Cold and Hot Nuclear Effects on Heavy Flavors and Quarkonia

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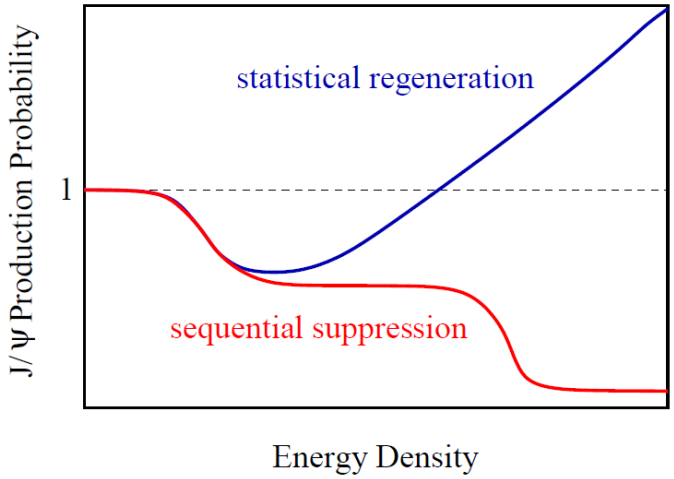
How hot is the QGP ?

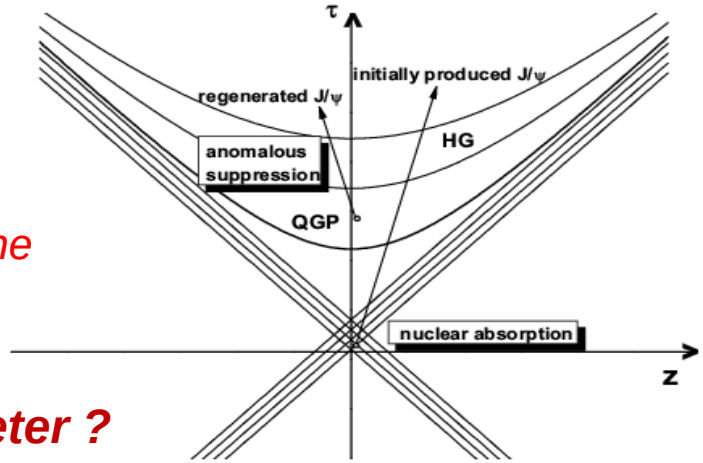


- *color screening (Matsui, Satz, …)*
  → sequential quarkonium suppression is a thermometer

- *statistical regeneration (Braun-Munzinger & Stachel, Thews et al., Rapp et al, …)*
  → quarkonium enhancement

- *the cancellation between the two hot nuclear effects weakens the sensitivity of the thermometer*

- *cold nuclear effects (EPS, EKS, …) (shadowing effect, Cronin effect, energy loss, nuclear absorption,…) affect the thermometer too*



How to increase the sensitivity of the thermometer ?

Outline

1. ***Heavy Quark Potential***
2. ***Cold Nuclear Matter Effects***
3. ***Extracting QGP Properties***
4. ***Ω_{ccc} and Ξ_{cc} in A+A***
5. ***Summary***

1. Heavy Quark Potential

$V = F$ or $V = U$?

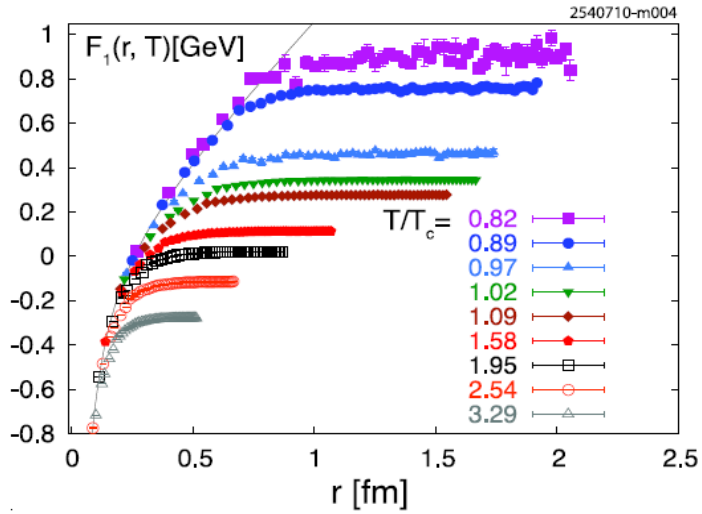
Lattice calculated heavy quark free energy F, what is the heavy quark potential V ? (Digal et al. 2001, Shuryak & Zahed 2004, Wong 2004, Alberico et al. 2005, Mocsy & Petreczky 2005,…)

By solving Schroedinger equation,

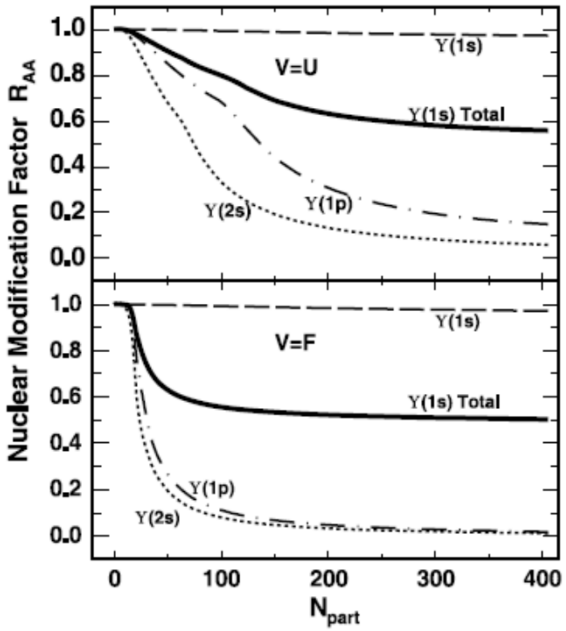
$$V = F: \qquad T_D^{J/\psi} = 1.2T_c$$

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

A big difference in the dissociation temperature !



Petreczky, 2010



Liu et al., arXiv: 1009.2585

excited Υ states are sensitive to the heavy quark potential

Entropic Force

*H.Satz (arXiv: 1501.03940 and the talk at ECT*2015):*

force on $Q\bar{Q} \sim$ *pressure* $P = -\frac{\partial V}{\partial r}$

for $F = \frac{\sigma}{\mu}(1 - e^{-\mu r})$ $with\ screening\ mass\ \mu(T)$

$V = F$: $attractive\ force\ P = -\sigma e^{-\mu r}\ for\ binding$

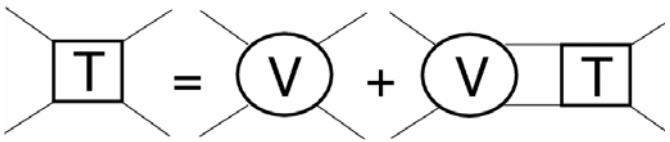
$V = U$: $the\ force\ contains\ a\ repulsive\ part\ (entropic\ force)$

$\Rightarrow \boldsymbol{V = F}$

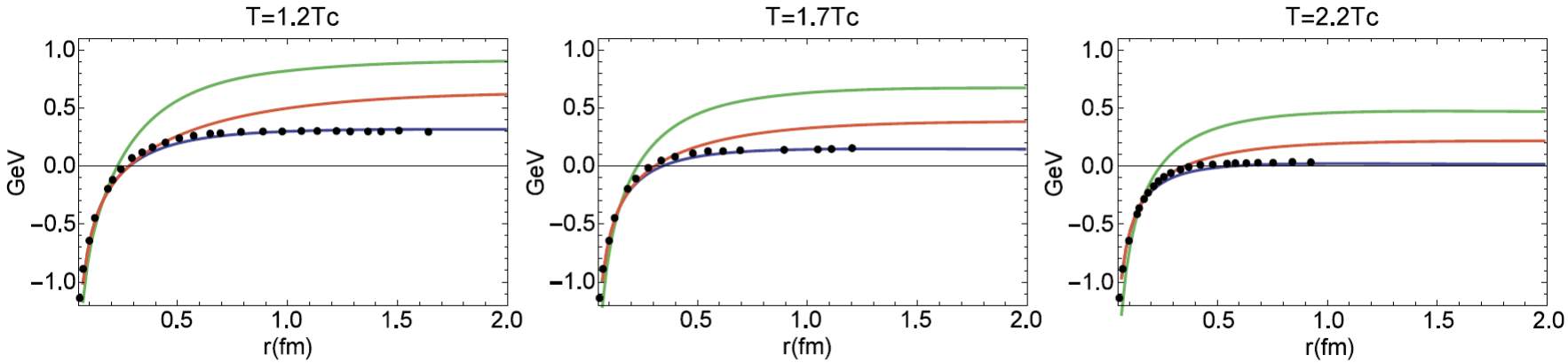
For details, see also the work by K.Hashimoto & D.Kharzeev: Phys. Rev. D90, 125012(2014).

T-matrix Approach

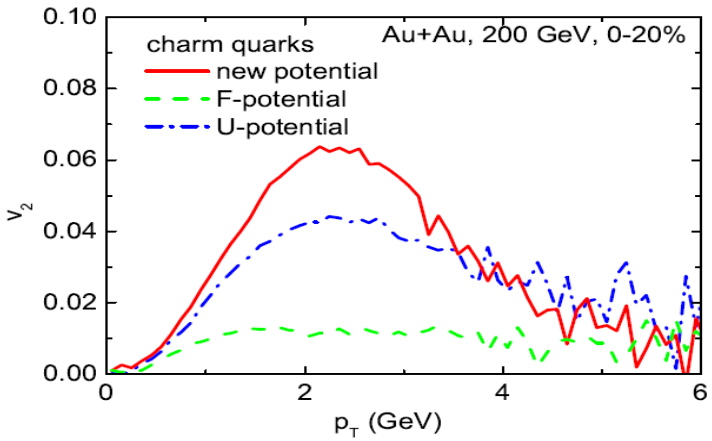
S.Liu & R.Rapp (arXiv: 1501.07892): T-matrix approach with complex potential:



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.***



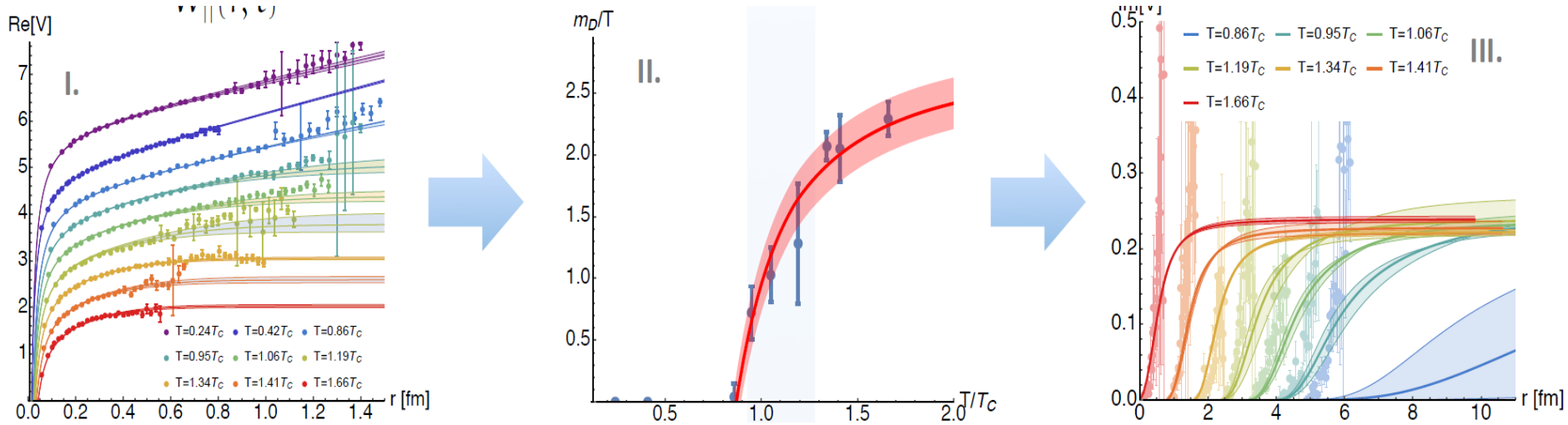
Lattice Simulation

Burnier, Kaczmarek, Rothkopf (arXiv: 1509.07366)

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 $m_D(T)$

A.Rothkopf, Quarkonia, Tuesday AM



Other lattice simulation ***(H.Ohno, Quarkonia, Wednesday AM):***

the limit temperature of J/ψ is 1.25 T_c supports V=F

The complex potential is used to describe quarkonium (ϒ) suppression at LHC ***(G.Wolschin, Quarkonia, Wednesday AM)***

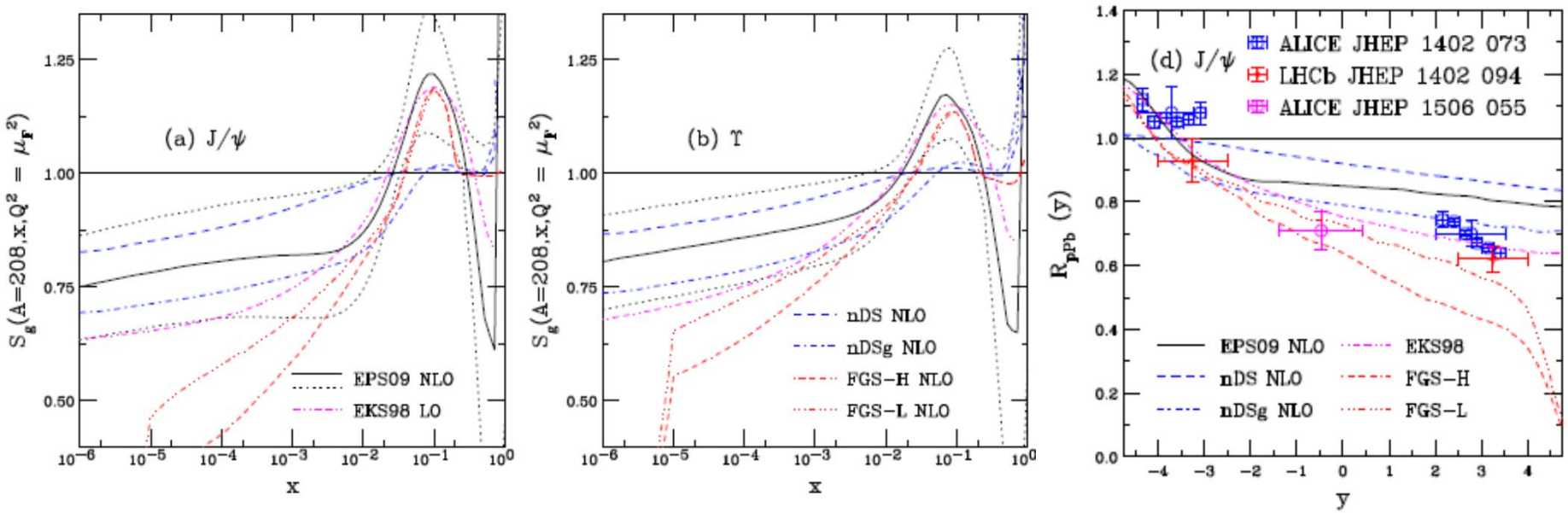
2. Cold Nuclear Matter Effects

Shadowing and Antishadowing in p+A

nuclear shadowing factor

$$R_i^A(x,\mu_F) = \frac{f_i^A(x,\mu_F)}{A f_i(x,\mu_F)}, i = q, \bar{q}, g.$$

R.Vogt, Quarkonia, Monday AM



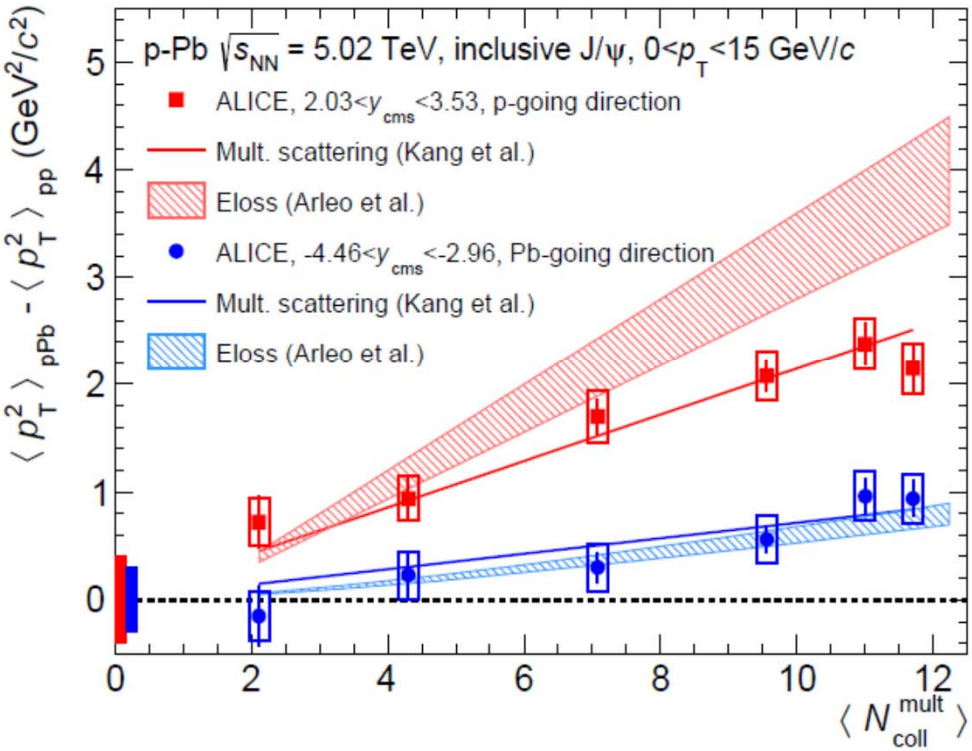
1) the LHC data can be explained by shadowing/antishadowing effect;

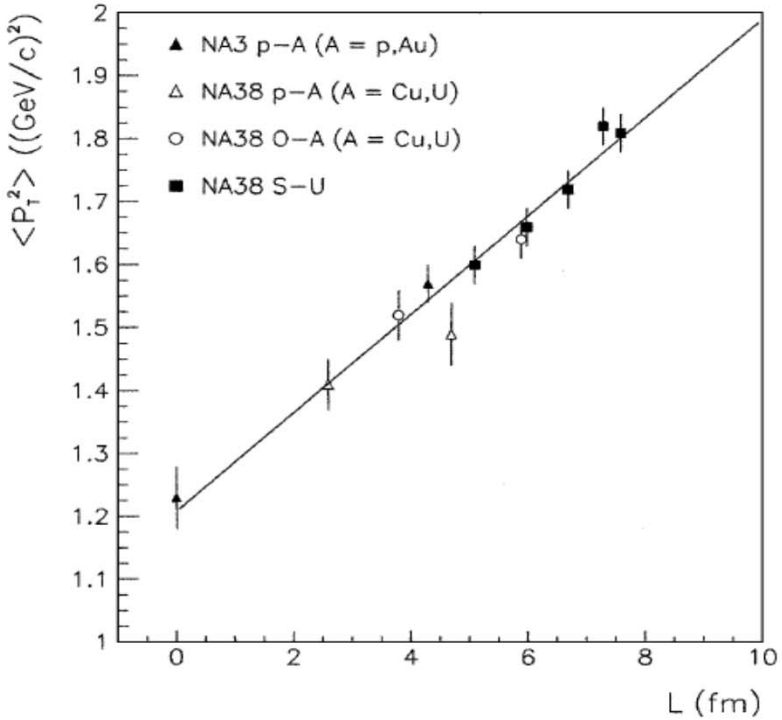
2) but the strong ψ' suppression in central collisions and no obvious centrality dependence of J/ψ suppression (Quarkonia, Q.Hu and M.Leoncino, Monday AM) may need a fireball with $T \lesssim T_c$.

