A workshop on QCD Physics & Study of the QCD Phase Diagram
Wei-Hai, July 17-25, 2019

Heavy Flavor Evolution with EM fields and Hot Medium

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Outline

1. Vector meson photoproduction from EM fields

2. Stochastic Schrodinger equation : (hot medium effect)

stochastic potential (open quantum system)

charm wave function evolution with SSE, Diffusion coefficient Ds

3. Schrodinger equation for charmonium:

transitions between 1S and 2S states

Different P_T physics

$c + \bar{c} \longrightarrow J/\psi + g$

regeneration

$p_T \sim 1/R_A \leq 0.1$ $\quad$ $3 \sim 5$ $\quad$ p_T (GeV/c)

$\gamma A \rightarrow J/\psi\, A$

Photoproduction

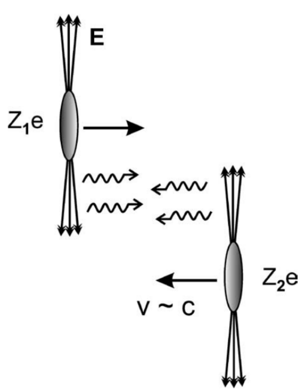
$gg(q\bar{q}) \rightarrow J/\psi\, g$

Initial production

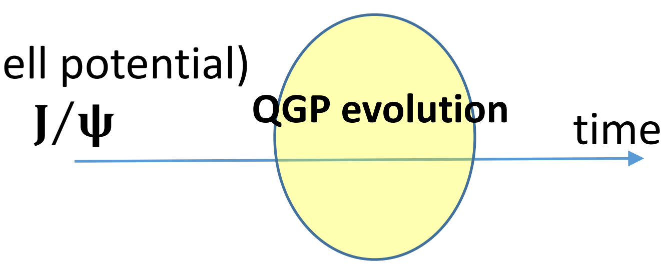
(1)Photoproduction
Low P_T
semi-central (peripheral)

(2)Charm thermalize

(3)Correlated $c\bar{c}$
$J/\psi\,,\psi(2S)$ transition



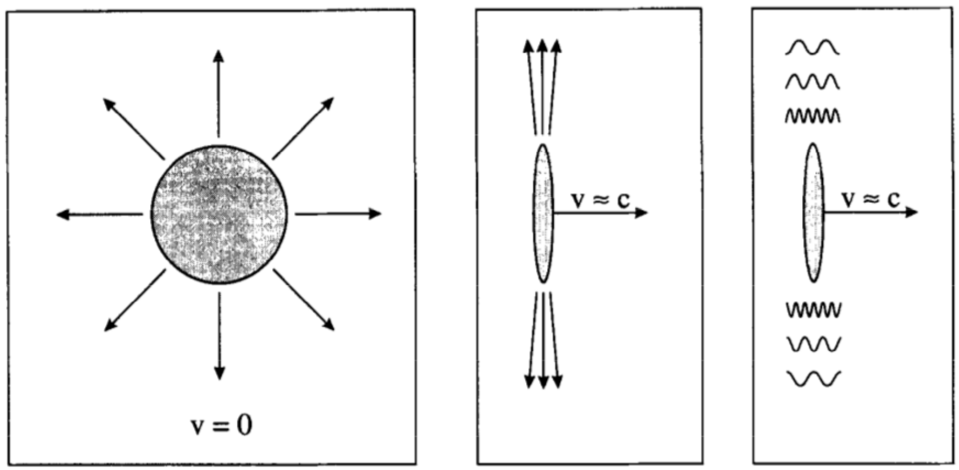
(Cornell potential)



Photoproduction from EM fields

Equivalent Photon Approximation

Prog.Part.Nucl.Phys. 39,503-564, 1997



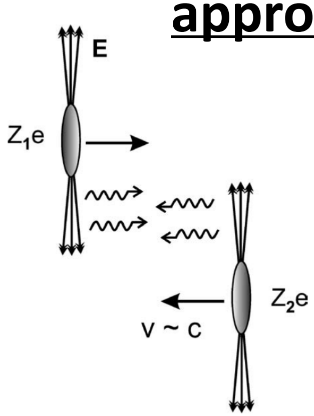
$\mathrm{eB} \sim m_\pi^2 \sim 10^{18} G$

Ultra-peripheral collisions

charges moves at nearly speed of light → produce E-B fields

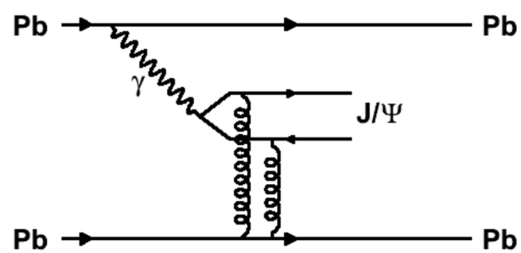
Strong Lorentz-contracted Electromagnetic field

approximated as longitudinally moving photons



Equivalent-Photon-Approximation

Fermi, 1924'



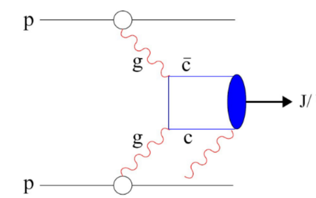
$\gamma + A \rightarrow J/\psi + A$

$\gamma\gamma \rightarrow c\bar{c}(l\bar{l})$

$$|\gamma\rangle = C_{\mathrm{pure}}|\gamma_{\mathrm{pure}}\rangle + C_{\rho^0}|\rho^0\rangle + C_\omega|\omega\rangle + C_\phi|\phi\rangle + C_{J/\psi}|J/\psi\rangle + \cdots + C_{q\bar{q}}|q\bar{q}\rangle$$

p_T dependence

- Compare the p_T dependence of **coherent photoproduction** and **hadroproduction**



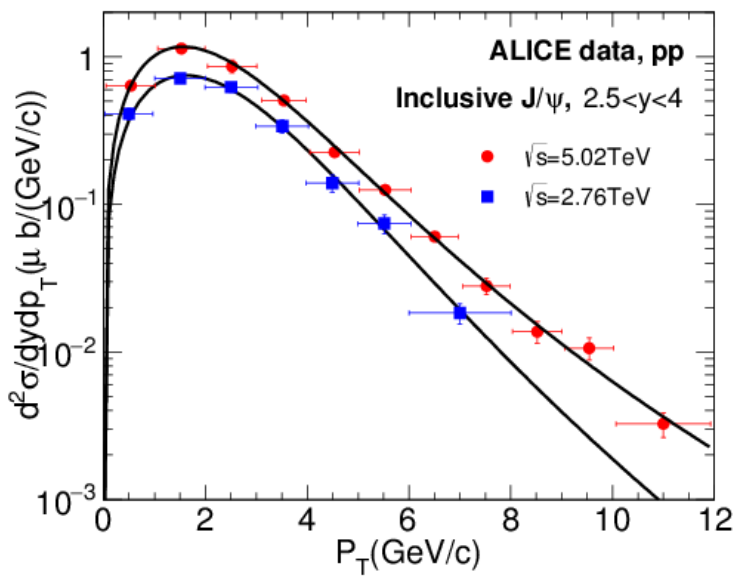
Normalized distribution $$\frac{d\sigma_{pp}^{J/\psi}}{2\pi p_T dp_T} = \frac{2(n-1)}{2\pi(n-2)<p_T^2>_{pp}^{J/\psi}}\left[1+\frac{p_T^2}{(n-2)<p_T^2>_{pp}^{J/\psi}}\right]^{-n}$$

- **2.76 TeV forward rapidity 2.5<y<4,**

$$<p_T^2>_{pp}^{J/\psi} = 7.8\ (GeV/c)^2 \qquad n \sim 4.0$$

At $p_T \to 0$, $\frac{d\sigma_{pp}^{J/\psi}}{dp_T} \propto p_T$

Hadronic cross section drops to zero at $p_T \to 0$



J. Zhao, B. Chen, Phys.Lett. B776 (2018) 17-21

p_T dependence

Coherent photoproduction: Photons interact with entire nucleus,

$p_T \sim 1/R_A \sim 0.03$ GeV/c **Exp.** $\boldsymbol{< p_T >= 0.055}$ **GeV/c**

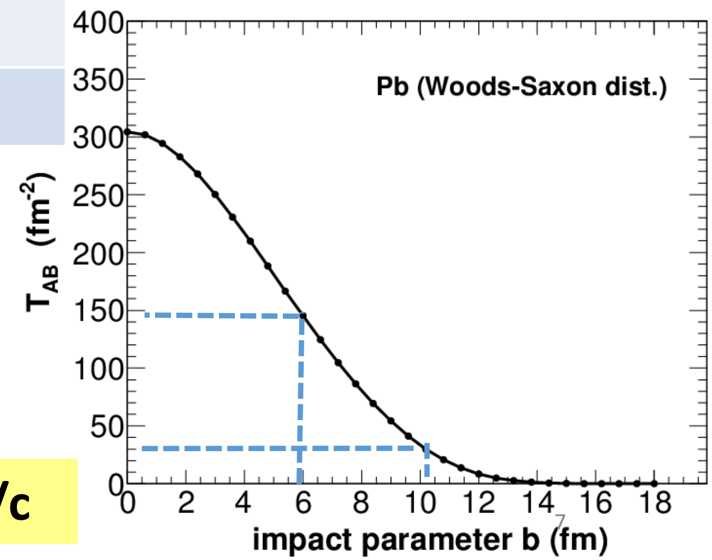
PRL 116, 222301 (2016)

b=10.2 fm	**Hadroproduction** $2.5 < y < 4$	**photoproduction**
$0 < p_T < 0.04$ GeV/c	$\mathbf{0.47 \times 10^{-5}}$	5.54×10^{-5}
$0 < p_T < 0.1$	$\mathbf{2.4 \times 10^{-5}}$	$\mathbf{15.7 \times 10^{-5}}$
$0 < p_T < 0.5$	$\mathbf{50 \times 10^{-5}}$	$\mathbf{\sim 16 \times 10^{-5}}$
$0 < p_T < 1$	$\mathbf{179 \times 10^{-5}}$	
$0 < p_T < 3$	$\mathbf{772 \times 10^{-5}}$	

