Heavy quark and quarkonium evolutions in heavy ion collisions

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Topics

--$\psi(2S)$

1) **Heavy quarkonium production mechanisms** in the Quark Gluon Plasma

primordial production, regeneration, photoproduction, transitions,…

2) **Charm diffusions** in the QGP

Langevin + Wigner function for single charm evolutions and recombination

large v_2 "puzzle" of J/ψ, v_2 between J/ψ and $\psi(2S)$

,

3) **Quantum effects inside ccbar dipole by color screening**

QGP screened heavy quark potential → transitions between different bound states,
wave function evolutions (depend on T)

4) **Charmonium photoproduction from EB fields, even at $b < 2R_A$**

important at extremely low p_T<0.1 GeV/c

J/ψ , $\psi(2S)$

5) **pA collisions (still QGP existence ?)**

Phys.Lett. B 765, 323(2017)

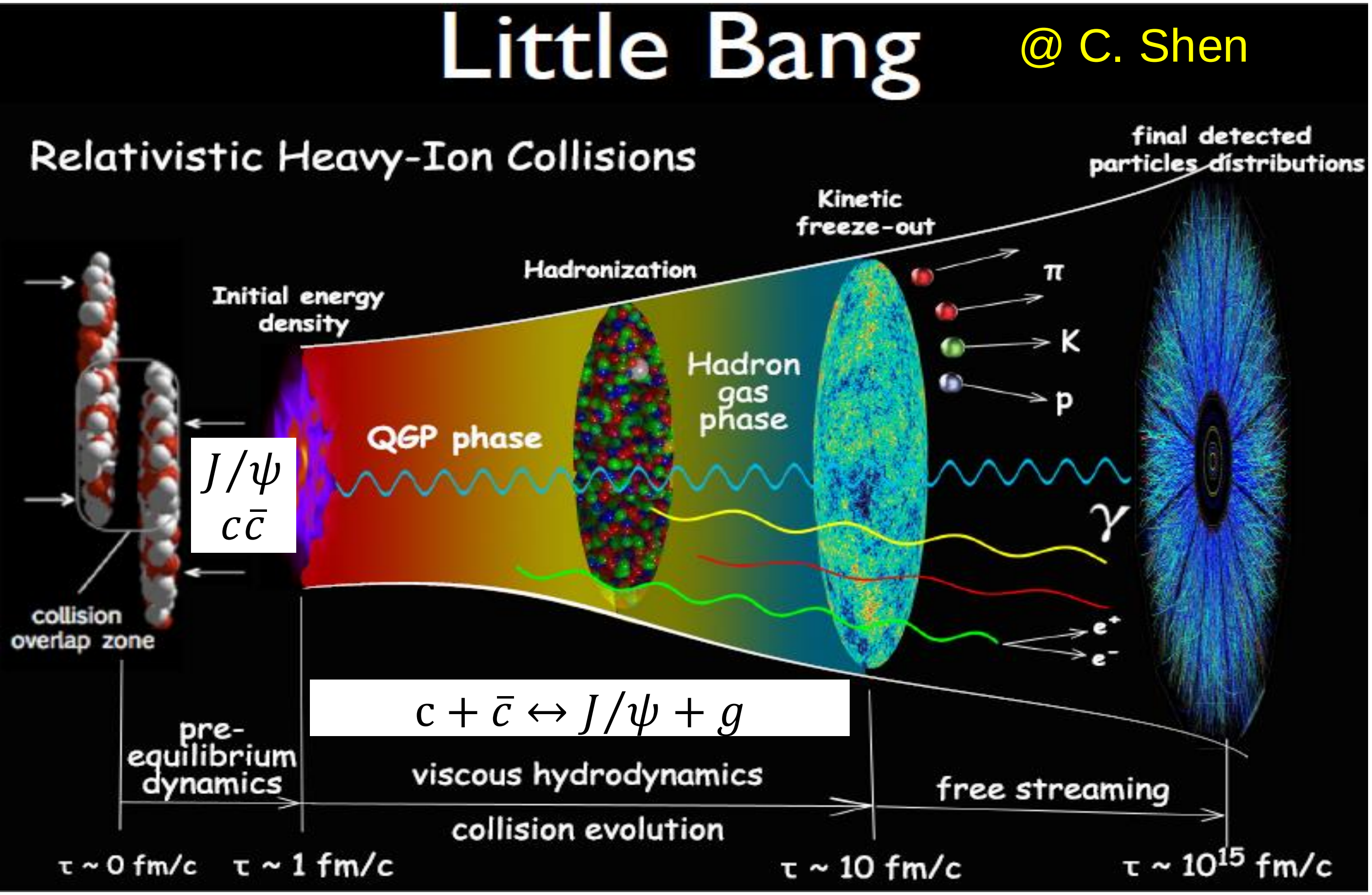
6) Ds/D0 enhancement: strange enhancement and **charm conservation**

background

$V = U$

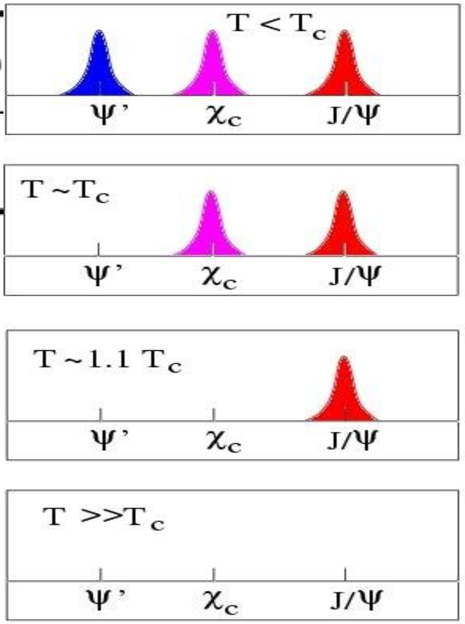
State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60

Satz, et al



J/ψ
$c\bar{c}$

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



Sequential dissociation

background

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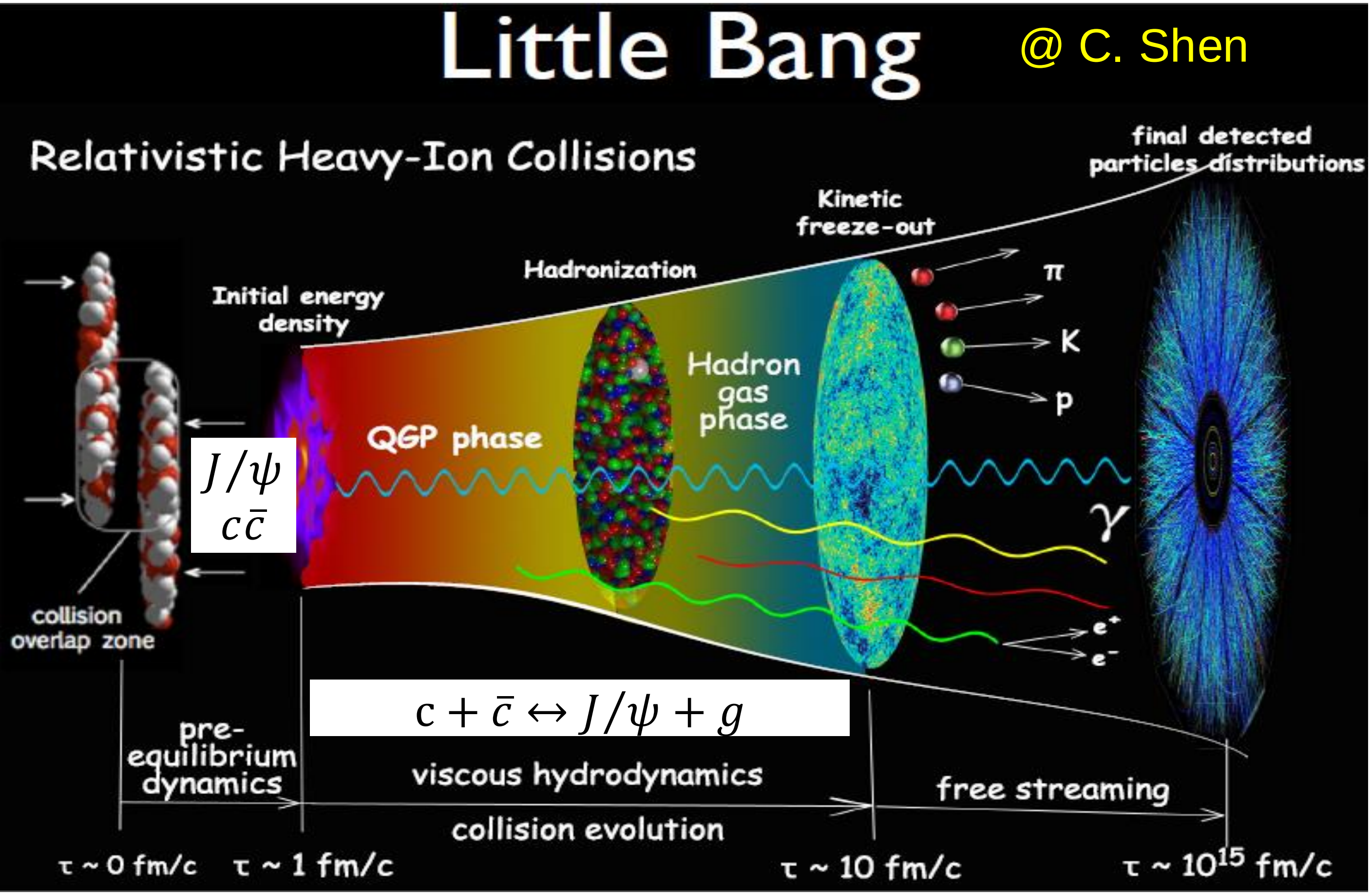

@ C. Shen

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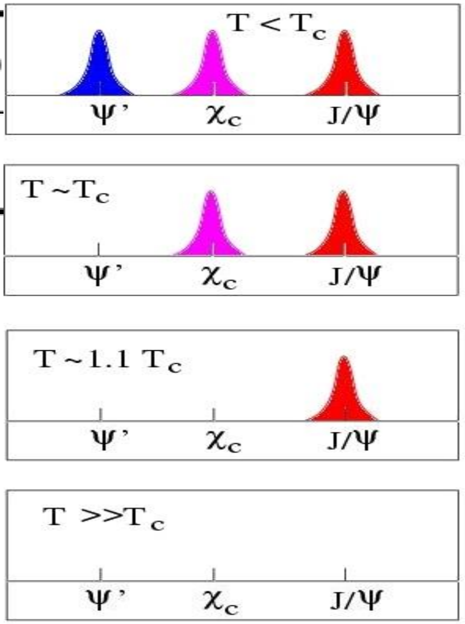


Sequential dissociation

Heavy Ion:

light hadron spectra;
Jet energy loss;
heavy quark thermalize;
quarkonium dissociation
thermal photons;
B induced chiral effect

Heavy quarkonium as a probe of QGP

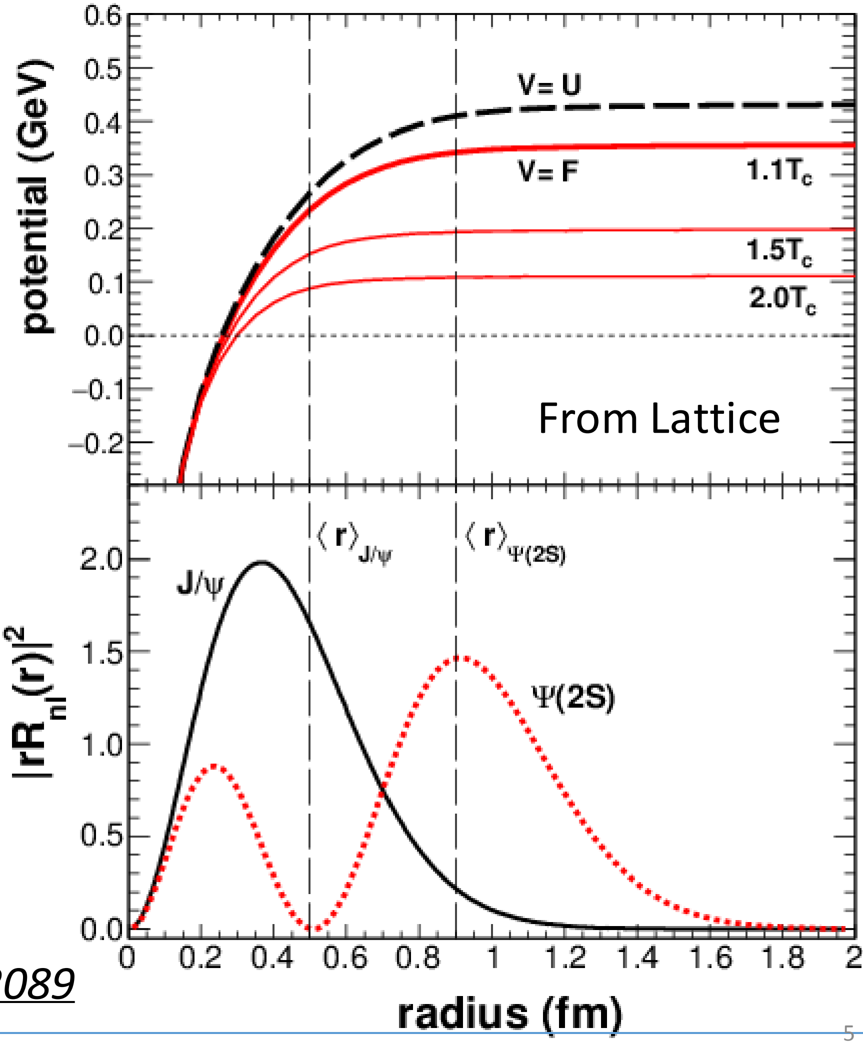
J/ψ as a probe of QGP：

J/ψ suffer color screening end inelastic collisions of partons in QGP

J/psi production in AA collisions (with cold and hot matter effects)

$$R_{AA}^{J/\psi} = \frac{N_{AA}^{J/\psi}}{N_{pp}^{J/\psi} N_{coll}}$$

J/psi production in pp collisions (without CNM and HM)



<u>*BC, Du, Rapp, arXiv:1612.02089*</u>

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1. Charmonium production mechanisms in HIC

Heavy quarkonium as a probe of QGP

Transport model

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

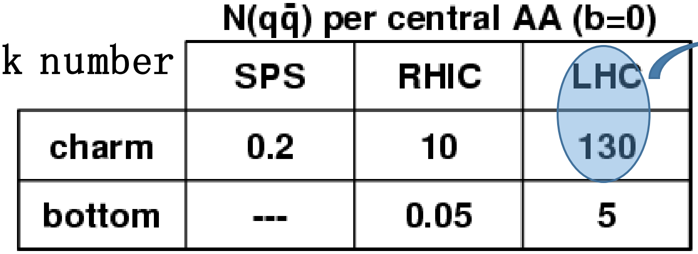
$J/\psi + g \to c + \bar{c}$
$c + \bar{c} \to J/\psi + g$

$$\alpha_\psi(\vec{p}_t, \vec{x}_t, \tau, \vec{b}) = \frac{1}{2E_t} \int \frac{d^3\vec{k}}{(2\pi)^3 2E_g} \sigma_{g\psi}(\vec{p}, \vec{k}, T) 4F_{g\psi}(\vec{p}, \vec{k}) f_g(\vec{k}, T)$$

$$\beta_\psi(\vec{p}_t, \vec{x}_t, \tau, \vec{b}) = \frac{1}{2^4 (2\pi)^9 E_t} \int \frac{d^3\vec{k}}{E_g} \frac{d^3\vec{q}_c}{E_c} \frac{d^3\vec{q}_{\bar{c}}}{E_{\bar{c}}} W_{c\bar{c}}^{\psi g}(\vec{q}_c, \vec{q}_{\bar{c}}) \boxed{f_c(\vec{q}_c, T)\ f_{\bar{c}}(\vec{q}_{\bar{c}}, T)} \times (2\pi)^4 \delta^{(4)}(p + k - q_c - q_{\bar{c}})$$

