Probing Hot Mediums at SPS, RHIC and LHC by Quarkonia

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A Hard Probe of QGP

Matsui and Satz, 1987:

charmonia as a probe of QGP formation in heavy ion collisions.

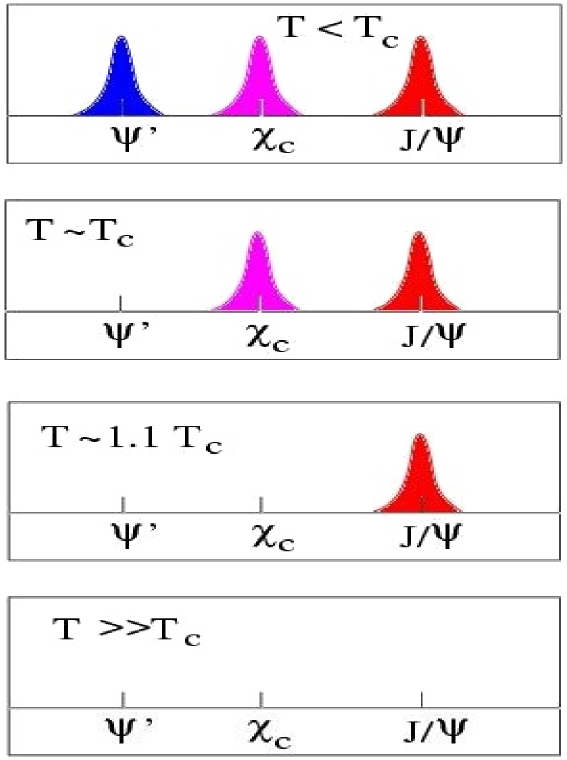
dissociation temperature from non-relativistic potential model :

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

relativistic correction (Guo, Shi, Zhuang, 2013):

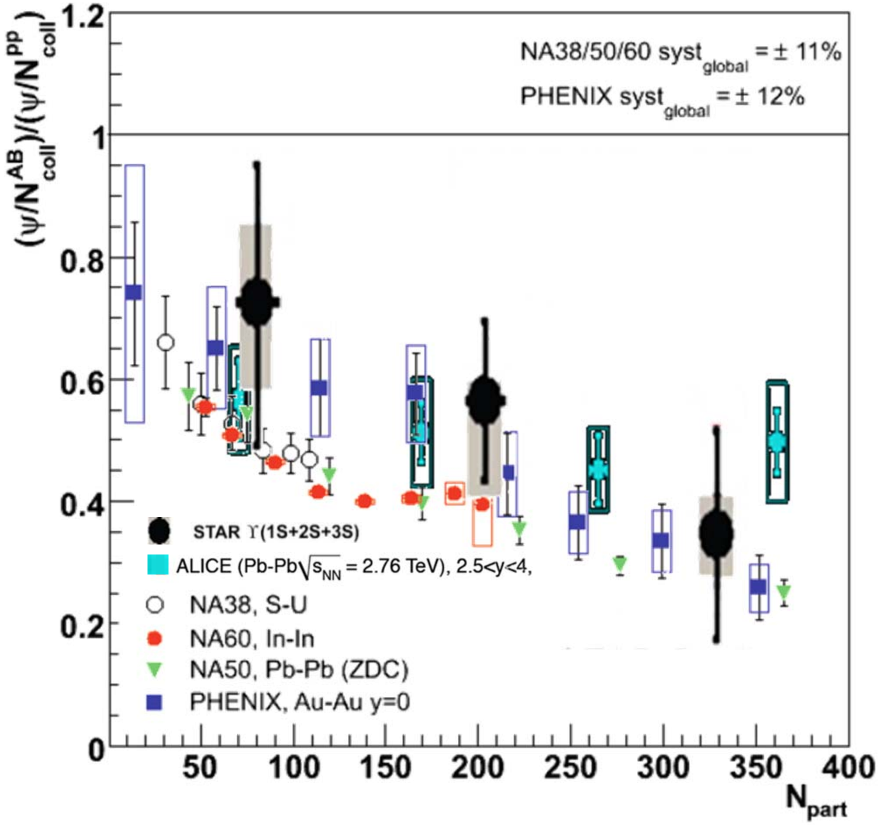
$\approx 10\%$

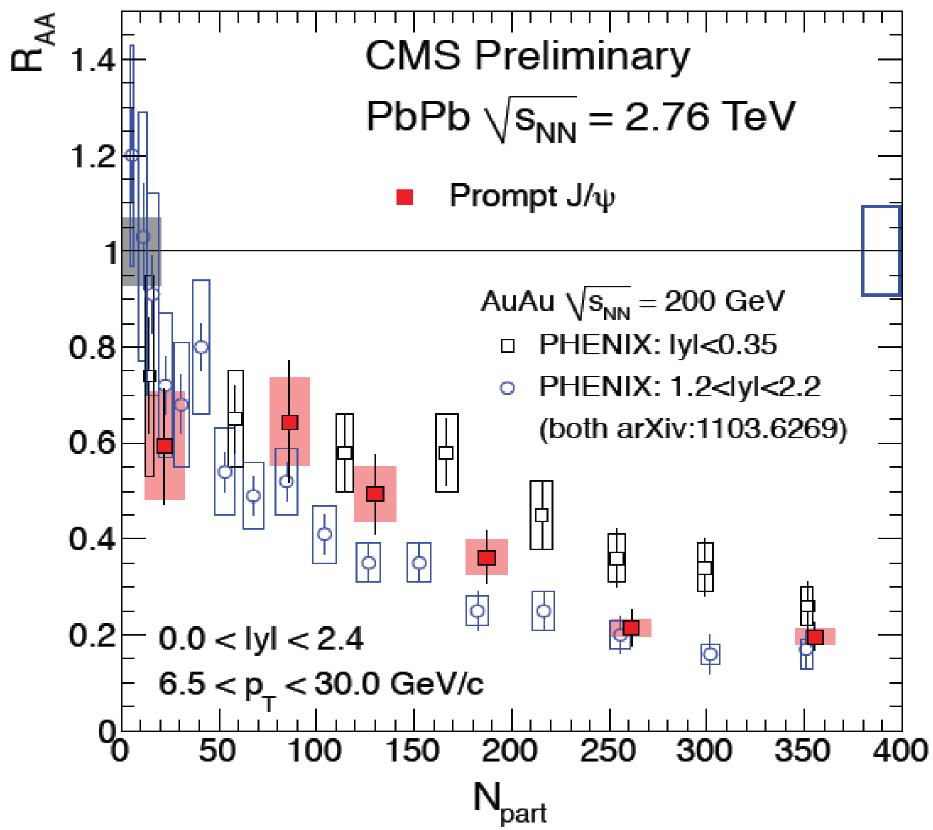
sequential suppression:



Nuclear Modification Factor R_{AA}

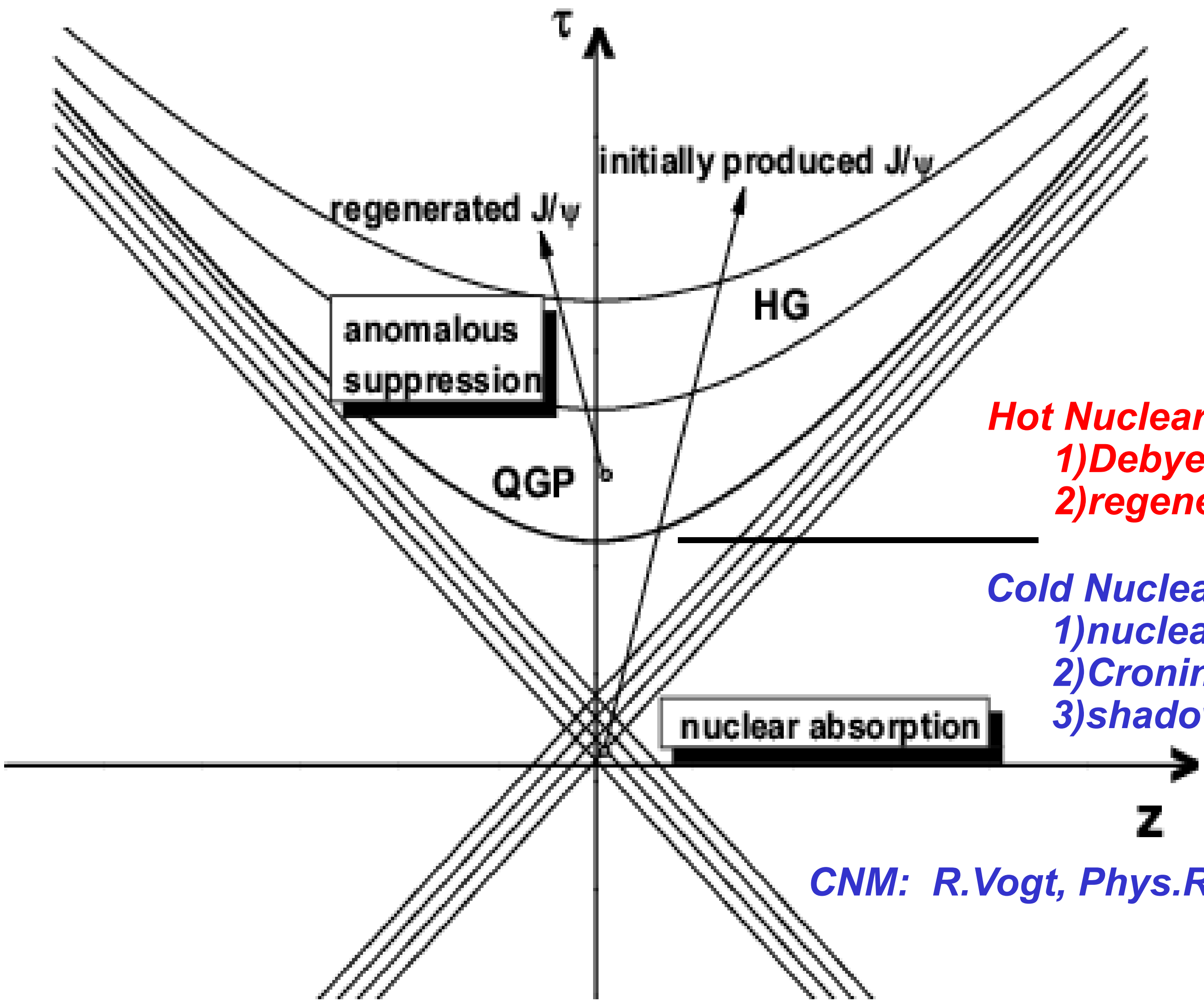
$$R_{AA} = \frac{N_{AA}}{N_{pp} N_{coll}}$$





