Theory overview on quarkonium

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EXPLORING HIGH-MUB MATTER WITH RARE PROBES

Different P_T quarkonium

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

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

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

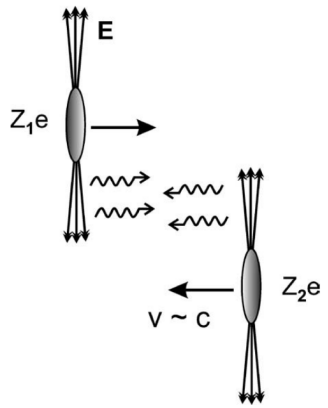
(1)Photoproduction
Low P_T
semi-central (peripheral)

(2) Charm diffusion → ψ
sequential regeneration

(3)Correlated $c\bar{c}$
sequential dissociation

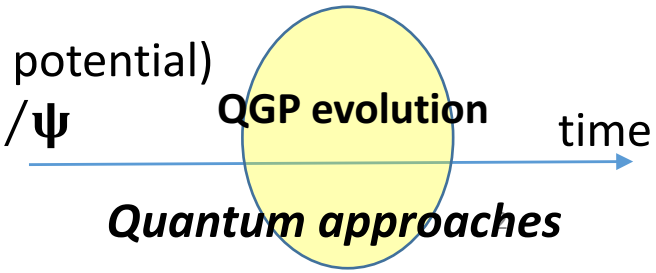
$R_{AA}^{1S} > R_{AA}^{2S} > R_{AA}^{3S}$

$R_{AA}(p_T)$-shape of J/ψ, $\psi(2S)$,



(Cornell potential)

$\mathbf{J/\psi}$



Quantum approaches

Outline

1) Charmonium (J/ψ, $\psi(2S)$) in large QCD medium (AA)

$R_{AA}^{J/\psi}$, $R_{AA}^{\psi(2S)}$: $R_{AA}(N_p, p_T, y)$

charmonium v_1, v_2, v_3,

bottomonium (1S, 2S, 3S) R_{AA}

exotic hadrons in AA

2) Charmonium in small colliding system (pA)

$R_{AA}^{J/\psi}$, $R_{AA}^{\psi(2S)}$: **color screening + dissociation**

3) Photoproduction from EM fields, **($R_{AA} > 1$ at p_T<0.1)**

EM field → $\gamma + A \rightarrow J/\psi + A$

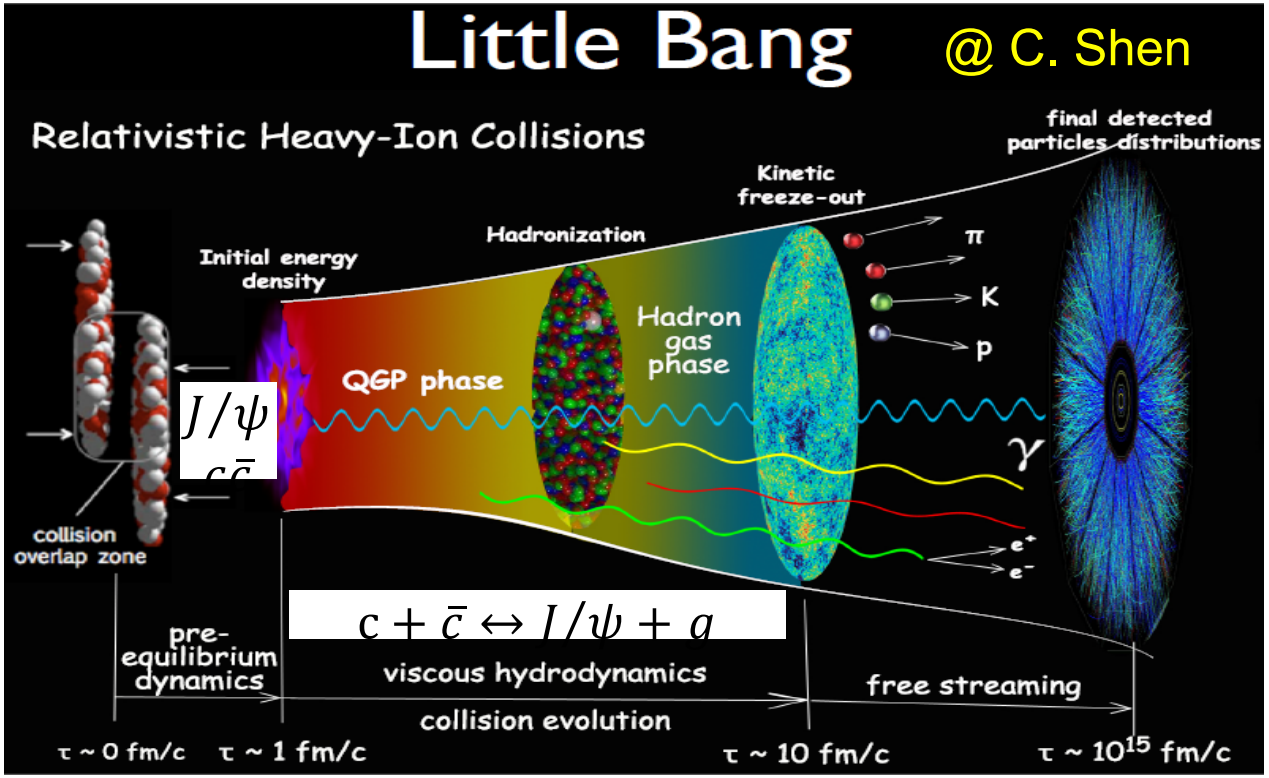
charmonium at $p_T < 0.1$ GeV ~ $1/R_A$

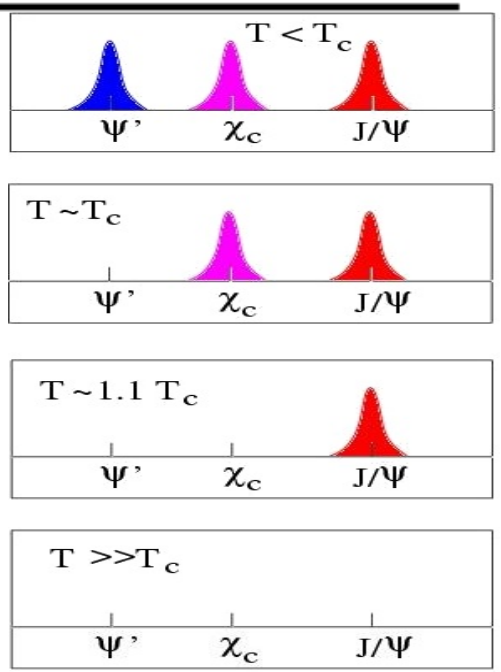
Heavy ion collisions

$V = U$

State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

Satz, J. Phys. G 32, R25 (2006)





Sequential dissociation
For both charmonium
And bottomonium

Color screening + parton inelastic collision

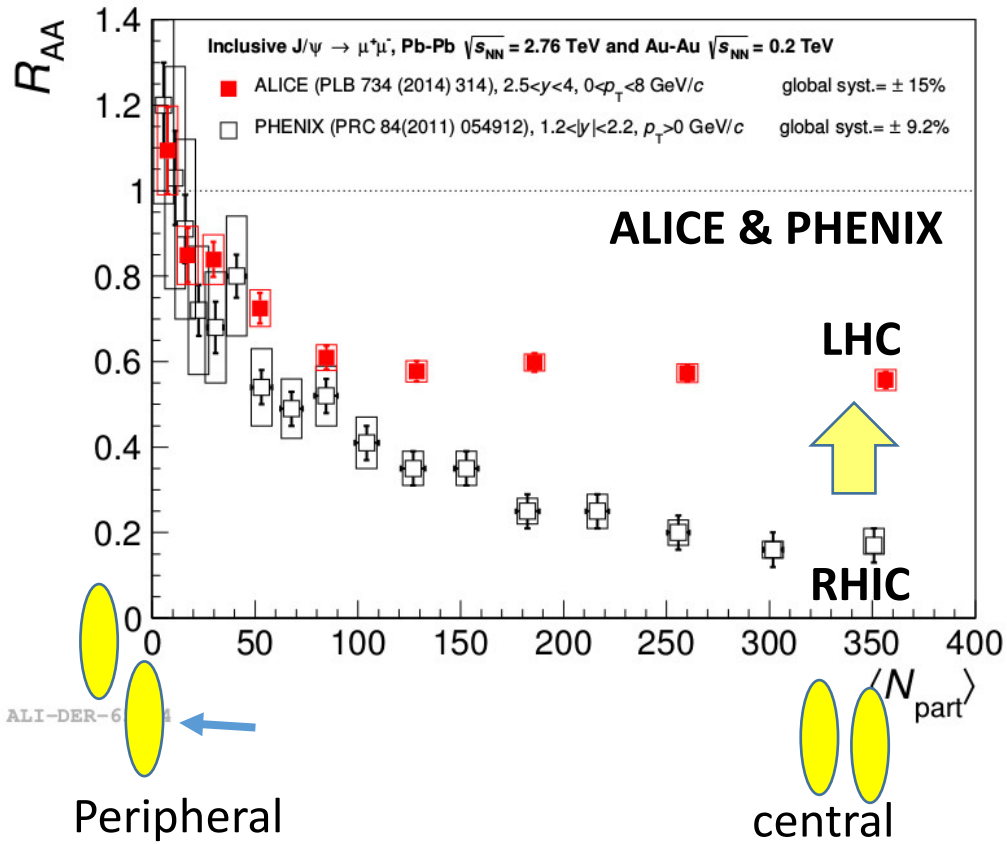
Quarkonium $\boldsymbol{R_{AA}}(N_p, p_T, y)$

