What is New in Quarkonium Production at RHIC and LHC ?

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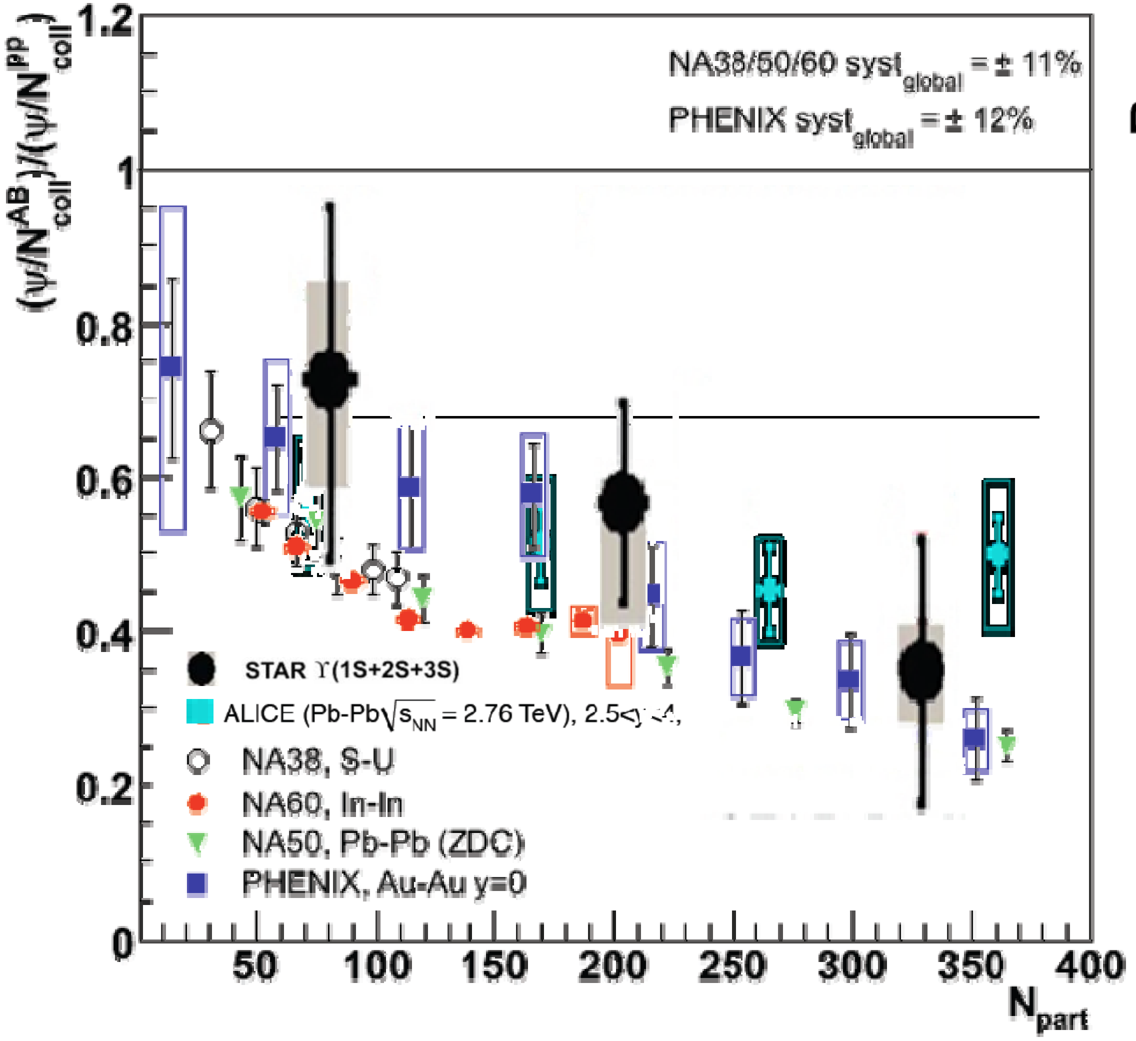
- Introduction
- A Full Transport Approach
- P_t Distribution and V_2 Distribution
- Υ Production and Heavy Quark Potential
- Summary

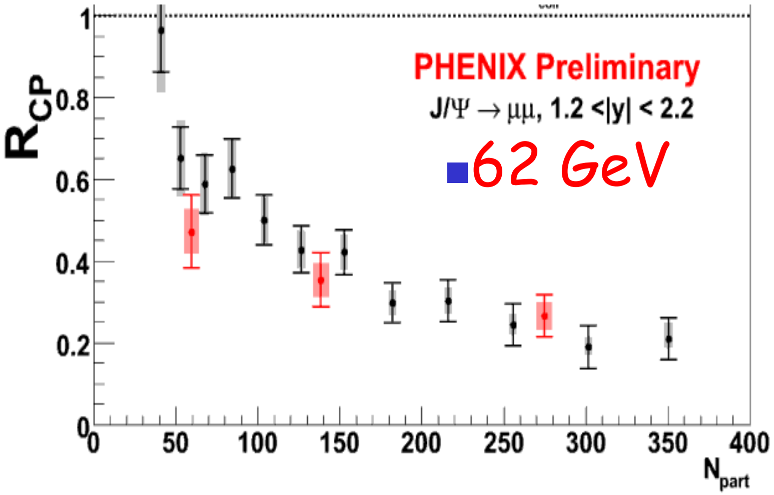
Thanks to Yunpeng LIU, Kai ZHOU and Dr. Nu XU

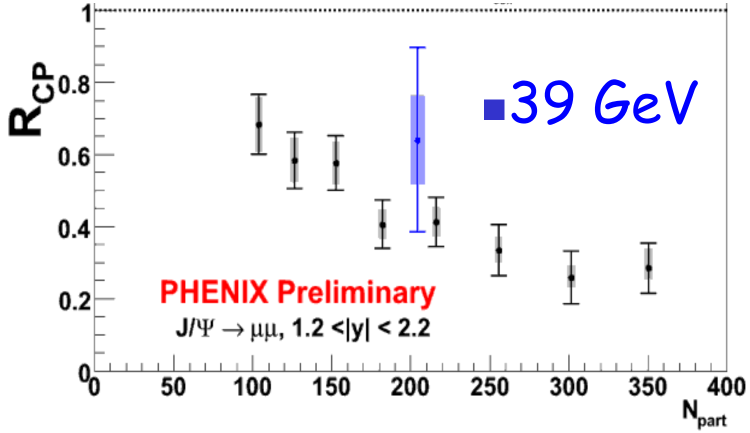
EMMI Workshop: Quarkonia in Deconfined Matter

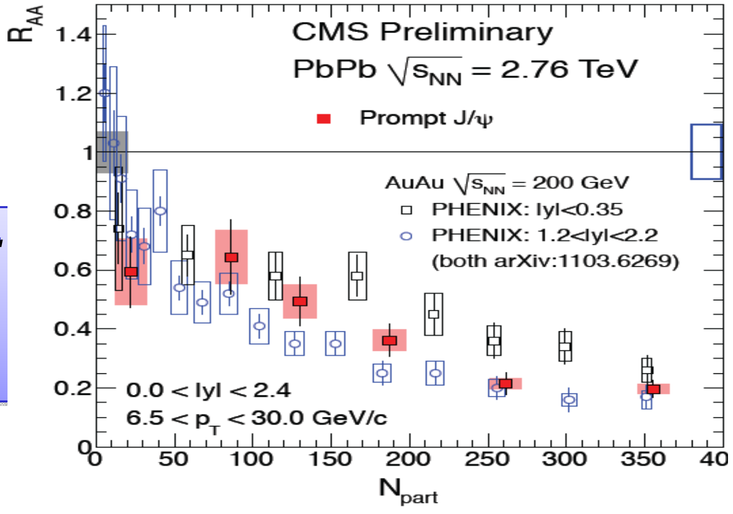
Acitrezza, Italy, September 28-30, 2011

Introduction



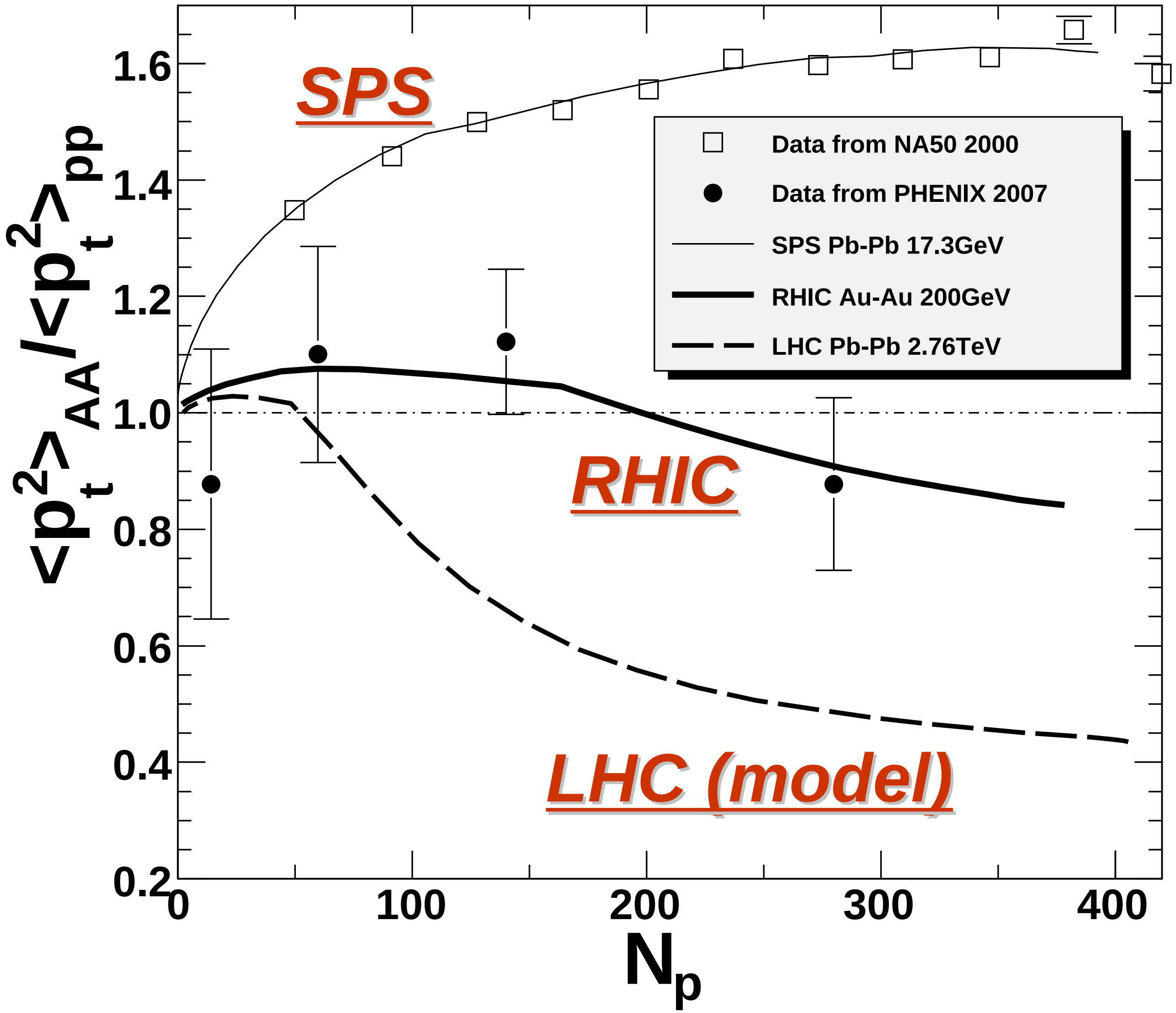






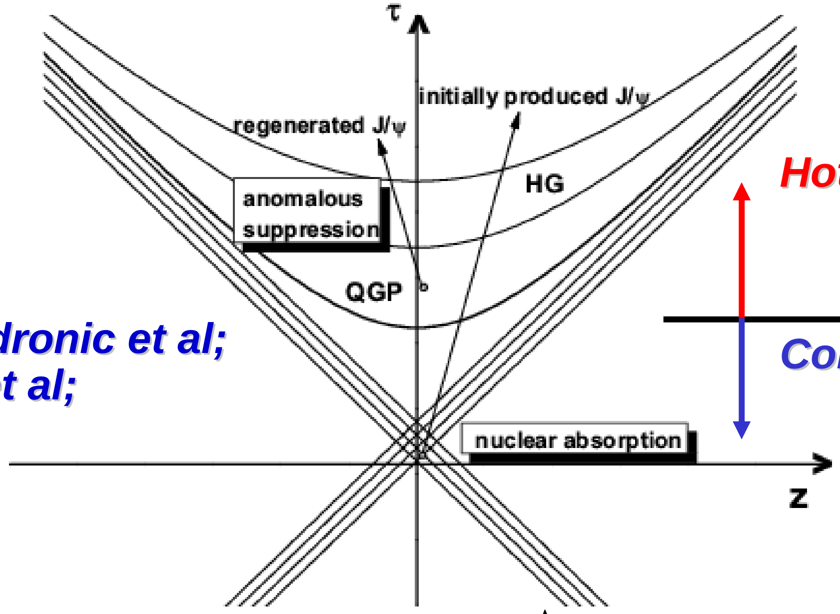
SQM2011 experimental summary by K.Safarik:
overall suppression of J/ψ is nearly identical between SPS, RHIC & LHC !

