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

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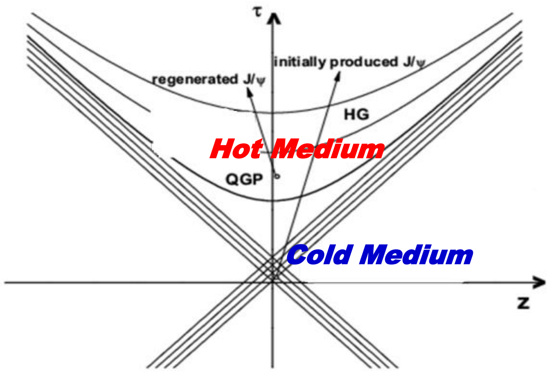
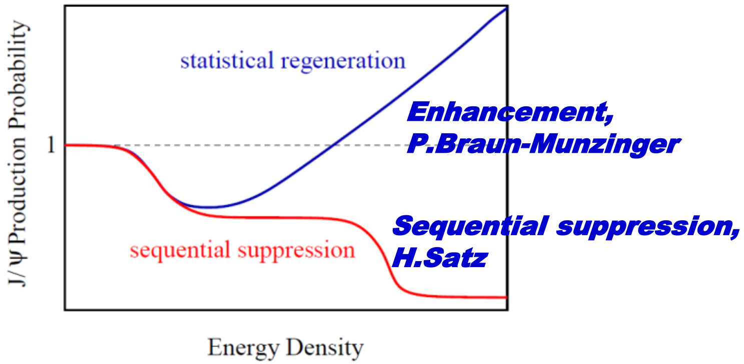
- *Quarkonia as a thermometer of QGP*

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*

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

- *quarkonium motion in hot medium*

detailed balance between suppression and regeneration

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

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

- *analytic solution*

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

- *we need to know*

$$f_\Psi(\tau_0)(\text{cold}\ medium), \quad \alpha_\Psi(hot\ medium), \qquad f_c(cold\ and\ hot\ mediums)$$

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

$$g+g \dashrightarrow g+\Psi$$

$$f_\Psi\left(\vec{p},\vec{x},\tau_0|\vec{b}\right)\sim\int dz_A dz_B \varrho_A(\vec{x},z_A)\varrho_B\left(\vec{x}-\vec{b},z_B\right)$$

$$\times R_g\left(x_g,\mu_F,\vec{x}\right)R_g\left(x_g,\mu_F,\vec{x}-\vec{b}\right)\bar{f}_\Psi^{pp}(\vec{p},\vec{x},z_A,z_B)$$

