Thermal Charm and Charmonium Production in QGP

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Quarkonium is a probe of QGP (Matsui & Satz**).**

In comparison with p+p collisions, there are two sources for heavy quark and quarkonium production in A+A collisions:

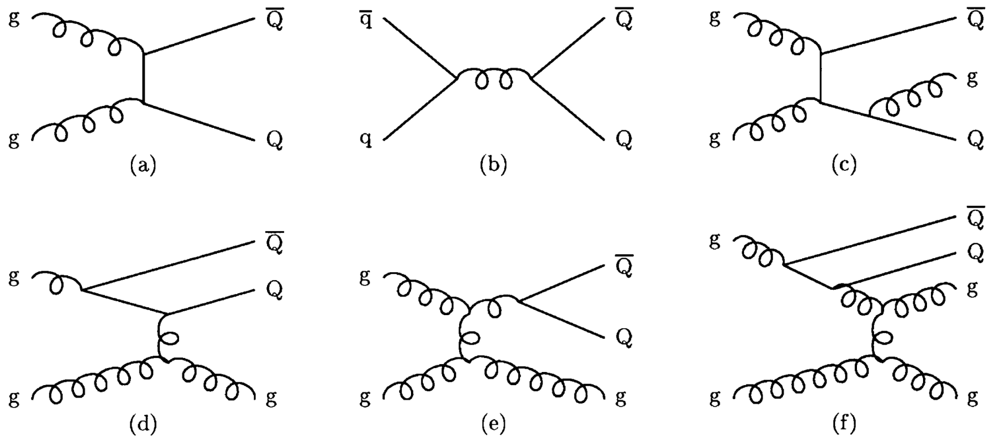
one is the initial production which is an effective superposition of p+p collisions (including cold nuclear matter effect), and the other is the thermal production (regeneration) in the hot medium *(PBM, Thews, Rapp,……).*

The second source makes heavy quarks and quarkonia more sensitive to the hot medium.

Heavy Quark Production in QGP

Thermal charm production in QGP becomes important at high energies:

P.Levai, B.Muller and X.Wang, PRC51, 3326(1995).
B.Kaempfer and O.Pavlenko, PLB391, 185(1997).
J.Uphoff, O.Fochler, Z.Xu and C.Greiner, PRC82, 044906(2010).
B.Zhang, C.Ko and W.Liu, PRC77, 024901(2008)



(a) gluon fusion, (b) quark-antiquark annihilation, (c) pair creation with gluon emission, (d) flavor excitation, (e) gluon splitting, (f) together gluon splitting and flavor excitation.

Question: Contribution to quarkonium regeneration

Charm Quark Evolution in QGP

K.Zhou, Z.Chen, C.Greiner, and PZ,. Phys.Lett. B758， 434(2016)

$$\frac{1}{\cosh\eta}\partial_\tau n_c + \nabla_T \cdot (n_c \mathbf{v}_T) + \frac{1}{\tau\cosh\eta} n_c = r_{gain} - r_{loss}$$

gain rate:

$$r_{12} = \frac{dn}{d^4x} = \frac{1}{\nu}\int \frac{d^3\mathbf{p}_1}{(2\pi)^3 2E_1}\frac{d^3\mathbf{p}_2}{(2\pi)^3 2E_2} 4F_{12}\sigma_{12} f_1 f_2,$$

*NLO production cross section

P.Nason, S.Dawson, and R.Ellis, NPB 303, 607(1988); 327, 49(1989).
M.L.Mangano, P.Nason and G.Ridolfi, NPB373, 295(1992).

