

J/ ψ production in pp and Heavy Ion Collisions

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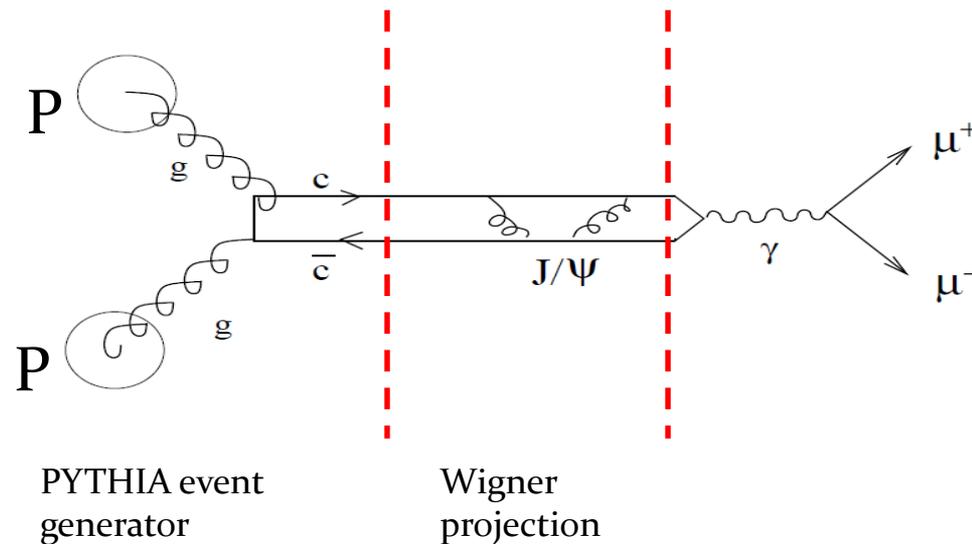
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J/ ψ production in p+p collisions

How to describe a composite object if perturbative QCD deals only with quarks and gluons

Need for **non perturbative** information/ assumptions.

Our approach: Wigner density formalism (as successful at lower energies)



Wigner Density Formalism

Interaction depends on relative coordinates only, -> plane wave of CM

Starting point: Wave function (w.f.) of the relative motion of state i : $|\Phi_i\rangle$

w.f \rightarrow density matrix $|\Phi_i\rangle\langle\Phi_i|$

Fourier transform of density matrix in relative coord. \rightarrow Wigner density of $|\Phi_i\rangle$
(close to classical phase space density)

$$\Phi_i^W(\mathbf{r}, \mathbf{p}) = \int d^3y e^{i\mathbf{p}\cdot\mathbf{y}} \langle \mathbf{r} - \frac{1}{2}\mathbf{y} | \Phi_i \rangle \langle \Phi_i | \mathbf{r} + \frac{1}{2}\mathbf{y} \rangle .$$

$$\mathbf{R} = \frac{\mathbf{r}_1 + \mathbf{r}_2}{2}, \quad \mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2,$$

$$\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2, \quad \mathbf{p} = \frac{\mathbf{p}_1 - \mathbf{p}_2}{2}.$$

$$n_i(\mathbf{R}, \mathbf{P}) = \int d^3r d^3p \Phi_i^W(\mathbf{r}, \mathbf{p}) n^{(2)}(\mathbf{r}_1, \mathbf{p}_1, \mathbf{r}_2, \mathbf{p}_2)$$

$n^{(2)}(\mathbf{r}_1, \mathbf{p}_1, \mathbf{r}_2, \mathbf{p}_2)$ two body c cbar density matrix

In momentum space given by PYTHIA (Innsbruck tune)

In coordinate space $\sim r^2 \exp\left(-\frac{r^2}{2\delta^2}\right)$ $\delta^2 = \langle r^2 \rangle / 3 = 4 / (3m_c^2)$

Wigner Density Formalism

If there are N c cbar pairs in the system the phase space density of state $|\Phi_i\rangle$

$$n_i(\mathbf{R}, \mathbf{P}) = \sum \int \frac{d^3 r d^3 p}{(2\pi)^3} \Phi_i^W(\mathbf{r}, \mathbf{p}) \prod_j \int \frac{d^3 r_j d^3 p_j}{(2\pi)^3} n^{(N)}(\mathbf{r}_1, \mathbf{p}_1, \mathbf{r}_2, \mathbf{p}_2, \dots, \mathbf{r}_N, \mathbf{p}_N) \quad (5)$$

Sum over all possible c cbar pairs;

Product over all $N-2$ left particles.

Multiplicity of $|\Phi_i\rangle$

$$P_i = \int \frac{d^3 R d^3 P}{(2\pi)^3} n_i(\mathbf{R}, \mathbf{P})$$

Momentum distribution

$$\frac{dP_i}{d^3 P} = \int \frac{d^3 R}{(2\pi)^3} n_i(\mathbf{R}, \mathbf{P})$$

Wigner Density Formalism

The Wigner density of the state $|\Phi_i\rangle$ is different for S and P states

We choose the simplest possible parametrization

$$\Phi_S^W(\mathbf{r}, \mathbf{p}) = 8 \frac{D}{d_1 d_2} \exp \left[-\frac{r^2}{\sigma^2} - \sigma^2 p^2 \right],$$

$$\Phi_P^W(\mathbf{r}, \mathbf{p}) = \frac{16}{3} \frac{D}{d_1 d_2} \left(\frac{r^2}{\sigma^2} - \frac{3}{2} + \sigma^2 p^2 \right) \times \exp \left[-\frac{r^2}{\sigma^2} - \sigma^2 p^2 \right],$$

$$r = r_c - r_{\bar{c}}$$

$$p = \frac{p_c - p_{\bar{c}}}{2}$$

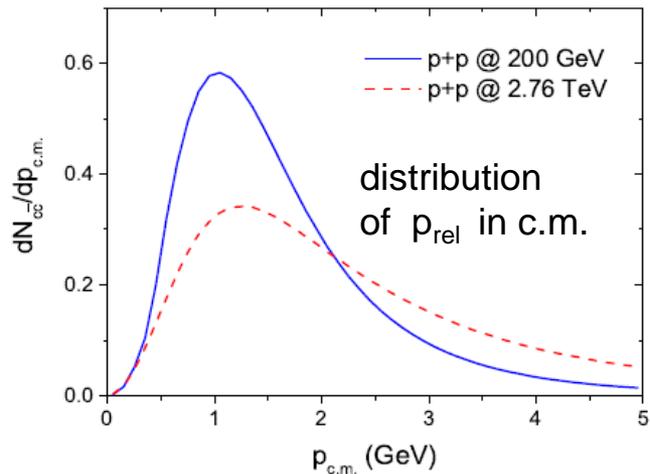
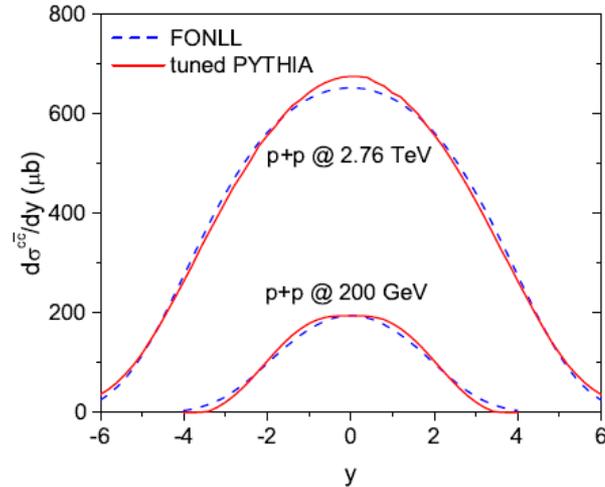
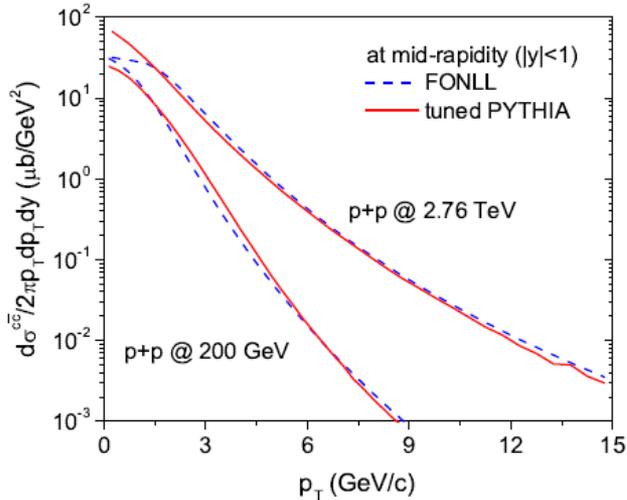
D : degeneracy of Φ
 d_1 : degeneracy of c
 d_2 : degeneracy of cbar
 $\sigma \sim$ radius of Φ