Dynamical evolution

$N^{c\bar{c} \to J/\psi} \sim (N^{c\bar{c}})^2$



N(qq̄) per central AA (b=0)

Quark number	SPS	RHIC	LHC
charm	0.2	10	130
bottom	---	0.05	5

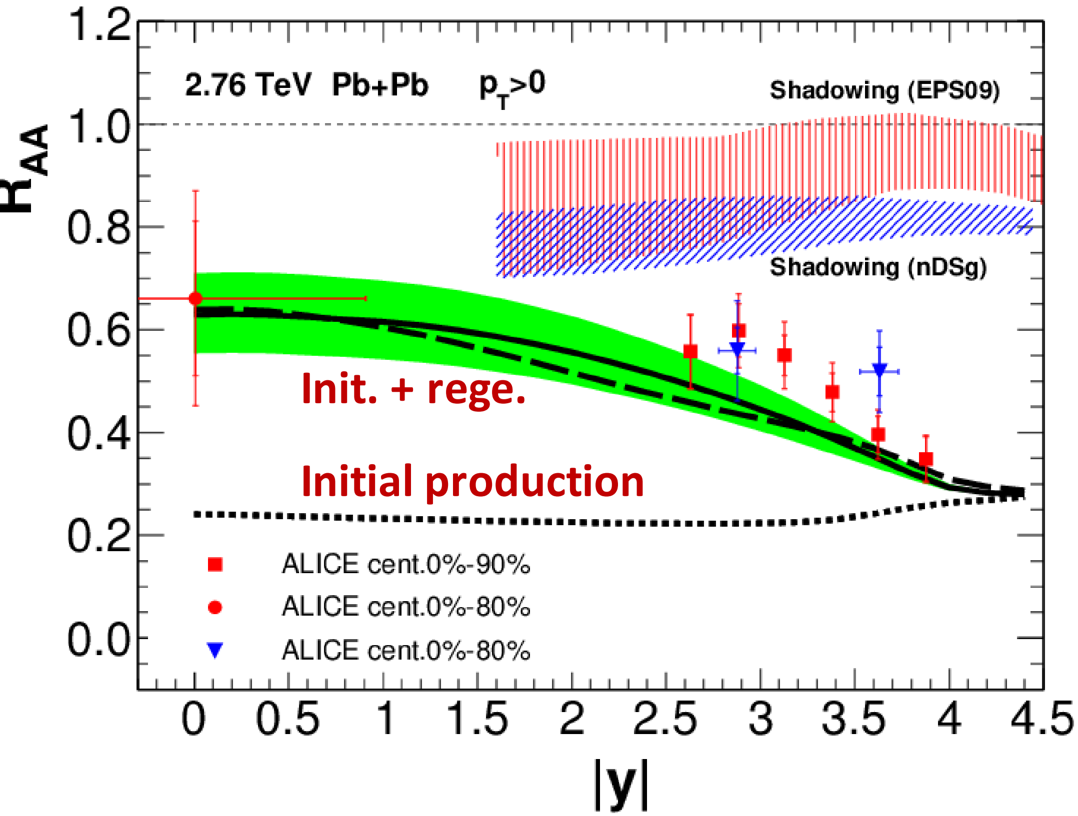
✓ Higher temperature, larger α_ψ, less initial production

✓ Larger $N_{c\bar{c}}$, larger β_ψ, more regeneration

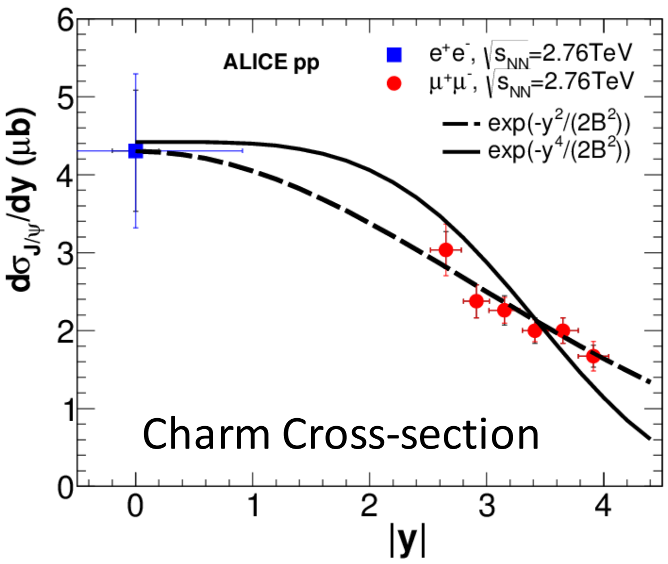
Initially produced ψ: **from parton hard scatterings, carry large p_T**

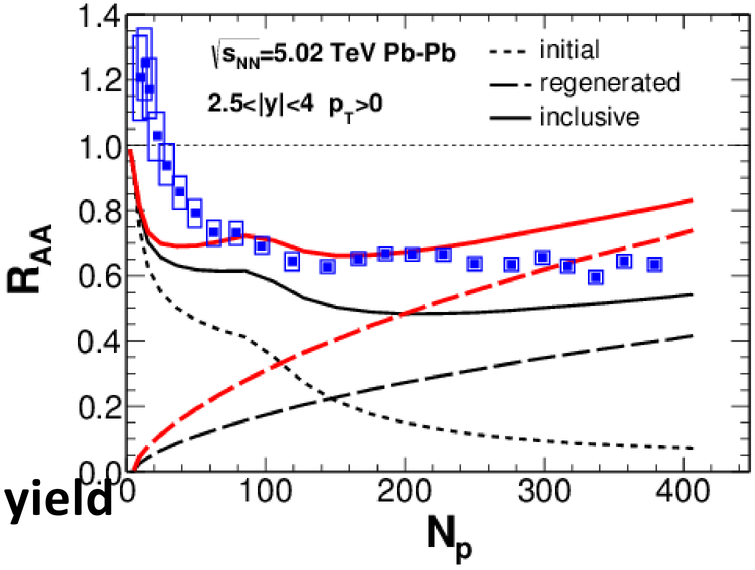
Regenerated: **charm interact with QGP, loss energy, carry QGP collective flow**

Charmonium in QGP



B. Chen, PRC 93, 054905(2016)





Summary:

Regeneration dominates at low p_T, and total yield

Initial production dominates at high p_T

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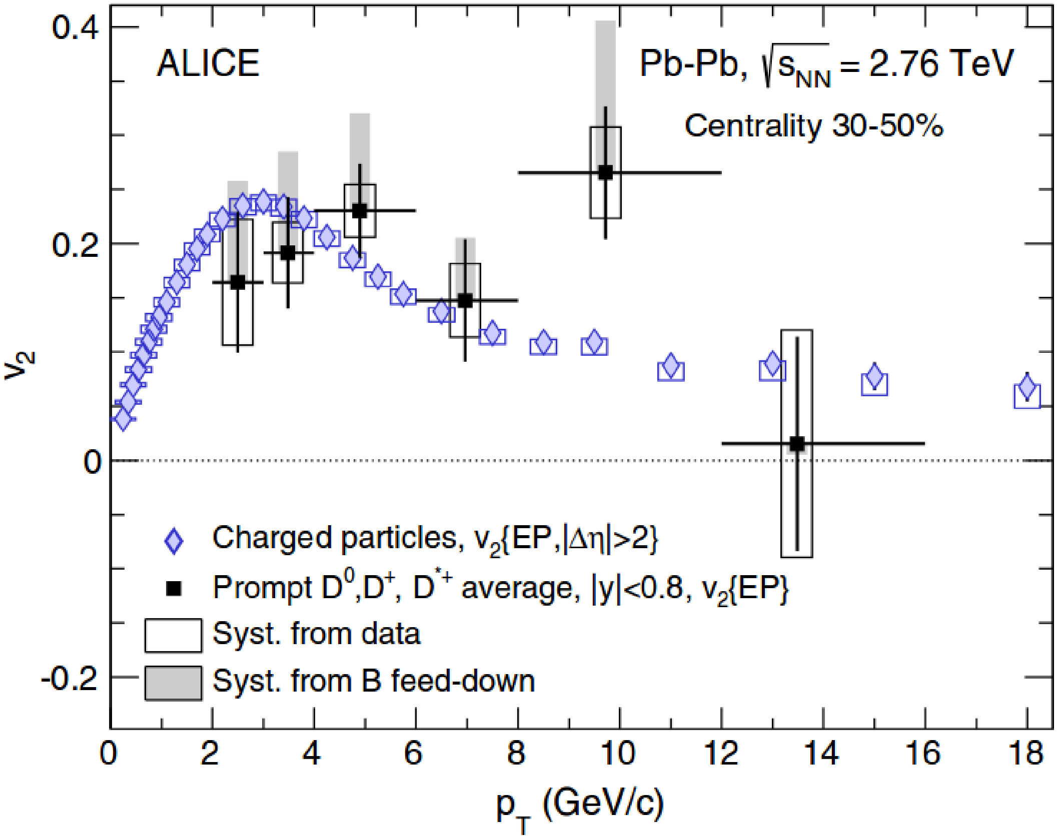
2. Charm diffusion in the expanding QGP

Charm diffusion

D mesons obtain the similar collective flows like light hadrons

→ indicate the momentum thermalization of charm quarks at the QGP hadronization.



PRL, 111, 102301(2013)

However,
how and **when** charm quarks reach thermalization ?

Depending on:
QGP temperature,
coupling strength,
Charm momentum, etc

How does charm diffusion suppress the Ψ regeneration process?

Charm diffusion

First, Let’s assume an instant charm thermalization

1) Local momentum distribution

$$f_c(p)=\frac{N^{norm}}{e^{p^\mu u_\mu/T}+1}$$

in local fliud cell

u_μ: velocity of QGP cell

2) Charm distribution in coordinate space

$$\boldsymbol{\partial_\mu(\rho_c(r)u^\mu)=0}$$

Conservation of charm quark number;

Strong diffusion **(controlled by $\mathbf{u^\mu}$)**

Large mass of charm quark: Not chemical equilibrium

Full distribution in phase space $f_c(r,p)=\rho_c(r)f_c(p)$

3) Charm initial distribution from hard scatterings,

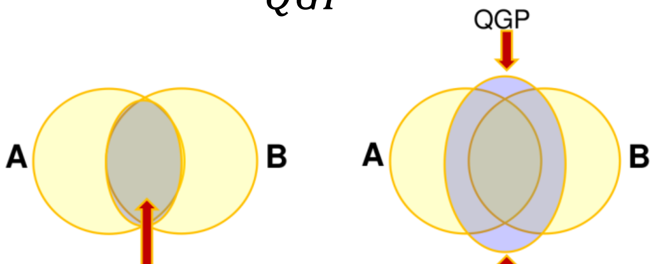
$$\rho_c(\tau_0,x_T,\eta)=\frac{T_A(x_T)T_B(x_T-b)cosh\eta}{\tau_0}\,\frac{d\sigma_{pp}^{c\bar{c}}}{d\eta}$$

Usually with uncertainties ~ 50%

Charm diffusion and kinetic equilibrium

Remember that $N_{J/\psi} \sim \int dV \, \frac{N_c}{V_{QGP}} \, \frac{N_{\bar{c}}}{V_{QGP}} W_{combine} \sim \frac{(N_{c\bar{c}})^2}{V_{QGP}}$

Charm expands outside with QGP



a) Charm distributed at $\tau \geq \tau_0$

b) Charm distributed at $\tau \geq \tau_0$

Beam-line View

- **coalescence model** J. Zhao, B. Chen, arXiv:1705.04558

$c + \bar{c} \rightarrow$ J/ψ +g

$$\frac{dN_{J/\psi}}{d^2\vec{P}_T d\eta} = C \int \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3} \frac{d^4r d^4p}{(2\pi)^3} W(r,p) \boldsymbol{f_c(\vec{r}_1,\vec{p}_1,t) f_{\bar{c}}(\vec{r}_2,\vec{p}_2,t)}$$

C=1/12 for vector meson (J/psi)

- Wigner function describes the recombination probability of one c and $\bar{c}$:

$$W(\vec{r},\vec{p}) = \int d^3y e^{-i\vec{p}\cdot\vec{y}} \psi(\vec{r} + \frac{\vec{y}}{2}) \psi^*(\vec{r} - \frac{\vec{y}}{2})$$

$\boldsymbol{\psi(\vec{r})}$: wavefunction of charmonium eigenstate. (from time-independent Schrodinger equation)

Charm diffusion and kinetic equilibrium

Remember that $N_{J/\psi} \sim \int dV \, \frac{N_c}{V_{QGP}} \frac{N_{\bar{c}}}{V_{QGP}} W_{combine} \sim \frac{(N_{c\bar{c}})^2}{V_{QGP}}$

