Quarkonium production in pp and Heavy Ion Collisions

J. Aichelin

J. Zhao, D. Arrebato Villar, P.B. Gossiaux, K. Werner
(Subatech, Nantes)

T. Song, E. Bratkovskaya
(GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt)

work in progress

pp: PRC 96,014907
2305.10750

AA: first results for:
PRC107,054913

WPCF 2023 Resonance Workshop

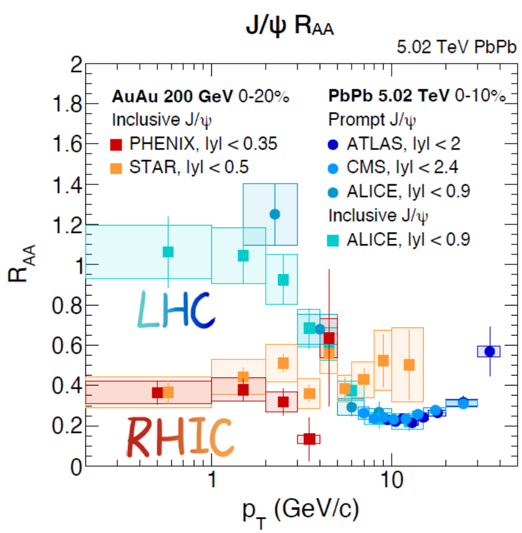
Catania, November 6-10, 2023

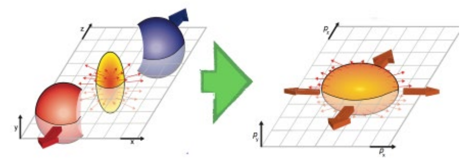
Why do we study J/ψ production in heavy-ion collisions?

J/ψ mesons

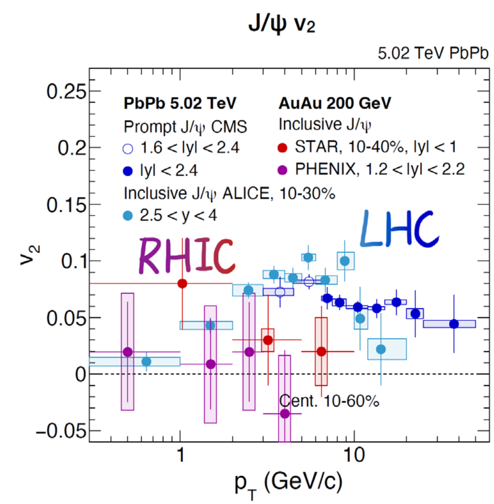
- are a hard probe: test quark-gluon plasma from creation to hadronization
- no consistent microscopical theory available yet
- show quite different results for key observables at RHIC and LHC which are not fully understood yet:

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





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

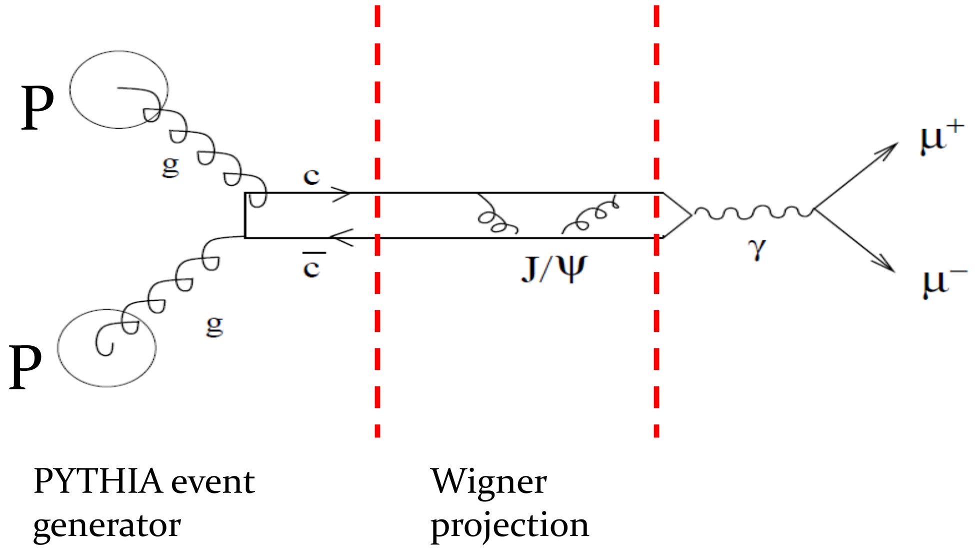


J/ψ production in p+p collisions

How to describe a bound state like a c-cbar in QCD?

It involves low momenta and needs non perturbative input ➔ assumptions.

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



Wigner Density Formalism

c-cbar interaction depends on relative p and r only, → plane wave of CM

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

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

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

(close to classical phase space density)

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

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

$$n_i(\mathbf{R},\mathbf{P}) = \sum_{\text{all } c\bar{c} \text{ pairs}} \int \frac{d^3r d^3p}{((2\pi)^3} \Phi_i^W(\mathbf{r},\mathbf{p}) \prod_{\text{all other particles}} \int \frac{d^3r_j d^3p_j}{(2\pi)^{3(N-2)}} \rho_N^W(\mathbf{r_1},\mathbf{p_1}....\mathbf{r_N},\mathbf{p_N})$$

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

The results are obtained using a relativ. formulation

pp: In momentum space given by tuned PYTHIA

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

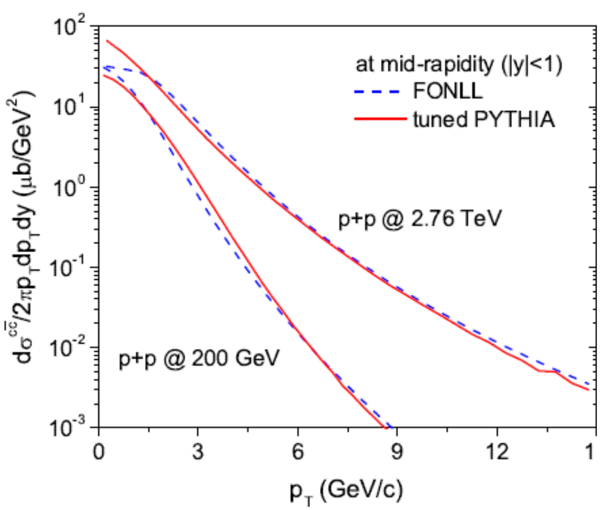
The Wigner density of the state $|\Phi_i>$ is different for S and P states.
Simplest possible (harmonic oscillator) parametrization:

