Quarkonium production in pp and Heavy Ion Collisions

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work in progress

pp: PRC 96,014907
2305.10750

AA: first results for:
PRC107,054913

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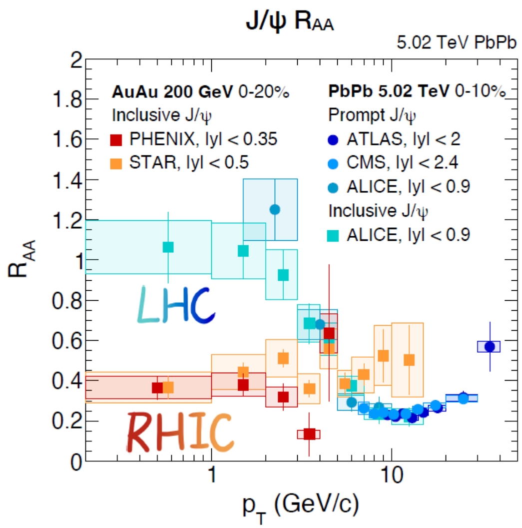
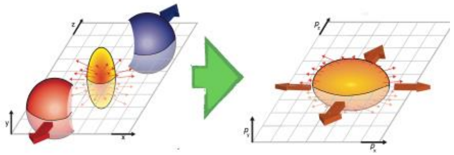
Why do we study J/ψ production in heavy-ion collisions?

J/ψ mesons

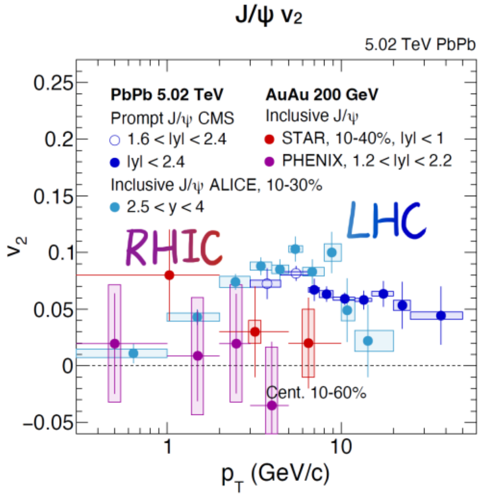
- are a hard probe: test quark-gluon plasma from creation to hadronization
- no consistent microscopical theory available yet
- show quite different results for key observables at RHIC and LHC which are not fully understood yet:

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





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

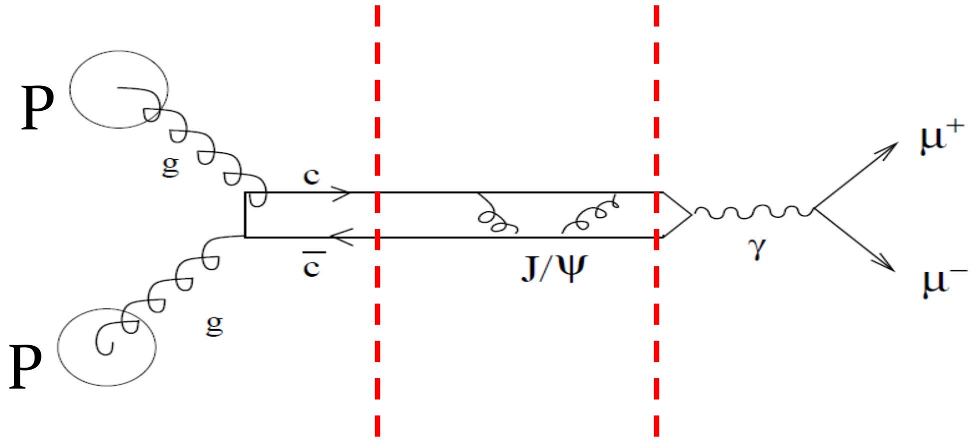


J/ψ production in p+p collisions

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)



PYTHIA event generator

Wigner projection

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

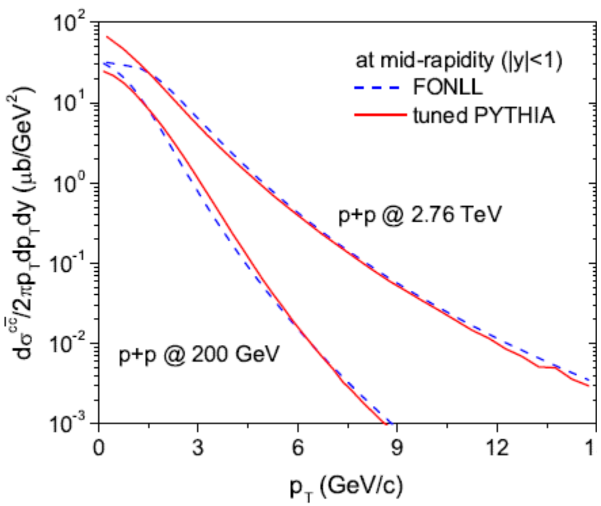
The Wigner density of the state $|\Phi_i>$ is different for S and P states.
Simplest possible (harmonic oscillator) parametrization:

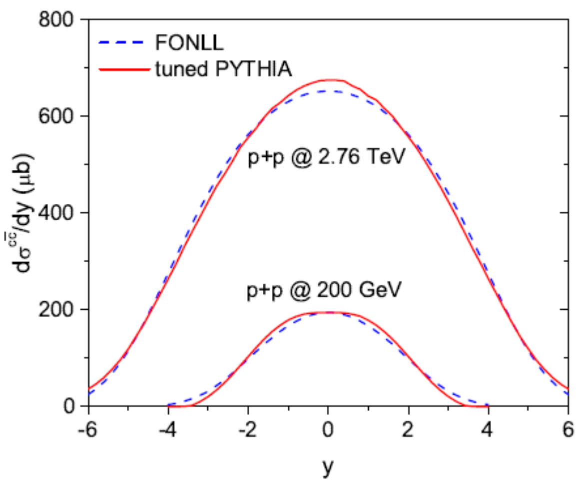
$$\Phi_S^W(\mathbf{r},\mathbf{p}) = 8\frac{D}{d_1 d_2} exp[-\frac{r^2}{\sigma^2} - \sigma^2 p^2] \qquad \Phi_P^W(\mathbf{r},\mathbf{p}) = \frac{16}{3}\frac{D}{d_1 d_2}(\frac{r^2}{\sigma^2} - \frac{3}{2} + \sigma^2 p^2) exp[-\frac{r^2}{\sigma^2} - \sigma^2 p^2]$$

