Quarkonium production in pp and Heavy Ion Collisions

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work in progress

pp: PRC 96 014907
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first results for AA:
PRC107,054913

exploreQGPworkshop
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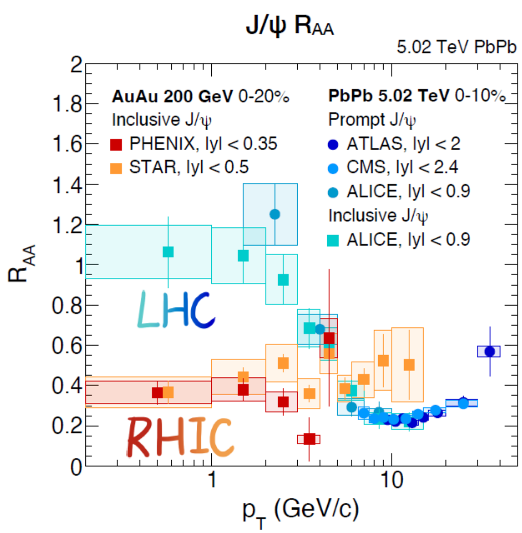
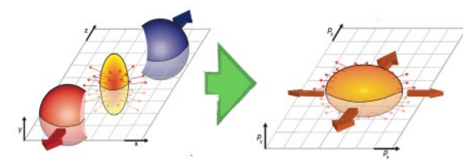
Why do we study J/ψ production in heavy-ion collisions?

J/ψ mesons

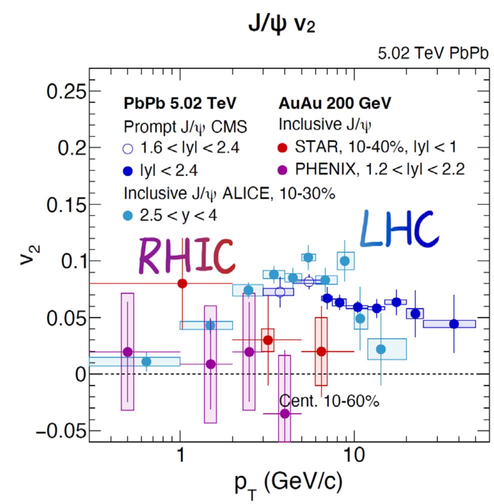
- are a hard probe: tests quark gluon plasma from creation to hadronization
- no consistent microscopical theory available yet
- show quite different results for key observables at RHIC and LHC which are not understood yet:

$$R_{AA}(p_T) = \frac{dN_D^{AA}/dp_T}{\langle N_{coll} \rangle dN_D^{pp}/dp_T}$$





$$\frac{dN}{d\phi} \propto 1 + 2v_1 cos\phi + 2v_2 cos(2\phi).....$$

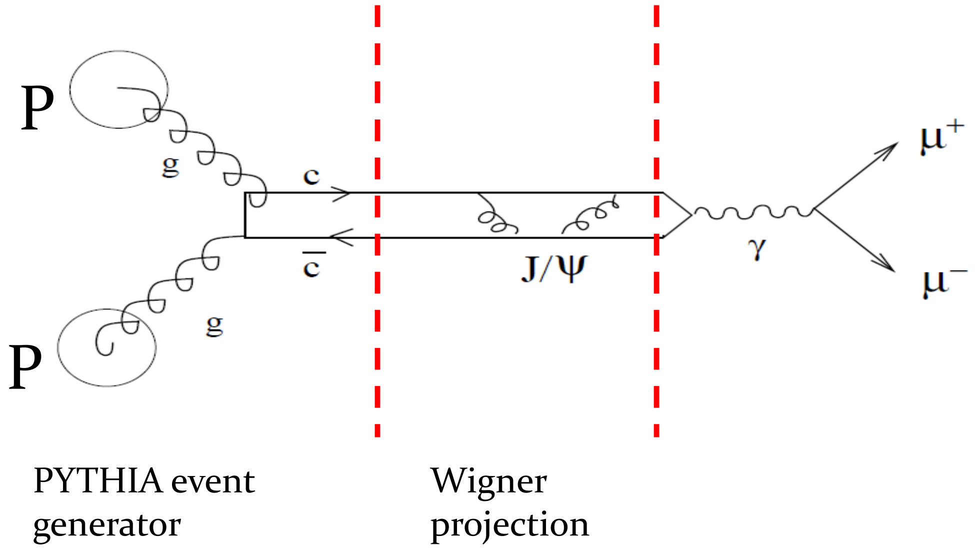


J/ψ production in p+p collisions

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

Need non perturbative input ➔ 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: $|\Phi_i>$

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

Fourier transform of density matrix in relative coord. → Wigner density of $|\Phi_i>$

(close to classical phase space density)

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

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

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

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

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

pp: 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 states $|\Phi_i>$

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

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

Sum over all possible ccbar pairs after integration of the relative coordinates
Integration over all N-2 left particles.

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 (harmonic oscillator) 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

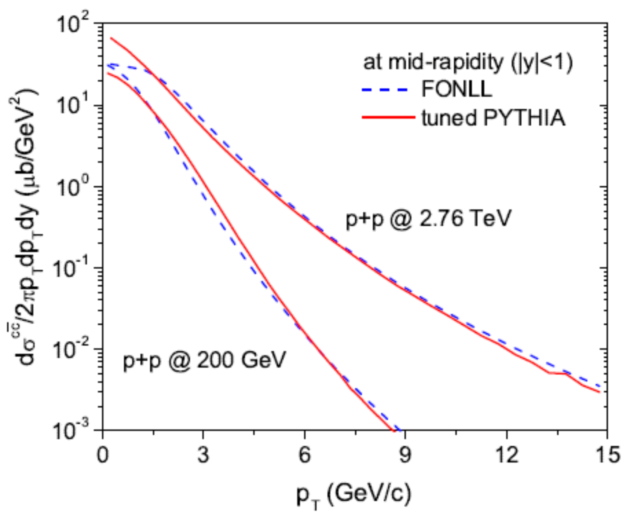
σ ~ radius of Φ

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

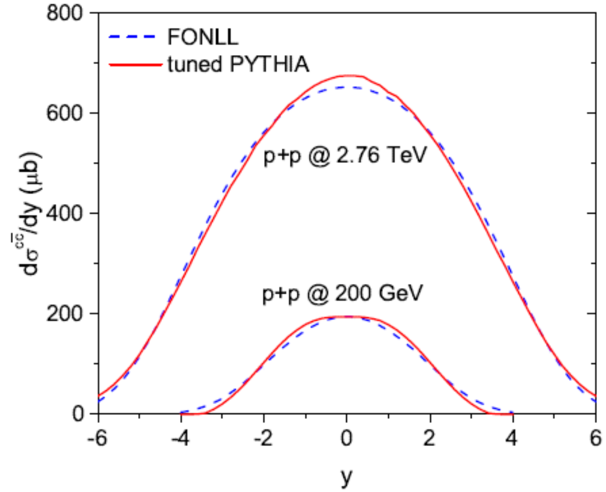
$$\Phi = J/\psi(1S), \qquad \chi(1P),\ \psi'(2S)$$

