

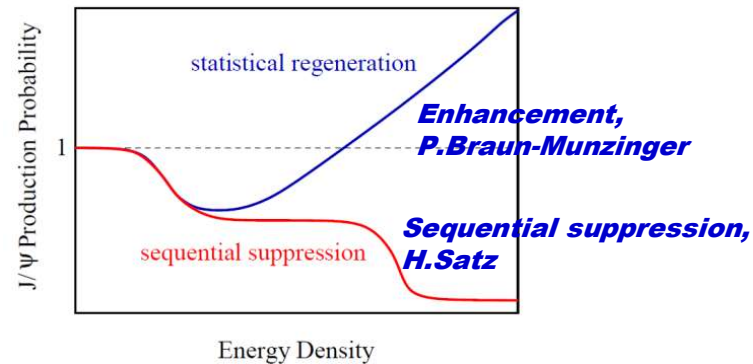
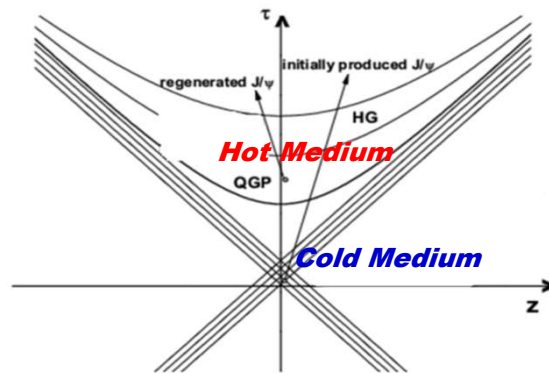
# Cold and Hot Medium Effects on Quarkonium Production in a Transport Approach

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## ● Quarkonia as a thermometer of QGP

However, the cold medium effects (shadowing, Cronin, energy loss, nuclear absorption, ... [EKS, EPS, Vogt, ...]) and hot medium effects (color screening [Matsui, Satz], regeneration [PBM, Thews, Rapp, ...], ...) are complicated.



The competition among them may weaken the sensitivity of the thermometer !

## ● How to increase the sensitivity of the thermometer ?

## Outline

- *A Quarkonium Transport Approach with Cold and Hot Medium Effects*
- *Medium Effects in p+A Collisions at LHC*
- *Medium Effects in A+A Collisions at SPS, RHIC, LHC and FCC*

## Quarkonium Motion in Hot Medium

Transport + hydrodynamics: L. Yan, N. Xu and PZ, PRL97, 232301(2006)

- QGP evolution

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

- quarkonium motion in *hot medium*

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

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

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

*detailed balance between  
suppression and regeneration*

- analytic solution

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

- we need to know

$f_\Psi(\tau_0)$  (cold medium),  $\alpha_\Psi$  (hot medium),  $f_c$  (cold and hot mediums)

## $f_{\Psi}(\tau_0)$ with Cold Medium Effects

$$g + g \rightsquigarrow g + \Psi$$

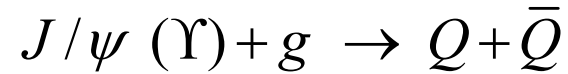
$$f_{\Psi}(\vec{p}, \vec{x}, \tau_0 | \vec{b}) \sim \int dz_A dz_B \rho_A(\vec{x}, z_A) \rho_B(\vec{x} - \vec{b}, z_B) \\ \times R_g(x_g, \mu_F, \vec{x}) R_g(x_g, \mu_F, \vec{x} - \vec{b}) \bar{f}_{\Psi}^{pp}(\vec{p}, \vec{x}, z_A, z_B)$$

*shadowing effect: EPS09 NLO, Vogt*

*Cronin effect:*

$$\overline{\langle \vec{p}^2 \rangle}_{pp} \Psi = \langle \vec{p}^2 \rangle_{pp} \Psi + a_{gN} l$$