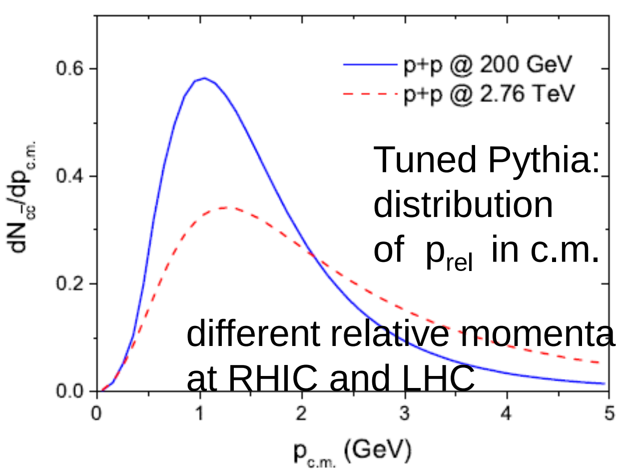
Where σ reproduces the rms radius of the vacuum c cbar state

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

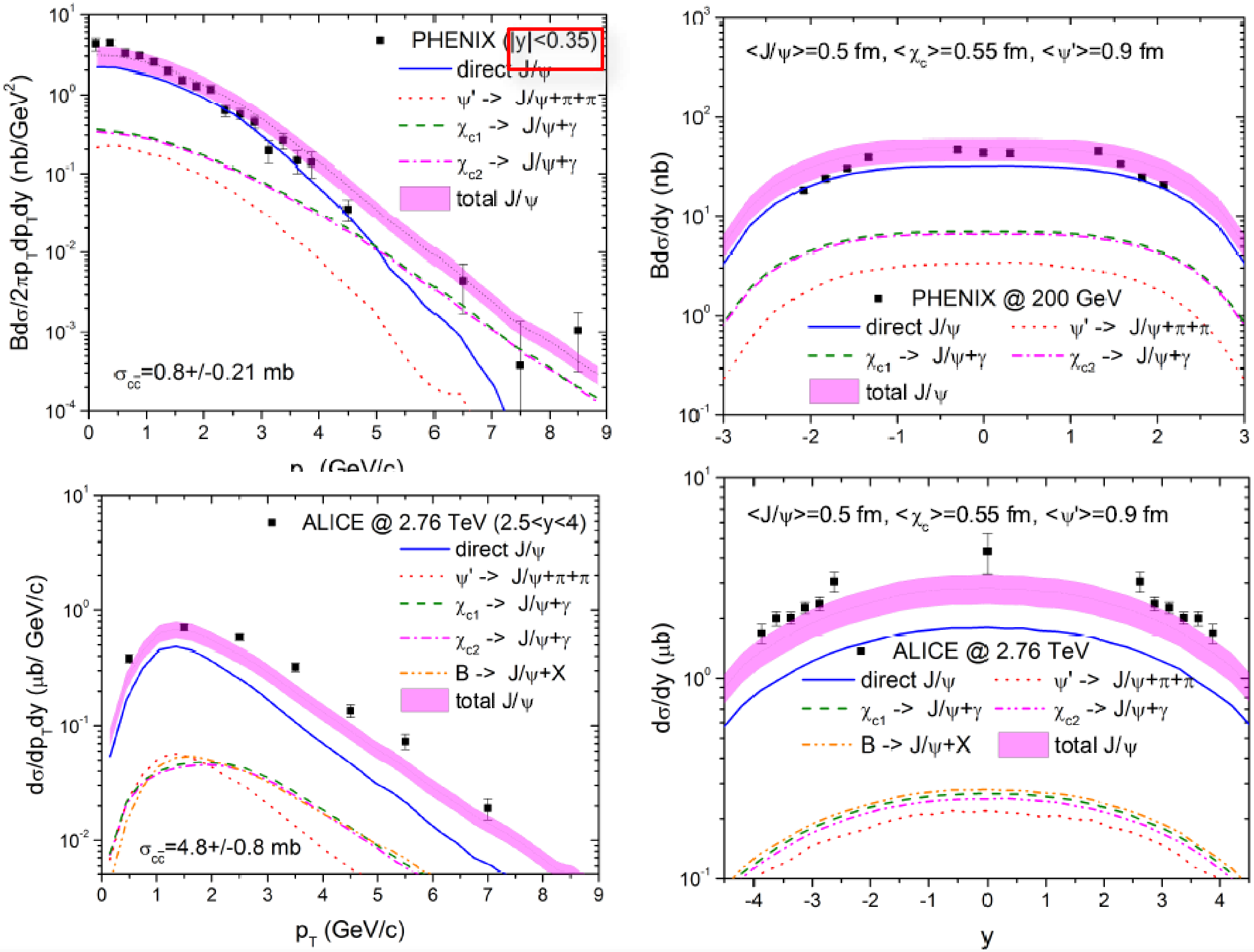
The tuned PYTHIA reproduces FONLL charm quark calculations
but J/Ψ multiplicity depends in addition on the ccbar correlation (not known in FONLL)







