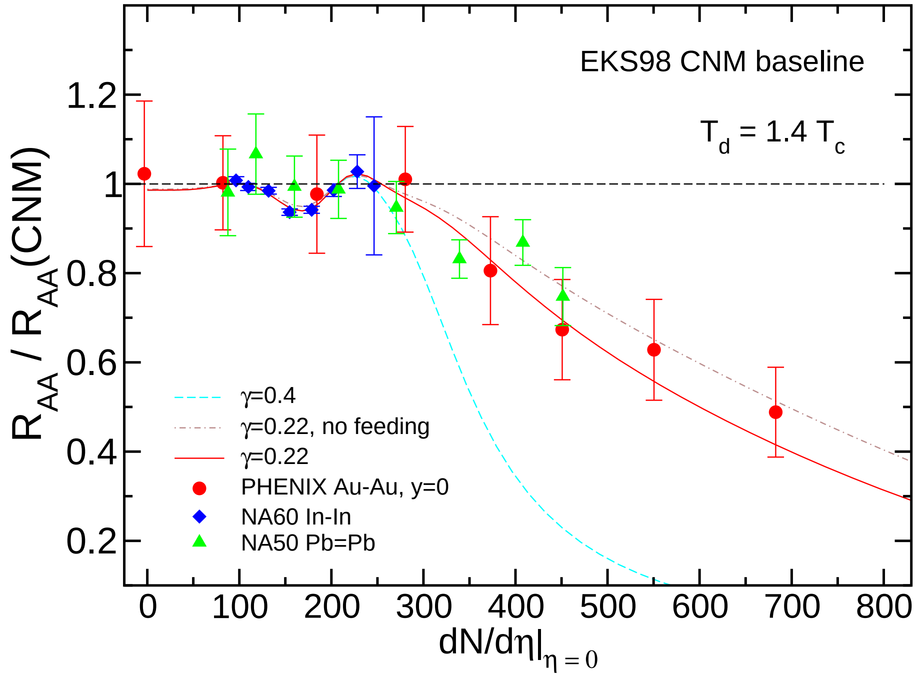




D.B., C. Peña, Nucl. Phys. Proc. Suppl. 214 (2011) 137; arxiv:1106.2519

THE NA60 IN-IN "DIP" - A HINT FOR SUBTLE CORRELATIONS?

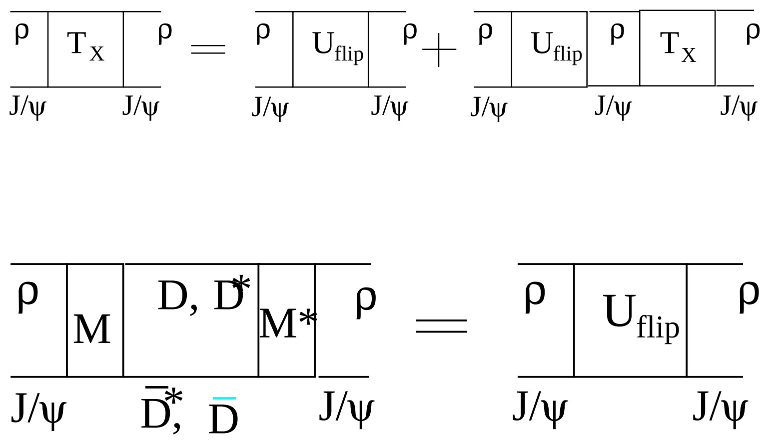


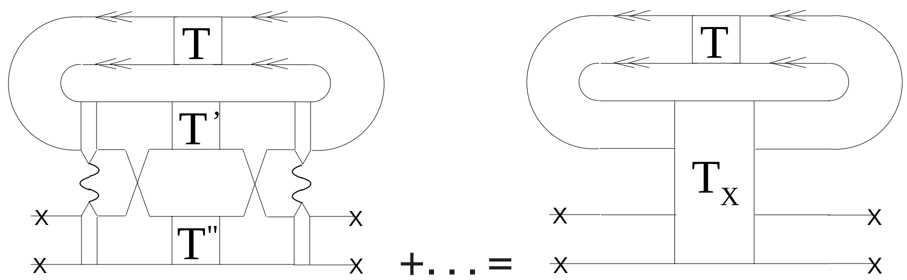


D.B., C. Peña, Nucl. Phys. Proc. Suppl. 214 (2011) 137; arxiv:1106.2519

THE NA60 IN-IN "DIP" - A CONJECTURE ...

Close to T_c a resonant J/ψ - ρ interaction gives a contribution to the plasma Hamiltonian which could lead to a "pocket" in the effective interaction potential ...





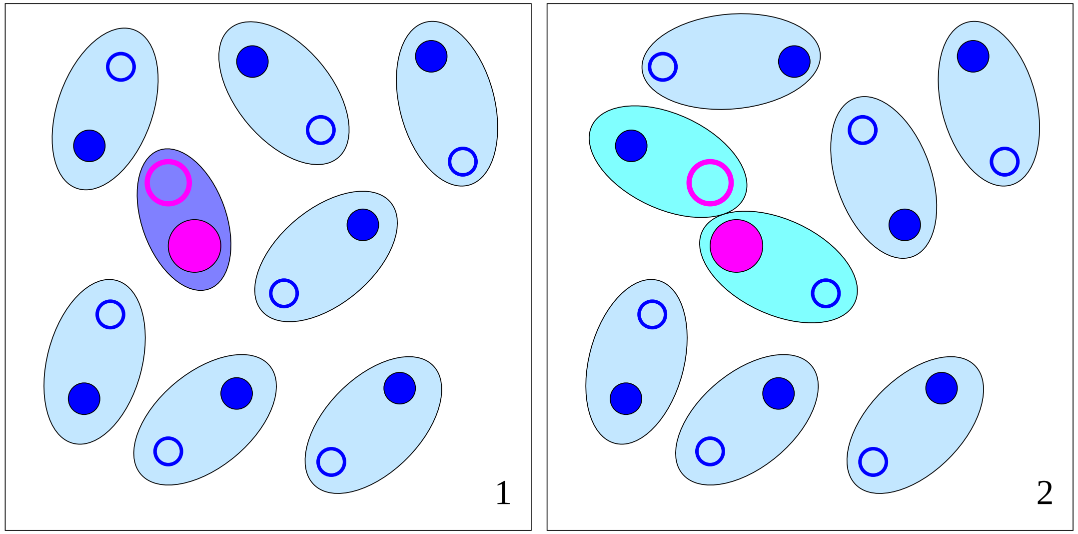
High density of ρ-like states in the medium is required for this contribution to be sizeable.

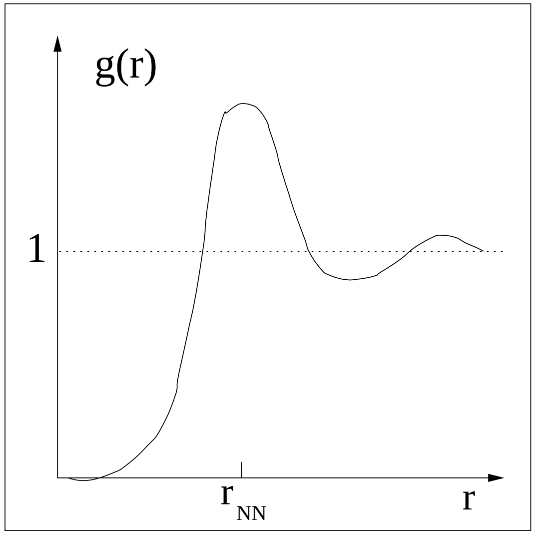
C. Peña, D.B., arxiv:1302.0831

see talk by Carlos Pena (24.07.2013)

A SNAPSHOP OF THE sQGP

The Picture: String-flip (Rearrangement) $\Longleftrightarrow$ Pair correlation





Horowitz et al. PRD (1985), D.B. et al. PLB (1985), Röpke, Blaschke, Schulz, PRD (1986)

Thoma,[hep-ph/0509154] Gelman et al., PRC 74 (2006)

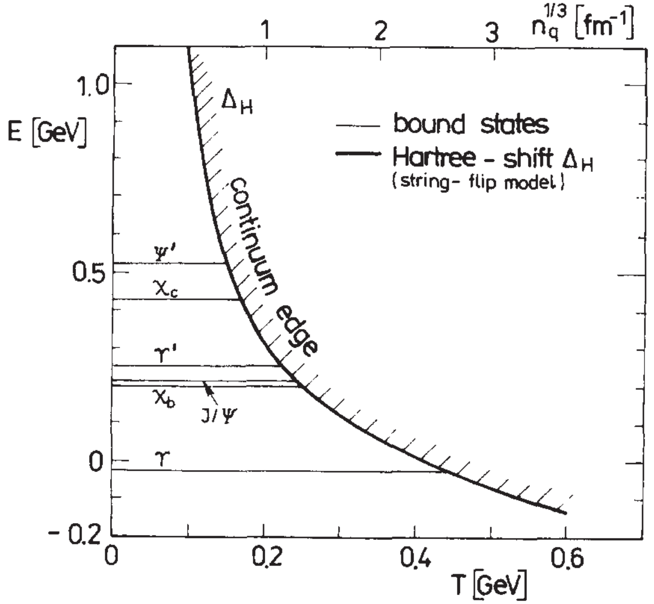
- Strong correlations present: hadronic spectral functions above T_c (lattice QCD)
- Finite width due to rearrangement collisions (higher order correlations)
- Liquid-like pair correlation function (nearest neighbor peak)

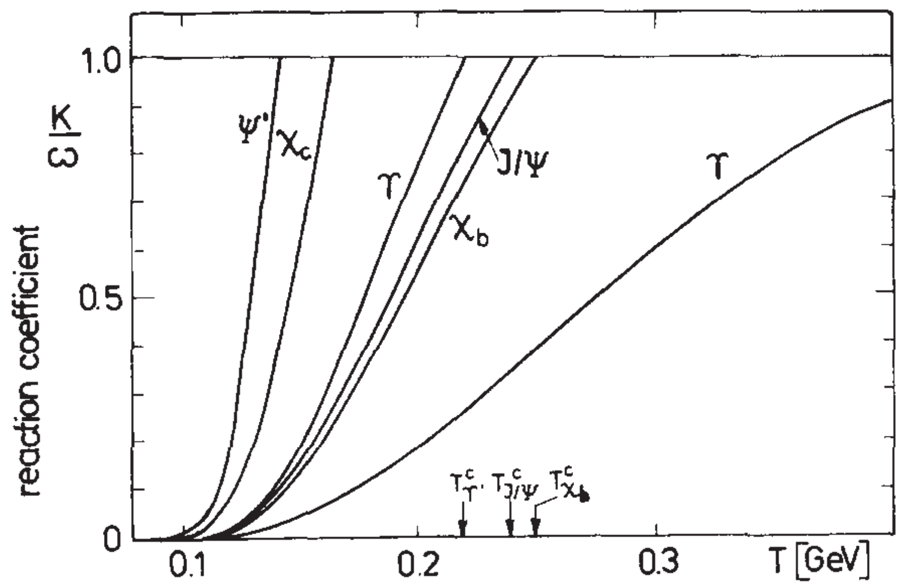
String-flip model for quarkonia suppression