## Dissociation Rate at Finite Temperature



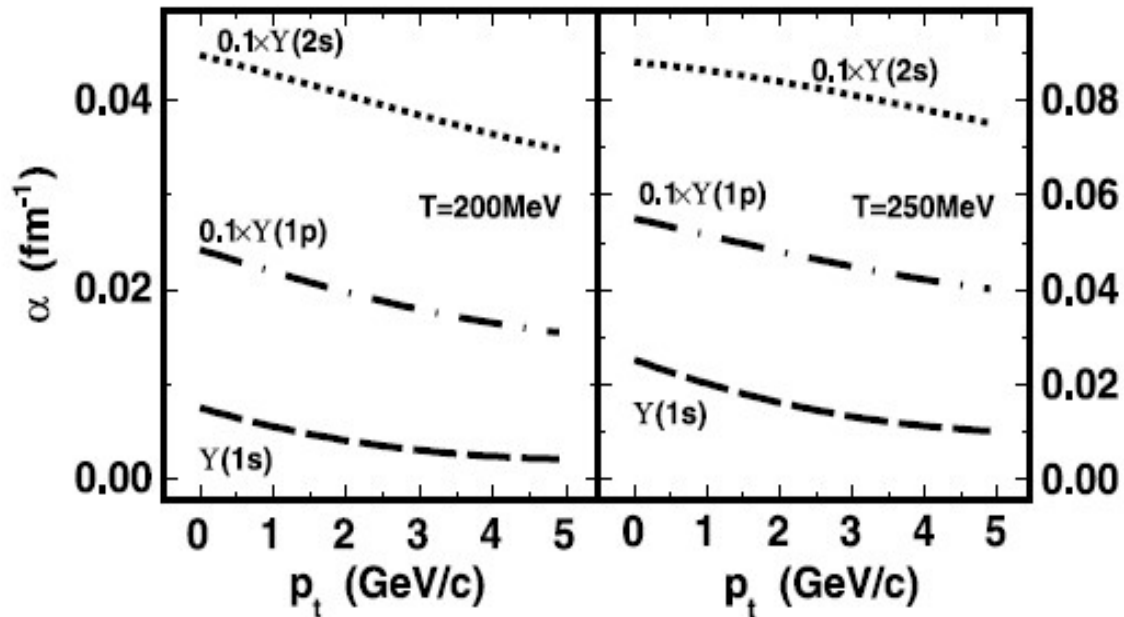
- gluon dissociation cross section calculated by OPE (Bhanot, Peskin, 1999):

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

- at finite temperature, we use the classical relation

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

- $\Upsilon$  dissociation rate



## Heavy Quark Production in QGP

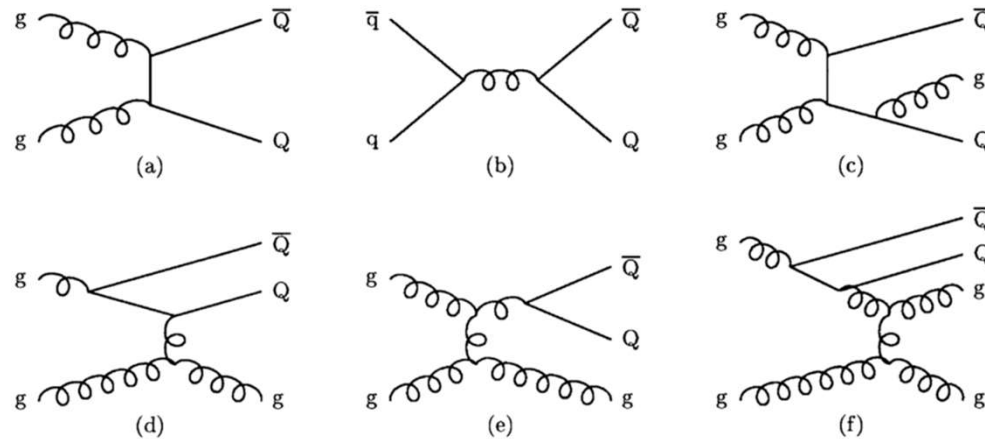
Thermal charm production in QGP becomes important at high energies:

*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).*

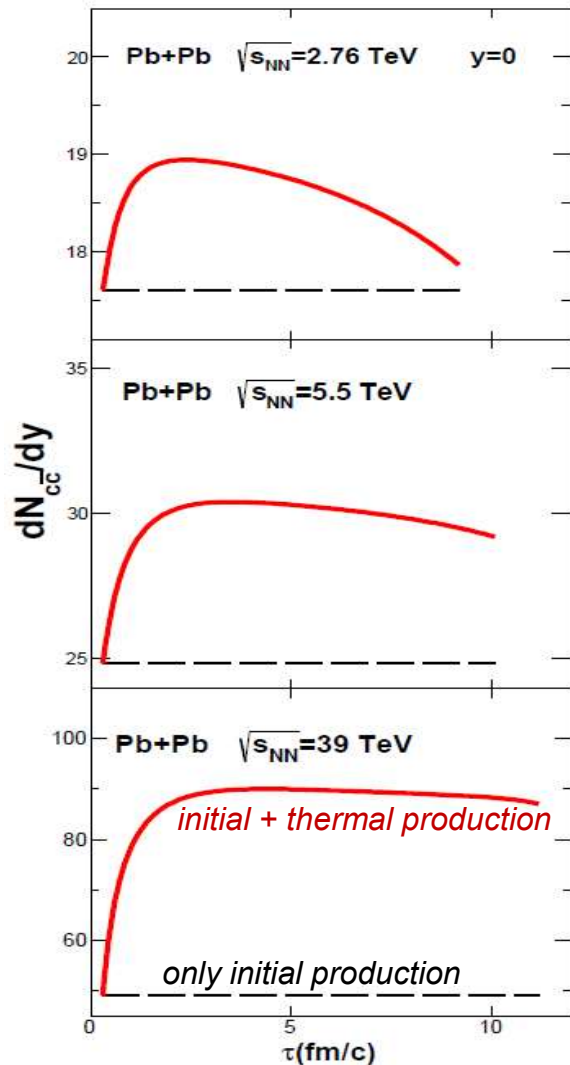
*B.Zhang, C.Ko and W.Liu, PRC77, 024901(2008)*



(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.

**What is the effect on quarkonium regeneration ?**

## Heavy Quark Evolution in GGP



assuming thermally but not chemically equilibrated charm distribution

$$n_c(t, \mathbf{x}) = \int d^3\mathbf{p}/(2\pi)^3 f_c(t, \mathbf{x}, \mathbf{p})$$

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

loss and gain rates:

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

\*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 in initial distribution

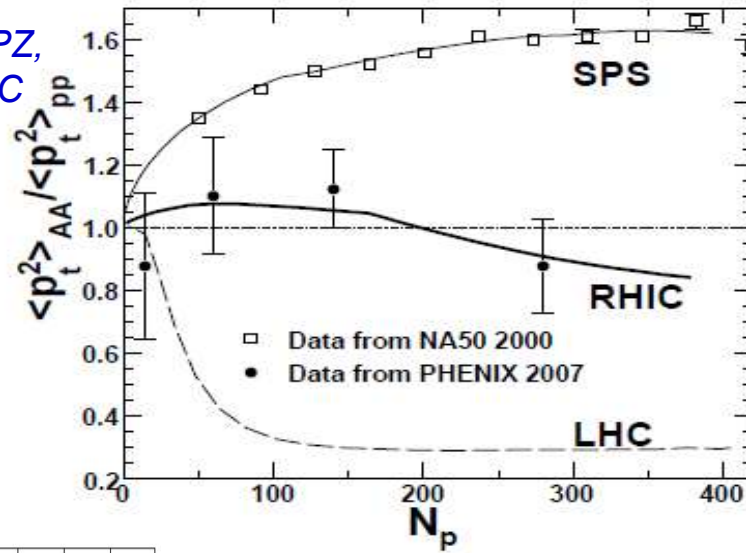
**significant charm quark enhancement (~80%) at FCC !**