pp: comparison with PHENIX and ALICE data



Little feed down

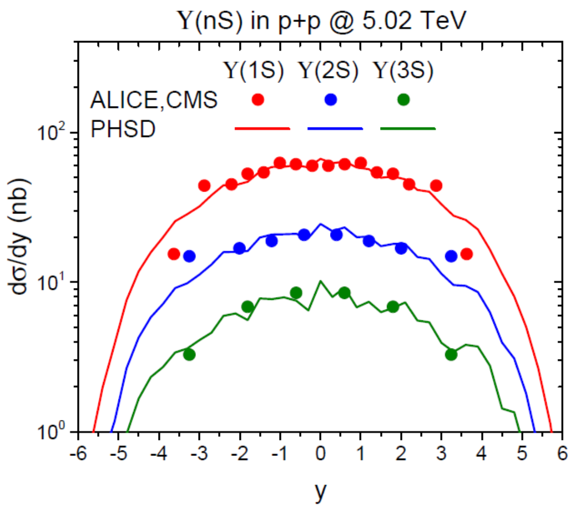
Feed down important

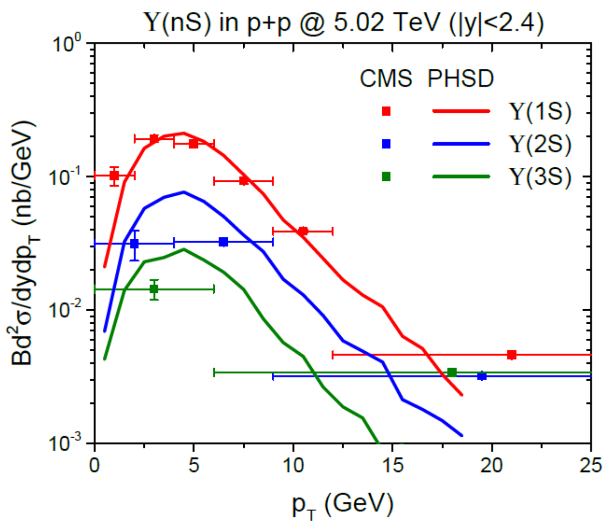
Wigner density based model reproduced pp J/Ψ data

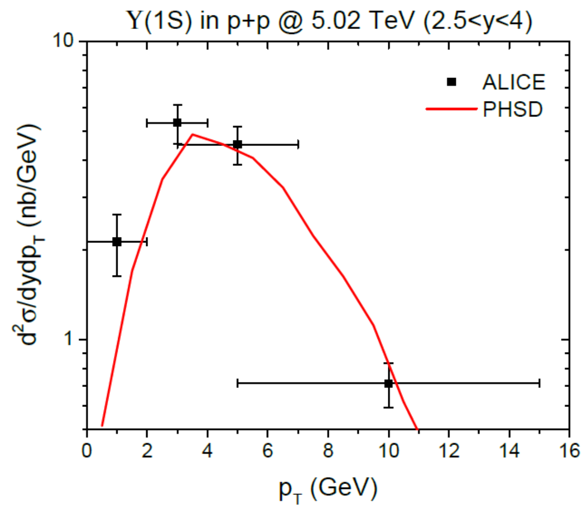
pp: comparison of Υ(nS) with CMS/ALICE data

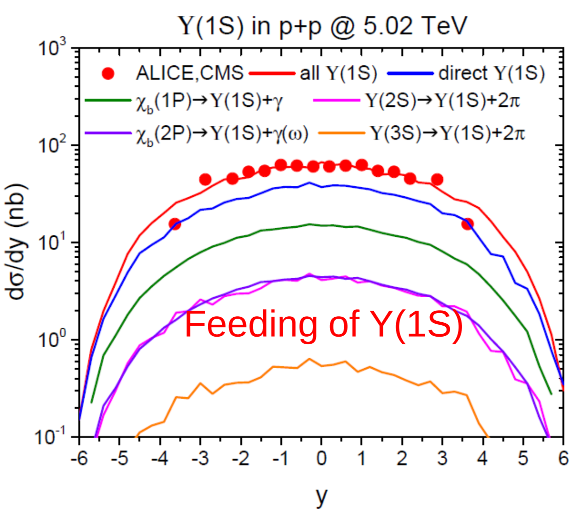
2305.10750 [nucl-th]

Wigner density approach works also for Υ(nS)









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

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

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

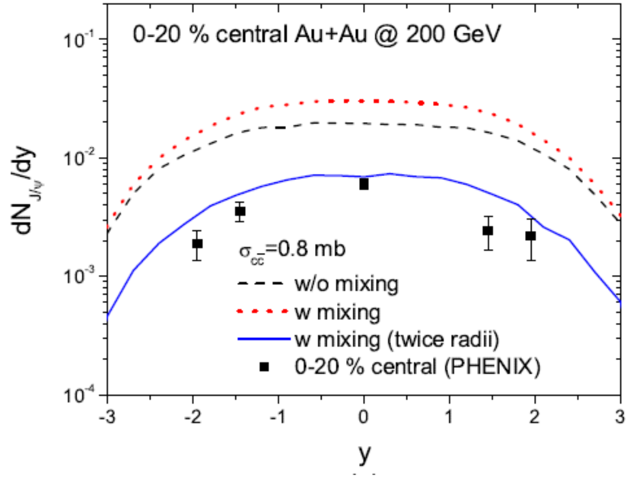
With this validation of the new approach for quarkonium production in pp we are ready for AA collisions

AA collisions

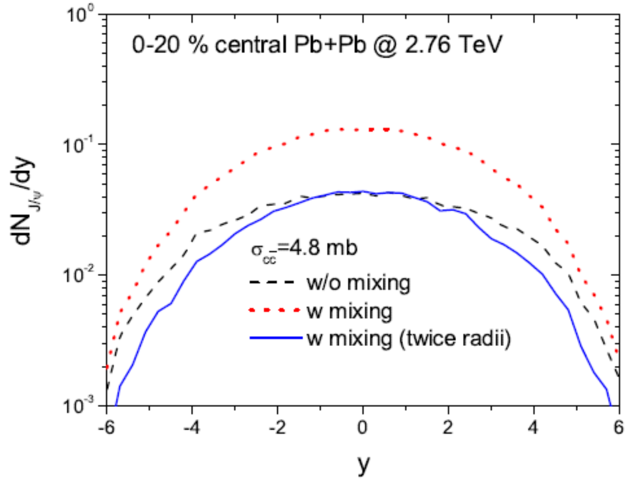
Primary production of J/Ψ in AA

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

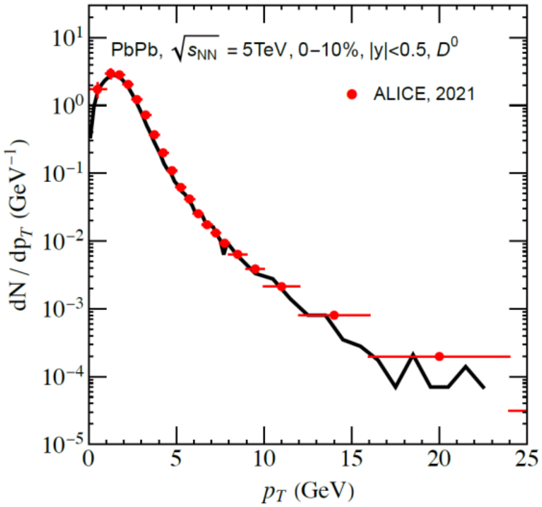
all c and cbar interact with QGP as those observed finally as D-mesons

