5. Heavy Flavor in A+A Collisions

5.3 A Dynamic Transport Approach

All models for J/ψ yields - with and without the assumption of a QGP and with and without regeneration mechanism - describe the observed J/ψ yield after at least one parameter is adjusted.

The transverse momentum distribution depends more directly on the production and regeneration mechanisms and therefore contain additional information about the nature of the medium and J/ψ, thus helping to distinguish between different scenarios.

Quarkonium transport equations:

The quarkonium distribution function $f_\psi(p_t, x_t, y, \tau|b)$ ($\psi = J/\psi, \psi', \chi_c$) is controlled by (L.Yan, N.Xu and P.Zhuang, Phys. Rev. Lett. 97, 232301(2006))

$$\left[\cosh(y_\Psi - \eta)\frac{\partial}{\partial\tau} + \frac{\sinh(y_\Psi - \eta)}{\tau}\frac{\partial}{\partial\eta} + \mathbf{v}_t^\Psi \cdot \nabla_t\right] f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi,$$

Lose and gain terms:

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

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

with the transition probabilities $W_{g\psi}^{c\bar{c}}(T)$ and $W_{c\bar{c}}^{g\psi}(T)$ (or $\sigma_{g\psi}^{c\bar{c}}(T)$ and $\sigma_{c\bar{c}}^{g\psi}(T)$).

Analytic solution of the transport equation:

$$f_\Psi(\mathbf{p}_t, y_\Psi, \mathbf{x}_t, \eta, \tau) = f_\Psi(\mathbf{p}_t, y_\Psi, \mathbf{X}_\Psi(\tau_0), H_\Psi(\tau_0), \tau_0)\, e^{-\int_{\tau_0}^{\tau} d\tau' \alpha_\Psi(\mathbf{p}_t, y_\Psi, \mathbf{X}_\Psi(\tau'), H_\Psi(\tau'), \tau')/\Delta(\tau')} + \int_{\tau_0}^{\tau} d\tau' \beta_\Psi(\mathbf{p}_t, y_\Psi, \mathbf{X}_\Psi(\tau'), H_\Psi(\tau'), \tau')/\Delta(\tau') \times e^{-\int_{\tau'}^{\tau} d\tau'' \alpha_\Psi(\mathbf{p}_t, y_\Psi, \mathbf{X}_\Psi(\tau''), H_\Psi(\tau''), \tau'')/\Delta(\tau'')}$$

with

$$\mathbf{X}_\Psi(\tau') = \mathbf{x}_t - \mathbf{v}_t^\Psi[\tau\cosh(y_\Psi - \eta) - \tau'\Delta(\tau')],$$
$$H_\Psi(\tau') = y_\Psi - \operatorname{arcsinh}(\tau/\tau' \sinh(y_\Psi - \eta)),$$
$$\Delta(\tau') = \sqrt{1 + (\tau/\tau')^2\sinh^2(y_\Psi - \eta)}.$$

Cold nuclear matter effects:

The cold nuclear matter effects (shadowing, Cronin effect, and nuclear absorption) are reflected in the initial distribution $f_\psi(p_t, y, x_t, \tau_0)$.

Charm quark distribution:

Thermal gluon distribution f_g.

From the experimental data at RHIC and LHC, the observed large elliptic flow (A.Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 98, 172301(2007); B.Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. 111, 102301(2013)) for charmed mesons indicate that the charm quarks interact strongly with the medium. Therefore, ***one can reasonably take a kinetically thermalized phase space distribution $f_c = 1/\left(e^{q\cdot u/T}+1\right)$ for charm quarks.***

Medium evolution:

The local temperature $T(x,t)$ and fluid velocity $u_\mu(x,t)$, used in the gluon and charm quark distribution functions and the lose and gain cross sections, are determined by the ideal hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0$$

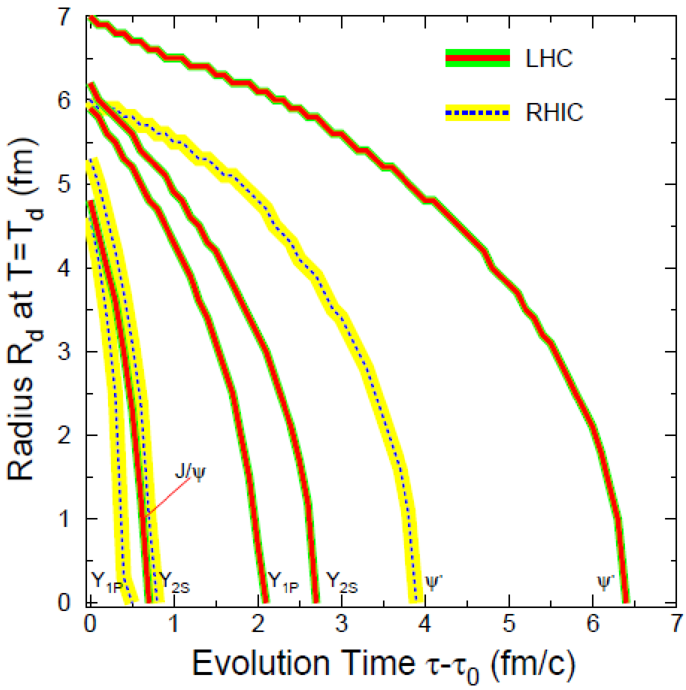
EoS:

1)Lattice simulated EoS (sQGP)

2)Ideal gas of gluons and massless u and d quarks plus 150 MeV mass s quarks, and ideal gas of all known hadrons and resonances with mass up to 2 GeV (J. Sollfrank, P.Huovinen, M.Kataja, P.V.Ruuskanen, M.Prakash, and R.Venugopalan, Phys. Rev. C55, 392(1997)).

