QM EVOLUTION OF QUARKONIUM IN A HOT, DENSE PLASMA

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Heavy Quark Workshop, Purdue Univ., 05.01.2011

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Outline:

- 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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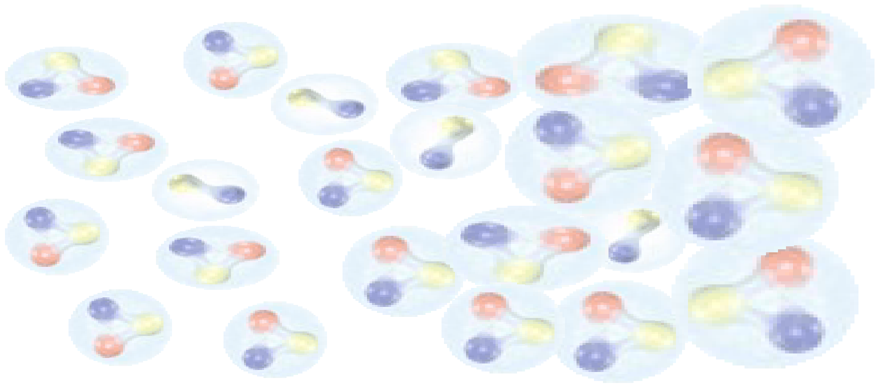
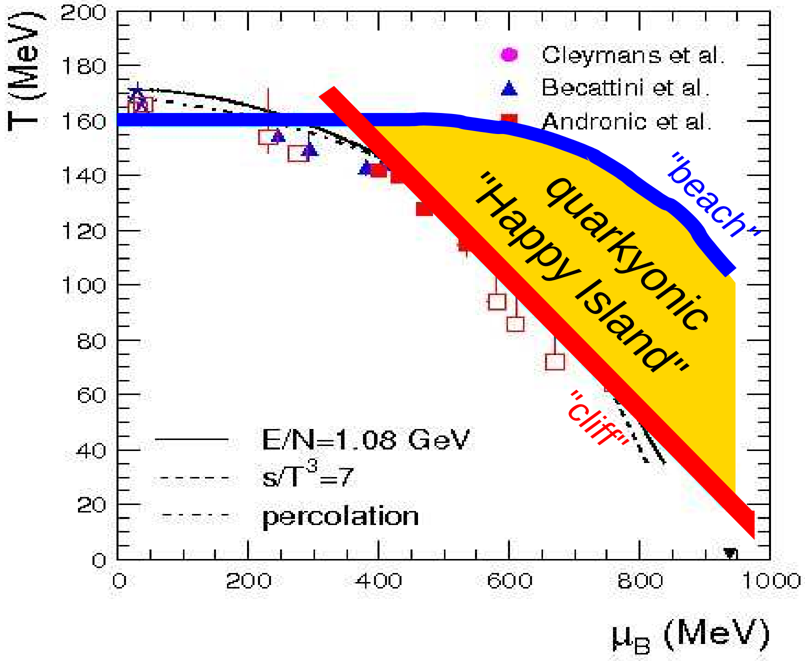
WHAT HAPPENS ON "HAPPY ISLAND"?



Andronic et al., arxiv:0911.4806



"beach": hadron resonances $\longrightarrow$ QGP

"cliff":

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

Explanation:

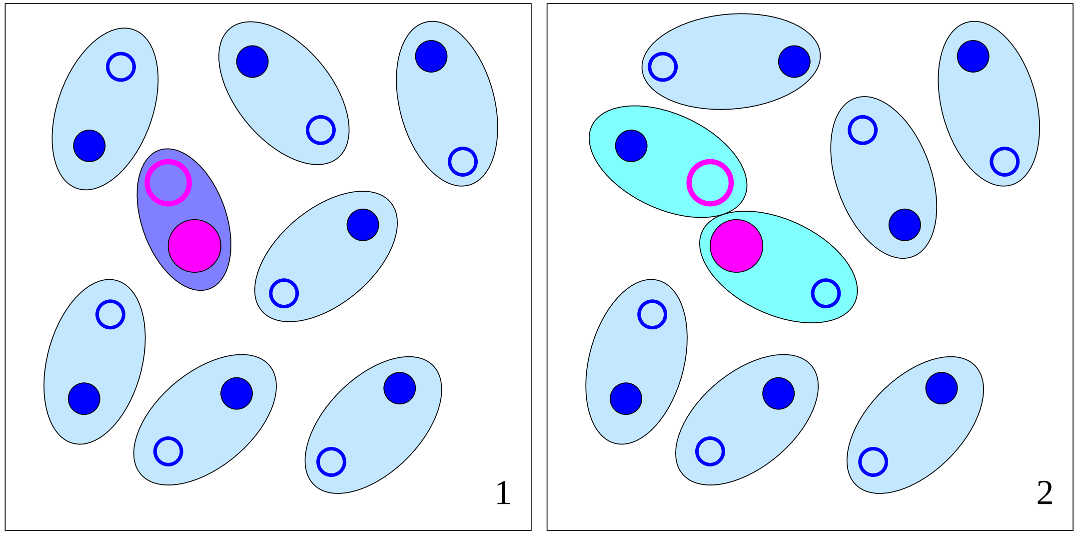
Strong medium dependence of rates
for flavor (quark) exchange processes

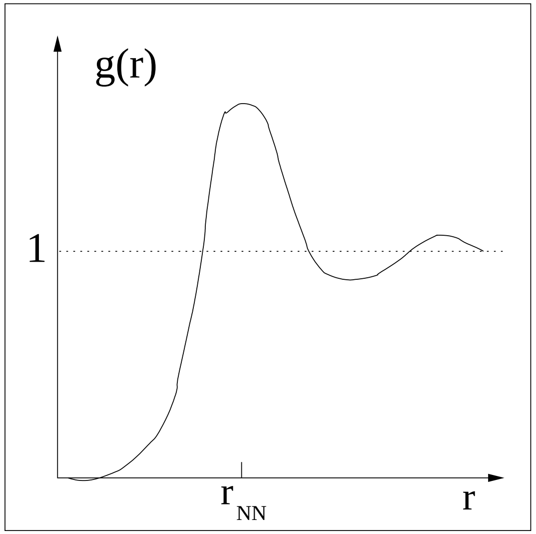
Reason:

- lowering of thresholds
- increase of hadron size (Pauli principle)
  $\rightarrow$ geometrical overlap (percolation)

A SNAPSHOP OF THE sQGP

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



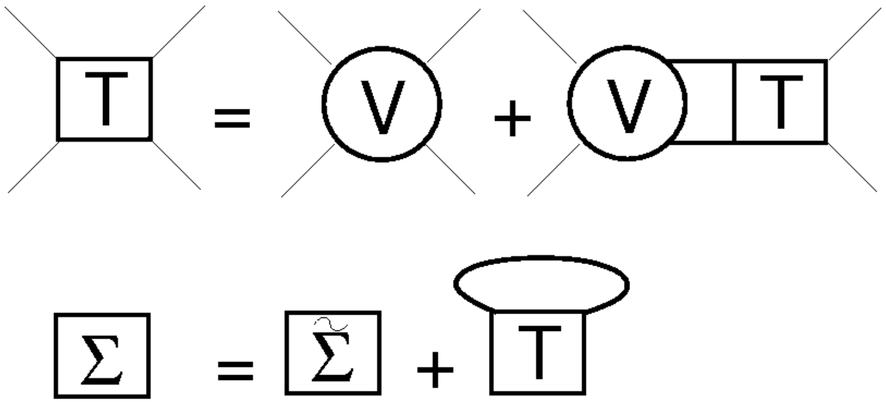


Horowitz et al. PRD (1985), D.B. et al. PLB (1985), Röpke, Blaschke, Schulz, PRD (1986)

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)

T-MATRIX APPROACH TO QUARKONIA IN THE QGP

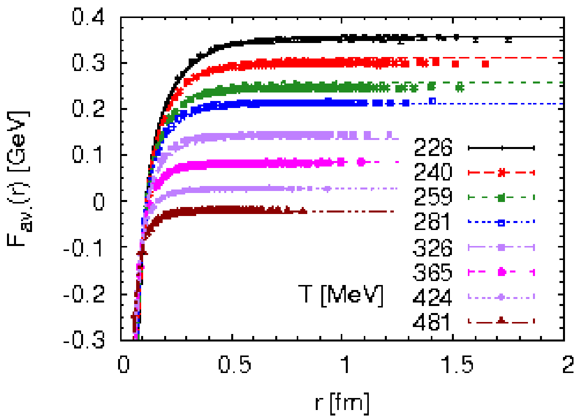


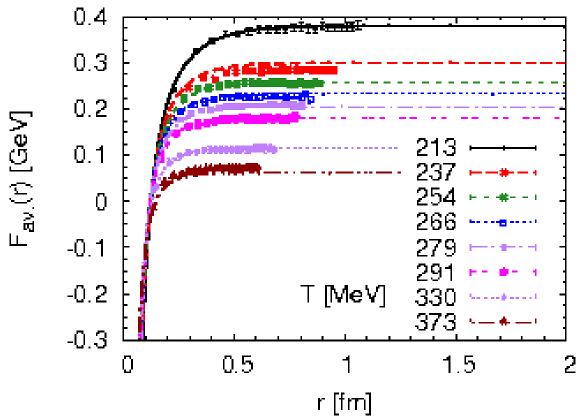
Riek & Rapp, PRC 82 (2010); arxiv:1005.0769

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





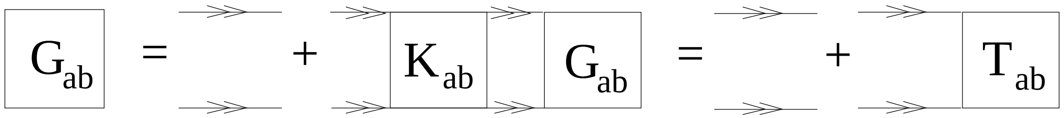
Field theoretic input: Megias et al. JHEP (2006)

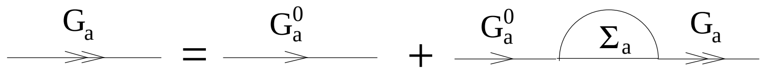
$$D_{00}(\vec{k}) = D_{00}^{P}(\vec{k}) + D_{00}^{NP}(\vec{k})$$
$$D_{00}^{P}(\vec{k}) = \frac{1}{\vec{k}^2 + m_D^2}$$
$$D_{00}^{NP}(\vec{k}) = \frac{m_G^2}{(\vec{k}^2 + \tilde{m}_D^2)^2}$$

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

Bound states in strongly coupled plasmas (I)