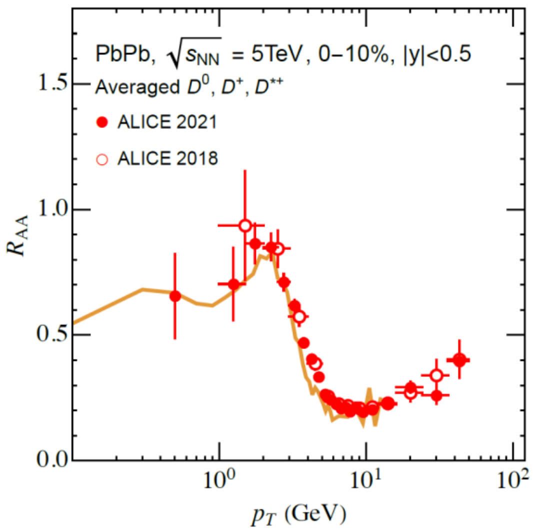
all c and cbar interact among themselves

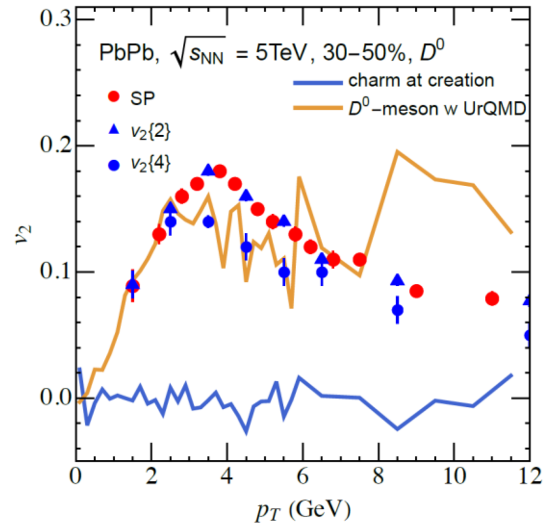
uses EPOS2 to describe the expanding QGP

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 ..

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

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:

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

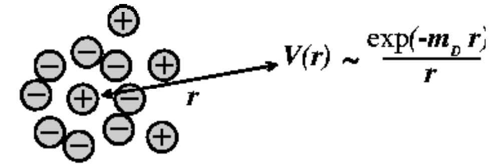
$$U_{12} = \sum_{j \leq 3}(V_{1j} + V_{2j})$$

elastic HQ interactions with the QGP

Phys.Rev.C 78 (2008) 014904

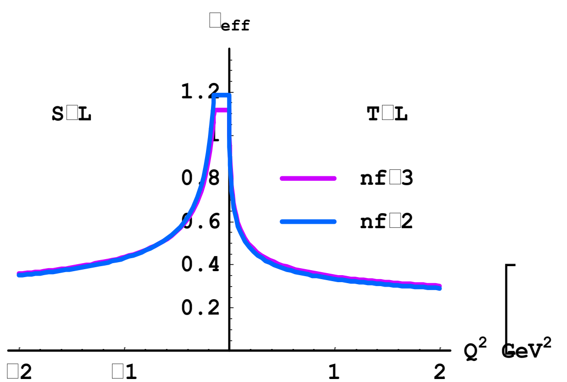
The interaction between HQ and q and g is described by Born type diagrams

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



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

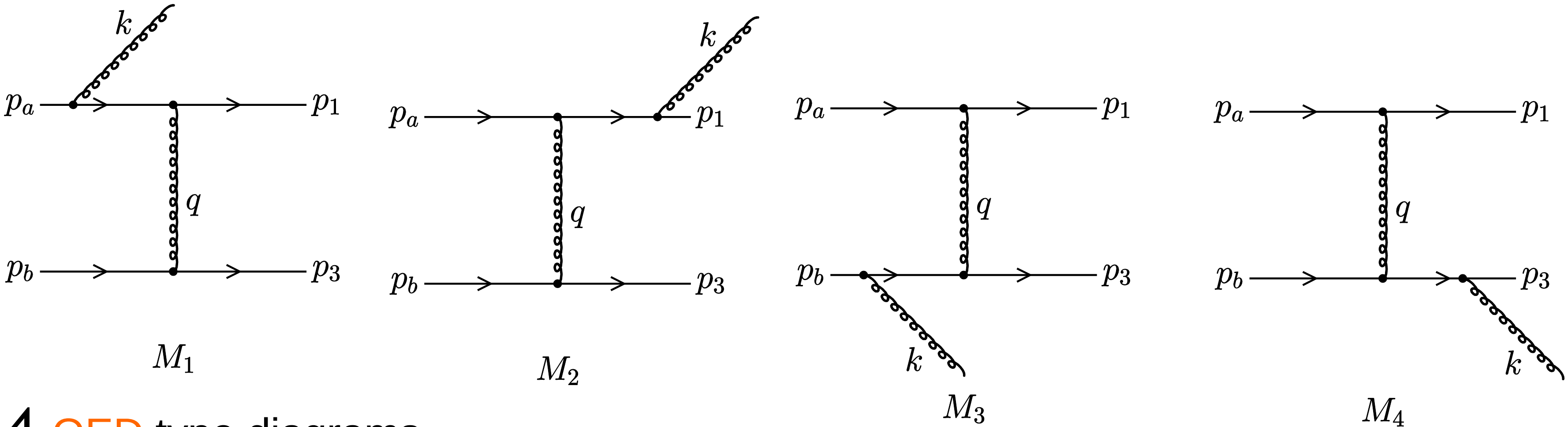
(Braaten and Thoma PRD44 1298,2625) for QED:
Energy loss indep. of the artificial scale t* which
separates the regimes
Extension to QCD (PRC78:014904)