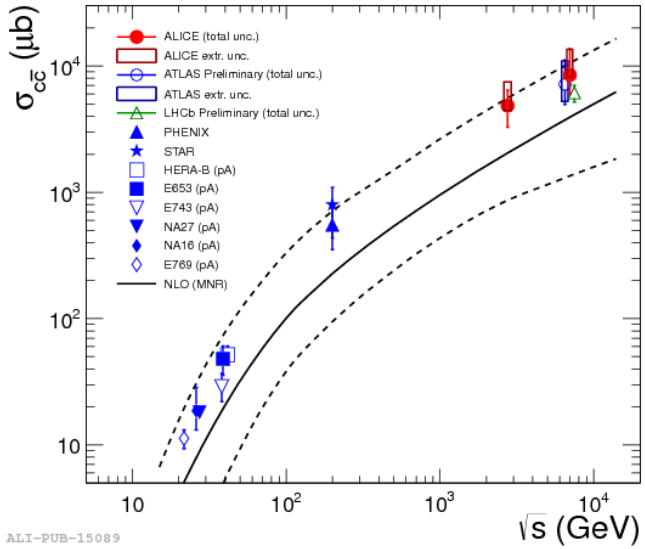
LHC collision energy

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

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

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



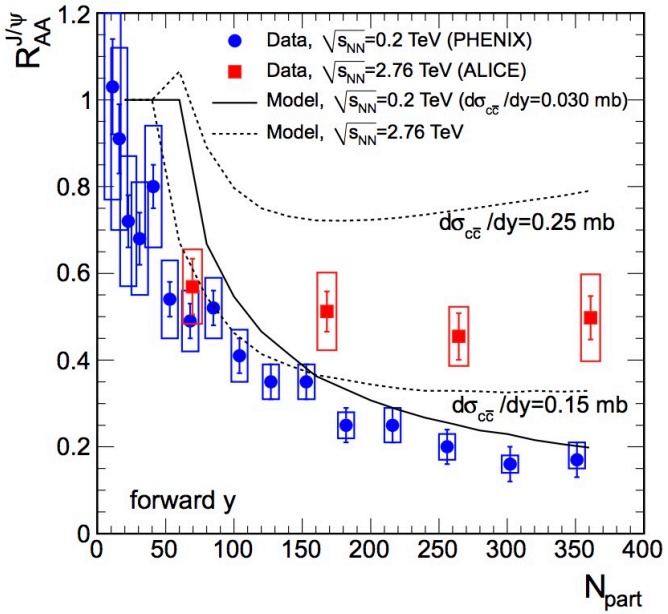


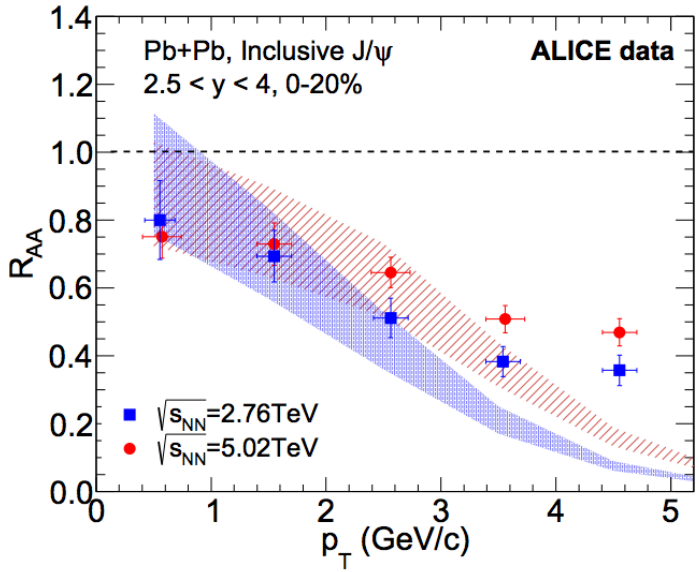
N($q\bar{q}$) per central AA (b=0)

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

More heavy quark pairs in higher collision energy

Theoretical models





Statistical hadronization model,

Andronic, et al, J.Phys.G 38 (2011) 124081

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}.$$

$$g_c(T) \sim 1/N_D^{th} \sim e^{\frac{m_D}{T}}, \quad N_{J/\psi}(T) = g_c^2 N_{J/\psi}^{th} \sim e^{\frac{2m_D - m_{J/\psi}}{T}}$$

Coalescence model (quarkonium),

Greco, Ko, Rapp, PLB 595 (2004) 202-208

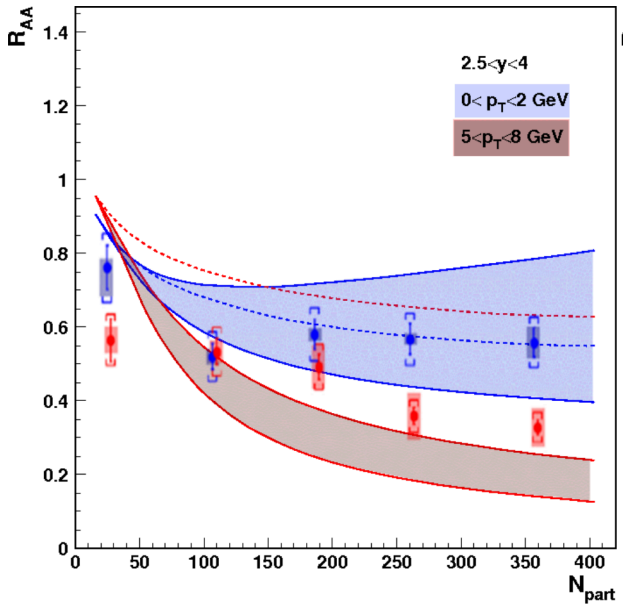
Thews, Schroedter , Rafelski, PRC 63, 054905 (2001)

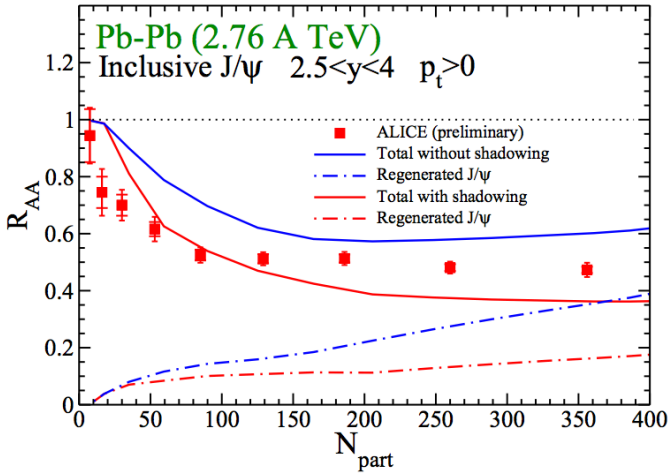
Zhao, BYC, Phys.Lett.B 776 (2018) 17-21

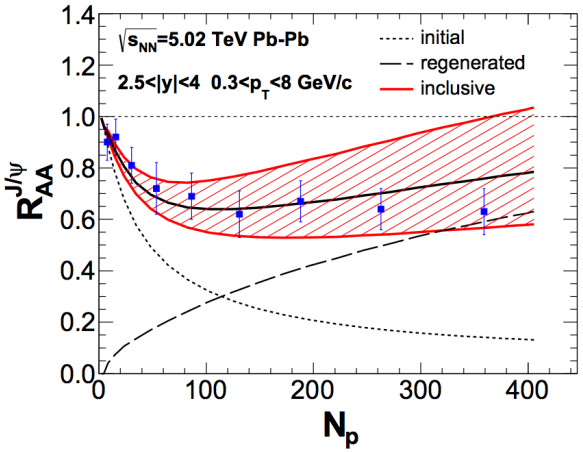
$$\frac{d^2 N_M}{d\mathbf{p}_T^2} = g_M \int \prod_{i=1}^{2} \frac{p_i \cdot d\sigma_i d^3\mathbf{p}_i}{(2\pi)^3 E_i} \; f_q(x_1, p_1) \; f_{\bar{q}}(x_2, p_2)$$
$$\times f_M(x_1, p_1; x_2, p_2) \; \delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{1T} - \mathbf{p}_{2T}) \; ,$$

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

Theoretical models







Co-mover model (loss+gain terms),
***Ferreiro**, et al,*
PLB 731 (2014) 57-63
Eur.Phys.J.C 58 (2008) 437-444

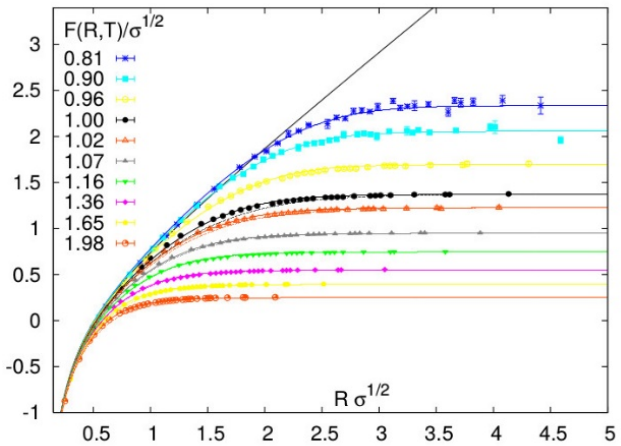
Transport model (TAMU)
Ralf Rapp, Xingbo Zhao, Loic Grandchamp, Xiaojian Du, et al
Phys.Rev.C 82 (2010) 064905
Phys.Lett.B 664 (2008) 253-257
Nucl.Phys.A 943 (2015) 147-158

Taesoo Song, Su Houng Lee, Ko, et al, PRC 81 (2010) 034914
Phys.Rev.C 91 (2015) 4, 044909

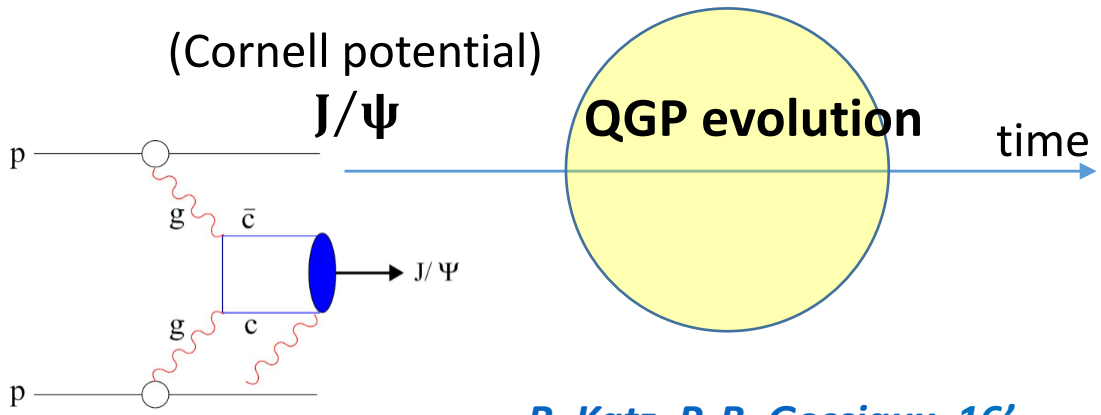
Transport model (Tsinghua)
Pengfei Zhuang, Li Yan, Yunpeng Liu, Kai Zhou, Baoyi Chen, et al,
Phys. Lett. B 607, 107 (2005)
Phys. Rev. Lett. 97, 232301 (2006)
Phys. Lett. B 726, 725 (2013)

Two-component models: primordial + regenerated

Theoretical models



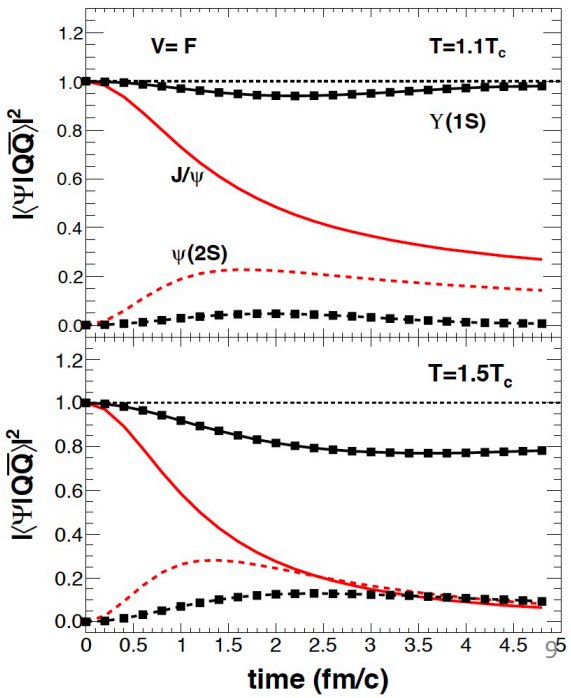
(Cornell potential)