Bethe-Salpeter Equation and Plasma Hamiltonan





$$G_{ab} = G^0_{ab} + G^0_{ab}\, K_{ab}\, G_{ab} = G^0_{ab} + G^0_{ab}\, T_{ab}\, G^0_{ab} \qquad G_a = G^0_a + G^0_a \Sigma_a G_a$$

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

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

with Plasma Hamiltonian

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

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

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

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

Example: Heavy quarkonia in a relativistic quark plasma

$$\Pi^{\mathrm{RPA}}_{ab}(q, z) = 2\delta_{ab}\int \frac{d^3p}{(2\pi)^3}\frac{f_a(E^a_p) - f_a(E^a_{p-q})}{E^a_p - E^a_{p-q} - z} \; .$$

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

$$\Pi^{\mathrm{RPA}}_{ab}(q \to 0, 0) = 2\delta_{ab}\int \frac{d^3p}{(2\pi)^3}\frac{df_a(E^a_p)}{dE^a_p} = -2\delta_{ab}\int_0^\infty \frac{dp\, p}{\pi^2} f_\Phi(p) = -\frac{\delta_{ab}}{6\pi^2} I(\Phi)T^2 \; ,$$

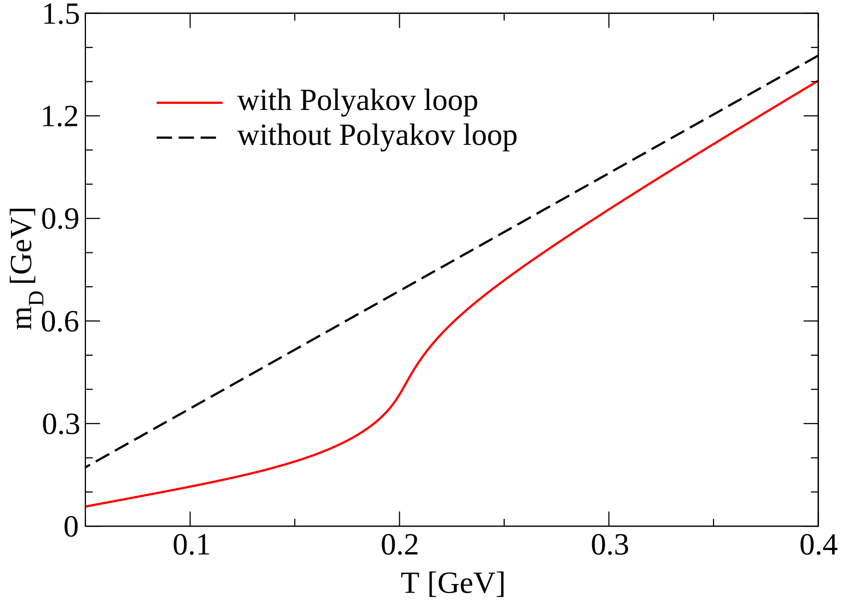
where $I(\Phi) = (12/\pi^2)\int_0^\infty dx x f_\Phi(x)$ and $f_\Phi(x) = [\Phi(1+2e^{-x})e^{-x} + e^{-3x}]/[1+3\Phi(1+e^{-x})e^{-x} + e^{-3x}]$ is the generalized quark distribution function (Hansen et al 2006).

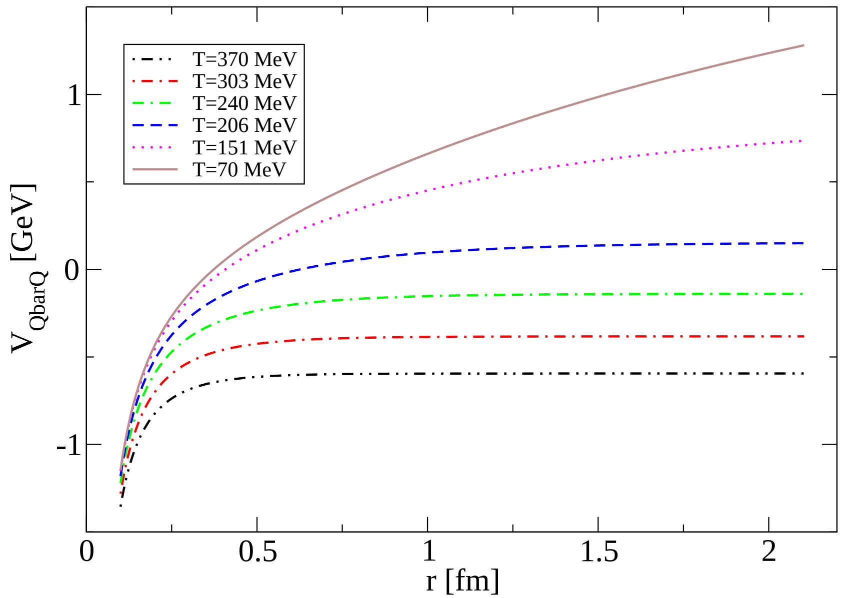
Bound states in strongly coupled plasmas (IV)

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 $\tilde{m}_D \neq m_D$





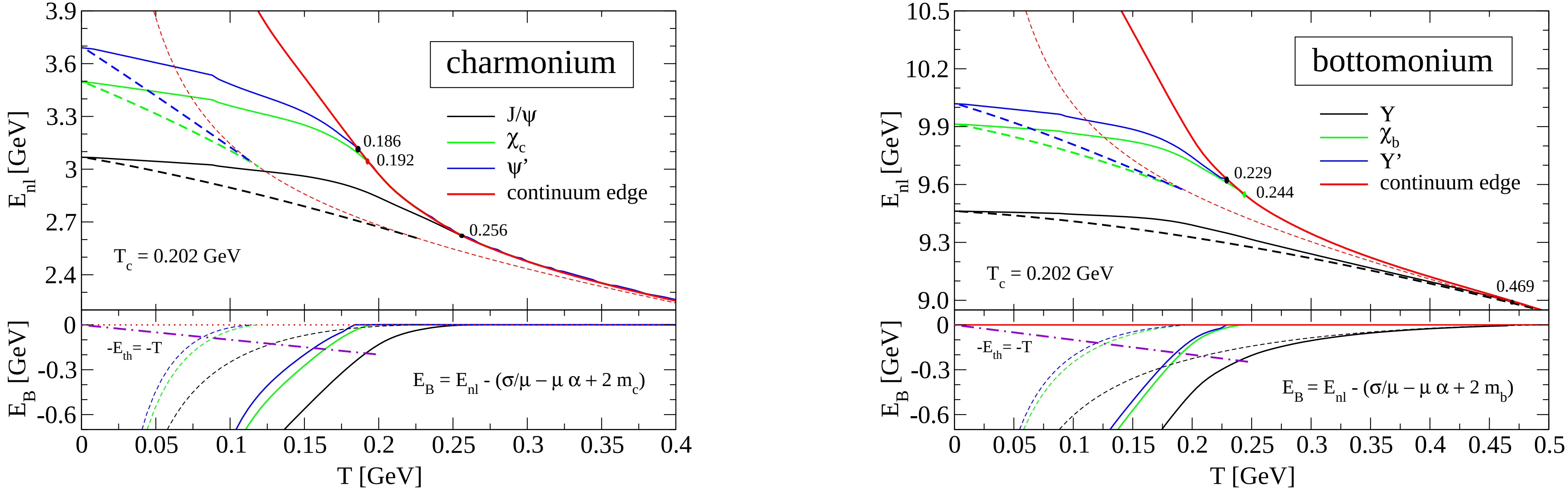
Temperature dependent Debye mass (left) with PL-suppressed screening and corresponding statically screened Cornell potential (right) [Jankowski, DB, Proceedings CPOD-2010].

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

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

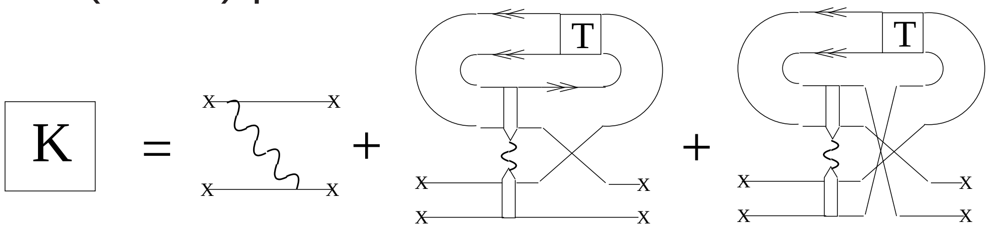
for the plasma Hamiltonian $H^{\rm pl}(r;T) = 2m_Q - \alpha\mu_D(T) - \vec{\nabla}^2/m_Q + V_{Q\bar{Q}}(r;T)$

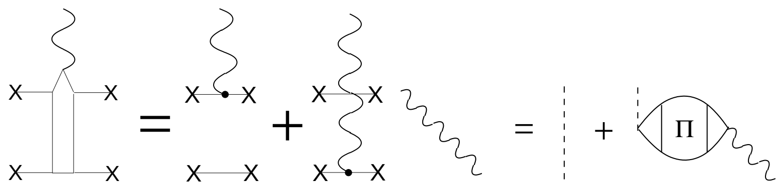


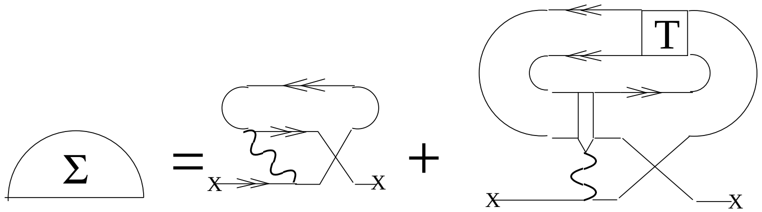
Two-particle energies of charmonia (left) and bottomonia (right) in a statically screened Cornell potential, [Jankowski, DB, Grigorian, Acta Phys. Pol. B (PS) 3, 747 (2010)].