*K.Zhou, Z.Chen, C.Greiner, and PZ., Phys.Lett. B758 (2016) 434-439*

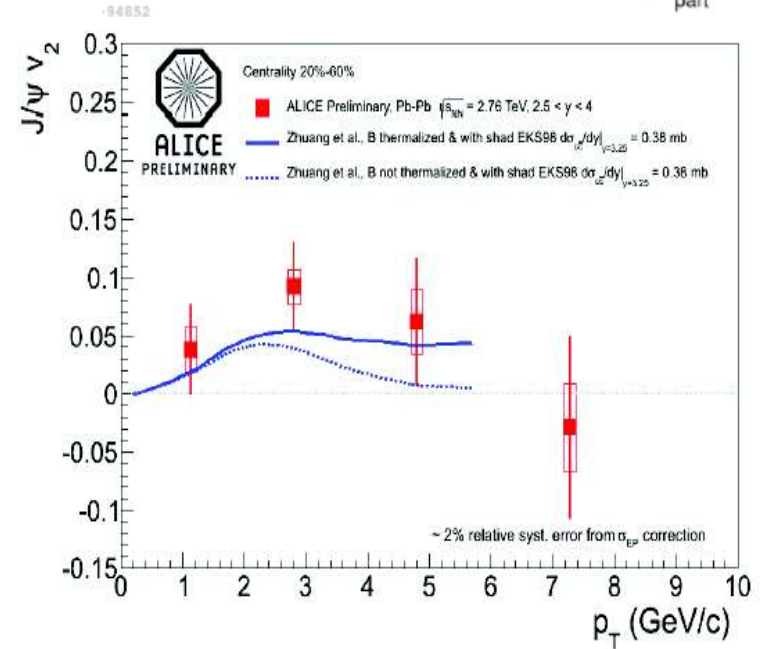
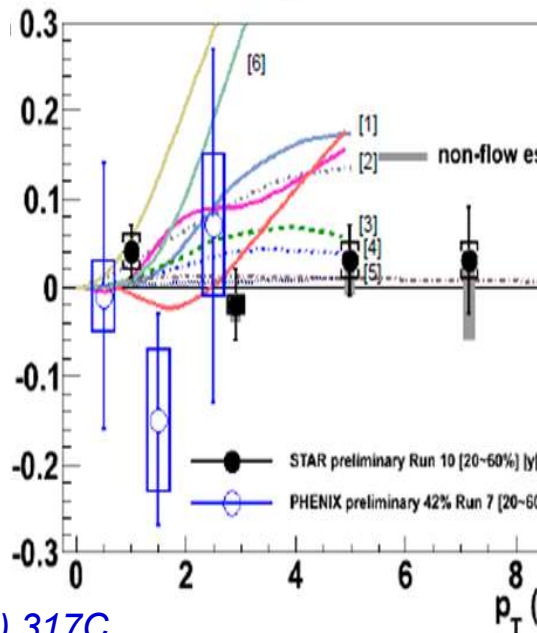
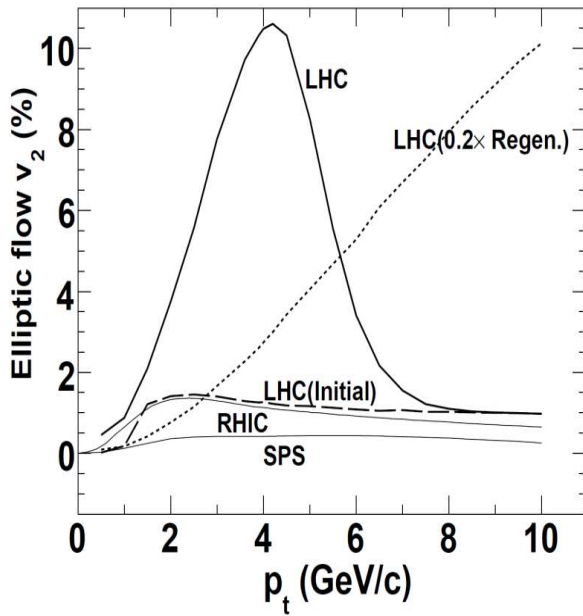
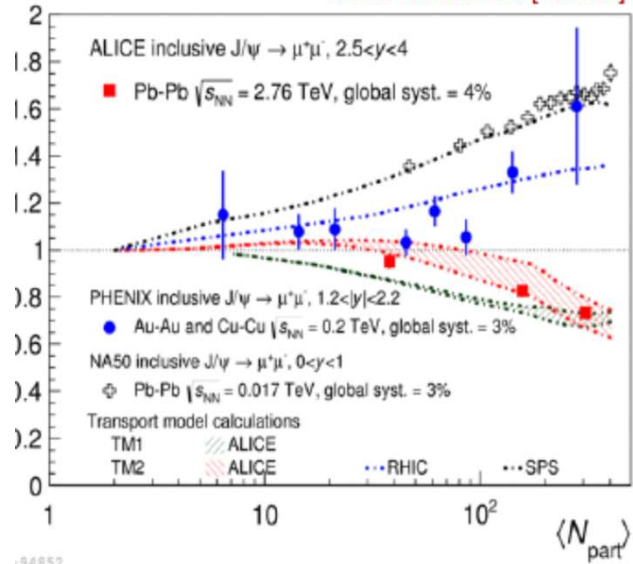
# $J/\psi$ Transverse Momentum Distributions in A+A