R. Katz, P. B. Gossiaux, 16'
B.Z. Kopeliovich, et al, PRC, 15'
Taesoo Song, et al, PRC, 15'

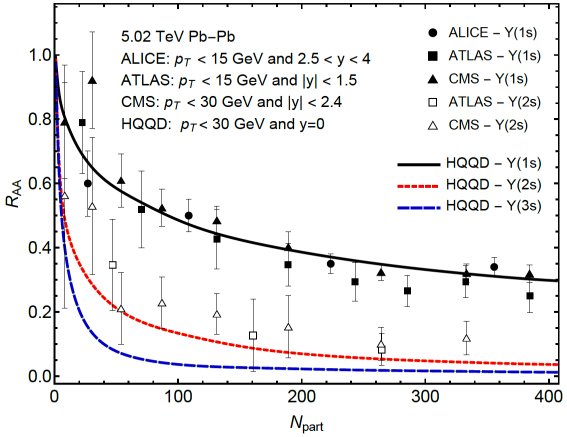
$$i\hbar\frac{\partial}{\partial t}\psi(r,t) = [-\frac{\hbar^2}{2m_\mu}\nabla^2 + V(r,t)]\psi(r,t)$$

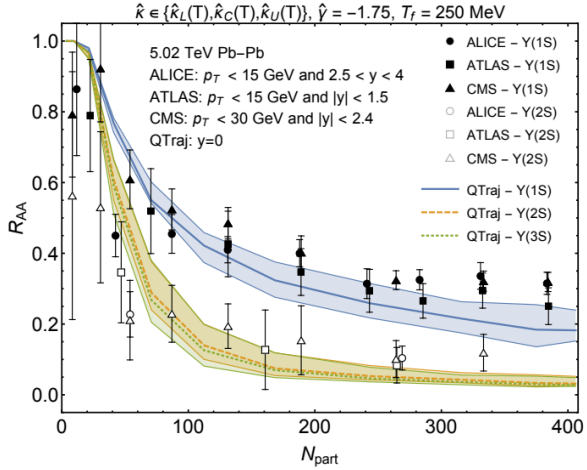
$$|c\bar{c}>= c_{1S}(t)|J/\psi> + c_{2S}(t)|\psi(2S)> + \cdots$$

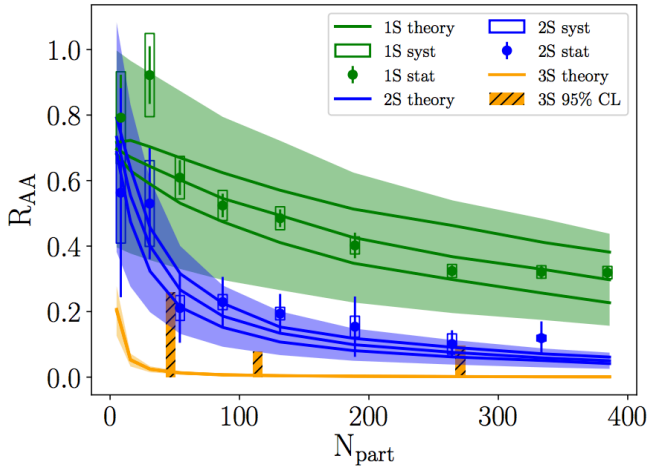


Open quantum approaches are necessary for quarkonium evolution in the medium.

Theoretical models







Schrodinger model
(quantum trajectory method)
Michael Strickland, et al,
Phys.Lett.B 811 (2020) 135949
JHEP 03 (2021) 235,
JHEP 21 (2020) 235

Lindblad equation model,
Brambilla, Escobedo,Strickland, et al
JHEP 05 (2021) 136

Quantum transport model,
Xiaojun Yao, Weiyao Ke, Yingru Xu, et al,
JHEP 01 (2021) 046
JHEP 02 (2021) 062

Schrödinger–Langevin model
Roland Katz, Pol B. Gossiaux
Ann. Phys. 368 (2016) 267-295

Schrödinger model
BYC, Du, Rapp, et al,
Nucl.Part.Phys.Proc. 289-290 (2017) 475-478

Others:
Kopeliovich, et al, PRC, 15'
Taesoo Song, et al, PRC, 15'
Alexander Rothkopf, Akamatsu, et al, *JHEP* 07 (2018) 029
Blaizot, et al, *JHEP* 06 (2018) 034

Quarkonium is treated as an open quantum system

Theoretical models

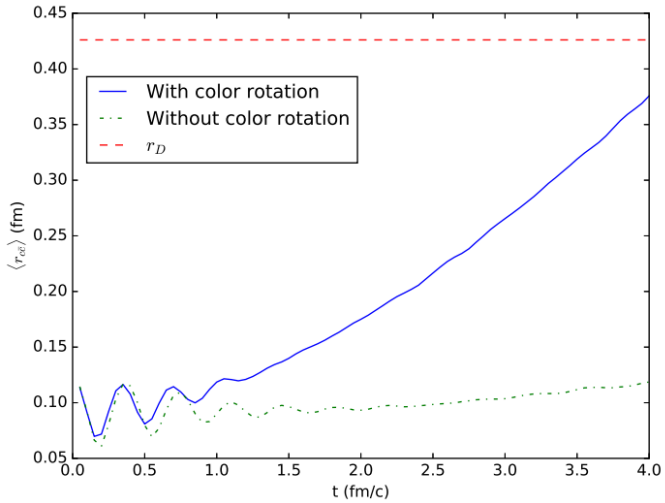
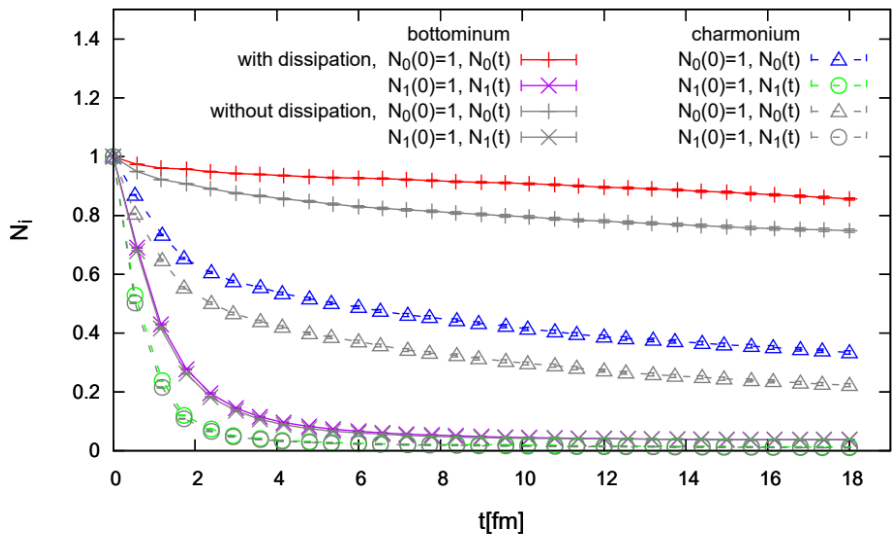


Figure 13: Comparison of the evolution of a pair of heavy quarks initially prepared in a J/Ψ state with or without considering the transition into octet states. The screening radius is $r_D = m_D^{-1}$.



Density matrix (singlet-octet),

Blaizot, Escobedo, *JHEP* 06 (2018) 034

Weak coupling between HQ and medium,

$$\frac{\mathrm{dD_s}}{\mathrm{d}t} = iC_F[V_{12} - V_{1'2'}]\, D_\mathrm{s}$$
$$\frac{\mathrm{d}D_\mathrm{o}}{\mathrm{d}t} = -\frac{i}{2N_c}[V_{12} - V_{1'2'}]D_\mathrm{o}.$$

Lindblad equation

Alexander Rothkopf, Akamatsu, et al,

JHEP 07 (2018) 029

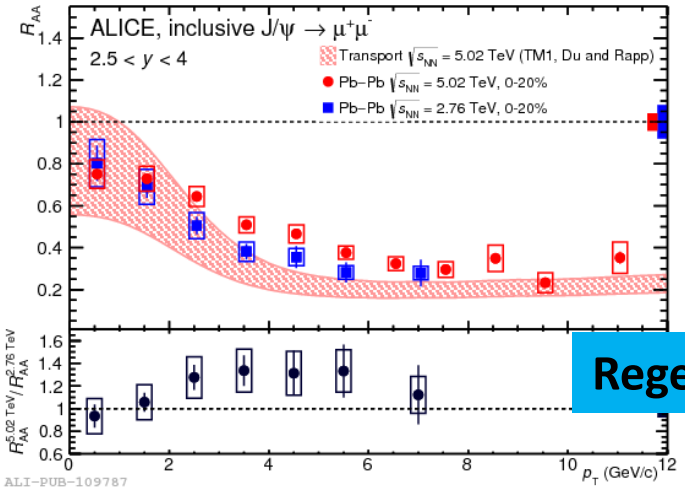
Phys.Rev.D 101 (2020) 3, 034011

Time evolution of the occupation numbers of the ground state and the 1st excited state in Cornell potential.

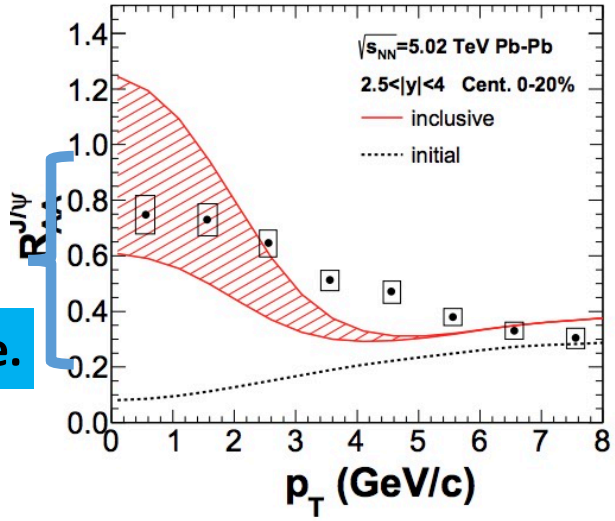
Quarkonium is treated as an open quantum system

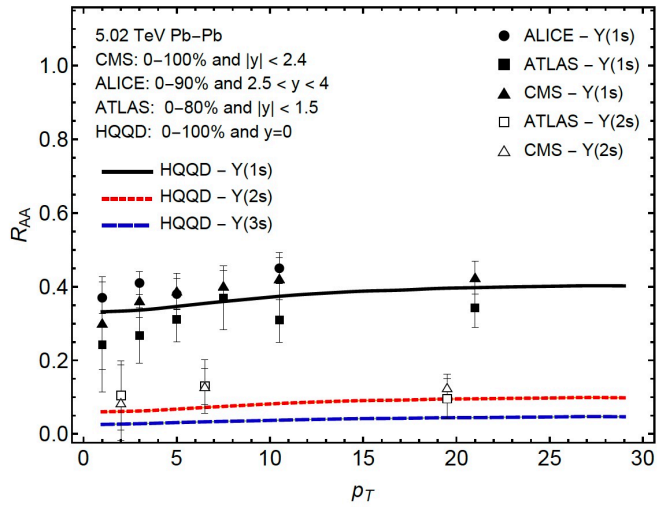
p_T dependence

Primordial production V.S. **regeneration**



Rege.





