Quarkonium in Heavy Ion Collisions

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1) **Quarkonium TMD**

J/ψ: K.Zhou, N.Xu, Z.Xu, PZ, PRC2014

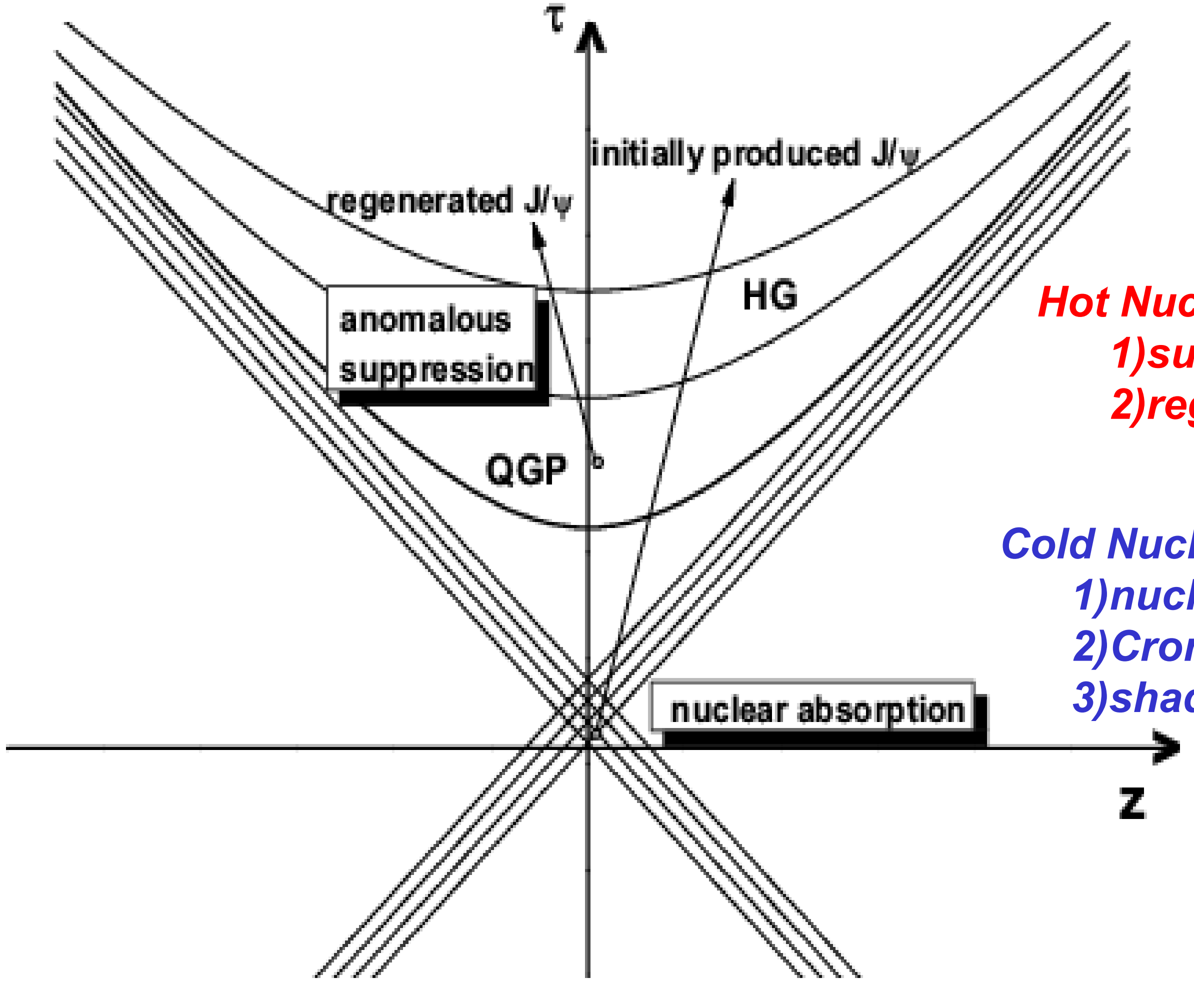
Υ: K.Zhou, N.Xu, PZ, arXiv: 1408.3900

2) Ω_{ccc} **Production**

H.He, Y.Liu, PZ, arXiv: 1409.1009

Quarkonium 2014, November 10-14, CERN

Cold and Hot Nuclear Matter Effects



Hot Nuclear Matter effects in medium:

1)suppression
2)regeneration

Cold Nuclear Matter effects before QGP:

1)nuclear absorption
2)Cronin effect
3)shadowing effect

CNM: see for instance, R.Vogt, 1999
Dissociation: Matsui and Satz, 1986
Regeneration: see for instance PBM 2000, Thews 2001, Rapp 2001

