Theoretical overview of charmonium evolutions in the hot medium

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CHARM 2018: The 9th International Workshop on Charm Physics
21 - 25 May, Novosibirsk, Russia;

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Xiaojian Du, Jiaxing Zhao, Wei Shi

Outline

1. **Background:**

   Quark Gluon Plasma,
   Parton inelastic scattering, medium color screening on HQ potential

2. **Theoretical models:**

   Transport models, Coalescence model, potential models (Schrodinger et al)
   Co-mover model, et al;

3. **Topics:**
   1) **Pb-Pb: charm quark diffusion on Ψ (regeneration, collective flows)**
   2) **p-Pb : final state interactions onΨ**

   3) **Transitions between charmonia by in-medium potential**
   4) **photoproduction V.S. hadroproduction in semi-central collisions with QGP**

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

4. **Summary**

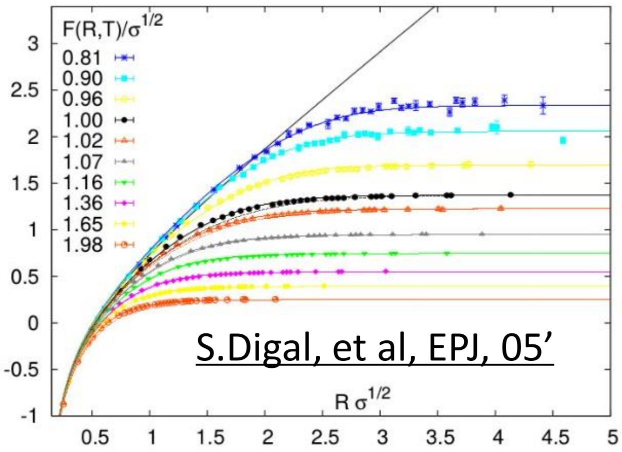
background

J/ψ as a probe of QGP：

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

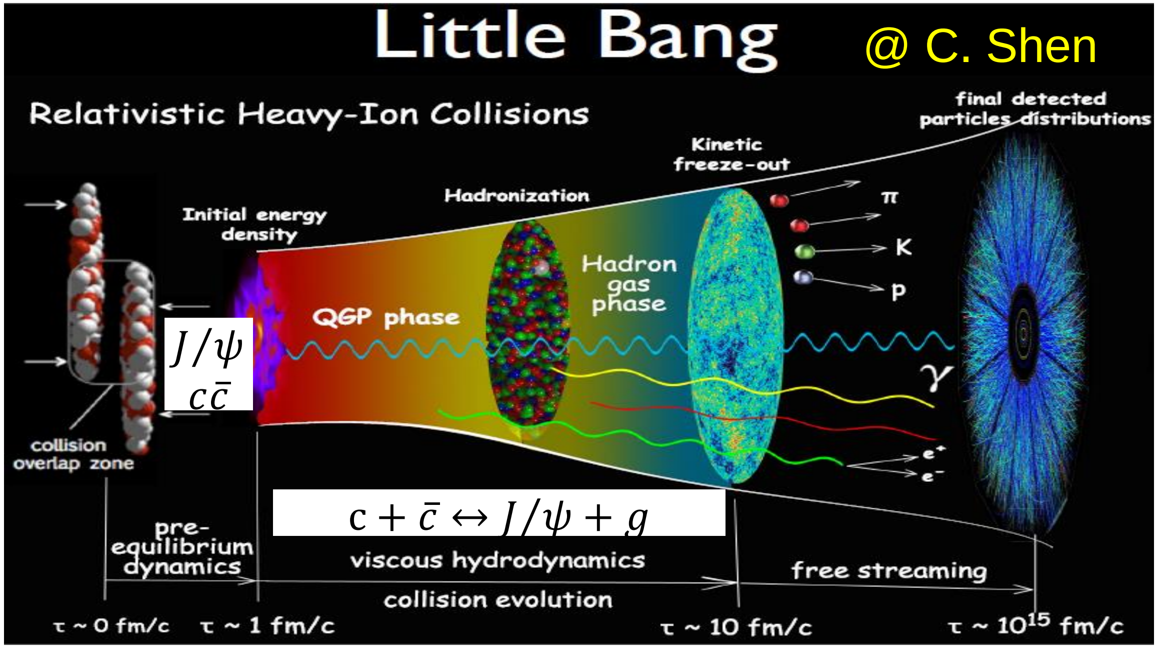
$$R_{AA}^{J/\psi} = \frac{N_{AA}^{J/\psi}}{N_{pp}^{J/\psi} N_{coll}}$$

QGP: color screening on HQ potential; parton scatterings



S.Digal, et al, EPJ, 05’

Heavy quark potential is screened



@ C. Shen

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

$V_{c\bar{c}} = U$

Satz, et al

State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

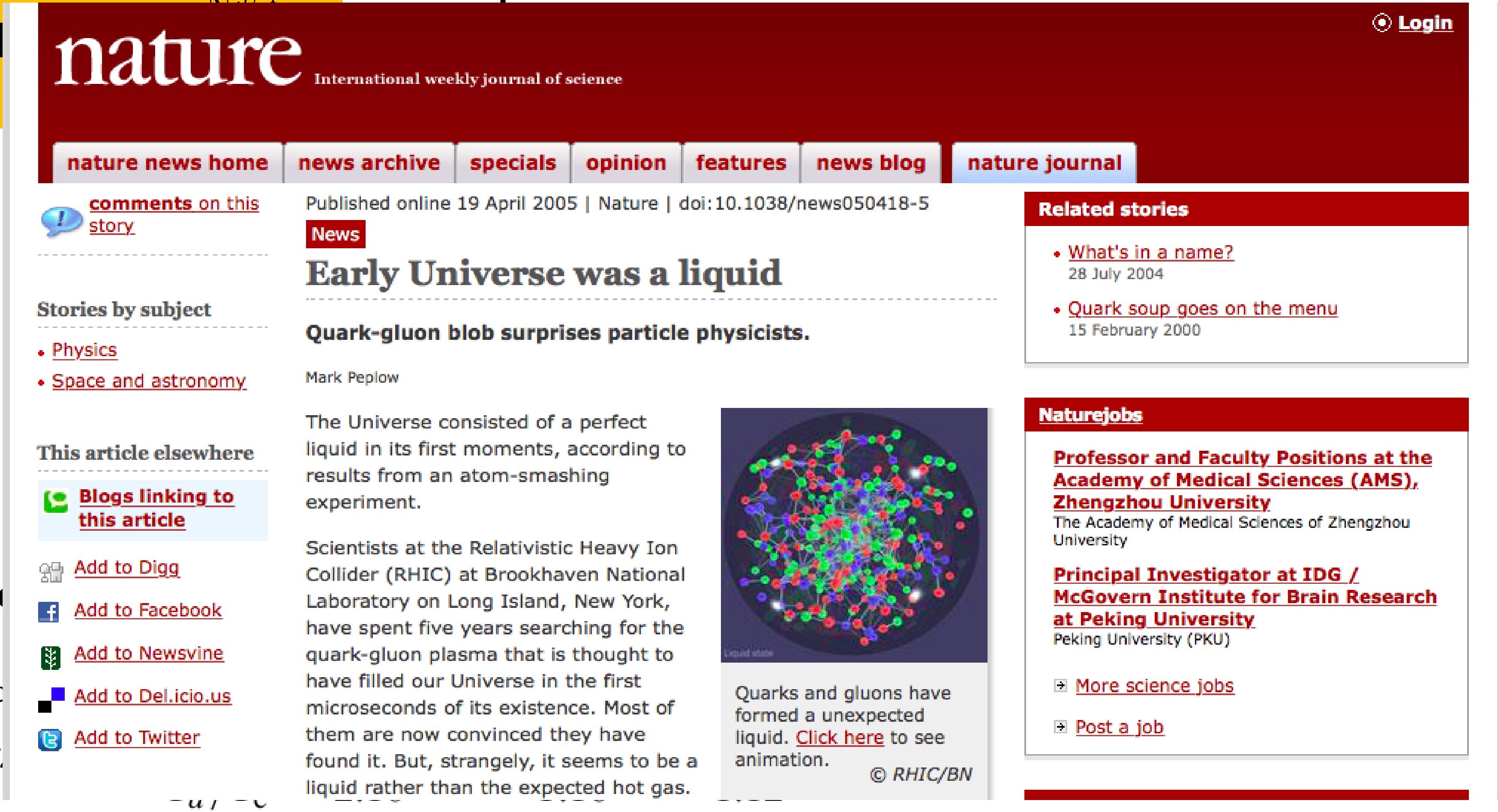
dissociation temperature

background

J/ψ as a probe of QGP:

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

$N_{J/\psi}$



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Published online 19 April 2005 | Nature | doi:10.1038/news050418-5

News

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Quarks and gluons have formed a unexpected liquid. Click here to see animation.

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- Quark soup goes on the menu
  15 February 2000

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Principal Investigator at IDG / McGovern Institute for Brain Research at Peking University
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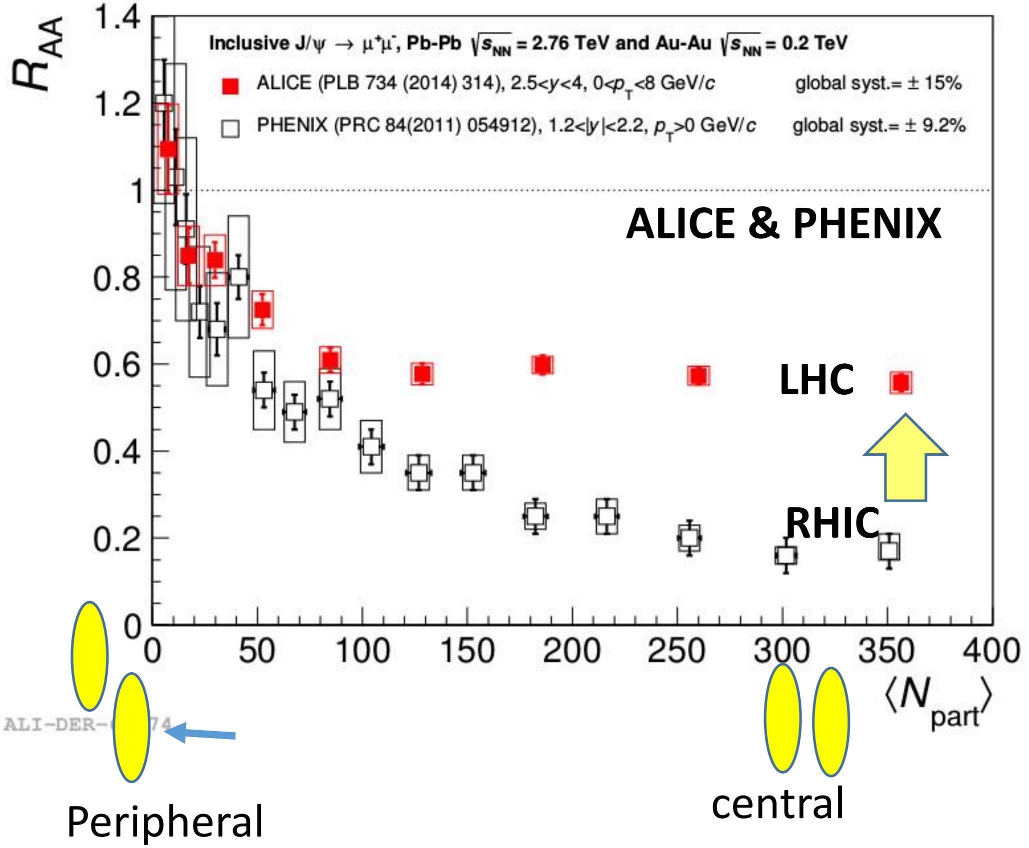
Regeneration + suppression

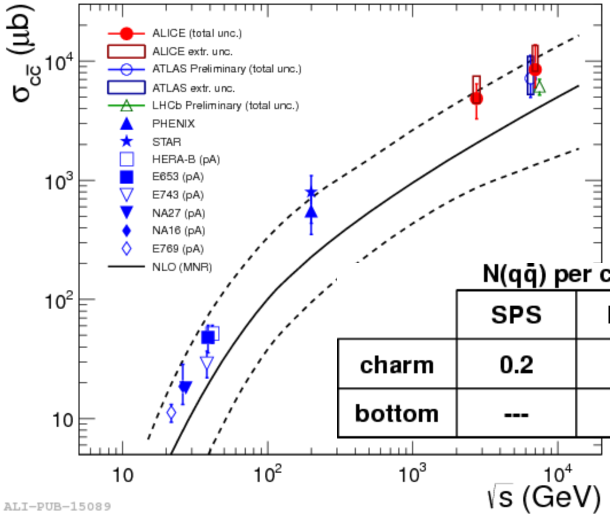
- J/ψ yield enhanced by **regeneration** in experiments at LHC

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

Threws, Schroedter, Rafelski,
Andronic, Braun-Munzinger,
Rapp, Zhao, Du (TAMU)
Zhuang, Liu, Zhou, BC (Tsinghua)



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



N(qq̄) per central AA (b=0)

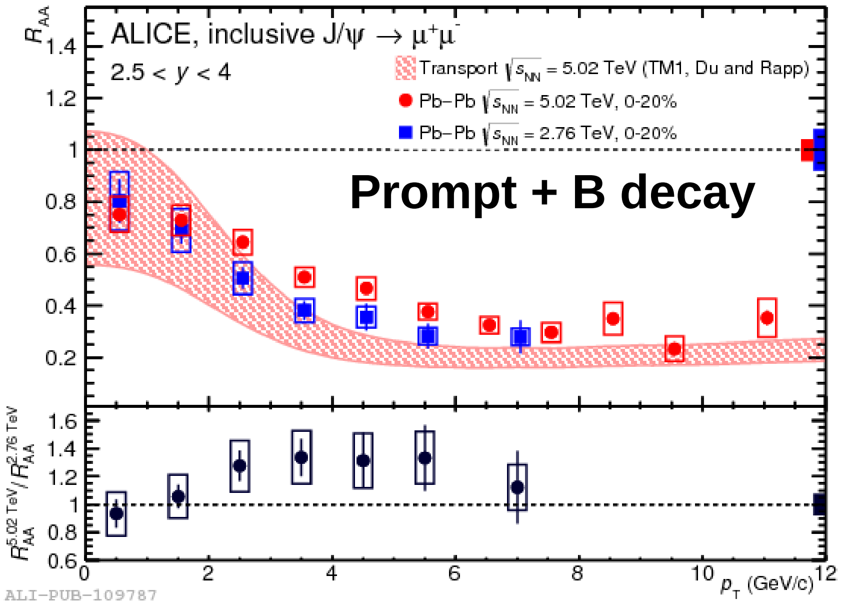
	SPS	RHIC	LHC
charm	0.2	10	130
bottom	---	0.05	5