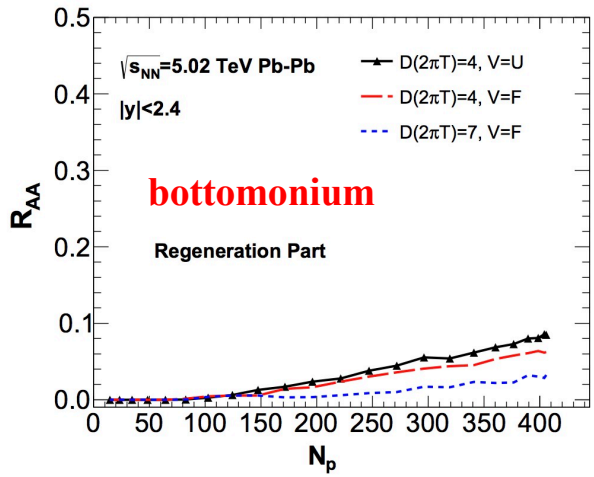
TAMU Transport, *2015 NPA*

Tsinghua Transport, *2019 CPC*

Schrodinger model, *Michael strickland, 2020 JHEP*

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

Initially produced ψ:
at large p_T
Regenerated ψ:
at small p_T



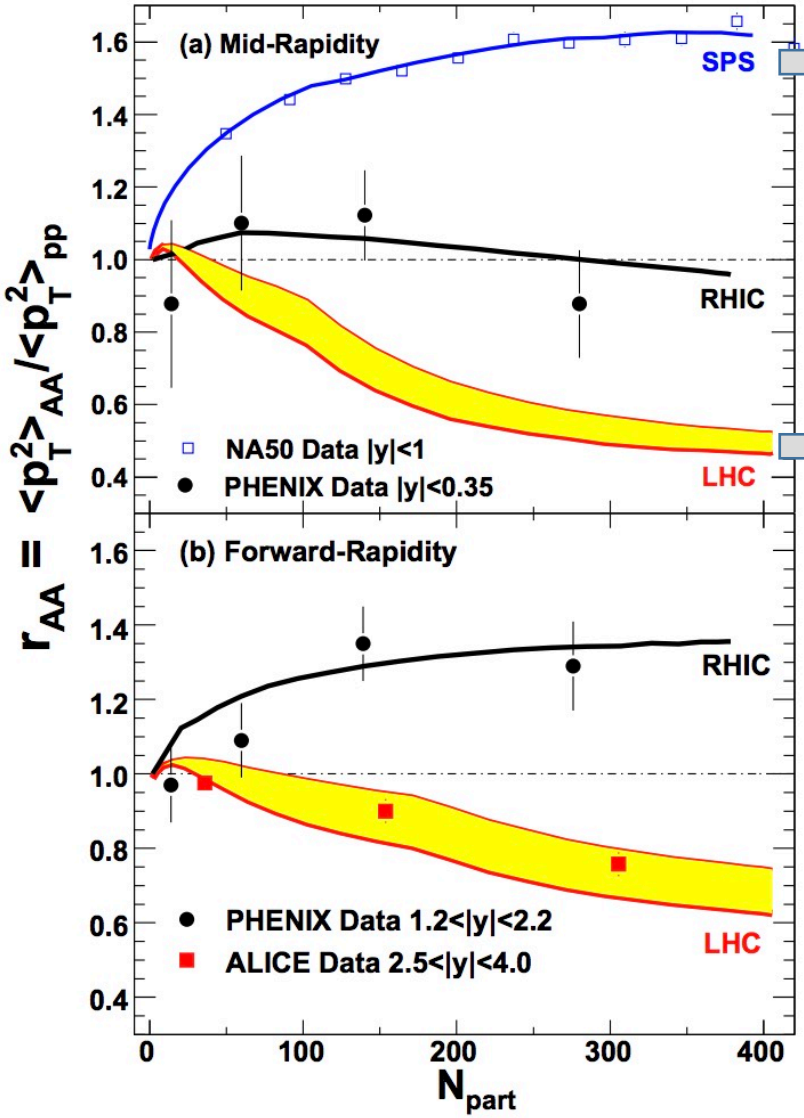
Bottomonium:
Weak regeneration

Langevin +coalescence (non-equilibrium bottom → bottomonium)
BYC, Zhao,
Phys.Lett.B 772 (2017) 819-824

p_T dependence

Transport model (**two-component competition**)

$$r_{AA} = \frac{< p_t^2 >_{AA}}{< p_t^2 >_{pp}}$$



Cronin effect (cold nuclear matter)

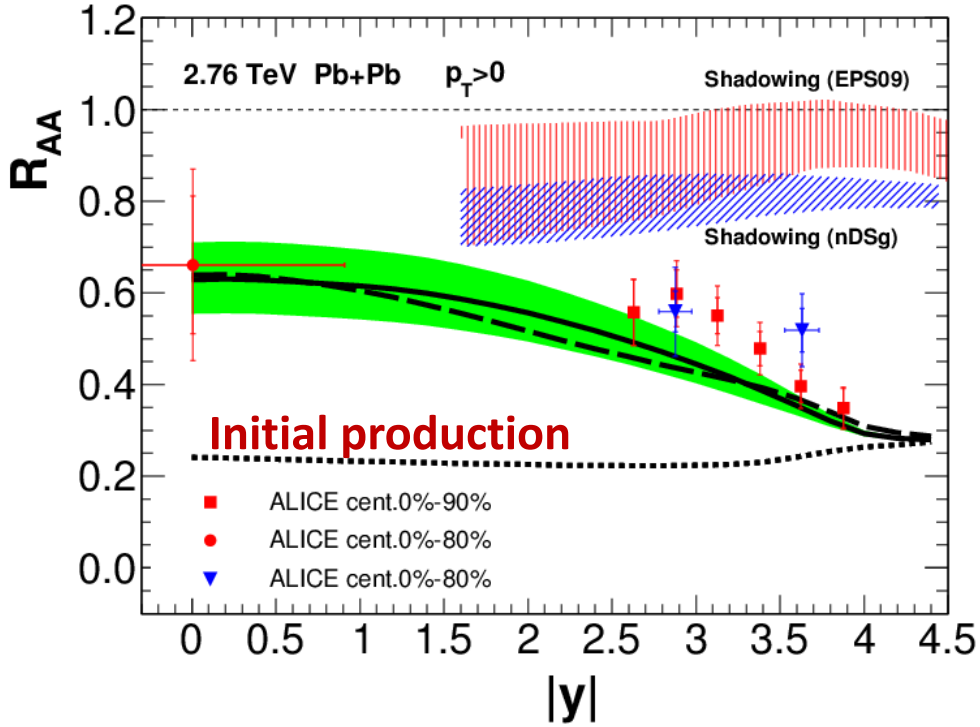
charm energy loss in hot medium and $c + \bar{c} \leftrightarrow J/\psi + g$

- ✓ Regeneration contribution dominates
- ✓ Significant charm energy loss (thermalization)

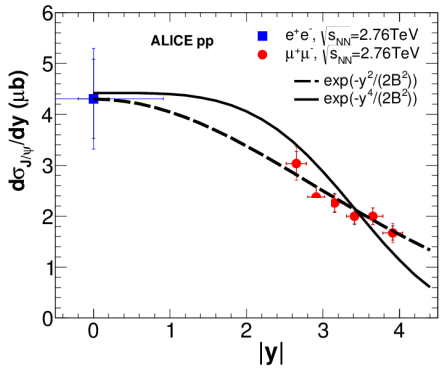
Tsinghua transport,
Pengfei Zhuang, Kai Zhou, et al,
Phys.Rev.C 89 (2014), 054911

Rapidity dependence

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

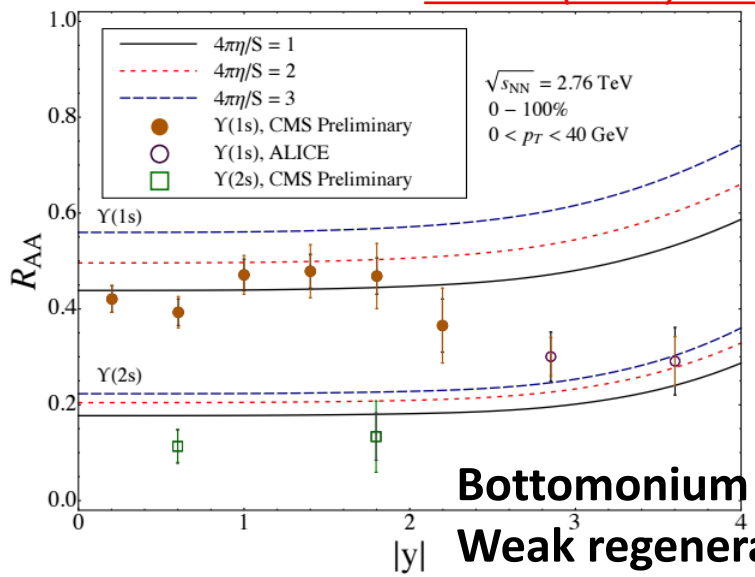


BYC, PRC 93 (2016) 054905



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

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



Bottomonium
Weak regeneration

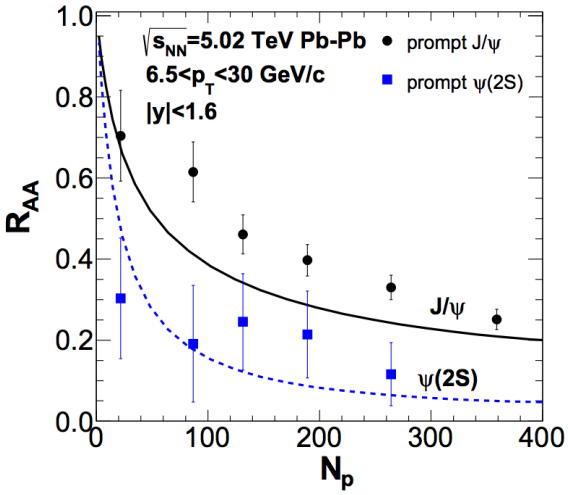
➢ **Regeneration shape is consistent with the rapidity dependence of $c\bar{c}$ production cross-section**

More bottomonium reference:

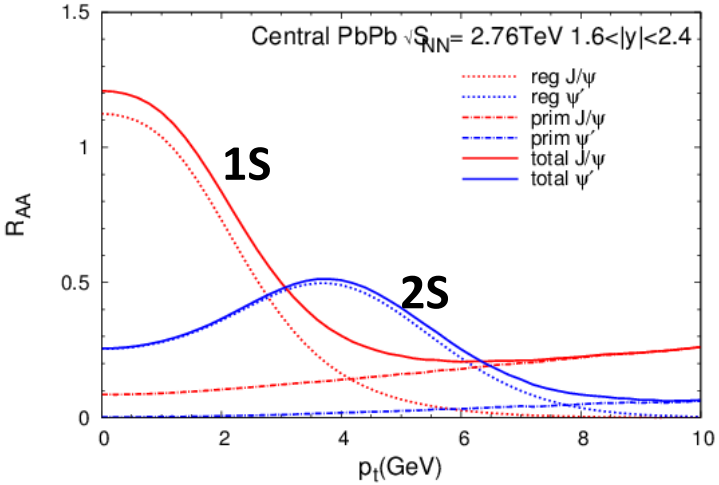
Du, Rapp, He: PRC 96 (2017) ,054901
Blaizot, Escobedo: *PRD* 98 (2018), 074007
BYC, Zhao: PLB 772 (2017) 819-824

Sequential Regeneration (1S,2S)