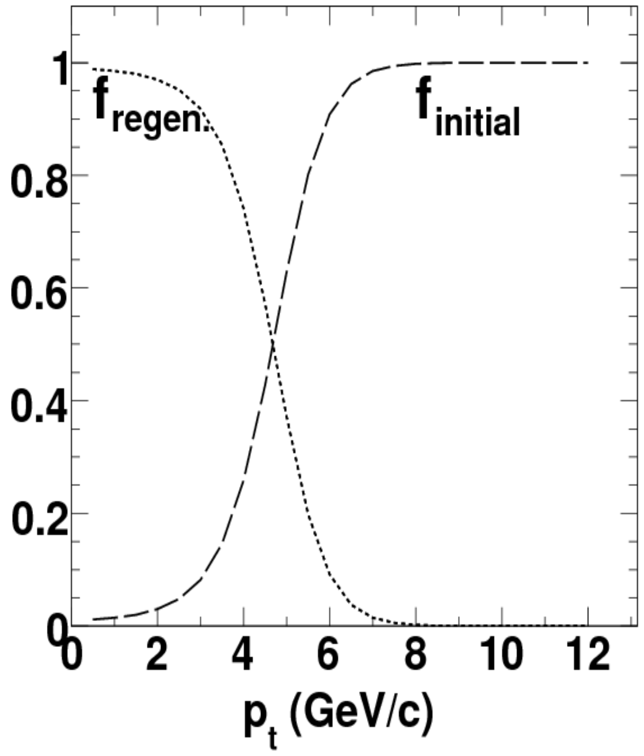
Quarkonium TMD

The transverse motion is dynamically created during the evolution of the system, it should be more sensitive to the nature of the fireball.

$$f_\Psi = f_\Psi^{ini} + f_\Psi^{reg}$$

Initially produced quarkonia:
1)Cronin effect leads to a p_t broadening,
2)High p_t part is less suppressed.

Regenerated quarkonia:
produced in the later stage and carry low p_t .



Conclusion:
Quarkonium TMD can signal the regeneration (medium properties) !

A Dynamic Transport Approach for Quarkonium Motion

Tsinghua Group + Nu XU (LBNL) 2006-

- **QGP evolution**

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu n^\mu = 0$$ + QCD equation of state

- **quarkonium motion** $(\Psi = J/\psi,\ \psi',\ \chi_c)$

$$\frac{\sigma(T)}{\sigma(0)} = \frac{\langle r^2\rangle(T)}{\langle r^2\rangle(0)}$$

$$\partial f_\Psi/\partial\tau + \mathbf{v}_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi .$$

gluon dissociation cross section controlled by OPE and potential model

$$\alpha_\Psi(\mathbf{p}_t, \mathbf{x}_t, \tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g} W_{g\Psi}^{c\bar{c}}(s) f_g(\mathbf{p}_g, \mathbf{x}_t, \tau)\Theta\left(T(\mathbf{x}_t, \tau|\mathbf{b}) - T_c\right),$$

$$\beta_\Psi(\mathbf{p}_t, \mathbf{x}_t, \tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}\frac{d^3\mathbf{p}_c}{(2\pi)^3 2E_c}\frac{d^3\mathbf{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} W_{c\bar{c}}^{g\Psi}(s) f_c(\mathbf{p}_c, \mathbf{x}_t, \tau|\mathbf{b}) f_{\bar{c}}(\mathbf{p}_{\bar{c}}, \mathbf{x}_t, \tau|\mathbf{b}) \times (2\pi)^4\delta^{(4)}(p + p_g - p_c - p_{\bar{c}})\Theta\left(T(\mathbf{x}_t, \tau|\mathbf{b}) - T_c\right),$$

