Quarkonium and the Properties of QGP

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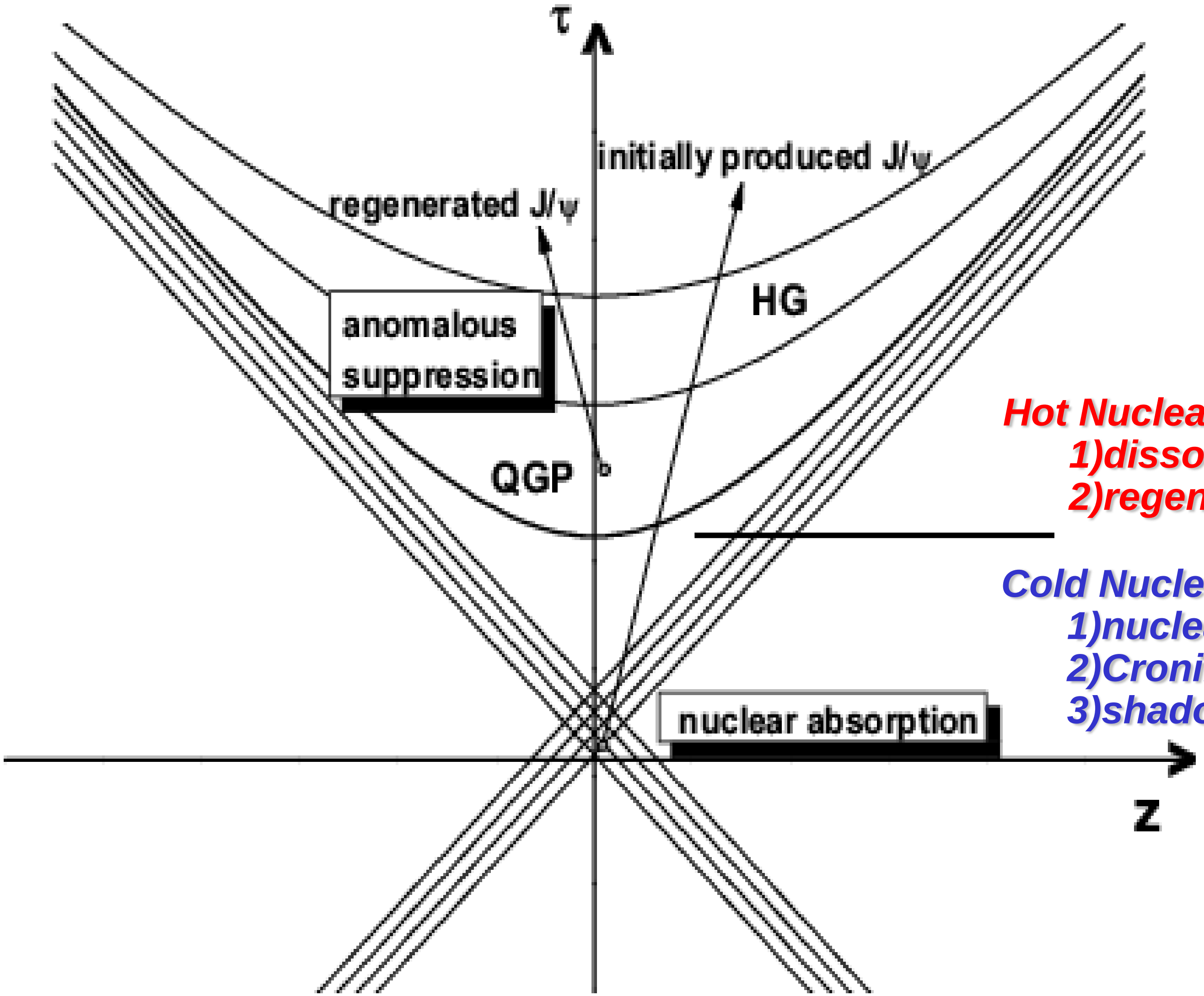
1) Dissociation versus Regeneration
2) Transverse Momentum Distribution

Collaboration with Yunpeng Liu, Nu Xu, Kai Zhou and Xianglei Zhu

Erice School of Nuclear Physics, September 22, 2012

The Quarkonium Motion in Hot Medium



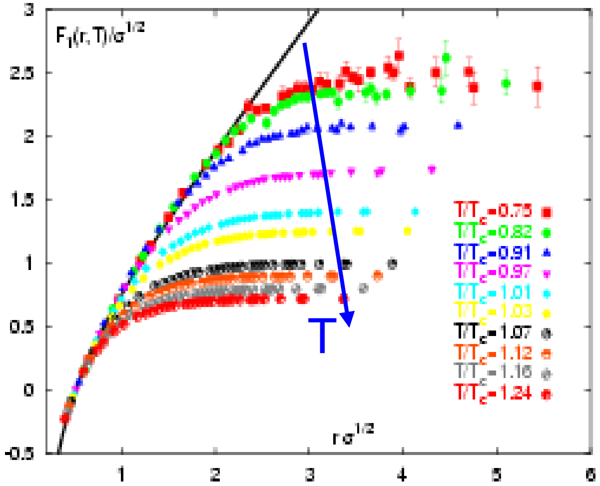
Hot Nuclear Matter effects:
- 1)dissociation
- 2)regeneration

Cold Nuclear Matter effects:
- 1)nuclear absorption
- 2)Cronin effect
- 3)shadowing effect

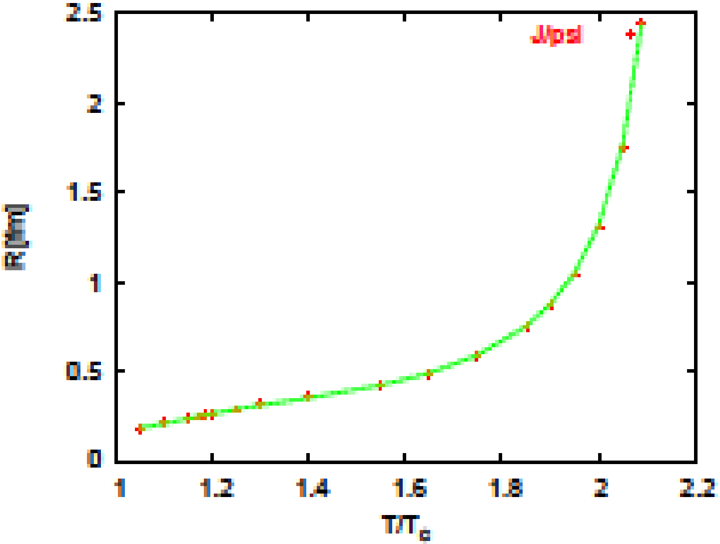
CNM:
R.Vogt, Phys.Rept.310, 197(1999)
C.Gerschel, J.Hufner, Annu.Rev.Nucl.Part.Sci. 49, 225(1999)

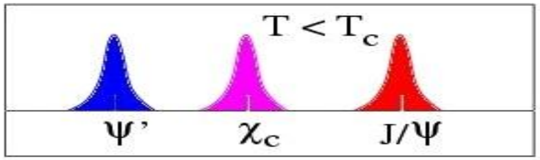
Quarkonium Dissociation

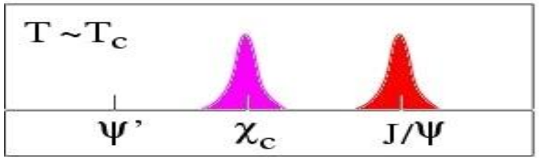
Kaczmarek et al., hep-lat/0312015

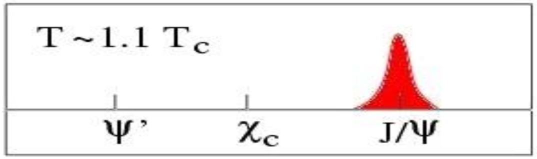


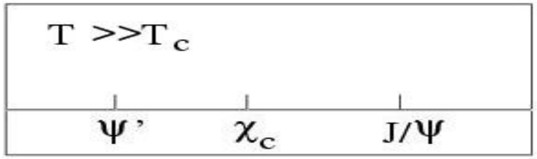
Schroedinger equation at finite T:











Dissociation temperature:

$$\langle r \rangle (T_D) \to \infty$$

H.Satz et al 1996

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

sequential suppression

Competition between Dissociation and Regeneration

there are two sources for quarkonium production in HI:
initial production and regeneration
both suffer from the dissociation

important regeneration at RHIC and LHC:

in QGP

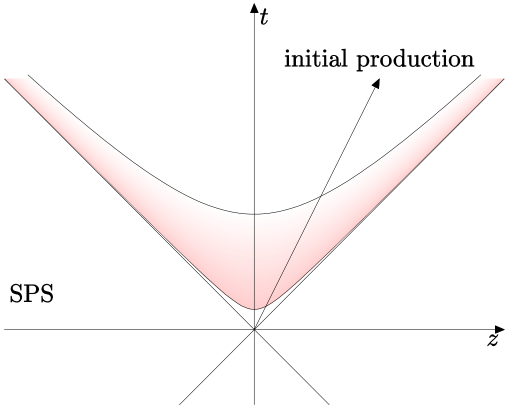
$$c+\overline{c}\to J/\psi+g$$

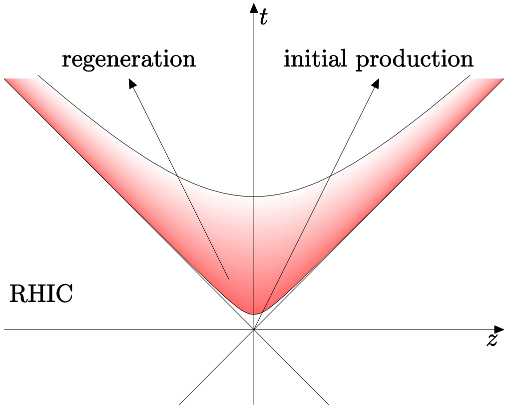
in hadron gas

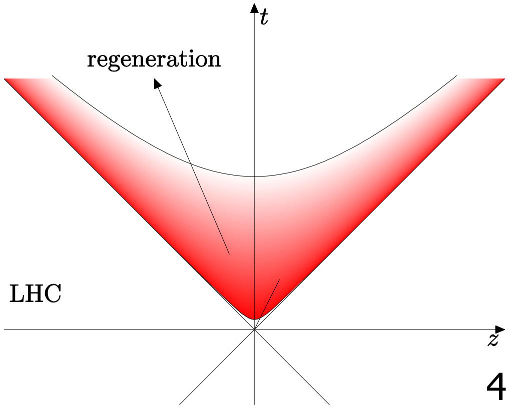
$$D+\bar{D}\to J/\psi+\text{ mesons}$$

PBM and Stachel, 2000
Thews, Schroedter, Rafelski, 2001
Grandchamp, Rapp, Brown, 2004
Gorenstein, Kostyuk, Stoecker, Greiner, 2001
Greco, Ko, Rapp, 2004, ……

SPS: dominant dissociation
RHIC: strong competition between dissociation and regeneration
LHC: dominant regeneration







A Full Transport Approach for Quarkonia in HI

Y.Liu, K.Zhou, N. Xu, PZ, 2005-2012

to extract medium properties from quarkonium production, we need a dynamical description for both the quarkonium motion and QGP evolution.

- ***QGP hydrodynamics***

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

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

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

α: suppression β: regeneration

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

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

both initial production and regeneration suffer from dissociation !

- ***CNM will change the charm quark distribution***

Dissociation and Regeneration Rate

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

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

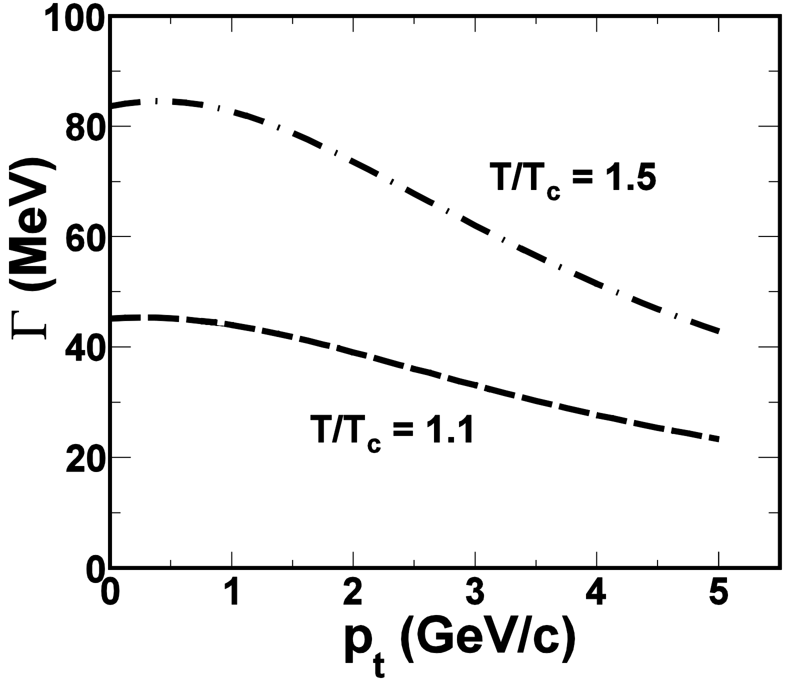
$$\sigma(p_\psi, p_g)$$

- at finite temperature, we use the classical relation

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

$\langle r^2\rangle(T)$ is calculated through the Schroedinger equation

- J/Ψ dissociation rate



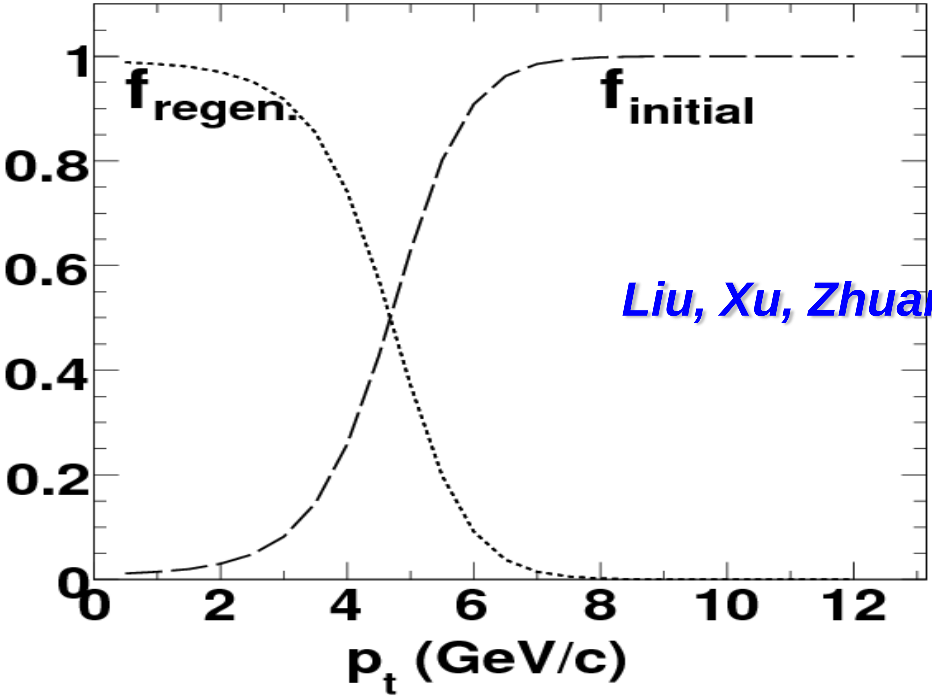
B. Chen et al, 2012

- regeneration rate is determined by the detailed balance

Pt Dependence of the Two Production Mechanisms

Due to interaction with the medium, charm quarks lose energy in the medium, and therefore the regeneration happens only in the low pt region.