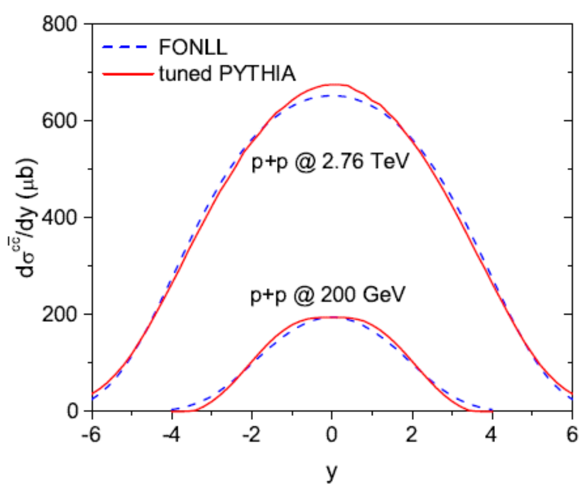
$$\Phi_S^W(\mathbf{r},\mathbf{p}) = 8\frac{D}{d_1 d_2} exp[-\frac{r^2}{\sigma^2} - \sigma^2 p^2] \qquad \Phi_P^W(\mathbf{r},\mathbf{p}) = \frac{16}{3}\frac{D}{d_1 d_2}(\frac{r^2}{\sigma^2} - \frac{3}{2} + \sigma^2 p^2) exp[-\frac{r^2}{\sigma^2} - \sigma^2 p^2]$$

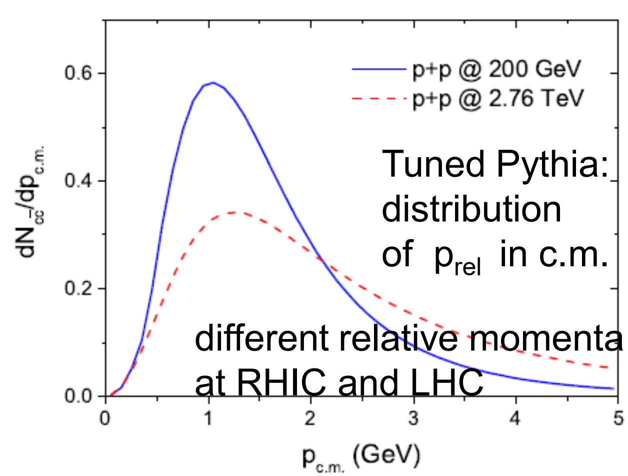
Where σ reproduces the rms radius of the vacuum c cbar state

D : degeneracy of Φ
d_1 : degeneracy of c
d_2 : degeneracy of cbar
σ ~ radius of Φ

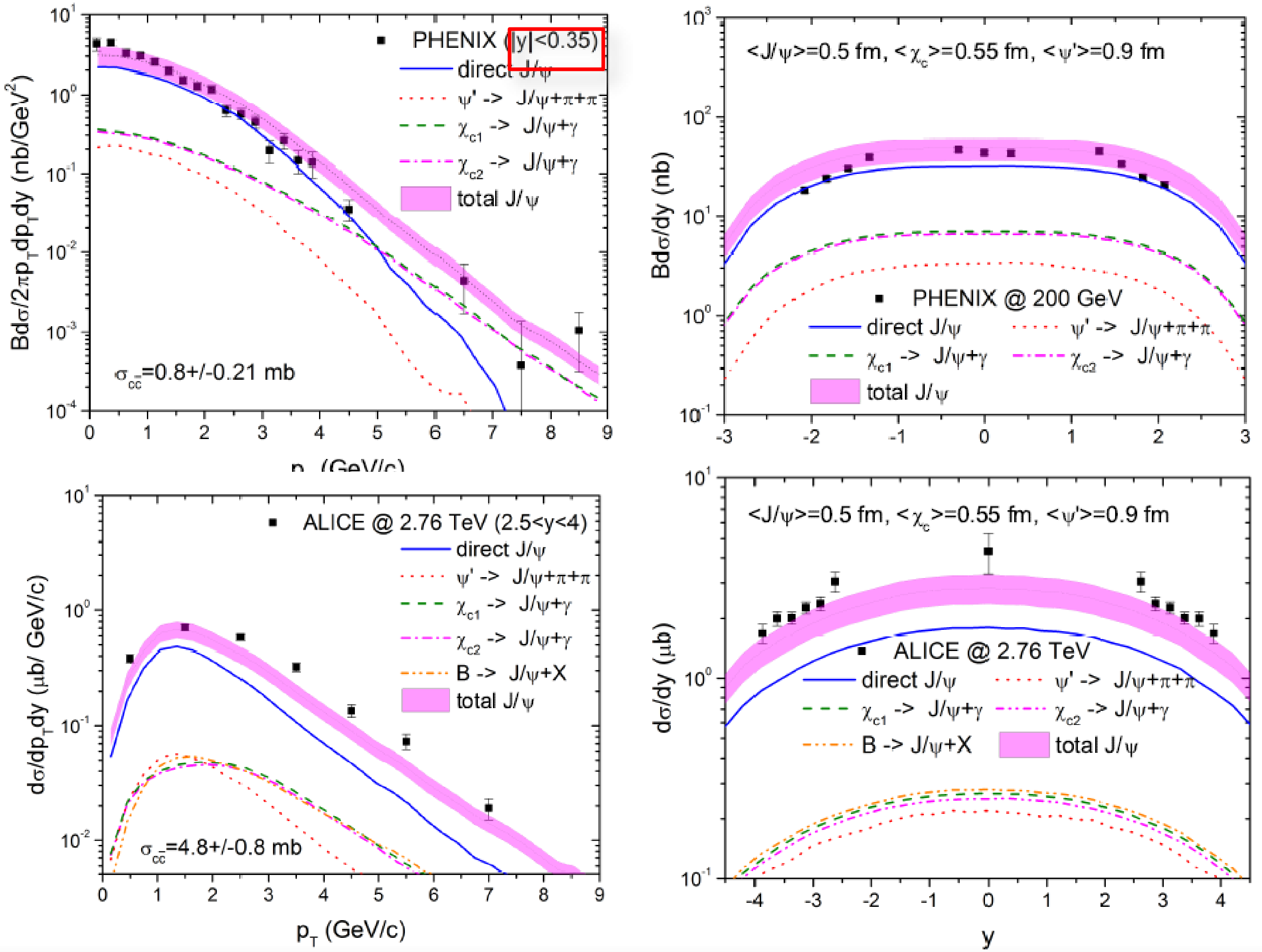
The tuned PYTHIA reproduces FONLL charm quark calculations
but J/ψ multiplicity depends in addition on the ccbar correlation (not known in FONLL)







pp: comparison with PHENIX and ALICE data



Little feed down

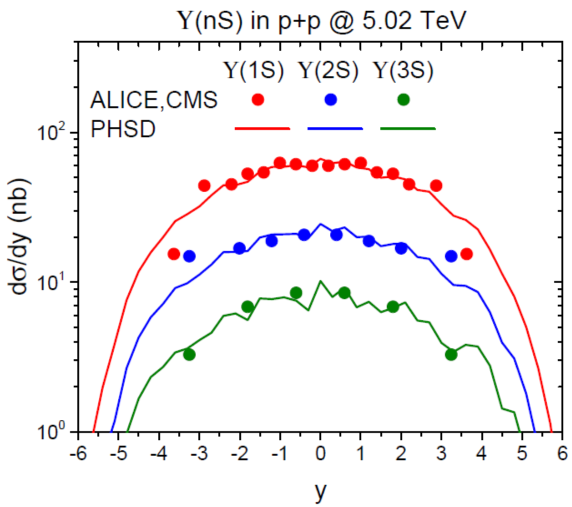
Feed down important

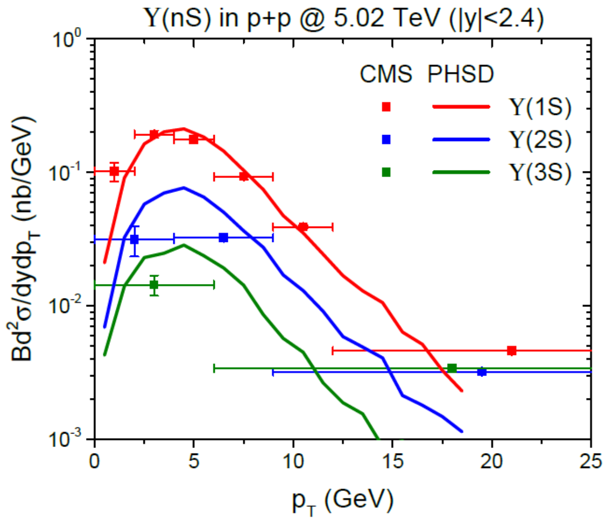
Wigner density based model reproduced pp J/Ψ data

