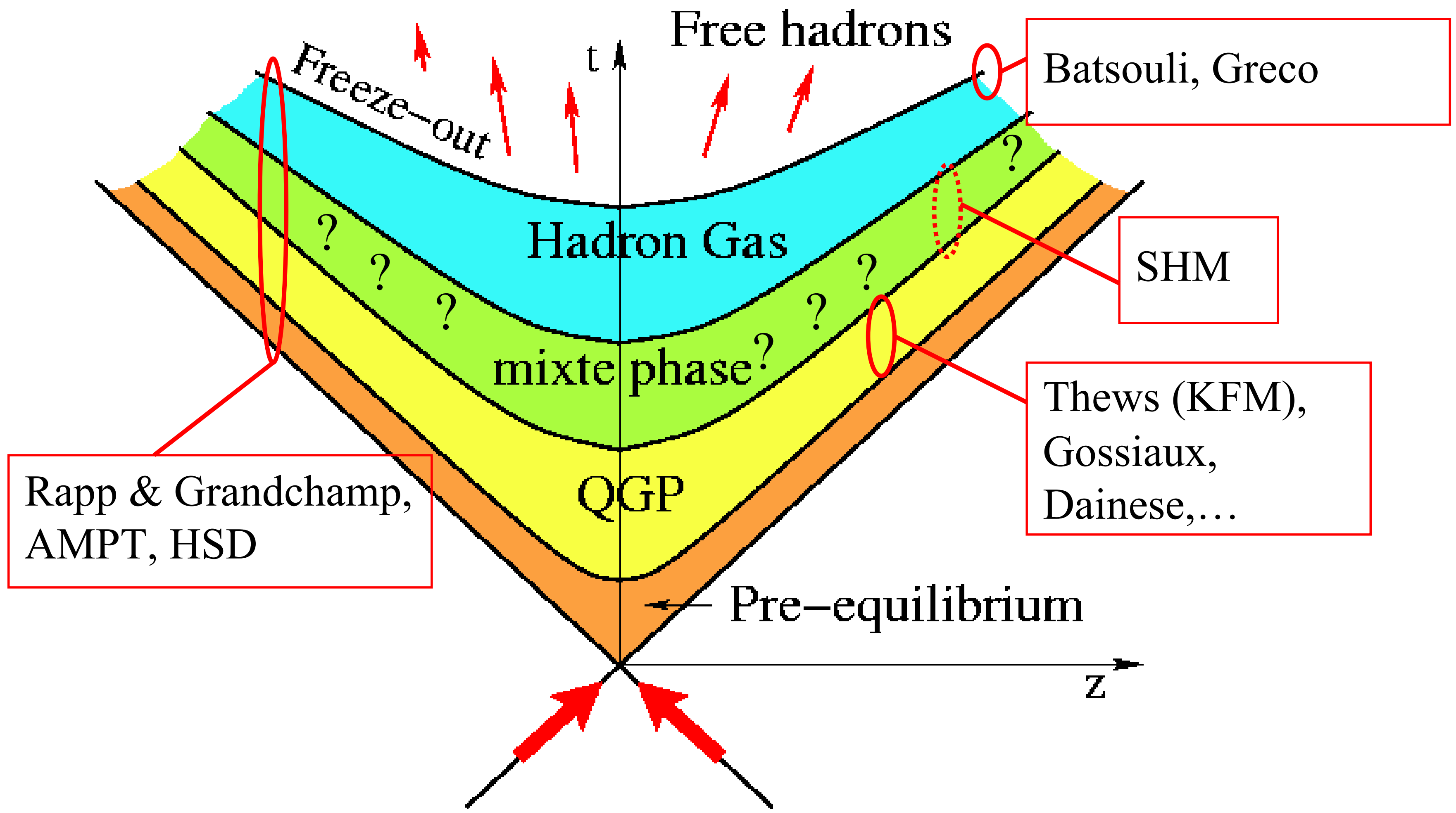
Production, suppression & secondary production of quarkonia in A-A collisions

P.-B. Gossiaux

(SUBATECH)

A schematic A-A collision



I: Production

Quarkonia production in UR A-A

- Factorization: expected for large pt only

- At low pt : “At present, there is no complete, rigorous theory to account for all of the effects of multiple scattering, and we must resort to “QCD-inspired” models. A reasonable requirement for models is they be constructed so that they are compatible with the factorization result in the large-pT limit. Many models treat interactions of the pre-quarkonium with the nucleus as on-shell scattering (Glauber scattering)”

Quarkonia production in UR A-A

Phenomenologically: In p-A collisions, quarkonia production is well reproduced by

$$\sigma_{pA\to J/\psi} = A \times \sigma_{pN\to J/\psi} \times S_{pA}^{glob}$$

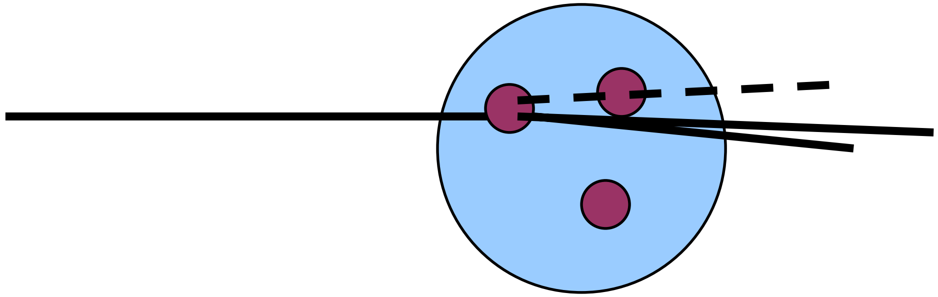
with the Glauber suppression factor

$$S_{pA}^{glob} = \int d^2b\, dz\; \rho_A(b,z)\, S_A(b,z)$$

where

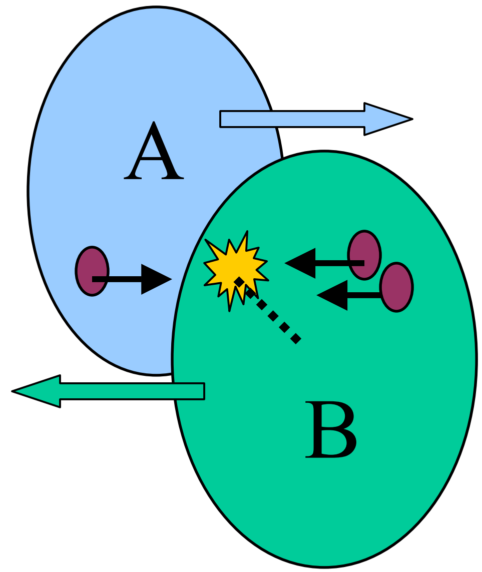
$$S_A(b,z) = \exp\left\{ -(A-1) \int_z^\infty dz'\, \rho_A(b,z')\, \sigma_{abs} \right\}$$

is the suppression of the J/ψ created at the point (b,z).
Markovian process; independent collisions



Quarkonia production in UR A-A : The baseline

"Natural" extension for A-B: a J/ψ created in the overlapping region of 2 colliding nuclei A and B can be destroyed by nucleons of both nuclei:



Baseline :
$$\frac{d^2\sigma_{AB\to J/\psi}}{d^2b} = A \times B \times \sigma_{NN\to J/\psi} \times \int d^2s\, dz\, dz'\, \rho_A(s,z)\, \rho_B(b-s,z')\, S_A(s,z) S_B(b-s,z')$$

Suppression :
$$S_{AB}(b) = \frac{\int d^2s\, dz\, dz'\, \rho_A(s,z)\, \rho_B(b-s,z')\, S_A(s,z) S_B(b-s,z')}{\int d^2s\, dz\, dz'\, \rho_A(s,z)\, \rho_B(b-s,z')}$$