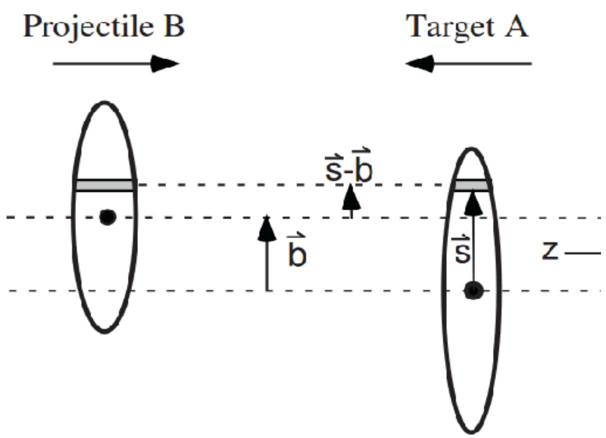
From impact parameter b~10 fm to more central collisions, hadroproduction increase significantly.

$$N_{AA}^{J/\psi} = \sigma_{pp}^{J/\psi} \int d^2 x_T T_A(x_T) T_B(x_T - b)$$

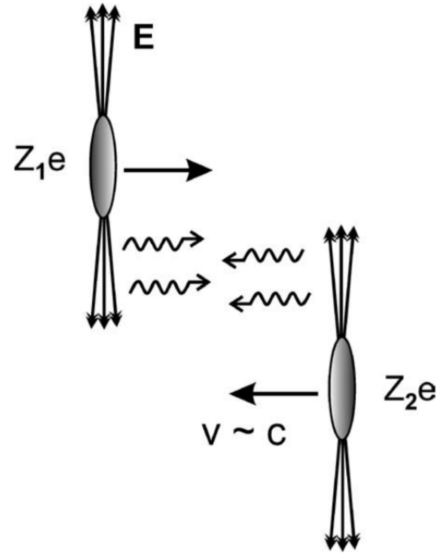
At $b \sim R_A$, they are at the same order in pT<0.1 GeV/c



hadro- and photo- production



$\mathbf{b} < 2R_A$



$\mathbf{b} < 2R_A$ *or* $b \geq 2R_A$

Heavy quarks (quarkonium)
+ light partons (QGP)
Produced in the *overlap area*.

Produced in the entire nucleus surface

$$\mathbf{gg(q\bar{q})} \rightarrow J/\psi + g$$
$$\rightarrow c + \bar{c}$$

$$\gamma A \rightarrow J/\psi\ A$$

Shi, Zha, BC, Phys.Lett. B777 (2018) 399-405

Transport model (heavy quarkonium)

$$\frac{\partial f_\psi}{\partial t} + \frac{\vec{p}_\psi}{E} \cdot \vec{\nabla}_x f_\psi = -\alpha_\psi f_\psi + \beta_\psi$$

Hydrodynamics (light partons)

$$\partial_\mu T^{\mu\nu} = 0$$

$$N_\psi^{\gamma A} \propto \int dw \frac{dN_\gamma}{dw} \sigma_{\gamma A \rightarrow J/\psi A} \Gamma_{QGP}^{decay}$$

$$\mathrm{R_{AA}} = \frac{\mathrm{N}^{\gamma A} + \mathrm{N}^{\mathrm{hadro}}}{\mathrm{N}^{\mathrm{hadro}}}$$

J/ψ from EM field

Mainly ingredients: $N_\psi^{\gamma A} \propto \int dw \frac{dN_\gamma}{dw} \sigma_{\gamma A\to J/\psi A} \Gamma_{QGP}^{decay}$

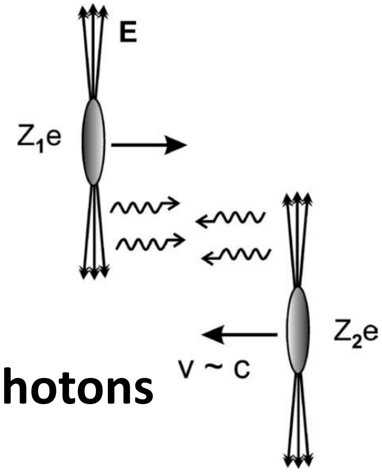
From transport model

- **Photon density $\frac{dN_\gamma}{dw}$** emitted by one nucleus

Poynting vector $\vec{S}(\vec{r},t) = \vec{E}(\vec{r},t) \times \vec{B}(\vec{r},t) \xrightarrow{v\to c} |\vec{E}(\vec{r},t)|^2 \vec{v}$

$$\int_{-\infty}^{\infty} dt \int d\vec{x_\perp} \cdot \vec{S}(\vec{r},t) \stackrel{!}{=} \int_0^{\infty} d\omega \int d\vec{x_\perp}\, \omega\, n(\omega, \vec{x_\perp})$$

Energy flux of the fields **Energy flux of equivalent photons**



$$\frac{dN_\gamma}{dw} = n(w) = \frac{1}{\pi w}\int d\vec{x}_T |\vec{E}_T(\vec{r},w)|^2$$

Photon density $$= \frac{(Ze)^2}{\pi w}\int_0^\infty \frac{d^2\vec{k}_T}{(2\pi)^2}\left[\frac{F((\frac{w}{v\gamma})^2 + k_T^2)}{(\frac{w}{v\gamma})^2 + k_T^2}\right]^2 \frac{k_T^2}{v^2}$$

Nuclear charge form factor is the Fourier transform of Woods-Saxon distribution.
For point particle, it's 1

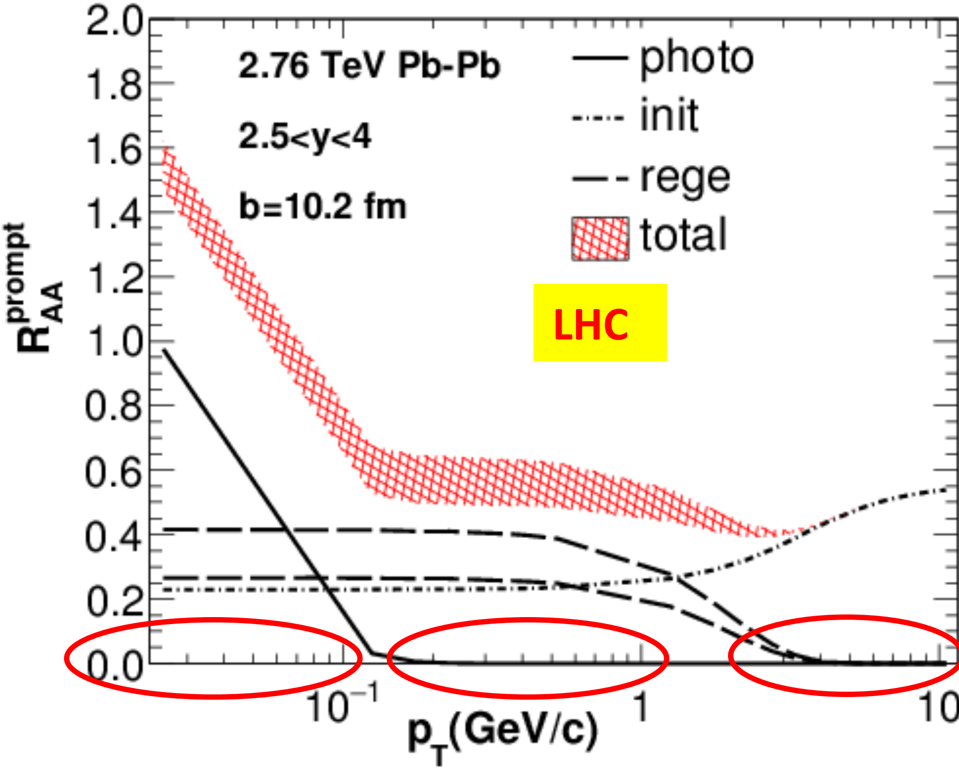
- **Photon-nucleus cross section $\sigma_{\gamma A\to J/\psi A}$**

  Widely studied in UPC

$$\sigma(\gamma A \to J/\psi A) = \frac{d\sigma(\gamma A \to J/\psi A)}{dt}\Big|_{t=0} \int_{-t_{min}}^{\infty} |F(t)|^2 dt$$

S.R.Klein, J. Nystrand, PRC, 1999
Physics Roports, G.Baur, et al, 2002

Total J/ψ from EM field + QGP



At Np~ 100, $T_0^{QGP} \sim 2T_c$

$$R_{AA} = \frac{N^{\gamma A} + N_{AA}^{initial} + N_{AA}^{rege}}{N_{pp*ncoll}^{J/\psi}}$$

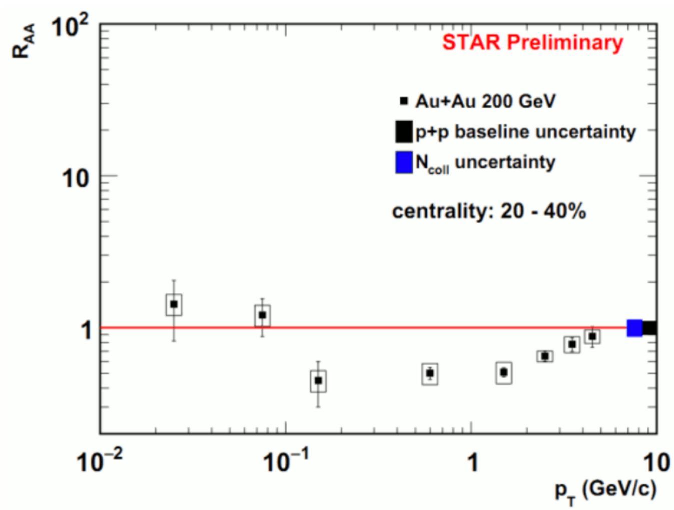
$c + \bar{c} \longrightarrow J/\psi + g$
regeneration

$\leq$ 0.1 — 3 ~ 5 — p_T (GeV/c)

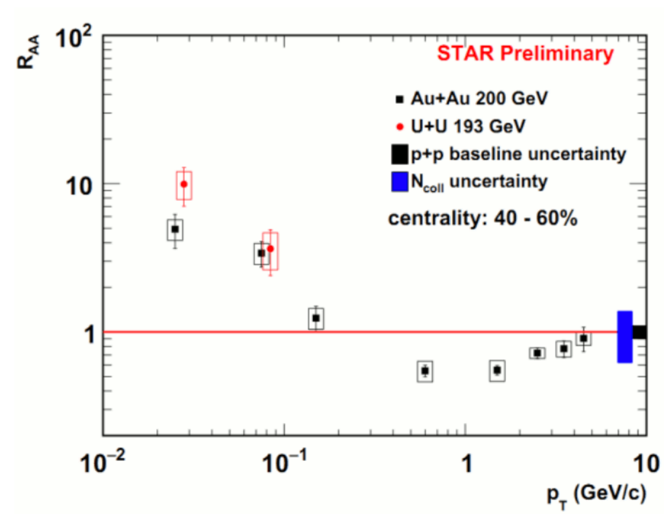
$\gamma A \rightarrow J/\psi\, A$
Photoproduction