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

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



arXiv:1506.08804 [nucl-ex]



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

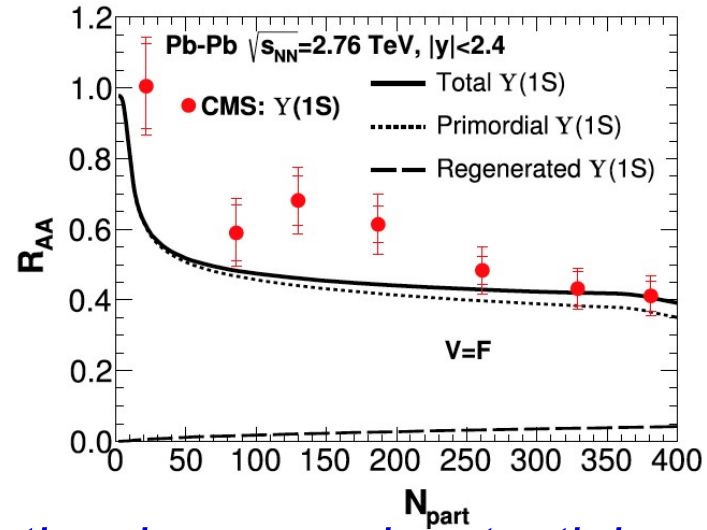
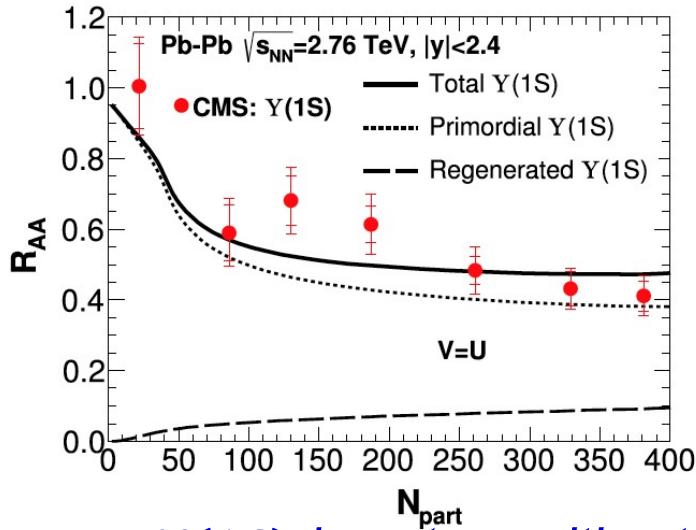
Pengfei Zhuang

Workshop for Ulrich's 60<sup>th</sup> Birthday, CERN, 201607

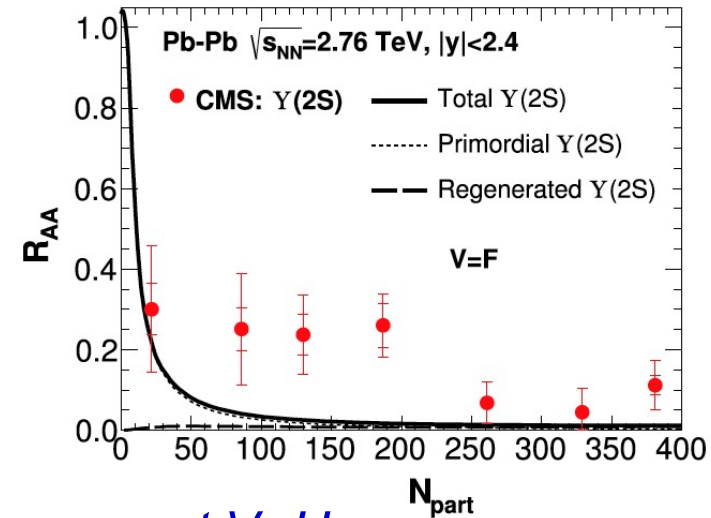
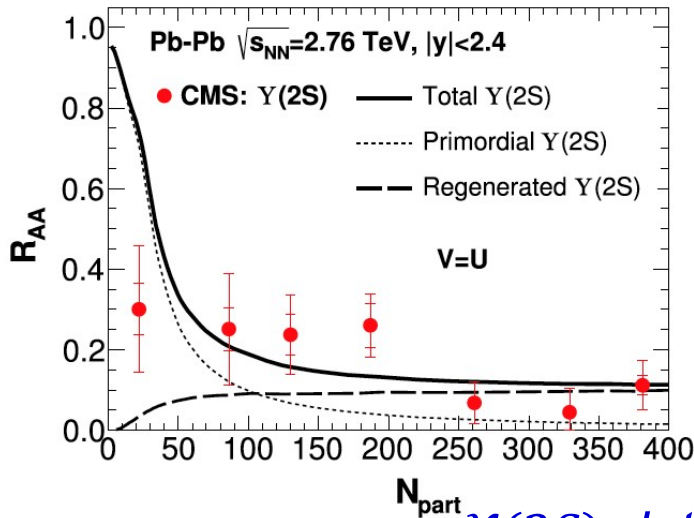