Bare potential $V(r) = \sigma r - \alpha_{\rm eff}/r$ only acts within a sphere of nearest neighbors (saturation of color interaction), i.e. with probability $c(r) = n_q/3\exp(-4\pi r^3/9)$. Results in Hartree shift of continuum edge

$$\Delta^H = \int d^3r\; V(r)c(r) = (4\pi/9)^{-1/3}\Gamma(4/3)\sigma/n_q^{1/3} - (4\pi/9)^{1/3}\Gamma(2/3)\alpha_{\rm eff}n_q^{1/3}$$

Law of mass action: $n_{\bar{Q}Q}/(n_{\bar{Q}}n_Q) = (\Lambda_Q^3/3\sqrt{2})\exp[-(E_{\bar{Q}Q} - 2m_Q - \Delta^H)/T]$
reaction coefficient: $k_{\bar{Q}Q+\bar{q}q\leftrightarrow Q\bar{q}+\bar{Q}q} \propto \omega\exp(-A/T),\; A = 2m_Q + \Delta^H - E_{\bar{Q}Q}$

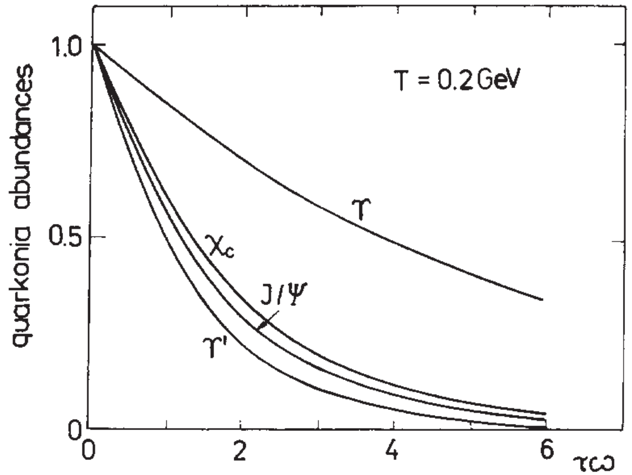




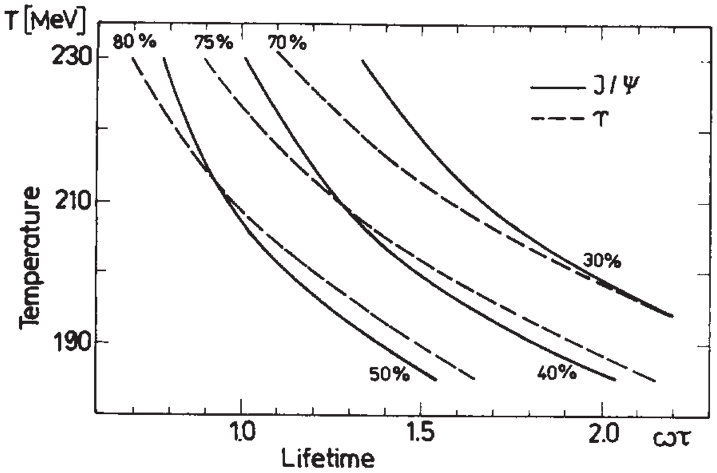
[Röpke, DB, Schulz, PLB **202**, 479 (1988)]

String-flip model for quarkonia suppression (II)

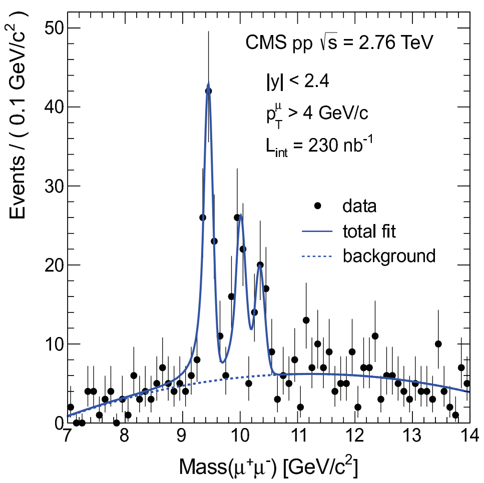
"Boiling-off" of Quarkonia

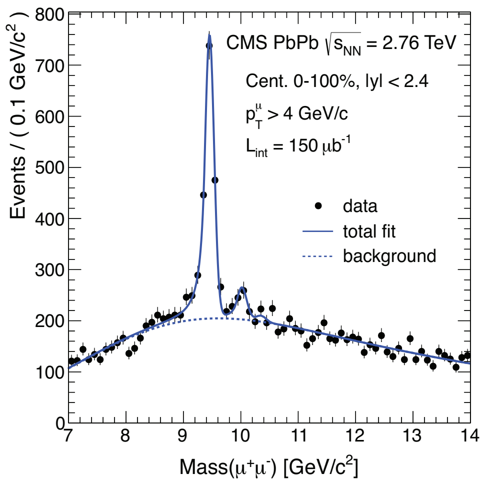


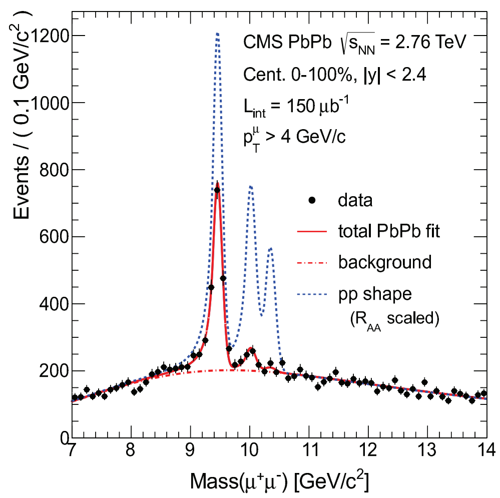
Relative suppression of Quarkonia



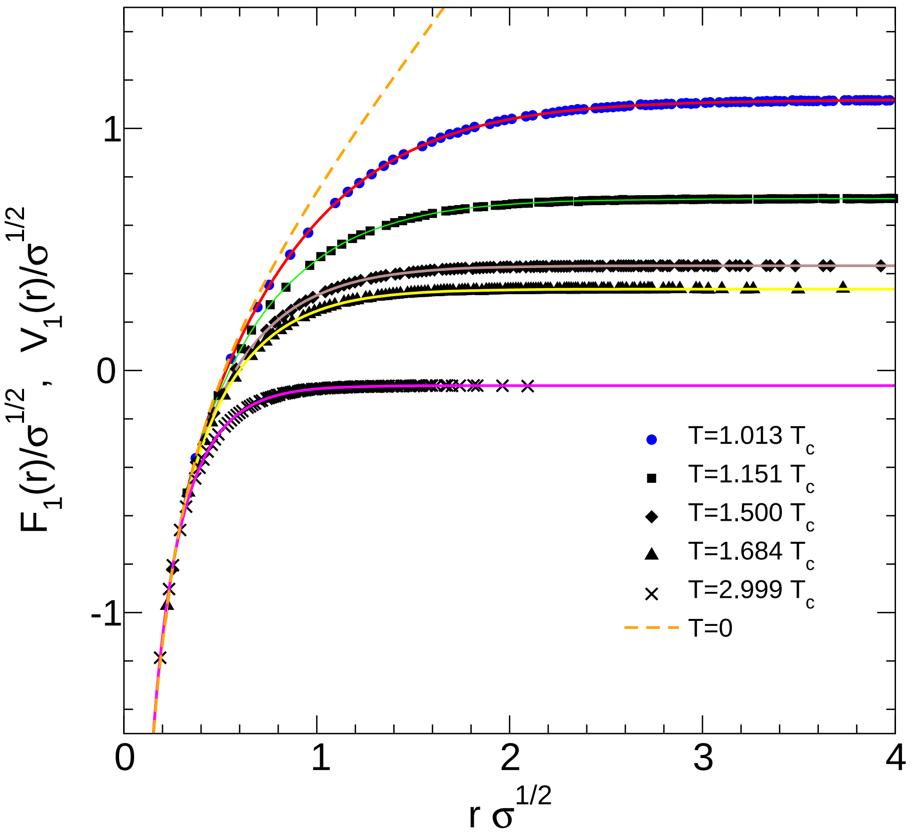
Bottomonium suppression at LHC (CMS collaboration, preliminary)







HEAVY QUARK POTENTIAL FROM LATTICE QCD



Blaschke, Kaczmarek, Laermann, Yudichev, EPJC 43, 81 (2005); [hep-ph/0505053]

Color-singlet free energy F_1 in quenched QCD

$$\langle \mathrm{Tr}[L(0)L^\dagger(r)]\rangle = \exp[-F_1(r)/T]$$

Long- and short- range parts

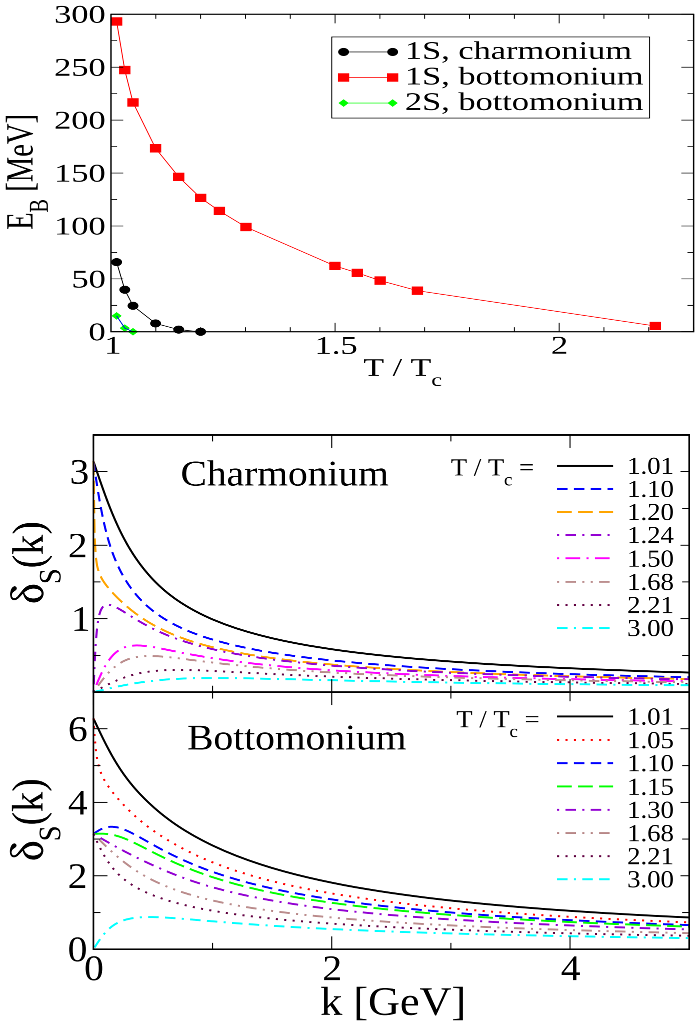
$$F_1(r,T) = F_{1,\mathrm{long}}(r,T) + V_{1,\mathrm{short}}(r)e^{-(\mu(T)r)^2}$$

$$\begin{aligned} F_{1,\mathrm{long}}(r,T) &= \text{'screened' confinement pot.} \\ V_{1,\mathrm{short}}(r) &= -\frac{4}{3}\frac{\alpha(r)}{r}, \ \alpha(r) = \text{running coupl.} \quad (1) \end{aligned}$$

Quarkonium ($Q\bar{Q}$)	1S	1P$_1$	2S
Charmonium ($c\bar{c}$)	J/ψ(3097)	χ_{c1}(3510)	ψ' (3686)
Bottomonium ($b\bar{b}$)	Υ (9460)	χ_{b1} (9892)	Υ' (10023)