Bound states in strongly coupled plasmas (VI)

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







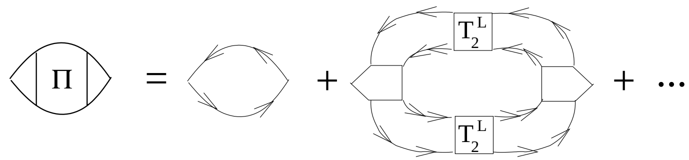
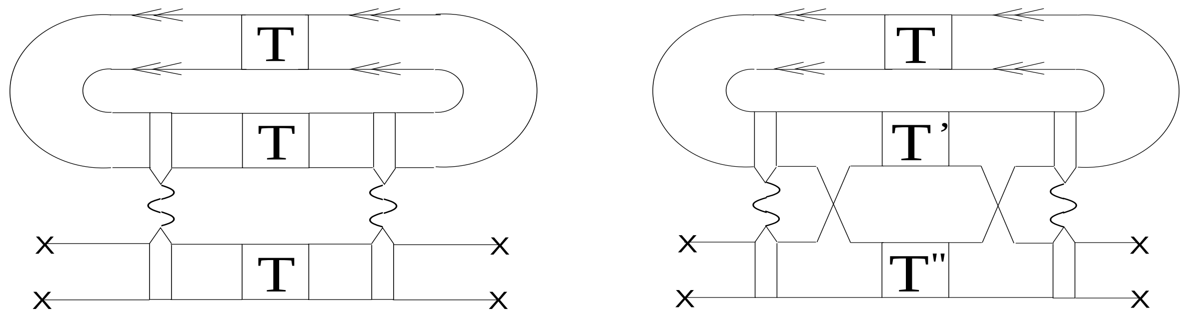


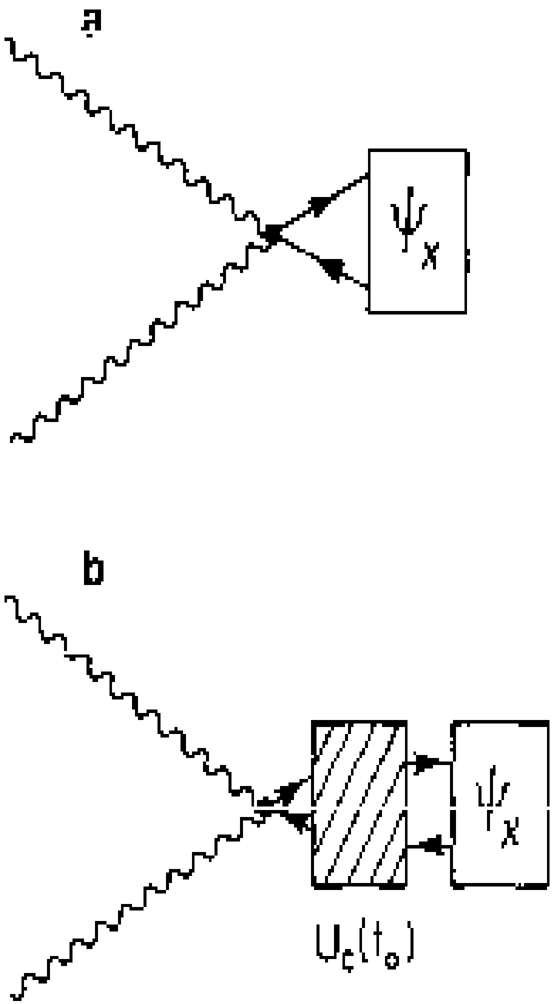
Diagram expansion for 1st and 2nd Born order cluster-cluster interactions



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

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

Supression ratio (survival probability)

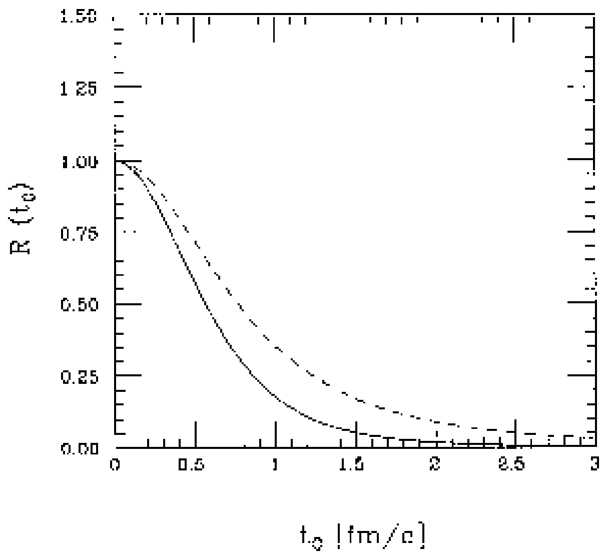
$$R_\psi(t_0) = \frac{|\langle c\bar{c}, \psi | U_c(t_0) H_{2g\to c\bar{c}} | 2g, k_0 \rangle|^2}{|\langle c\bar{c}, \psi | H_{2g\to c\bar{c}} | 2g, k_0 \rangle|^2}$$

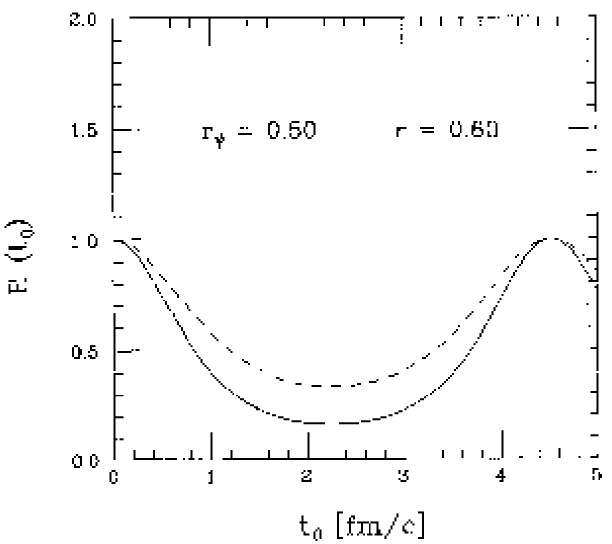
Result for pseudoscalar state

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

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

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





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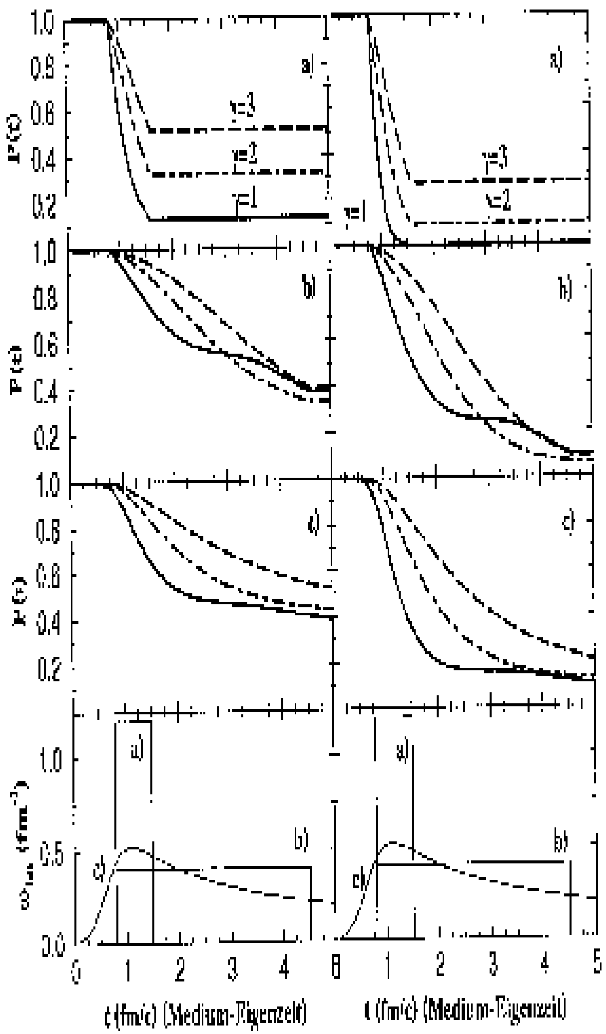
Lower Fig.: $\omega \neq 0$, $r = \sqrt{2/(m_c\omega)} = 0.6$ fm

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 for infinitesimal time intervals Δt

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

Supression ratio (survival probability) can oscillate ...
Reasonable assumptions for time dependencies:

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

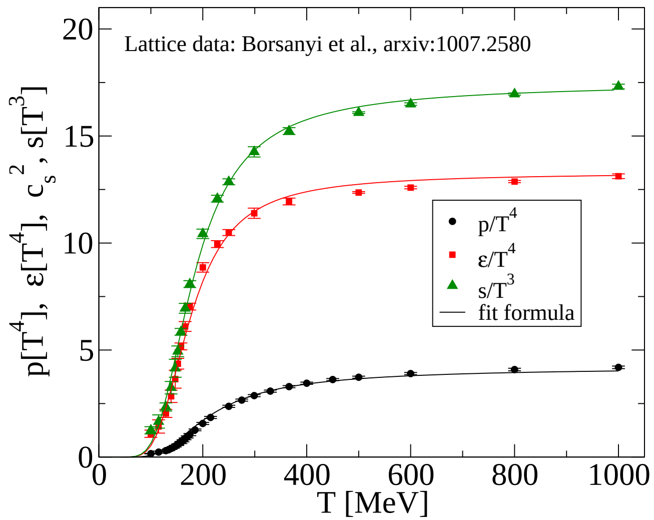
$t > t_0: \quad \omega_R = \omega_R(t): \ \omega_I = \omega_I(t)$

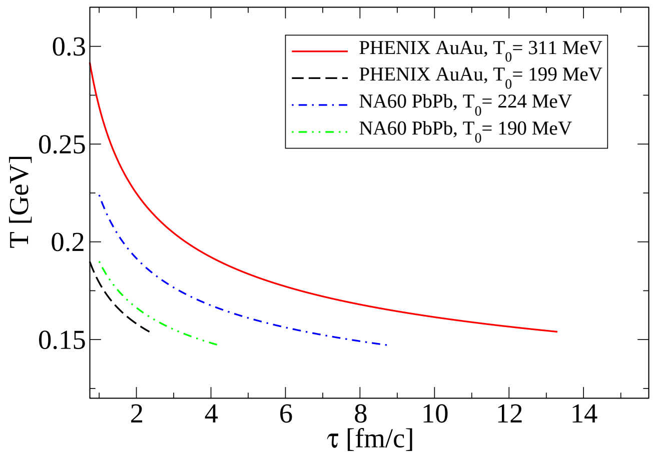
$\rightarrow$ results for the survival probability $P(t)$, see Figure

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

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

Time-dependence of complex frequency: T-evolution





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

$T(t)$ 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)