However, *the transverse momentum distribution is sensitive to the quarkonium production mechanism !*



A Full Transport Approach

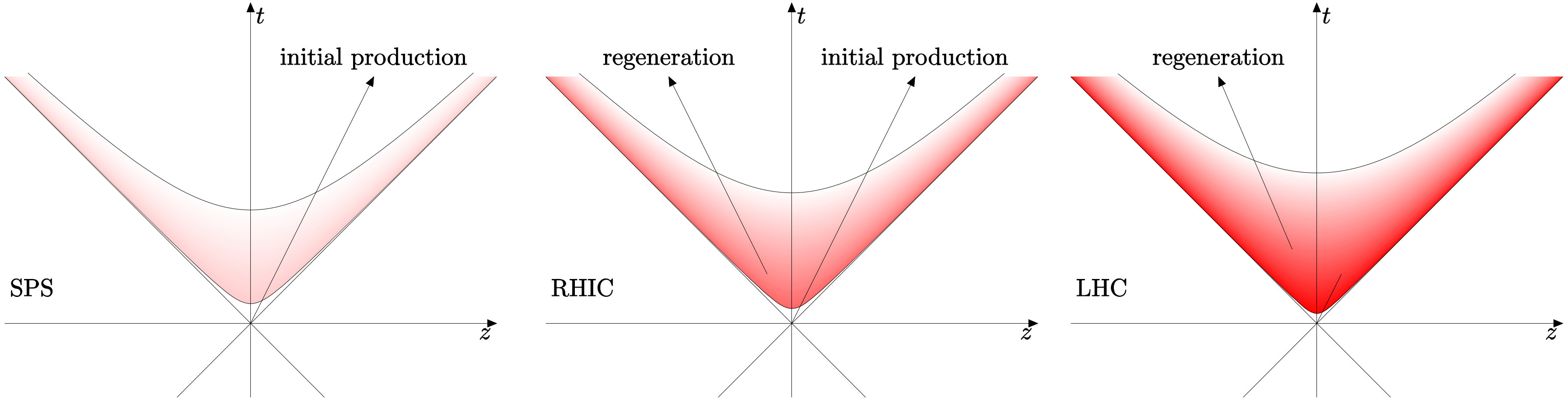
Quarkonium Production Picture



Regeneration:
PBM, Stachel, Andronic et al;
Thews,Mangano et al;
Rapp, Zhao et al;

Hot nuclear matter effects:
1. **suppression in QGP and HG**
2. **regeneration in QGP and HG**

Cold nuclear matter effects:
1. **nuclear absorption**
2. **Cronin effect**
3. **shadowing effect**



screening only, screening + regeneration

- **initial production controls high pt region**
- **regeneration becomes important at low pt**

A Full Transport Approach for Quarkonia in HIC

Yan, Zhu, Xu, Zhuang, 2005-2011

- ***QGP hydrodynamics***

$$\begin{aligned}\partial_\tau E + \nabla\cdot\mathbf{M} &= -(E+p)/\tau\ ,\\ \partial_\tau M_x + \nabla\cdot(M_x\mathbf{v}) &= -M_x/\tau - \partial_x p\ ,\\ \partial_\tau M_y + \nabla\cdot(M_y\mathbf{v}) &= -M_y/\tau - \partial_y p\ ,\\ \partial_\tau R + \nabla\cdot(R\mathbf{v}) &= -R/\tau\end{aligned}$$

+ equation of state (ideal gas or strongly coupled matter from lattice)

- ***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

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

- ***analytic solution***

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

- ***initial production*** $f(\vec{p},\vec{x},t_0)$ ***including CNM, correlation between the cold and hot nuclear matter effect***

Dissociation Cross Section

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

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

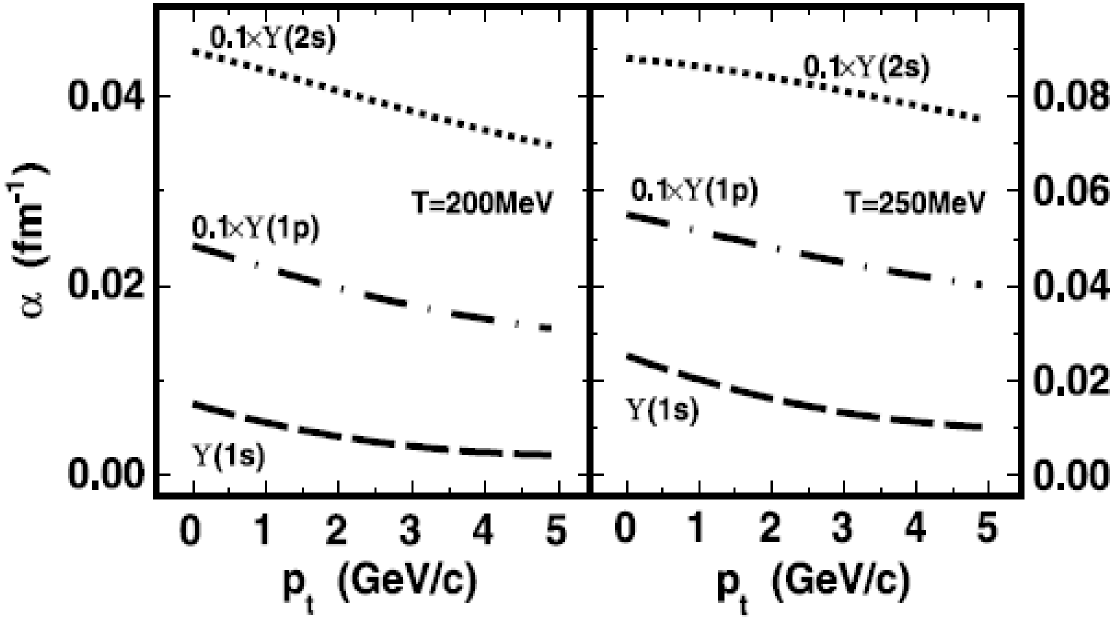
$$\sigma(p_\psi, p_g)$$

- at finite temperature, we use the classical relation

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

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

- dissociation rate of Υ at a fixed medium velocity v=0.5 and for V=U:

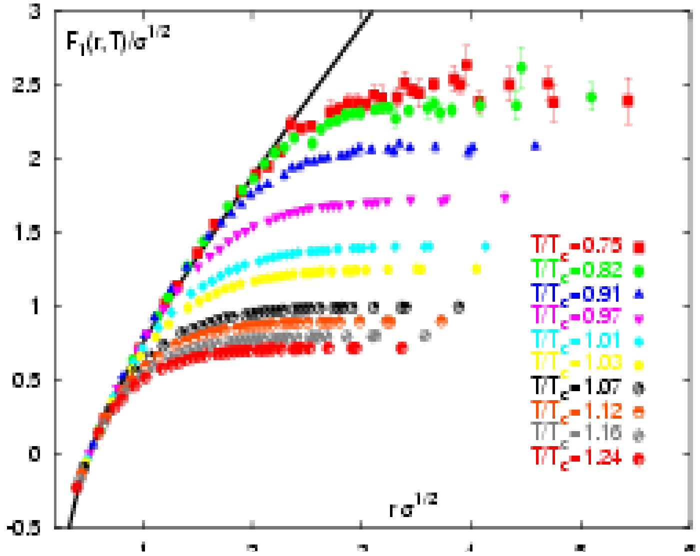


1)T-dependence of the differential cross section is still an open problem;
2) we did not consider quasi-free processes which may play an important role at high $T<T_d$.

- regeneration rate is determined by the detailed balance

Dissociation Length $\langle r^2\rangle(T)$ in Potential Model

Lattice calculated free energy F for a pair of $Q\bar{Q}$



two limits of the potential:

$$V(r,T)=\begin{cases} F, & \text{slow dissociation} \\ U=F+TS, & \text{rapid dissociation} \end{cases}$$

Schroedinger equation at finite T:

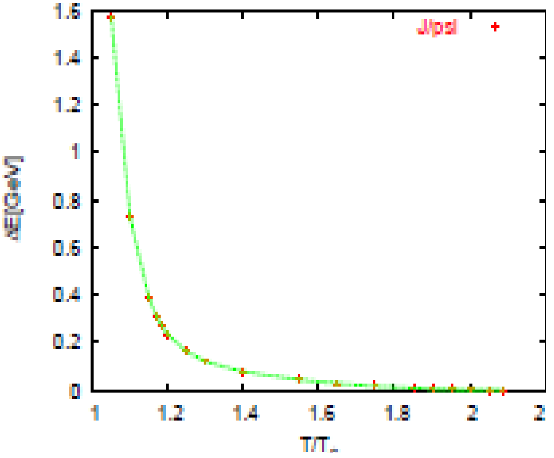
average distance $\langle r\rangle(T)$

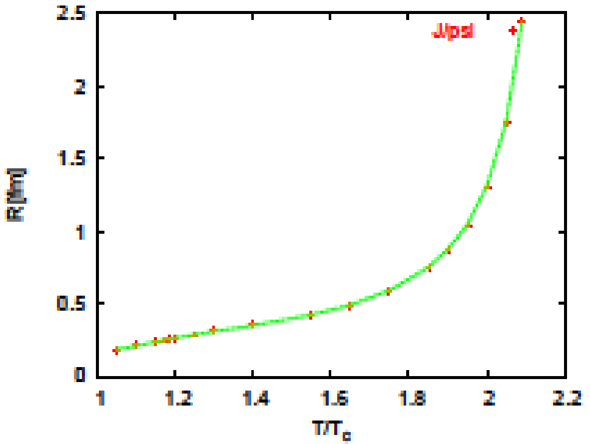
binding energy $\varepsilon(T)$

dissociation temperature

$$\langle r\rangle(T_D)\to\infty,\quad \varepsilon(T_D)\to 0$$

for V=U (Satz et al)