*temperature dependent parton masses and coupling constant

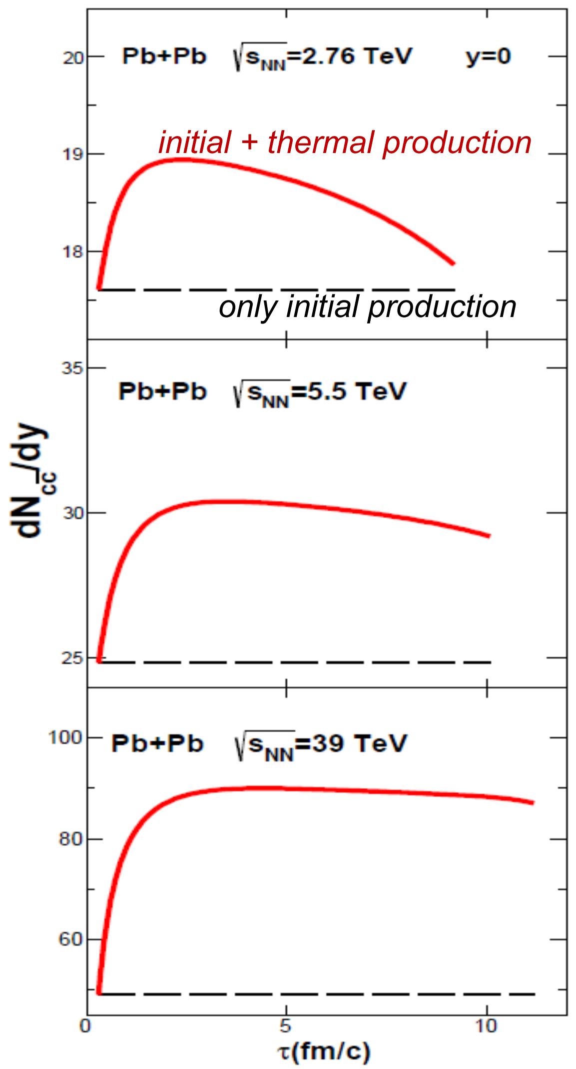
E.Braaten and R.Pisarski, PRD45, 1827(1992).
S.Plumari, W.M.Alberico, V.Greco and C.Ratti, PRD84, 094004(2011)

*hydrodynamics for QGP evolution

*detailed balance between loss and gain terms

*shadowing effect on initial distribution (EPS09s NLO)

significant charm enhancement (~80%) at FCC !



Quarkonium Evolution in QGP

L.Yan, N.Xu and PZ, PRL97, 232301(2006)

- QGP evolution

$$\partial_\mu T^{\mu\nu} = 0, \qquad \partial_\mu n^\mu = 0 \quad + \text{EoS}$$

- quarkonium motion in QGP

detailed balance between suppression and regeneration

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

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

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

- analytic solution

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

Questions: 1) Initial distribution including cold medium effect
2) Loss and gain terms

$f_\Psi(\tau_0)$ with Cold Medium Effect

shadowing effect: EPS09s NLO

$$f_\Psi(p, x, \tau_0 | b) \sim \int dz_A\, dz_B\, \rho_A(x, z_A)\rho_B(x-b, z_B) \times R_g(x_g, \mu_F, x) R_g(x_g, \mu_F, x-b) f_\Psi^{pp}(p, x, z_A, z_B)$$

Cronin effect:

$$\langle p^2 \rangle_{pp}^{\Psi} = \langle p^2 \rangle_{pp}^{\Psi} + a_{gN}\, l$$

Dissociation Rate at Finite Temperature

$$J/\psi\ (\Upsilon) + g \rightarrow Q + \bar{Q}$$

- gluon dissociation cross section calculated by OPE (Bhanot, Peskin,1999):