$gg(q\bar{q}) \rightarrow J/\psi\, g$
Initial production

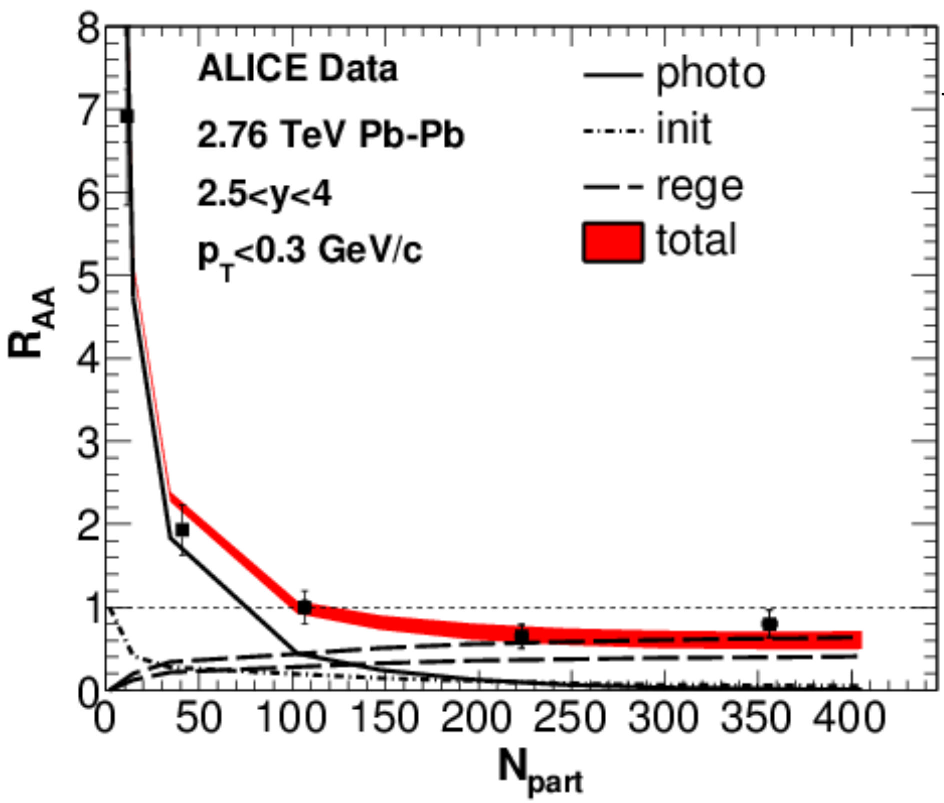
R_{AA} decreases, then increases with pT
photoproduction → rege. → init.



RHIC



Total J/ψ from EM field + QGP



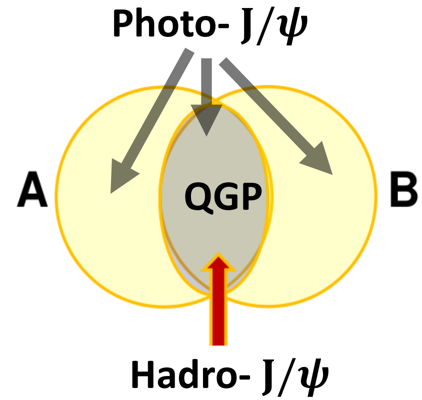
Shi, Zha, BC, Phys.Lett. B777 (2018) 399-405

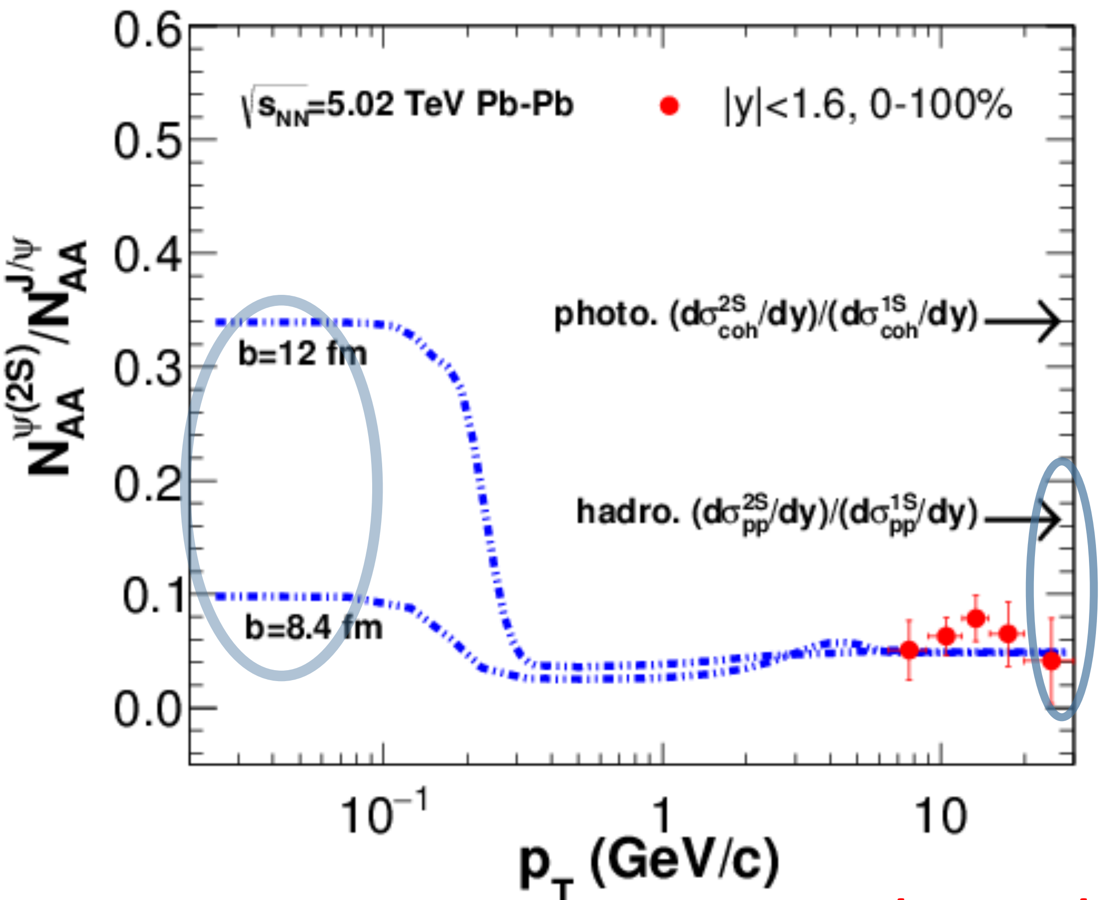
$$R_{AA} = \frac{N^{\gamma A} + N_{AA}^{initial} + N_{AA}^{rege}}{N_{pp*ncoll}^{J/\psi}}$$

- Also **significant enhancement at** $\mathrm{N_p} \approx 100$, where $T_0^{QGP} = 2T_c$, **similar with T at** **RHIC 200 GeV Au-Au (most central)**
- **When** N_{part} **→ 0** $(\mathrm{b} > 2\mathrm{R_A})$,
  hadroproduction → 0, photoproduction → nonzero, R_{AA} **→ infinity**

Photoproduced 2S/1S

Hadroproduction:
in the overlap area of two nuclei
Photoproduction:
over the entire nuclear region





Enhancement:
additional photoproduction on both 1S and 2S

Suppression: **QGP effect.**

B.Chen, P. Zhuang, et al, arXiv:1801.01677

SSE and Stochastic potential

Thermal medium effect

Quantum approach (**open quantum system**):

-Lindblad equation [Lindblad et al, 1976, …]

-Solid theoretical foundation for open quantum system,

-Evolving density matrices, computationally-intensive, approx. needed

-Schrödinger-Langevin equation

-Originates from Heisenberg-Langevin equation

-Nonlinear in $|\phi\rangle$ [Gossiaux et al, 2016, …]

- Generalized Langevin approach J. P. Blaizot, et al
- pNRQCD X. Yao, B. Muller

- Stochastic Schrodinger equation (our approach)

Can be employed in

Spin thermal theory,

Bose-Einstein conden.

Thermalization process, *et al.*

Framework of SSE

$$i\frac{d}{dt}|\Psi\rangle = H|\Psi\rangle$$

HQ: sub-system
QGP: thermal bath(environment)

$$H = H_Q + H_I + H_B$$

H_Q: HQ, H_B: medium,
H_I: interactions between HQ and the medium

$$|\Psi\rangle \approx |\psi\rangle \otimes |M\rangle \approx e^{-\frac{E_{tot}-E_p}{2T}}|\psi\rangle$$

Wavefunction : heavy quark + medium

Ignore medium part

$$i\frac{d}{dt}\psi(p,t)e^{\frac{E_p}{2T}} = \Sigma_{p'}(H_I + H_Q)\psi(p',t)\, e^{\frac{E_{p'}}{2T}}$$

Switch to interaction picture

$$i\frac{d}{dt}|\psi\rangle = V_I^r|\psi\rangle$$

E_{tot}: entire system (constant)

$E_p = \sqrt{p^2+m^2}$: heavy quark energy

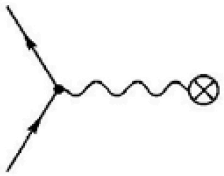
$$|M >= \Sigma_n \sqrt{\frac{e^{-E_B/T}}{Z_B}}|n >$$

Z_B: partition function of thermal bath

$$V_I^r = H_I e^{\frac{E_{p'}-E_p}{2T}} e^{i(E_p - E_{p'})t}$$

Heavy quark-Medium interaction

Like QED



- We model the medium with gluon field:

$$H_I = \int d^3 x g\bar{\psi}\gamma^{\mu}\psi A_{\mu}$$

- Take non-relativistic approximation and keep only zeroth component:

$$H_I = \int d^3 x g\bar{\psi}\gamma^{0}\psi A_{0}$$

- A_0 in momentum space

$$A_0(\vec{x})=\int \frac{d^3 p_g}{(2\pi)^3}\sqrt{\frac{2}{E_{pg}}}\,a(\vec{p})e^{-i\vec{p}\cdot\vec{x}}$$