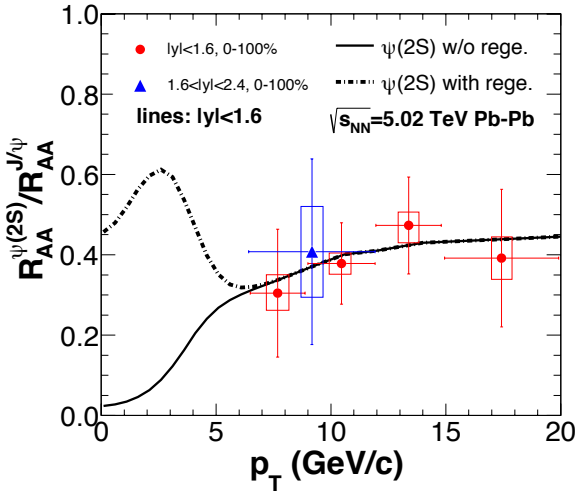
Primordial production



BYC, CPC 43 (2019) , 124101



Du, Rapp, NPA 2015



Tsinghua transport, CPC 2019

Sequential dissociation

Proposed by Satz, et al

Sequential regeneration

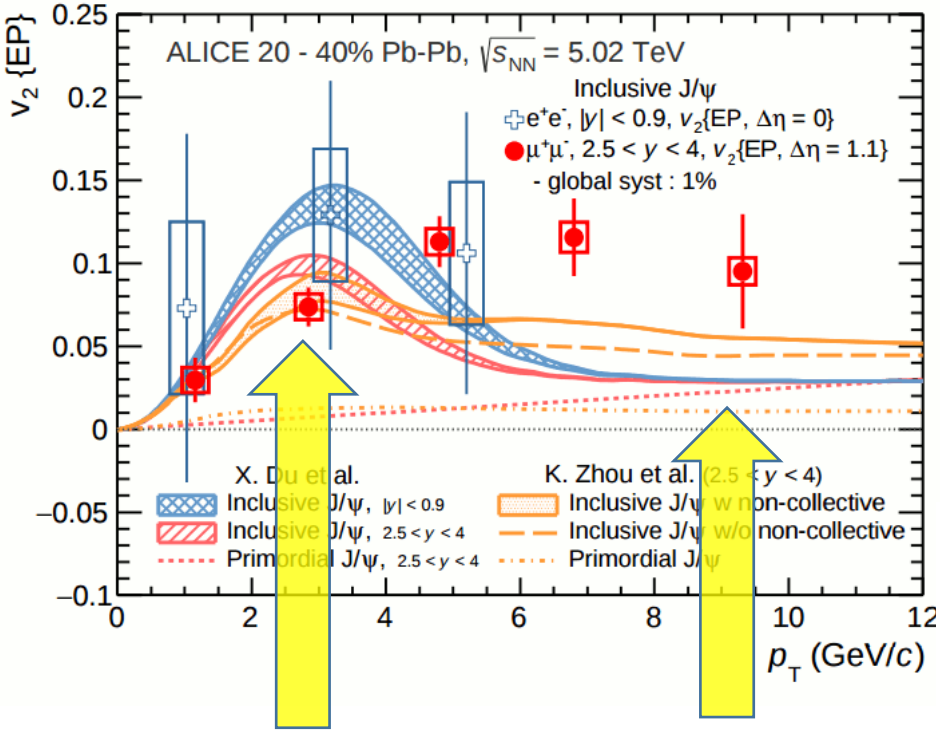
$\partial_\mu(\rho_c u^\mu_{QGP}) = 0$ **for charm diffusion**

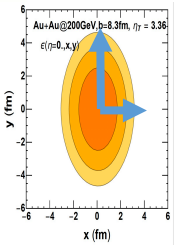
QGP expansion → charm flow→ inherited by rege. Ψ

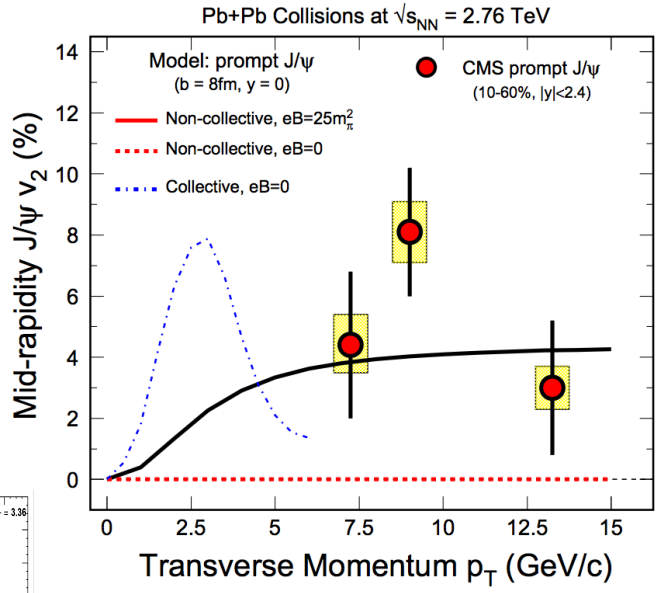
Quarkonium collective flows

(v_1, v_2, v_3)

Elliptic flow v_2







Quantum transition

Charm diffusion + recombination

path-length-difference

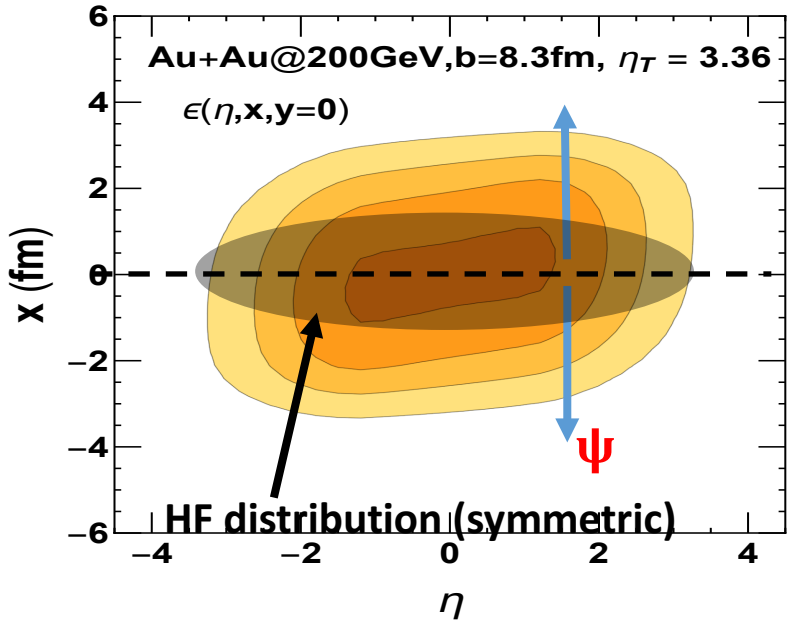
Electromagnetic fields
Pengfei Zhuang, et al,
PLB 751 (2015) 215-219

Source: Charm recombination, Path-length-difference electromagnetic fields

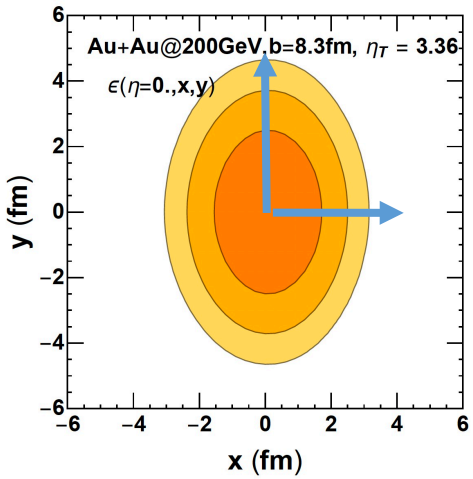
Directed flow v_1

200 GeV, Au-Au, semi-central collisions

tilted medium: S. Chatterjee, et al, PRL 2018



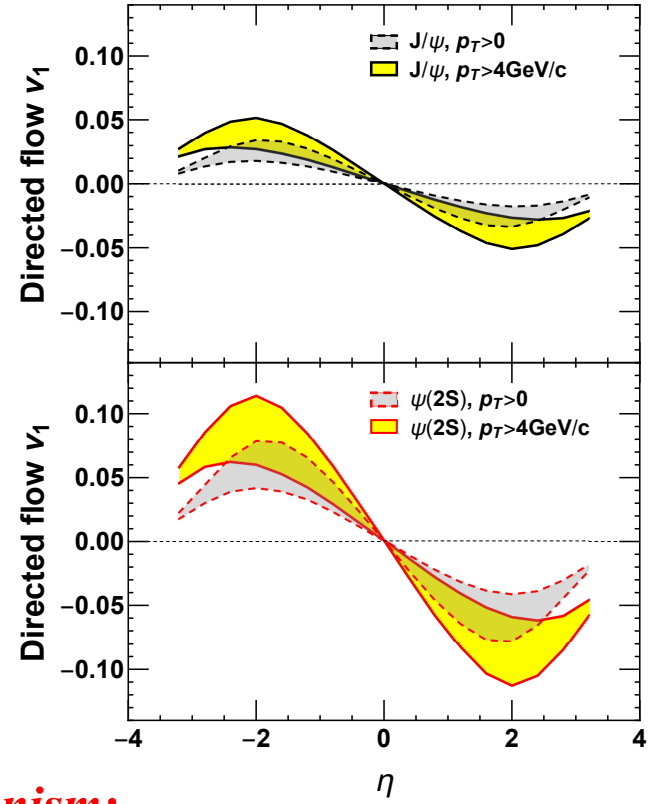
For directed flow



For elliptic flow

Bottomonium escape mechanism:
Partha, Nicolas, et al,
Phys.Rev.C 100 (2019) 5, 051901

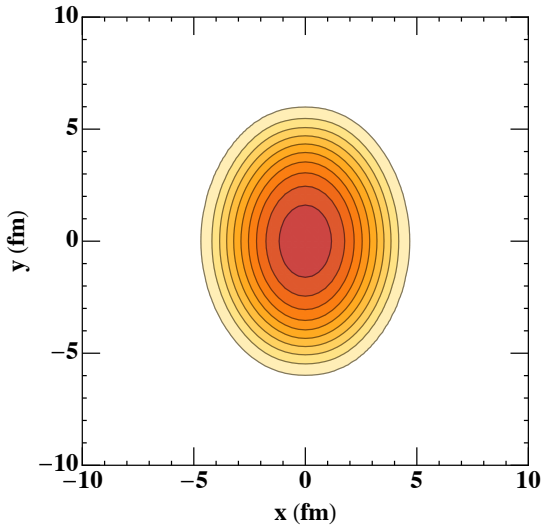
Charmonium directed flows

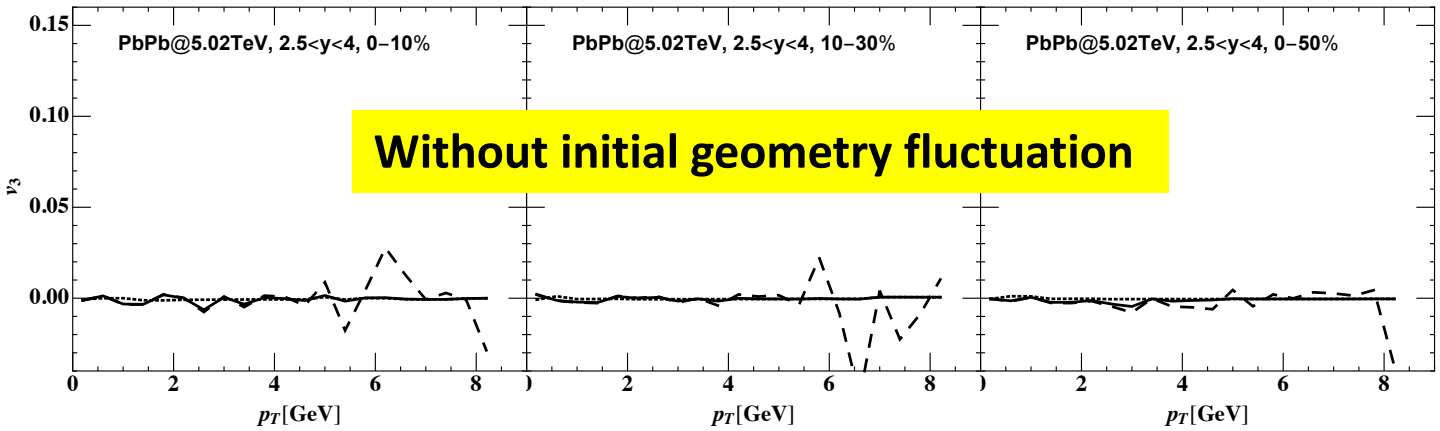


BYC, Zhao, et al,
PLB 802 (2020) 135271

Charmonium directed flows:→Different magnitudes of dissociation in ±x directions
Charm directed flows:→ charm carry collective flows from QGP expansion