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

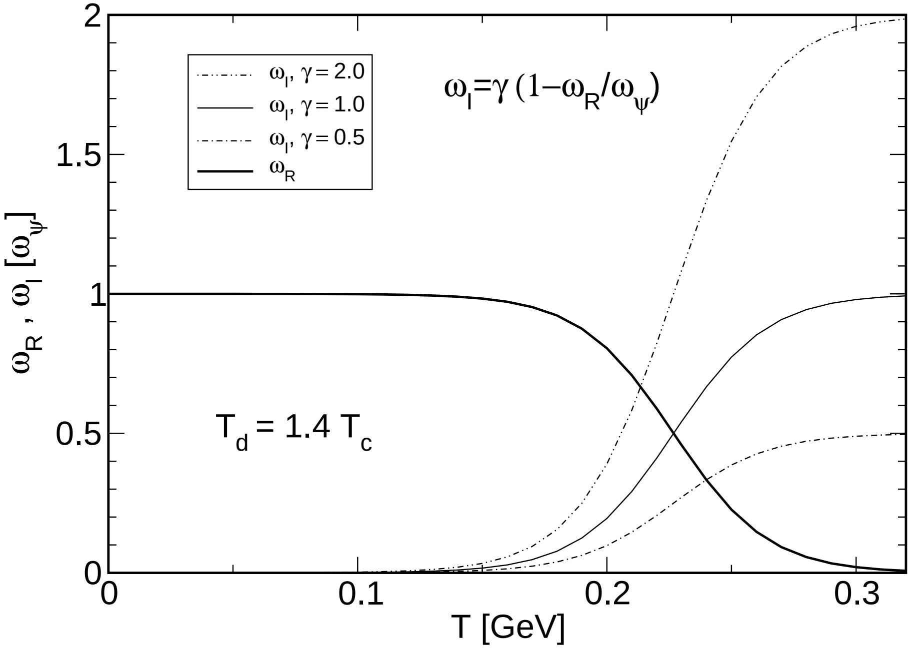
Time evolution operator

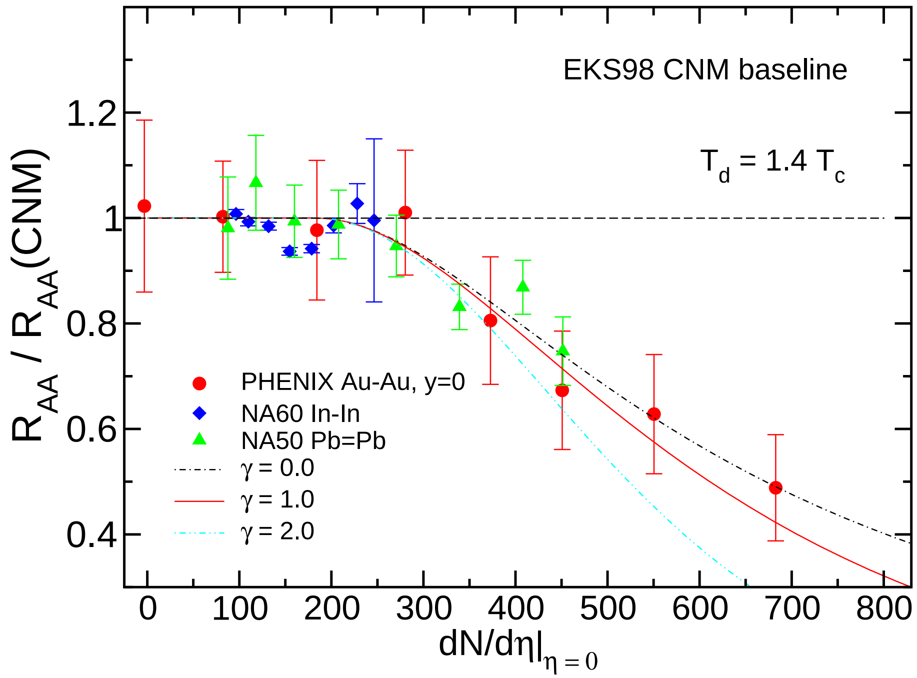
$$U(t_f;t_i) = \left[\frac{\mu\ \rho_f\ \rho_i^{-1}\dot{\phi}_f}{2\pi i\sin(\phi_f - \phi_i)}\right]^{3/2} \mathrm{e}^{iS_{\mathrm{cl}}} \ ,$$

Supression ratio (survival probability)

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

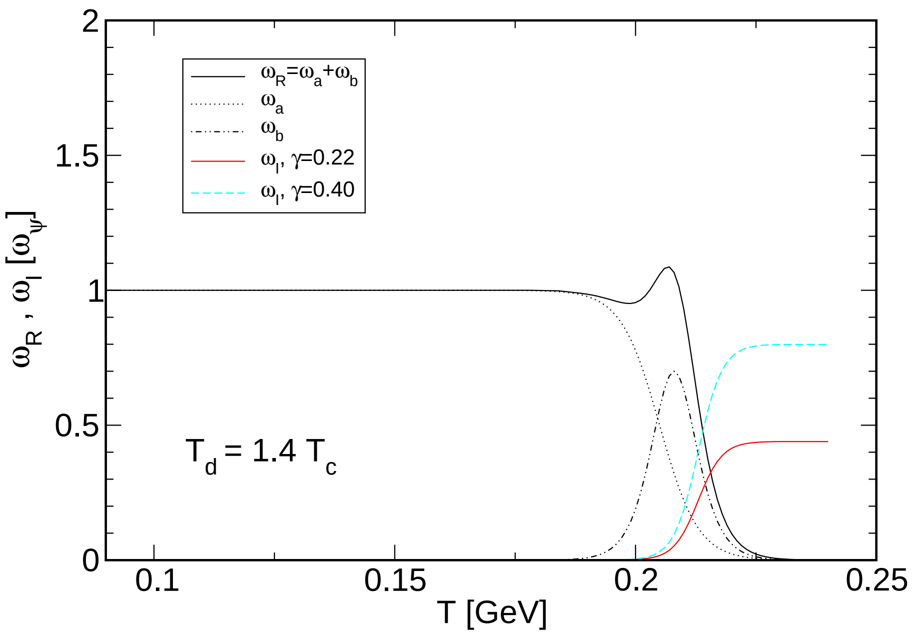
Combined description of RHIC and SPS centrality dependence

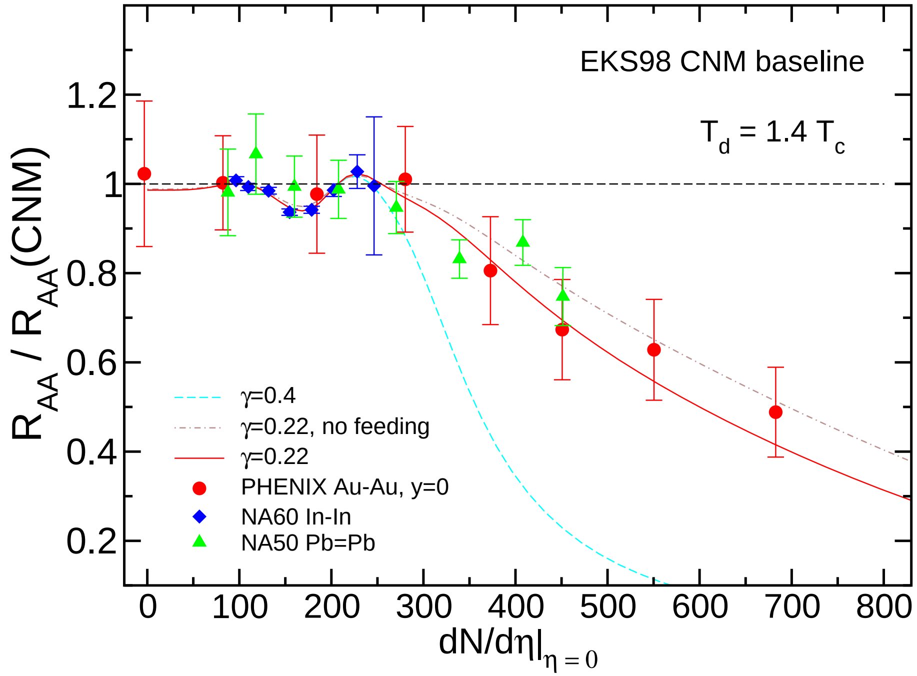




C. Peña, D.B., in preparation.

THE NA60 IN-IN “DIP” - A HINT FOR SUBTLE CORRELATIONS?

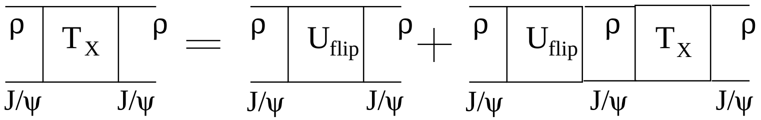


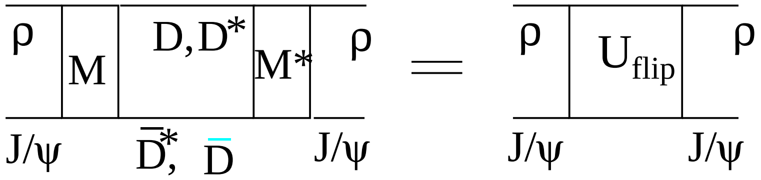


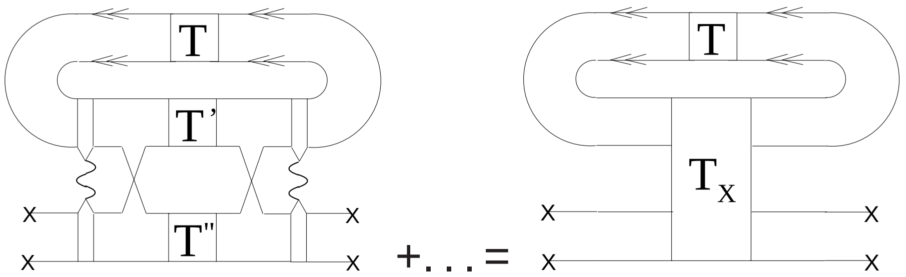
C. Peña, D.B., in preparation.

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 ...