Quarkonium dissociation region *(K.Zhou, N.Xu and P.Zhuang, arXiv:1309.7520)**:***

$$T(R_d, y, \tau) = T_d$$

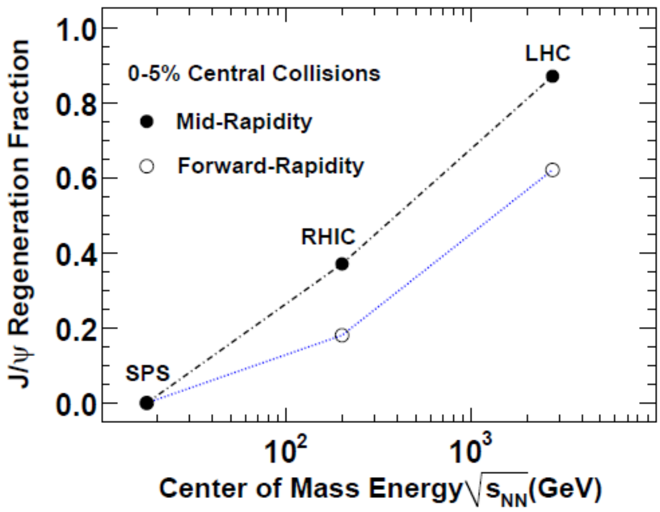


5.4 J/ψ State

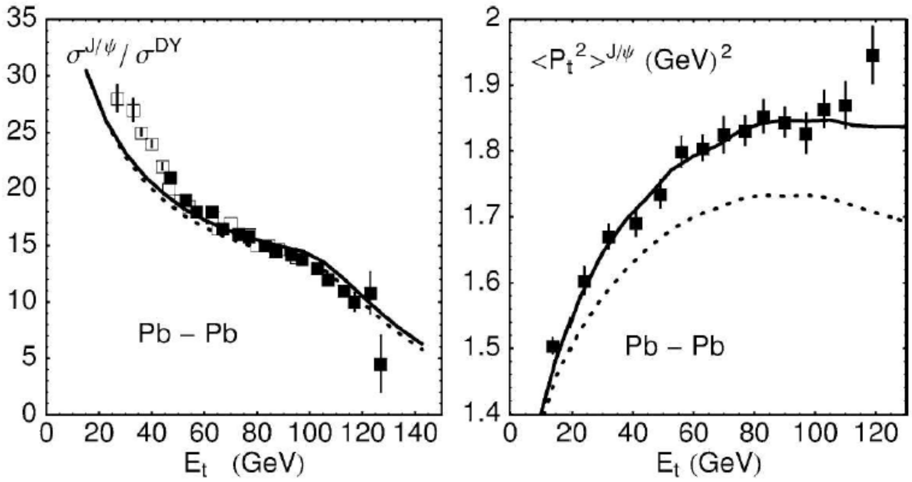
$$f_\psi = f_\psi^{ini} + f_\psi^{reg}$$

Integrating the distribution over the freeze-out hyper-surface via using the Cooper-Frye formula *(F.Cooper and G.Frye, Phys. Rev. D10, 186(1974)),* we obtain the finally observed quarkonium yield $N_\psi = N_\psi^{ini} + N_\psi^{reg}$ and the regeneration fraction *(K.Zhou, N.Xu and P.Zhuang, arXiv:1309.7520)*

$$g_\psi = \frac{N_\psi^{reg}}{N_\psi}.$$



Yield and Pt distribution at SPS *(J.Hufner and P.Zhuang, Phys. Lett. B559, 193(2003))****:***



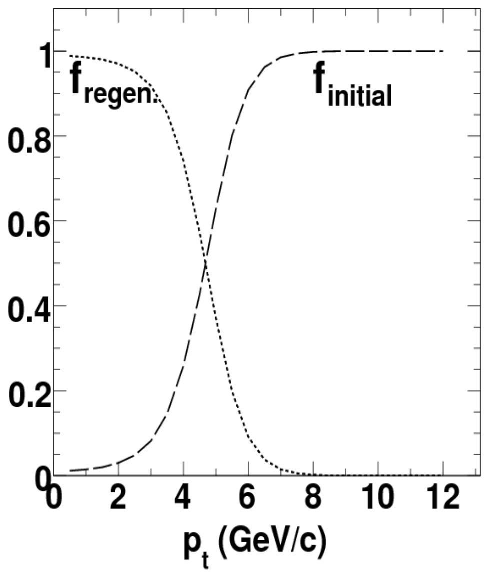
Regeneration can be neglected.

The calculation without leakage (dashed line) does not fit the data for $\langle p_t^2 \rangle_\psi$*, even in the domain of low transverse energy* E_t*.*

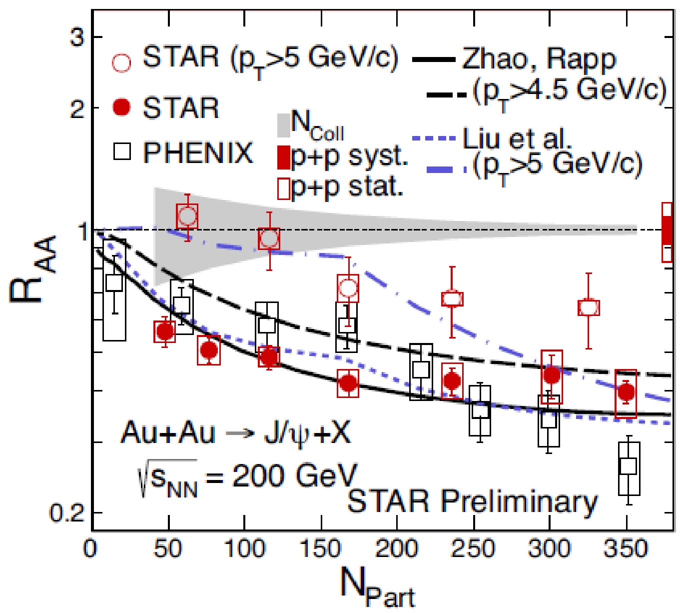
Pt dependence of the initial production and regeneration:

Initial production: Considering the Pt broadening due to Cronin effect and the gluon dissociation (mainly at low Pt), the surviving J/ψs are mainly distributed in high Pt region.