In-medium potential $\Longrightarrow$ Schrödinger Eqn. $\Longrightarrow$ Bound/scatt. states $\Longrightarrow$ Mott effect

Schroedinger eqn: bound & scattering states



Quarkonia bound states at finite T:

$$[-\nabla^2/m_Q + V_{\rm eff}(r,T)]\psi(r,T) = E_B(T)\psi(r,T)$$

Binding energy vanishes $E_B(T_{\rm Mott}) = 0$: Mott effect

Scattering states:

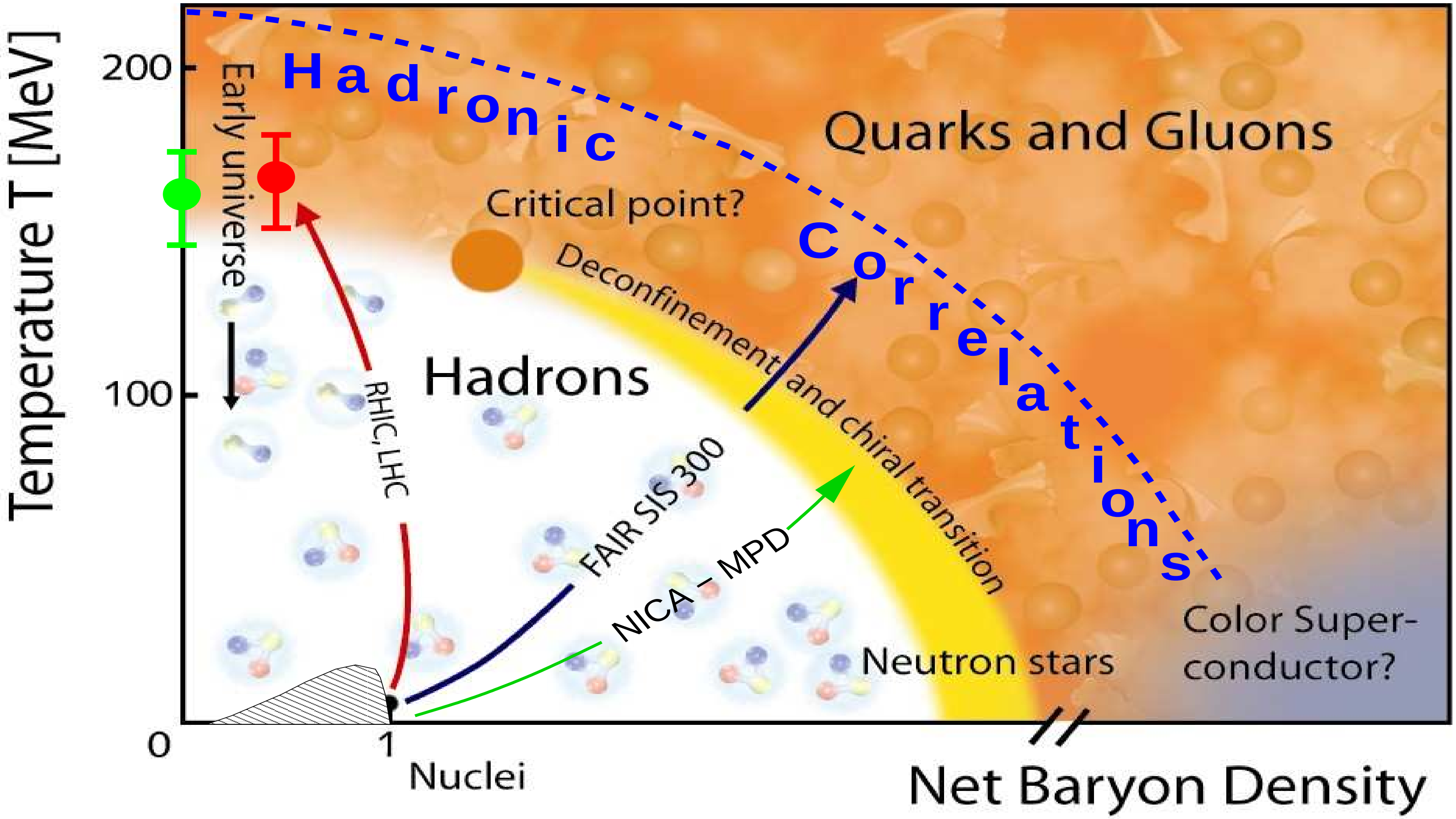
$$\frac{d\delta_S(k,r,T)}{dr} = -\frac{m_Q V_{\rm eff}}{k}\sin(kr + \delta_S(k,r,T))$$

Levinson theorem:

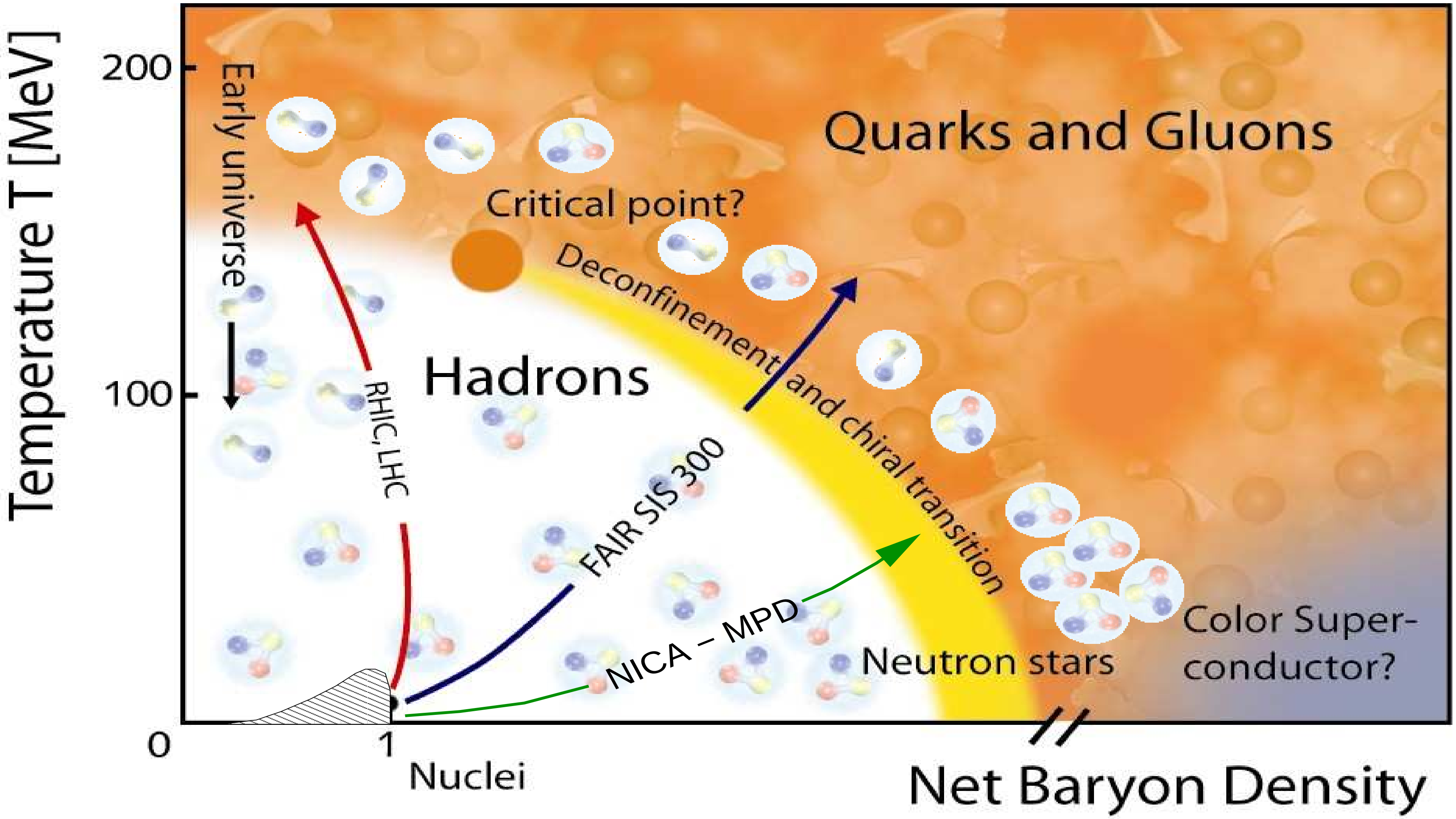
Phase shift at threshold jumps by π when bound state $\rightarrow$ resonance at $T = T_{\rm Mott}$ (Mott effect)

Blaschke, Kaczmarek, Laermann, Yudichev EPJC 43, 81 (2005); [hep-ph/0505053]

