J/ψ production in pp and Heavy Ion Collisions

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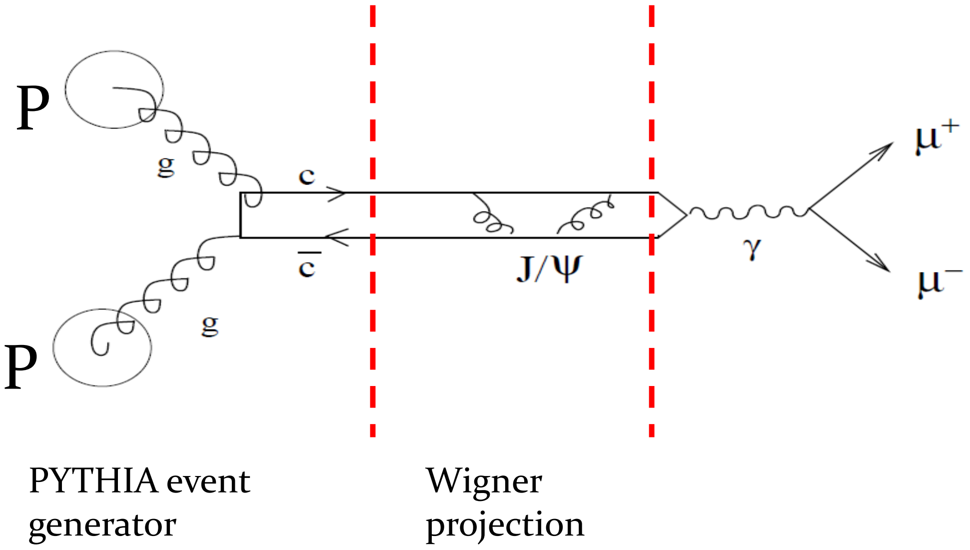
J/ψ production in p+p collisions

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

Need for non perturbative information/ assumptions



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: $|\Phi_i>$

w.f → density matrix $|\Phi_i><\Phi_i|$

Fouriertransform of density matrix in relative coord. → Wigner density of $|\Phi_i>$ (close to classical phase space density)

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

$$\mathbf{R} = \frac{\mathbf{r_1}+\mathbf{r_2}}{2}, \quad \mathbf{r} = \mathbf{r_1} - \mathbf{r_2},$$
$$\mathbf{P} = \mathbf{p_1}+\mathbf{p_2}, \quad \mathbf{p} = \frac{\mathbf{p_1}-\mathbf{p_2}}{2}.$$

$$n_i(\mathbf{R},\mathbf{P}) = \int d^3r d^3p \; \Phi_i^W(\mathbf{r},\mathbf{p}) n^{(2)}(\mathbf{r_1},\mathbf{p_1},\mathbf{r_2},\mathbf{p_2})$$

$n^{(2)}(\mathbf{r_1},\mathbf{p_1},\mathbf{r_2},\mathbf{p_2})$ two body c cbar density matrix

In momentum space given by PYTHIA (Innsbruck tune)

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

Wigner Density Formalism

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

$$n_i(\mathbf{R},\mathbf{P}) \;=\; \sum \int \frac{d^3r d^3p}{(2\pi)^3}\; \Phi_i^W(\mathbf{r},\mathbf{p}) \prod_j \int \frac{d^3r_j d^3p_j}{(2\pi)^3}$$

$$n^{(N)}(\mathbf{r_1},\mathbf{p_1},\mathbf{r_2},\mathbf{p_2},...,\mathbf{r_N},\mathbf{p_N}) \qquad (5)$$

Multiplicity of $|\Phi_i>$

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

Momentum distribution

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

Wigner Density Formalism

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

We choose the simplest possible parametrization

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

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

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

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

D : degeneracy of Φ

d_1 : degeneracy of c

d_2 : degeneracy of anti-c

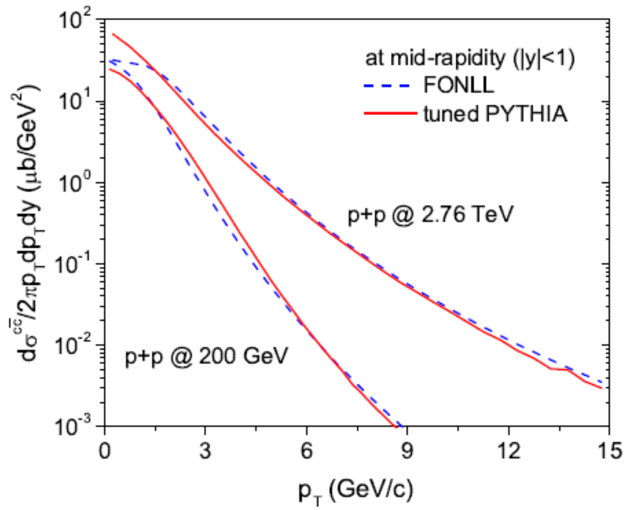
σ ~ radius of Φ

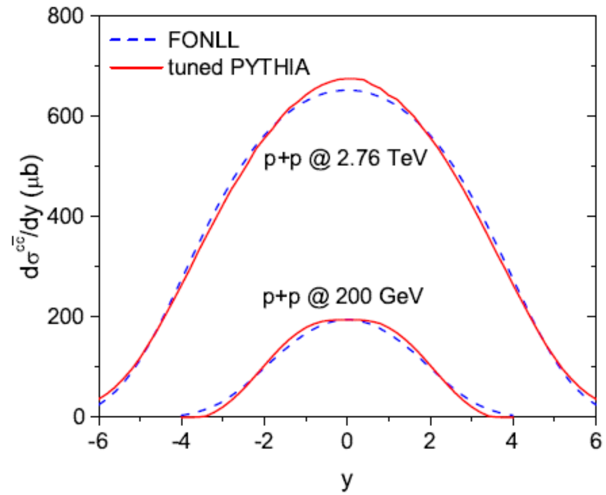
Where σ reproduces the rms radius of the vacuum c cbar state $|\Phi_i>$