R_{AA} < 1 at SPS, RHIC and LHC and the trend is similar.
momentum distribution should be more sensitive to the nature of the medium !

Cold and Hot Nuclear Matter Effects



Hot Nuclear Matter effects:
1)Debye screening
2)regeneration

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

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

Both Cold & Hot Nuclear Matter Effects on Quarkonium Production !

Competition between Dissociation and Production

important regeneration at RHIC and LHC:

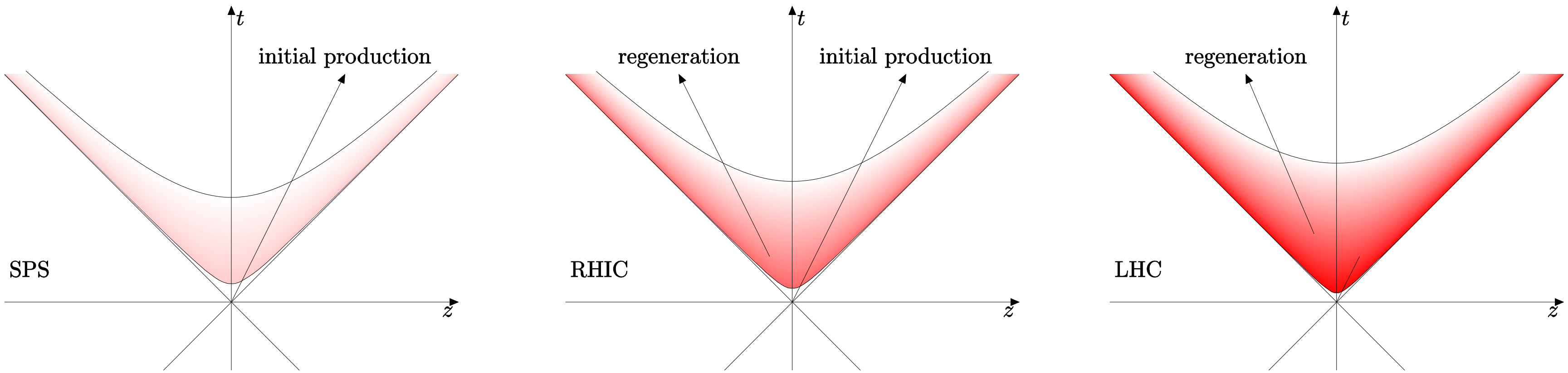
in QGP

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

in hadron gas

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

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



SPS: dominant initial production
RHIC: both initial production and regeneration are important
LHC: dominant regeneration

A Full Transport Approach

- **medium evolution**

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

- **hot nuclear matter effects on quarkonium production**

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

α: dissociation β: regeneration

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

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

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

both initial production and regeneration suffer from dissociation !

- **cold nuclear matter effects on the initial quarkonium distribution and 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):***