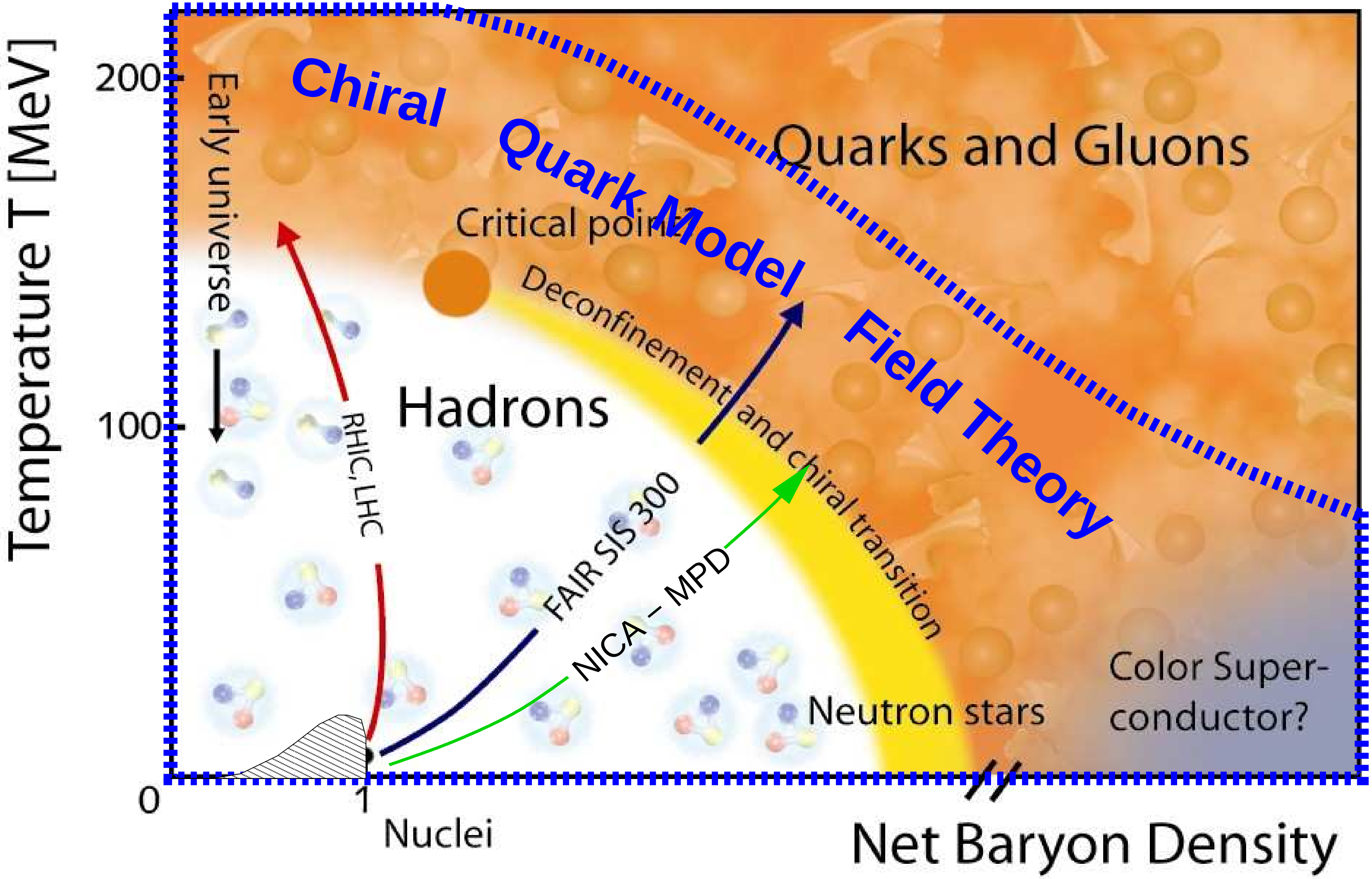
HADRONIC CORRELATIONS IN THE PHASEDIAGRAM OF QCD



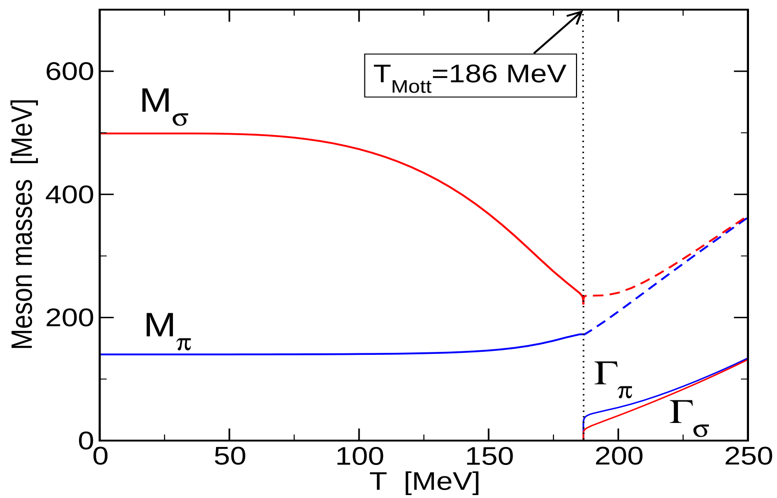
HADRONIC CORRELATIONS IN THE PHASEDIAGRAM OF QCD

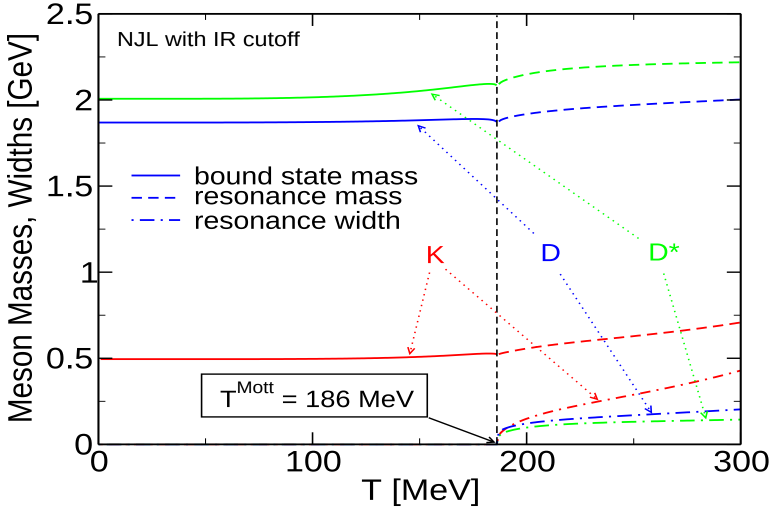


PHASEDIAGRAM OF DEGENERATE QUARK MATTER

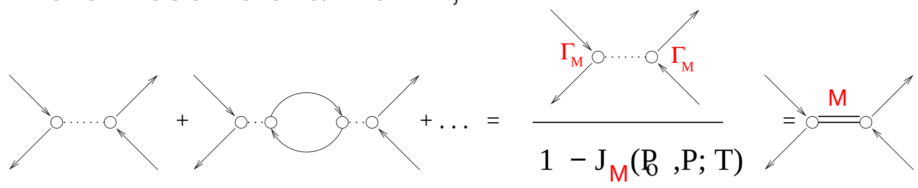


MOTT EFFECT: NJL MODEL PRIMER





RPA-type resummation of quark-antiquark scattering in the mesonic channel M,



defines Meson propagator ($J_M = 2G\Pi_M$)

$$D_M(P_0, P; T) \sim [1 - J_M(P_0, P; T)]^{-1},$$

by the complex polarization function J_M
$\rightarrow$ Breit-Wigner type spectral function

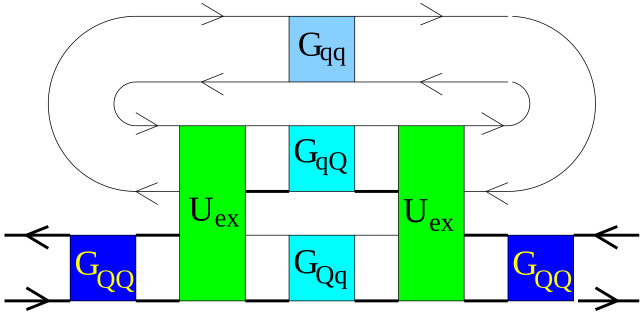
$$\mathcal{A}_M(P_0, P; T) = \frac{1}{\pi}\mathrm{Im}\, D_M(P_0, P; T) \sim \frac{1}{\pi}\frac{\Gamma_M(T)M_M(T)}{(s - M_M^2(T))^2 + \Gamma_M^2(T)M_M^2(T)}$$

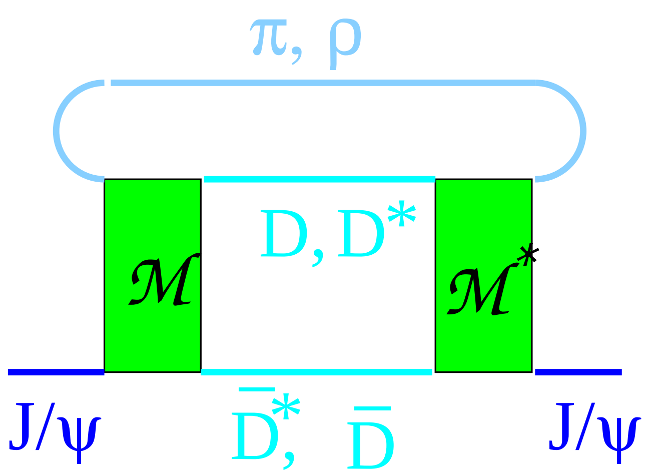
For $T < T_{\rm Mott}$: $\Gamma \to 0$, i.e. bound state
$\mathcal{A}_M(P_0, P; T) = \delta(s - M_M^2(T))$

Light meson sector:
Blaschke, Burau, Volkov, Yudichev: EPJA **11** (2001) 319

Charm meson sector:
Blaschke, Burau, Kalinovsky, Yudichev,
Prog. Theor. Phys. Suppl. **149** (2003) 182

QUANTUM KINETIC APPROACH TO J/ψ BREAKUP ($\mu_B \approx 0$)





$\tau^{-1}(p) = \Gamma(p) = \Sigma^{>}(p) \mp \Sigma^{<}(p)$

$$\Sigma^{\gtrless}(p,\omega) = \int_{p'}\int_{p_1}\int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} |\mathcal{M}|^2 \, G_\pi^{\lessgtr}(p') \, G_{D_1}^{\gtrless}(p_1) \, G_{D_2}^{\gtrless}(p_2)$$

$G_h^{>}(p) = [1 \pm f_h(p)] A_h(p)$ and $G_h^{<}(p) = f_h(p) A_h(p)$

low density approximation for the final states

$f_D(p) \approx 0 \quad \Rightarrow \quad \Sigma^{<}(p) \approx 0$

$$\tau^{-1}(p) = \int_{p'}\int_{p_2}\int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} |\mathcal{M}|^2 \, f_\pi(p') \, A_\pi(p') \, A_{D_1}(p_1) \, A_{D_2}(p_2)$$

$$\frac{d\sigma}{dt} = \frac{1}{16\pi} \frac{|\mathcal{M}(s,t)|^2}{\lambda(s, M_\psi^2, s')} \, ,$$

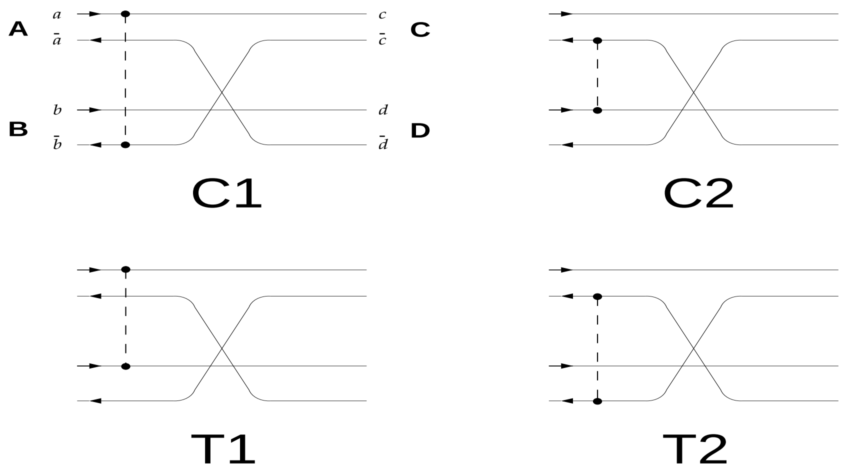
$$\tau^{-1}(p) = \int \frac{d^3\mathbf{p}'}{(2\pi)^3} \int ds' \quad f_\pi(\mathbf{p}', s') \, A_\pi(s') v_{\rm rel} \, \sigma^*(s)$$

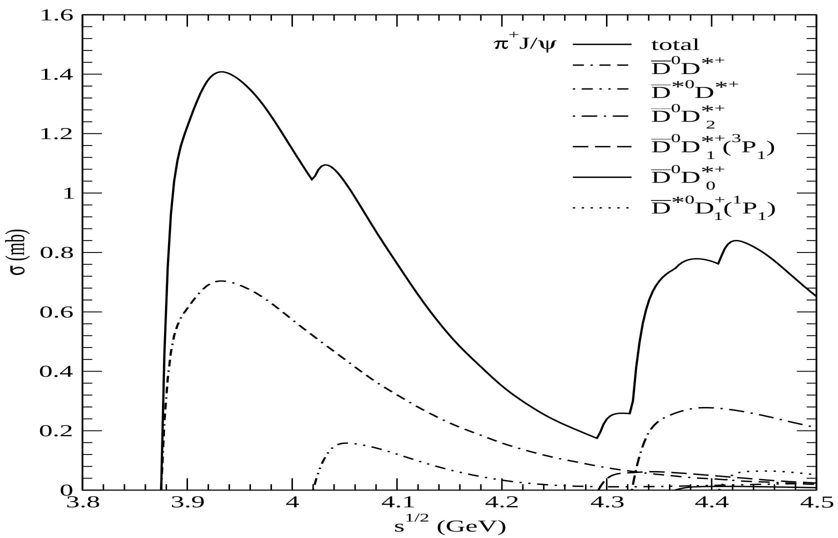
In-medium breakup cross section

$$\sigma^*(s) = \int ds_1 \, ds_2 \, A_{D_1}(s_1) \, A_{D_2}(s_2) \, \sigma(s; s_1, s_2)$$