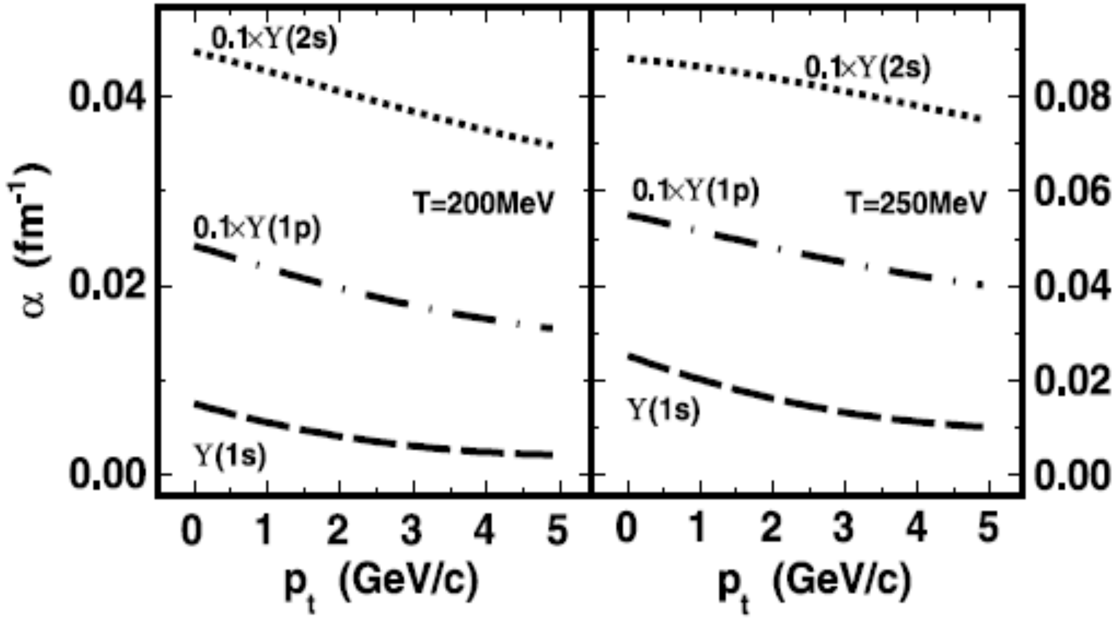
$$\sigma(p_\psi, p_g)$$

- at finite temperature, we use the classical relation

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

$\langle r^2\rangle(T)$ from potential model

- Υ dissociation rate

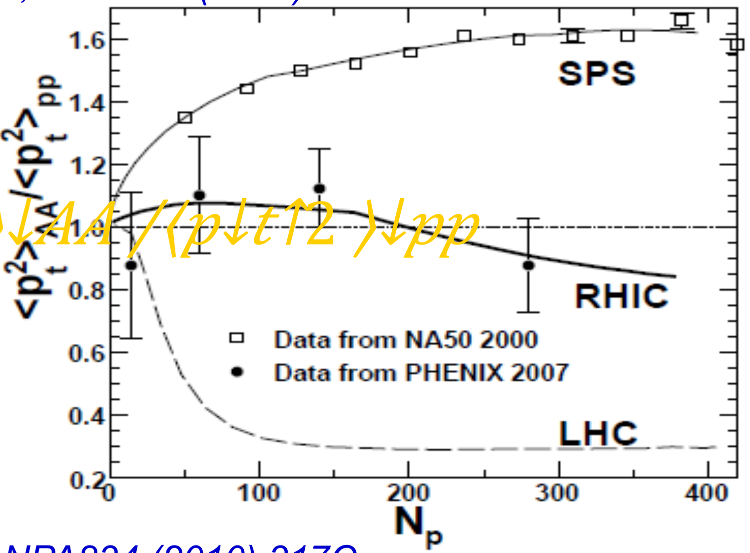


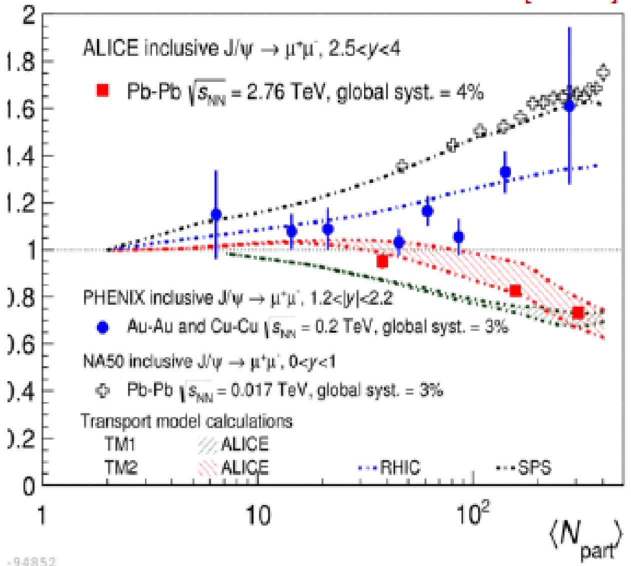
J/ψ Transverse Momentum Distributions in A+A