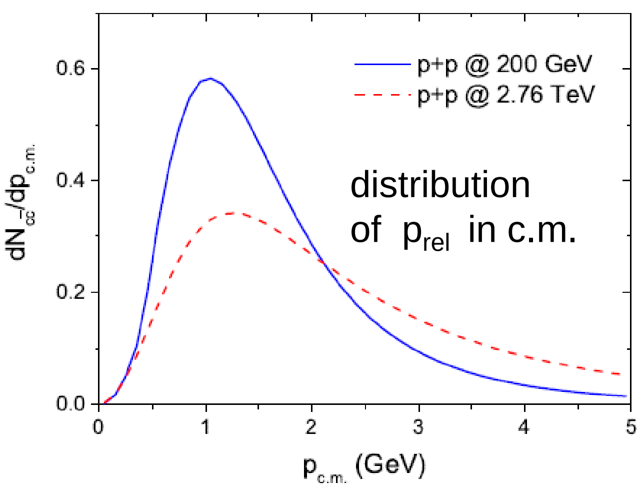
$$\Phi = J/\psi(1S), \qquad \chi_c(1P),\ \psi'(2S)$$

Wigner Density Formalism

The tuned PYTHIA reproduces FONLL calculation
but in addition it keeps the ccbar correlation

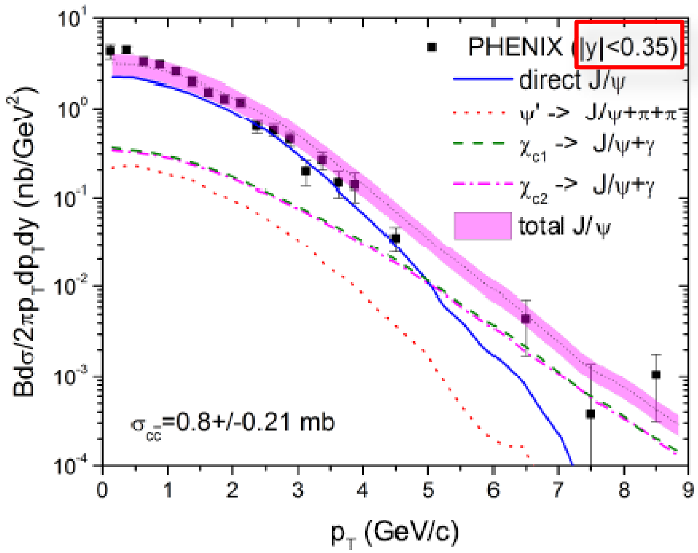


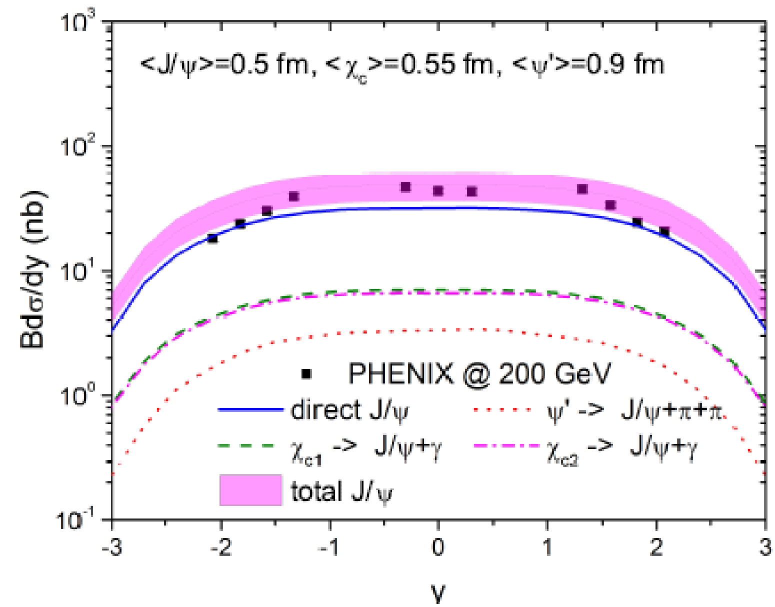


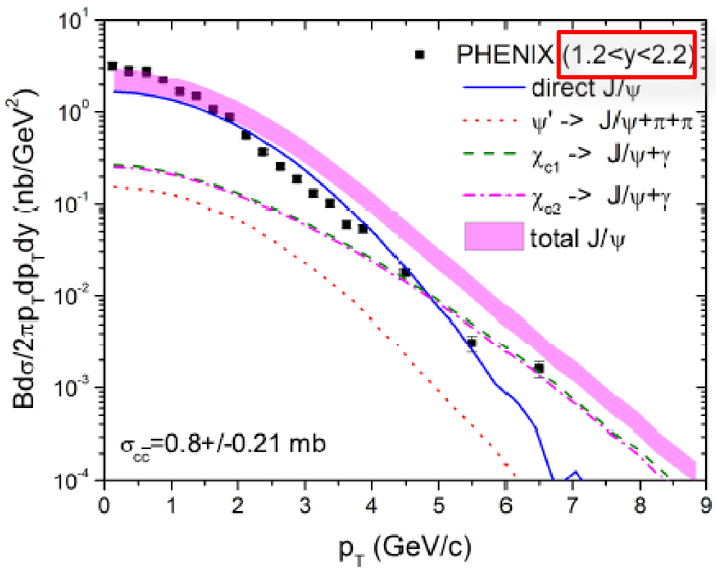


quite different relative momenta
at RHIC and LHC

pp: comparison with Phenix data





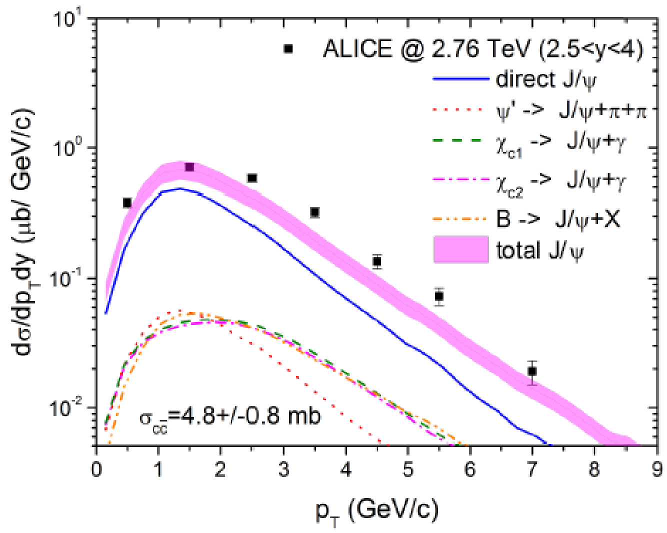


Good agreement for
rapidity spectrum
pt spectrum at |y| < 0.35
pt spectrum at 1.25 < |y| < 2.2