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

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

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

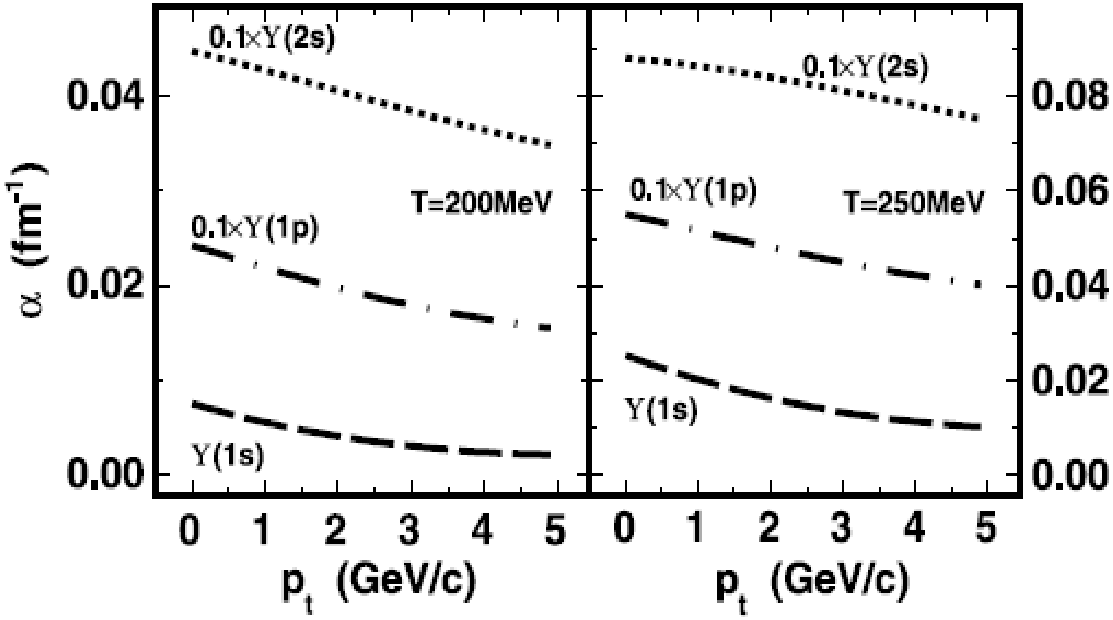
$$\sigma(p_\psi, p_g)$$

- 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

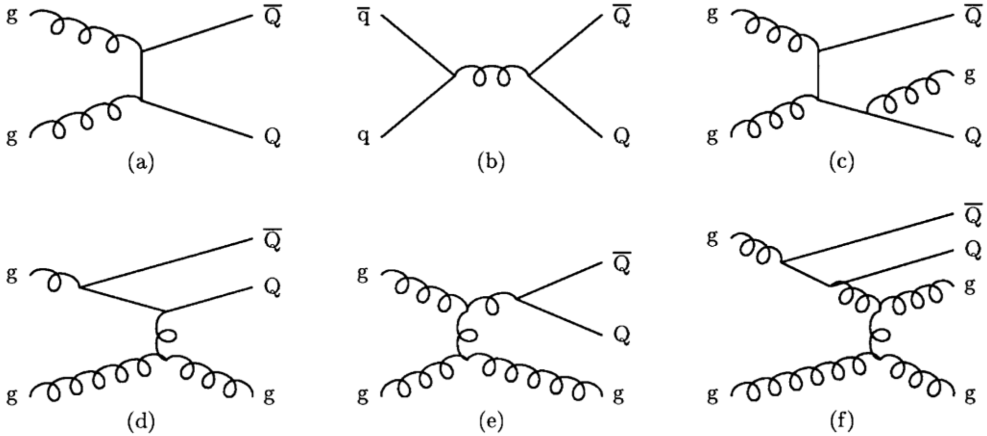
- Υ dissociation rate



Heavy Quark Production in QGP

Thermal charm production in QGP becomes important at high energies:

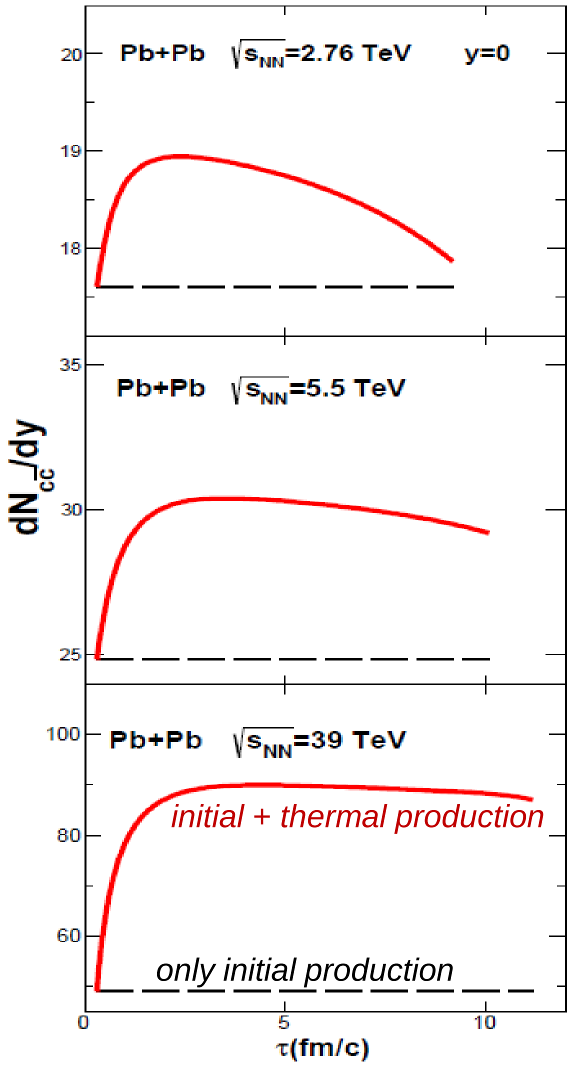
P.Levai, B.Muller and X.Wang, PRC51, 3326(1995).
B.Kaempfer and O.Pavlenko, PLB391, 185(1997).
J.Uphoff, O.Fochler, Z.Xu and C.Greiner, PRC82, 044906(2010).
B.Zhang, C.Ko and W.Liu, PRC77, 024901(2008)



(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



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

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:

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

*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

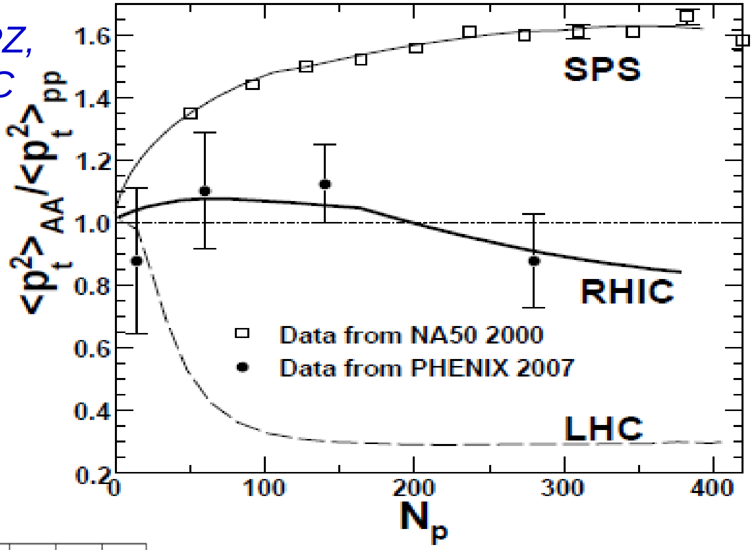
*shadowing effect in initial distribution

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

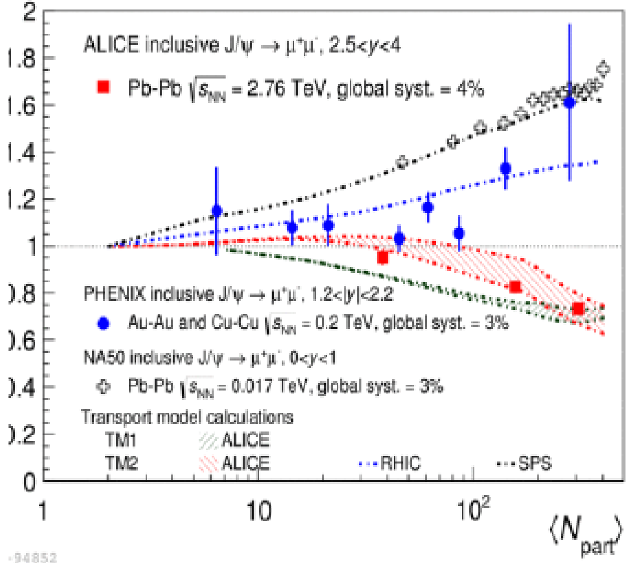
J/ψ Transverse Momentum Distributions in A+A

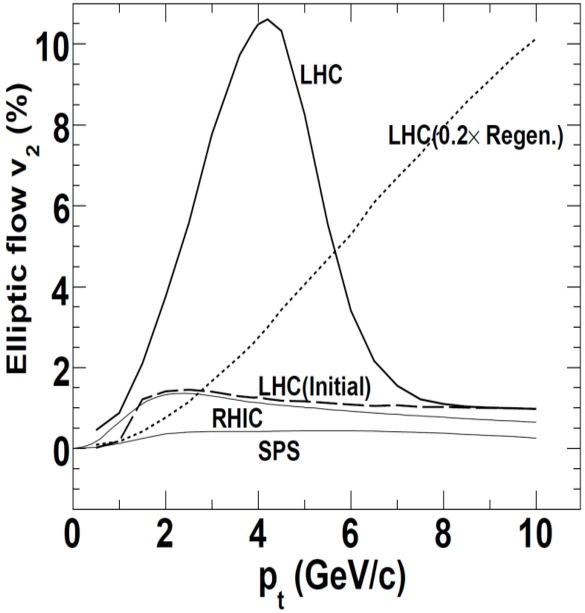
K.Zhou, N.Xu, and PZ, NPA834 (2010) 249C

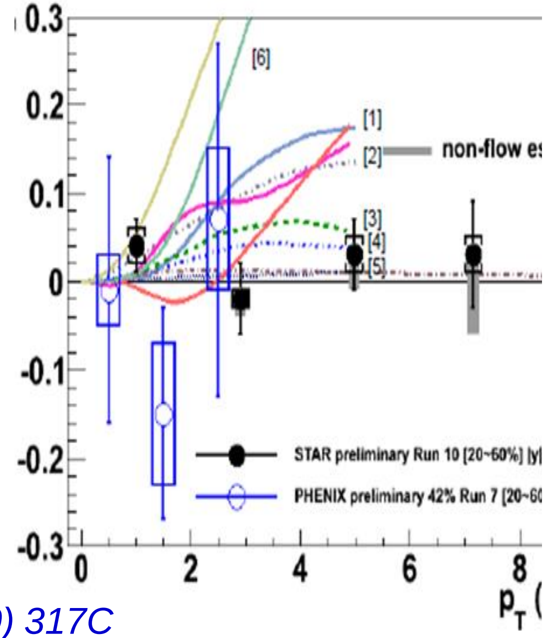
$$r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$$

