Quarkonia as a Probe of QGP

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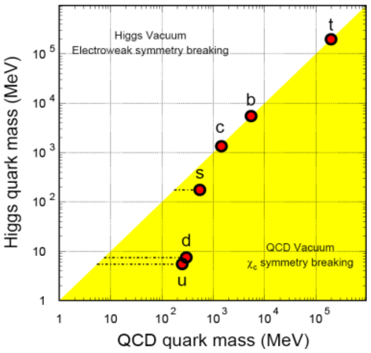
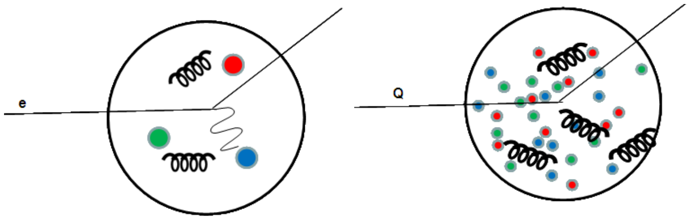
- *Why is quarkonium a thermometer of QGP ?*

Unlike light quarks which can be largely produced in hot medium,
1) heavy quarks are mainly created in the initial impact of the collisions, and
2) the production process is controlled by pQCD.
Similar to electrons which are used to probe the QED structure of a nucleon,
heavy quarks can signal the QCD structure of the fireball in heavy ion collisions.



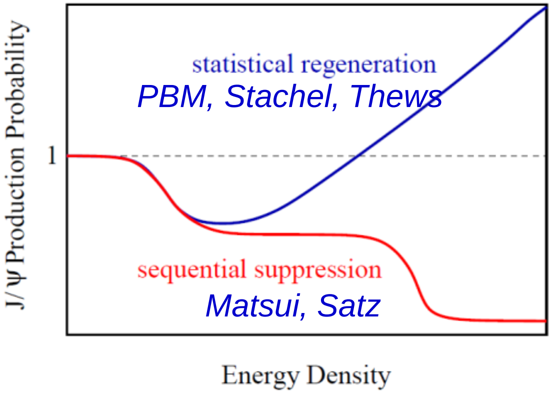


electrons and heavy quarks as QED and QCD probes

Zhu, Bleicher, Huang, Schweda, Stoecker, Xu, Zhuang, PLB647 (2007) 366-370

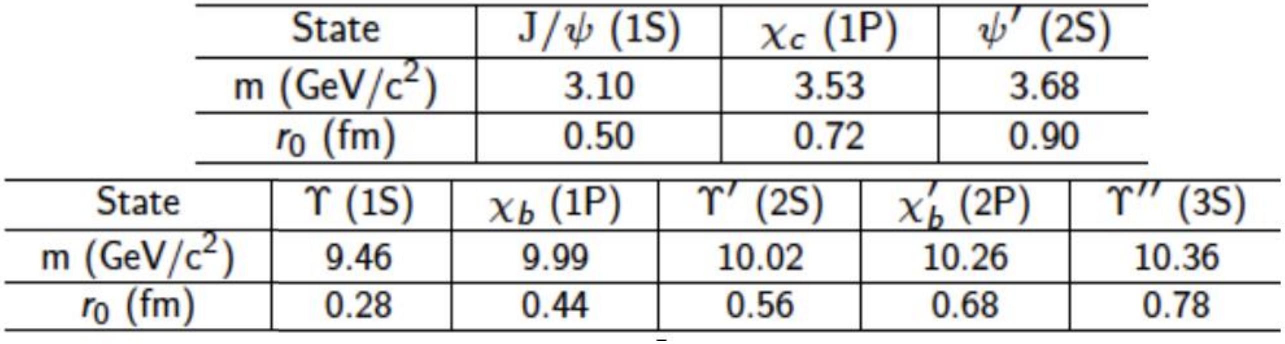
- *Cancellation between suppression and regeneration*

- *How to increase the sensitivity of the thermometer ?*



- *Quarkonia in Vacuum*
- *Cold Nuclear Matter Effects on Quarkonia*
- *Hot Nuclear Matter Effects on Quarkonia*
- *Quarkonia in A+A Collisions*
- *Exotic Multicharmed Baryon States*

Quarkonium Properties in Vacuum



State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

State	Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
m (GeV/c^2)	9.46	9.99	10.02	10.26	10.36
r_0 (fm)	0.28	0.44	0.56	0.68	0.78

Contribution to the observed ground state $\Upsilon(1S)$

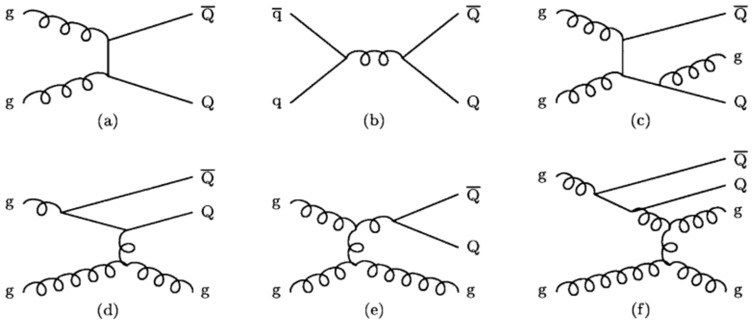
$\Upsilon(1S)$	$\Upsilon(1P)$	$\Upsilon(2S)$	$\Upsilon(2P)$	$\Upsilon(3S)$
51%	27%	11%	10%	1%

Contribution to the observed ground state J/ψ

J/ψ	χ_c	ψ'
60%	30%	10%

Potential Model in Vacuum

$Q\bar{Q}$ *production:*



Quarkonium formation:

radial equation for the relative motion between Q *and* $\bar{Q}$

$$\left[\frac{1}{m_c}\left(-\frac{1}{r}\frac{d^2}{dr^2}r+\frac{l(l+1)}{r^2}\right)+\left(V(r)-\varepsilon_{nl}\right)\right]R_{nl}(r)=0 \qquad V(r)=-\frac{\alpha_c}{r}+\sigma r$$

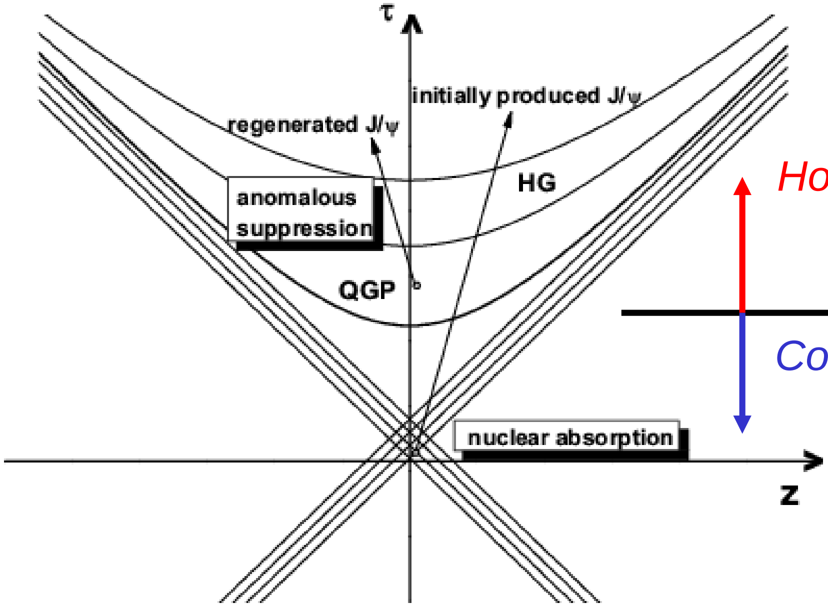
three parameters by fitting the quarkonium masses

$$M_1=M_{J/\psi},\quad M_2=M_{\psi'},\quad M_3 \quad \rightarrow \quad \alpha_c=0.29,\quad \sigma=(0.18\ \mathrm{GeV})^2,\quad \mathrm{m}_c=1.84\ \mathrm{GeV}$$

Solution:

binding energy ε_{nl} *and radial wave function* $R_{nl}(r)$

Cold and Hot Nuclear Matter Effects



Hot Nuclear Matter effects:

1)suppression in fireball

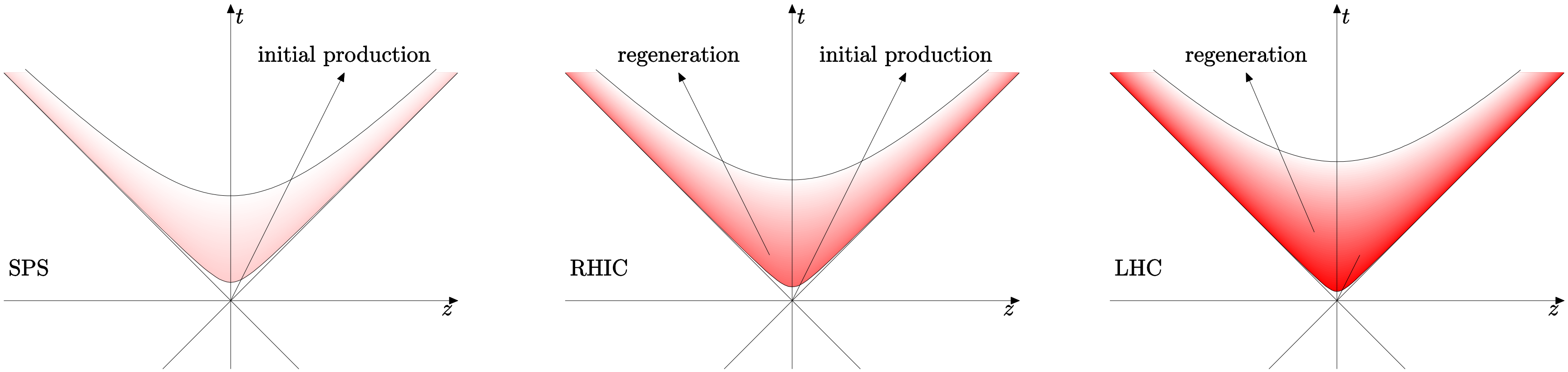
2)regeneration in fireball

Cold Nuclear Matter effects:

1)shadowing effect

2)Cronin effect

3)nuclear absorption

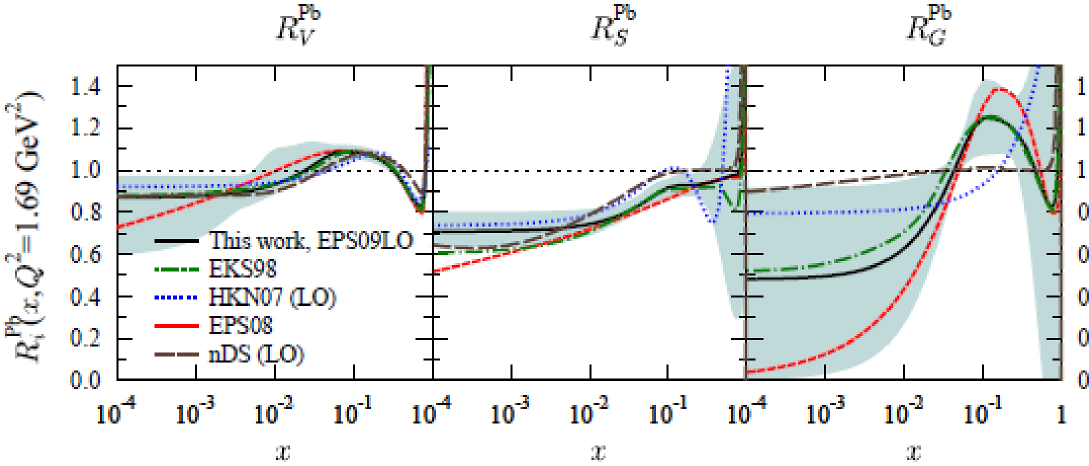


from screening to regeneration

Shadowing Effect

parton distribution function (PDF) in a nucleus is different from a simple superposition (Glauber model) of the PDF in a free nucleon.