Cronin Effect

Cronin effect:
multiscattering in initial stage broadens the quarkonium transverse momentum distribution

$$\langle p_T^2 \rangle_{J/\psi}^{pA} = \langle p_T^2 \rangle_{J/\psi}^{pp} + \sigma_{gN} \langle p_T^2 \rangle_{gN} \rho_0 L_i,$$





Gerschel & Hufner, 1999

ALICE, arXiv: 1506.08808

3. Extracting QGP Properties

$R_{AA}(\psi)/R_{AA}(D)$

1) $R_{AA} = \frac{N_{AA}(\psi)}{N_{coll}N_{pp}(\psi)}$ *contains both cold and hot nuclear matter effects.*

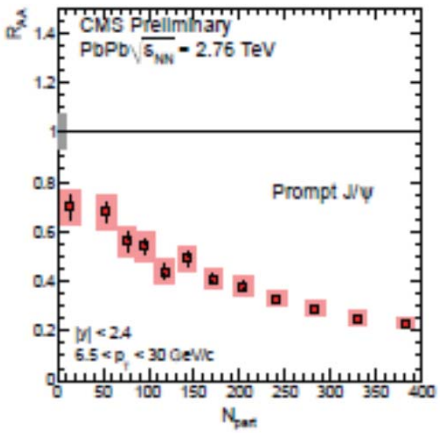
2) $N_{AA}(D) \sim N_c,\ N_{AA}(\psi) \sim \begin{cases} N_c & for\ initial\ production \\ N_c^2 & for\ regeneration \end{cases}$

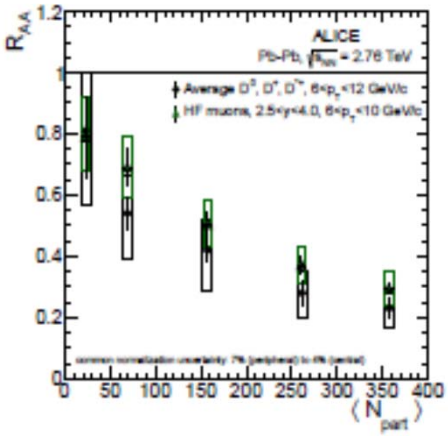
Braun Munzinger & Stachel, 2001

Liu, Qu, Xu, Zhuang, arXiv:0907.2723

⇒ to eliminate the cold effects as possible as one can, one may

need to measure $\begin{cases} \frac{R_{AA}(\psi)}{R_{AA}(D)} & at\ high\ p_t \\ \frac{R_{AA}(\psi)}{R_{AA}^2(D)} & at\ low\ p_t \end{cases}$ *H.Satz, arXiv:1303.3493*





$\frac{R_{AA}(\psi)}{R_{AA}(D)} \sim$ *const at high* p_t,

H.Satz, talk at ECT 2015*

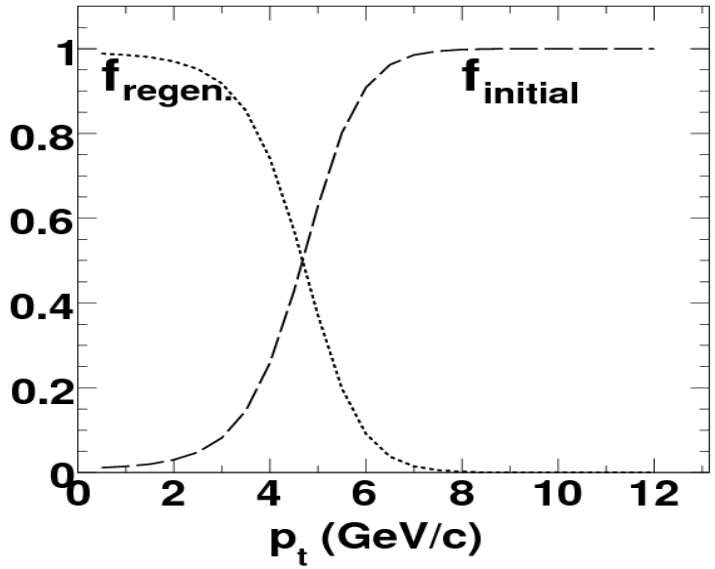
how is $\frac{R_{AA}(\psi)}{R_{AA}^2(D)}$ *at low* p_t *?*

P_t Distribution

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

initially production:
1)Cronin effect in the initial stage,
2)strong low p_t suppression and high p_t leakage effect
⇒ initial p_t broadening

regeneration:
1) coalescence mechanism
2) energy loss induced thermalization
⇒ low p_t regeneration



5.5TeV central Pb+Pb,
Liu et al., 2009

while $f(p)$ is nPDF dependent, the averaged transverse momentum

$$\langle p_t^2 \rangle = \frac{\int p_t^2 f(p_t) dp_t}{\int f(p_t) dp_t}$$

Is not sensitive to the nPDF and controlled by the hot effects.

Quarkonium dynamical evolution:
kinetic approach (R.Rapp et al.)
Schroedinger-Langevin approach (P.Gossiaux, Quarkonia, Wednesday AM)
Langevin approach (J.Blaizot et al., arXiv:1503.03857)
……

Transport Approach

- *QGP evolution* — *Yan et al., 2004, 2006*

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

- *quarkonium motion* $(\Psi = J/\psi,\ \psi',\ \chi_c)$

hot nuclear matter effects: suppression (gluon dissociation) & regeneration (detailed balance)

$$\partial f_\Psi/\partial\tau + \mathbf{v}_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi .$$

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

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

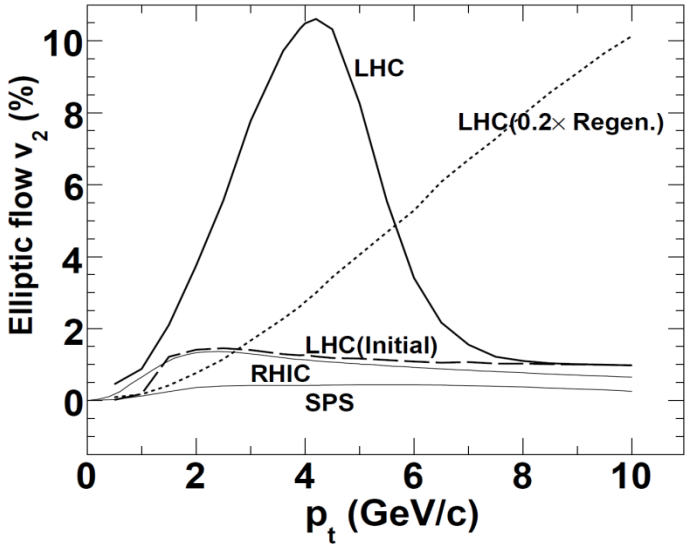
- *analytic solution*

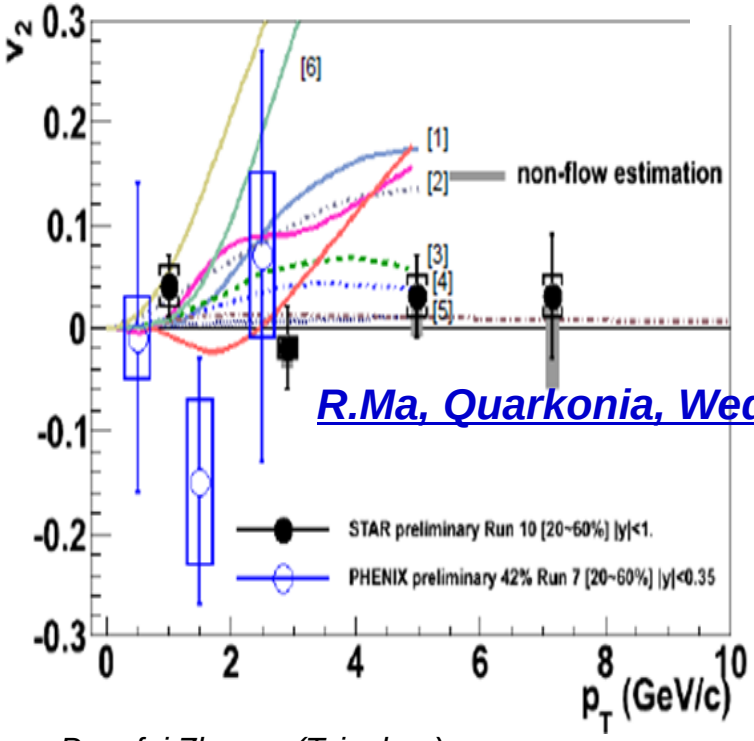
$$f_\Psi(\mathbf{p}_t, \mathbf{x}_t, \tau|\mathbf{b}) = f_\Psi(\mathbf{p}_t, \mathbf{x}_t - \mathbf{v}_\Psi(\tau - \tau_0), \tau_0|\mathbf{b}) e^{-\int_{\tau_0}^{\tau} d\tau' \alpha_\Psi(\mathbf{p}_t, \mathbf{x}_t - \mathbf{v}_\Psi(\tau - \tau'), \tau'|\mathbf{b})}$$
$$+ \int_{\tau_0}^{\tau} d\tau' \beta_\Psi(\mathbf{p}_t,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