Medium effects in spectral functions A_h and $\sigma(s; s_1, s_2)$

Quark Rearrangement I: NRQM Born diagrams





Short history:

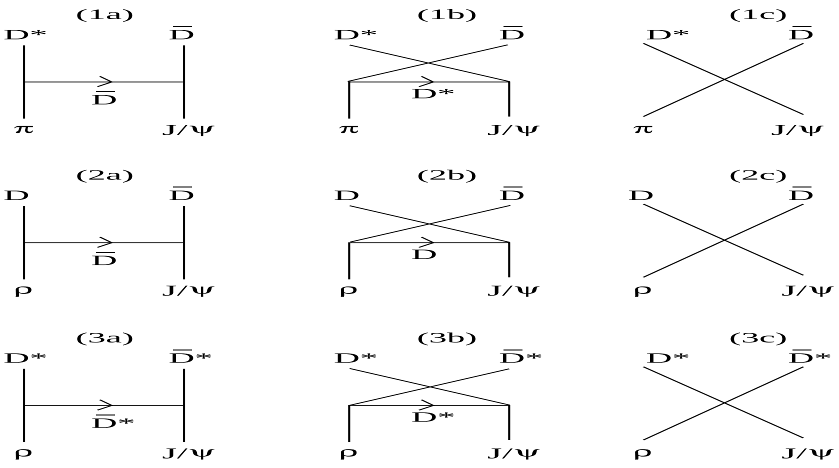
- Quark (+gluon) exchange model of short-range NN int.
  Holinde, PLB 118 (1982) 266; ...
- Born approx. to quark exchange in meson-meson scatt.
  Barnes, Swanson: PRD 46 (1992) 131
- Appl. to Charmonium dissociation: J/ψ+π $\to D + \bar{D}, \ldots$
  Martins, D.B., Quack: PRC 51 (1995) 2723
- Extension to other light mesons and excited charmonia
  Barnes, Swanson, Wong, Xu: PRD 68 (2003) 014903

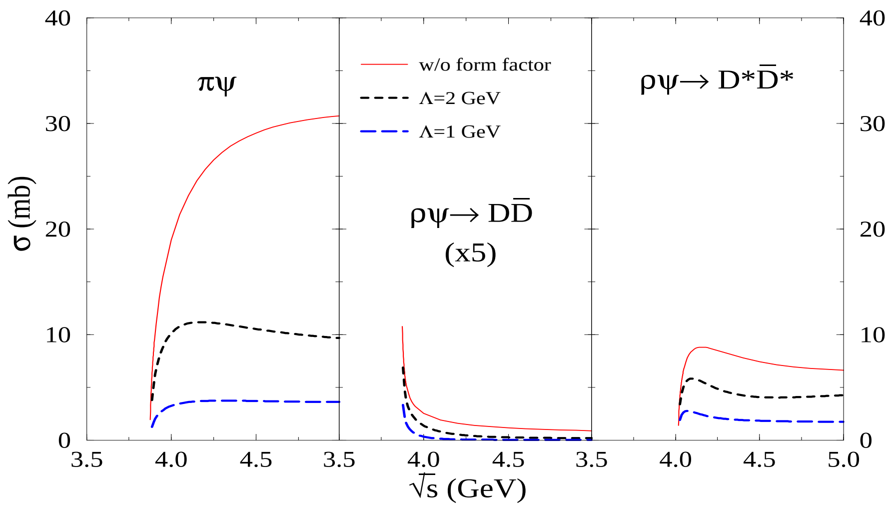
(C)apture Diagrams:
$\to$ interaction can be absorbed into the 'ladder' of a meson
(T)ransfer Diagrams:
$\to$ interaction between quarks from different mesons

Comments:

- Post-prior ambiguity for capture diagrams
- Interaction in capture and transfer diagrams different?
- Chiral symmetry restoration: problem in HFS term

QUARK REARRANGEMENT II: CHIRAL LAGRANGIAN APPROACH





Short history:

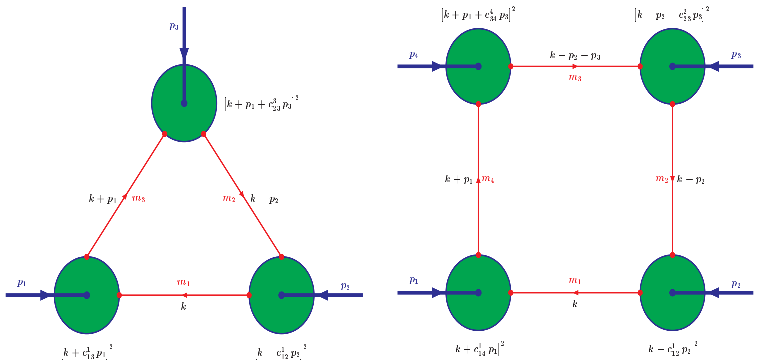
- Meson exchange model for NN interaction
  Yukawa(1935); Walecka, Ann. Phys. 83 (1974) 491; ...
- Application to charmonium diss: J/ψ+$\pi, \rho \rightarrow D + \bar{D}, \ldots$
  Matinyan, Müller, PRC 63 (1998) 2994
- Inclusion of formfactors for the meson-hadron vertices
  Haglin, PRC 61 (2000) 031902
  Lin, Ko, PRC 62 (2000) 034903
  Oh, Song, Lee, PRC 63 (2001) 034901
  D.B., Grigorian, Kalinovsky, hep-ph/0808.1705

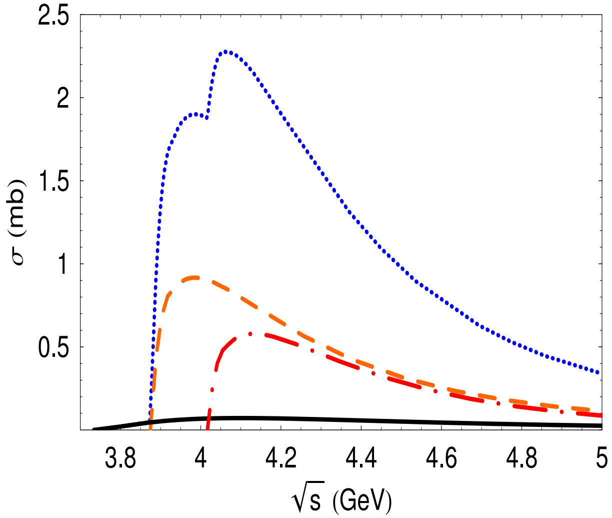
Meson exchange Diagrams:
$\rightarrow$ Transfer diagrams: mesonic 'ladder' replaced by Born term
Contact Diagrams:
$\rightarrow$ Capture diagrams: BS eq. at quark-meson vertex

Comments:

- Formfactors ad hoc, not part of the χL approach
- Quark substructure effects absent, or hidden in FF
- Finite $T,\ \mu$ (and momentum-) behavior of vertices ?

QUARK REARRANGEMENT III: RQM (DSE-BASED)





Short history:

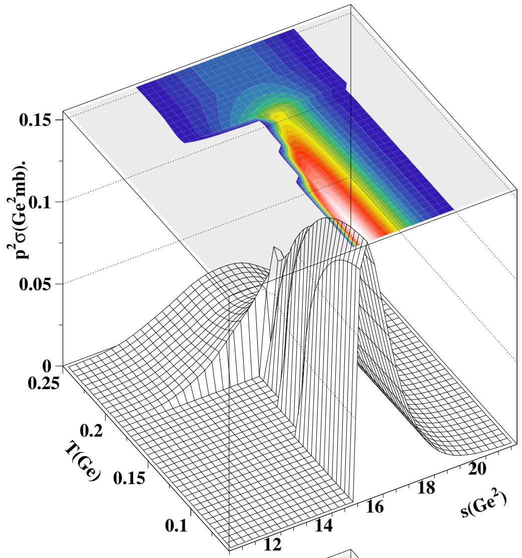
- Dyson-Schwinger approach to hadronic processes
  Roberts, Williams, PPNP 33 (1994) 477
- Application to D-mesons
  Ivanov, Kalinovsky, Roberts, PRD 60 (1999) 034018
- Calculation of J/ψ+ $\pi \;\rightarrow\; D + \bar{D}$
  D.B., Burau, Ivanov, Kalinovsky, Tandy, hep-ph/0002047
  Ivanov, Körner, Santorelli, PRD 70 (2004) 014005
  Bourque, Gale, PRC 80 (2009) 015204

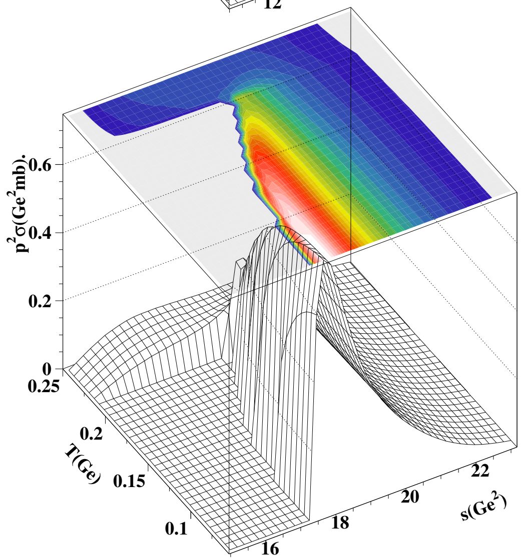
(Double) Triangle Diagrams:
$\rightarrow$ Meson exchange $\rightarrow$ Transfer diagrams
Box Diagrams:
$\rightarrow$ Contact Diagrams $\rightarrow$ Capture diagrams

Comments:

- Post-prior problem solved: covariant, chiral quark model
- Quark substructure effects in triangle and box diagrams
- BS amplitudes and quark propagators encode
  - Chiral restoration/ deconfinement
  - Mott effect: bound state dissociation

IN-MEDIUM J/ψ BREAKUP BY π AND ρ IMPACT





Approximation: $\sigma(s; s_1, s_2) \approx \sigma^{\rm vac}(s; s_1, s_2)$

Variety of models exists for $\sigma^{\rm vac}(s; s_1, s_2)$, use a relativistic one

Blaschke, et al. Heavy Ion Phys. **18** (2003) 49;
Ivanov, et al. PRD **70** (2004) 014005

Spectral function for D-mesons as Breit-Wigner

$$A_h(s) = \frac{1}{\pi} \frac{\Gamma_h(T)\, M_h(T)}{(s - M_h^2(T))^2 + \Gamma_h^2(T) M_h^2(T)} \longrightarrow \delta(s - M_h^2)$$

resonance $\Leftarrow$ Mott-effect $\Leftarrow$ bound state

See NJL model calculations at finite temperature,

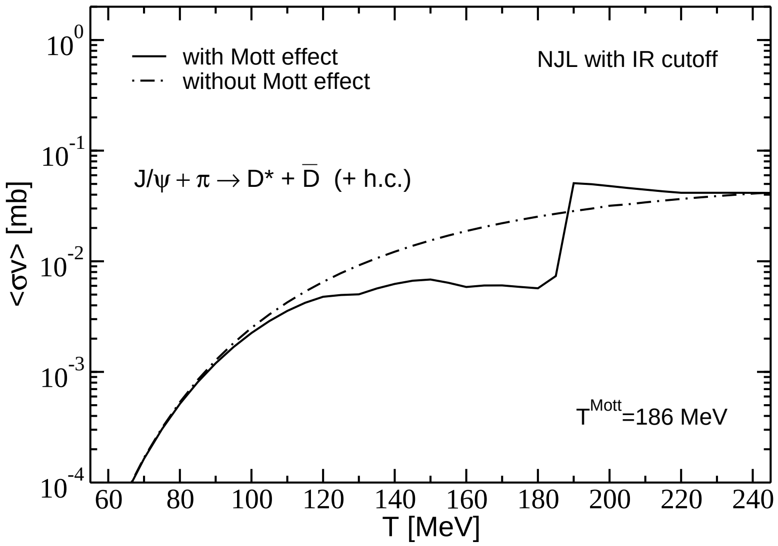
Blaschke et al.: Eur. Phys. J. **A 11** (2001) 319
Hüfner et al.: Nucl. Phys. **A 606** (1996) 260
Blaschke et al.: Nucl. Phys. **A 592** (1995) 561