Where σ reproduces the rms radius of the vacuum c cbar state $|\Phi_i\rangle$

$$\Phi = J/\psi(1S), \quad \chi_c(1P), \quad \psi'(2S)$$

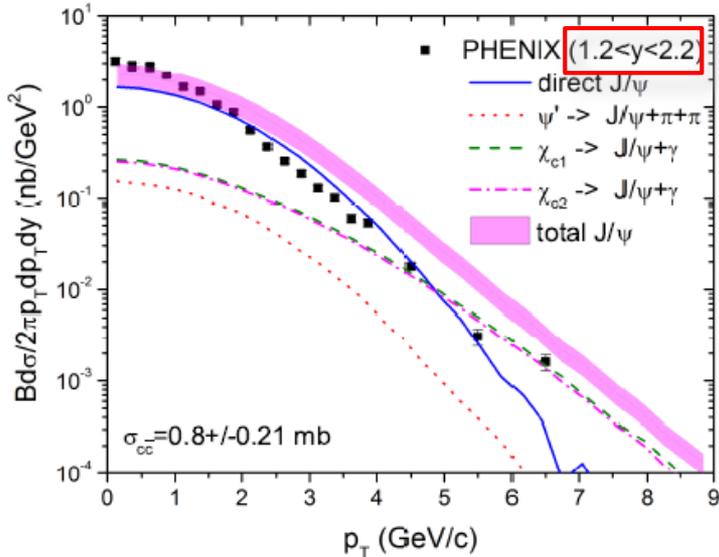
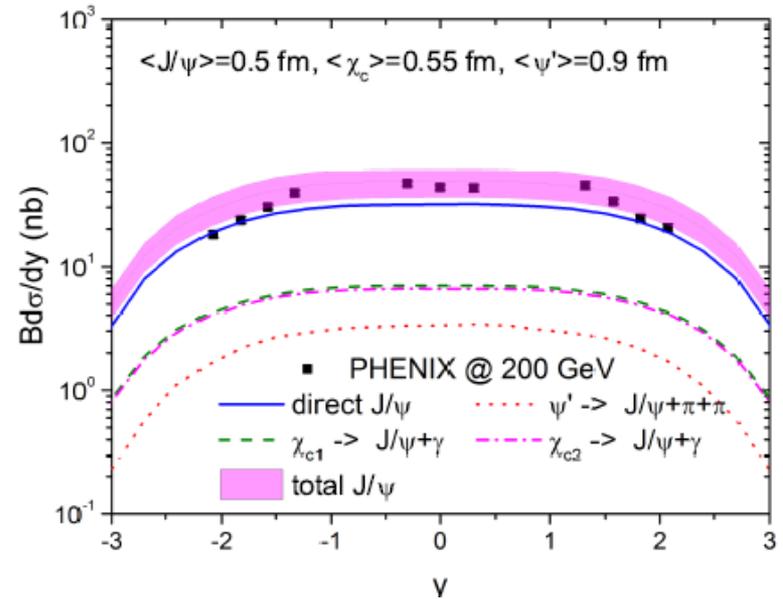
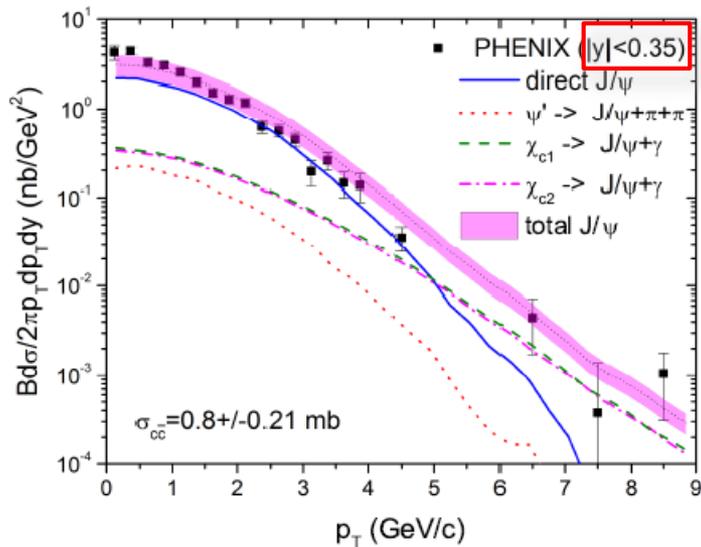
Wigner Density Formalism

The (Innsbruck) tuned PYTHIA reproduces FONLL calculation but in addition it keeps the $c\bar{c}$ correlation (not known in FONLL)



quite different relative momenta at RHIC and LHC

pp: comparison with Phenix data

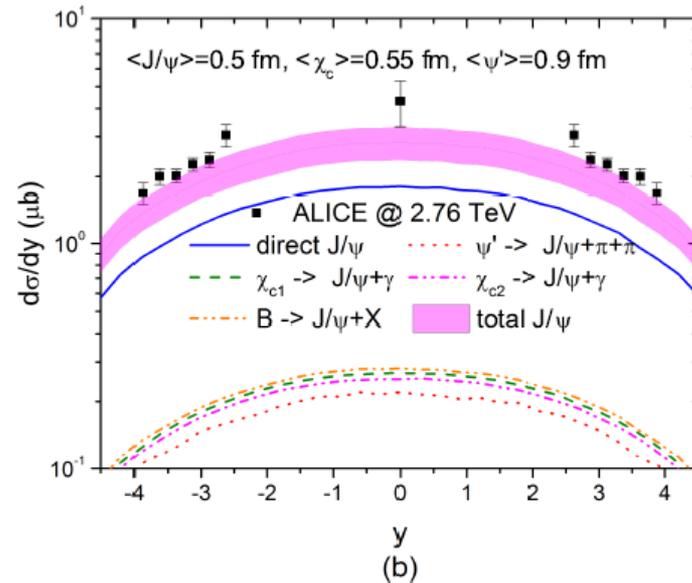
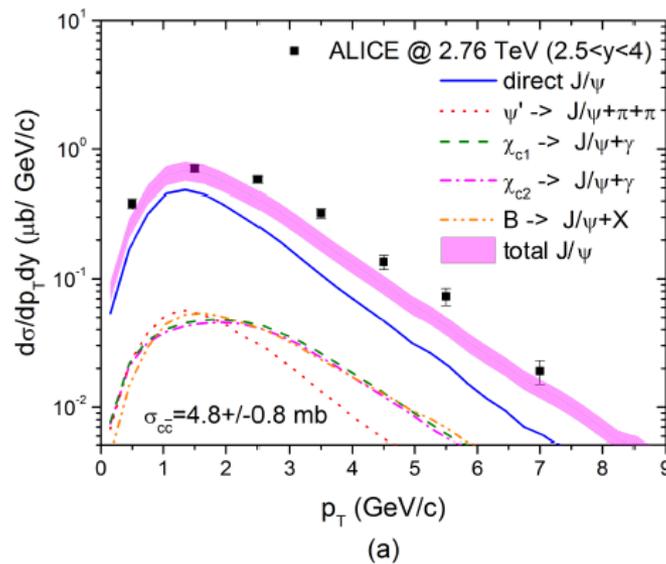