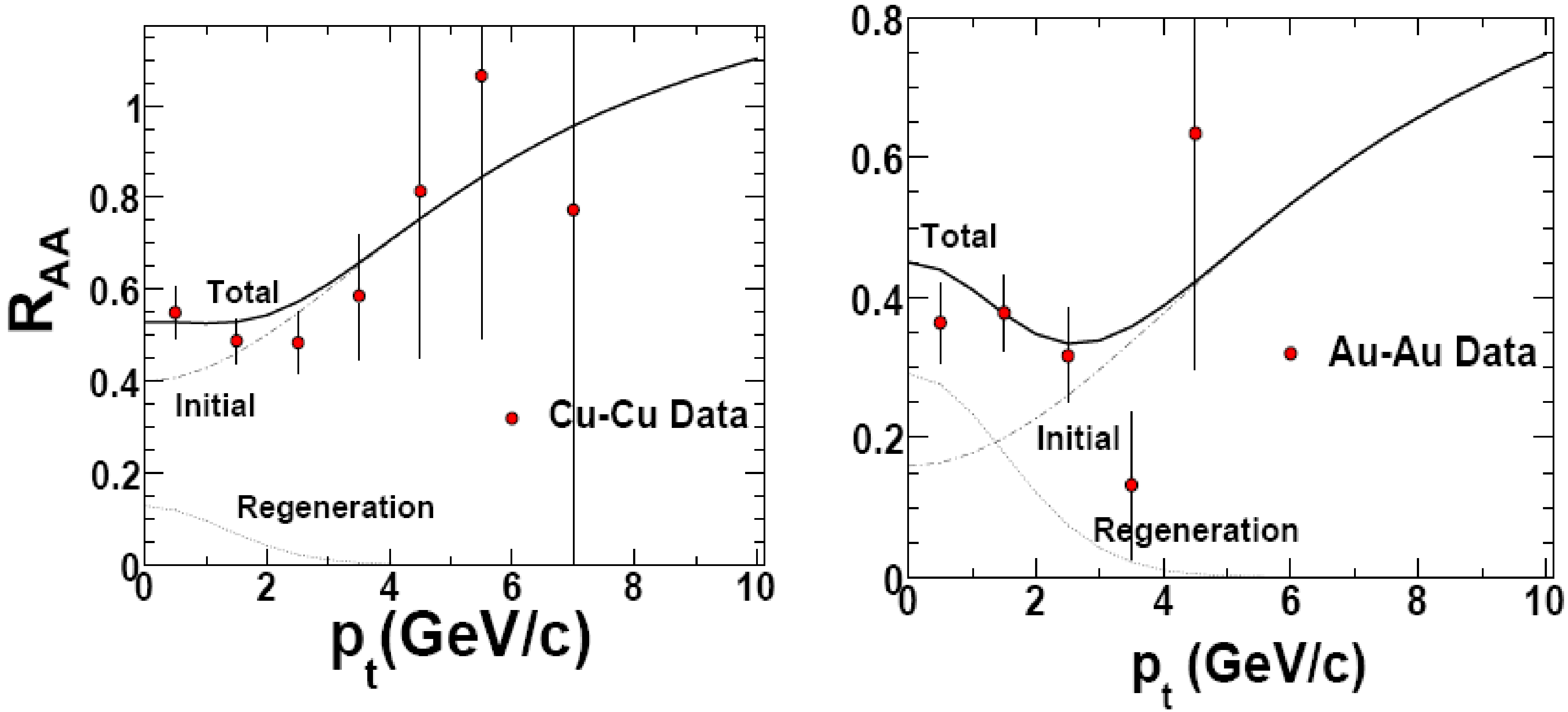


state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

P_t Distribution and V_2 Distribution

$J/\psi\ R_{AA}\ (p_t)$ at RHIC

Liu, Qu, Xu, Zhuang: arXiv:0901.2757,PLB2009



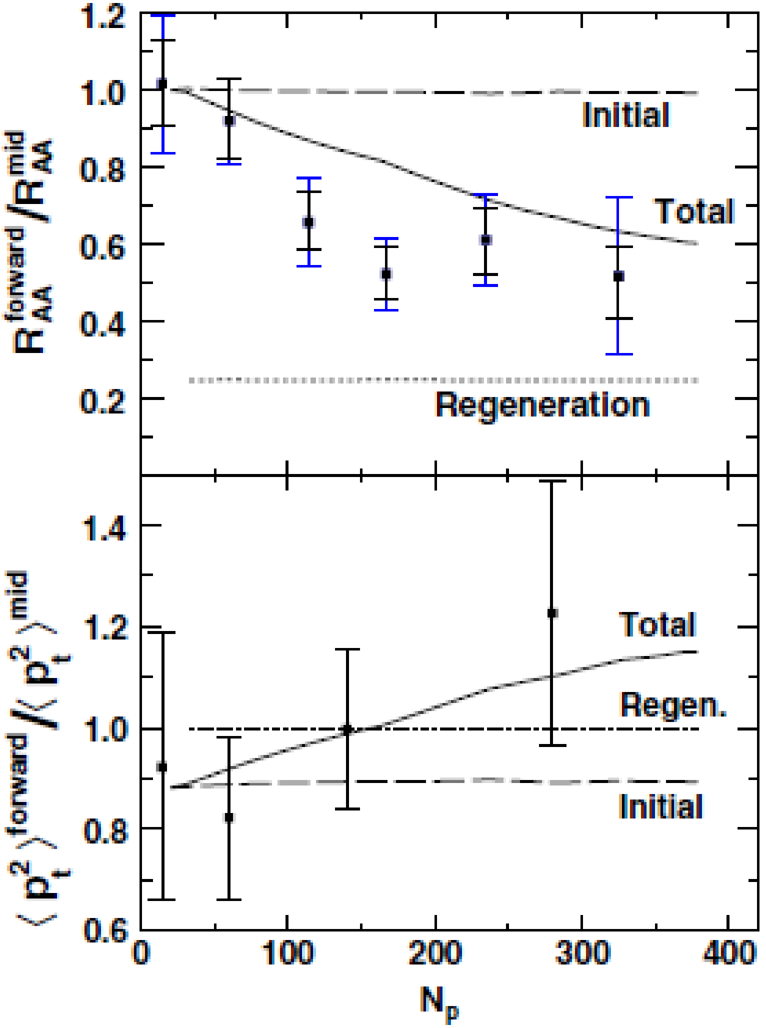
the competition between initial production and regeneration leads to a minimum, a signature for the coexistence of both production mechanisms.

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

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

J/ψ Rapidity Dependence at RHIC

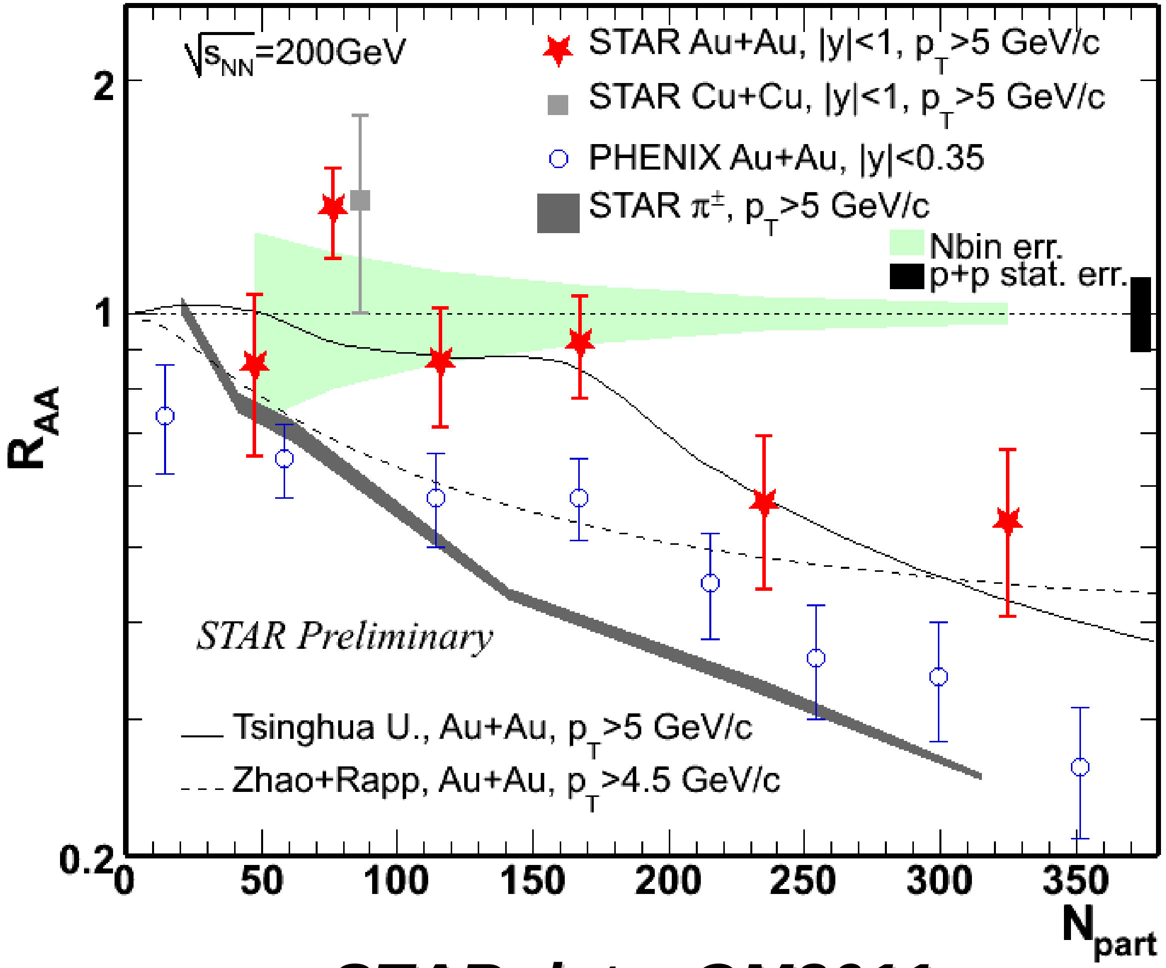
Liu, Xu, Zhuang: arXiv:0907.2723,JPG2010



less regeneration in forward rapidity explains the two puzzles naturally.

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

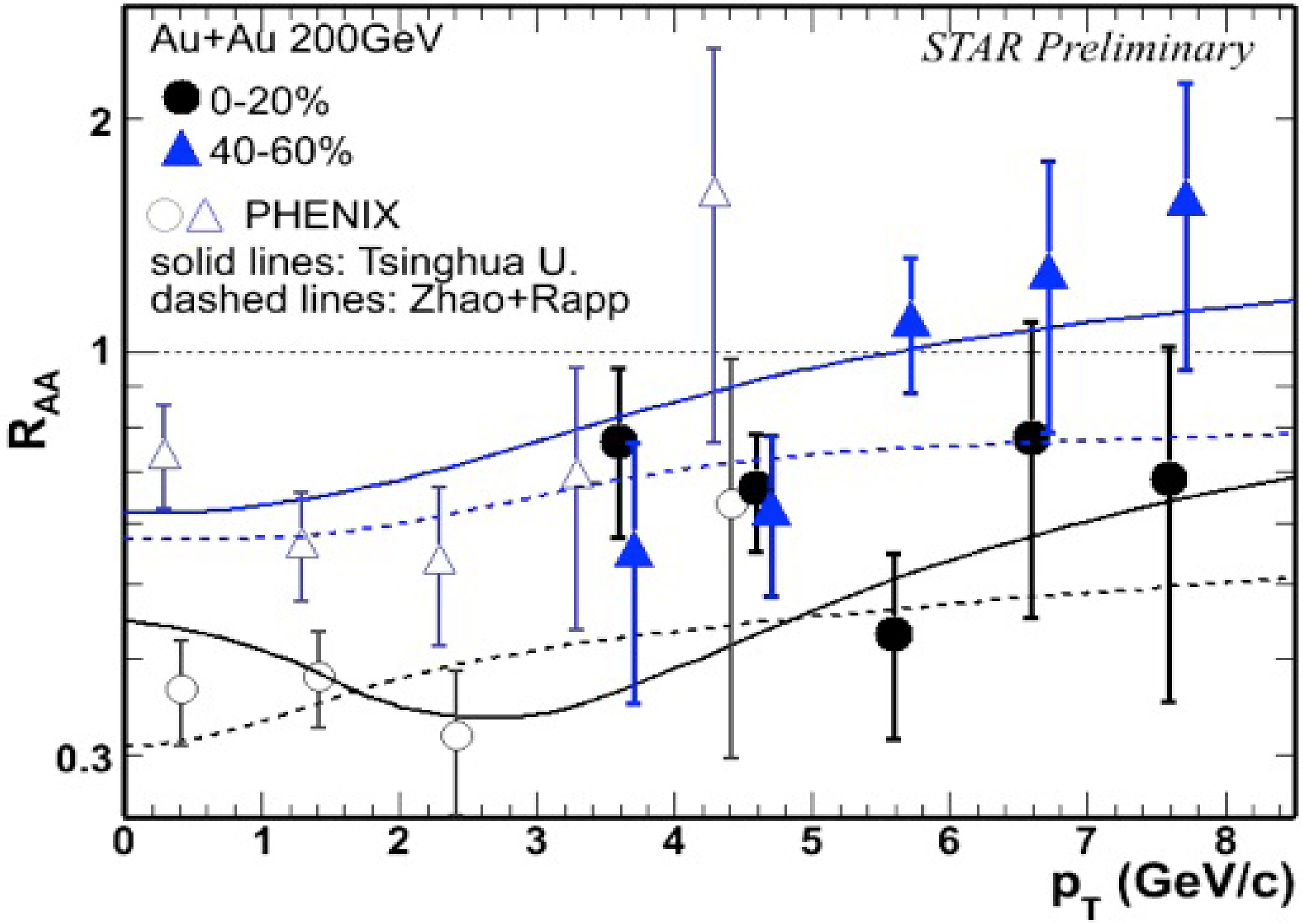
J/ψ R_{AA} (N_p) at high pt at RHIC



STAR data, QM2011

high pt particles can survive in hot medium.