From observed D-meson flow at RHIC, charm quarks seem to be thermalized, we take thermal distribution for charm quarks in the medium.



Liu, Xu, Zhuang, NPA2010

Initial and regeneration fractions for J/Ψ production in central Pb+Pb collisions at LHC energy, with thermal charm quark distribution.

initial production controls high pt and regeneration governs low pt.

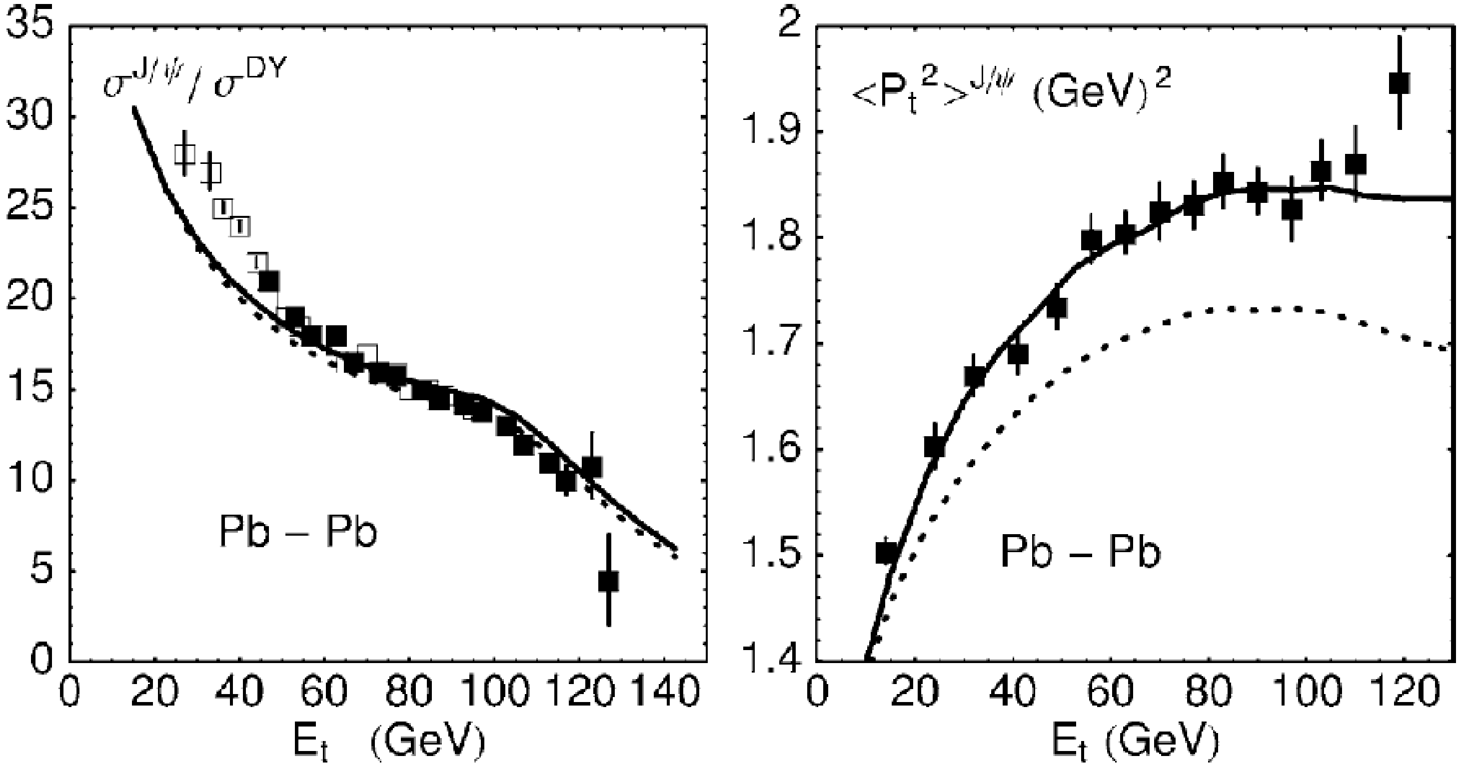
Why Pt Distribution

The Pt distribution is more sensitive to the dynamics of the system and should tell us more about the nature of the medium. It can be used to distinguish from the dissociation and production mechanisms.