$\kappa \approx 0.2$

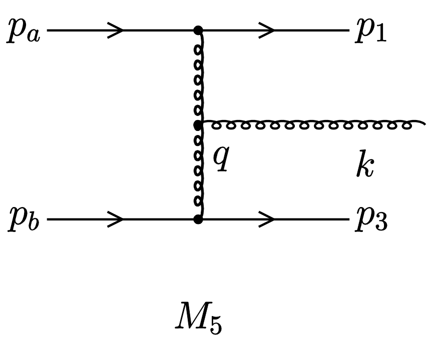
Inelastic Qq → Qqg collisions

Low mass quarks : radiation dominantes energy loss

Charm and bottom: radiation of the same order as collisional



4 QED type diagrams



1 QCD diagram

Commutator of the color SU(3) operators

$$T^b T^a = T^a T^b - i f_{abc} T^c$$

M1-M5 : 3 gauge invariant subgroups

$$M^1_{QED} = T^a T^b (M_1 + M_2) \quad M^2_{QED} = T^a T^b (M_3 + M_4)$$

$$M_{QCD} = i f_{abc} T^c (M_1 + M_3 + M_5)$$

M_{QCD} dominates the radiation

M^{SQMD} in light cone gauge

In the limit $\sqrt{s} \to \infty$ the radiation matrix elements factorize in

$$M^2_{tot} = M^2_{elast} \cdot P_{rad}$$

k_t , ω = transv mom/ energy of gluon   E = energy of the heavy quark

$$P_{rad} = C_A \left(\frac{\vec{k}_t}{k_t^2 + (\omega/E)^2 m^2} - \frac{\vec{k}_t - \vec{q}_t}{(\vec{q}_t - \vec{k}_t)^2 + (\omega/E)^2 m^2} \right)^2$$

Emission from heavy q

Emission from g

leading order: no emission from light q

m=0 -> Gunion Bertsch

heals colinear divergences

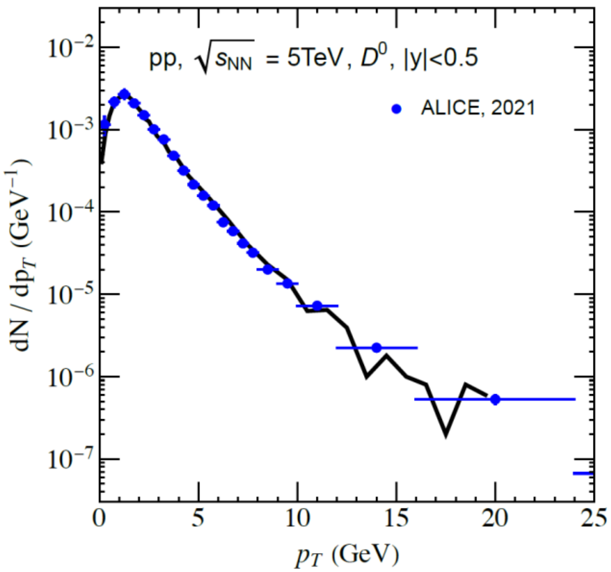
Energy loss:

$$\frac{\omega d^4\sigma^{rad}}{dx d^2k_t dq_t^2} = \frac{N_c \alpha_s}{\pi^2}(1-x) \cdot \frac{d\sigma^{el}}{dq_t^2} \cdot P_{rad}$$

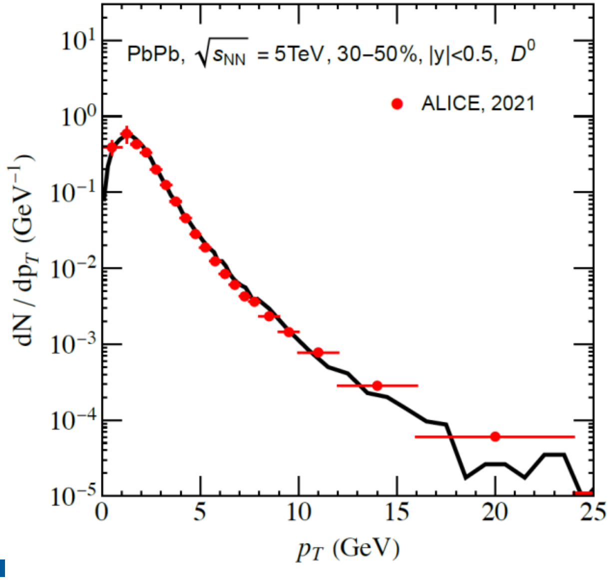
x=ω/E

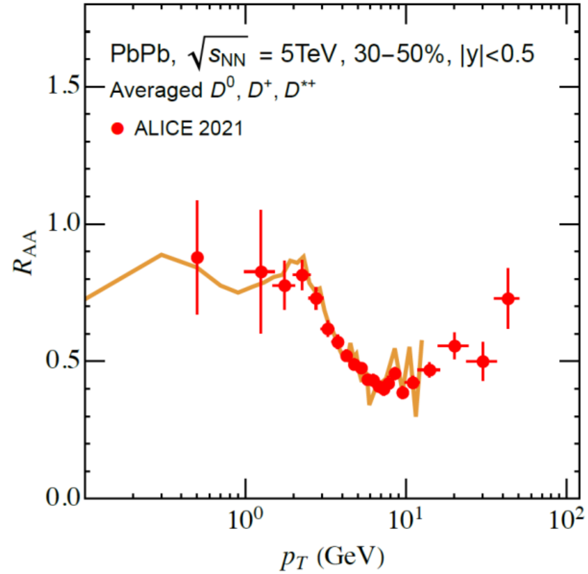
$$M_{QCD} = M_{SQCD}\left(1 - \frac{(\omega/E)^2}{(1-\omega/E)^2}\right)$$