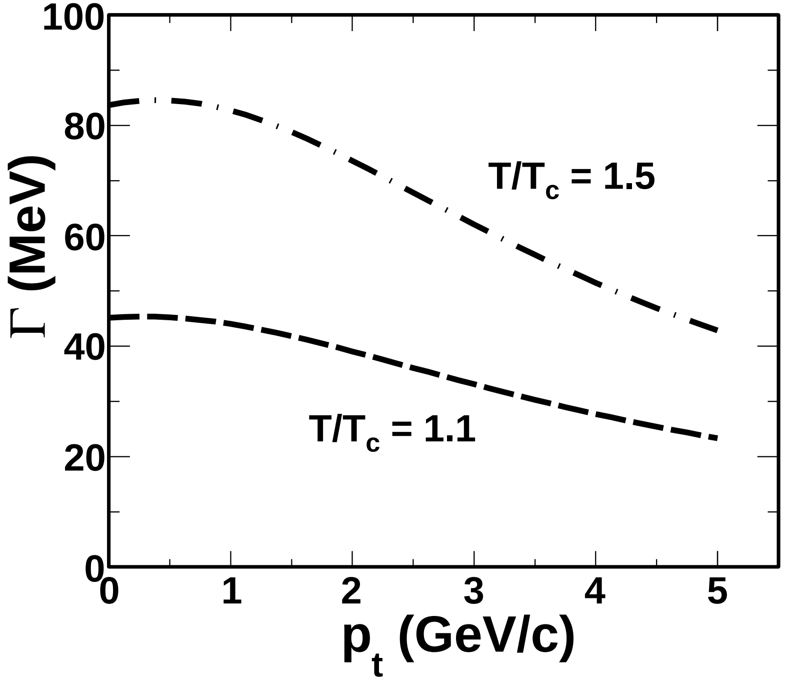
$$\sigma(p_\psi, p_g)$$

- *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***

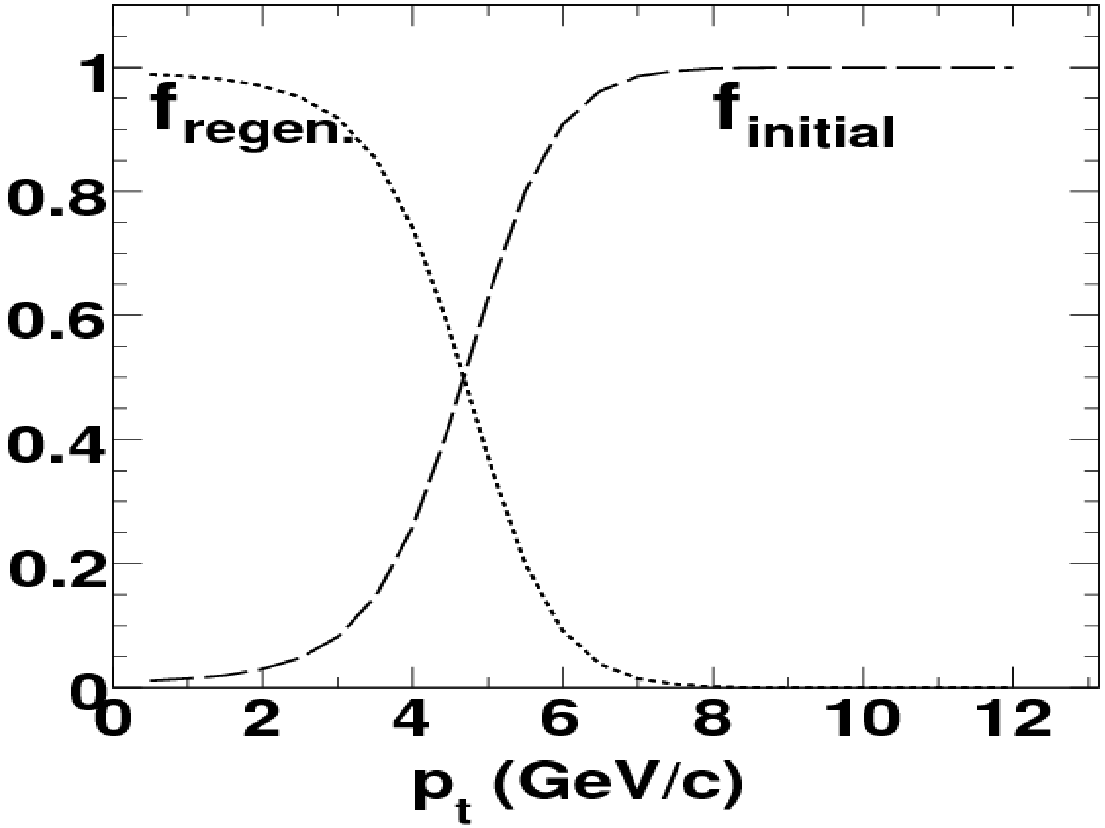
- ***J/Ψ dissociation rate***



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

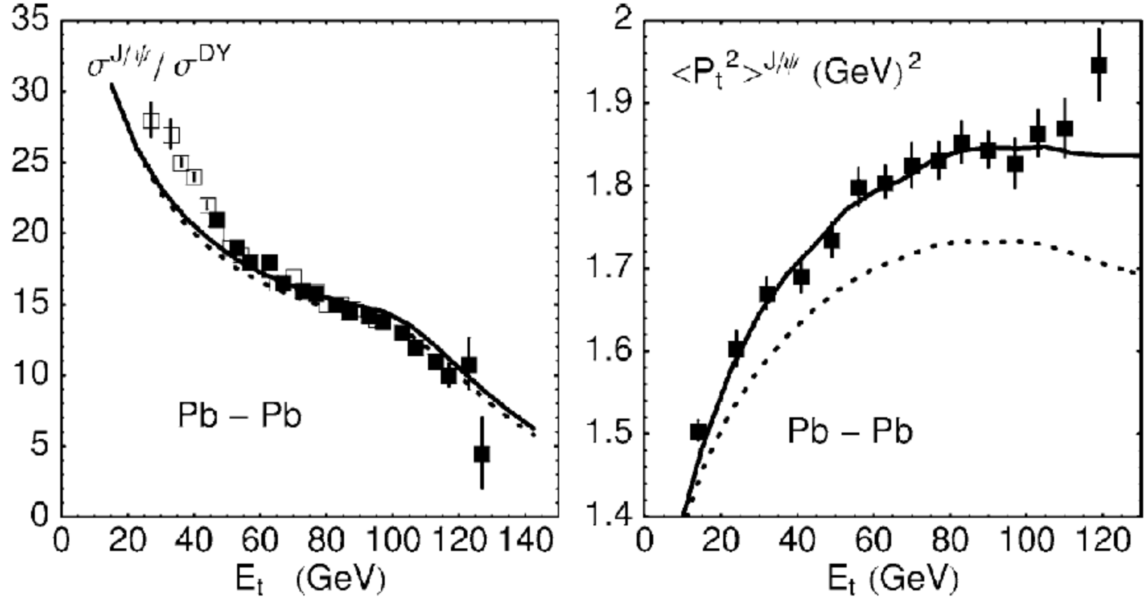
Pt Dependence of the Two Production Mechanisms

Initial production through hard process controls high pt,
regeneration in hot medium is important at low pt.

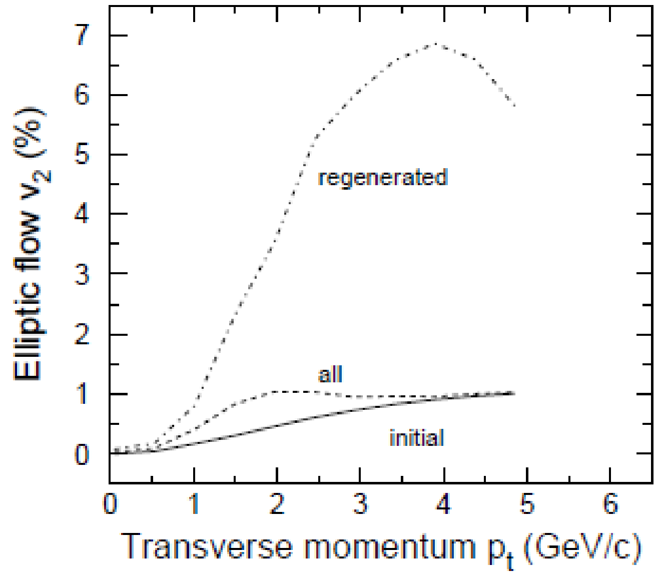


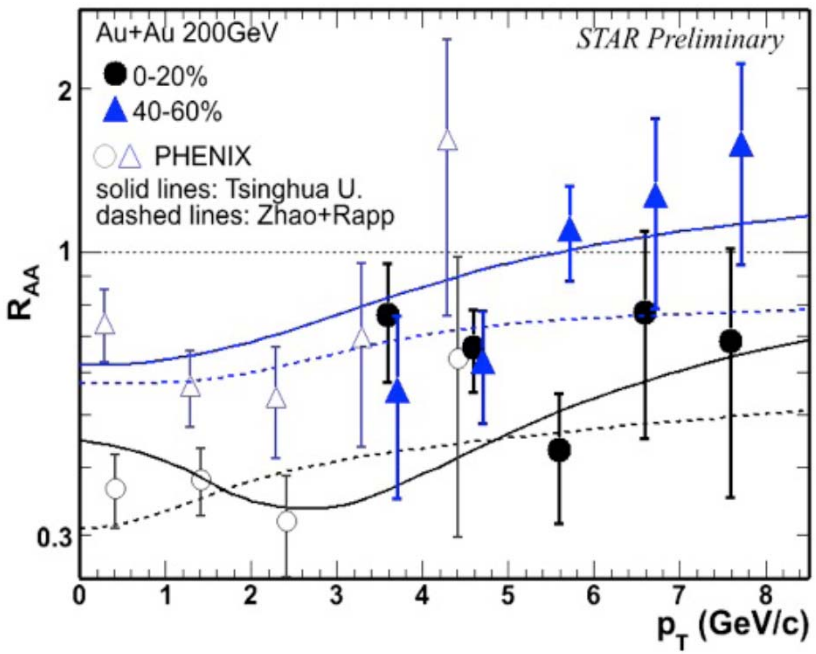
Initial and regeneration fractions
for J/Ψ in central Pb+Pb collihsions at LHC energy