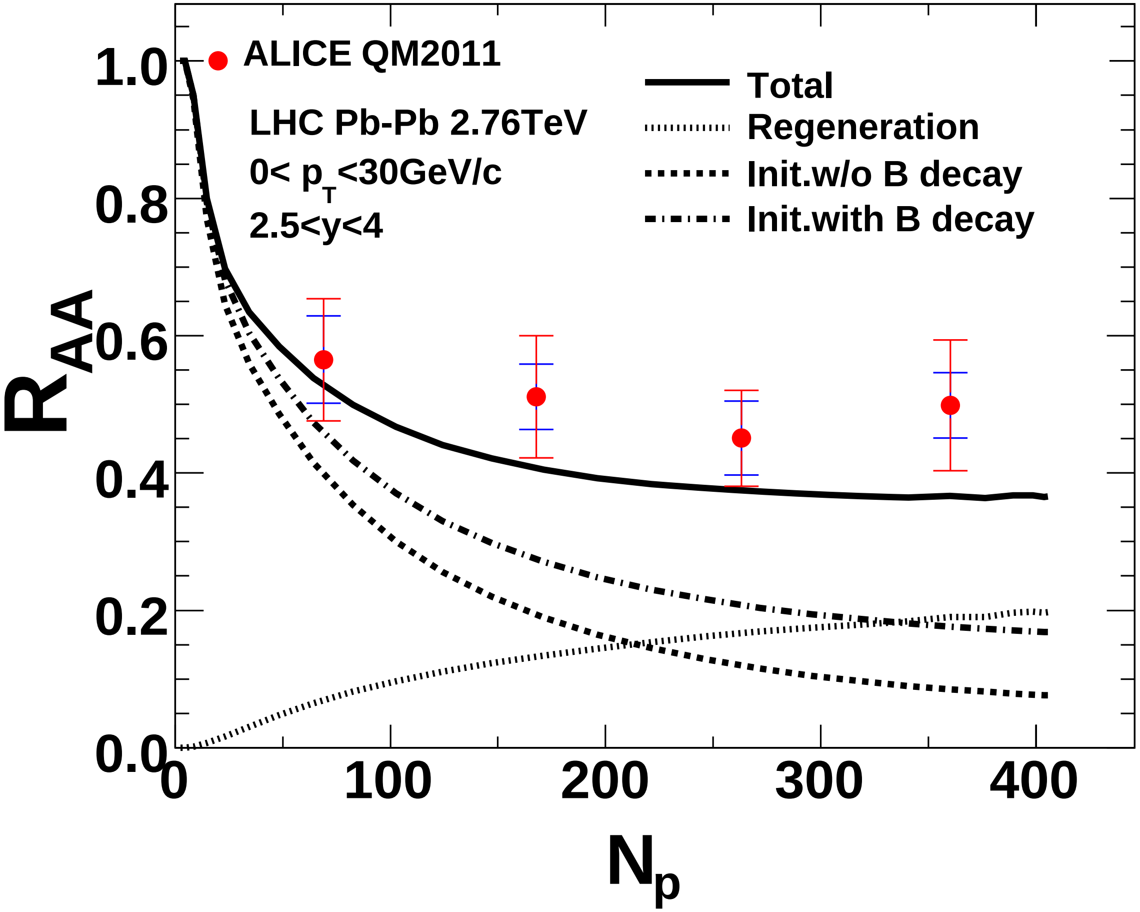
centrality dependence of J/ψ R_{AA} (p_t) at RHIC



STAR data, QM2011

more suppression in central collisions

J/ψ R_{AA} (N_p) at LHC

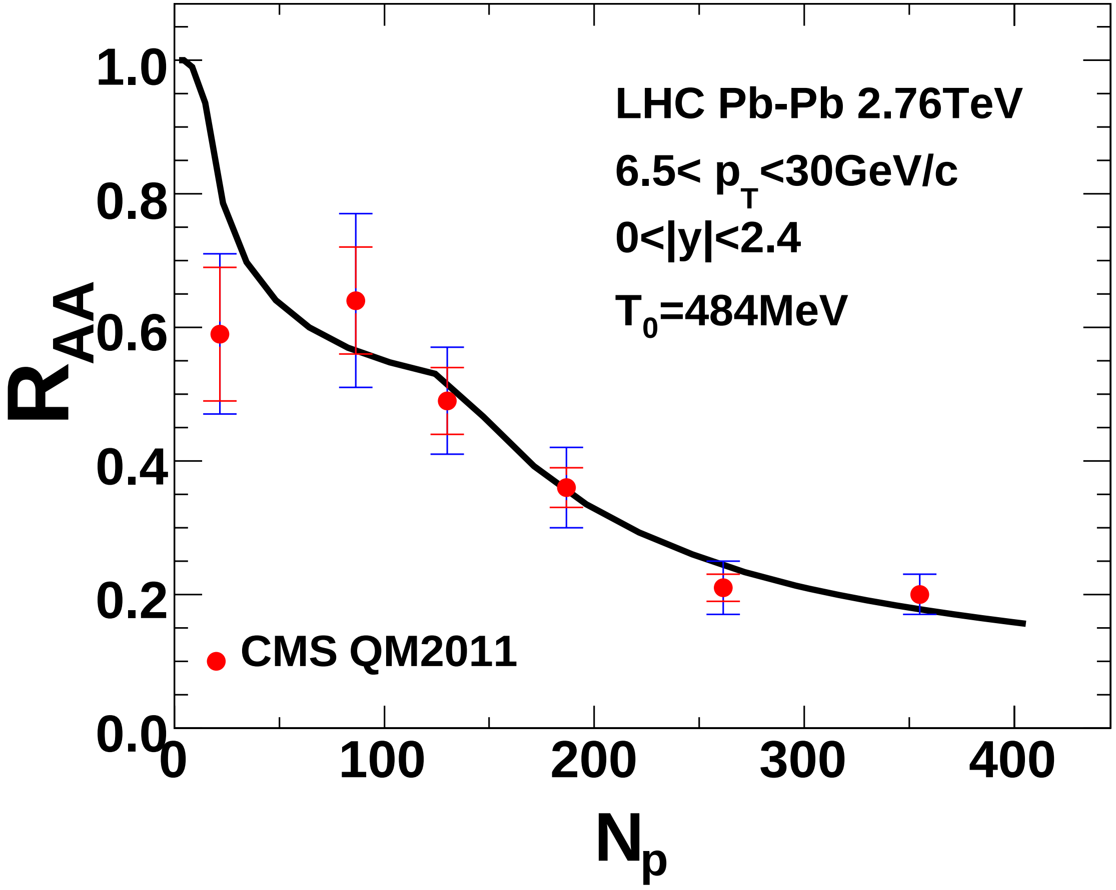


more regeneration at LHC $\rightarrow$ $R_{AA}^{ALICE} > R_{AA}^{PHENIX}$

$\tau_0 = 0.6\ fm$, $T_0 = 430$ MeV (Hirano, Heinz),

$\sigma_{pp}^{J/\psi} = 2.33\mu b$ (arXiv:1107.0137), $\sigma_{pp}^{c\bar{c}} = 3.45nb$ (total, QM2011 talk by Dainese)

$J/\psi\ R_{AA}\,(N_p)$ at high pt at LHC

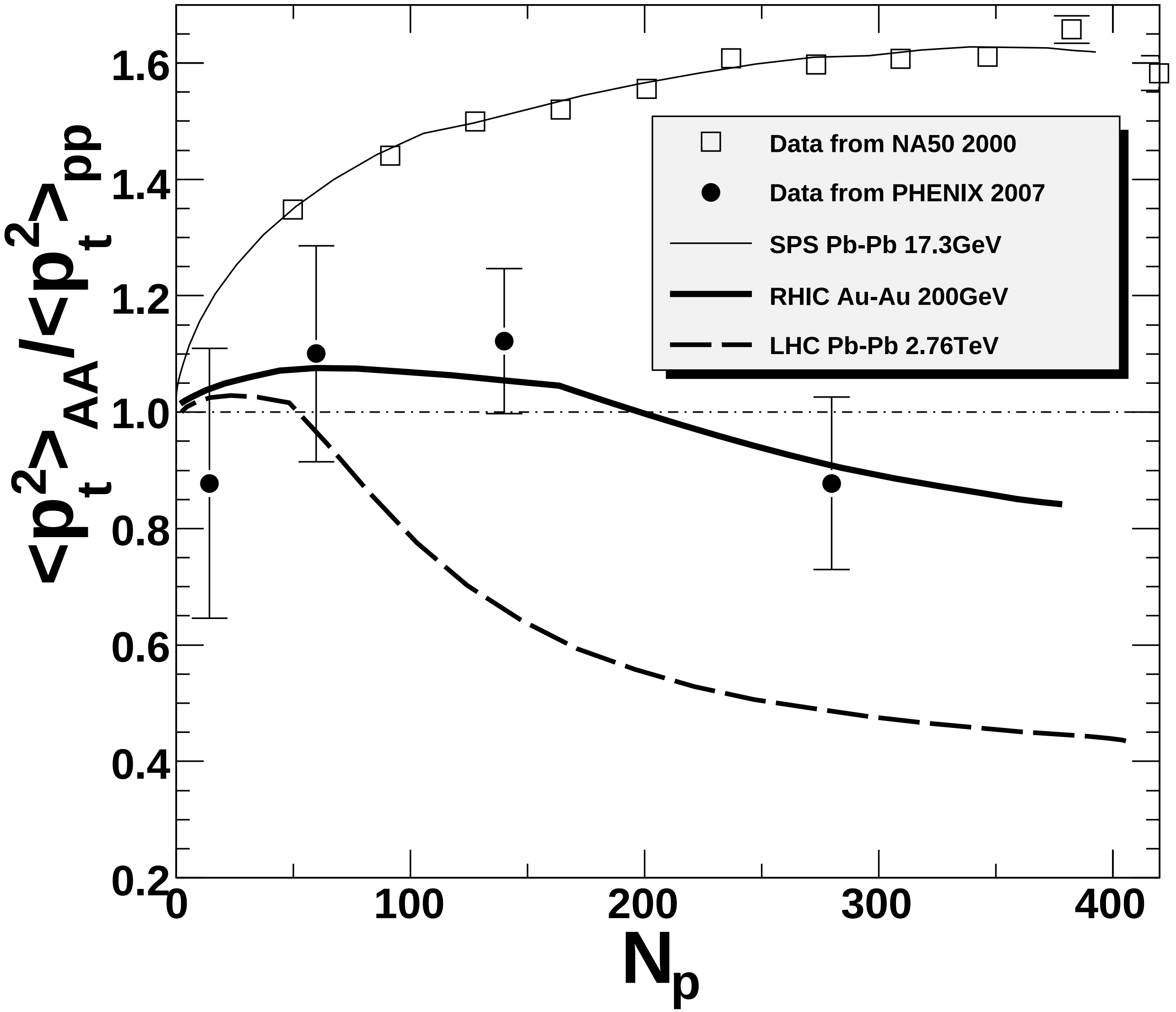


more regeneration at low pt $\rightarrow\ R_{AA}^{ALICE} > R_{AA}^{CMS}$

$\tau_0 = 0.6\ fm,\quad T_0 = 484$ MeV (Hirano, Heinz),

$d\sigma_{pp}^{J/\psi}/dy = 3.5\ \mu b$ (arXiv:1107.0137)