- **Large number of charm pairs enhance the regeneration**

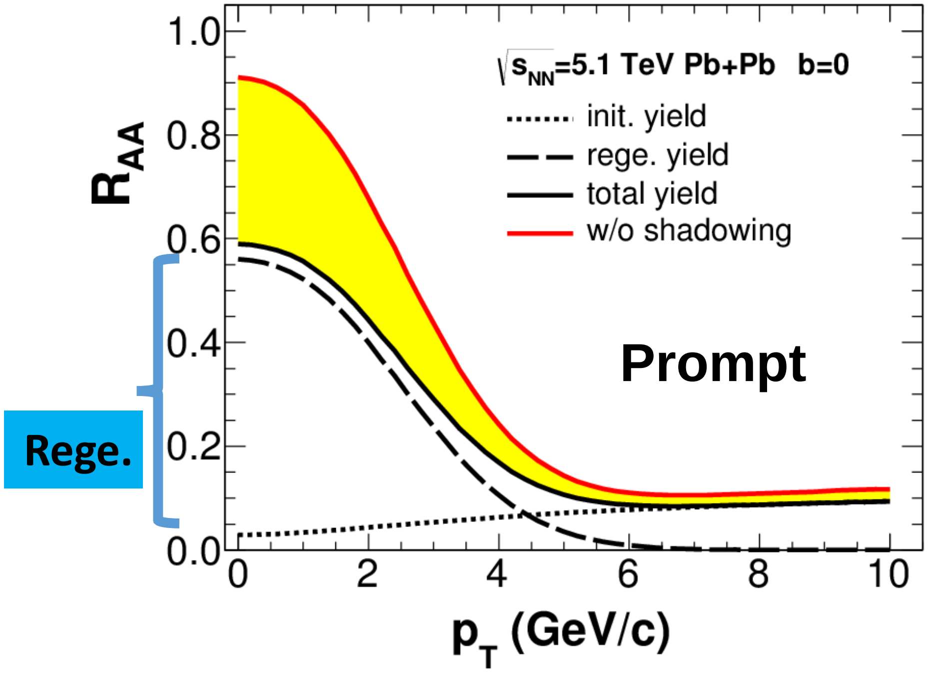
p_T dependence

p_T - dependence

Primordial production V.S. **regeneration**



Rapp, Du, ***TAMU Transport***



Zhuang, BC, ***Tsinghua Transport***

$p_T^{charm} \sim 2T_{QGP}$ **~ 0.5 GeV/c**

Regenerated J/ψ from **uncorrelated** c and $\bar{c}$:

charm suffer energy loss in QGP → J/ψ in LOW p_T

QGP expansion → charm → rege. Ψ

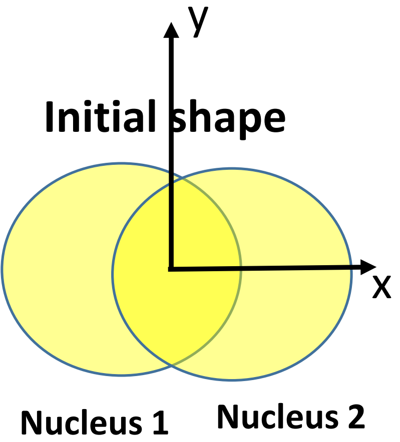
- **At LHC energies of Pb-Pb,**

  more than 90% of total J/ψ are from $c+\bar{c} \leftrightarrow J/\psi + g$

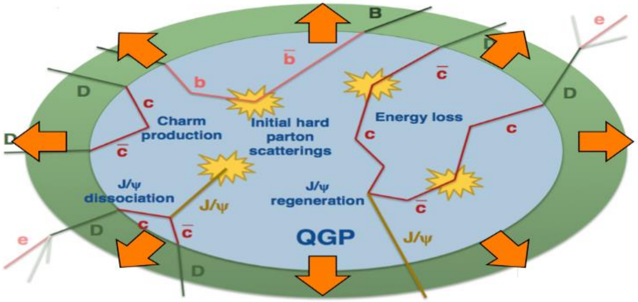
Hidden charm (J/ψ, $\psi(2S)$) open charm (D mesons)

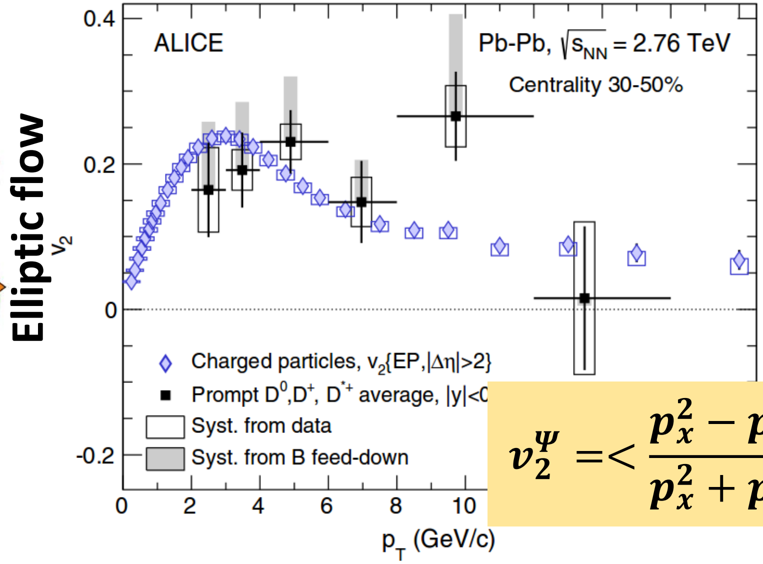
are closely connected with

Anisotropy of spatial density ⟷ QGP Coupling Strength ⟷ Anisotropy of momentum distri.



Expanding QGP (elliptic)





$$v_2^{\Psi} = < \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} >$$

Coalescence models:

Che-ming Ko, Rapp, R.J. Fries, V. Greco, P. Sorensen, Threws, Schroedter, Rafelski, Andronic, Braun-Munzinger, et al

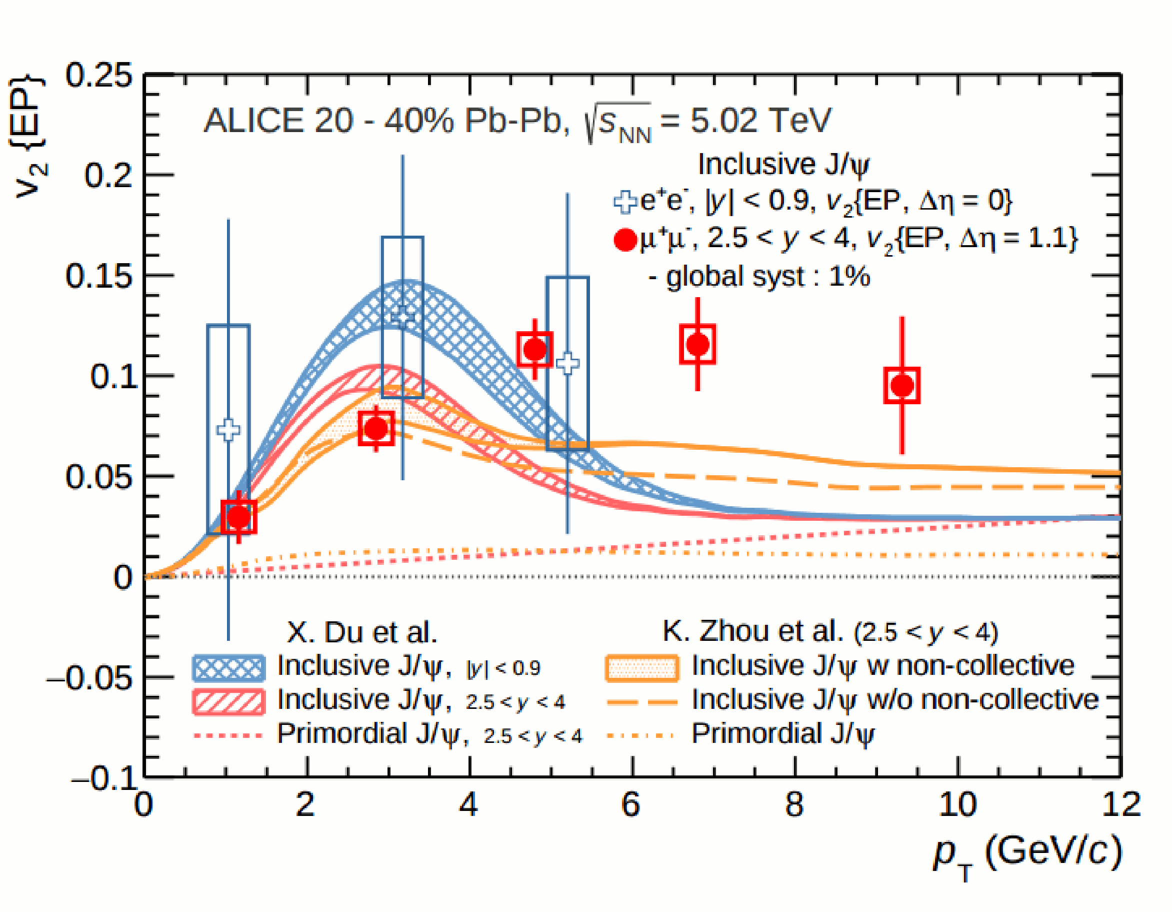
D meson elliptic flow,

charm momentum thermalized ?

PRL, 111, 102301(2013)

QGP expansion → charm → rege. Ψ

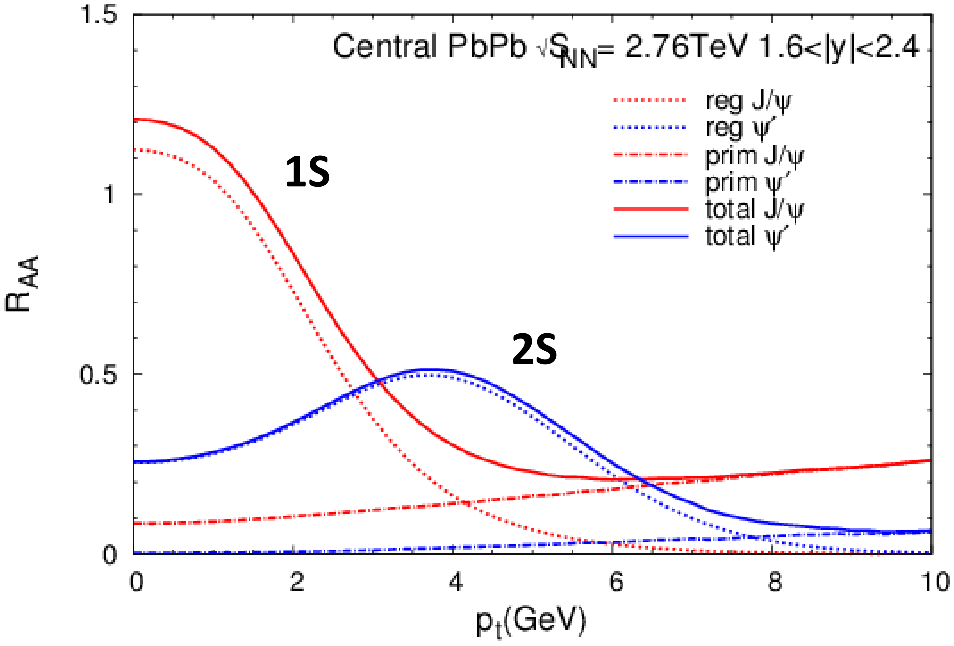
- ✓ **Charm diffusion (thermalization) results in large v_2^{Ψ}**

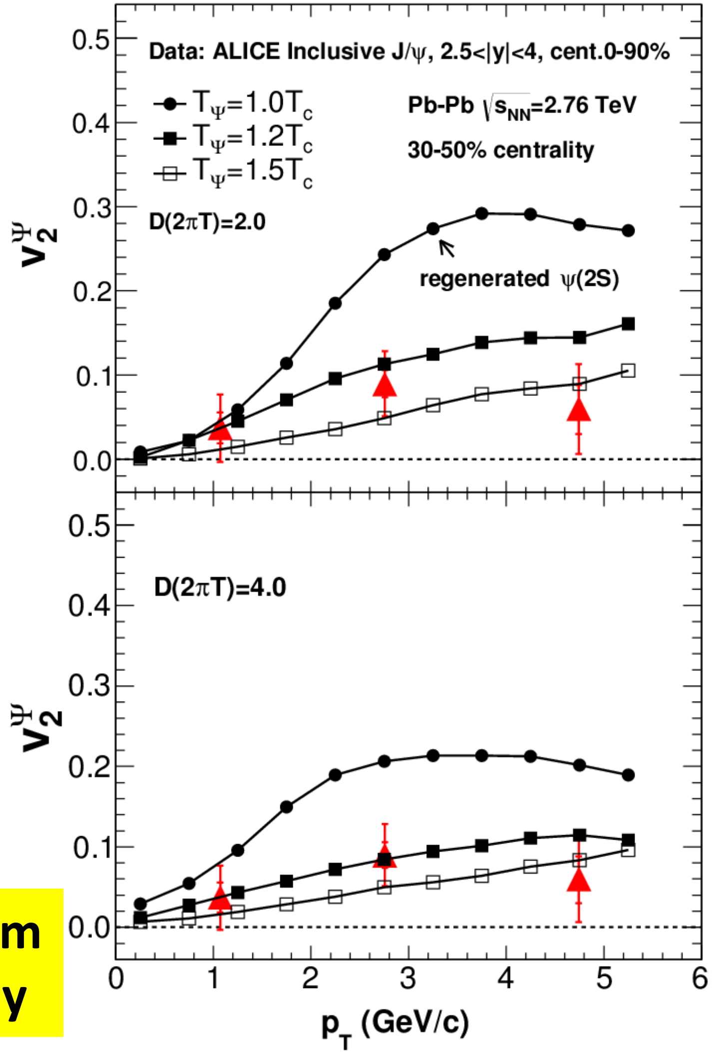


arXiv: 1711.03369

QGP expansion → charm → rege. Ψ

- ✓ **Charm diffusion (thermalization) results in large v_2^{Ψ}**
- ✓ **Charm diffusions affect 1S and 2S**