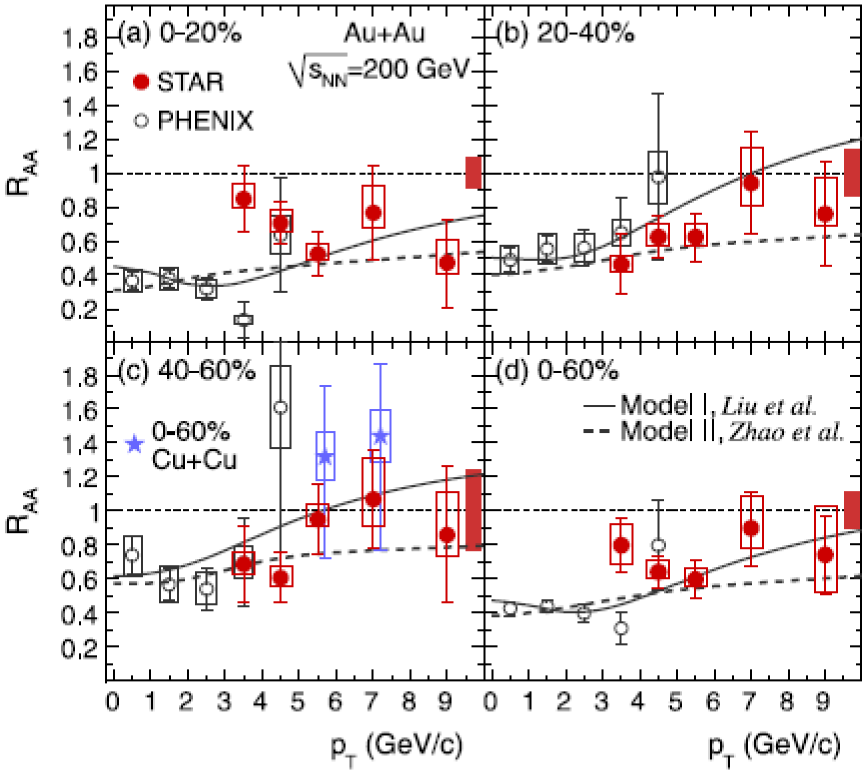
Regeneration: It happens in the fireball, the produced J/ψs carry low Pt.



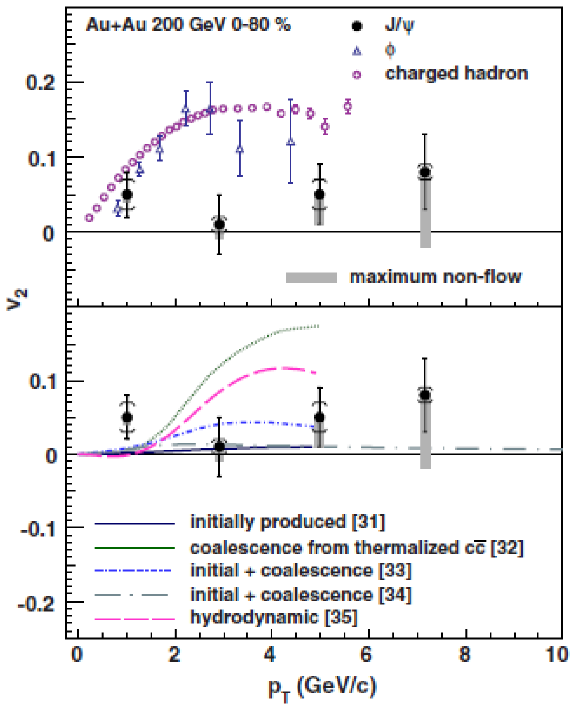
Integrated R_{AA} at RHIC *(B.Trzeciak for the STAR Collaboration, Nucl. Phys. A904–905, 607c(2013)):*



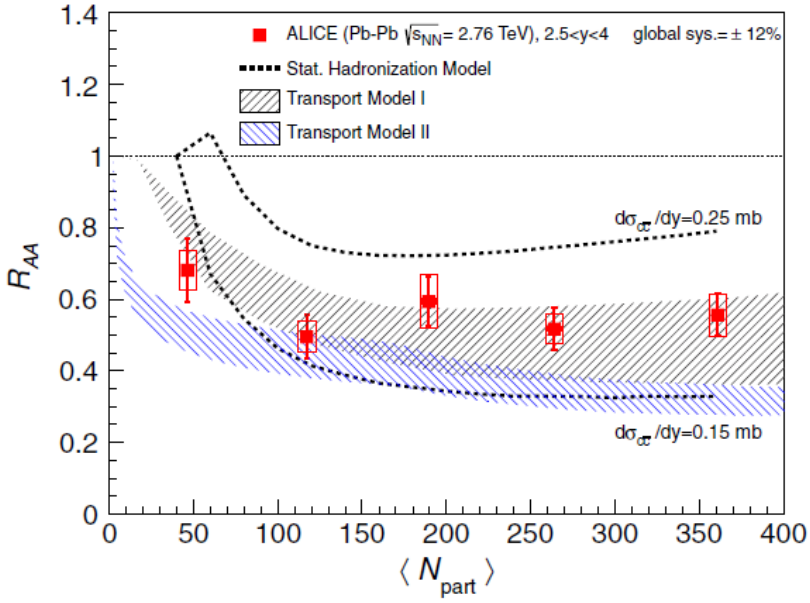
Differential R_{AA} ***at RHIC*** *(L.Adamczyk et al. [STAR Collaboration], Phys. Lett. B 722, 55(2013)):*



