Transport Study on Heavy Quarkonium production in HIC

Kai Zhou (FIAS/ITP, Frankfurt U.)
Pengfei Zhuang (Tsinghua U.)

collaborated with: **Zebo Tang, Zhe Xu, Nu Xu**

zhou@th.physik.uni-frankfurt.de

Outline

- Introduction
- Transport Model
- Numerical Results at LHC
- Thermal charm production
- Summary

Introduction

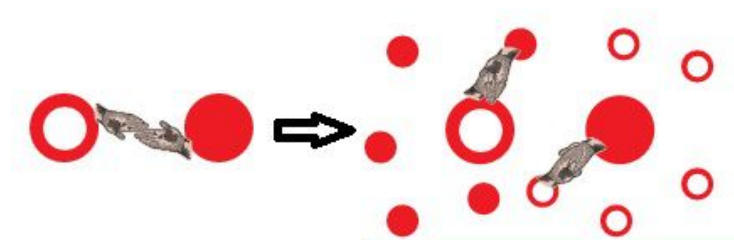
Large mass scale $m_Q >> \Lambda_{QCD}, T$

- Produced via Hard Processes from early stage

- "Calibrated" QCD Force---Heavy quark interaction

  - In vacuum **NR potential (or NRQCD)** e.g $V(r) = -\alpha_c / r + kr$
    ---spectroscopy well described

  - In medium **Color screening**



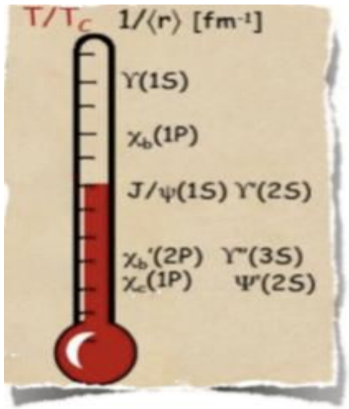
Satz and Matsui, PLB178, 416(1986):
J/Psi suppression as a probe of QGP in HIC

Introduction

- Thermometer

e.g for **V=U=F+TS** (Satz et al, 06) F from lQCD :

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



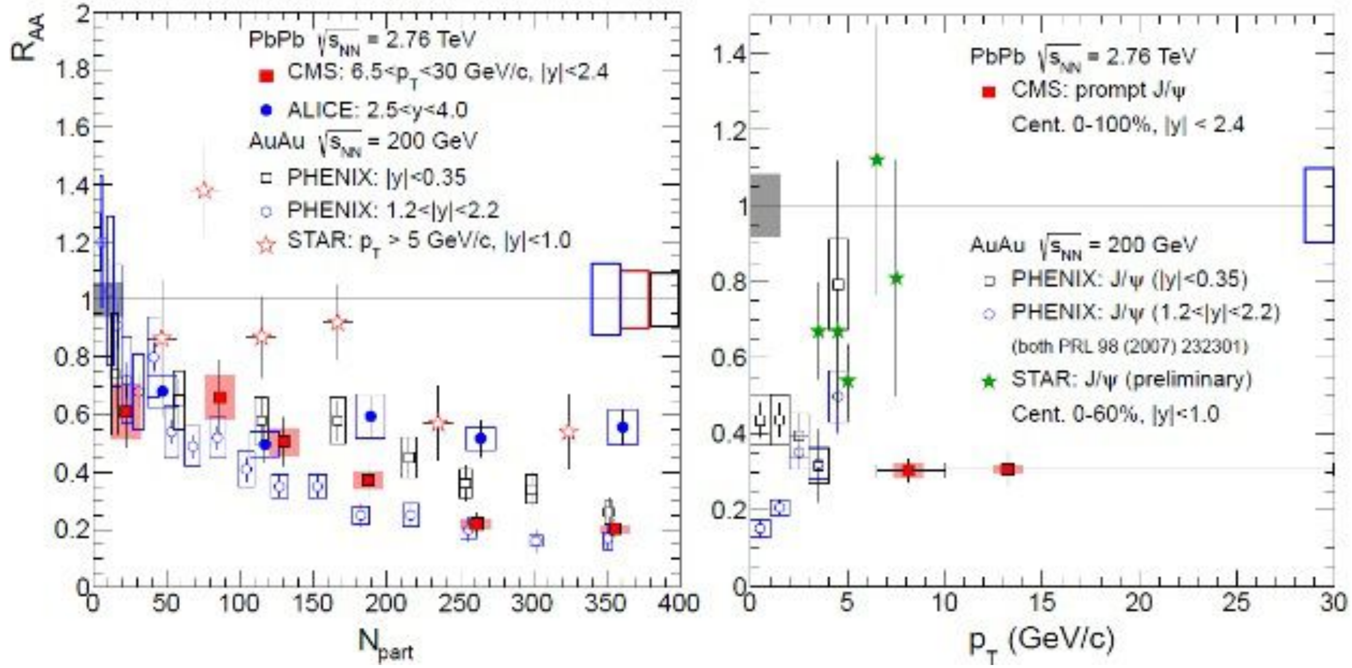
- Not so simple, many other effects affecting...

  - Cold matter effects: nuclear absorption, (A.Capella et al) Cronin, (J.W.Cronin et al) Shadowing (A.H.Mueller, R.Vogt, et al)
  - Collisional break-up: gluo-diss. (G.Bhanot and M.H.Peskin) quasi-free diss. (R.RAPP)
  - Regeneration/recombination: coalescence (PBM, Thews, R.Rapp...)

- Observation $R_{AA} = \frac{N^{AA}_{J/\psi}}{N_{coll} N^{pp}_{J/\psi}} \sim \frac{"QCD_{medium}"}{"QCD_{vacuum}"}$
  - **= 1 No effect**
  - **< 1 Suppression**
  - **> 1 Enhancement**