Yield

Du, Rapp, NPA 2015

Momentum anisotropy

v_2 of 1S and 2S

BC, PRC 2017

$\psi(2S)$ **physics**

expected to be more interesting than J/ψ

$\psi(2S)$ with B meson decay

In AA collisions:

Ψ inclusive yield = initial + regenerated + B-meson decay

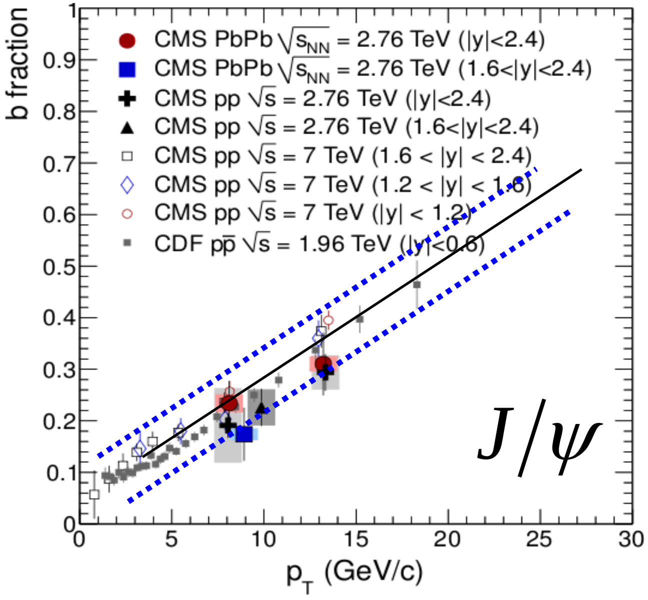
bottom quark energy loss

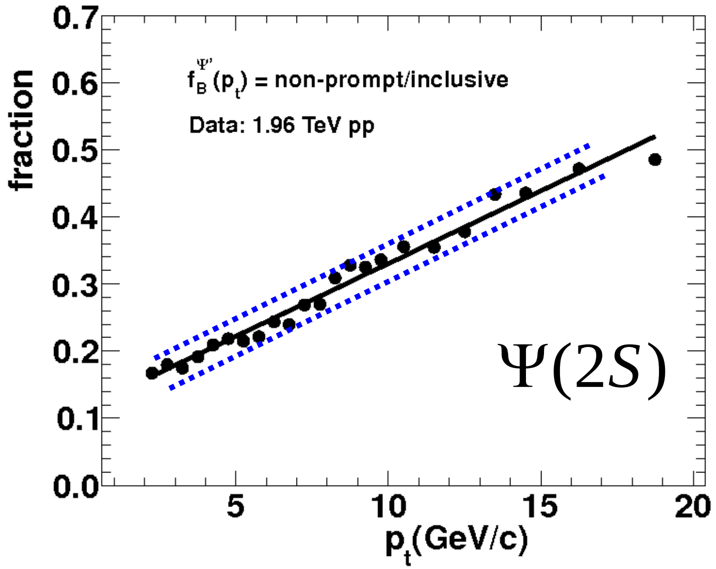
In pp collisions:

~ 10% of inclusive 1S are from B-decay

~ 15% of inclusive 2S are from B-decay

Very different from AA collisions (with QGP production).

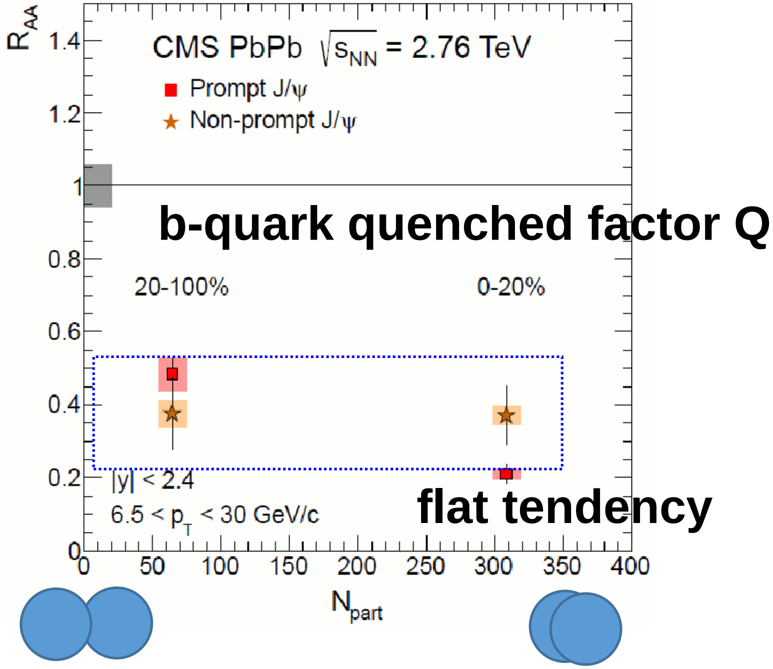




non-prompt fraction in pp collisions

$\psi(2S)$ with B meson decay

B-decay part



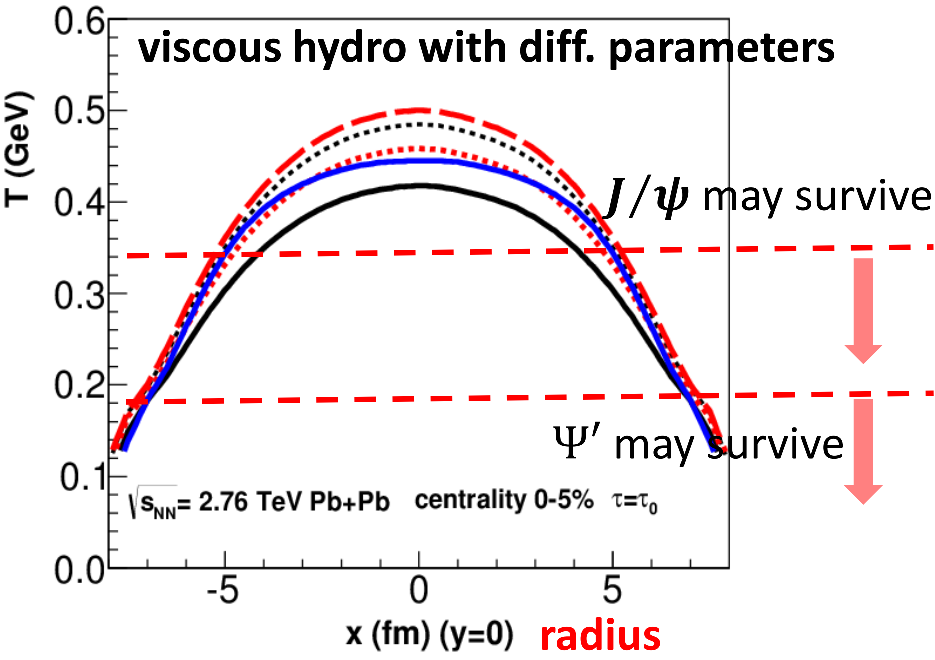
b-quark quenched factor Q

flat tendency

Bottom quark energy loss

Show weak N_p-dependence

Prompt part



viscous hydro with diff. parameters

J/ψ may survive

Ψ' may survive

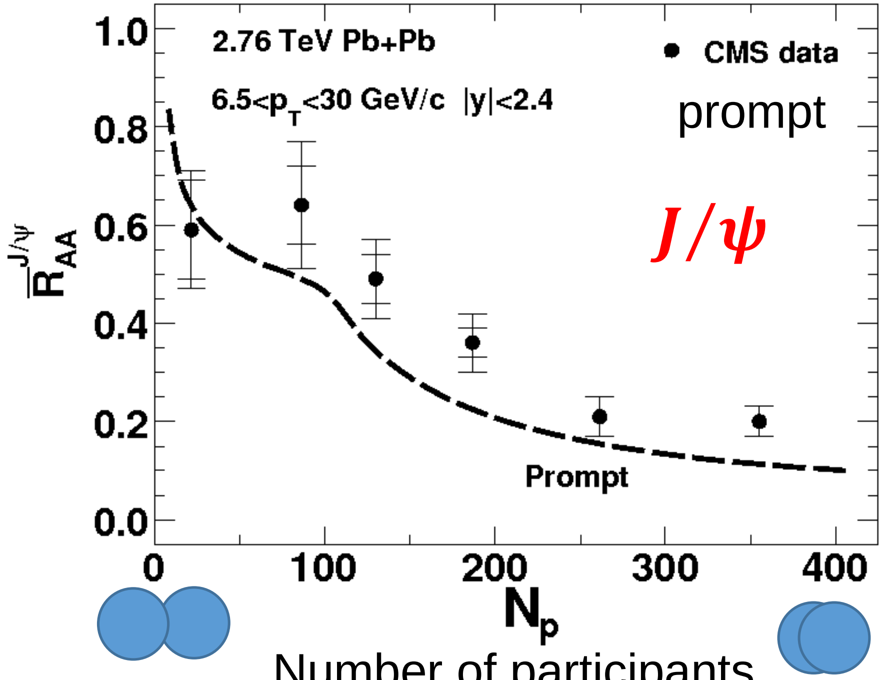
radius

Dissociation temperature

State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
T_d/T_c	2.10	1.16	1.12

- **Based on sequential suppression, Our calculated ratio is around ~ 0.2 for prompt 2S/1S**

$\psi(2S)$ with B meson decay



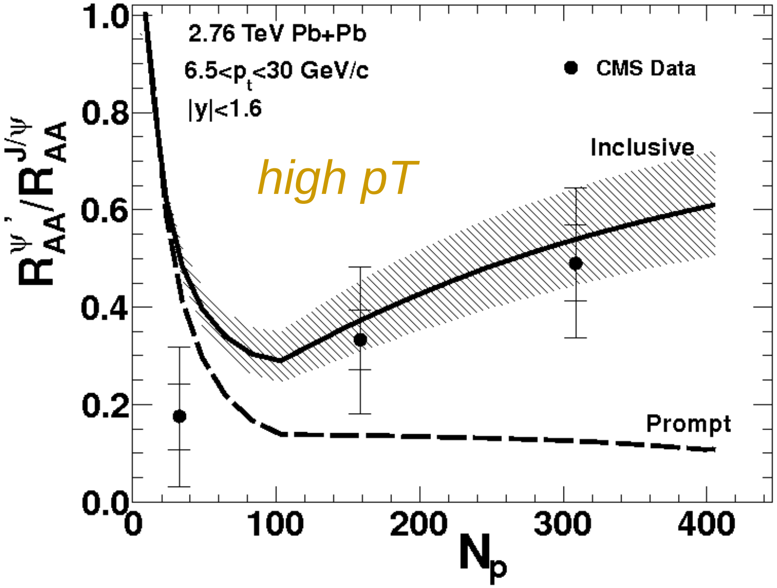
Number of participants

For high pT, no regeneration

With V=U
(satz. et al)

$$T_d^{J/\psi}/T_c \approx 2.1$$
$$T_d^{\psi'}/T_c \approx 1.1$$

- For inclusive J/psi, ~30% from B decay
- For inclusive Psi(2s), ~90% from B decay



With B-decay contribution, double ratio increase with centrality.

$$\frac{R_{AA}^{\psi'}}{R_{AA}^{J/\psi}} = \frac{R_{AA}^{\psi'}(N_p) + \boxed{R_{AA}^{B\to\psi'}}}{\boxed{R_{AA}^{J/\psi}(N_p)} + R_{AA}^{B\to J/\psi}}$$

Const.

