Quarkonium sequential suppression and heavy-quark potential in p-Pb and Pb-Pb

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Phys.Lett.B 839 (2023) 137774
Chin.Phys.C 46 (2022) 11, 114102

Outline

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1. **Introduction**

   heavy ion collisions & Schrodinger equation + complex V

2. **Wave functions of charmonium in p-Pb**

   Color screening

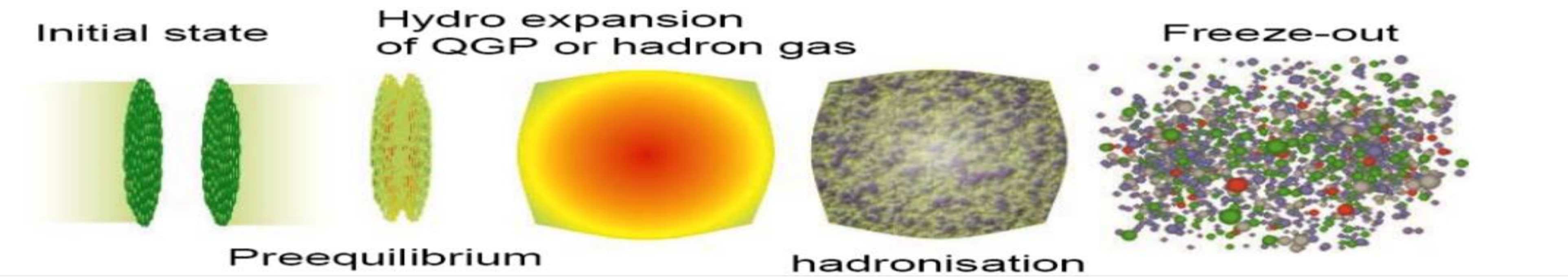
   parton inelastic scatterings (imaginary potential)

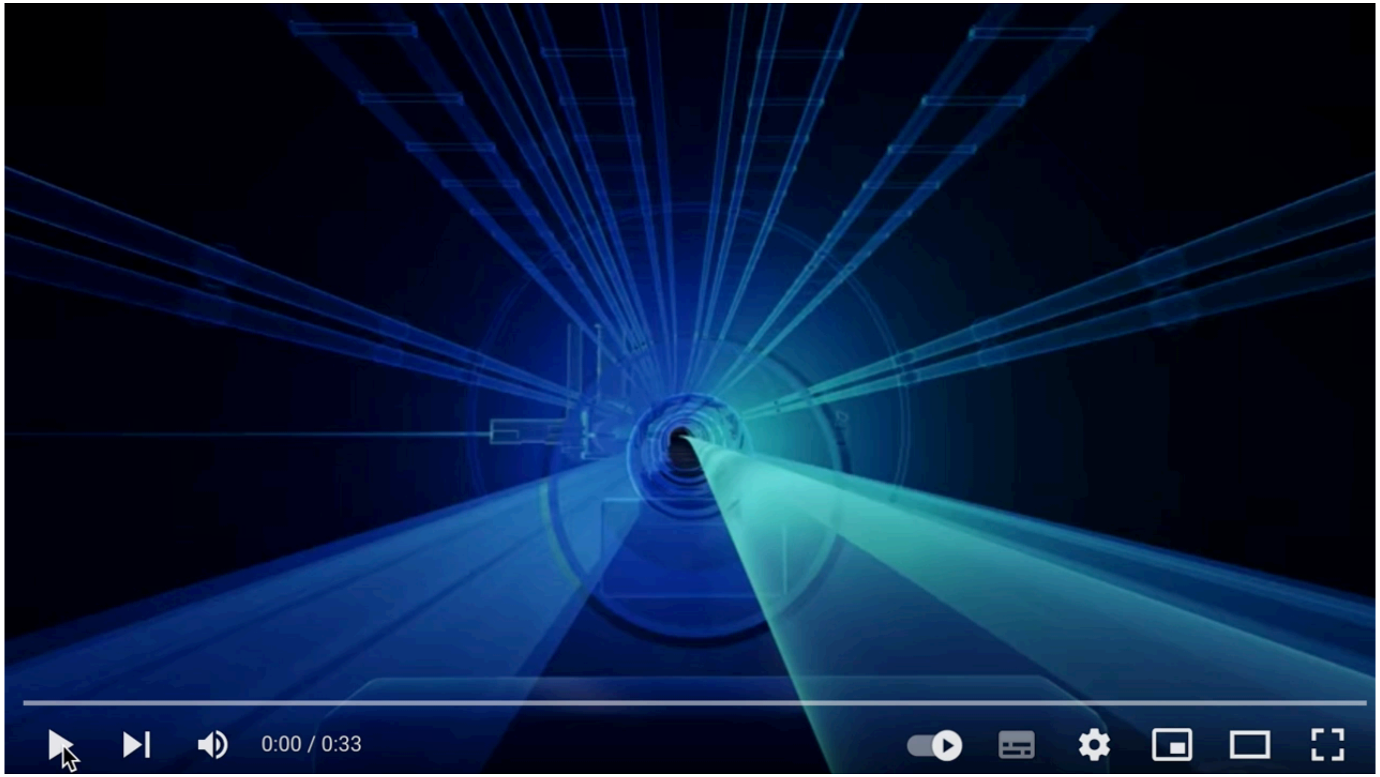
   R_{AA} **of** J/ψ **and** $\psi(2S)$

3. **Bottomonium (1S, 2S, 3S) in Pb-Pb**

4. **Summary**

outline


Initial state
Hydro expansion
of QGP or hadron gas
Freeze-out
Preequilibrium
hadronisation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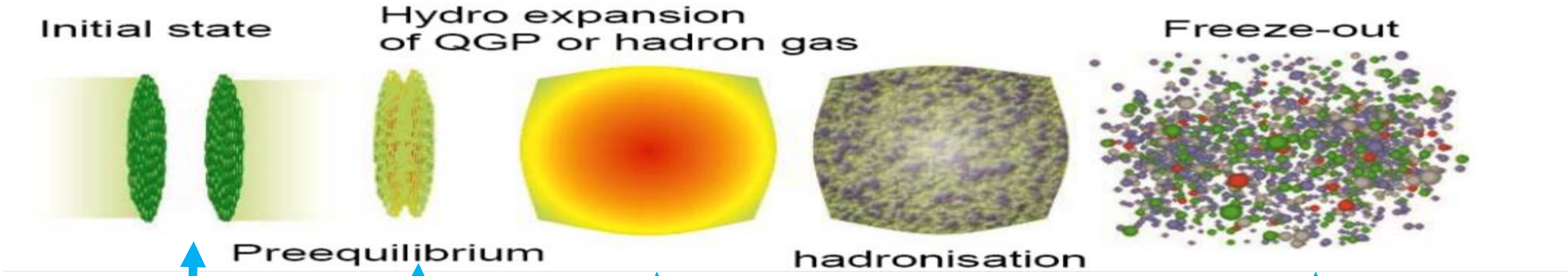
outline



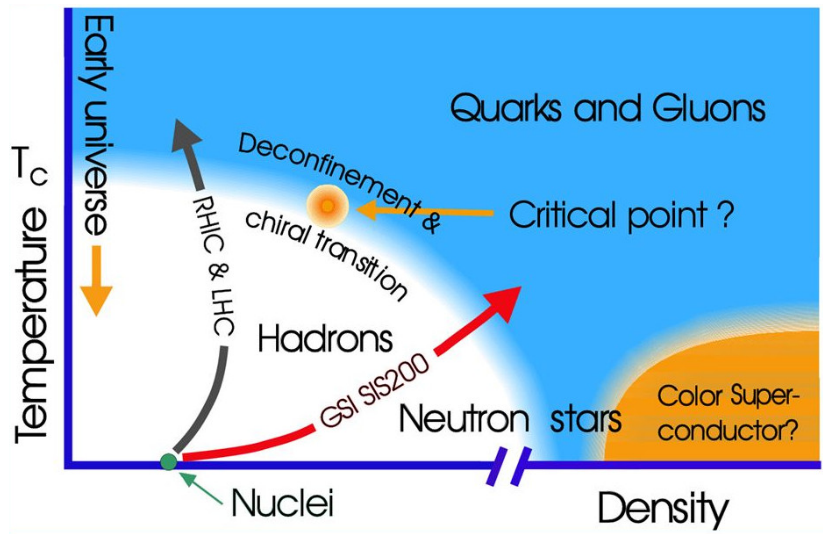
Lorentz contraction.
parton distribution at small x;
Strong EB fields;
etc;