R.Vogt, Phys.Rept.310, 197(1999)

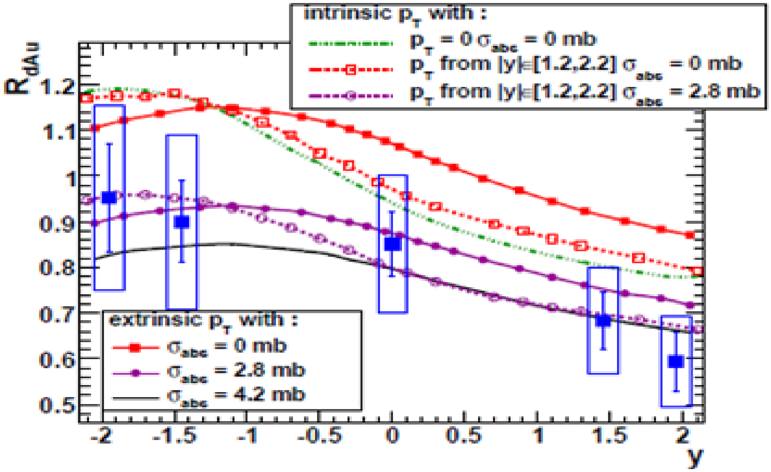


shadowing correction factor:

$$R_i^A(x,\mu_F) = \frac{f_i^A(x,\mu_F)}{A f_i^{nucleon}(x,\mu_F)},$$

$$\frac{d^2\sigma_{AB\to J/\psi X}}{dy_\Psi dp_t d\vec{x}_t} = \int_0^1 dx_1 dx_2 \int d\vec{x}_t dz_A dz_B \mathcal{F}_g^A(x_1,\vec{x}_t,z_A,\mu_F)\mathcal{F}_g^B(x_2,\vec{x}_t-\vec{b},z_B,\mu_F)2\hat{s}p_t \frac{d\sigma_{gg\to J/\psi+g}}{d\hat{t}}\delta(\hat{s}+\hat{t}+\hat{u}-M^2) S_{abs}$$

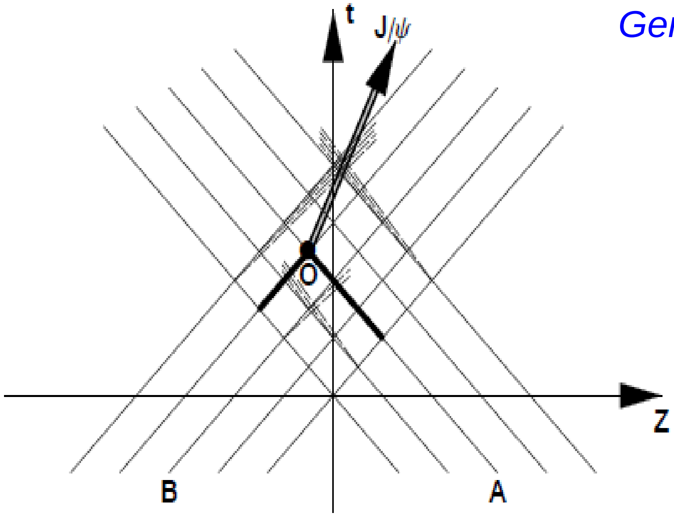
$$R_{AA} = \frac{\sigma_{AA}^{J/\psi}}{N_c\sigma_{pp}^{J/\psi}} = \begin{cases} 1, & \text{no medium effect} \\ <1, & J/\psi \ \text{suppression} \\ >1, & J/\psi \ \text{enhancement} \end{cases}$$



shadowing effect + nuclear absorption can explain the pA data at RHIC.

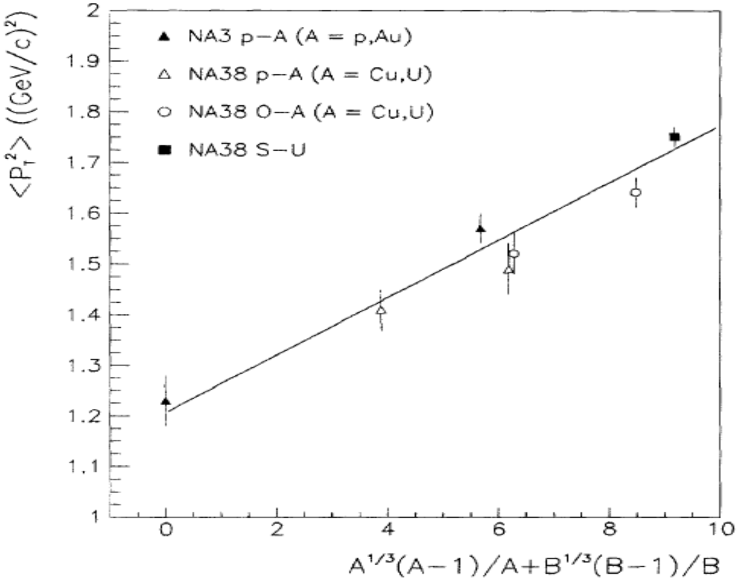
Cronin Effect

transverse momentum broadening due to gluon multiscattering with nucleons before they fuse into a pair of $Q\bar{Q}$:



Gerschel and Huefner, Ann. Rev. Nucl. Part. Sci. 49, 255(1999)

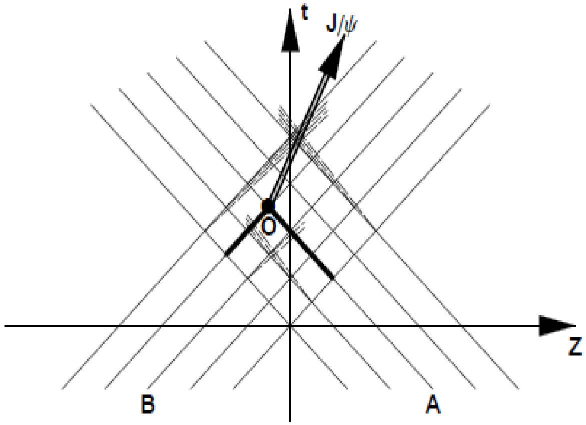
$$\left\langle p_t^2 \right\rangle^{pA} = \left\langle p_t^2 \right\rangle^{pp} + a_{gN} L$$



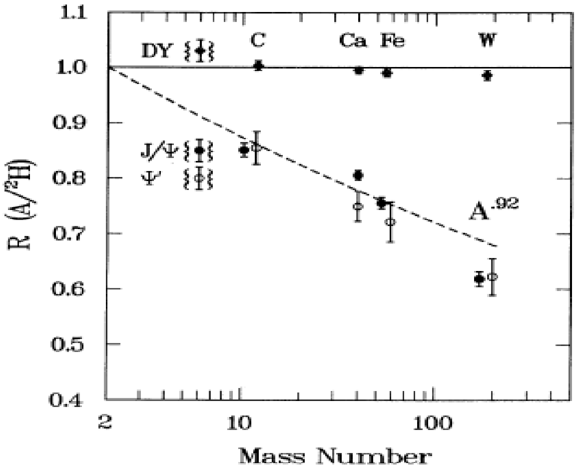
pA and light nuclear collisions at SPS are controlled by cold medium effects.

Nuclear Absorption

formed quarkonia are absorbed by the surrounding nucleons before they enter the QGP phase



$$S_{J/\psi} = \frac{1}{A}\int d^2\mathrm{b}dz\,\rho(\mathrm{b},z)e^{-\int_z^\infty dz'\sigma_{abs}\rho(\mathrm{b},z')}$$



J/ψ formation time τ_f □ 0.5 fm

collision time $\tau_c = 2R_A / \mathrm{c}h\, y_c$

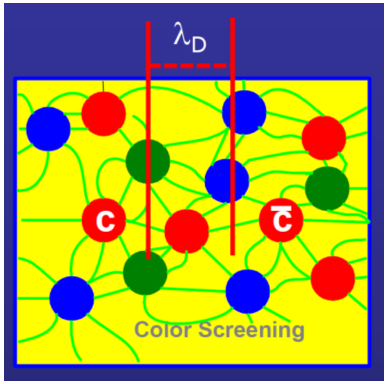
nuclear absorption can be ignored at high energies (LHC).

Debye Screening in QGP

medium effects on $Q\bar{Q}$ potential:

1) string tension in deconfinement phase $\sigma(T > T_c)$ □ 0

2) charge rearrangement ⟶ *Debye screening, the charge density seen by Q becomes small*



Coulomb potential $-\dfrac{\alpha_c}{r} \longrightarrow$ *Yukawa potential* $-\dfrac{\alpha_c}{r} e^{-r/\lambda_D}$

Debye screening length $\lambda_D = 1/m_D$

Debye screening mass m_D

$$\lambda_D = \begin{cases} \sqrt{\dfrac{6}{g_q e_q^2}}\dfrac{1}{T}, & \text{Abelian approximation} \\ \dfrac{1}{\sqrt{\left(\dfrac{N_c}{3}+\dfrac{N_f}{6}\right)g^2}}\dfrac{1}{T}, & \text{pQCD with colored gluons} \end{cases}$$

Estimation of Quarkonium Dissociation Temperature

Hamiltonian of the $Q\bar{Q}$ *system at* $T > T_c$*:* $H = \frac{p^2}{m_c} - \frac{\alpha_c}{r} e^{-r/\lambda_D}$

from uncertainty relation $p^2 \sim 1/r^2$

average energy $E = \frac{1}{m_c r^2} - \frac{\alpha_c}{r} e^{-r/\lambda_D}$

stability condition $\frac{dE}{dr} = 0, \qquad -\frac{2}{m_c r^3} + \frac{\alpha_c (1 + r/\lambda_D) e^{-r/\lambda_D}}{r^2} = 0$

$$\frac{2}{0.84\alpha_c m_c} > \lambda_D(T)$$

dissociation temperature

$$\frac{2}{0.84\alpha_c m_c} = \lambda_D(T_D)$$

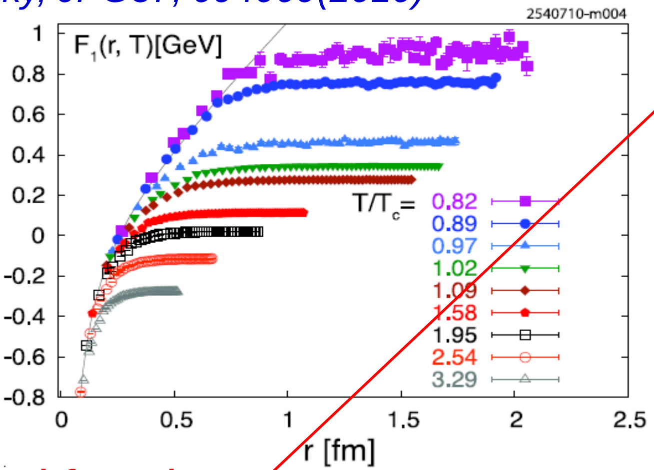
from pQCD calculated $\lambda_D(T)$

$$T_D = 209 \text{ MeV} \ \text{ for } \mathrm{J}/\psi$$

$V = F$ or $V = U$

Lattice simulated heavy quark free energy F

Petreczky, JPG37, 094009(2010)



Potential model:

What is the heavy quark potential V ?