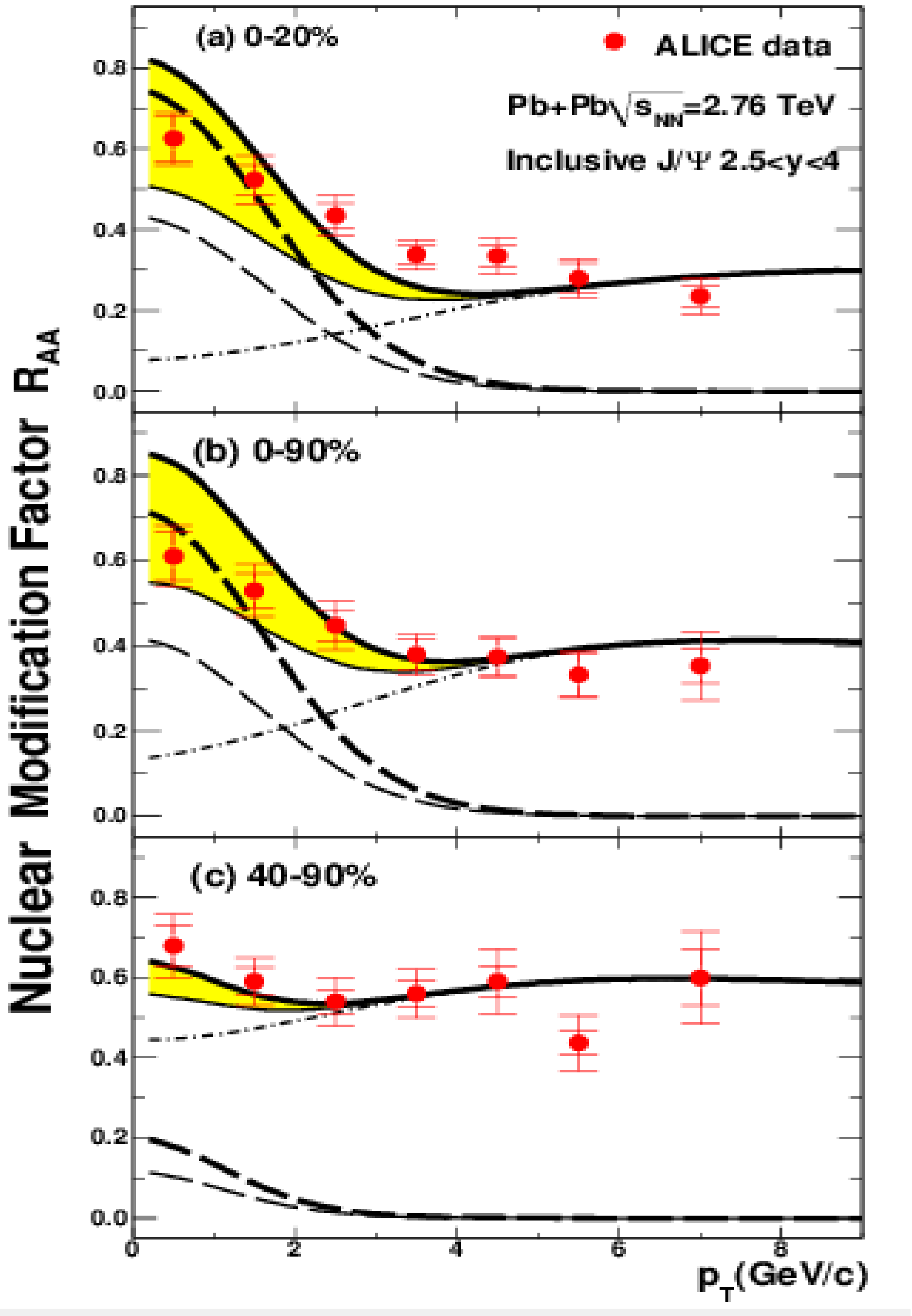
detailed balance

- **analytic solution**

$$f_\Psi(\mathbf{p}_t, \mathbf{x}_t, \tau|\mathbf{b}) = f_\Psi(\mathbf{p}_t, \mathbf{x}_t - \mathbf{v}_\Psi(\tau - \tau_0), \tau_0|\mathbf{b}) e^{-\int_{\tau_0}^{\tau} d\tau' \alpha_\Psi(\mathbf{p}_t, \mathbf{x}_t - \mathbf{v}_\Psi(\tau - \tau'), \tau'|\mathbf{b})} + \int_{\tau_0}^{\tau} d\tau' \beta_\Psi(\mathbf{p}_t, \mathbf{x}_t - \mathbf{v}_\Psi(\tau - \tau'), \tau'|\mathbf{b}) e^{-\int_{\tau'}^{\tau} d\tau'' \alpha_\Psi(\mathbf{p}_t, \mathbf{x}_t - \mathbf{v}_\Psi(\tau - \tau''), \tau''|\mathbf{b})}.$$