K.Zhou, N.Xu, and PZ, NPA834 (2010) 249C

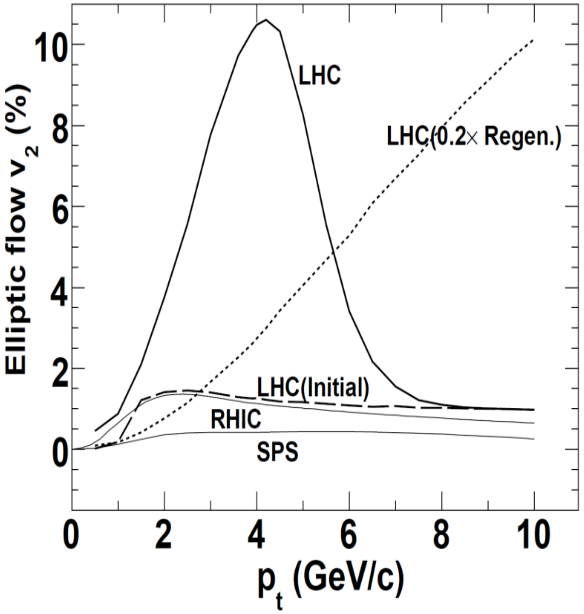
arXiv:1506.08804 [nucl-ex]

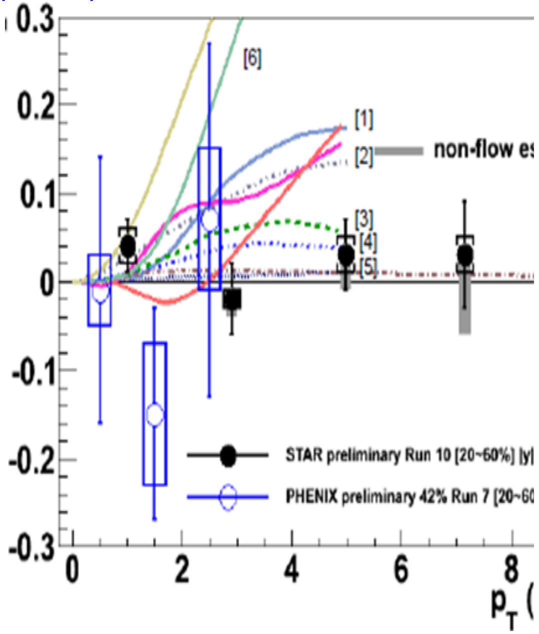
$$r_{AA} = \langle p_t^2 \rangle_{AA} / \langle p_t^2 \rangle_{pp}$$