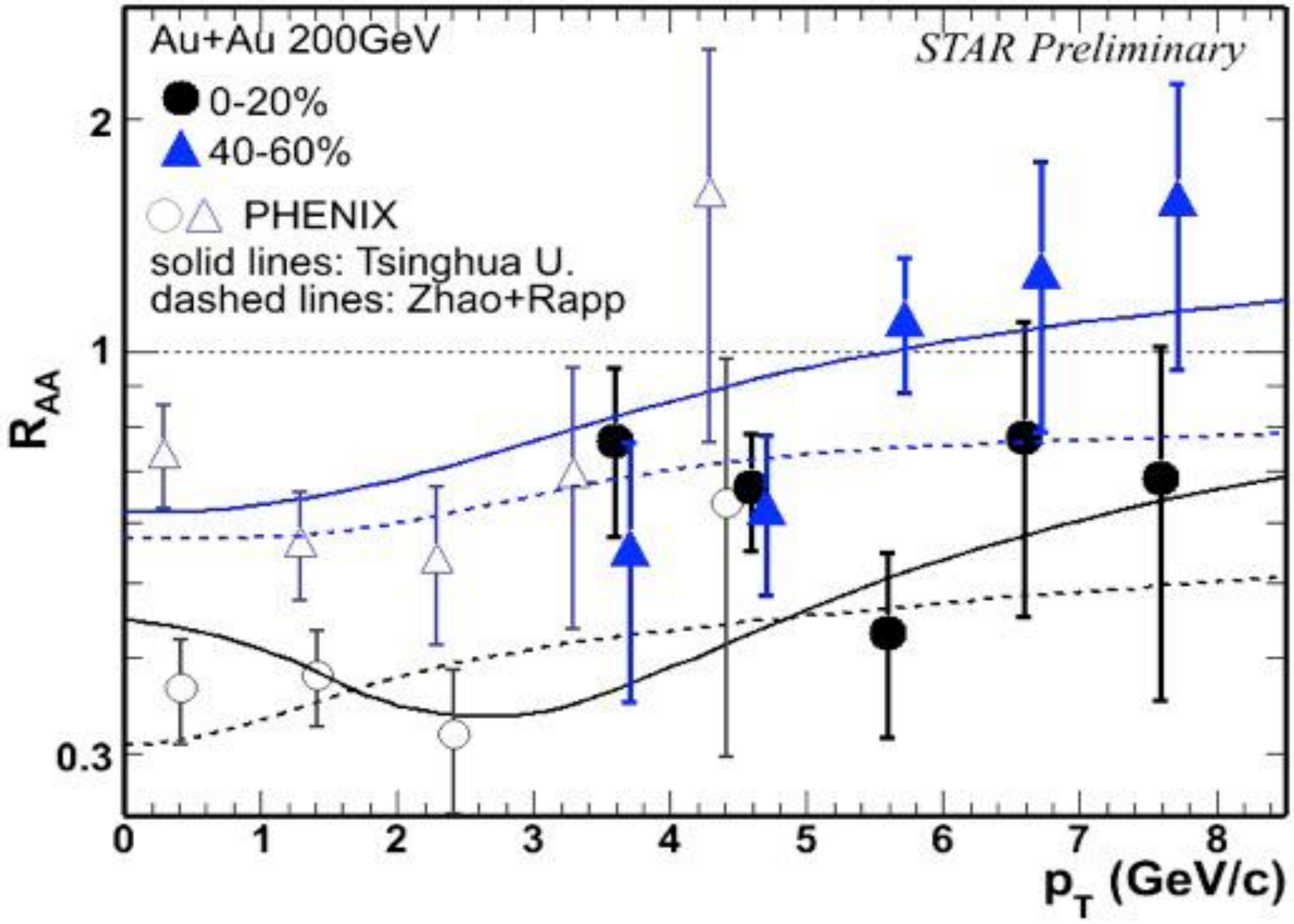
Pt Distribution at SPS

J.Hufner and PZ, PLB2002,2003

no regeneration at SPS

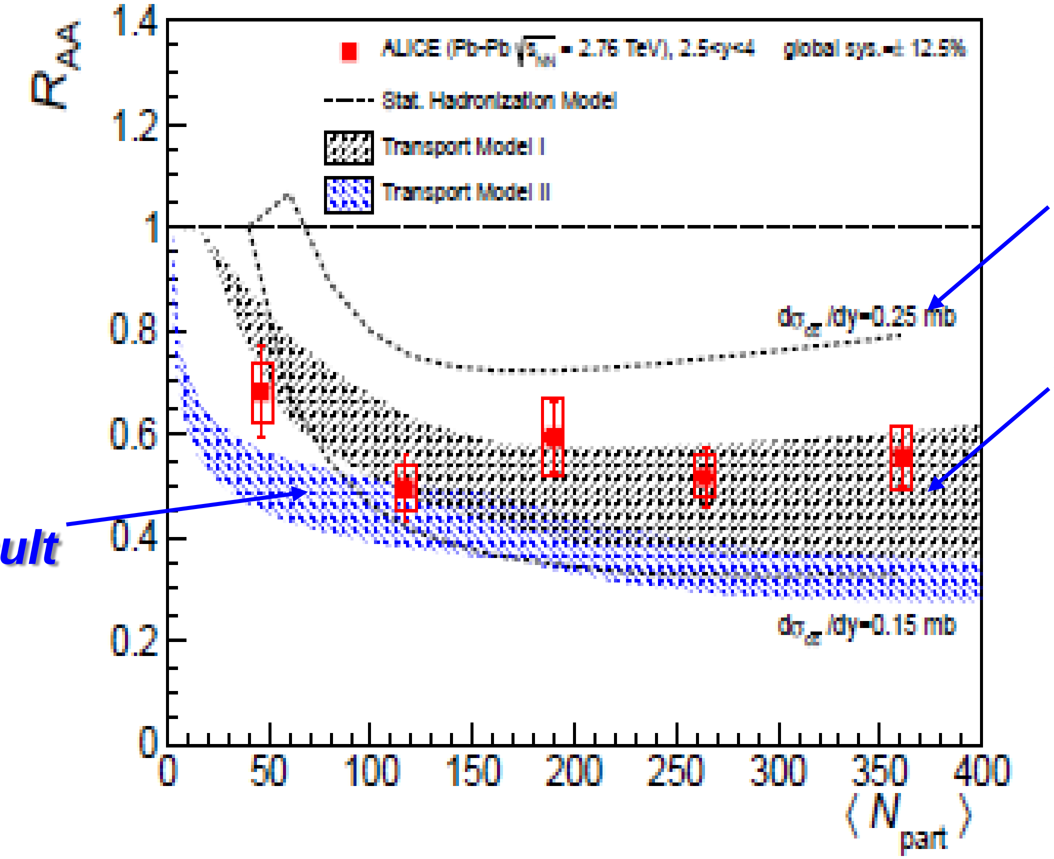


Pt Distribution at RHIC



from talk by Z.Tang at QM2011

Centrality Distribution at LHC



PBM group

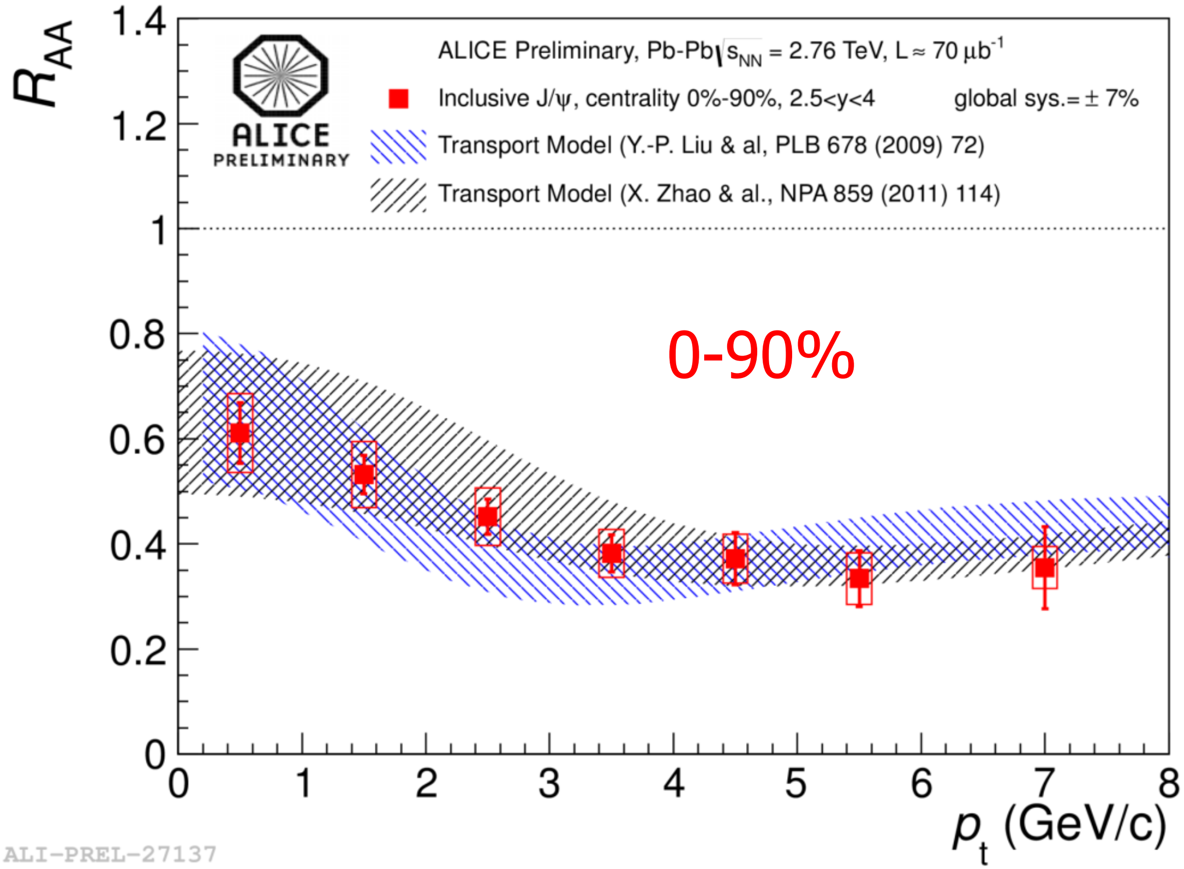
Rapp group

Our result

from talk by J.Wiechula at Hard Probe 2012

the yield is sensitive to the charm quark cross section and the shadowing effect

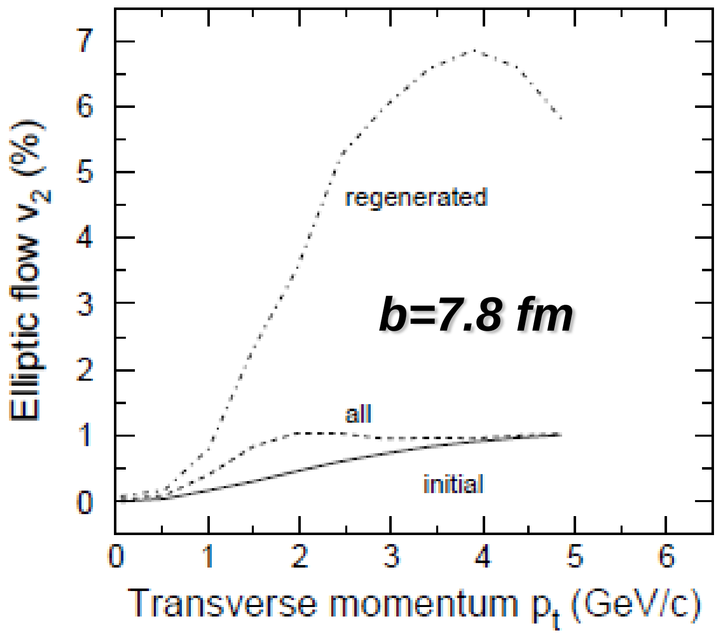
Pt Distribution at LHC



from talk by R.Arnaldi at QM2012

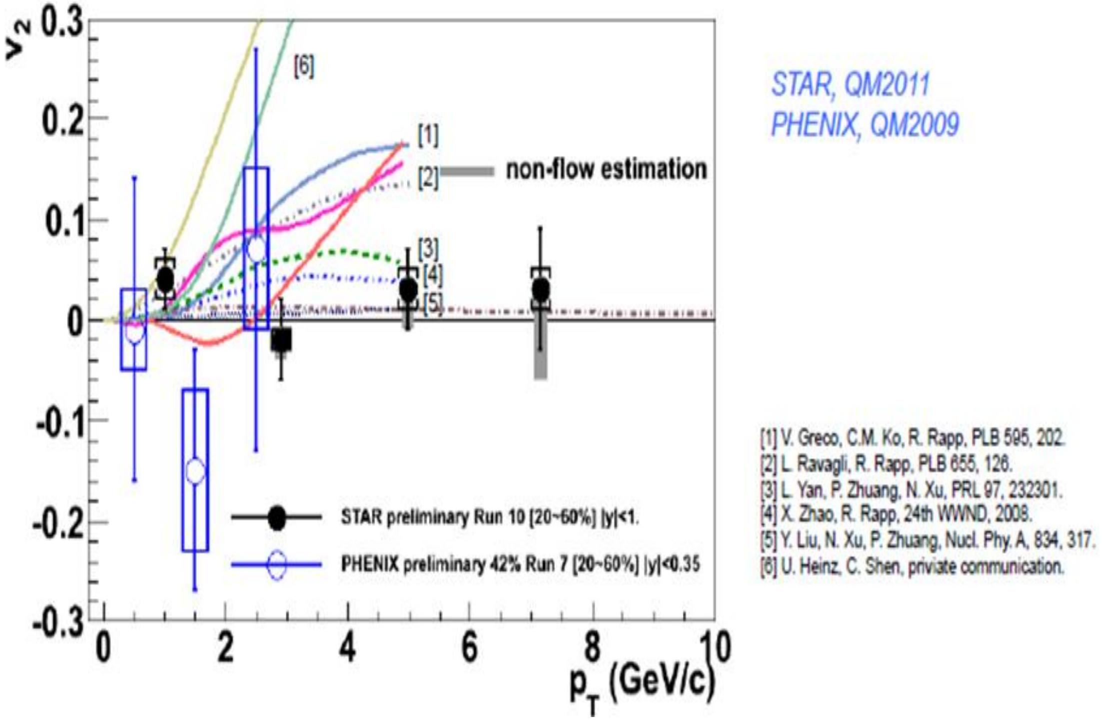
Elliptic Flow at RHIC

Yan, Xu, Zhuang, PRL2006



almost no v2 at RHIC !

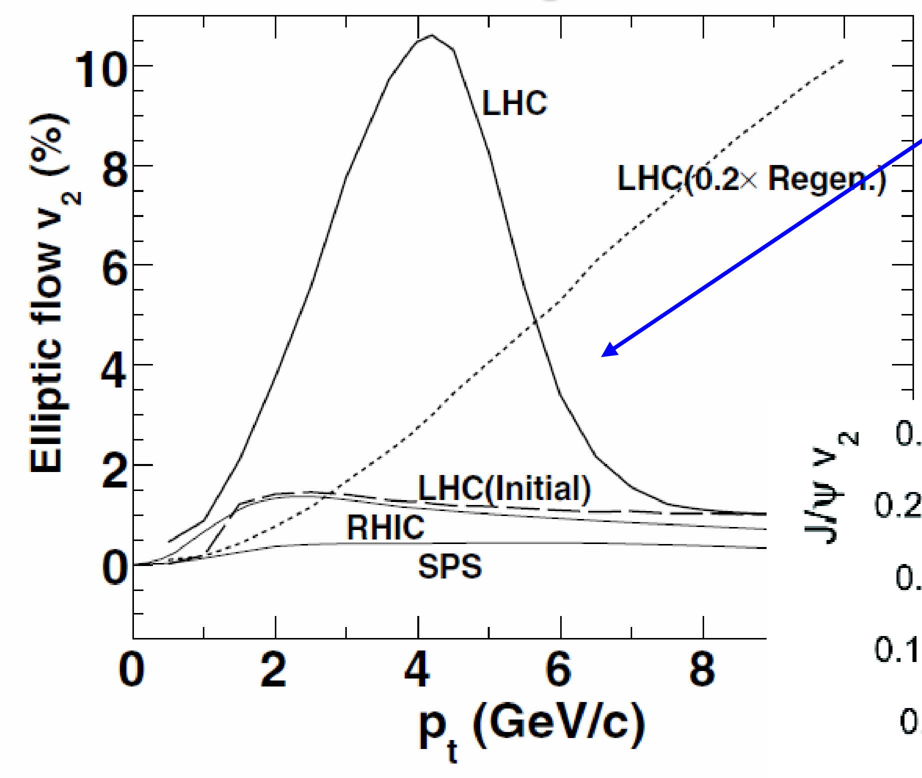
from talk by Z.Tang at QM2011



[1] V. Greco, C.M. Ko, R. Rapp, PLB 595, 202.
[2] L. Ravagli, R. Rapp, PLB 655, 126.
[3] L. Yan, P. Zhuang, N. Xu, PRL 97, 232301.
[4] X. Zhao, R. Rapp, 24th WWND, 2008.
[5] Y. Liu, N. Xu, P. Zhuang, Nucl. Phy. A, 834, 317.
[6] U. Heinz, C. Shen, private communication.

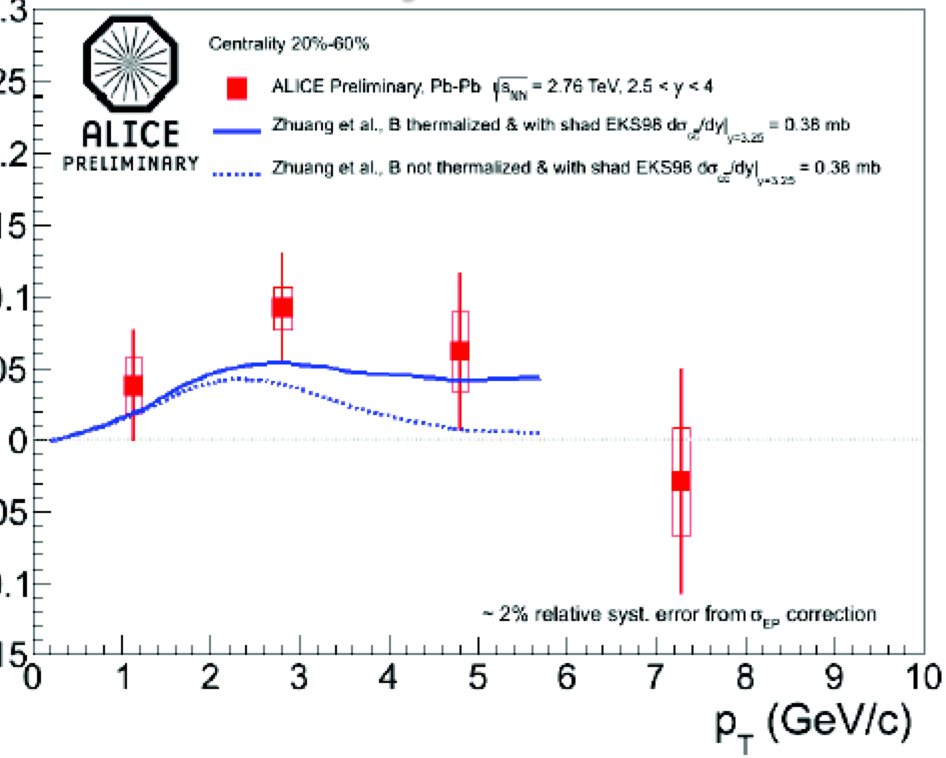
Elliptic flow at LHC

Liu, Xu, Zhuang, NPA2010



5.5 TeV
b=7.8 fm
prompt J/ψ
no shadowing

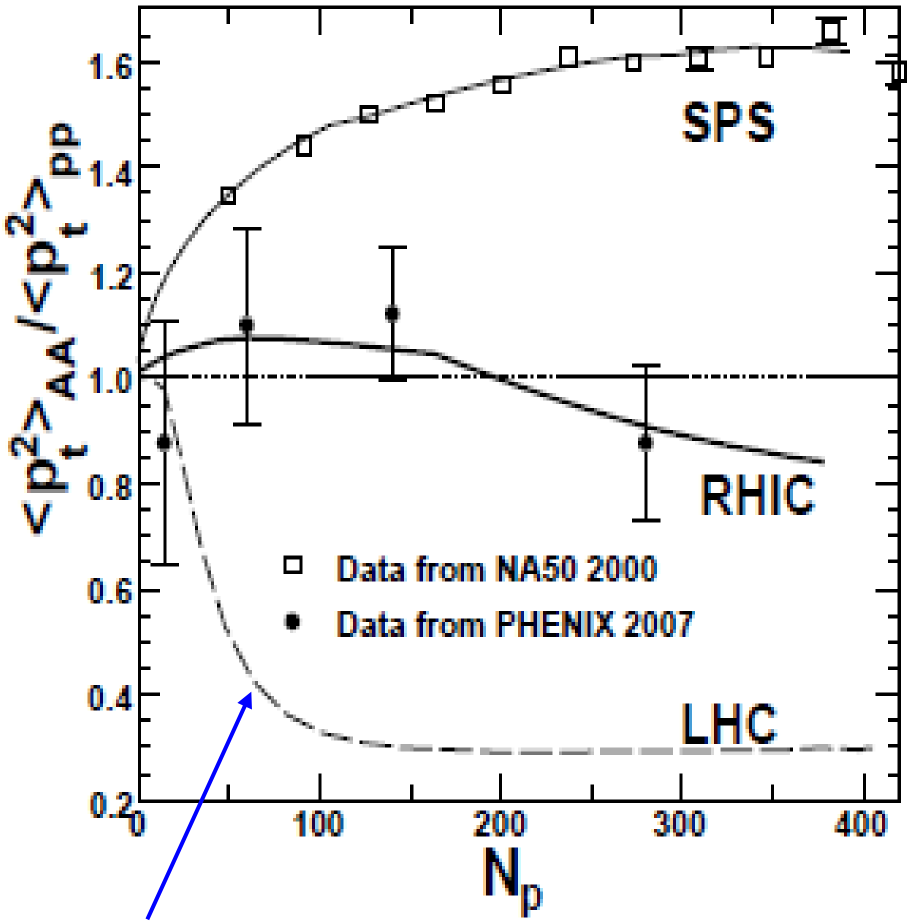
from talk by PBM at NN2012



remarkable v2 due to important regeneration !

Averaged Transverse Momentum

Zhou, Xu, Zhuang, NPA2010



for prompt J/ψs at 5.5 TeV in mid rapidity

$$r_{AA} = \left\langle p_t^2 \right\rangle_{AA} / \left\langle p_t^2 \right\rangle_{pp}$$

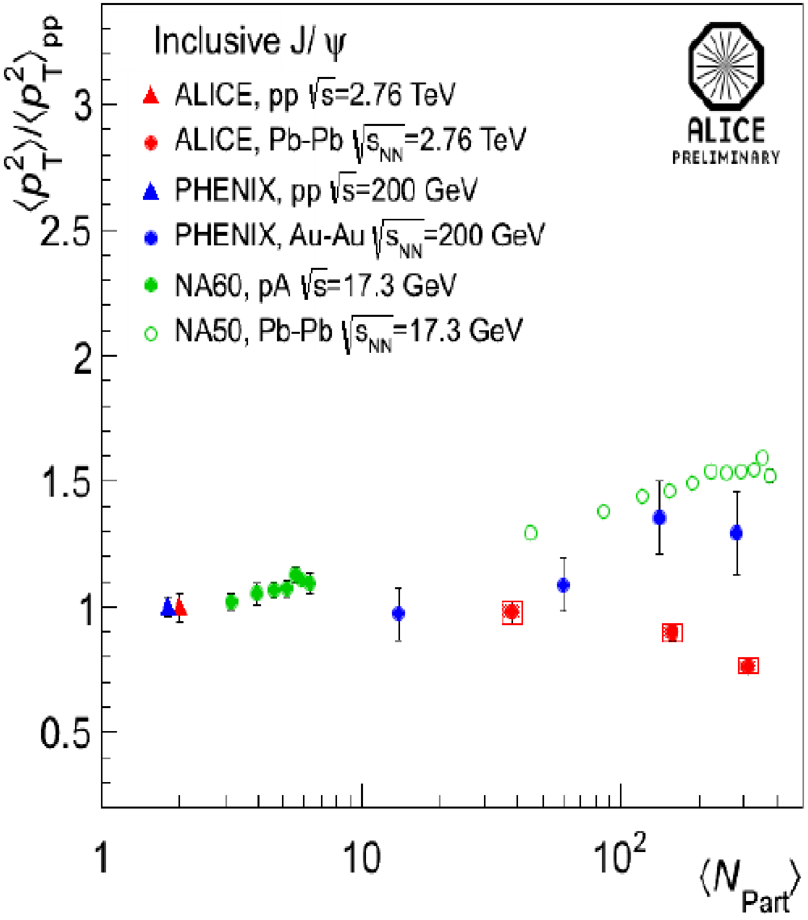
$r_{AA} > 1$ **at SPS by Cronin effect**