Averaged Transverse Momentum



SPS:

Cronin effect

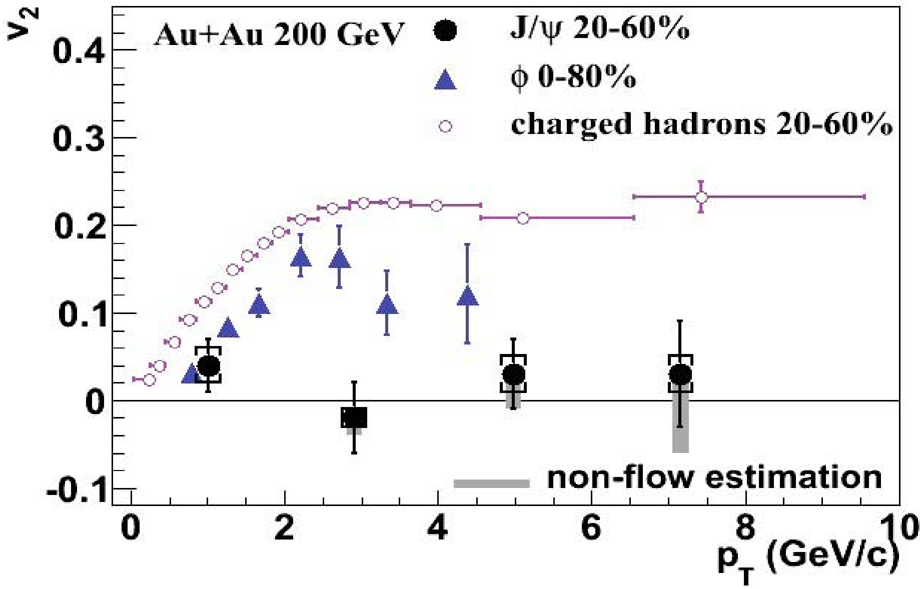
RHIC:

competition between the two sources

LHC:

dominant regeneration

J/psi elliptic flow at RHIC

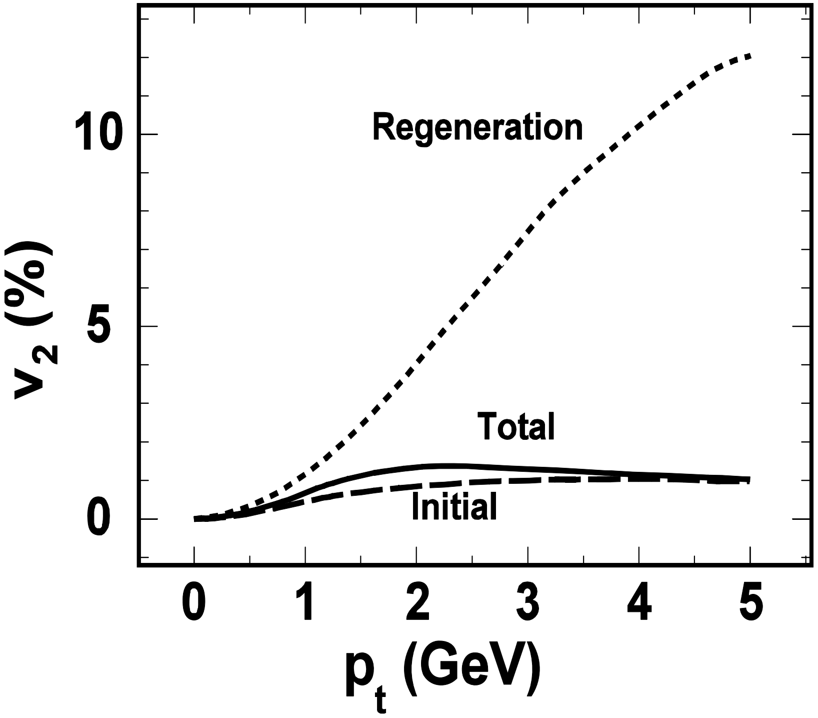


STAR data, QM2011

our prediction:

Yan, Xu, Zhuang: nucl-th/0608010,PRL2006

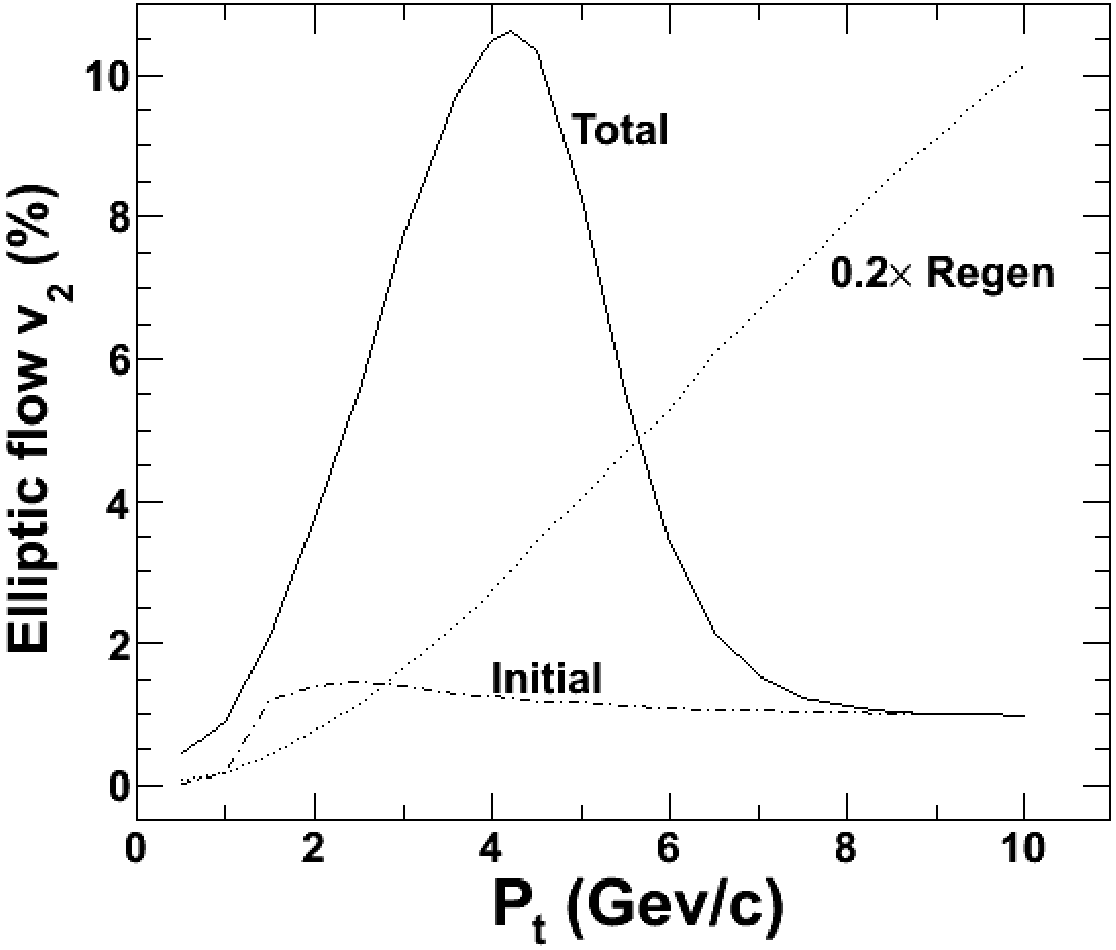
impact parameter b=7.8 fm



no J/psi V2 at RHIC, but remarkable v2 at LHC !

J/psi elliptic flow at LHC

our prediction at \sqrt s = 5.5 TeV, b=7.8 fm (NPA2010) :



remarkable v2 at LHC !

Υ Production and Heavy Quark Potential

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 anomalous suppression during the evolution of the hot medium.

ϒ:

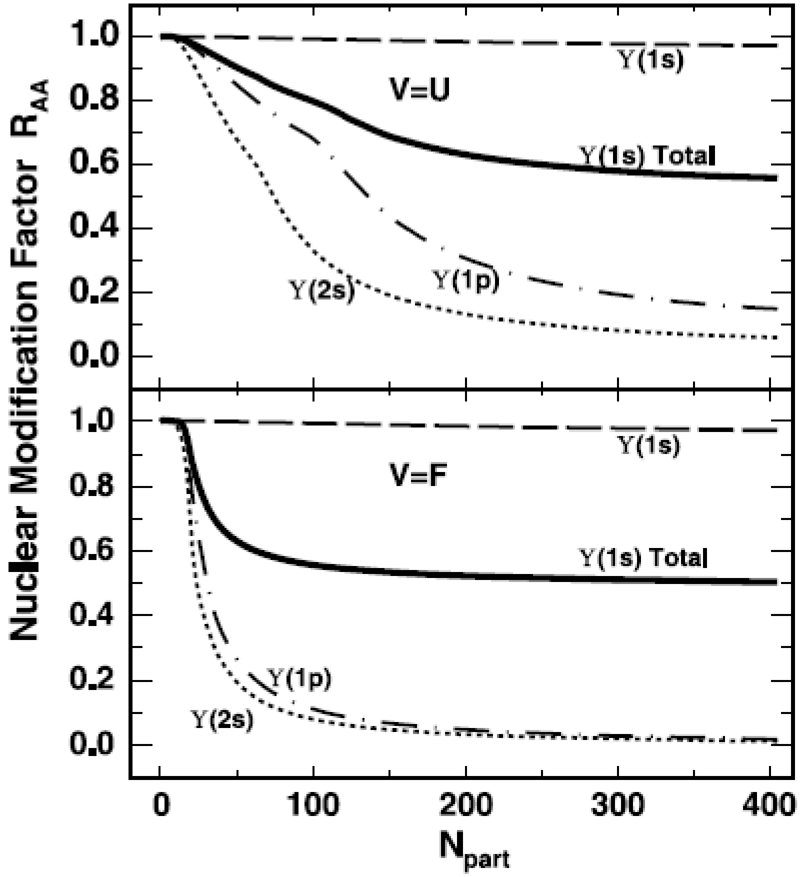
1) the regeneration can be safely neglected;

2) there is almost no feed-down for ϒ ;