cold nuclear matter effects

hot nuclear matter effects



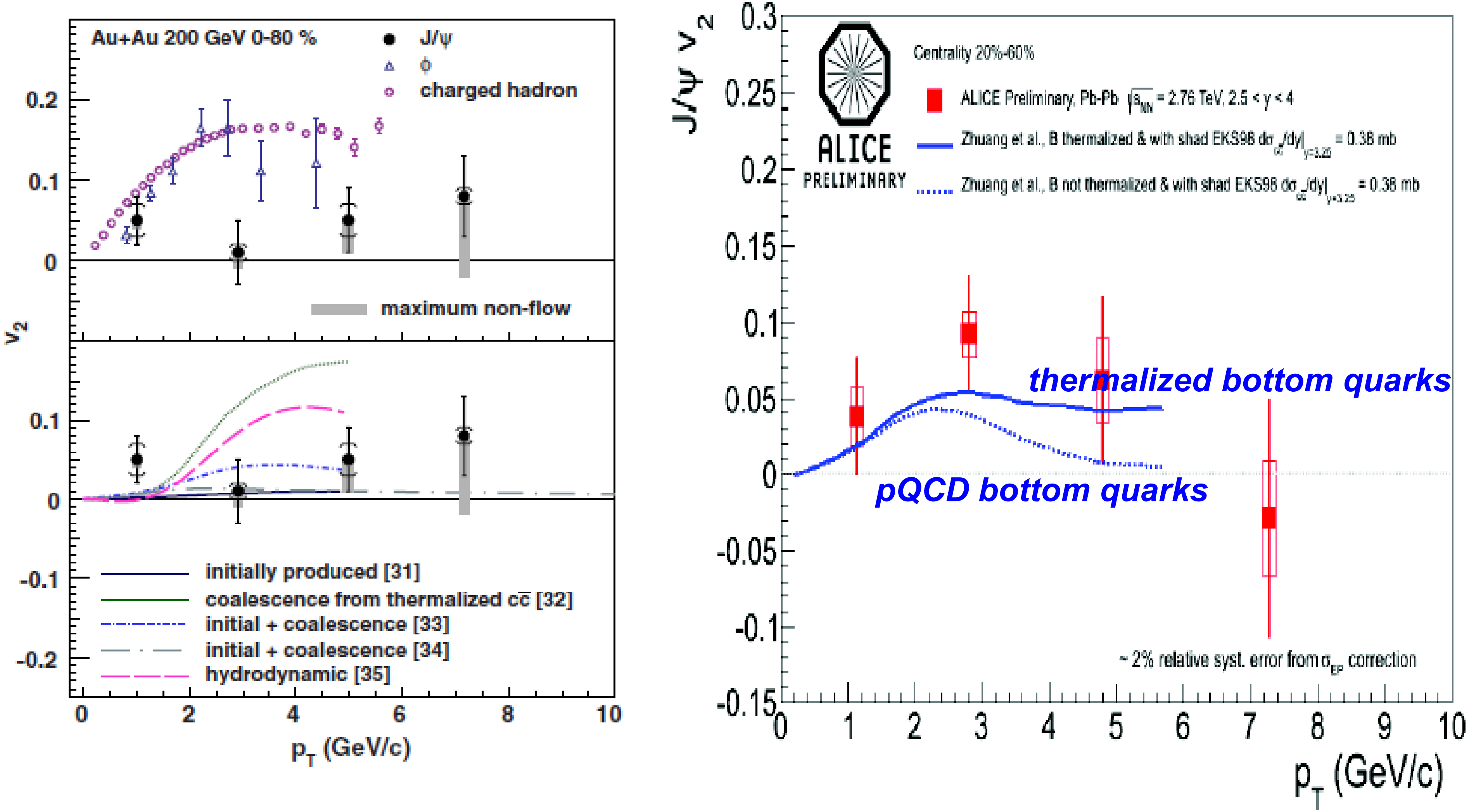
R_{AA} (p_t) in different centrality bins

dominant regeneration in central collisions

the band comes from the uncertainty in charm quark cross section

dominant initial production in peripheral collisions

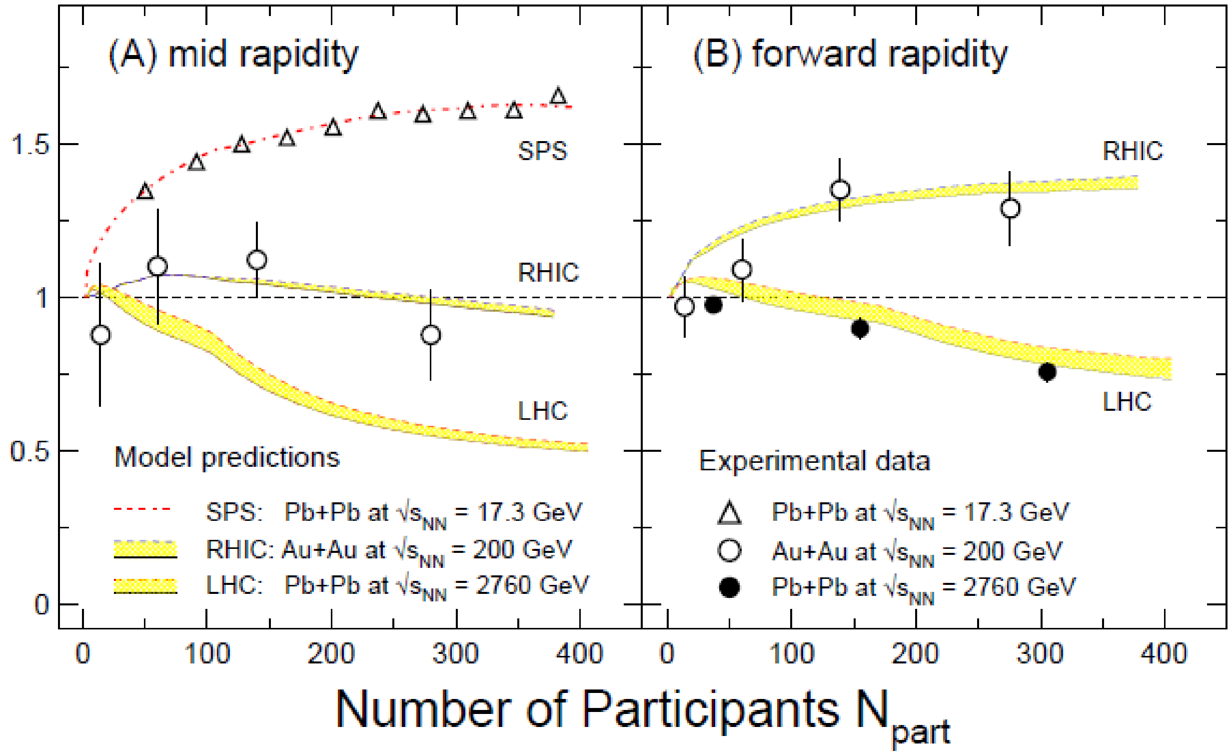
Elliptic Flow: from 0 at RHIC to ~10% at LHC