Parton local equilibrium;
Initial energy fluctuations;

Hadron gas:
hadron inelastic scattering;
In-medium properties;

Chemical freeze out;
Kinetic freeze out;
etc;

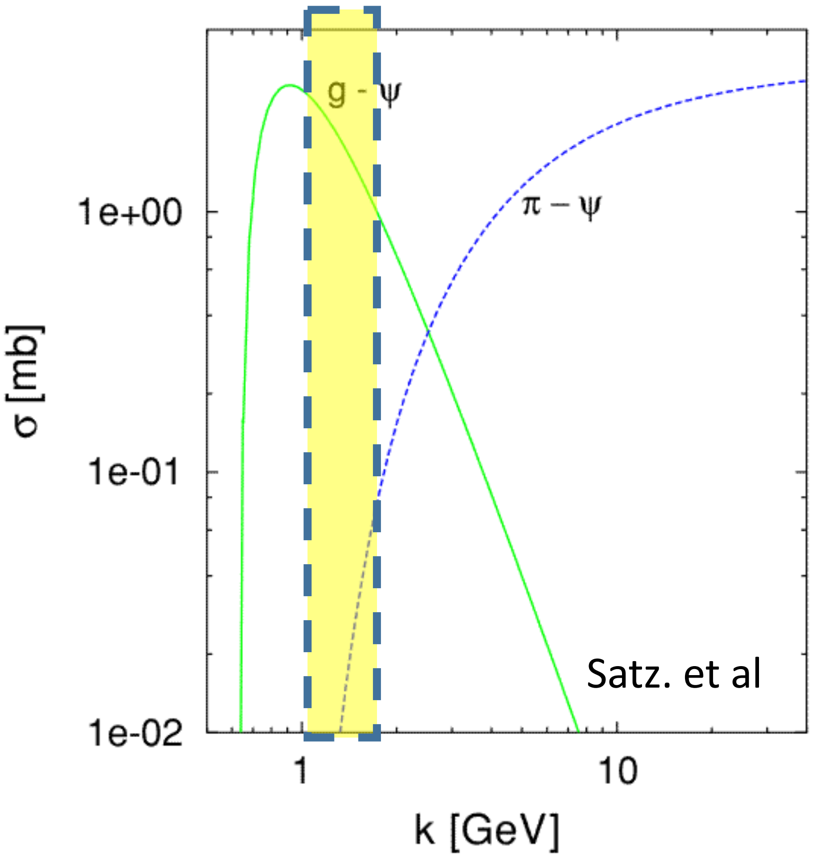
QGP collective expansion:
strong coupling system
transport coefficient
initial temperature
heavy quark potential

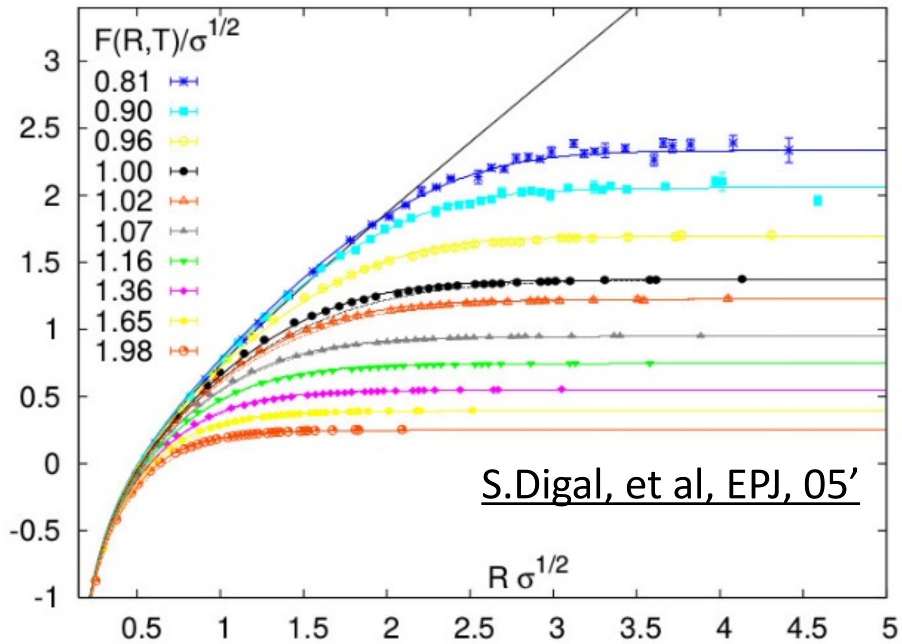


Quark gluon plasma created in HIC is a very strong coupling medium.

Abnormal suppression of charmonium

Abnormal suppression of J/psi: one signal of QGP by Matsui & Satz





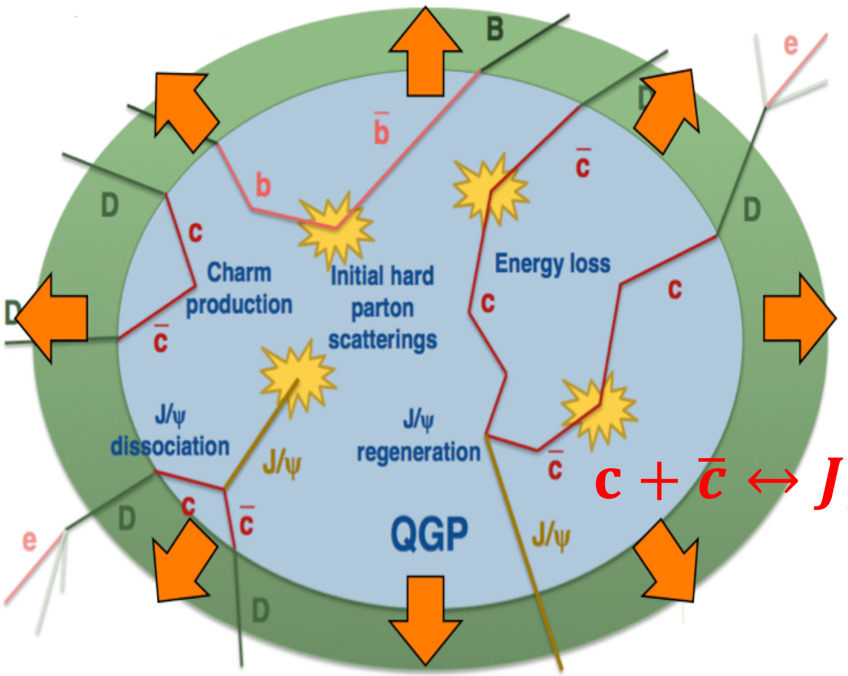
- **Color screening:**
  no attractive force inside "bound states" at high T

$$V_{c\bar{c}} = -\frac{\alpha}{r} + \sigma r$$

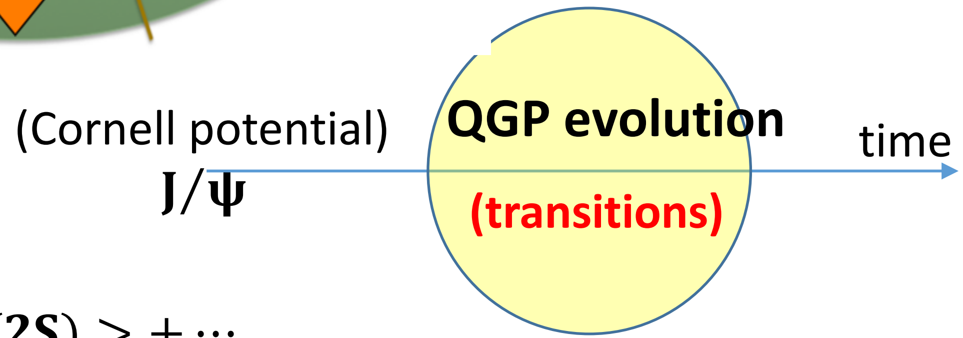
- **Parton scatterings:**
  medium temperature (LHC) ~ 0.3-0.5 GeV,