3) weaker CNM effect

Υ at RHIC: $R_{AA}(N_p)$

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

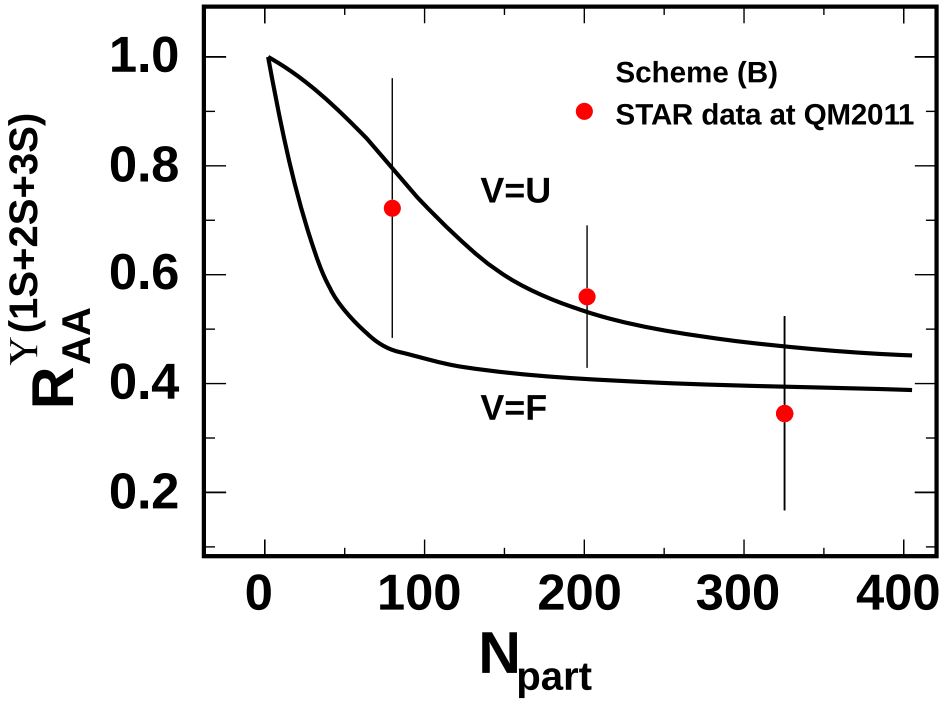


for minimum bias events:

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

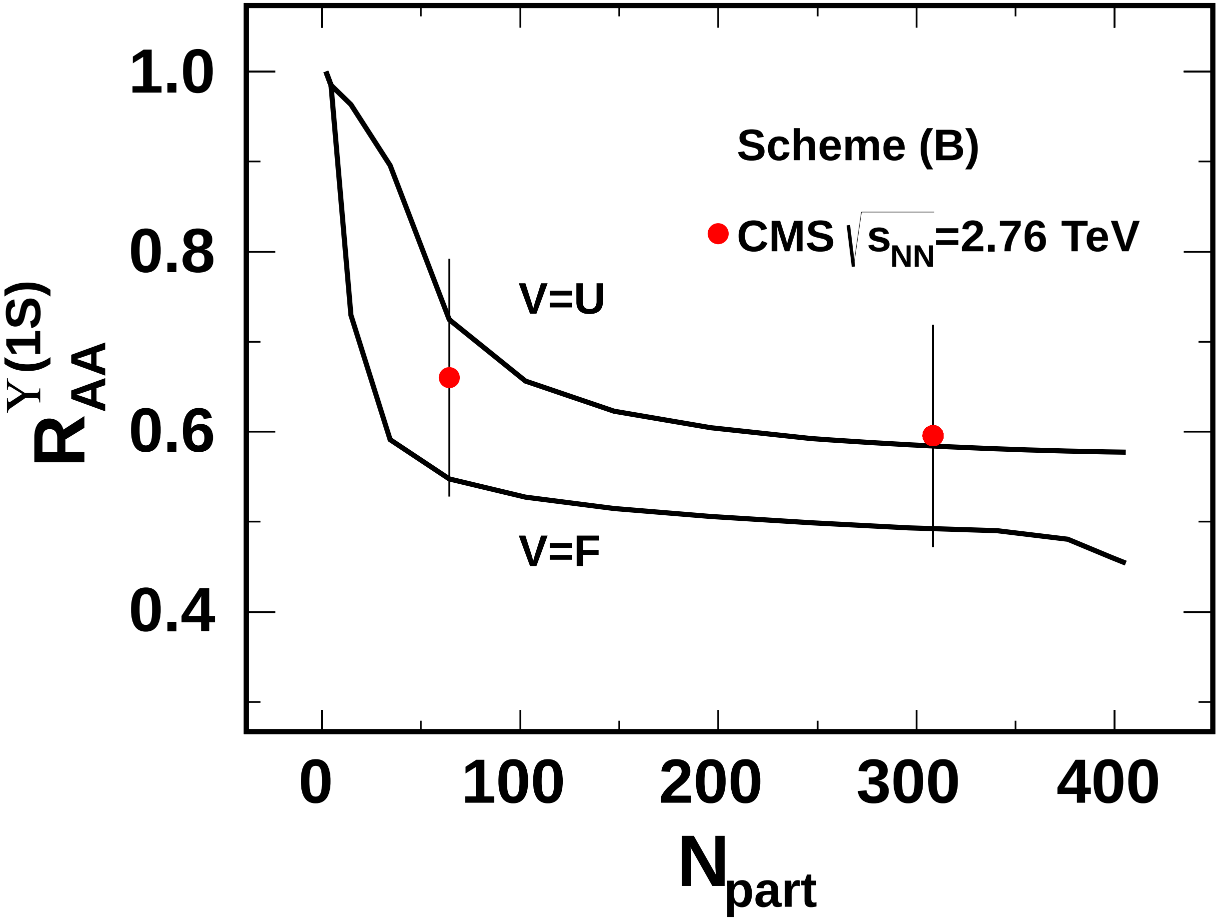
our result: R_{AA} = 0.63 for V=U

R_{AA}= 0.53 for V=F



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

ϒat LHC: $R_{AA}(N_p)$



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

- *again, V is close to U.*

Conclusions:

- *pt dependence is more sensitive to the production and suppression mechanism.*
- *regeneration is important at RHIC and LHC.*
- *competition between initial production and regeneration can explain systematically the data from SPS to LHC.*
- *Upsilon production at RHIC and LHC supports V=U.*

Uncertainty analysis:

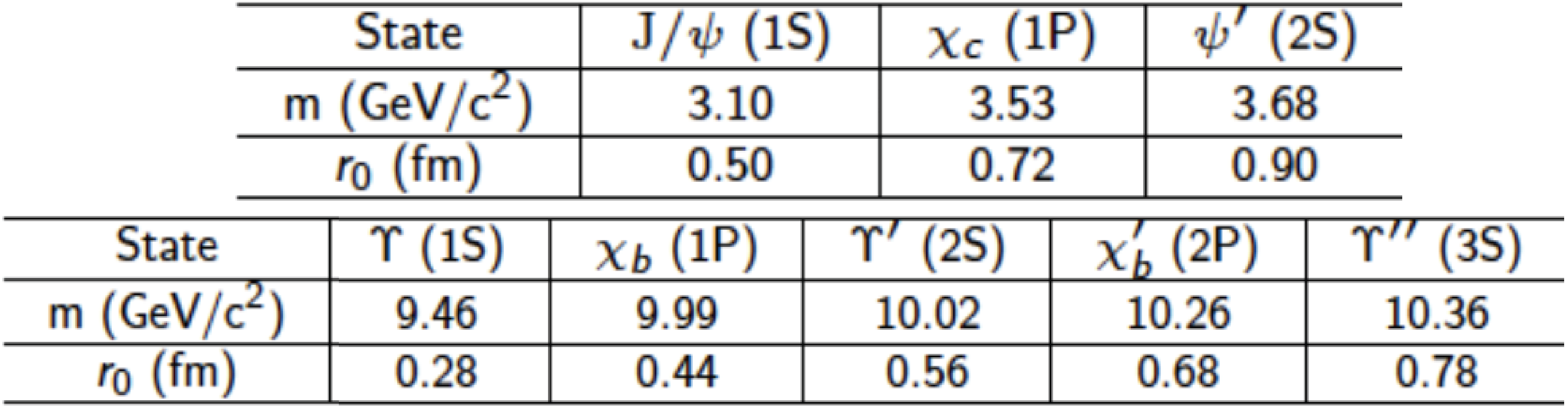
pp collision, shadowing effect, EoS, time scales, ……

Suggestions:

- *measure D-Dbar correlation at LHC (Zhu, Bleicher, Huang, Schweda, Stoecker, Xu, Zhuang, PLB2007, Zhu, Xu, Zhuang, PRL2008)*
- *measure J/psi-D correlation at LHC (since both are from the same source)*
- *measure quarkonium v2 at LHC (which is very sensitive to the production and suppression mechanisms).*

BACKUP

Quarkonium 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 $\Upsilon(1S)$

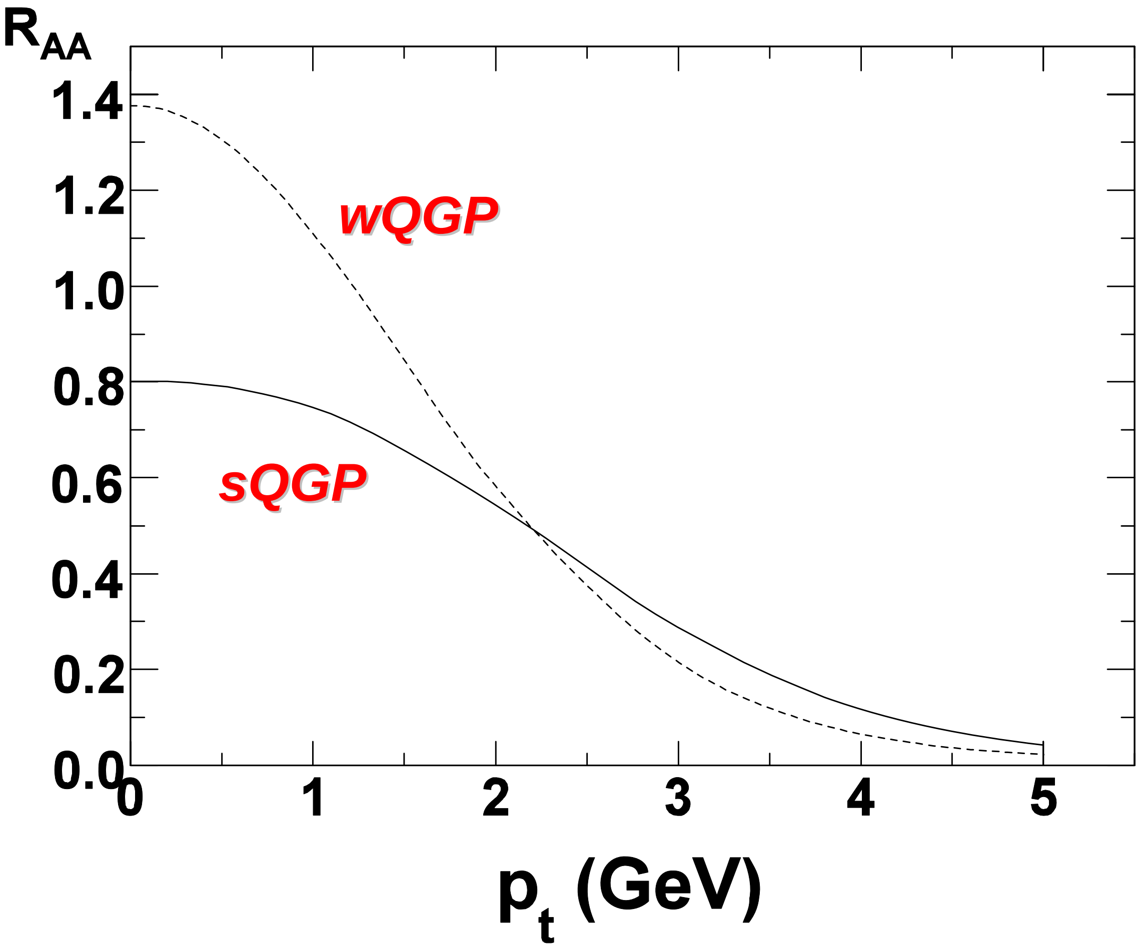
$\Upsilon(1S)$	$\Upsilon(1P)$	$\Upsilon(2S)$	$\Upsilon(2P)$	$\Upsilon(3S)$
51%	27%	11%	10%	1%