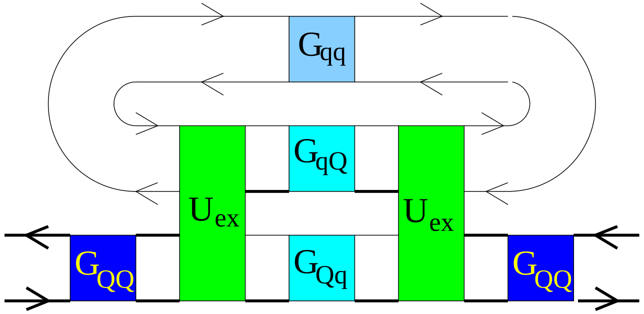


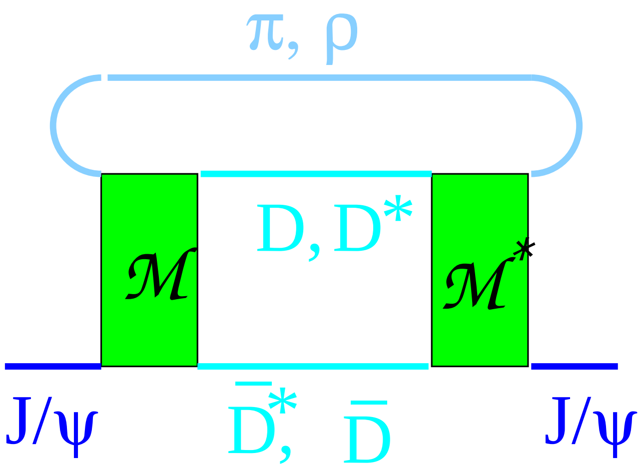




C. Peña, D.B., in preparation.

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

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

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

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

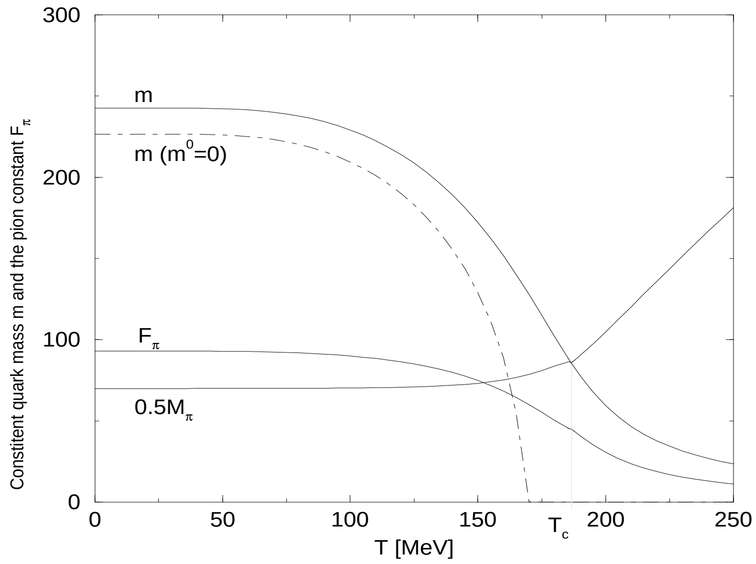
$$\tau^{-1}(p) = \int \frac{d^3\mathbf{p}'}{(2\pi)^3} \int ds' \quad f_\pi(\mathbf{p}', s') \, A_\pi(s') v_{\rm rel} \, \sigma^*(s)$$

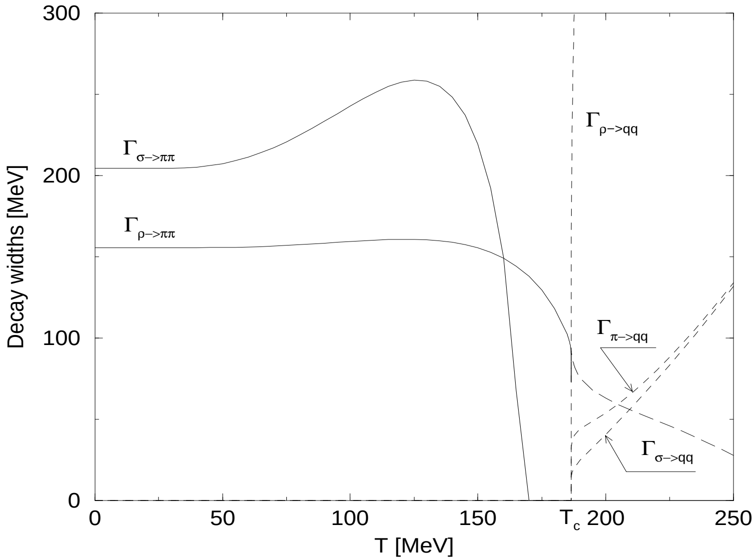
In-medium breakup cross section

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

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

Mott effect: NJL model primer





Meson propagator: RPA-type resummation,

$$D_h(P) \sim [1 - G\Pi_h(P)]^{-1},$$

e.g. Pion Pseudoscalar polarization fuction ($m_q = m_{\bar{q}} = m$)

$$\Pi_\pi(\bar{M}_\pi, \vec{0}) = -\frac{N_c}{8\pi^2}\left\{2A(m) - (M_\pi - i\Gamma_\pi/2)^2\, B(M_\pi, \vec{0}; m, m)\right\}$$

Finite temperature (Matsubara)

$$A(m) \;=\; -4\int_\Lambda dp \frac{p^2}{\sqrt{E(p)}} \tanh(E(p)/2T) \quad \text{real}$$

$$B(P_0, \vec{0}; m, m) \;=\; 8\int_\Lambda dp \frac{p^2 \tanh(E(p)/2T)}{E(p)[4E^2(p) - P_0^2]} \quad \text{real for } T < T_c$$

Complex polarization function
$\Rightarrow$ Breit-Wigner type spectral function

$\Longleftarrow$ Blaschke, Burau, Volkov, Yudichev: EPJA **11** (2001) 319

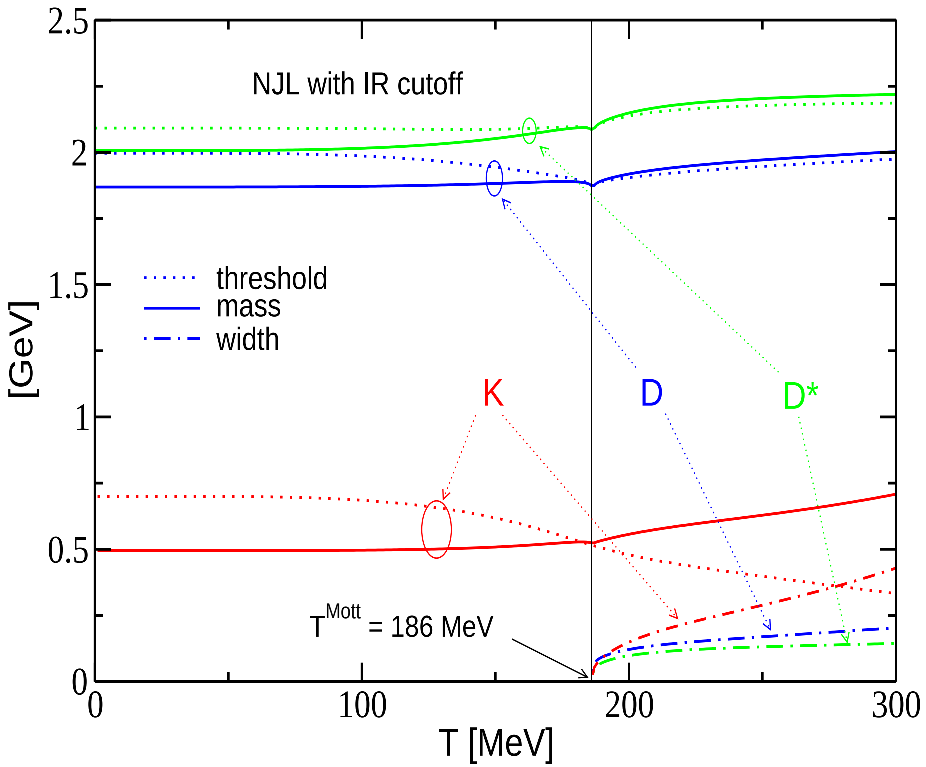
Charm meson sector, see
Gottfried, Klevansky, PLB **286** (1992) 221

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

Mott effect: Heavy meson generalization

$$\Pi_D(P^2;T) = 4I_1^\Lambda(m_u;T) + 4I_1^\Lambda(m_c;T) + 4\left(P^2 - (m_u - m_c)^2\right) I_2^{(\lambda_P,\Lambda)}(P^2, m_u, m_c;T),$$

$$I_2^{(\lambda_M,\Lambda)}(M, m_u, m_c;T) = \frac{N_c}{8\pi^2 M}\int_{\lambda_P}^{\Lambda} dp\, p^2 \left[\frac{\widetilde{E}_{uc}\tanh(E_u/2T)}{E_u(E_u^2 - \widetilde{E}_{uc}^2)} + \frac{\widetilde{E}_{cu}\tanh(E_c/2T)}{E_c(E_c^2 - \widetilde{E}_{cu}^2)}\right],$$



$$\widetilde{E}_{ij} = (m_i^2 - m_j^2 + M^2)/2M,$$

Infrared cutoff ($M_\pi(T_c) = 2m_u(T_c) = 2m_u^{\rm cr}$)

$$\lambda_P = [m_u^{\rm cr}\,\theta(m_u - m_u^{\rm cr}) + m_u\,\theta(m_u^{\rm cr} - m_u)] \times\theta(P^2 - 4(m_u^{\rm cr})^2)\sqrt{P^2/(2\,m_u^{\rm cr})^2 - 1},$$

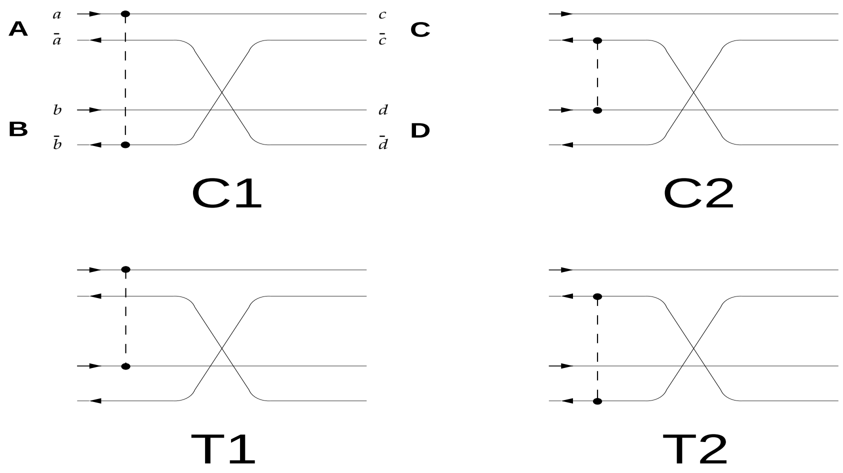
Meson spectral properties (mass M, width Γ)

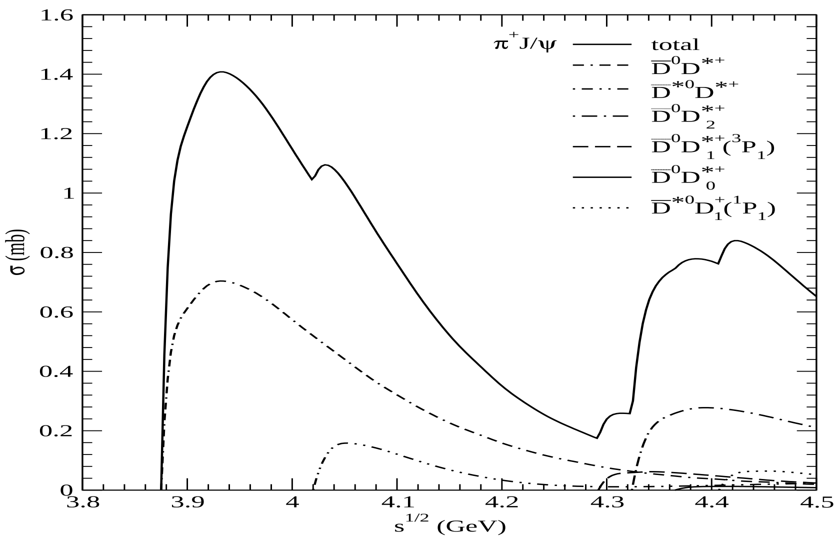
$$G\,{\rm Re}\Pi(P^2 = M^2;T) = 1$$

$$\Gamma(T) = {\rm Im}\Pi(M^2;T)/[M(T)\,{\rm Re}\Pi'(M^2;T)]$$

$\Longleftarrow$ Blaschke, Burau, Kalinovsky, Yudichev, Prog. Theor. Phys. Suppl. **149** (2003) 182.