Introduction

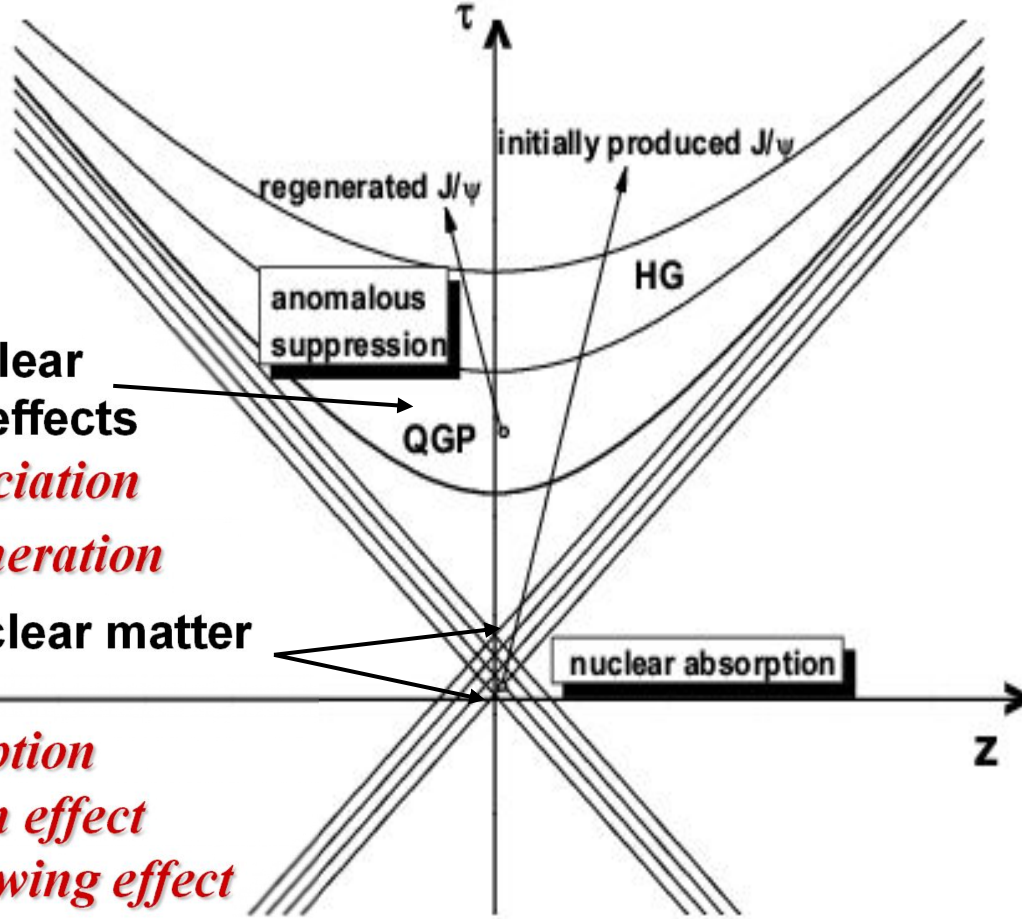
from SPS, to RHIC, Now, we are at LHC era



- ✓ Unifed model including interplay of Cold and Hot matter effects
- ✓ With increasing coll.energy, will hot medium effects increase? where?
- ✓ To higher energies (eg. FCC) what would happen? (thermal charm ?)

Transport Model

Transport(cold&hot) + Hydrodynamic



hot nuclear matter effects

1)Dissociation

2)Regeneration

cold nuclear matter effects

1)Absorption

2)Cronin effect

3)Shadowing effect

Transport Equation

Hydrodynamic Evolution

$$\begin{cases} \partial_\mu T^{\mu\nu} = 0 \\ \partial_\mu j^\mu = 0 \end{cases}$$

+ EoS

Transport Model- transport equation & *hot effects*

- quarkonium distribution function in phase space $f_\psi(\vec{p},\vec{x},t)$

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

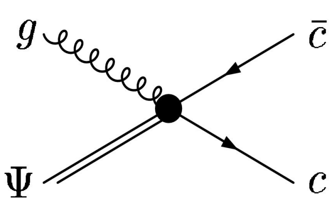
$$g + \Psi \leftrightarrow Q + \overline{Q}$$

α (→) β (←)

1) Gluon dissociation :

$$\alpha = \frac{1}{2E_T}\int \frac{d^3\vec{k}}{(2\pi)^3 2E_g} \sigma_{g\Psi} \cdot 4F_{g\Psi} f_g(k,x)$$

$f_g(k,x) \leftarrow N_g / (e^{p_g^\mu u_\mu / T} - 1)$

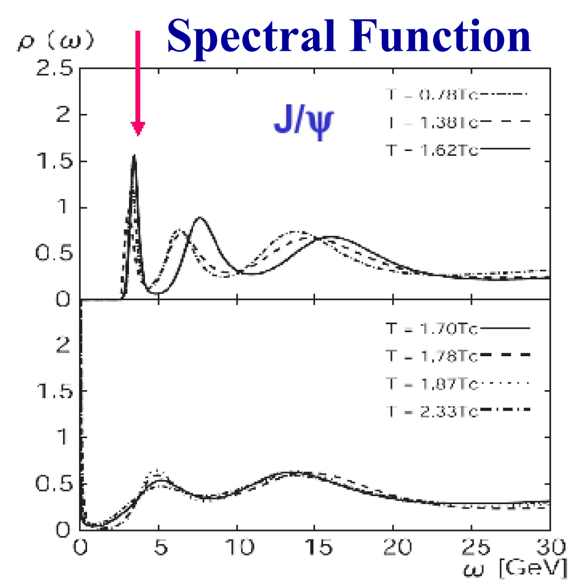


in Vacuum — OPE (Peskin,1979)

$$\sigma_g(\omega) = A_0 \cdot \frac{(\omega/\epsilon_\psi - 1)^{3/2}}{(\omega/\epsilon_\psi)^5}$$

$$\epsilon_\psi = \text{const, for } T_c < T < T_d,$$

in Medium — spectral peak dissapear above some tem. Td



Transport Model- transport equation & *hot effects*

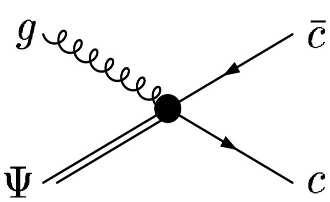
- quarkonium distribution function in phase space $f_\psi(\vec{p},\vec{x},t)$

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

$$g + \Psi \leftrightarrow Q + \overline{Q}$$
$$\alpha \rightarrow \qquad \leftarrow \beta$$

1) Gluon dissociation :

$$\alpha = \frac{1}{2E_T}\int \frac{d^3\vec{k}}{(2\pi)^3 2E_g}\sigma_{g\Psi}\cdot 4F_{g\Psi} f_g(k,x) \leftarrow N_g/(e^{p_g^\mu u_\mu/T}-1)$$



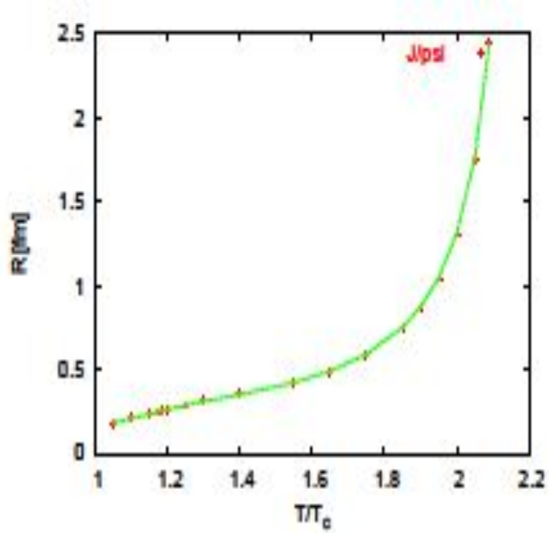
in Vacuum

OPE (Peskin,1979)

$$\sigma_g(\omega) = A_0 \cdot \frac{(\omega/\epsilon_\psi - 1)^{3/2}}{(\omega/\epsilon_\psi)^5}$$
$$\epsilon_\psi = \text{const, for } T_c < T < T_d,$$

in Medium

$$\sigma_{g\Psi}(T) = \sigma_{g\Psi}(T=0)\frac{< r_\Psi{}^2 > (T)}{< r_\Psi{}^2 > (T=0)}$$