Quarkonia production in UR A-A : The baseline

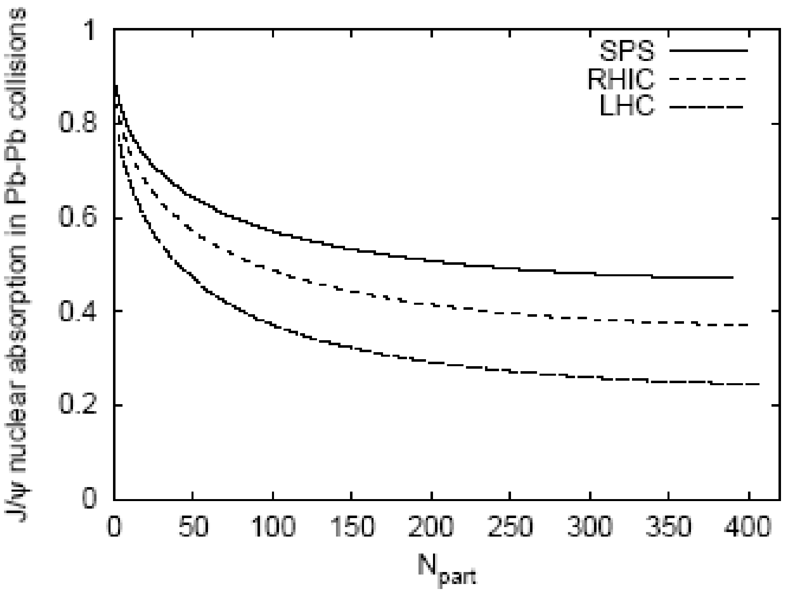


Fig. 24: The dependence of $S_{J/\psi}$ on $N_{\rm part}$ for Pb+Pb collisions at SPS, RHIC and LHC energies.

Extracted from « hard probes in Heavy-ion collisions at the LHC » CERN Yellow report – 2004 -- 009

$\sigma_{abs}(\text{SPS}) \approx 5\text{mb}$

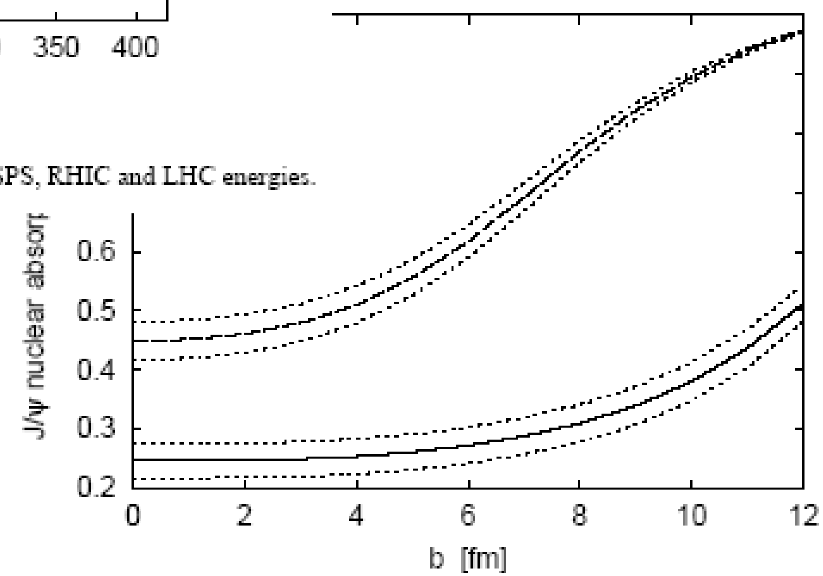


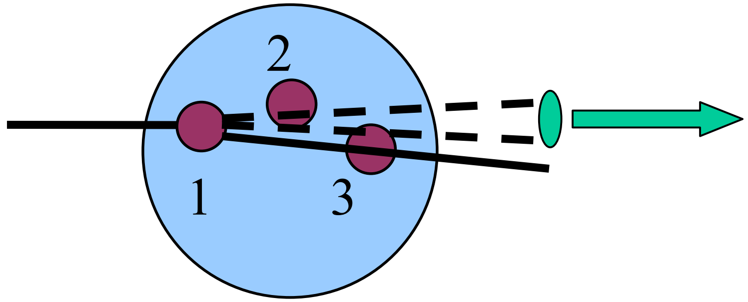
Fig. 22: The impact parameter dependence of $S_{J/\psi}$ in Pb+Pb and Ar+Ar collisions at the LHC. We assume $\sqrt{s} = 5.5$ TeV for both systems. In both cases, the survival probabilities in the central curves are calculated with the median $\sigma_{\rm abs}$ extrapolated to LHC energies while the upper and lower curves give the uncertainty in $S_{J/\psi}$ due to the absorption cross section.

Quarkonia production in UR A-A : Coherence

J/ψ at mid-rapidity at SPS :

$$\tau_{form}(J/\psi) \approx 0.5 \text{ fm/c} \approx R_{Pb}/\gamma > \text{internucleonic distance}/\gamma \Rightarrow$$

1. Charmonia are not produced (on shell) on a single nucleon.
2. Possible effects due to coherence



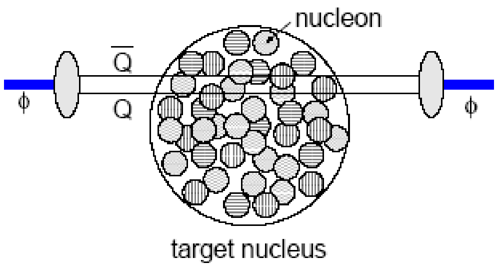
3. Even assuming that the $Q\overline{Q}$ pair is produced on a single nucleon, the object that interacts with subsequent nucleons is not (yet) a J/ψ (sometimes called "precursor"). At the best σ_{abs} can be considered as an effective cross section (why so large ?)

Quarkonia production in UR A-A : Coherence vs Glauber

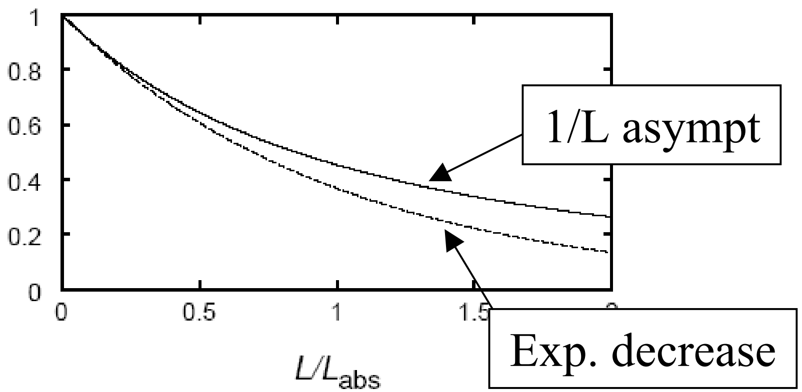
One sometimes hears / reads "Glauber model relies on *independent* stochastic collisions and thus does not apply in the case of *coherent* multiple scattering".

In fact original Glauber model was deduced in the frame of quantum mechanics and naturally implements interference effects. Semi classical stochastic behaviour appears only as a result of statistical average on the scattering centers.

Recent study of H.Fujii and T. Matsui in Phys.Lett.B 545 (2002). Also : evidence for superpenetration :



Schematic picture of color dipole propagating in nucleus which is viewed as a source of random field.



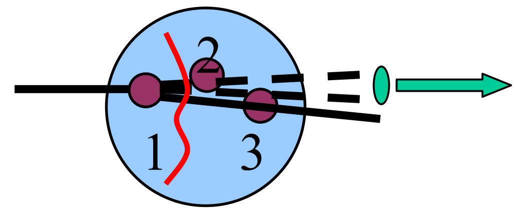
Penetration probability of the SU(3) color singlet state as a function of the target thickness L/L_{abs} .