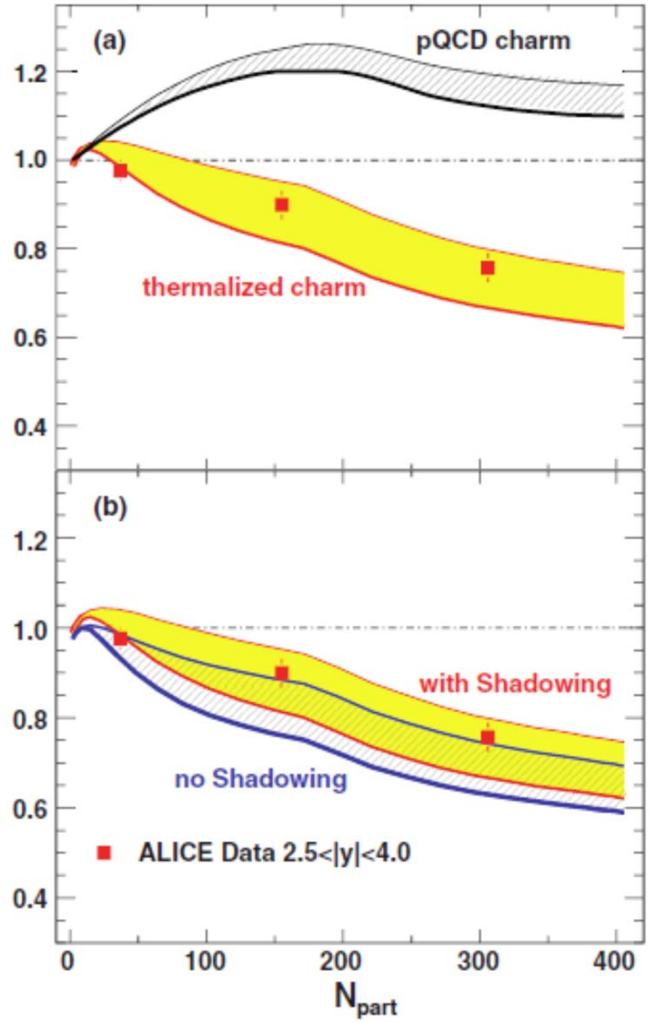


regeneration + heavy quark thermalization lead to J/Ψ v_2 !