Good agreement for
 rapidity spectrum
 pt spectrum at $|y| < 0.35$
 pt spectrum at $1.25 < |y| < 2.2$

Feeding at RHIC not very important

pp: comparison with ALICE data

same charmonia radii as at RHIC



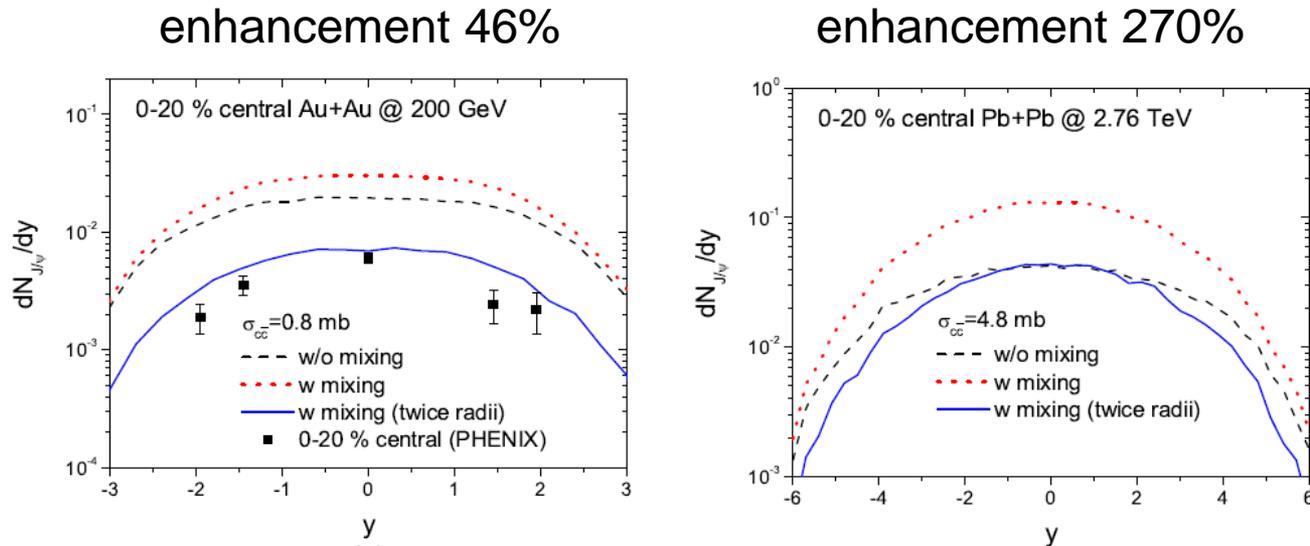
Important contribution of feeding

The observed J/ψ data in pp at RHIC and LHC can be well described by Wigner dens.

AA collisions

AA: without any QGP

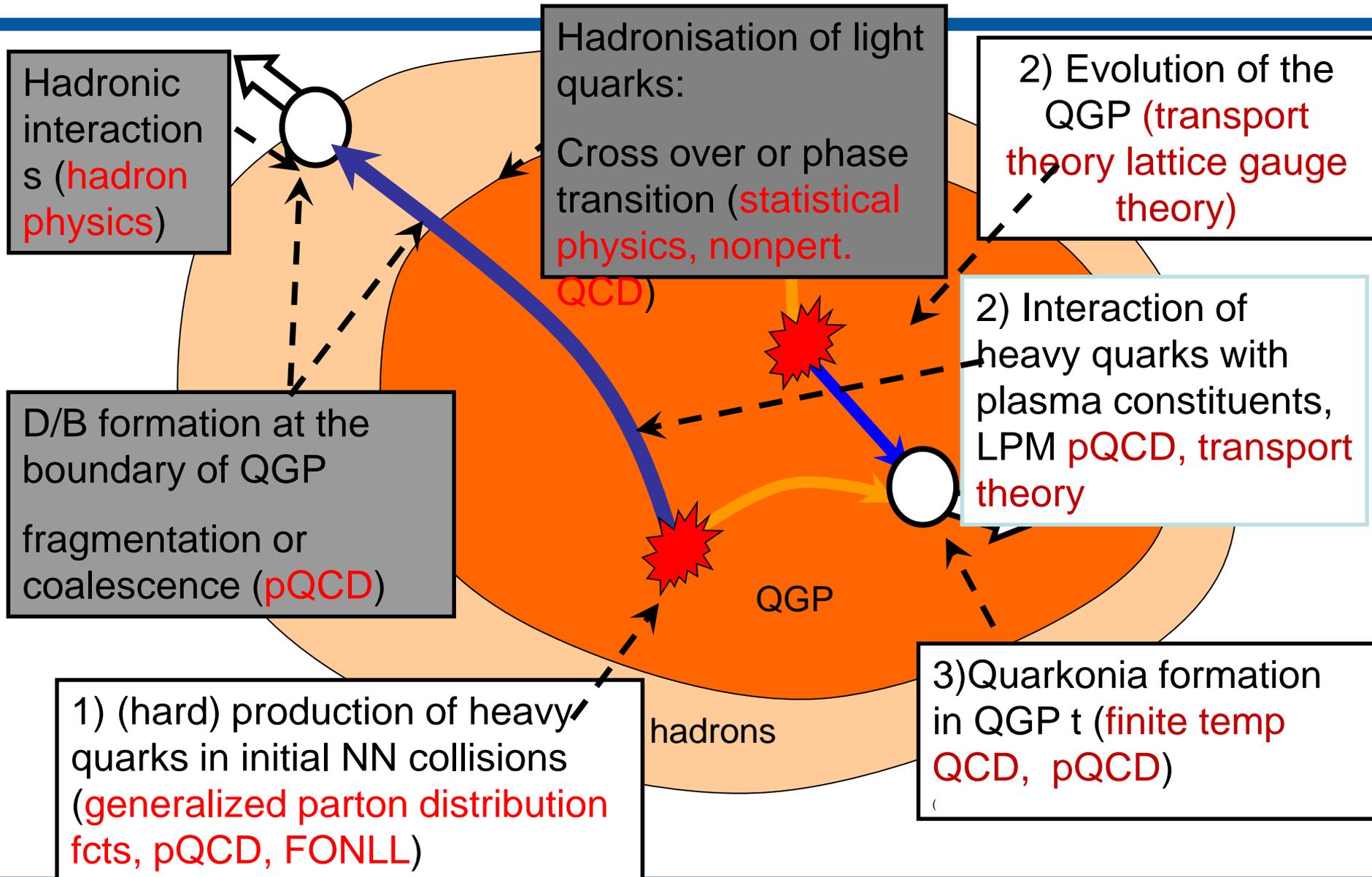
Without the formation of a QGP we expect a (large) **enhancement of the J/ψ production** because c and $c\bar{c}$ **from different vertices** can form a J/ψ .



but experiments show suppression

Reason: J/ψ production in HI collisions is a very complex process

Complexity of heavy quark physics in HI reactions



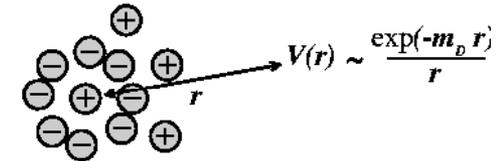
The different processes which influences the J/ψ yield