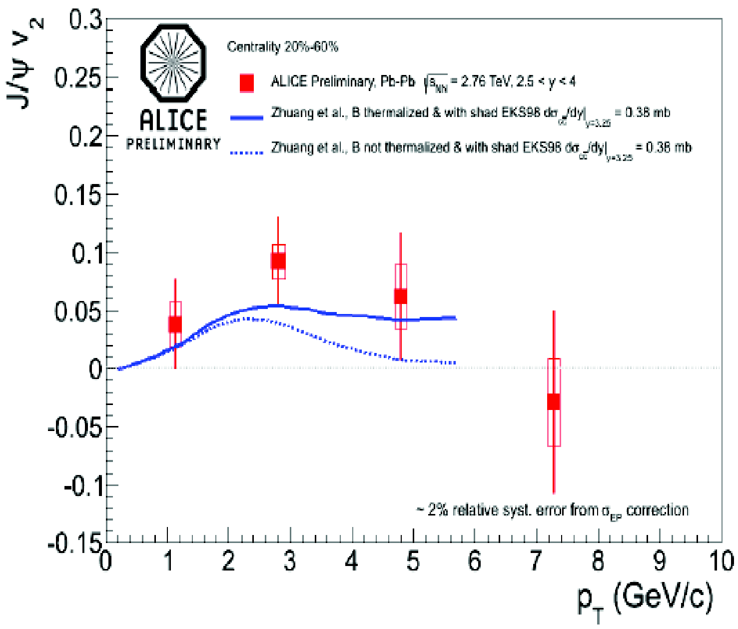


arXiv:1506.08804 [nucl-ex]