Digal et al. 2001, Shuryak & Zahed 2004, Wong 2004, Alberico et al. 2005, Mocsy & Petreczky 2005,…

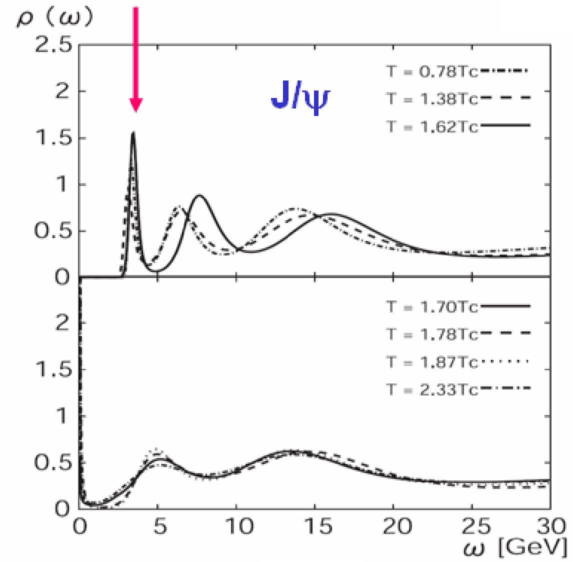
By solving Schroedinger equation,

Digal, Kaczmarek, Karsch, Satz, EPJC43, 71(2005)

$$V = F: \qquad T_D^{J/\psi} = 1.2T_c$$

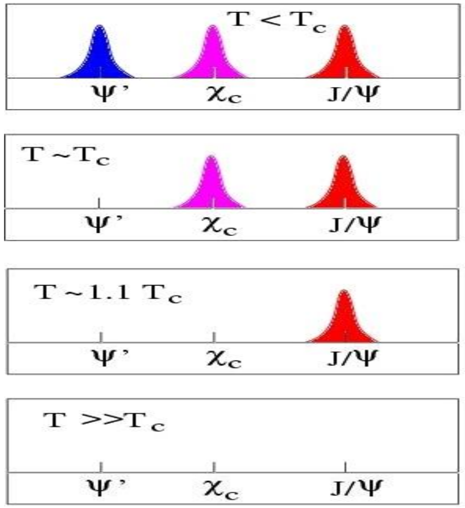
$$V = U = F + TS: \qquad T_D^{J/\psi} = 2.1T_c$$

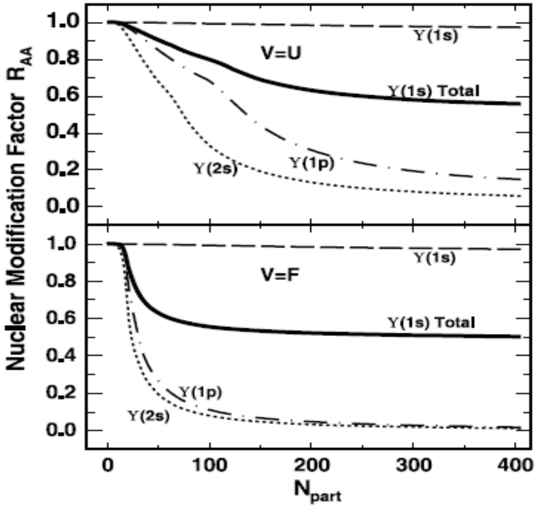
Spectral function



Asakawa and T.Hatsuda, PRL92, 012001(2004)

sequential suppression





Liu, Chen, Xu, Zhuang, PLB697, 32(2011)

excited Υ states are sensitive to the potential !

Relativistic Correction

the Dirac equation can be expressed as a group of covariant relativistic Schrodinger equations for the spin triplet (u_1^0, u_1^+, u_1^-) *and spin singlet* (u_0)*:*

H.W.Crater, J.Yoon, and C.Wong, PRD79, 034011(2009

$$\Big[-\frac{d^2}{dr^2}+\frac{J(J+1)}{r^2}+2m_w B+B^2-A^2+2\epsilon_w A+\Phi_D$$

$$-2\Phi_{SO}+\Phi_{SS}+2\Phi_T-2\Phi_{SOT}\Big]u_1^0=b^2u_1^0,$$

$$\Big[-\frac{d^2}{dr^2}+\frac{J(J-1)}{r^2}+2m_w B+B^2-A^2+2\epsilon_w A+\Phi_D$$

$$+2(J-1)\Phi_{SO}+\Phi_{SS}+\frac{2(J-1)}{2J+1}(\Phi_{SOT}-\Phi_T)\Big]u_1^+$$

$$+\frac{2\sqrt{J(J+1)}}{2J+1}(3\Phi_T-2(J+2)\Phi_{SOT})u_1^-=b^2u_1^+,$$

$$\Big[-\frac{d^2}{dr^2}+\frac{(J+1)(J+2)}{r^2}+2m_w B+B^2-A^2+2\epsilon_w A+\Phi_D$$

$$-2(J+2)\Phi_{SO}+\Phi_{SS}+\frac{2(J+2)}{2J+1}(\Phi_{SOT}-\Phi_T)\Big]u_1^-$$

$$+\frac{2\sqrt{J(J+1)}}{2J+1}(3\Phi_T+2(J-1)\Phi_{SOT})u_1^+=b^2u_1^-$$

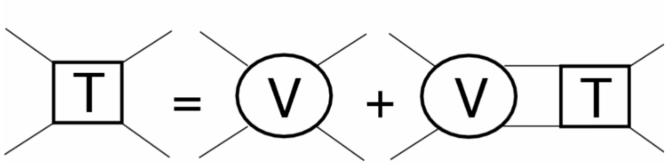
At finite temperature (Guo, Shi and Zhuang, PLB718, 143(2012)):

In comparison with the non-relativistic calculation, the J/ψ T_D *increases from 1.26Tc to 1.35Tc for V=F and from 2.1Tc to 2.38Tc for V=U.*

T-matrix Approach

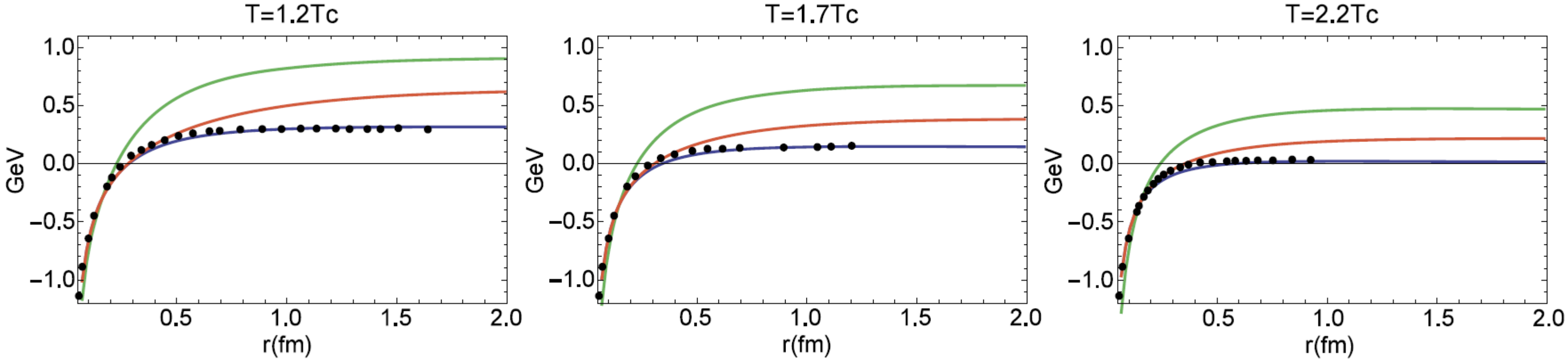
Liu & Rapp, NPA941, 179(2015):

T-matrix approach with complex potential:

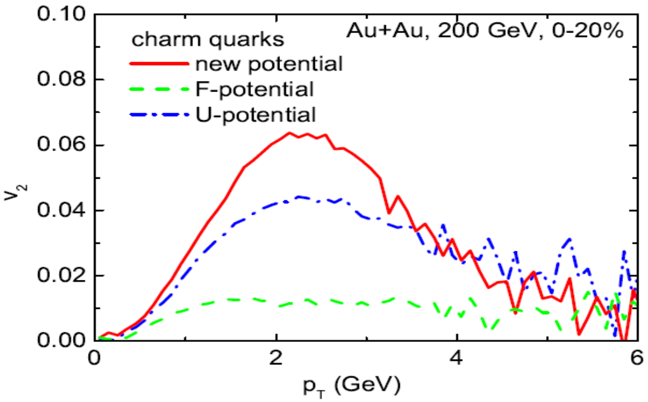


[Lipman-Schwinger equation]

by fitting the lattice calculated F, ⇒ the real potential → F < Re[V] < U

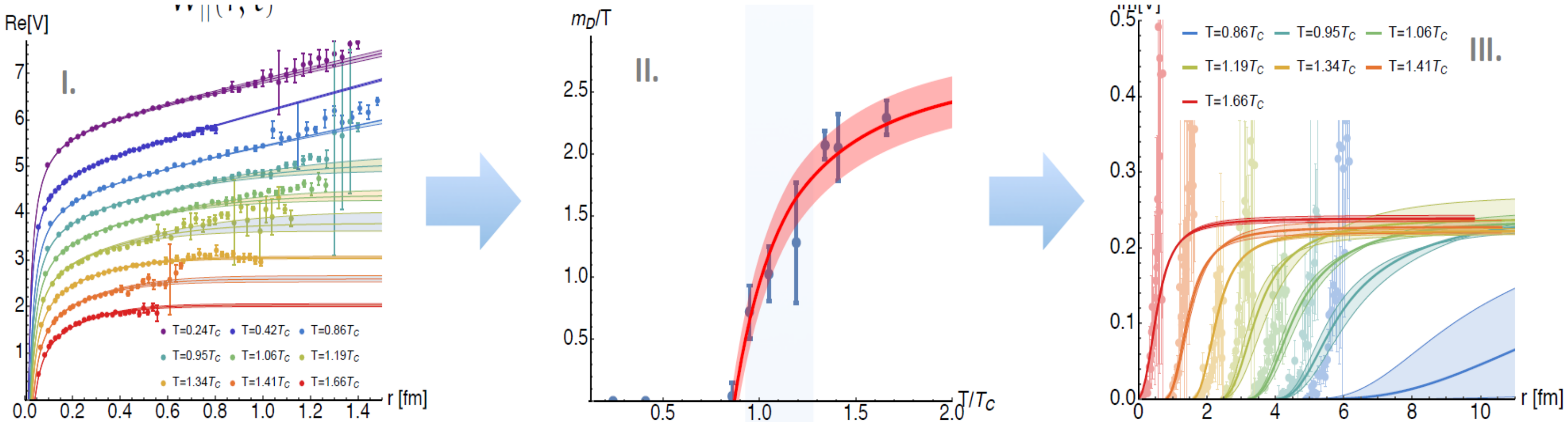


however, by calculating transport coefficients like heavy quark v_2 → Re[V] is close to U.



Lattice Simulation

Burnier, Kaczmarek, Rothkopf, JHEP1610, 032(2016):
1) extracting potential V=Re[V] + i Im[V] from lattice simulated spectral function
→ Re[V] is close to F.
2) parametrization of the potential via an extended Gauss law
→ Debye screening mass $m_D(T)$.

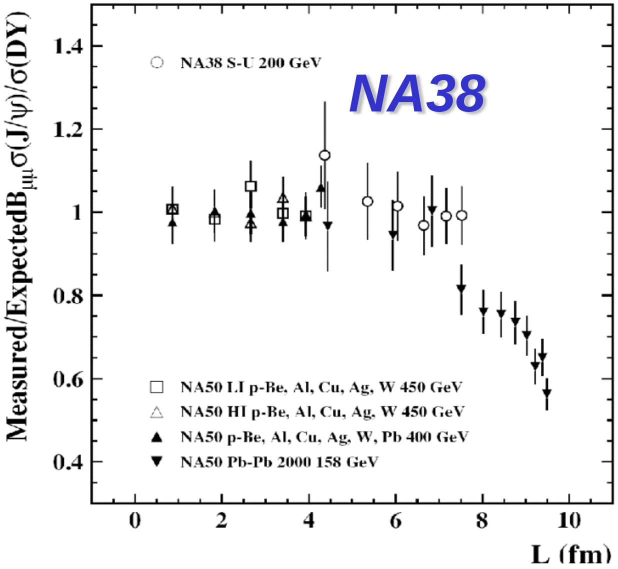


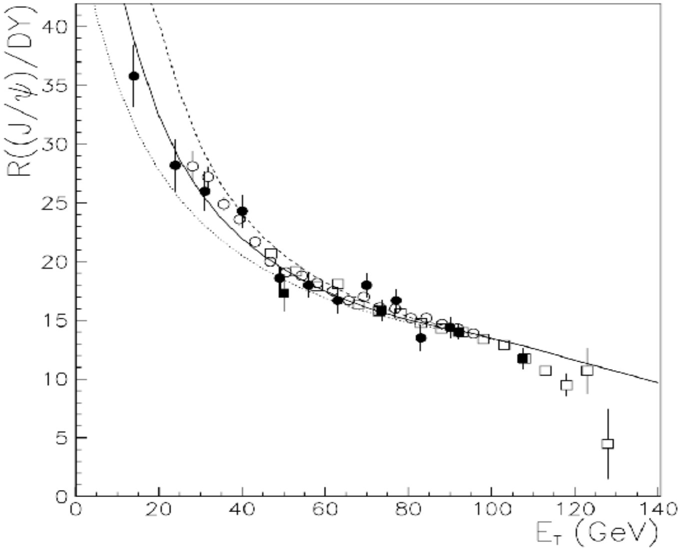
Other lattice simulation (H.Ohno):
the limit temperature of J/ψ 1.25 T_c supports V=F.