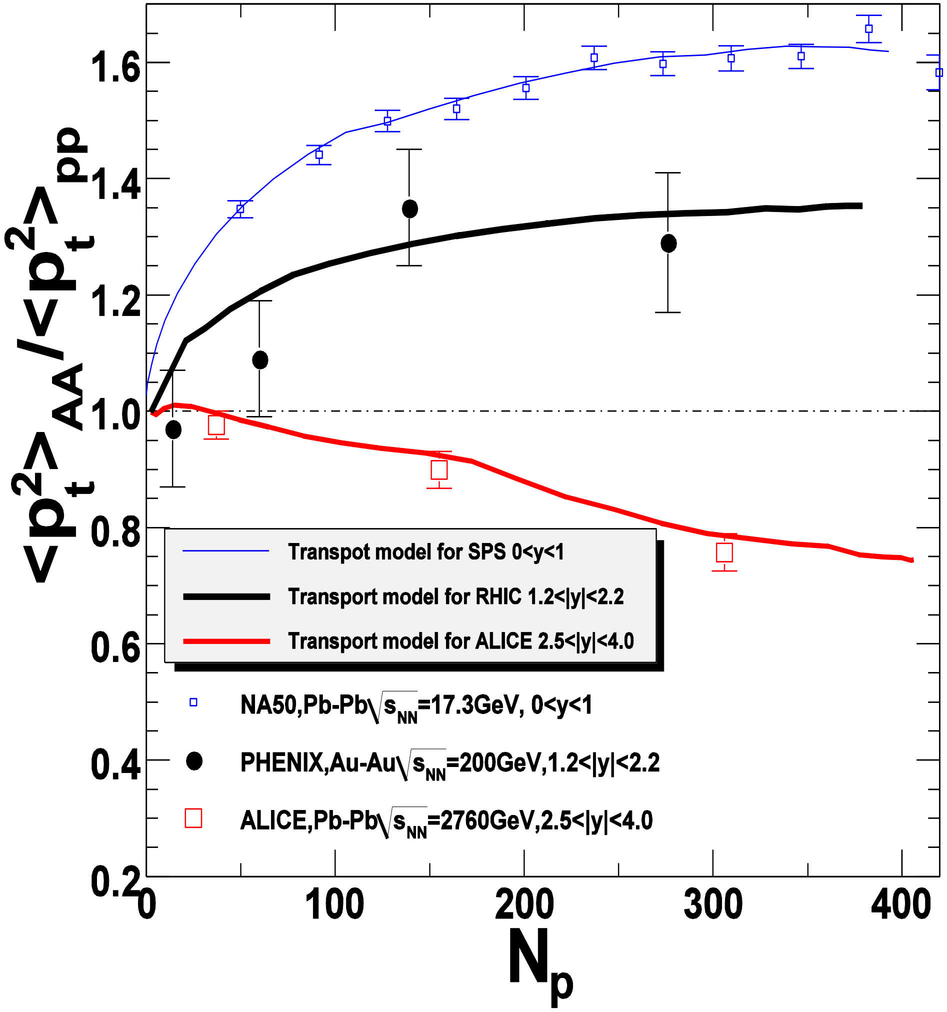
$r_{AA} \approx 1$ **at RHIC by competition between initial production and regeneration**

$r_{AA} < 1$ **at LHC by dominant regeneration**

Averaged Transverse Momentum at ALICE

from talk by PBM at XQCD2012





the ratio is not sensitive to the shadowing effect , but very sensitive to the charm quark thermolization !

Υ, a Cleaner Probe at RHIC

J/ψ :

the production and suppression mechanisms are complicated: there are primordial production and nuclear absorption in the initial state and regeneration and dissociation during the evolution of the hot medium.

Υ :

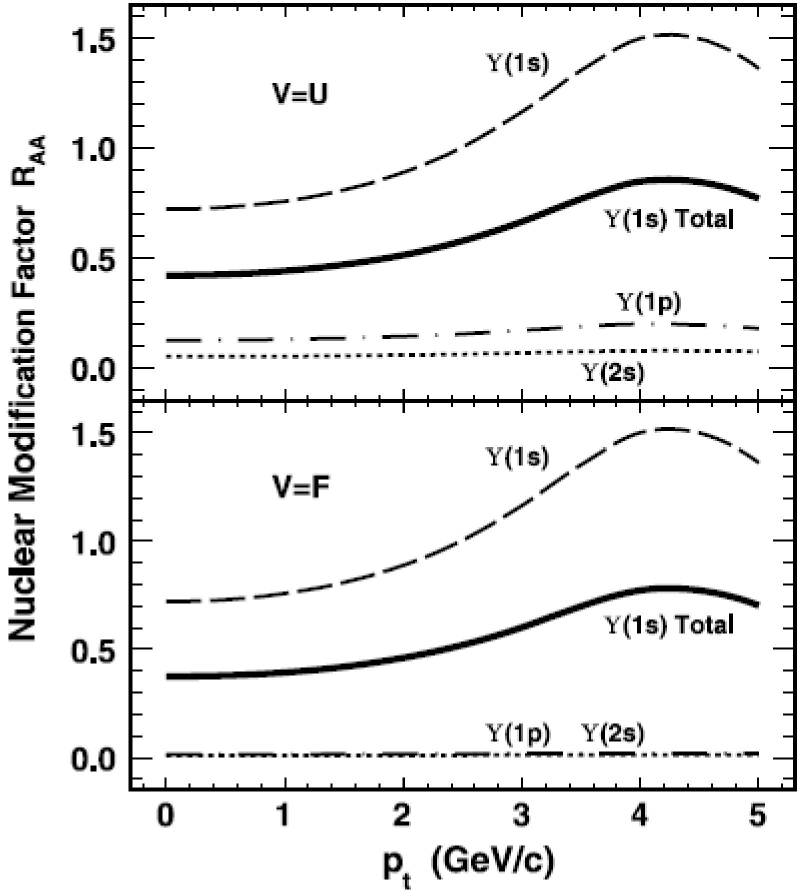
1) the regeneration can be safely neglected;

2) there is almost no feed-down forΥ ;

3) weaker CNM effect

Υ at RHIC: $R_{AA}(p_t)$

Liu, Chen, Xu, Zhuang: arXiv:1009.2585,PLB2011



central Au+Au at $\sqrt{s}$=200 GeV

- *strong Cronin effect*

Υ at RHIC: $\langle p_t^2\rangle (N_p)$

relation between Υ at RHIC and J/ψ at SPS:

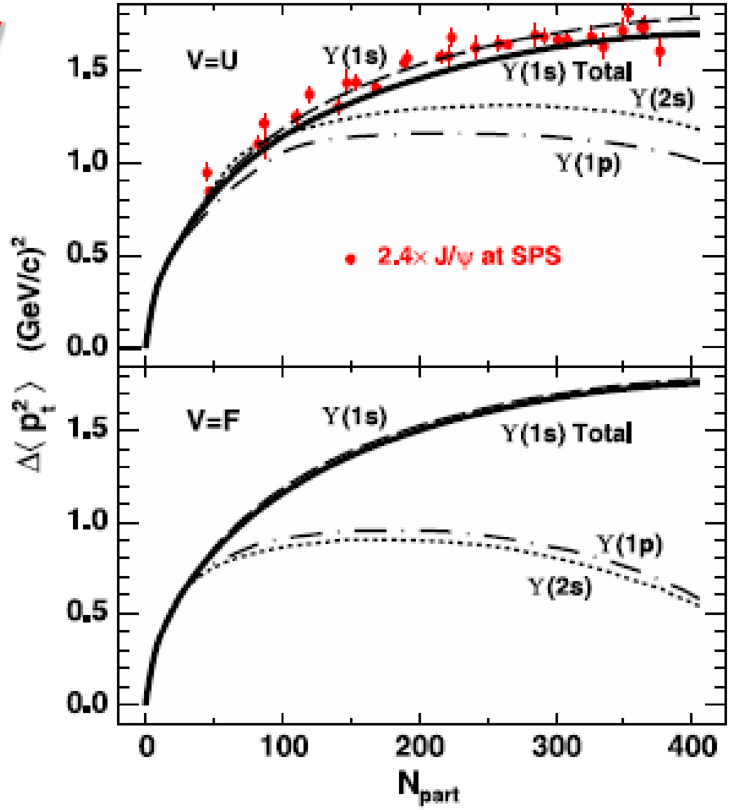
- **no Υ regeneration at RHIC and no J/ψ regeneration at SPS**
- $T_D^{\Upsilon(1s)} = 4T_c > T_{RHIC}$ **no Υ(1s) suppression at RHIC**

  $T_D^{J/\psi} = 2T_c > T_{SPS}$ **no J/ψ suppression at SPS**

both are controlled by the Cronin effect !

$$\Delta\left\langle p_t^2\right\rangle = \left\langle p_t^2\right\rangle_{AA} - \left\langle p_t^2\right\rangle_{pp} = a_{gN} L$$

$$\Delta\left\langle p_t^2\right\rangle_{\Upsilon}^{RHIC} = \frac{a_{gN}^{RHIC} R_{Au}}{a_{gN}^{SPS} R_{Pb}} \Delta\left\langle p_t^2\right\rangle_{J/\psi}^{SPS} = 2.4\Delta\left\langle p_t^2\right\rangle_{J/\psi}^{SPS}$$



Au+Au at √s=200 GeV

Liu, Chen, Xu, Zhuang: arXiv:1009.2585,PLB2011

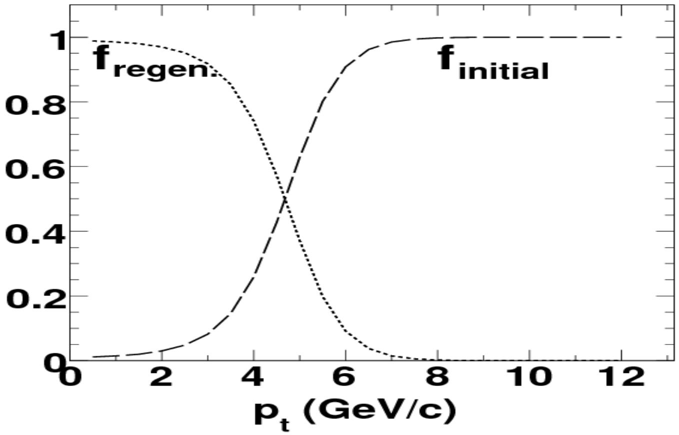
Conclusions

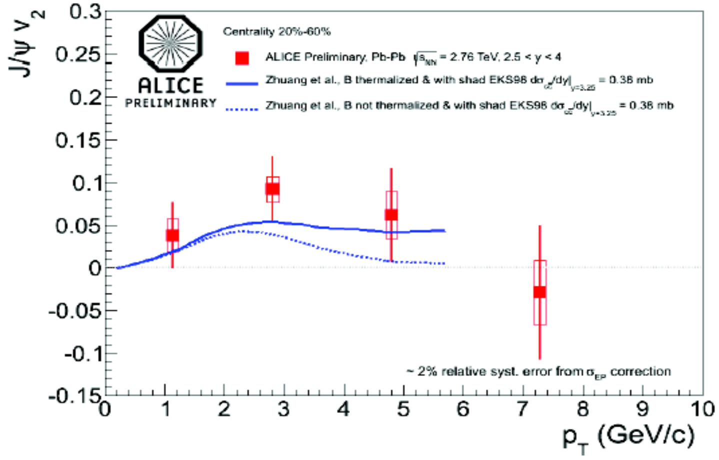
1) A group of coupled dynamical equations:

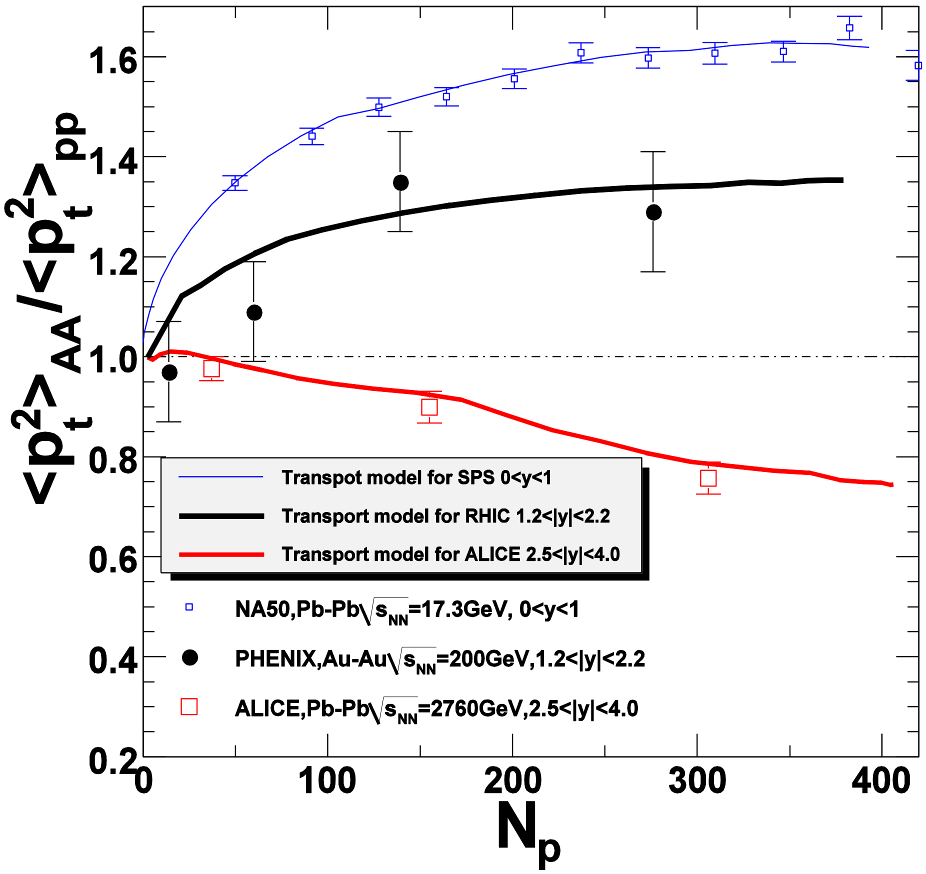
transport for quarkonium + hydrodynamics for QGP

2) Regeneration at low Pt and initial production at high Pt.

3) Pt distribution, a sensitive signature of QGP.







parameters

Input

- **medium evolution**

$$RHIC:\ \tau_0 = 0.6\ fm,\ \ \sigma_{\mathrm{pp}} = 41\ mb,\ \ T_0 = 344\ \mathrm{MeV}$$

$$LHC:\ \tau_0 = 0.6\ fm,\ \ \sigma_{\mathrm{pp}} = 62\ mb,$$

$$T_0 = 430 \text{ and } 484 \text{ MeV for forward and mid rapidity}$$

- **initial production**

$$RHIC:\ \sigma_{abs} = 0,\ a_{gN} = 0.1\ \mathrm{GeV}^2 / fm,$$

$$\sigma_{pp}^{J/\psi} = 0.42 \text{ and } 0.74\ \mu\text{b for forward and mid rapidity}$$

$$LHC:\ \sigma_{abs} = 0,\ a_{gN} = 0.15\ \mathrm{GeV}^2 / fm,$$

$$\sigma_{pp}^{J/\psi} = 2.33 \text{ and } 3.5\ \mu\text{b for forward and mid rapidity}$$

- **regeneration**

$$RHIC:\ \sigma_{pp}^{c\bar{c}} = 0.04 \text{ and } 0.12 mb \text{ for forward and mid rapidity}$$

$$LHC:\ \sigma_{pp}^{c\bar{c}} = 0.38 \text{ and } 0.6\ mb \text{ for forward and mid rapidity}$$

V=U for T_d

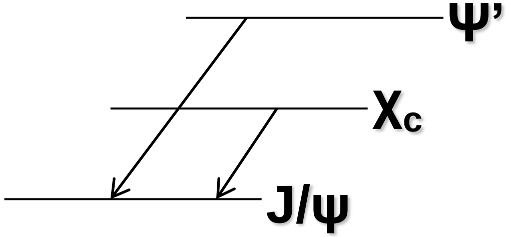
cold nuclear matter effects

Charmonium in pp Collisions

observation: $J/\psi, \psi' \to \mu^+\mu^-$, $\quad \dfrac{\sigma^{pp\to\psi' X}\cdot B(\psi' \to \mu^+\mu^-)}{\sigma^{pp\to J/\psi X}\cdot B(J/\psi \to \mu^+\mu^-)} \simeq 1.5\%$

difficult to observe ψ' !