Quarkonium in hot medium

Heavy quark in-medium potential



$\mathbf{c} + \bar{c} \leftrightarrow J/\psi + g$



$|\mathbf{c}\bar{\mathbf{c}}> = \mathbf{c}_{1S}(\mathbf{t})|\,\mathbf{J}/\psi > + \mathbf{c}_{2S}(\mathbf{t})|\psi(2S) > + \cdots$

$c\bar{c}$ dipole potential in QGP is COLOR SCREENED. Wave function evolution

Schrodinger type models

Previous studies:

(1) X. Guo, S. Shi, P. Zhuang, et al

Time-independent relativistic Schrodinger *Phys.Lett.B* 2012

J/ψ dissociation temperature is changed by ~ 10% after considering relativistic correction

(2) P. Gaussian, R. Katz, et al

Schrodinger-Langevin equation *Annals Phys. 368 (2016) 267-295*

Hamiltonian includes a white noise term and a damping term, which affects the expansion and contraction of the wave function

(3) A. Rothkopf, Y. Akamatsu, et al,

Stochastic Schrodinger equation *Phys.Rev.D 97 (2018) 1, 014003*

Potential includes stochastic terms, wave function decoherence to dissociate quarkonium states

(4) M. Strickland et al,

Time-dependent Schrodinger, with complex potential *Phys.Lett.B 2020*

Bottomonium suppression with real and imaginary potential

And many other references…….

Time-dependent Schrodinger equation

Radial Schrodinger equation:

$$i\hbar\frac{\partial}{\partial t}\psi(r,t) = [-\frac{\hbar^2}{2m_\mu}\frac{\partial^2}{\partial r^2} + \frac{L(L+1)\hbar^2}{2m_\mu r^2} + V(r,t)]\psi(r,t)$$

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

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

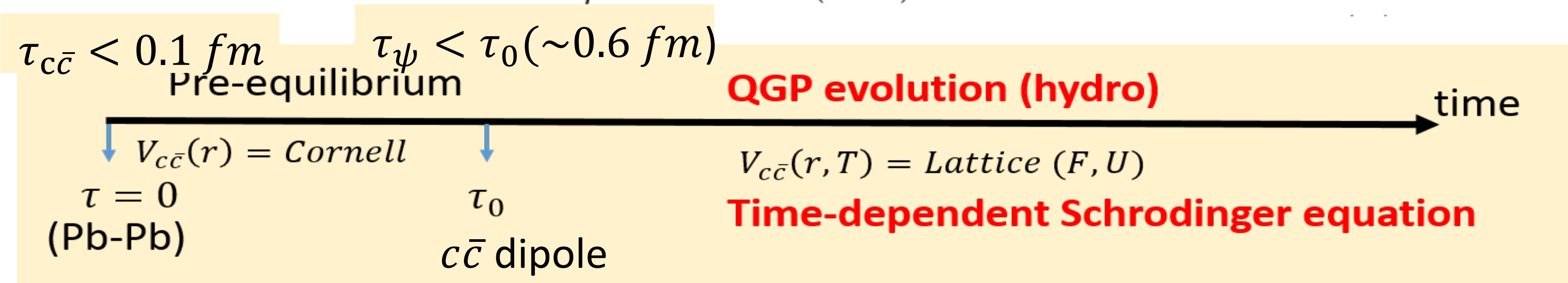
$$\frac{\psi(r,t)}{r} = \sum_m c_m(t)e^{-iE_m t}R_{mS}(r)$$

Wavefunction of eigenstates:

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

Numerical form: Crank-Nicolson method

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



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$= i\Delta t$

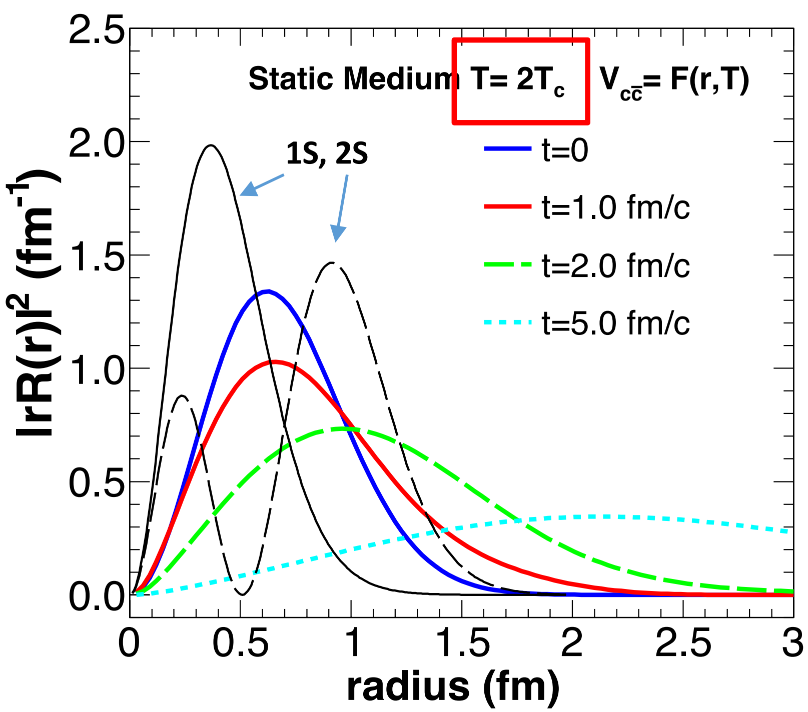
Δt = 0.001 fm/c

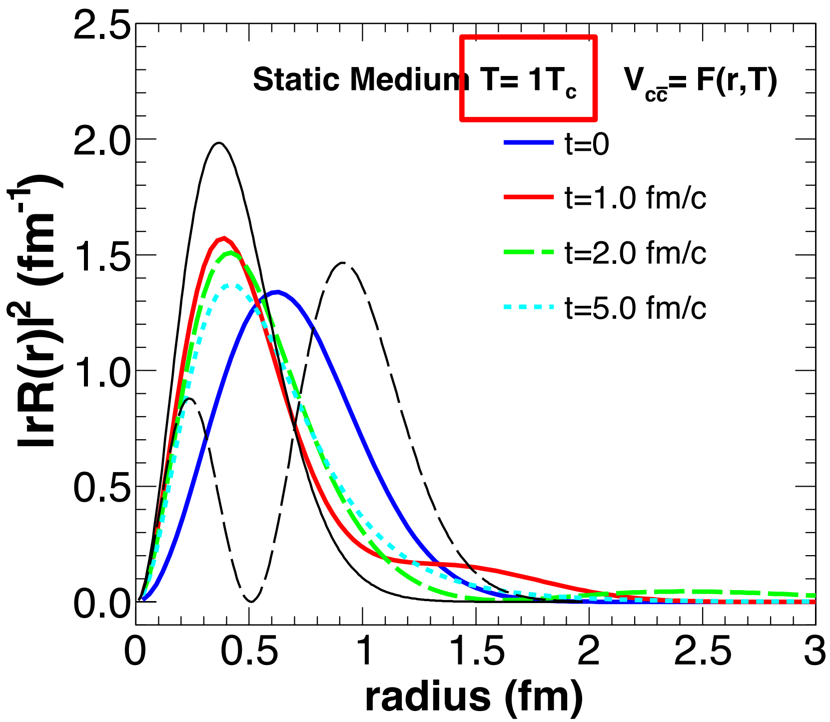
Δr = 0.03 fm

- **mS eigenstate components** in one dipole:

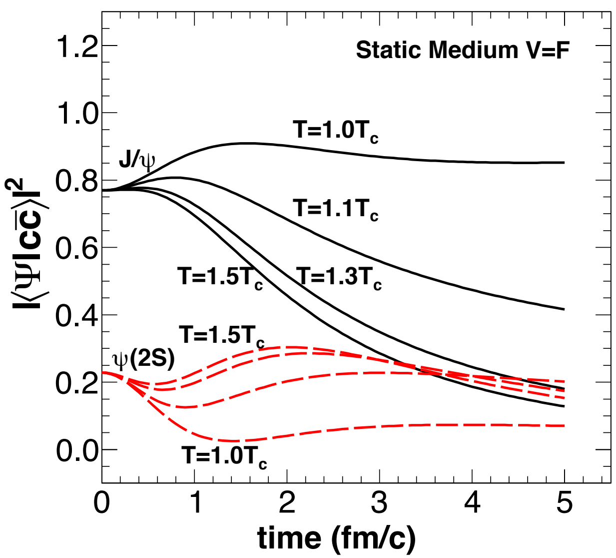
$$c_{mS}(t) = \langle R_{mS}(r)|\frac{\psi(r,t)}{r}\rangle = \int R_{mS}(r)\psi(r,t)\cdot r dr$$

Evolution in static medium





Snapshot of the $c\bar{c}$ wavefunction at different time



At high T, wavefunction expand outside, $J/\psi \longrightarrow \psi(2S)$

At low T, wavefunction contracts, $\psi(2S) \longrightarrow J/\psi$

Initial conditions (heavy-ion)

1. $c\bar{c}$ internal Initial wavefunction:

Taken as quarkonium eigenstates
(neglect the pre-equilibrium effect)

$$\psi_{c\bar{c}}(\tau = \tau_0) = \phi_{1S,2S}(\mathbf{r})$$

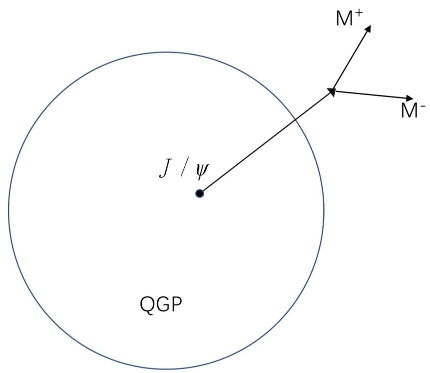
Initial direct yields

$$f_{pp}^{J/\psi} : f_{pp}^{\chi_c} : f_{pp}^{\psi(2S)} = 0.68 : 1 : 0.19$$

2. The initial momentum and spatial distribution of the center of $c\bar{c}$ dipole

$$f_\Psi(\mathbf{p}, \mathbf{x}|\mathbf{b}) = (2\pi)^3 \delta(z) T_{\mathrm{p}}(\mathbf{x}_T) T_{\mathrm{A}}(\mathbf{x}_T - \mathbf{b}) \times \mathcal{R}_{\mathrm{g}}(x_g, \mu_{\mathrm{F}}, \mathbf{x}_{\mathrm{T}} - \mathbf{b}) \frac{d\bar{\sigma}_{pp}^{\Psi}}{d^3\mathbf{p}},$$

Shadowing effect from EPS09 NLO



The initial momentum of $c\bar{c}$ dipoles in pp,
(neglect the mass difference)

$$\frac{dN_{J/\psi}}{2\pi p_T dp_T} = \frac{(n-1)}{\pi(n-2)\langle p_T^2\rangle_{pp}}[1 + \frac{p_T^2}{(n-2)\langle p_T^2\rangle_{pp}}]^{-n}$$

n = 3.2 $\quad \langle p_T^2\rangle(y) = \langle p_T^2\rangle(y=0)[1 - (\frac{y}{ymax})^2]$

$ymax = \ln(\sqrt{s_{NN}}/m_\Psi)$

Including Cronin effect

$$\frac{d\bar{\sigma}_{pp}^{\Psi}}{d^3\mathbf{p}} = \frac{1}{\pi a_{gN} l} \int d^2\mathbf{q}_T e^{\frac{-\mathbf{q}_T^2}{a_{gN} l}} \frac{d\sigma_{pp}^{\Psi}}{d^3\mathbf{p}}$$

$$a_{gN} = 0.15(GeV/c)^2$$

RAA definition

- **The initial yields of charmonium eigenstates**

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

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

- **Charmonium direct R_{AA} with hot medium effects,**

$$R_{pA}^{\text{direct}}(nl) = \frac{\langle |c_{nl}(t)|^2\rangle_{\text{en}}}{\langle |c_{nl}(t_0)|^2\rangle_{\text{en}}}$$

$$= \frac{\int d\mathbf{x}_\Psi d\mathbf{p}_\Psi |c_{nl}(t, \mathbf{x}_\Psi, \mathbf{p}_\Psi)|^2 \frac{dN_{pA}^{\Psi}}{d\mathbf{x}_\Psi d\mathbf{p}_\Psi}}{\int d\mathbf{x}_\Psi d\mathbf{p}_\Psi |c_{nl}(t_0, \mathbf{x}_0, \mathbf{p}_\Psi)|^2 \frac{dN_{pA}^{\Psi}}{d\mathbf{x}_\Psi d\mathbf{p}_\Psi}}$$

$$R_{pA}(J/\psi) = \frac{\sum_{nl} \langle |c_{nl}(t)|^2\rangle_{\text{en}} f_{pp}^{nl} \mathcal{B}_{nl\to J/\psi}}{\sum_{nl} \langle |c_{nl}(t_0)|\rangle^2\rangle_{\text{en}} f_{pp}^{nl} \mathcal{B}_{nl\to J/\psi}}$$

$c\bar{c}$ dipoles move inside QGP

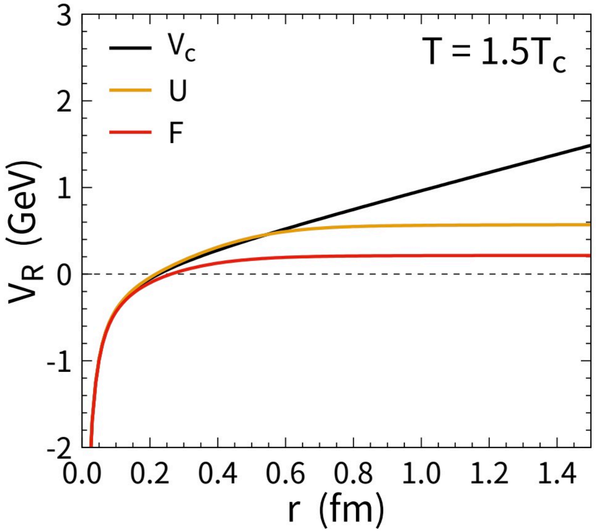
$$\mathbf{R}_{c\bar{c}}(\tau + \Delta\tau) = \mathbf{R}_{c\bar{c}} + \mathbf{v}_{c\bar{c}} \cdot \Delta\tau$$

Charmonium in p-Pb collisions

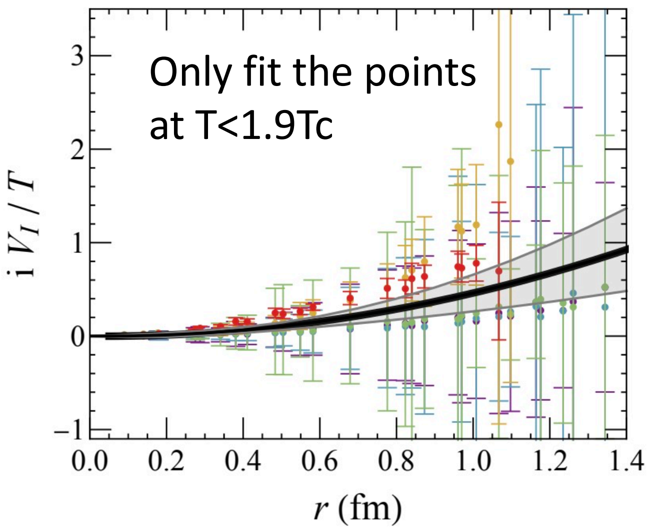
- **Is charmonium 1S and 2S states color screened (weak potential) in the small collision system ?**