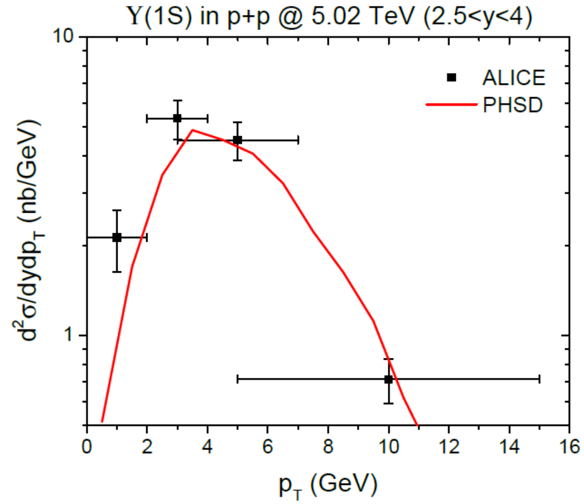
pp: comparison of Υ(nS) with CMS/ALICE data

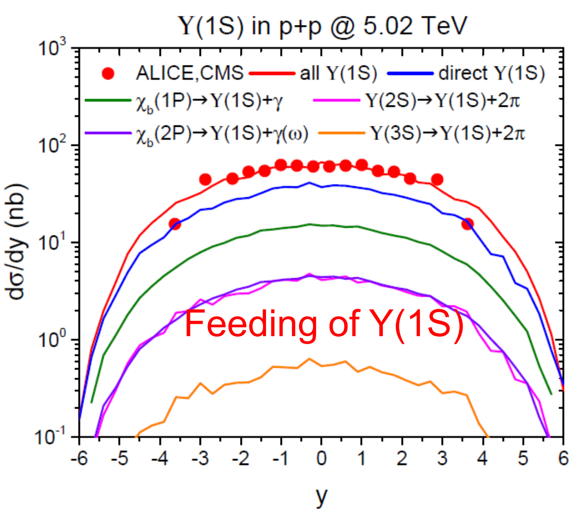
2305.10750 [nucl-th]

Wigner density approach works also for Υ(nS)









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

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

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

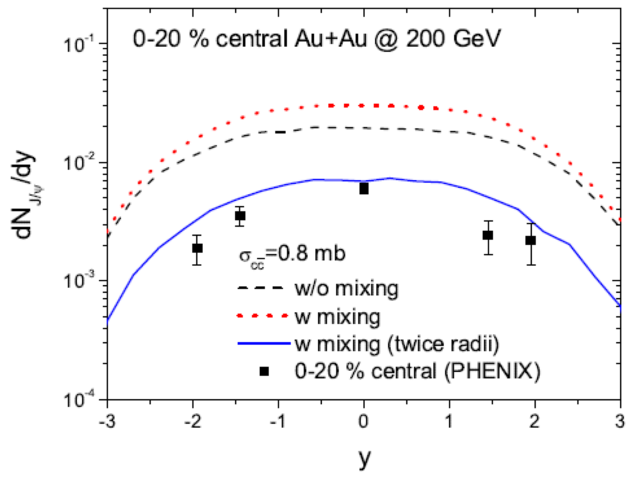
With this validation of the new approach for quarkonium production in pp we are ready for AA collisions

AA collisions

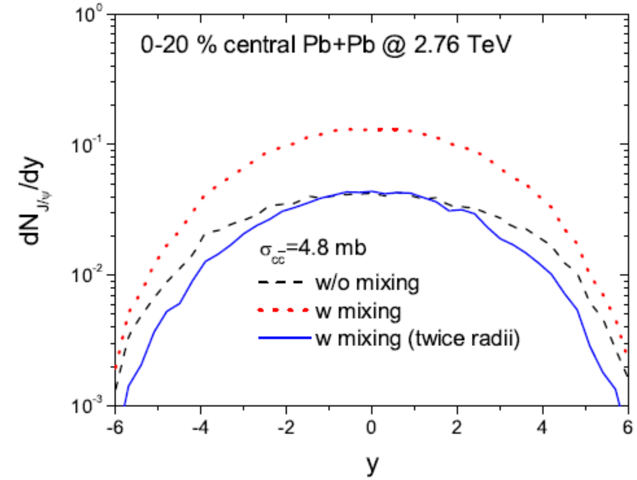
Primary production of J/Ψ in AA

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

T. Song et al., PRC 96 (2017) 1, 014907

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

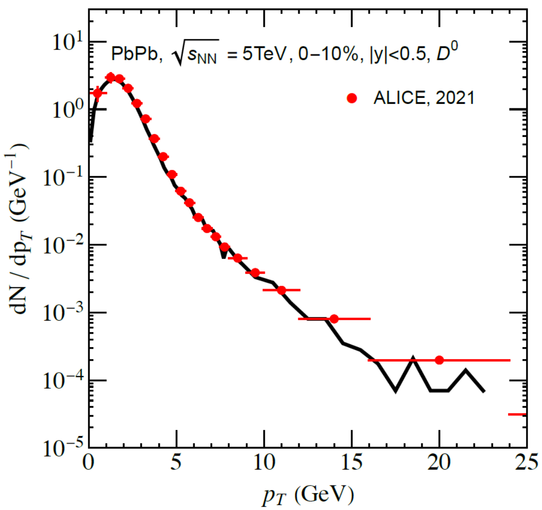
all c and cbar interact with QGP as those observed finally as D-mesons

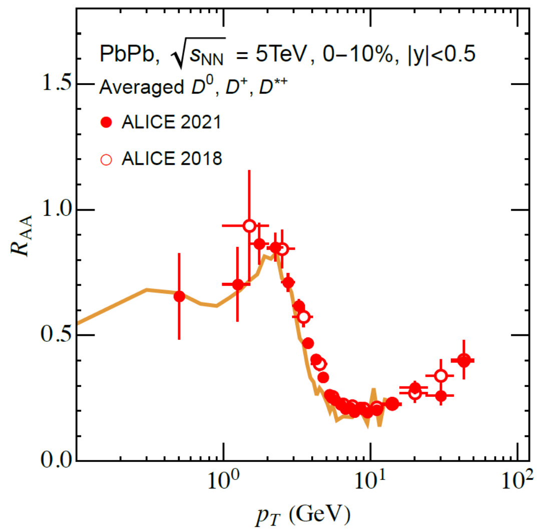
all c and cbar interact among themselves