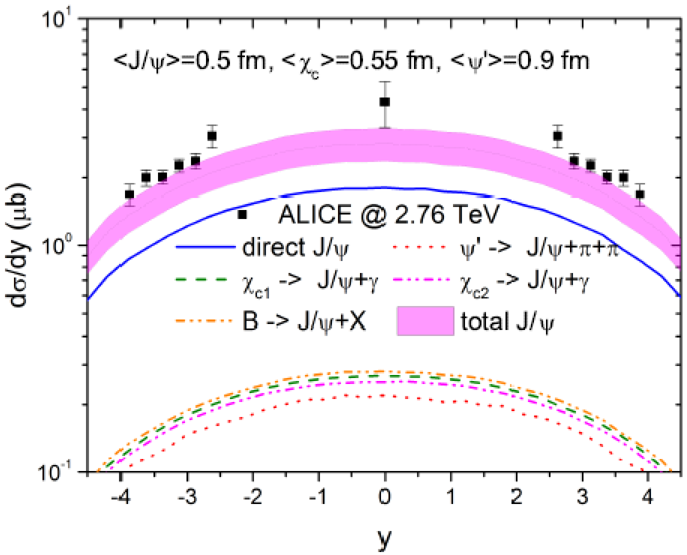
Feeding at RHIC not very important

pp: comparison with ALICE data

we use the same charmonia radii as at RHIC



(a)



(b)

The Wigner density formalism describes the observed J/ψ data in pp at RHIC and LHC

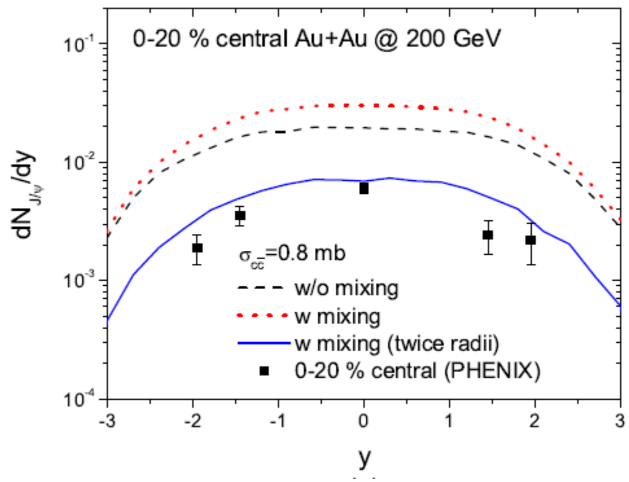
Important contribution of feeding

AA collisions

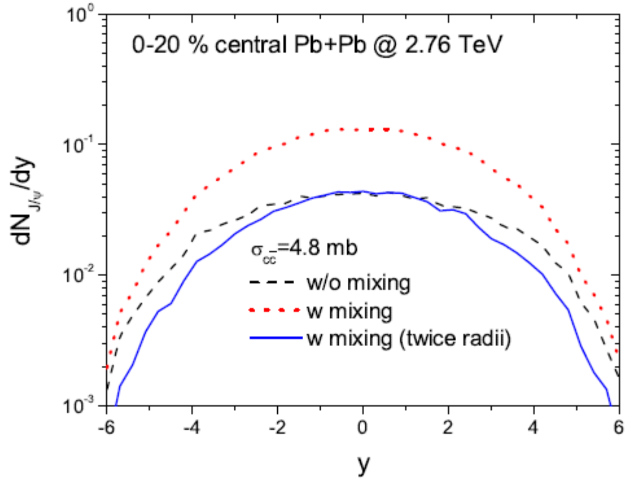
AA: without any QGP

Without the formation of a QGP we expect a (large) enhancement of the J/ψ production because c and cbar from different vertices can form a J/ψ.