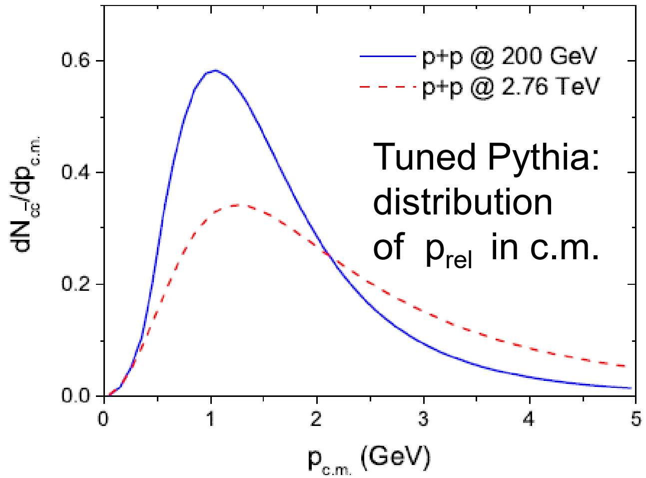
Wigner Density Formalism

The (Innsbruck) tuned PYTHIA reproduces FONLL calculations
but in addition it keeps the ccbar correlation (not known in FONLL)



Distribution of charm quarks agrees





but quite different relative momenta at RHIC and LHC

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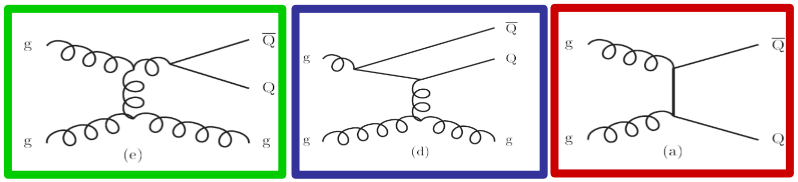
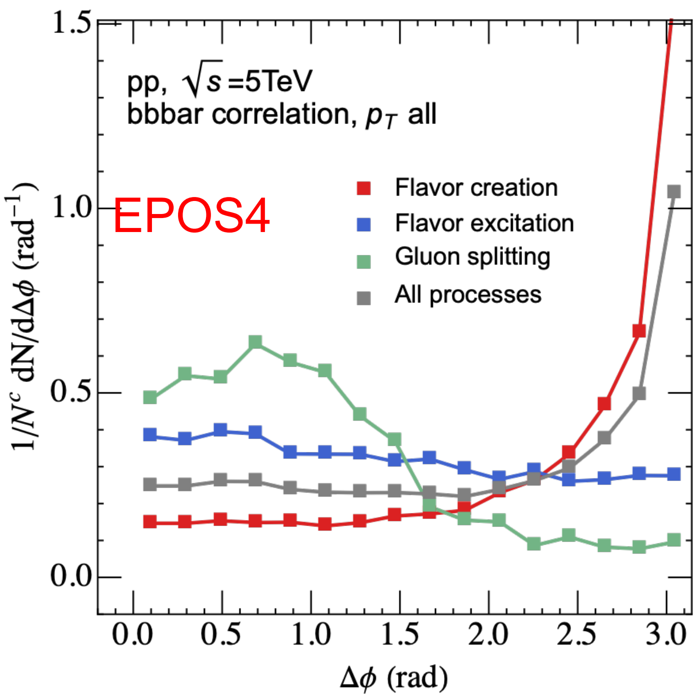
Azimuthal correlations in EPOS4 and PHSD

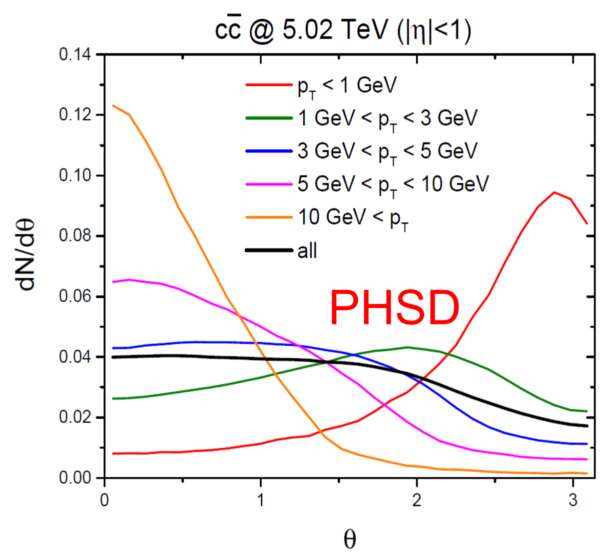
FONLL: only single quark p_T spectrum
for J/ψ or Y we need
c cbar and b bbar correlations

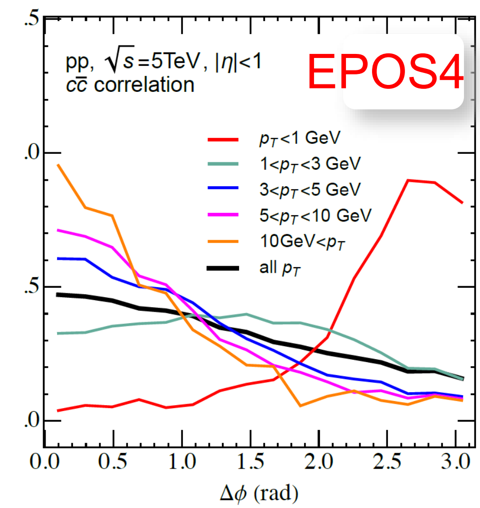
azimuthal correlations of EPOS4 and PHSD
between c and cbar agree
even as a function of p_T