- Based on Boltzmann distribution: $\left|a\left(p_g\right)\right|^2 = \rho(p_g) = d_g V e^{-\beta E_g}$, we conjecture

$$a(\vec{p})=\sqrt{\frac{d_g V}{e^{-\beta E_g}}}\,e^{-i\theta^r_{px}}e^{-i\theta^r_{py}}e^{-i\theta^r_{pz}}$$

where $\theta_{pp'} \equiv \theta_p - \theta_{p'}$ is a random phase with $\theta_{pp'} = -\theta_{p'p}$ (Hermiticity)

as $a(-\vec{p}) = a^*(\vec{p})$, $\qquad \theta^r_{-p} = -\theta^r_p$

Numerical results show that $A_0(\mathrm{x})^2$s' mean value are intensive, not extensive

Stochastic Schrodinger Equation (SSE)

$$\langle c|\mathcal{H}_I|c'\rangle = \langle c|\int d^3x g\bar{\psi}\gamma^0\psi A_0|c'\rangle,$$

c, c': p, p'

$$\langle c|\mathcal{H}_I|c'\rangle = \int \frac{g d^3x d^3p_3 d^3p_4 A_0(x)}{(2\pi)^3(2\pi)^3\sqrt{2E_{p_3}}\sqrt{2E_{p_4}}} \sum_{s_3,s_4} \langle 0|a_{p_1}^{s_1}(b_{p_3}^{s_3}\bar{v}^{s_3}(p_3)e^{-ip_3x} + a_{p_3}^{s_3\dagger}\bar{u}^{s_3}(p_3)e^{ip_3x})$$

$$\gamma^0(a_{p_4}^{s_4}u^{s_4}(p_4)e^{-ip_4x} + b_{p_4}^{s_4\dagger}v^{s_4}(p_4)e^{ip_4x})a_{p_{1'}}^{s_{1'}\dagger}|0\rangle$$

$$\{a_p^r, a_q^{s\dagger}\} = \{b_p^r, b_q^{s\dagger}\} = (2\pi)^3\delta^{(3)}(p-q)\delta^{rs}$$

$$< c|\mathrm{H}_I|c' >= \sqrt{\frac{2}{E_{p_{1'}-p_1}}}\, a(p_{1'} - p_1)$$

$$\delta(\mathbf{p}-\mathbf{q}) = \frac{1}{(2\pi)^3}\int_{-\infty}^{\infty} e^{i\mathbf{x}\cdot(\mathbf{p}-\mathbf{q})}dx^3$$

SSE in momentum space and interaction picture

$$i\frac{d}{dt}\psi(p,t) = \Sigma_{p'}\sqrt{\frac{d_g V}{e^{\beta E_g}}}\, e^{i(E_p - E_{p'})t/2}\, e^{i\theta_{pp'}}\, e^{\beta(E_{p'}-E_p)/2}\psi(p',t)$$

Square root of distribution of gluon field

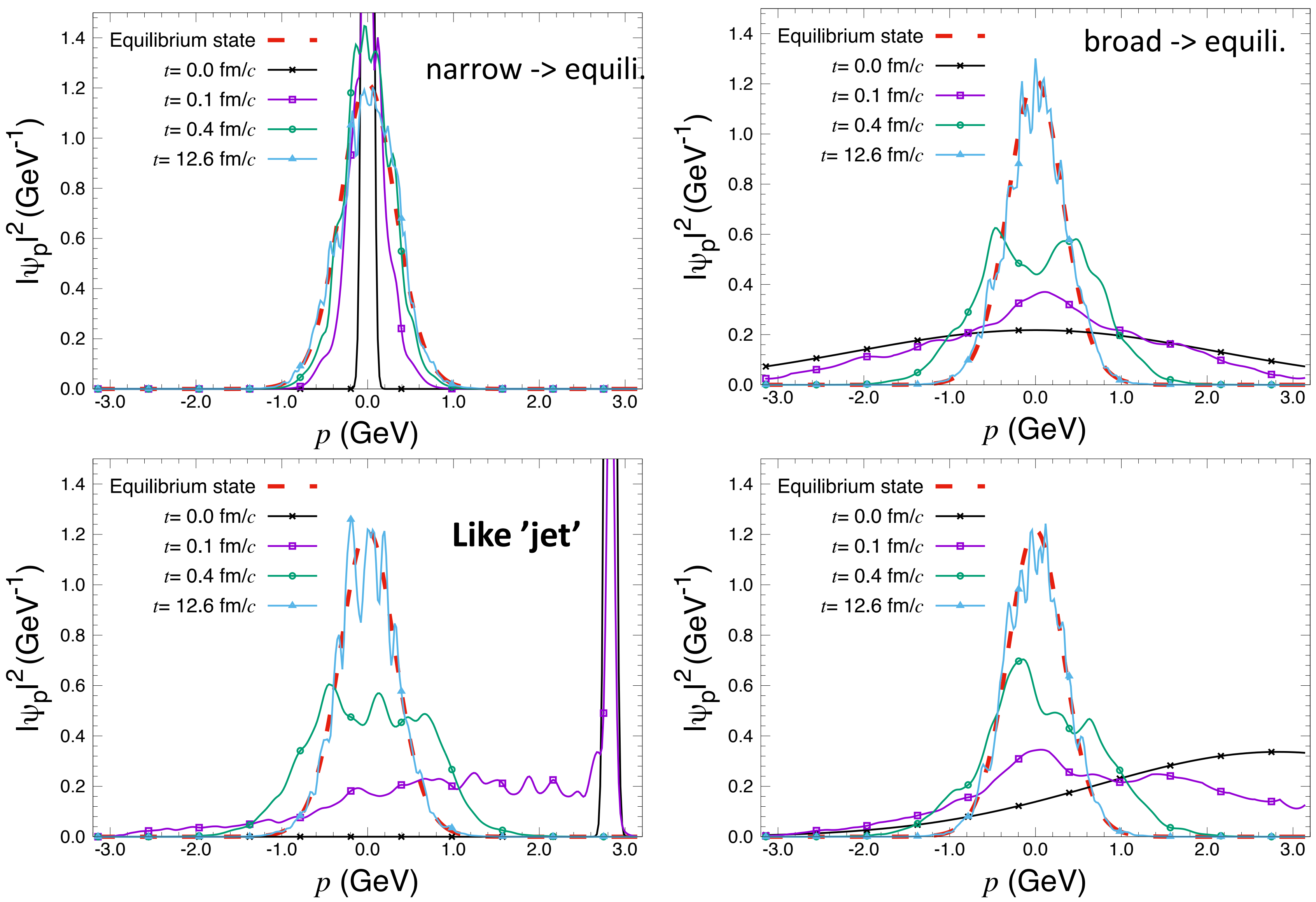
"damping" factor: from ensemble average; weighting transition matrix elements with number of microscopic states of the medium

$\theta_{pp'}$ is time-dependent, updating period is a parameter, currently is taken at $1/T$.

$E_{p'} - E_p$ lead to non-Hermitian Hamiltonian $\quad E_g \sim |E_p - E_{p'}|$

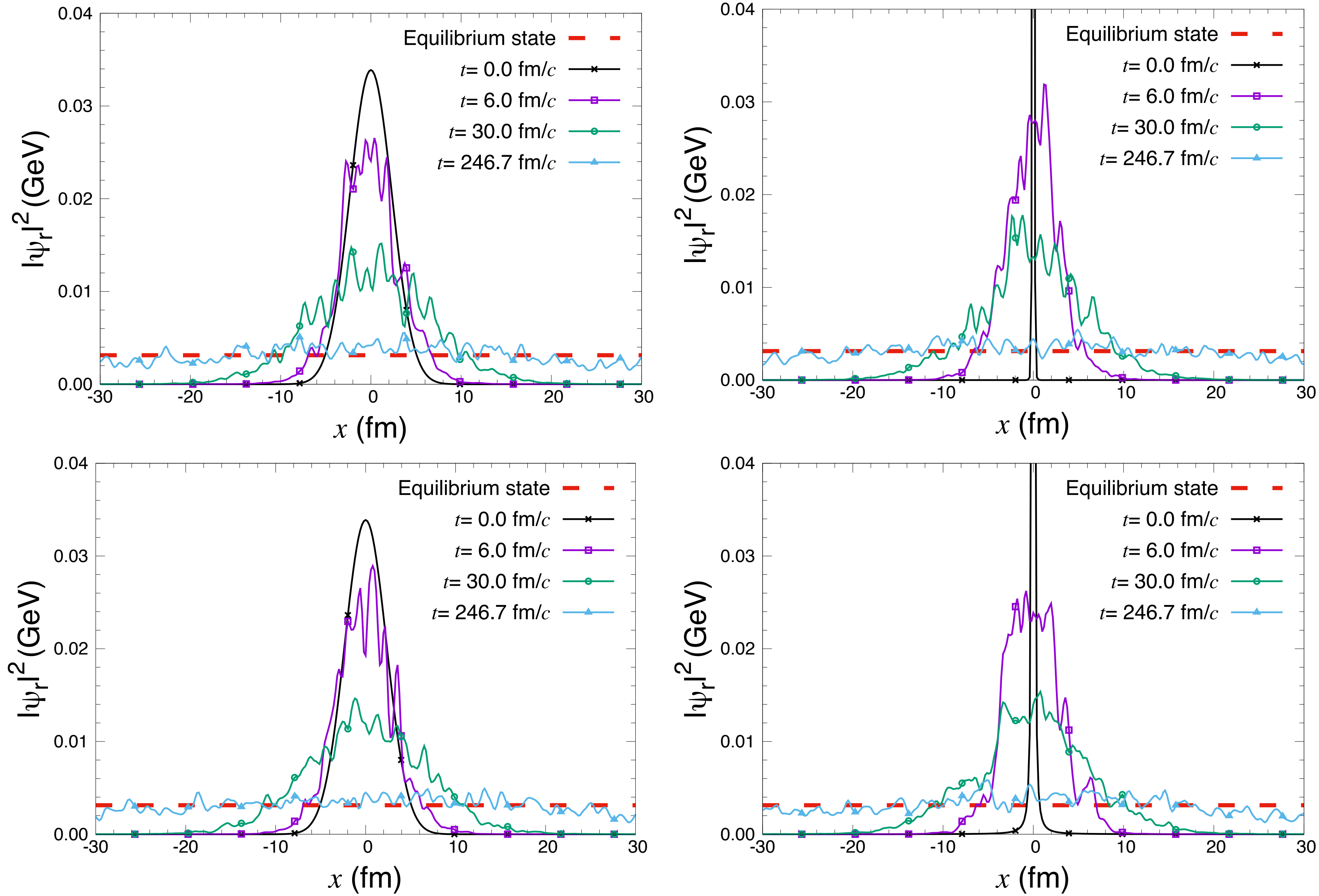
Wave function in momentum space

$\tau_c = 0.03\ \mathrm{fm}/c,\ p_c = 0.3\ \mathrm{GeV},\ \mathrm{L} = 64\mathrm{fm}/c$