Ψ' and χ_c decay into J/ψ:



$$P(\chi_c \to J/\psi + \gamma) \simeq 30\%$$

$$P(\psi' \to J/\psi + 2\pi) \simeq 10\%$$

$$\text{direct production } \simeq 60\%$$

mechanisms for quarkonium production in pp:

it is difficult to describe quarkonium formation due to confinement problem

1) color evaporation model:

$$gg \to \text{colored } [c\bar{c}] \xrightarrow{\text{color evaporation}} J/\psi$$

2) color-singlet model:

$$gg \to [c\bar{c}]_{J/\psi} + g$$

3) color-octet model:

$$\sum_n \left(gg \to [c\bar{c}]_n + X\right)$$

n: quantum numbers of color, angular momentum and spin

Cold Effect: Nuclear Absorption

Nuclear Modification Factor:

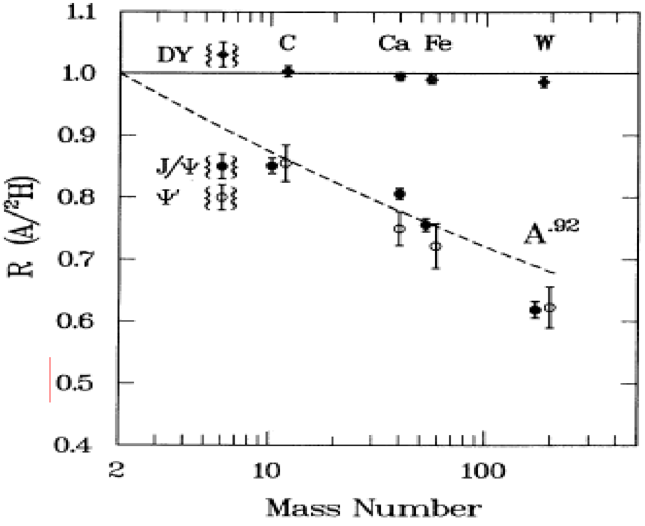
$$R_{AA}=\frac{\sigma_{AA}^{J/\psi}}{N_c\sigma_{pp}^{J/\psi}}=\begin{cases}1, & no\ medium\ effect\\ <1, & J/\psi\ supression\\ >1, & J/\psi\ enhancement\end{cases}$$

Matsui and Satz, 1986:

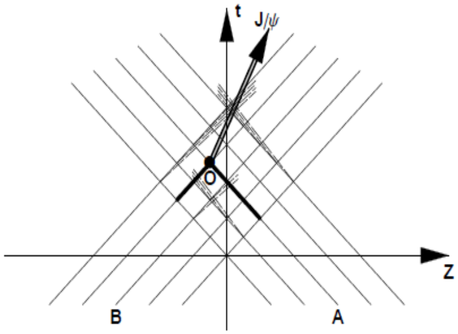
J/ψ suppression as a probe of QGP in AA collisions

However,

1) **suppression is observed in pA collisions where QGP is not expected !**
2) **J/ψ and ψ' have the same suppression !**



theoretical explanation: nuclear absorption



J/ψ formation time $\tau_f \approx 0.5$ fm

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

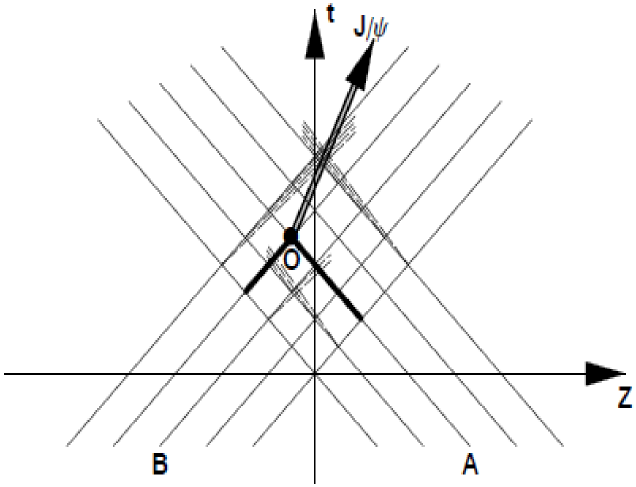
$$\sigma_{abs}^{SPS} > \sigma_{abs}^{RHIC} > \sigma_{abs}^{LHC}$$

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

Cold Effect: Cronin Effect

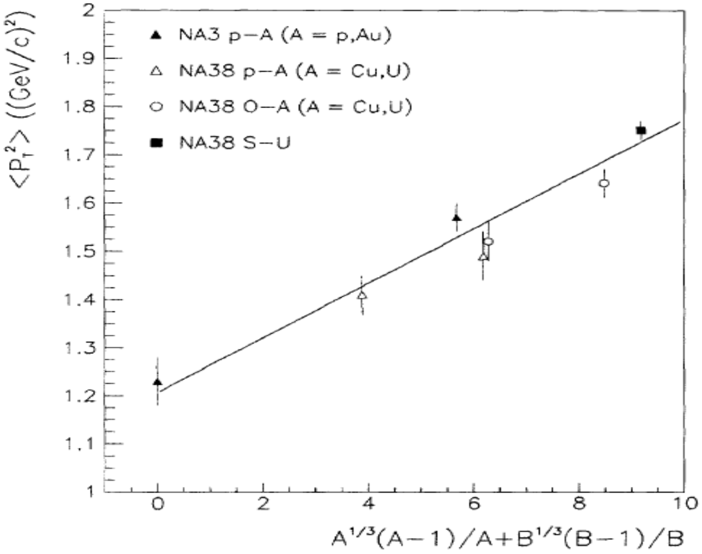
Cronin effect:

gluon multi scattering with nucleons before they fuse into a cc pair.



transverse momentum broadening !

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



Cold Effect: Shadowing Effect

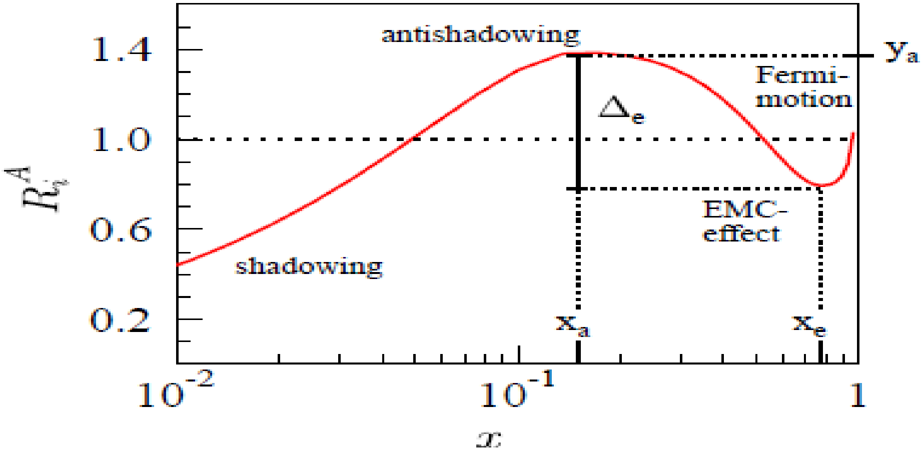
parton distribution function (PDF) in a nucleus is different from a simple superposition (Glauber model) of the PDF in a free nucleon.

shadowing correction factor:

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

x: momentum fraction,

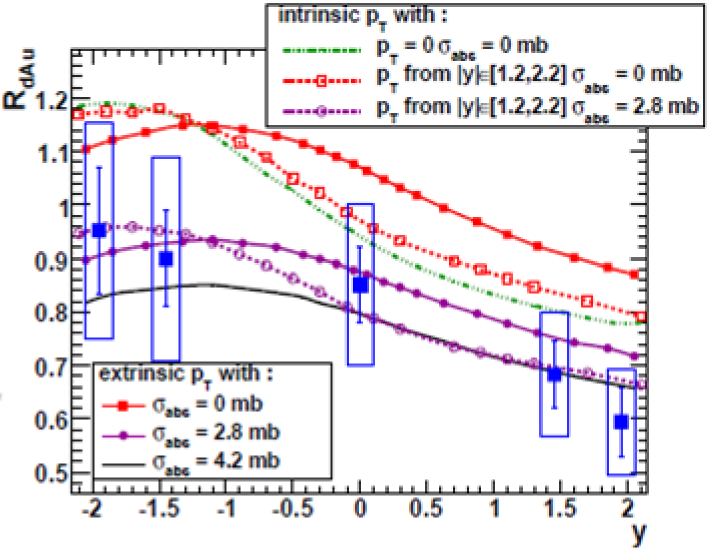
$\sqrt{\mu_F}$: transverse momentum



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

$$\mathcal{F}_g^A(x_1,\vec{x}_t,z_A,\mu_F) = \rho_A(\vec{x}_t,z_A)\mathcal{R}_g^A(\vec{x}_t,x_1,\mu_F)g(x_1,\mu_F)$$

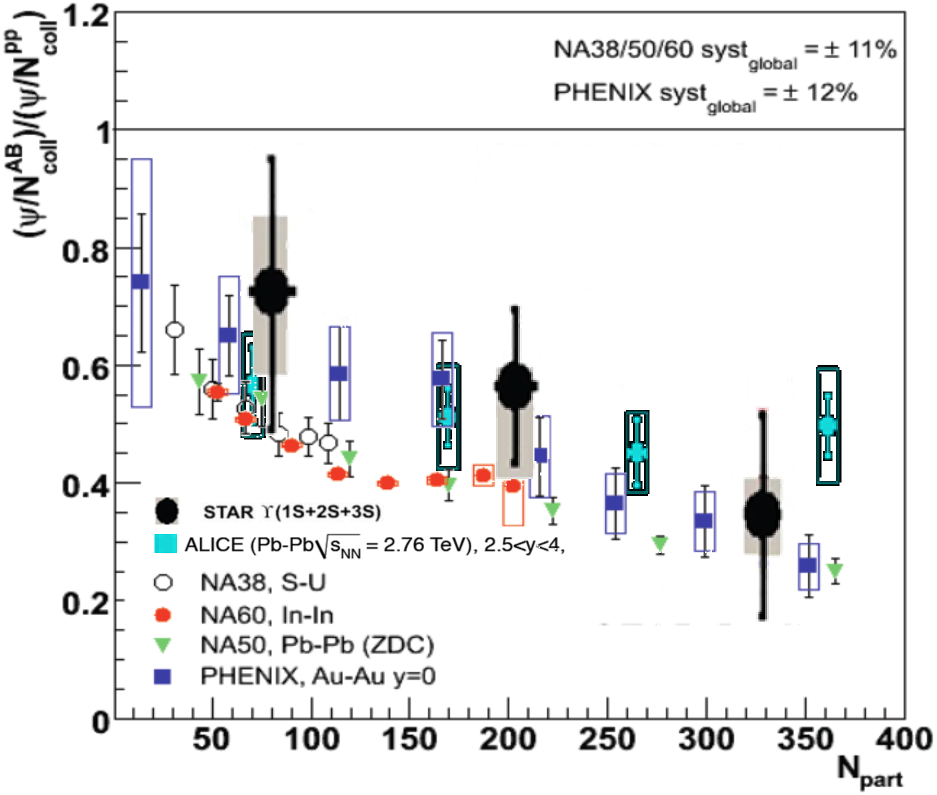
usual PDF

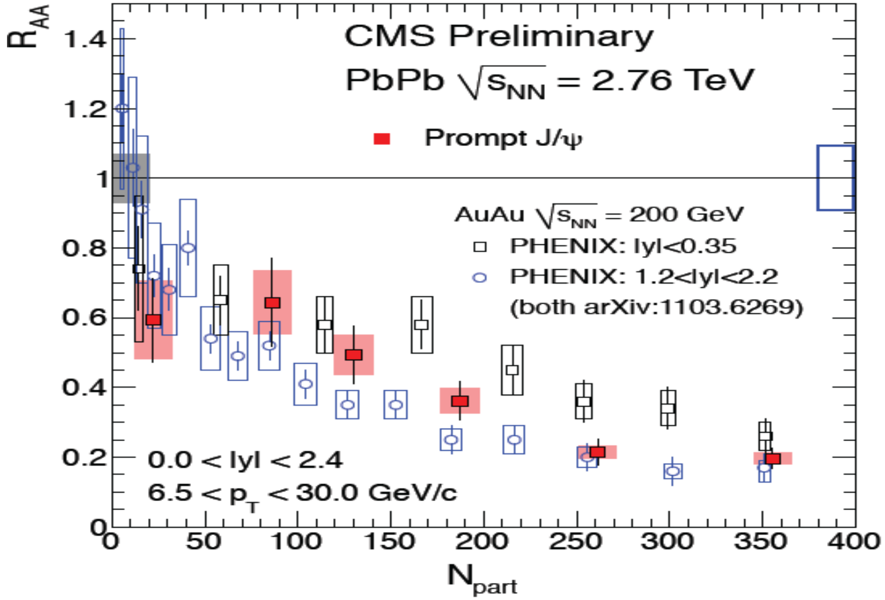


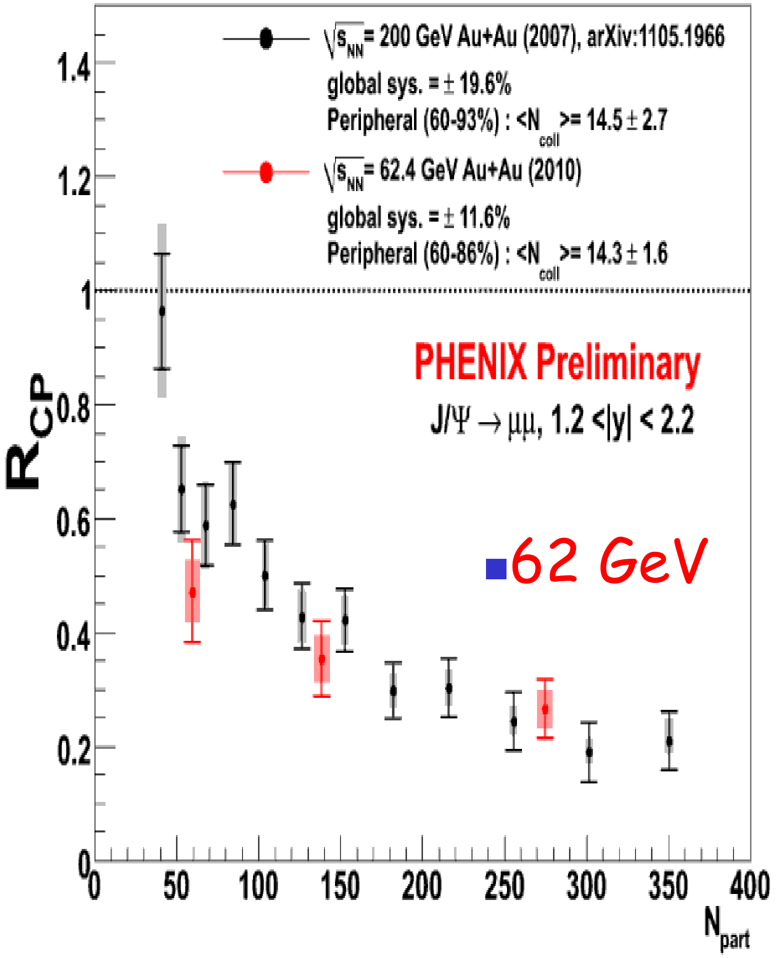
shadowing effect + nuclear absorption can explain the pA data at RHIC energy.