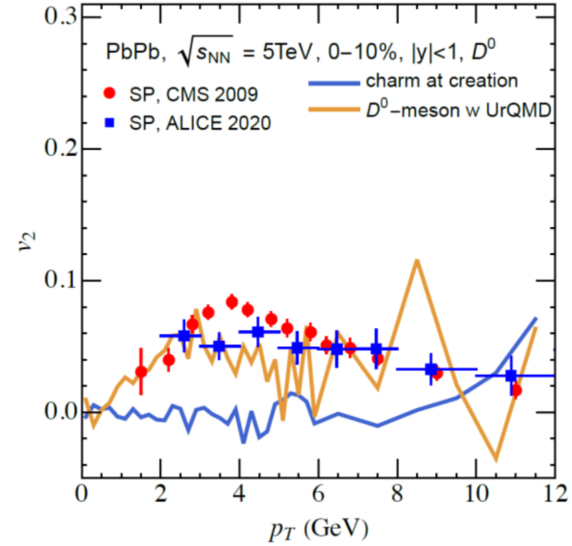
Open heavy flavor results in pp and AA from EPOS4



Energy loss of Q in medium can be controlled by comparing open Heavy flavour results with experiment







J/ψ creation in heavy ion collisions

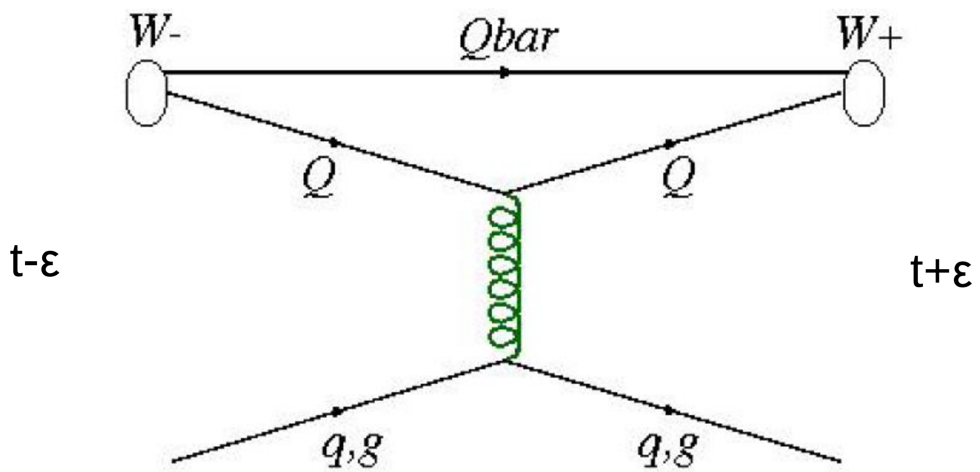
Γ^{Φ}(t) expressed in Wigner and classical phase space density:

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

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) :

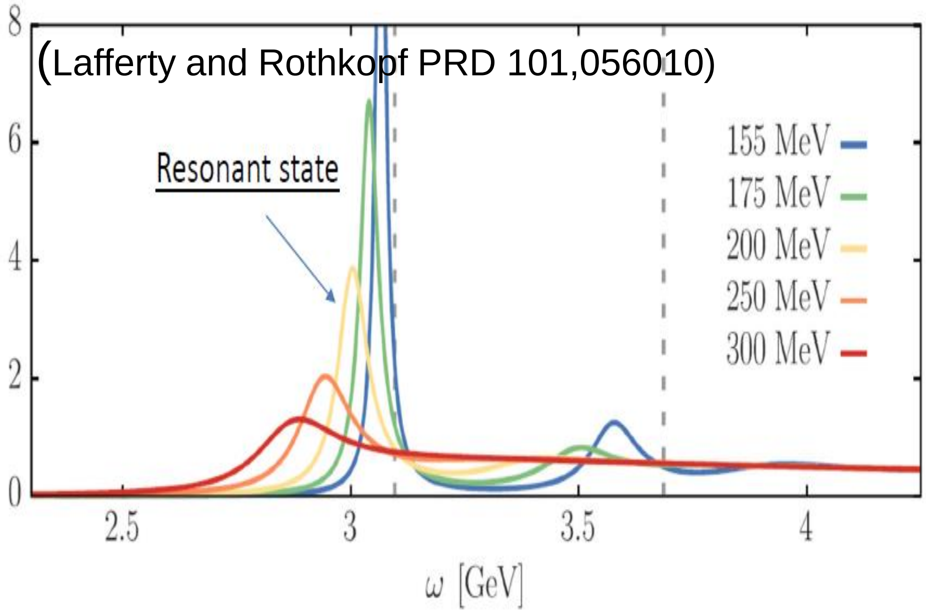
$$\Gamma^{\Phi}(t) = \sum_n \sum_{i=1,2} \sum_{j\geq 3} \delta(t-t_{ij}(n)) \prod_N \frac{d^3r_i d^3p_i}{(2\pi)^{3N}} W^{\Phi}(\mathbf{r},\mathbf{p})[\underbrace{W^{c}(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N},t+\epsilon)}_{W+} - \underbrace{W^{c}(\mathbf{r_1},\mathbf{p_1},...\mathbf{r_N},\mathbf{p_N},t-\epsilon)}_{W-}]$$

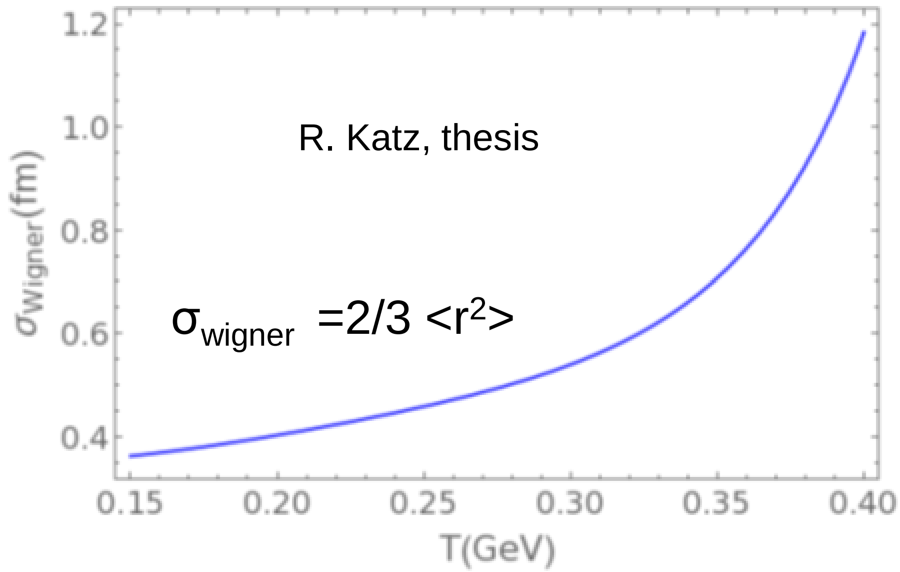


QGP parton

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/Ψ 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