basis for a model independent production
of quarkonia

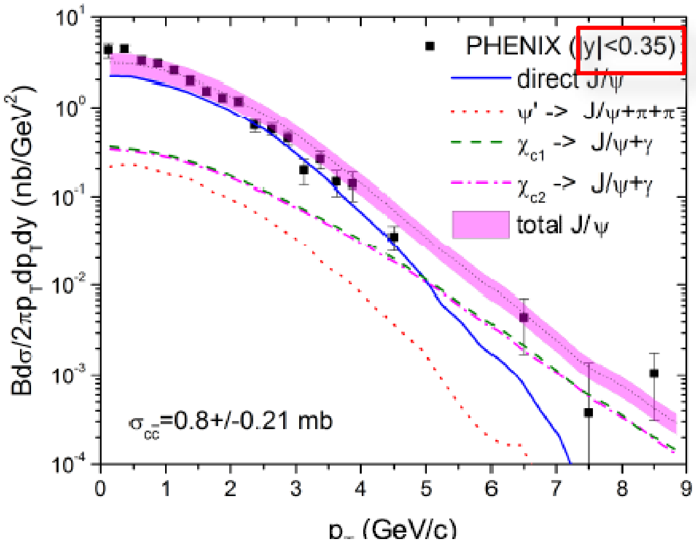


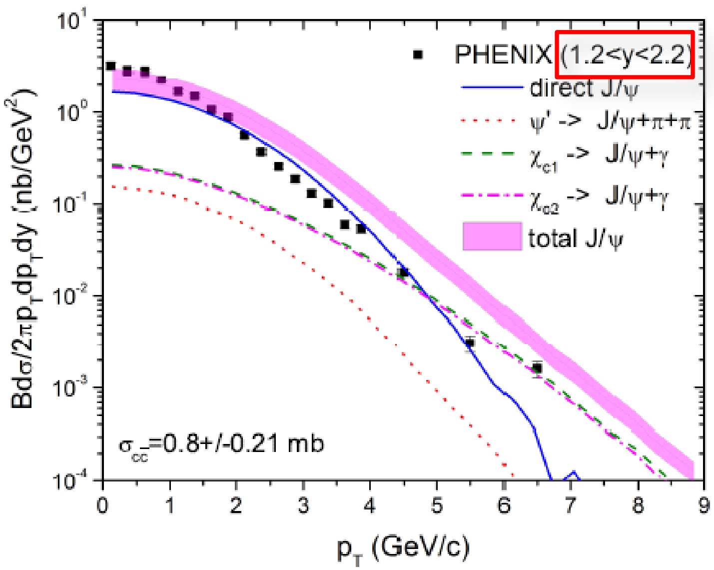


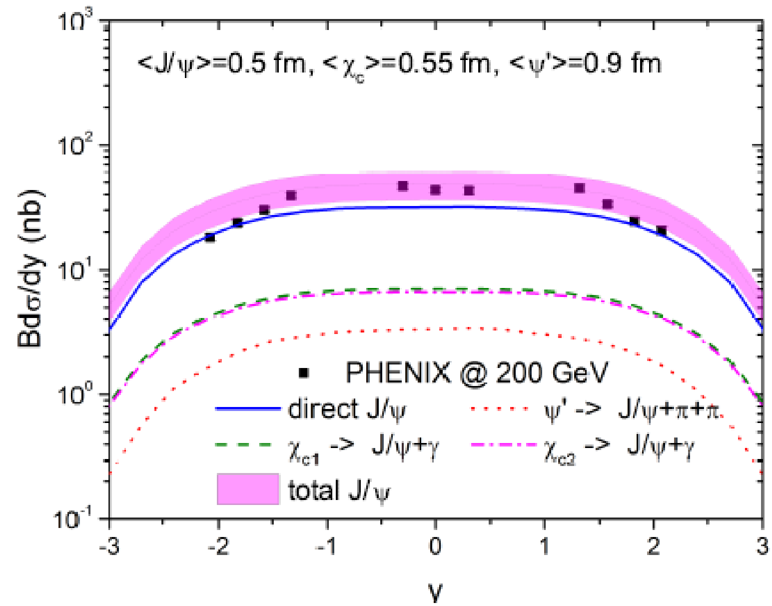




pp: comparison with PHENIX data







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

Feeding at RHIC not very important

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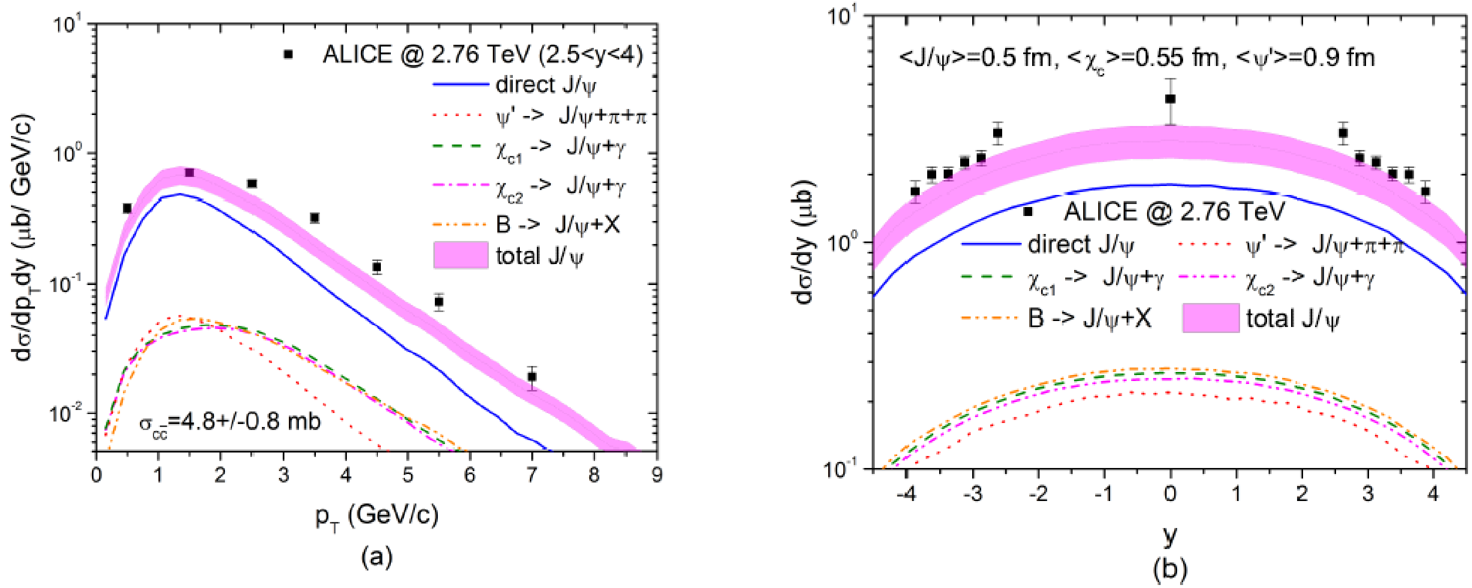
pp: comparison with ALICE data

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.

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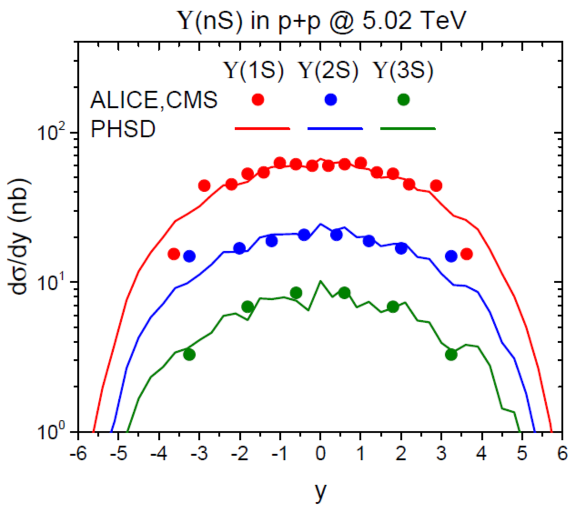
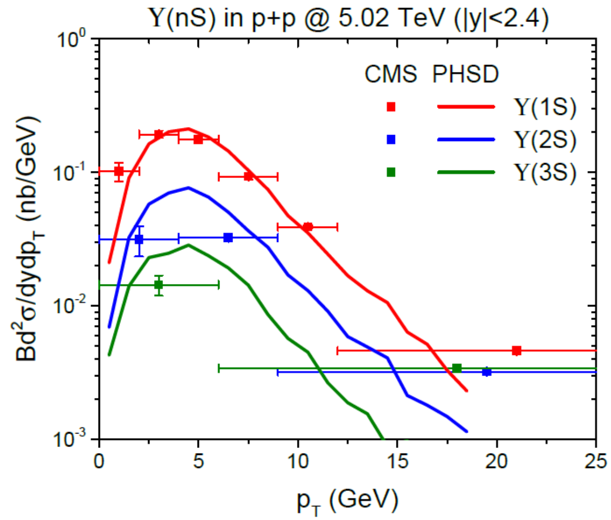
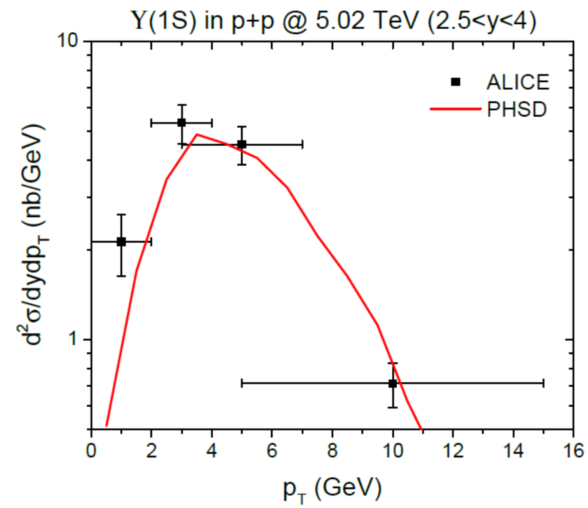
pp: comparison of Y(nS) with CMS/ALICE data