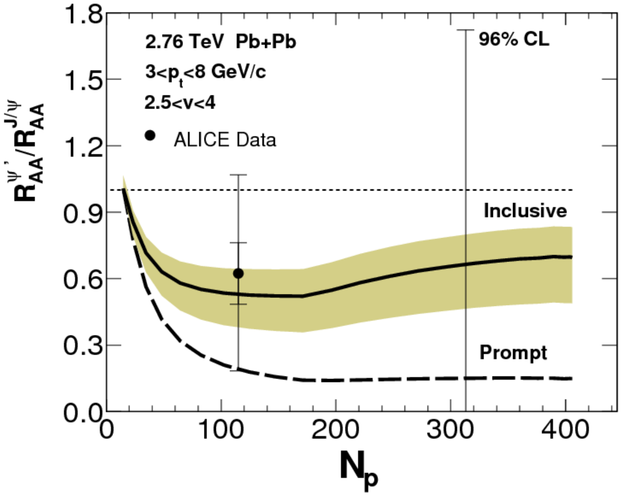
inclusive

decrease

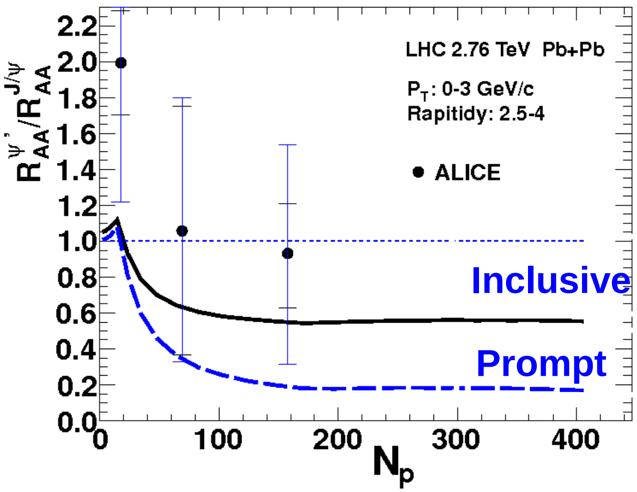
BC, Zhuang, et al, PLB 2013

$\psi(2S)$ with B meson decay

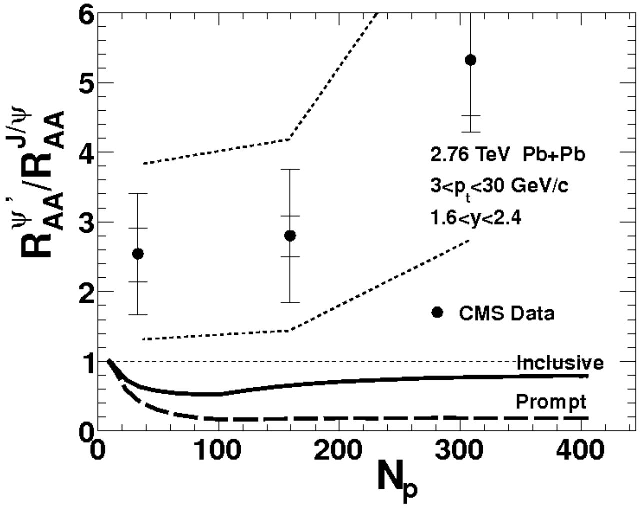
middle pT



Low pT



Inclusive yield

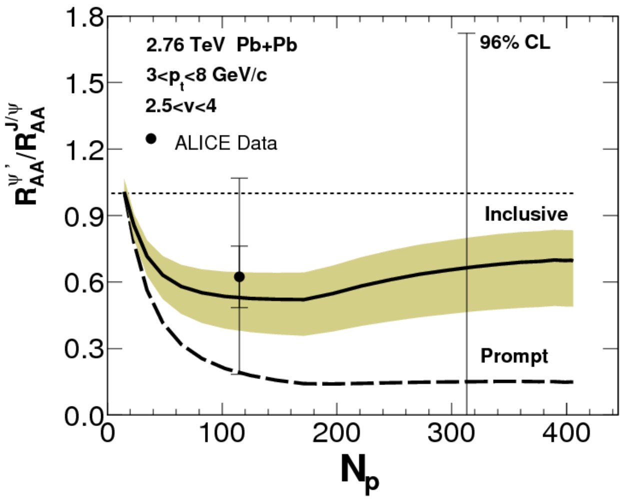


We still can not explain 2S > 1S ,

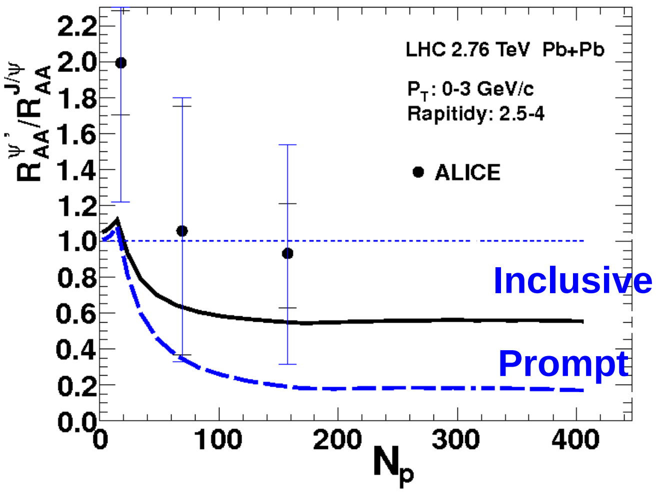
BC, Zhuang, et al, PLB726, 725-728 2013

$\psi(2S)$ with B meson decay

middle pT



Low pT

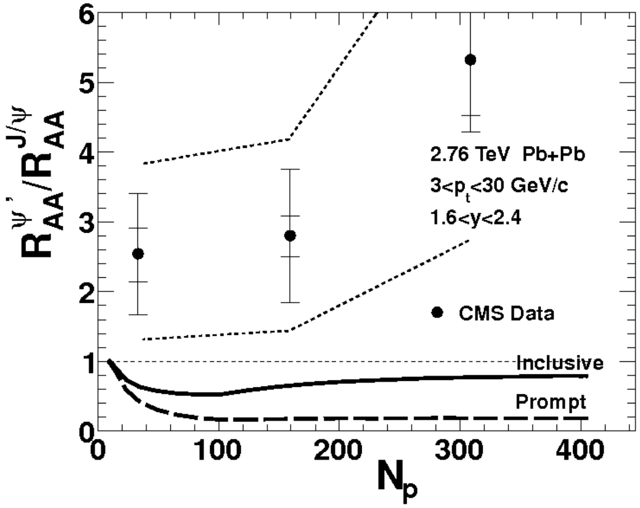


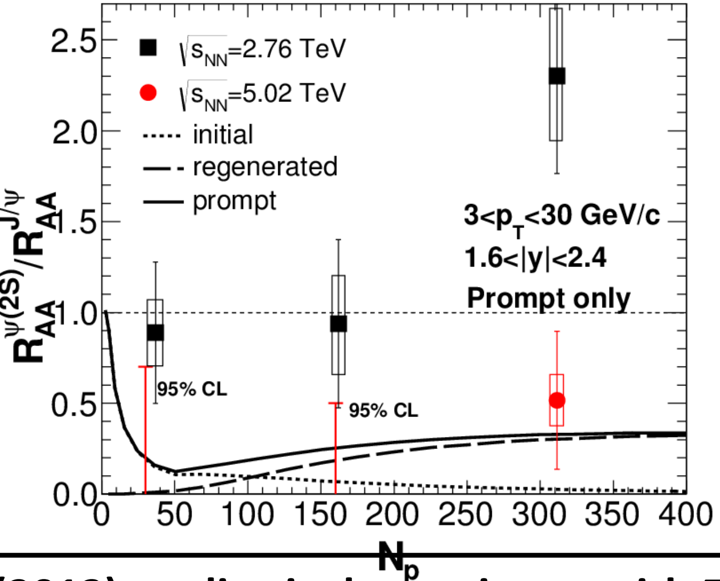
Inclusive yield

Prompt:

2.76 TeV PRL (2014)

5.02 TeV PRL (2017)





We still can not explain 2S > 1S ,

BC, Zhuang, et al, PLB726, 725-728 2013

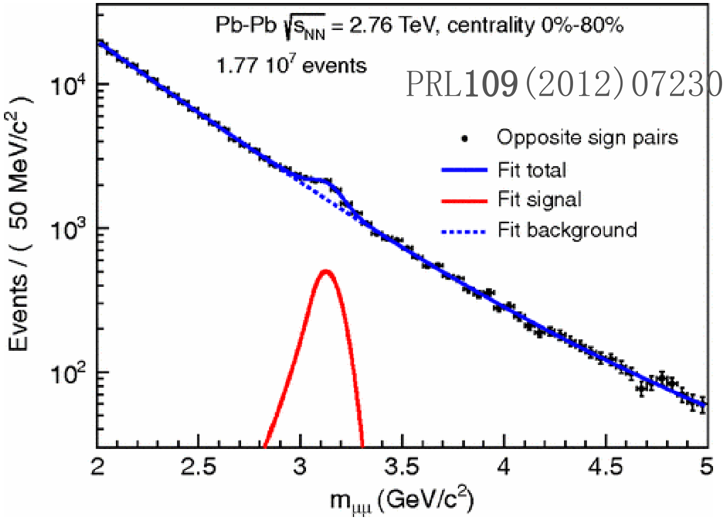
Our results(2013) qualitatively consistent with 5.02 TeV

$\psi(2S)$ in hot medium

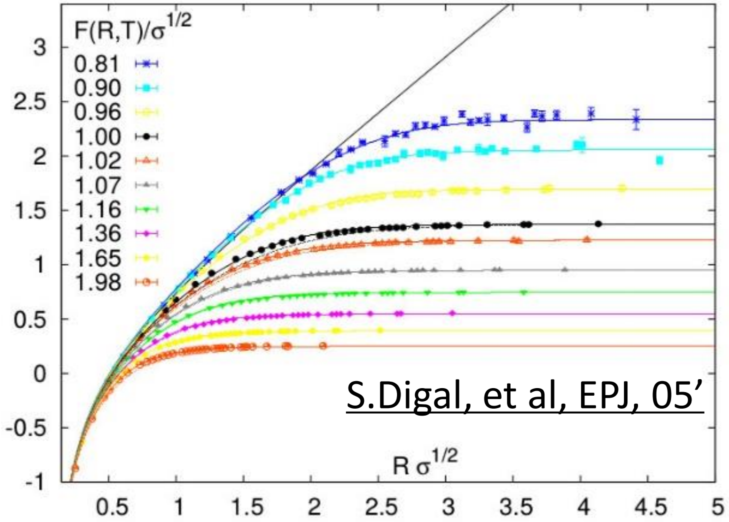
How is loosely bound $\psi(2S)$ produced in the QGP ?

Quarkonium as open quantum system

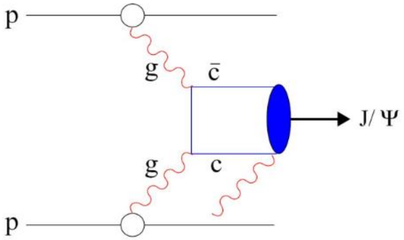
What is Experimentally Measured $\mathbf{J/\psi}$ and $\boldsymbol{\psi(2S)}$?

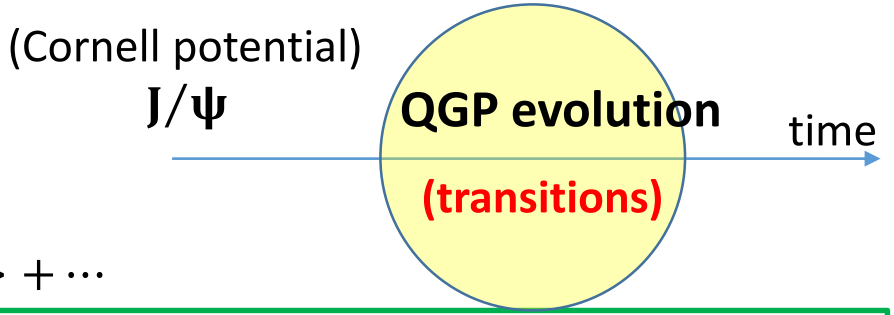


PRL**109** (2012) 072301



S.Digal, et al, EPJ, 05’





(Cornell potential)

$\mathbf{J/\psi}$

QGP evolution

(transitions)

time

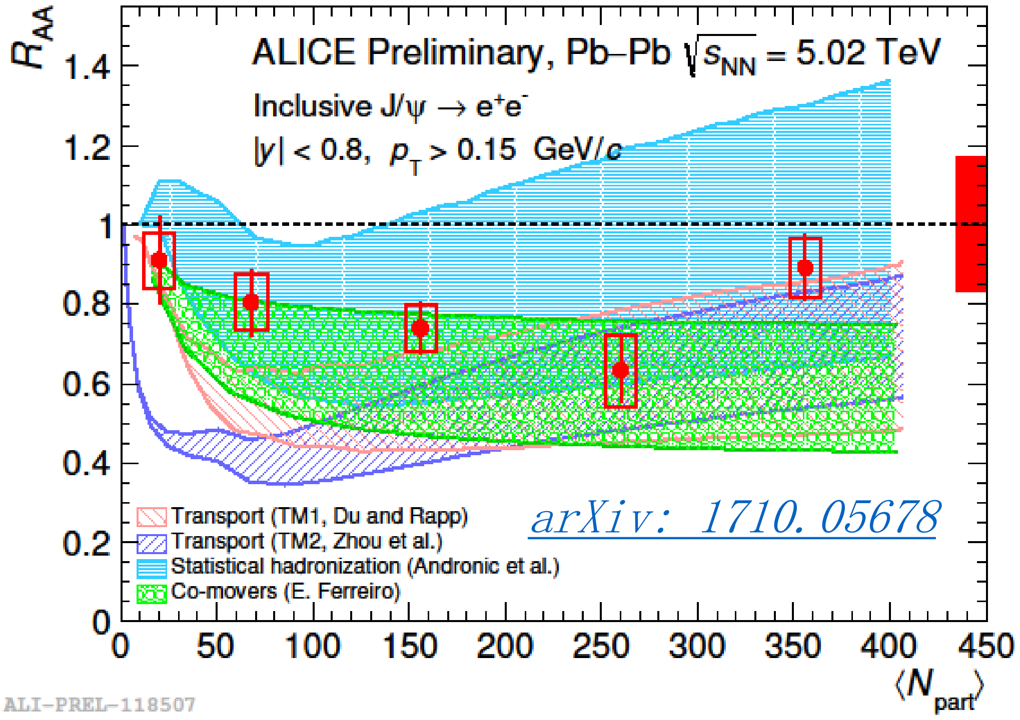
$$|\mathbf{c\bar{c}}> = \mathbf{c_{1S}(t)}|\,\mathbf{J/\psi}> + \mathbf{c_{2S}(t)}|\boldsymbol{\psi}(\mathbf{2S})> + \cdots$$

Exp. measure the eigenstates of Cornell potential (in vacuum);
by dilepton decay.

$c\bar{c}$ dipole potential in QGP is COLOR SCREENED. **transitions**

Transitions between charmonia

Why we didn’t focus on transitions of ψ before?