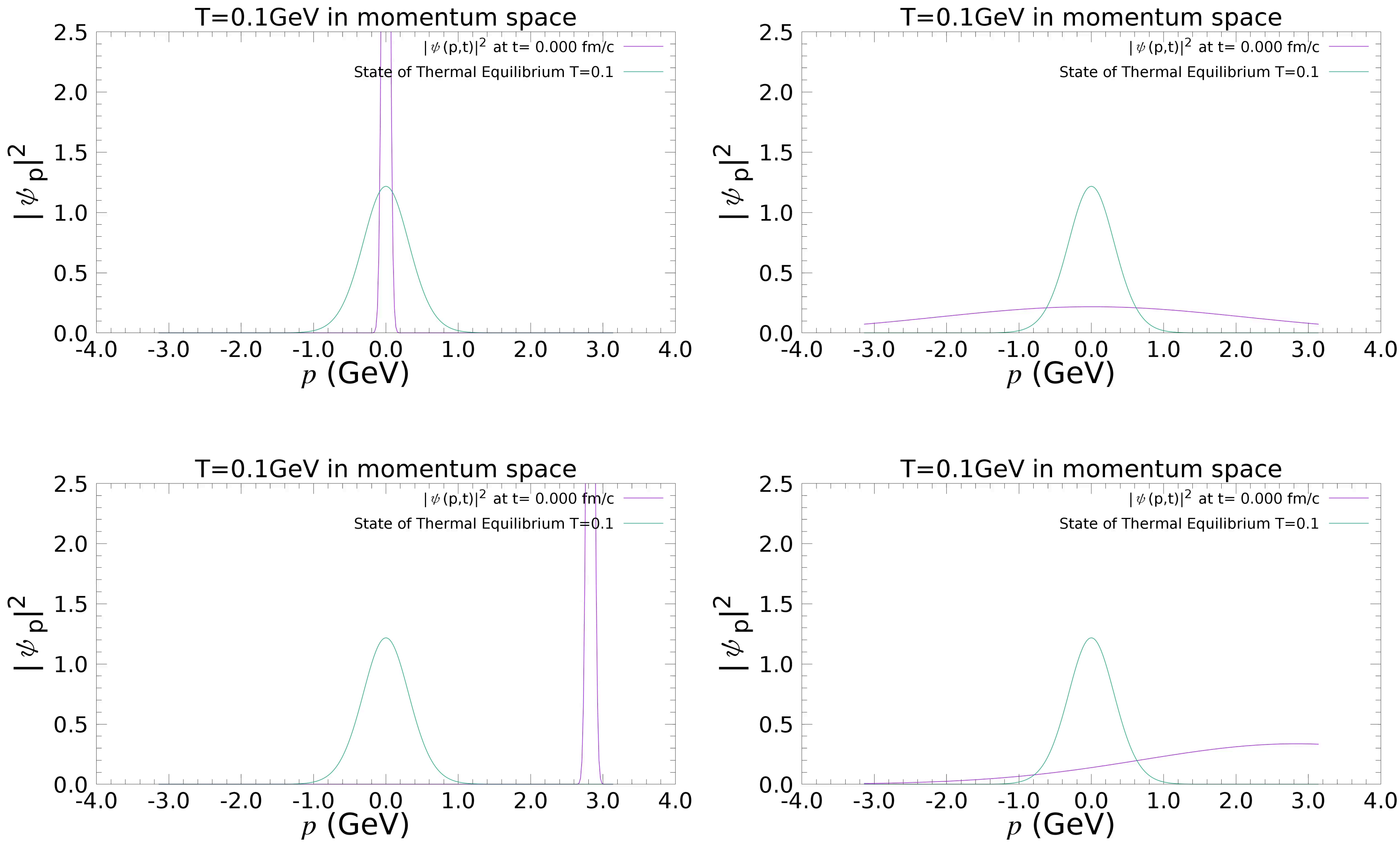
Wave function in spatial space

$\tau_c = 0.03\ \mathrm{fm}/c,\ p_c = 0.3\ \mathrm{GeV},\ \mathrm{L} = 64\mathrm{fm}/c$



Wave function in momentum space

$\tau_c = 0.03\ \mathrm{fm}/c,\ p_c = 0.3\ \mathrm{GeV},\ \mathrm{L} = 64\mathrm{fm}/c$



compare

Our SSE	Other SSE
(1) Equation (interaction picture) $$i\frac{d}{dt}\|\psi\rangle = V_I^{stochastic}\|\psi\rangle$$	J.Phys.Condens.Matter, 24(2012) 273201 $$i\frac{d}{dt}\|\psi\rangle = (H_Q + \lambda H_I)\|\psi\rangle$$ Taylor expansion of λ
(2) ingredients **External field A_0** for QGP (with random phase $e^{i\theta}$) **damping factor** $e^{-E_p/T}$ (from the information of environment) → Detailed balance	**environment wave function** (with random phase $e^{i\theta}$) **sub-system equilibrium condition:** $$\lim_{t\to\infty}\frac{d\rho_Q^{eq}(t)}{dt} = 0$$ → Detailed balance With a term $e^{-E/T}$
(3) properties of random phase term Introduce τ_c, p_c for its correlation in momentum and time.	Random phase term satisfies a **correlation function** (**not delta-function**)

Properties of noise & Ds

$\tau_c = 0.03\ \mathrm{fm}/c,\ p_c = 0.3\ \mathrm{GeV},\ \mathrm{L} = 64\mathrm{fm}/c$

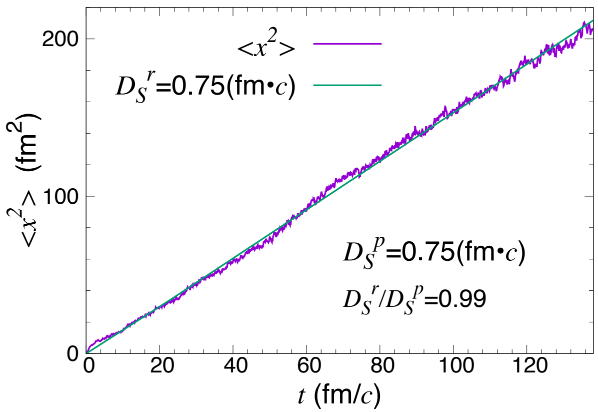
T= 0.1 GeV

Based on classical Langevin equation:

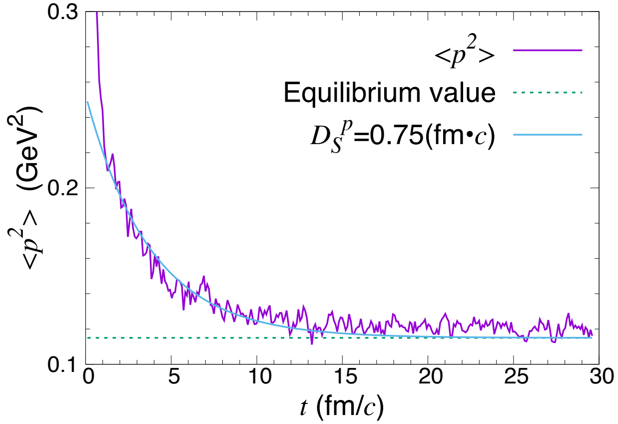
$$\frac{dp}{dt} = -\gamma p + f(t) \qquad D_S = \frac{kT}{\gamma m}$$

$$\langle x^2 \rangle = \frac{2kT}{\gamma m} t + C_1 e^{-\gamma t} + C_2, \qquad \langle p^2 \rangle = \frac{f^2}{2\gamma}(1 - e^{-2\gamma t})$$

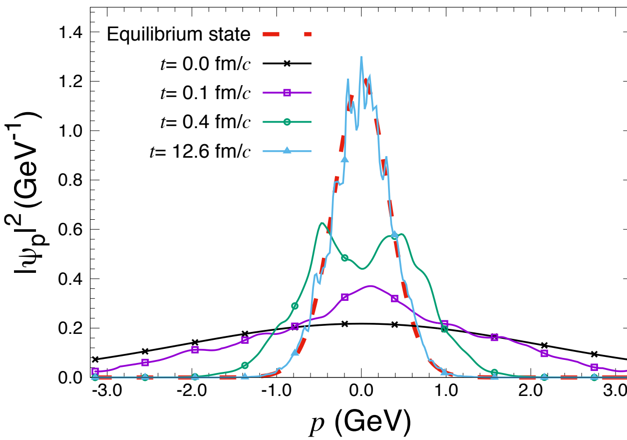
Wavefunction evol.