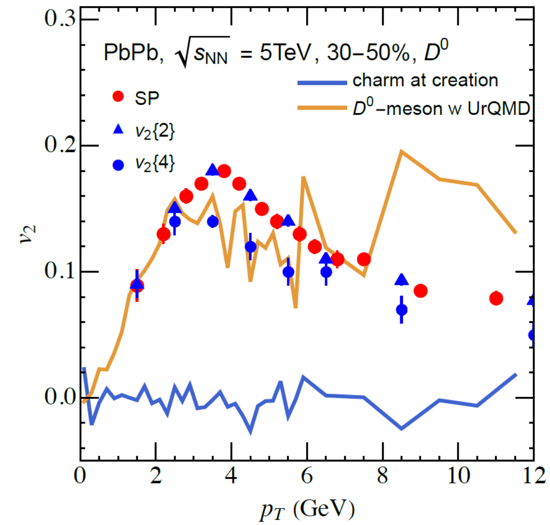
uses EPOS2 to describe the expanding QGP

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: PRD89 (2014) 074018







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

J/ψ dynamics 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 $H = \Sigma_i K_i + \Sigma_{i>j} V_{ij}$

$P^\Phi(t) = \mathrm{Tr}[\rho^\Phi \rho_N(t)]$ with $\rho^\Phi = |\Psi^\Phi >< \Psi_\Phi|$ gives the multiplicity of Φ at time t

This is the solution if we would know the quantal $\rho_N(t)$

$\rho_N(t)$ is unknown so we follow BUU,QMD ..

$$\rho_N = <W_N^{c(classical)}>$$

and replace $P^\Phi(t)$ by the integration over the rate:

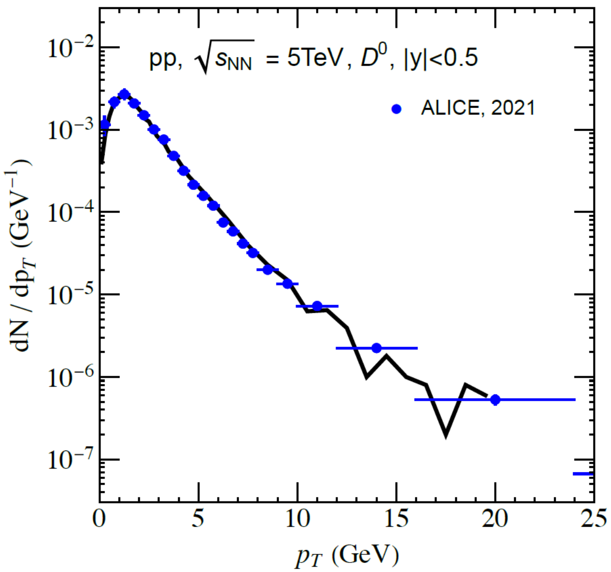
$$\Gamma^\Phi(t) = \frac{dP^\Phi}{dt} = \frac{d}{dt}\mathrm{Tr}[\rho^\Phi \rho_N(t)] \qquad P^\Phi(T) = \int_0^T \Gamma^\Phi(t)dt$$

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

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

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

Open heavy flavor results in pp and AA from EPOS4

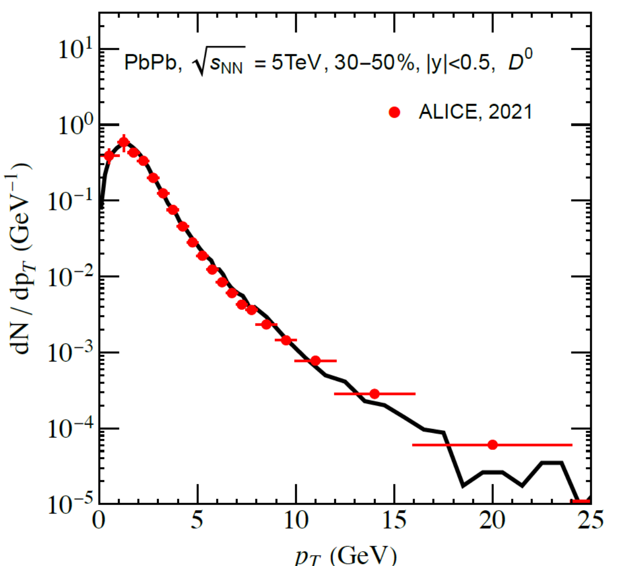


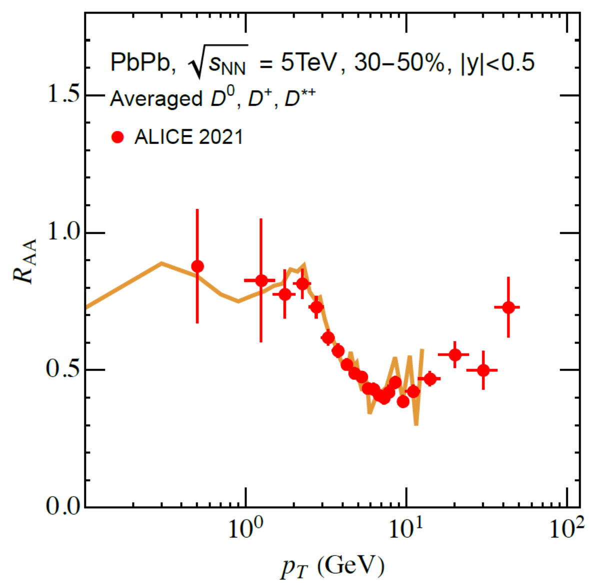
Elastic and enelastic energy loss of Q in medium

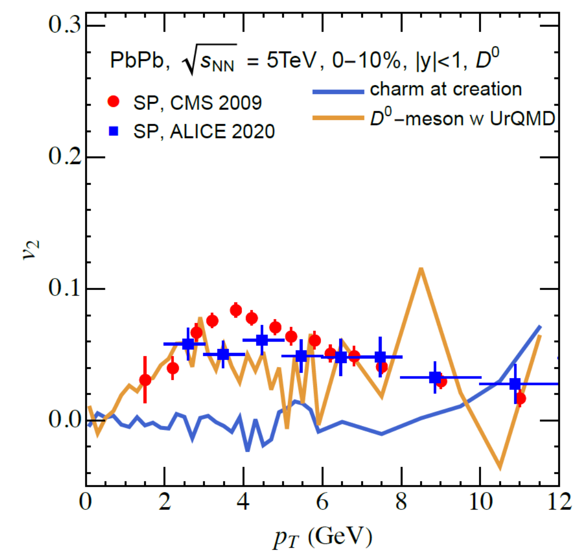
Beyond the scope of the talk

(PRC 78 (2008) 014904, PRD 89 (2014) 074018)

Energy loss is controlled by comparing open heavy flavour results with experiment.