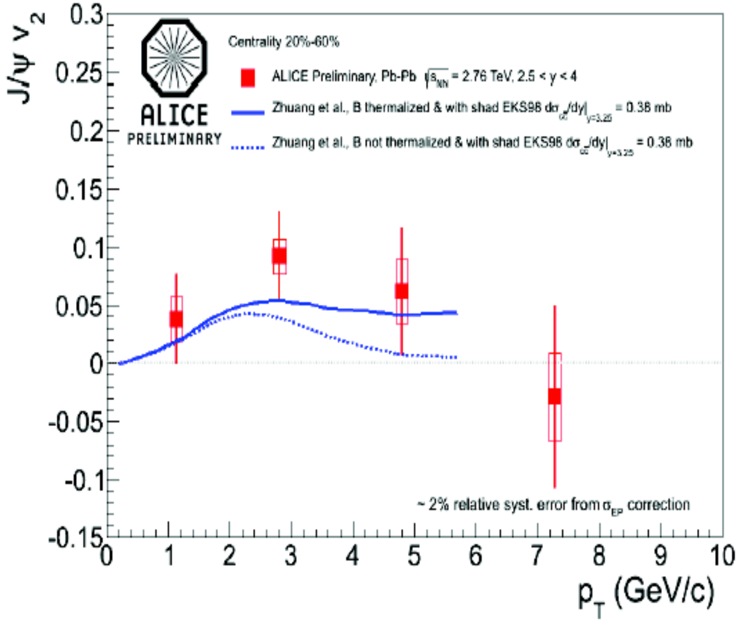




Y.Liu, N.Xu, and PZ, NPA834 (2010) 317C

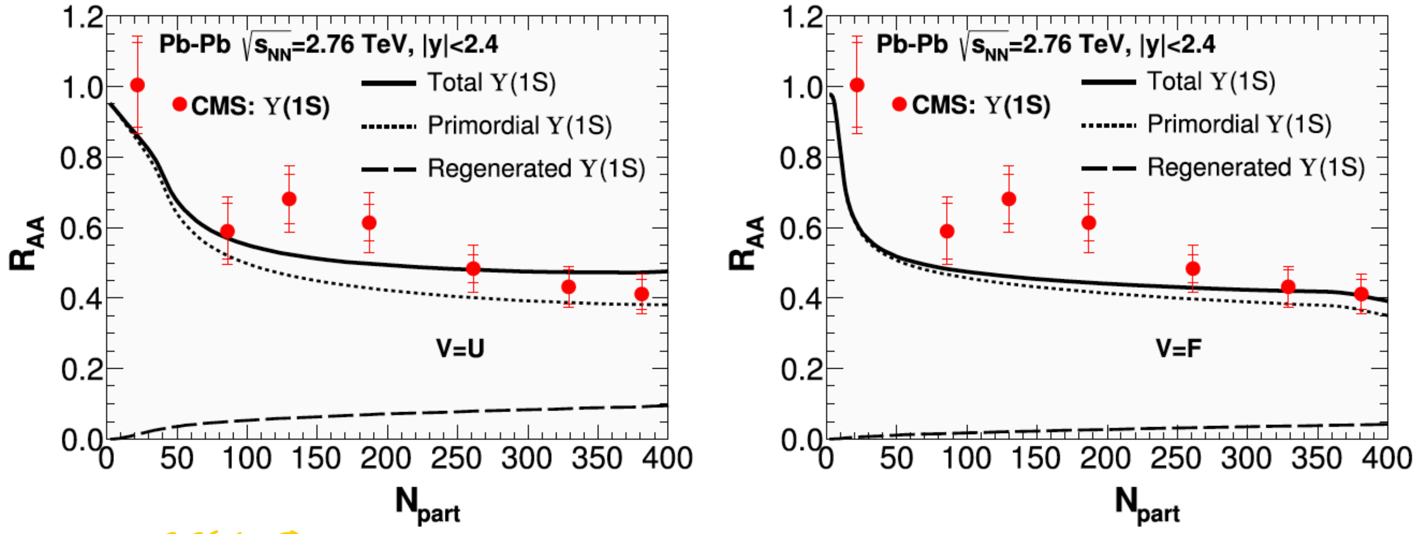




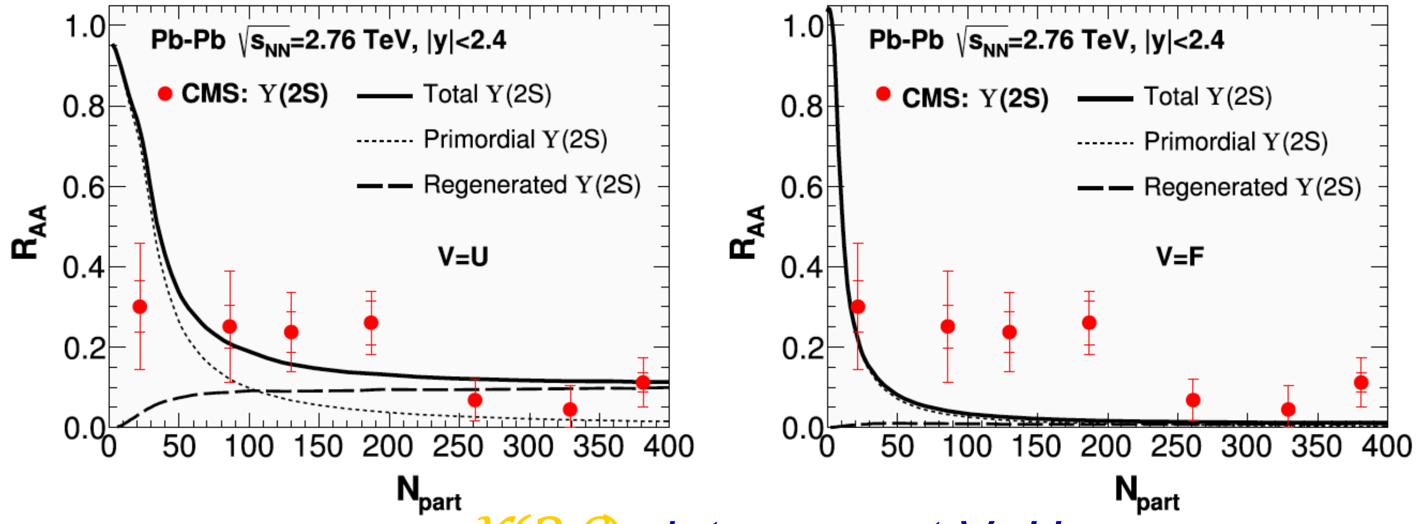


Υ in A+A at $\sqrt{s_{NN}}=2.76$ TeV