The complex potential is used to describe Υ suppression at LHC (G.Wolschin).

Anomalous Suppression at SPS

anomalous suppression



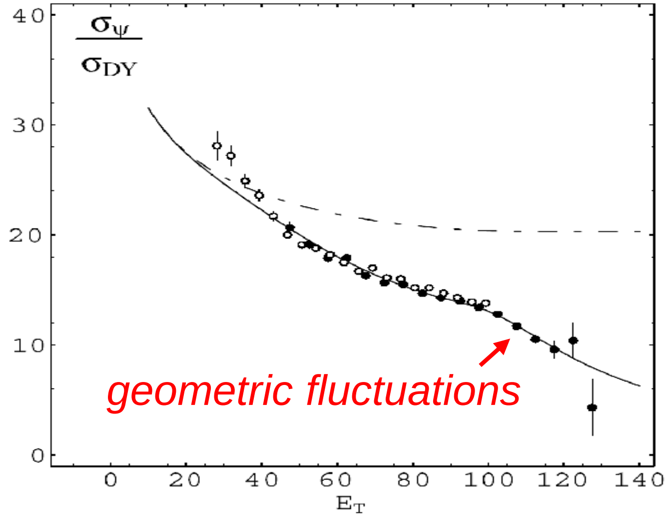


model 1: Debye screening (Matsui & Satz, 1986)

model 2: threshold model

(Blaizot, Dinh, Ollitrault, PRL85, 4010(2000)

$$S_{J/\psi}(b) = \int d^2 s S^{nucl}_{J/\psi}(b,s)\Theta(n_c - n_p(b,s)),$$



geometric fluctuations

model 3: comover interaction

(Capella, Feireiro, Kaidalov, PRL85, 2080(2000)

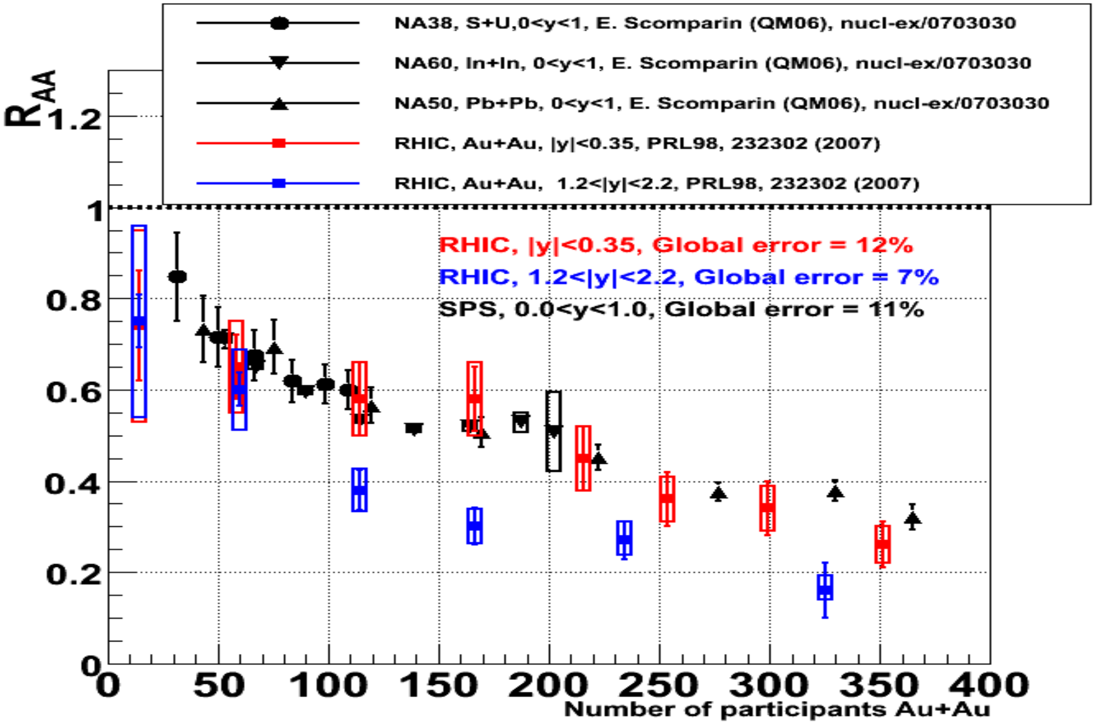
$$S^{co}_{J/\psi} = e^{-\int d\tau \langle v\sigma_{co}\rangle \rho_{co}(\tau)},$$

J/ψ Puzzles at RHIC

2 puzzles for J/psi production at RHIC:

R_{AA} (RHIC, $|y|<0.35$) ≈ R_{AA} (SPS)

R_{AA} ($|y|<0.35$) > R_{AA} ($1.2<|y|<2.2$)



The Debye screening picture can not explain the 2 puzzles.

how to explain the puzzles ?

Regeneration at RHIC (I)

about 10 pairs of $c\bar{c}$ in a central Au-Au collision at RHIC and more than 100 pairs at LHC !

→ J/ψ regeneration at high energies:

in QGP

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

in hadron gas

$$D+\bar{D}\to J/\psi+ \text{ mesons}$$

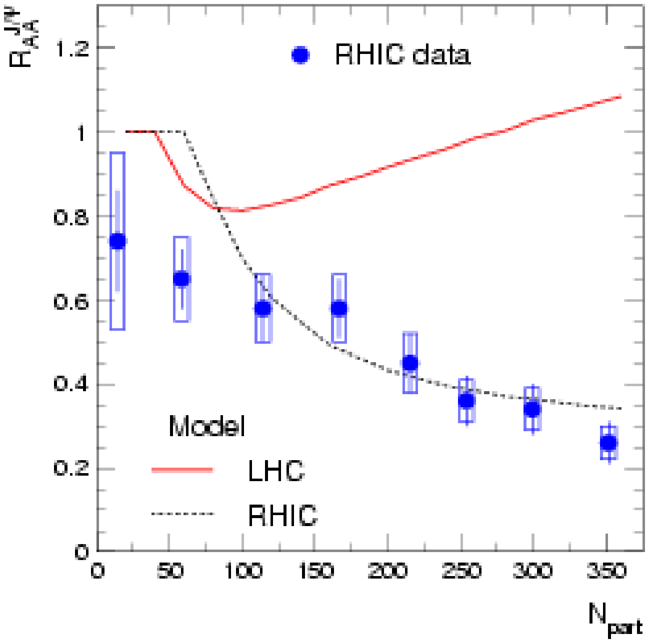
the competition between J/ψ suppression and regeneration leads to the question:

J/ψ suppression or enhancement at high energies?

model 1: (sudden) thermal production

(PBM, Stachel, PLB490, 196(2000)):

quarkonia are statistically produced at T=Tc, no suppression and no initial production



Regeneration at RHIC (II)

model 2: (continuous) production in QGP *(Thews, Mangano, PRC73, 014904(2006)):*

quarkonia are produced in the whole QGP,
including anomalous suppression but no initial production

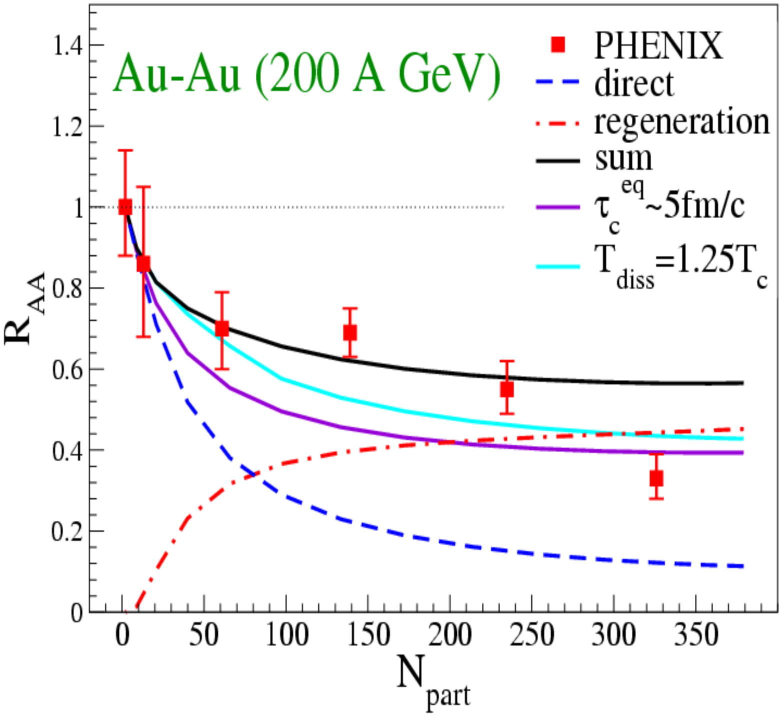
$$\frac{dN_{J/\psi}}{dt} = \lambda_F N_c N_{\bar{c}}/V(t) - \lambda_D N_{J/\psi}\rho_g, \qquad g+\Psi \leftrightarrow c+\bar{c}$$

** perturbative calculation with nonrelativistic Coulomb potential* *(Peskin, Bhanot, NPB156, 365(1979)*
** detailed balance*

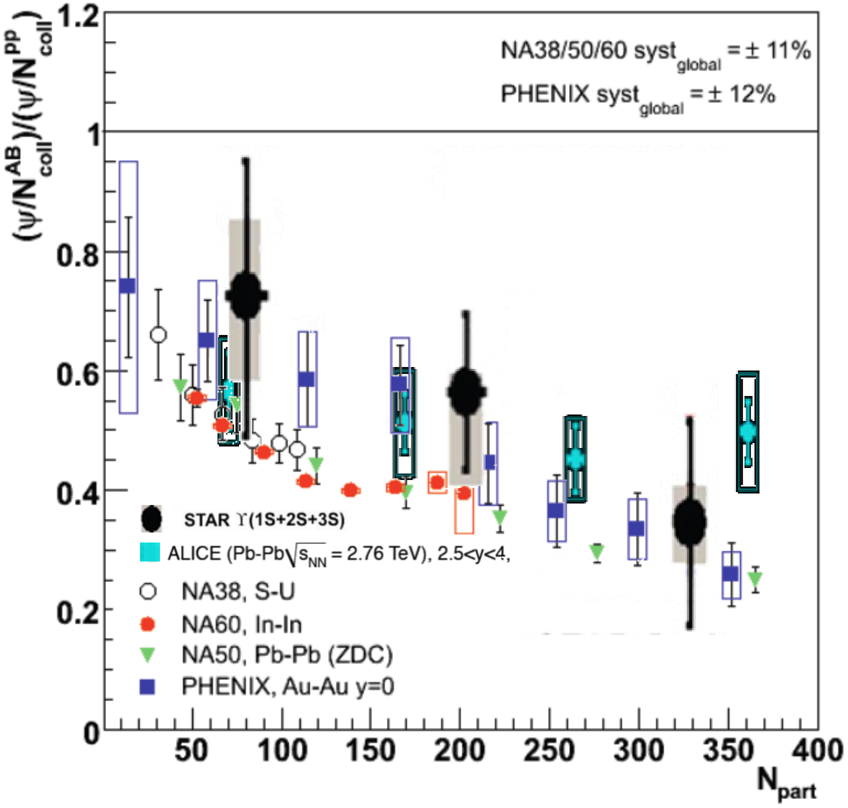
model 3: two-component model
(Grandchamp, Rapp, Brown, PRL92, 212301(2004):

initial production + regeneration

$$N_{J/\psi} = N^{dic}_{J/\psi} + N^{th}_{J/\psi},$$



Is Regeneration Necessary ?



SQM2011 summary by K.Safarik:
overall suppression of J/ψ is nearly identical between SPS and RHIC !

if we take V = U, the J/ψ *dissociation temperature (Young and Shuryak, PRC79, 034907(2009)*

$T_D = 2.7\, T_c$ *> maximum T at RHIC > maximum temperature at SPS*

→ no big difference between SPS and RHIC !