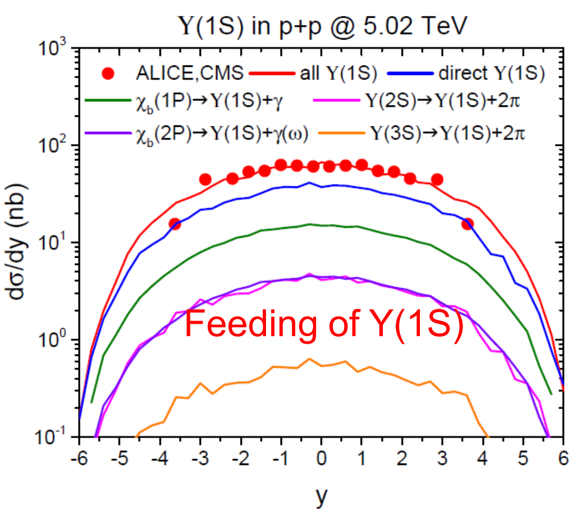
Wigner density approach works also for Y(nS)

2305.10750 [nucl-th]









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

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

$$\sigma^2 = 2/3\langle r^2\rangle \text{ for } S\text{−state}$$
$$\sigma^2 = 2/5\langle r^2\rangle \text{ for } P\text{−state}$$

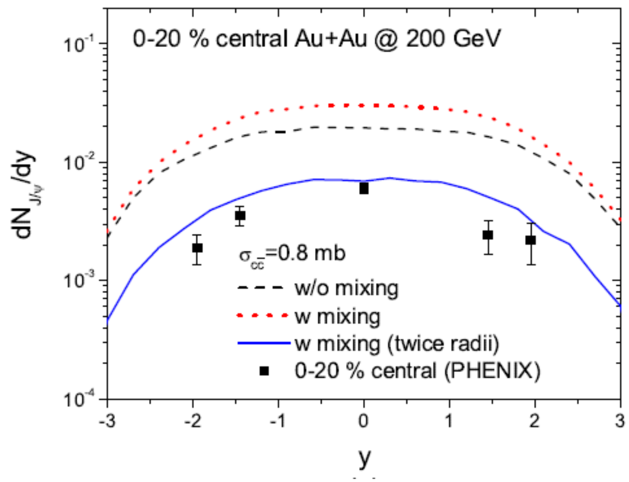
With this validation of the new approach for quarkonium production in pp we are ready for AA collisions

AA collisions

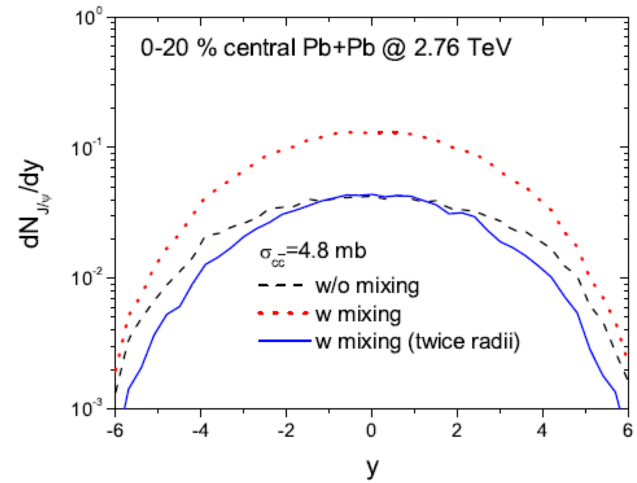
AA: without any QGP

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

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The different processes which influence 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 hadronizes
- J/ψ can be further suppressed or created by hadronic interaction
  (task for the future → Torres-Rincon)
- There are in addition J/ψ from the corona (do not pass the QGP)

Our model follows the time evolution of all c and cbar quarks,

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

assumes that

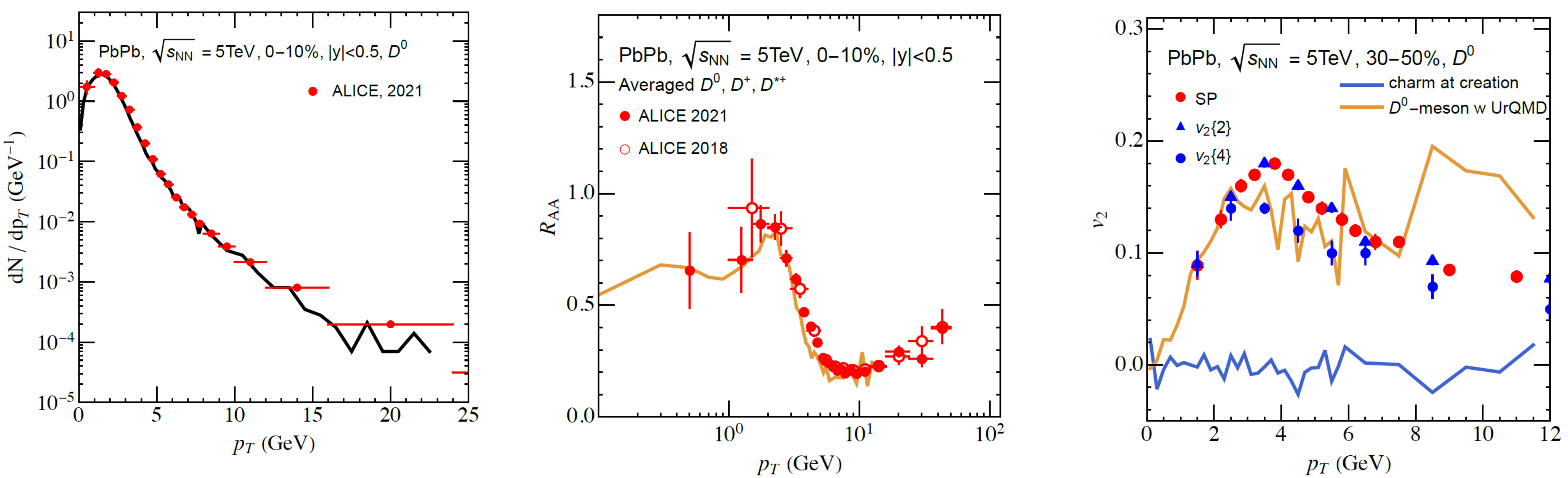
all c and cbar interact with the medium as those observed finally as D-mesons

all c and cbar interact among themselves

uses EPOS2 to describe the expanding QGP

HQ interactions with QGP verified by D meson results

D mesons test the energy loss and v_2 of heavy quarks in a QGP
energy loss tests the initial phase
v_2 the late stage of the expansion
Two mechanisms : collisional energy loss: PRC78 (2008) 014904
radiative energy loss: PRD 89 (2014) 074018



EPOS4HQ reproduces dN/dp_T, R_{AA} and v_2 quite well
→ Heavy quark dynamics in the medium under control