Large uncertainties of **theoretical calculations** and **experimental data**

Transitions between charmonia

Quantum evolutions about quarkonium:

BC, Du, Rapp, arXiv: 1612.02089
Gossiaux, Katz, ZPC, 93’, 16’
Kopeliovich, et al, PRC, 15’
Taesoo Song, et al, PRC, 15’
Akamatsu, et al, arXiv: 1805.00167
Blaizot, arXiv: 1711.10812

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

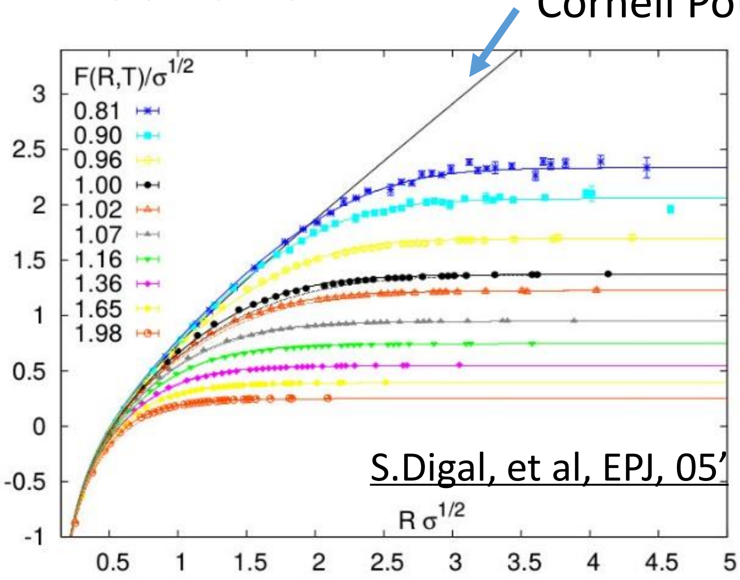
- **mS eigenstate components** in one dipole:

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

- **Heavy quark potential**
  From Lattice QCD calculations.
  - **Static color screening**
  - **Parton inelastic scattering**

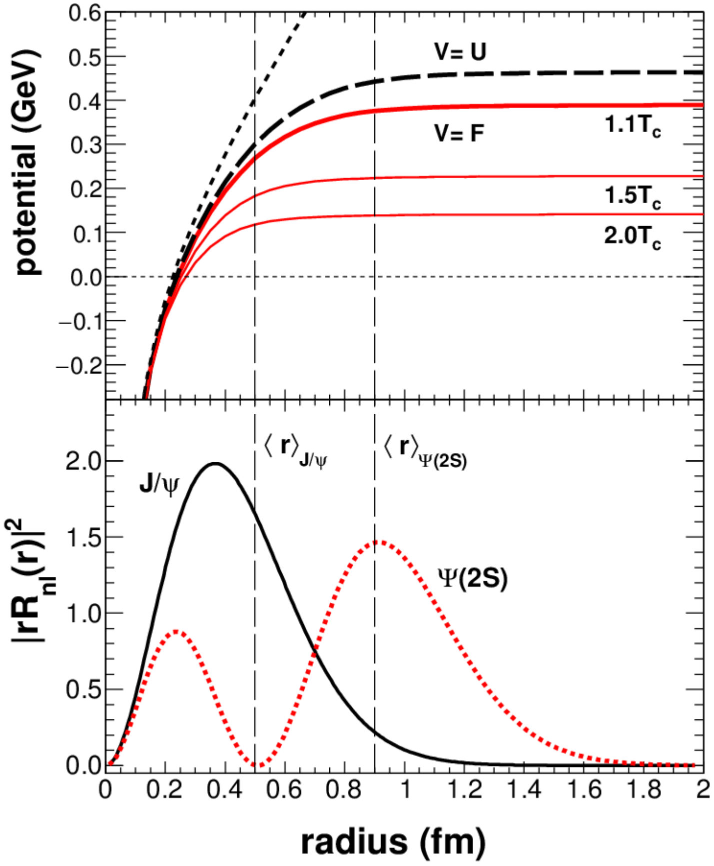
M. Laine, et al, JHEP, 07’
M. Strickland, PRC, 15’

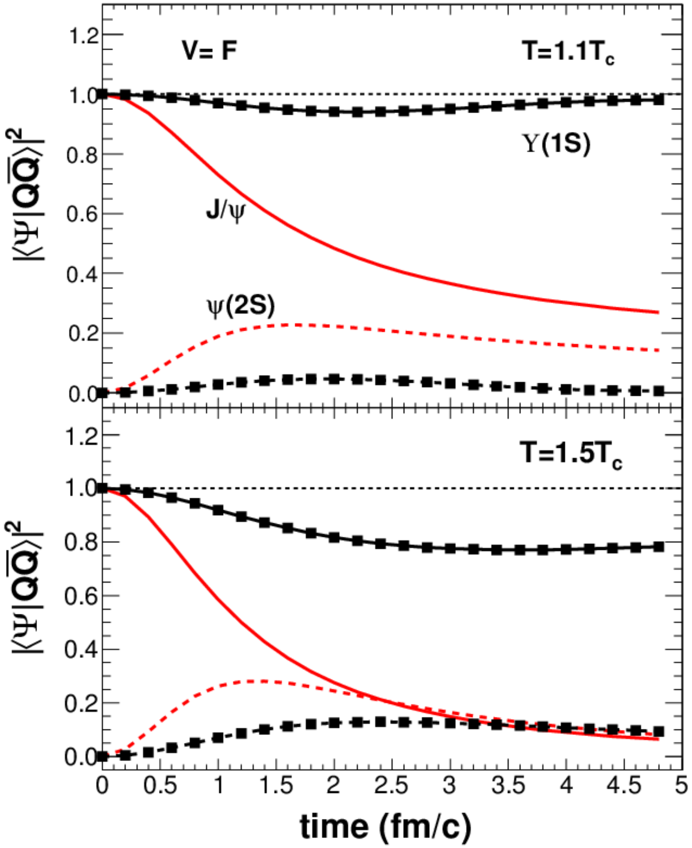
Cornell Potential



S.Digal, et al, EPJ, 05’

Transitions between charmonia





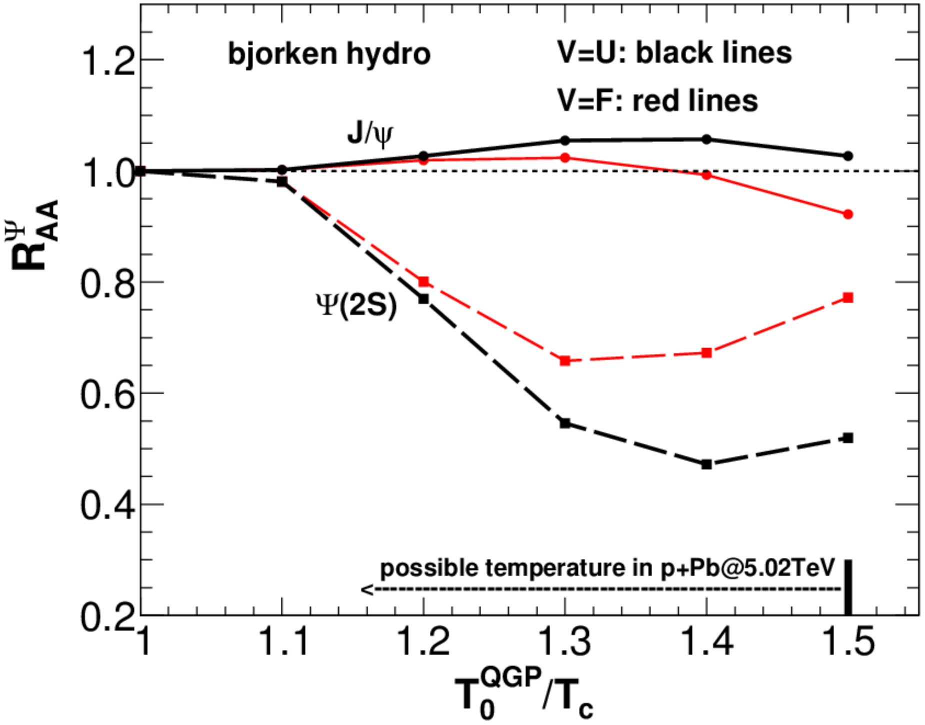
- **Weak attractive force inside $c\bar{c}$ at high temperature.**
- **Potential restored for ground state at low temperature**

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

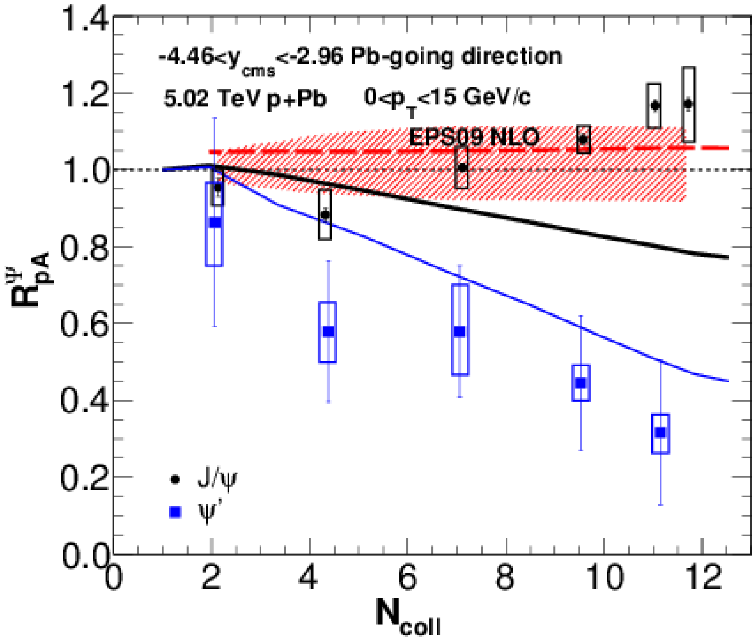
Put one ground state in static hot medium

There are transitions.

Transitions between charmonia



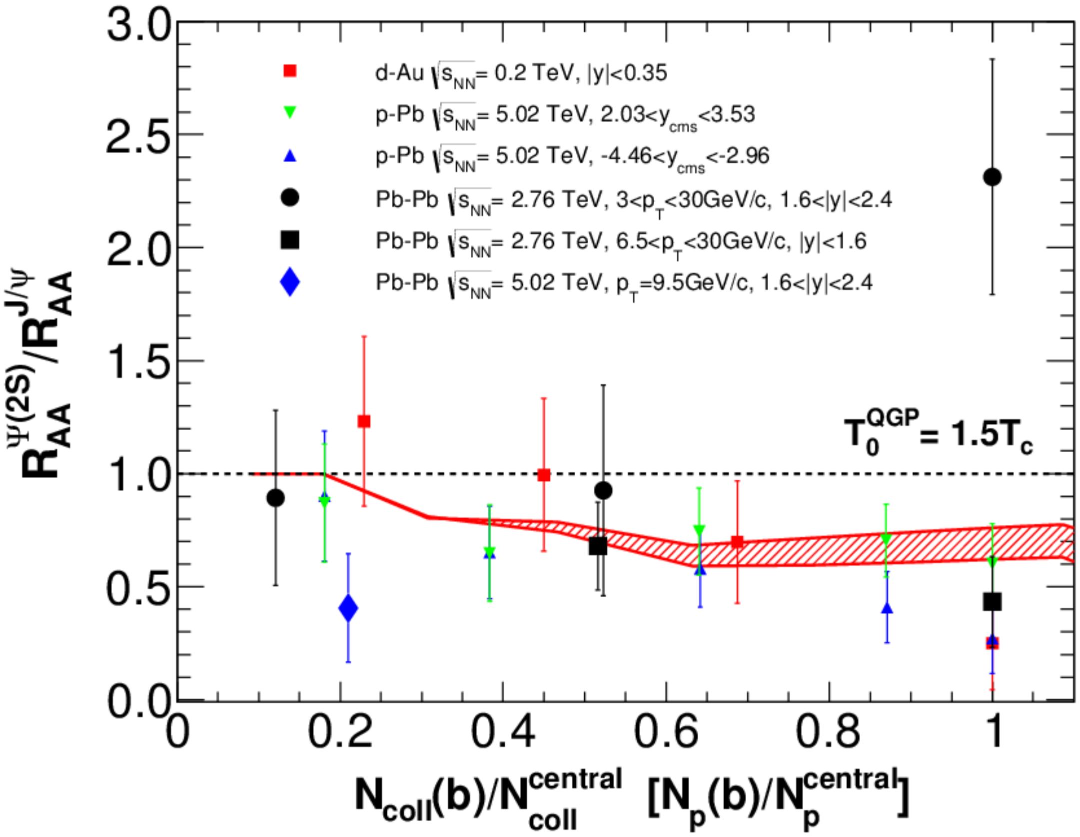
BC, Du, Rapp, in preparation



$c\bar{c}$ evolutions in Bjorken hydro,
With only transition mechanism.

Transport model
With dissociations
No transitions.
BC, Zhuang, PLB 2017

Transitions between charmonia

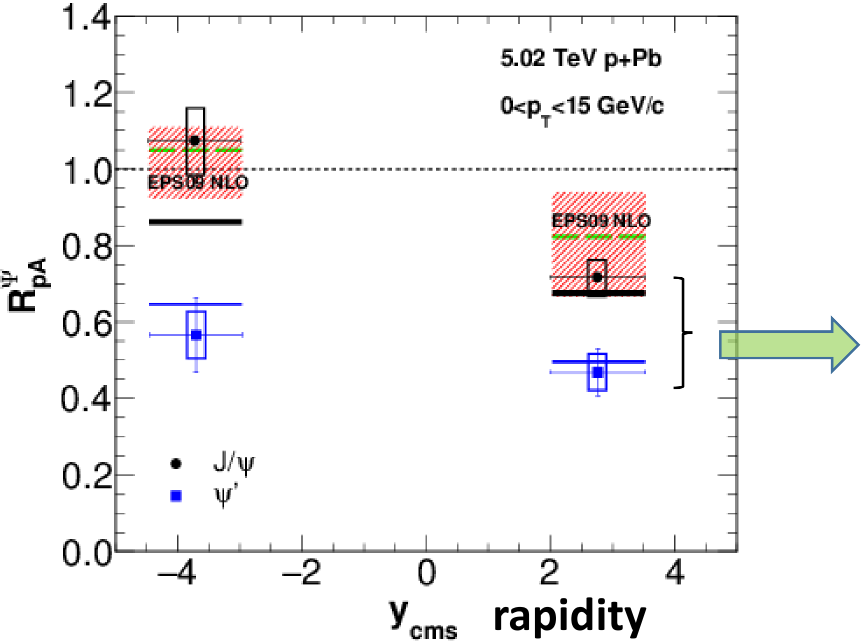


BC, Du, Rapp, in preparation

Very preliminary (pre-mature) comparison between **calculations with transitions** and **experimental data.**

Small QGP in p-Pb @5.02 TeV

charmonium production



Final prompt J/psi :