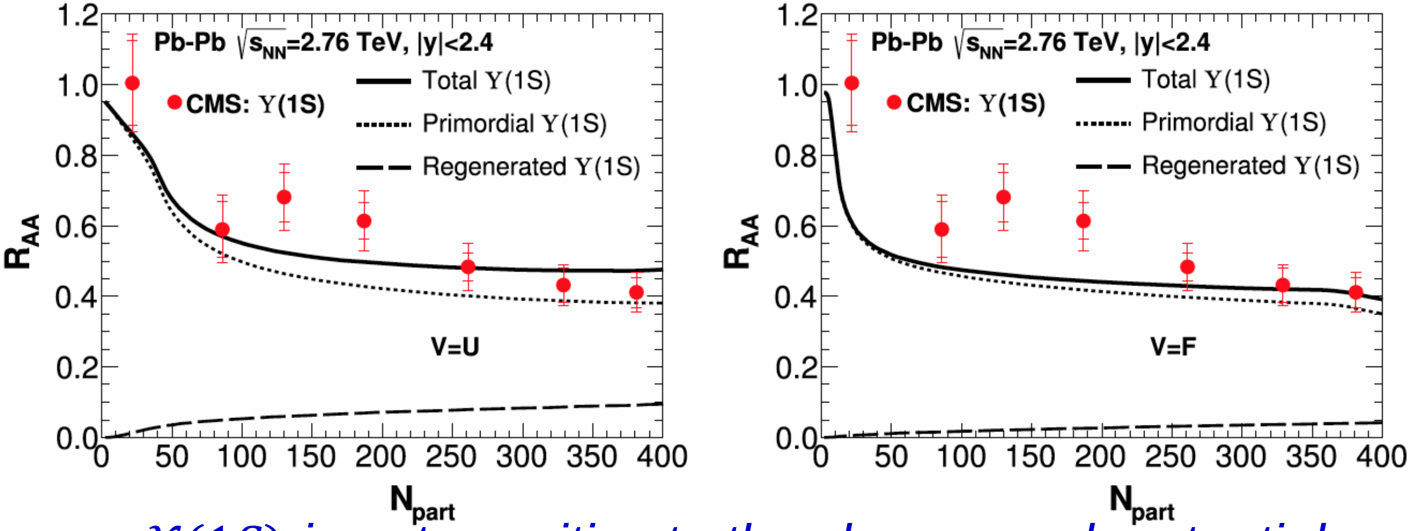




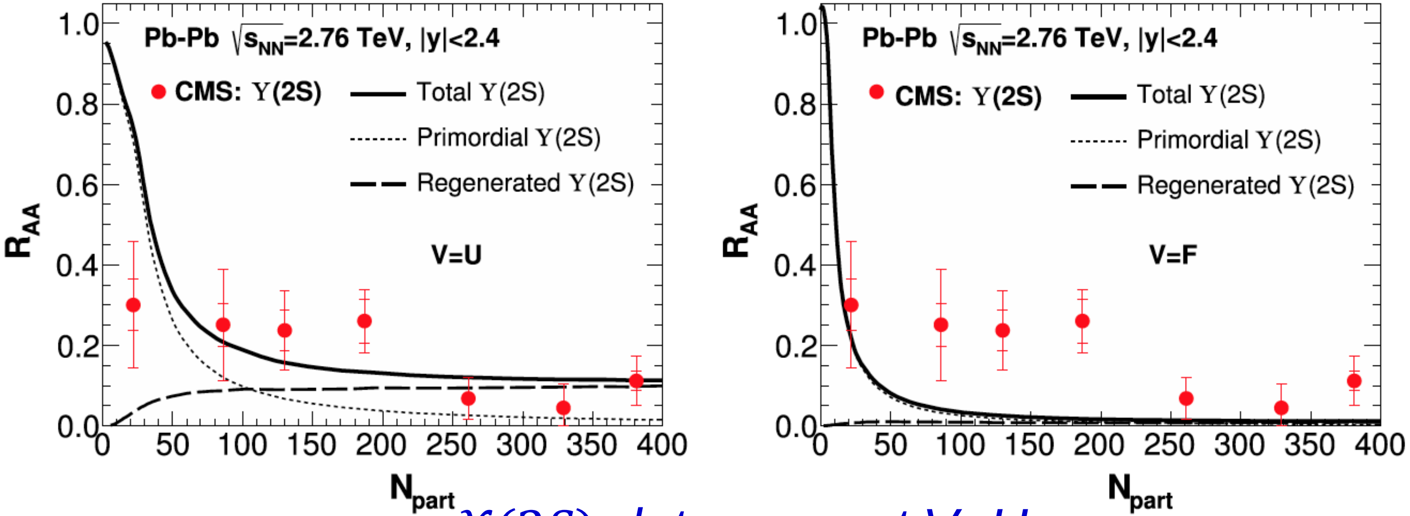
Y.Liu, N.Xu, and PZ, NPA834 (2010) 317C

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.



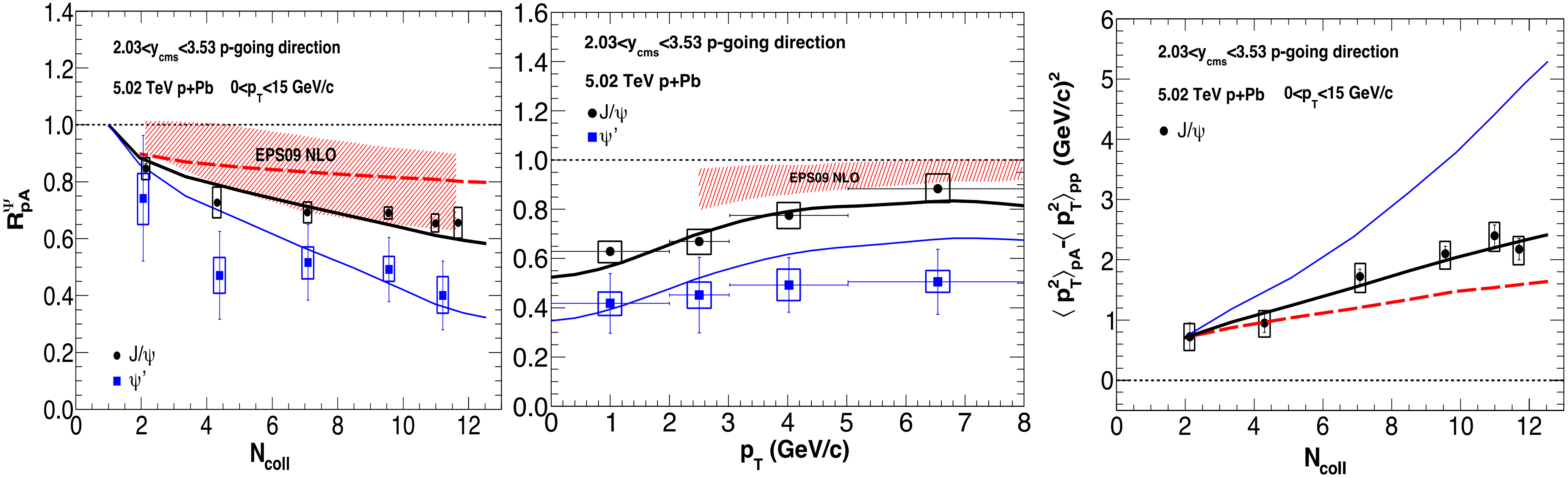
$\Upsilon(2S)$ data support V=U.