cold nuclear matter effects: shadowing and Cronin

Flow

5.5TeV central Pb+Pb, Liu et al., 2009

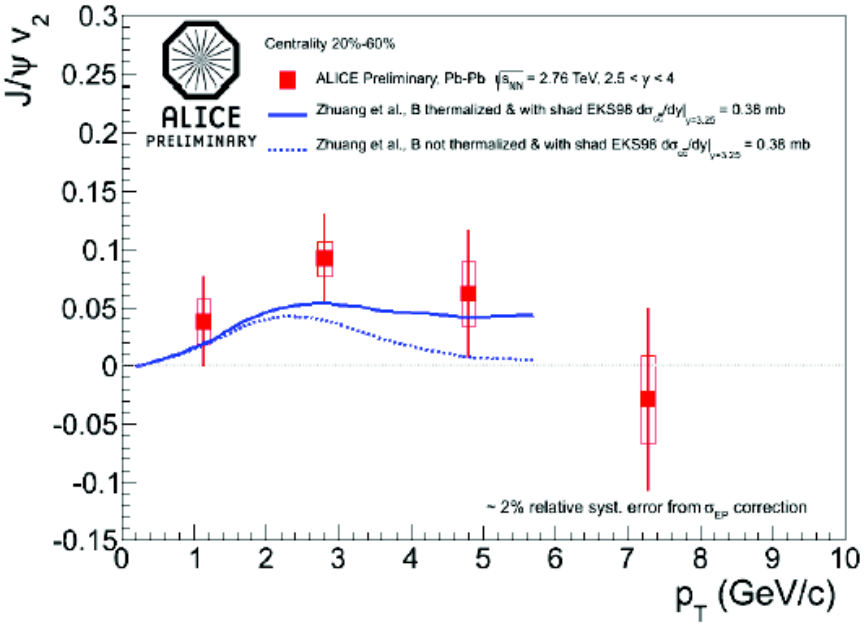




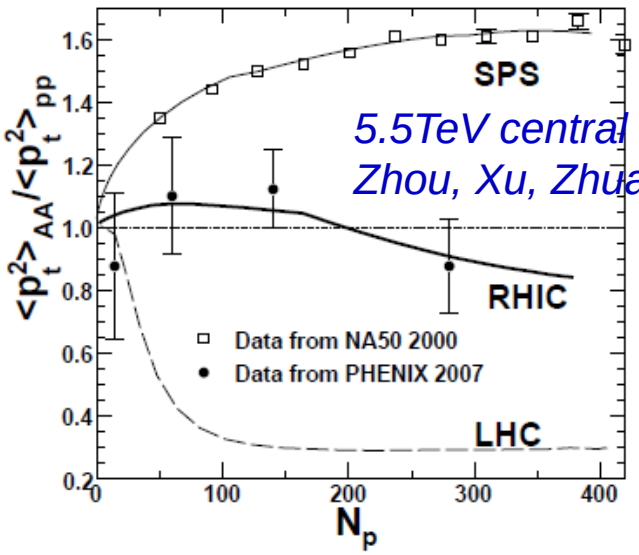
STAR, QM2011
PHENIX, QM2009

R.Ma, Quarkonia, Wednesday AM

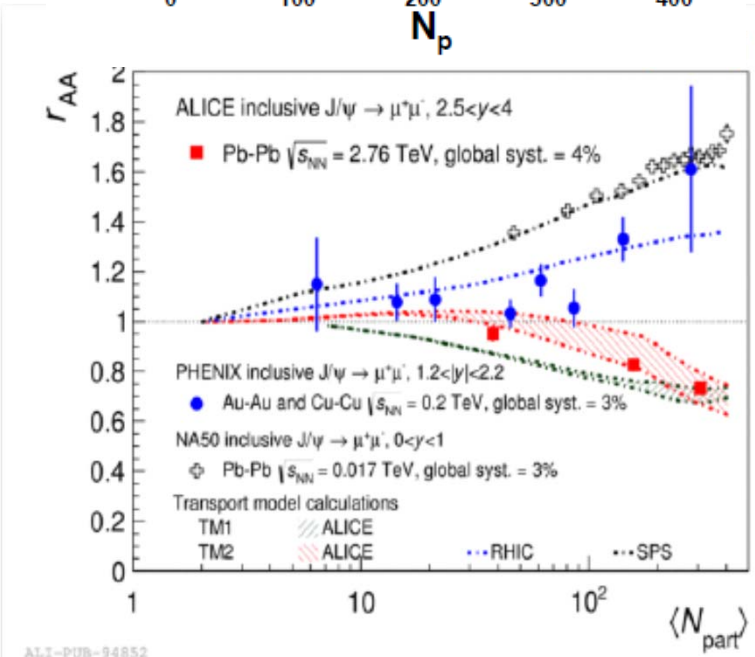
[1] V. Greco, C.M. Ko, R. Rapp,
[2] L. Ravagli, R. Rapp, PLB 65
[3] L. Yan, P. Zhuang, N. Xu, PR
[4] X. Zhao, R. Rapp, 24th WW
[5] Y. Liu, N. Xu, P. Zhuang, Nuc
[6] U. Heinz, C. Shen, priviate c

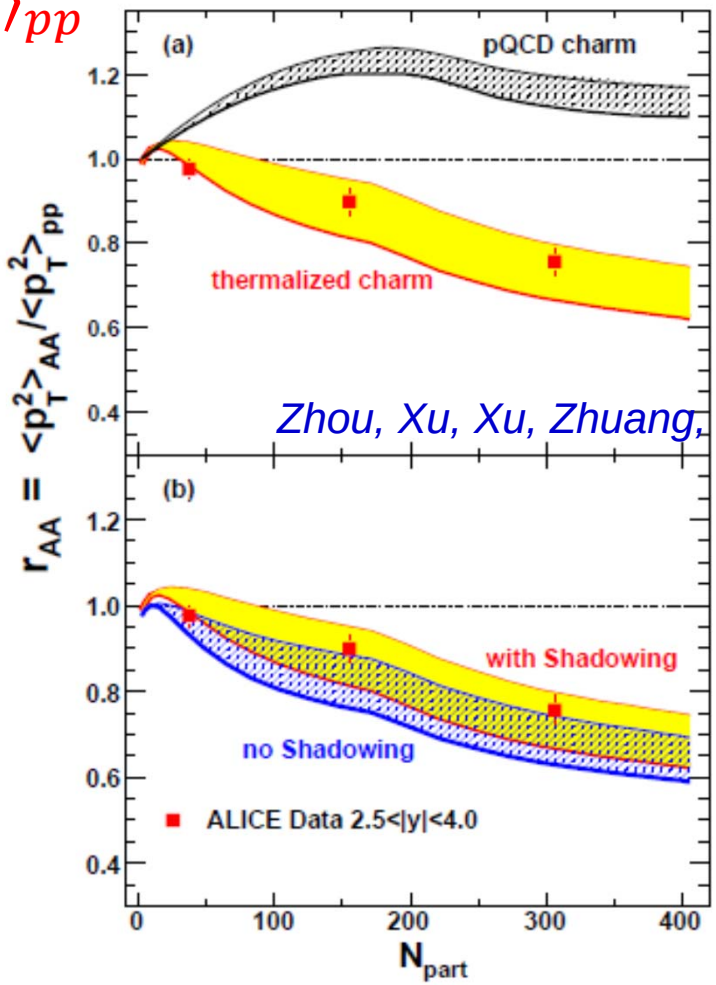


$$r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$$



5.5TeV central Pb+Pb, Zhou, Xu, Zhuang, 2009





Zhou, Xu, Xu, Zhuang, 2014

shadowing effect is partly (largely) eliminated, r_{AA} can be considered as a sensitive thermometer.

H.Costa, Quarkonia, Tuesday AM

4. Ω_{ccc} and Ξ_{cc} in A+A

Motivation

1) Ω_{ccc} *and* Ξ_{cc} *can hardly be produced in pp collisions,* $\sigma(\Omega_{ccc}) = 0.06 \sim 0.13$ *nb at 7 GeV and 0.1 ~ 0.2 nb at 14 GeV (J.D.Bjorken 1986 and Y.Chen, 2011) and* $\sigma(\Xi_{cc}) \sim 10$ *nb at 1.8 TeV (Phys.Rev.Lett.89 (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 increase 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) *The Wigner function (the coalescence probability) for* Ω_{ccc} *and* Ξ_{cc} *can be calculated via Schroedinger equation.*

Three-body Schroedinger Equation

He et al., arXiv: 1409.1009

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

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

hyperspherical method (widely used in atomic physics):

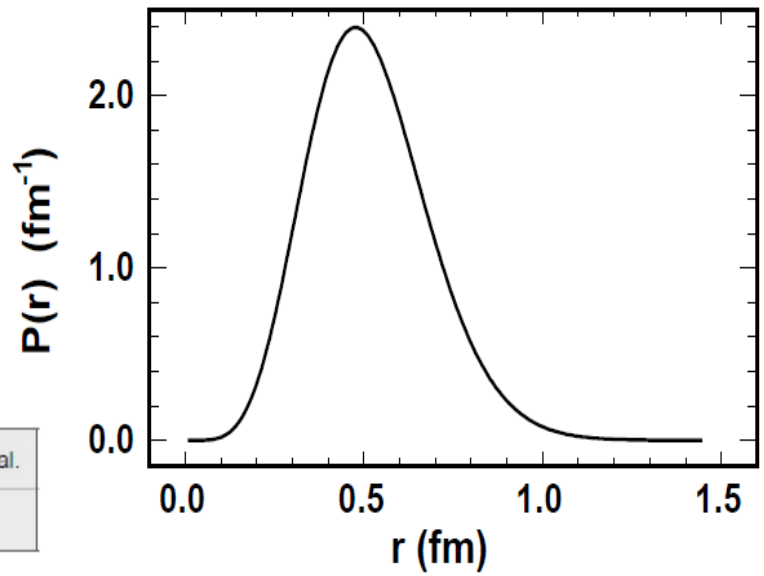
$$v(r) = \frac{8}{\pi}\int_0^{\pi/2}\sum_{i<j} V_{cc}\left(\sqrt{2}r\sin\alpha\right)\sin^2\alpha\cos^2\alpha d\alpha$$

$m_\Omega = 4.75$ *GeV* *(4.8 GeV from LQCD)*

$\epsilon_\Omega = 900\ MeV$

$\langle r_\Omega\rangle = 0.5\ fm \simeq \langle r_{J/\psi}\rangle$

$P(r)=|\varphi(r)|^2 r^5$



For Ξ_{cc}, we take the first order relativistic correction,

Ξ_{cc}	our work	Martynenko	D.Ebert et.al.	R.Roncaglia et.al.
mass(GeV)	3.64	3.51	3.62	3.66

Wigner Function and Coalescence

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

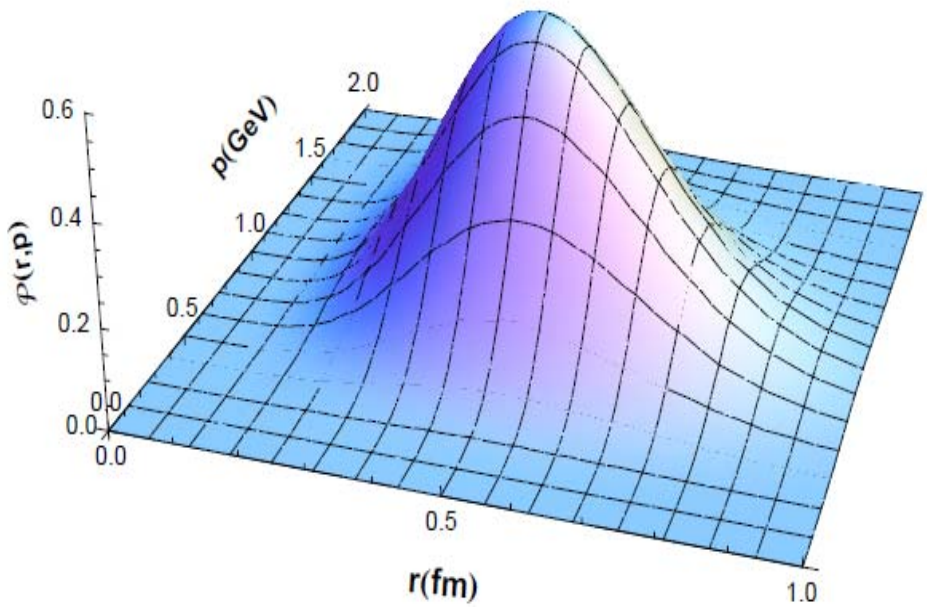
$$\frac{dN}{d^3\mathbf{P}} = C\int \frac{d^3\mathbf{R}}{(2\pi)^3}\int \frac{d^3\mathbf{r}_x d^3\mathbf{r}_y d^3\mathbf{p}_x d^3\mathbf{p}_y}{(2\pi)^6} f(r_1,p_1)f(r_2,p_2)f(r_3,p_3)W(\mathbf{r}_x,\mathbf{r}_y,\mathbf{p}_x,\mathbf{p}_y)$$