Diffusion in coordinate space



Diffusion in momentum space



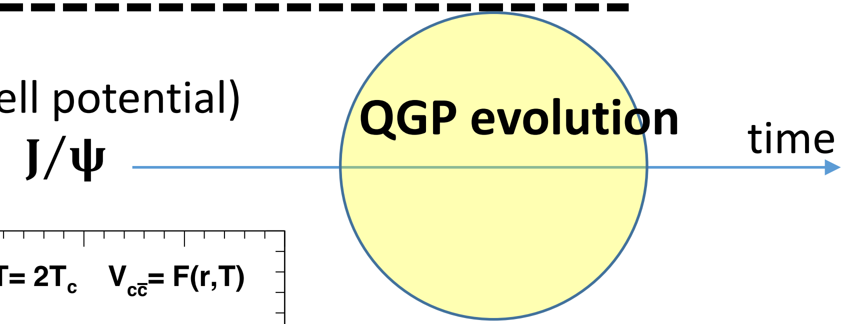
Preliminary: $2 < D_S(2\pi T) < 3$

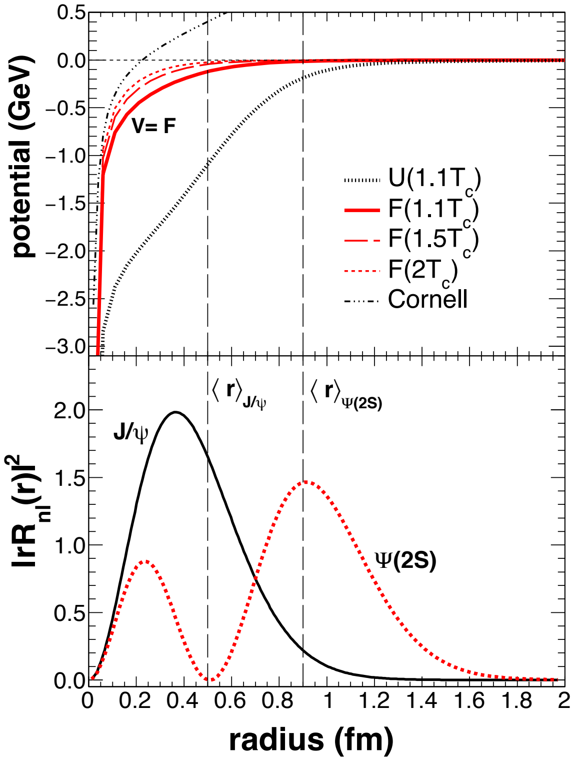
Charmonium (two-body)

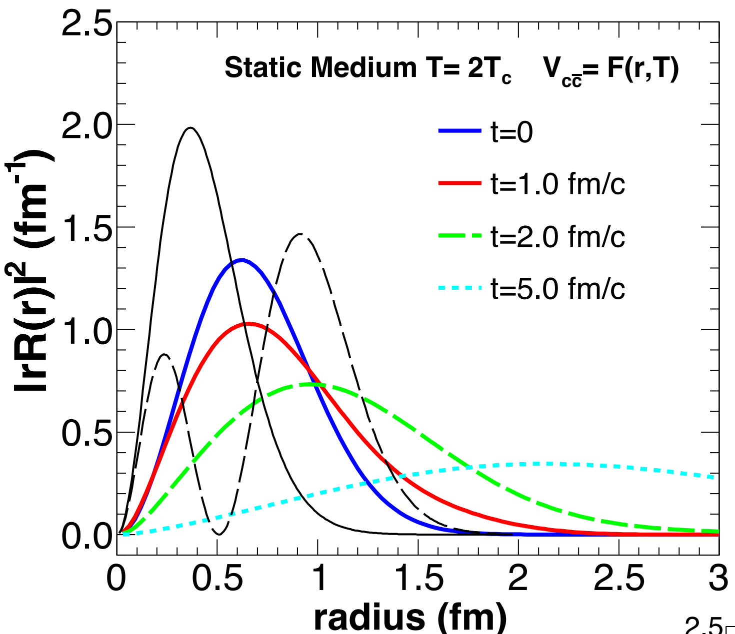
What is Experimentally Measured J/ψ and $\psi(2S)$?

Baoyi, Xiaojian, Carsten, Ralf, in preparation

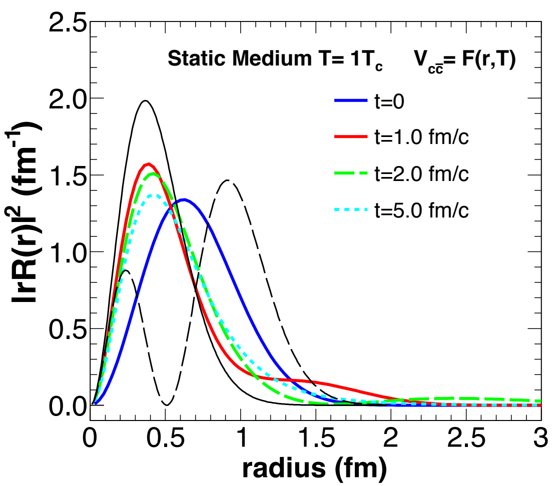
(Cornell potential)







Wave-function evolve



color screened potential

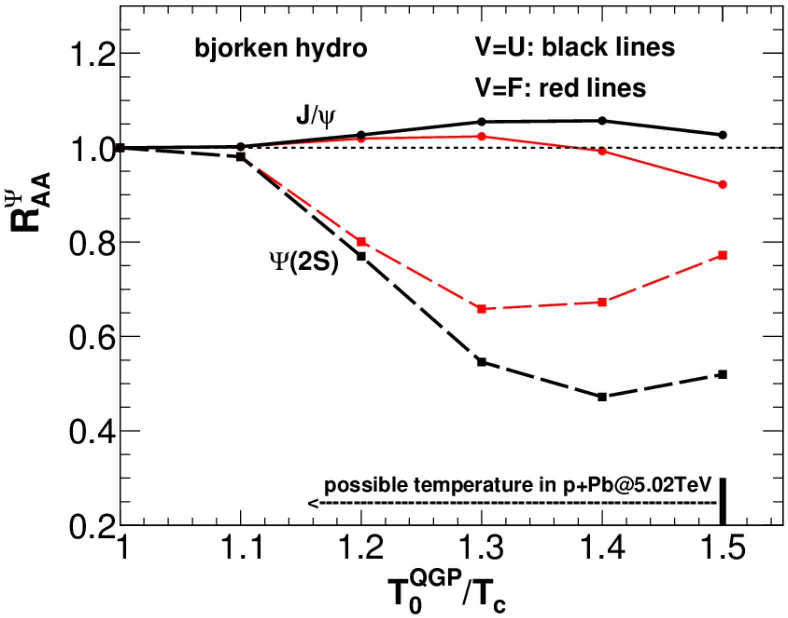
$$i\frac{d}{dt}|\psi\rangle = (H_{kinetic} + V_{screened})|\psi\rangle$$

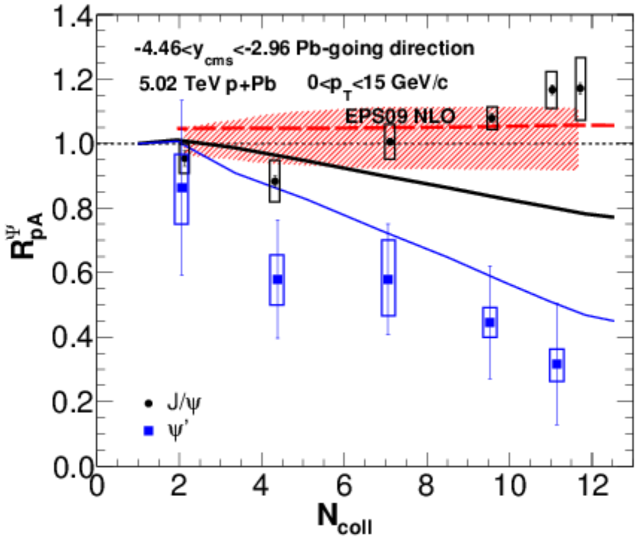
Charmonium with **color screened potential in QGP,**

treated as an **isolated system** temporarily.

Lack of stochastic potential (particle scattering).

Transitions between charmonia





$c\bar{c}$ evolutions in Bjorken hydro,

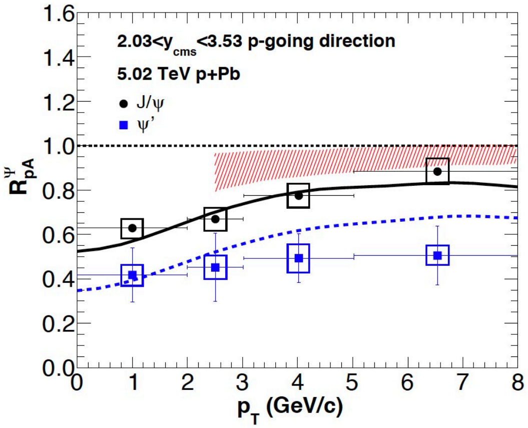
With only **transition mechanism**.

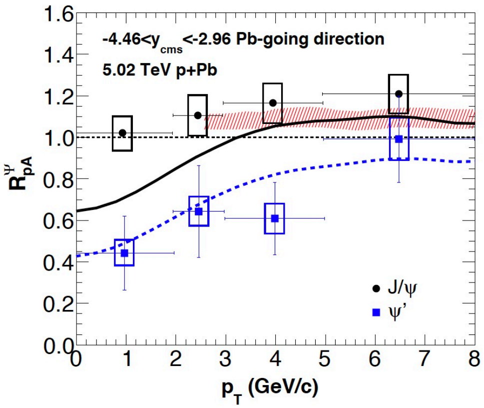
V.S.

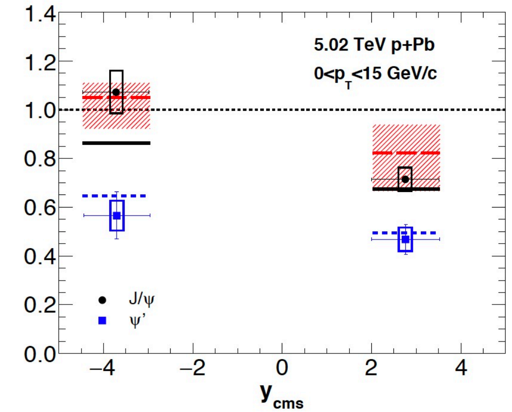
Transport model

With dissociations, No transitions.