Pt Distribution at SPS and RHIC

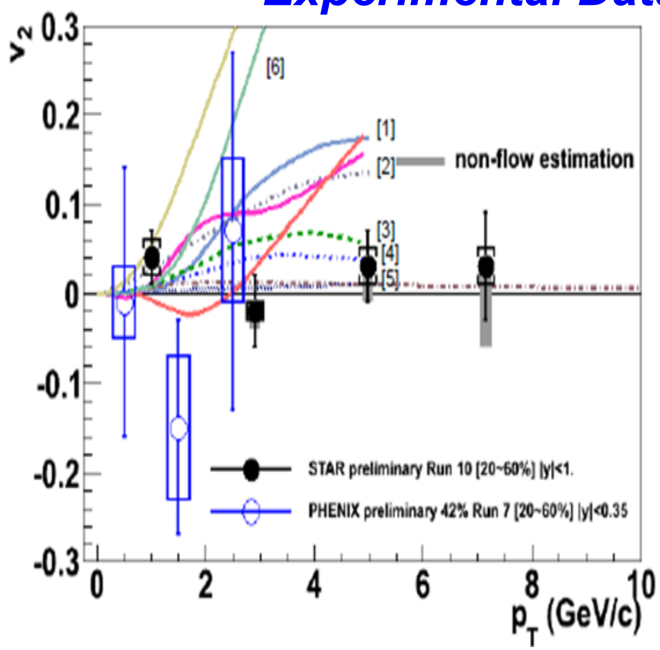


Theory Prediction 2006





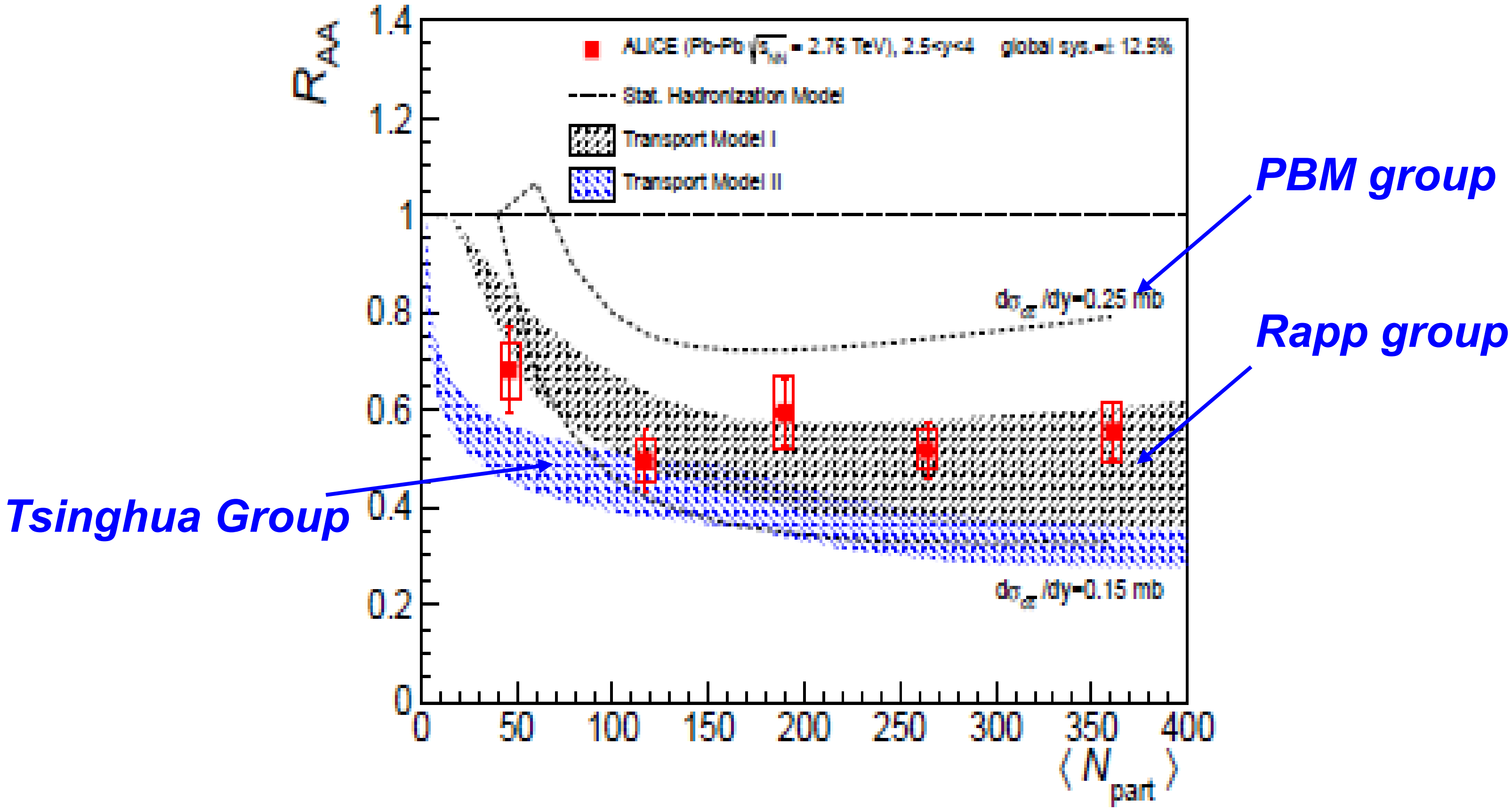
Experimental Data 2011



STAR, QM2011
PHENIX, QM2009

[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.

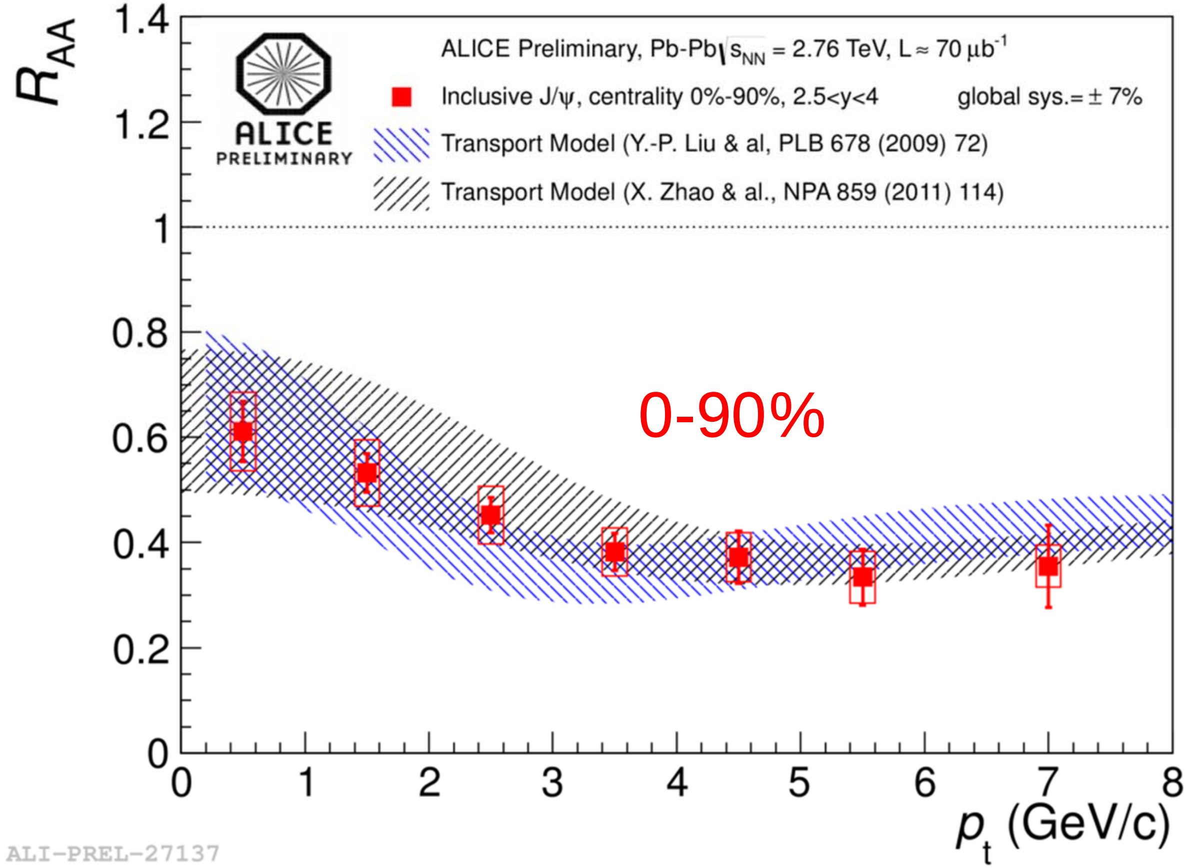
Prediction on Centrality Distribution at LHC