J/ψ creation in heavy ion collisions

$\Gamma^\Phi(t)$ expressed in Wigner and classical phase space density:

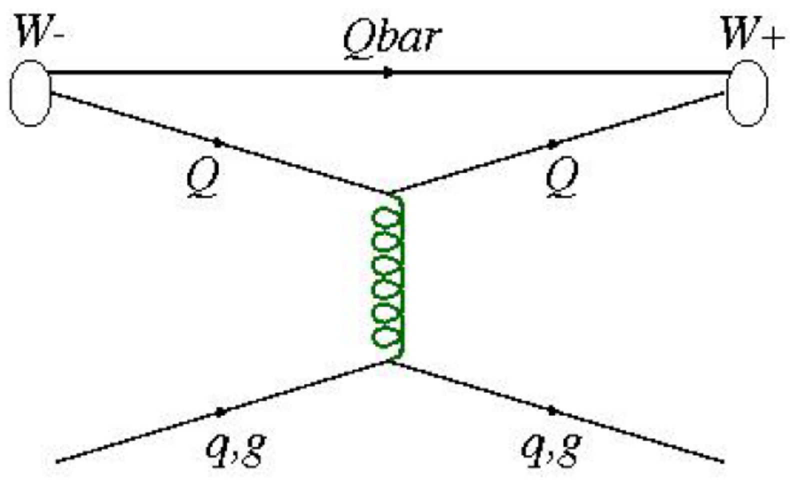
$$\Gamma^\Phi(t) = \frac{dP^\Phi(t)}{dt} = \frac{d}{dt} Tr[\rho^\Phi, \rho_N(t)] \approx \frac{d}{dt} \prod \frac{d^3 r_i d^3 p_i}{(2\pi)^{3N}} W^\Phi(\mathbf{r},\mathbf{p}) W^c(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N})$$

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

(1,2 are charm quark, n=number of collision of i and j, $t_{ij}(n)$=time of n-th collision of ij) :

$$\Gamma^\Phi(t) = \sum_n \sum_{i=1,2} \sum_{j\geq 3} \delta(t - t_{ij}(n)) \prod_N \frac{d^3 r_i d^3 p_i}{(2\pi)^{3N}} W^\Phi(\mathbf{r},\mathbf{p}) [\underbrace{W^c(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N}, t+\epsilon)}_{W^+} - \underbrace{W^c(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N}, t-\epsilon)}_{W^-}]$$

t-ε

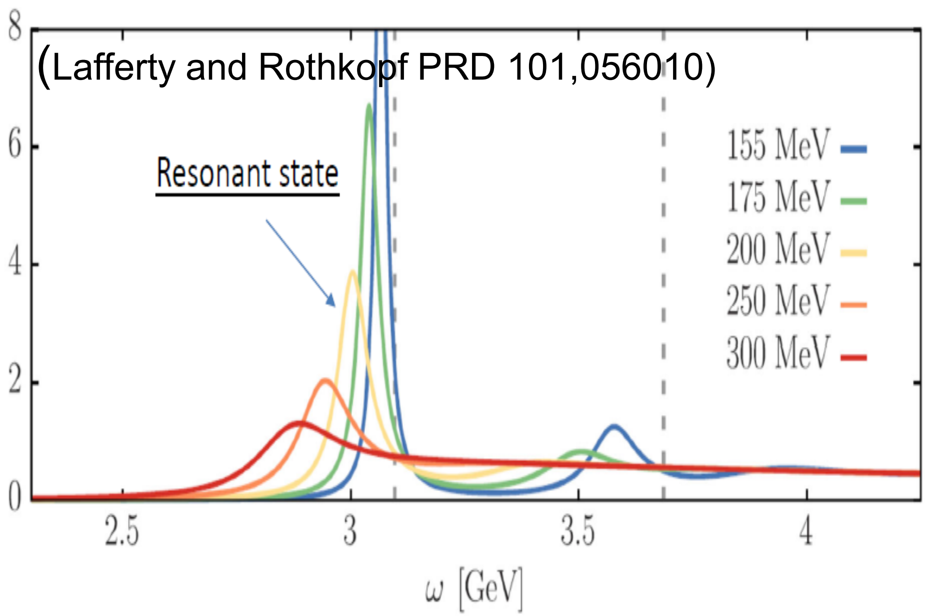


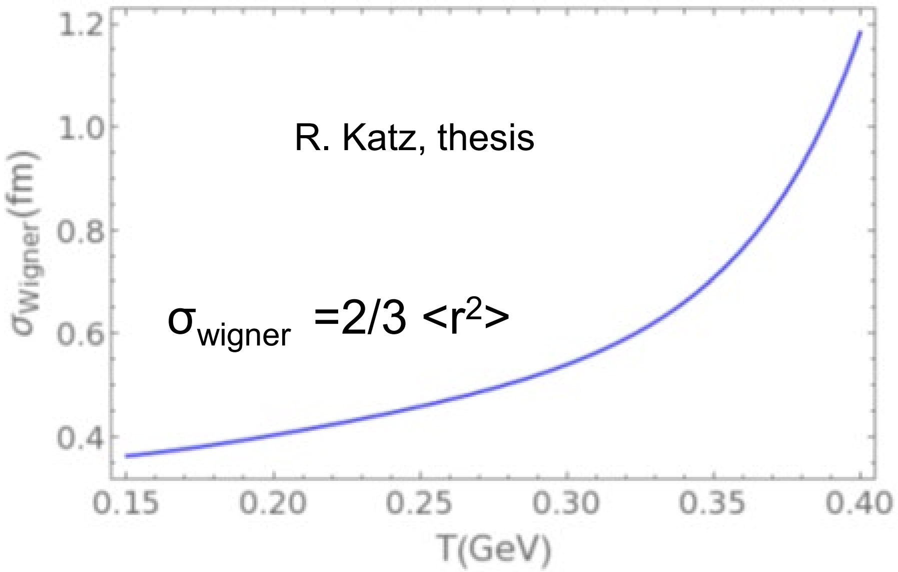
t+ε

QGP parton

J/ψ creation in heavy ion collisions

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





This creates an additional rate, called local rate

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

Final multiplicity of J/ in heavy-ion coll with a dissociation temperature

$$P(t) = P^{prim}(t_{init}) + \int_{t_{init}}^{t} [\Gamma_{coll}(t') + \Gamma_{loc}(t')] dt' \quad \rightarrow \quad P(t \rightarrow \infty)$$ = asympt. multiplicity

Interaction of c and cbar in the QGP

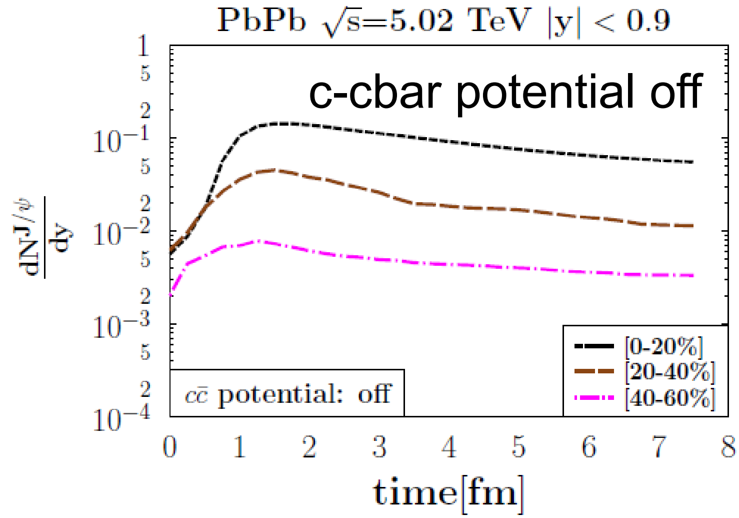
V(r) = attractive potential between c and cbar (PRD101,056010)