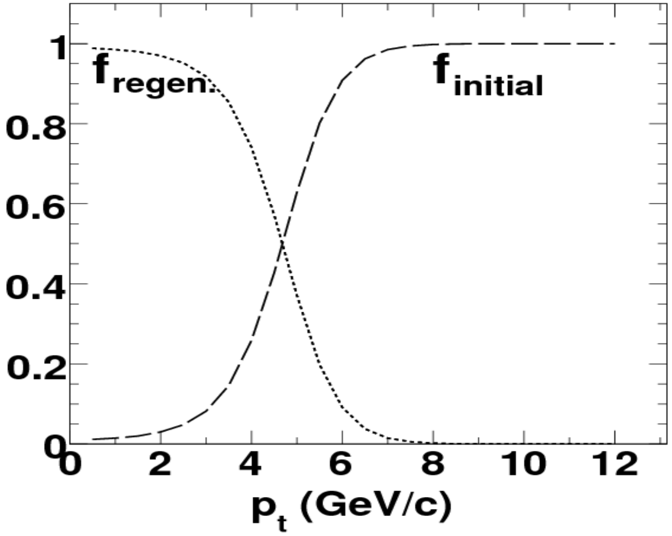
regeneration looks not necessary !?

How to distinguish Hot Mediums: Quarkonium P_t Distribution

$$f(p) = f_{ini}(p) + f_{reg}(p)$$

initial production:
p_t broadening due to Cronin effect and leakage effect

regeneration:
p_t suppression due to heavy quark energy loss and coalescence at later stage.



J/ψ in 5.5TeV central Pb+Pb
Liu, Xu, Zhuang, NPA834, 317C(2010).

p_t distribution depends directly on the production and suppression mechanisms and contains additional information about the nature of the medium, it may help to distinguish between different scenarios.

A Transport Approach

Dynamical approaches for quarkonia evolution in QGP:
kinetic approach (Rapp et al.),
Schroedinger-Langevin approach (Gossiaux),
Langevin approach (Blaizot), ……

Zhu, Xu, Zhuang, PLB607, 107(2005),
Yan, Nu, Zhuang, PRL97, 232301(2006):

- *quarkonium motion*

hot nuclear matter effects: gluon dissociation (OPE) and regeneration (detailed balance)

$$\partial f_\Psi/\partial\tau + \mathbf{v}_\Psi\cdot\nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi . \quad (\Psi = J/\psi,\ \psi',\ \chi_c)$$

$$\alpha_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int\frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g} W_{g\Psi}^{c\bar{c}}(s) f_g(\mathbf{p}_g,\mathbf{x}_t,\tau)\Theta\left(T(\mathbf{x}_t,\tau|\mathbf{b})-T_c\right),$$

$$\beta_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int\frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}\frac{d^3\mathbf{p}_c}{(2\pi)^3 2E_c}\frac{d^3\mathbf{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} W_{c\bar{c}}^{g\Psi}(s) f_c(\mathbf{p}_c,\mathbf{x}_t,\tau|\mathbf{b}) f_{\bar{c}}(\mathbf{p}_{\bar{c}},\mathbf{x}_t,\tau|\mathbf{b}) \times(2\pi)^4\delta^{(4)}(p+p_g-p_c-p_{\bar{c}})\Theta\left(T(\mathbf{x}_t,\tau|\mathbf{b})-T_c\right),$$

$$\sigma(p_\psi, p_g, T) \approx \frac{\langle r^2\rangle(T)}{\langle r^2\rangle(0)}\sigma(p_\psi, p_g)$$

- *analytic solution*

$$f_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = f_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau_0),\tau_0|\mathbf{b})e^{-\int_{\tau_0}^{\tau}d\tau'\alpha_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau'),\tau'|\mathbf{b})} + \int_{\tau_0}^{\tau}d\tau'\beta_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau'),\tau'|\mathbf{b})e^{-\int_{\tau'}^{\tau}d\tau''\alpha_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau''),\tau''|\mathbf{b})}.$$

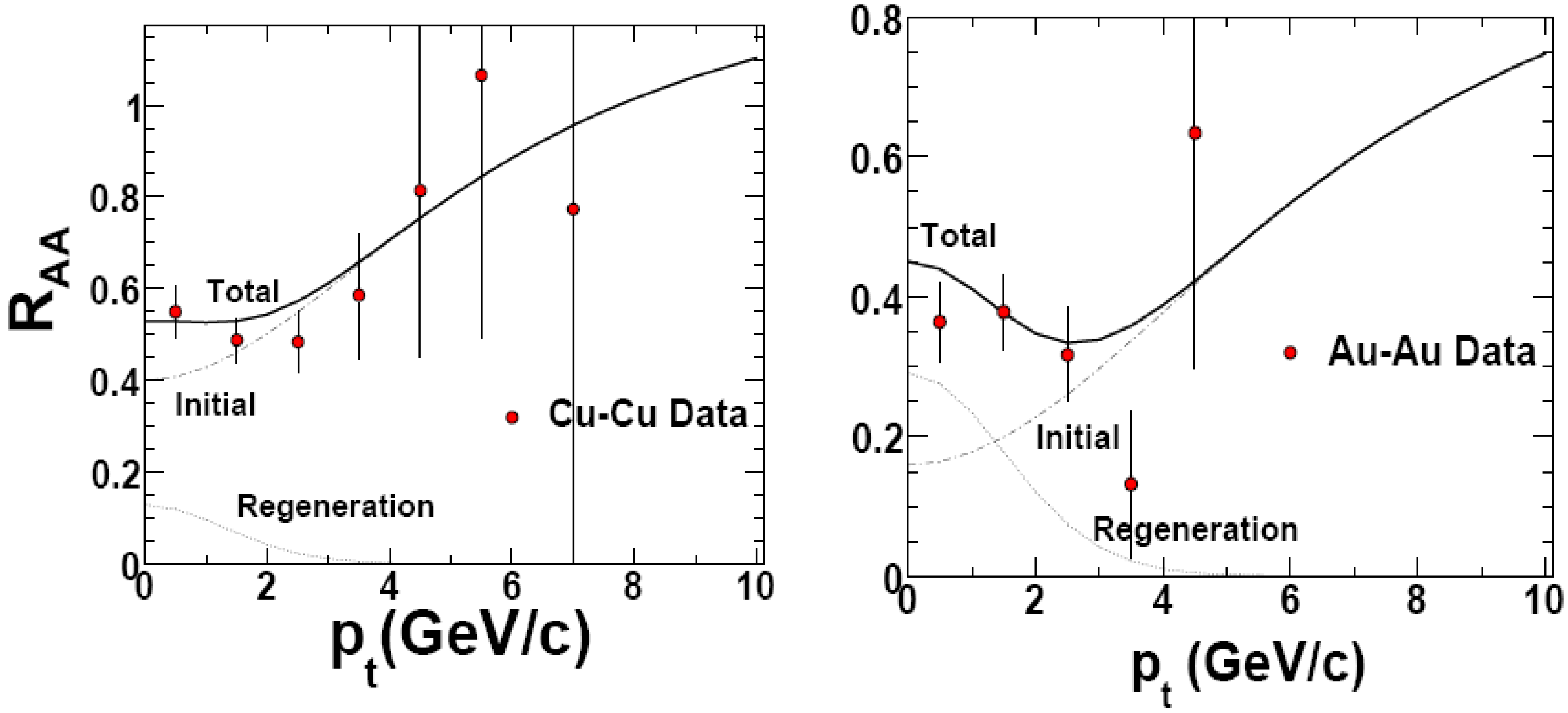
cold nuclear matter effects: shadowing and Cronin

- *QGP evolution*

$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu n^\mu = 0$ *+ Lattice QCD equation of state*

J/ψ $R_{AA}\,(p_t)$ at RHIC

Liu, Qu, Xu, Zhuang, PLB2009

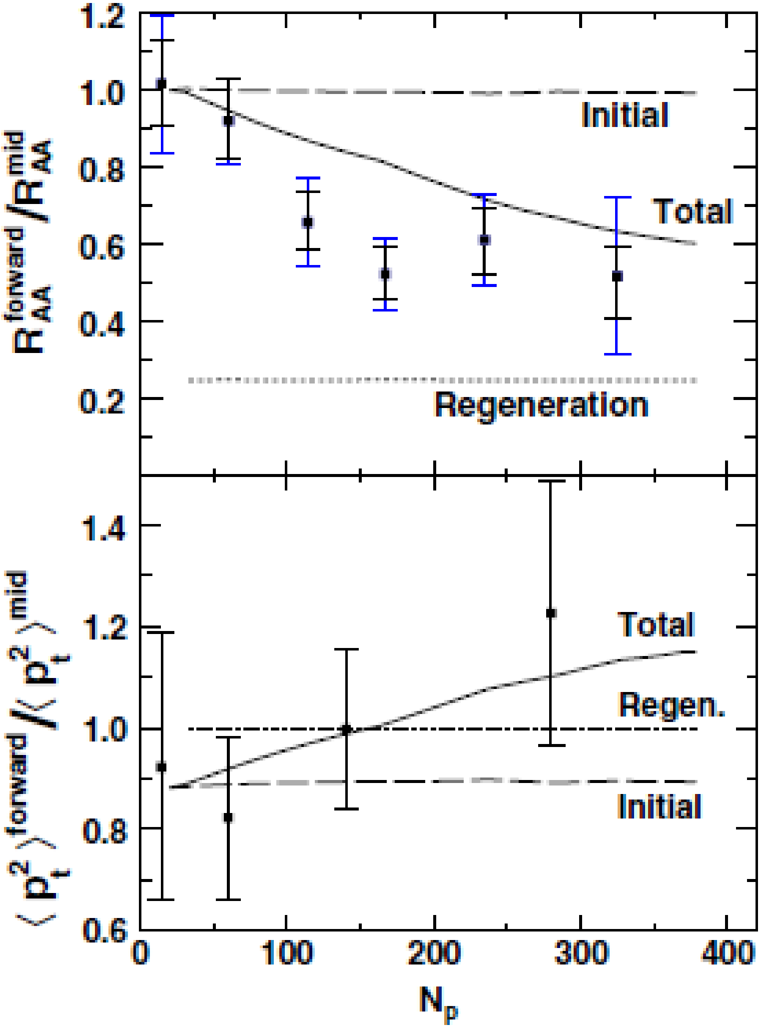


$\tau_0 = 0.6\ fm, \quad T_0 = 344\ \text{MeV}\ ,$

$\sigma_{pp}^{J/\psi} = 0.74\mu b, \quad \sigma_{pp}^{c\bar{c}} = 0.12nb$ (PHENIX pp data) at mid rapidity