Elliptic flow at RHIC *(L.Adamczyk et al.[STAR Collaboration], Phys. Rev. Lett. 111, 52301(2013)):*

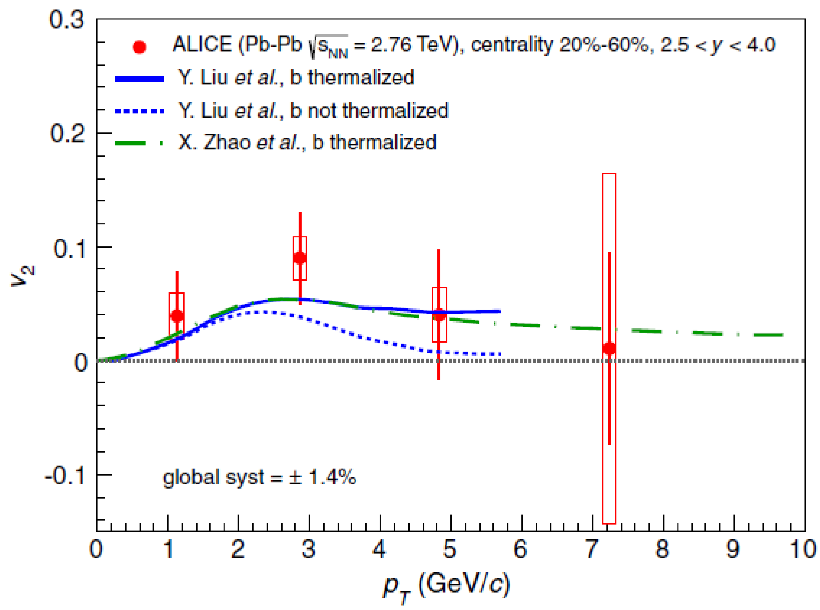


Integrated R_{AA} at LHC *(B.Abelev et al. [ALICE Collaboration], Phys. Rev. Lett. 109, 072301(2012)):*



The band is due to the uncertainty in the charm quark cross section. We take $d\sigma_{c\bar{c}}^{pp}/dy$ = 0.4 and 0.5 mb at forward rapidity.

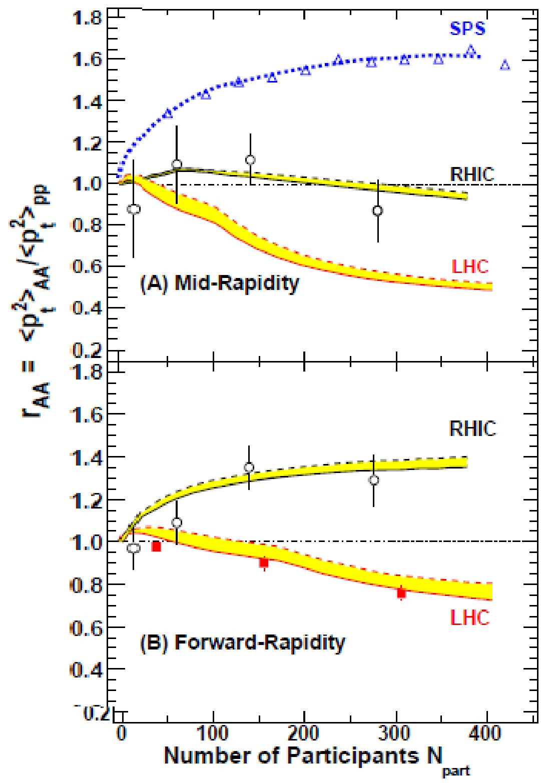
Inclusive v_2 at LHC *(E.Abbas et al. [ALICE Collaboration], Phys. Rev. Lett. 111, 162301(2013)):*



B quark thermalization controls the high Pt v2.

A new ratio (K.Zhou, N.Xu and P.Zhuang, Nucl. Phys. A834, 249(2010)),

$$r_{AA}(p_t^2) = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}},$$



Calculation from K.Zhou, N.Xu and P.Zhuang, arXiv:1309.7520 and LHC data at forward rapidity from E.Scomparin et al., [ALICE Collaboration], Quark Matter 2012 talk.