Color screening V.S. **Inelastic scatterings**

Real part

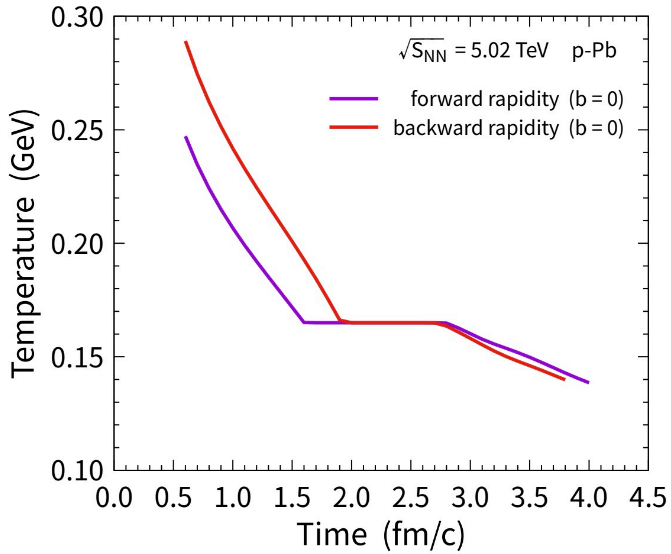


imaginary part



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

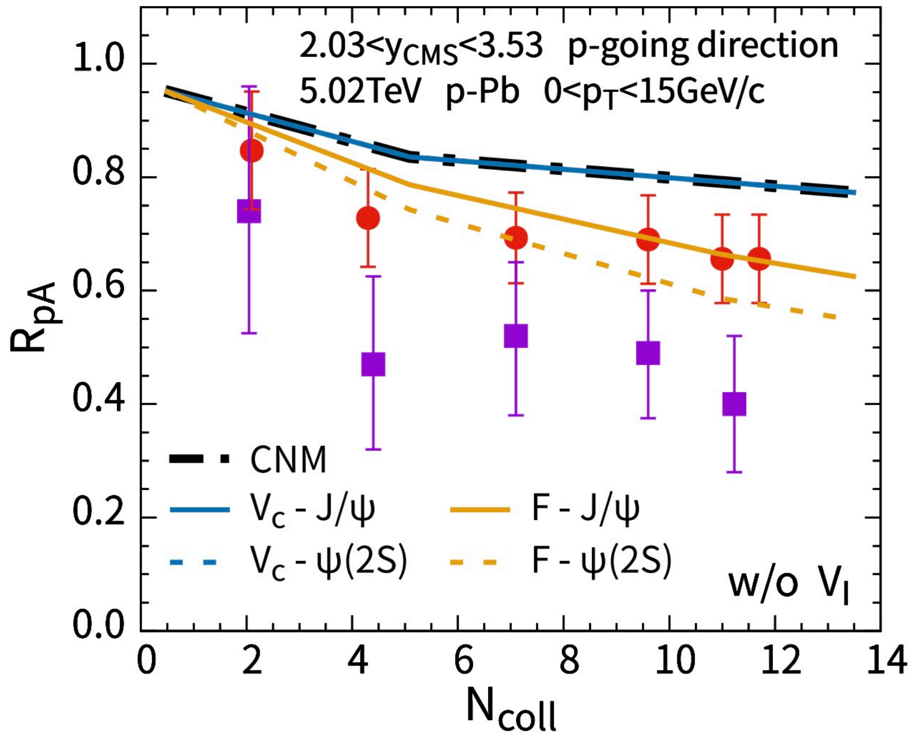
$$V_I(T,\bar{r}) = -i\,T(a_1\,\bar{r} + a_2\bar{r}^2)$$



Hot medium in p-Pb (x=y=0)

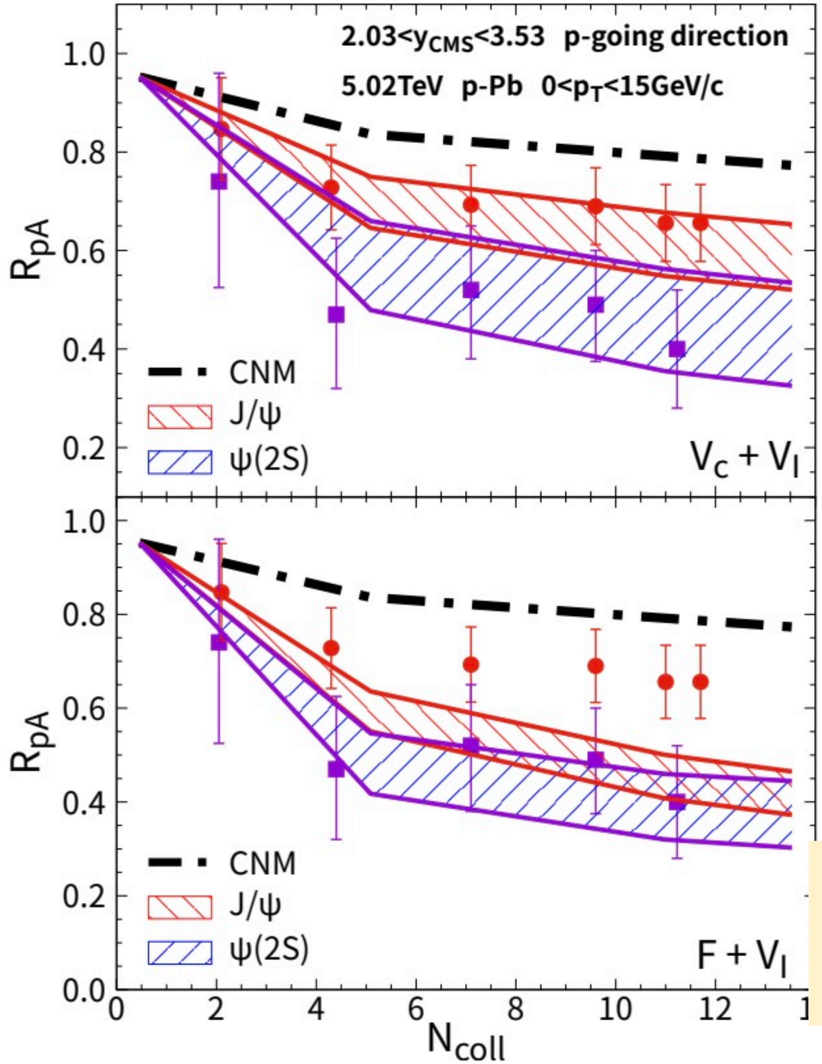
2+1 dimensional ideal hydrodynamci equations

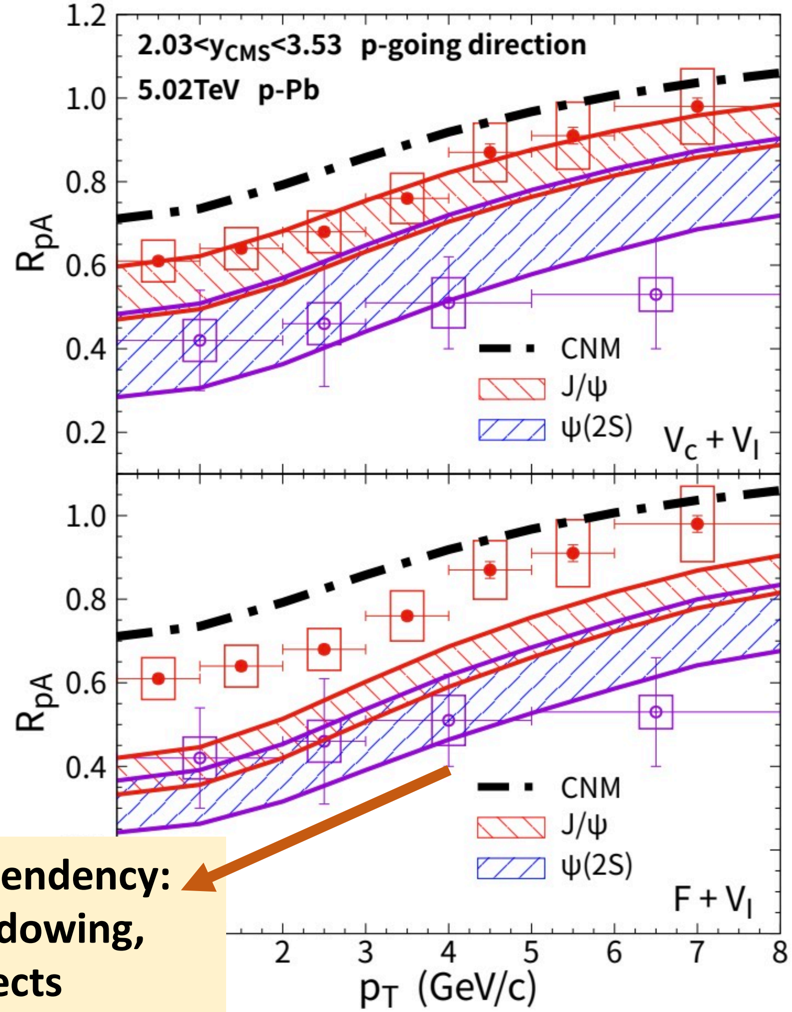
Charmonium in p-Pb collisions



Only color screening effect
+ cold nuclear effect
(Cronin+shadowing)