Quark Rearrangement I: NRQM Born diagrams





Short history:

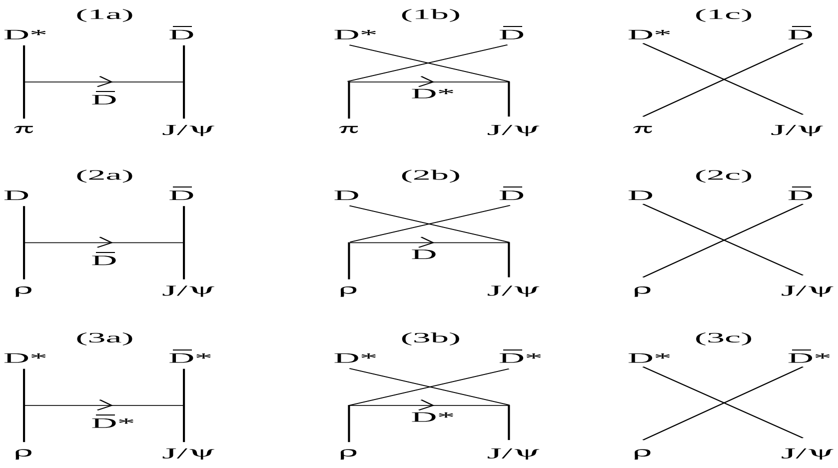
- Quark (+gluon) exchange model of short-range NN int.
  Holinde, PLB 118 (1982) 266; ...
- Born approx. to quark exchange in meson-meson scatt.
  Barnes, Swanson: PRD 46 (1992) 131
- Appl. to Charmonium dissociation: J/ψ+π $\rightarrow$ $D + \bar{D}, \ldots$
  Martins, D.B., Quack: PRC 51 (1995) 2723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

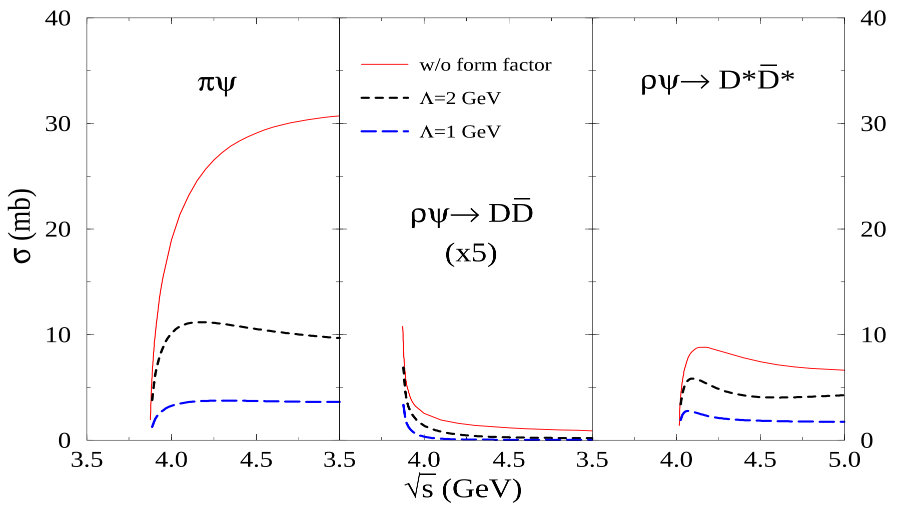
(C)apture Diagrams:
$\rightarrow$ interaction can be absorbed into the 'ladder' of a meson
(T)ransfer Diagrams:
$\rightarrow$ interaction between quarks from different mesons

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:

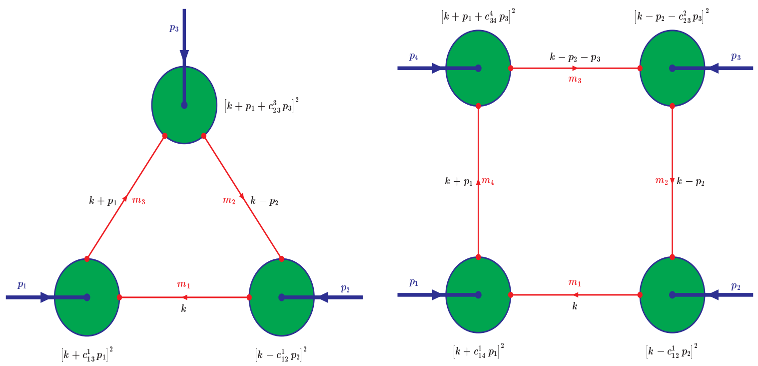
- Meson exchange model for NN interaction
  Yukawa(1935); Walecka, Ann. Phys. 83 (1974) 491; ...
- Application to charmonium diss: J/ψ+$\pi, \rho \longrightarrow D + \bar{D}, \ldots$
  Matinyan, Müller, PRC 63 (1998) 2994
- Inclusion of formfactors for the meson-hadron vertices
  Haglin, PRC 61 (2000)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

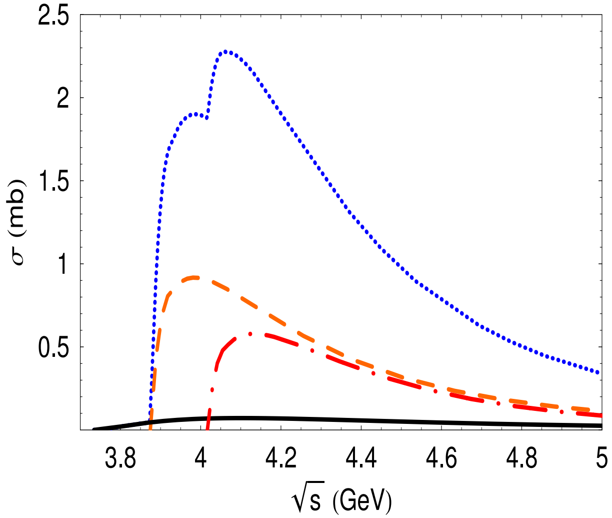
Meson exchange Diagrams:
$\longrightarrow$ Transfer diagrams: mesonic 'ladder' replaced by Born term
Contact Diagrams:
$\longrightarrow$ Capture diagrams: BS eq. at quark-meson vertex

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:

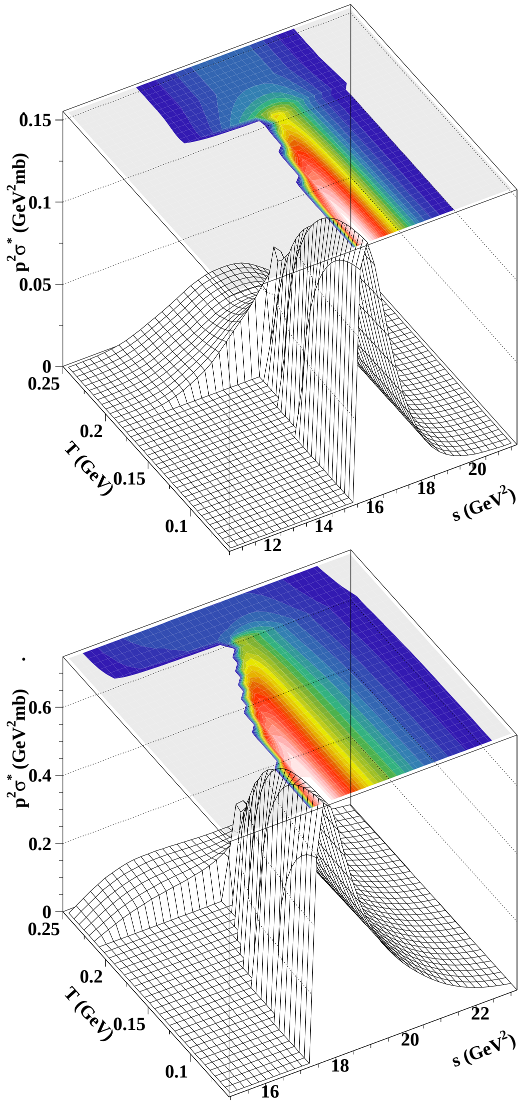
- Dyson-Schwinger approach to hadronic processes
  Roberts, Williams, PPNP 33 (1994) 477
- Application to D-mesons
  Ivanov, Kalinovsky, Roberts, PRD 60 (1999) 034018
- Calculation of J/ψ+ $\pi \quad \longrightarrow \quad D + \bar{D}$
  D.B., Burau, Ivanov, Kalinovsky, Tandy, hep-ph/0002047
  Ivanov,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

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

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

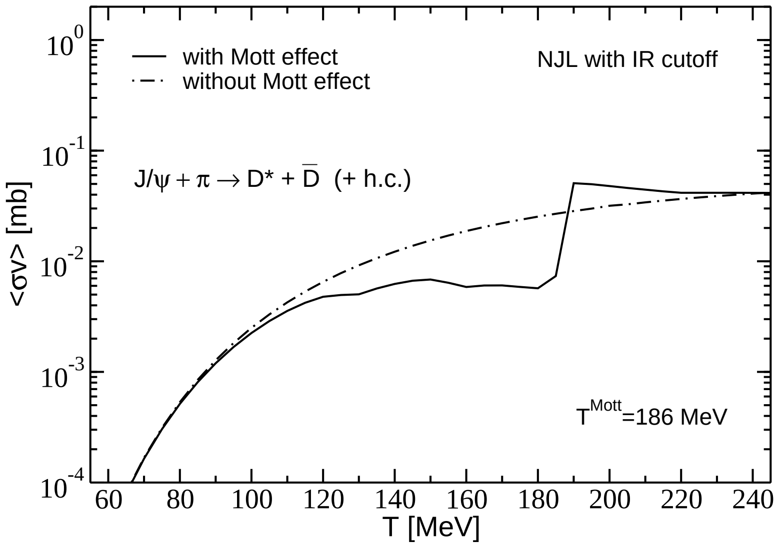
resonance $\Leftarrow$ Mott-effect $\Leftarrow$ bound state