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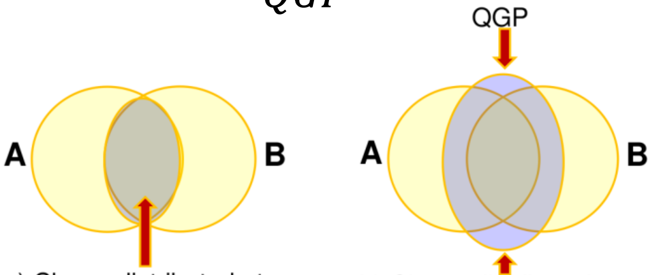


a) Charm distributed at $\tau \geq \tau_0$

b) Charm distributed at $\tau \geq \tau_0$

Beam-line View

- **2.76 TeV** V.S. **5.02 TeV**

(Pb-Pb collisions):

larger initial T_0^{QGP}, larger QGP volume at hadronization

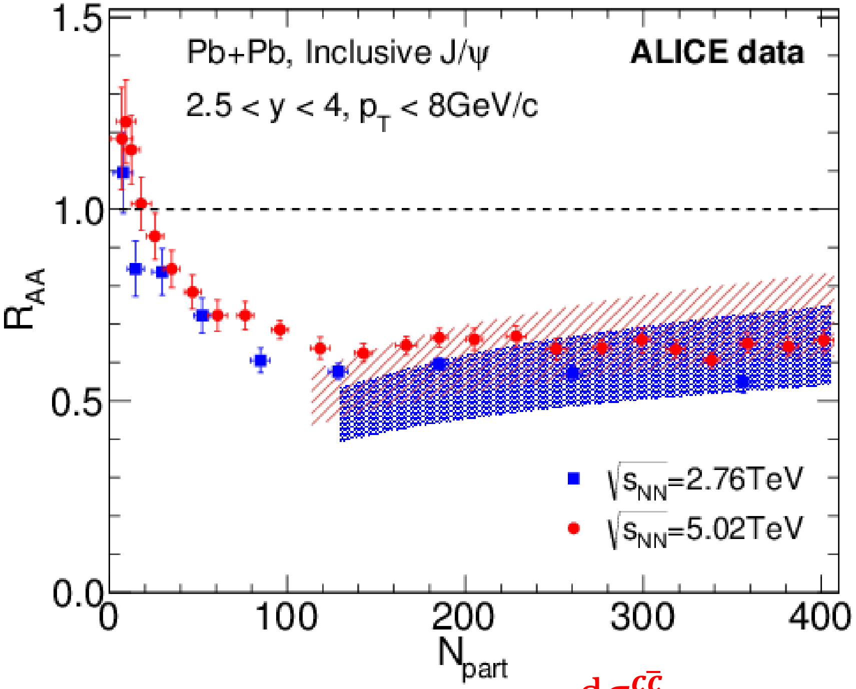
charm number enhanced by more than 50%

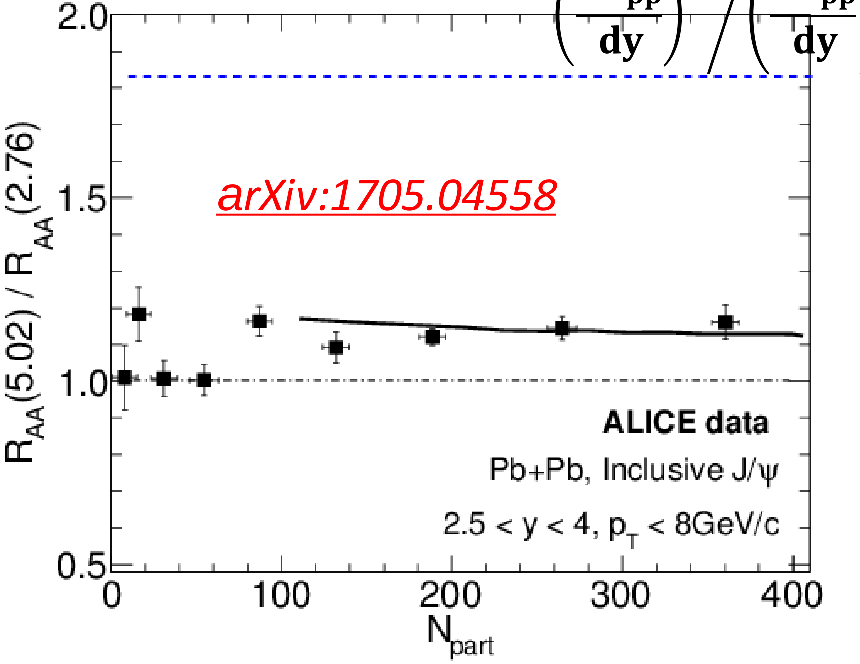
→ Accelerating expansion makes $V_{QGP}(T = T_c, 5.02)$ larger

→ $N_{J/\psi}(5.02)$ does not become $\sim 1.5^2$ times, (see exp. Data later)

Experimental data gives: $R_{AA} = \frac{N_{AA}^{c+\bar{c}\to J/\psi+g}}{N_{pp}^{J/\psi} N_{coll}}$

J/ψ R_{AA} at 2.76 and 5.02 TeV





$$\left(\frac{\mathbf{d}\sigma_{\mathbf{pp}}^{\mathbf{c\bar{c}}}}{\mathbf{dy}}\right)^{2} \Big/ \left(\frac{\mathbf{d}\sigma_{\mathbf{pp}}^{\psi}}{\mathbf{dy}}\right)$$

arXiv:1705.04558

Cross section: $\left\{ \begin{array}{l} \frac{d\sigma_{pp}^{c\bar{c}}}{dy} = \mathbf{0.33mb}\ (\mathbf{0.57mb})\ \ \textbf{for 2.76 (5.02) TeV} \\ \text{Upper limit: } \frac{d\sigma_{pp}^{c\bar{c}}}{dy} \text{ enhanced by 20\%} \end{array} \right.$

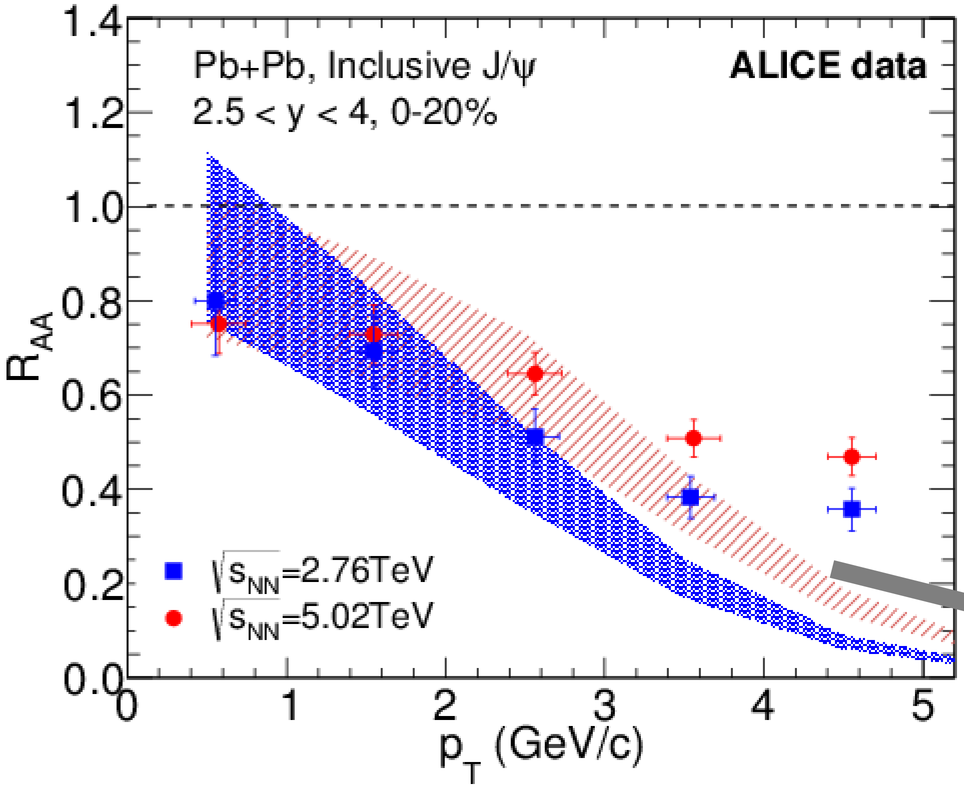
The ratio of charm quark number at 5.02 and 2.76 TeV is around 1.7 with large uncertainty,

(1) with the same QGP, we expect R_{AA} **ratio ≈ charm ratio ≈ 1.7**

(2) with different QGP, R_{AA} **ratio ≈ 1.1**

→ Strong diffusion of charm suppress J/ψ regeneration.

J/ψ R_{AA} at 2.76 and 5.02 TeV



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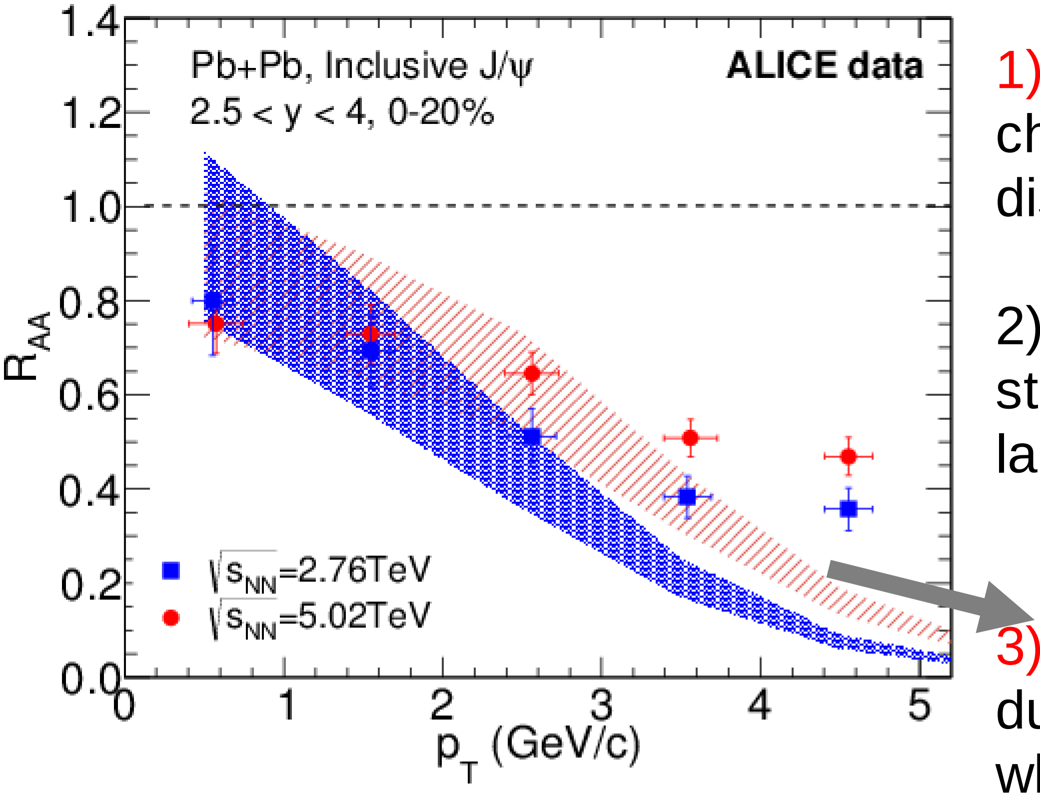
1). Charm collective flow also change the regenerated J/ψ p_T distribution

2). At 5.02 TeV, QGP expansion stronger, push charm quark to larger p_T bin

3). Underestimation at high p_T is due to the lack of initial production, which dominate the high p_T region.

J/ψ R_{AA} at 2.76 and 5.02 TeV



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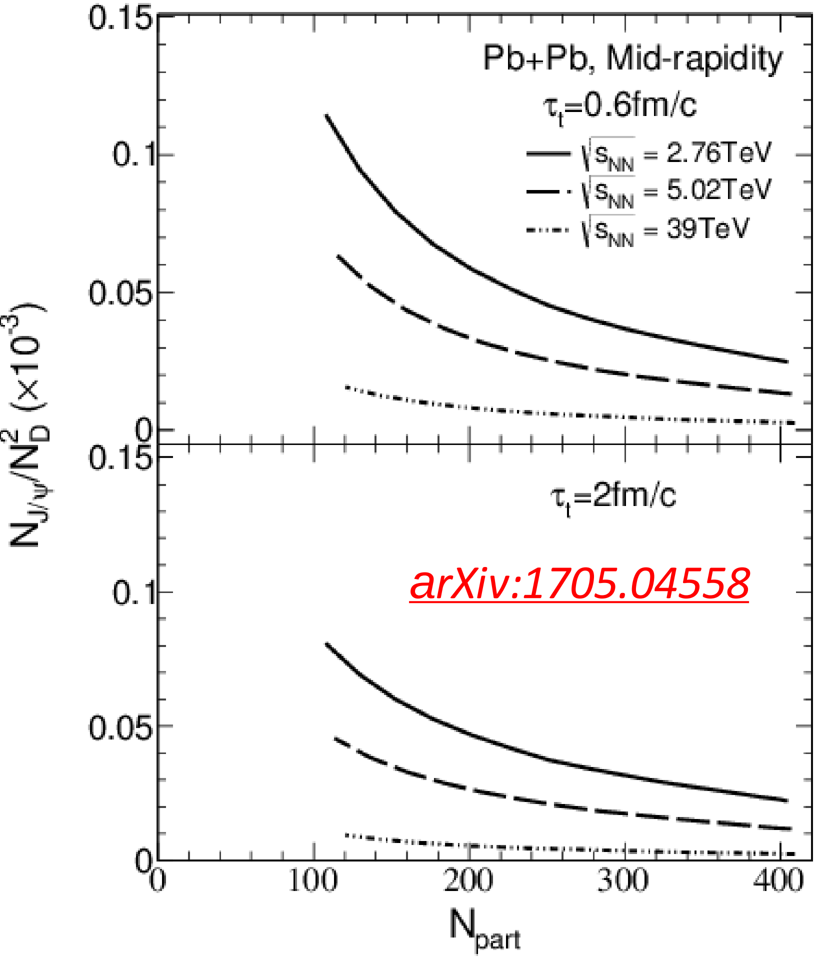
- Can we define an observable to measure the charm diffusion effect ?

independent of charm cross section, shadowing effect, etc

$N_{J/\psi}/N_D^2$



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Hot Medium Effect

$$\frac{N_{J/\psi}}{(N_D)^2} \sim \int dV\, f_c^{norm} f_{\bar{c}}^{norm} W_{combine}$$

This ratio in AA collisions:

① eliminate the shadowing effect.

② Does NOT depend on $\frac{d\sigma_{pp}^{c\bar{c}}}{d\eta}$

③ Contains hot medium effects on charm (collective flows of QGP change f_c^{norm})

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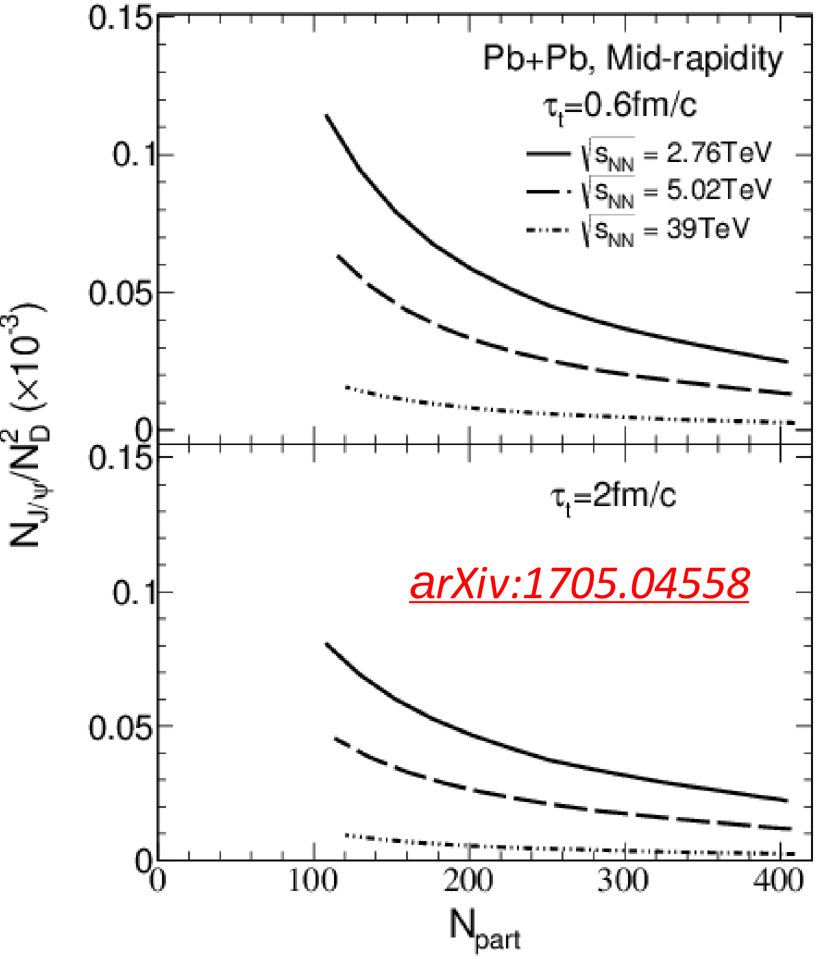