***Chen, Zhuang,* PLB 765 (2017) 323-327**

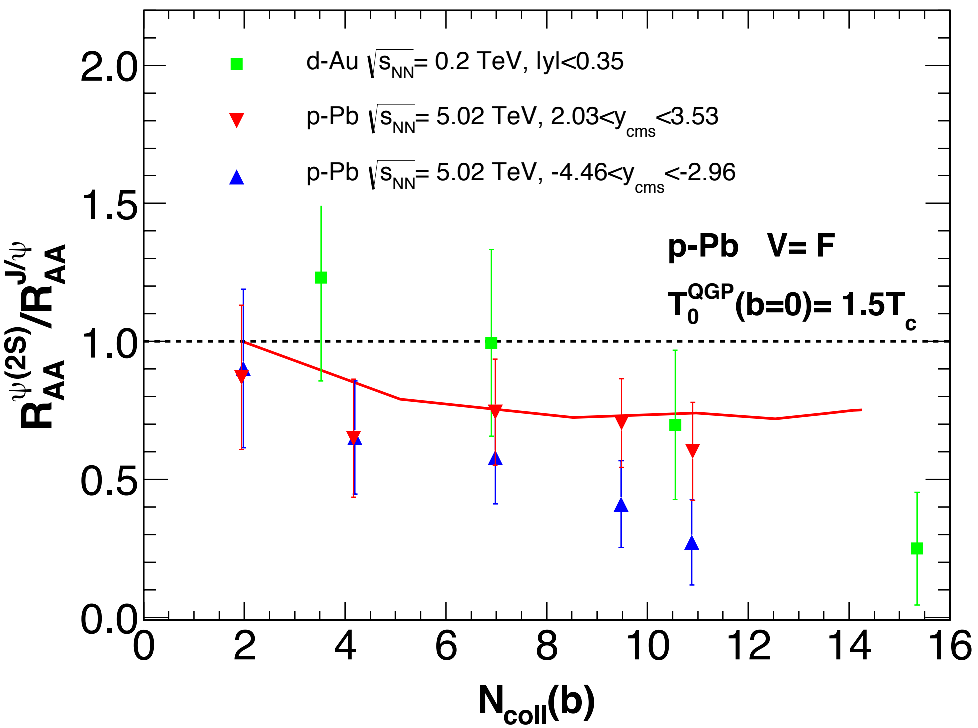






Transitions between charmonia

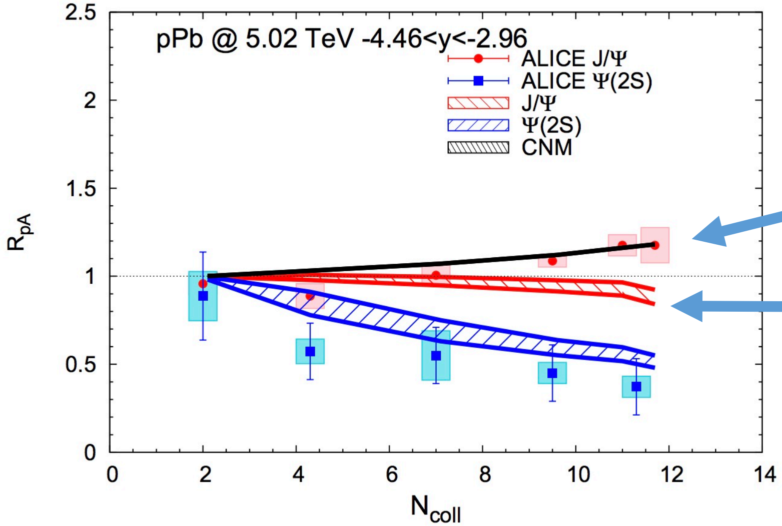
Baoyi, Xiaojian, Carsten, Ralf, in preparation



Its suppression is mainly due to the internal evolution of wavefunction,
Particle inelastic dissociation is now absent.

P-Pb system:
More suitable to study the internal evolutions of ccbar system.
Such as 1S-2S transition mechanism

If without Transitions

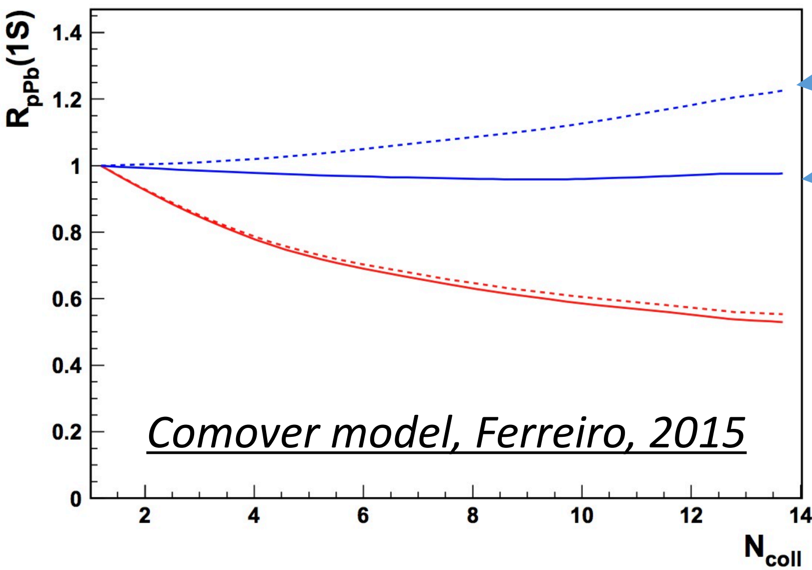


Transport, Ralf, et al, 2018

Only anti-shadowing

anti-shadowing + QGP

(60%, 30%,10%) of total J/psi from direct J/psi, decay of (1P, 2S)



Comover model, Ferreiro, 2015

Only anti-shadowing

anti-shadowing + QGP

Always R_(pA) < 1
from
Tsinghua transport
TAMU transport
Comover model.

Summary

- ***Photoproduction from EM fields***

  charmonium **photo-production** from strong electromagnetic fields and **hadro-production**

- ***Stochastic-Schrodinger-Equation (SSE)***

  We construct the **Stochastic Schrodinger Equation (SSE)** and **stochastic potential** to study the wave function evolutions of heavy quark.

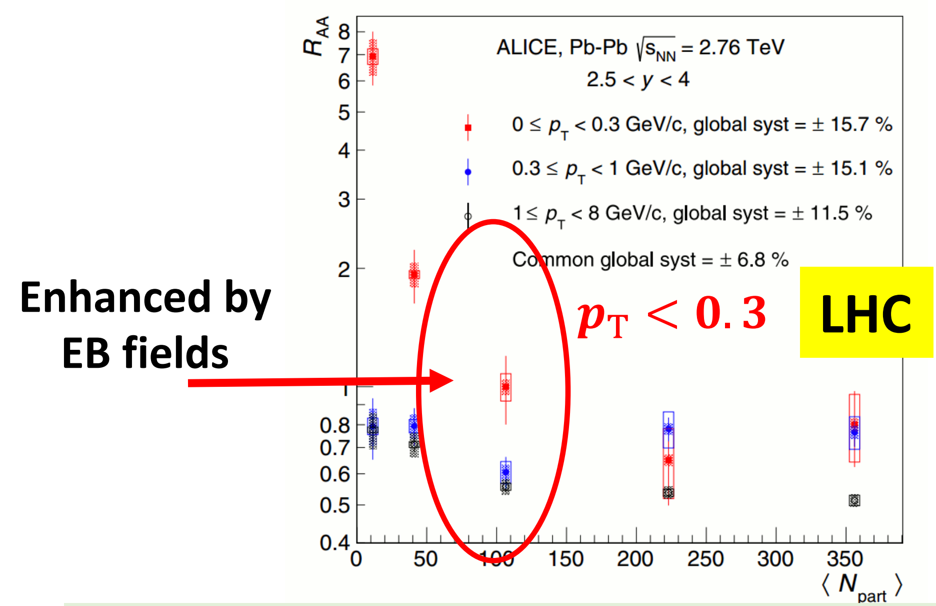
  *SSE can provide a way to include both **particle collision process** and **color screening** in Schrodinger equation for charm and ψ.*

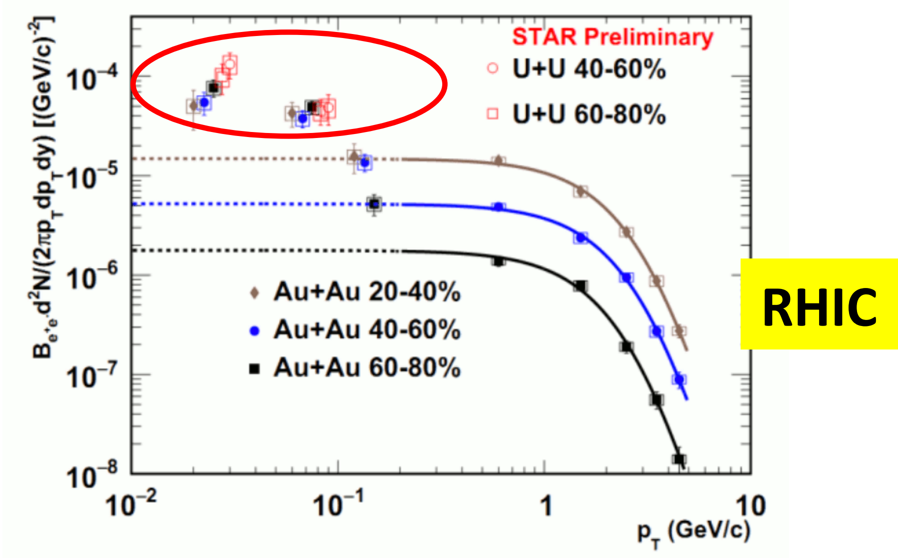
- ***Charmonium transition within Schrodinger***

  Charmonium (1S, 2S) transitions based on Schrodinger equation are also studied in small systems (p-Pb)

More slides

Photoproduction contribution





- Significant enhancement of J/ψ yield in low $p_T < 0.1$ GeV/c, and peripheral and semi-central collisions

- At Np=100, $T_0^{QGP} = 2T_c$

QGP effect important !
Photoproduction important !

TABLE I: Information of QGP based on (2+1)D ideal hydrodynamics

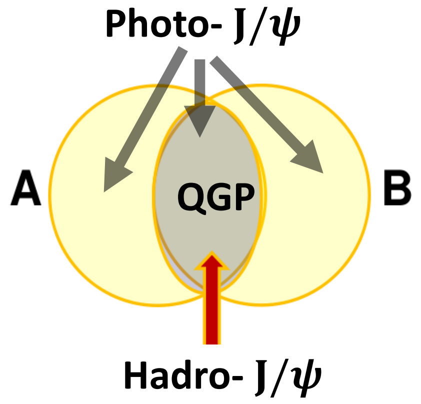
Hydro in LHC $\sqrt{s_{NN}}$=2.76 TeV Pb-Pb, $2.5 < y < 4$			
b(fm)	N_p	T_0^{QGP}/T_c	τ_f^{QGP} (fm/c)
0	406	2.6	7.3
9	124	2.1	4.2
9.6	103	2.06	3.9
10.2	83	1.95	3.5
10.8	64	1.84	3.1