K.Zhou, N.Xu and PZ, Nucl.Phys. A931 (2014) 654-658



$\Upsilon(1S)$ is not sensitive to the charm quark potential.



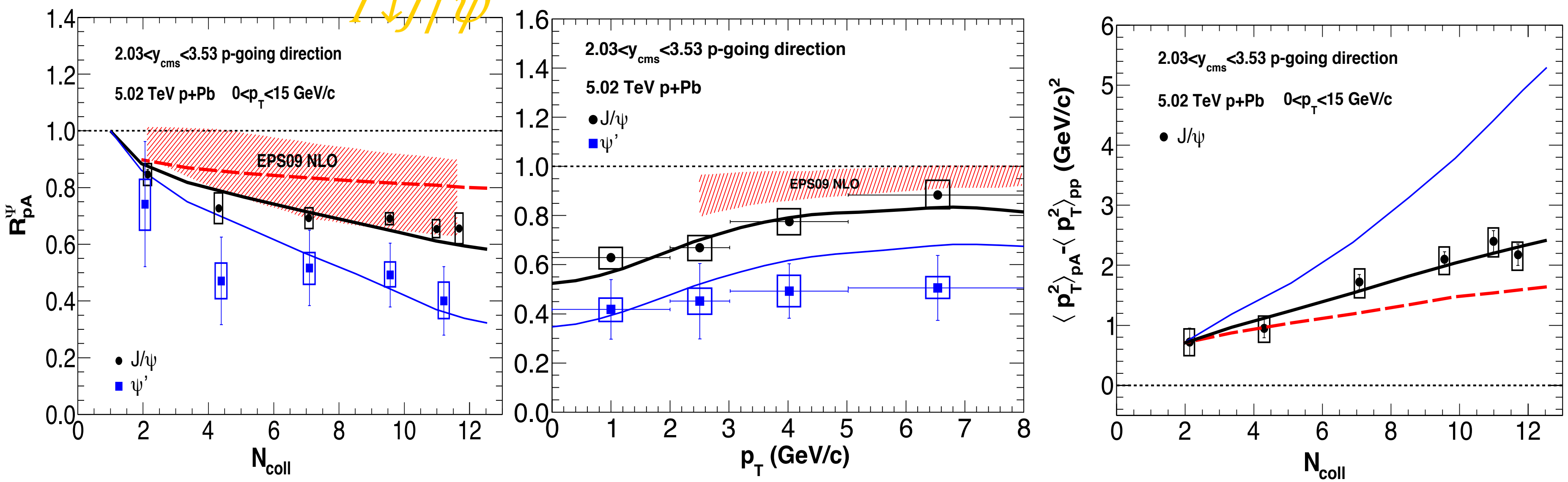
$\Upsilon(2S)$ data support V=U.

