$\psi(2S)$ production at energies available at LHC

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Outline

1. Introduce the time-dependent Schrodinger equation
2. Heavy quark potential at finite temperature
3. **$\mathbf{c}\bar{\boldsymbol{c}}$ dipole evolution in the Static medium**
    1). Testing codes
    2). A $\mathbf{c}\bar{\boldsymbol{c}}$ dipole evolution in the Static medium
    3). $R_{AA}(2S)/R_{AA}\ (1S)$ evolution in the Static medium
4. **Applying to Heavy ion collisions**
    1). Hydro profile: important for the transitions between Eigenstates
    2). The evolution of $c\bar{c}$ dipoles in heavy ion collisions
5. Summary

Experimental data

Strong enhancement of prompt $\psi(2S)$ production at middle pT bin: 3<pT<30 GeV/c

X. Du, R. Rapp, 15'

(uncorrelated $c\bar{c}$)

$$c + \bar{c} \longrightarrow \psi(2S)$$

regeneration (Coalescence)

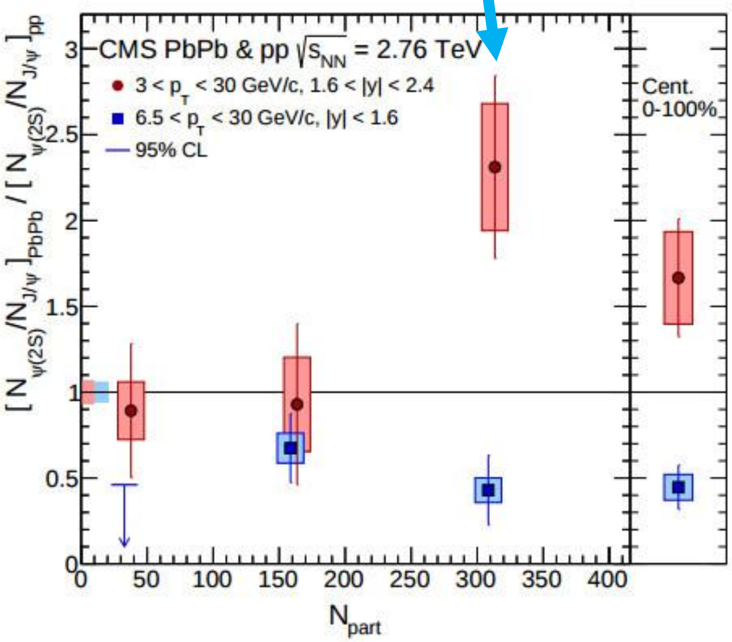
(Explain the data well)

?

(correlated $c\bar{c}$)

$$c\bar{c}(J/\psi) \longrightarrow \psi(2S)$$

Formation process



$R_{AA}(2S)/R_{AA}(1S)$

CMS, PRL113 (2014) no.26, 262301

Time-dependent Schrodinger equation

Radial Schrodinger equation:

$$i\hbar\frac{\partial}{\partial t}\psi(r,t) = [-\frac{\hbar^2}{2m_\mu}\nabla^2 + V(r,t)]\psi(r,t)$$

r: relative distance between c and $\bar{c}$

$m_\mu = m_c/2$: scaling mass

$$\frac{\psi(r,t)}{r} = \sum_m c_m(t)e^{-iE_m t}R_{mS}(r)$$

Wavefunction of eigenstates:

$$\Psi_{klm}(\vec{r}) = R_{kl}(r)Y_{lm}(\theta,\varphi)$$

Numerical form:

$$i\frac{\psi_j^{n+1}-\psi_j^n}{\Delta t} = \frac{1}{2}[-\frac{1}{2m_\mu}\frac{\psi_{j+1}^n - 2\psi_j^n + \psi_{j-1}^n}{(\Delta x)^2} + V_j^n\psi_j^n - \frac{1}{2m_\mu}\frac{\psi_{j+1}^{n+1} - 2\psi_j^{n+1} + \psi_{j-1}^{n+1}}{(\Delta x)^2} + V_j^{n+1}\psi_j^{n+1}]$$

n: time point; t= $t_0 + n\cdot\Delta t$ Δt: step of the time

j: coordinate point; $r = r_0 + j\cdot\Delta r$ Δr: step of the radius

Time-dependent Schrodinger equation

Simplify the numerical form as:

$$\begin{pmatrix} \mathbf{T}_{0,0}^{n+1} & \mathbf{T}_{0,1}^{n+1} & 0 & 0 & \cdots \\ \mathbf{T}_{1,0}^{n+1} & \mathbf{T}_{1,1}^{n+1} & \mathbf{T}_{1,2}^{n+1} & 0 & \cdots \\ 0 & \mathbf{T}_{2,1}^{n+1} & \mathbf{T}_{2,2}^{n+1} & \mathbf{T}_{2,3}^{n+1} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \psi_0^{n+1} \\ \psi_1^{n+1} \\ \psi_2^{n+1} \\ \psi_3^{n+1} \\ \cdots \end{pmatrix} = \begin{pmatrix} \Gamma_0^n \\ \Gamma_1^n \\ \Gamma_2^n \\ \Gamma_3^n \\ \cdots \end{pmatrix}$$

Matrix elements:

$$\mathbf{T}_{j,j}^{n+1} = 2 + 2a + bV_j^{n+1}$$
$$\mathbf{T}_{j,j+1}^{n+1} = \mathbf{T}_{j+1,j}^{n+1} = -a$$

$$a = i\,\Delta t/(2m_\mu(\Delta r)^2)$$
b= $i\Delta t$

Coefficient of each eigenstate:

$$c_{mS}(t) = \langle R_{mS}(r)|\frac{\psi(r,t)}{r}\rangle = \int R_{mS}(r)\psi(r,t)\cdot r dr$$

At each time step, the fraction of mS (m=0,1,..) eigenstate in a $\boldsymbol{c\bar{c}}$ dipole $=|c_{\mathrm{mS}}(t)|^2$

Initialization of $c\bar{c}$ wavefunction

1) Gaussian wave: $$\phi_0(r) = Ae^{\frac{-r^2}{2\sigma_0^2}}$$

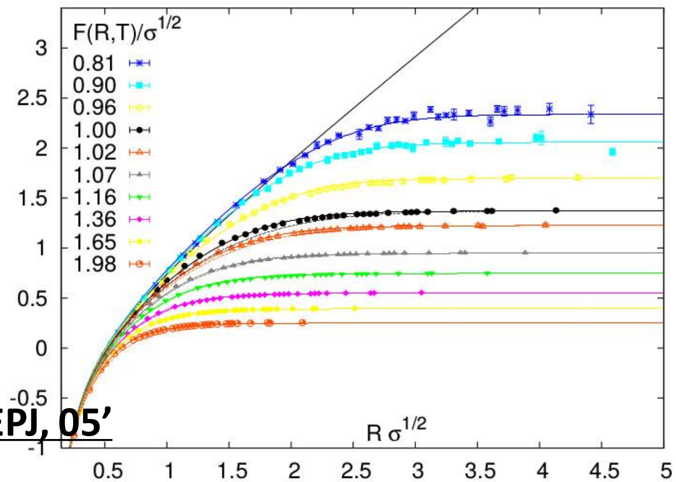
fixed by pp data

$$\int dr \cdot r^2 |\phi_0\ (r)|^2 = 1$$

$$A = \frac{2}{\pi^{1/4}\sigma_0^{3/2}}$$

2) Heavy quark potential :