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

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

Initial fireball temperature

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

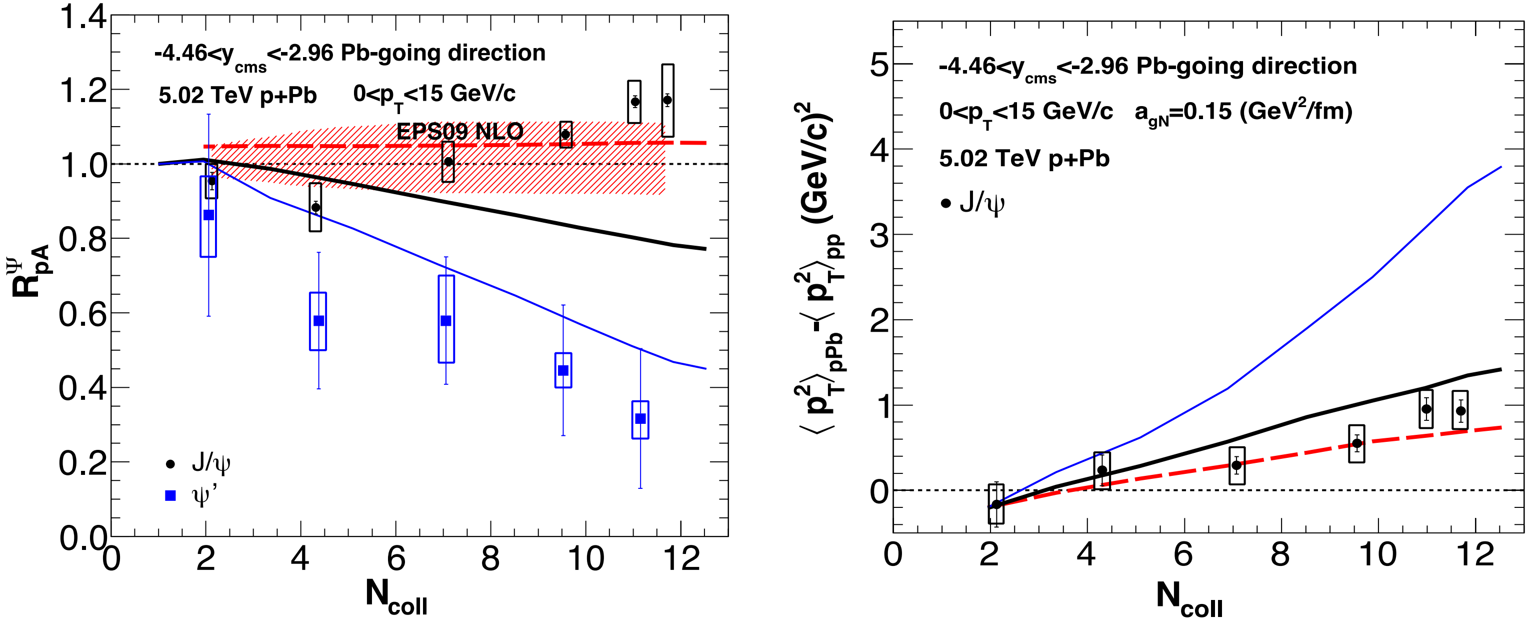


1) Cold + Hot medium effects work well at forward rapidity.

2) Very strong p_T broadening for 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