Should we change the baseline ? «Although our calculation…is not directly applicable to the quarkonium production problem in nuclear collision, our result suggests that a special caution is needed to use the naive nuclear absorption model of quarkonium suppression at high energies, especially at RHIC and LHC energies. »

Quarkonia production in UR A-A : Coherence

J/ψ at mid-rapidity at SPS : $\tau_{form}(c\bar{c}) \approx 0.1$ fm/c ≈ internucleonic distance /γ

⇒ $c\bar{c}$ pairs at mid rapidity could be mostly produced during single N-N collision, while the asymptotic charmonia appear after the (coherent) (re)interaction of $c\bar{c}$ with other nucleons. Approximate factorization.



Non trivial effect, also on the charmonia integrated production. Cf J.Qiu, J.P. Vary and X.Zhang (Nucl.Phys. A698 (2002) 571-574). Permits some interpretation of the quantity σ_{abs}

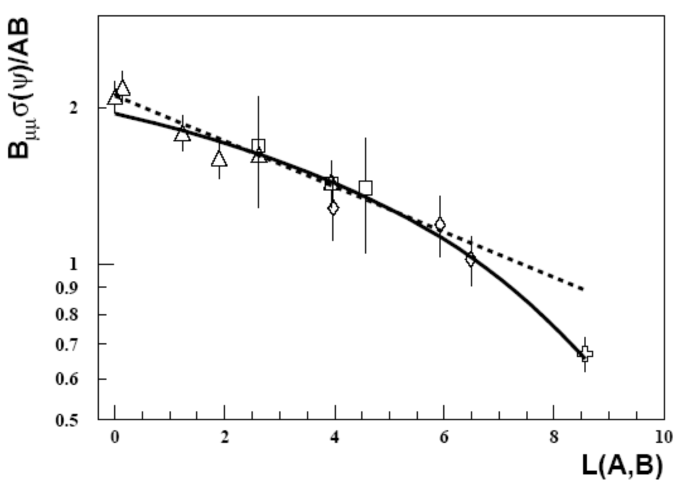


Figure 2. J/ψ cross section to $\mu^+\mu^-$

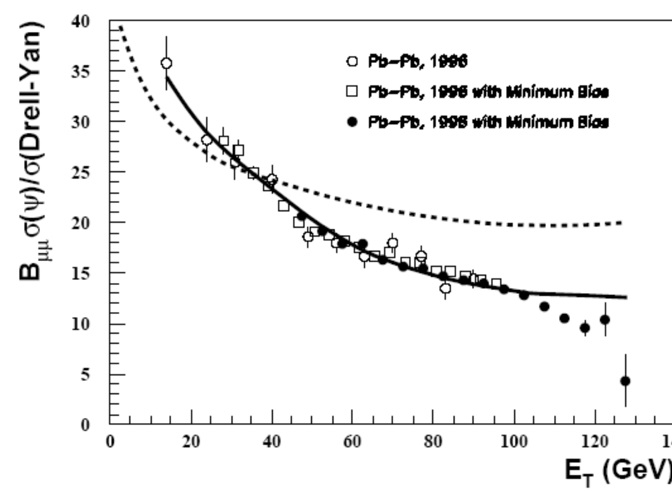


Figure 3. Ratio of J/ψ over Drell-Yan

II: (Anormal) Suppression

Quarkonia at finite temperature: general stuff

« Real time » QCD on the Lattice ! or Matsui & Satz on the Lattice !

Two point retarded and advanced functions for the mesonic channel H:

$$D_H^{>}(x_0,\vec{x},T) = \left\langle J_H(x_0,\vec{x}), J_H(0,\vec{0}) \right\rangle_T \quad \text{and} \quad D_H^{<}(x_0,\vec{x},T) = \left\langle J_H(0,\vec{0}), J_H(x_0,\vec{x}) \right\rangle_T$$

Related by KMS condition, so that any combination inholds the same information about mesonic propagation in a heat bath.

Spectral function :

$$\sigma_H(p_0,\vec{p},T) = \int \frac{d^4x}{(2\pi)^5} \left[D_H^{>}(x_0,\vec{x},T) - D_H^{<}(x_0,\vec{x},T) \right] e^{ipx}$$

Quarkonia at finite temperature: general stuff

A stable mesonic state contributes a δ function-like to the spectral function:

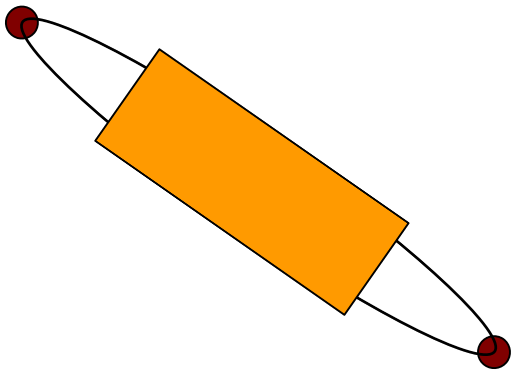
$$\sigma_H(p_0,\vec{p},T) = \left|\langle 0 | J_H | H \rangle\right|^2 \varepsilon(p_0)\, \delta(p^2\text{-}m^2)$$

For an unstable particle: smoother peak (Breit-Wigner).

⇒ Program is clear:

1. Choose your channel:

$$J_H = \begin{array}{lll} \bar{c}c & {}^3P_0 & \chi_c^0 \\ \bar{c}\gamma_5 c & {}^1S_0 & \eta_c \\ \bar{c}\gamma_\mu c & {}^3S_1 & J/\psi \\ \bar{c}\gamma_\mu\gamma_5 c & {}^3P_1 & \chi_c^1 \end{array}$$



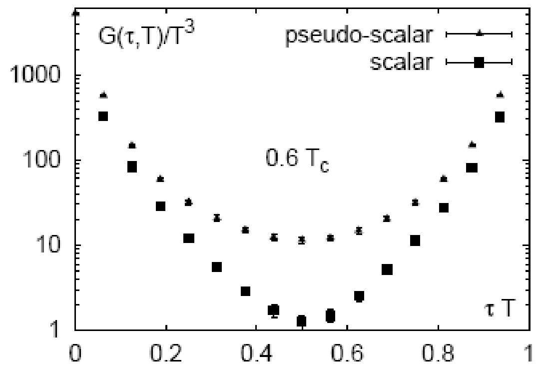
2. Evaluate the two point functions and then the spectral function,…

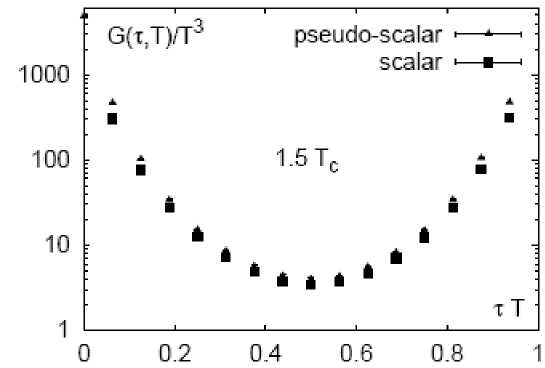
3. …and look at the hidden charm mesons.

Quarkonia at finite temperature: Lattice implementation

Euclidean time:

$$G_H(\tau,\vec{p}) = D^>(-i\tau,\vec{p}) = \int d^3x e^{i\vec{p}.\vec{x}} \langle T_\tau J_H(\tau,\vec{x}) J_H(0,\vec{0})\rangle_T$$





Results for *quenched* QCD (Lattice too small for light quarks to live !!!)