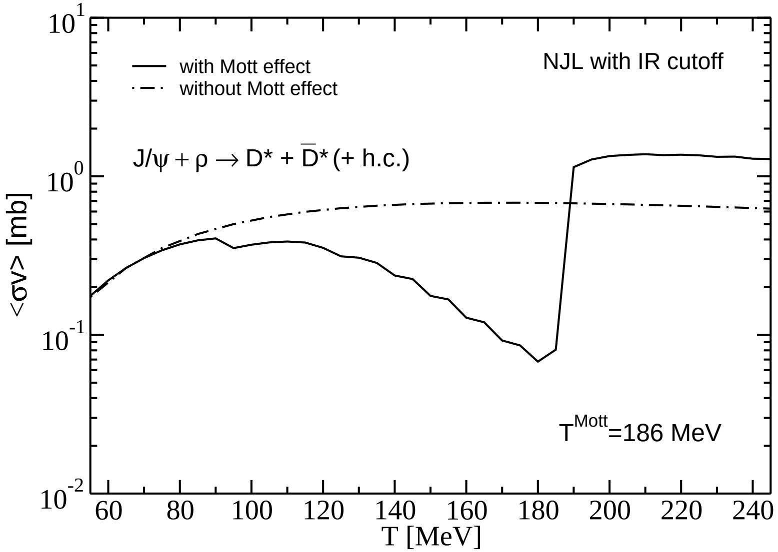
See NJL model calculations at finite temperature,
Blaschke et al.: Eur. Phys. J. **A 11** (2001) 319
Hüfner et al.: Nucl. Phys. **A 606** (1996) 260
Blaschke et al.: Nucl. Phys. **A 592** (1995) 561
Behaviour above the Mott temperature ($T \sim T_h^{\rm Mott}$)

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

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

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





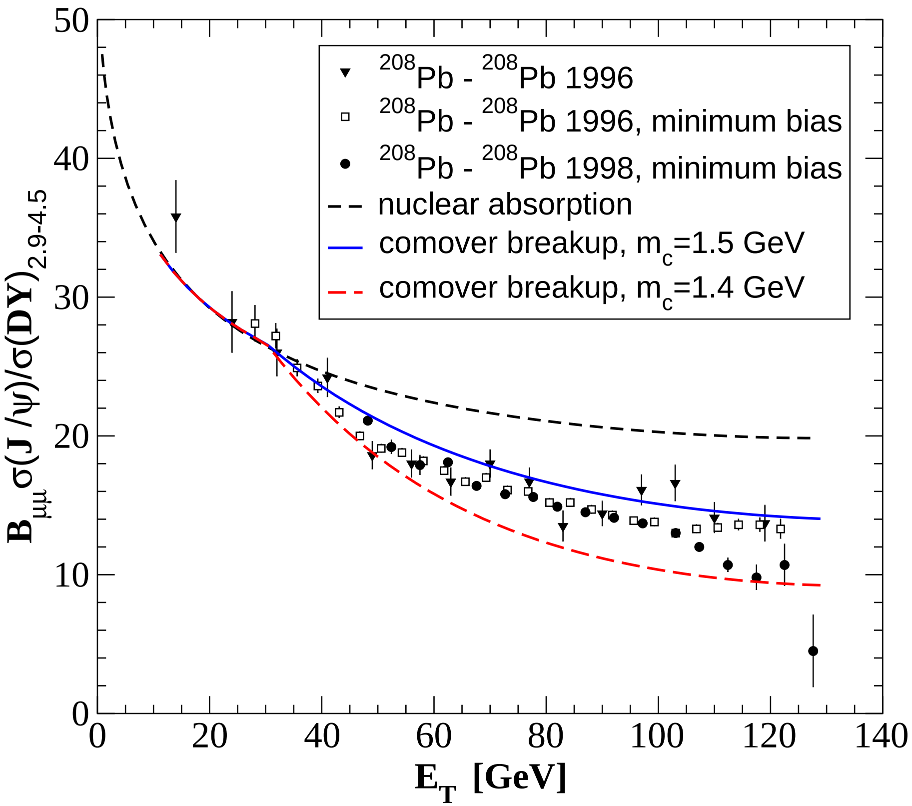
Dissociation rate for a J/ψ at rest in a hot resonance gas ($h = \pi, \rho$)

$$\begin{aligned}\tau^{-1}(T) &= \tau_\pi^{-1}(T) + \tau_\rho^{-1}(T) \\ \tau_h^{-1}(T) &= \int \frac{d^3p}{(2\pi)^3} \int ds' A_h(s';T) f_h(p,s';T) j_h(p,s') \sigma_h^*(s;T) \\ &= \langle \sigma_h^* v_{\rm rel} \rangle n_h(T) \ ,\end{aligned}$$

$$f_h(p,s;T) = g_h\{\exp[(\sqrt{p^2+s}-\mu)/T] - 1\}^{-1}$$
$$s(p,s') = s' + M_\psi^2 + 2M_\psi\sqrt{p^2+s'}$$

- 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 $n_0(E_T)$:

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

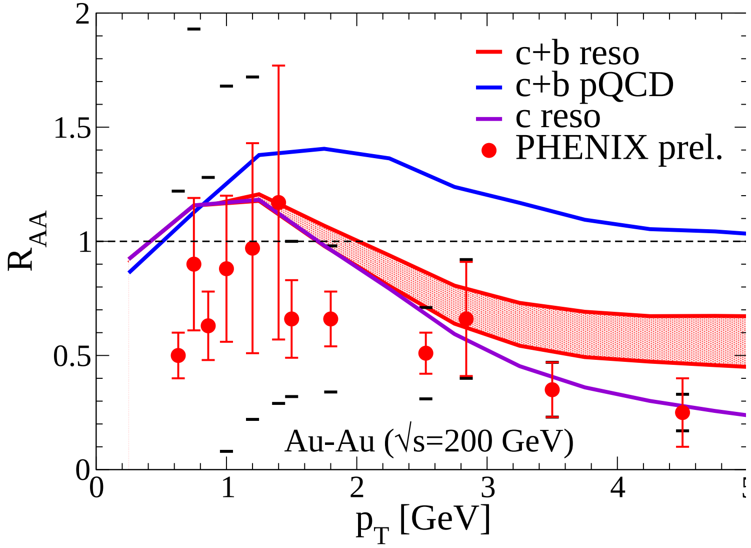
$n_0(b)/\mathrm{fm}^{-3} = 1.2\sqrt{1 - (b/10.8\ \mathrm{fm})^2}$.

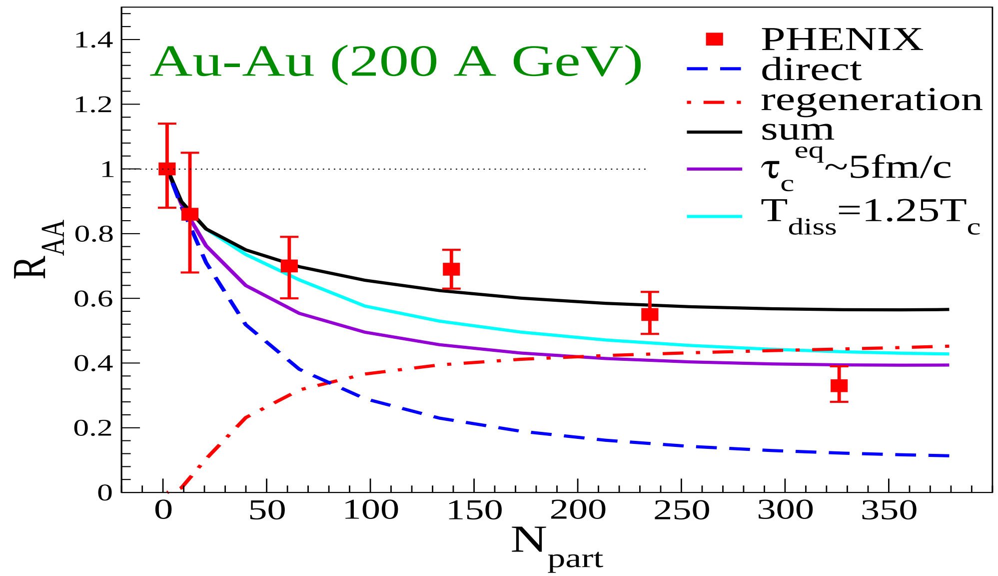
Threshold: Mott effect for D-Mesons

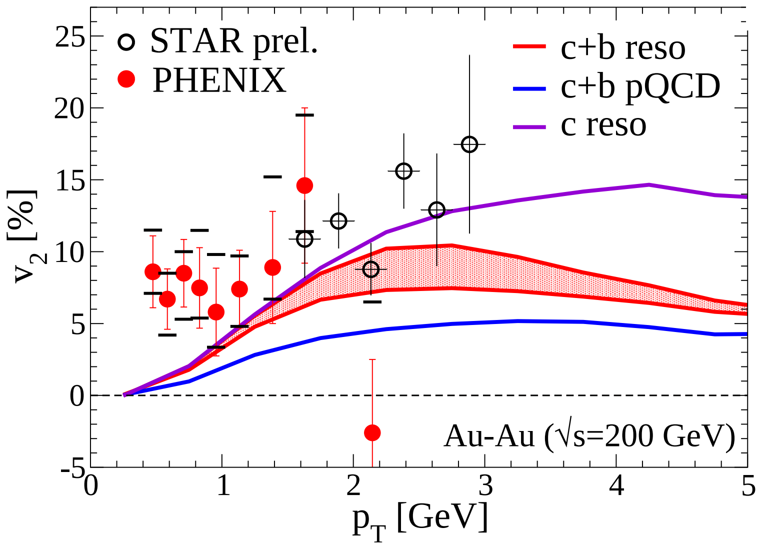
More detailed description: additional resonances, gain processes (D-fusion), HIC simulation

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)

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

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

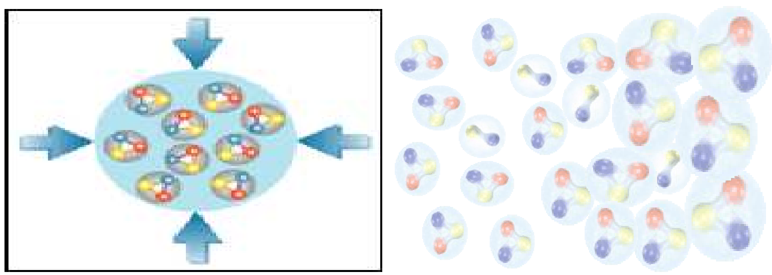
Nuclear modification factor R_{AA} and elliptic flow v_2 of semileptonic $D-$ and $B-$ meson decay-electrons in $b = 7$ fm Au-Au ($\sqrt{s} = 200$ GeV) collisions at RHIC