<u>Real part:</u>
<u>(Lattice)</u>



<u>S.Digal, et al, EPJ, 05'</u>

<u>imaginary part(HTL):</u>

$$\mathbf{Im}V(r) = -\frac{g^2 C_F T}{4\pi}\widetilde{f}(\hat{r})$$

$$\widetilde{f}(\hat{r}) = 2\int_0^{\infty} dz \frac{z}{(z^2+1)^2}[1 - \frac{\sin(z\hat{r})}{z\hat{r}}]$$

<u>M. Strickland, PRD, 09'</u>

$V = F$

$V = U = F + T(-\partial F/\partial T)$

Pre-equilibrium

QGP evolution (hydro)

time

$V_{c\bar{c}}(r) = Cornell$

$\tau = 0$
(Pb-Pb)

τ_0
(input)

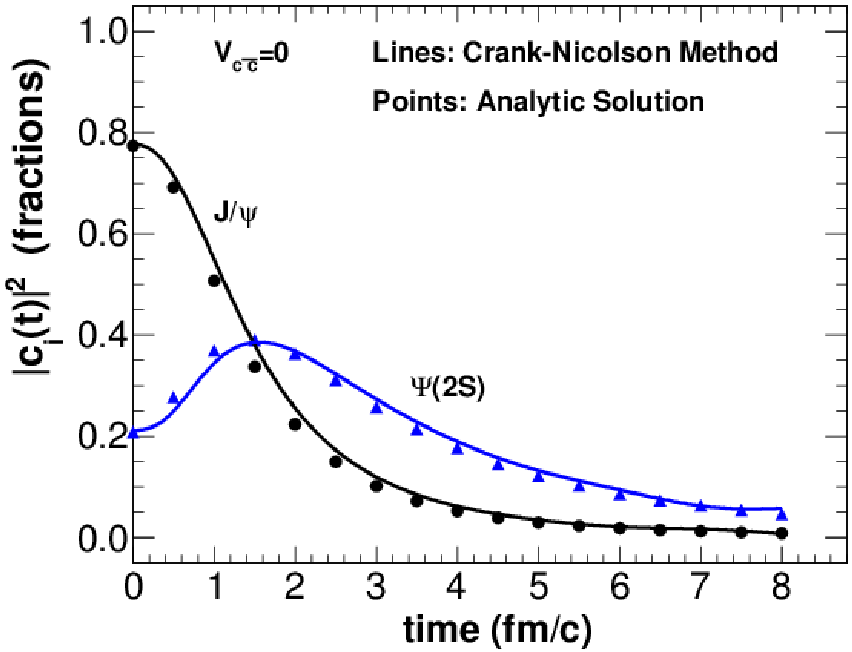
Initial Gaussian width (pp data)