Transport Model- transport equation & *hot effects*

- quarkonium distribution function in phase space $f_\psi(\vec{p},\vec{x},t)$

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

$$g + \Psi \leftrightarrow Q + \overline{Q}$$

α → ← β

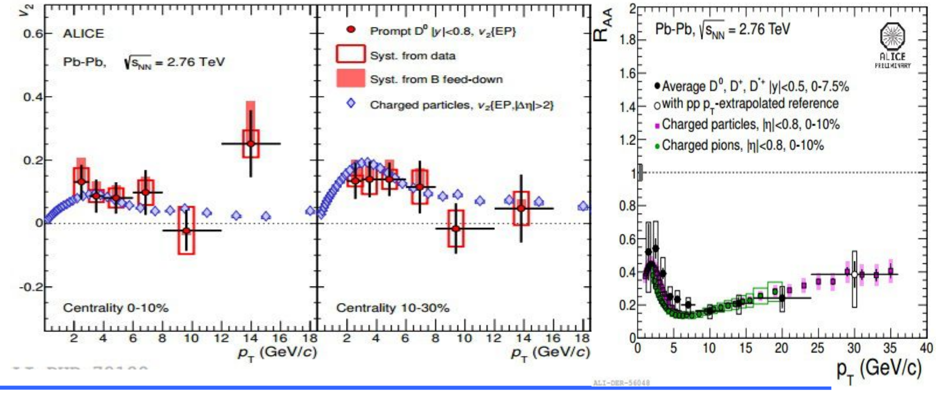
2) in-Medium Regeneration :

$$\beta = \frac{1}{2m_t}\int \frac{d^3\vec{k}}{(2\pi)^3 2E_g}\frac{d^3\vec{q}_1}{(2\pi)^3 2E_Q}\frac{d^3\vec{q}_2}{(2\pi)^3 2E_{\overline{Q}}}(2\pi)^4\delta^4(p+k-q_1-q_2)W_{pro}(s)f_Q(k,x)f_{\overline{Q}}(k,x)$$

- Detailed balance : $\sigma_{reg.}(s) = \frac{4}{3}\frac{(s-m_\Psi^2)^2}{s(s-4m_Q^2)}\sigma_{diss.}(s)$

- heavy quarks are assumed to be kinetically thermalized:

$$f_Q(k,x) = N(x)n_Q(x)/(e^{k^\mu u_\mu/T}+1)$$



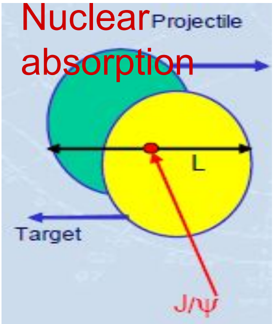
Transport Model- transport equation & *cold effects*

- Initial condition $f(\vec{p},\vec{x},t_0)$ for transport eq.

Glauber superposition from pp collisions along with modification from cold medium effects:

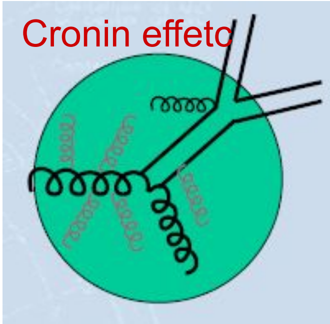
Cold Effects

Absorption

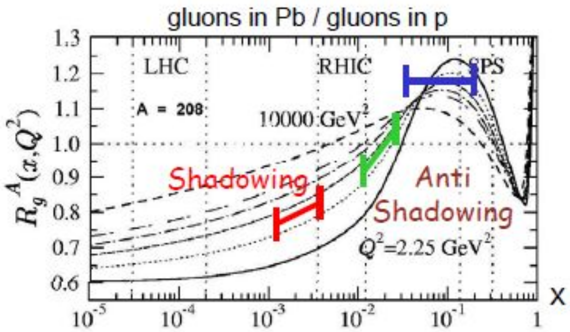


$t_{coll} << t_{\Psi}$ so it's neglected at LHC

Cronin   Gassian smearing treatment



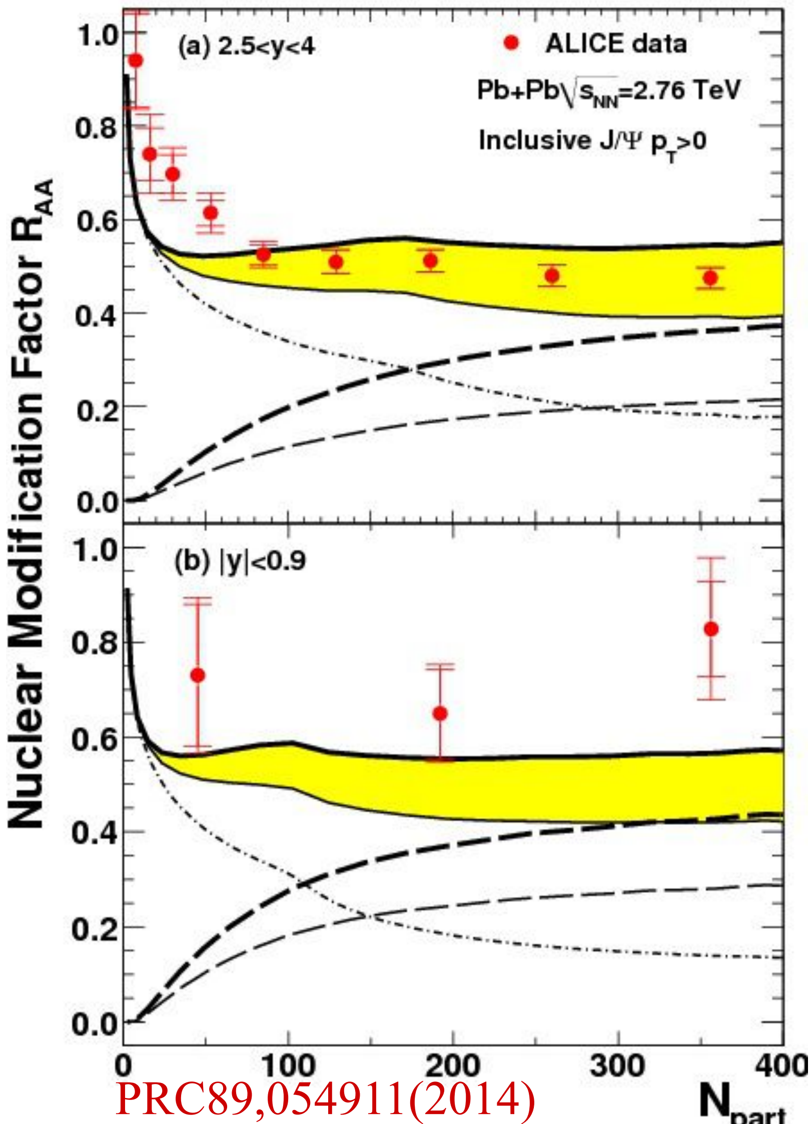
Shadowing



nPDF vs. free PDF

R.Vogt et al. PRL91 (2003) 142301.PRC71(2005) 054902

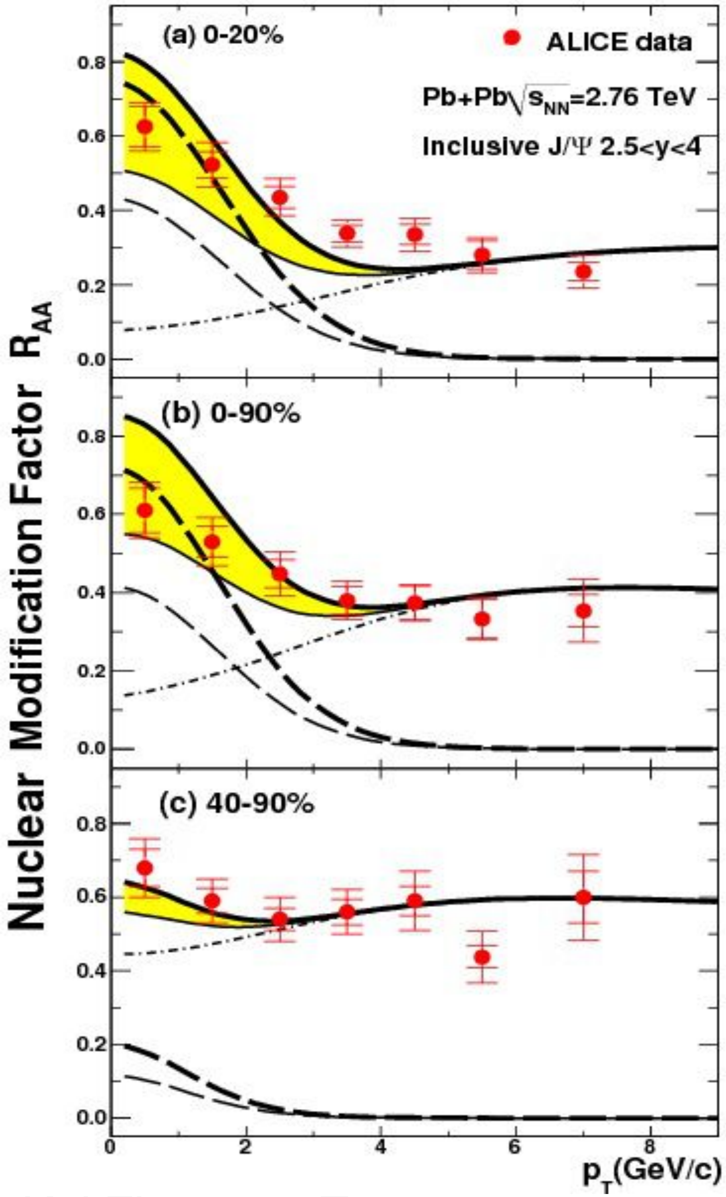
Results—Yield's *Centrality dependence*



PRC89,054911(2014)

- **Regeneration plays an important roll in most of centralities, and can be dominant.**
- **Competition leads to platform structure in most centralities.**

Results—*pT dependence* : RAA(pT)

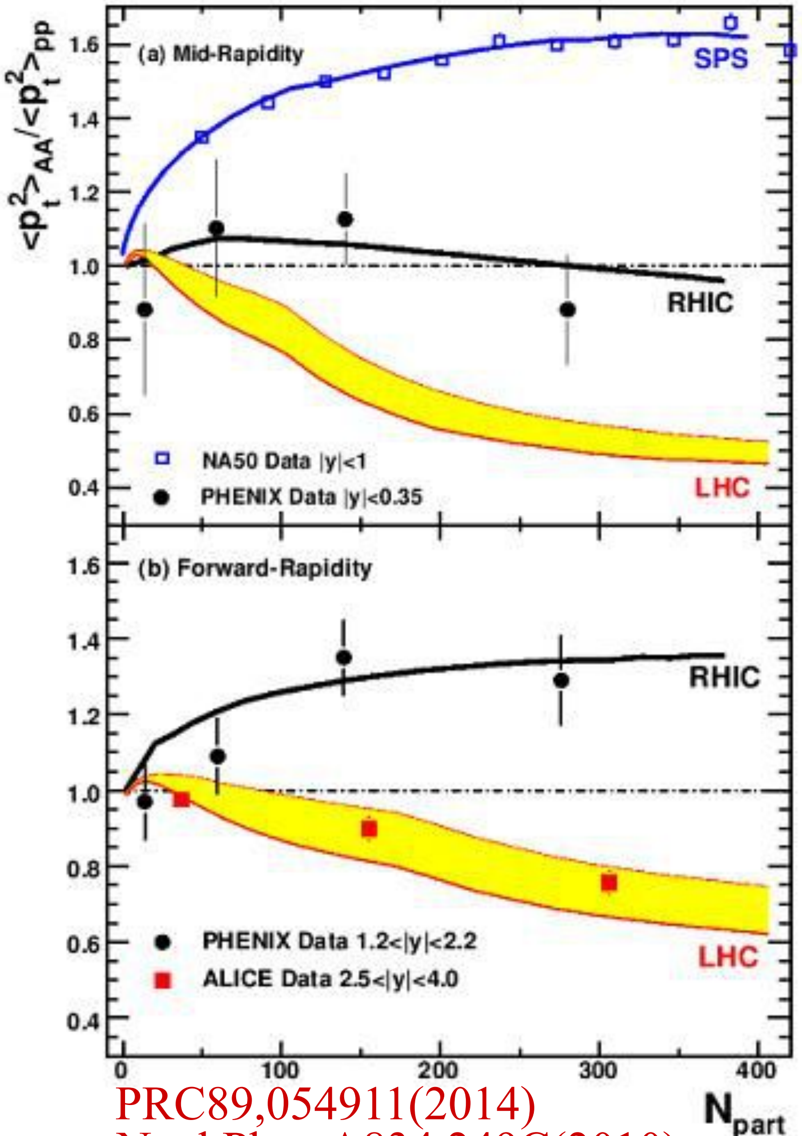


- ## Initial production:
  - Cronin effect in initial stage
  - strong <u>low pt suppression</u> and <u>high pt leakage</u> effect
    ⇨ *initial pt broadening*

- ## Regeneration:
  - coalescence mechanism
  - energy loss induced thermalization
    ⇨ *low pt regeneration*

PRC89,054911(2014)

Results—Modification for Trans. pT : rAA



PRC89,054911(2014)
Nucl.Phys.A834,249C(2010)