Contribution to the observed ground state J/ψ

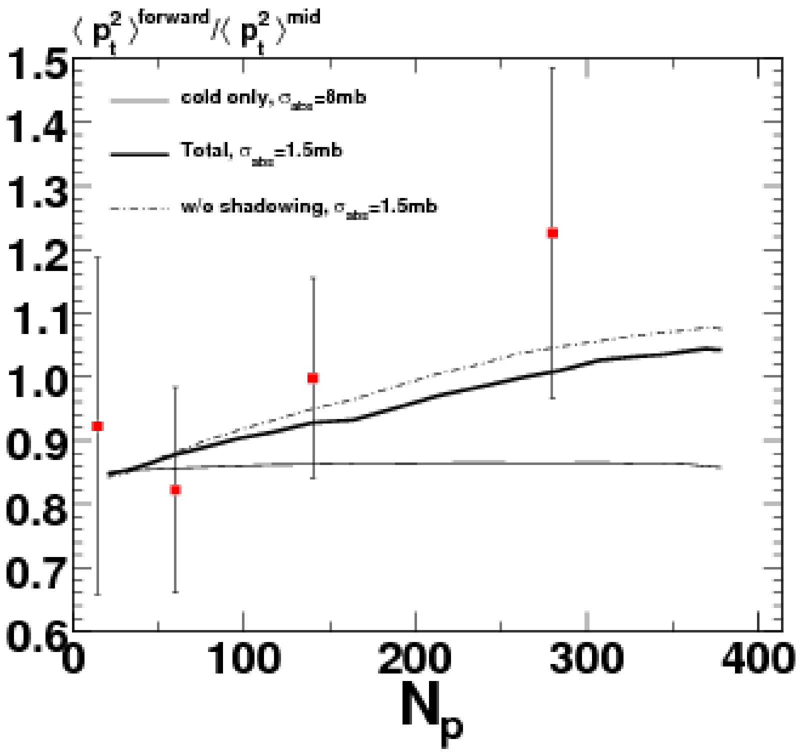
J/ψ	χ_c	ψ'
60%	30%	10%

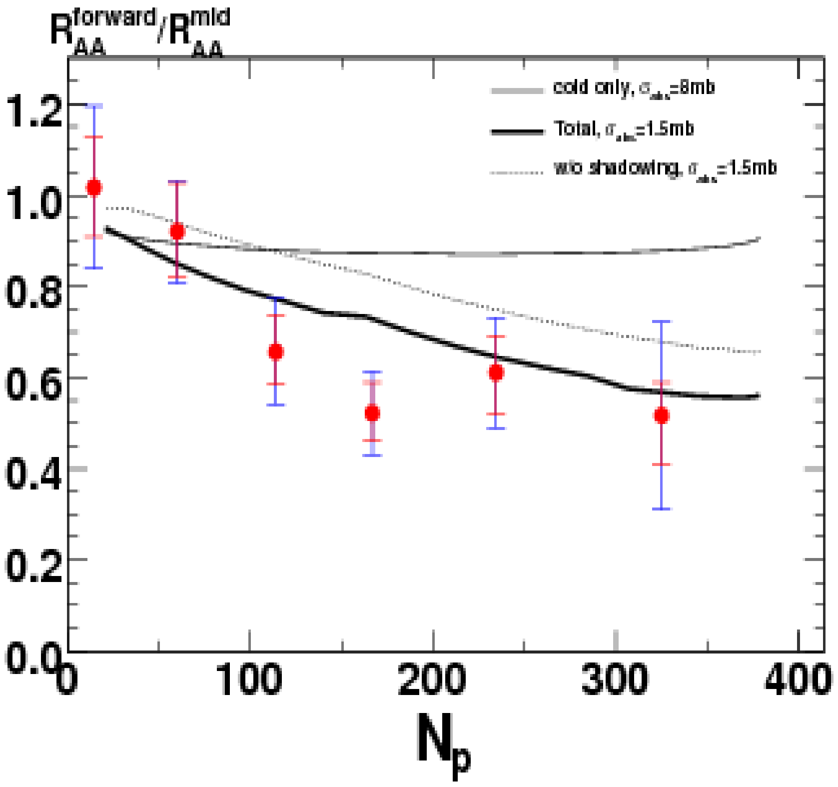
Dependence on EoS

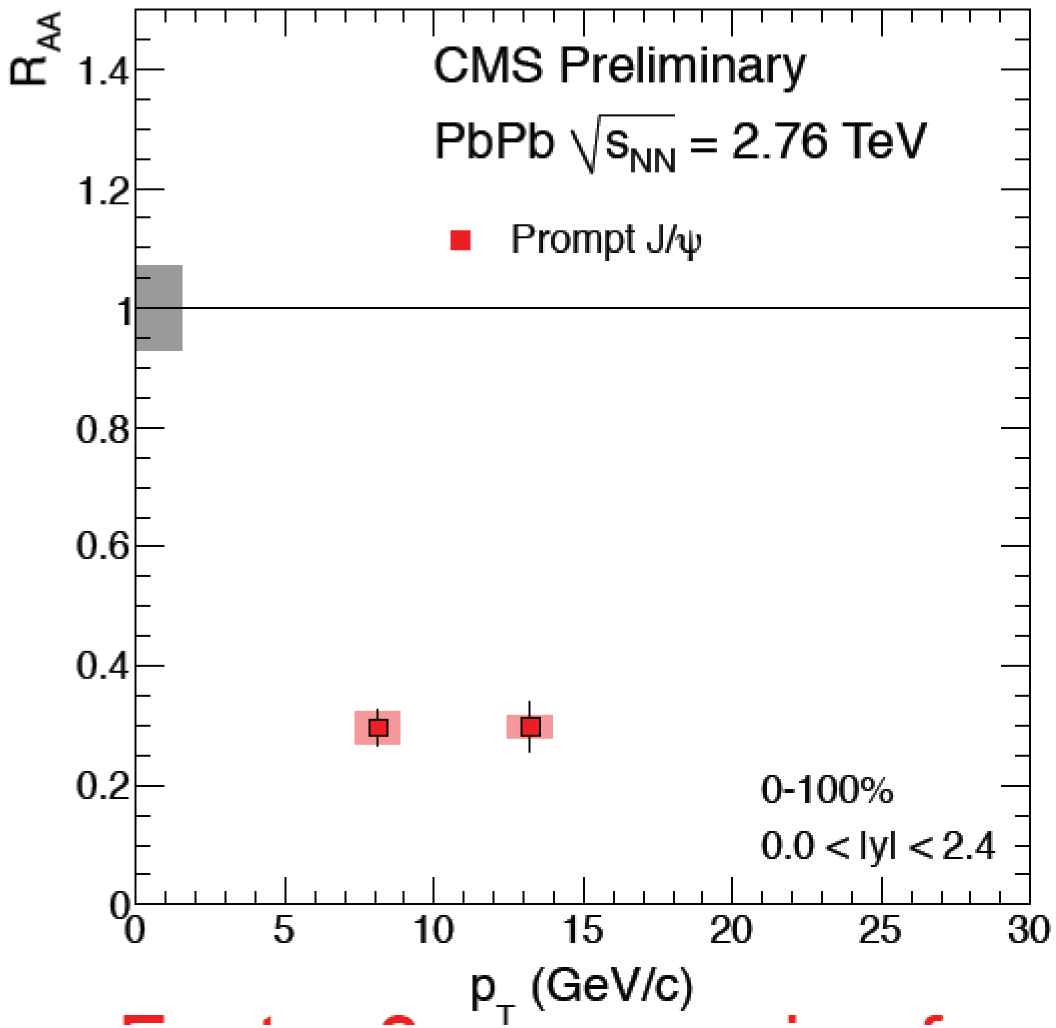
J/Psi Pt distribution at LHC where EoS plays an essential role!



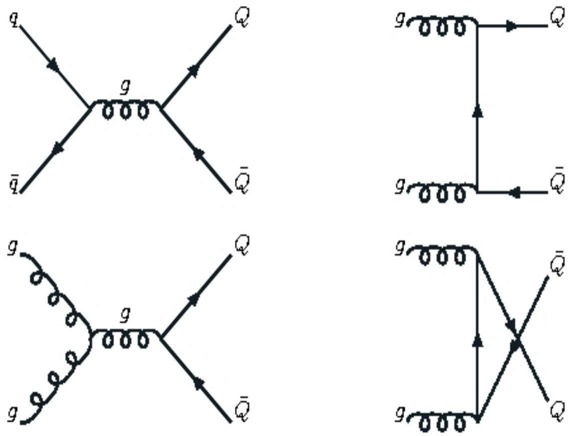
Only Cold Nuclear Matter Effect ?



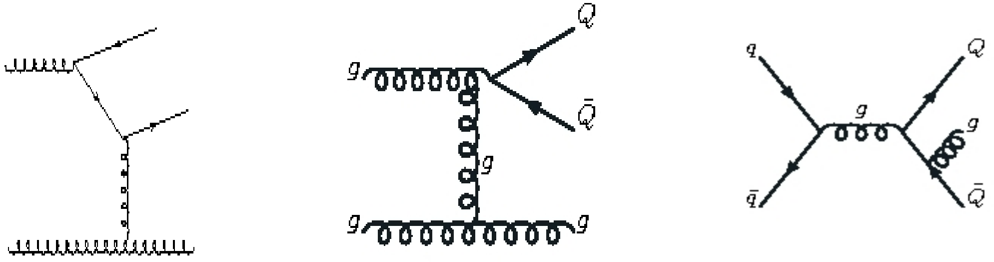


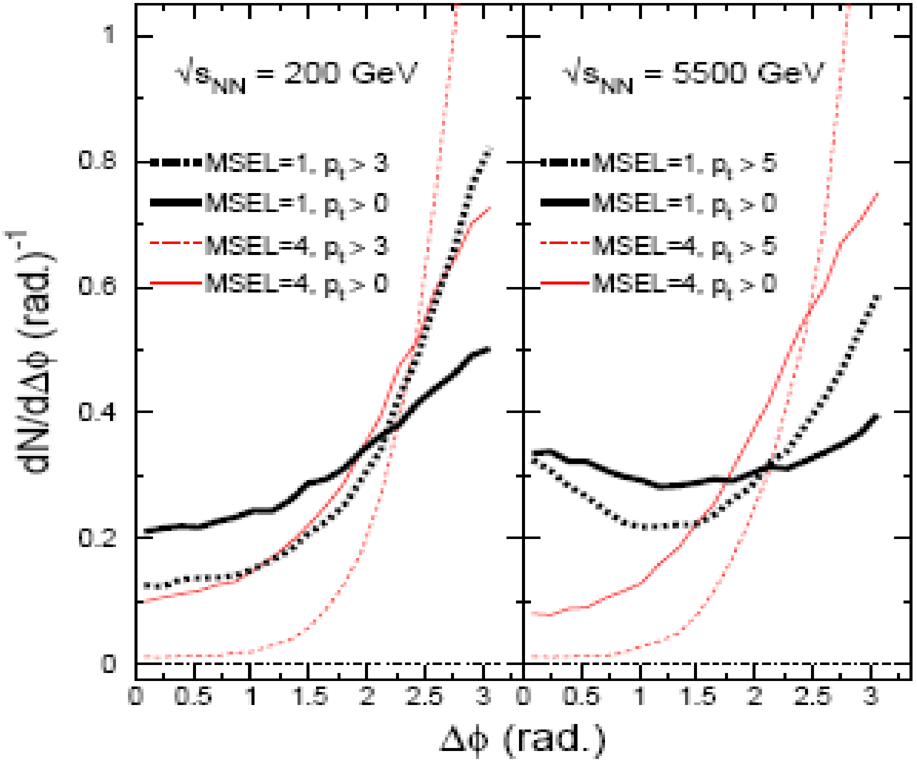

CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
🟥 Prompt J/ψ
0-100%
0.0 < |y| < 2.4
R_{AA}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
p_T (GeV/c)