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

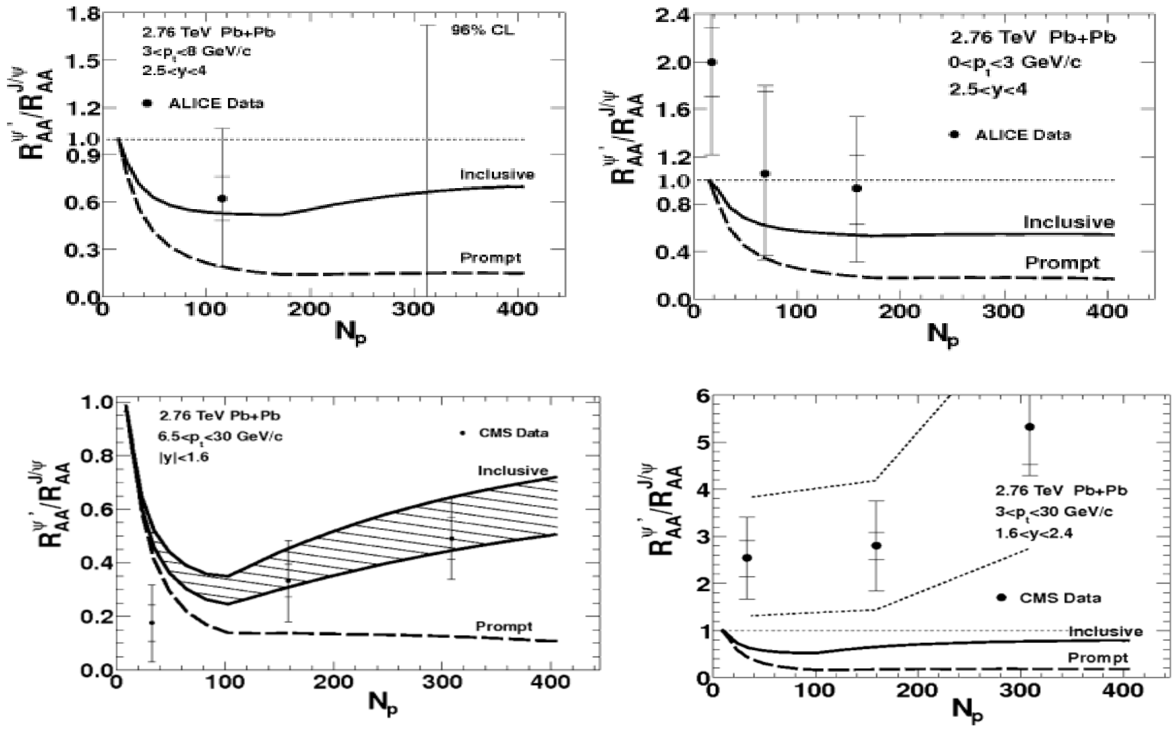
Shadowing effect ?

One may ask if the behavior of r_{AA} is dominated by the initial shadowing effect. Different from the integrated yield which depends strongly on both the cold and hot nuclear matter effects, the averaged transverse momentum is a normalized quantity, the shadowing induced change in the parton distribution is therefore minimized in the p_t r_{AA}. The narrow band is the result of shadowing effect which is taken from the EKS98 in our calculation. At RHIC energy the band becomes very narrow.

5.4 Excited States

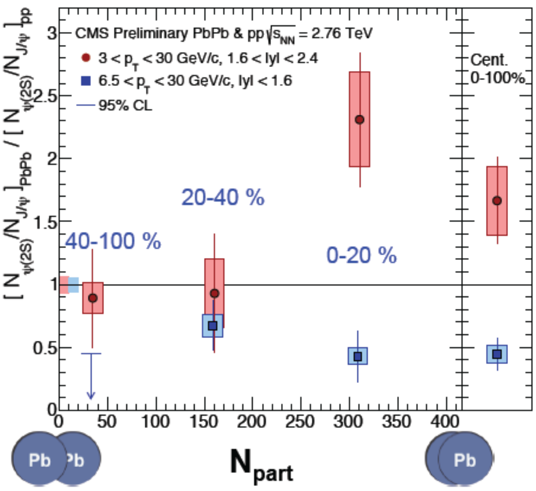
The ALICE (Nucl. Phys. A904, 202c(2013)) and CMS (arXiv:1209.1084) measured the double ratio for ***inclusive*** ψ' *and J/ψ,*

$$\frac{N_{AA}^{\psi'}/N_{AA}^{J/\psi}}{N_{pp}^{\psi'}/N_{pp}^{J/\psi}} = \frac{R_{AA}^{\psi'}}{R_{AA}^{J/\psi}},$$



B.Chen, Y.Liu, K.Zhou and P.Zhuang, Phys. Lett. B726, 725(2013)

Since the dissociation temperature for ψ' ***is low, the prompt*** ψ'***s are dissociated by the hot medium. In this case, the B decay contribution becomes dominant.***