~ 60% from direct,

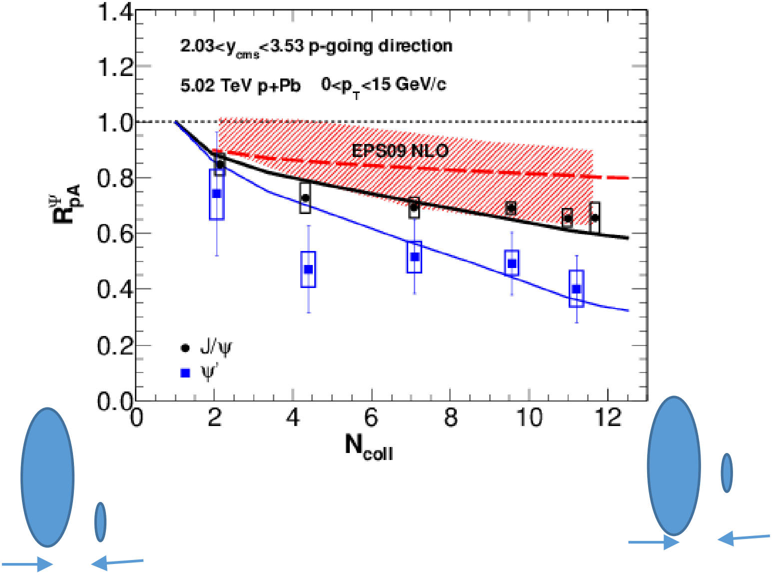
~(30%, 10%) from (1P, 2S) decay

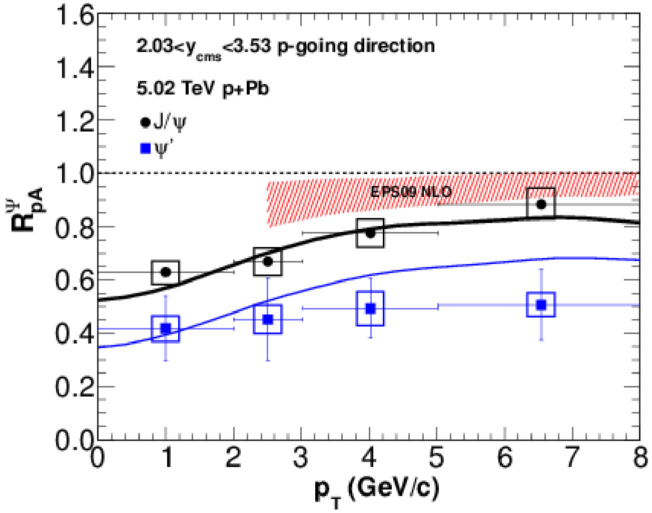
- **Difference of J/ψ and psi' R_{pA}** indicates the **final state interaction**

Hadron gas ? QGP ?

$$T_d^{\psi'} < T_{QGP}^{max}(pA) \approx 1.2T_c < T_d^{J/\psi}$$

BC, Zhuang, et al, PLB 2017



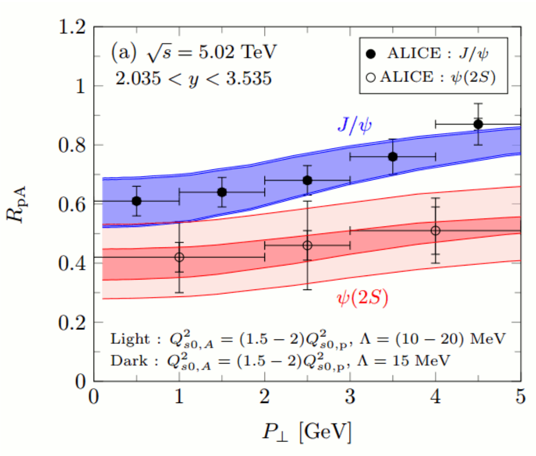


Transverse momentum

Flash comparisons

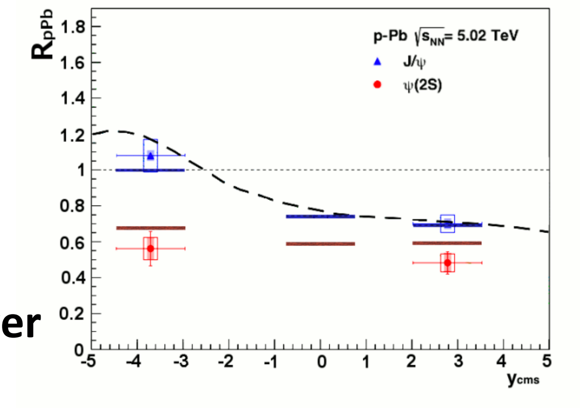
Models:

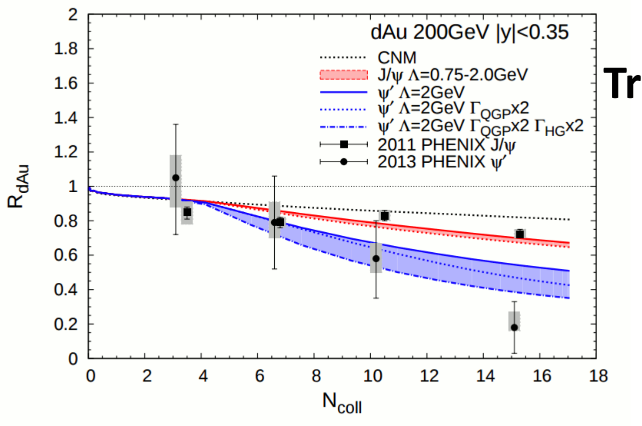
- Y. Q. Ma, et al, CGC+ICEM, PRC 2018
- Ferreiro, Co-mover interactions, PLB 2015
- Transport model (Du, Rapp), QGP+HG NPA 2015
- Transport model (BC, Zhuang) , QGP PLB 2017



CGC+ICEM

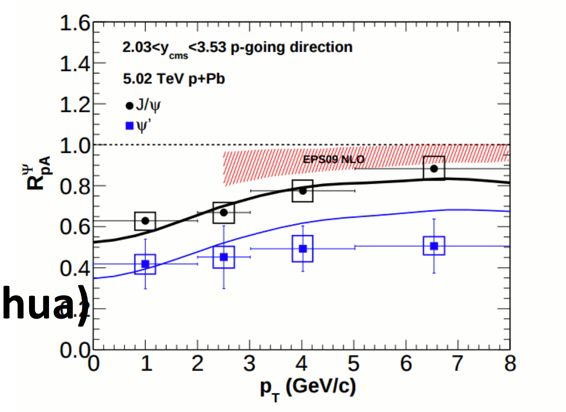
Co-mover





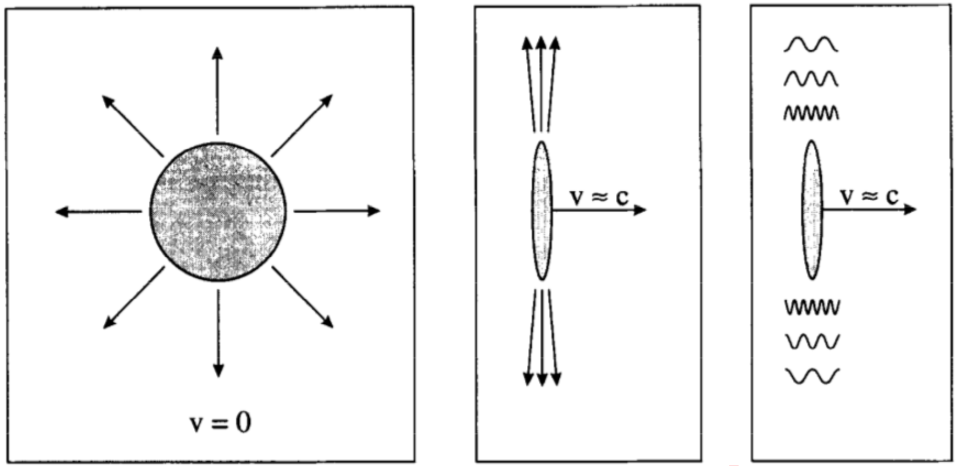
Transport (TAMU)

Transport (Tsinghua)



Equivalent Photon Approximation

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

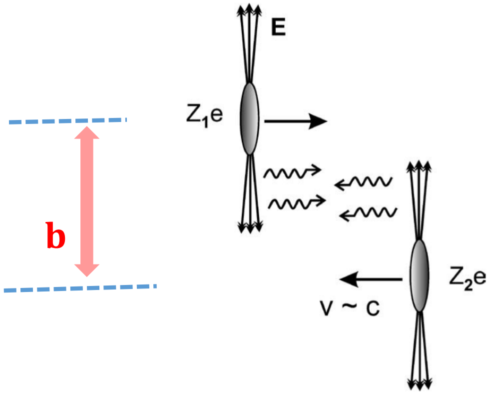


$eB \sim m_\pi^2 \sim 10^{18} G$

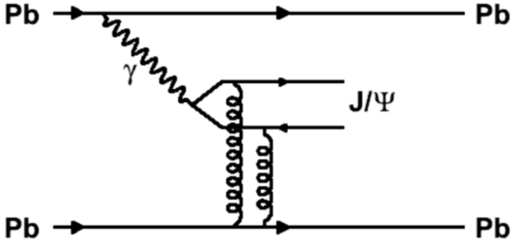
charges moves at nearly speed of light → produce E-B fields

Equivalent-Photon-Approximation

Fermi, 1924'



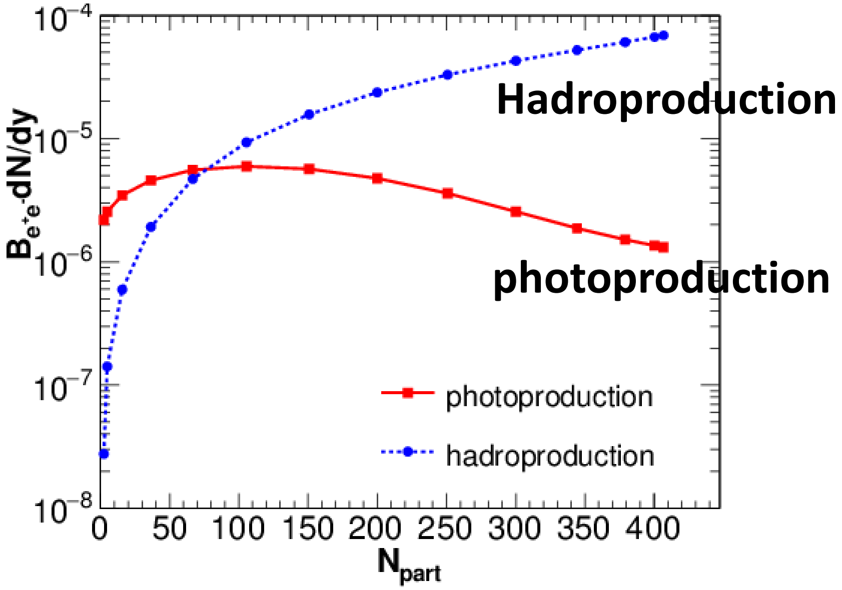
$$\gamma + A \rightarrow J/\psi + A$$

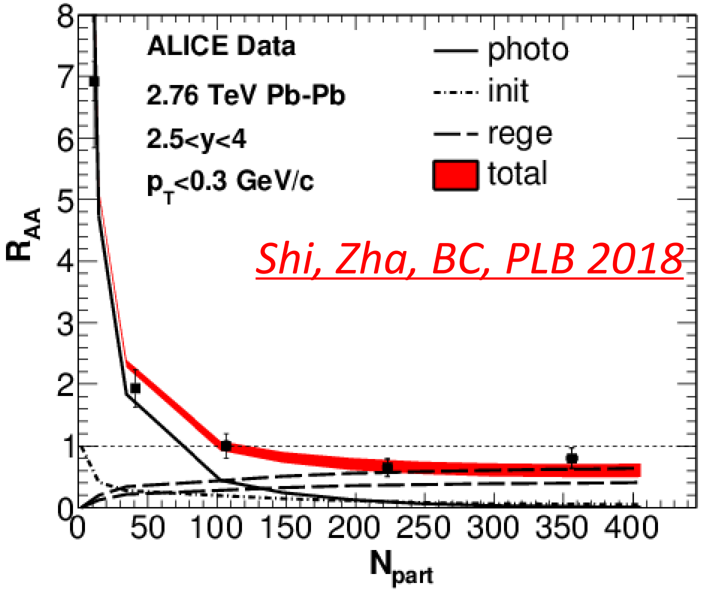


$$|\gamma\rangle = C_{\text{pure}}|\gamma_{\text{pure}}\rangle + C_{\rho^0}|\rho^0\rangle + C_\omega|\omega\rangle + C_\phi|\phi\rangle + C_{J/\psi}|J/\psi\rangle + \cdots + C_{q\bar{q}}|q\bar{q}\rangle$$

J/ψ from EM field + QGP

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



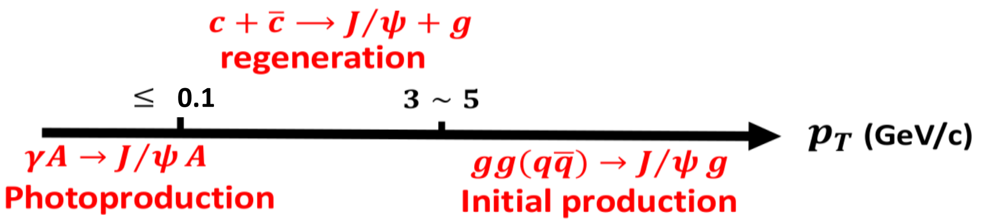


Shi, Zha, BC, PLB 2018

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

- **Significant enhancement at $N_p \approx 80$,** where $T_0^{QGP} = 2T_c$
- When N_{part} → 0 $(b > 2R_A)$,
  hadroproduction → 0, photoproduction → non-zero, R_{AA} → infinity

Summary



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

- **Charm quark evolutions affect the behavior of regenerated charmonia.**
- **$\psi(2S)$ may come from transitions in the correlated charm pair, or recombination of un-correlated charm pairs.**
  B hadron decay is important for inclusive $\psi(2S)$ yield.
- **Photoproduction from strong EM fields are still important in extremely low pT and semi-central collisions.**

Some reference related to the talk:

BC, Zhuang, et al,	PLB 765, 323-327(2017)	p-Pb
BC,	PRC 95, 034908 (2017)	2S elliptic flows
Zhao, BC,	PLB 776, 17-21, (2018)	Charm diffusions
BC, Rapp, et al,	in preparation, (and 1612.02089)	Charmonium transitions in QGP
BC, Zhuang, et al,	1801.01677	EM fields and QGP on 2S/1S
Shi, Zha, BC	PLB 777, 399-405, (2018)	$\gamma A\rightarrow J/\psi\, A$
BC,	PRC 93, 054905 (2016)	Rapidity dependence