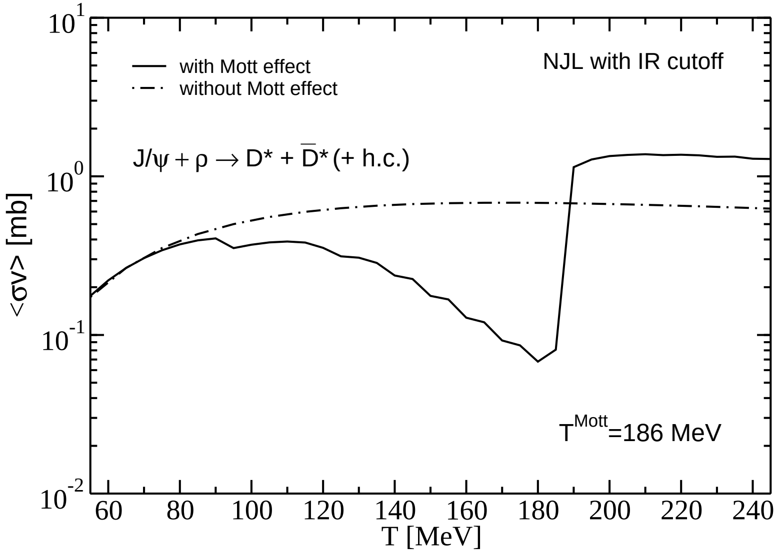
Behaviour above the Mott temperature ($T \sim T_h^{\rm Mott}$)

$$\Gamma_h(T) \sim (T - T_h^{\rm Mott})^{1/2}\ \Theta(T - T_h^{\rm Mott}) ,$$
$$M_h(T) = M_h(T_h^{\rm Mott}) + 0.5\, \Gamma_h(T)$$

NJL model with IR cutoff: $T_h^{\rm Mott} = 186$ MeV universal

J/ψ DISSOCIATION RATE IN A π/ρ RESONANCE GAS





Dissociation rate for a J/ψ at rest in a hot resonance gas ($h = \pi, \rho$)

$$\tau^{-1}(T) = \tau_\pi^{-1}(T) + \tau_\rho^{-1}(T)$$

$$\tau_h^{-1}(T) = \int \frac{d^3p}{(2\pi)^3} \int ds' A_h(s';T) f_h(p,s';T) j_h(p,s') \sigma_h^*(s;T)$$

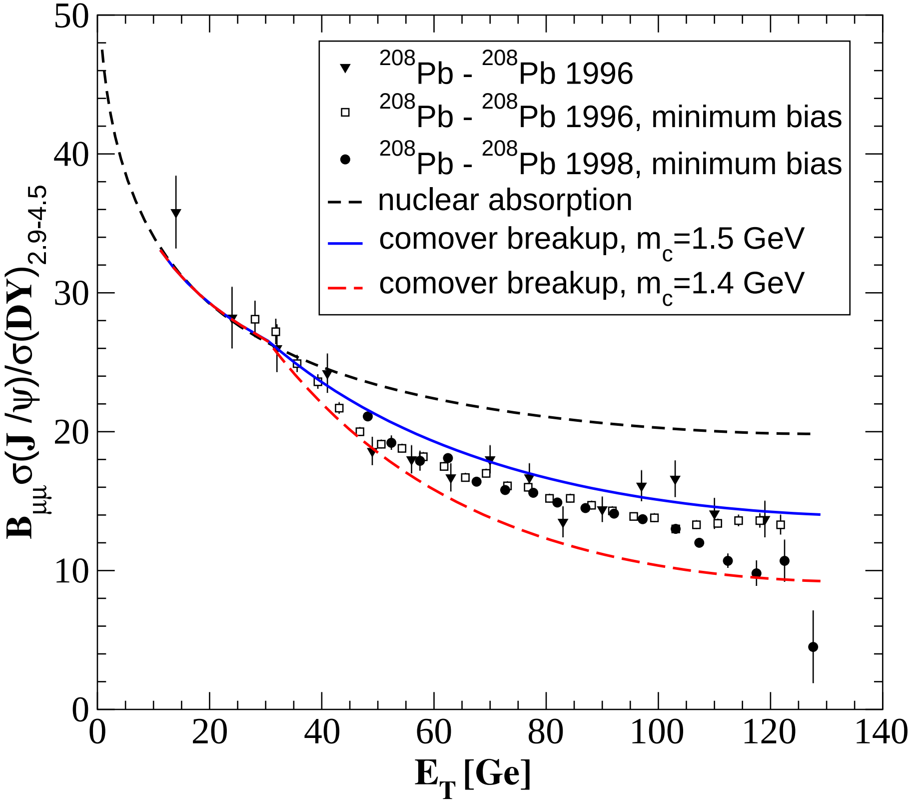
$$= \langle \sigma_h^* v_{\rm rel} \rangle n_h(T) \ ,$$

$$f_h(p,s;T) = g_h \{\exp[(\sqrt{p^2+s} - \mu)/T] - 1\}^{-1}$$

$$s(p,s') = s' + M_\psi^2 + 2M_\psi \sqrt{p^2+s'}$$

- Masses slightly rising below $T^{\rm Mott}$
  $\Rightarrow$ reduction of breakup rate
- Mott-effect for intermediate states at $T^{\rm Mott}$
  $\Rightarrow$ breakup enhancement - “subthreshold” process
- Structure in the breakup rate at $T = T^{\rm Mott}$
- Additional J/ψ absorption channel opens
  $\Rightarrow$ “anomalous” suppression

"Anomalous" J/ψ suppression at CERN-SPS



Blaschke, Burau, Kalinovsky, Proc. HQP-5, Dubna (2000); [nucl-th/0006071]

Modified Glauber model calculation

Wong, PRL**76** (1996) 196;

Martins, Blaschke, Proc. HQP-4; [hep-ph/9802250]

$$S(E_T) = S_N(E_T)\exp\left[-\int_{t_0}^{t_f} dt\, \tau^{-1}(n(t))\right] = S_N(E_T)\exp\left[\int_{n_0(E_T)}^{n_f} dn < \sigma^* v_{\rm rel} >\right]$$

Nucl. abs: $S_N(E_T) = 18 + 36\ \exp(-0.26\sqrt{E_T})$

Longitudinal expansion: $n(t) = n_0(E_T)t_0/t$

Impact parameter representation of $n_0(E_T)$:

$E_T(b)/\mathrm{MeV} = 130 - b/\mathrm{fm}$

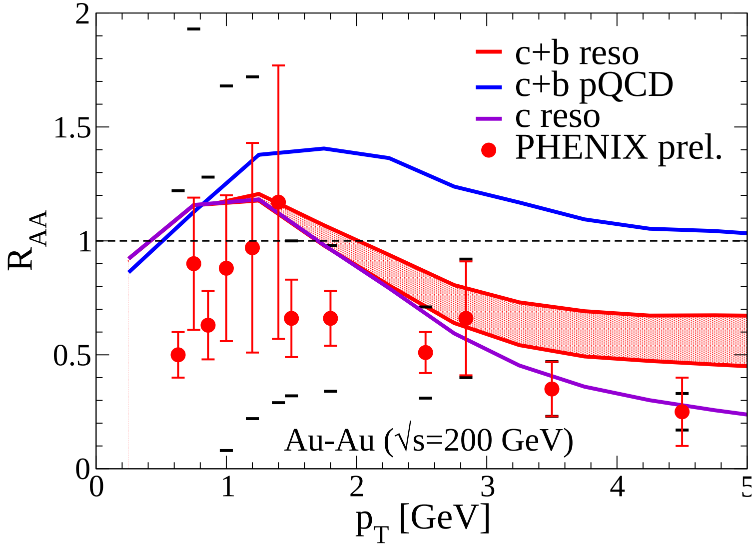
$n_0(b)/\mathrm{fm}^{-3} = 1.2\sqrt{1-(b/10.8\ \mathrm{fm})^2}$.

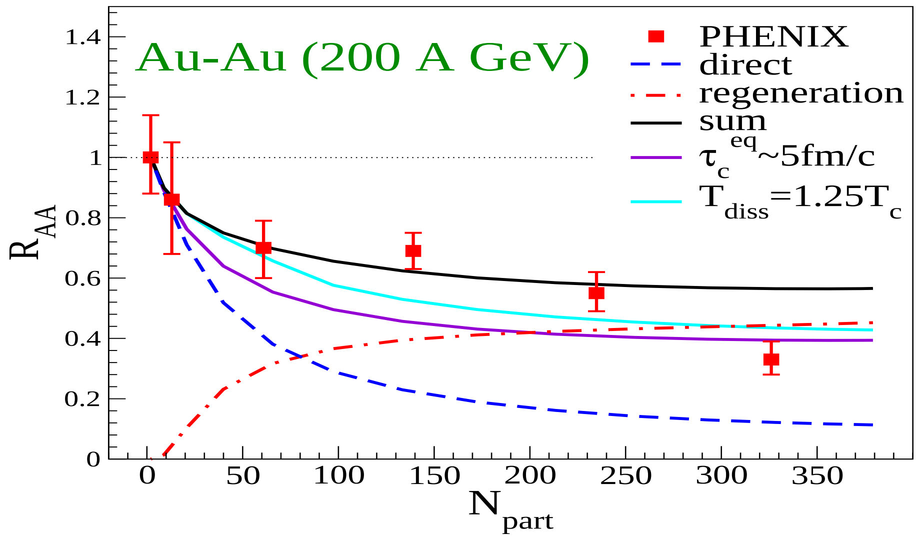
Threshold: Mott effect for D-Mesons

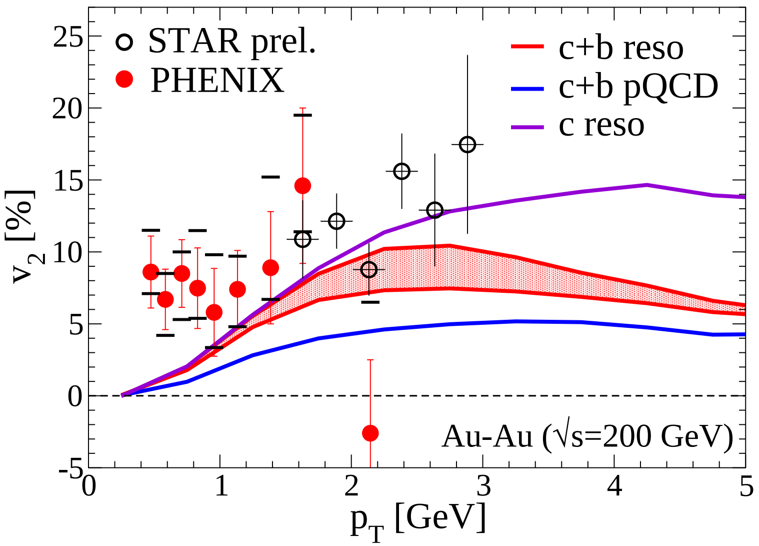
More detailed description: additional resonances, gain processes (D-fusion), HIC simulation

Grandchamp et al., PL B523 (2001); NP A709 (2002) 415; PRL 92 (2004) 212301; J. Phys. G 30 (2004) S1355.