J/Ψ

J/ψ Yield at SPS, RHIC and LHC



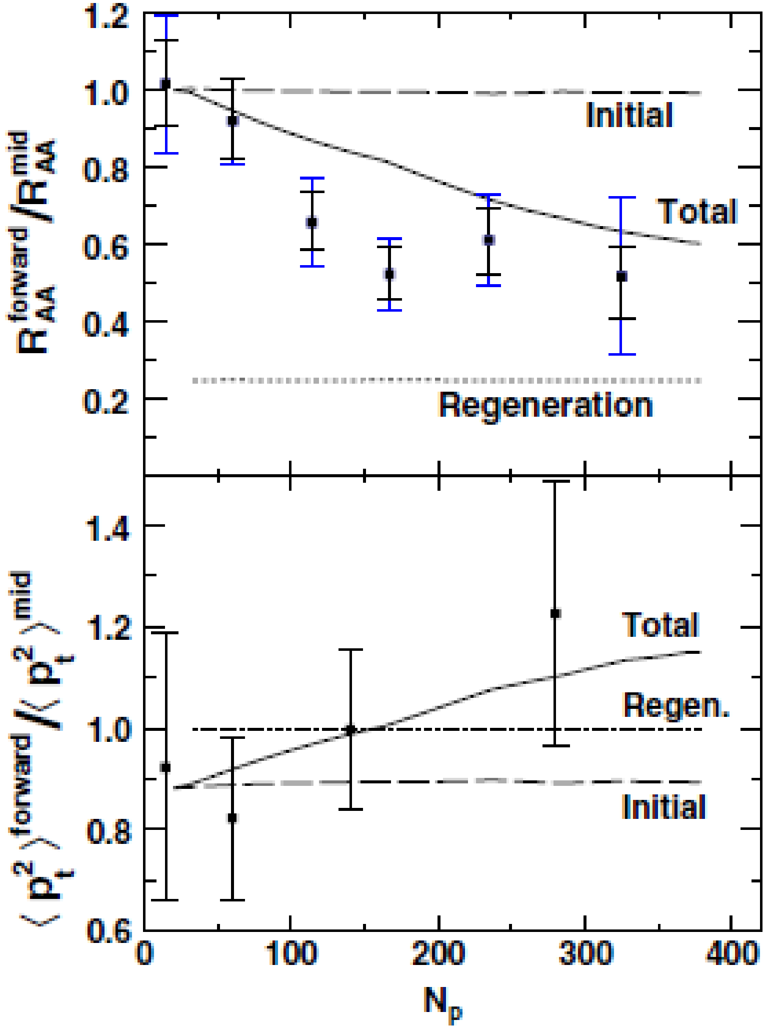




■62 GeV

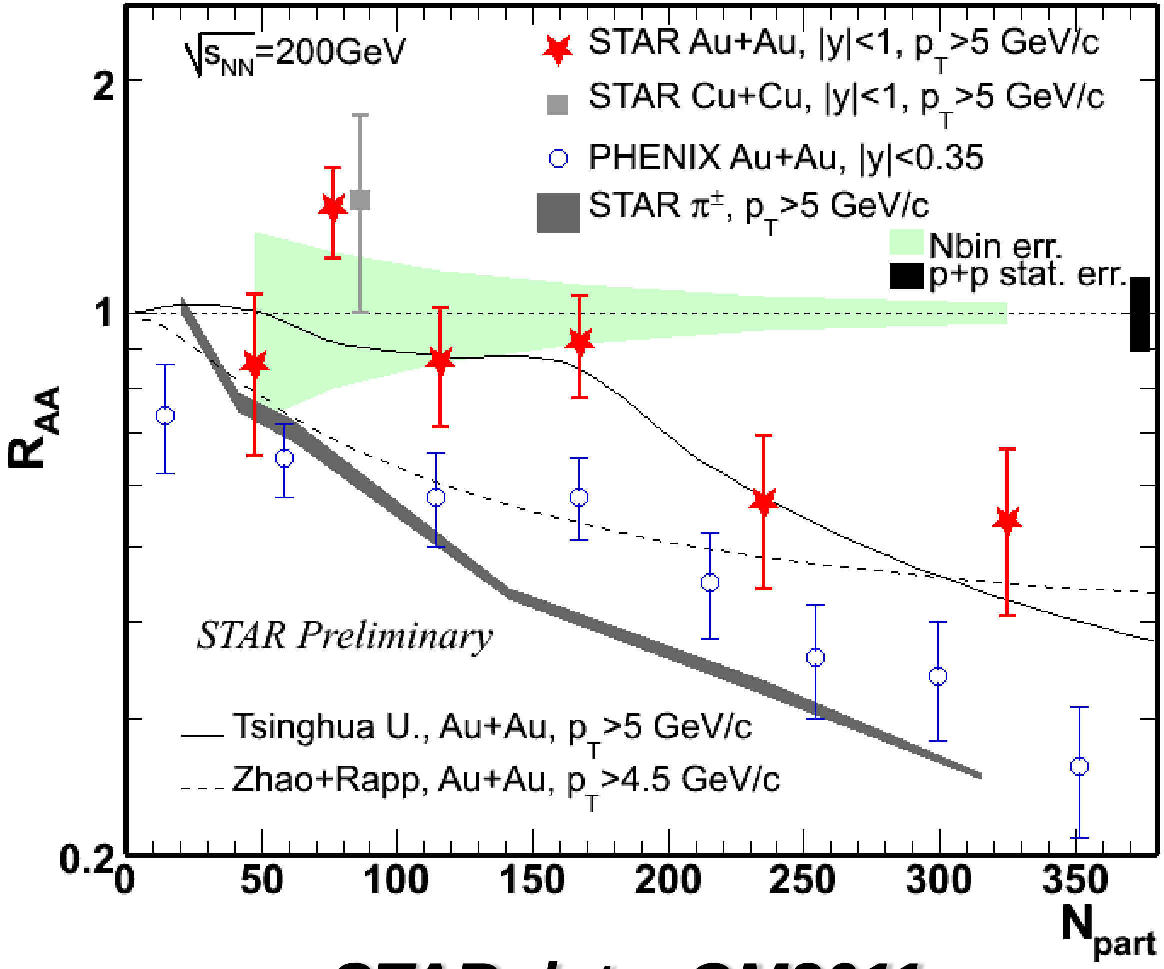
Rapidity Dependence at RHIC

Y.Liu, N.Xu, PZ, JPG2010



less regeneration in forward rapidity

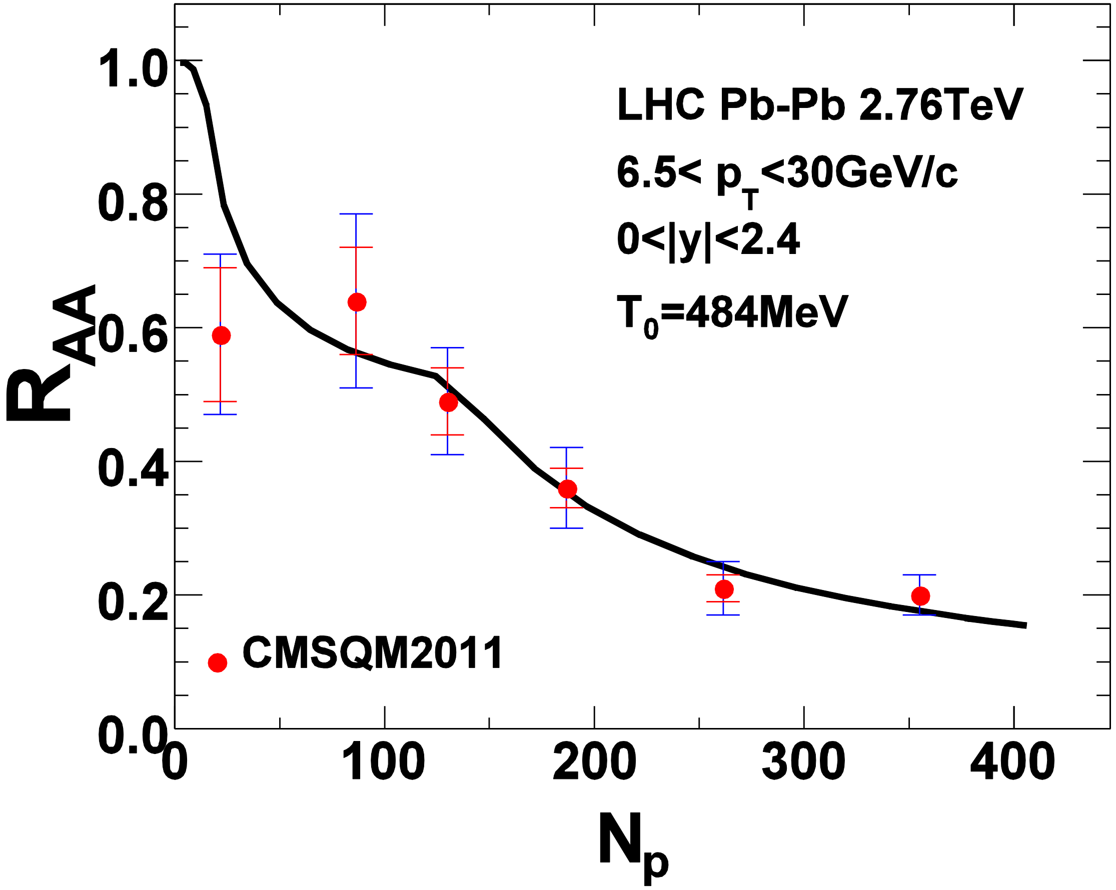
Transverse Momentum Dependence at RHIC



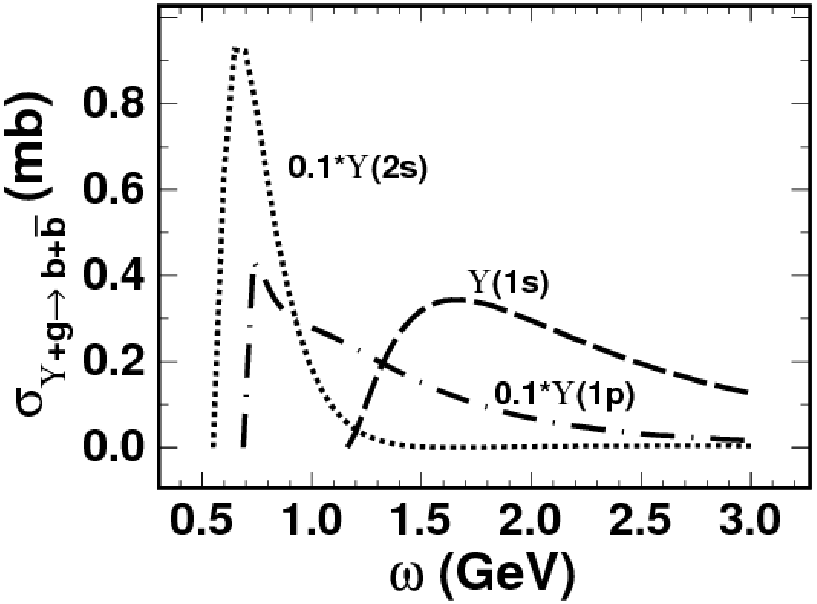
STAR data, QM2011

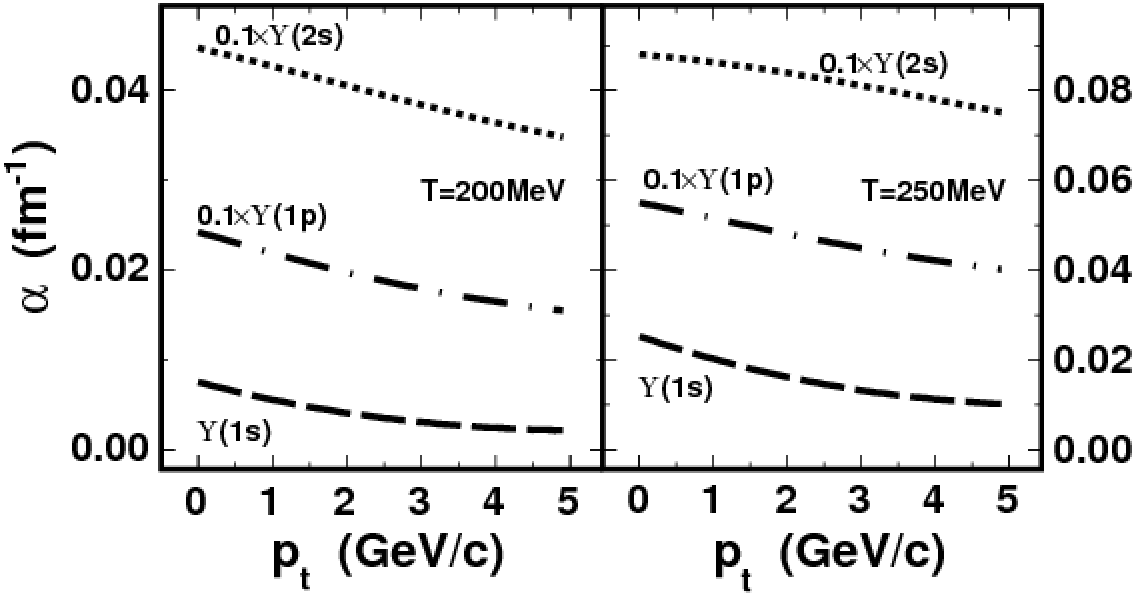
high pt J/psi's are from the initial production and can survive in hot medium.