# $Y$ in $A+A$ at $\sqrt{s_{NN}} = 2.76$ TeV

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



*$Y(1S)$  is not sensitive to the charm quark potential.*



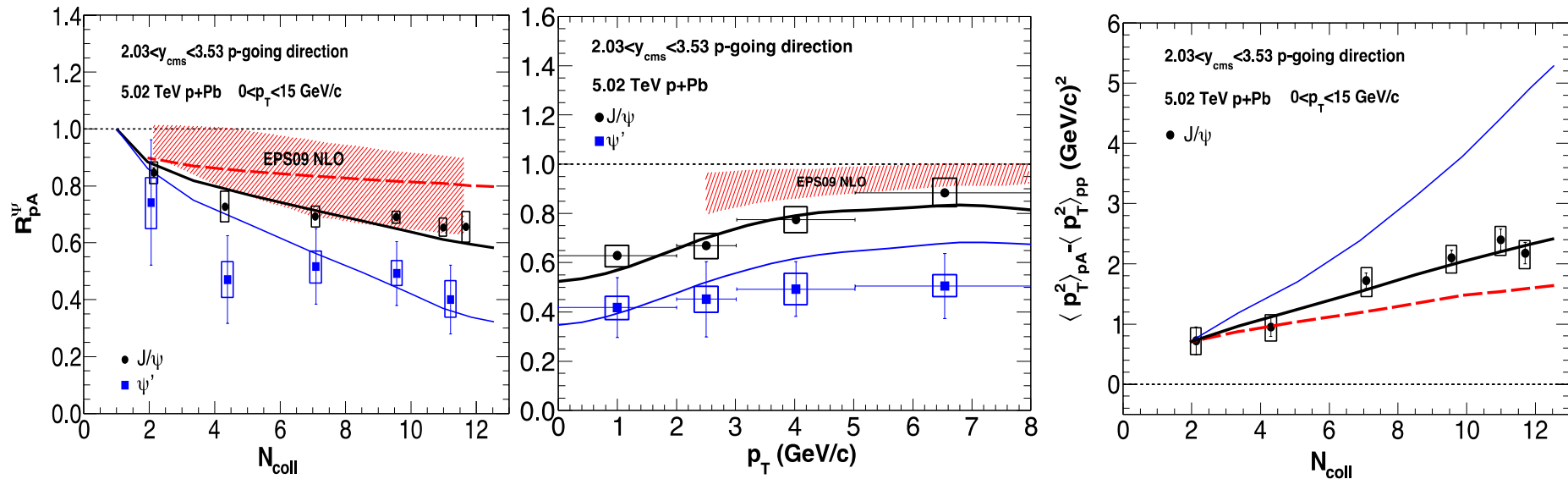
*$Y(2S)$  data support  $V=U$ .*

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

B.Chen, T.Guo, Y.Liu, and PZ, arXiv:1607.nnnnn