Charm and charmonium production @ RHIC







Recombination of open charm (regeneration of ψ)

$$dN_\psi/dt = -\Gamma_\psi[N_\psi - N_\psi^{eq}(T)]$$

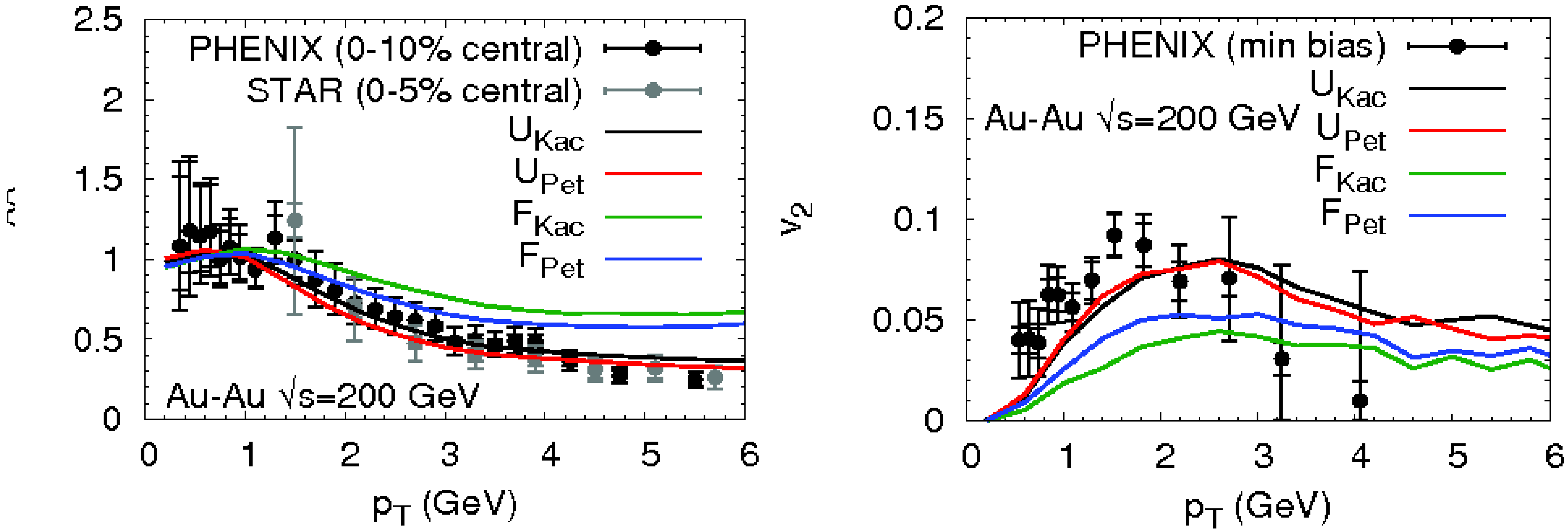
Hees, Mannarelli, Greco, Rapp, PRL 100, 192301 (2008)

Nuclear modification factor R_{AA} and elliptic flow v_2 of semileptonic $D-$ and $B-$ meson decay-electrons in $b = 7$ fm Au-Au ($\sqrt{s} = 200$ GeV) collisions at RHIC

$\Longleftarrow$ **Hees, Greco, Rapp, PRC 73, 034913 (2006)**

R_{AA} and Flow from non-photonic e^- at RHIC

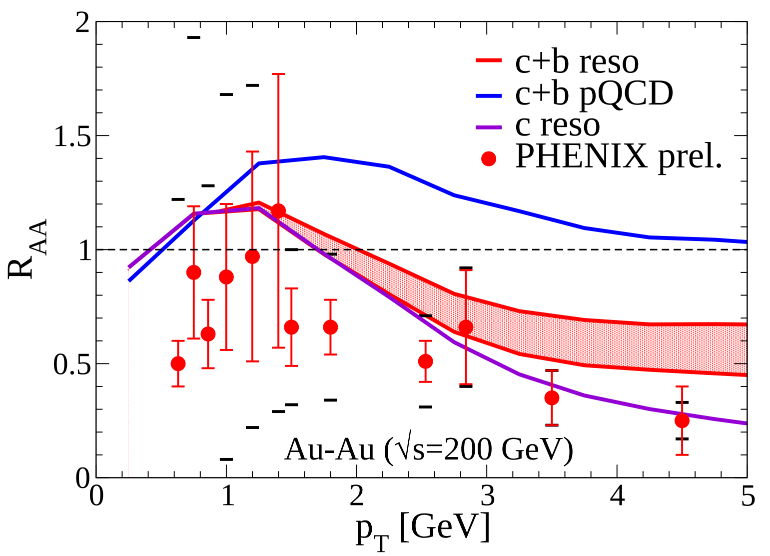
- quark coalescence+fragmentation $\rightarrow D/B \rightarrow e + X$

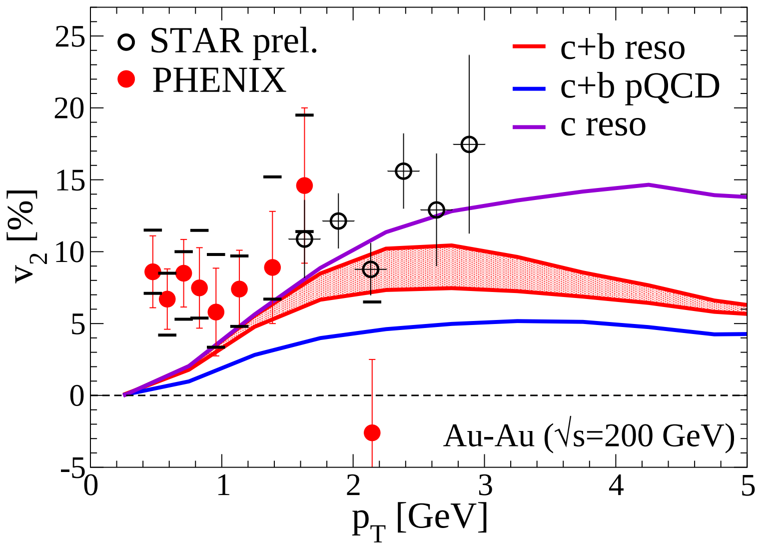


- coalescence crucial for description of data
- increases both, R_{AA} and v_2 $\Leftrightarrow$ "momentum kick" from light quarks!
- "resonance formation" towards T_c $\Rightarrow$ coalescence natural

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

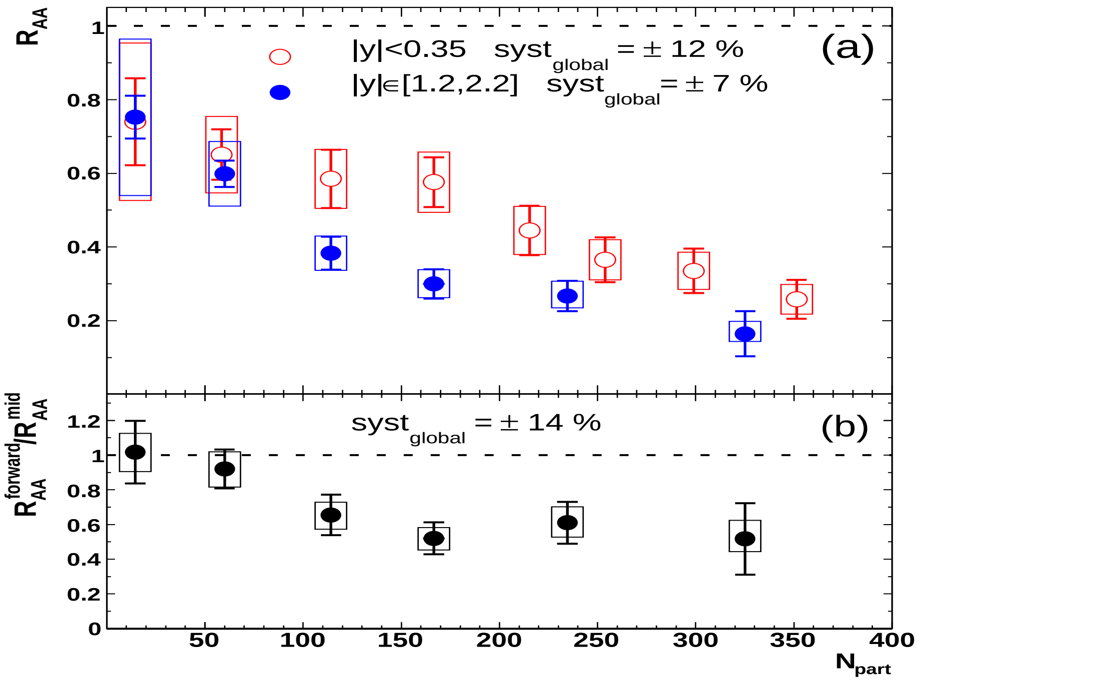
Charm and charmonium production @ RHIC





Nuclear modification factor R_{AA} and elliptic flow v_2 of semileptonic $D-$ and $B-$ meson decay-electrons in $b = 7$ fm Au-Au ($\sqrt{s} = 200$ GeV) collisions at RHIC $\Longleftarrow$

J/ψ suppression in forward stronger than in central rapidity: signal for charmonium regeneration? $\downarrow$

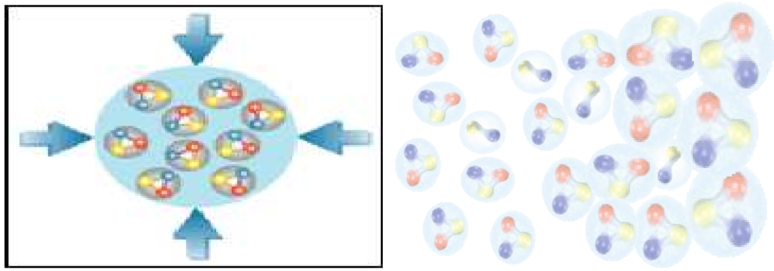


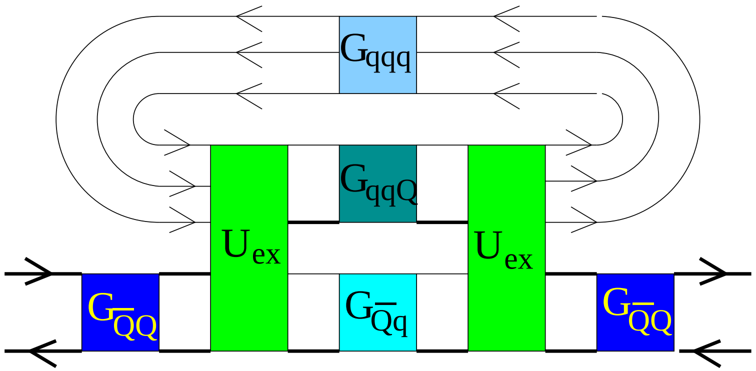
Hees, Greco, Rapp, PRC 73, 034913 (2006)