We work with

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

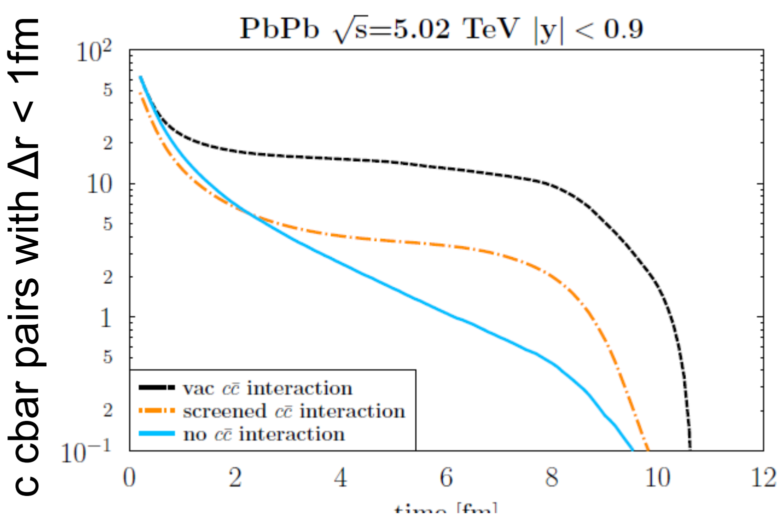
$$p^2 = p_r^2 + p_\theta^2 / r^2$$

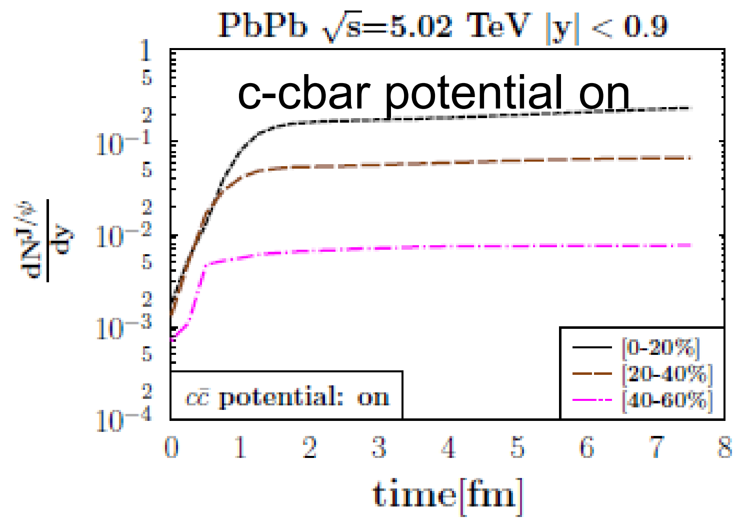
$$\gamma^{-1} = \sqrt{1 - v^2/c^2}$$



Has to be improved to describe high p_T J/ψ

Position and momentum of each c-cbar pair evolve according to Hamiltons equations



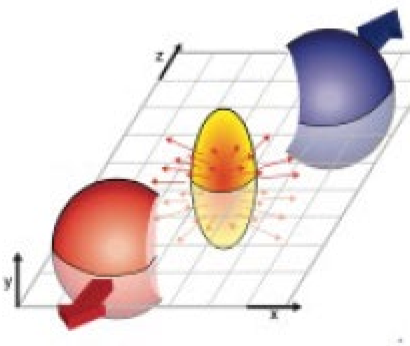


c-cbar potential keeps the quarks together → increases multiplicity

Influence of the Corona

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 (2306.10277)

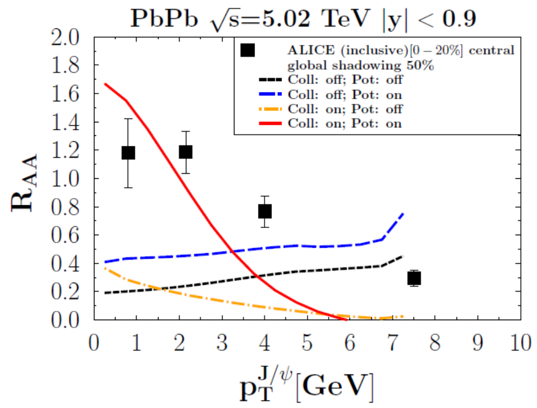
For J/ψ mesons we use as working description:

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.