from talk by J.Wiechula at Hard Probe 2012

the band is due to the uncertainty in charm quark production cross section

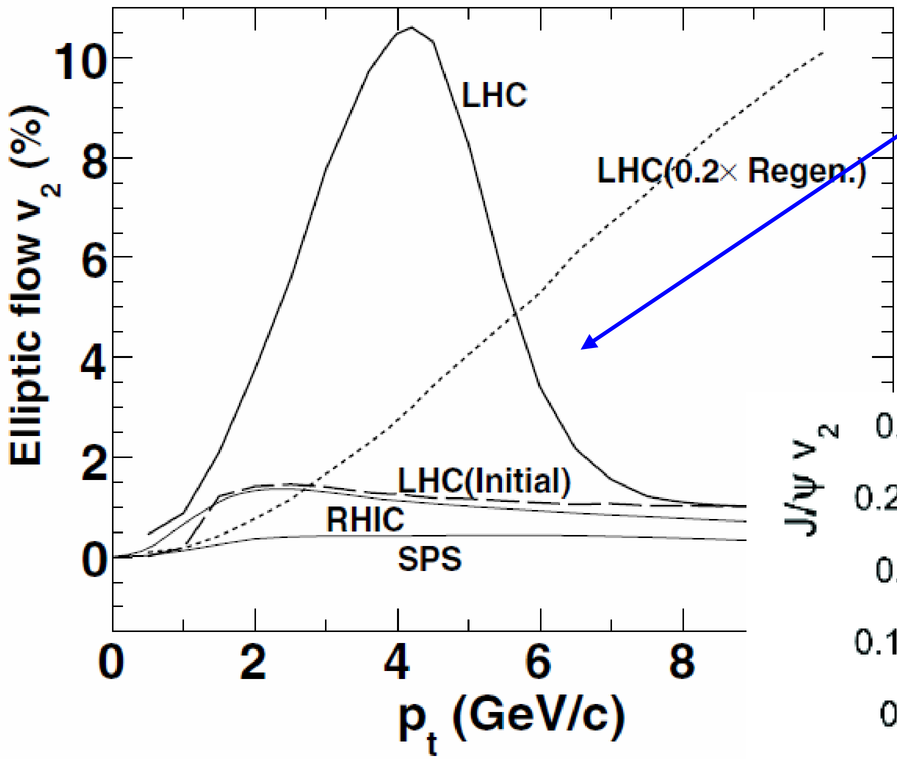
Prediction on Pt Distribution at LHC



from talk by R.Arnaldi at QM2012

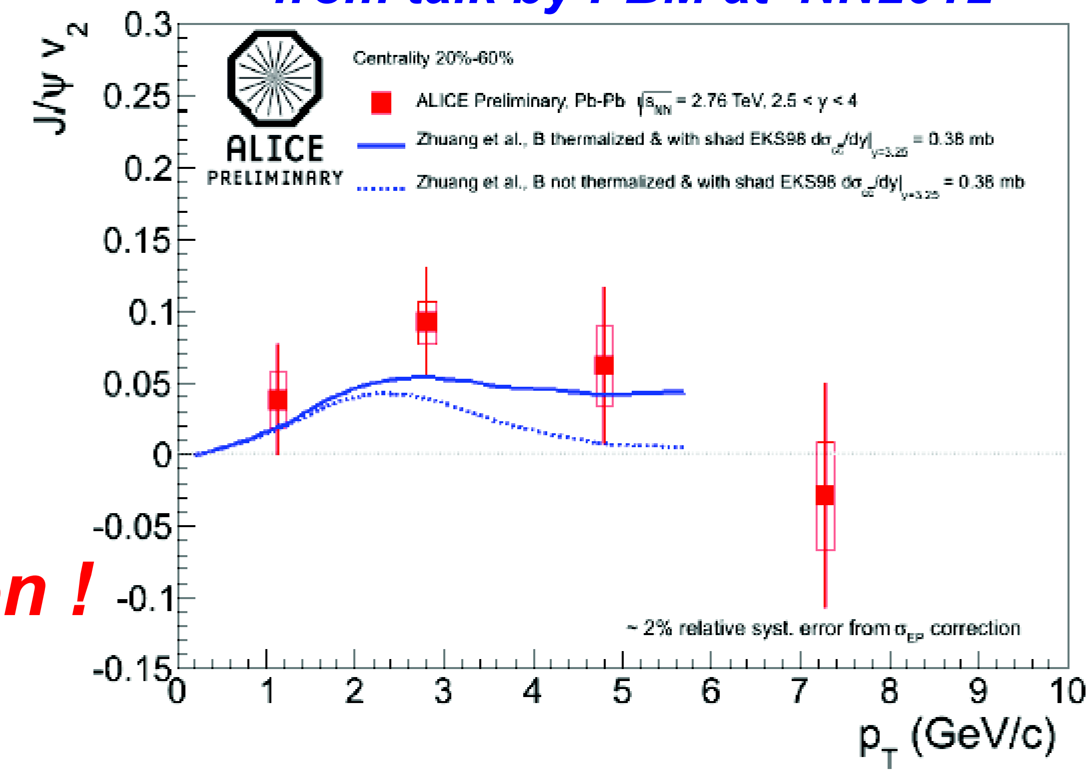
Prediction on Elliptic flow at LHC

Theory Prediction 2010



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

from talk by PBM at NN2012

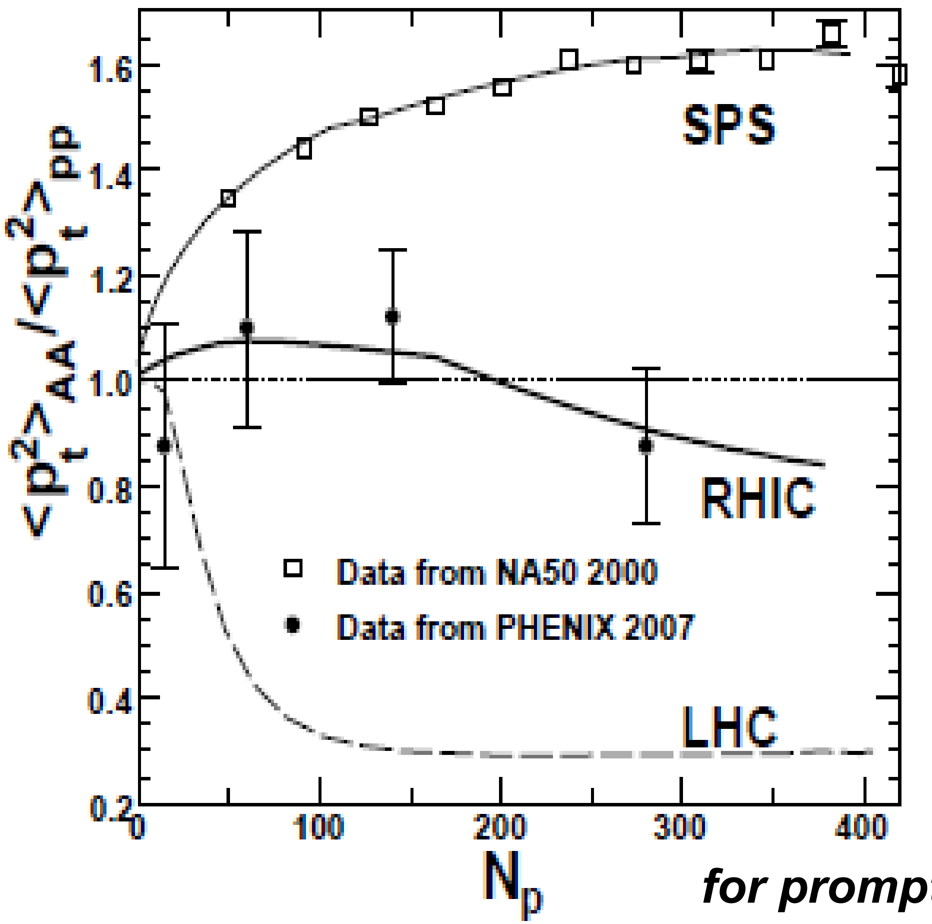


remarkable v2 due to important regeneration !

A New Nuclear Modification Factor

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

Theory Prediction 2010



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

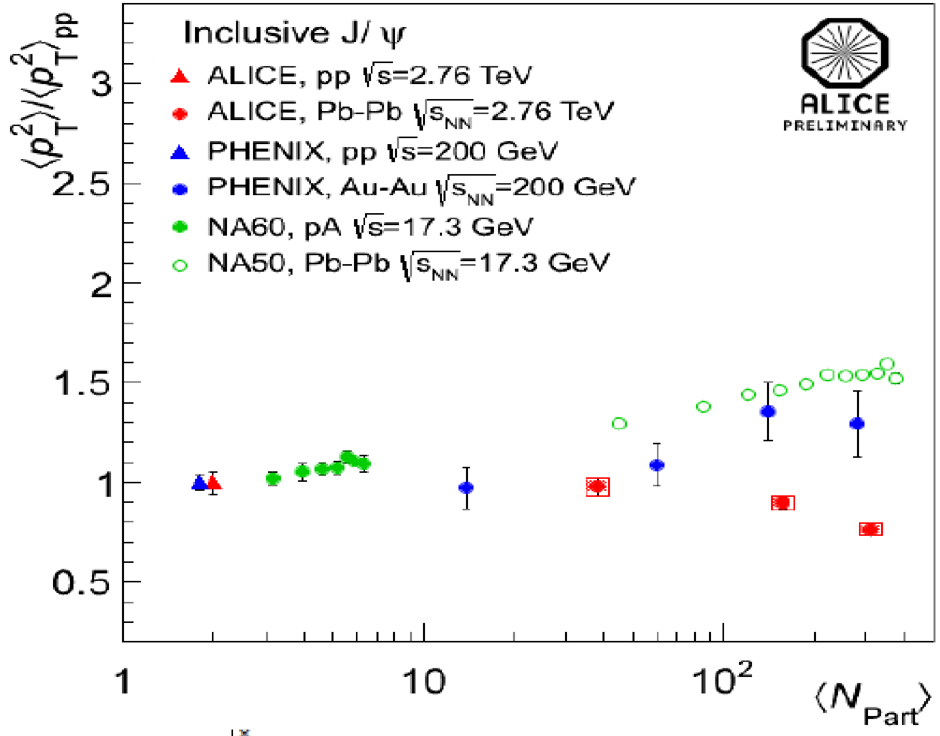
$r_{AA} \approx 1$ ***at RHIC by competition between initial production and regeneration***

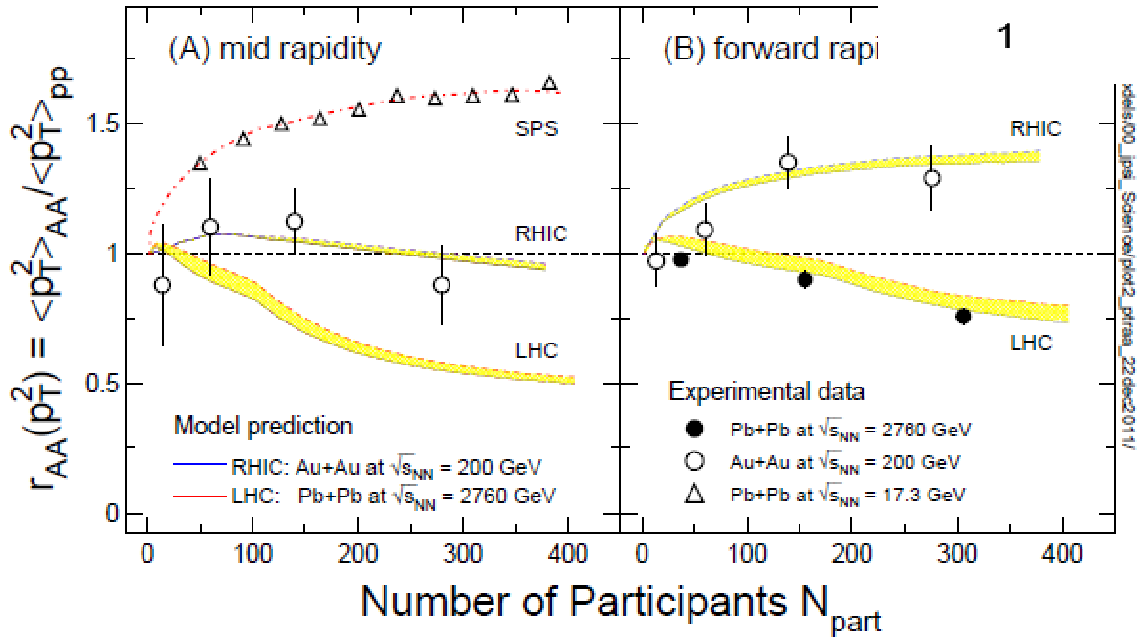
$r_{AA} < 1$ ***at LHC by dominant regeneration***