Key relation:

$$G_H(\tau,\vec{p}) = \int_0^\infty d\omega \sigma_H(\omega,\vec{p}) \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}$$

Ill-defined inverse problem (although positiveness of σ helps)

Quarkonia at finite temperature: Lattice implementation

<u>The Breakthrough:</u> Maximum Entropy Method (Y. Nakahara, M. Asakawa and T. Hatsuda, Phys. Rev. D 60, 091503 (1999), Prog. Part. Nucl. Phys. 46, 459 (2001))

Minimize the « free energy » $L - \alpha S$, where

- $L = \dfrac{\chi^2}{2}$ is the likelihood
- $S = \int_0^\infty d\omega[\sigma(\omega) - m(\omega) - \sigma(\omega)\log(\sigma(\omega)/m(\omega))]$ is the Shannon entropy

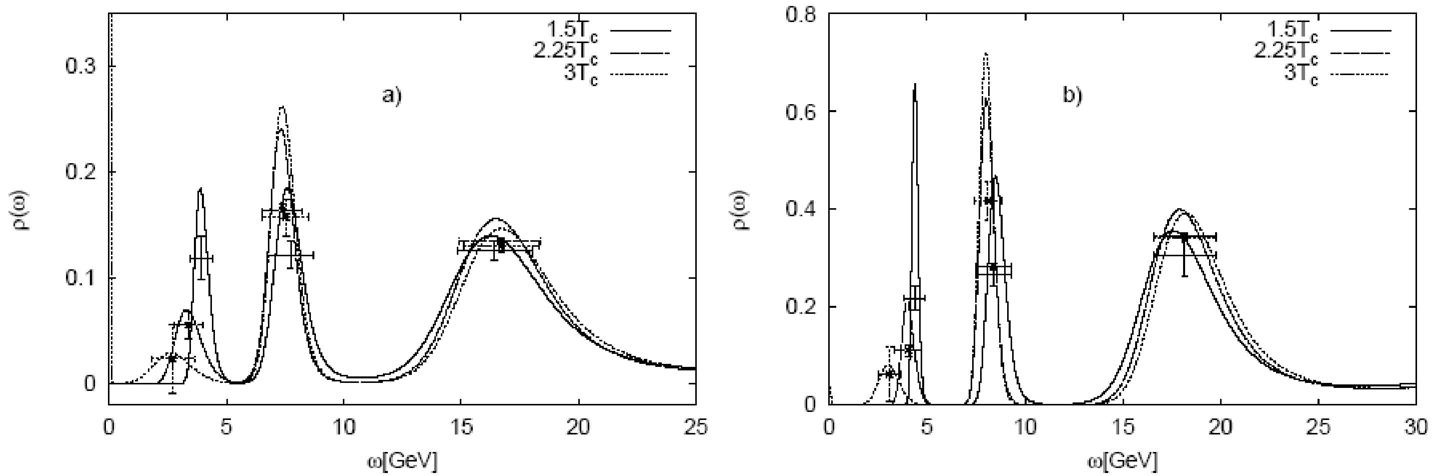


Fig. 7.6: Spectral functions above deconfinement for (a) pseudo-scalar and (b) vector channels [39]. Here lattice spacing $a \approx 0.02$ fm and $m_{J/\psi} \approx 3.6$ GeV.

Quarkonia at finite temperature: Lattice implementation

Essential results:

1. J/ψ and η_c peaks are significant up to $T_D \approx 1.5\ T_c$; masses deviate little from their vacuum values.
2. Other channels exhibit no resonance from $T_D \approx 1.1\ T_c$ on (screening more efficient, due to larger radii).
3. Using extended operator, Umeda, K. Nomura and H. Matsufuru (hep-lat/0211003), could extract some widths:

$$
\begin{aligned}
{}^1S_0 : \Gamma(T = 1.08\, T_c) &= 0.12 \pm 0.03\,\mathrm{GeV}, \\
{}^3S_1 : \Gamma(T = 1.08\, T_c) &= 0.21 \pm 0.03\,\mathrm{GeV}.
\end{aligned}
$$

4. Some results for spectral functions at finite momentum.

Soon (hopefully):

$$
S_{QGP} \approx \exp\left(-\int_{\tau_0}^{\tau_c} \Gamma(T(\tau))\, d\tau\right) \quad \text{if } T_0 < T_D
$$

$$
S_{QGP} \approx 0 \quad \text{if } T_0 > T_D
$$

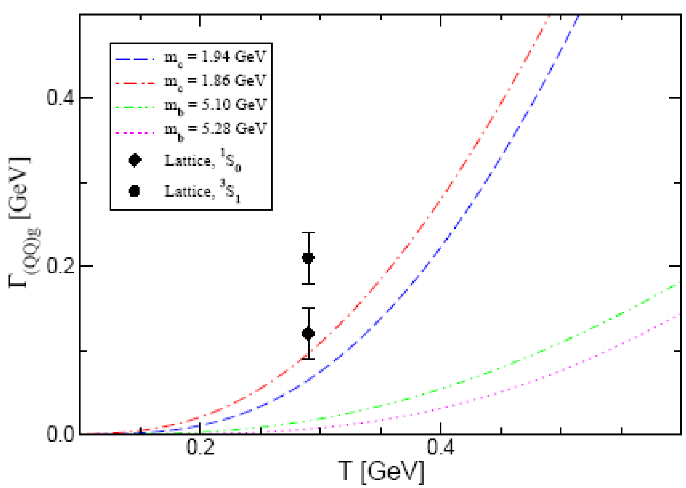
Consequences for A-A collisions

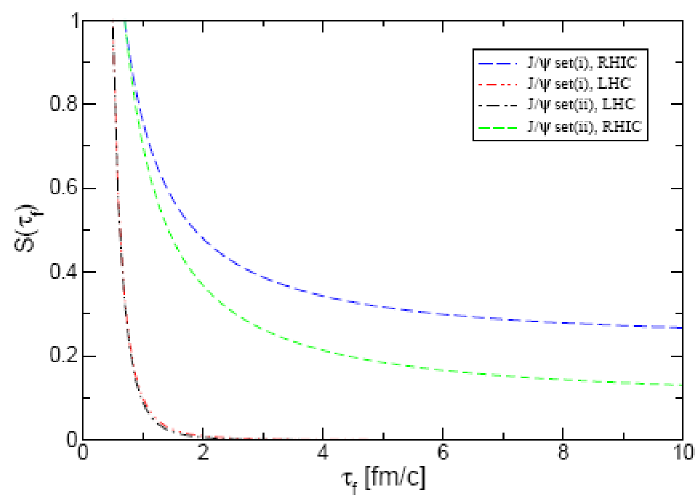
Today:

- Losely bound states should be dissociated mostly by thermal activation (Kharzeev, McLerran and Satz)
- Deeply bound states a dissociated by gluon impact, with dissociation cross section (Bhanot and Peskin):

$$\sigma_{(Q\overline{Q})g}(\omega) = \frac{2^{11}}{3^4}\alpha_s \pi a_0^2 \frac{(\omega/\varepsilon(0) - 1)^{3/2}}{(\omega/\varepsilon(0))^5}\Theta(\omega - \varepsilon(0))$$

- Considering a heat bath of massless gluons at temperature T distributed according to $n_g(\omega)$, one gets $\Gamma_{(Q\overline{Q})g}(T) = \langle \sigma_{(Q\overline{Q})g}(\omega) n_g(\omega) \rangle_T$





III: Secondary production of quarkonia…

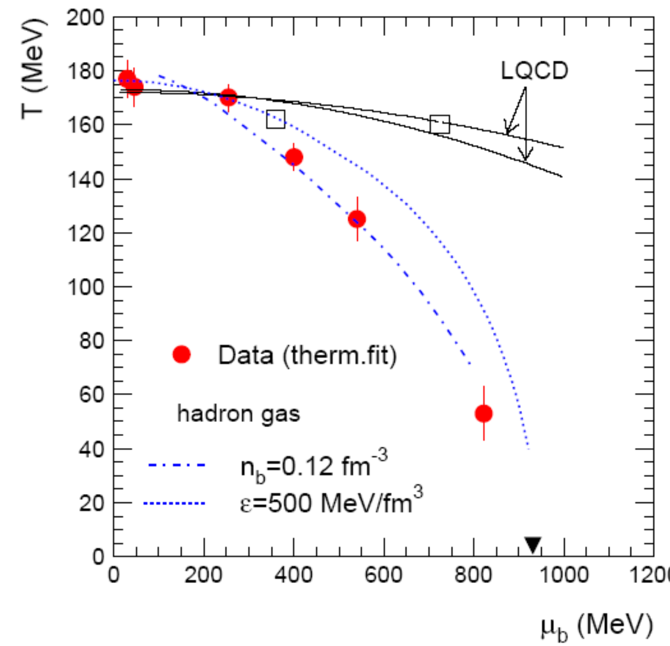
…Still more uncertainties ?