P_t Ratio: from broadening at SPS to suppression at LHC

$$r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}.$$

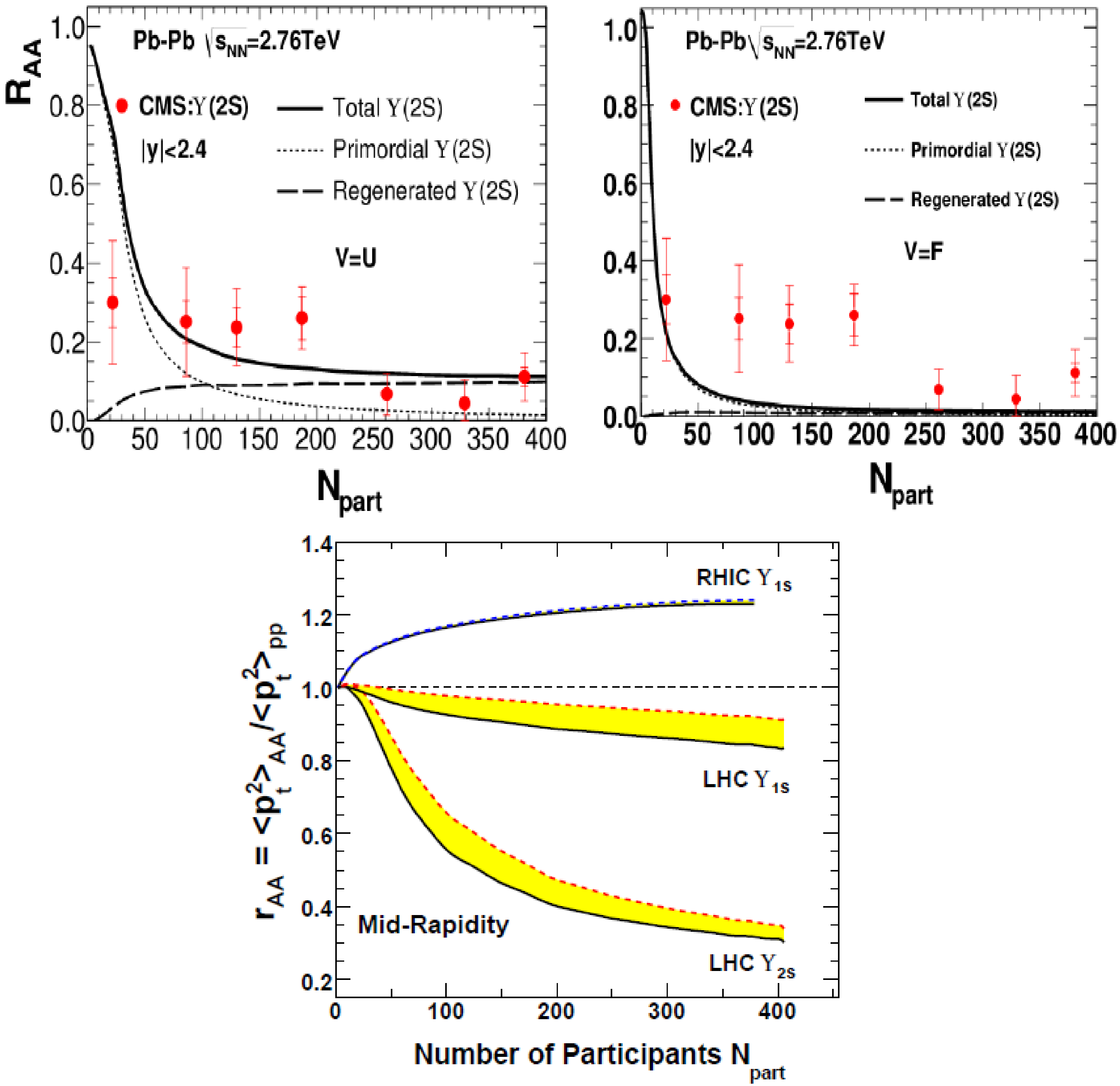




$$r_{AA} \begin{cases} >1 & \text{SPS} \\ \approx 1 & \text{RHIC} \quad \text{at midrapidity} \\ <1 & \text{LHC} \end{cases}$$

r_{AA} is a sensitive probe of QGP !

Upsilon



Pb-Pb $\sqrt{s_{NN}}$=2.76TeV
CMS:Υ(2S)
|y|<2.4
Total Υ(2S)
Primordial Υ(2S)
Regenerated Υ(2S)
V=U
R_{AA}
N_{part}
Pb-Pb $\sqrt{s_{NN}}$=2.76TeV
CMS:Υ(2S)
|y|<2.4
Total Υ(2S)
Primordial Υ(2S)
Regenerated Υ(2S)
V=F
N_{part}
RHIC Υ_{1S}
LHC Υ_{1S}
LHC Υ_{2S}
Mid-Rapidity
$r_{AA} = \langle p_t^2 \rangle_{AA} / \langle p_t^2 \rangle_{pp}$
Number of Participants N_{part}

Why Ω_{ccc}

Ω_{ccc}, ***the ground bound state of 3 charm quarks.***

1) Ω_{ccc} ***production in a p+p collision needs at least 3 pairs of $c\bar{c}$, the production cross section is very small at LHC energy, see Yuqi CHEN and Suzhi WU, JHEP08, 144(2011)***

2) However, coalescence among uncorrelated charm quarks in A+A collisions leads to a large production cross section,

$$N(\Omega_{ccc}) \sim N_c^3 \sim \left(10^2\right)^3 \text{ at LHC !}$$

- ***It may become probable to discover Ω_{ccc} at LHC (and RHIC) !***
- ***If yes, it should be a clean signature of QGP formation !***

3)The Wigner function (the coalescence probability) for Ω_{ccc} can be calculated via Schroedinger equation using the lattice potential.

Schroedinger Equation

$$\hat{H}\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = E_T\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) \qquad \hat{H} = \sum_{i=1}^{3}\frac{\hat{\mathbf{p}}_i^2}{2m_c} + V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)$$

$$V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = \sum_{i<j} V_{cc}(\mathbf{r}_i,\mathbf{r}_j). \qquad V_{cc} = V_{c\bar{c}}/2. \qquad V_{c\bar{c}}(\mathbf{r}_i,\mathbf{r}_j) = -\frac{\alpha}{|\mathbf{r}_{ij}|} + \sigma|\mathbf{r}_{ij}|,$$

α, σ, m_c cab be determined by fiting the J/ψ and ϒ masses

1) $\vec{r}_1,\vec{r}_2,\vec{r}_3 \;\rightarrow\; \vec{R}\ (baryon\ coordinate), \vec{r}_x, \vec{r}_y\ (relative\ coordinates)$

$\psi(\vec{r}_1,\vec{r}_2,\vec{r}_3) \;\rightarrow\; \Phi(\vec{R})\psi(\vec{r}_x,\vec{r}_y)$

2) $\vec{r}_x,\vec{r}_y \rightarrow\; r, \theta_x, \phi_x, \theta_y, \phi_y, \alpha = arctg\frac{r_y}{r_x}\ (hyperspherical\ coordinates)$

Problem: since $V(|\vec{r}_i - \vec{r}_j|)$ depends on the 5 angels, one can not separate the relative motion into a radial part and an angular part.