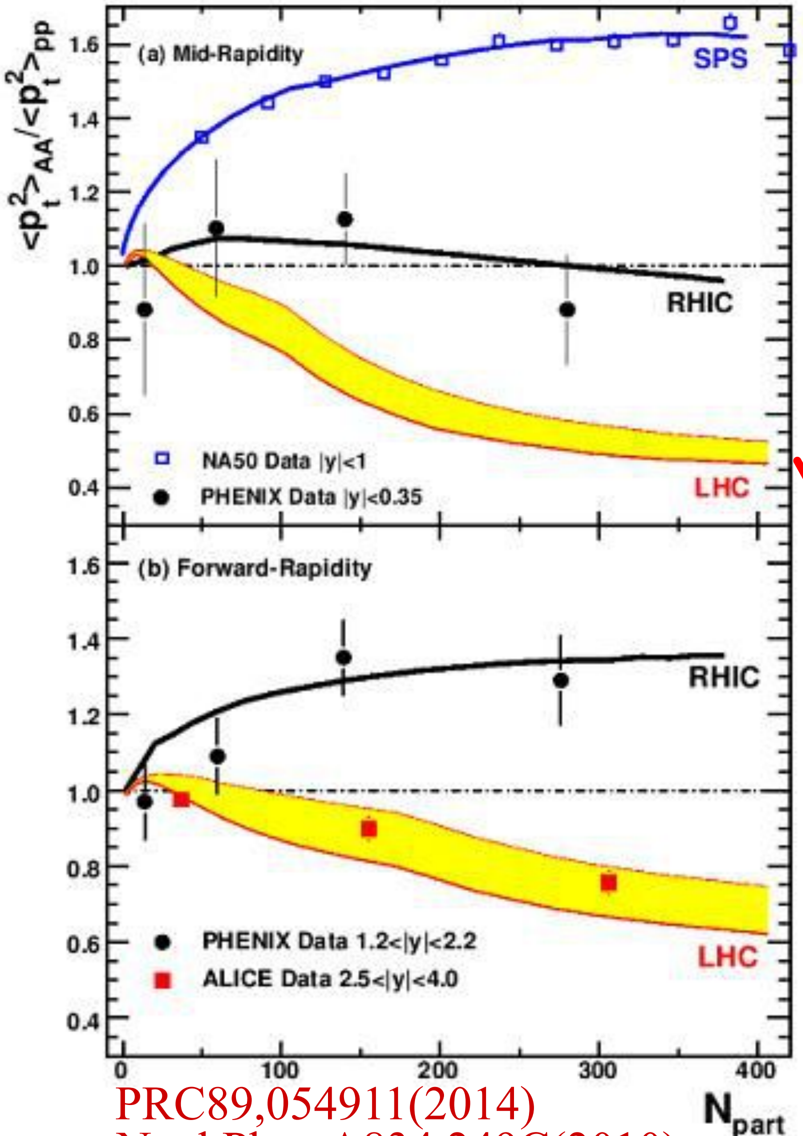
SPS: Cronin effect for ***initial production***

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

RHIC: competition betw. ***initial*** *Vs.* ***regeneration***

LHC: dominant ***regeneration***

Results—Modification for Trans. pT: rAA



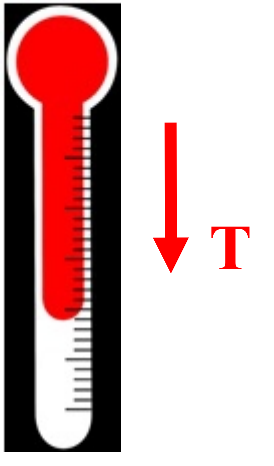
PRC89,054911(2014)
Nucl.Phys.A834,249C(2010)

$\sqrt{s_{NN}} \uparrow \quad QGP \uparrow$

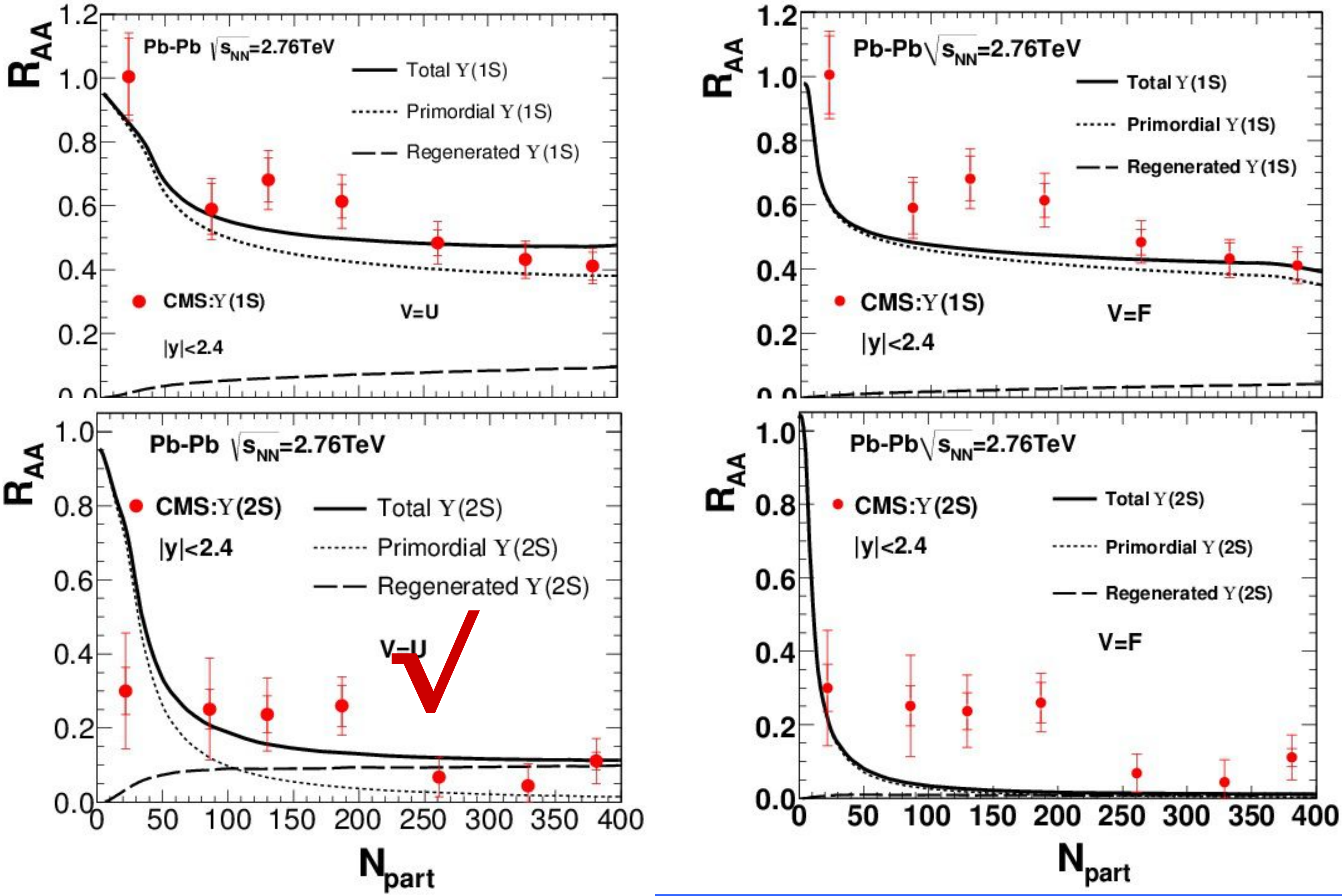
hotter

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

Clearly showes a hotter medium been created at LHC !