J/ψ creation in heavy ion collisions

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

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

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

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

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

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

For time independent ρ^Φ

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

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

J/ψ creation in heavy ion collisions

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

$$W_N = \langle W_N^{c(\text{classical})} \rangle$$

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

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

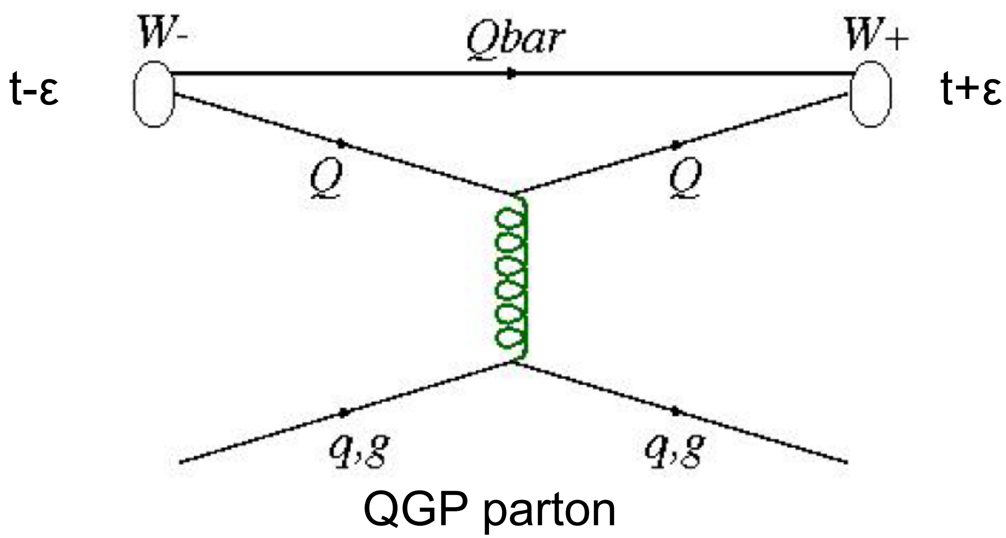
with

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

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

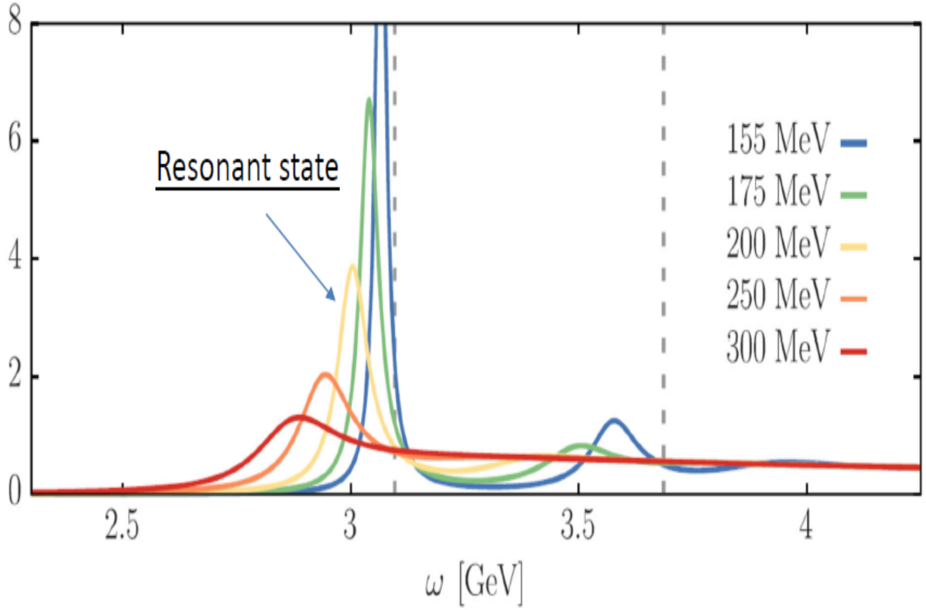
$$\Gamma^{\Phi}(t) = \sum_{i=1,2} \sum_{j\geq 3} \delta(t - t_{ij}(n)) \prod_{k=1}^{N} \int d^3\mathbf{r}_i d^3\mathbf{p}_i \cdot W^{\Phi}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{p}_1, \mathbf{p}_2) \cdot [W_N(\{\mathbf{r}, \mathbf{p}\}; t + \epsilon) - W_N(\{\mathbf{r}, \mathbf{p}\}; t - \epsilon)]$$

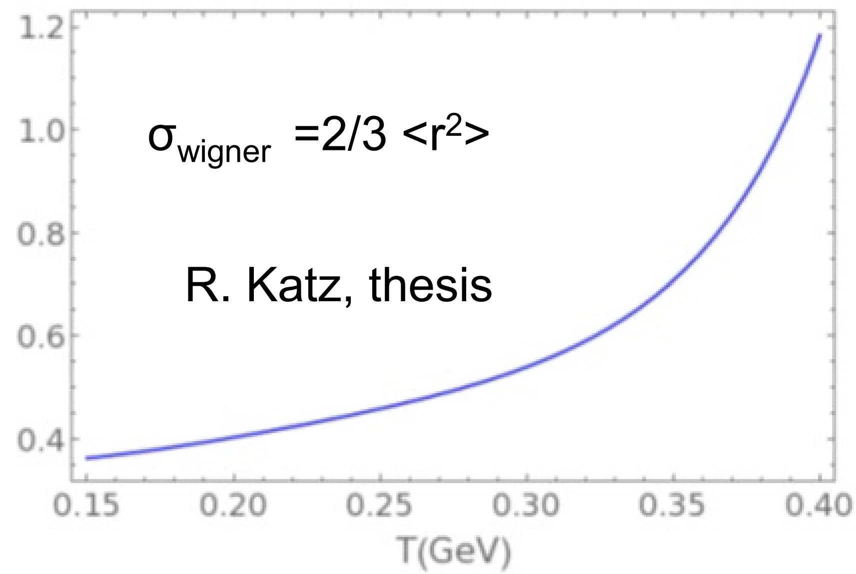


J/ψ creation in heavy ion collisions

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 $_{diss}$ =400 MeV a local J/ψ prod. rate

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

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

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 →∞ 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}

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

Time evolution equation:

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

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

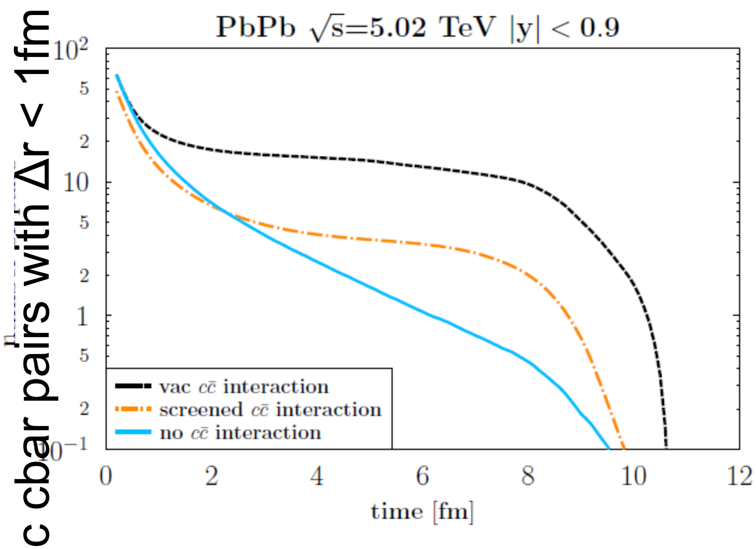
$$\dot{\theta} = \frac{\partial H}{\partial p_\theta} = \frac{p_\theta}{r^2\sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}}}$$