- Creation of heavy quarks (shadowing)
- J/ψ are first unstable in the quark gluon plasma and are created later
- c and cbar interact with the QGP
- c and cbar interact among themselves (<-lattice QCD)
- If QGP arrives at the dissociation temperature T_{diss} , stable J/ψ are possible
- J/ψ creation ends when the QGP thermalizes
- J/ψ can be further suppressed or created by hadronic interaction (task for the future -> Torres-Rincon)

The model we developed follows the time evolution of all c and cbar quarks based, as our pp calculation, on the Wigner density formalism
assumes that before and after the J/ψ formation
the c and cbar interact with the medium as those observed finally as D-mesons
the c and cbar interact among themselves
uses EPOS2 to describe the expanding QGP

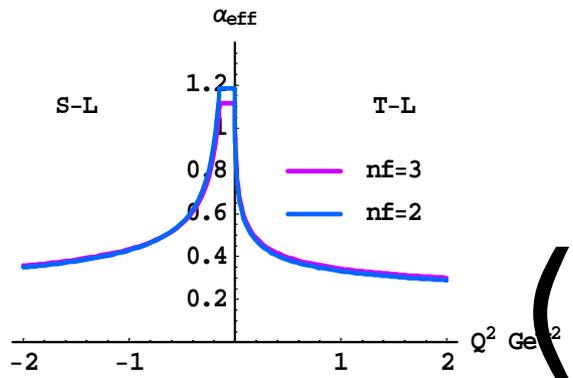
The interaction between HQ and q and g is described by Born type diagrams

$$\frac{d\sigma_F}{dt} = \frac{g^4}{\pi(s - M^2)^2} \left[\frac{(s - M^2)^2}{(t - \kappa m_D^2)^2} + \frac{s}{t - \kappa m_D^2} + \frac{1}{2} \right]$$



q/g is randomly chosen from a Fermi/Bose distribution with the hydro cell temperature

coupling constant and infrared screening are input



If t is small ($\ll T$) : Born has to be replaced by a **hard thermal loop (HTL)** approach

For $t > T$ Born approximation is (almost) ok

(Braaten and Thoma PRD44:1298,2625) for QED: Energy loss indep. of the **artificial scale t^*** which separates the regimes

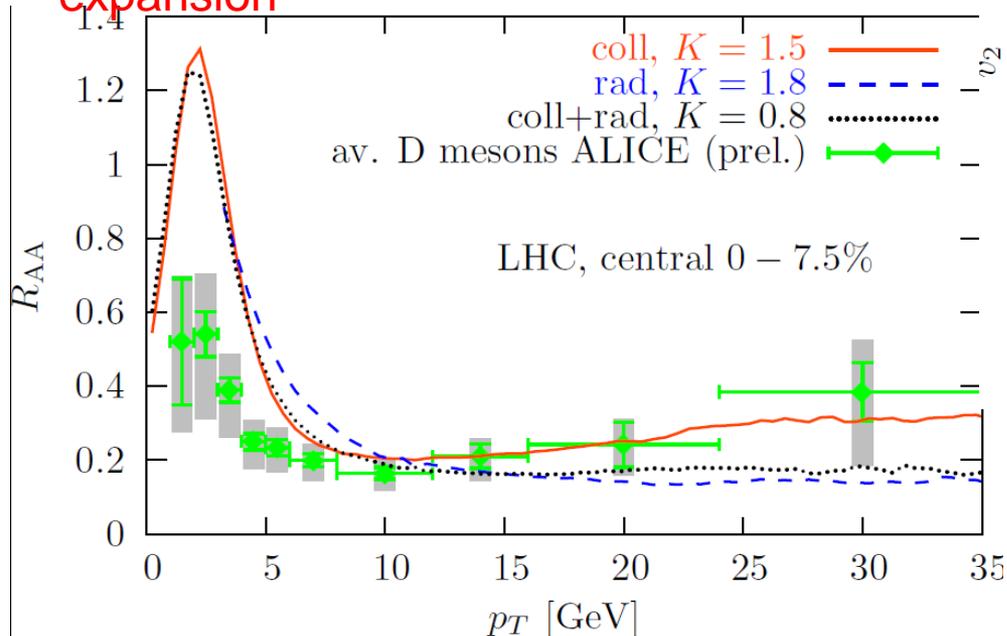
Extension to QCD (PRC78:014904)

$$\kappa \approx 0.2$$

Peshier 0801.0595
based on universality
constraint of Dokshitzer

D meson result

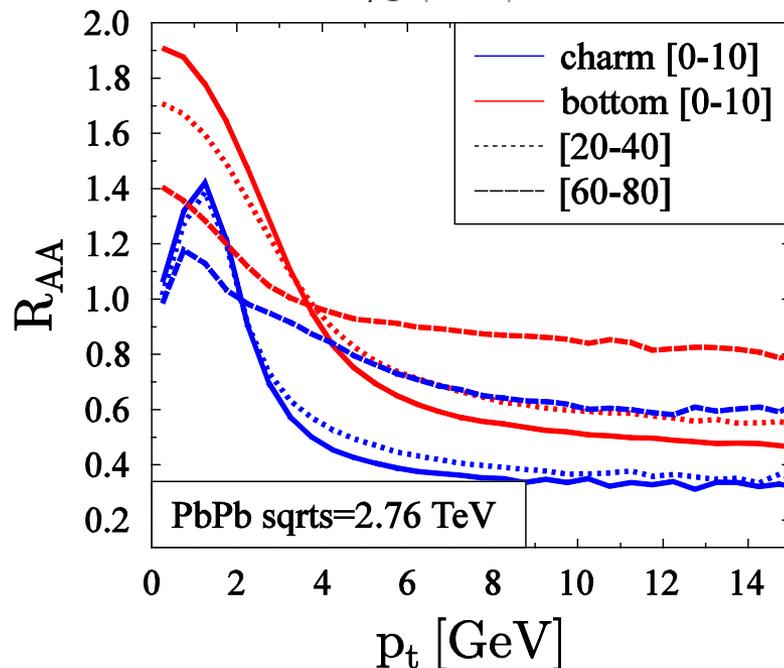
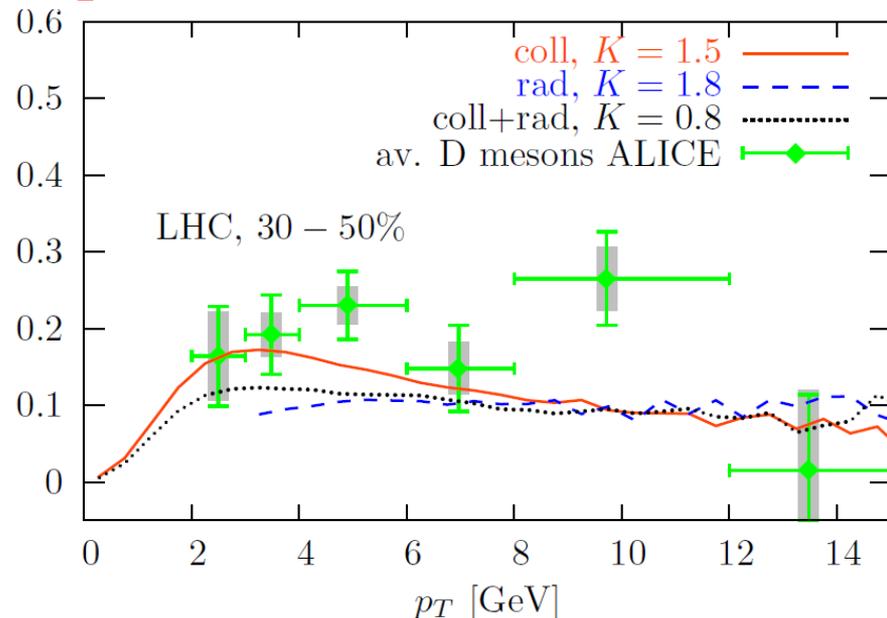
Energy loss tests the initial phase of the expansion