J/ψ from electromagnetic field

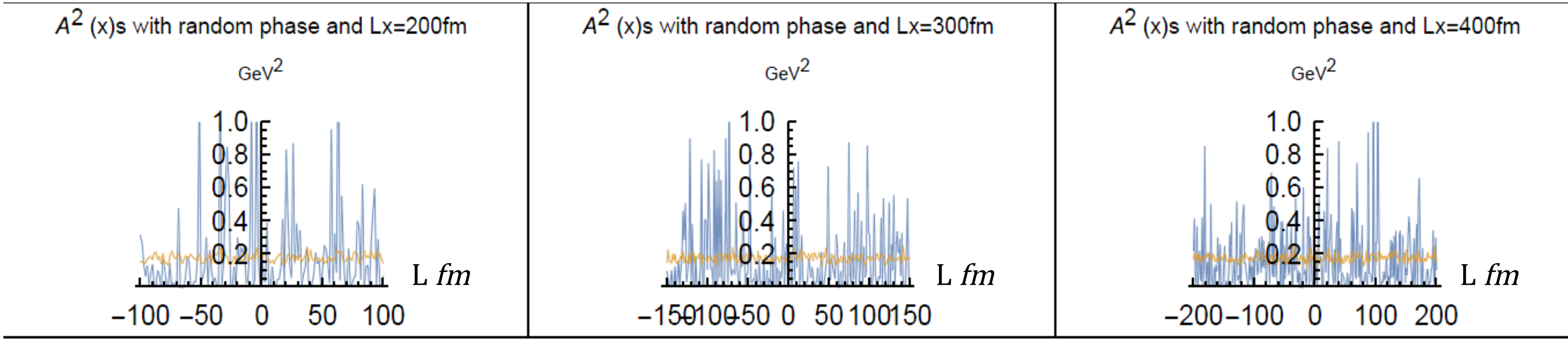
- **Our formula for J/ψ photo-production with QGP effect**

$$\frac{d\widetilde{N}_{J/\psi}}{dy}(y|b) = \int d^2\mathbf{x}_T w n_\gamma(w,b)\sigma_{\gamma A\to J/\psi A}(w) \times f^{norm}(\mathbf{x}_T+\mathbf{b}/2) \times [\mathcal{R}_g(\mathbf{x}_T+\mathbf{b}/2,x,\mu)]^2 \times e^{-\int_{\tau_0}^{\tau_f} d\tau \alpha_\Psi(\mathbf{x}_T,\mathbf{b},\tau)}$$
$$+ (y\to -y, \mathbf{b}/2 \to -\mathbf{b}/2)$$

shadowing QGP



$A_0(\vec{x})$ field is intensive



$$A_0(\vec{x}) = \sum_{p>0} 2\sqrt{\frac{2d_g}{|\vec{p}|L}}\exp\left(-\frac{|\vec{p}|}{2T}\right)\cos(p_x x - \theta_{p_x})$$

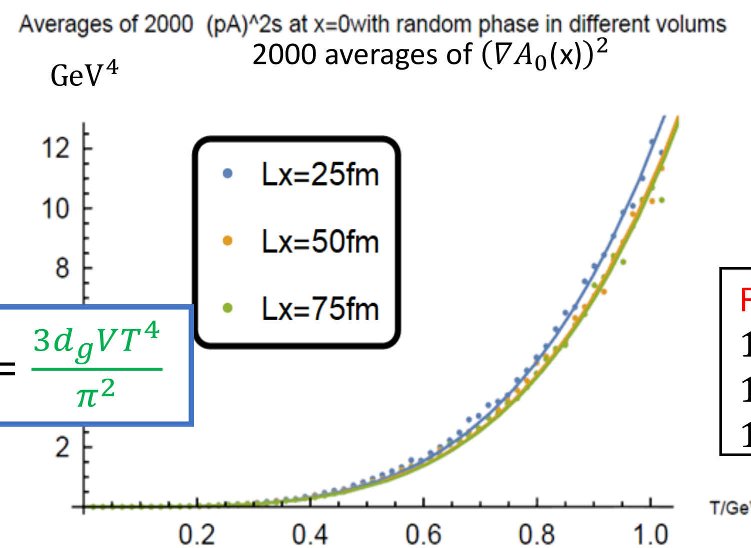
$$\Delta p = \frac{2\pi}{L} \qquad d_g = 16$$

$E[(\nabla A_0(x))^2]$ is independent of x

(Choose the point $x = 0$)

Field energy | Gluon gas energy

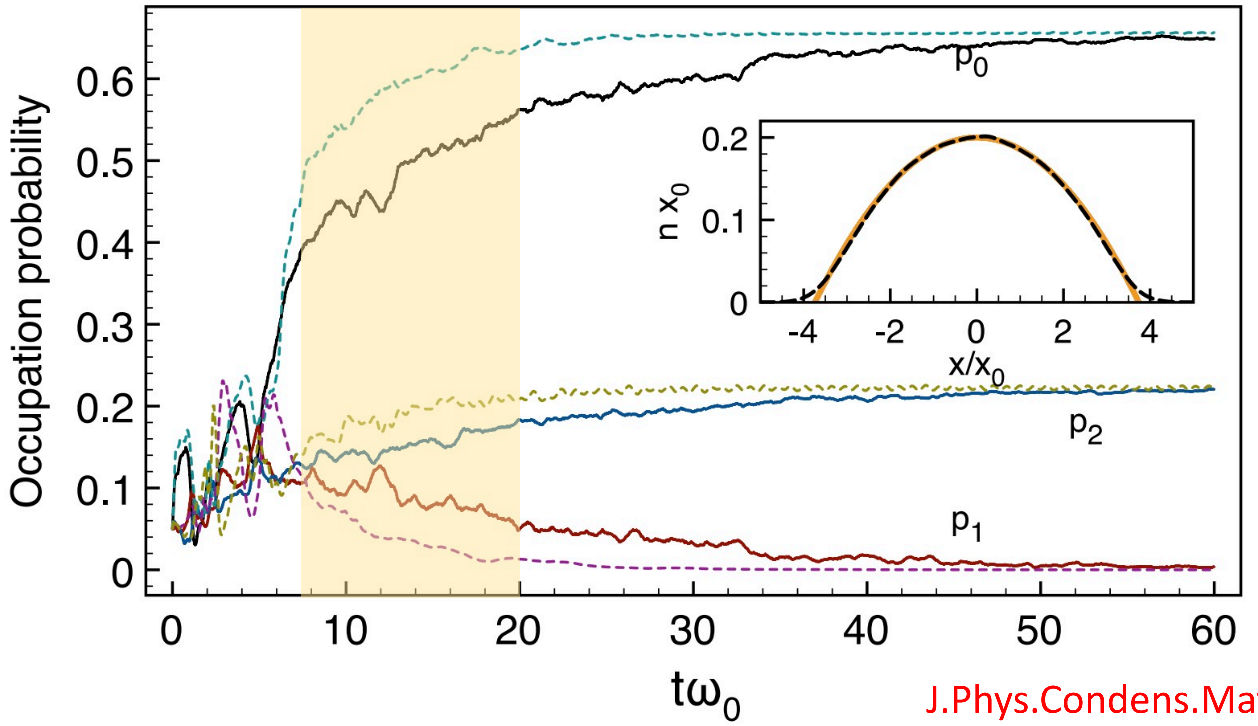
$$U = \int d^3x \frac{1}{2}(\nabla A_0(x))^2 = \int \frac{d^3p}{(2\pi)^3} E_p\, a^2(\vec{p}) = \frac{3 d_g V T^4}{\pi^2}$$



Fittings
$11.87\, T^4$
$10.78\, T^4$
$10.58\, T^4$

Numerical results show that $A_0(x)^2$s' mean value are intensive, not extensive

Compare with master equation

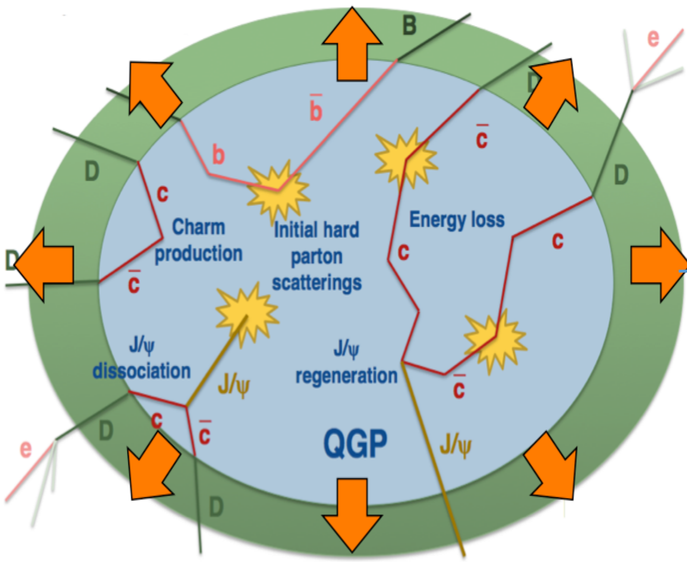


J.Phys.Condens.Matter, 24(2012) 273201

Thermalization process from SSE and master equation of density matrix are diefferent.

Classical Theoretical Models

Boltzmann transport models



Primordial production

Transport two-component model

Tsinghua Group:

Chen, Zhuang, Phys.Lett. B726 (2013) 725-728

Chen, Zhuang, Phys.Lett. B765 (2017) 323-327

TAMU group:

Xingbo, Ralf, Nucl.Phys. A859 (2011) 114-125

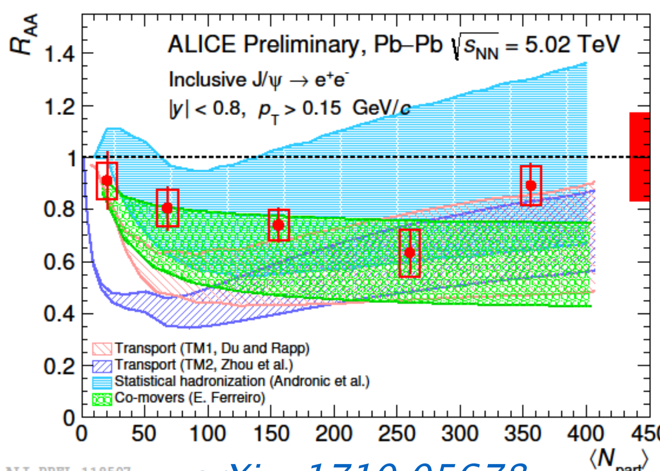
Recombination of $c\bar{c}$ during QGP expansion

$\mathbf{c} + \bar{\mathbf{c}} \leftrightarrow J/\psi + g$ ***dominates in AA***

Che-ming Ko, Ralf Rapp, R. L. Thews, P. Braun-Munzinger

Jiaxing Zhao, Baoyi Chen

$N_{J/\psi} \propto N^2_{N_{c\bar{c}}}$



arXiv: 1710.05678

- **Large uncertainties** of ($N_{c\bar{c}}$) **theoretical calculations** and **experimental data**