3) ***assumption of hyperspherical symmetry***

E.Nielsen et al., Phys. Rep. 347, 373(2001), I.narodetskii et al., JETP Lett. 90, 232(2009)

$$v(r) = \frac{8}{\pi}\int_0^{\pi/2}\sum_{i<j} V_{cc}\left(\sqrt{2}r\sin\alpha\right)\sin^2\alpha\cos^2\alpha d\alpha$$

$$\left[\frac{1}{2m_c}\left(-\frac{d^2}{dr^2} - \frac{5}{r}\frac{d}{dr}\right) + v(r)\right]\varphi(r) = E\varphi(r)$$

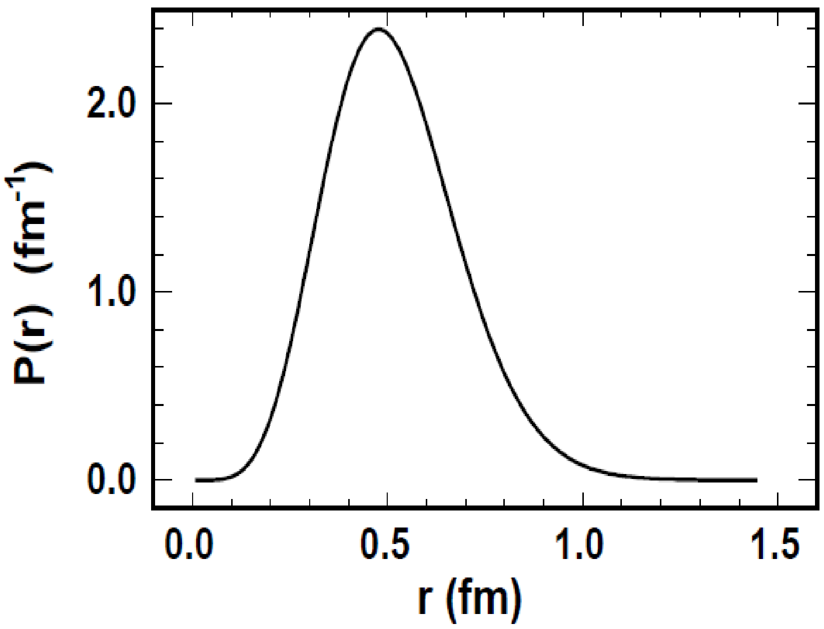
Wave Function and Wigner Function

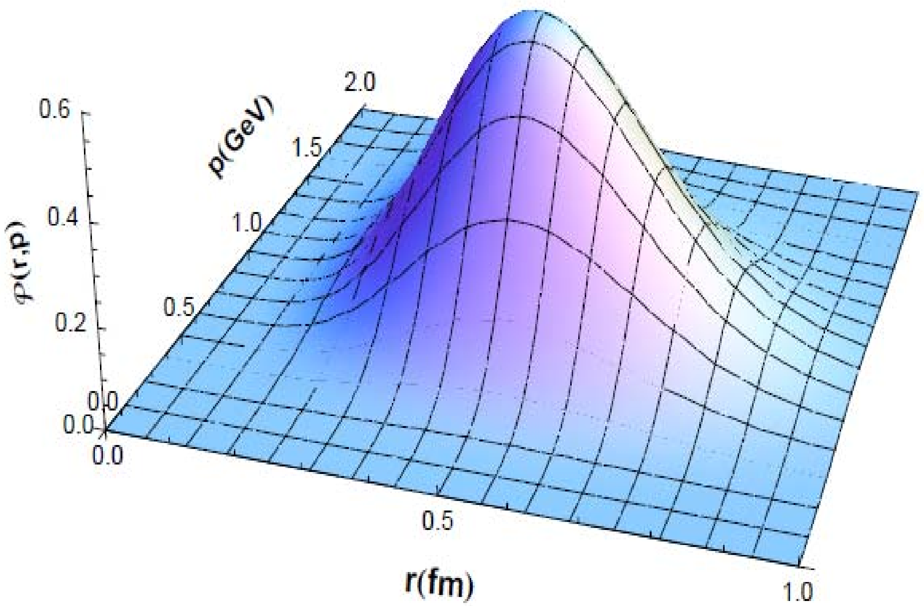
$\mathbf{m_\Omega = 4.75}$ **GeV** (*4.8 GeV, LQCD, Nilmani Mathur, this meeting*)

$$W(\mathbf{r},\mathbf{p}) = \int d^6\mathbf{y} e^{-i\mathbf{p}\cdot\mathbf{y}} \psi\left(\mathbf{r}+\frac{\mathbf{y}}{2}\right)\psi^*\left(\mathbf{r}-\frac{\mathbf{y}}{2}\right)$$

$$\mathbf{P(r)=|\varphi(r)|^2 r^5}$$

$$\mathcal{P}(r,p) = \frac{1}{24\pi} r^5 p^5 \int_0^\pi W(r,p,\theta)\sin^4\theta d\theta$$