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

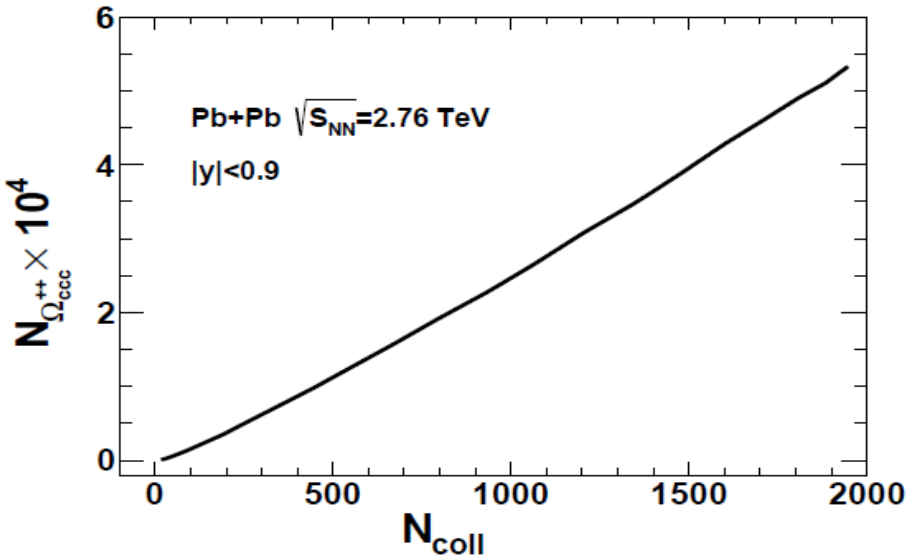
$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int_\Sigma \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\int \frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6} f(r_1,p_1)f(r_2,p_2)f(r_3,p_3)W(\mathbf{r}_x,\mathbf{r}_y,\mathbf{p}_x,\mathbf{p}_y)$$

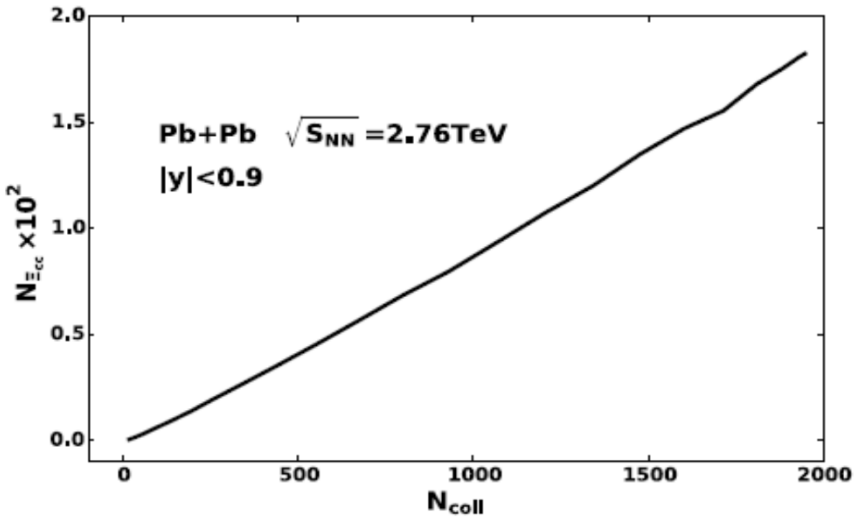
$$f(\vec{r},\vec{p}\,) = \frac{1}{e^{p^\mu u_\mu/T}+1}$$

$$\mathcal{P}(r,p) = \frac{1}{24\pi} r^5 p^5 \int_0^\pi W(r,p,\theta)\sin^4\theta d\theta$$



Significant Enhancement in A+A





The magnitude is consistent with the statistical model estimation (discussion with Peter Braun-Munzinger)

effective cross section per binary collision:

$$\sigma_\Omega \equiv \frac{N_\Omega}{N_{coll}\Delta\eta}\sigma_{pp} \qquad \sigma_{pp} = 62\ mb \ \rightarrow \quad \sigma_\Omega = 9\ nb$$

for Ξ_{cc}, $\sigma_\Xi = 320\ nb$

in comparison with the cross section in p+p, the effective cross section in A+A increases at least 2 orders for Ω_{ccc} and 1 order for Ξ_{cc}.

5. Summary

1) *A big progress in understanding the (complex) heavy quark potential.*

2) *Cold medium effects dominate heavy flavors and quarkonia in p+A, but there is already some hot medium effect.*

3) *To extract QGP properties, we need to focus on those observables where cold effects can be largely eliminated.*

4) *Quarkonium* v_2 *and* $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$ *can distinguish hot mediums at SPS, RHIC and LHC：from pt broadening at SPS to pt suppression at LHC.*

5) *It is most probable to discover doubly and triply charmed baryons in A+A, and the discovery is a unique signature of QGP formation.*

6) *Still some puzzles, like double ratio* ψ'/ψ *and excess of low* p_t *J/*ψ*. We need more precise data and more theoretical works.*

Backup

Heavy Quark Thermal Production

Zhou et al., 2015

assuming thermalized charm quark distribution:

$$f_c(x,q) \sim \frac{1}{e^{q^\mu u_\mu/T}+1}, \quad u_\mu(x) \text{ and } T(x) \text{ determined by hydrodynamics}$$

heavy quark equation of motion

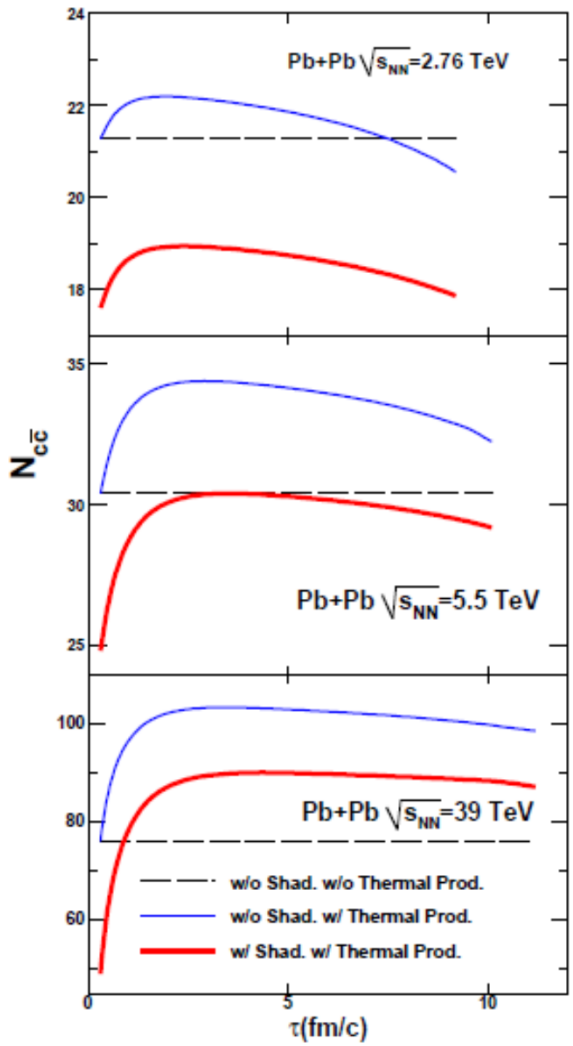
$$\partial_\mu(f_c u^\mu) = R_{gain} - R_{loss}$$

$$f_c(\tau_0) = \frac{T_A(\vec{x})T_B(\vec{x}-\vec{b})\cosh(\eta)}{\tau_0}\frac{d\sigma_{pp}^{c\bar{c}}}{d\eta}$$

$$R_{gain} = R_{gg\to c\bar{c}} + R_{q\bar{q}\to c\bar{c}}$$

(*Nason, Dawson, Ellis, 1988*)

R_{loss}: *determined by detailed balance with* R_{gain}



thermal production in Pb+Pb becomes remarkable at 5.5 TeV and 39 TeV.

Dissociation and Regeneration Rates

$$J/\psi\ (\Upsilon) + g \rightarrow Q + \bar{Q}$$

- ***gluon dissociation cross section calculated by OPE (****Bhanot, Peskin,1999****):***

$$\sigma(p_\psi, p_g)$$

- ***at finite temperature, we use the classical relation***

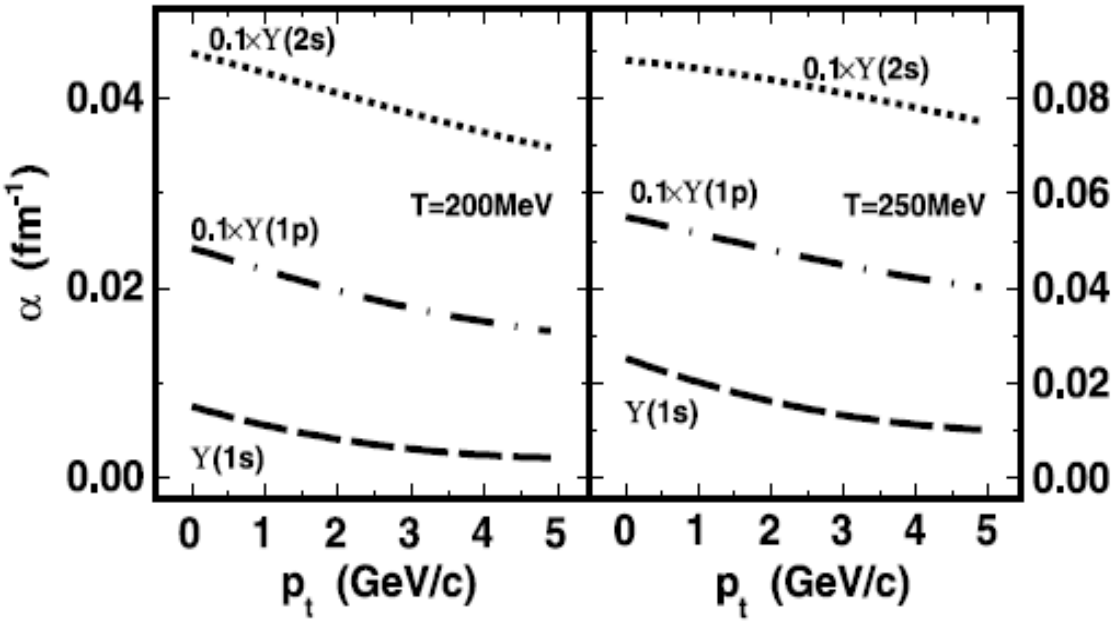
$$\sigma(p_\psi, p_g, T) = \frac{\langle r^2 \rangle (T)}{\langle r^2 \rangle (0)} \sigma(p_\psi, p_g)$$