Statistical Hadronization Model
Braun-Munzinger, Stachel, Redlich, Andronic

P.Braun-Munzinger, J.Stachel, PLB 490 (2000) 196

- all charm quarks are produced in primary hard collisions
- ... and thermalize in QGP (thermal, but not chemical equilibrium)
- charmed hadrons are formed at freeze-out together with all hadrons (stat. laws, quantum no conservation; stat. hadronization $\neq$ coalescence)

freeze-out is at phase boundary



Implications

- no J/ψ surv. in QGP (full screening)
  LQCD: J/ψ may survive up to $1.5T_c$
- QGP was a stage of the collision

Method and inputs

- Thermal model calculation (grand canonical) T, μ_B: $\rightarrow n_X^{th}$
- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$
- $N_{c\bar{c}} << 1 \rightarrow$ Canonical (J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137):

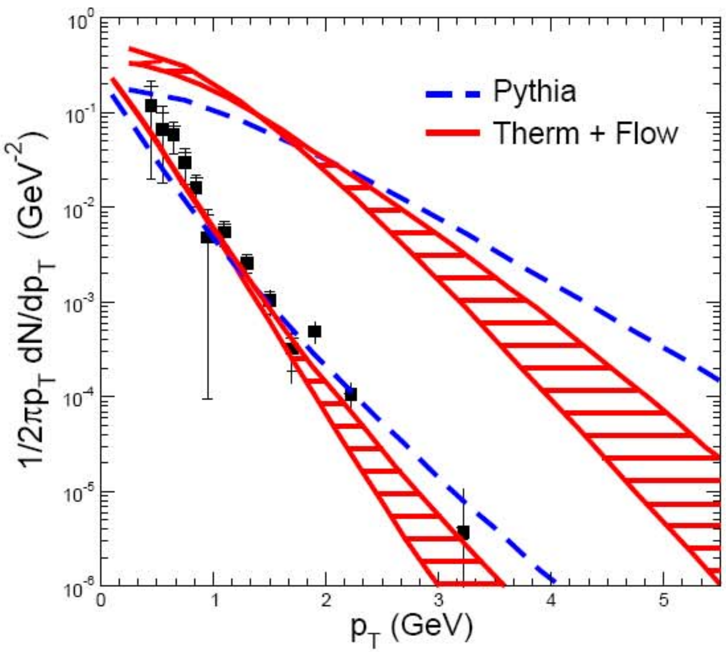
$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c$$

Outcome: $N_D = g_c V n_D^{th} I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

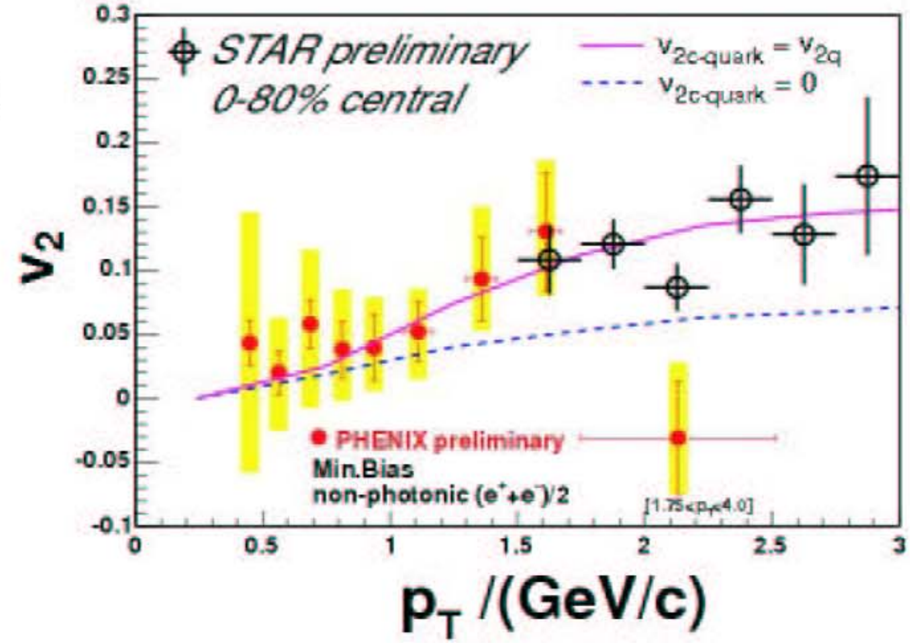
Inputs: T, μ_B, $\quad V = N_{ch}^{exp}/n_{ch}^{th}$, $\quad N_{c\bar{c}}^{dir}$ (pQCD)

Charm thermalization

- Batsouli et al., PLB 557 (2003) 26
  p_t electrons from D; v_2 proposed
- Greco, Ko, Rapp, PLB 595 (2004) 202
  coalescence of c quarks: p_t, $v_2 \Rightarrow$