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

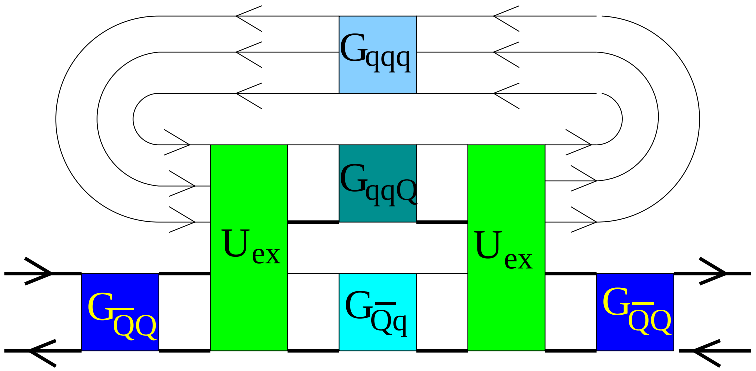
CHARM AND CHARMONIUM PRODUCTION @ FAIR-CBM

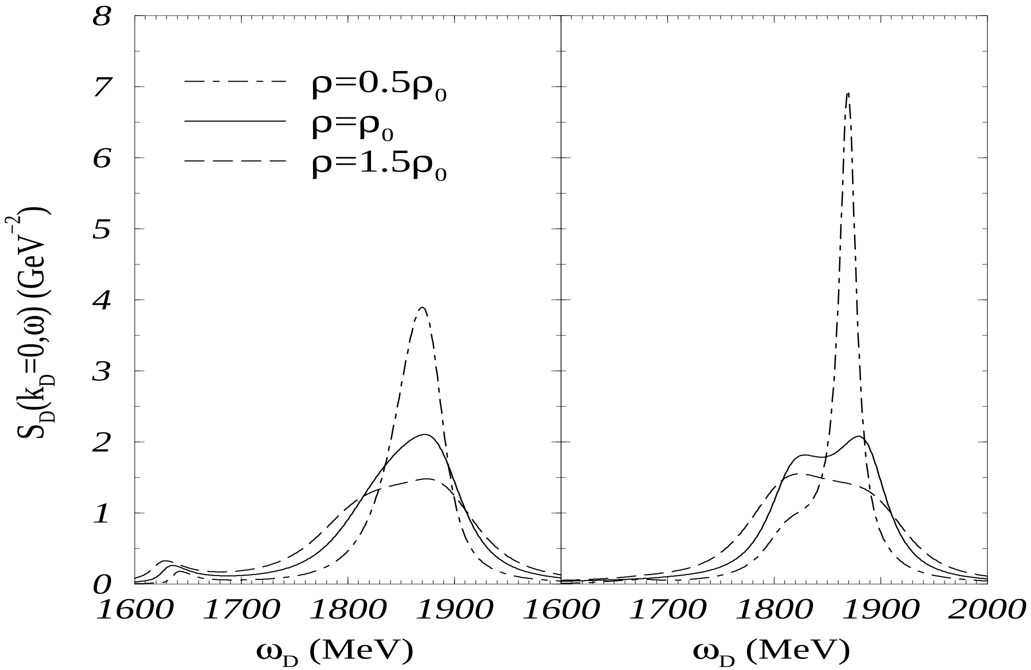
J/ψ dissociation process in dense baryonic matter at FAIR-CBM: spectral functions for open charm hadrons (D-meson, Λ_c) are essential inputs!

$\Longleftarrow$



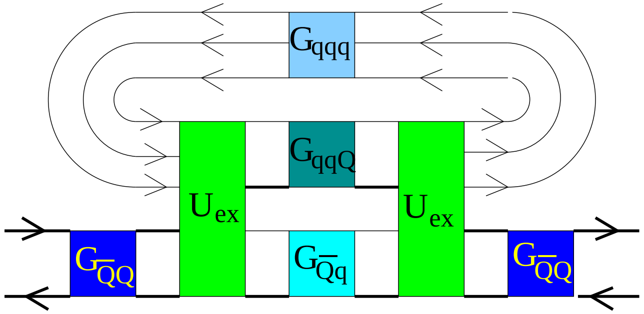
D-meson spectral function in cold dense nuclear matter from a G-matrix approach $\downarrow$

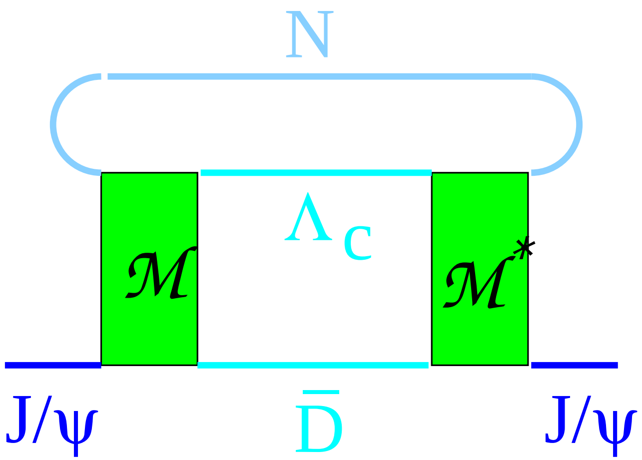




Tolos et al., EPJC (2005); nucl-th/0501151

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

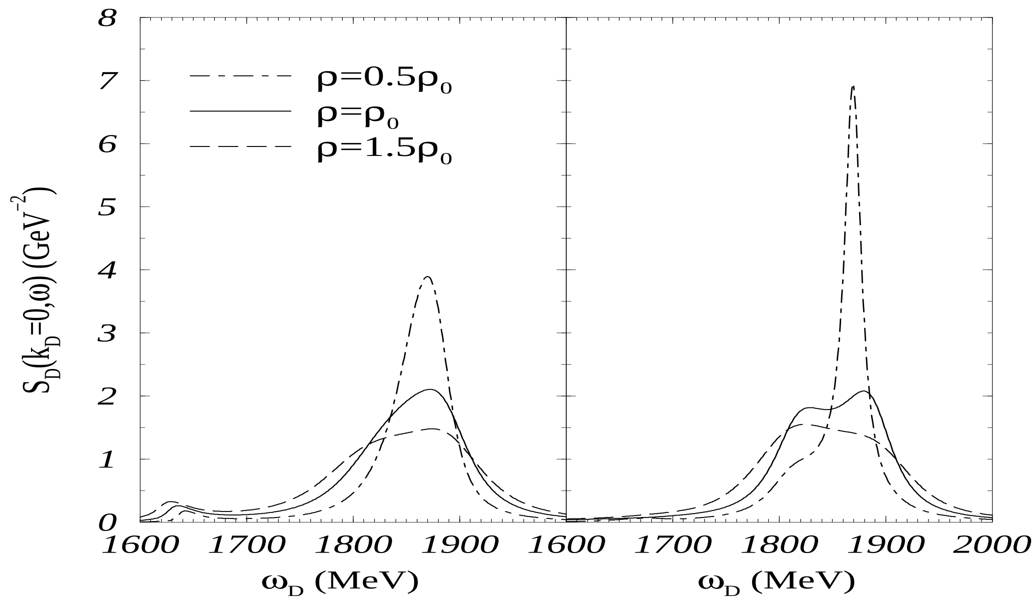




Charmonium lifetime in a dense nuclear medium ($f_D \approx 0$)

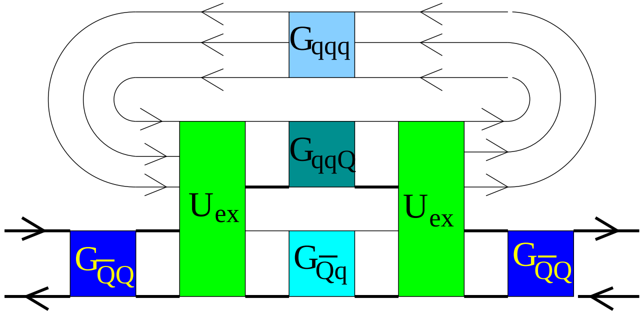
$$\tau^{-1}(p) \;=\; \int_{p'}\int_{p_2}\int_{p_2} (2\pi)^4 \delta_{p,p';p_1,p_2} \left|\mathcal{M}\right|^2 f_N(p')\; A_N(p')\; A_\Lambda(p_1)\; A_D(p_2)$$

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 ↓ ($N,\ \Lambda_c$ similar)



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

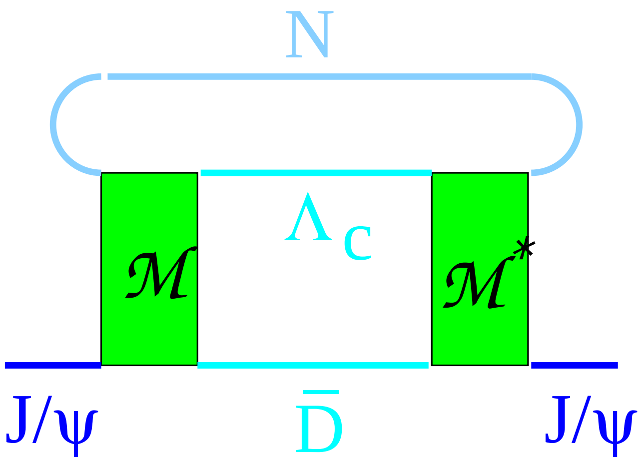
QUANTUM KINETICS OF J/ψ DISSOCIATION @ CBM ($\mu_B \neq 0$)

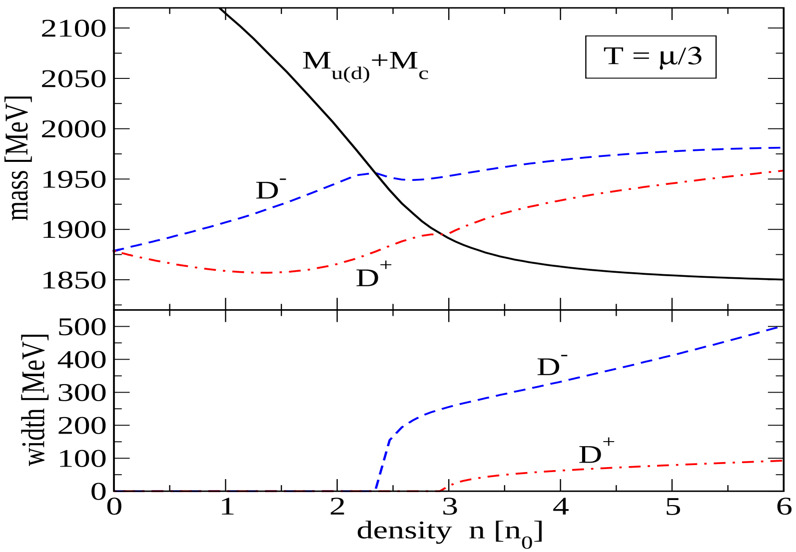


Charmonium lifetime in a dense nuclear medium ($f_D \approx 0$)

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

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





D.B., P. Costa, Yu. Kalinovsky, in preparation

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

THREE DAYS ON HAPPY ISLAND - WROCLAW, MAY 2011