for prompt J/ψs at 5.5 TeV in mid rapidity

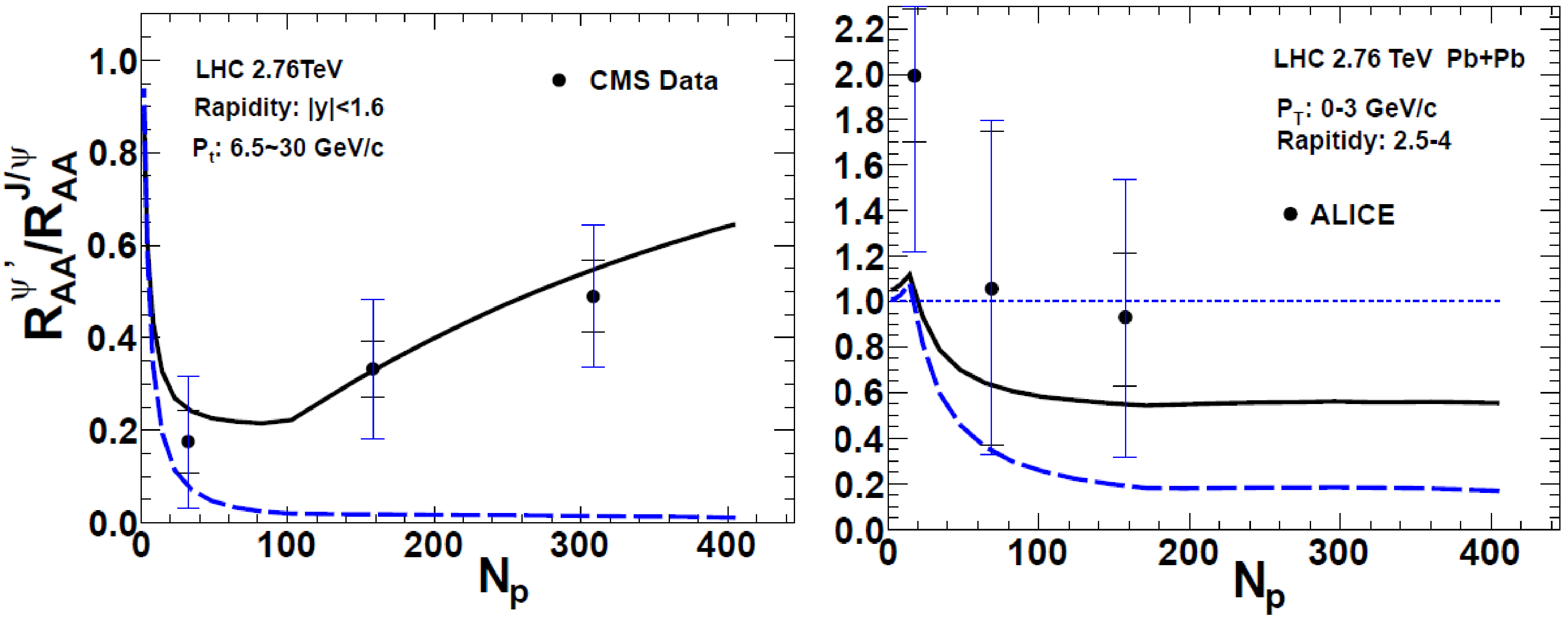
Experimantal Data from ALICE

from talk by PBM at XQCD2012





Double Ratio and B Decay Contribution



Conclusions

1) Transverse momentum distribution is more sensitive to the nature of the medium.

2)

$$r_{AA} = \frac{\left\langle p_t^2 \right\rangle_{AA}}{\left\langle p_t^2 \right\rangle_{pp}} = \begin{cases} >1 & \text{SPS} \\ \approx 1 & \text{RHIC} \\ <1 & \text{LHC} \end{cases}$$

is a more sensitive probe of QGP.

3) Charm quarks are likely thermalized in the medium.

Input

- ***medium evolution***

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

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

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

- ***initial production***

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

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

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

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

- ***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

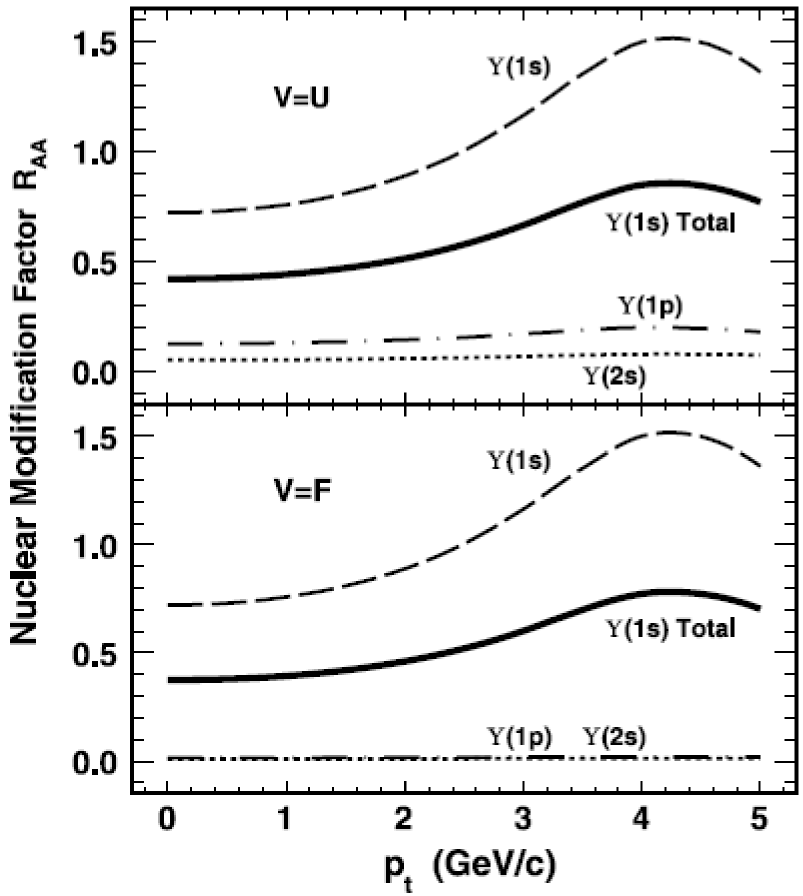
Υ, a Cleaner Probe at RHIC

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 for Υ ;
3) weaker CNM effect

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*

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

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

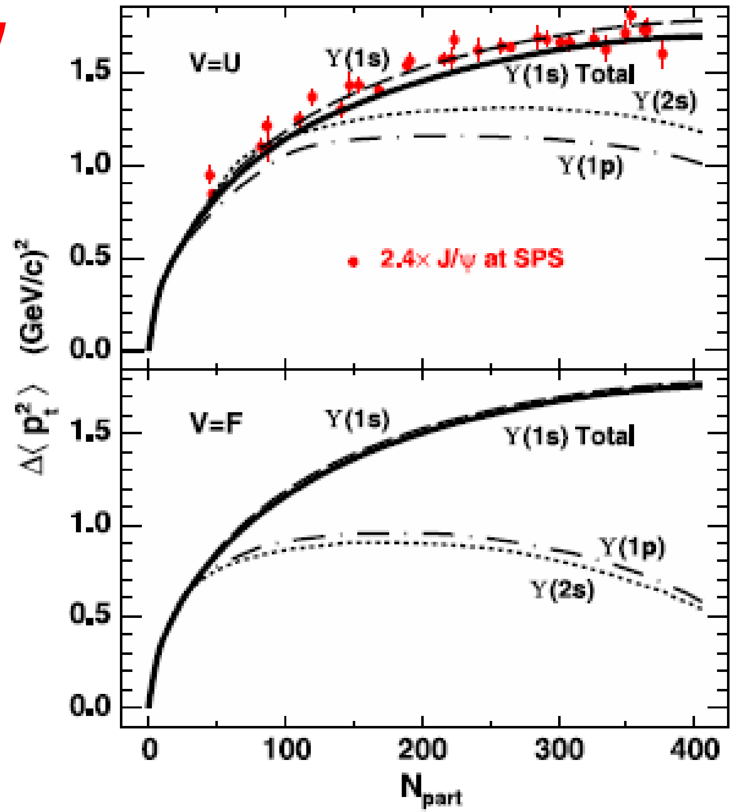
- **no Υ regeneration at RHIC and no J/ψ regeneration at SPS**
- $T_D^{\Upsilon(1s)} = 4T_c > T_{RHIC}$ **no Υ(1s) suppression at RHIC**

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

both are controlled by the Cronin effect !