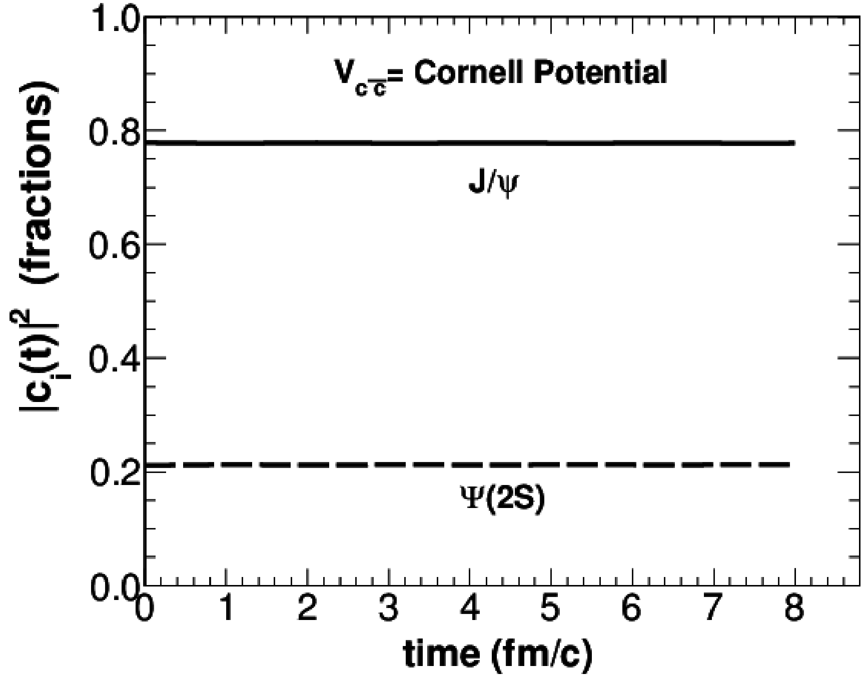
$V_{c\bar{c}}(r,T) = Lattice\ (F,U)$

Time-dependent Schrodinger equation

Testing codes

Evolutions of one $c\bar{c}$ with different potential





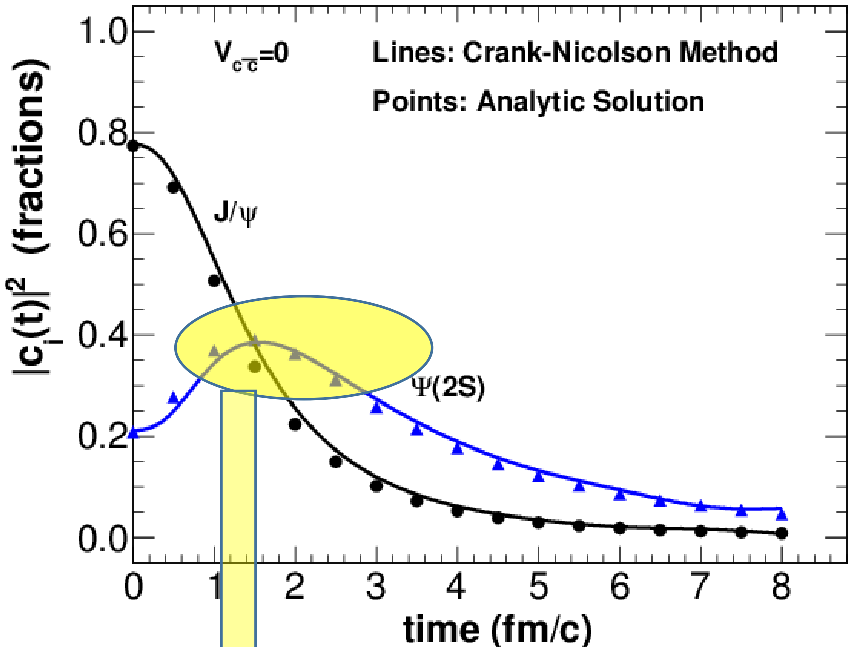
$V_{c\bar{c}}(r) = 0$

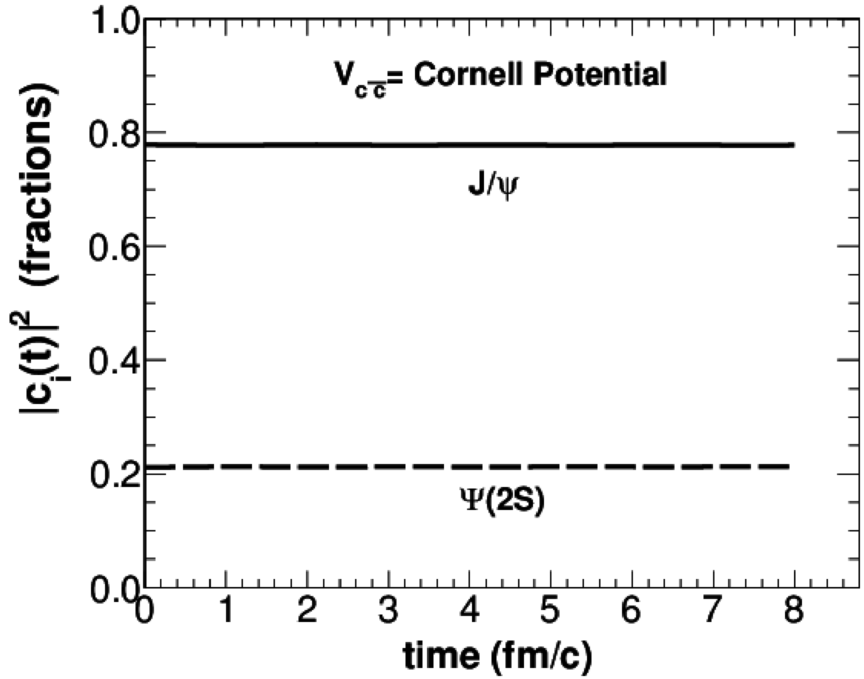
$V_{c\bar{c}}(r) =$ **Cornell Potential**

Numerical evolutions are reliable.

Testing codes

Evolutions of one $c\bar{c}$ with different potential





$V_{c\bar{c}}(r) = 0$

$V_{c\bar{c}}(r) =$ **Cornell Potential**

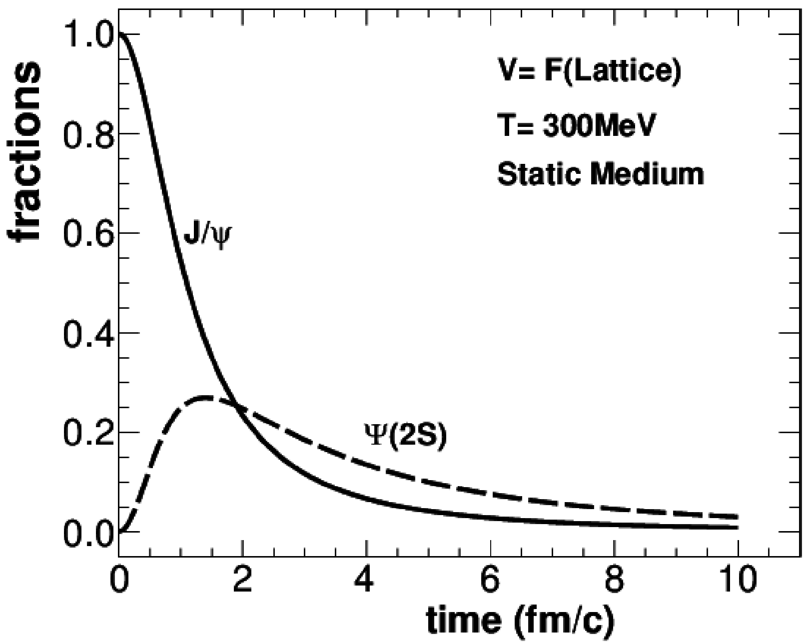
With weak potential, the $c\bar{c}$ dipole becomes a loosely bound dipole, its wavefunction expands outside.

the overlap between $\boldsymbol{\psi_{c\bar{c}}}(\mathrm{r},\mathrm{t})$ and $\boldsymbol{\Psi(2S)}$ increase at first, then decrease

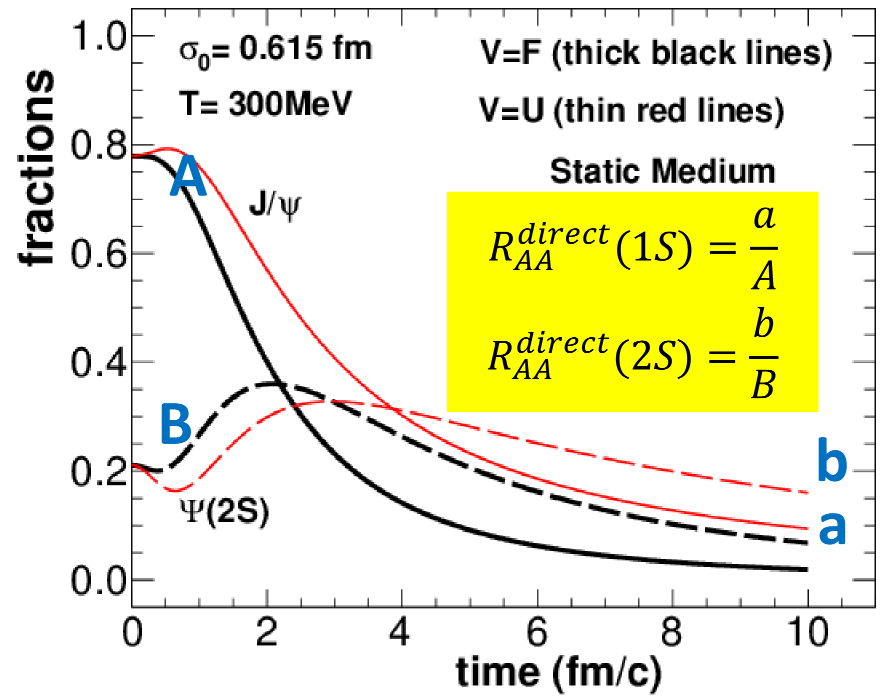
<u>This behavior depends on the initial shape of the $c\bar{c}$ dipole</u>

Evolutions of $c\bar{c}$ in the Static Medium

Prompt yield: direct yield(60%) + decay from excited states(1P:30%, 2S:10%)