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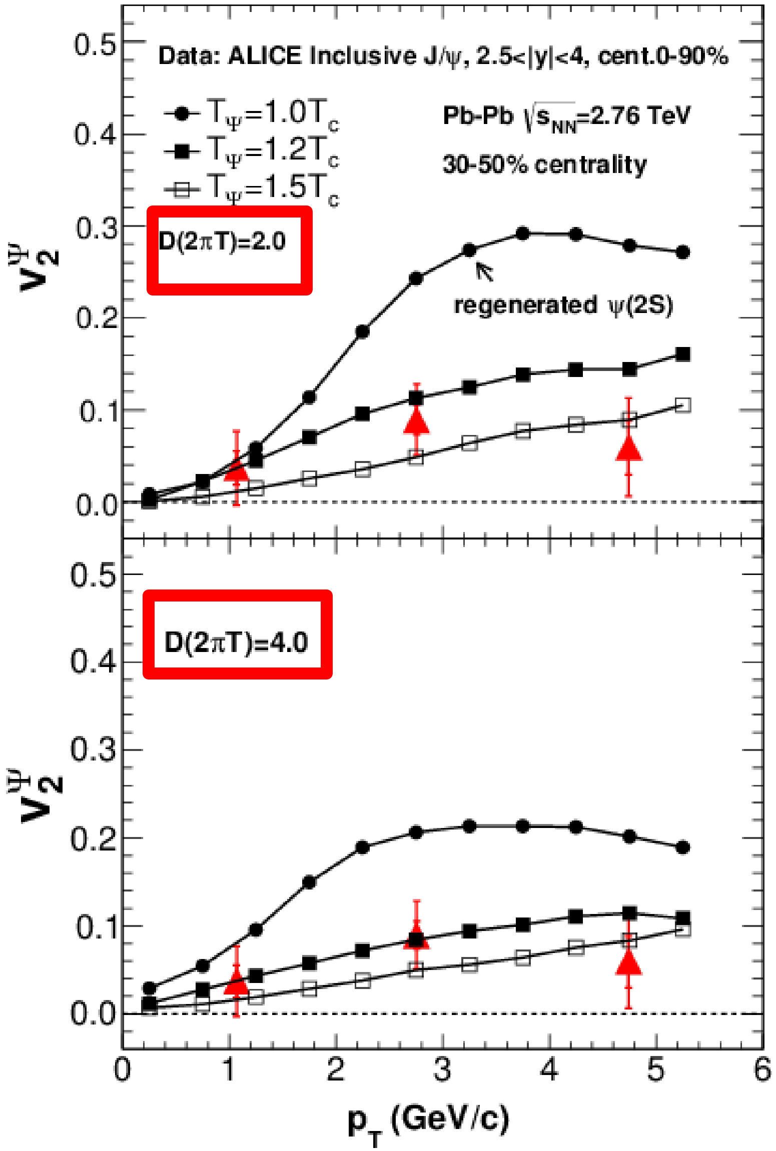
- **Centrality dependence**

  from semi-central to central collisions:

  larger $\boldsymbol{T_0^{QGP}}$, stronger QGP expansion, recombination probability of *ONE* c and $\bar{c}$ decreases.

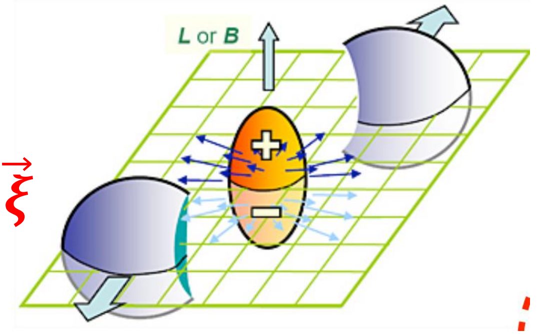
- $\sqrt{s_{NN}}$ **Dependence:** higher $\sqrt{s_{NN}}$, QGP expansion also stronger.

ψ(2S) v.s. J/ψ



B. Chen, PRC 95 (2017) 034908

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



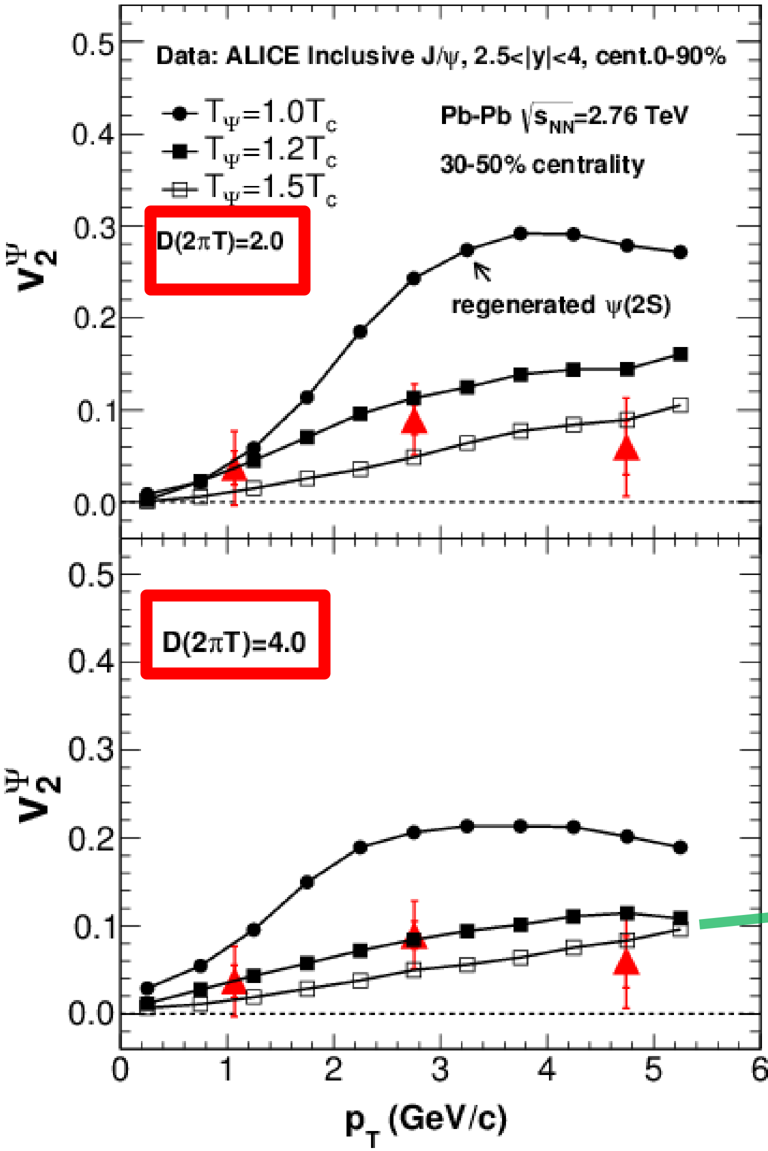
$$\eta_D = \frac{T}{DE_c} \quad D: spatial\ diffusion\ coeff.$$

ψ(2S) will be regenerated in the later stage of QGP expansion,

→ ψ(2S) Carry relatively larger collective flows

independent of c coupling strength

ψ(2S) v.s. J/ψ



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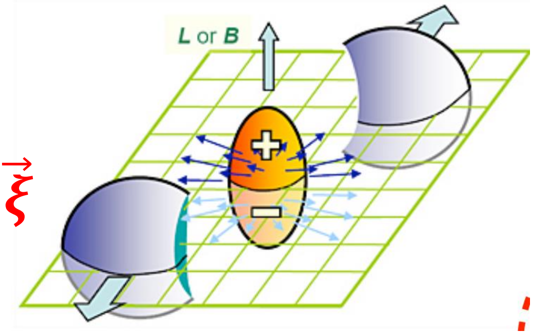

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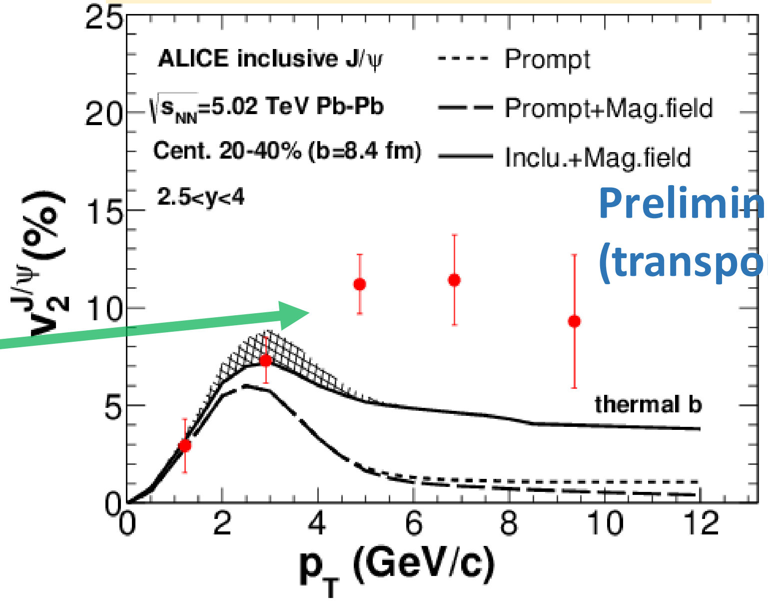
"non-thermal charm + coalescence" can explain J/ψ v_2 at 5.02 TeV?

Shape of v_2 is important !

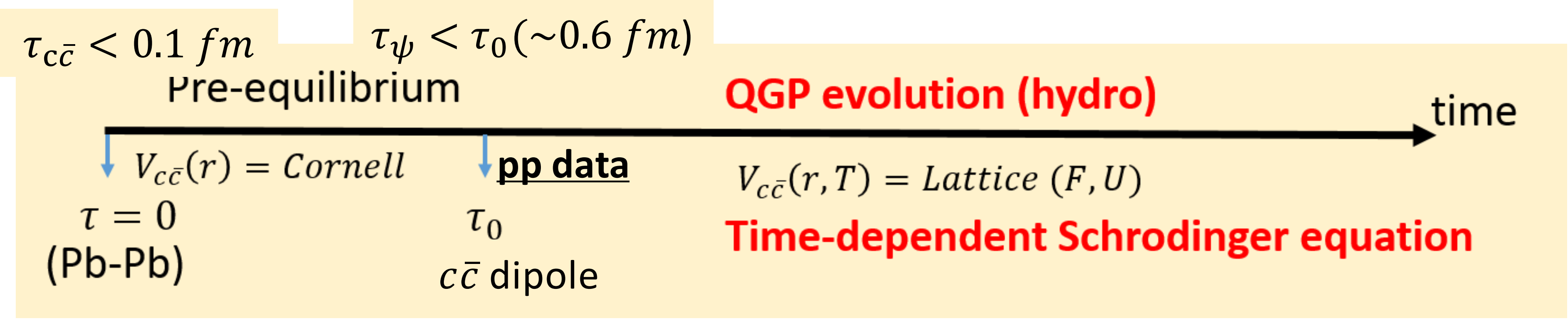


Preliminary (transport model)

$\psi(2S)$ production

3. Internal evolutions of $c\bar{c}$ dipole wave function

Time-dependent Schrodinger equation



$\tau_{c\bar{c}} < 0.1\ fm$

$\tau_{\psi} < \tau_0(\sim 0.6\ fm)$

Pre-equilibrium

QGP evolution (hydro)

time

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

pp data

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

$\tau = 0$

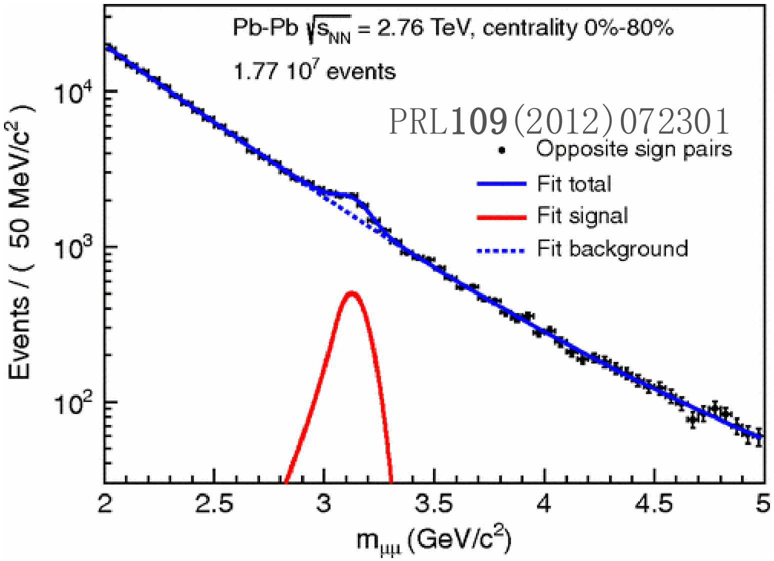
(Pb-Pb)

τ_0

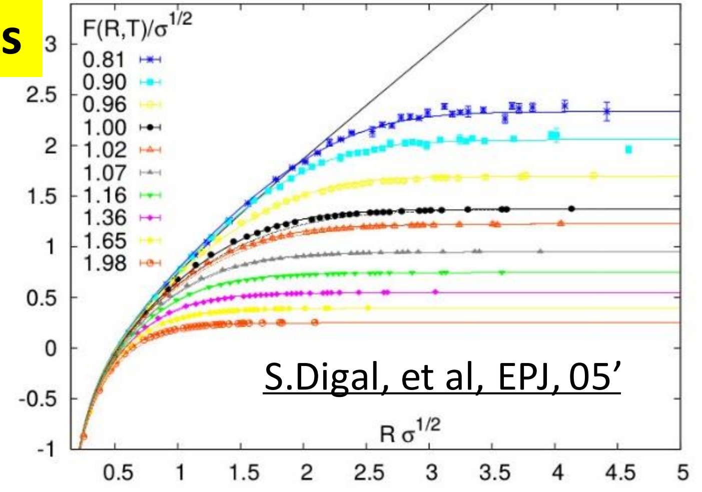
$c\bar{c}$ dipole

Time-dependent Schrodinger equation

J/ψ and $\psi(2S)$ measurements in experiments



PRL109(2012)072301

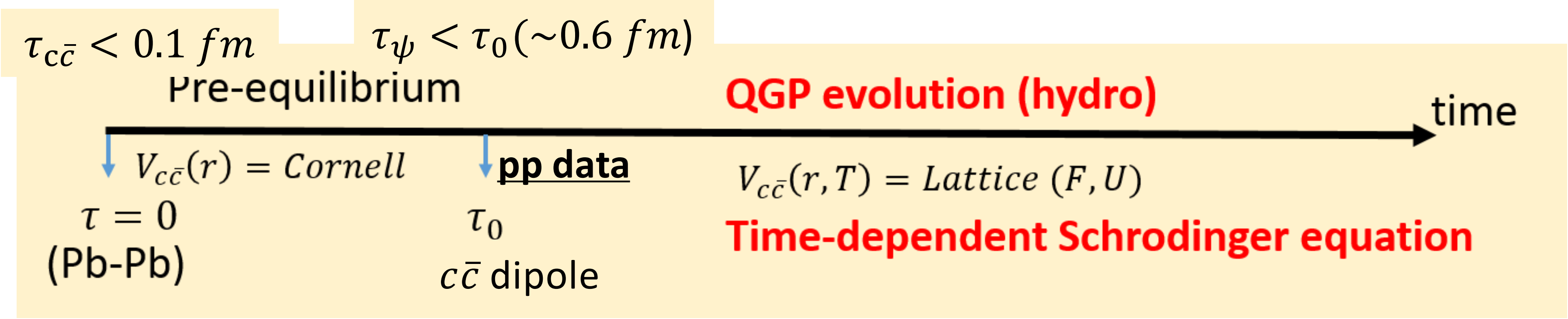


S.Digal, et al, EPJ, 05'