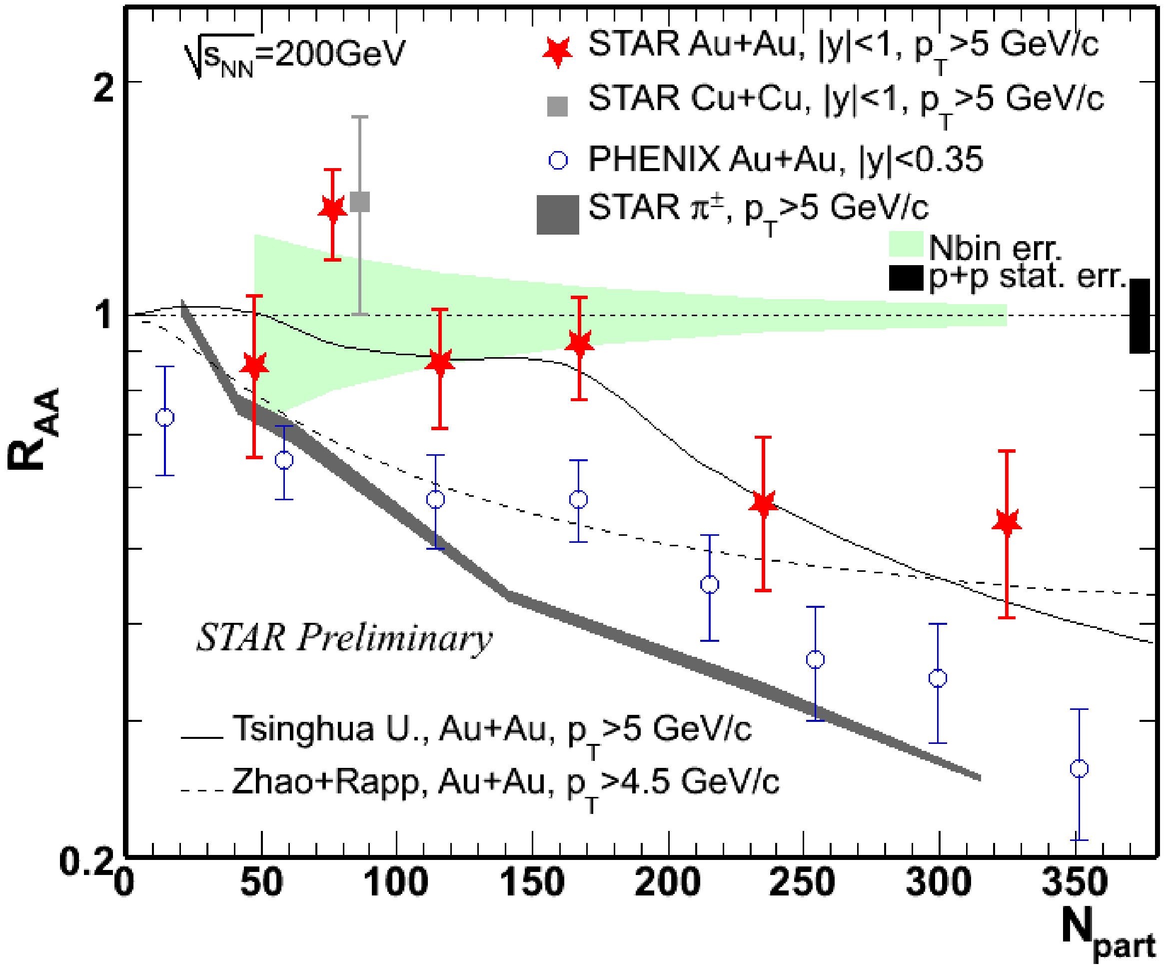
J/ψ Rapidity Dependence at RHIC

Liu, Xu, Zhuang, JPG2010

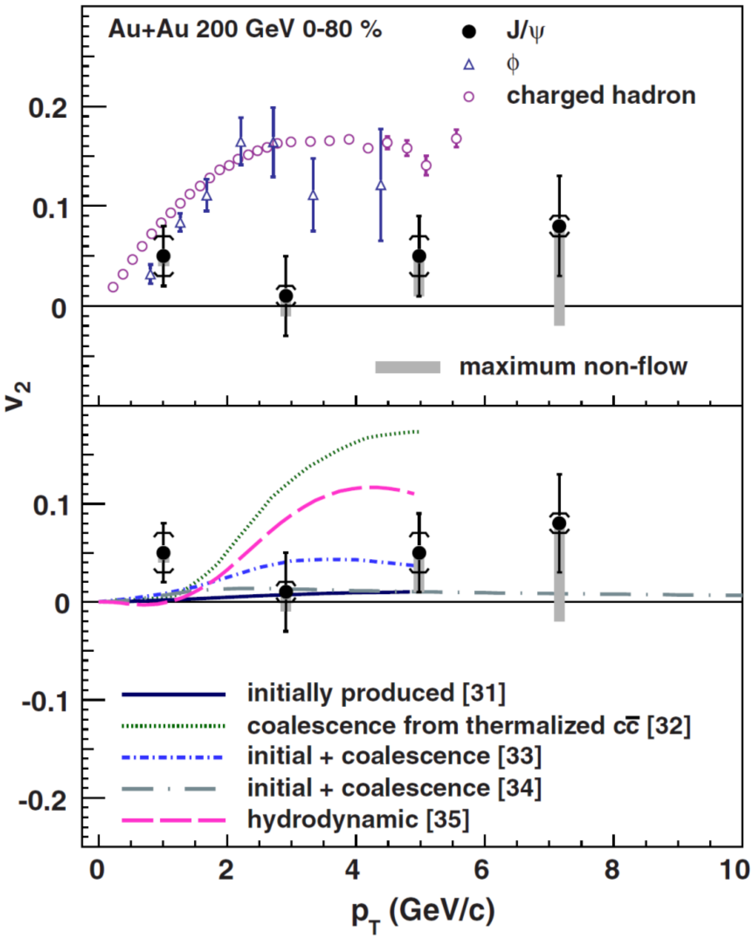


$$\sigma_{pp}^{J/\psi} = 0.42\mu b, \qquad \sigma_{pp}^{c\bar{c}} = 0.04nb \text{ at forward rapidity}$$

J/ψ R_{AA} (N_p) at high pt at RHIC



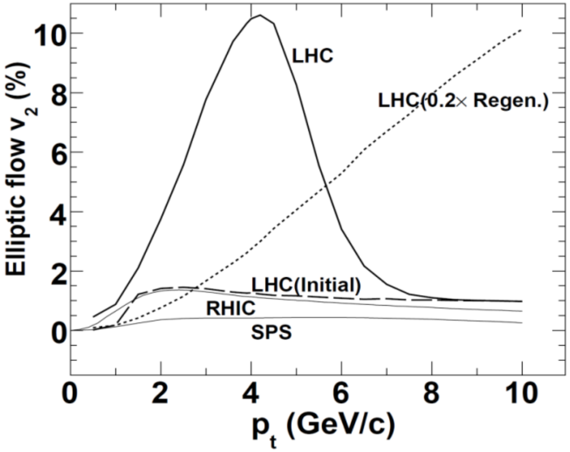
Flow

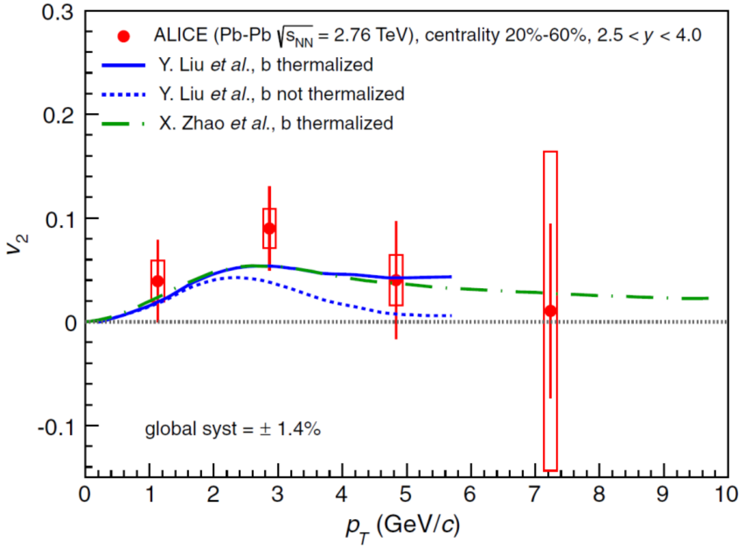


STAR Collaboration, PRL111, 052301(2013)

J/ψ elliptic flow in 5.5TeV central Pb+Pb,

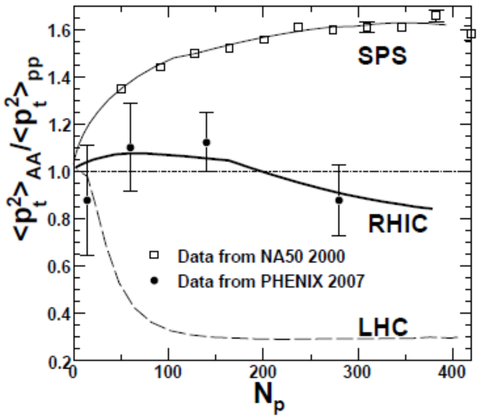
Liu, Xu, Zhuang, NPA834, 317C(2010).



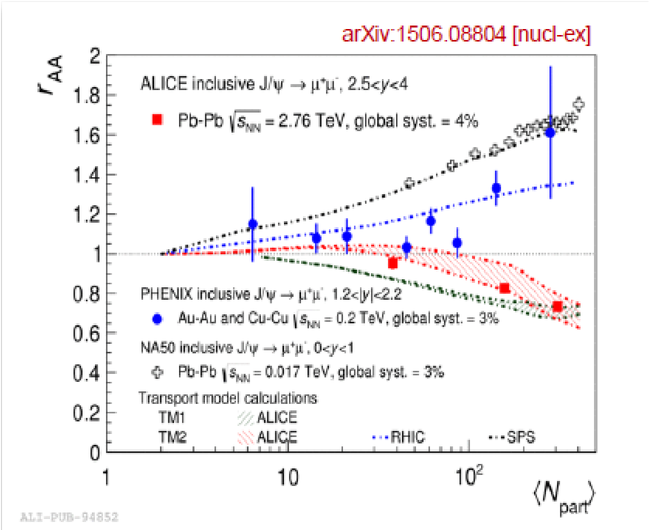


ALICE Collaboration, PRL111, 162301(2013)

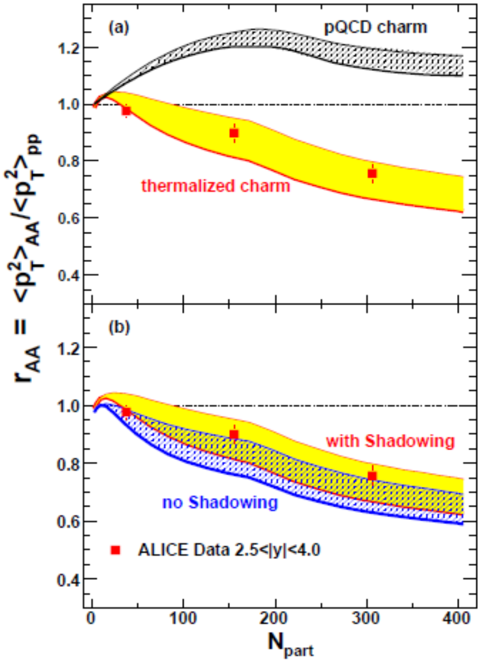
$$r_{AA}=\frac{\langle p_t^2\rangle_{AA}}{\langle p_t^2\rangle_{pp}}$$



J/ψ r_{AA} in 5.5TeV central Pb+Pb,
Zhou, Xu, Zhuang, NPA834, 249C(2010).



ALICE Collaboration, JHEP1605, 179(2016)

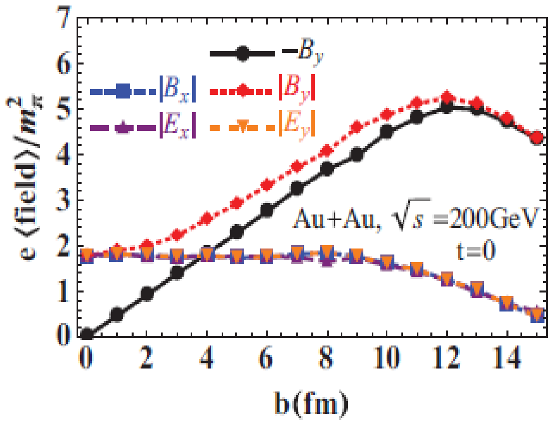


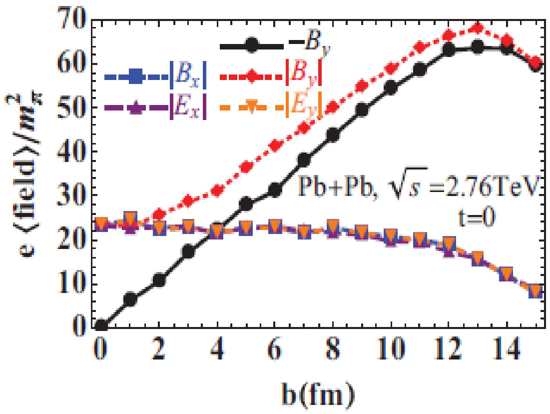
J/ψ r_{AA} in 2.76TeV central Pb+Pb,
Zhou, Xu, Xu, Zhuang, PRC89, 054911(2014)

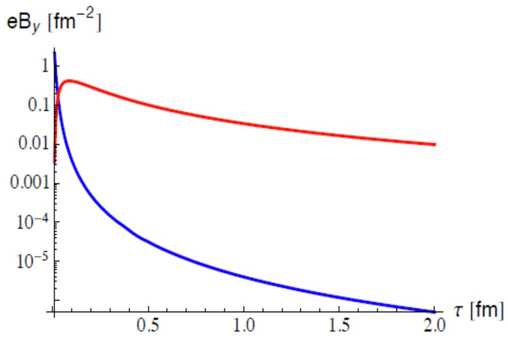
Charmonium Production in Magnetic field

strong magnetic field in heavy ion collisions at RHIC and LHC

(Deng, Huang, PRC85, 044907(2012), Gursoy, Kharzeev, Rajagopal, PRC89, 054905(2014))