J/ψ survival probability



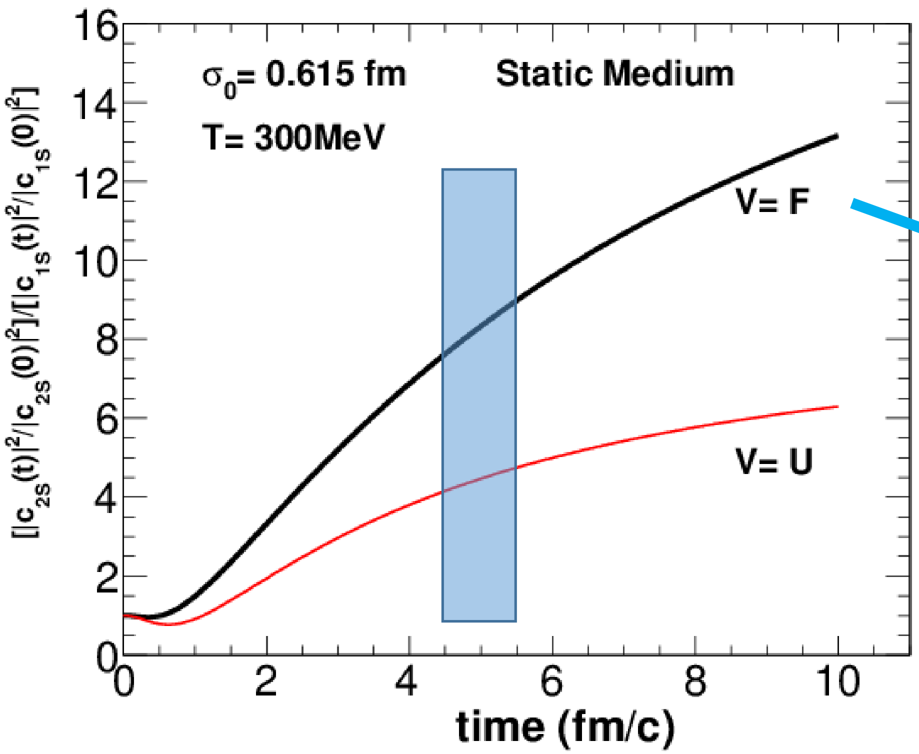
Fit the ratio of charmonium yields in pp collisions:

$$N_{2S}^{direct}/N_{1S}^{direct} = 0.6/(0.1/f^{2S\rightarrow 1S})$$

Initial Gaussian width $\rightarrow$ $\sigma_0 = 0.615$ fm

Evolutions of $c\bar{c}$ in the Static Medium

Double ratio in the static medium, with Lattice potential.



$$\frac{R_{AA}^{direct}(2S)}{R_{AA}^{direct}(1S)}$$

- With weaker potential , the wavefunction of $c\bar{c}$ dipole expand outside more easily.
- Color screening effect enhance the RAA of 2S and the double ratio

Considering the size of QGP, and the velocity of $c\bar{c}$ dipoles, most of $c\bar{c}$ dipoles can move out of QGP at $\tau \sim 5fm/c$

Stay longer in QGP → Smaller RAA of 1S, Larger double ratio (2S/1S)

Generating $c\bar{c}$ dipoles in Pb-Pb

1. Generating $c\bar{c}$ dipoles in momentum space,

Assuming that the momentum distribution of the center of $c\bar{c}$ dipoles is similar to the momentum distribution of J/ψ, then we can generate the $c\bar{c}$ dipoles based on the relative probabilities ,

$$\boxed{F_{c\bar{c}}^{pp}(p_T, y) = p_T f_\Psi^{\mathrm{Norm}}(p_T|y) \cdot \frac{d\sigma_\Psi^{pp}/dy(y)}{d\sigma_\Psi^{pp}/dy(y=0)}}$$

2. Generating $c\bar{c}$ dipoles in coordinate space,

$$\boxed{F_{c\bar{c}}^{PbPb}(\mathbf{x}_T|\mathbf{b}) = \frac{T_{Pb}(\mathbf{x}_T)T_{Pb}(\mathbf{x}_T - \mathbf{b})}{T_{Pb}(0)T_{Pb}(0)}}$$

The distribution of $c\bar{c}$ dipoles in full space,

$$n_{c\bar{c}}(\mathbf{x}_T, p_T|\mathbf{b}, y) = n_0 \times F_{c\bar{c}}^{PbPb}(\mathbf{x}_T|\mathbf{b}) \times F_{c\bar{c}}^{pp}(p_T, y) \times \mathcal{R}^{Pb}(x_1, Q^2, \mathbf{x}_T)\mathcal{R}^{Pb}(x_2, Q^2, \mathbf{x}_T - \mathbf{b})$$

n_0: constant ($c\bar{c}$ events)

Shadowing effect from EPS09 NLO

Generating $c\bar{c}$ dipoles in Pb-Pb

The initial yields of charmonium eigenstates

$$n_{mS}^{t=0}(\mathbf{x}_T, p_T|\mathbf{b}, y) = n_{c\bar{c}}(\mathbf{x}_T, p_T|\mathbf{b}) \times |\langle R_{mS}(r)|\phi_0(r)\rangle|^2$$

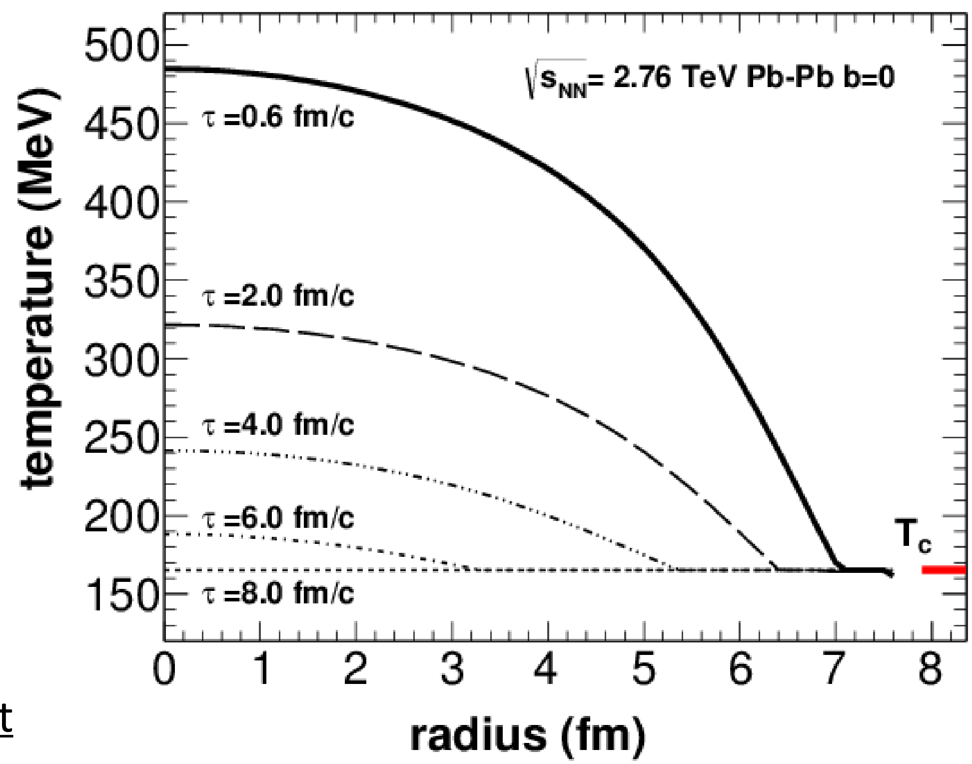
$$|c_{mS}(t=0|\mathbf{b})|^2 = \int d\mathbf{x}_T \int_{p_{T1}}^{p_{T2}} dp_T \; n_{mS}(\mathbf{x}_T, p_T|\mathbf{b})$$