The new CMS data for ***prompt*** *charmonia (D. Moon, QM2014 at Darmstadt)*

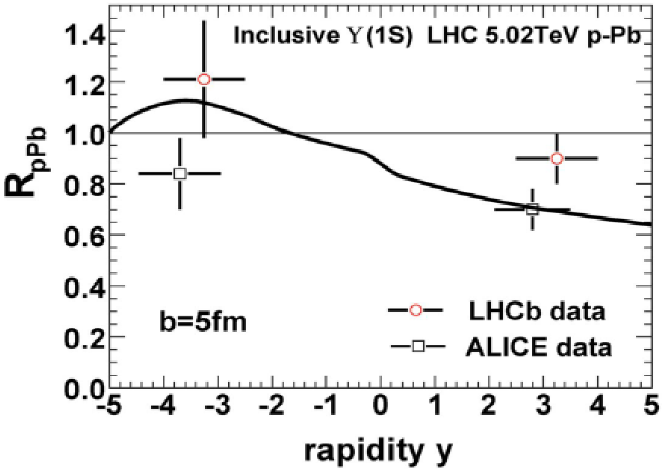
5.6 Υ States

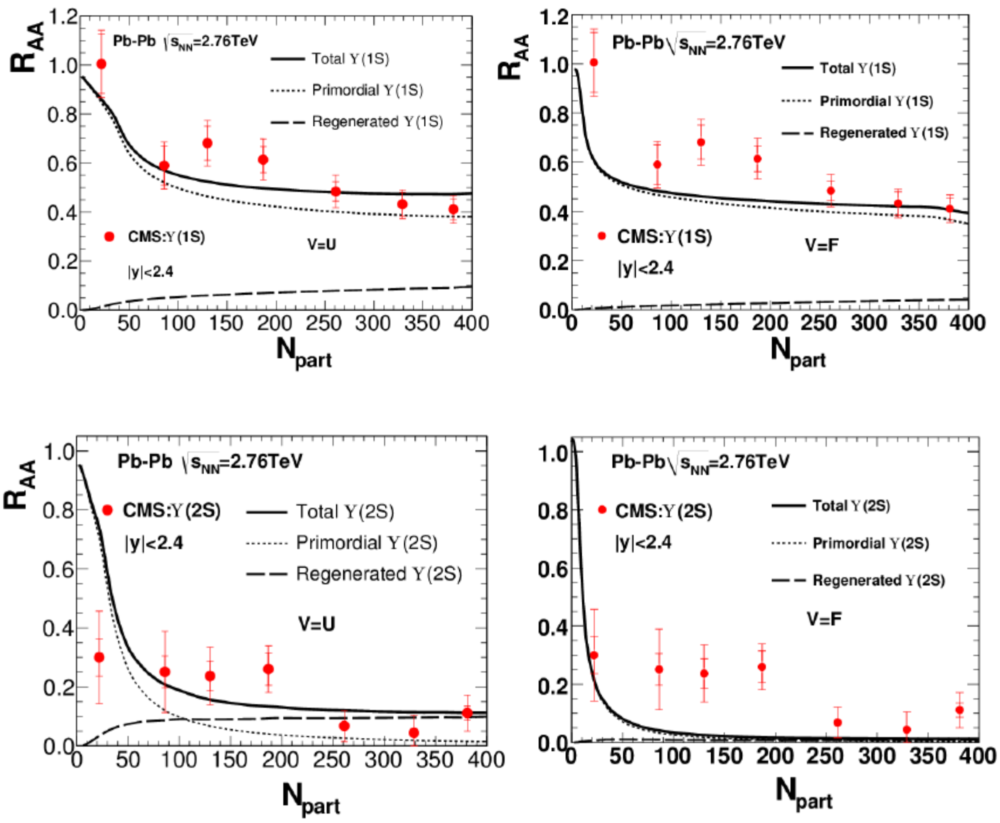
At RHIC and LHC energy, there are three advantages in studying Υ:

1) Υ regeneration can be neglected at RHIC, the initial production dominates;

2) Υs are so heavy, there is almost no feed-down from the heavier quarks;

3) The cold nuclear matter effect is weak *(C.Hadjidakis for the ALICE collaboration, arXiv:1405.1177; R Aaij for the LHCb Collaboration, Nucl. Phys. B873, 275(2013))*.





Calculation from *K.Zhou, N.Xu and P.Zhuang, in progress and data from CMS Collaboration, Nucl. Phys. A910, 91(2013).*

1) $\Upsilon(1s)$ is not sensitive to the medium

2) but $\Upsilon(2s)$ can be used to distinguish between F and U.

5.7 Heavy Quark Thermal Production

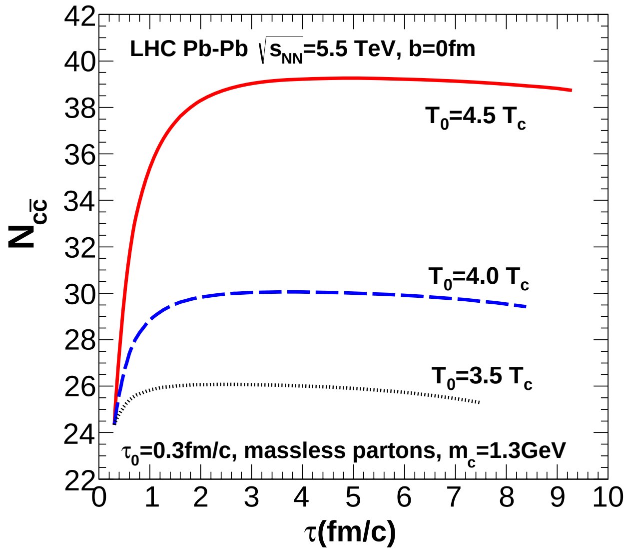
Sizeable thermal production at LHC ?

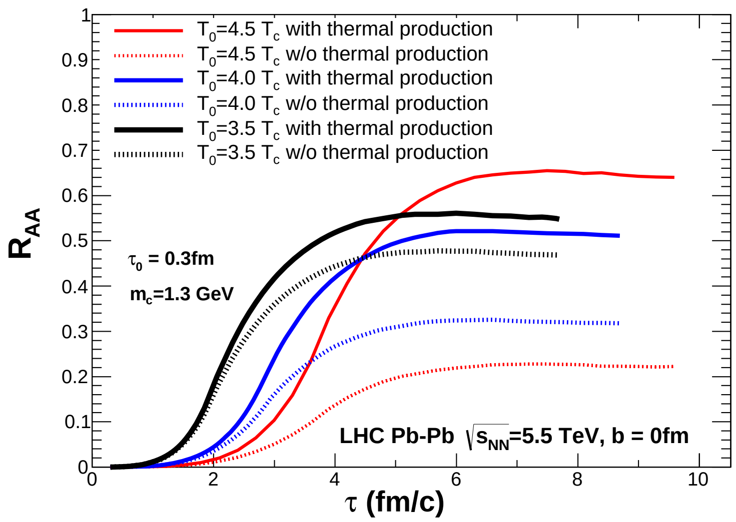
Sizeable contribution to quarkonia ($N_\psi \sim N_c^2$) ?