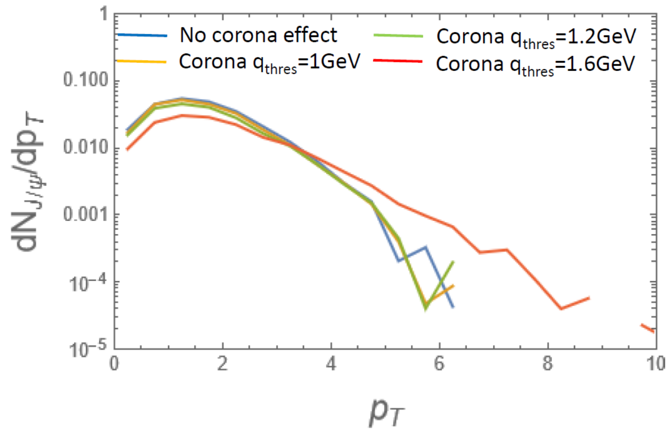
Comparison with ALICE data

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

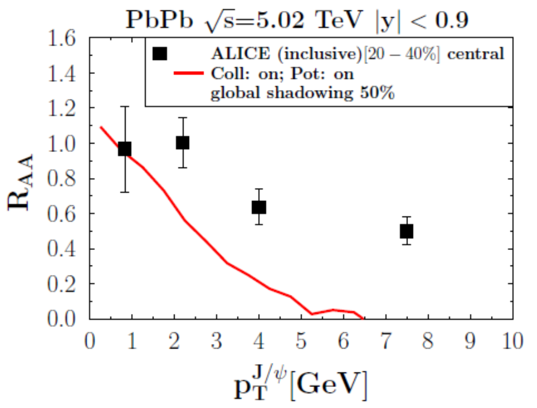
[0-20%]   no corona

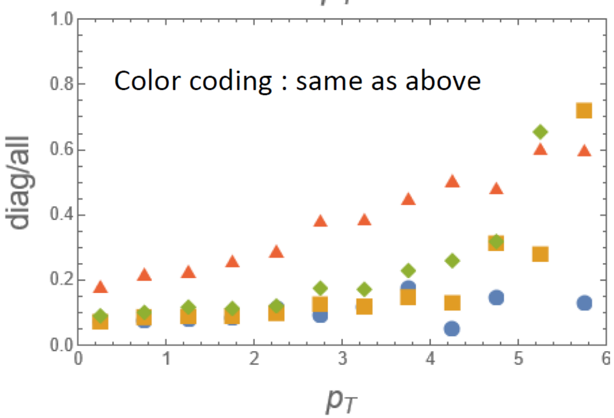


influence of the corona



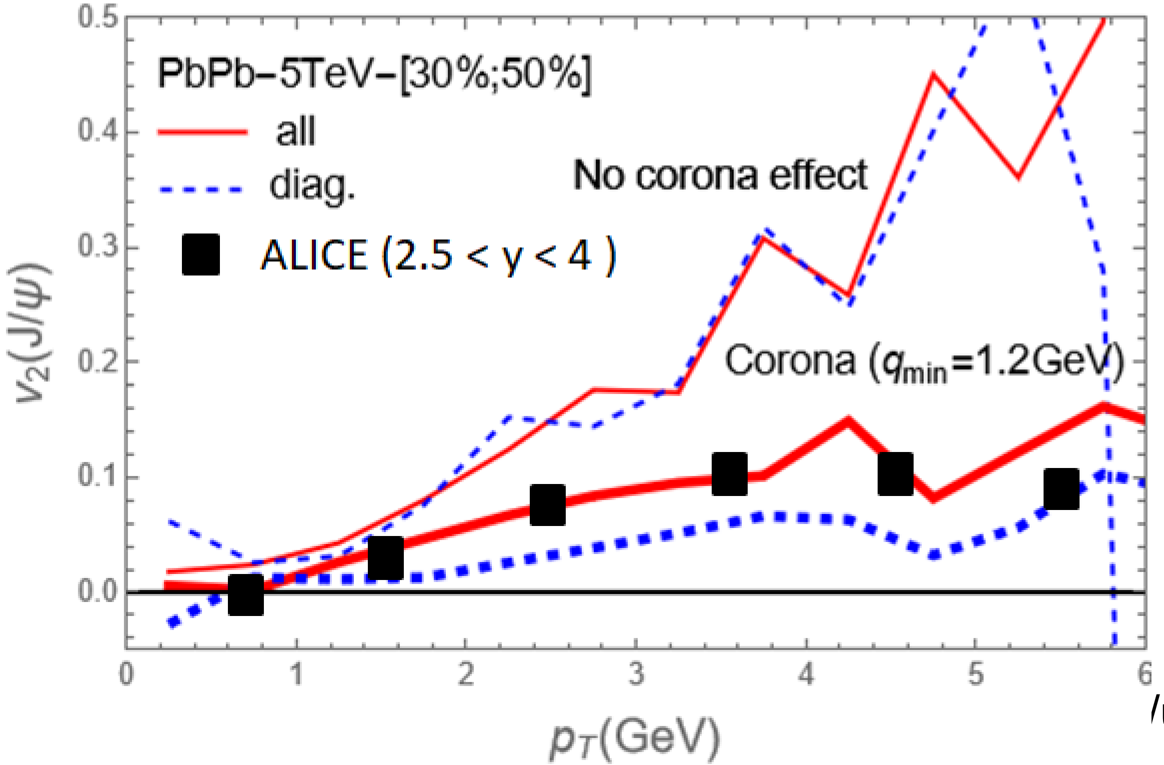
[20-40%] no corona





Comparison with ALICE data

[30-50%]



/ψ

- brings 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 Wigner density matrix

It describes the y and p_T dependence of the spectra for J/Ψ, χ 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

based on $\partial \rho_N / \partial t = -i[H, \rho_N]$ (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
- We observe an enhancement of R_{AA} (J/Ψ) at low p_T at LHC, as seen experimentally

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 ($r < \lambda_{gluon}$) 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

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

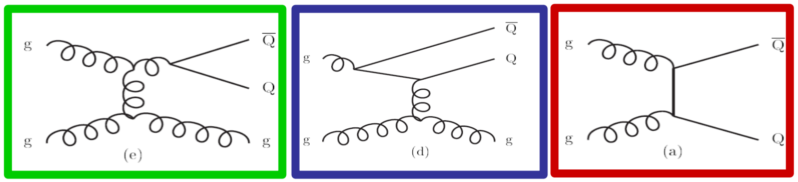
Lindblad eq. (open quantum systems) in the quantal Brownian motion regime

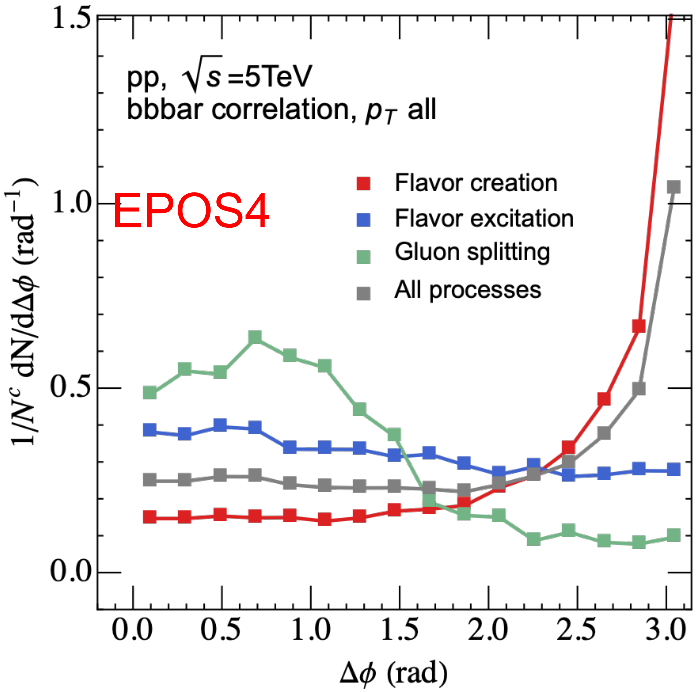
$$\frac{d}{dt}\rho(t) = -i\left[\frac{p^2}{M} + \Delta H, \rho\right] + \sum_n \int \frac{d^3k}{(2\pi)^3}\left[C_n(\vec{k})\rho C_n^\dagger(\vec{k}) - \frac{1}{2}\left\{C_n^\dagger(\vec{k})C_n(\vec{k}), \rho\right\}\right]$$

Miura, Akamatsu , 2205.15551

Azimuthal correlations in EPOS4 and PHSD

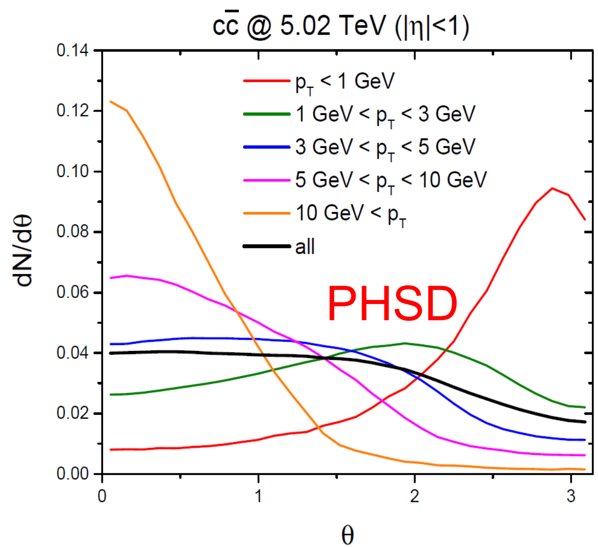
FONLL: only single quark p_T spectrum
for J/ψ or Y we need
c cbar and b bbar correlations