1). $c\bar{c}$ dipoles move inside QGP,

$$\mathbf{R}_{c\bar{c}}(\tau + \Delta\tau) = \mathbf{R}_{c\bar{c}} + \mathbf{v}_{c\bar{c}} \cdot \Delta\tau$$

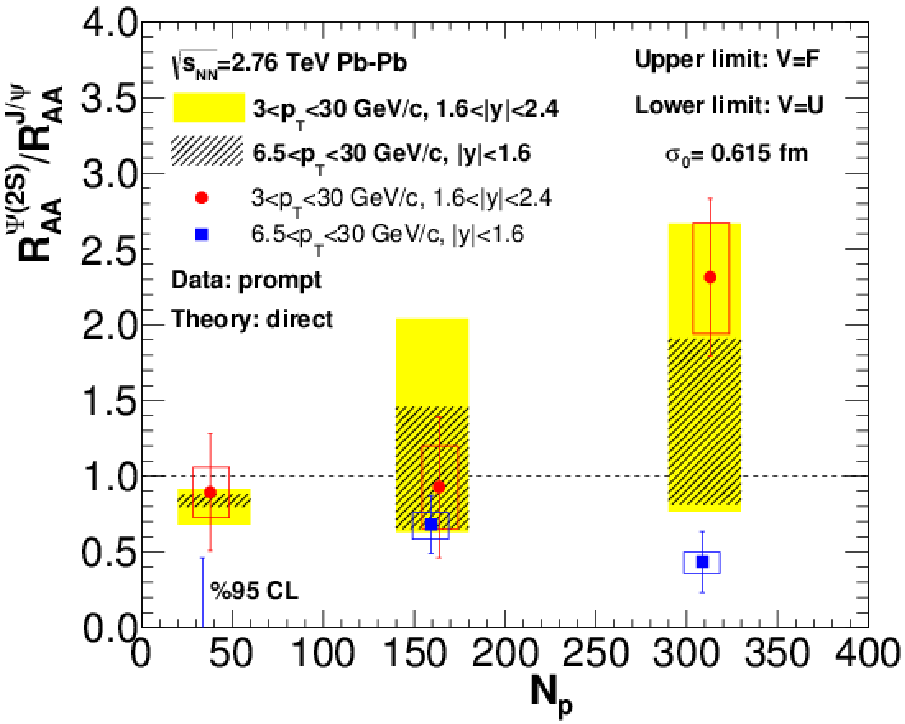
2). During each time step, wavefunctions of $c\bar{c}$ dipoles are evolved with the Schrodinger equation.

<u>At different (τ, $R_{c\bar{c}}$),
the temperature of QGP is different</u>



$R_{AA}(2S)/R_{AA}(1S)$ in Pb-Pb

Double ratio of direct 1S and 2S states,



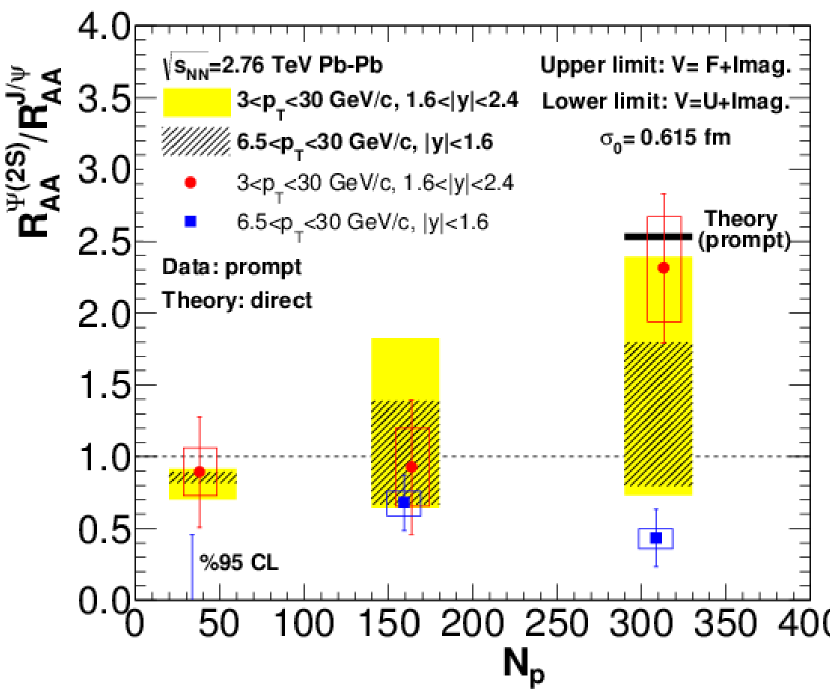
Real potential
(without imaginary part)

- Yellow region → red data points (3<pT<30 GeV/c)
- Shadowing region →blue data points (6.5<pT<30 GeV/c)