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

Exp. measure the eigenstates of Cornell potential (in vacuum);
by dilepton decay.
$c\bar{c}$ dipole potential in QGP is COLOR SCREENED. transitions

Time-dependent Schrodinger equation



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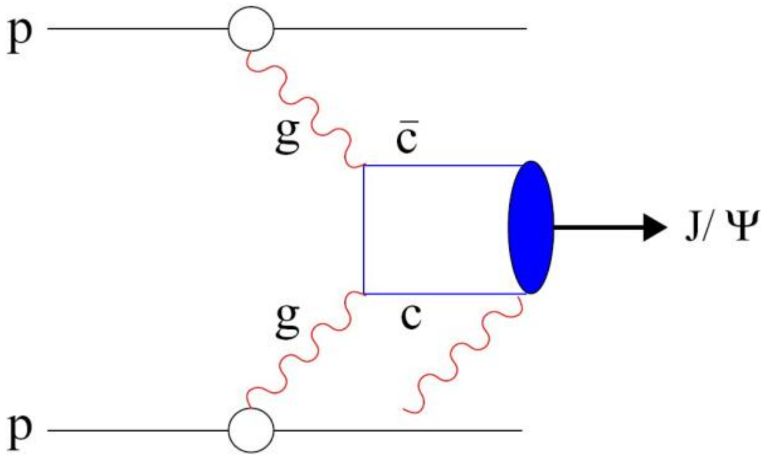


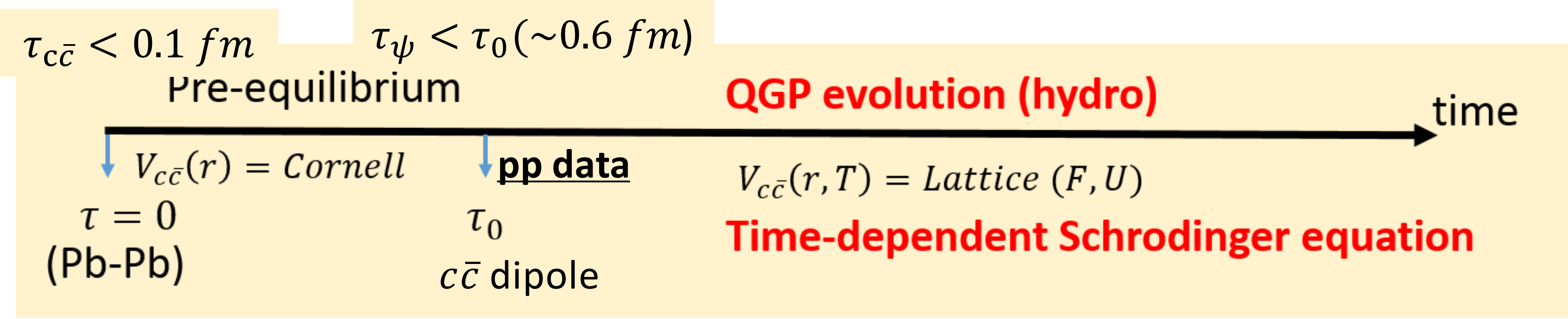
$$r_{c-\bar{c}} \sim 1/(2m_c) \sim 0.07\ fm$$

Radii of J/ψ and $\psi(2S)$ **: 0.5 fm and 0.9 fm**

It takes some time to evolve into a charmonium,
Shorter for ground state, longer for 2S

Color screening change ccbar dipole wave function evolutions,
Change fractions of 1S and 2S in the dipole.

Time-dependent Schrodinger equation



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(Pb-Pb)

τ_0

$c\bar{c}$ dipole

Time-dependent 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. Katz, P. B. Gossiaux, 16’
B.Z. Kopeliovich, et al, PRC, 15’
Taesoo Song, et al, PRC, 15’

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

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

Wavefunction of eigenstates:

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

- Numerical form:

$$\begin{pmatrix} \mathbf{T}^{n+1}_{0,0} & \mathbf{T}^{n+1}_{0,1} & 0 & 0 & \cdots \\ \mathbf{T}^{n+1}_{1,0} & \mathbf{T}^{n+1}_{1,1} & \mathbf{T}^{n+1}_{1,2} & 0 & \cdots \\ 0 & \mathbf{T}^{n+1}_{2,1} & \mathbf{T}^{n+1}_{2,2} & \mathbf{T}^{n+1}_{2,3} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \psi^{n+1}_0 \\ \psi^{n+1}_1 \\ \psi^{n+1}_2 \\ \psi^{n+1}_3 \\ \cdots \end{pmatrix} = \begin{pmatrix} \Gamma^n_0 \\ \Gamma^n_1 \\ \Gamma^n_2 \\ \Gamma^n_3 \\ \cdots \end{pmatrix}$$

Matrix elements:

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

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

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

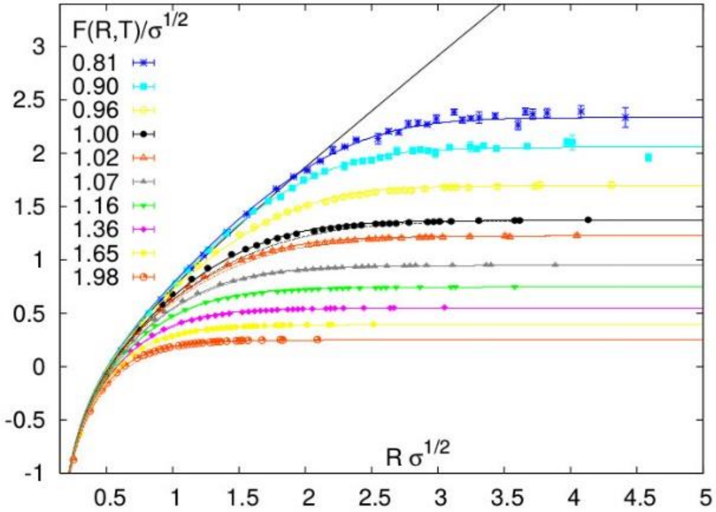
b= $i\Delta t$

Heavy quark potential at finite temperature

- mS eigenstate components in one dipole:

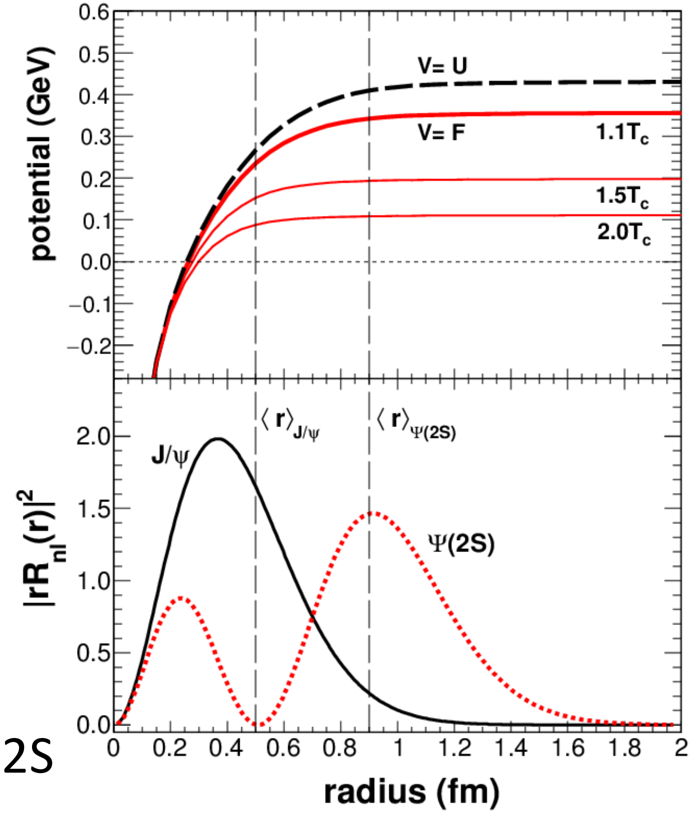
$$c_{mS}(t) = \langle R_{mS}(r) | \frac{\psi(r,t)}{r} \rangle = \int R_{mS}(r)\psi(r,t) \cdot r dr$$

- **Heavy quark potential :**



S.Digal, et al, EPJ, 05'

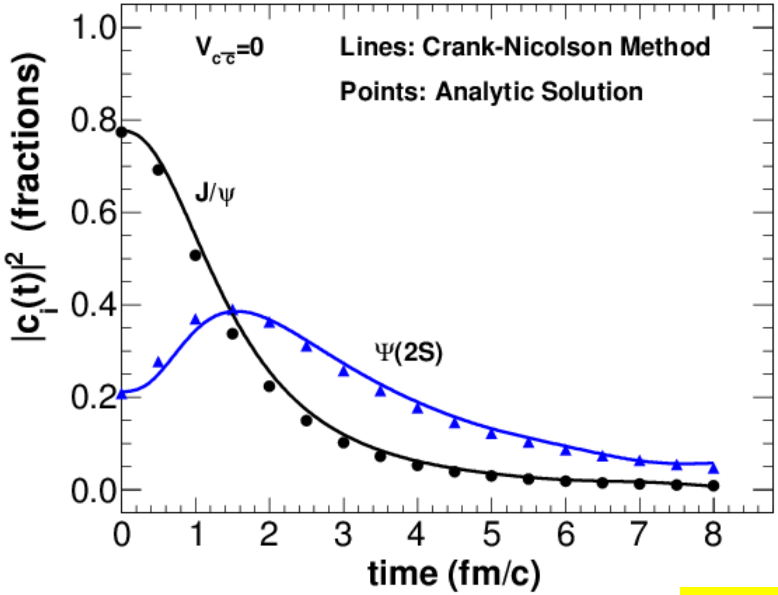
BC, Du, Rapp, arXiv:1612.02089

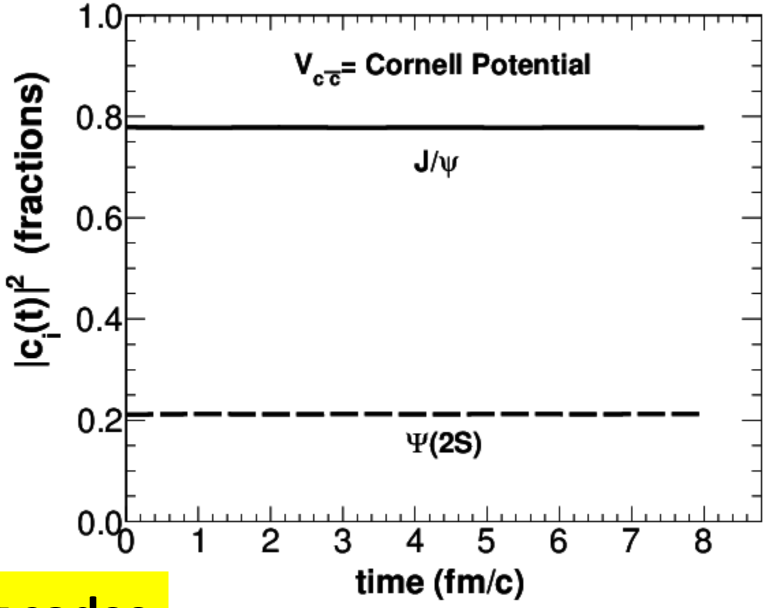


- At ~2Tc, Strong color screenin for 1S and 2S
- At ~1Tc, potential recover at <r(1S)>

Initialization of $c\bar{c}$ wavefunction

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





Testing codes

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

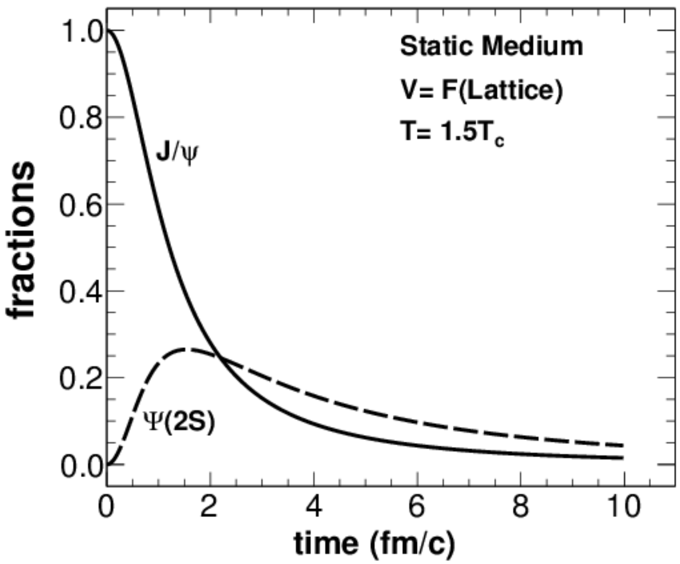
$V_{c\bar{c}}(r) =$ **Cornell Potential**

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

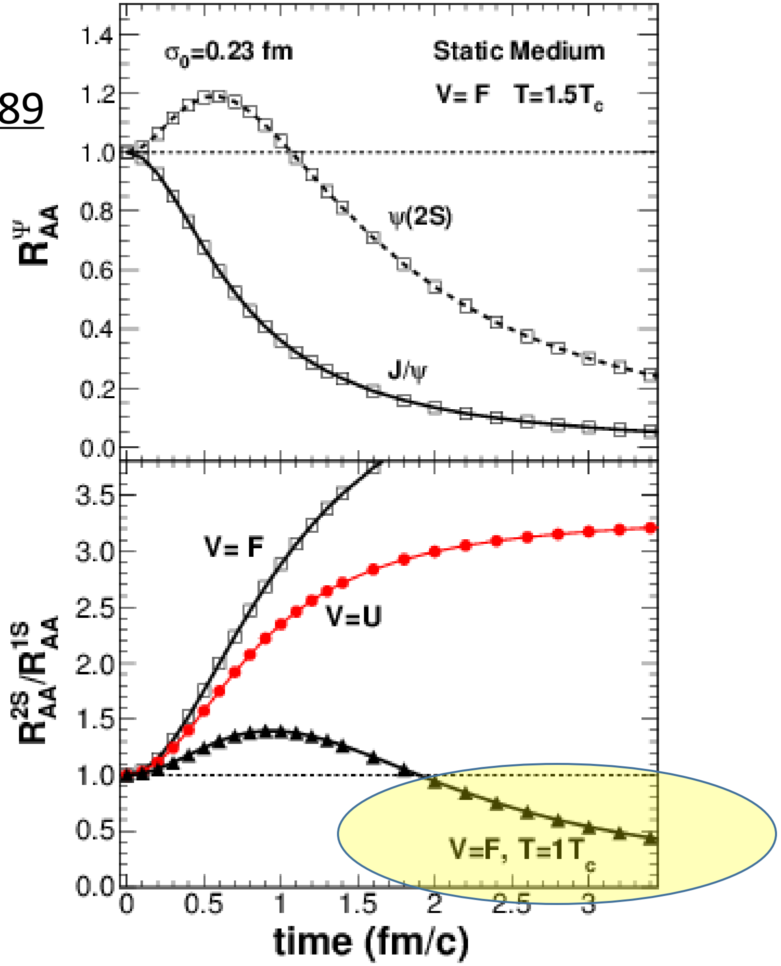
➡ the overlap between $\boldsymbol{\psi}_{c\bar{c}}(\mathrm{r},\mathrm{t})$ and $\boldsymbol{\Psi(2S)}$ increase at first, then decrease

Heavy quark dipole in **Static Medium**

With real part of heavy quark potential (color screening)



arXiv:1612.02089



- **At high T**, Large density of partons, $c\bar{c}$ **wavefunction expand outside,** **correspond transitions of 1S -> 2S**

- **At low T**, recovering of potential at mean radius of 1S: **1S well constrainted, mainly transitions of 2S->1S**

Additional parton inelastic scatterings may change the game.