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

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

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

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

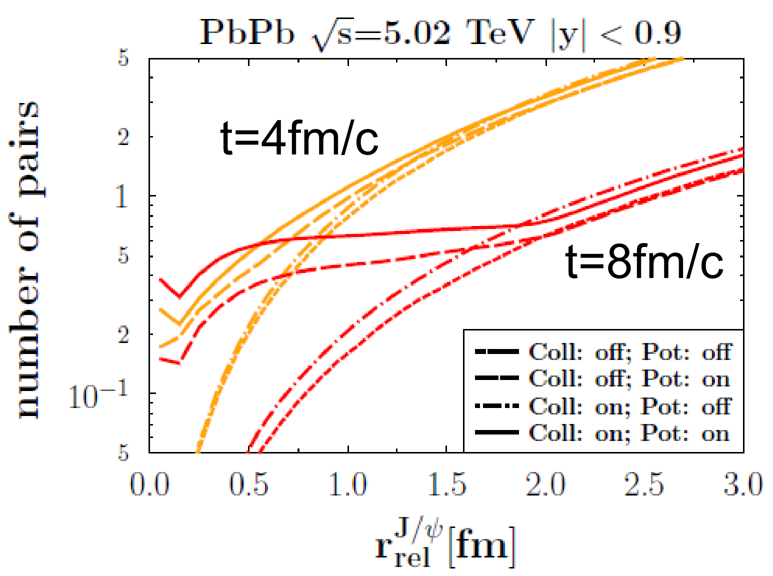


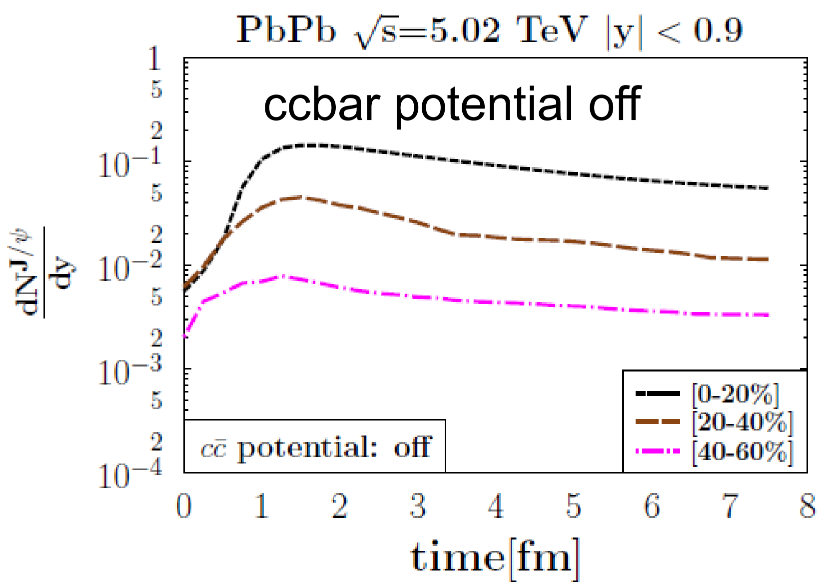
Consequences of the c cbar Interaction

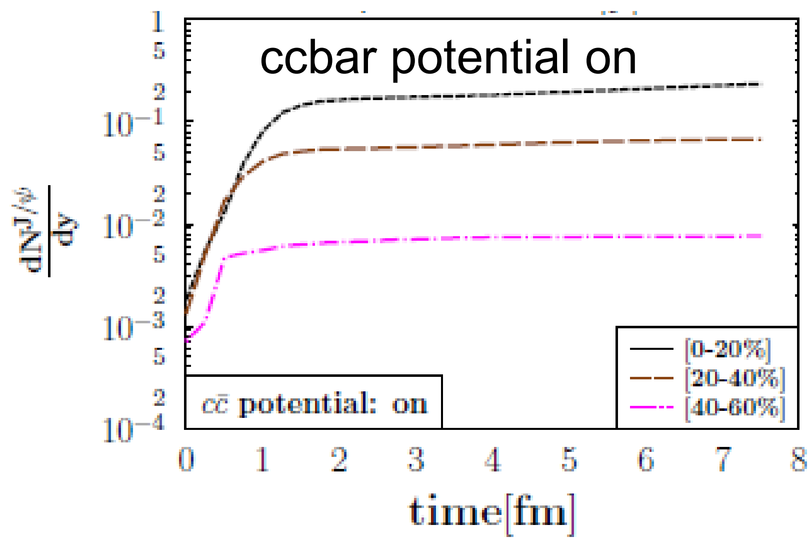
Qq and Qg collisions shift p_T spectra to lower values

(as for D mesons)

QQbar potential interaction increases the production rate



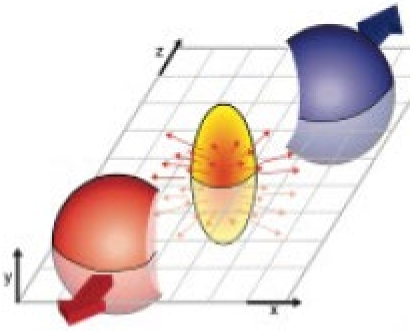




Influence of the Corona

Standard hydrodynamical calculations (EPOS 2) show two classes of particles of initially produced particles:

- Core particles which become part of QGP
- Corona particles from the surface of the interaction zone (energy density too low, no collision after production → like pp) importent for high pt and for v2



Confirmed by centrality dependence of multiplicity

For elementary particles it is easy to define corona and core particle

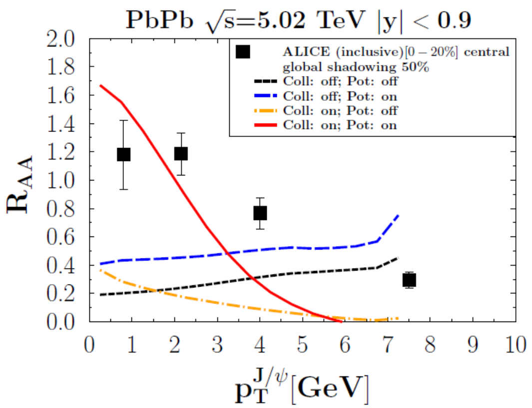
For J/ψ mesons we use working description:

Corona J/ψ are those where none of its constituents suffers from a momentum change of $q > q_{thres}$. Larger q would destroy a J/ψ.