enhancement 46%



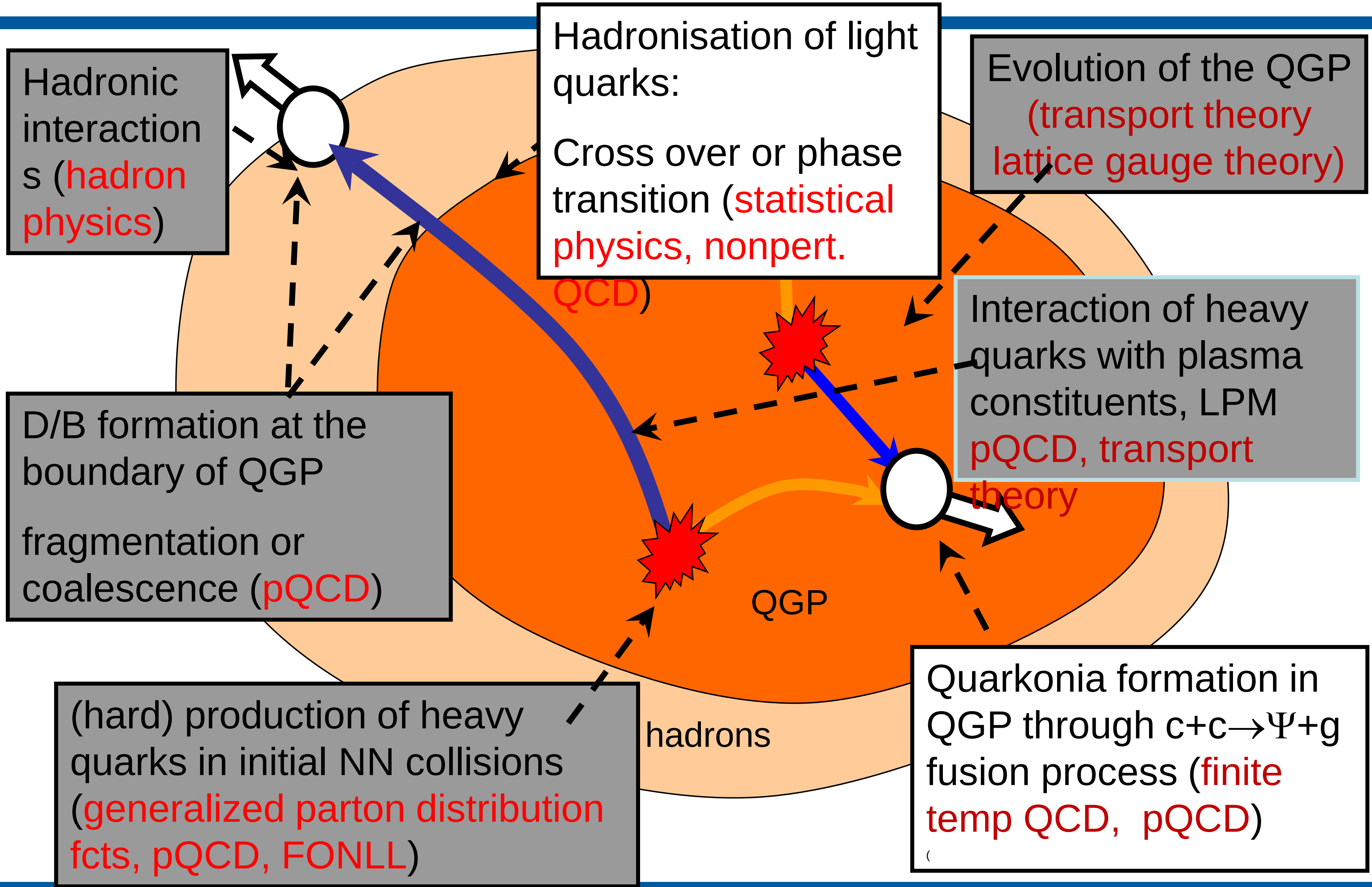
enhancement 270%



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 (similar as in pp)
- J/ψ are unstable in the quark gluon plasma created a bit 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 by hadronic interaction (what we neglect)

The model we developed

is based, as our pp calculation, on the Wigner density formalism

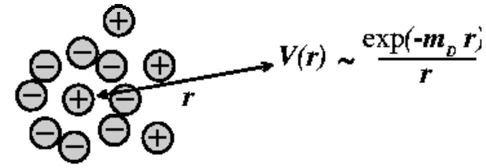
assumes that before the J/ψ formation the c and cbar interact with the medium as those observed finally as D-mesons

uses EPOS2 to describe the expanding QGP

HQ interactions with the QGP

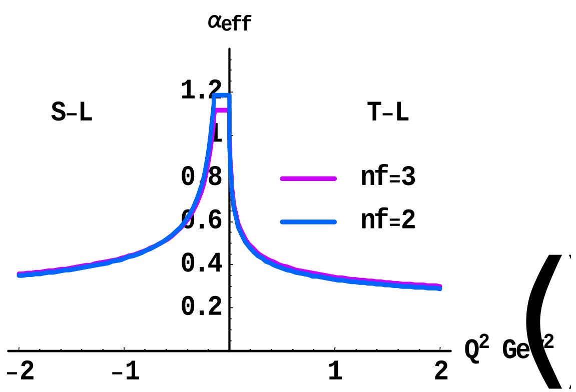
The interaction between HQ and q and g is described by Born type diagrams

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



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

coupling constant and infrared screening are input



Peshier 0801.0595
based on universality
constraint of Dokshitzer

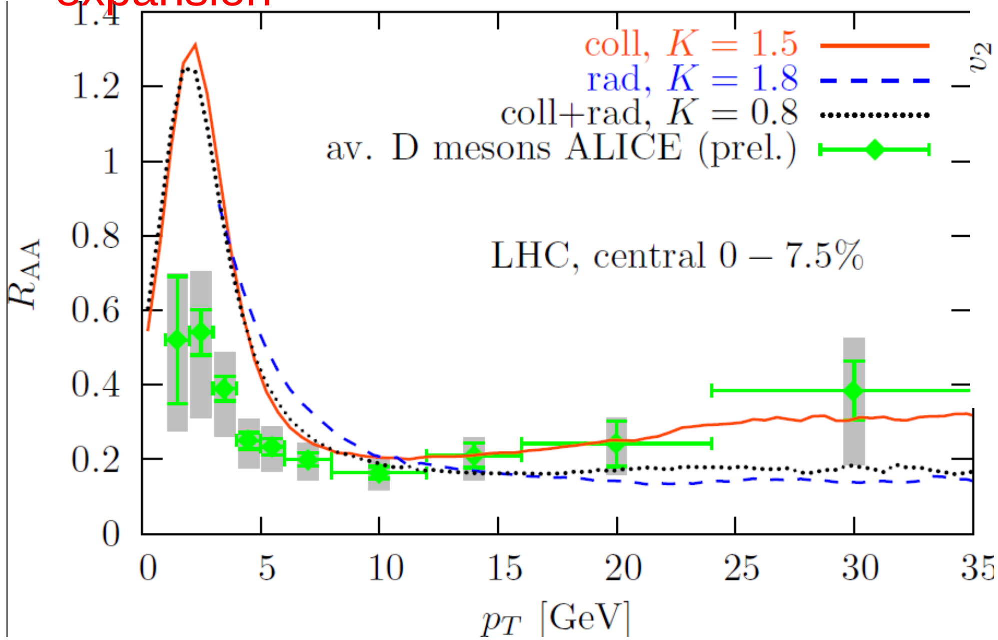
If t is small (<<T) : Born has to be replaced by a hard thermal loop (HTL) approach
For t>T Born approximation is (almost) ok