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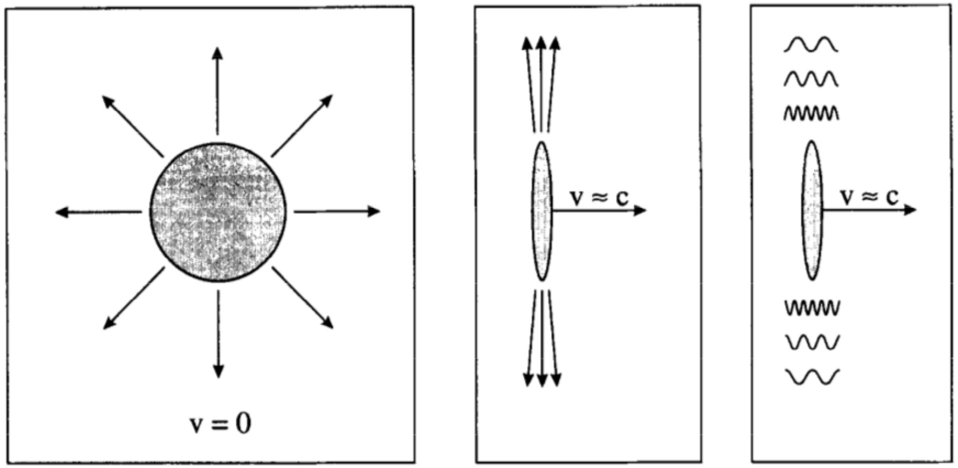
4. Photoproduction from electromagnetic fields at $\boldsymbol{b < 2R_A}$

Equivalent Photon Approximation

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



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

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

Strong Lorentz-contracted Electromagnetic field (transverse)

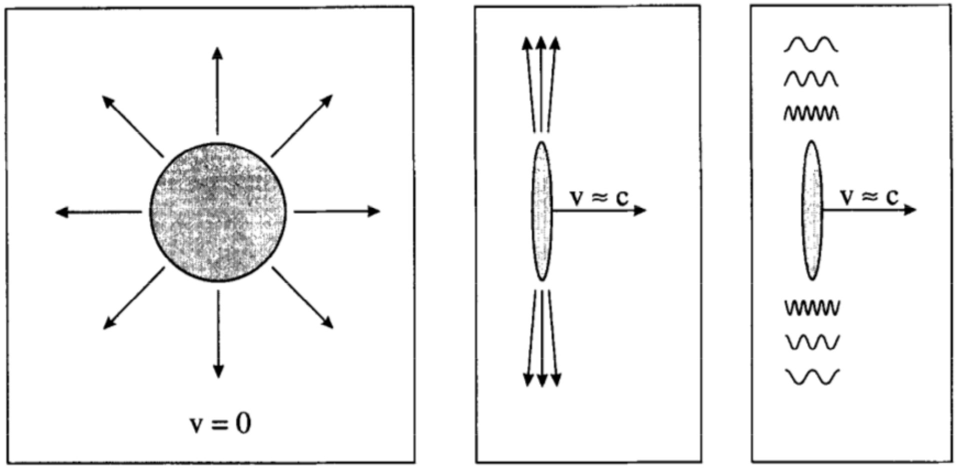
approximated as longitudinally moving photons

Equivalent-Photon-Approximation

Fermi, 1924'

Equivalent Photon Approximation

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

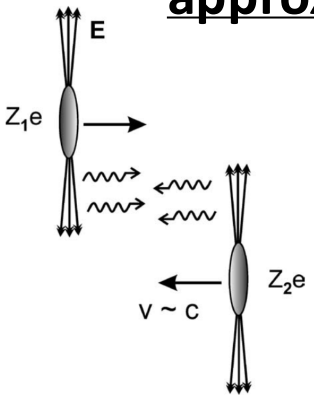


$\mathrm{eB} \sim m_\pi^2 \sim 10^{18} G$

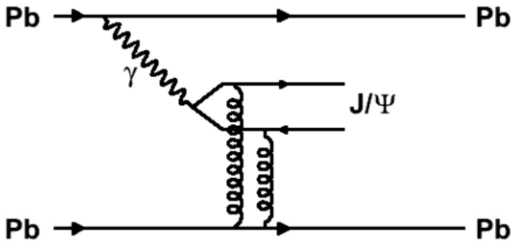
Ultra-peripheral collisions

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

Strong Lorentz-contracted Electromagnetic field (transverse)
approximated as longitudinally moving photons



Equivalent-Photon-Approximation
Fermi, 1924'



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

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

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

p_T and b dependence

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

Charmonium hadro-production (**initial distributions**) in Pb-Pb collisions, can be extracted from the scaling with pp collisions.

Normalized distribution

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

Works well for RHIC and LHC

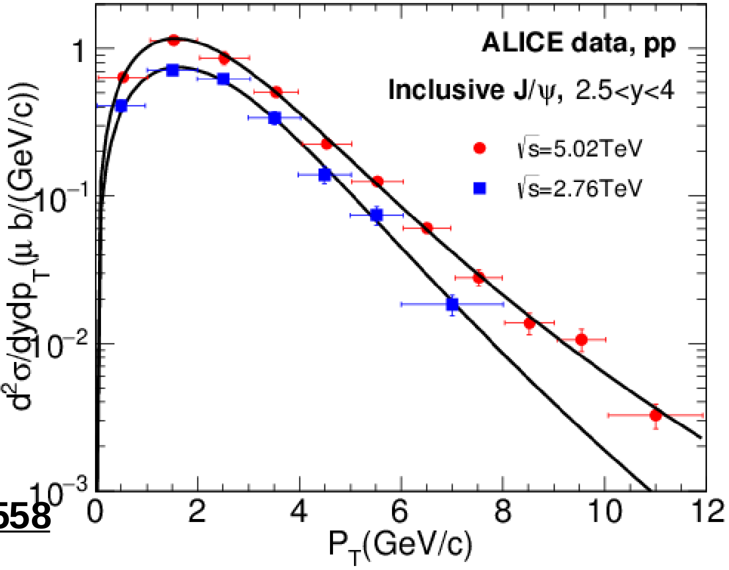
- **2.76 TeV forward rapidity 2.5<y<4, inclusive J/ψ**

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

$$n = 4$$

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, arXiv: 1705.04558
Physics Letters B 2017

p_T and b dependence

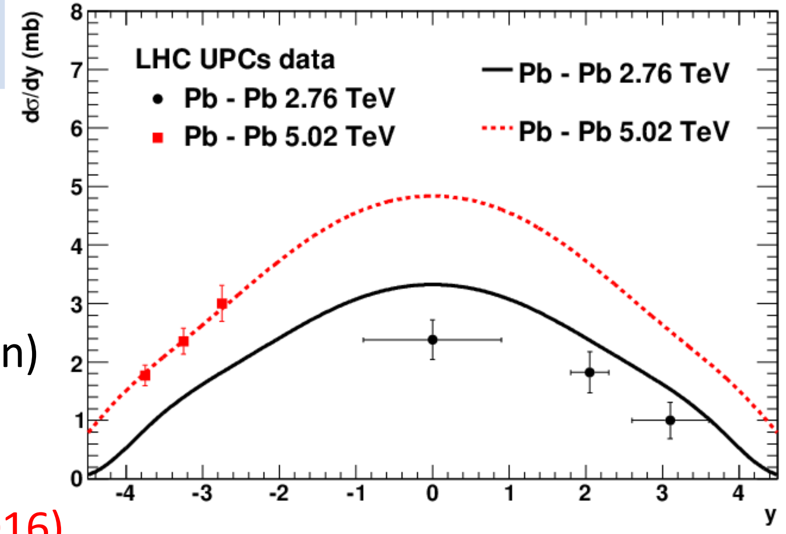
Fractions of hadronic cross sections in different pT region

p_T range (GeV/c)	$\sigma_{p_{T1}-p_{T2}}/\sigma_{total}$
$0-0.01$	1.9×10^{-5}
$0-0.05$	4.8×10^{-4}
$0-0.1$	0.19%
$0-0.5$	4.5%
$0-1$	15%

Rapidity differential cross section at 2.76 TeV   2.5<y<4

$$\frac{d\sigma_{pp}^{J/\psi}}{dy} = 2.3\ \mu b$$

$$\frac{d^2\sigma_{pp}^{J/\psi}}{2\pi p_T dp_T dy} = \frac{d\sigma_{pp}^{J/\psi}}{2\pi p_T dp_T}\cdot\frac{d\sigma_{pp}^{J/\psi}}{dy}$$



Coherent photoproduction:
Photons interact with entire nucleus,

$$p_T \sim 1/R_A \sim 0.03\ \mathrm{GeV/c}$$

Ultra-peripheral collisions (photoproduction)

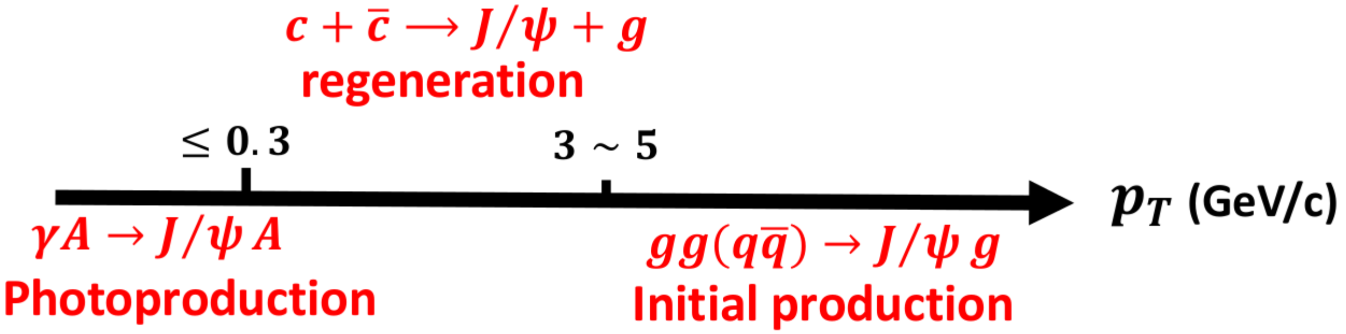
Exp. $<p_T>= 0.055\ \mathrm{GeV/c}$ PRL 116,, 222301 (2016)

pT and b dependence

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

$$= 30\, fm^{-2} (b = 10.2)$$

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



pT and b dependence

Hadonic **initial** yield
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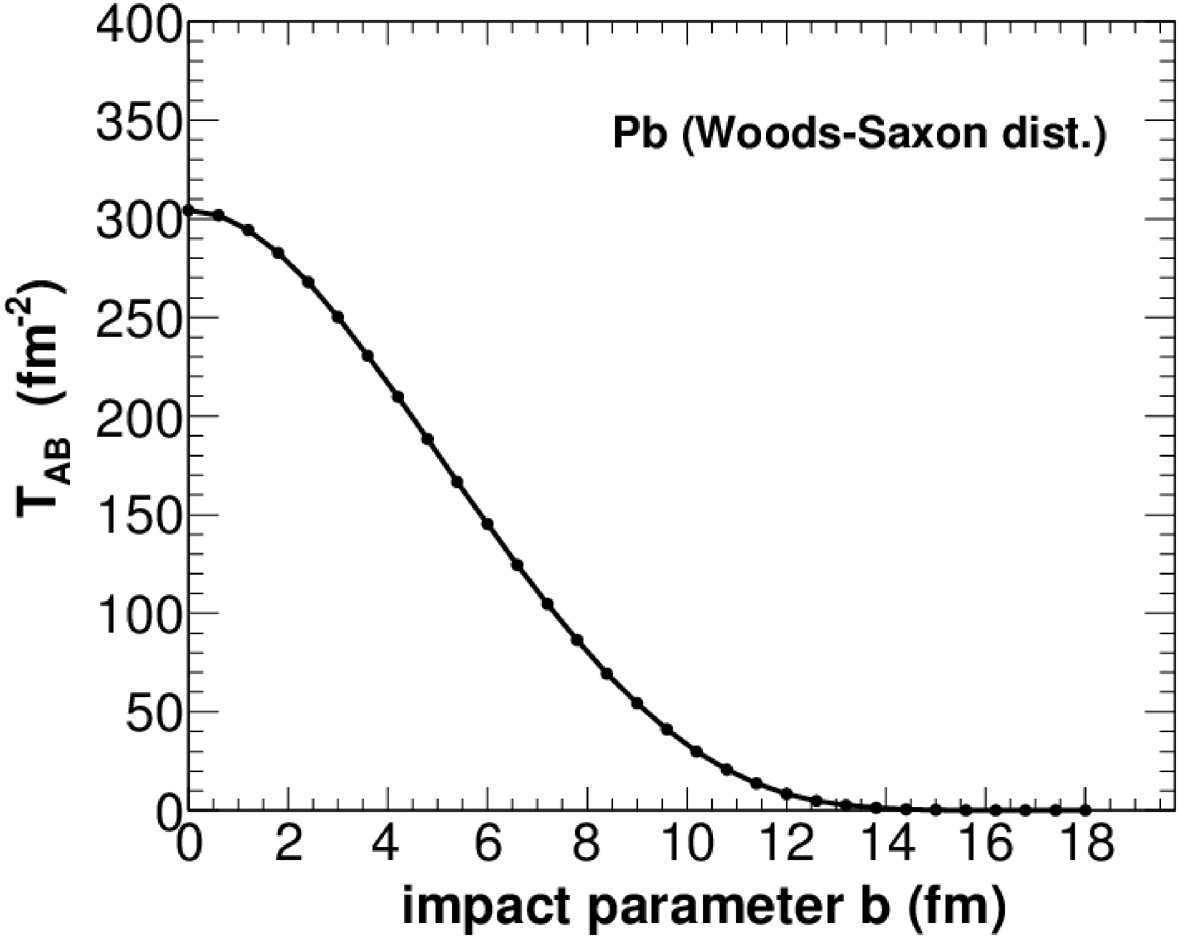
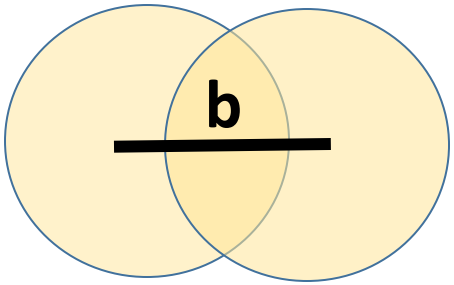
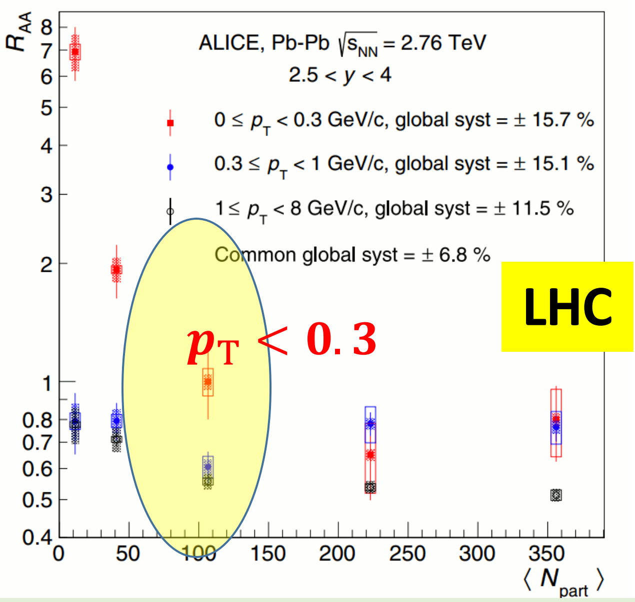
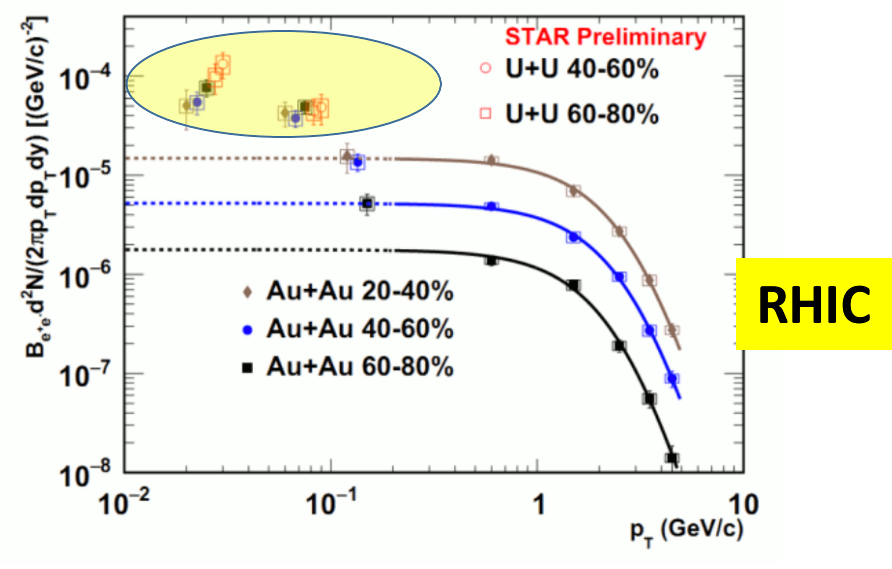


Overlap area between two colliding nuclei,
~ the hadronic yields.