$$\langle r^2 \rangle (T)$$

potential model

Digal, Kaczmarek, Karsch, Satz, 2005

- ***ϒ dissociation rate***

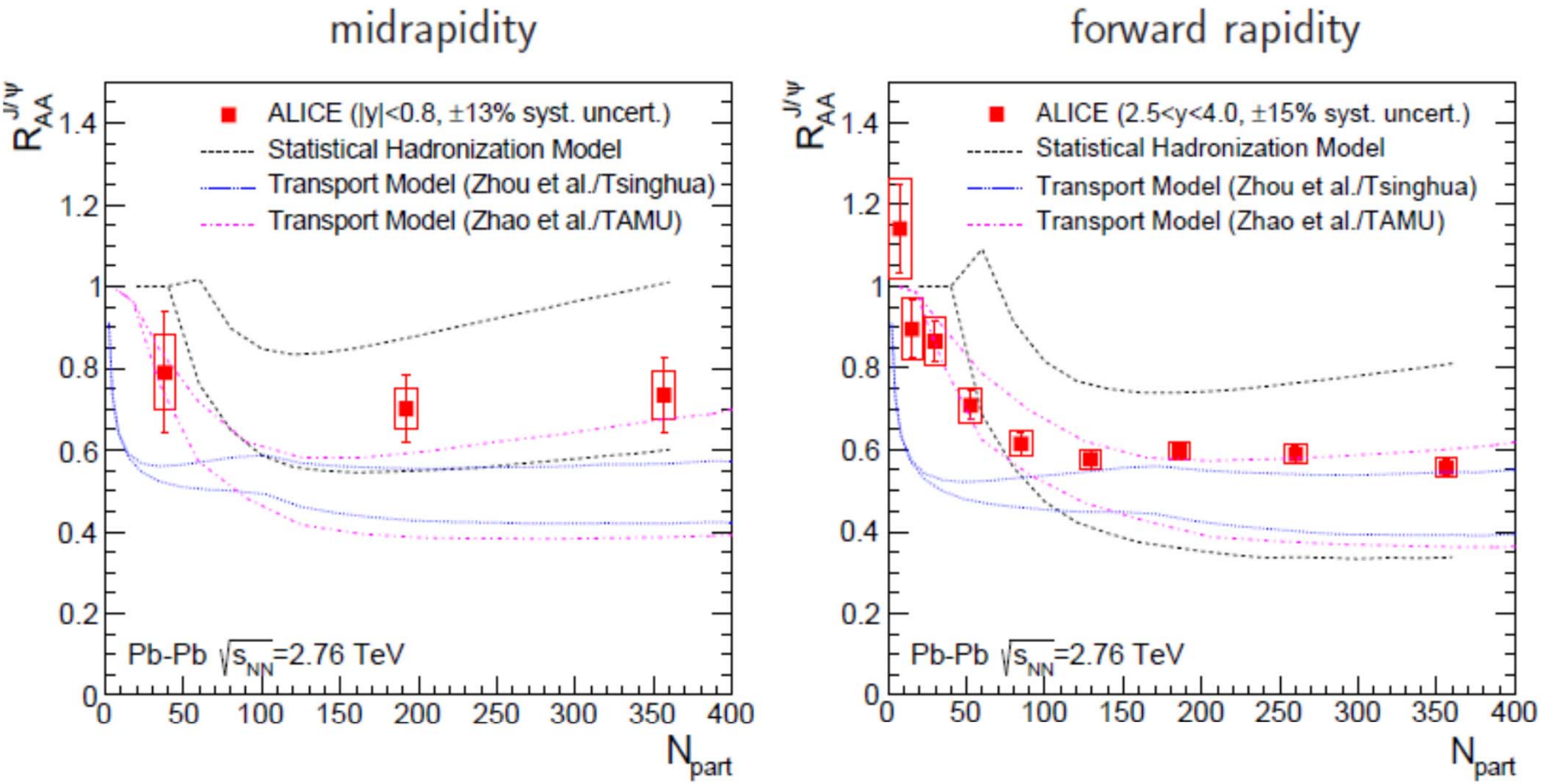


Liu, Chen, Xu, Zhuang, 2011

- ***regeneration rate is determined by the detailed balance***

Model comparisons for the LHC

A.Andronic@GSI.de



Both model categories reproduce the data ...$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ values rather different:

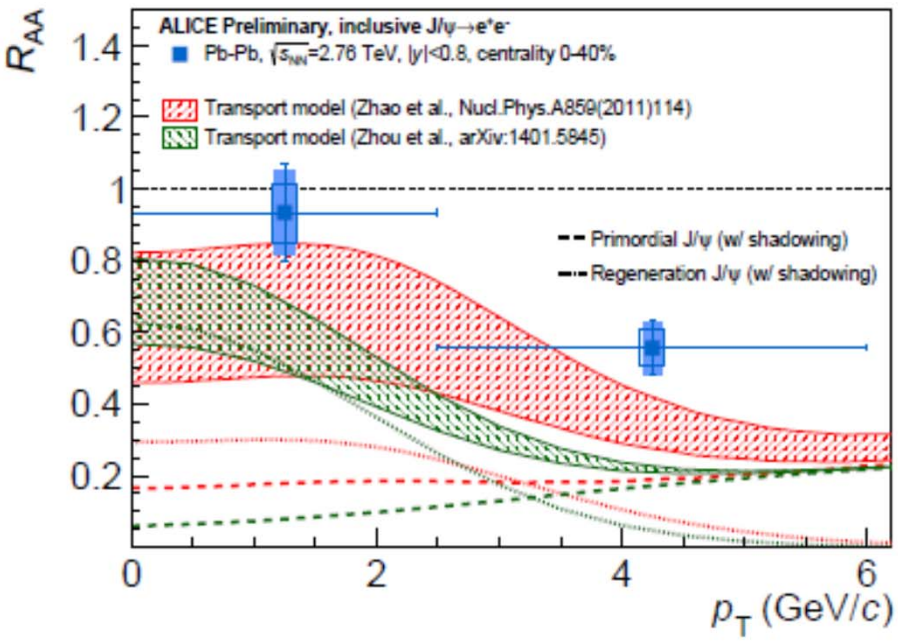
midrapidity: Stat. Hadr.: 0.3-0.4 mb

Transport: 0.5-0.75 mb (TAMU), 0.65-0.8 mb (Tsinghua)

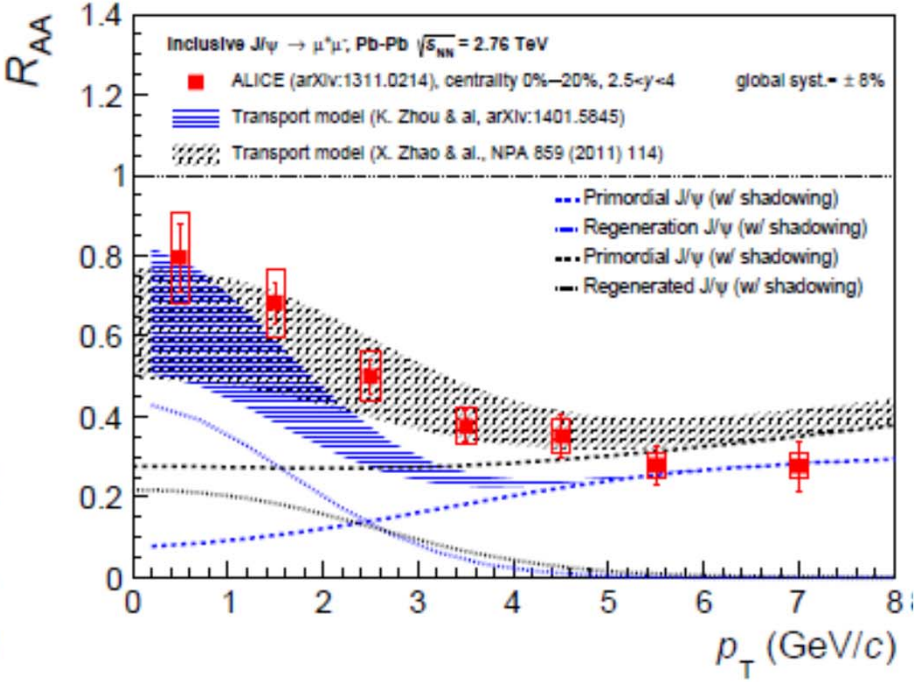
J/ψ vs. p_T - data and models

A.Andronic@GSI.de

midrapidity



forward rapidity



(re)generation models describe the LHC data well ...with a healthy fraction of J/ψ newly produced

ALICE, arXiv:1311.0214 (& prelim., Book, HF 4)

decay modes of Ω_{ccc}

Decay through weak interaction, for instance

nonleptonic cascade decay mode (Chen 2011):

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

semileptonic decay mode (Bjorken, 1986):

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

Ξ_{cc} Decay mode and experiment status

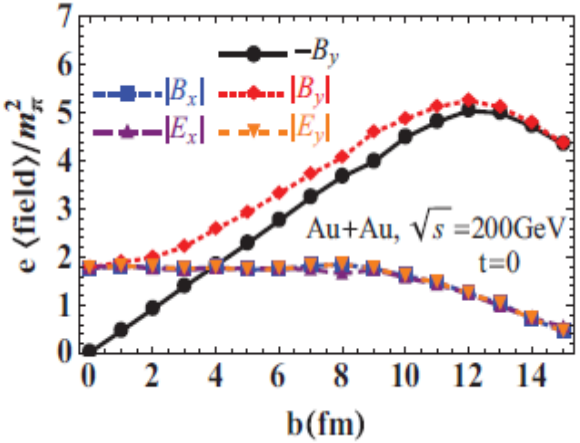
- $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ (Observation reported by SELEX 2003)
- $\Xi_{cc}^{+} \to D^{0} p K^{-} \pi^{+}$ (Searched by Belle2006)
- $\Xi_{cc}^{+} \to D^{+} p K^{-}$ (Searched by FOCUS 2003, Belle2006)
- $\Xi_{cc}^{+} \to \Xi_c^{+} \pi^{+} \pi^{-}$ (Searched by BarBar2006)
- $\Xi_{cc}^{+}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