(Braaten and Thoma PRD441298,2625) for QED:
Energy loss indep. of the artificial scale t* which separates the regimes
Extension to QCD (PRC78:014904)

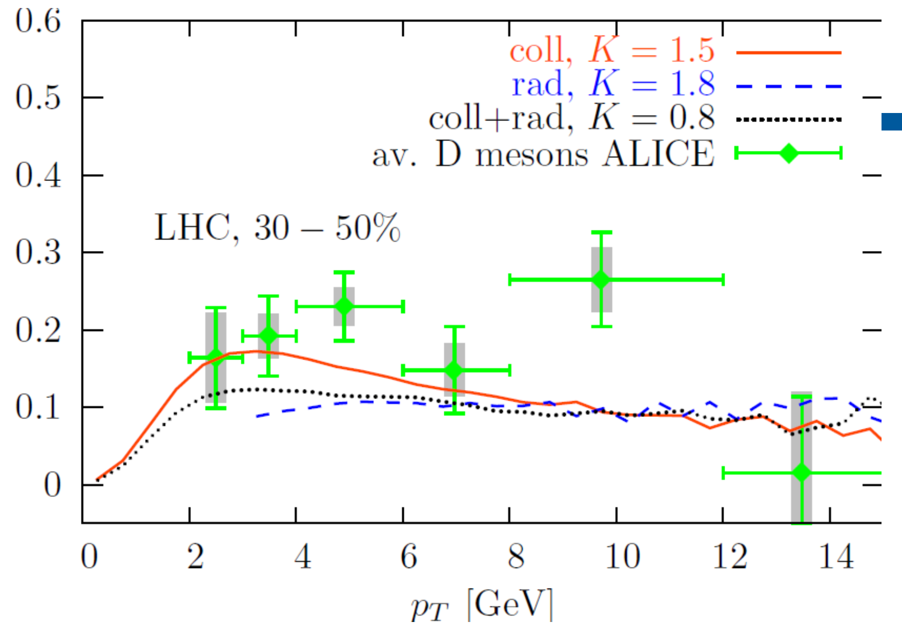
$\kappa \approx 0.2$

D meson result

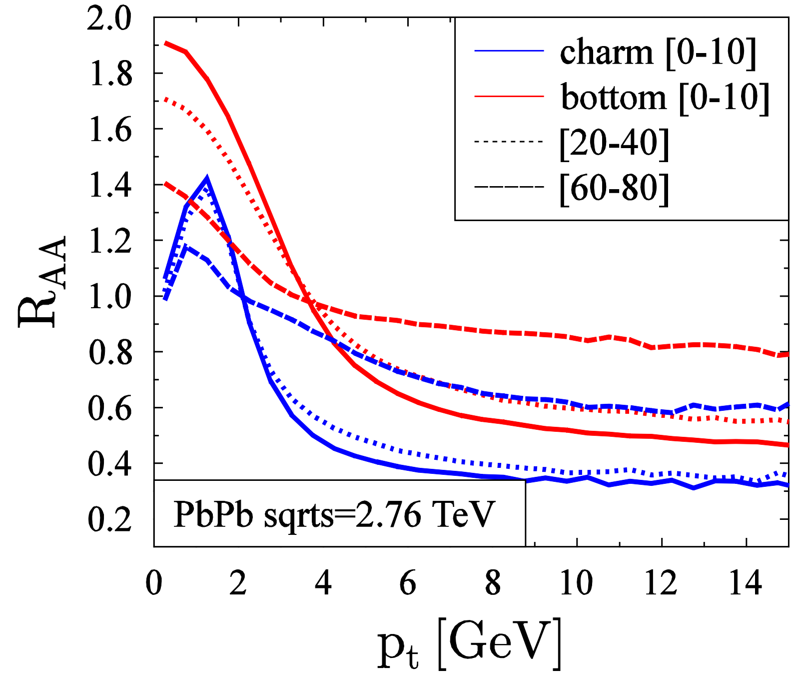
Energy loss tests the initial phase of the expansion



v_2 tests the late stage 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

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}

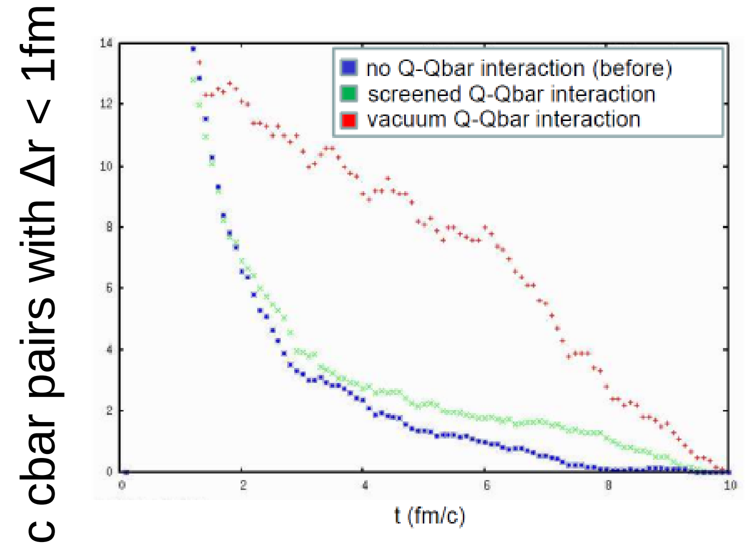
$$\mathcal{L} = -\gamma^{-1} mc^2 - V(r) \qquad H = \sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}} + V(r) \qquad p^2 = p_r^2 + p_\theta^2/r^2$$

Time evolution equation:

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

$$\begin{aligned}
\dot{r} &= \frac{\partial H}{\partial p_r} = \frac{p_r}{\sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}}} \\
\dot{\theta} &= \frac{\partial H}{\partial p_\theta} = \frac{p_\theta^2 r^2}{\sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}}} \\
\dot{p}_r &= -\frac{\partial H}{\partial r} = \frac{p_\theta^2 r}{\sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}}} - \frac{\partial V}{\partial r} \\
&= \frac{p_\theta \dot{\theta}}{r} - \frac{\partial V}{\partial r} \\
\dot{p}_\theta &= -\frac{\partial H}{\partial \theta} = 0 \rightarrow p_\theta = const = L
\end{aligned}$$

position and momentum of each c cbar pair evolve according to



J/ψ creation in heavy ion collisions

Starting point: von Neumann equation for the density matrix of all particles

$\partial \rho_N / \partial t = -i[H, \rho_N]$ with $H = \Sigma_i K_i + \Sigma_{i>j} V_{ij}$

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

$P^\Phi(t) = \mathrm{Tr}[\rho^\Phi \rho_N(t)]$ with $\rho^\Phi = |\Psi^\Phi >< \Psi_\Phi|$

Not very usefull for heavy ion collision: for large t distance between the heavy quarks is large and therefore P(t) is small

Solution: we study the rate Γ(t):

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

can be converted into (for time independent W^Φ):

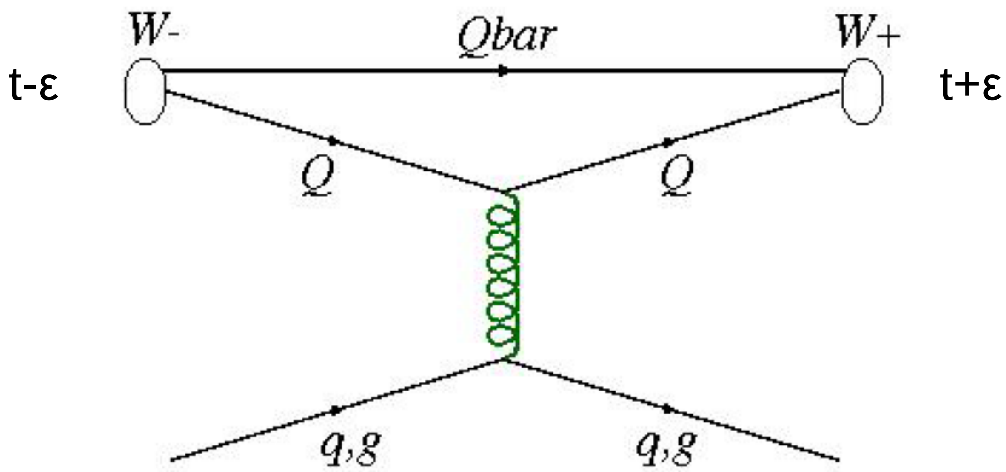
$$\frac{dP^\Phi(t)}{dt} = \prod_j^N \int d^3\mathbf{r}_j d^3\mathbf{p}_j \; W^\Phi \frac{d}{dt} W_N^c(t)$$

J/ψ creation in heavy ion collisions

If heavy quarks interact only by collisions with the QPG partons and each collision is point like in time:

$$\Gamma^{\Phi}(t) = \sum_{i=1,2}\sum_{j\geq 3}\delta(t-t_{ij}(n))\prod_{k=1}^{N}\int d^3\mathbf{r}_i d^3\mathbf{p}_i$$
$$\cdot \quad W^{\Phi}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{p}_1,\mathbf{p}_2)$$
$$\cdot \quad [W_N(\{\mathbf{r},\mathbf{p}\};t+\epsilon) - W_N(\{\mathbf{r},\mathbf{p}\};t-\epsilon)]$$

If $W^{\Phi}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{p}_1,\mathbf{p}_2)$ Is time independent



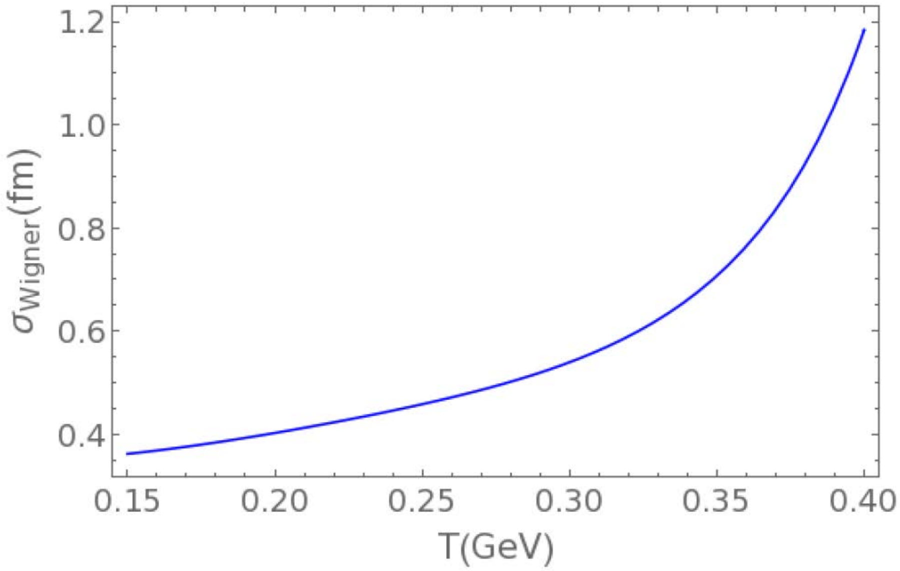
QGP parton

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)

σ_{wigner} 2/3 <r^{2}>



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

$$\Gamma_{loc} = (2\pi\hbar)^3 \int d^3r d^3p \, W_{Q\bar{Q}}(\mathbf{r},\mathbf{p},t)\dot{W}_{\Phi}(\mathbf{r},\mathbf{p},T(t)).$$

$$= \int d^3r d^3p \quad \frac{16}{(\pi)^3}\dot{\sigma}(T(t))\left(\frac{\mathbf{r}^2}{\sigma^3(T)} - \frac{\sigma(T)\mathbf{p}^2}{\hbar^2}\right)e^{-\left(\frac{\mathbf{r}^2}{\sigma^2}+\frac{\sigma^2\mathbf{p}^2}{\hbar}\right)}$$