Guo, Shi, Xu, Xu, Zhuang, PLB751, 215(2015):

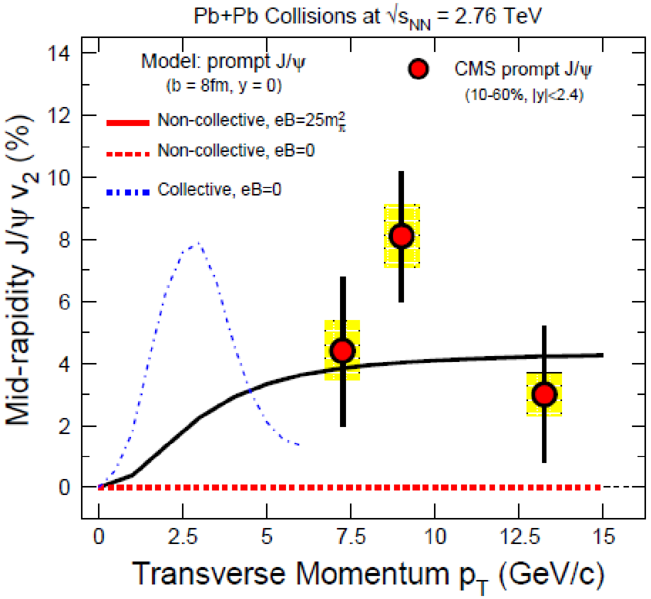
$c\bar{c}$ *state evolution:* $i\frac{\partial}{\partial t}|c\bar{c}\rangle = \hat{H}(B(t))|c\bar{c}\rangle$

$$\hat{H}(r,R,B(t)) = \frac{(\vec{p}_c - q_c\vec{A}_c)^2}{2m_c} + \frac{(\vec{p}_{\bar{c}} - q_{\bar{c}}\vec{A}_{\bar{c}})^2}{2m_c} - \frac{(q_c\vec{s}_c + q_{\bar{c}}\vec{s}_{\bar{c}})\cdot\vec{B}}{m_c} + V_{c\bar{c}}(r)$$

$$V_{c\bar{c}}(r) = -\frac{\alpha}{r} + \sigma r + \beta e^{-\gamma r}\vec{s}_c\cdot\vec{s}_{\bar{c}}$$

$|c\bar{c}\rangle = \sum_\psi \langle\psi|c\bar{c}\rangle|\psi\rangle$

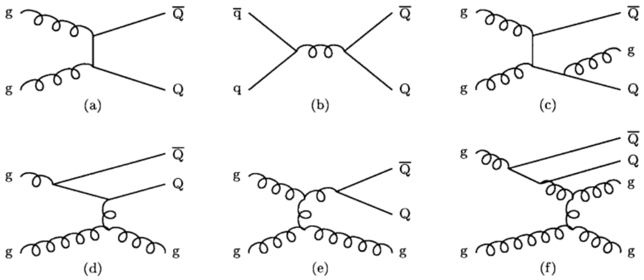
the probability for the $c\bar{c}$ *to be in the charmonium state* $|\psi\rangle$*:*
$|\langle\psi|c\bar{c}\rangle|^2$



Non-collective v_2 *at high* P_t *created by B field !*

Heavy Quark Production at FCC

Heavy quark production in QGP:



Levai, Muller and Wang, PRC51, 3326(1995).
Kaempfer and Pavlenko, PLB391, 185(1997).
Uphoff, Fochler, Xu and Greiner, PRC82, 044906(2010).
Zhang, Ko and Liu, PRC77, 024901(2008),……

Charm quark evolution in QGP

Zhou, Chen, Greiner, Zhuang, PLB758, 434(2016)

$$\frac{1}{\cosh\eta}\partial_\tau n_c + \nabla_T \cdot (n_c \mathbf{v}_T) + \frac{1}{\tau\cosh\eta} n_c = r_{gain} - r_{loss}$$

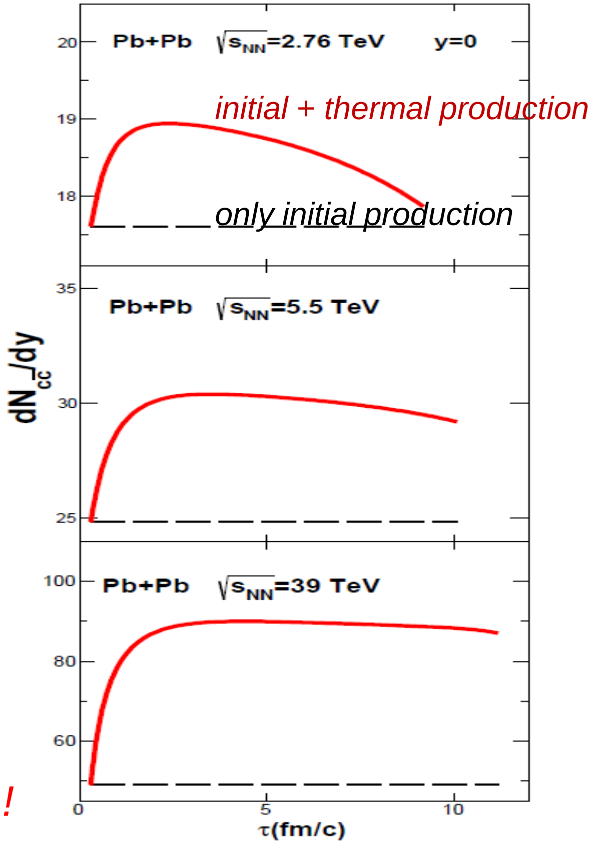
*NLO production cross section

*T-dependent parton mass and coupling

*hydrodynamics for QGP evolution

*detailed balance between loss and gain terms

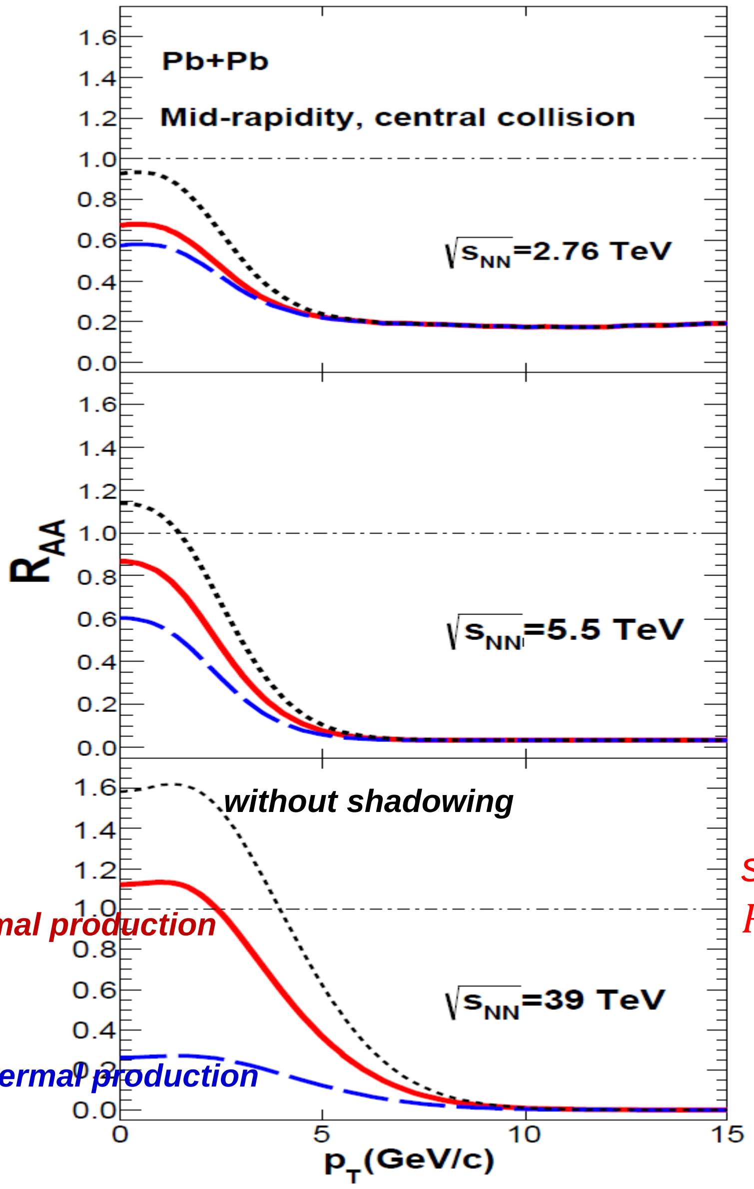
*shadowing effect on initial distribution (EPS09s NLO)



significant charm enhancement (~80%) at FCC !

Charmonia at FCC

Zhou, Chen, Greiner, Zhuang, PLB758, 434(2016)



with charm thermal production

without charm thermal production

significant J/ψ enhancement at low p_T:

$R_{AA}(p_t) < 1 \ \rightarrow \ R_{AA}(p_t) > 1$!

Motivation to Study Multi-charmed Baryons

1) Ω_{ccc} *and* Ξ_{cc} *are hardly produced in pp collisions,*
$\sigma(\Omega_{ccc})$ = *0.06~0.13 nb at 7 GeV and 0.1~0.2 nb at 14 GeV* *(Bjorken 1986 and Chen, 2011)*
$\sigma(\Xi_{cc})$*~10 nb at 1.8 TeV* *(PRL89 (2002) 112001).*

SELEX Collaboration claimed the observation of Ξ_{cc}*, but FOCUS, BaBar, Belle, LHCb failed to reproduce it in elementary collisions.*

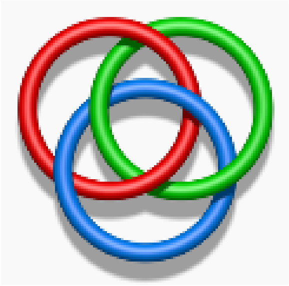
2) *However, coalescence among uncorrelated charm quarks in A+A may significantly enhance the production probability,*

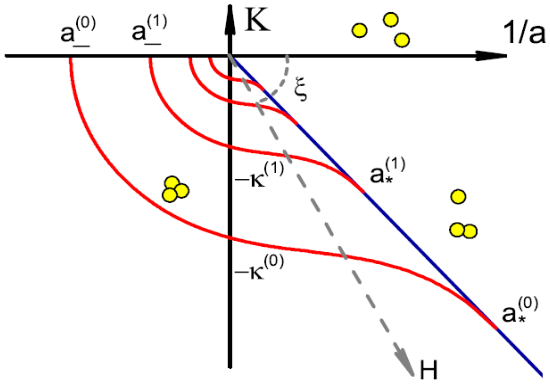
$$N(\Xi_{cc}) \sim N_c^2, \quad N(\Omega_{ccc}) \sim N_c^3, \qquad N_c \sim 100 \text{ at LHC !}$$

3) *If they are discovered in A+A collisions, it is a unique signal of QGP!*

4) *Exotic baryon states at quark level ?*

1) Borromean rings





2) Efimov states (PLB33, 563(1970)), discovered in cold atom gas (T.Kraemer et al., Nature 440, 315(2006)).