Adare et al. (PHENIX Collaboration); nucl-ex/0611020

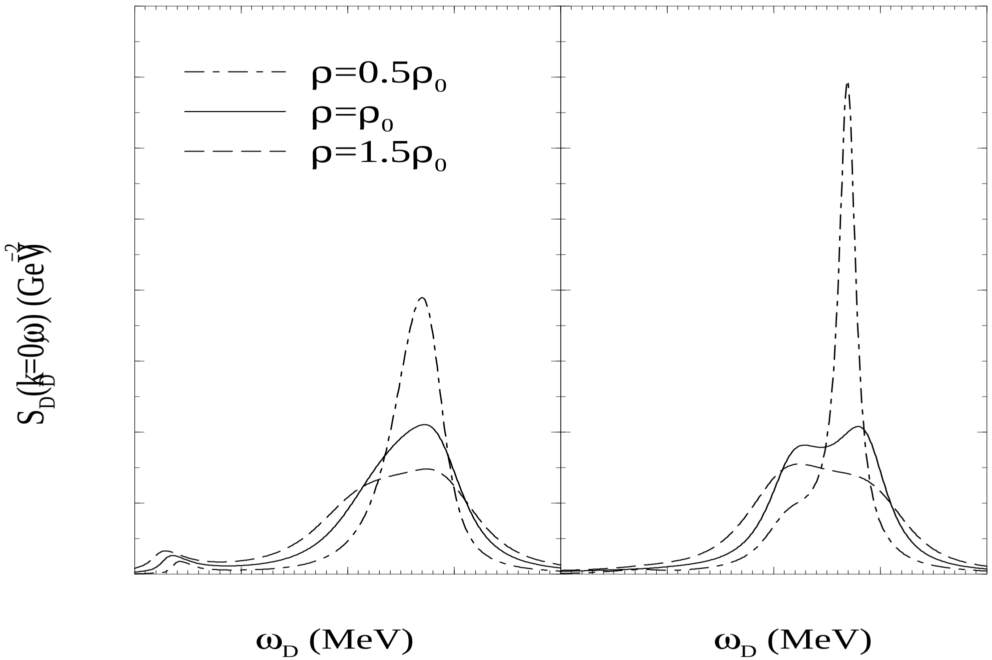
CHARM AND CHARMONIUM PRODUCTION @ FAIR-CBM

J/ψ dissociation process in dense baryonic matter at FAIR-CBM: spectral functions for open charm hadrons (D-meson, Λ_c) are essential inputs! $\Longleftarrow$



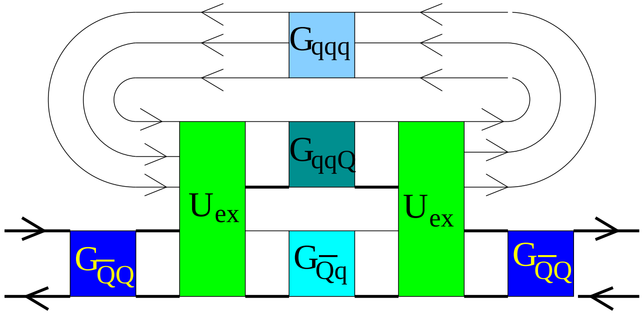


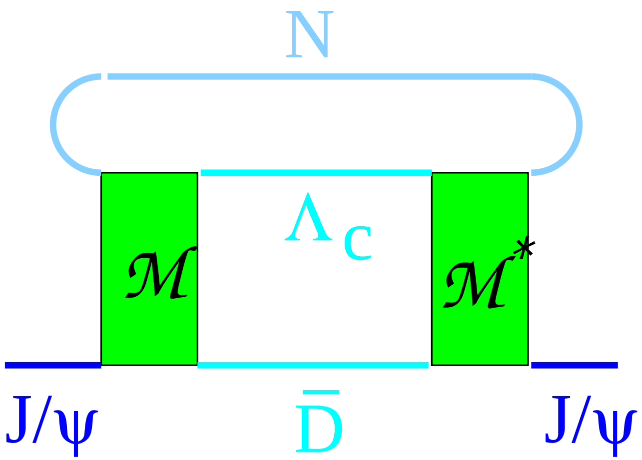
D-meson spectral function in cold dense nuclear matter from a G-matrix approach $\downarrow$



Tolos et al., EPJC (2005); nucl-th/0501151

QUANTUM KINETICS OF J/ψ DISSOCIATION @ CBM ($\mu_B \neq 0$)

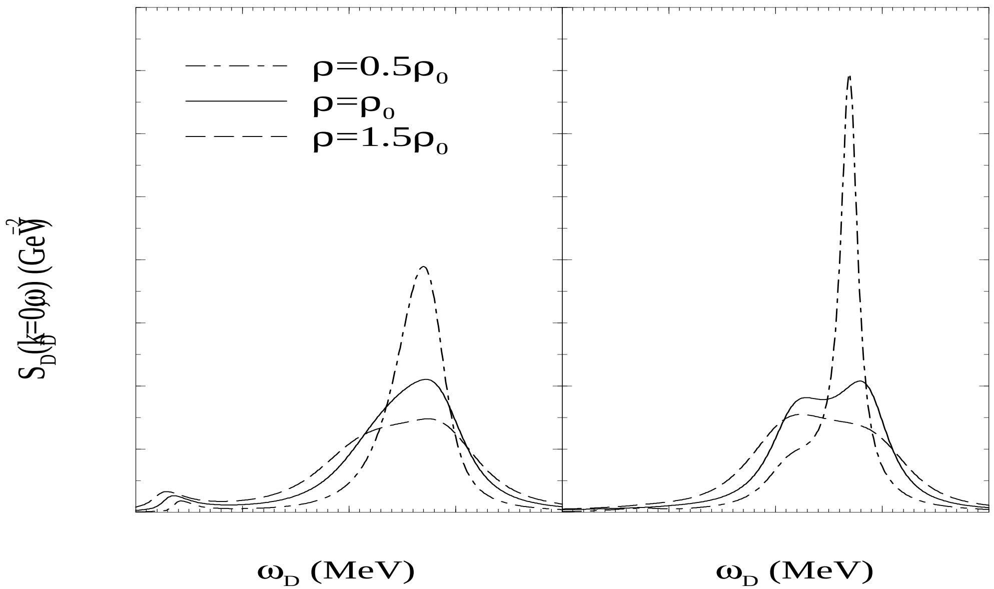




Charmonium lifetime in a dense nuclear medium ($f_D \approx 0$)

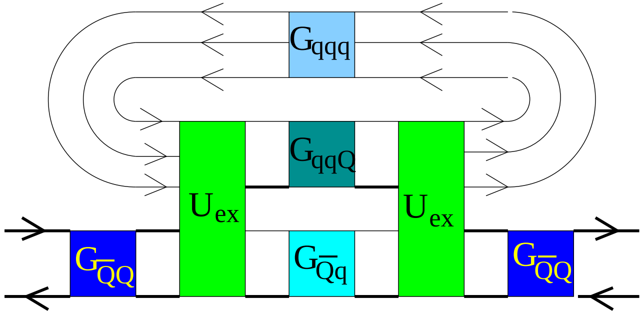
$$\tau^{-1}(p) = \int_{p'} \int_{p_2} \int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} |\mathcal{M}|^2 f_N(p') A_N(p') A_\Lambda(p_1) A_D(p_2)$$

Medium effects in hadronic spectral functions A_h and $\sigma(s; s_1, s_2)$
D-meson spectral function in cold dense nuclear matter from a G-matrix approach ↓ (N, Λ_c similar)



Tolos et al., EPJC (2005); PRC 80, 065202 (2009)

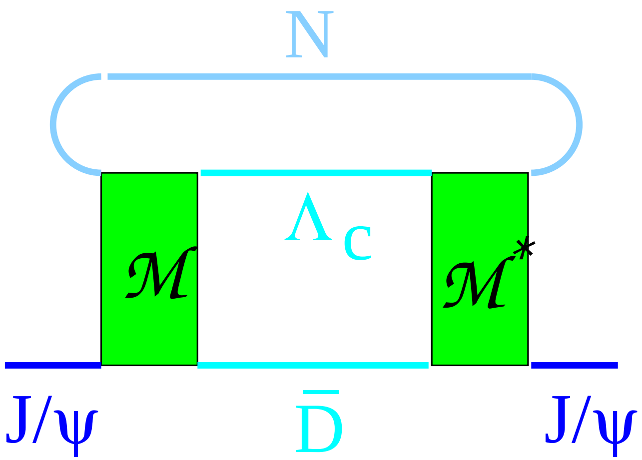
QUANTUM KINETICS OF J/ψ DISSOCIATION @ CBM ($\mu_B \neq 0$)

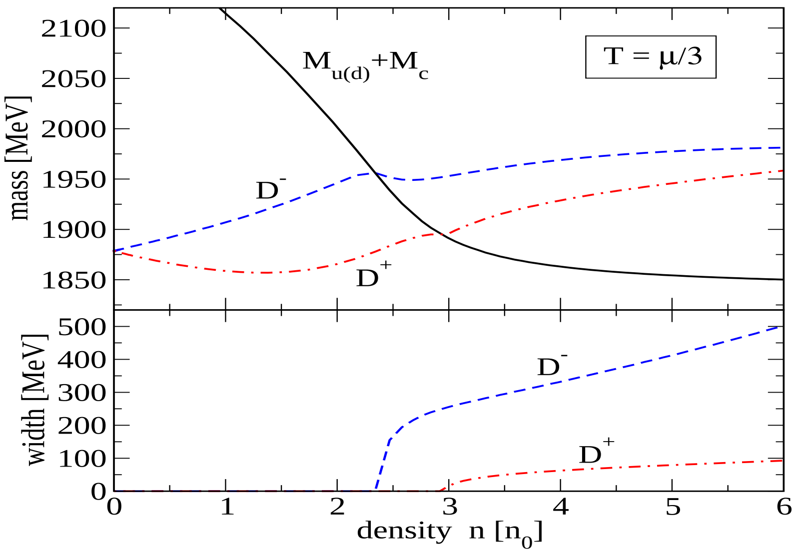


Charmonium lifetime in a dense nuclear medium ($f_D \approx 0$)

$$\tau^{-1}(p) = \int_{p'} \int_{p_2} \int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} |\mathcal{M}|^2 f_N(p') A_N(p') A_\Lambda(p_1) A_D(p_2)$$

Medium effects in hadronic spectral functions A_h and $\sigma(s; s_1, s_2)$
D-meson spectral function in hot, dense quark matter from a NJL model approach ↓ (N, Λ_c similar)





D.B., P. Costa, Yu. Kalinovsky, arxiv:1107.2913

SUMMARY

- Diagram expansions in strongly correlated quark plasma guided by plasma physics
- Microscopic formulation of the hadronic Mott effect within a chiral quark model
- Mesonic (hadronic) correlations important for $T > T_c$
- Step-like enhancement of threshold processes due to Mott effect
- Reaction kinetics for strong correlations in plasmas applicable @ SPS and RHIC
- Prospects for CBM: Anomalous suppression expected, eventually (more) steplike!

PLANS FOR THE FUTURE

- Bridge Lattice QCD and Phenomenology: spectral functions
- Calculate J/ψ breakup with baryon impact $\Longrightarrow$ CBM @ FAIR GSI
- Mott effect in dense baryonic matter: nucleon dissociation!
- EoS for hot, dense matter with Mott-effect, encoded in hadronic spectral functions

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