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

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

For t →∞ P(t) is the J/ψ multiplicity

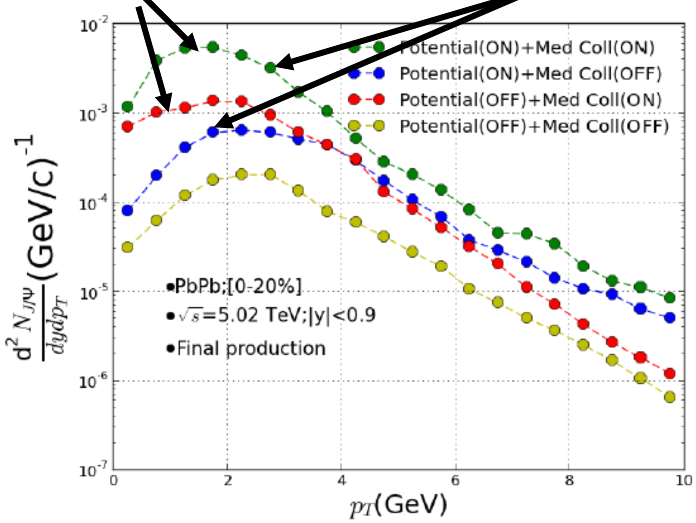
Results

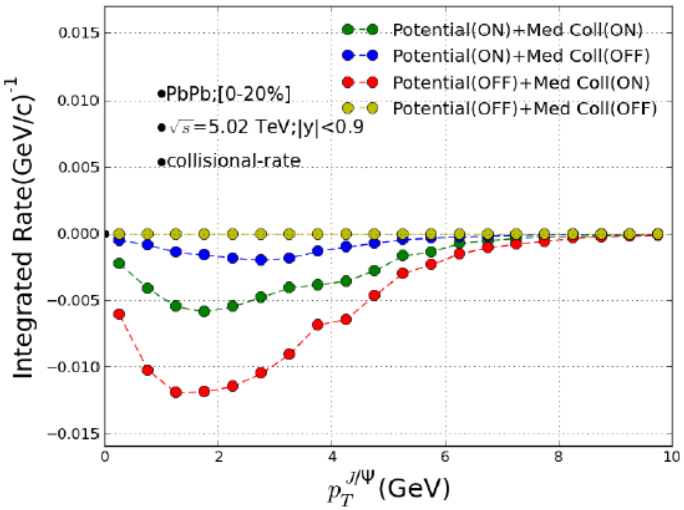
Qq and Qg collisions shifts p_T spectra to lower values

(as for D mesons)

Qqbar potential interaction increases the production rate

pot off/on coll off/on

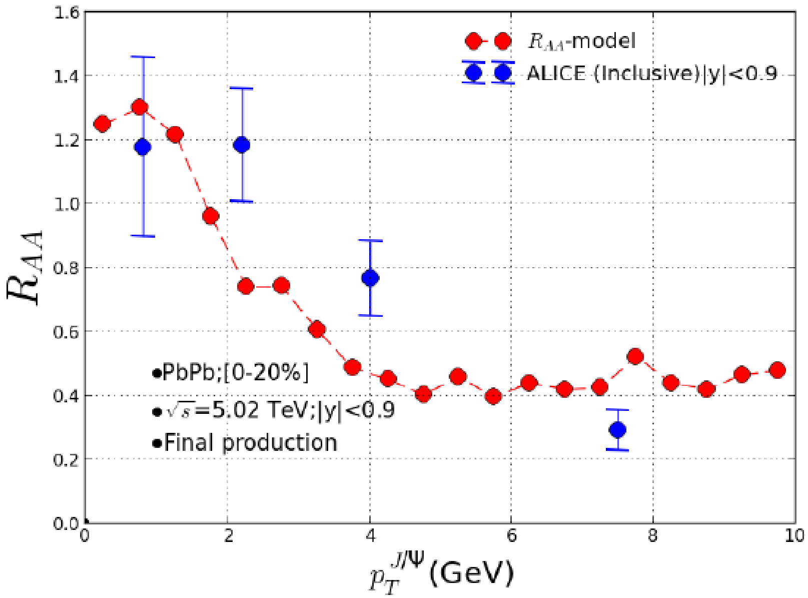




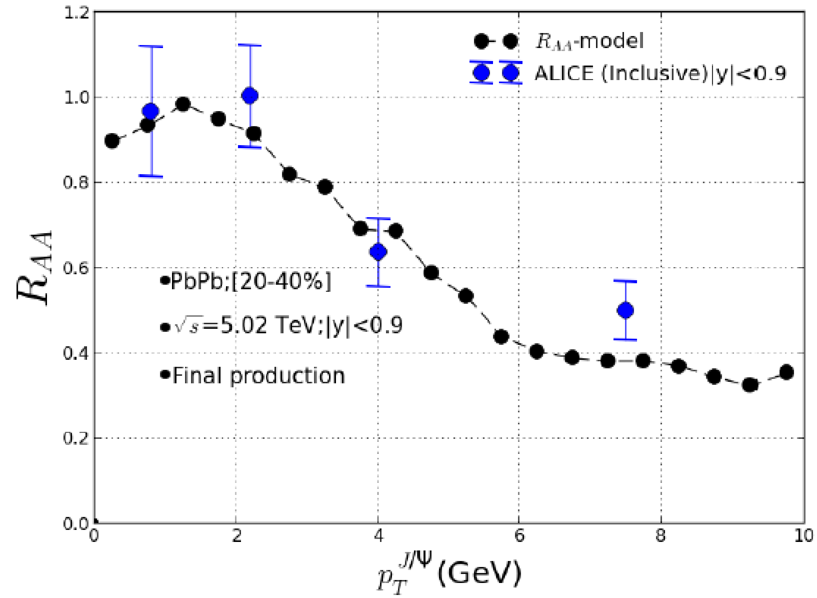
Collisions lower the J/ψ multiplicity at intermediate p_T

Comparison with ALICE data

[0-20%]