Photoproduction contribution





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

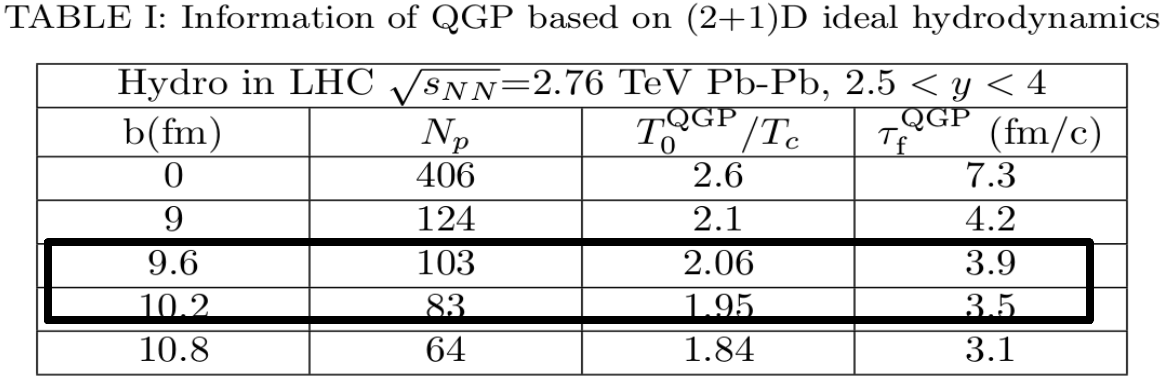
- At Np=100, $T_0^{QGP} = 2T_c$

Similar with maximum T at RHIC Au-Au

QGP effect important !

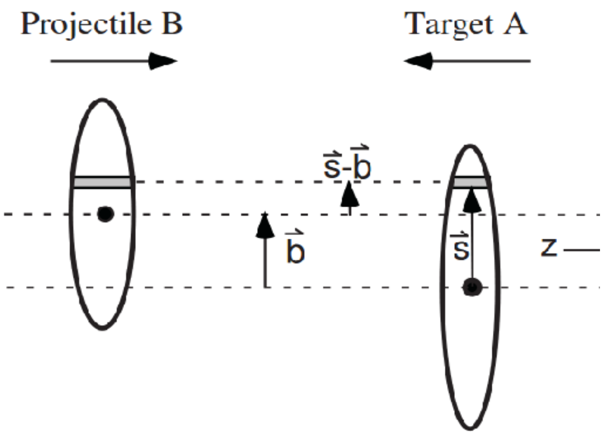
Photoproduction important !

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 hadro-production and EB field



$\mathbf{b} < 2R_A$

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

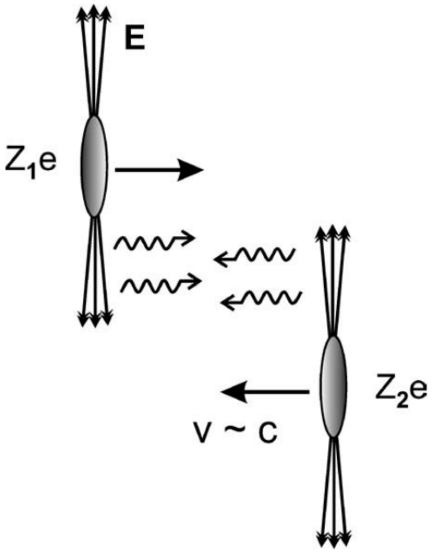
$$\mathbf{gg}(\mathbf{q}\bar{q}) \rightarrow J/\psi + g$$
$$\rightarrow c + \bar{c}$$

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)

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



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

Produced in the entire nucleus surface

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

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

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

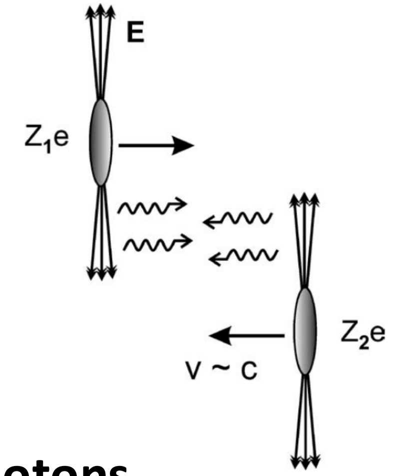
J/ψ from electromagnetic field

Mainly three ingredients:

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

Already Given before

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



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

$$\int_{-\infty}^{\infty} \mathrm{d}t \int \mathrm{d}\vec{x}_{\perp} \cdot \vec{S}(\vec{r},t) \overset{!}{=} \int_{0}^{\infty} \mathrm{d}\omega \int \mathrm{d}\vec{x}_{\perp} \, \omega \, n(\omega, \vec{x}_{\perp})$$

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

Photon density

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

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

Nuclear charge form factor is the Fourier transform of Woods-Saxon distribution

J/ψ from electromagnetic field

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

Widely studied in UPC

Start from photon-proton $\sigma_{\gamma p}$

S.R.Klein, J. Nystrand, PRC, 1999

Physics Roports, G.Baur, et al, 2002

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

With the optical theorem, above cross section can be written as $J/\psi - A$ total cross section. With Geometry scale,

$$\sigma_{tot}(J/\psi A) = \int d^2\vec{x}_T (1 - e^{-\sigma_{tot}(J/\psi p) T_A(\vec{x}_T)})$$

Using optical theorem again, and finally

$$\frac{d\sigma_{\gamma p\rightarrow J/\psi p}}{dt}|_{t=0} = B_{J/\psi} X_{J/\psi} W_{\gamma p}^{\epsilon_{J/\psi}}$$

Measured by HERA data.
(main input of photo-production)

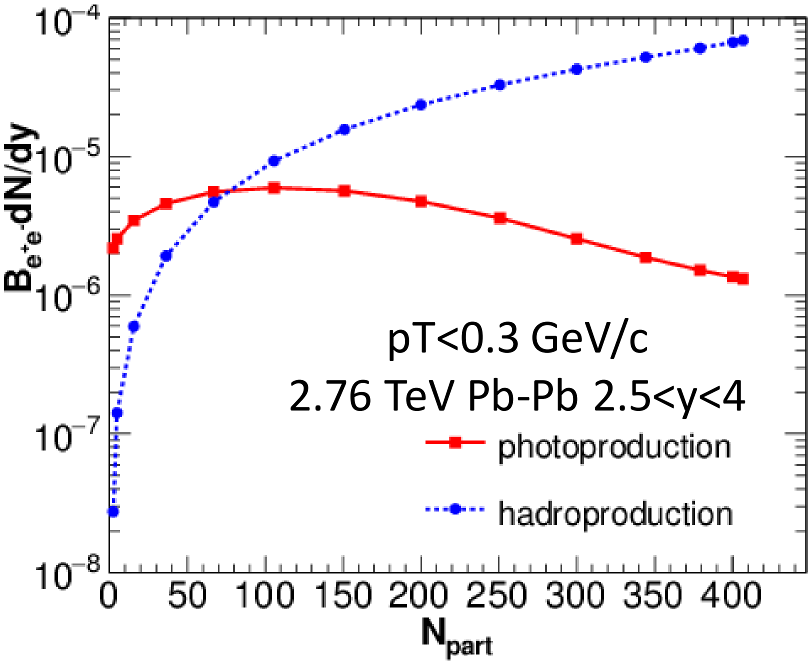
Center of mass energy of photon and proton

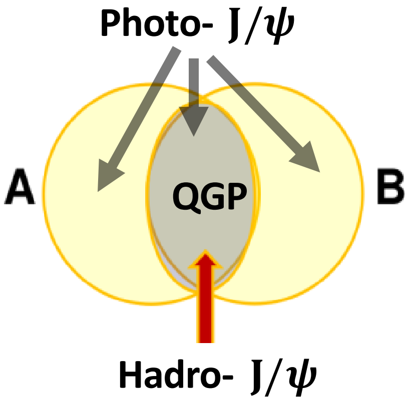
J/ψ from EB field + QGP

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

$$\frac{dN_{J/\psi}}{dy}(y) = w\cdot\frac{1}{\pi R_A^2}\int_0^{R_A} rdr\int_0^{2\pi} d\phi\,\frac{d^3 r N_\gamma(w,b+r\cos(\phi))}{dwdrd\phi}\sigma_{\gamma A\to J/\psi A}(w)\times e^{-\int_{\tau_0}^{\tau_f} d\tau\alpha_{QGP}(r,\phi,b,\tau)}$$
$$+\,(y\to -y \quad term.)$$

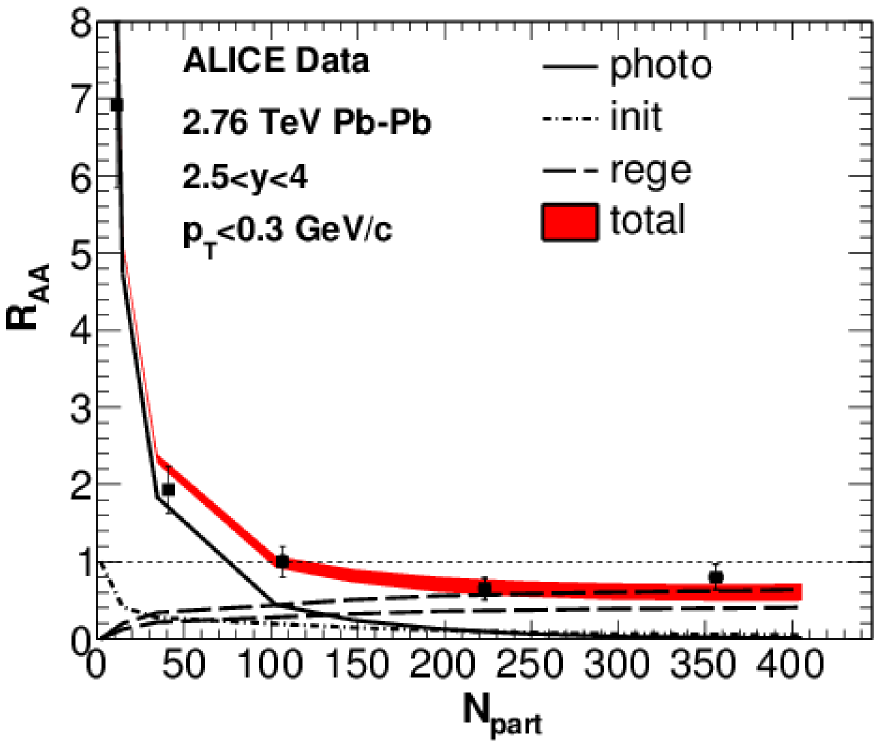
Hadroproduction **V.S.** **Photoproduction (without QGP Effect)**

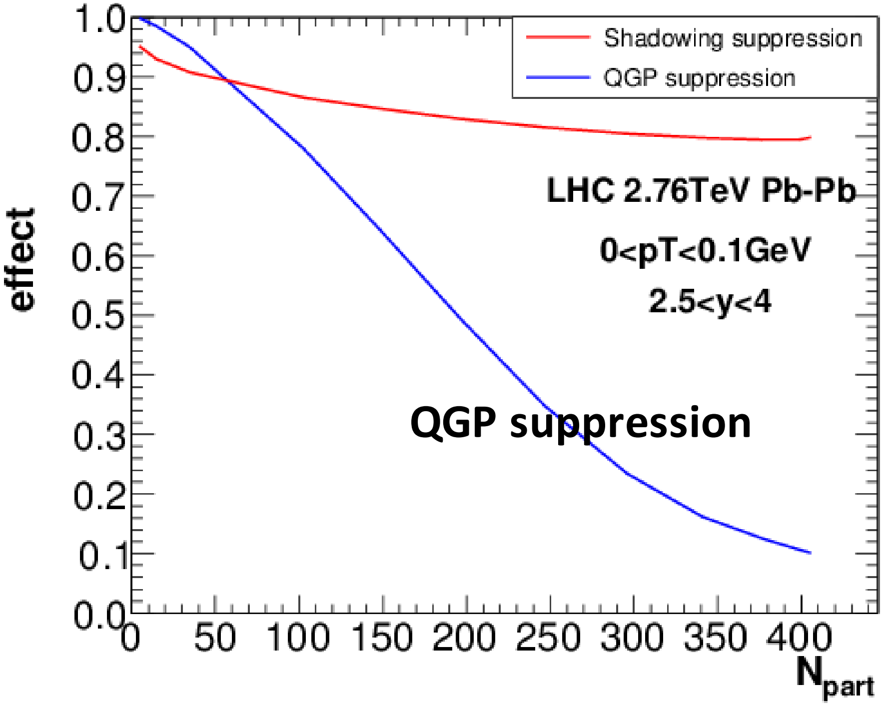




- **hadroproduction** show **strong dependence** on **impact parameter** (overlap between nucleus A and B).