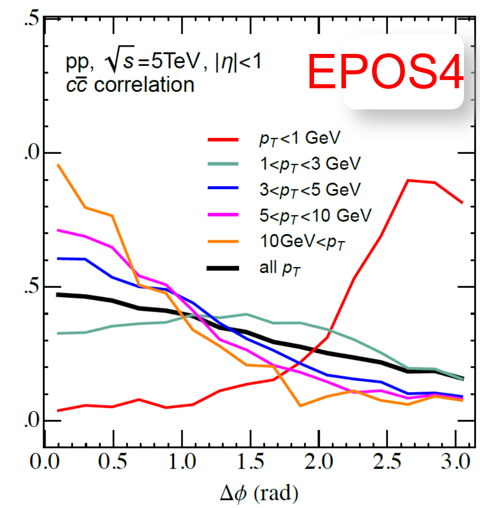




azimuthal correlations of EPOS4 and PHSD
between c and cbar agree
even as a function of p_T

basis for a model independent production
of quarkonia





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

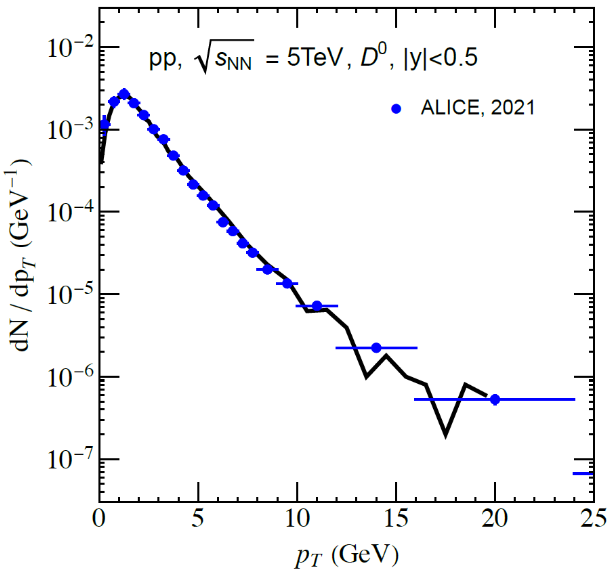
yields

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

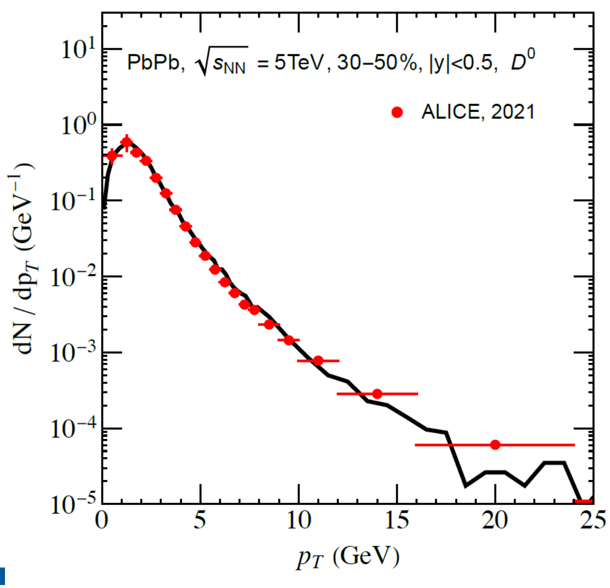
Lindblad eq. (open quantum systems) in the quantal Brownian motion regime

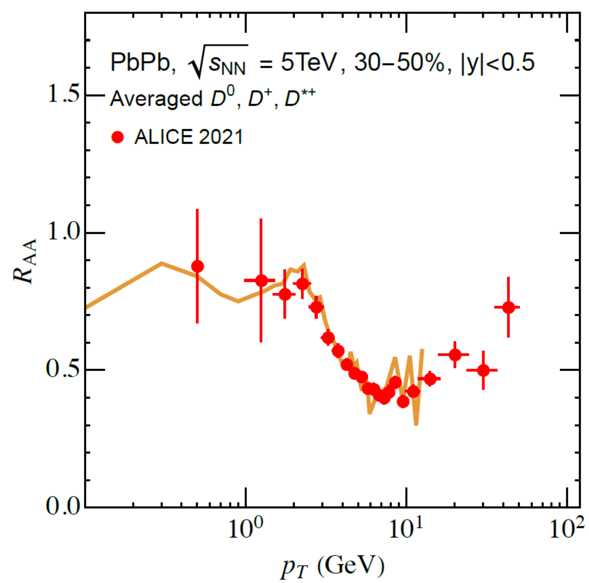
$$\frac{d}{dt}\rho(t) = -i\left[\frac{p^2}{M} + \Delta H, \rho\right] + \sum_n \int \frac{d^3k}{(2\pi)^3}\left[C_n(\vec{k})\rho C_n^\dagger(\vec{k}) - \frac{1}{2}\left\{C_n^\dagger(\vec{k})C_n(\vec{k}), \rho\right\}\right]$$

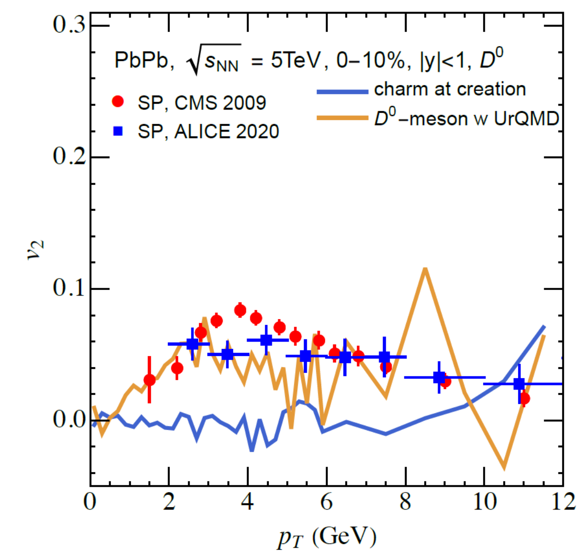
Miura, Akamatsu , 2205.15551



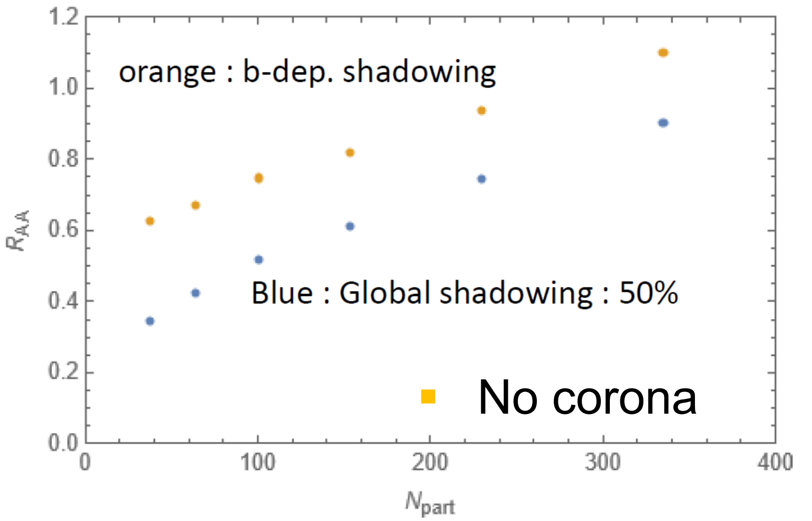
First EPOS4HQ results







Comparison with ALICE data



Corona J/ψ bring

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