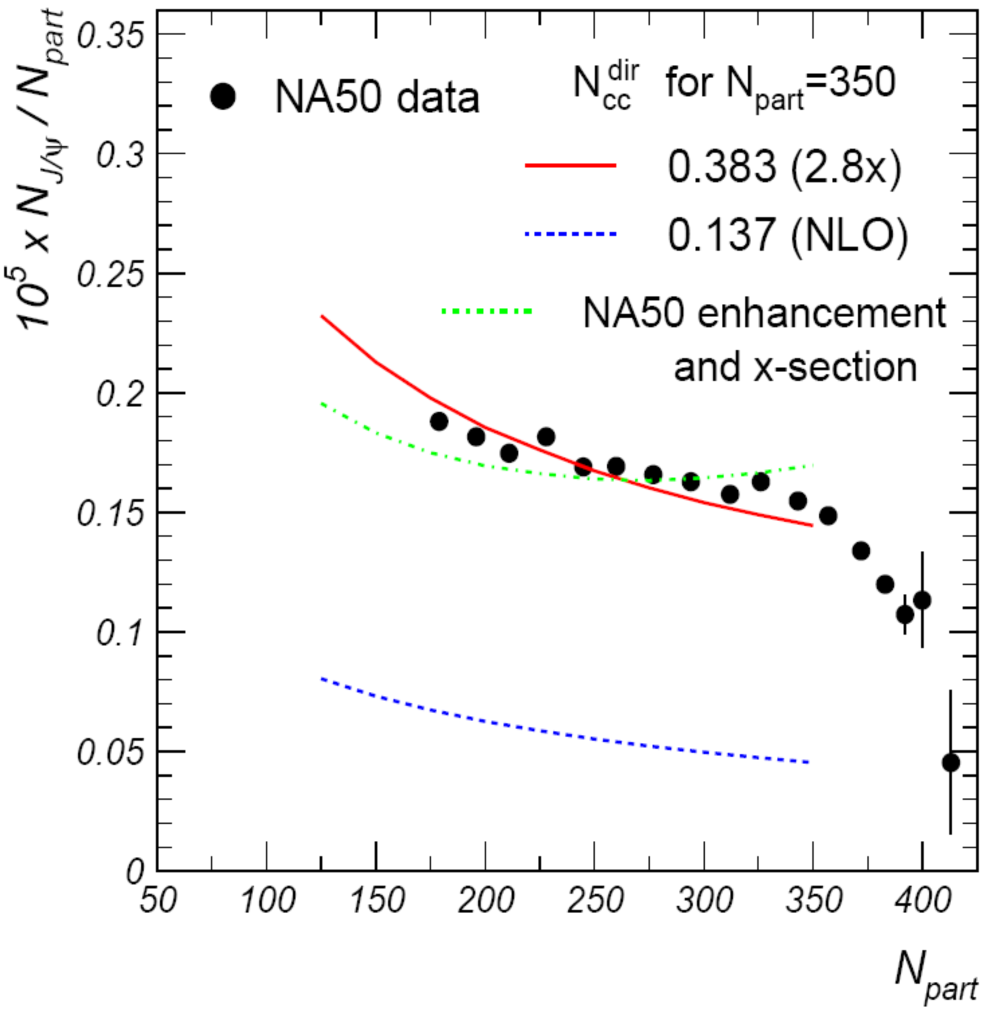
F.Laue, nucl-ex/0111007



- earlier c-quark coalescence v_2:
  Lin,Molnar, PRC 68 (2003) 044901

there is good hope that charm quarks thermalize (in QGP)

J/ψ at SPS (4π)



$N_{c\bar{c}}$ enhancement (2.8×NLO)

to explain **NA50 data (MinB):**

J.Gosset et al., EPJ C13 (2000) 63

NA50, PLB 450 (1999) 456; PLB 477 (2000) 28

NA50 enhancement (interm. mass):

NA50, NPA 698 (2002) 539c

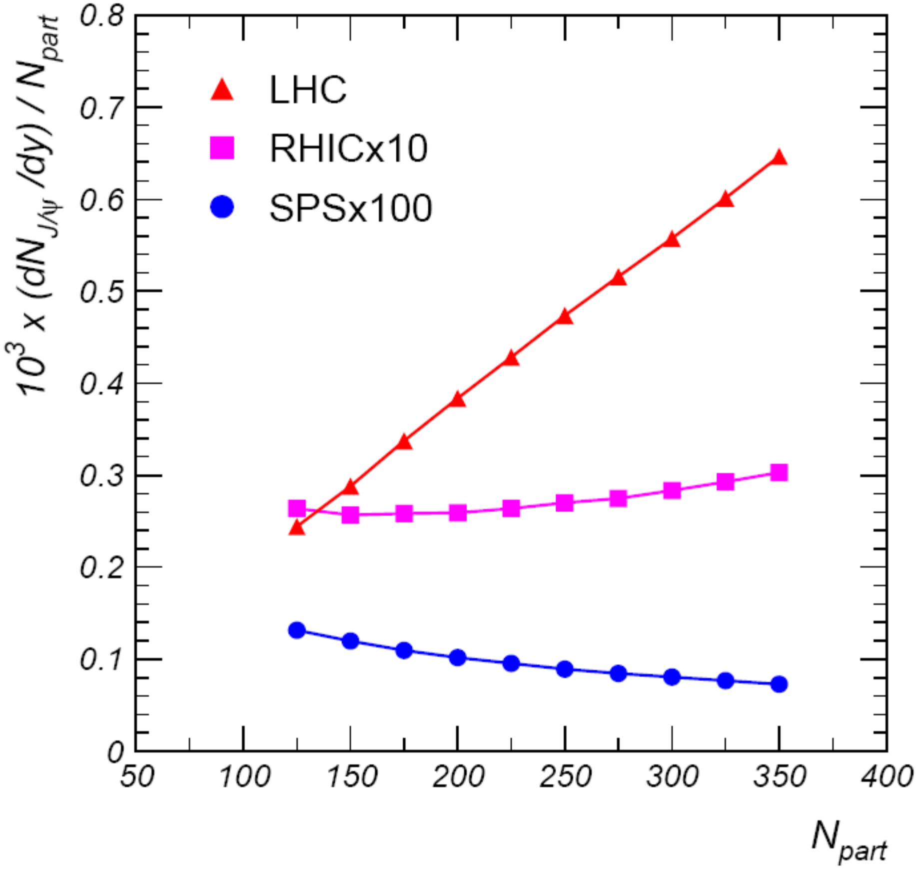
$\sigma_{pp} \simeq 1.6\times$NLO (pp, 450 GeV)
2× for N_{part}=250

attributed to charm → agreement

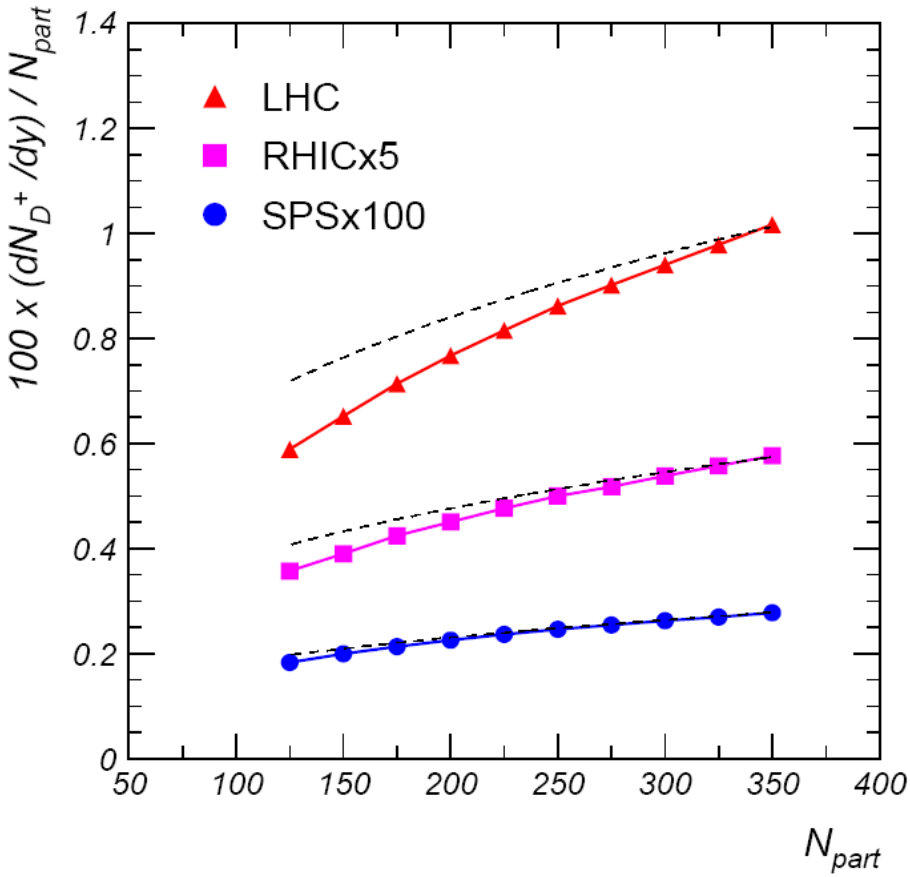
alternative: thermal radiation
Rapp, Shuryak, PLB 473 (2000) 13
Gallmeister et al., PLB 473 (2000) 20

Centrality dependences at SPS, RHIC and LHC

$$\mathrm{d}N_{J/\psi}/\mathrm{d}y = g_c^2 n_{J/\psi}^{th} V_{\Delta y=1}$$



$$\mathrm{d}N_{D+}/\mathrm{d}y = g_c I_1/I_0 n_{D+}^{th} V_{\Delta y=1}$$



J/ψ: very different trends (besides yields) in the 3 regimes

Summary and outlook

- A simple model that starts from QGP and hadronizes charm quarks (which were produced exclusively in hard collisions and thermalize in QGP)
- Centrality dependence of J/ψ is explained at SPS... ☹ with charm enhancement ($\sim 3\times$ NLO pQCD)
- Definite predictions on open and hidden charm observables... which can be tested experimentally (at RHIC right now)
- The inputs (NLO pQCD charm cross sections) are not (yet?) rock-solid more theoretical AND experimental insights are needed
- There are differences between various implementations inputs need clarifications to understand the intrinsic differences
- Charm is charming in the models, but difficult in experiments... hopefully (SPS) RHIC and LHC will contribute to further excitement