Total J/ψ from EB field + QGP



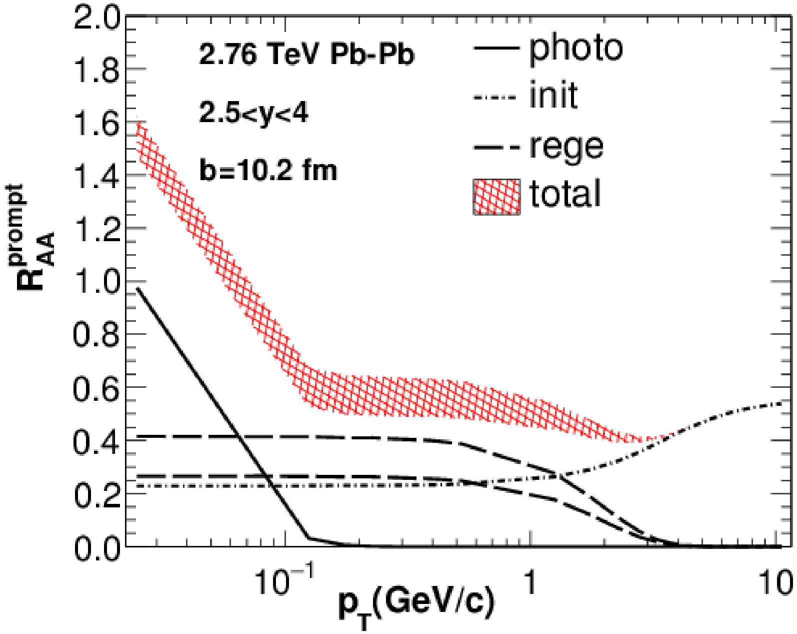


W. Shi, W. Zha, B. Chen, arXiv:1710.00332

- Also **significant enhancement at $N_p \approx 100$**, where $T_0^{QGP} = 2T_c$**, similar with RHIC 200 GeV Au-Au (most central)**

- **When $N_{part} \rightarrow 0$ $(b > 2R_A)$,**
  hadroproduction → 0, photoproduction → nonzero, $R_{AA} \rightarrow$ infinity

Total J/ψ from EB field + QGP



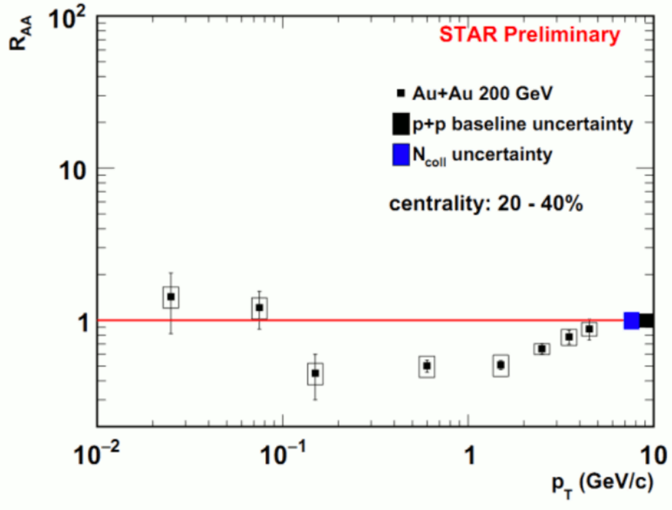
W. Shi, W. Zha, B. Chen, arXiv:1710.00332

LHC

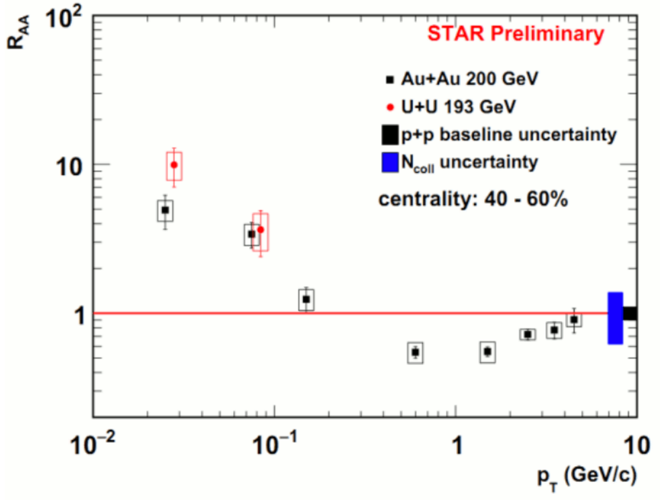
- pT<0.05, $\gamma A \to J/\psi\, A$ important
- 0.1<pT<2-4, $c + \bar{c} \longrightarrow J/\psi + g$
- pT>4 primordial production

R_{AA} decreases, then increases with pT

photoproduction → rege. → init.



RHIC



Photoproduced 2S/1S

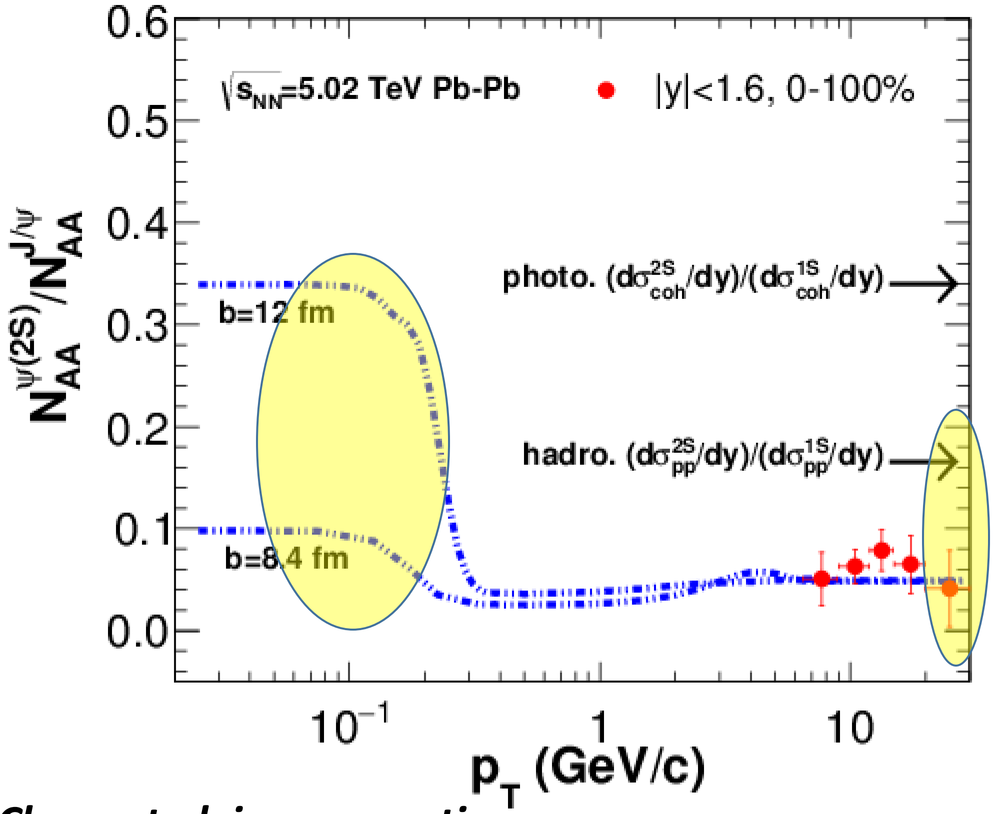
- Photoproduction is usually studied in Ultra-peripheral Collisions, absent of hadronic collisions and QGP

Can photoproduction and QGP be BOTH important ?

Photoproduced 2S/1S

- Photoproduction is usually studied in Ultra-peripheral Collisions, absent of hadronic collisions and QGP

Can photoproduction and QGP be BOTH important ?



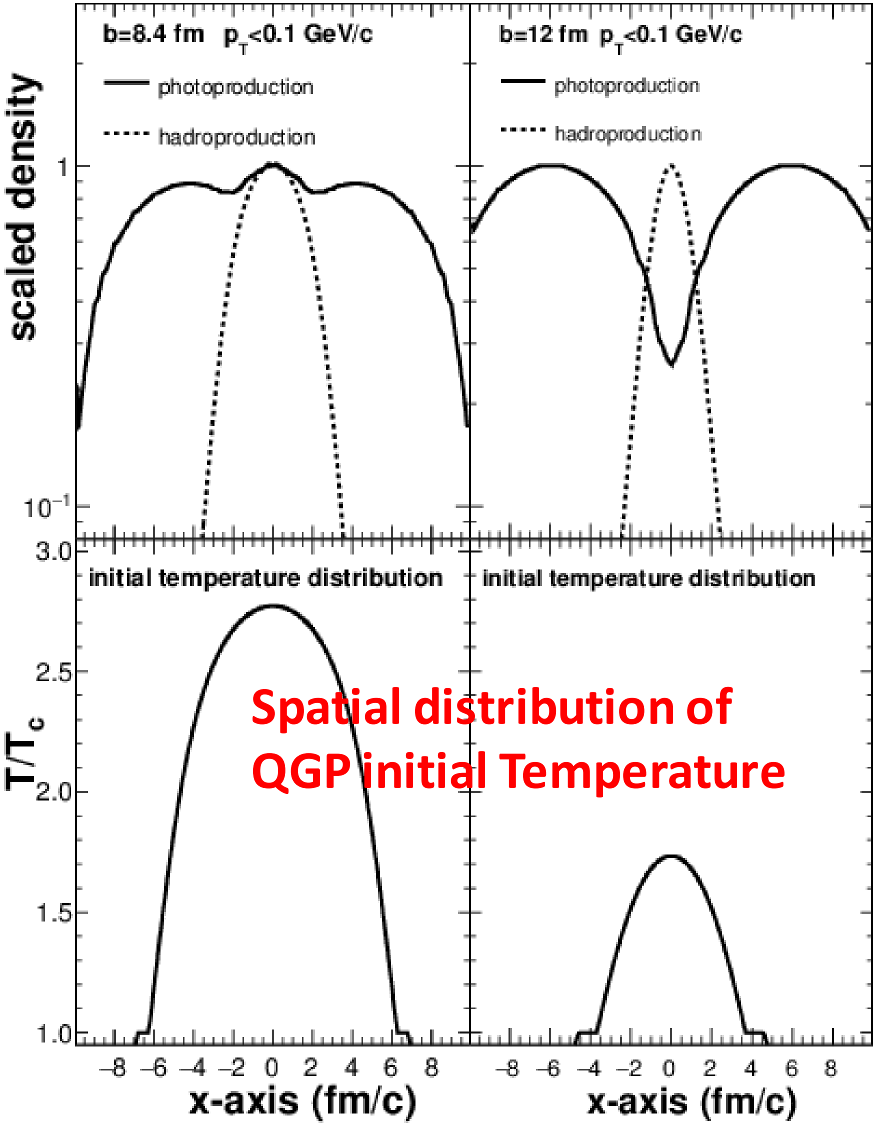
Enhancement:
additional photoproduction on both 1S and 2S

Suppression: QGP effect.

Independent of initial nuclear effects

B.Chen, et al, in preparation

Photoproduced 2S/1S



Spatial distribution of
QGP initial Temperature

Spatial distribution of hadroproduction and coherent photoproducti

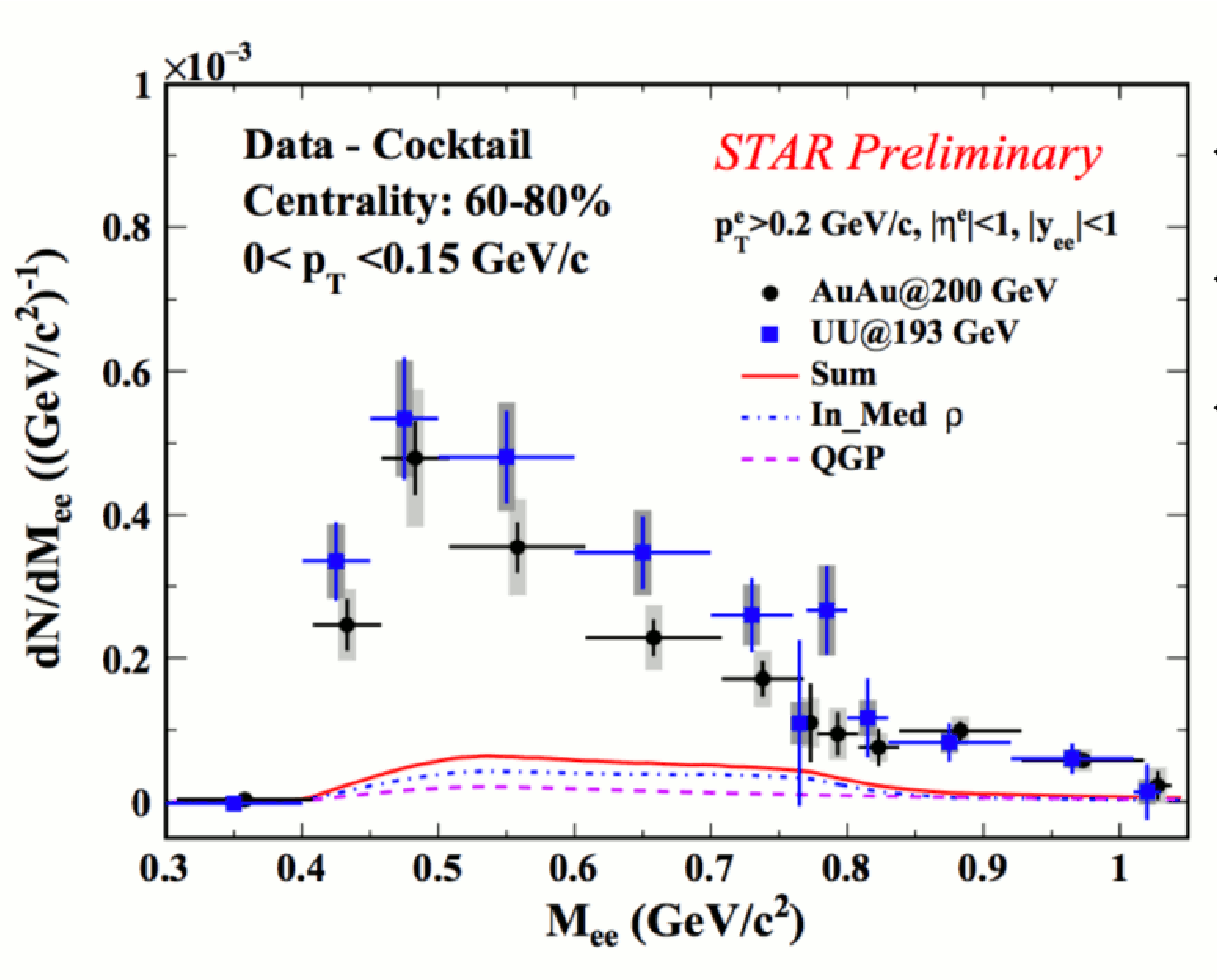
- **Hadroproduction:**
  in the overlap area of two nuclei, where QGP are also produced.

- **Photoproduction:**
  over the entire nucleare surface
  photons interact with entire nucleus

2S/1S shape needs 3 factors:

1) QGP existence,
2) abundant photoproduction,
3) different spatial distributions

Photoproduction at RHIC



At RHIC, photoproduction from $\gamma + A \to \rho + A, \quad \gamma\gamma \to e^+e^-$ **?**

Summary

◆ We study the charmonium production in the heavy ion collisions with QGP.
When most of final charmonia are from c and $\bar{c}$ combination,
charmonia behavior is closely **connected with charm diffusions in the expanding QGP.**

◆ **$\psi(2S)$ production is an interesting topic, and internal evolutions (transitions between 1S and 2S) should be crucial for 2S/1S obvervables**

◆ **In the extremely low p_T regions, even at $b < 2R_A$,**
photoproduction from strong electromagnetic fields
can be larger than the hadroproduction in certain centralities.

◆ **We also propose the strong enhancement at p_T<0.1 GeV/c and suppression at high p_T of 2S/1S, to be an probe for both photoproduction and QGP effects**

Future interests:
electromagnetic fields induced particle production, EB-QGP, particle correlations, etc