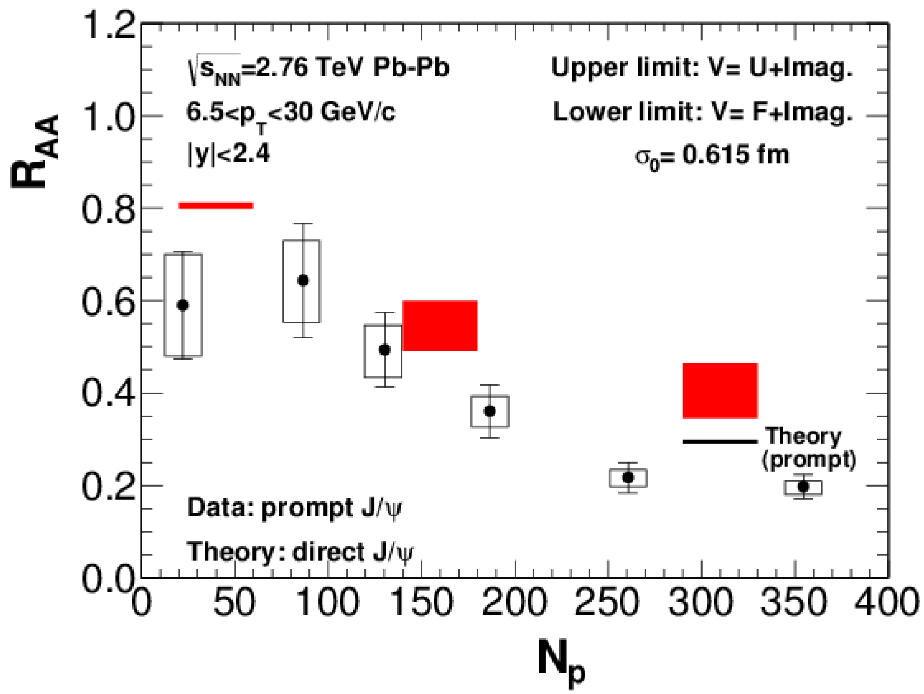
- **High pt region:** move out of QGP quickly.
- **Middle pt region:** stay longer in QGP
- **Low pt region:** regeneration will increase the yield of J/psi by ~10 times.
  regeneration of J/psi pull down the double ratio,
  color screening effect increases the double ratio.
  → difficult to draw a conclusion at this pT bin

$R_{AA}(2S)/R_{AA}(1S)$ in Pb-Pb

Double ratio,



RAA（1S）



<u>6.5<pT<30 GeV/c</u>

<u>3.0<pT<30 GeV/c</u>

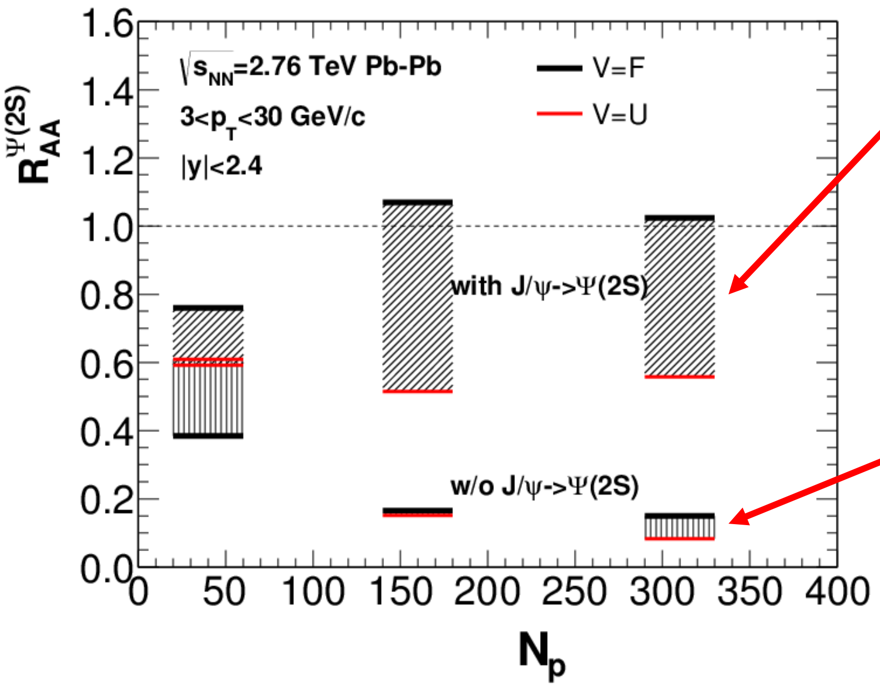
<u>6.5<pT<30 GeV/c</u>

<u>Both: Complex potential</u>

Black solid line: estimation of prompt value

Estimate prompt RAA

Nuclear modification factor of 2S



Initialize the wavefunction of $c\bar{c}$ dipole with **Gaussian function** (contains both 1S and 2S fractions)

Initialize the wavefunction of $c\bar{c}$ dipole with **2S eigenstate**

➢ **Estimate prompt value** at Np=320, (at pt: 3-30 GeV/c):

$$R_{AA}^{\text{prompt}}(J/\psi) = R_{AA}^{\text{direct}}(J/\psi) \times 0.6 + R_{AA}^{\text{direct}}(\chi_c) \times 0.3 + R_{AA}^{\text{direct}}(\Psi(2S)) \times 0.1$$

(We assume that the suppression of 1P eigenstates is similar to 2S eigenstate.)

Summary

- In QGP, color screening effect makes $c\bar{c}$ become a loosely bound dipole. This changes the yields of charmonium 1S and 2S states.
  The formation process is important for charmonium 2S eigenstate in heavy ion collisions.

- Predictions:
  Upsilon is a tightly bound state,
  at FCC (39TeV), the temperature of QGP is very high.
  Is there a similar phenomena for upsilon observables (1S,2S,3S) at FCC ? We are already working on this.

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part 2

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part 2

How to distinguish two mechanisms of $\psi(2S)$ production ?

(uncorrelated $c\bar{c}$)

$$\boldsymbol{c+\bar{c}\longrightarrow\psi(2S)}$$

regeneration (Coalescence)

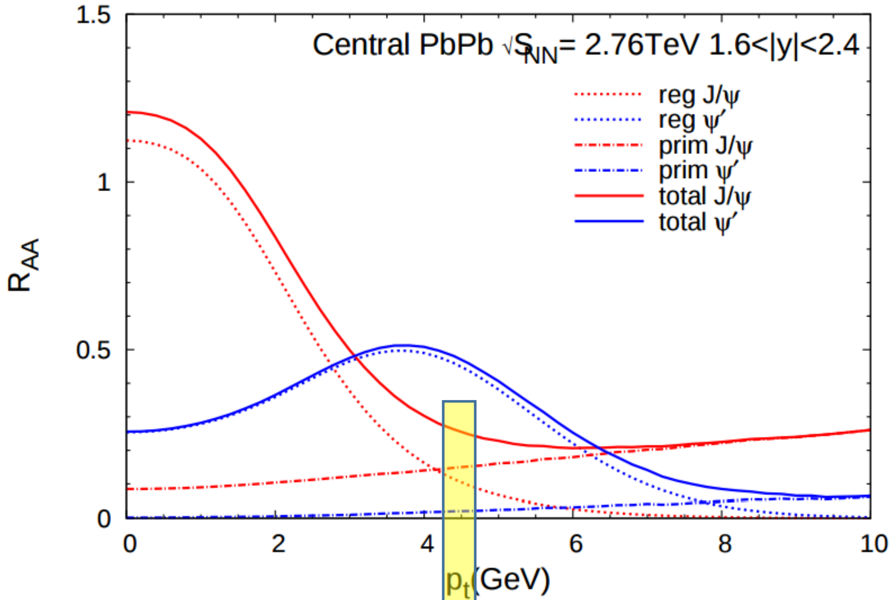
(correlated $c\bar{c}$)

$$\boldsymbol{c\bar{c}(J/\psi)\longrightarrow\psi(2S)}$$

transition (formation)

$\boldsymbol{v_2^{\psi(2S)}}$ $(\mathrm{p}_{\boldsymbol{T}})$ may be a sensitive probe for the psi(2S) production mechanisms.