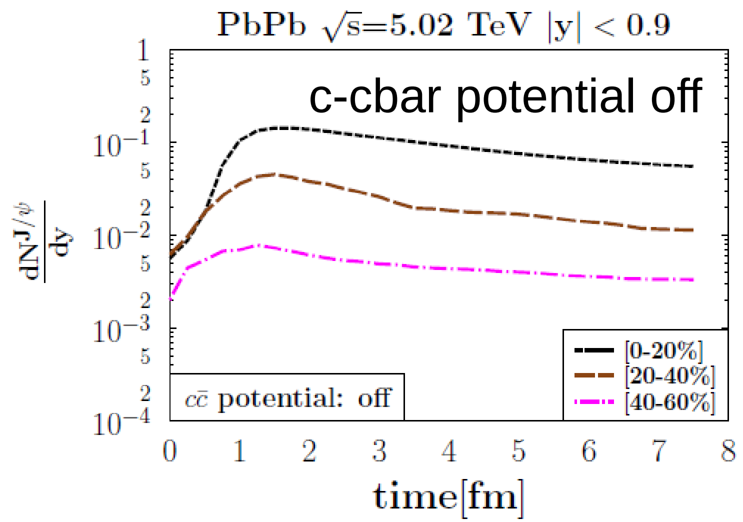
$$\mathcal{L} = -\gamma^{-1} m c^2 - V(r) \qquad H = \sqrt{m^2 + p_r^2 + \frac{p_\theta^2}{r^2}} + V(r)$$

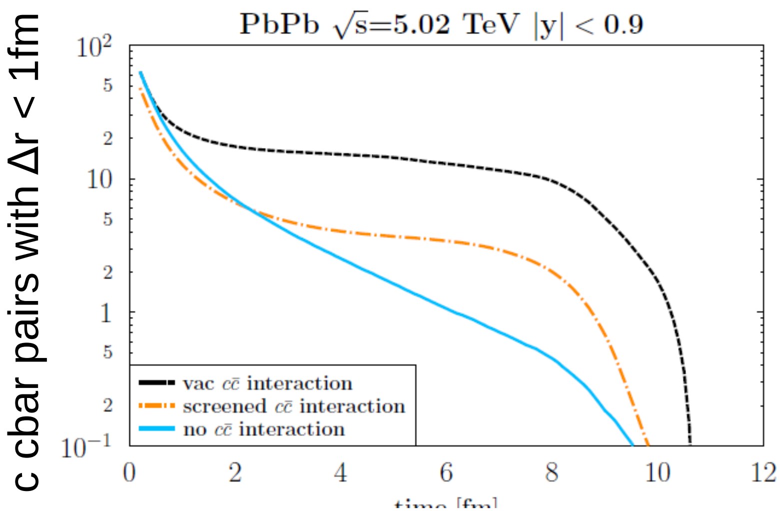
$$p^2 = p_r^2 + p_\theta^2 / r^2$$

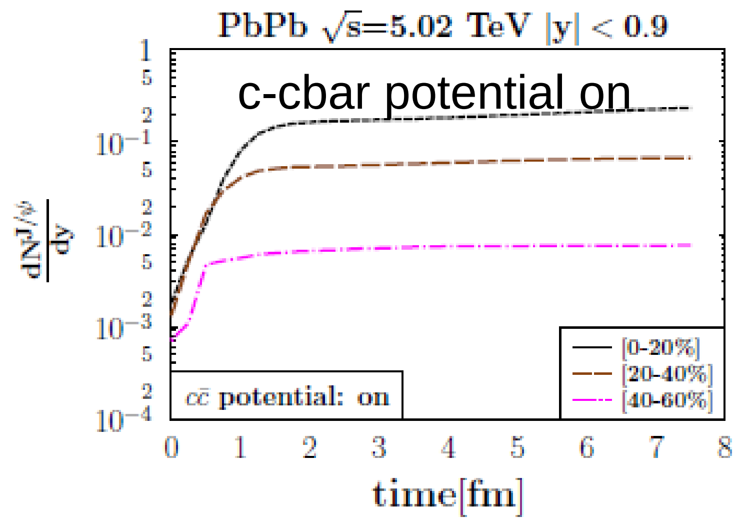
$$\gamma^{-1} = \sqrt{1 - v^2/c^2}$$

Has to be improved to describe high p_T J/Ψ

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





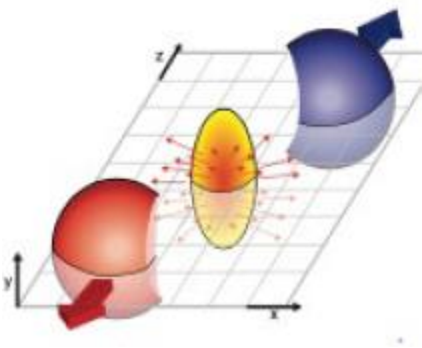


c-cbar potential keeps the quarks together → increases multiplicity

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)

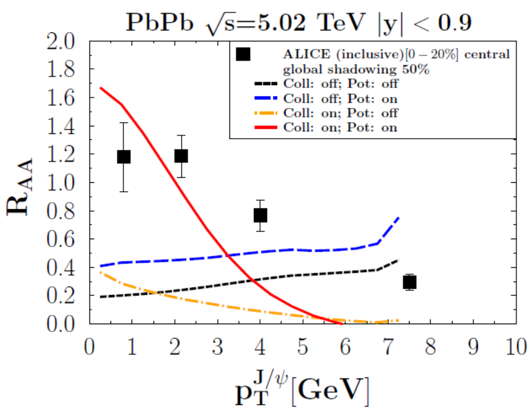
For J/ψ mesons we use as working description:

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.