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

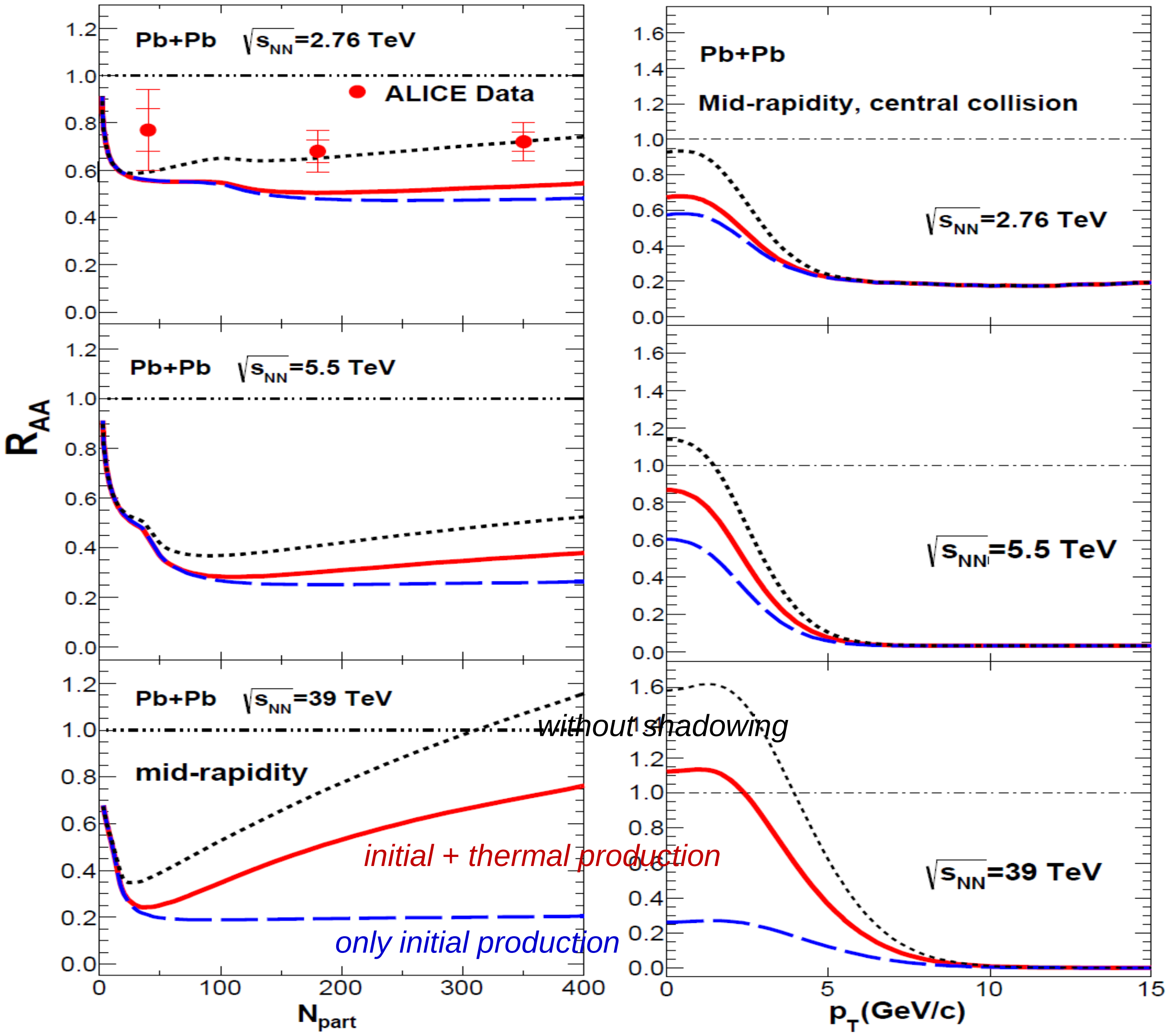


Cold + Hot medium effects can not reproduce simultaneously the J/ψ yield and p_T enhancement, there is something new at backward rapidity.

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



without shadowing

initial + thermal production

only initial production

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 pt broadening at SPS to pt 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:

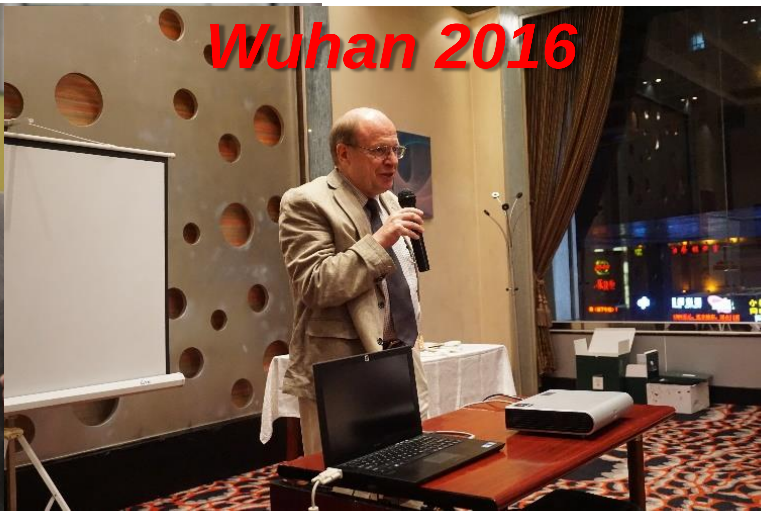
   $T_{\psi'} < T < T_{J/\psi}$.