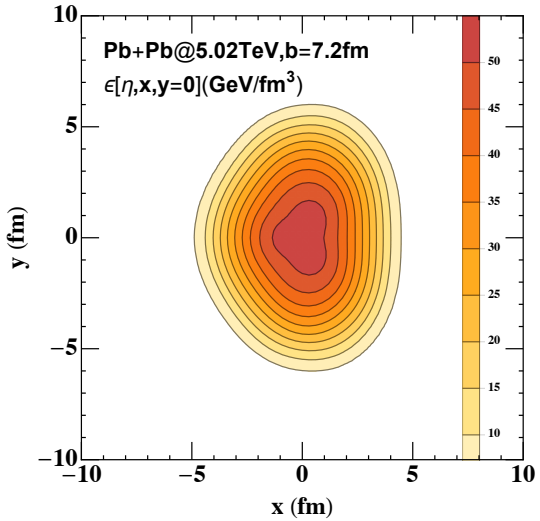
triangular flow v_3

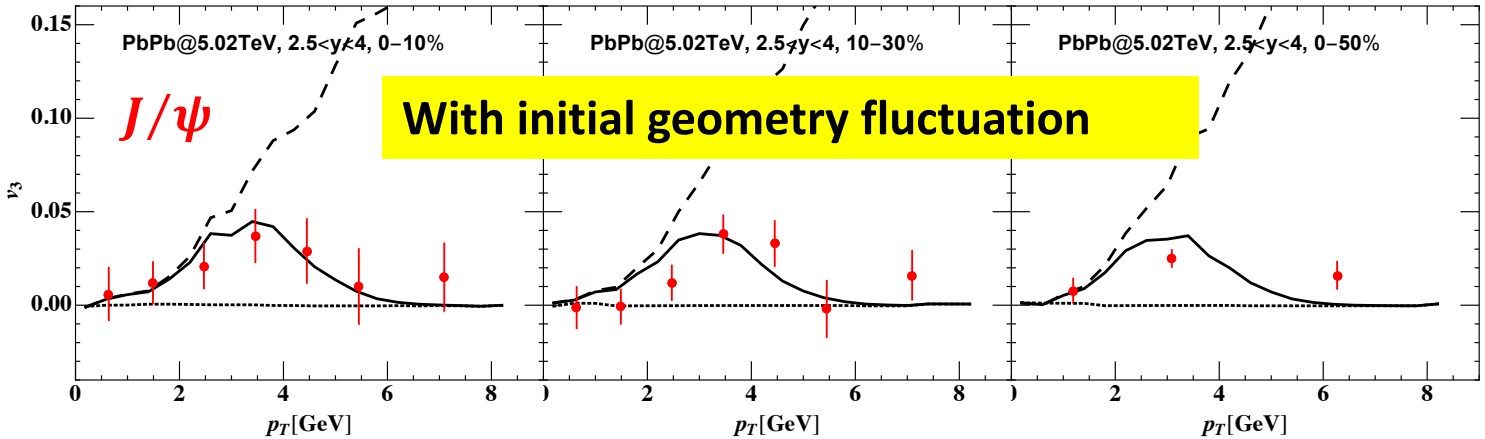




Data: 2020 ALICE

Theory: Jiaxing Zhao, BYC, et al, in preparation





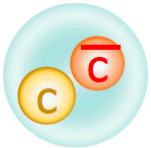
Source: fluctuation of QGP initial energy density

Exotic hadrons in AA

$(c\bar{c}q\bar{q})$

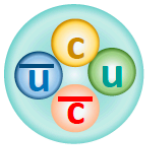
Exotic hadron $(c\bar{c}q\bar{q})$ in AA

Charmonium



PLB 590 209-215 (2004)

Tetraquark (4q)

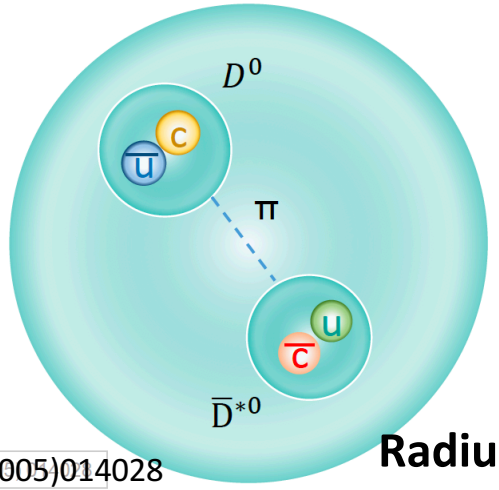


$r_{4q} \approx r_{c\bar{c}}$

≈ 0.3 fm

PRD 71 (2005) 014028

$D^0 - \bar{D}^{*0}$ molecule



PRD71(2005)014028

Radius: a few fm

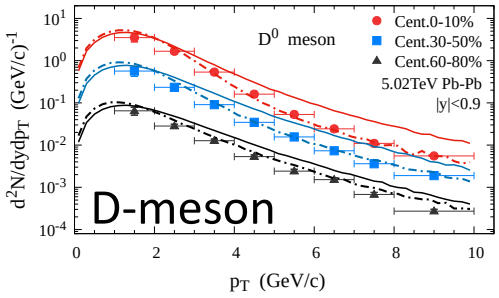
Some reference about X(3872) production in HIC:

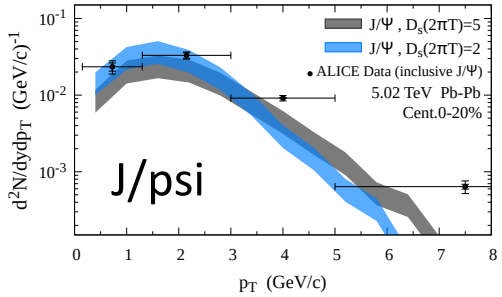
Cho. Prog.Part.Nucl.Phys. 95,279-322 (2017);
B. Wu, Rapp, EPJA 57 , 122 (2021);
Zhang, Liao, et al, PRL 126, 012301 (2021) ;
BYC, Liu, et al, 2107.00969
Zhao, Zhuang, et al, Phys.Rev.D 102 (2020) 11, 114001 ***(fully-heavy tetraquark)***

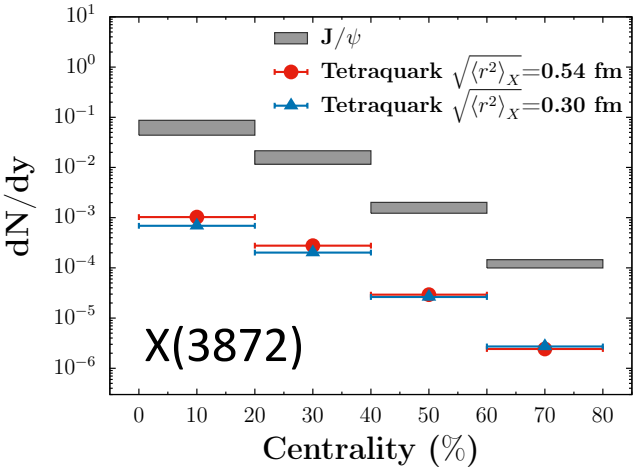
In pp:

Braaten, et al, Phys.Rev.D 103 (2021) 7, L071901
Esposito, Ferreiro, et al, Eur.Phys.J.C 81 (2021) 669
Huang, Zhao, Zhuang, Phys.Rev.D 103 (2021) 5, 054014
F.K. Guo, Liu, et al, Rev. Mod. Phys. 90, 015004 (2018)

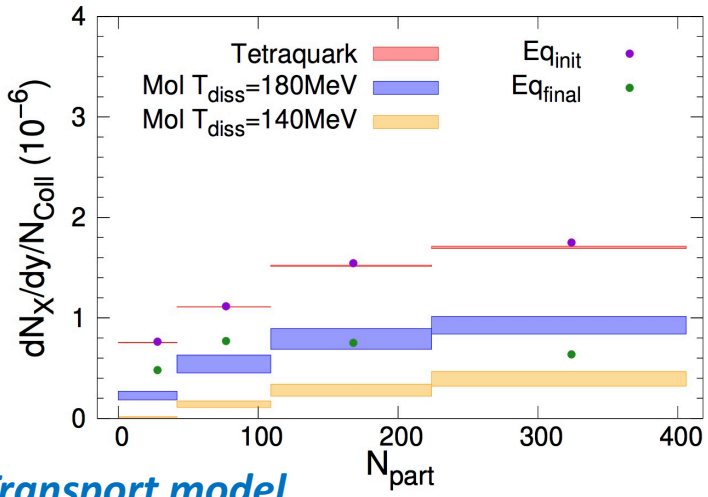
Exotic hadron $(c\bar{c}q\bar{q})$ in AA



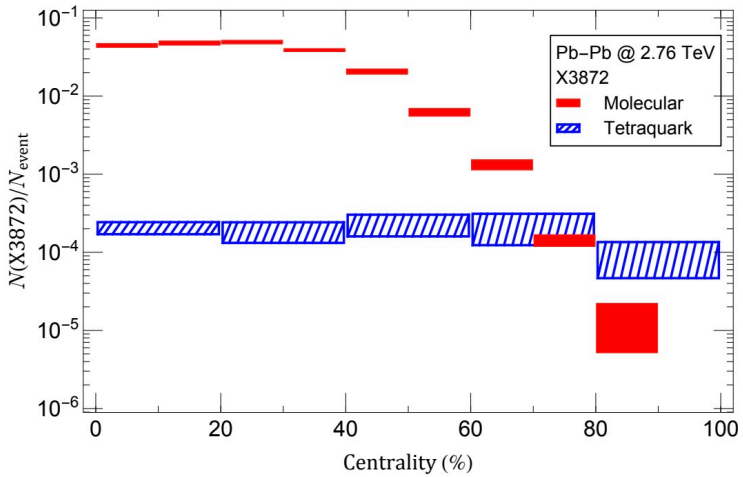




coalescence model,
BYC, Liu, et al, 2107.00969



Transport model,
Wu, Rapp, Du, Eur.Phys.J.A 57 (2021) 4, 122



AMPT model,
Zhang, Liao, et al, PRL 126, 012301 (2021) ;