Charmonium in p-Pb collisions





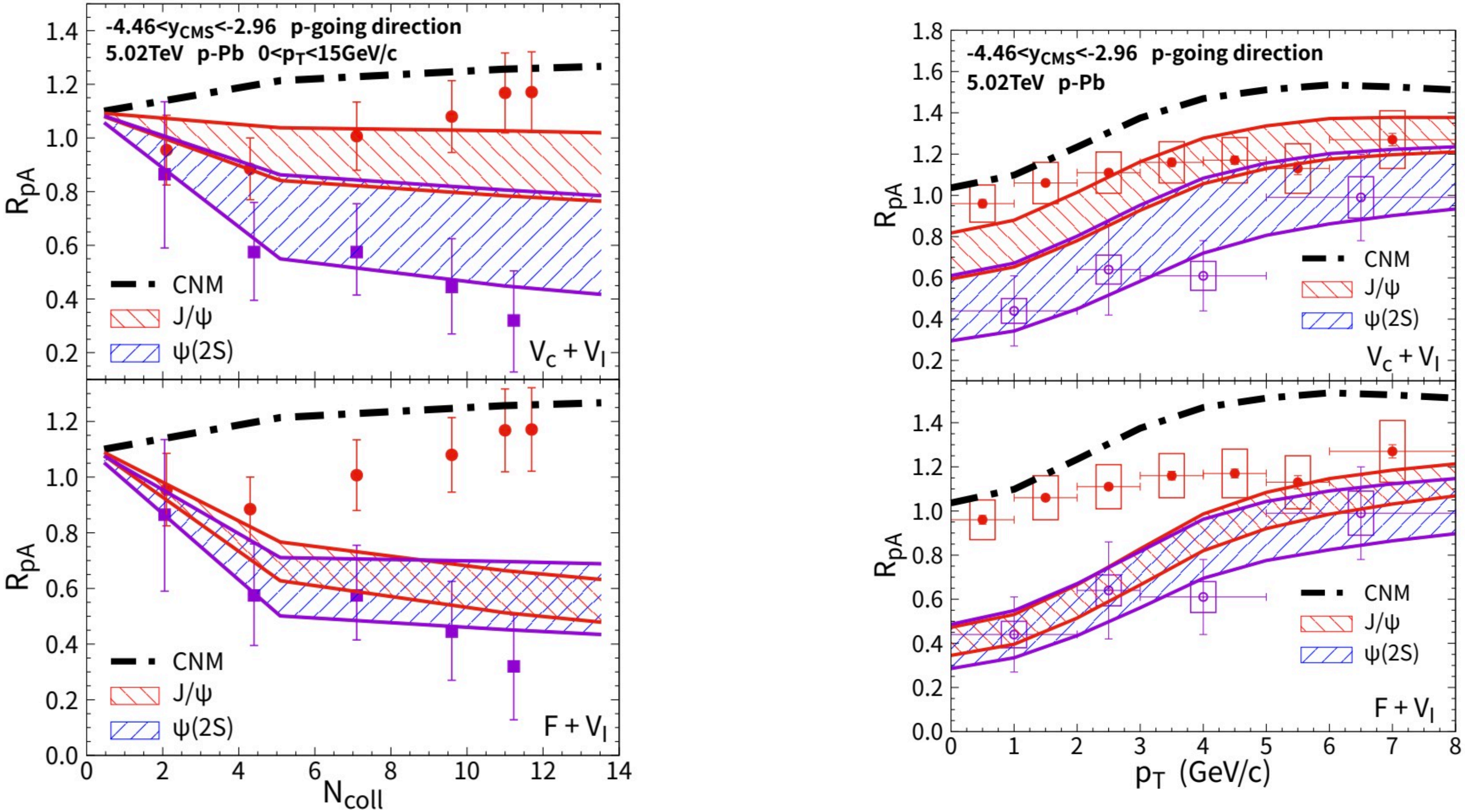
Increasing tendency: Cronin, shadowing, leakage effects

Band comes from the uncertainty in V_I

- R_{pA} as a function of N_{coll}
- R_{pA} as a function of p_T

Very **weak** in-medium potential **V=F**
Strong in-medium potential **V=Vc**

Charmonium in p-Pb collisions



Backward rapidity

- R_{pA} as a function of N_{coll}
- R_{pA} as a function of p_T

Strong potential (in the limit V=U) can explain data relatively well

Bottomonium in Pb-Pb collisions

- **Initial momentum distribution in pp**

$$\frac{dN^{\Upsilon}_{pp}}{d\phi p_T dp_T} = \frac{(n-1)}{\pi(n-2)\langle p_T^2\rangle_{pp}}[1+\frac{p_T^2}{(n-2)\langle p_T^2\rangle_{pp}}]^{-n}$$

$< p_T^2 >= (80, 55, 28)(GeV/c)^{\uparrow}2$

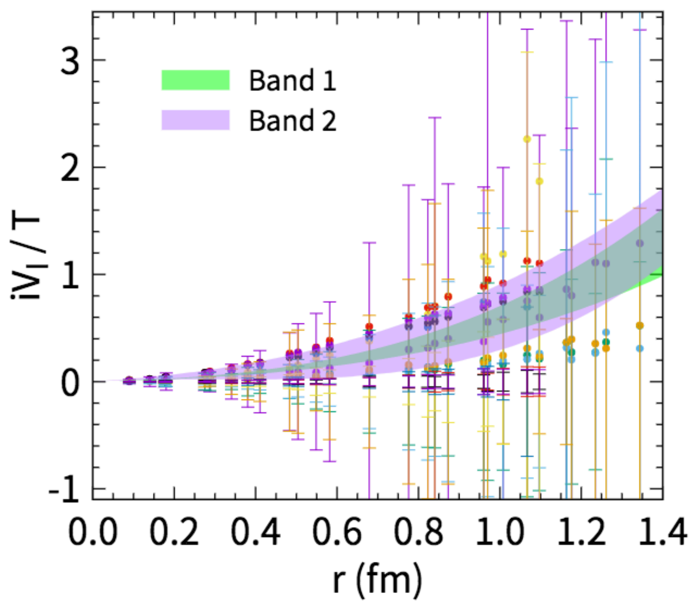
At 5020, 2760, 200 GeV

$n = 2.5$

- **Direct yields of bottomonium states at 5.02 TeV**

State	$\Upsilon(1s)$	$\chi_b(1p)$	$\Upsilon(2s)$	$\chi_b(2p)$	$\Upsilon(3s)$
$\sigma_{\text{exp}}(nb)$	57.6	33.51	19	29.42	6.8
$\sigma_{\text{direct}}(nb)$	37.97	44.2	18.27	37.68	8.21