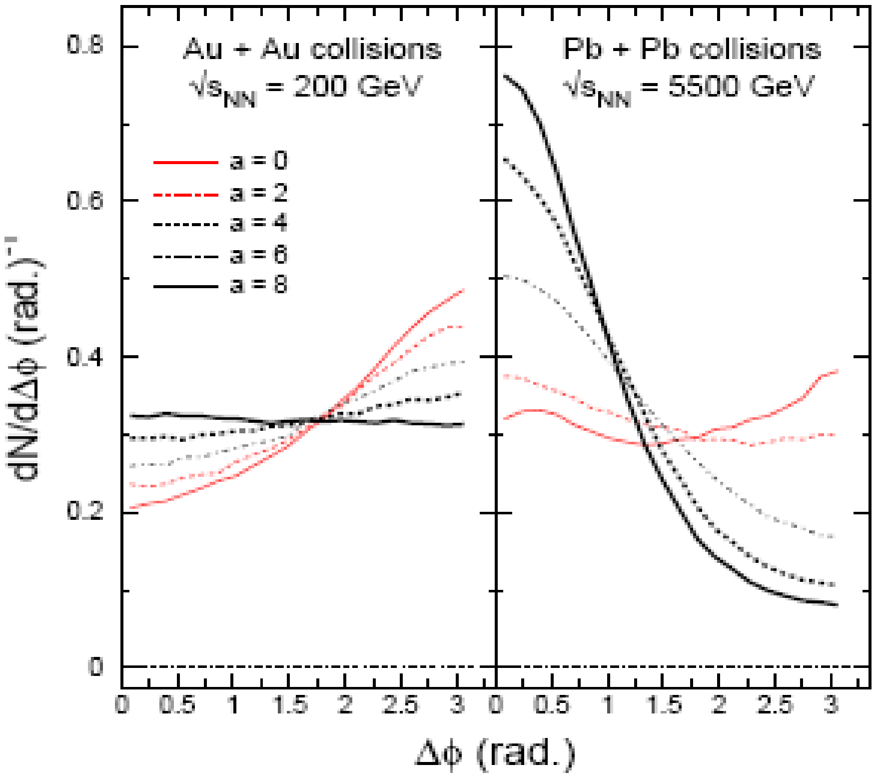
D D Correlation



NN collisions: ***back-to-back correlation***
RHIC: ***almost no correlation***
LHC: ***near-side correlation***

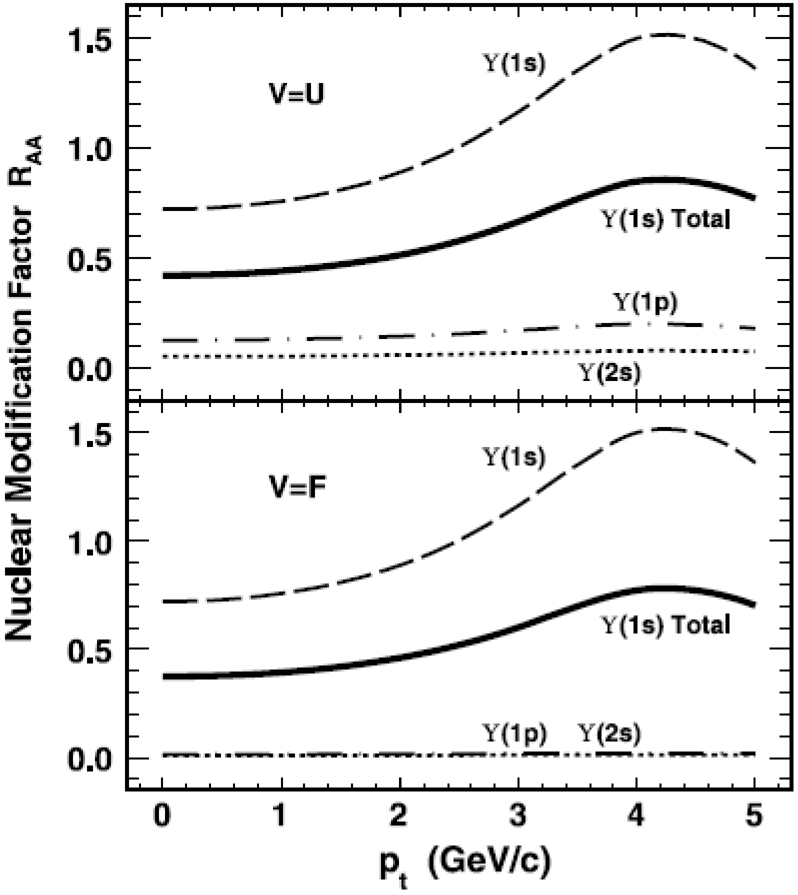






Υ at RHIC: $R_{AA}(p_t)$

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



central Au+Au at √s=200 GeV

- *strong Cronin effect for survived ground state*
- *no pt dependence for disappeared excited states*

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

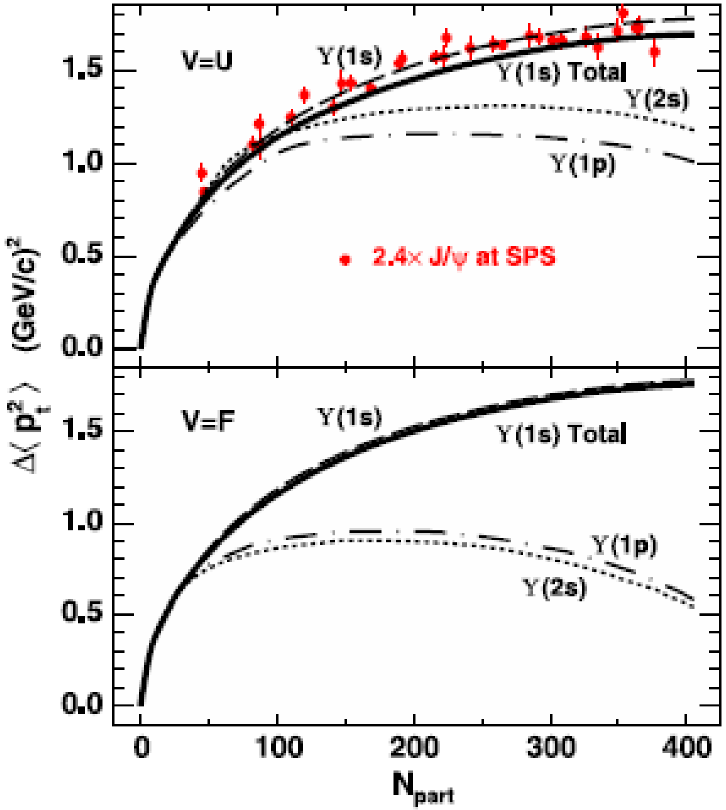
- $T_D^{\Upsilon(1s)} = 4T_c > T_{RHIC}$ **no Υ(1s) suppression at RHIC**

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

both are controlled by the Cronin effect !

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

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

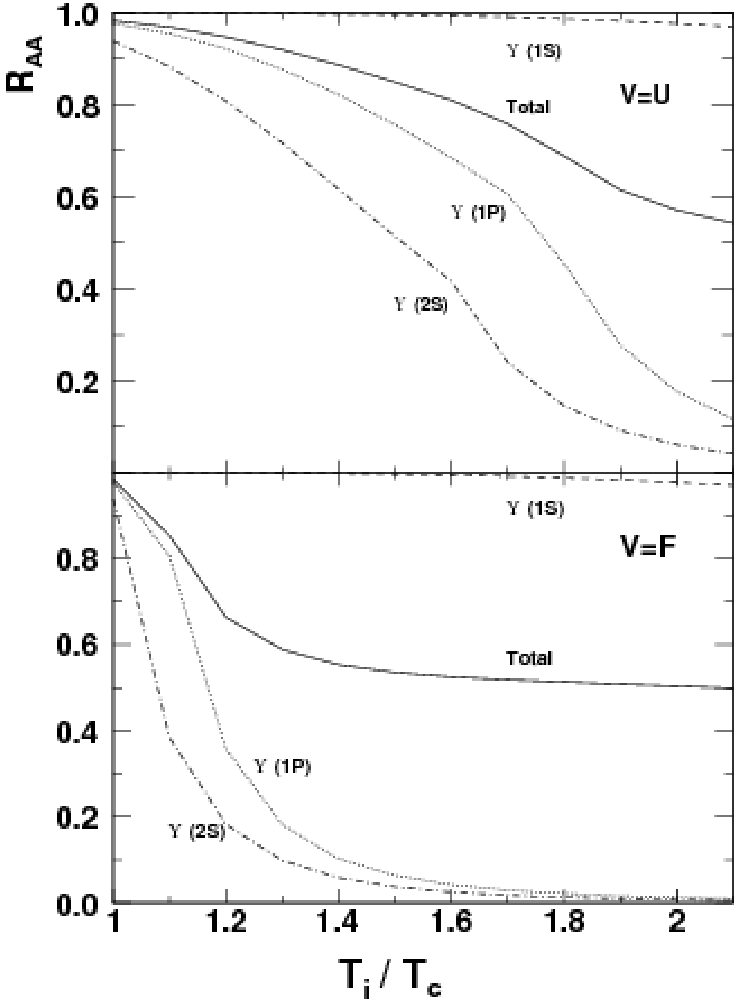


Au+Au at √s=200 GeV

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

Measuring RHIC Temperature by Excited ϒ States

initial temperature dependence of R_{AA}

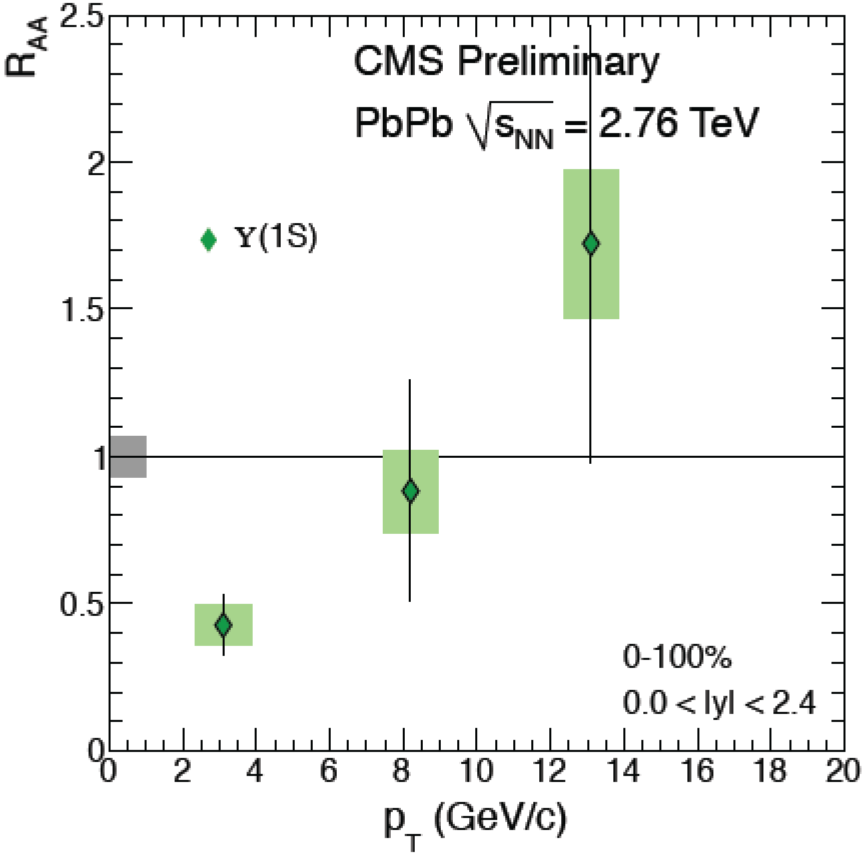


central Au+Au at √s=200 GeV

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

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

ϒ at LHC: $R_{AA}(p_t)$



high pt is controlled by initial production !