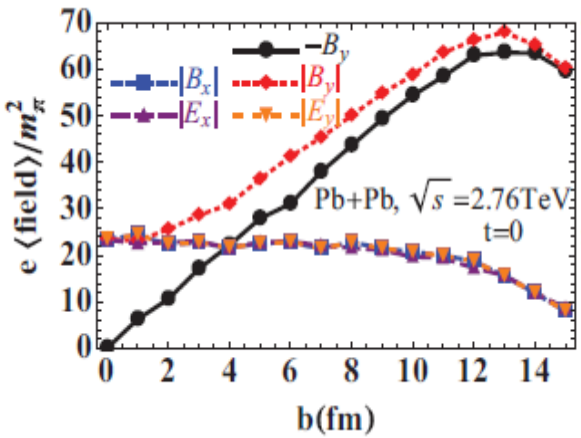
"The improved LHCb and Belle II (2019) is promising in observing Ξ_{cc} "

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

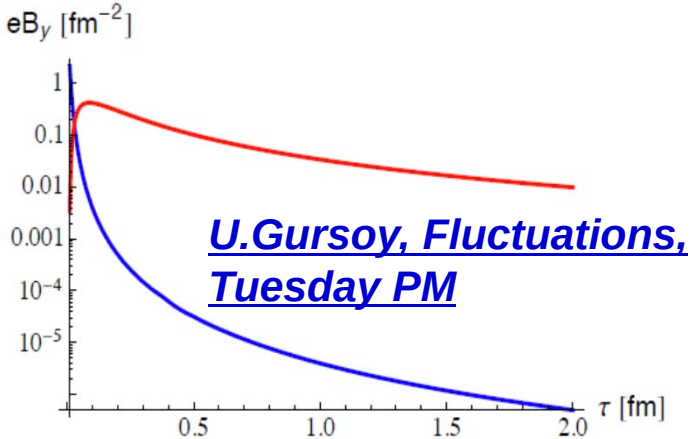
Probing the strongest field with J/ψ

Deng and Huang, 2012:





Gursoy, Kharzeev, and Rajagopal, 2014:



U.Gursoy, Fluctuations, Tuesday PM

the strongest magnetic field in nature but lasts ~0.1 fm/c, however, inducting medium may lead to a long life time.

ideal probes of the initial B field:

- *created in the early stage,*
- *sensitive to the B field,*
- *not affected by the later hot medium.*

⇒ high p_t J/ψ is such an ideal probe !

idea: the evolution of a $c\bar{c}$ state $|c\bar{c}\rangle$, $i\frac{\partial}{\partial t}|c\bar{c}\rangle = \hat{H}(B(t))|c\bar{c}\rangle$,

the B field leads to an anisotropic formation probability $|\langle\Psi|c\bar{c}\rangle|^2$.

Schroedinger Equation

Guo, Shi, Xu, Xu, Zhuang, 2015

$$\hat{H}(r,R,t) = \frac{\left(\vec{p}_c - q_c\vec{A}_c\right)^2}{2m_c} + \frac{\left(\vec{p}_{\bar{c}} - q_{\bar{c}}\vec{A}_{\bar{c}}\right)^2}{2m_c} - \frac{(q_c\vec{s}_c + q_{\bar{c}}\vec{s}_{\bar{c}})\cdot\bar{B}}{m_c} + V_{c\bar{c}}(r) = \hat{H}_0 + \hat{H}_B$$

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

$$\hat{H}_B = -\frac{(q_c\vec{s}_c + q_{\bar{c}}\vec{s}_{\bar{c}})\cdot\bar{B}}{m_c} - \frac{q_c}{2m_c}\left(\vec{P}_{ps}\times\vec{B}\right)\cdot\vec{r} + \frac{q^2}{4m_c}\left(\vec{B}\times\vec{r}\right)^2$$

magnetic coupling is much larger than strong coupling $\left|\frac{q_c p_t B}{2m_c}\right| \gg \sigma$ ***at high*** p_t.

expanding Φ *in terms of the charmonium states:*

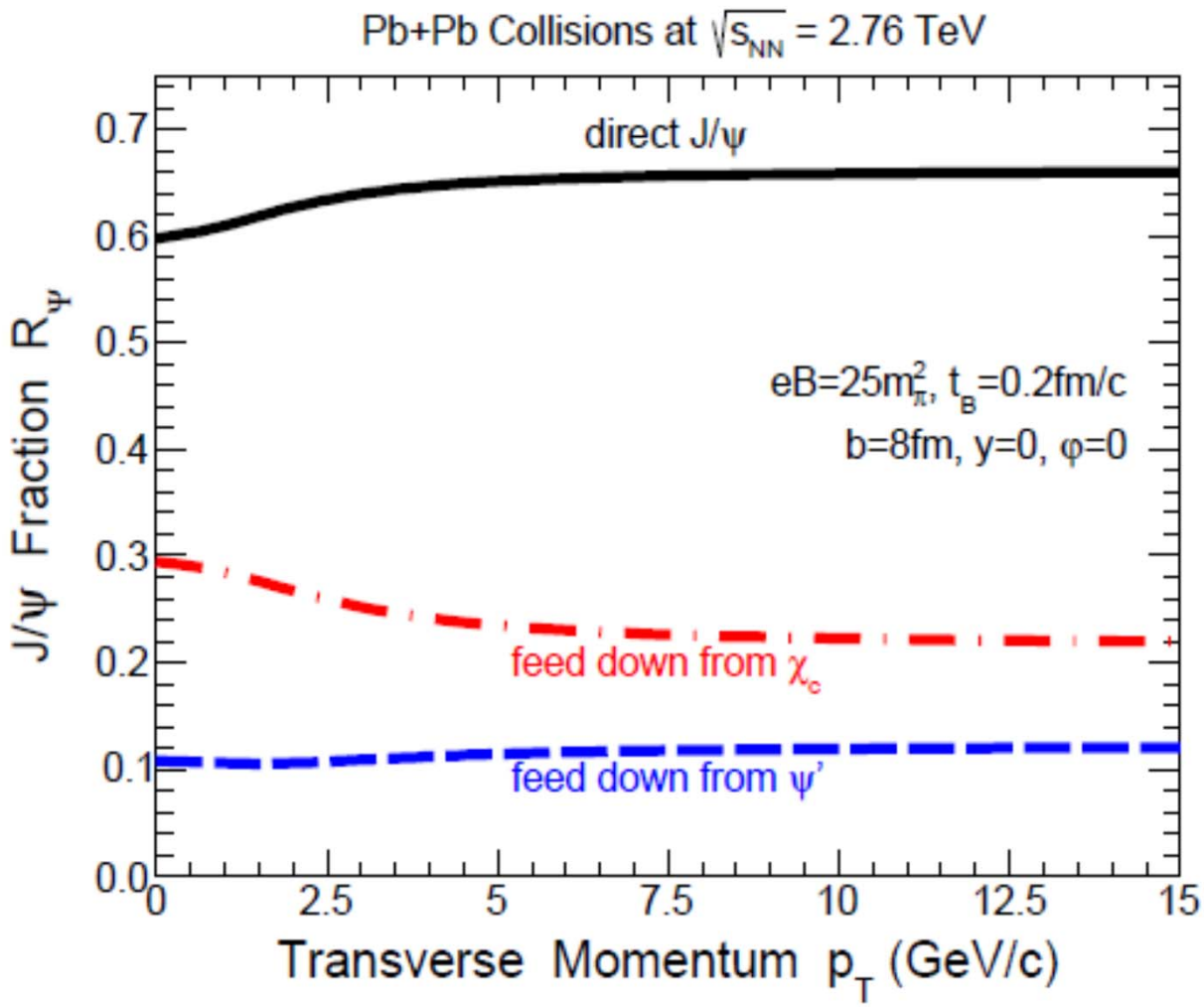
$$\Phi\left(\vec{P}_{ps},\vec{R},\vec{r},t\right) = \frac{1}{\sqrt{2\pi}} e^{i\left(\vec{P}_k\cdot\vec{R} - \frac{\vec{P}_{ps}t}{4m_c}\right)} \sum_\psi C_\psi\left(\vec{P}_{ps},t\right) e^{-iE_\psi t}\psi(\vec{r}),$$

the probability for the $c\bar{c}$ *to be in the charmonium state* $|\psi\rangle$ *is* $\left|C_\psi\left(\vec{P}_{ps},t\right)\right|^2$

$$B(r,t) = \begin{cases} B\vec{e}_y, & 0 < t < t_B \quad and \quad \dfrac{x^2}{(R_A - b/2)^2} + \dfrac{y^2}{(b/2)^2} + \dfrac{\gamma^2 z^2}{(b/2)^2} < 1 \\ 0, & otherwise \end{cases}$$

$b = 8\,fm$, $R_A = 6.6\,fm$, $\mathrm{eB} = 25 m_\pi$, $t_B = 0.2 fm$ at LHC

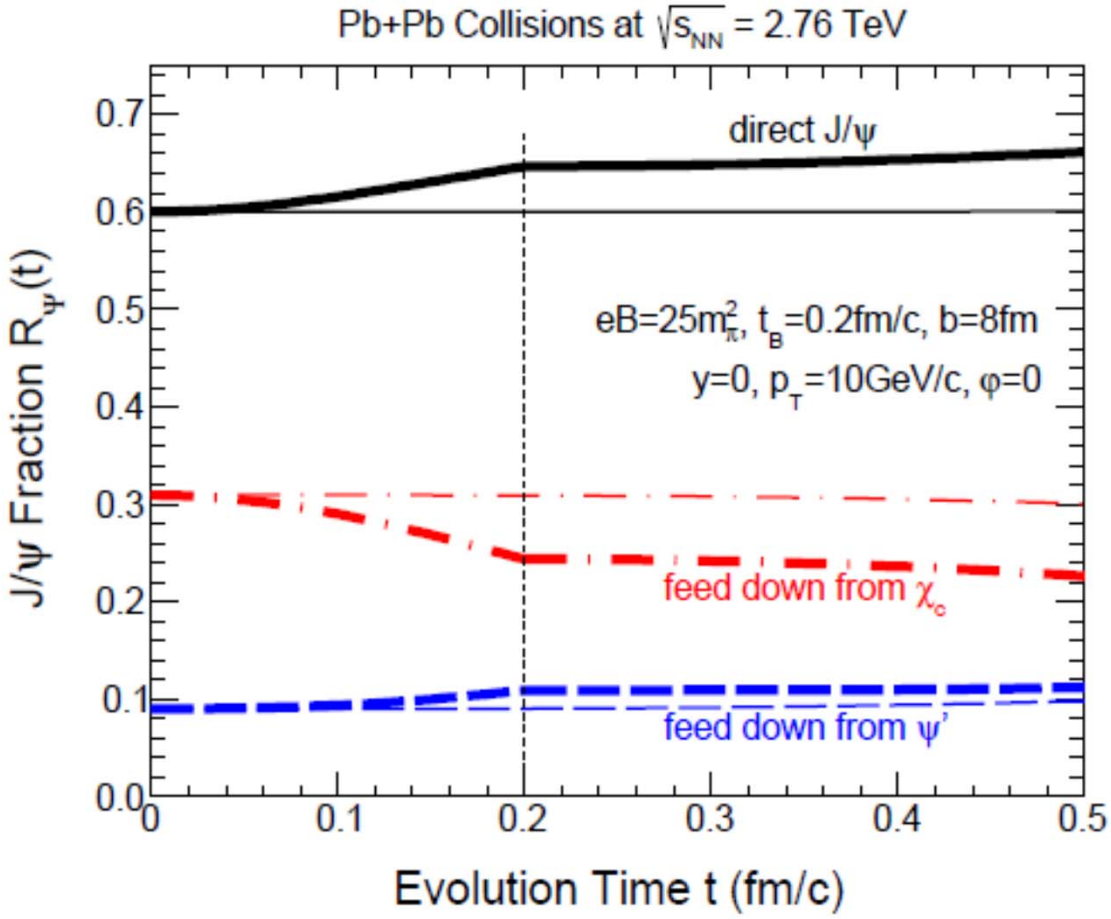
P_t dependence



strong enhancement or suppression at high P_t, due to the Lorentz force.