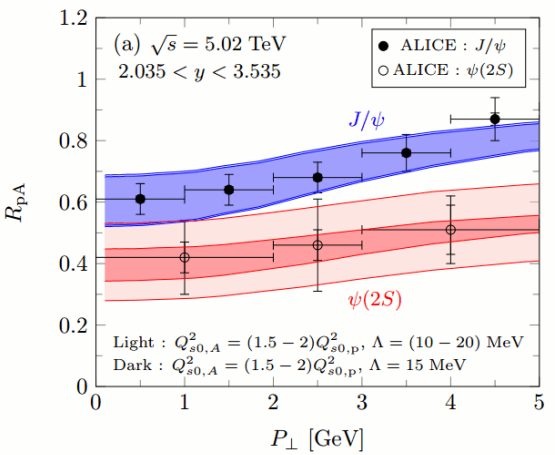
Cho. Review paper:
Prog.Part.Nucl.Phys. 95,279-322 (2017);

quarkonium in p-Pb @5.02 TeV

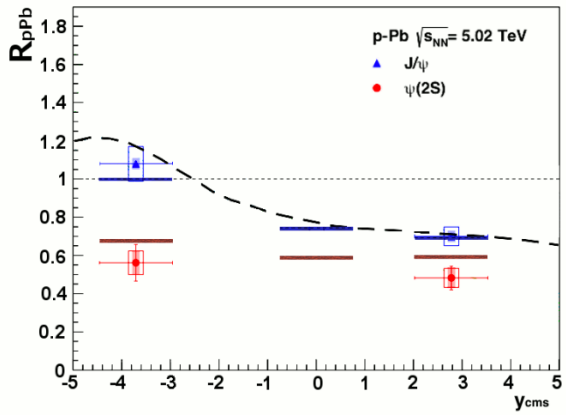
Nuclear modification factor

Models:

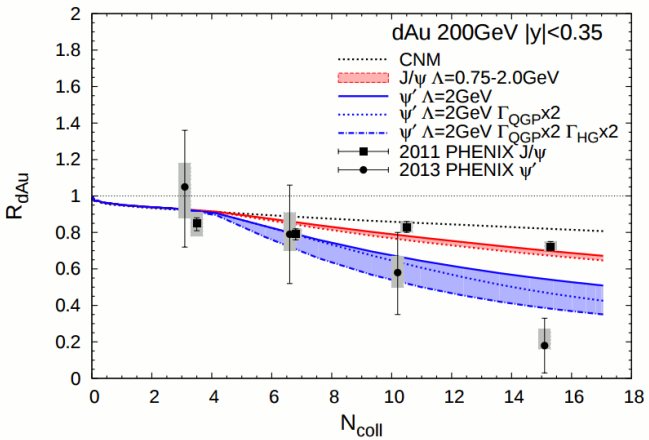
- Y. Q. Ma, et al, CGC+ICEM, PRC 2018
- Ferreiro, Co-mover interactions, PLB 2015
- Transport model (Du, Rapp), QGP+HG NPA 2015
- Transport model (BYC, Zhuang) , QGP PLB 2017



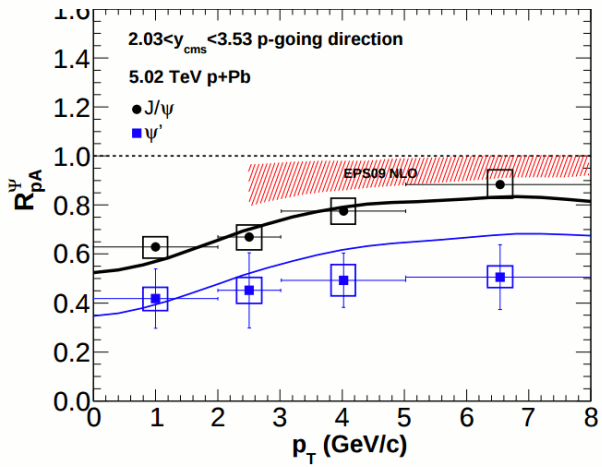
CGC+ICEM



Co-mover



Transport 1 (TAMU)

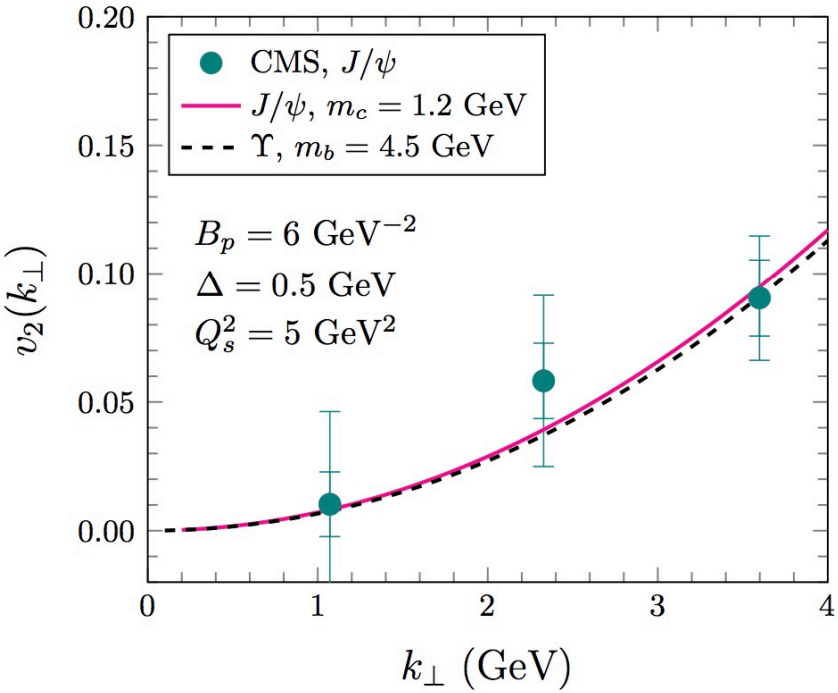


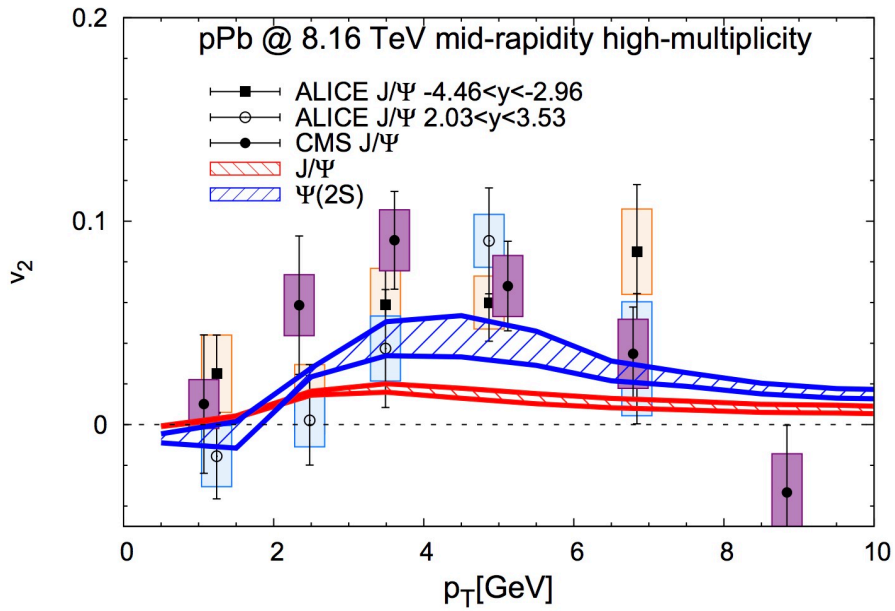
Transport 2 (Tsinghua)

Final state interaction is needed to explain different R_{AA} of 1S and 2S.

Collective flow

elliptic flows in small colliding system





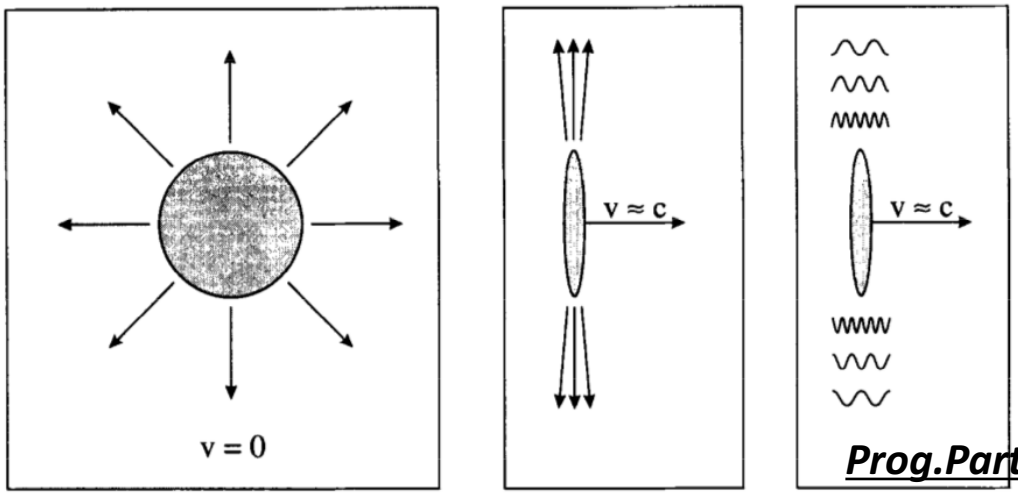
CGC model,
Bo-wen Xiao, et al, PRL 122 (2019) 17, 172302

Transport model,
Du, Rapp, JHEP 03 (2019) 015

In pA:
Cold nuclear matter effect dominate the heavy quarkonium elliptic flows.

Quarkonium photoproduction

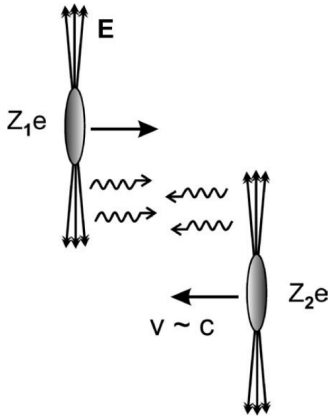
Photoproduction by EM fields



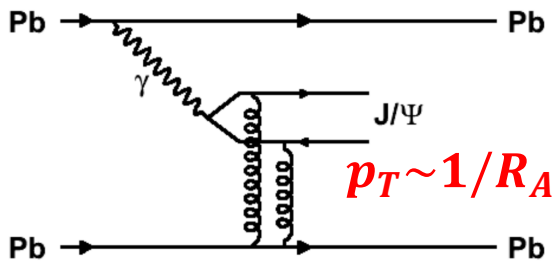
$eB \sim m_\pi^2 \sim 10^{18} G$

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

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



Equivalent-Photon-Approximation
Fermi, 1924'



$p_T \sim 1/R_A$

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

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

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

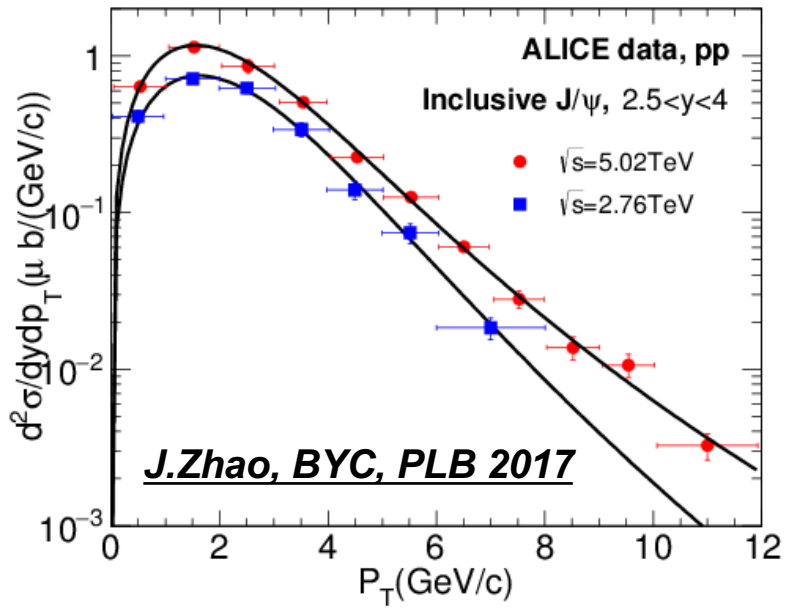
Photoproduction by EM fields

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

- 2.76 TeV forward rapidity 2.5<y<4, inclusive J/ψ $< p_T^2 >_{pp}^{J/\psi} = 7.8\ (GeV/c)^2$