More slides

Transport equation

Transport model

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

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

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

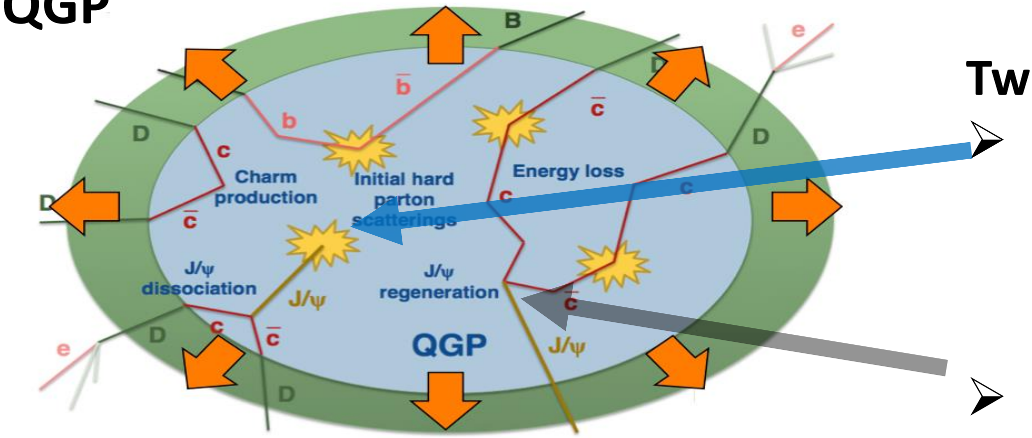
$$\boldsymbol{\partial_\mu(\rho_c u^\mu_{QGP}) = 0}$$

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

Dynamical evolution

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

Expanding QGP



Two components:

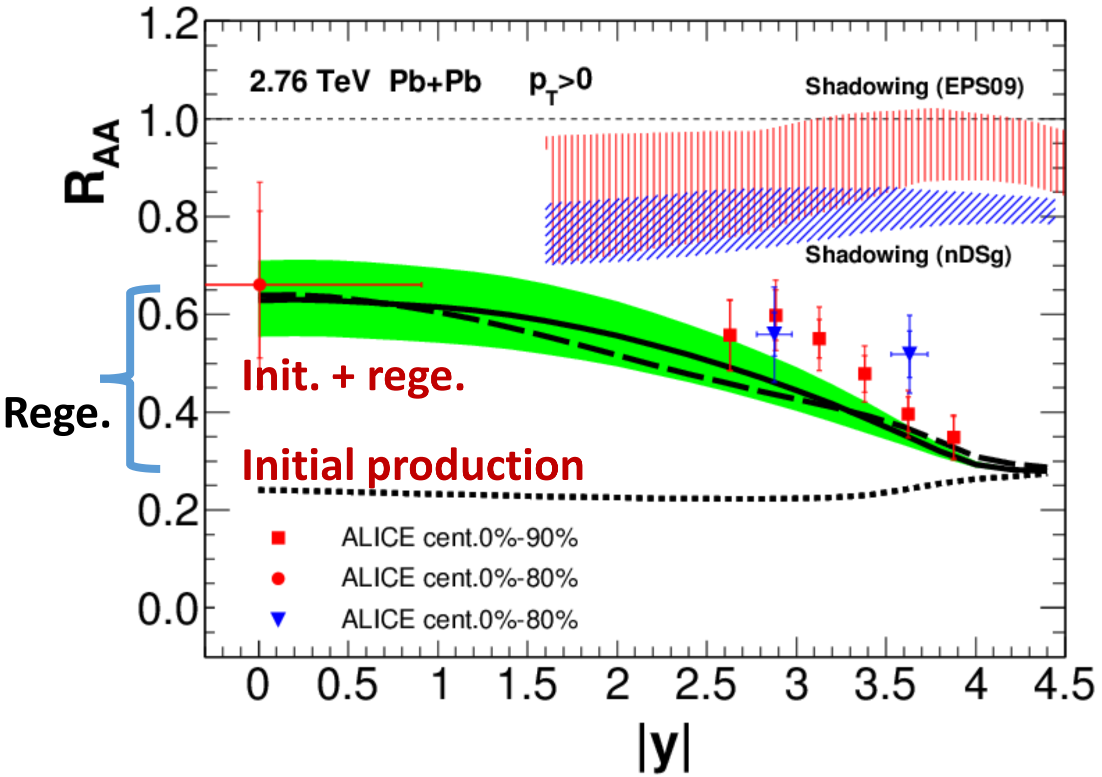
- ➢ Initial hard scattering before QGP formation
- ➢ Regeneration:

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

Rapidity dependence

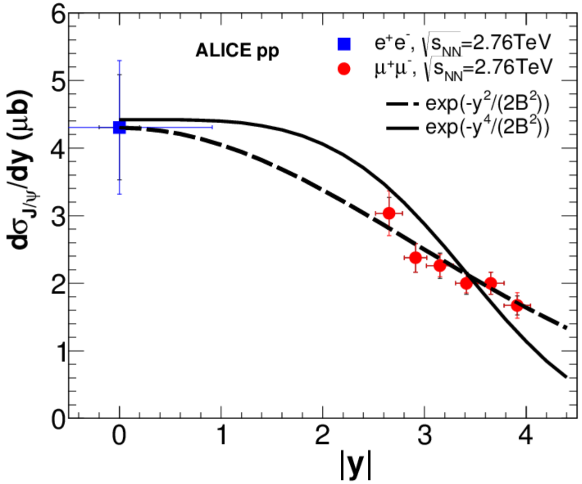
Rapidity - dependence

- **$R_{AA}(y)$ nuclear modification factor with rapidity**



BC, PRC 93 (2016) 054905

$$N^{rege}_{J/\psi} \sim \int dV\ \rho_c \rho_{\bar{c}} W_{combine}$$

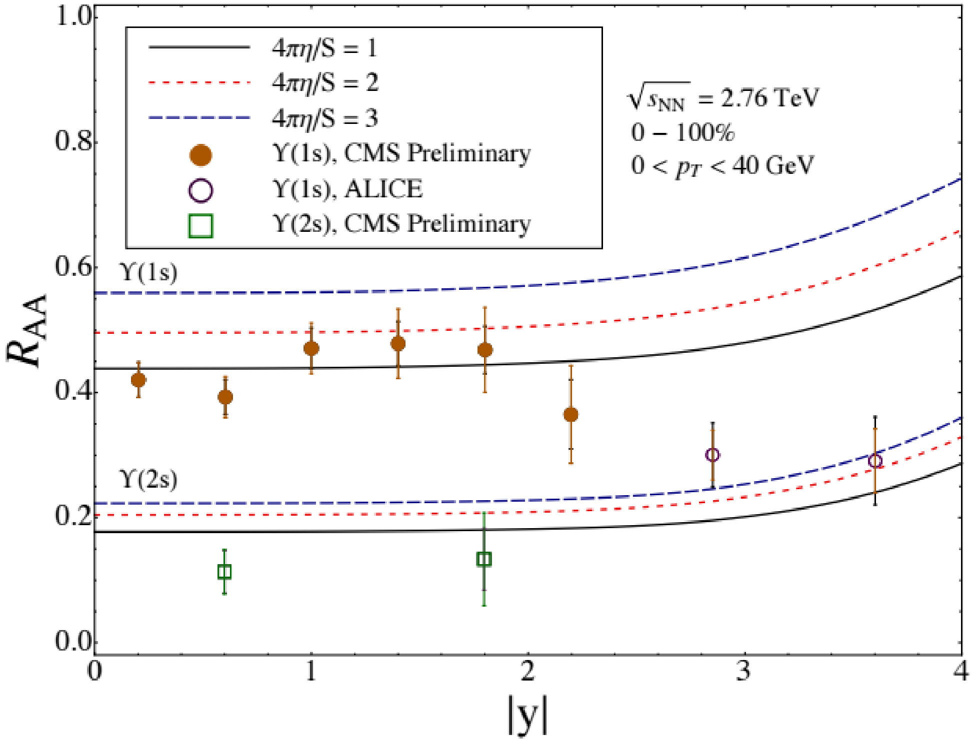


$c\bar{c}$ production cross-section

Regeneration dominates in central rapidity

Situation without recombination

- **If no regeneration, $R_{AA}(y)$? (such as bottomonium)**



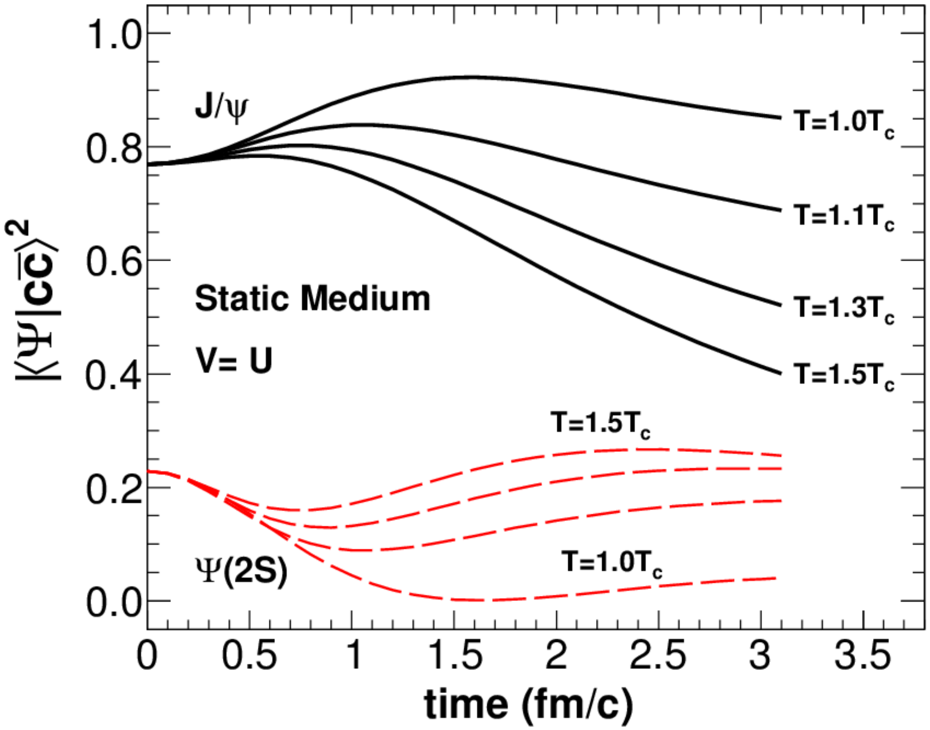
M. Strickland, et al, Potential model
PRC 92 (2015) 061901,

weak/no regeneration for Υ , due to less bottom pairs

More reference:

Du, Rapp, He:
PRC 96, (2017) ,054901
Blaizot, Escobedo: 1803.07996
BC, Zhao:
PLB 772 (2017) 819-824

Transitions between charmonia



The evolutions also need $c\bar{c}$ initial wave function

- Initialize $c\bar{c}$ dipole with more realistic wave function, Containing components of both 1S and 2S

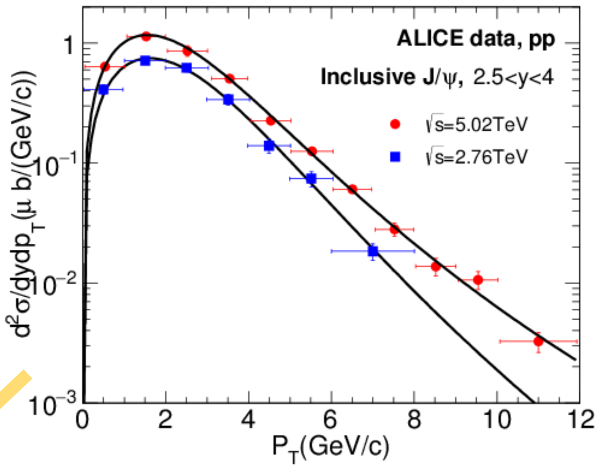
- **Different transitions happen at different T.**

(the normalization of $c\bar{c}$ wave function is conserved.)

p_T dependence

hadronic production in different pT region

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



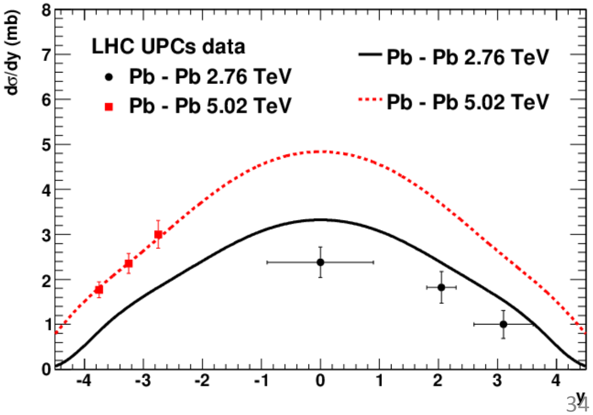
Zhao, BC, PLB 2017

Hadronic cross section

Mean p_T in hadroproduction $< \mathrm{p_T} >\sim 3\ \mathrm{GeV/c}$

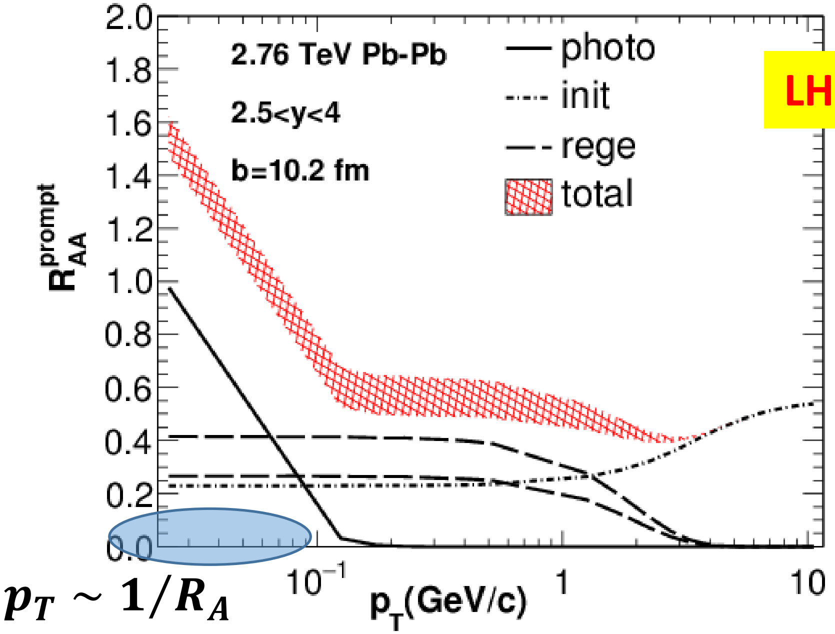
$$\gamma + A \rightarrow J/\psi + \mathrm{X} \quad p_T \sim 1/R_A \sim 0.03\ \mathrm{GeV/c}$$