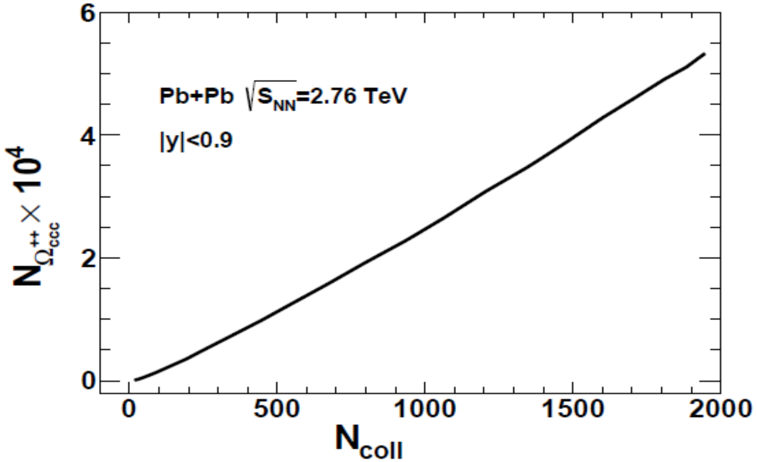


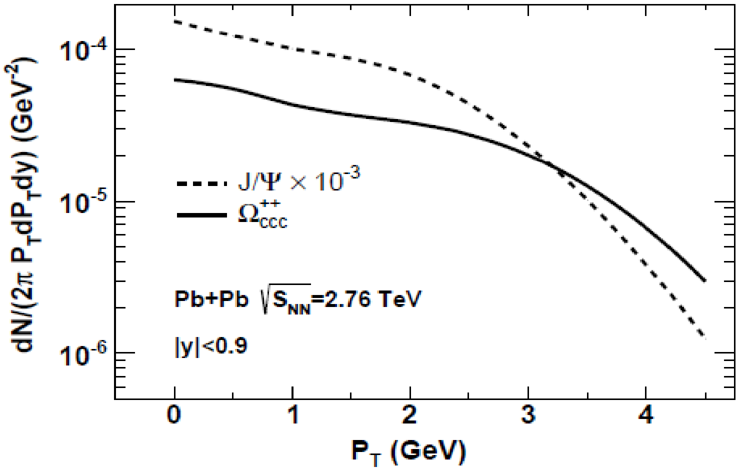


Coalescence

$$\frac{dN}{d^3\mathbf{P}} = C\int\frac{d^3\mathbf{R}}{(2\pi)^3}\int\frac{d^3\mathbf{r}_x d^3\mathbf{r}_y d^3\mathbf{p}_x d^3\mathbf{p}_y}{(2\pi)^6} f(r_1,p_1)f(r_2,p_2)f(r_3,p_3)W(\mathbf{r}_x,\mathbf{r}_y,\mathbf{p}_x,\mathbf{p}_y)$$

charm quark (thermal) distribution $f(\vec{r},\vec{p}\,) = \frac{1}{e^{p^\mu u_\mu/T}+1}$





Effective cross section per binary collision:

$$\sigma_\Omega \equiv \frac{N_\Omega}{N_{coll}\Delta\eta}\sigma_{pp}$$

$$\sigma_{pp} = 62\, mb \;\rightarrow\; \boldsymbol{\sigma_\Omega = 9\, nb}$$

In p+p collisions (CHEN and WU, JHEP08, 144(2011):

σ_Ω = **0.06-0.13 nb at 7 TeV**

0.1-0.2 nb at 14 TeV

Conclusion:

The cross section in A+A is at least two orders of magnitude larger than that in p+p !

Conclusions

1) Quarkonium TMD, especially v_2 and $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$, can distinguish the hot mediums between SPS, RHIC and LHC.

2) J/ψ v_2: the change from 0 at RHIC to about 10% at LHC signals the QGP formation and charm quark thermalization.

3) J/ψ p_t ratio: the change from broadening at SPS to suppression at LHC signals also the QGP formation and charm quark thermalization.

4) The Ω_{ccc} cross section in A+A is much larger than that in p+p. It is most probable to discover Ω_{ccc} in A+A at LHC.

5) The discovery of Ω_{ccc} in A+A is a clean signature of QGP.