- 3 options :
- Collisions only K factor = 1.5
 - Collision and radiation K = 0.8
 - Radiation only K= 1.8

R_{AA} and v_2 for coll and coll + radiative about the same
B much more suppressed

v_2 tests the late stage of the expansion



J/ψ creation in heavy ion collisions

Starting point: [von Neumann equation](#) for the density matrix of all particles

$$\partial\rho_N/\partial t = -i[H, \rho_N] \quad \text{with} \quad H = \sum_i K_i + \sum_{i>j} V_{ij}$$

gives the probability that at time t the state Φ is produced:

$$P^\Phi(t) = \text{Tr}[\rho^\Phi \rho_N(t)] \quad \rho^\Phi = |\Psi^\Phi\rangle\langle\Psi^\Phi|$$

This is the solution if we could calculate the quantal $\rho^N(t)$

In our semiclassical approach (correlations are lost) preferable to calculate the rate

$$\Gamma^\Phi(t) = \frac{dP^\Phi}{dt} = \frac{d}{dt}\text{Tr}[\rho^\Phi \rho_N(t)] \quad P^\Phi(T) = \int_0^T \Gamma^\Phi(t) dt$$

For time independent ρ^Φ

$$\Gamma^\Phi = \text{Tr}(\rho^\Phi d\rho^N(t)/dt) = -i\text{Tr}(\rho^\Phi [H, \rho^N(t)]) = -i\text{Tr}(\rho^\Phi [U_{12}, \rho^N])$$

$$U_{12} = \sum_{j \leq 3} (V_{1j} + V_{2j})$$

J/ψ creation in heavy ion collisions

Heavy ion studies (BUU,QMD,PHSD) have shown that we obtain very satisfying results if we assume

$$W = \langle W^{\text{classic}} \rangle$$

We assume in addition that heavy quarks and QGP partons interact by collisions only

$$\frac{dP^\Phi(t)}{dt} = \prod_j^N \int d^3\mathbf{r}_j d^3\mathbf{p}_j W^\Phi \frac{d}{dt} W_N^c(t).$$

with

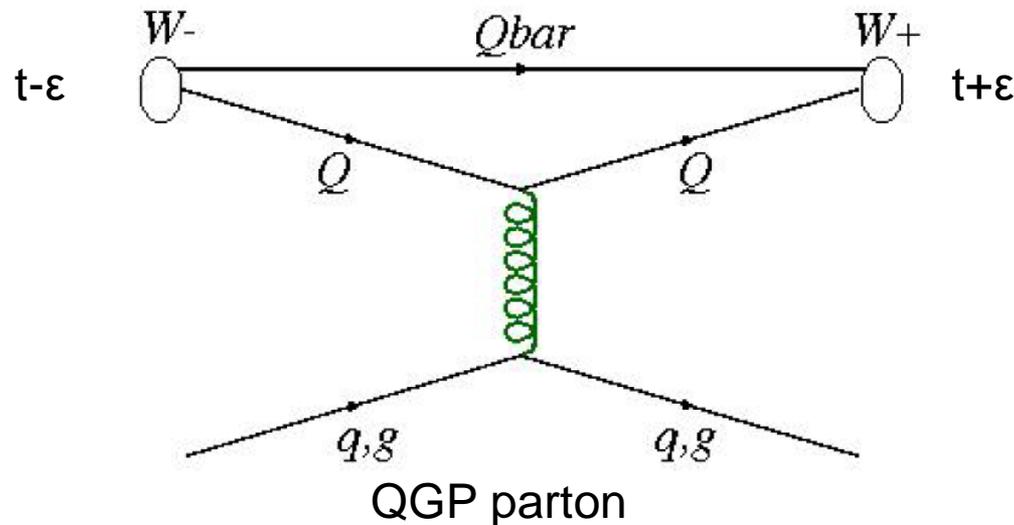
$$\begin{aligned} \frac{\partial}{\partial t} W_N^c(t) &= \sum_i v_i \cdot \partial_{r_i} W_N^c(\{\mathbf{r}\}, \{\mathbf{p}\}, t) \\ &+ \sum_{j \geq i} \sum_n \delta(t - t_{ij}(n)) \\ &\cdot (W_N^c(\{\mathbf{r}\}, \{\mathbf{p}\}, t + \epsilon) - W_N^c(\{\mathbf{r}\}, \{\mathbf{p}\}, t - \epsilon)). \end{aligned} \quad (19)$$

J/ψ creation in heavy ion collisions

If the collisions are point like in time and if $W^\Phi(\mathbf{r}_1, \mathbf{r}_2, \mathbf{p}_1, \mathbf{p}_2)$ is time independent

$$\Gamma^\Phi(t) = \sum_{i=1,2} \sum_{j \geq 3} \delta(t - t_{ij}(n)) \prod_{k=1}^N \int d^3 \mathbf{r}_i d^3 \mathbf{p}_i$$

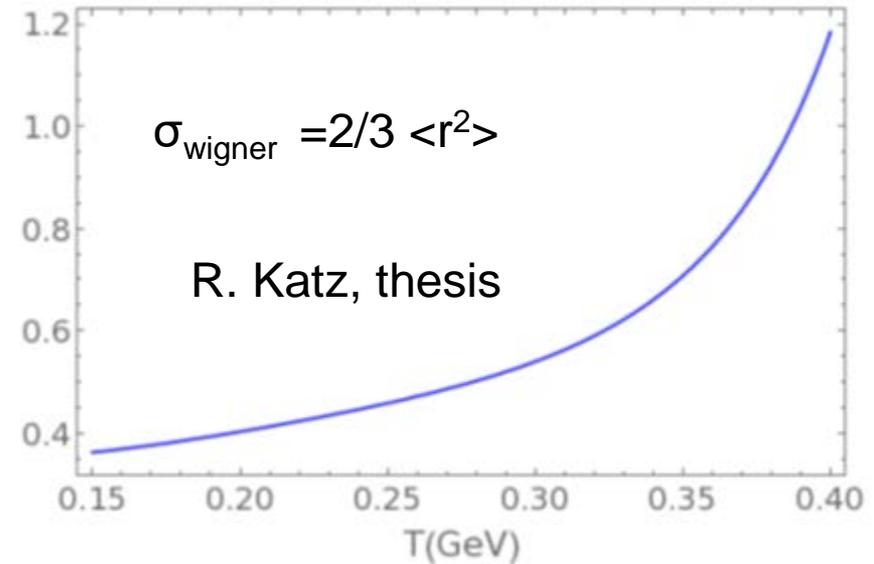
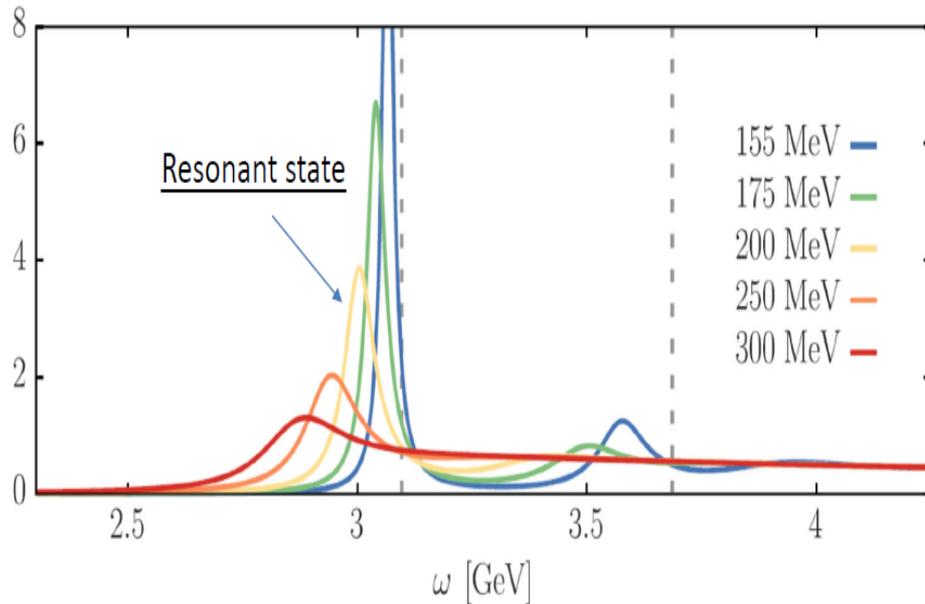
- $W^\Phi(\mathbf{r}_1, \mathbf{r}_2, \mathbf{p}_1, \mathbf{p}_2)$
- $[W_N(\{\mathbf{r}, \mathbf{p}\}; t + \epsilon) - W_N(\{\mathbf{r}, \mathbf{p}\}; t - \epsilon)]$