Kinetic Formation Model
Thews, Rafelski & Schroedter
Thews & Mangano

- The model in a nutshell
- Results for RHIC and LHC
- ☺ and ☹ (from my view point)

<u>Refs':</u>

Thews R L, Schroedter M and Rafelski J 2001 Phys. Rev. C 63 054905 [arXiv:hep-ph/0007323]

Thews R L 2002 Nucl. Phys. A 702 341 [arXiv:hep-ph/0111015]

…

Proceedings of Pan American Advanced Studies Institute on New States of Matter in Hadronic Interactions (**hep-ph/0206179**)

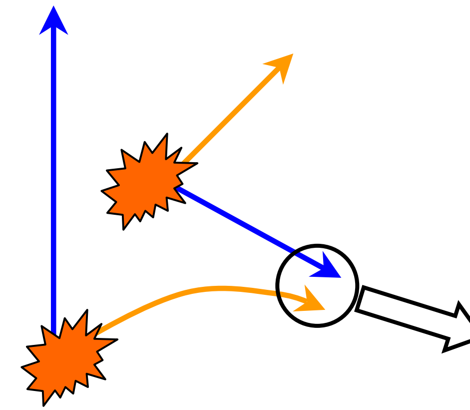
Journal of Phys G30 (2004) S369-S374 (SQM03)

Cern Yellow Report (Hard probes)

SQM04 (to appear in Journal of Phys G30)

Thews, Rafelski & Schroedter: Main ideas

Main focus: « …a direct extrapolation of anomalous suppression (of J/ψ) from the SPS energy range could be supplanted by a new formation mechanism fueled by the presence of multiple pairs of charm quarks in each nuclear collision at sufficiently high energy».



Uncorrelated quarks recombination => quadratic dependence in N_c. For a given c quark, the probability P to combine in order to form a J/ψ is

$$P \, \alpha \, \frac{N_{\bar{c}}}{N_{\bar{u},\bar{d},\bar{s}}} \, \alpha \, \frac{N_{c\bar{c}}}{N_{\mathrm{ch}}}.$$

True for each c-quark available (N_c c quarks available) => Number of J/ψ's through (uncorrelated) c-cbar « coalescence » :

$$N_{J/\psi} \, \alpha \, \frac{N_{c\bar{c}}^2}{N_{\mathrm{ch}}}$$

How much is α ???

Thews, Rafelski & Schroedter: Main ingredients

Kinetic formation model (KFM) considers J/ψ formation within the region of deconfinement, and calculates the net number remaining at hadronization due to a competition between formation and breakup reactions.

1. Bound J/ψ state (or J/ψ-like) far above the transition temperature (if c and cbar should recombine, the most efficient way is when they are still « close » together, i.e. when density in c-quark is high.

2. J/ψ can be destroyed via gluo-dissociation: g + J/ψ → c + cbar (σ_{dis} evaluated via OPE, à la Bhanot and Peskin), and formed via the reverse process (σ_{form} evaluated from σ_{dis} via detailed balance).

3. Distributions of c, cbar and J/ψ are taken either equilibrated or as those of initial particles (from cross section → reaction rates).

4. Rate equation: $$\frac{dN_{J/\psi}(\tau)}{d\tau} = \frac{\lambda_F(\tau)}{V(\tau)} N_c N_{\bar{c}} - \lambda_D(\tau)\rho_g(\tau) N_{J/\psi}(\tau)$$

Where $\lambda_{D/F} = \langle v_{rel}\,\sigma_{dis/form} \rangle$, V(τ) is the volume of deconfined spatial region and ρ_g is the gluon density

Thews, Rafelski & Schroedter: Simple solution

Analytical solution ☺ :

$$N_{J/\psi}(\tau_f) = \boxed{N_{J/\psi}(\tau_0) \times S(\tau_0, \tau_f)} + \boxed{N_{c\bar{c}}^2 \int_{\tau_0}^{\tau_f} \frac{\lambda_F(\tau)}{V(\tau)} \times S(\tau, \tau_f)\, d\tau}$$

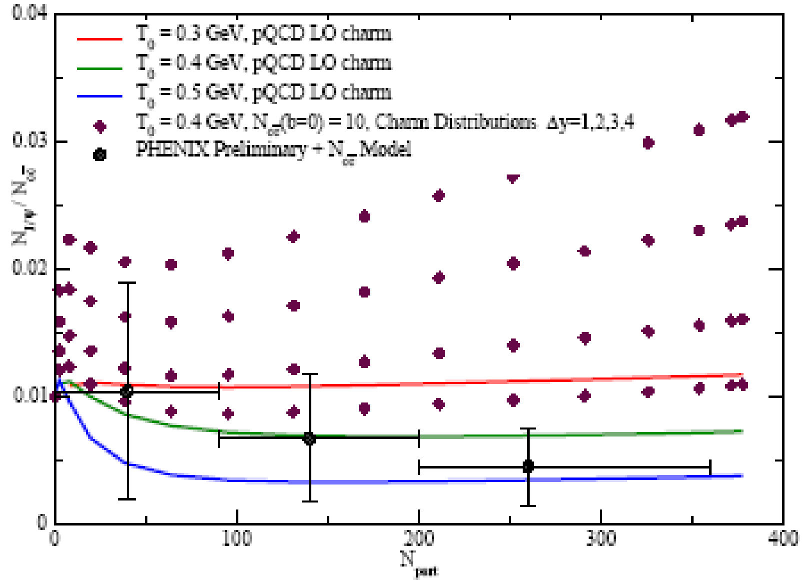
Suppression of prompt J/ψ's

Production from (initially) uncorrelated c-cbar pairs

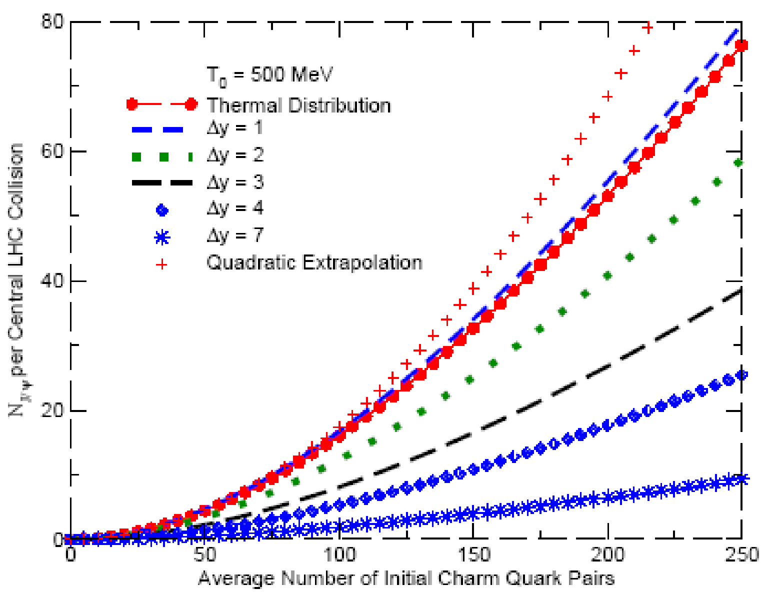
with : $S(\tau, \tau_f) = \exp\left(- \int_{\tau}^{\tau_f} \lambda_D(\tau') \rho_g(\tau') d\tau' \right)$ (gluo-dissociation)