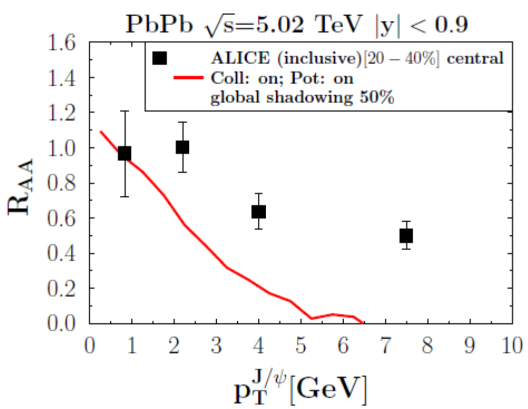
Comparison with ALICE data

Caution: excited states decay, b decay and hadronic rescattering not in yet

[0-20%]   no corona



[20-40%] no corona



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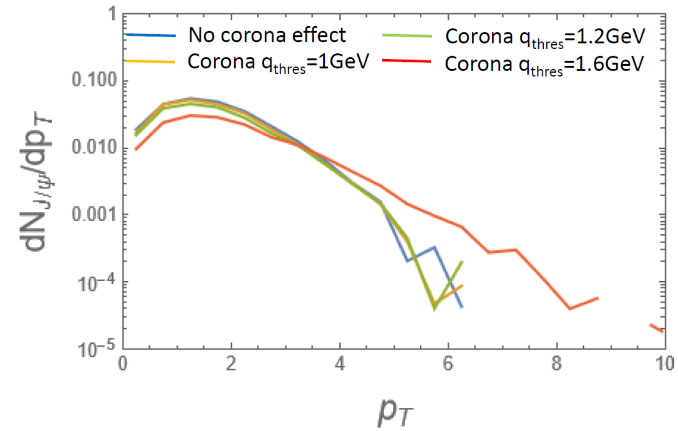
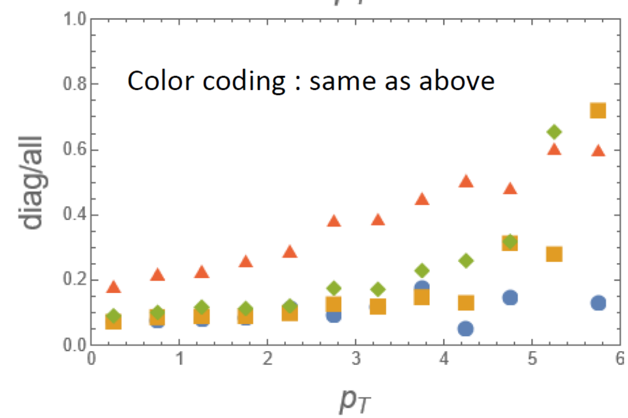
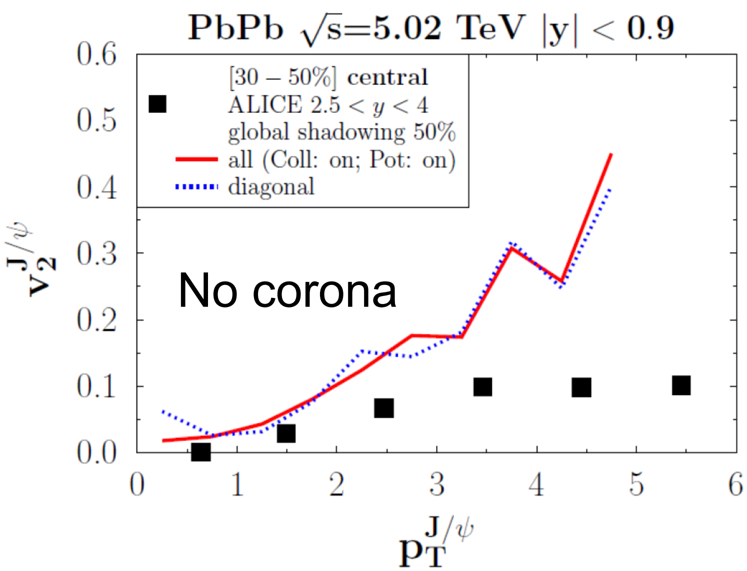
influence of the corona



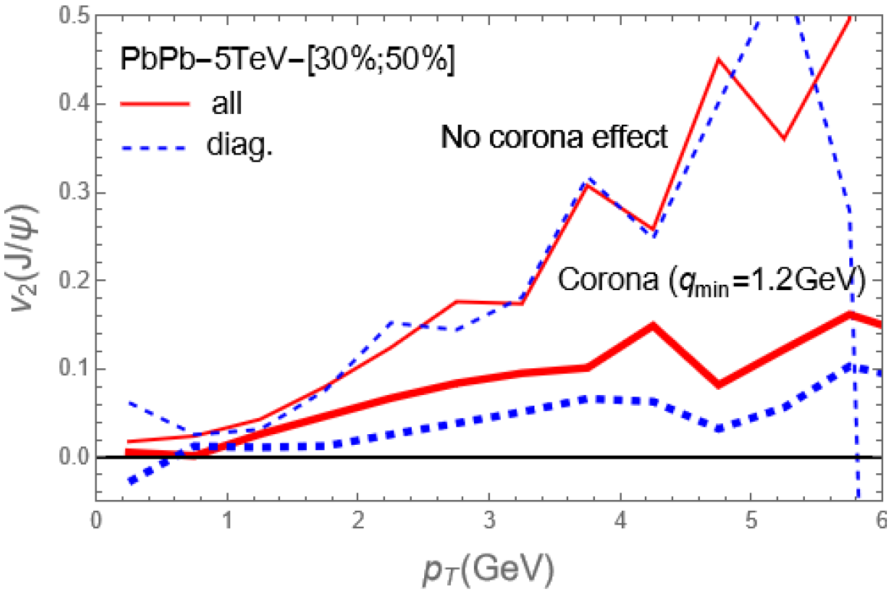


Comparison with ALICE data

[30-50%]



[30-50%]



Corona J/ψ

- bring v_2 closer to the experimental values
- create difference between diagonal and off-diagonal

caution:

comparison of mid and forward rapidities

Summary

We presented a new approach for quarkonia production in pp collision based on the quantal density matrix

It describes the y and p_T dependence of the spectra for J/ψ, □ and Y from RHIC to LHC

Based on these results we presented a new microscopic quantal approach for J/ψ production in AA 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 by collisions with q,g from QGP
- when $T < T_{diss} = 400$ MeV J/ψ can be formed (and later destroyed)
- formation described by Wigner density formalism (as in pp)

➢ Including corona J/ψ, preliminary 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

➢ Has many common features with open quantum system approach (however bottom up)

Outlook

a lot remains to be done:

- Follow the color structure, excited states
- Relativistic kinematics,
- J/ψ interaction in the hadronic expansion
  reduced cross section of preformed J/ψ ($r <$ □$_{gluon}$) with QGP partons
  (dipole cross section)
- ….

Our approach and open quantum systems

Von Neuman eq.

$$\partial \rho_N / \partial t = -\frac{i}{\hbar}[H, \rho_N] \qquad H = H_{1,2} + H_{N-2} + U_{1,2} \qquad U_{1,2} = \Sigma_j V_{1,j} + \Sigma_j V_{2,j}$$

Prob. to find quarkonium $P^\Phi(t) = \mathrm{Tr}[\rho^\Phi \rho_N(t)]$ with $[\rho^\Phi, H_{1,2}] = 0 \quad [\rho^\Phi, H_{N-2}] = 0$

Quarkonium rate: $\frac{dP^\Phi(t)}{dt} = \Gamma^\Phi(t) = \frac{-i}{\hbar} Tr[\rho^\Phi [U_{1,2}, \rho_N(t)]]$

$$\partial \rho_N(t)/\partial t = -\frac{i}{\hbar}\Sigma_j [K_j, \rho_N(t)] - \frac{i}{\hbar}\Sigma_{k>j}[V_{jk}, \rho_N(t)].$$

Interaction: coll. heavy quarks – partons: $-\frac{i}{\hbar}\Sigma_{k>j}[V_{jk}, \rho_N(t)] \equiv \langle \Sigma_{k>j}\Sigma_n \delta(t - t_{jk}(n)) \cdot (W_N^c(\{\mathbf{r}\}, \{\mathbf{p}\}, t+\epsilon) - W_N^c(\{\mathbf{r}\}, \{\mathbf{p}\}, t-\epsilon))\rangle.$

yields

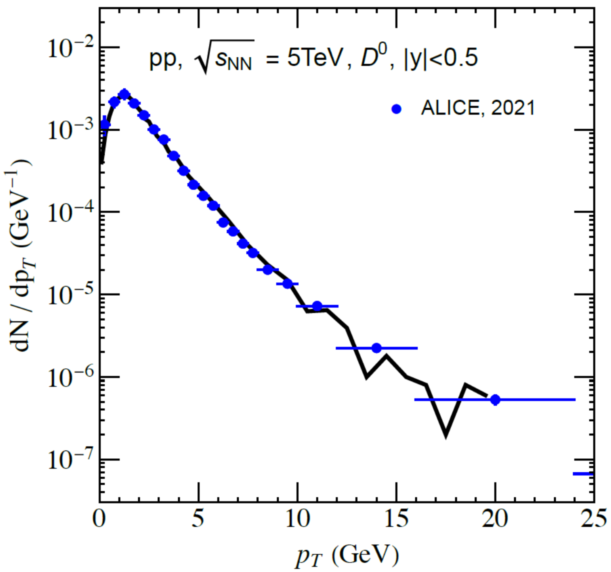
$$\frac{dP^\Phi(t)}{dt} = \Gamma^\Phi(t) = h^3 \frac{d}{dt}\int \prod_j^N d^3r_j d^3p_j W_{12}^\Phi W_N^c(t) = h^3 \int \prod_i^N d^3\mathbf{r}_j d^3\mathbf{p}_j \; W_{12}^\Phi \frac{\partial}{\partial t} W_N^c(t)$$