Initial fireball temperature

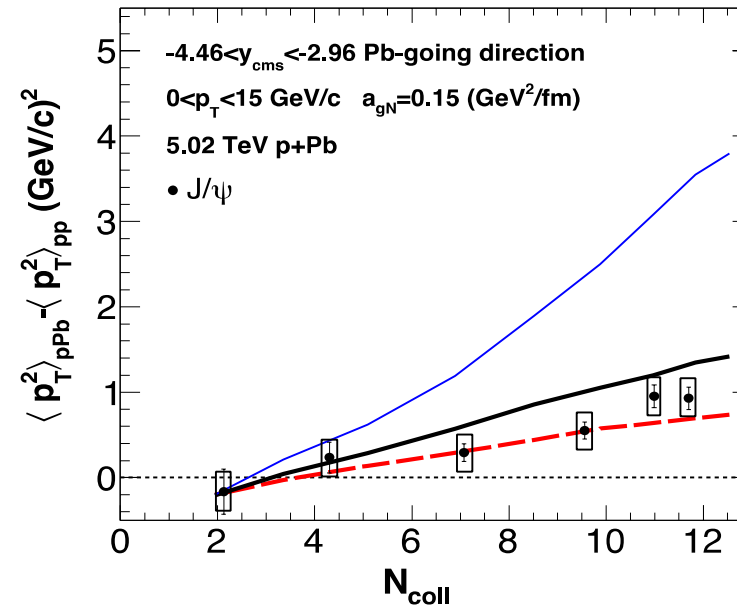
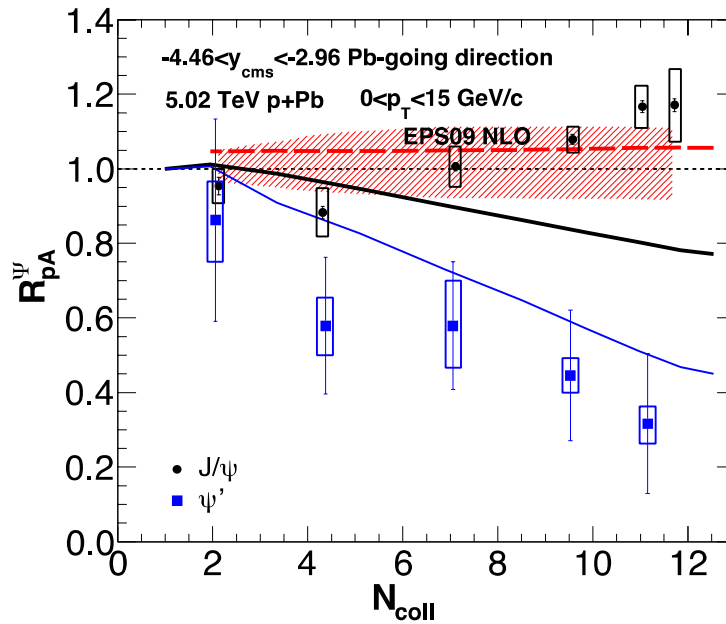
$$T_{\psi'} < T_0 = 180 \text{ MeV} < T_{J/\psi}$$



- 1) Cold + Hot medium effects work well at forward rapidity.
- 2) Very strong  $p_T$  broadening for  $\psi'$  due to the leakage effect, this need to be confirmed experimentally.