The thermal production cross section for heavy quarks can be calculated via pQCD at finite temperature. The charm quark number satisfies now the conservation:

$$\partial_\mu (n_c u^\mu) = R_{gain} - R_{loss}$$

with loss and gain terms.

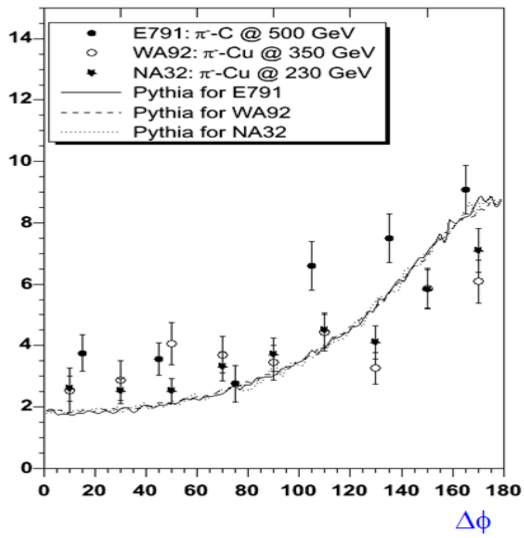




Thermal production becomes sizeable at T>3.5 Tc.

5.8 Heavy Quark Correlations

Heavy quark pairs are produced back to back at leading order in the final state $D\bar{D}$ angular correlation (C.Lourenco and H.K.Wohri, Phys. Rep. 433, 127(2006)).



Medium effects:

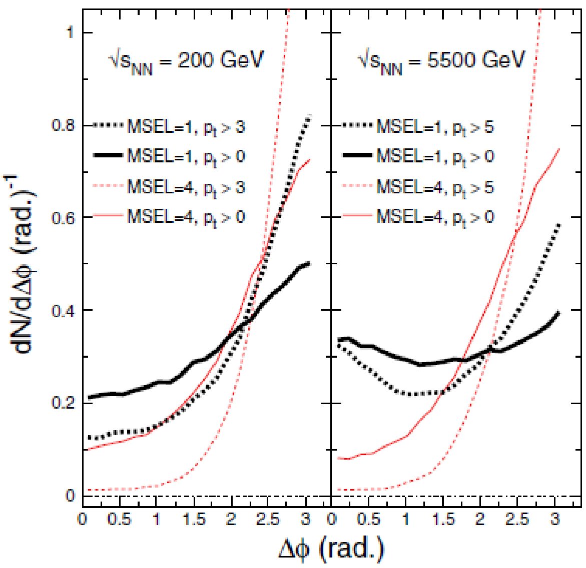
***1) Interaction with the medium** (X.Zhu et al., Phys. Lett. B647, 366(2007)).*

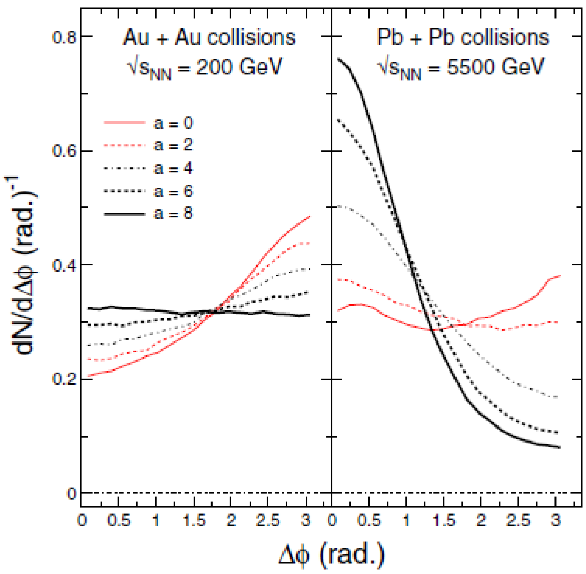
$$d\vec{p}/dt = -\gamma(T)\vec{p} + \vec{\eta}(T),$$

for the charm quark momentum p. A pQCD calculation (B.Svetitsky and A.Uziel, Phys. Rev. D55, 2616 (1997)) leads to the drag coefficient $\gamma(T) = aT^2$ with $a = 2 \times 10^{-6}(fm/c)^{-1}(MeV)^{-2}$. We take it as a parameter to describe the degree of interaction.

***2) Partonic wind** (X.Zhu, N.Xu and P.Zhuang, Phys. Rev. Lett. 100, 152301(2008)).*

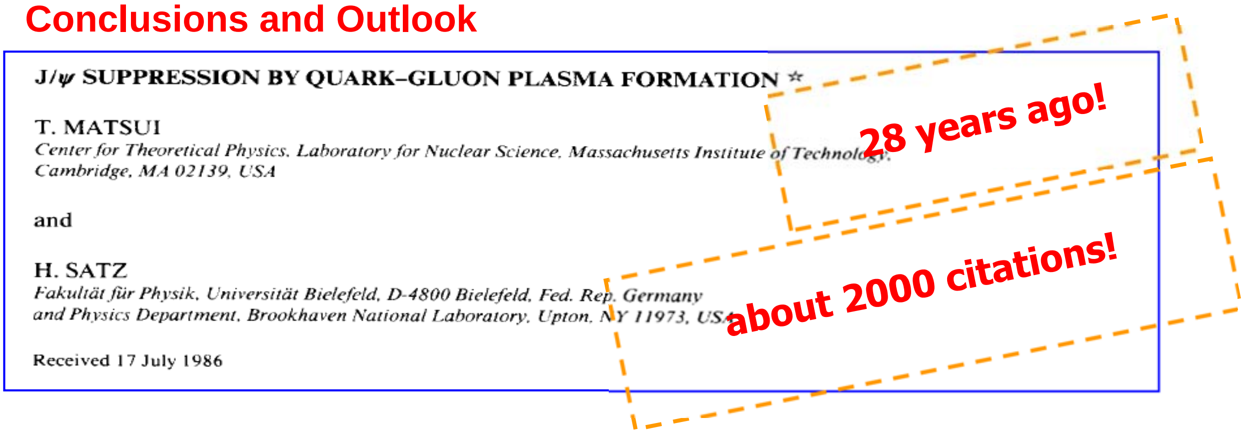
The heavy quarks experience the strong collective flow — the partonic wind.