J/ψ creation in heavy ion collisions

Lattice calc: In an expanding QGP $W^\Phi(\mathbf{r}_1, \mathbf{r}_2, \mathbf{p}_1, \mathbf{p}_2)$ depends on the temperature and hence on time

Parametrization of the lattice results (Lafferty and Rothkopf PRD 101,056010)



This creates an additional rate, called local rate.

Local Rate

Lattice : J/ψ wavefct is a function of the local QGP temperature

The QGP temperature decreases during the expansion

→ J/ψ wavefct becomes time dependent

creates for $T < T_{\text{diss}} = 400$ MeV a local J/ψ prod. rate

$$\begin{aligned}\Gamma_{loc} &= (2\pi\hbar)^3 \int d^3r d^3p W_{Q\bar{Q}}(\mathbf{r}, \mathbf{p}, t) \dot{W}_{\Phi}(\mathbf{r}, \mathbf{p}, T(t)). \\ &= \int d^3r d^3p \frac{16}{(\pi)^3} \dot{\sigma}(T(t)) \left(\frac{\mathbf{r}^2}{\sigma^3(T)} - \frac{\sigma(T)\mathbf{p}^2}{\hbar^2} \right) e^{-\left(\frac{\mathbf{r}^2}{\sigma^2} + \frac{\sigma^2\mathbf{p}^2}{\hbar^2}\right)}\end{aligned}$$

Total J/ψ multiplicity at time t is then given by

$$P_{Q\bar{Q}}(t) = P^{\text{prim}}(t_{\text{init}}^{Q,\bar{Q}}) + \int_{t_{\text{init}}^{Q,\bar{Q}}}^t (\Gamma_{\text{coll},Q\bar{Q}}(t') + \Gamma_{\text{loc},Q\bar{Q}}(t')) dt'$$

For $t \rightarrow \infty$ $P(t)$ is the observable J/ψ multiplicity

Interaction of c and cbar in the QGP

$V(r)$ = attractive potential between c and cbar (PRD101,056010)

We work in leading order in γ^{-1}

$$\mathcal{L} = -\gamma^{-1}mc^2 - V(r) \quad H = \sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}} + V(r) \quad p^2 = p_r^2 + p_\theta^2/r^2$$

Time evolution equation:

$$\gamma^{-1} = \sqrt{1 - v^2/c^2} \quad \frac{\partial \mathcal{L}}{\partial v_i} = p_i = \gamma m v_i$$

$$\dot{r} = \frac{\partial H}{\partial p_r} = \frac{p_r}{\sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}}}$$

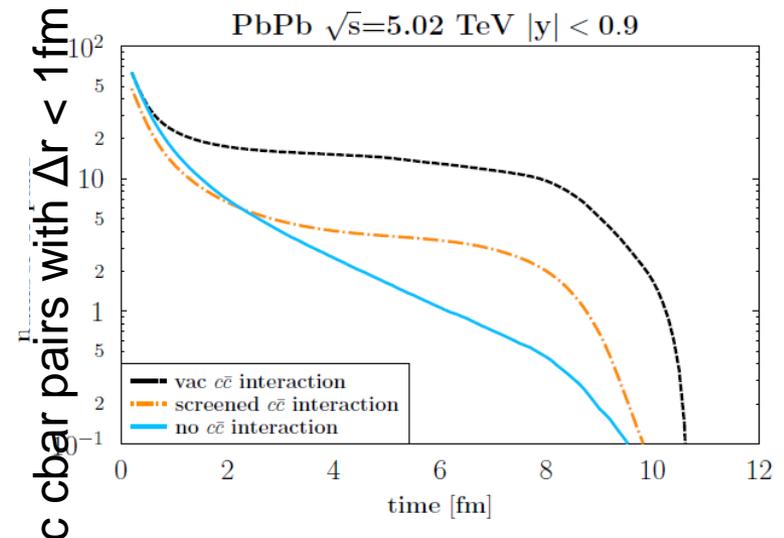
$$\dot{\theta} = \frac{\partial H}{\partial p_\theta} = \frac{p_\theta}{r^2 \sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}}}$$

$$\dot{p}_r = -\frac{\partial H}{\partial r} = \frac{p_\theta^2}{r^3 \sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}}} - \frac{\partial V}{\partial r}$$

$$= \frac{p_\theta \dot{\theta}}{r} - \frac{\partial V}{\partial r}$$

$$\dot{p}_\theta = -\frac{\partial H}{\partial \theta} = 0 \rightarrow p_\theta = \text{const} = L$$