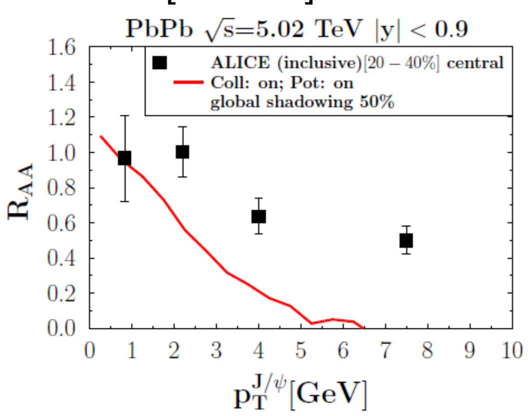
Comparison with ALICE data

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

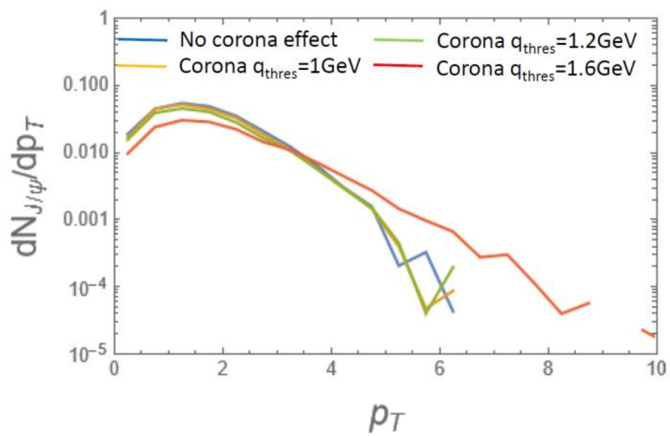
[0-20%] no corona

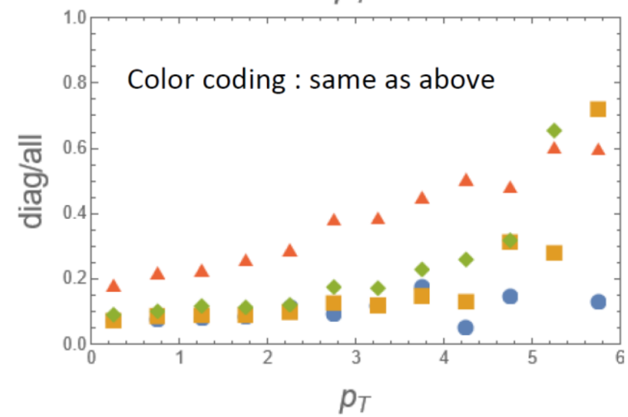


[20-40%] no corona



influence of the corona





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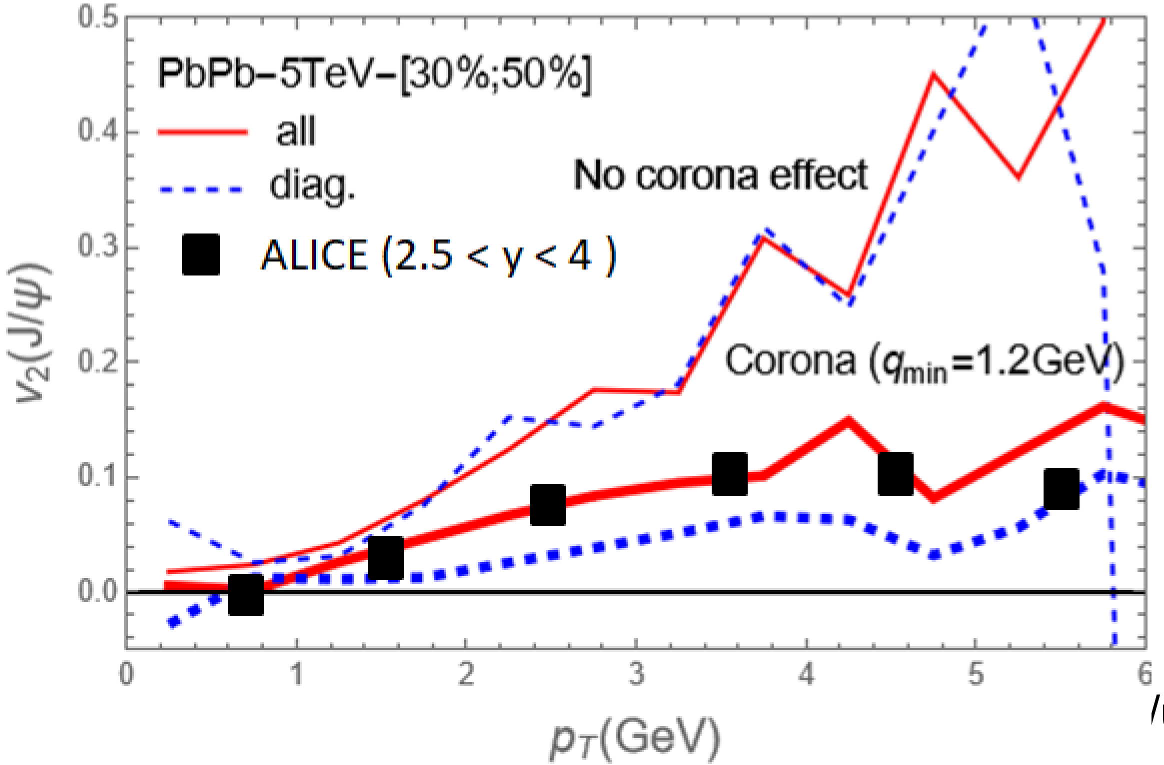
Comparison with ALICE data

[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

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

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 < λ_{gluon}) with QGP partons (dipole cross section)
- ….