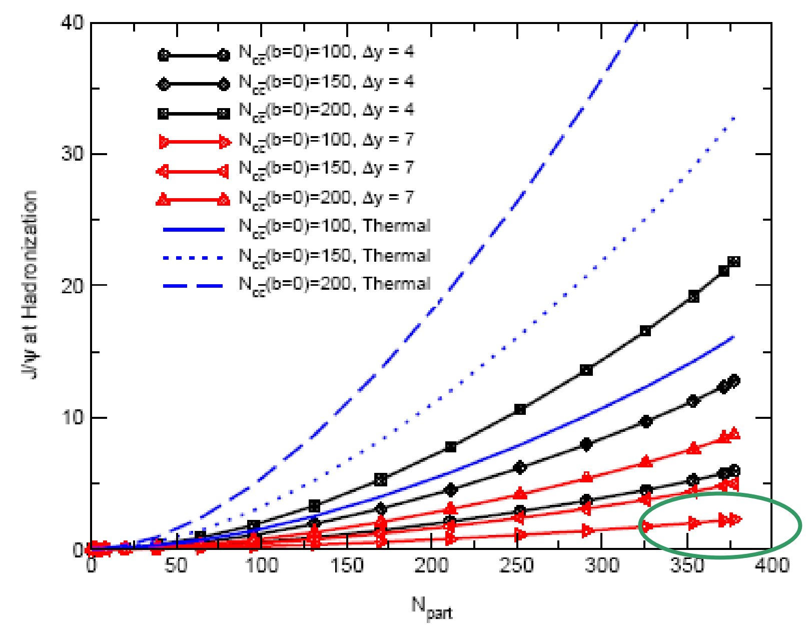
$N_{J/\psi}(\tau_f)$ becomes quadratic in $N_{c\bar{c}}$ provided the first term is negligeable.

Thews, Rafelski & Schroedter: Results



Quadratic dependence





Thews et al: ☺ and ☹

☺

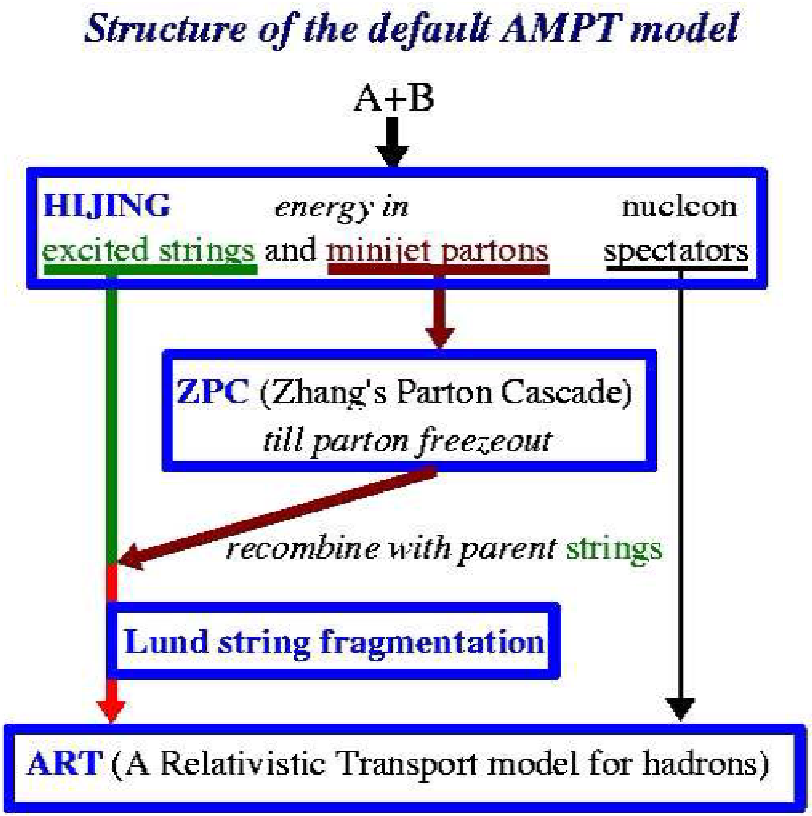
1. Simple, but may contain the essential physics as far as total quarkonia production is concerned.
2. Efficient ⇒ facilitates quick parametric study

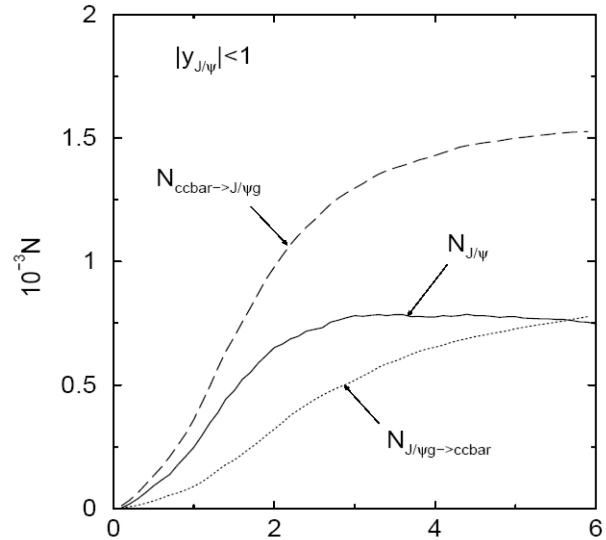
☹

1. Huge dependence w.r.t. the distributions of c quarks and quarkonia, which are inputs of the model and frozen
2. No realistic scenario of A+B collision
3. Global description (no dependence vs r neither p), and thus no differential spectra

Some improvement w.r.t. these problems have been given by Gossiaux et al. (SQM04, hep-ph0411324)

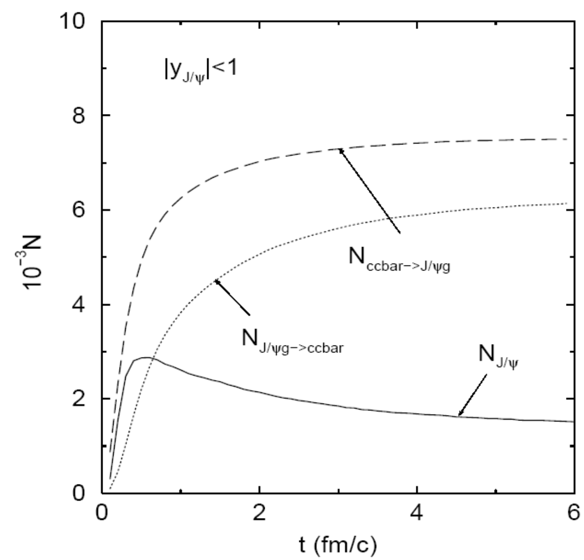
AMPT
(A Multi-Phase Transport Model for Relativistic Heavy Ion Collisions)
Zhang, Ko, Li & Lin





With color screening

Without color screening



"Scatterings among partons are modeled by Zhang's parton cascade (ZPC) which at present includes only two-body scatterings with cross sections obtained from the pQCD with screening masses."

IV: concluding remarks

1. With increasing colliding energy, one expects prompt quarkonia to be more and more suppressed and final quarkonia to be produced more and more via delayed mechanisms implying uncorrelated and .
2. Therefore, some « problems » (unkown aspects of the charmonia production, interaction with initial non-equilibrated thermal color field,…) will have less impact on the charmonia production. ☺
3. Delayed production also implies less interaction between quarkonia and QGP, and perhaps no interaction at all (for instance in SHM). Should we still call J/ψ a « hard probe of QGP » ? ☹
4. « Delayed » Quarkonia are mostly sensitive to the QGP through the previous interaction of and with this state. In the future, the joint analysis of open and hidden charm will be much fruitful
5. Precise knowledge of (fully formed) charmed meson with other hadrons in the hadronic phase is the prerequisite to the understanding of the previous phases.