position and momentum of each c cbar pair evolve according to these equations

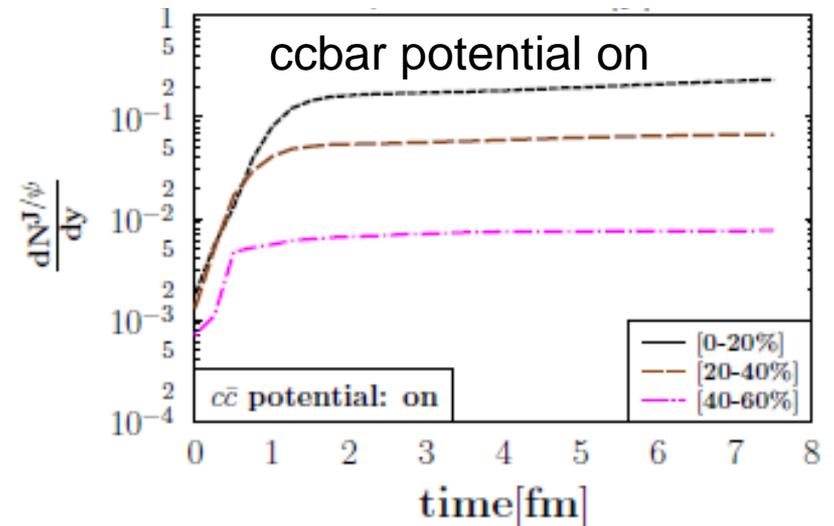
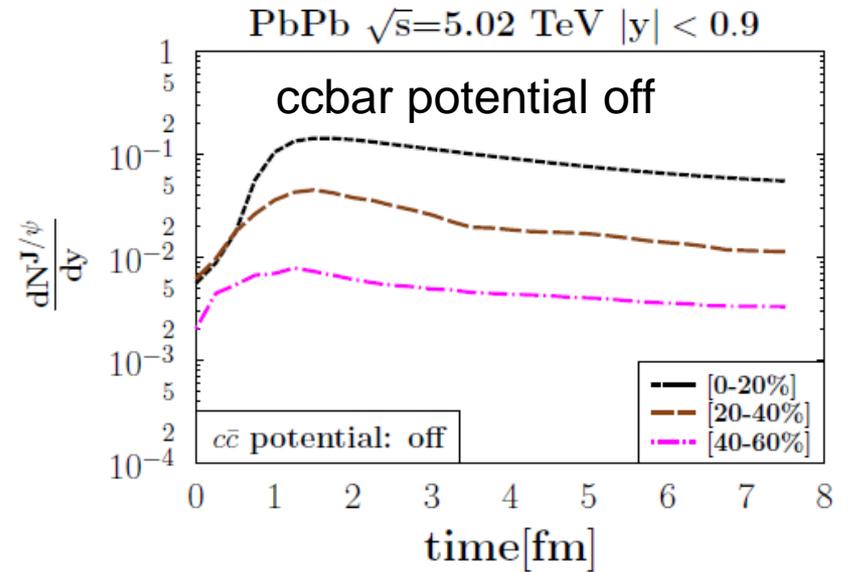
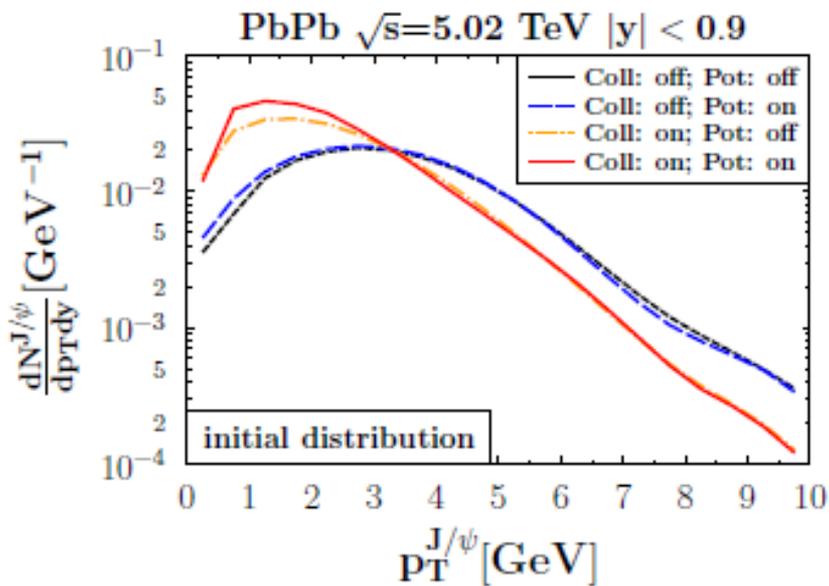


Results

Qq and Qg collisions shift p_T spectra to lower values

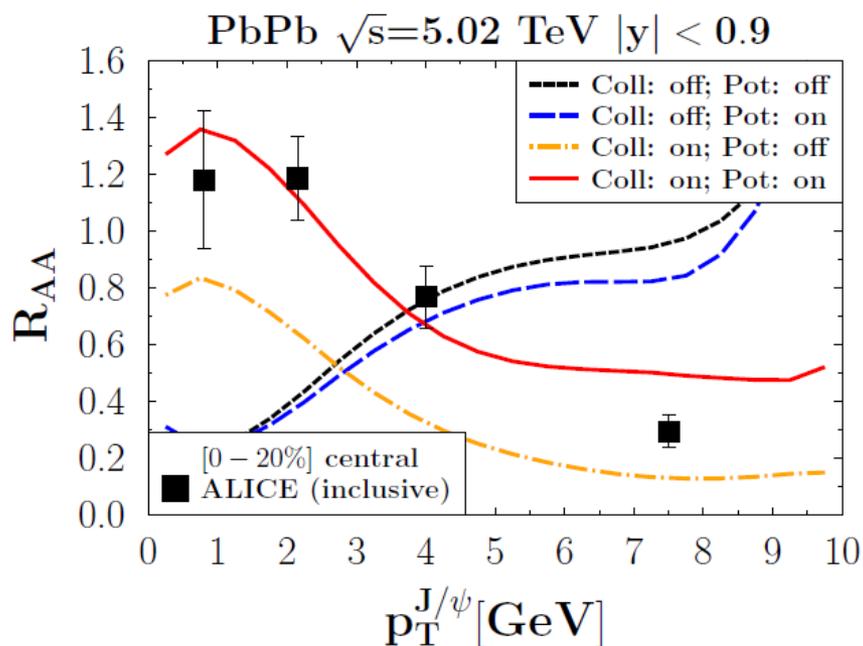
(as for D mesons)

QQbar potential interaction increases the production rate

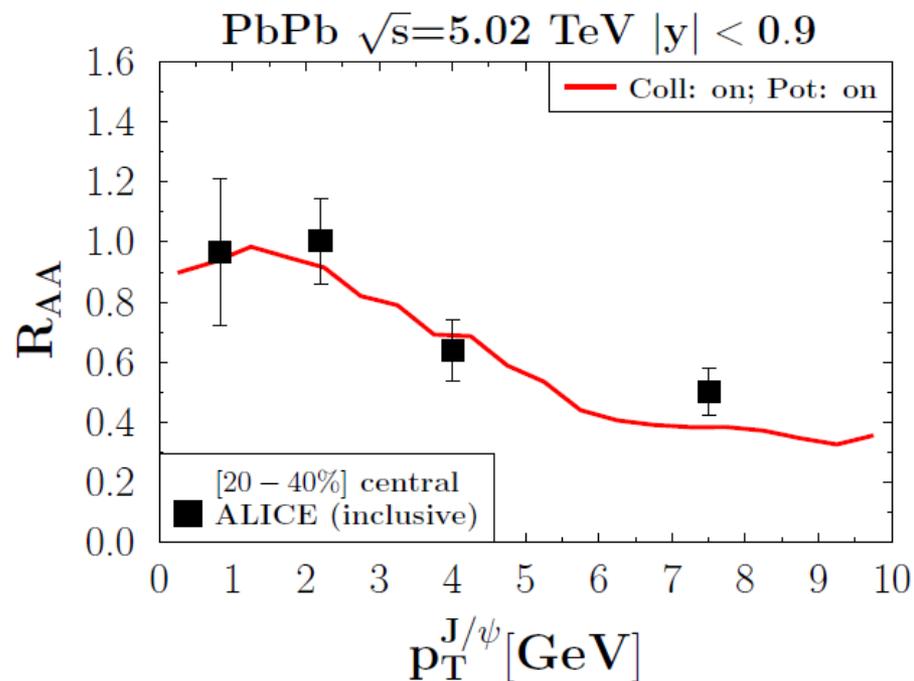


Comparison with ALICE data

[0-20%]