Results—Bottomonium differs V=U or V=F

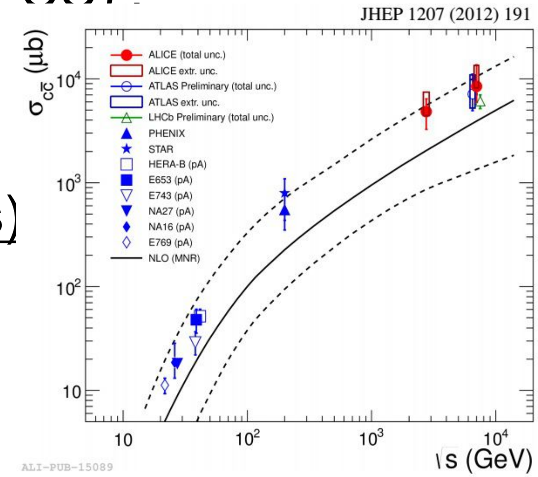


Thermal Charm Production--*Motivation*

When we go to higer and higer energy collisions (eg. FCC) :

the medium become much more hotter and denser

- hotter means thermal partons are more energetic (~ s)
- denser means a higher PDF in the medium

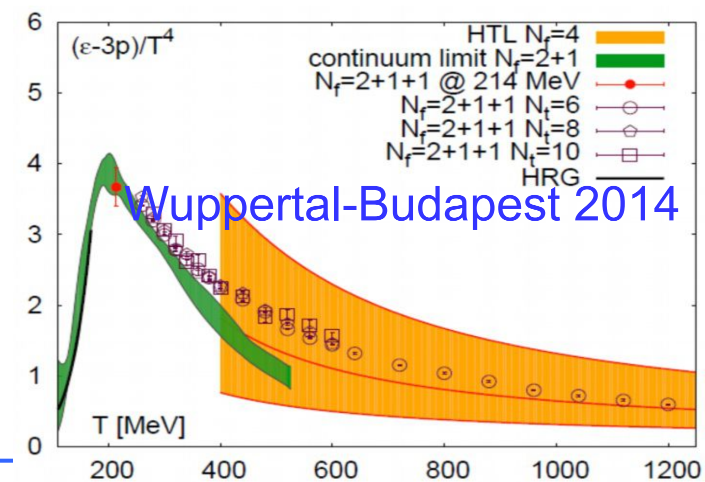


$$\sigma^{AB\to[c\bar{c}]}(s) = \sum_{i,j}\int dx_1 dx_2 \hat{\sigma}^{ij\to[c\bar{c}]}(x_1 x_2 s, m^2, \mu) f_i^A(x_1,\mu) f_j^B(x_2,\mu)$$

⟹ ***secondary in-medium thermal charm production rate can be large***

Theoretically, would dynamical Charm flavor also contribute to bulk medium properties? like EoS, transport coefficients...

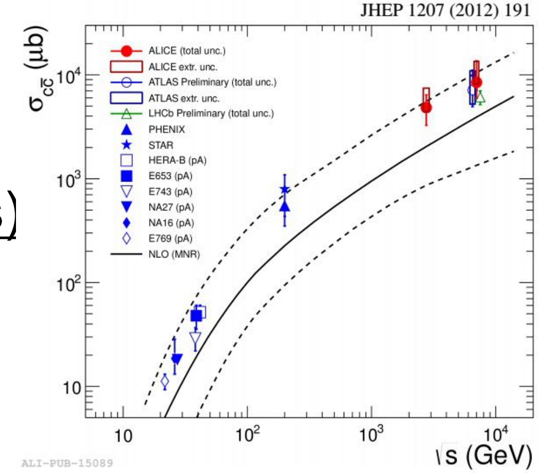
M.Laine, K.Sohrabi, Eur.Phys.J.C 75 (2015) 80



Thermal Charm Production--*Motivation*

When we go to higer and higer energy collisions (eg. FCC) :

JHEP 1207 (2012) 191



the medium become much more hotter and denser

- hotter means thermal partons are more energetic (~ s)
- denser means a higher PDF in the medium

$$\sigma^{AB\to[c\bar{c}]}(s) = \sum_{i,j}\int dx_1 dx_2 \hat{\sigma}^{ij\to[c\bar{c}]}(x_1x_2s, m^2, \mu) f_i^A(x_1,\mu) f_j^B(x_2,\mu)$$

⇒ *secondary in-medium **thermal charm production rate** can be large*

Phenomenologily, $n_{J/\psi}^{regeneration} \sim n_{c(\bar{c})}^2$

Charmonium Enhancement ?

Future Circular Collider 39TeV!

Thermal Charm Production

Rate equation for charm quark density:

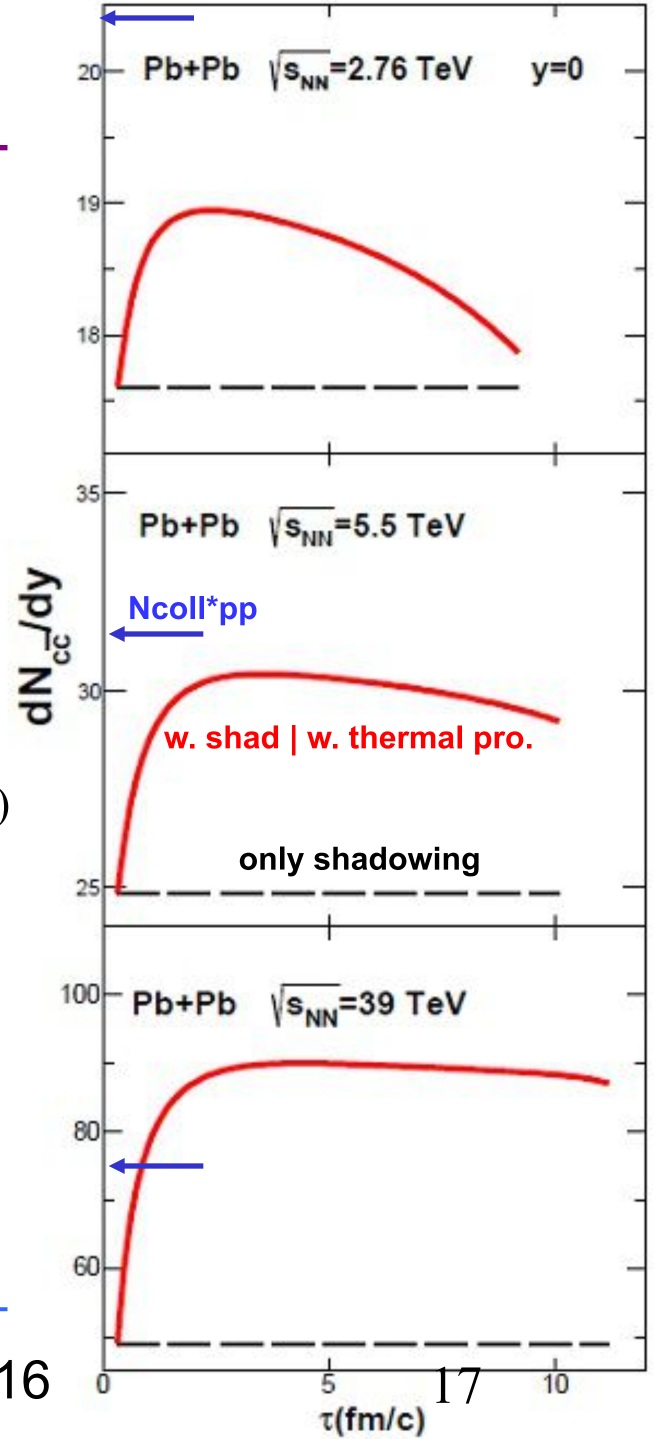
$$\partial_\mu n_c^\mu = R_{gain} - R_{loss}$$

$$R_{gain} = R_{gg\to c\bar{c}(g)} + R_{q\bar{q}\to c\bar{c}(g)}$$ (Nason, Dawson & Ellis, 1988)