Charmonia in $\sqrt{s_{NN}}=5.02$ TeV p+A at Forward Rapidity

B.Chen, T.Guo, Y.Liu, and PZ, arXiv:1607.07927

Initial fireball temperature

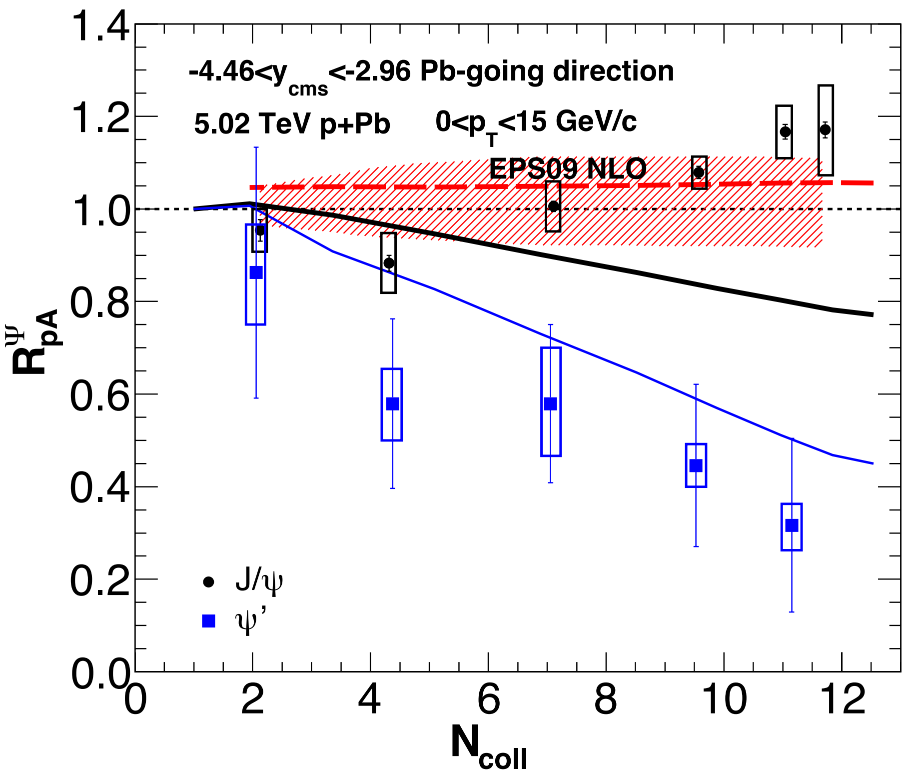
$T_{\psi'} < T_0 = 180\text{ MeV} < T_{J/\psi}$



1) Cold + Hot medium effects work well at forward rapidity.

2) Very strong p_T broadening for ψ' due to the leakage effect,
this need to be confirmed experimentally.