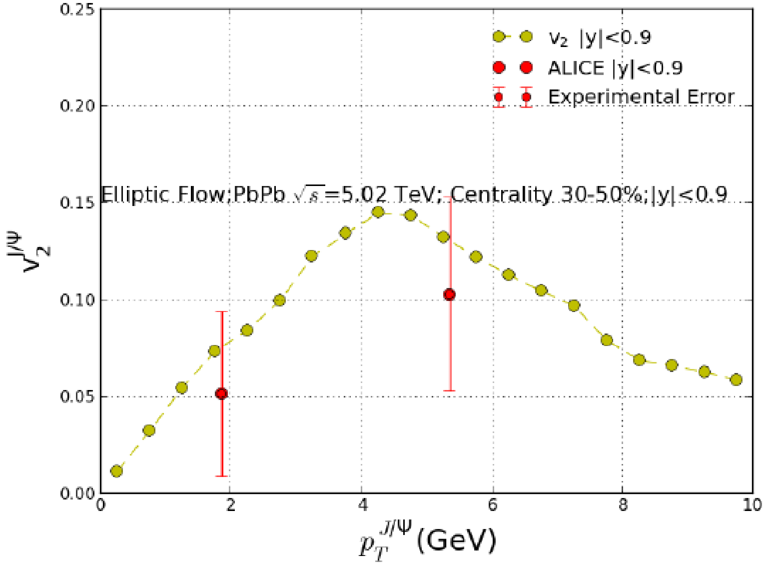
[20-40%]



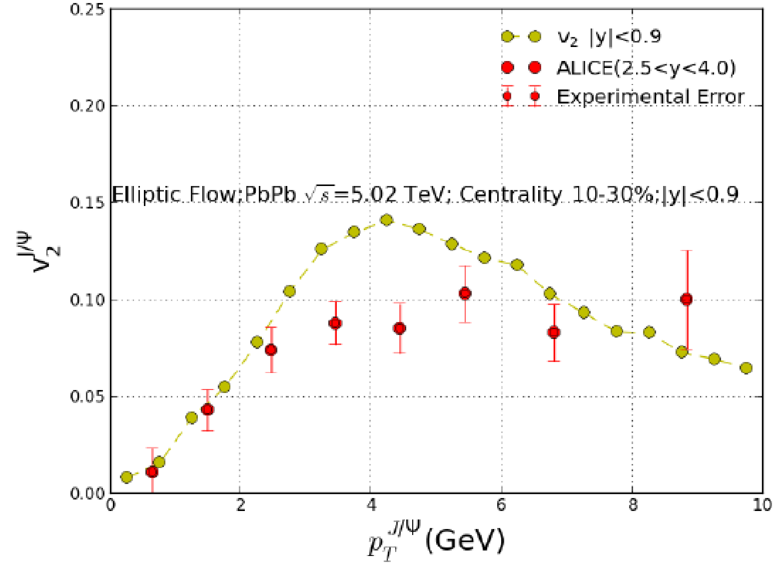
Caution: we compare inclusive ALICE data with calculation of direct prod.

Comparison with ALICE data

[30-50%]



[10-30%]

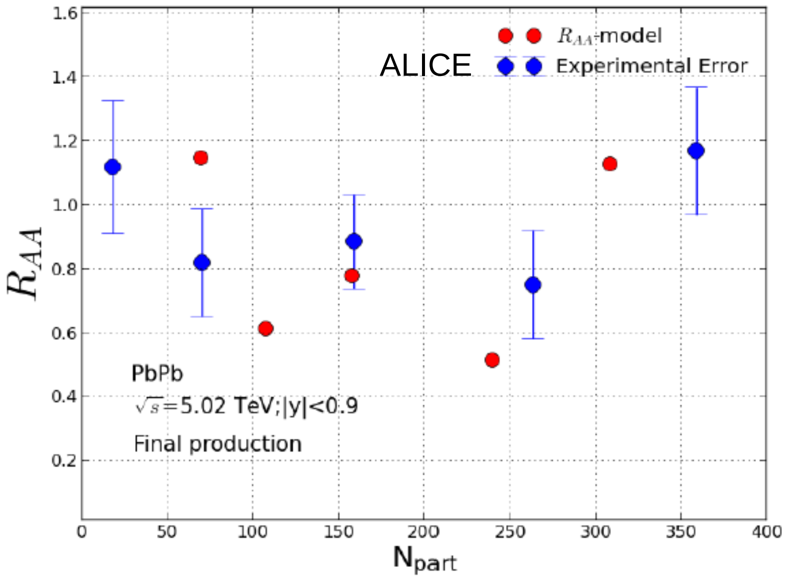


caution:

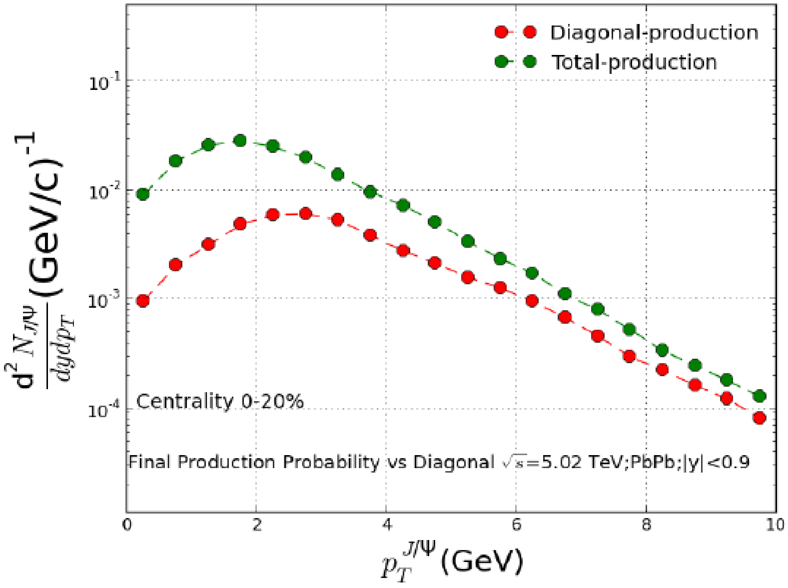
comparison of mid and forward rap

Comparison with ALICE data

Centrality dependence



importance of c and cbar from difference vertices



Summary

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

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 $T < T_{diss} = 400$ 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.