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

B.Chen, T.Guo, Y.Liu, and PZ, arXiv:1607.nnnnn

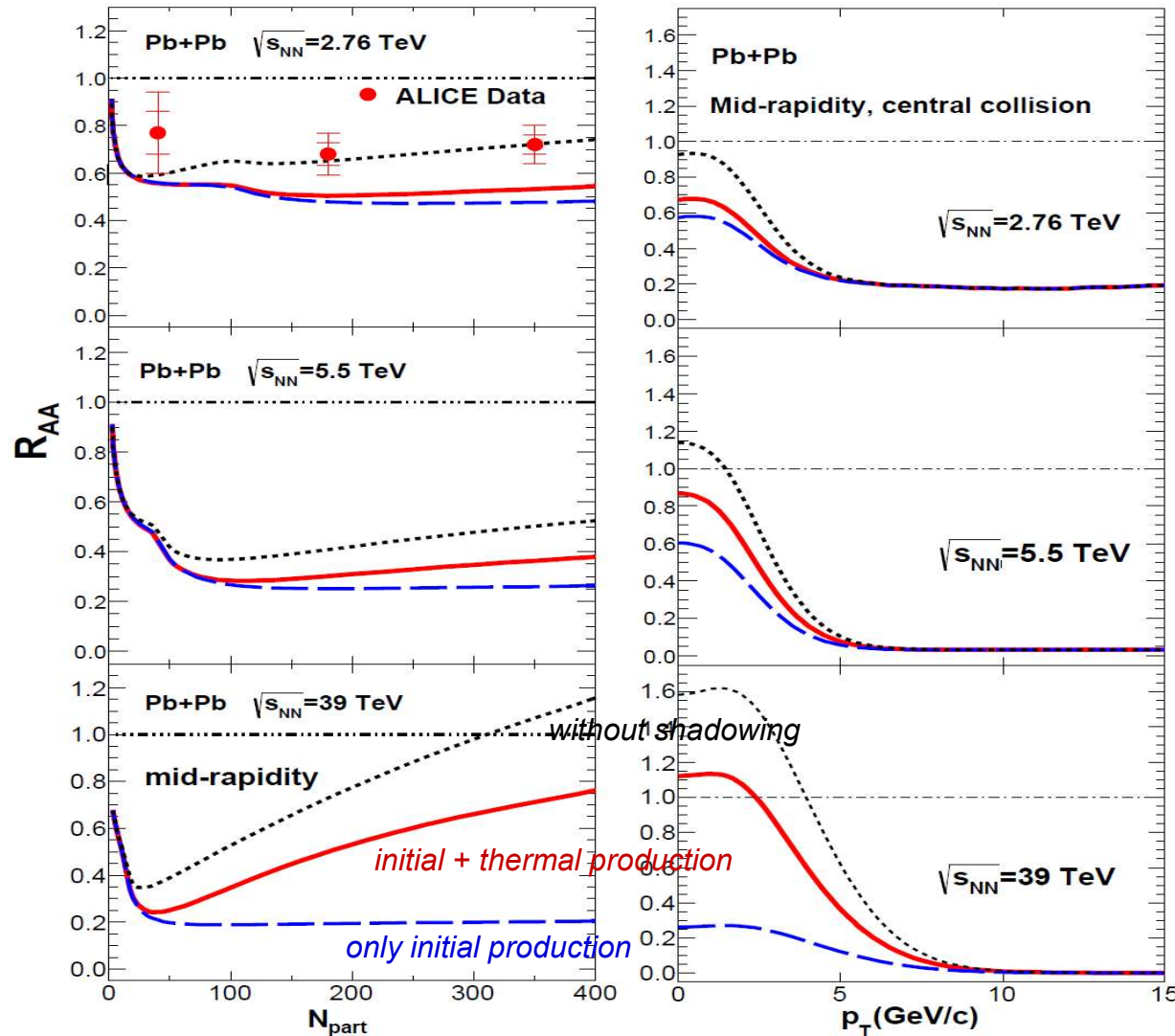


*Cold + Hot medium effects can not reproduce simultaneously the  $J/\psi$  yield and  $p_T$  enhancement, there is something new at backward rapidity.*

## Charmonia at LHC and FCC

Result at LHC: K.Zhou, N.Xu, Z.Xu and P.Zhuang, PRC89, 054911(2014)

Results at FCC: K.Zhou, Z.Chen, C.Greiner, and PZ, PLB758 (2016) 434



New phenomena at FCC:

- a valley in  $J/\psi$   $R_{AA}(N_p)$
- significant enhancement  
 $R_{AA}(N_p) = 0.2 \rightarrow 0.75$ ,  
 $R_{AA}(p_t) < 1 \rightarrow > 1$

## Conclusions

- 1) Quarkonium transverse momentum distribution can distinguish hot mediums at SPS, RHIC and LHC,  
from  $p_t$  broadening at SPS to  $p_t$  suppression at LHC,  
and from zero  $v_2$  at SPS and RHIC to sizeable  $v_2$  at LHC.
- 2) Fireball temperature in  $p+Pb$  Collisions at  $\sqrt{s_{NN}} = 5.02$  TeV:  
 $T_{\psi'} < T < T_{J/\psi}$ .
- 3) Charm quark thermal production changes significantly the  $J/\psi$  yield,  
from  $R_{AA} < 1$  at SPS, RHIC, LHC to  $R_{AA} > 1$  at FCC.
- 4) Still some puzzles, like backward rapidity in  $p+A$ , double ratio  $\psi'/\psi$  in  $A+A$ ,  
and excess of low  $p_t$   $J/\psi$  in peripheral  $A+A$ .



ANNALS OF PHYSICS **245**, 311–338 (1996)  
ARTICLE NO. 0011

*4 papers with Uli on equal-time quantum transport*

## Relativistic Quantum Transport Theory for Electrodynamics\*

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Received February 21, 1995; revised May 23, 1995

***Happy Birthday to Uli !***

We investigate the relationship between the covariant and the three-dimensional (equal-time) formulations of quantum kinetic theory. We show that the three-dimensional approach can be obtained as the energy average of the covariant formulation. We illustrate this state-