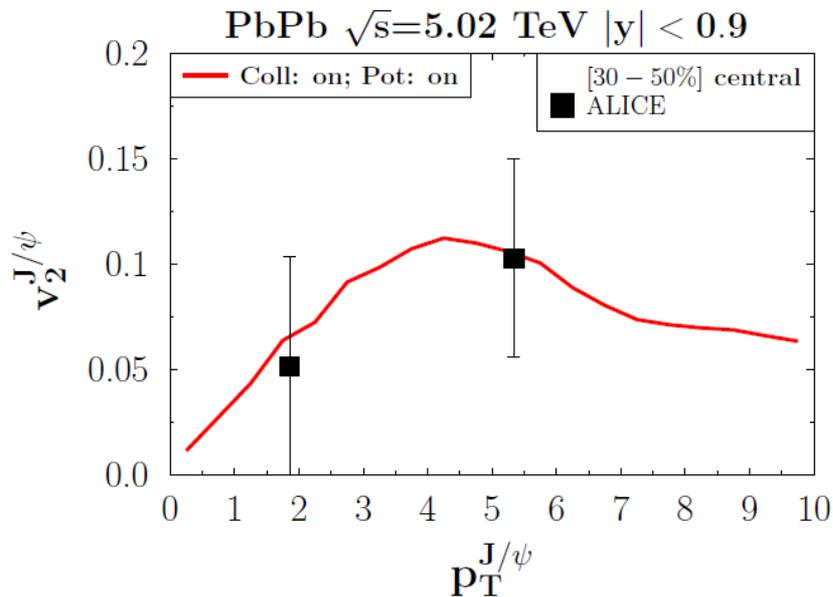
[20-40%]



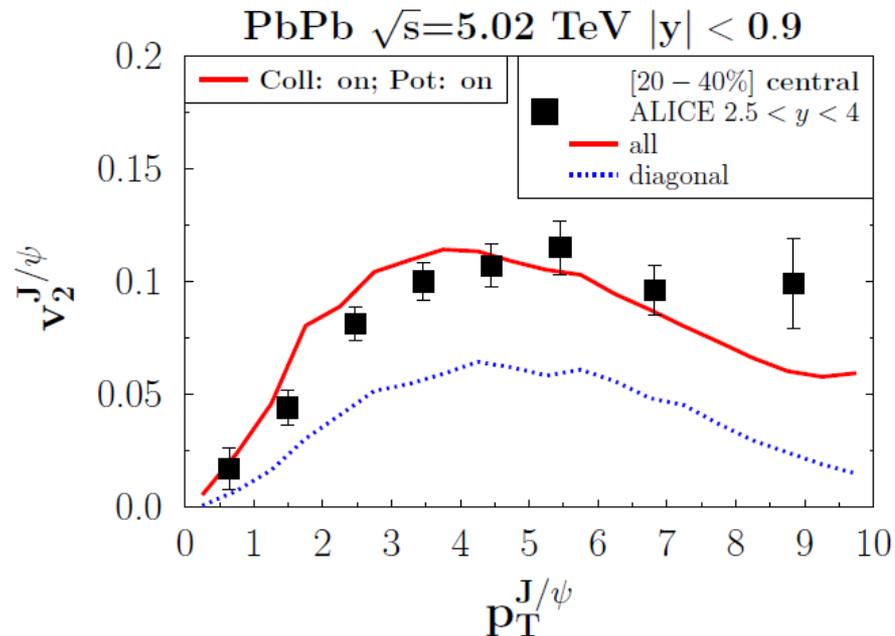
Caution: we compare inclusive ALICE data with calculation of direct prod.

Comparison with ALICE data

[30-50%]



[10-30%]

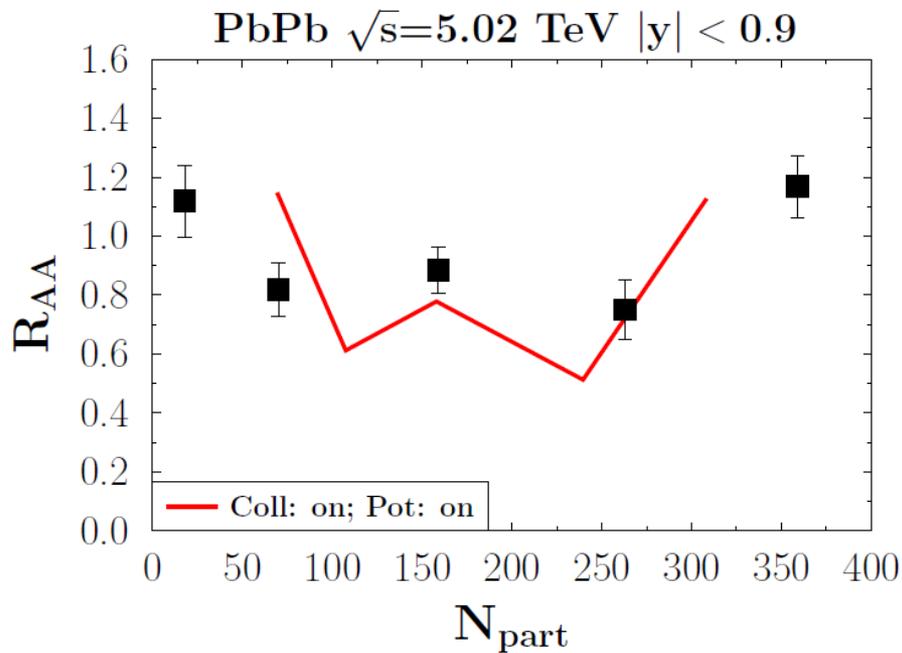


caution:

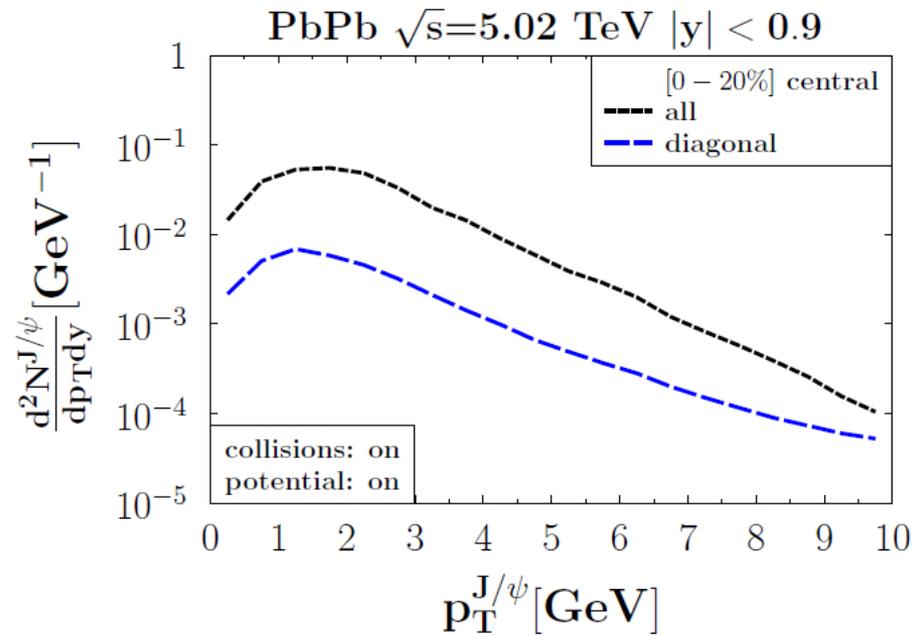
comparison of mid and forward rap

Comparison with ALICE data

Centrality dependence



importance of c and cbar from difference vertices



Summary

New approach **which follows each c and cbar from creation until detection as J/ψ**

(no rate equation, no Fokker Planck eq., no thermal assumptions)

c and cbar are created in initial hard collisions (controlled by pp data)

when entering the QGP J/ψ become unstable

c and cbar interact by potential interaction (lattice potential)

c and cbar interact with with q,g from QGP

When $T < T_{\text{diss}} = 400 \text{ MeV}$ J/ψ can be formed (and later destroyed)

described by Wigner density formalism (as in pp)

Results agree reasonably with ALICE data for R_{AA} as well as for v_2 .

The later production (over) compensates the expected multiplicity increase (with respect to pp) due to c and cbar from different vertices

A lot remains to be done.