Centrality Distribution for High pt J/ψs at LHC



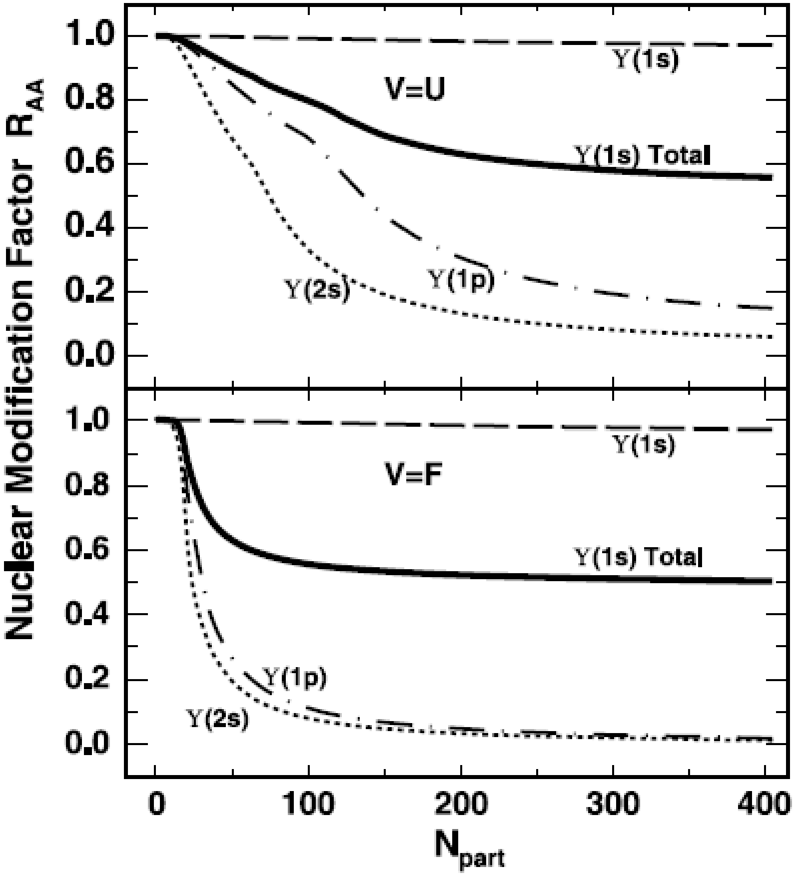
Upsilon


$\sigma_{\Upsilon+g\to b+\bar{b}}$ (mb)
0.8
0.6
0.4
0.2
0.0
0.1*Υ(2s)
Υ(1s)
0.1*Υ(1p)
0.5
1.0
1.5
2.0
2.5
3.0
ω (GeV)


α (fm^{-1})
0.04
0.02
0.00
0.1×Υ(2s)
0.1×Υ(1p)
Υ(1s)
T=200MeV
0.1×Υ(2s)
0.1×Υ(1p)
Υ(1s)
T=250MeV
0.08
0.06
0.04
0.02
0.00
0
1
2
3
4
5
p_t (GeV/c)
0
1
2
3
4
5
p_t (GeV/c)

Υ at RHIC: $R_{AA}(N_p)$

Y.Liu, B.Chen, N.Xu, PZ,PLB2011

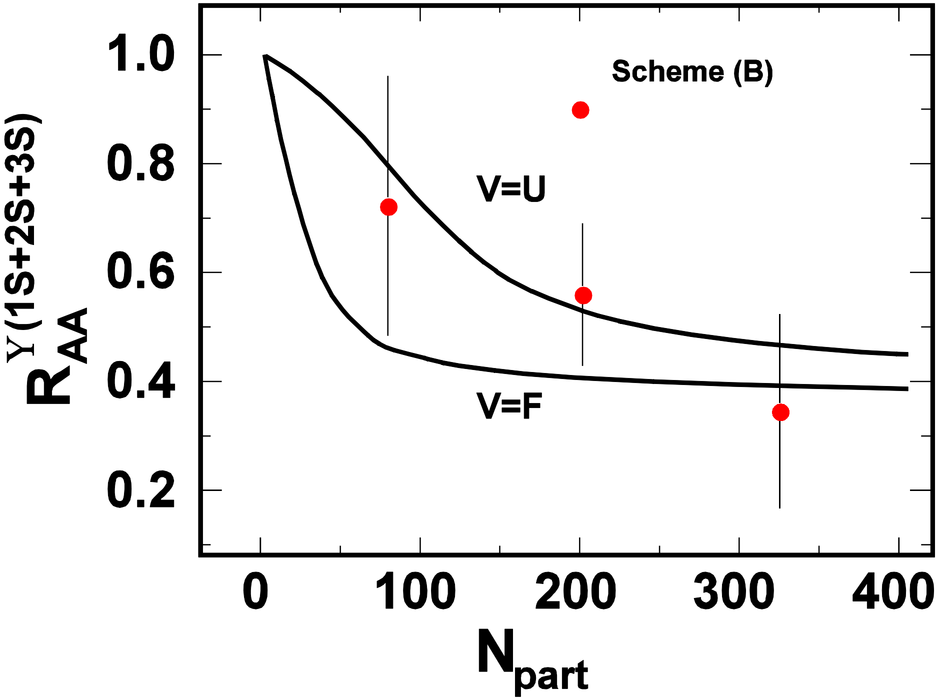


for minimum bias events:

PHENIX dada: $R_{AA}<0.64$ (NPA2009)

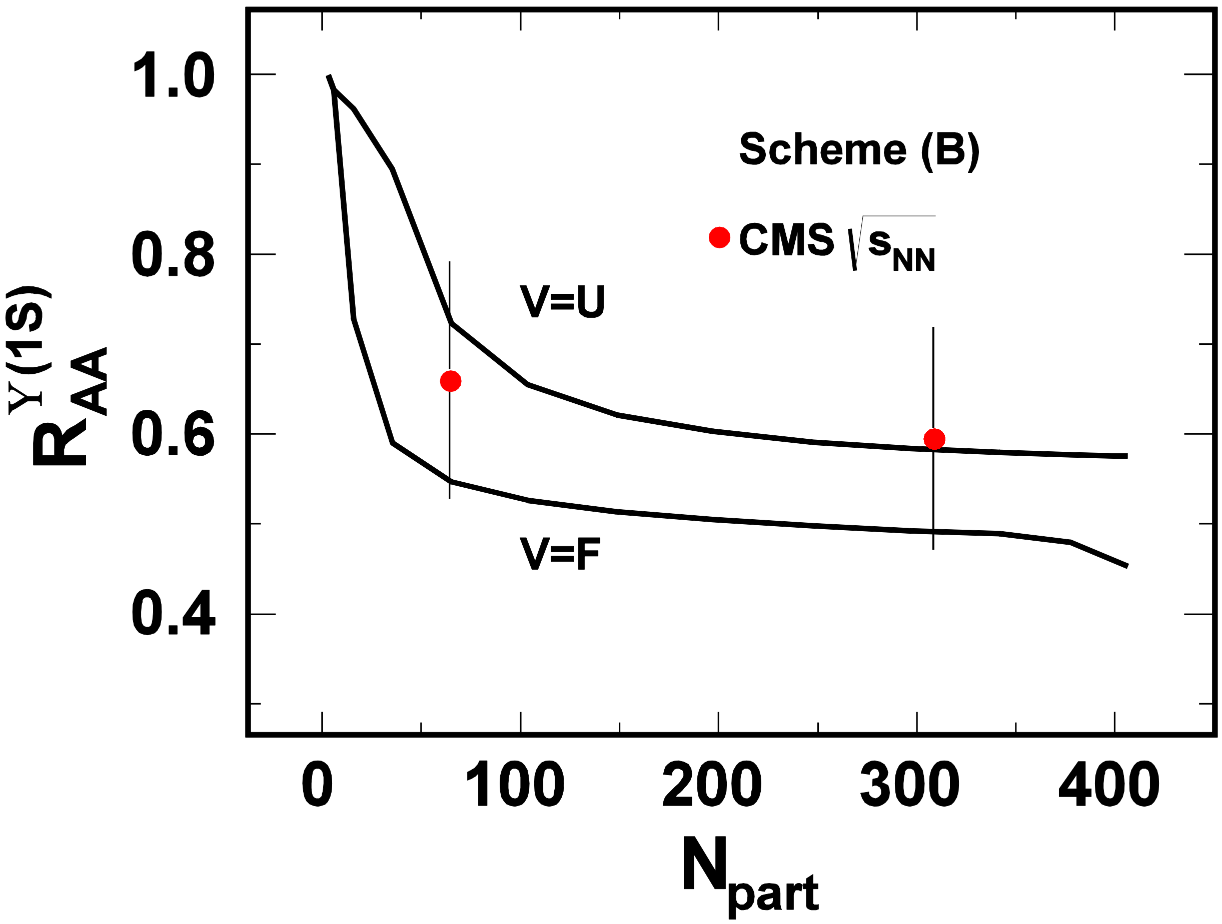
our result: $R_{AA}=0.63$ for V=U

$R_{AA}=0.53$ for V=F



- *from the comparison with data, V is close to U.*

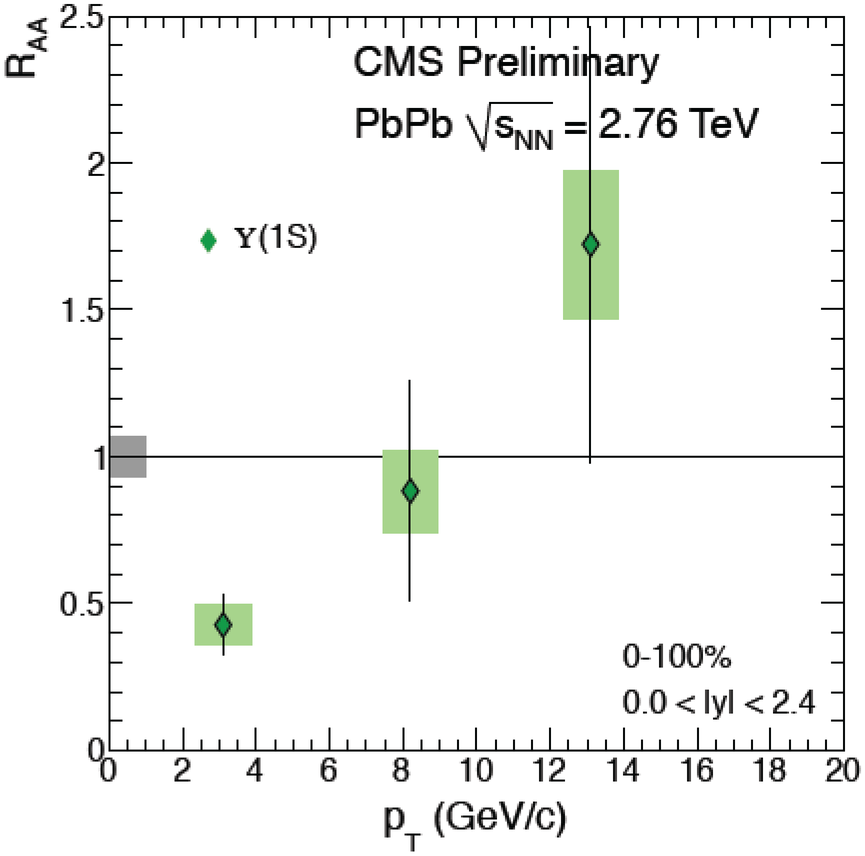
Υ at LHC: $R_{AA}(N_p)$



$$\sigma_{pp}^{\Upsilon}=14\mu b, \qquad \sigma_{pp}^{b\bar{b}}=43nb$$

- *again, V is close to U.*

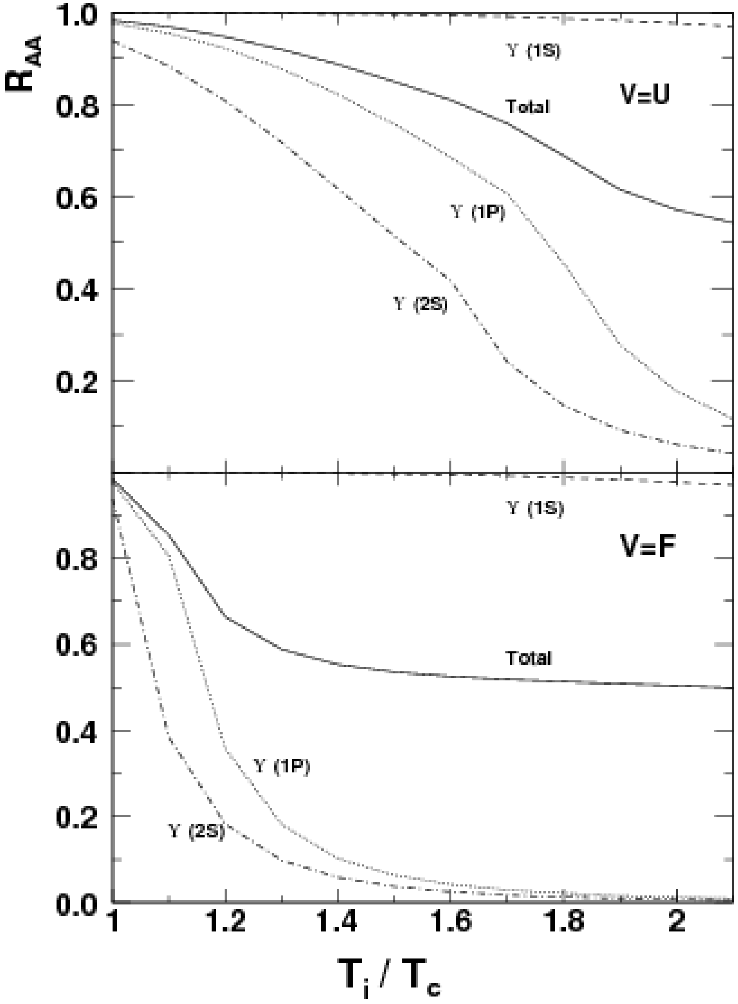
ϒ at LHC: $R_{AA}(p_t)$



high pt is controlled by initial production !