R_{loss} : from detailed balance with R_{gain}

$$n_c(\tau_0,\vec{x}_T|\vec{b}) = \frac{d\sigma_{c\bar{c}}/d\eta}{\tau_0} T_A(\vec{x}_T)T_B(\vec{x}_T-\vec{b})\Re_g^A(x_1,\vec{x}_T)\Re_g^B(x_2,\vec{x}_T-\vec{b})$$

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



NEW Results—RAA(Npart)

since $N_{regeneration} \sim N_{c\bar{c}}^2$, thermal charm production can enhance the charmonium regeneration

upper dotted-lines : without shadowing

@2.76TeV

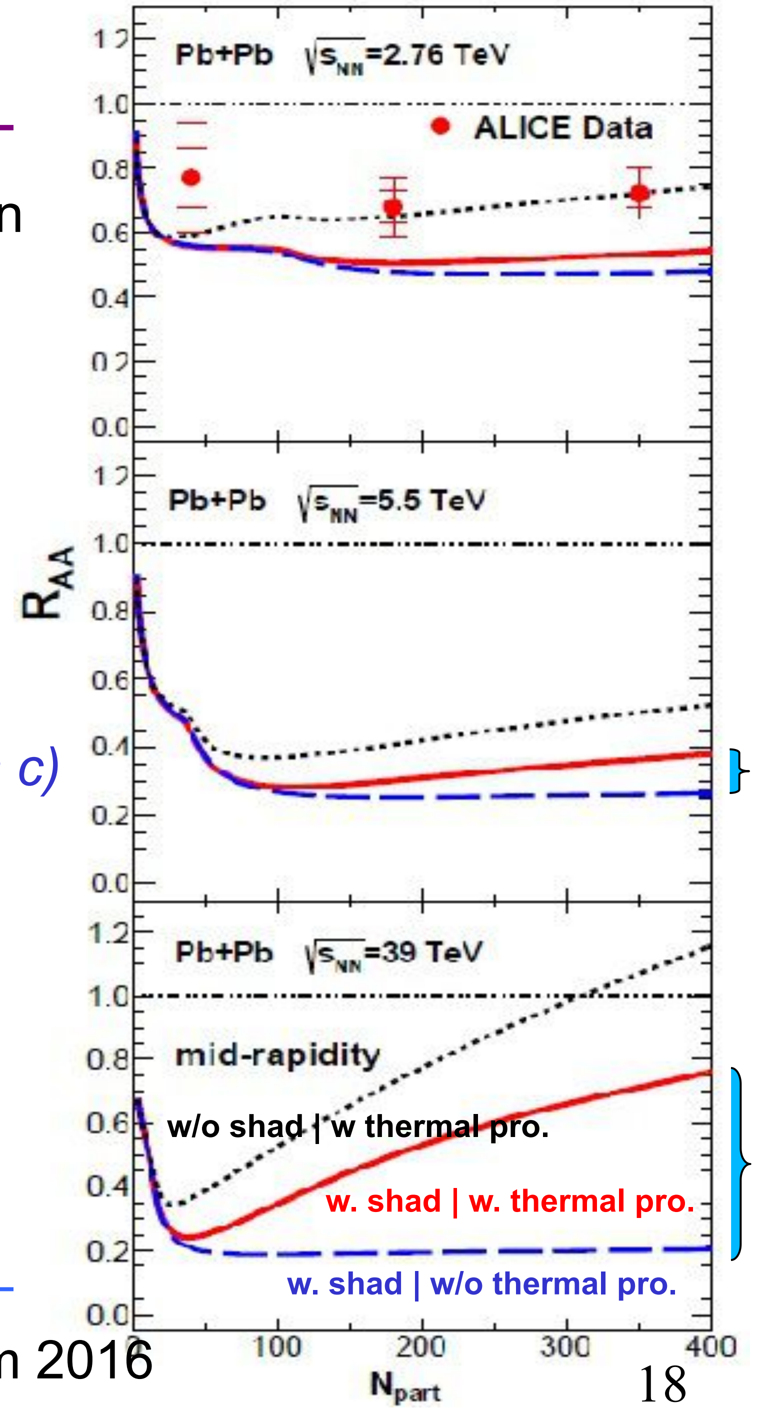
- *weak thermal charm production*

@5.5TeV

- *regeneration enhanced ~40% (quatratic in c)*

@39TeV

- *wide plateau → clearly increasing trend*
- *central coll. 0.2 → 0.75 (3 times!)*
- *production **sourced** directly from thermal medium but not initial produced charm*



Results—RAA(pT)

Initial production dominate high pT,
regenration dominate low pT.

@2.76TeV

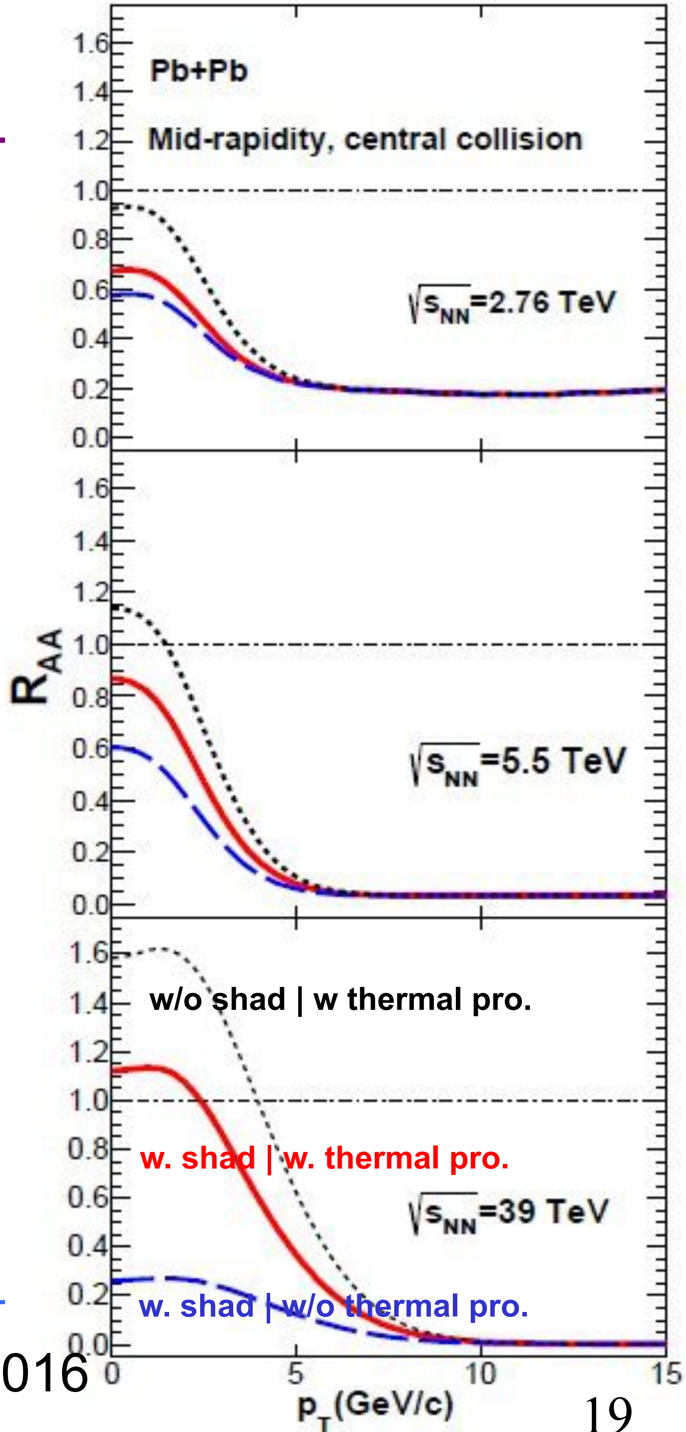
- *regeneration mostly from initial charm*