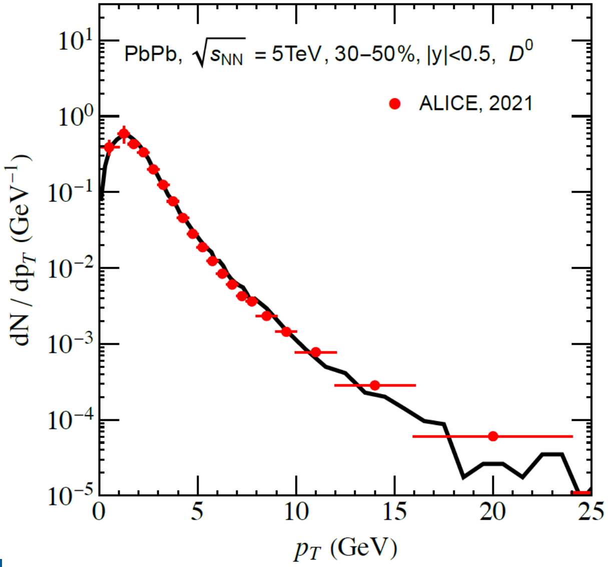
Lindblad eq. (open quantum systems) in the quantal Brownian motion regime

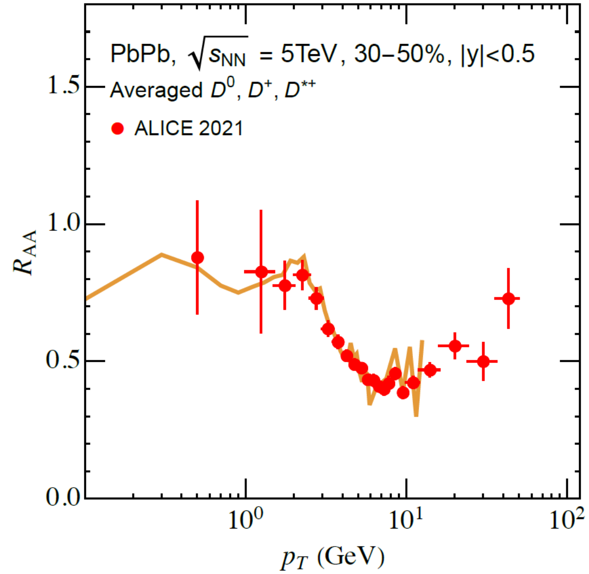
$$\frac{d}{dt}\rho(t) = -i\left[\frac{p^2}{M} + \Delta H, \rho\right] + \sum_n \int \frac{d^3k}{(2\pi)^3}\left[C_n(\vec{k})\rho C_n^\dagger(\vec{k}) - \frac{1}{2}\left\{C_n^\dagger(\vec{k})C_n(\vec{k}), \rho\right\}\right]$$

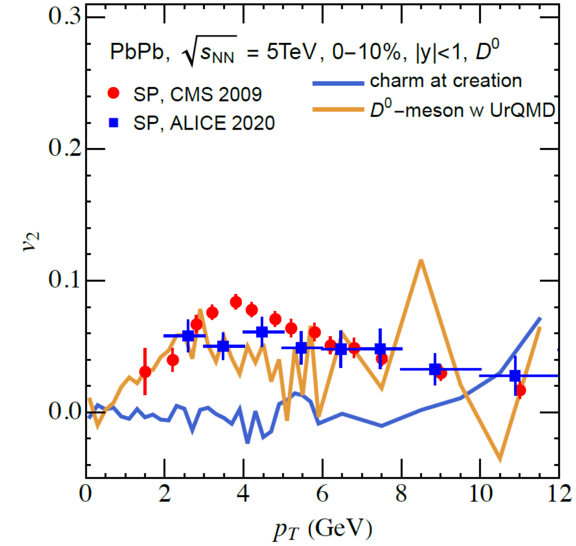
Miura, Akamatsu , 2205.15551

First EPOS4HQ results







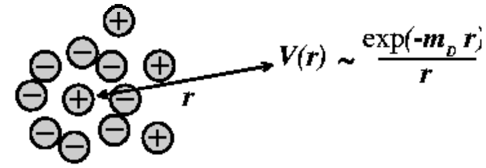


HQ interactions with the QGP

Phys.Rev.C 78 (2008) 014904

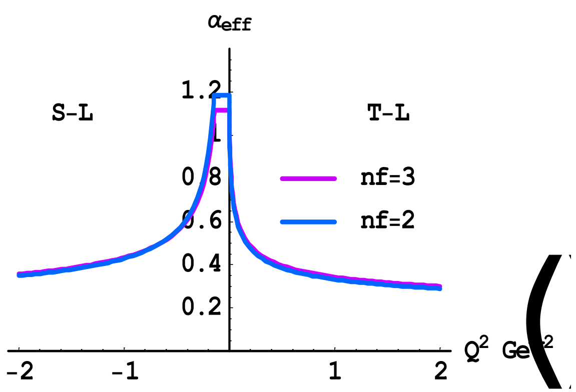
The interaction between HQ and q and g is described by Born type diagrams

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



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

coupling constant and infrared screening are input



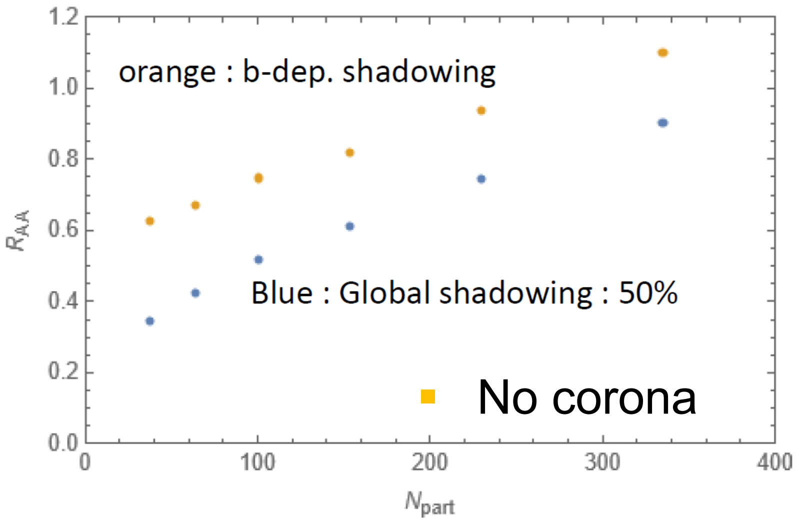
Peshier NPA 888, 7 based on universality constraint of Dokshitzer

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 PRD44 1298,2625) for QED:
Energy loss indep. of the artificial scale t* which separates the regimes
Extension to QCD (PRC78:014904)

$\kappa \approx 0.2$

Comparison with ALICE data



Corona J/ψ bring

- R_{AA} close to one for peripheral reactions
- the participant dependence close to data