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

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

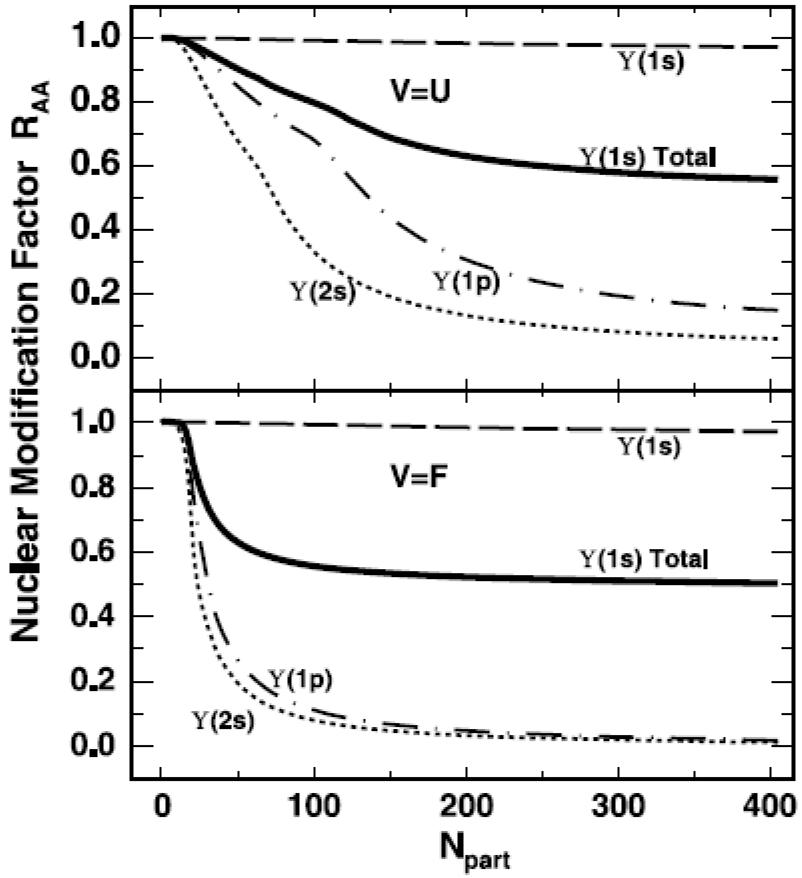


Au+Au at √s=200 GeV

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

Υ at RHIC: $R_{AA}(N_p)$

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

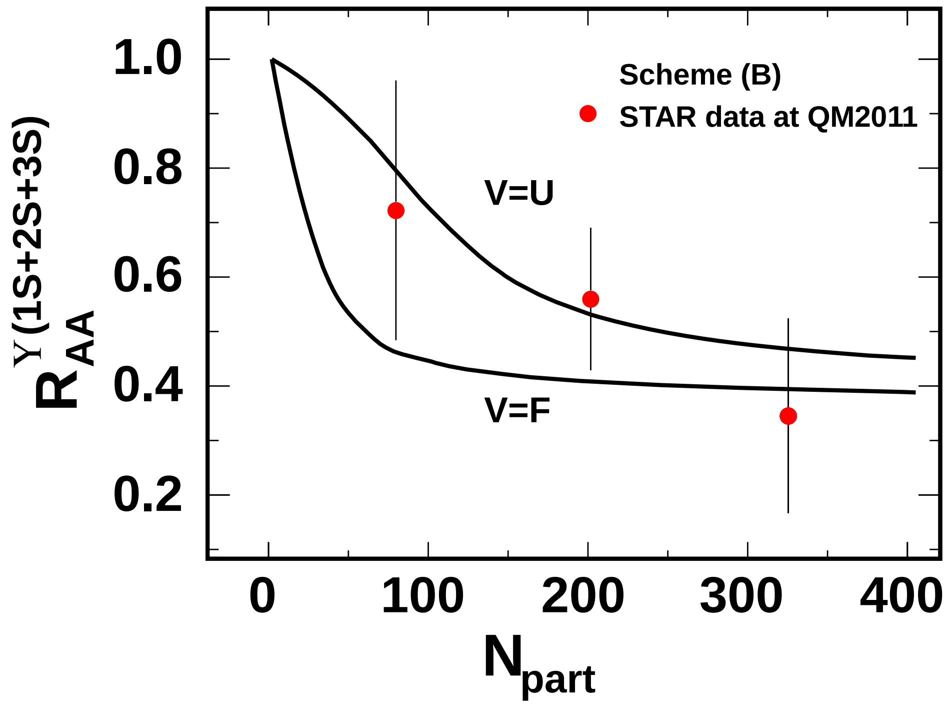


for minimum bias events:

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

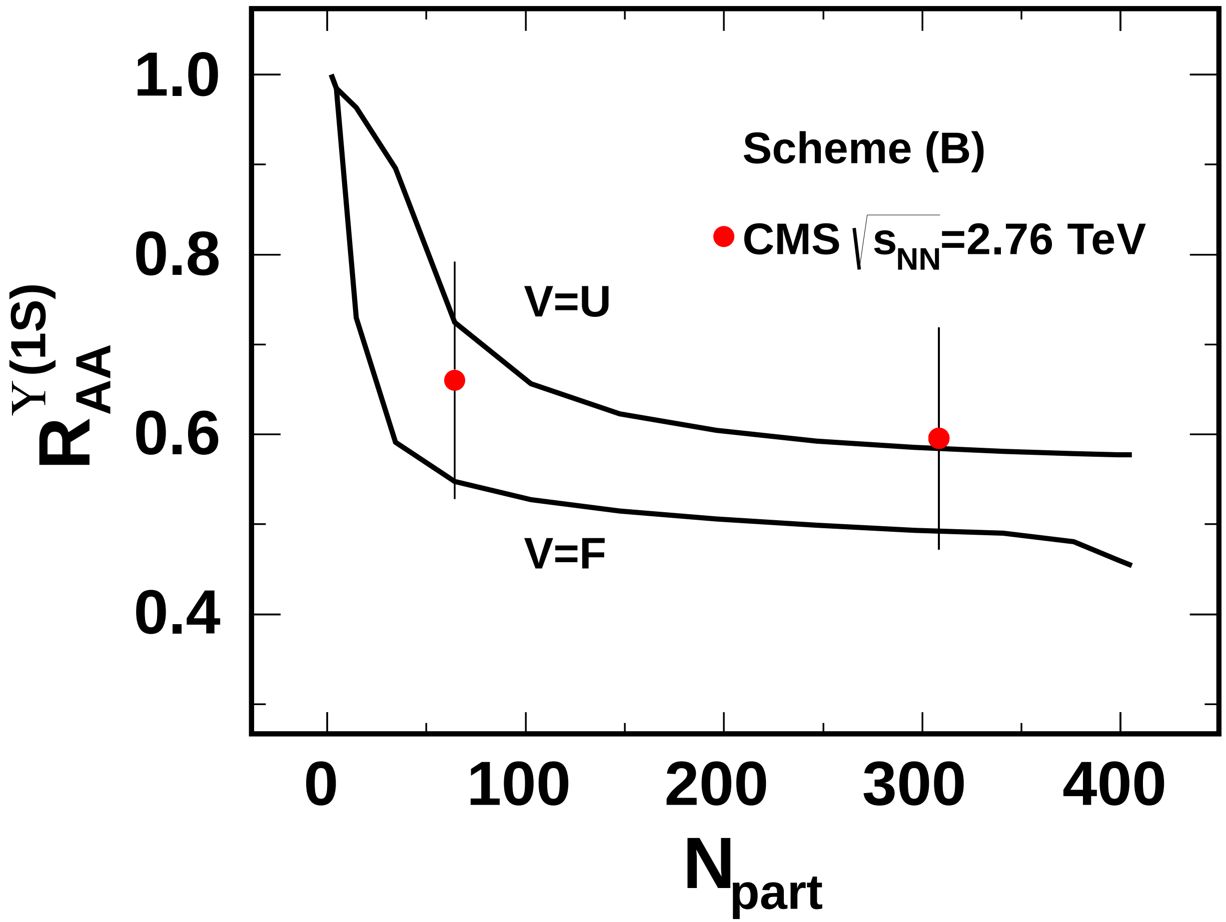
our result: R_{AA} = 0.63 for V=U

R_{AA} = 0.53 for V=F



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

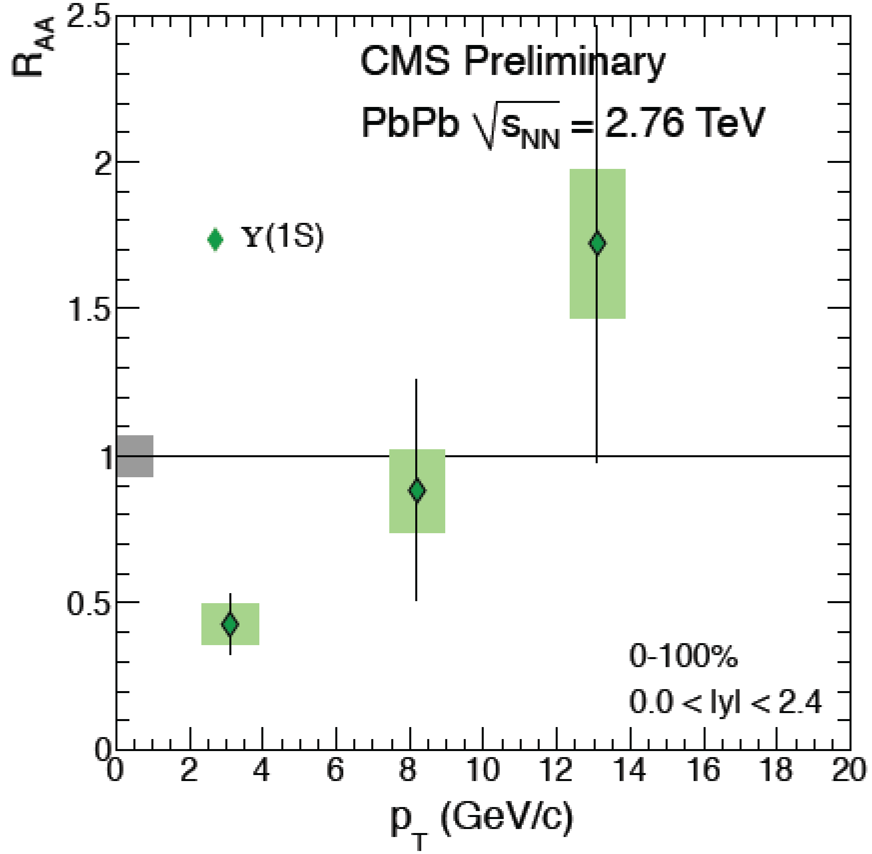
Υ at LHC: $R_{AA}(N_p)$



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

● *again, V is close to U.*

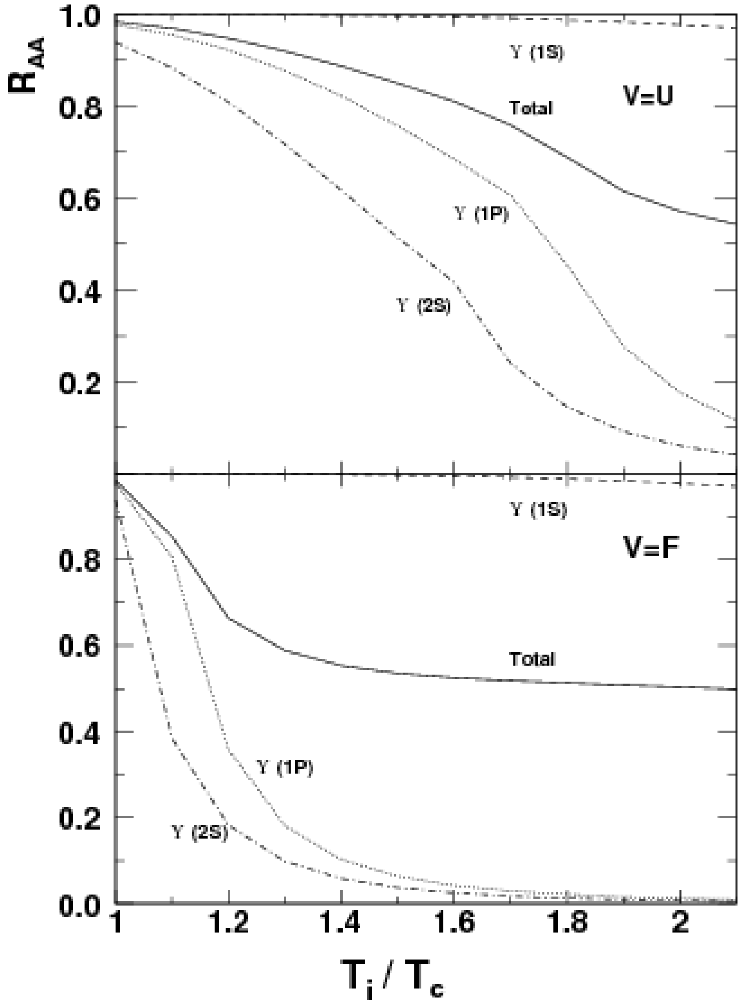
Υ at LHC: $R_{AA}(p_t)$



high pt is controlled by initial production !

Measuring RHIC Temperature by Excited Υ States

initial temperature dependence of R_{AA}



central Au+Au at √s=200 GeV

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

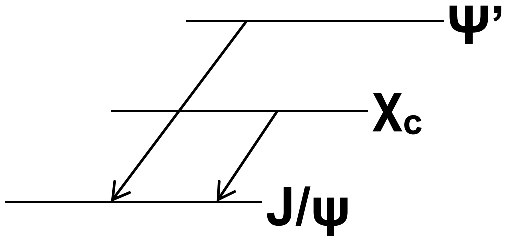
suppression of excited Υ states is sensitive to the fireball temperature !

Charmonium in pp Collisions

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

difficult to observe ψ' !

Ψ' and χ_c decay into J/ψ:



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

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

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

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:

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

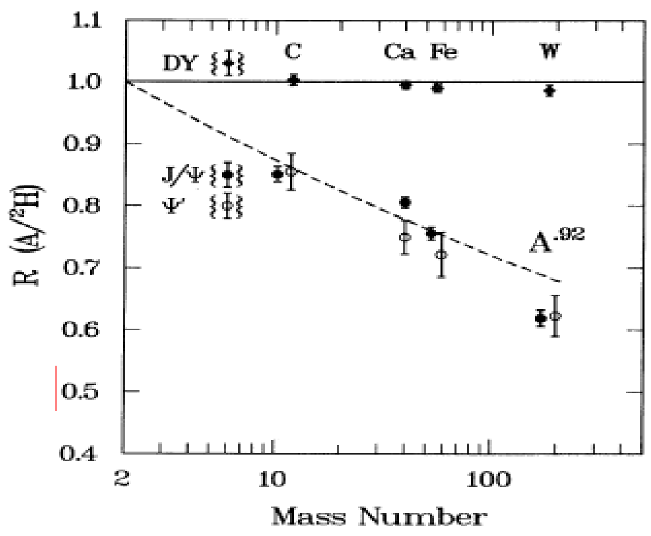
Matsui and Satz, 1986:

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

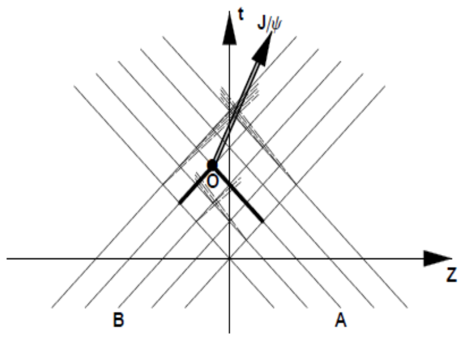
However,

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

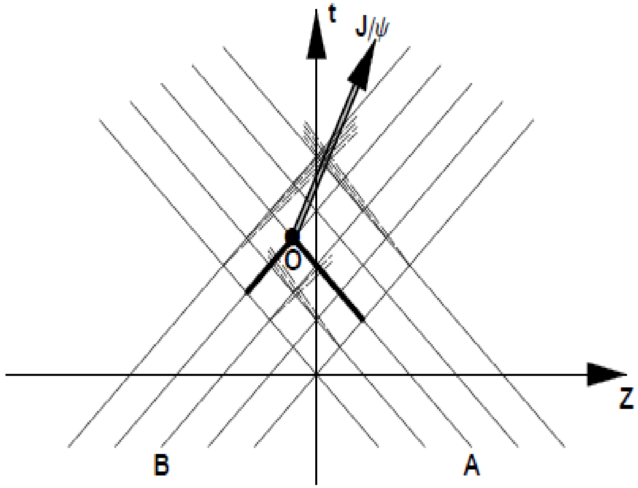
$$\sigma_{abs}^{SPS} > \sigma_{abs}^{RHIC} > \sigma_{abs}^{LHC}$$

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

Cold Effect: Cronin Effect

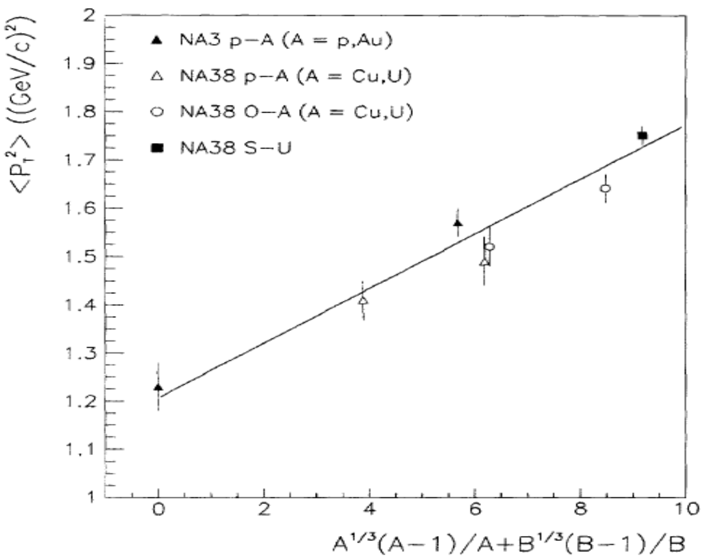
Cronin effect:

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

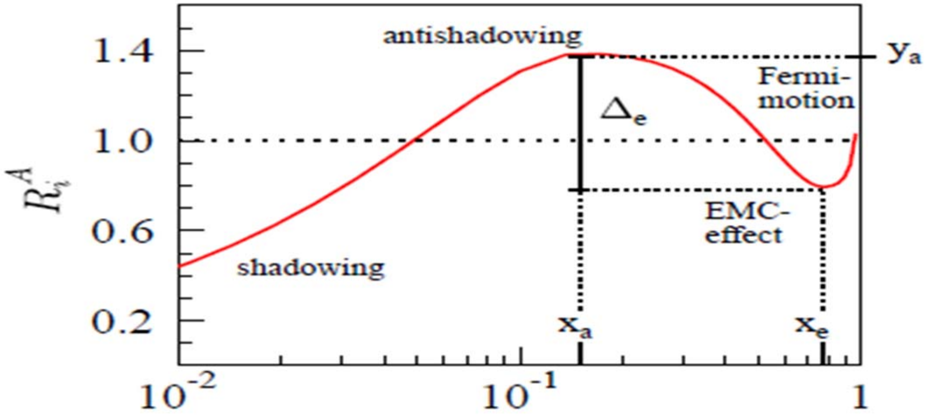
parton distribution function (PDF) in a nucleus is different from a simple superposition (Glauber model) of the PDF in a free nucleon.

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.