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



Shi, Zha, BC, PLB 2018

Total J/ψ from EB field + QGP

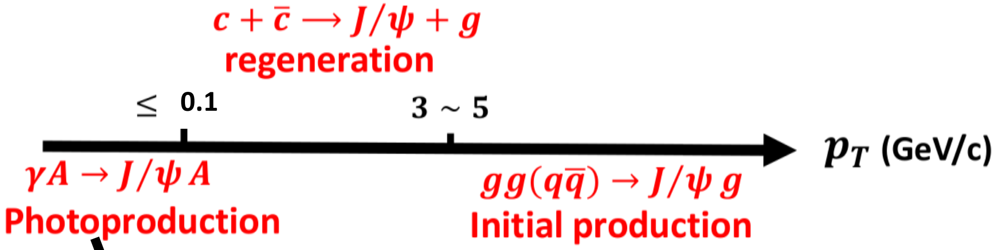


LHC

$p_T \sim 1/R_A$

Shi, Zha, BC, PLB 2018

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



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

regeneration

$\leq$ 0.1

3 ~ 5

p_T (GeV/c)

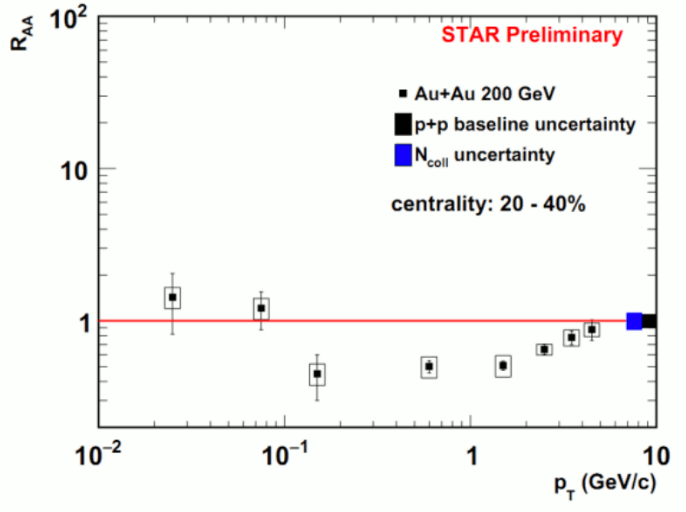
$\gamma A \rightarrow J/\psi\, A$

Photoproduction

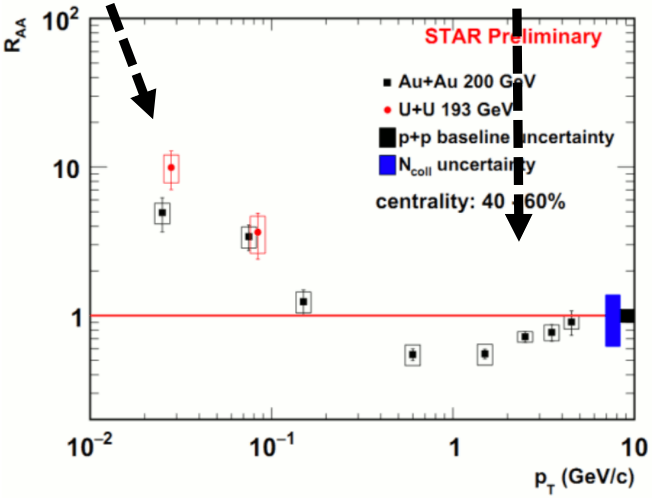
$gg(q\bar{q}) \rightarrow J/\psi\, g$

Initial production

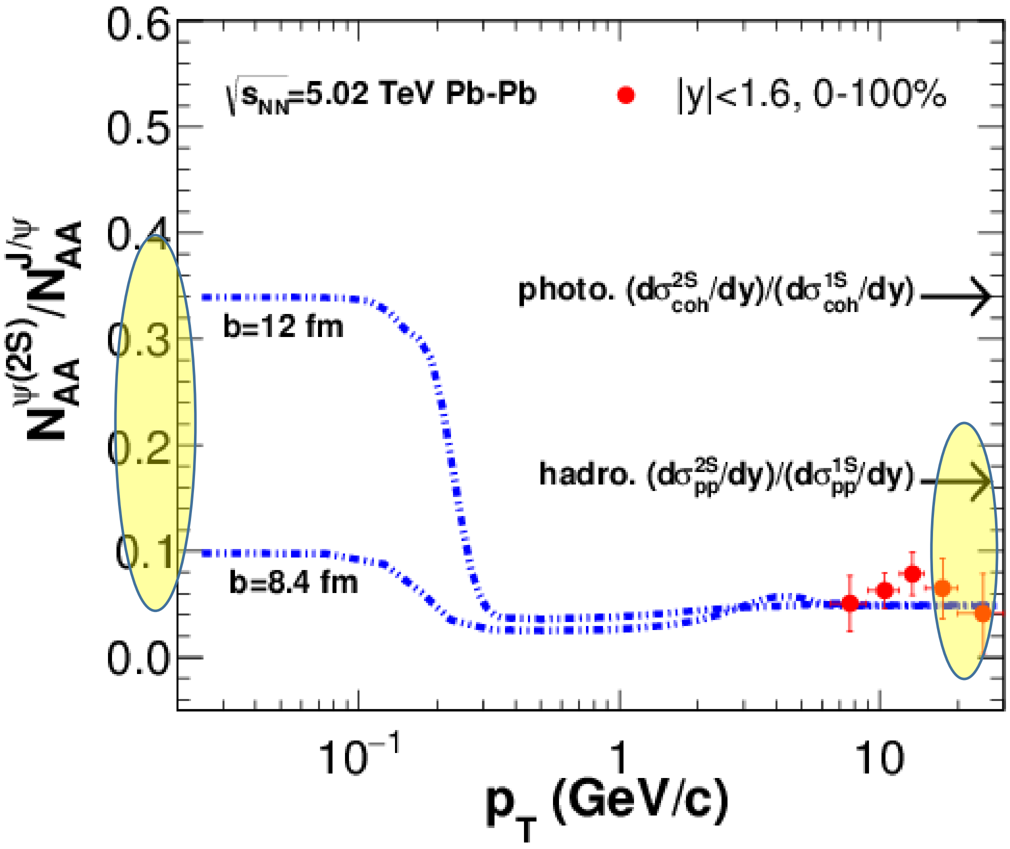
R_{AA} decreases, then increases with pT



RHIC



Photoproduced 2S/1S



BC, Zhuang, Carsten, et, arXiv: 1801.01677

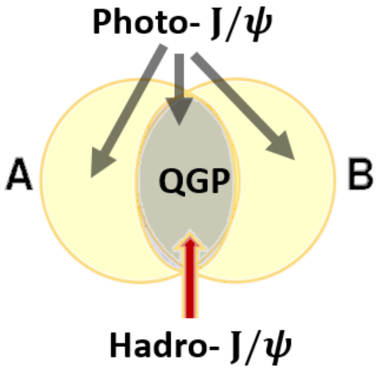
Our prediction in low p_T

- **Enhancement:** additional photoproduction + diff. spatial distribution

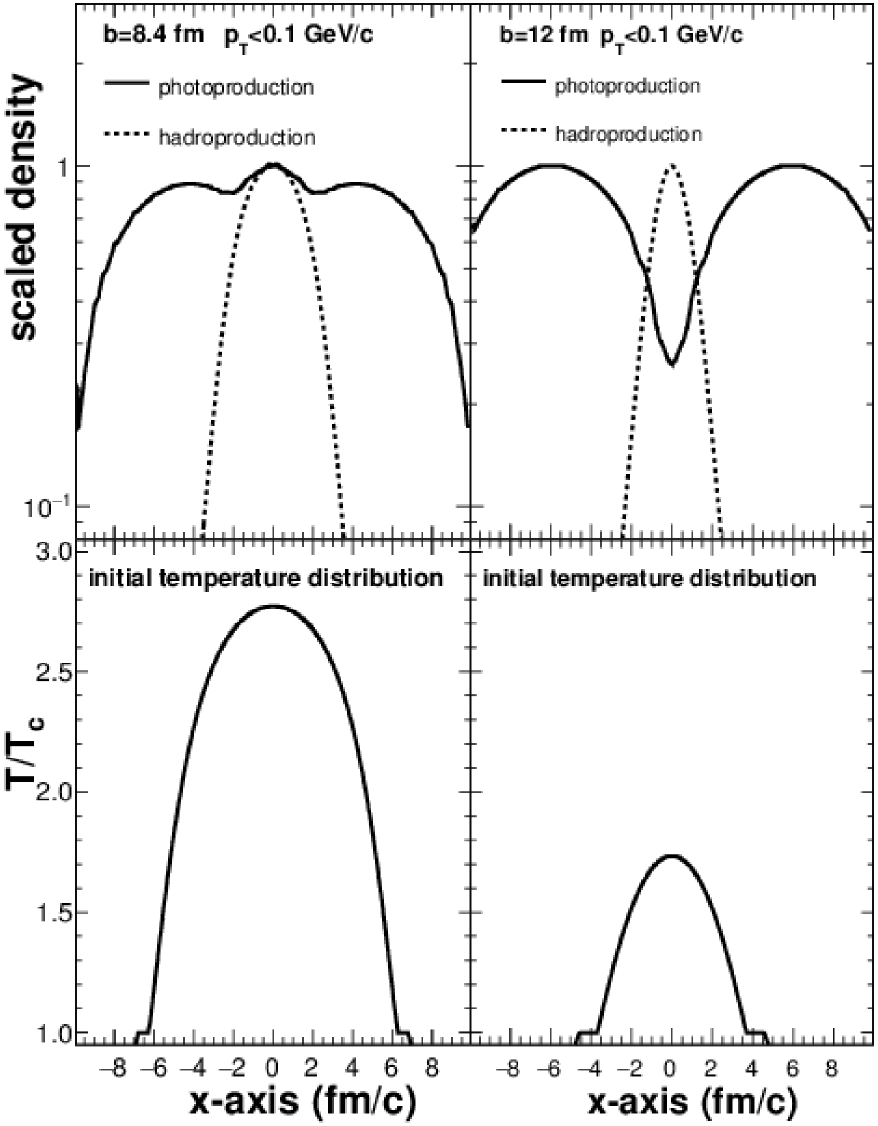
- **Suppression:** **QGP effect.**

- **Hadroproduction:** in the overlap area of two nuclei

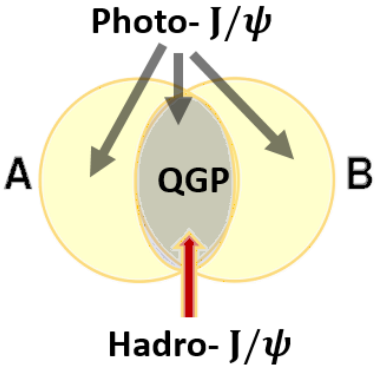
- **Photoproduction:** over the entire nuclear surface



Photoproduced 2S/1S



Spatial distributions of two productions



- **Hadroproduction:**
  in the overlap area of two nuclei
- **Photoproduction:**
  over the entire nuclear surface

Spatial distribution of medium Temperature

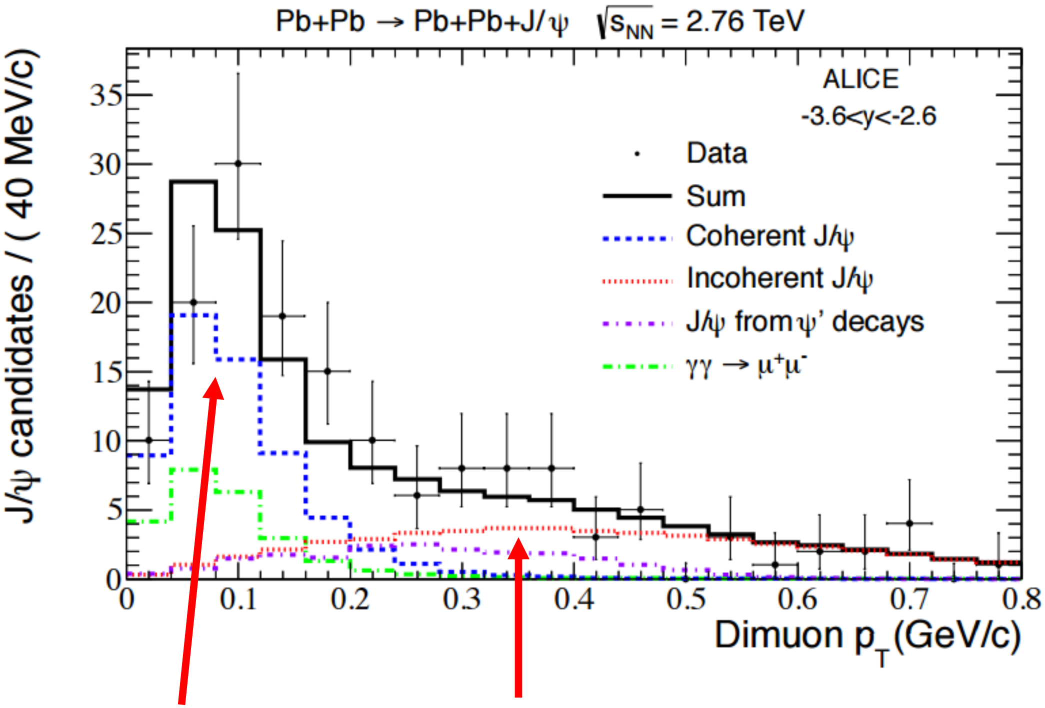
J/ψ coherent photoproduction

Vector meson dominant model

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

Coherent: $\boldsymbol{\gamma + A \to J/\psi + X}$

Incoherent: $\boldsymbol{\gamma + \mathrm{N} \to J/\psi + X}$



Coherent **Incoherent**

- In $p_T < 0.1$ GeV/c, coherent production dominates.

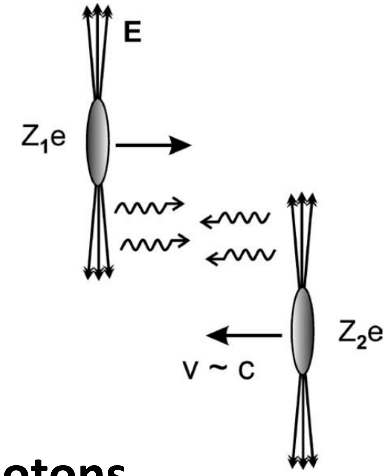
J/ψ from electromagnetic field

Mainly three ingredients:

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

Given latter

- **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**

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

Photon density

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

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

For point particle, it's 1