Wigner Function

He, Liu, Zhuang, PLB746, 59(2015)
Zhao, He, Zhuang, arXiv:1603.04524

$$\hat{H}\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)=E_T\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)$$

$$\hat{H}=\sum_{i=1}^{3}\frac{\hat{\mathbf{p}}_i^2}{2m_c}+V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\qquad V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)=\sum_{i<j}V_{cc}(\mathbf{r}_i,\mathbf{r}_j).\qquad V_{cc}=V_{c\bar{c}}/2.$$

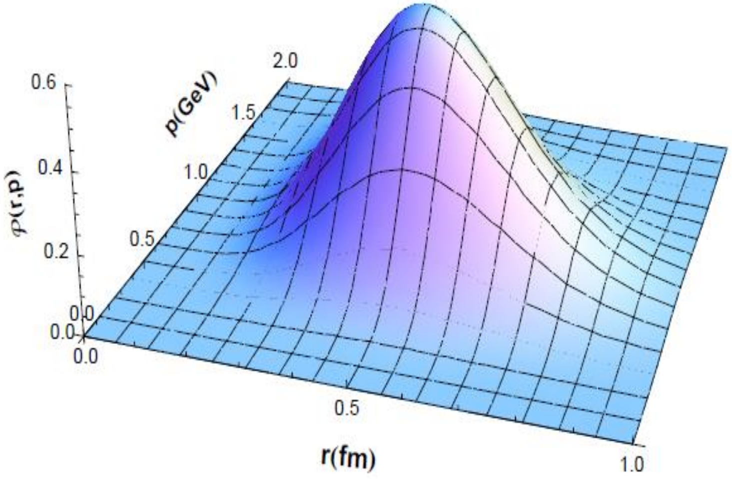
Methods to solve 3-body Schroedinger equation:
Hyperspherical method, Separable model, ……

Static properties:

$m_\Omega = 4.75$ GeV *(4.8 GeV from LQCD),* $\epsilon_\Omega = 900\ MeV,\quad \langle r_\Omega\rangle = 0.5\ fm \simeq \langle r_{J/\psi}\rangle$

Wigner function:

$$W(\mathbf{r},\mathbf{p})=\int d^6\mathbf{y}e^{-i\mathbf{p}\cdot\mathbf{y}}\psi\left(\mathbf{r}+\frac{\mathbf{y}}{2}\right)\psi^*\left(\mathbf{r}-\frac{\mathbf{y}}{2}\right)$$



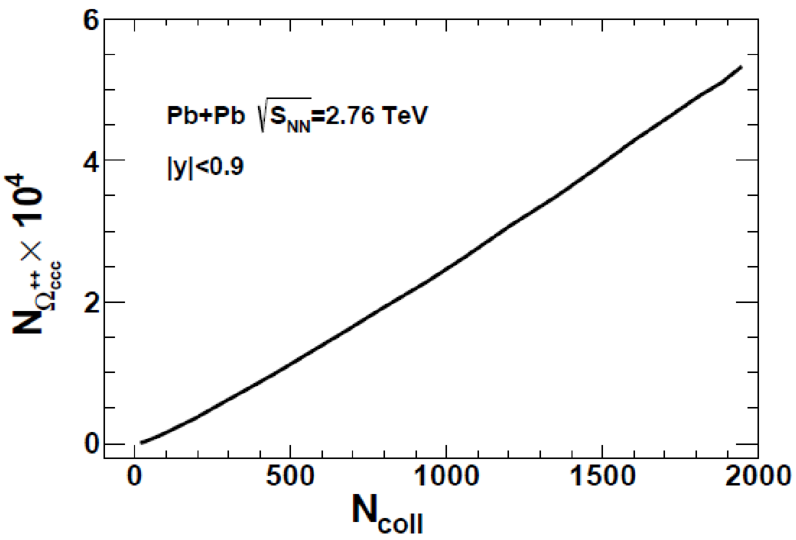
Significant Enhancement in A+A

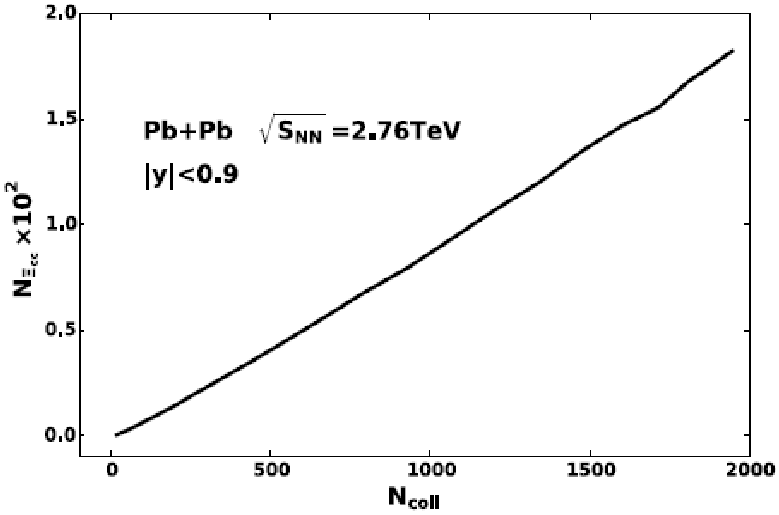
He, Liu, Zhuang, PLB746, 59(2015)
Zhao, He, Zhuang, arXiv:1603.04524

$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int_\Sigma \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\int \frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6} f(r_1,p_1)f(r_2,p_2)f(r_3,p_3)W(\mathbf{r}_x,\mathbf{r}_y,\mathbf{p}_x,\mathbf{p}_y)$$

$$f(\vec{r},\vec{p}\,) = \frac{1}{e^{p^\mu u_\mu/T}+1}$$

the coalescence happens on the hadronization hypersurface Σ determined by hydrodynamics.





$\sigma_\Omega \sim 3.5\times 10^4\ nb$ *for* $\sigma_{pp} = 62\ mb$ *in central Pb+Pb at 2.76 TeV*

in comparison with

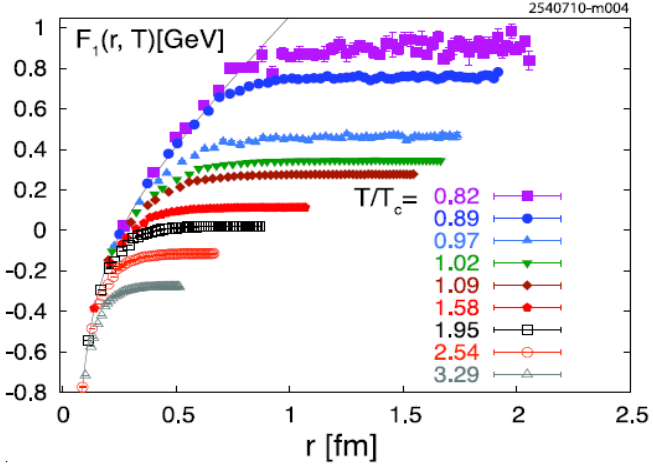
$\sigma_\Omega \sim 0.1$ *nb in p+p at 7* TeV*,*

the Ω_{ccc} *production in A+A is enhanced by 6 orders !*

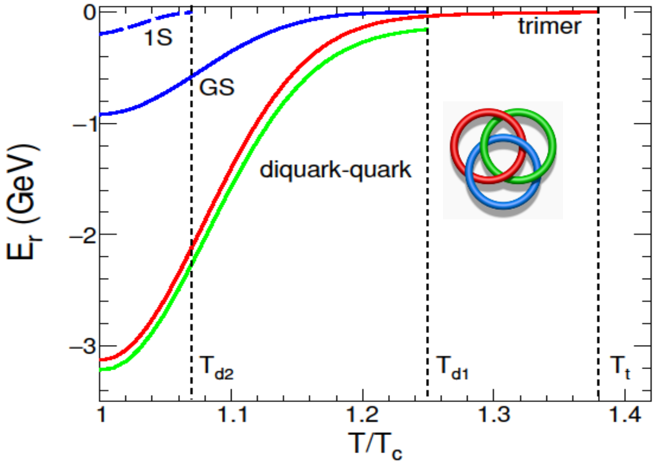
Exotic States of Ω_{ccc} at Finite Temperature

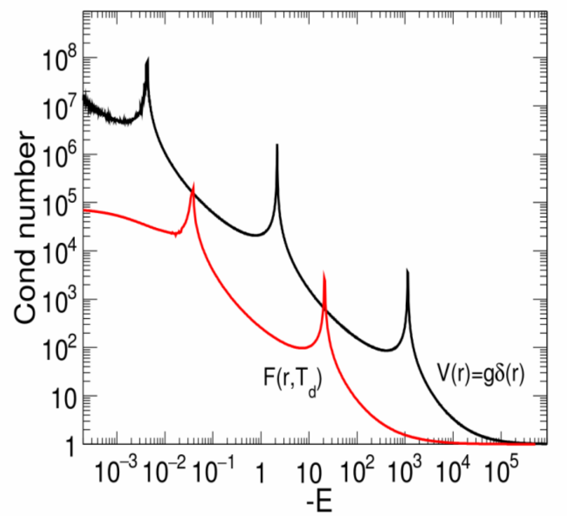
Zhao, Zhuang, in progress

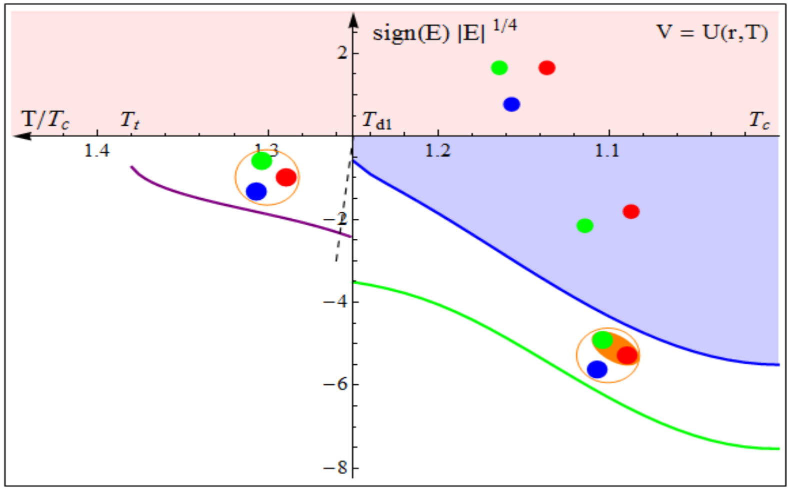
short range potential at high T



Borromean rings







$\frac{E_n}{E_{n+1}} = e^{2\pi/s_0} = 515$, *Efimov states*

the exotic states might be realized during the cooling down of the fireball in A+A collisions.

Summary

1) Quarkonium is still a smoking gun in probing QGP, the p_t distribution is sensitive to the fireball properties.

2) Cold medium effects dominate p+A at RHIC, but there is already a sizeable hot medium effect in p+A at LHC.

3) Quarkonium v_2, $r_{AA}=\frac{\langle p_t^2\rangle_{AA}}{\langle p_t^2\rangle_{pp}}$ and $R_{AA}(p_t)$ can distinguish hot mediums at SPS, RHIC and LHC： from pt enhancement at SPS to pt suppression at LHC !

4) It is most probable to discover Ω_{ccc} and Ξ_{cc} in A+A, and the discovery is a unique signal of QGP formation.

5) There are exotic baryon states at quark level, which might be realized during the cooling down of the fireball in heavy ion collisions.

6) There are still some puzzles, like double ratio $\frac{\psi'}{J/\psi}$, J/ψ enhancement in p+A, and excess of low p_t J/ψ.

Backup

decay modes of Ω_{ccc}

Decay through weak interaction, for instance

nonleptonic cascade decay mode (Chen 2011):

$$\begin{array}{llll}
\Omega_{ccc}^{++} \rightarrow & \Omega_{ccs}^{+} & + \pi^{+} \\
& \quad\downarrow & \\
& \Omega_{css}^{0} & + \pi^{+} \\
& \quad\downarrow & \\
& \Omega_{sss}^{-} & + \pi^{+}
\end{array}$$

semileptonic decay mode (Bjorken, 1986):

$$\Omega_{ccc}^{++} \rightarrow \Omega_{sss}^{-} + 3\mu^{+} + 3v_{\mu}.$$

Ξ_{cc} Decay mode and experiment status

- $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+} K^{-} \pi^{+}$ (Observation reported by SELEX 2003)
- $\Xi_{cc}^{+} \rightarrow D^{0} p K^{-} \pi^{+}$ (Searched by Belle2006)
- $\Xi_{cc}^{+} \rightarrow D^{+} p K^{-}$ (Searched by FOCUS 2003, Belle2006)
- $\Xi_{cc}^{+} \rightarrow \Xi_c^{+} \pi^{+} \pi^{-}$ (Searched by BarBar2006)
- $\Xi_{cc}^{+} \rightarrow \Xi_c^{0} \pi^{+}$

"The improved LHCb and Belle II (2019) is promising in observing Ξ_{cc} "

Search for the Doubly Charmed Baryon at LHCb, Ph.D thesis, ZHONG Liang (2015)