Measuring RHIC Temperature by Excited Υ States

initial temperature dependence of R_{AA}



central Au+Au at $\sqrt{s}$=200 GeV

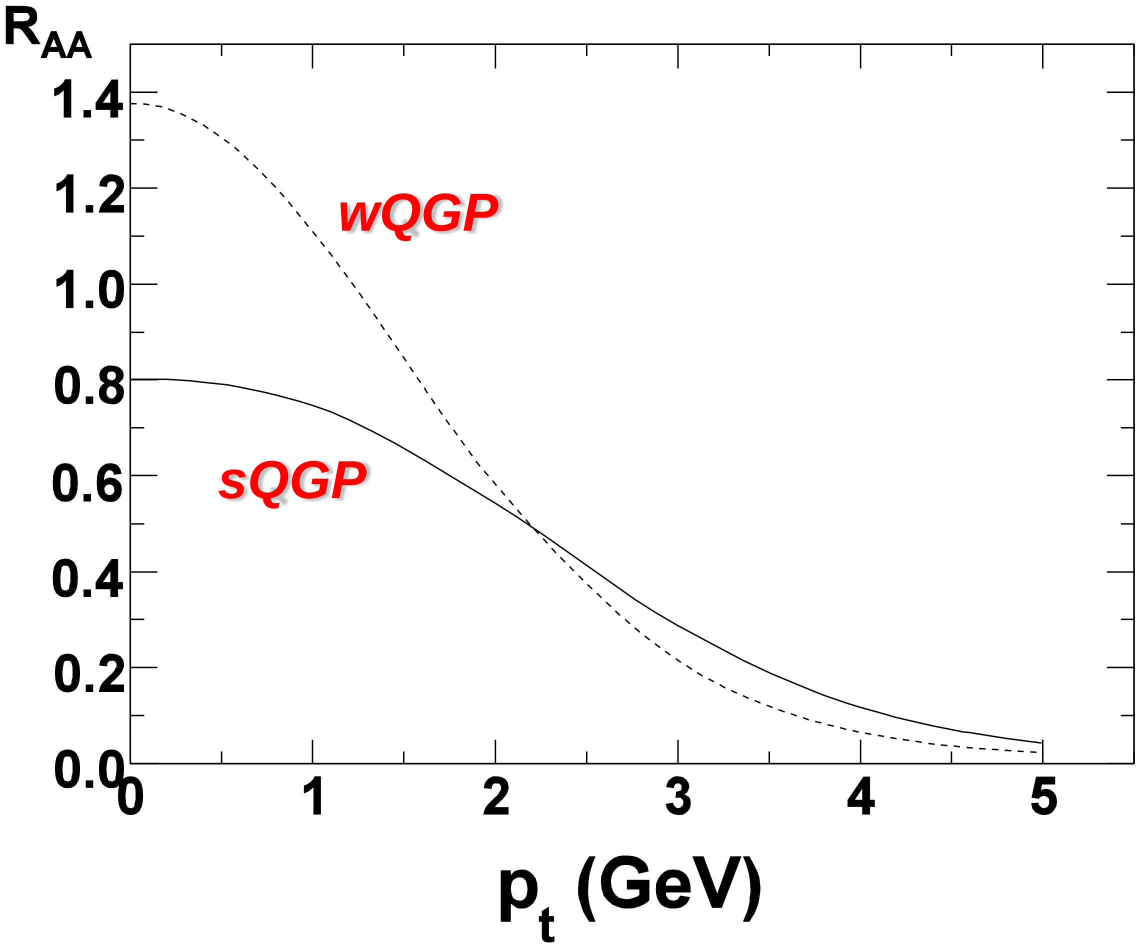
Liu, Chen, Xu, Zhuang: arXiv:1009.2585,PLB2011

suppression of excited Υ states is sensitive to the fireball temperature !

EoS

Dependence on EoS

J/Psi Pt distribution at LHC where EoS plays an essential role!



running dissociation temperature

Relativistic Correction

X.Guo et al, 2012

relativistic equations fro spin singlet and triplet at finite temperature:

H.Crater et al, PRD79, 034011(2009)

$$\left[-\frac{d^2}{dr^2}+\frac{J(J+1)}{r^2}+2m_wB+B^2-A^2+2\epsilon_wA+\Phi_D-3\Phi_{SS}\right]u_0=b^2u_0,$$

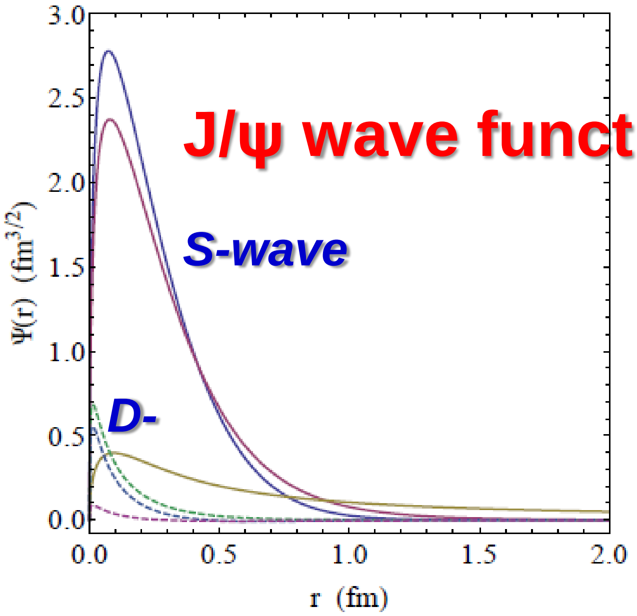
$$\left[-\frac{d^2}{dr^2}+\frac{J(J+1)}{r^2}+2m_wB+B^2-A^2+2\epsilon_wA+\Phi_D-2\Phi_{SO}+\Phi_{SS}+2\Phi_T-2\Phi_{SOT}\right]u_1^0=b^2u_1^0,$$

$$\left[-\frac{d^2}{dr^2}+\frac{J(J-1)}{r^2}+2m_wB+B^2-A^2+2\epsilon_wA+\Phi_D+2(J-1)\Phi_{SO}+\Phi_{SS}+\frac{2(J-1)}{2J+1}(\Phi_{SOT}-\Phi_T)\right]u_1^+$$
$$+\ \frac{2\sqrt{J(J+1)}}{2J+1}(3\Phi_T-2(J+2)\Phi_{SOT})\,u_1^-=b^2u_1^+,$$

$$\left[-\frac{d^2}{dr^2}+\frac{(J+1)(J+2)}{r^2}+2m_wB+B^2-A^2+2\epsilon_wA+\Phi_D-2(J+2)\Phi_{SO}+\Phi_{SS}+\frac{2(J+2)}{2J+1}(\Phi_{SOT}-\Phi_T)\right]u_1^-$$
$$+\ \frac{2\sqrt{J(J+1)}}{2J+1}(3\Phi_T+2(J-1)\Phi_{SOT})\,u_1^+=b^2u_1^- \tag{3}$$

$$V(r)=A(r)+B(r),$$

the J/ψ dissociation temperature increases 7% - 13%, when the quark potential varies between F and U.



Potential for Moving Heavy Quarks

Y.Liu et al, 2012

The screening effect is due to the rearrangement of the charged particles when a pair of heavy quarks (source) is put into the medium.

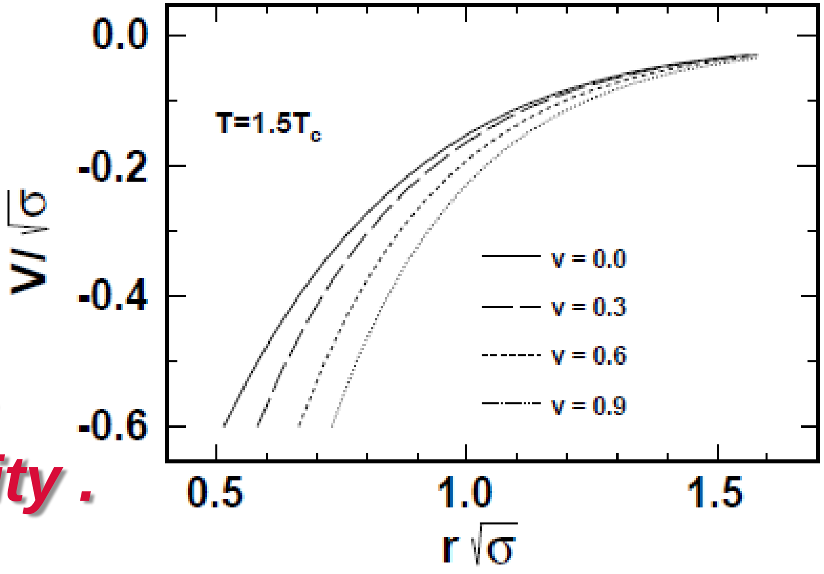
$$V(r) \sim \rho(r)$$

When the source moves in the medium, it costs some time for the screening charges to catch up with the source. This delay of response reduces the screening charges around the source and thus weakens the screening effect.

transport equation:

$$\partial_t \rho - \mathbf{v}\cdot\nabla\rho = -\left(\rho - \rho_0\right)/\tau,$$

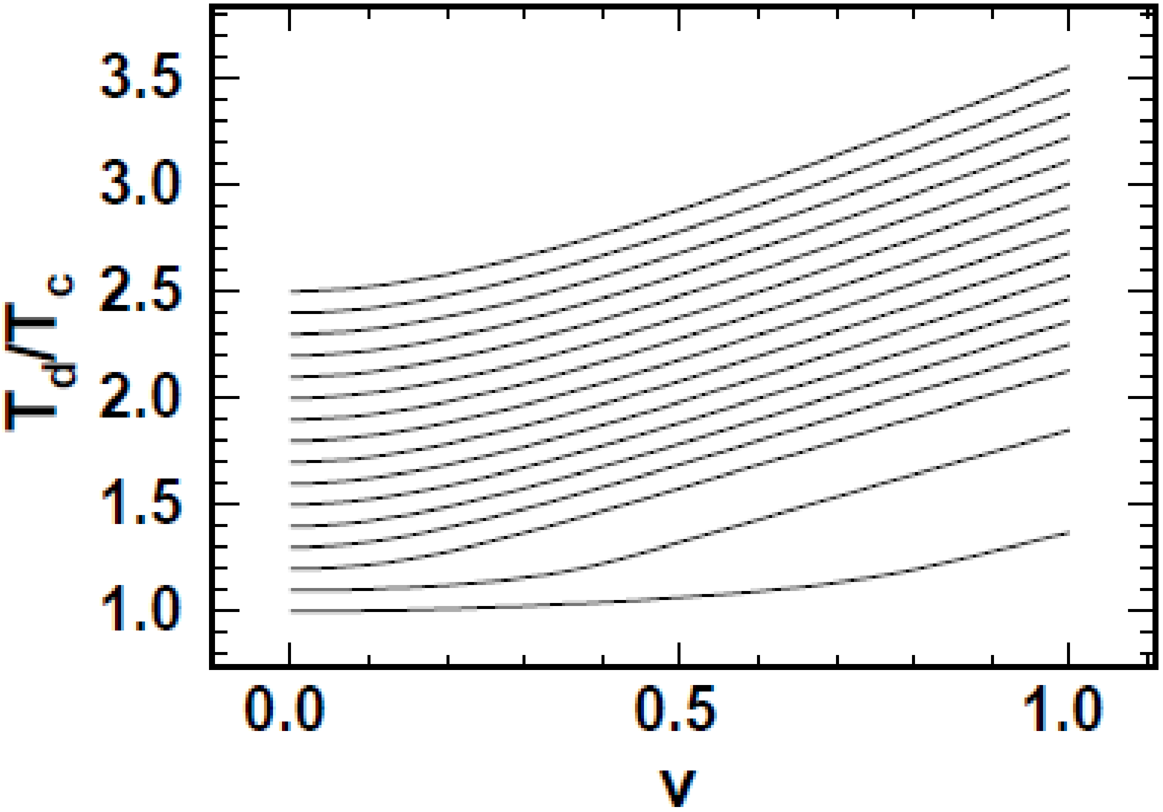
$$V(\mathbf{r},\mathbf{L}) = \int_0^\infty V_0(\mathbf{r}+\lambda\mathbf{L})e^{-\lambda}d\lambda. \qquad \mathbf{L} \equiv \mathbf{v}\tau$$



the quark potential well becomes deeper with increasing J/ψ velocity .

Running Dissociation Temperature

Y.Liu et al, 2012

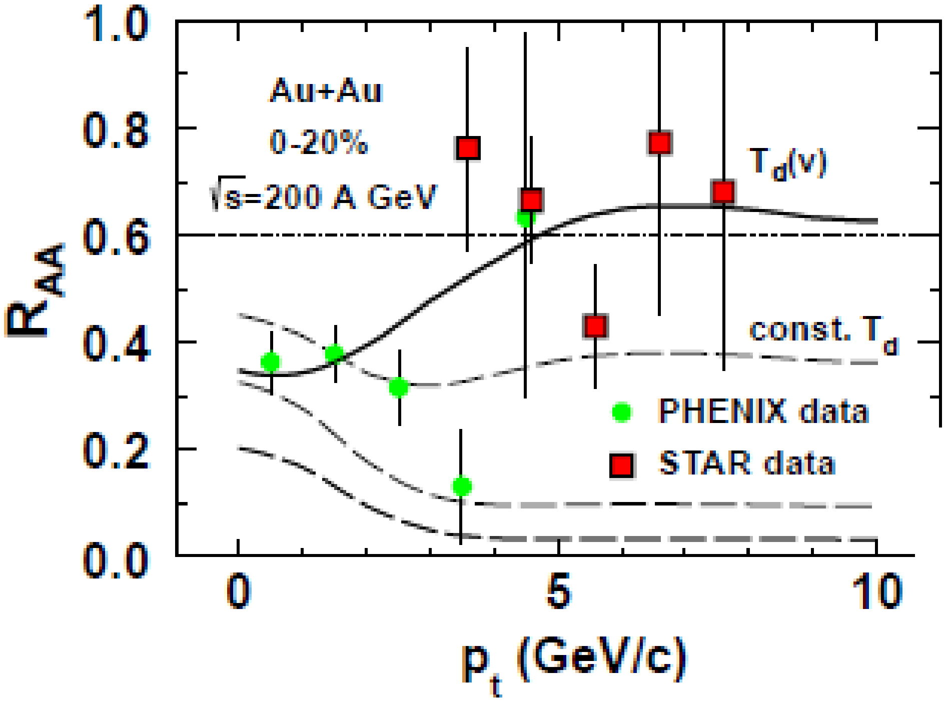


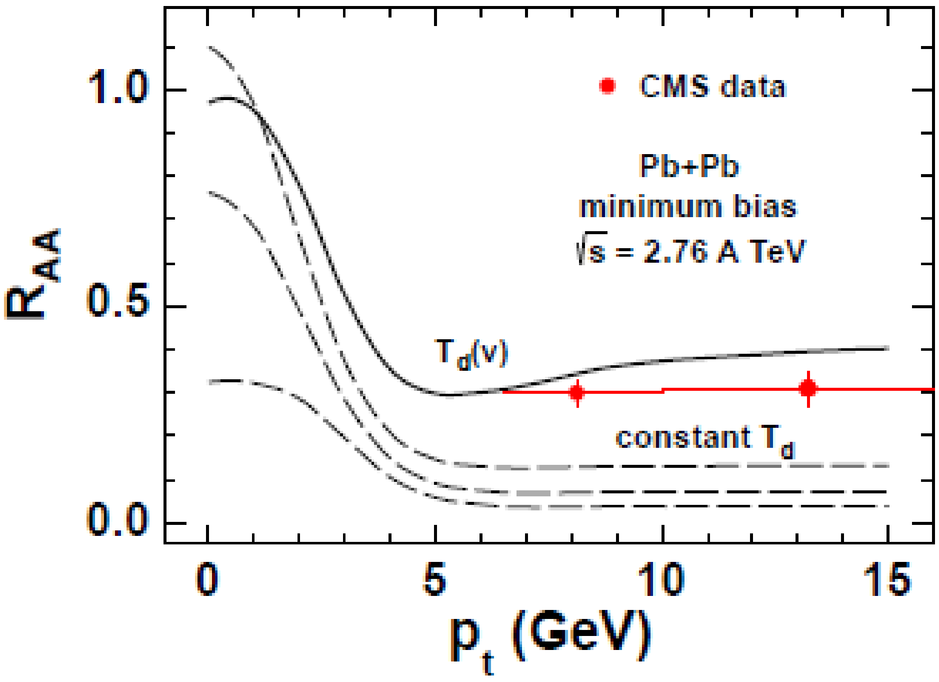
high momentum particles are not sensitive to the medium, their dissociation temperature should be higher than the soft particles

Few examples later

Running Dissociation Temperature

Y.Liu, N.Xu, PZ, 2012





running dissociation temperature is important at high Pt !