Differenet mechanisms



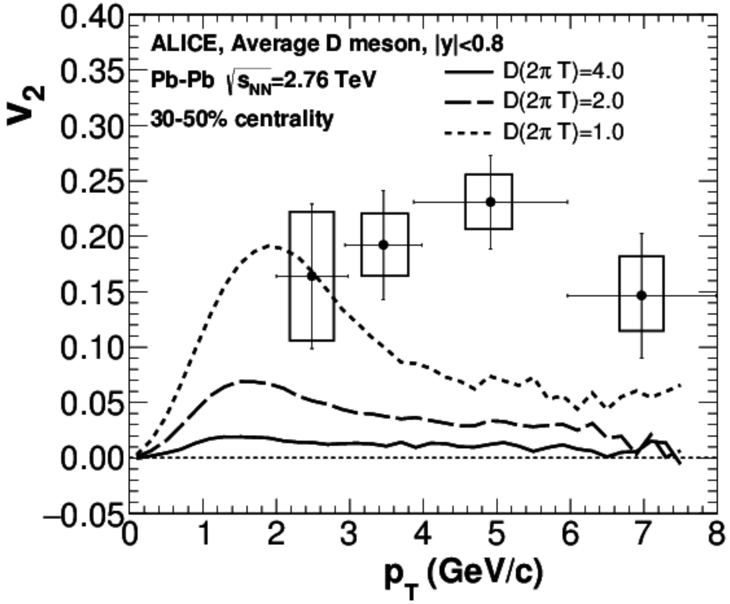
X. Du, R. Rapp, 16'

Sequential regeneration: almost all of the final psi(2S) are from the regeneration at T ~ Tc.

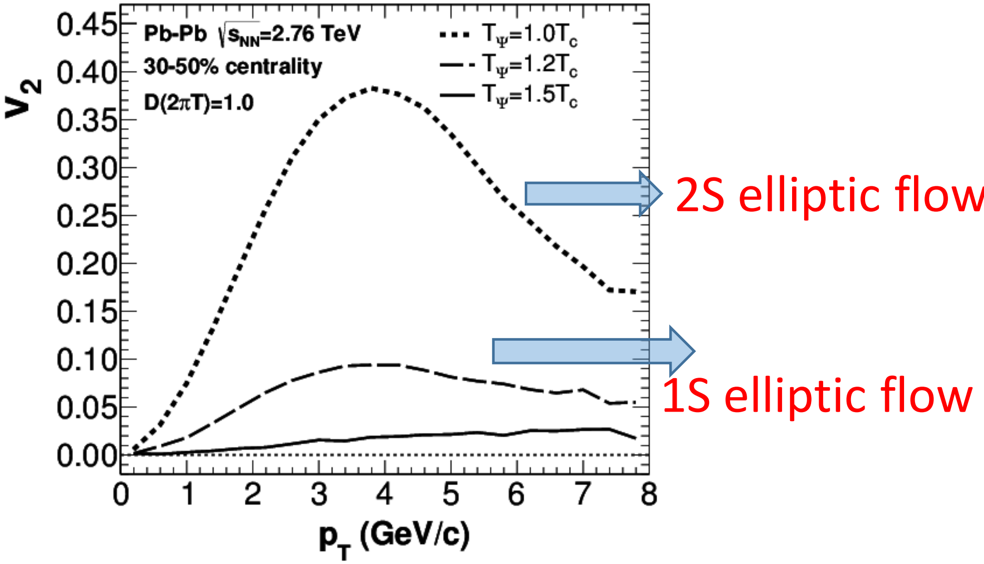
$$\boldsymbol{c\bar{c}(J/\psi) \longrightarrow \psi(2S)}$$

Psi(2S) are mainly from the initially produced $\boldsymbol{c\bar{c}}$ dipole

Charm elliptic flow



Charm quarks



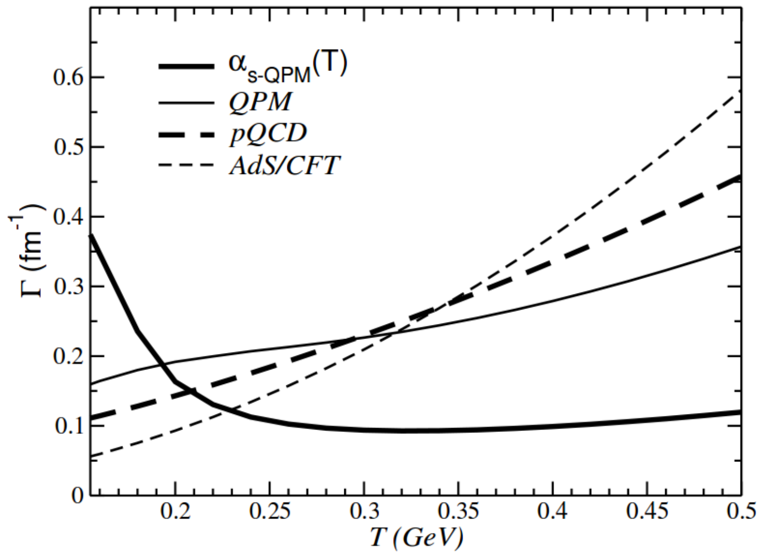
Regenerated charmonium

Quark number scaling: $v_2^{\psi}(pT) = 2v_2^{c}(pT/2)$

- Elliptic flow of charm quarks are mainly developed at the Later stage of QGP evolution. Charmonium produced at later stage will carry larger v2.
- Coalescence or fragmentation process will change the v2 of charm quarks by 20% around.