Medium temperature (b=0)
T(5.02TeV)=510 MeV
T(2.76TeV)=484 MeV
T(200GeV)=390 MeV

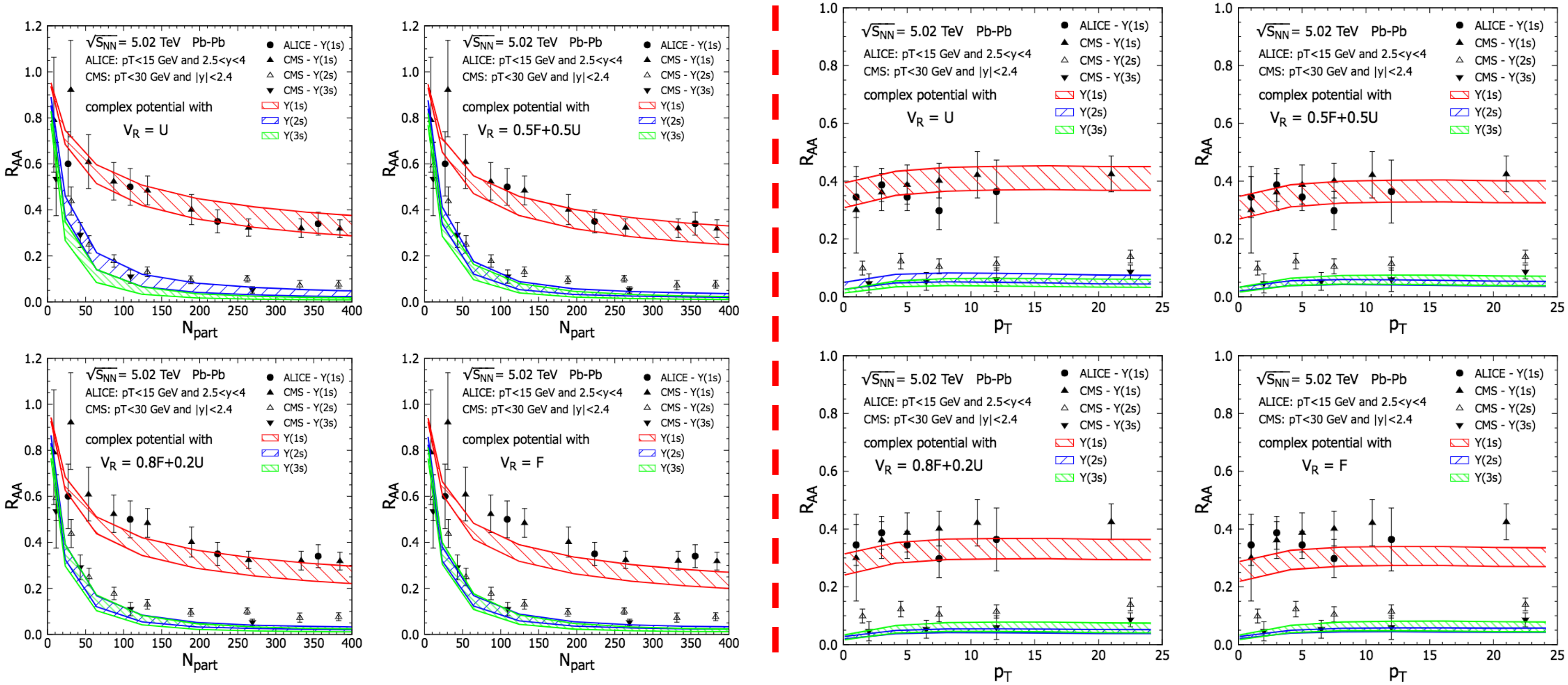


This ratio between different states are also used in 2.76 TeV and 200 GeV

Two kinds of imaginary potential are fitted

- Smaller band: fit the central value and shifted upward slightly to consider partial uncertainty.
- Larger band: one sigma uncertainty is included.

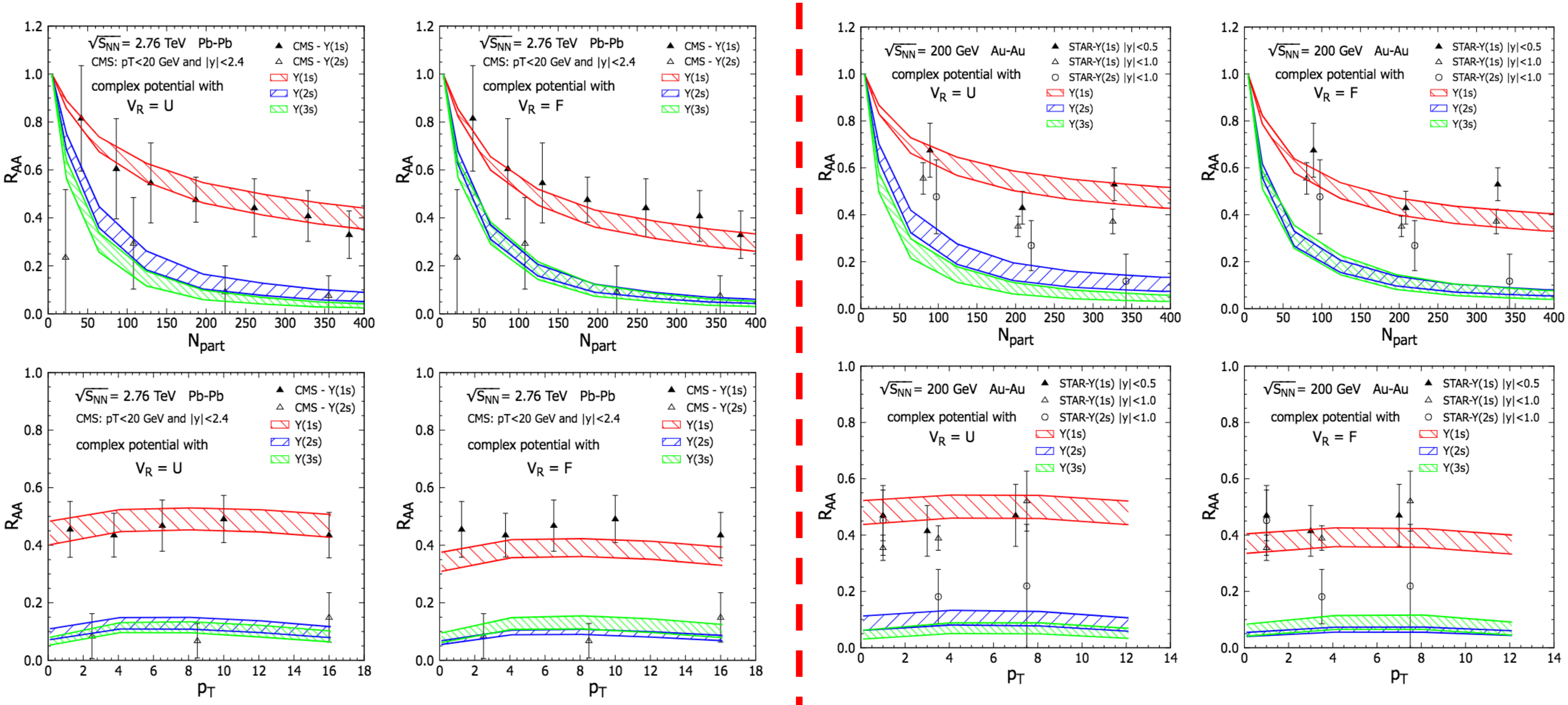
Bottomonium in Pb-Pb collisions



5.02 TeV Pb-Pb

- **Clear sequential suppression pattern is observed with V=U**
- **With V=F, weak potential makes the wave function expand outside.**