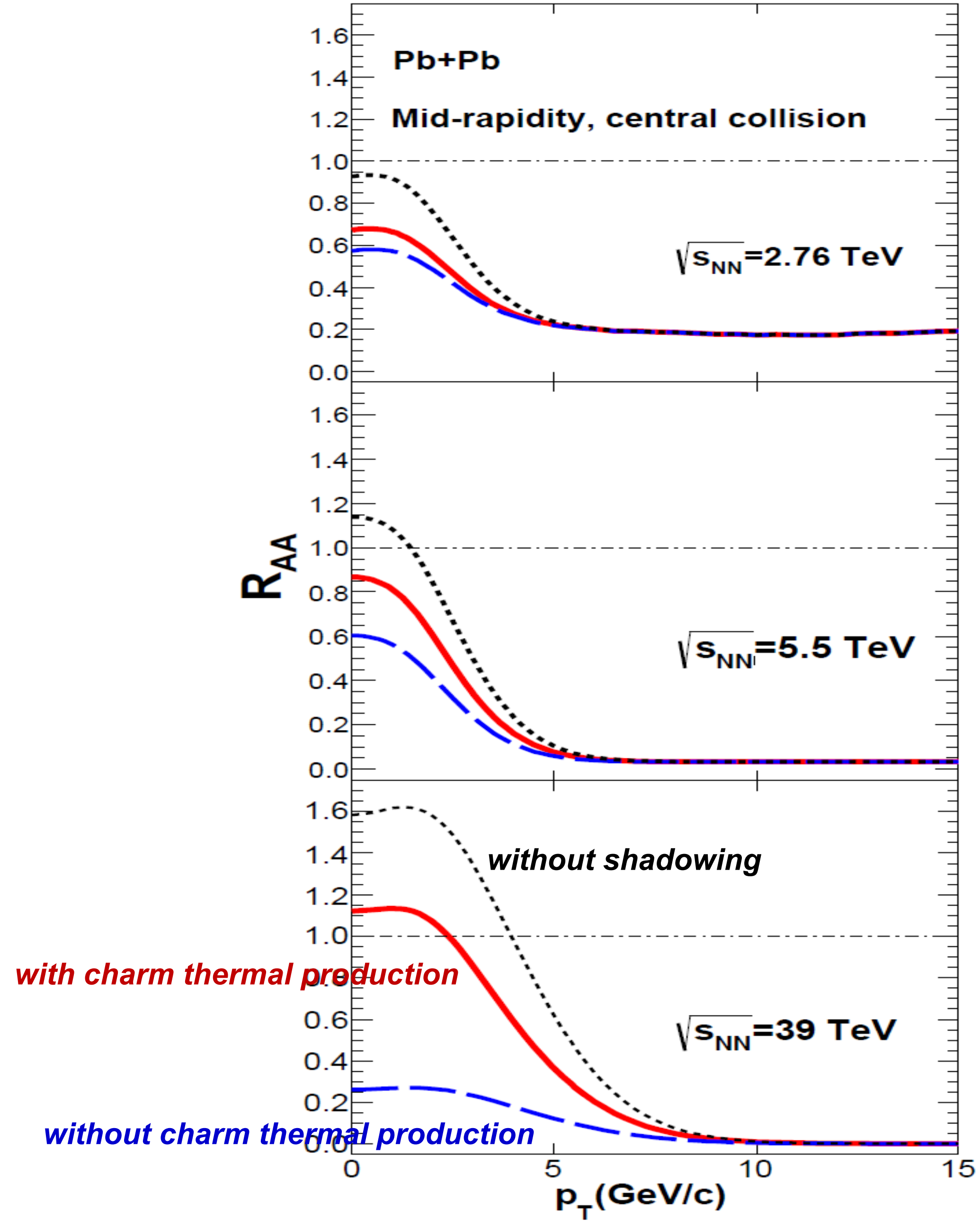
Charmonia in $\sqrt{s_{NN}}=5.02$ TeV p+A at Backward Rapidity



Cold + Hot medium effects can not reproduce the J/ψ enhancement at backward rapidity.

Charmonia at FCC

K.Zhou, Z.Chen, C.Greiner, and PZ, PLB758 (2016) 434



significant J/ψ enhancement at low p_T:

$R_{AA}(p_t)<1 \quad \rightarrow \quad R_{AA}(p_t)>1$

Conclusions

1) Charm quark thermal production is weak at RHIC and LHC but becomes very strong at FCC.

3) Quarkonium transverse momentum distribution can distinguish hot mediums at SPS, RHIC and LHC:
   a. from pt broadening at SPS to pt suppression at LHC,
   b. from zero v_2 at SPS and RHIC to sizeable v_2 at LHC.

3) Fireball temperature in p+Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV:
   $T_{\psi'} < T < T_{J/\psi}$.

4) Charm quark thermal production changes significantly the J/ψ yield, from J/ψ suppression at SPS, RHIC and LHC to J/ψ enhancement at FCC.