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

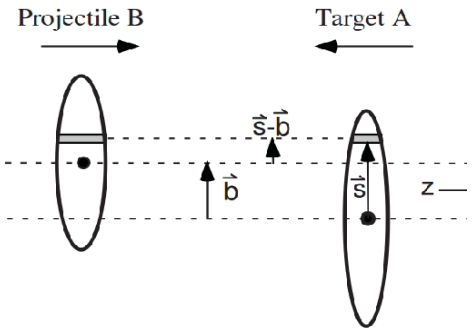
Photoproduction



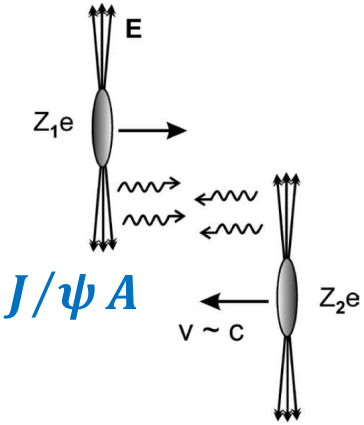
At $p_T \to 0$, $\frac{d\sigma_{pp}^{J/\psi}}{dp_T} \propto p_T$

Hadroproduction

Transport + photoproduction



$b < 2R_A$



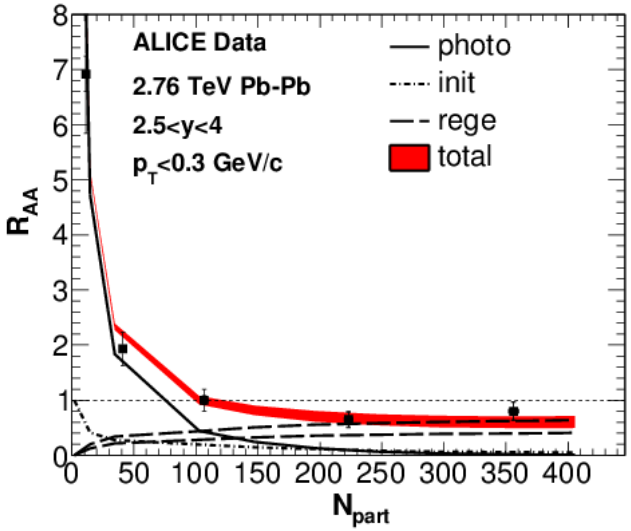
$\gamma A \rightarrow J/\psi\, A$

$b < 2R_A$ *or* $b \geq 2R_A$

Transport model (heavy quarkonium)

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

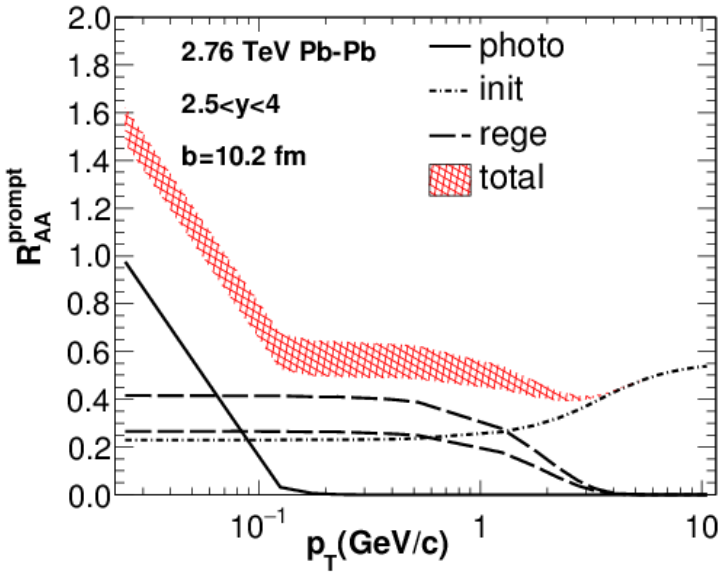
$$N_\psi^{\gamma A} \propto \int dw \frac{dN_\gamma}{dw} \sigma_{\gamma A \rightarrow J/\psi A}\, \Gamma_{QGP}^{decay}$$

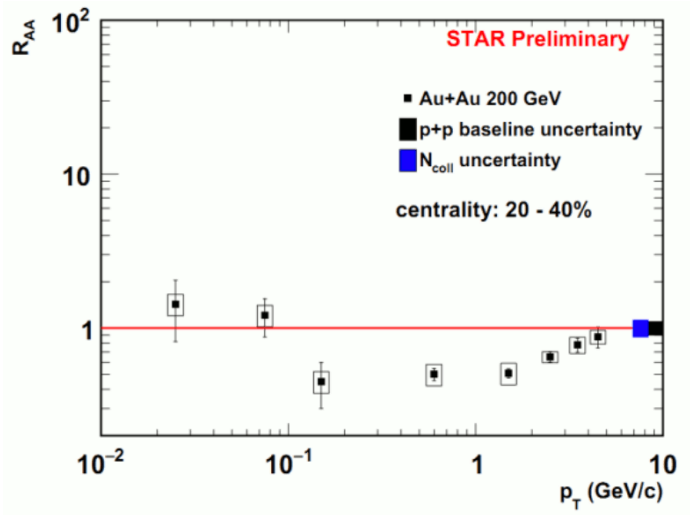


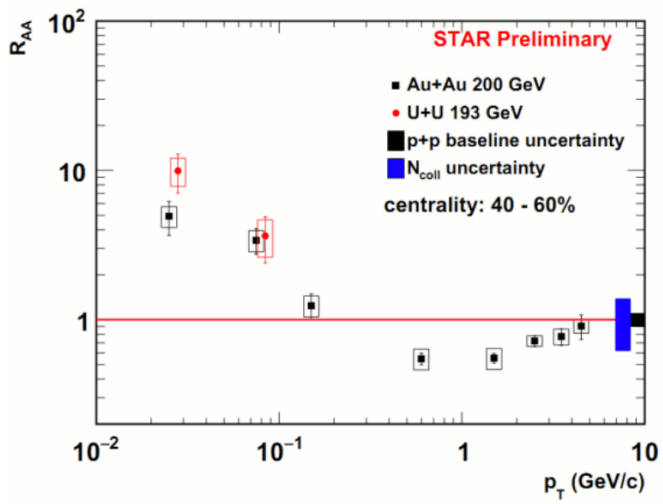
When $N_{part} \rightarrow 0$ ($b > 2R_A$),
hadroproduction → 0,
photoproduction → nonzero,
R_{AA} → infinity (pT<0.1)

Shi, Zha, BYC, PLB 777 (2018) 399-405

Transport + photoproduction







Sudden enhancement at pT<0.1 GeV/c

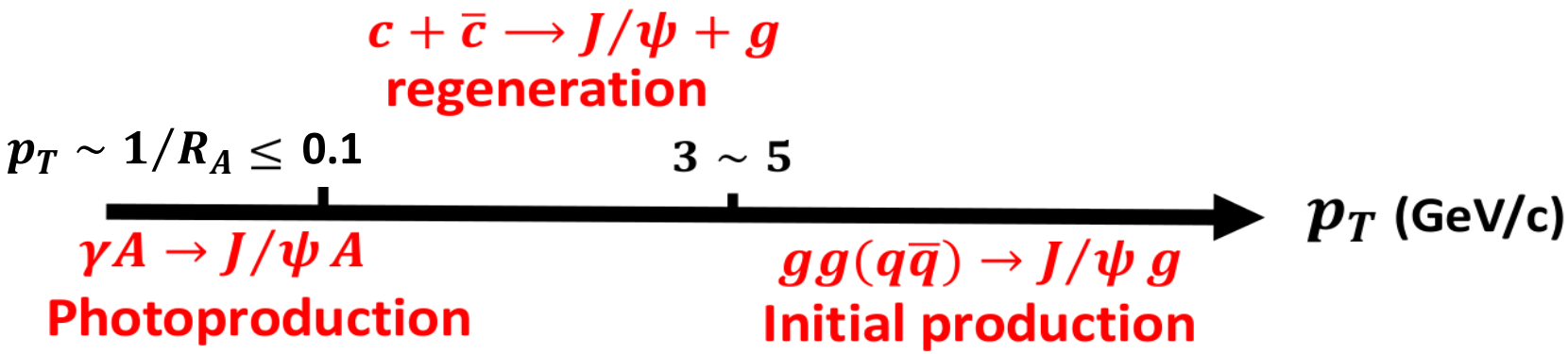
More charmonium photoproduction in HIC:

Klein, et al, PRL 92, 142003 (2004)
G.Baur, et al, Physics Roports, 2002
Wangmei Zha, zebo Tang, et al, PRC 99 (2019) 6, 061901
et al,…

summary

- We review some ***classical and quantum*** models developed recently for quarkonium evolutions **in the hot medium**.

- Quarkonium production mechanisms in ***different transverse momentum bins*** are discussed in different models.



Sequential dissociation, sequential regeneration, RAA(Np, pT, y)

Collective flows (v1, v2, v3) in AA and pA

X(3872) production

summary

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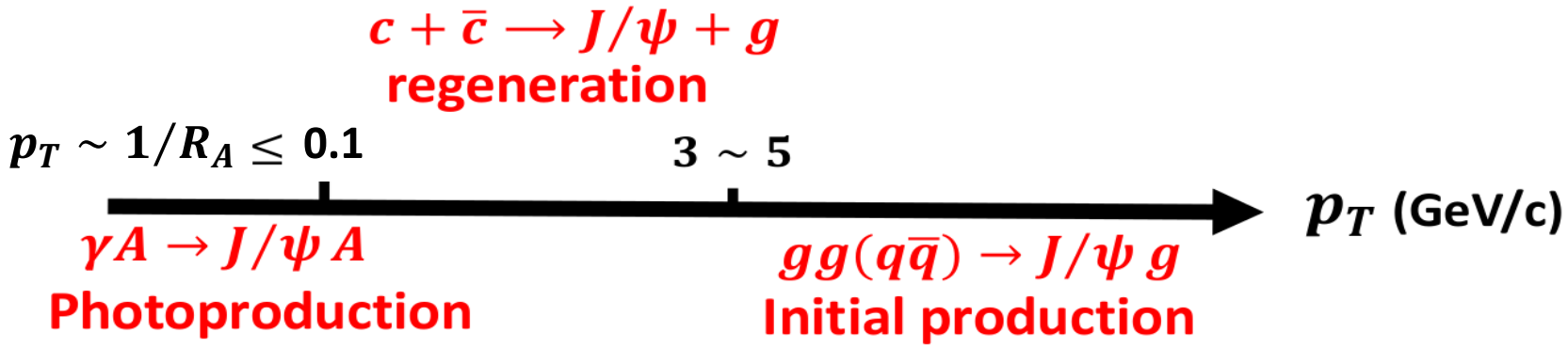
- Quarkonium production mechanisms in ***different transverse momentum bins*** are discussed in different models.



Thank you very much for your attention !