Summary 2:

1. With different drag coefficient, **<u>the relation between elliptic flows of 1S and 2S do not change.</u>**



S.K Das et al, arXiv: 1502.03757

Different drag coefficient

backup

H. Satz, JPG 06'

Cornell potential : $$V_{\text{Cornell}}(r) = \begin{cases} -\frac{\alpha}{r} + \sigma r & r < r_{D\bar{D}} \\ 2m_D - 2m_c & r \geq r_{D\bar{D}} \end{cases}$$

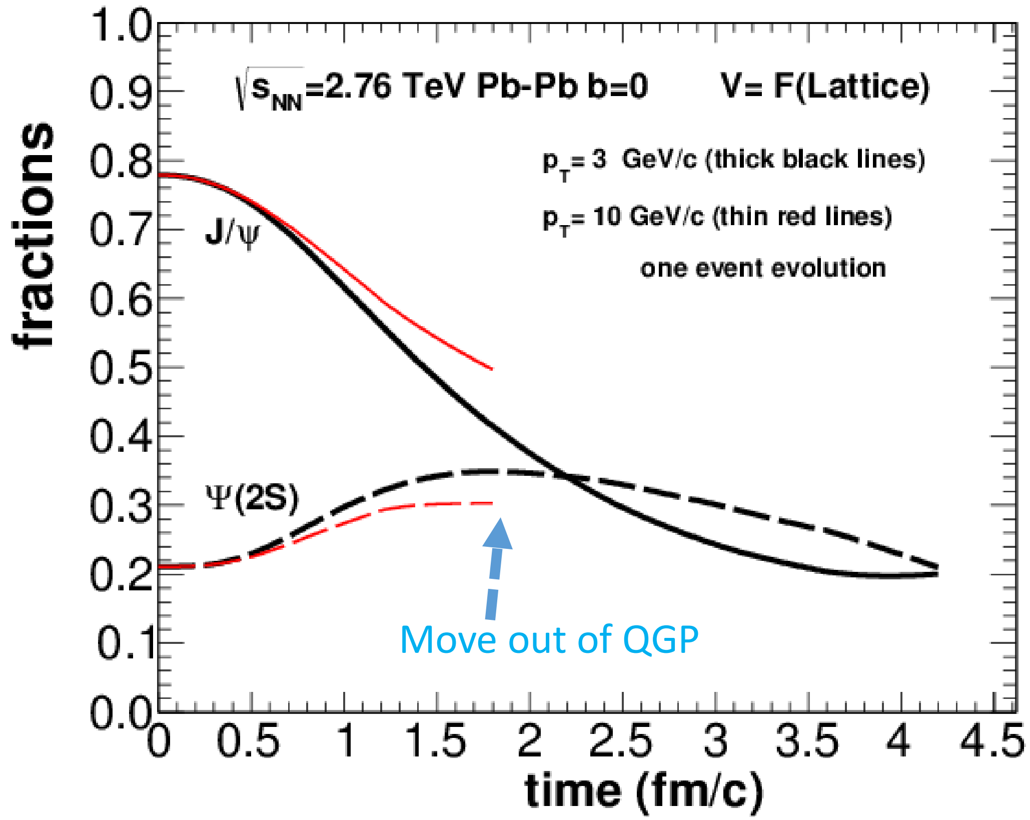
$$\alpha = \pi/12$$
$$\sigma = 0.2\ GeV^2$$

- **Estimate prompt value** at Np=320, (at pt: 3-30 GeV/c):

RAA(1S)(direct) = 0.16
RAA(2S)(direct) = 0.38
RAA(1p)(direct) = 0.056

One $c\bar{c}$ evolution in Pb-Pb

One $c\bar{c}$ dipole evolution in Pb-Pb, it is produced at the center of QGP



Expanding QGP

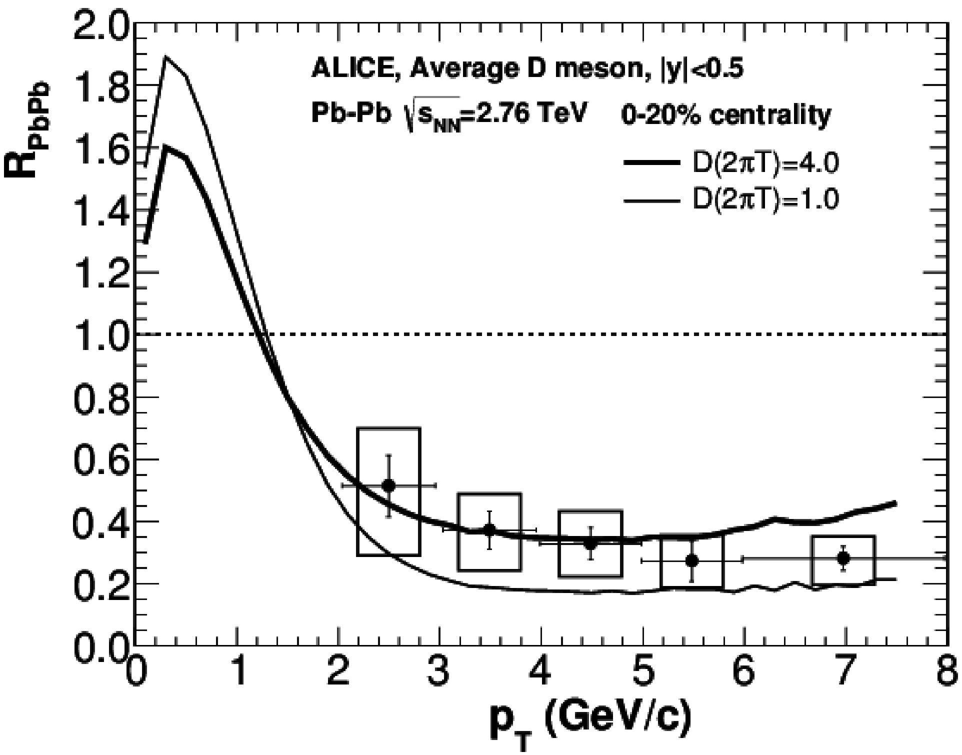
We want to explain the yields of 2S states in the momentum region: **3-30 GeV/c**, and **6.5-30 GeV/c**.

We choose two typical values of momentum (the center of the $c\bar{c}$ dipole)

Charm evolution

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

$$\eta_D(p) = \frac{\kappa}{2TE}$$



$$\langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$$

$$\eta_D(p) = \frac{\kappa}{2TE}$$

$$D = \frac{2T^2}{\kappa}$$

$$D = C/2\pi T$$

C: parameter,

Our values are similar to Guang-You Qing's

Initialization of $c\bar{c}$ wavefunction

Gaussian wave: $$\phi_0(r) = Ae^{\frac{-r^2}{2\sigma_0^2}}$$

given by pp data

$$\int dr \cdot r^2 |\phi_0\ (r)|^2 = 1$$

$$A = \frac{2}{\pi^{1/4}\sigma_0^{3/2}}$$

Heavy quark potential from Lattice Results:

Real part: $$F(T,r) = -\frac{\alpha}{r}e^{-\mu r} - \frac{\sigma}{2^{3/4}\Gamma[3/4]}(\frac{r}{\mu})^{1/2}K_{1/4}[(\mu r)^2]$$

imaginary part:

(HTL results)

$$\mathbf{Im}V(r) = -\frac{g^2 C_F T}{4\pi}\tilde{f}(\hat{r})$$

$$\tilde{f}(\hat{r}) = 2\int_0^\infty dz \frac{z}{(z^2+1)^2}[1 - \frac{\sin(z\hat{r})}{z\hat{r}}]$$

M. Strickland, PRD, 09'

The evolutions of $c\bar{c}$ dipoles with **real** and **complex** heavy quark potentials will be given respectively.