The back-to-back disappears at RHIC and becomes a near side correlation at LHC.

6. Conclusions and Outlook


J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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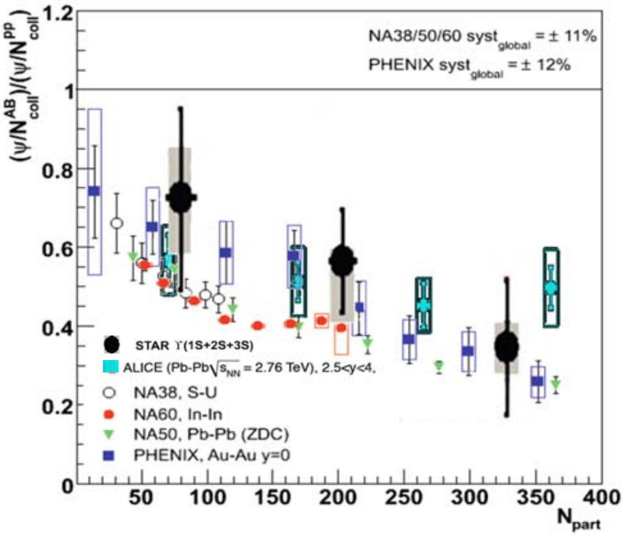
Received 17 July 1986

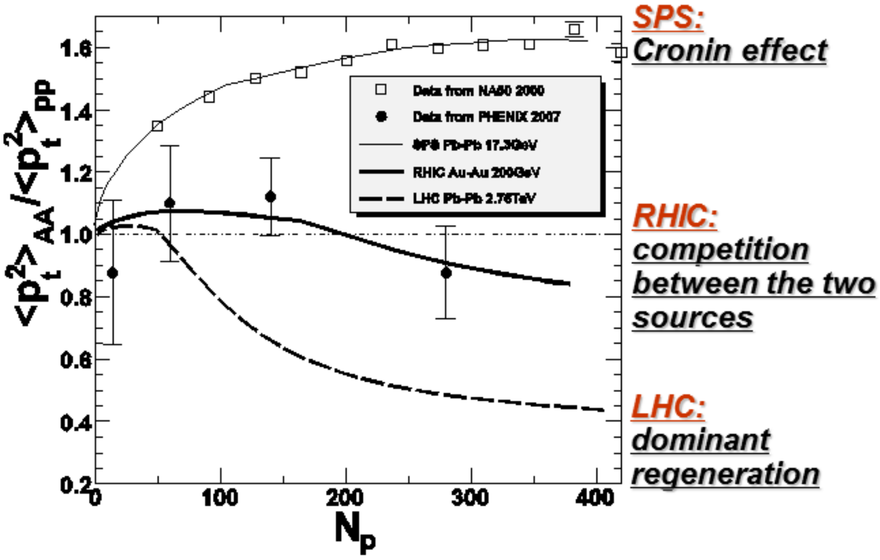
What we have learned from quarkonium study:

1) Strong nuclear matter effects at SPS, RHIC and LHC.

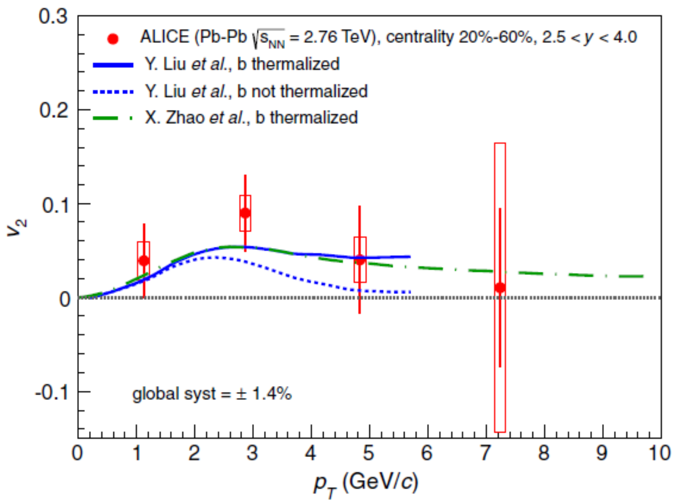
$$R_{AA}^{\psi} = \frac{N_{AA}^{\psi}}{N_{coll} N_{pp}^{\psi}} \neq 1$$



2. QGP formation at RHIC and LHC.



3. Thermalized charm quarks at LHC



What we suggest to do on quarkonium.

1) ***Heavy quark potential at finite temperature.***
   pNrQCD, LQCD, effective models, finite density effect, and sensitive quantities in heavy ion collisions.

2) ***Precise measurement of J/ψ elliptic flow and*** $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$ ***at mid and forward rapidity.***

3) ***Excited states and*** Υ ***production and high Pt J/ψ.***
   The mechanism is relatively simple,

4) ***Extreme particles.***
   Like Ω_{ccc} *which is hard to be produced in p+p (need 3 pairs of* $c\bar{c}$*) but relative easy to be produced via regeneration mechanism in A+A (the probability ~*N_c^3*!)*

5) ***……***

Thank You for Your Attention !