3) Charm quark thermal production changes significantly the J/ψ yield,

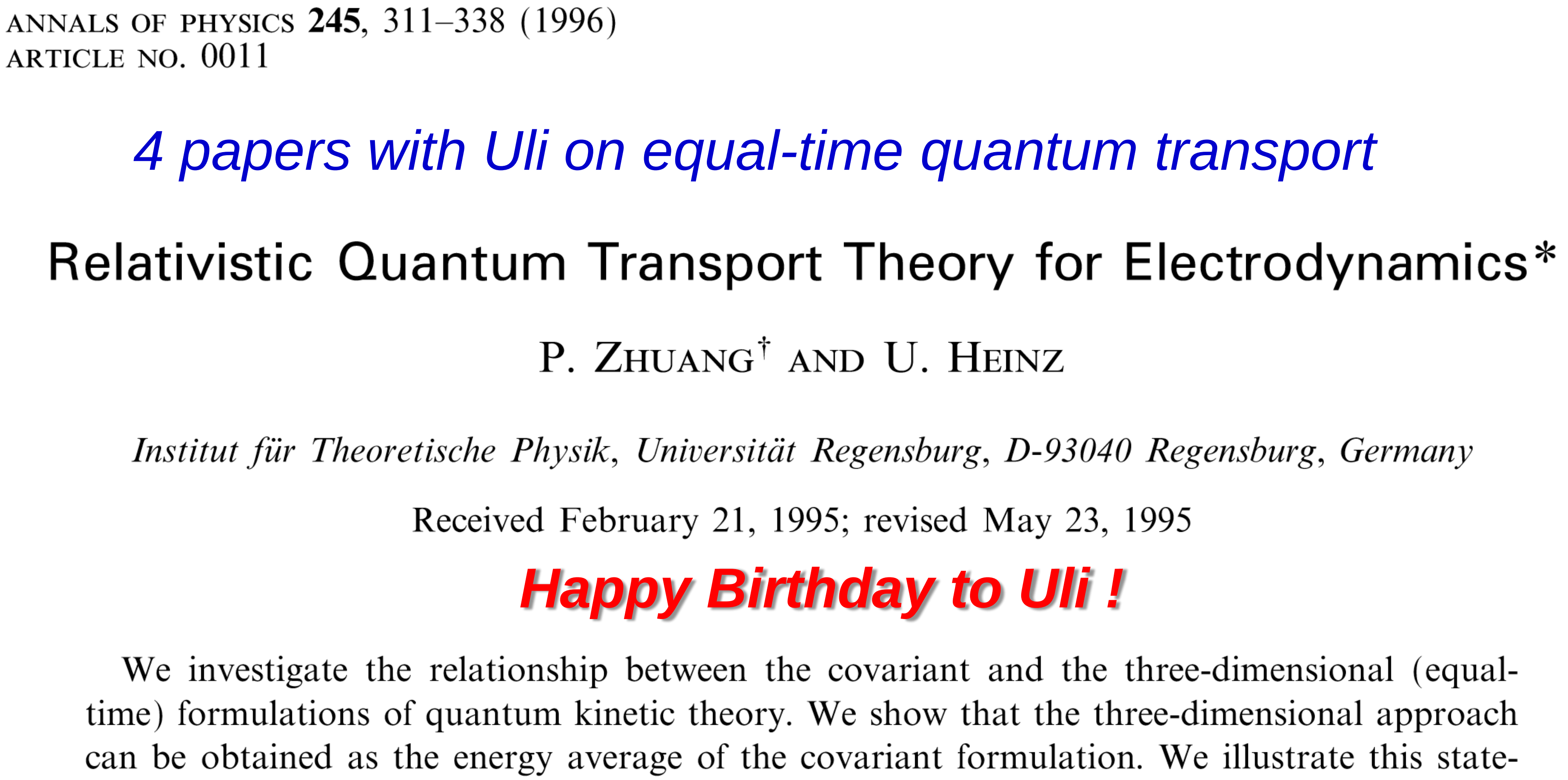
   from $R_{AA} < 1$ $at\ SPS, RHIC, LHC\ to$ $R_{AA} > 1$ $at\ FCC.$

4) Still some puzzles, like backward rapidity in p+A, double ratio ψ'/ψ in A+A, and excess of low p_t J/ψ in peripheral A+A.

Kobe 2015



Wuhan 2016



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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-