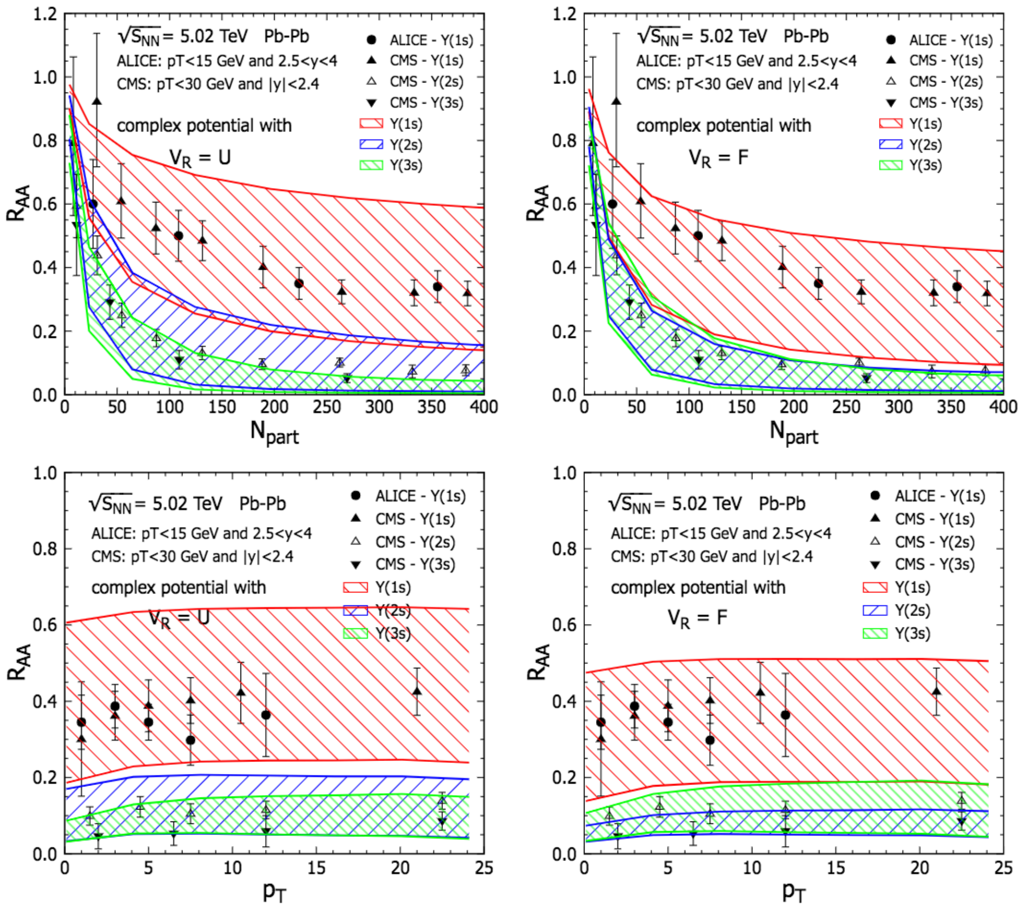
Bottomonium in Pb-Pb collisions



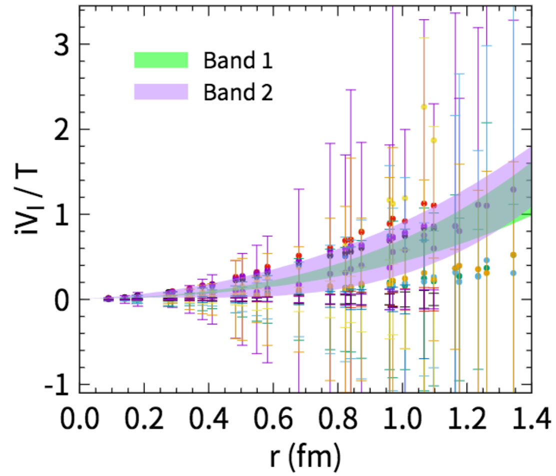
2.76 TeV Pb-Pb

200 GeV Au-Au

Bottomonium in Pb-Pb collisions



Calculation with band 2



- RAA with larger uncertainty in the imaginary potential.
- The sequential suppression pattern is still observed.

- Using quarkonium data to extract the imaginary potential ?

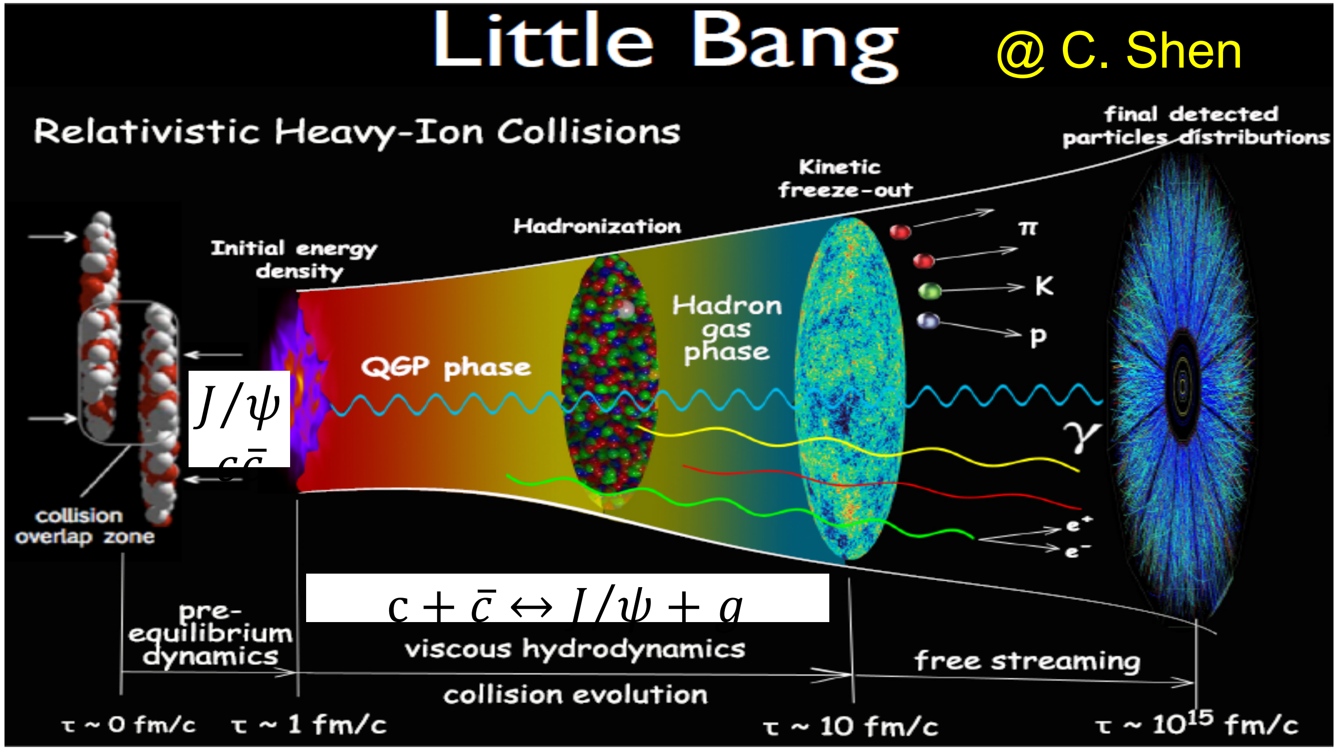
Summary

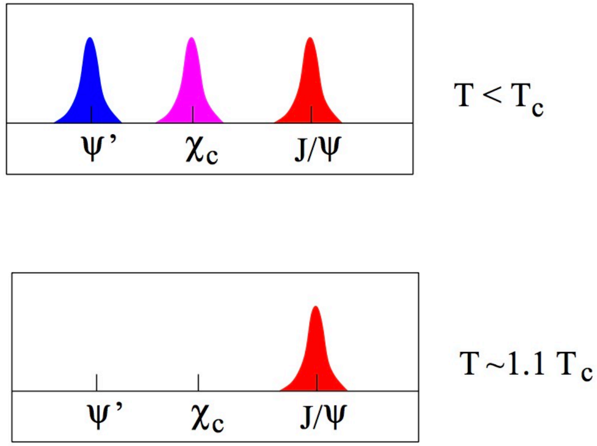
- We study the charmonium and bottomonium evolutions in **the small (p-Pb) and large (Pb-Pb) collision systems** respectively with the time-dependent Schrodinger equation.
  Both **color screened effect** and **inelastic scatterings** are included in the real and imaginary potential.

- In small collision system, **color screening effect is expected to be small**. While imaginary potential dominates the suppression.

- In large collision system, **a strong heavy quark potential is still expected** to get the sequential suppression pattern,
  which contains the quarkonium wave function in the medium.

Heavy ion collisions and heavy flavors





Satz. 2005

- significant **color screening** **+** **parton inelastic scatterings**