Time evolution

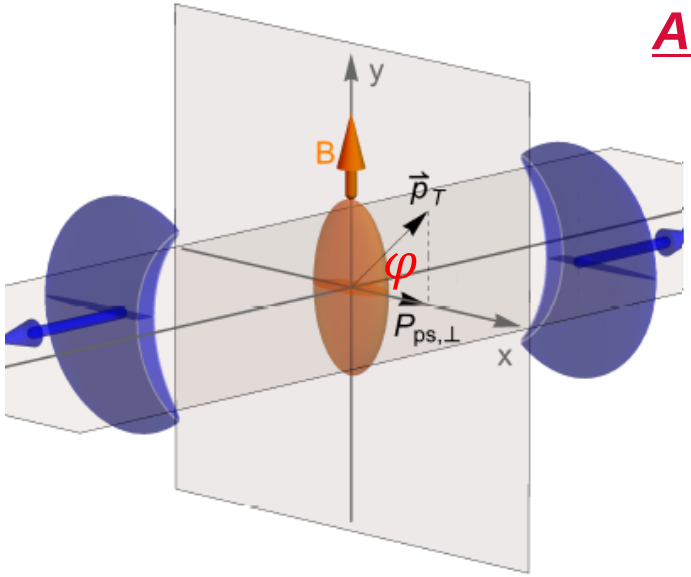
$$R_\Psi(t) = \frac{|C_\Psi(t)|^2 \mathcal{B}(\Psi \to J/\psi)}{\sum_\Psi |C_\Psi(t)|^2 \mathcal{B}(\Psi \to J/\psi)}$$

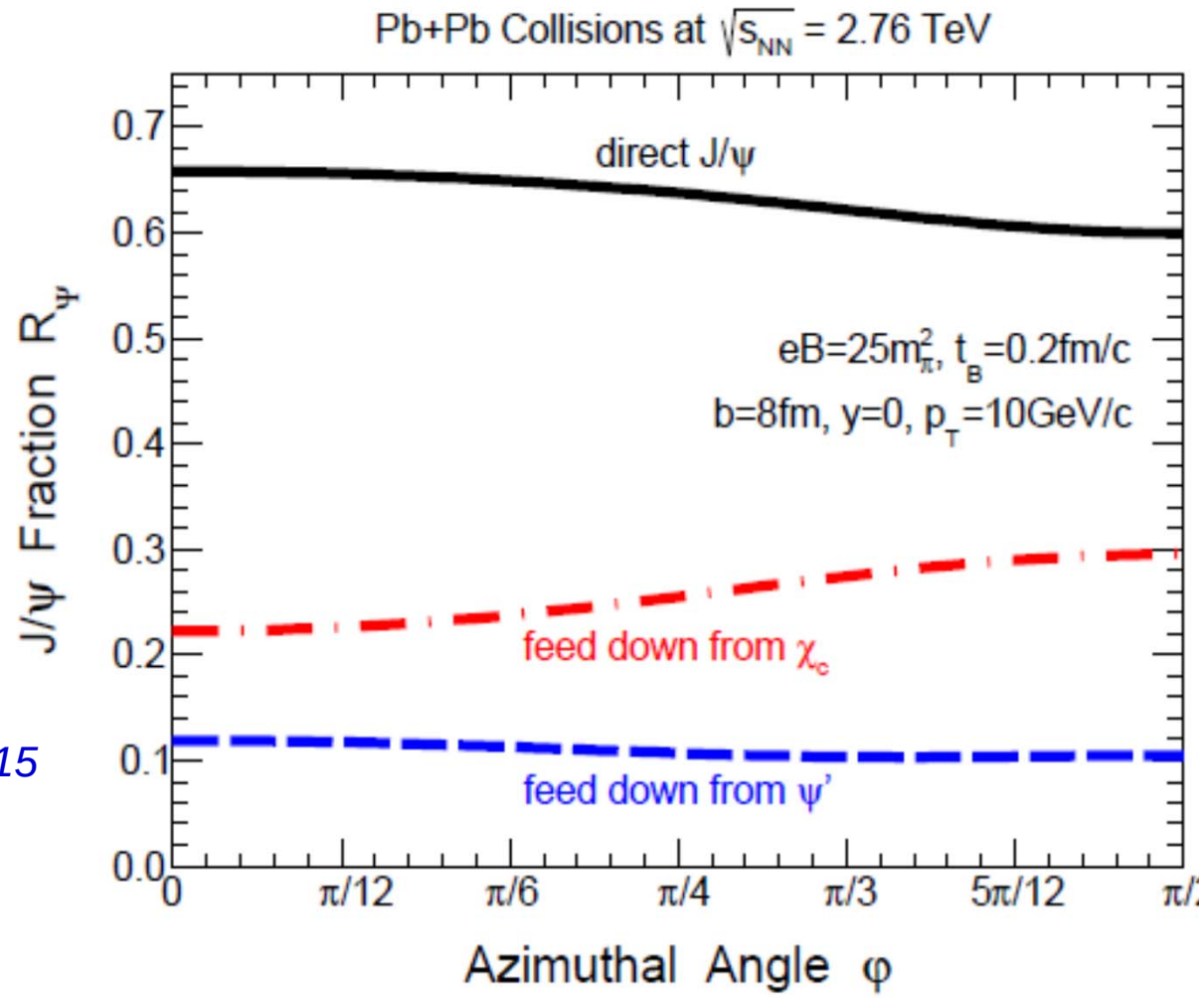


Guo, Shi, Xu, Xu, Zhuang, 2015

ψ' and J/ψ enhancement by 10% and χ_c suppression by 23%

Anisotropic production

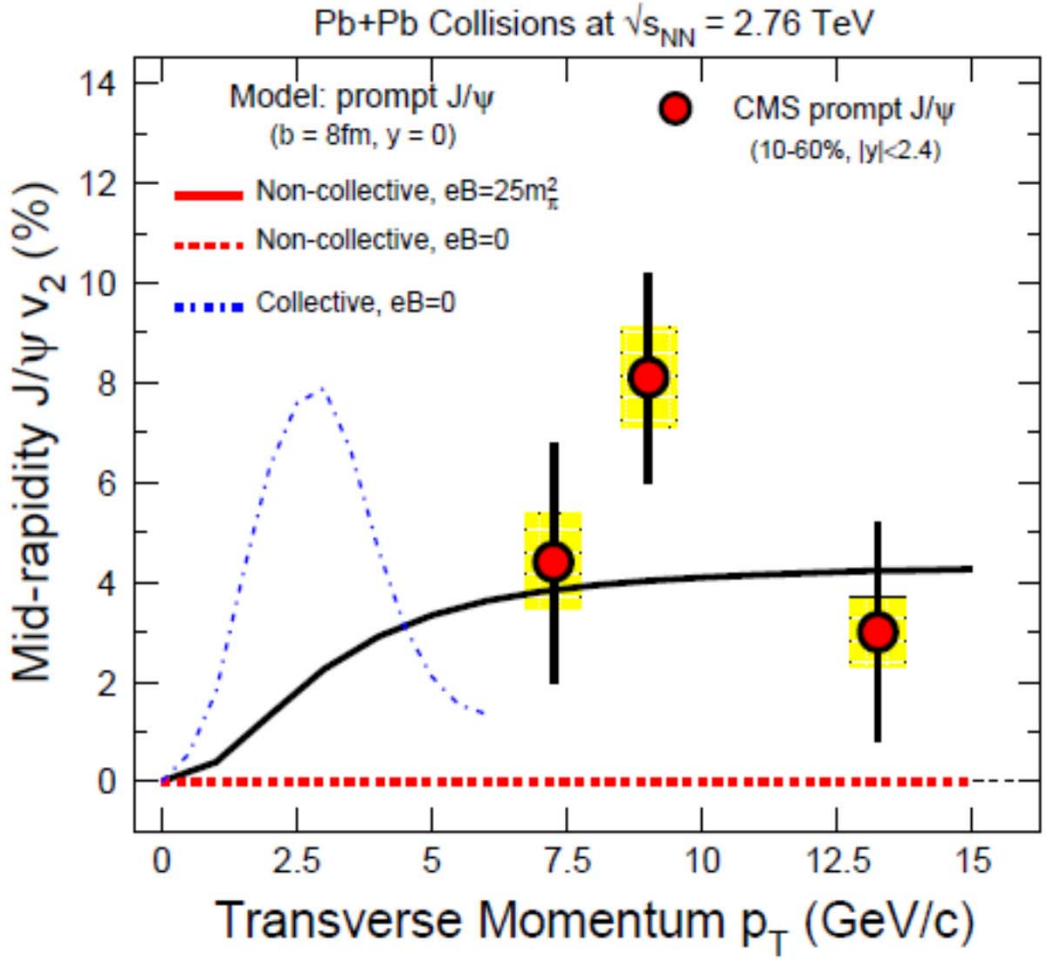




Guo, Shi, Xu, Xu, Zhuang, 2015

1) ***anisotropic charmonium formation in the B field.***
2) ***strong enhancement or suppression at $\varphi = 0$, but almost no change at $\varphi = \pi/2$.***

Non-collective v_2



X.Guo, Poster 0609

Non-collective v_2 at high P_t, created by the B field