@5.5TeV

- *sizeable enhancement ~ 40% at low pT*

@39TeV

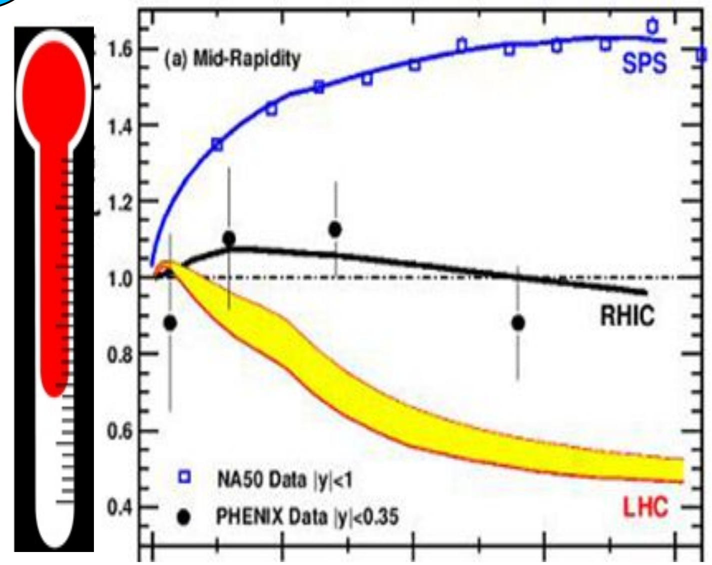
- *RAA >1 at low pT~enhancement*
- *slight bump impling thermalization (flow)*



Summary

$r_{AA} = \langle p_T^2 \rangle_{AA} / \langle p_T^2 \rangle_{pp}$

cold? hot?



not that hot

a little hot

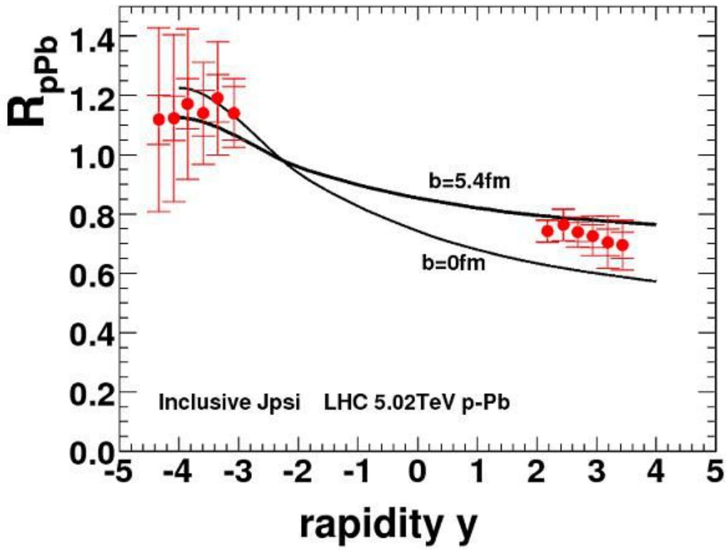
very hot !

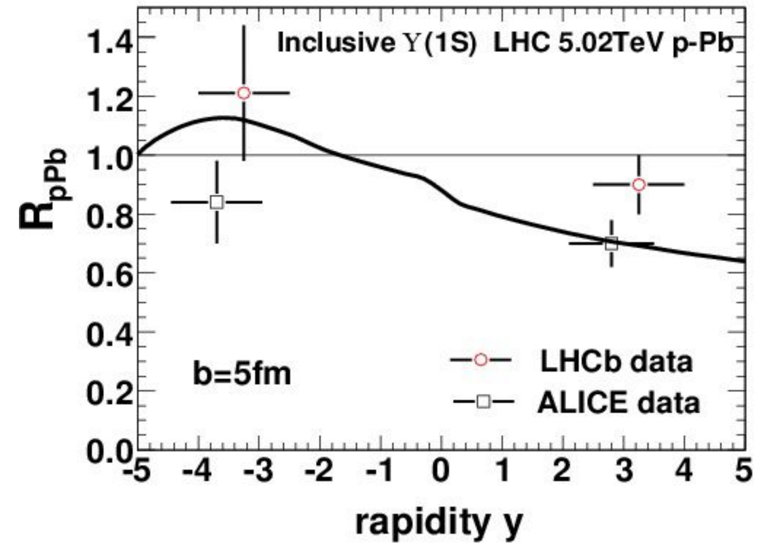
since $N_{regeneration} \sim N_{c\bar{c}}^2$, thermal charm production can enhance the charmonium regeneration, source for charmonium changed from initial hard charm to thermal charm directly from medium

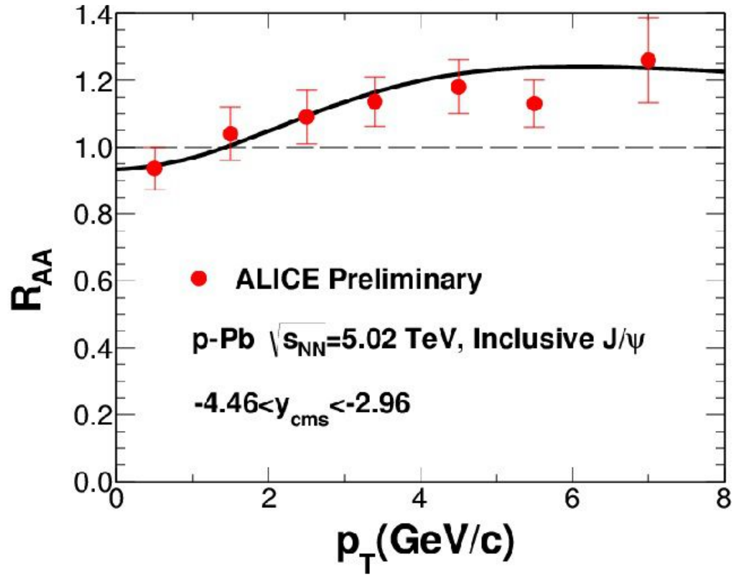
Future Circular Collider
39TeV!

Thank You !

Transport Model- test of cold matter in p-Pb



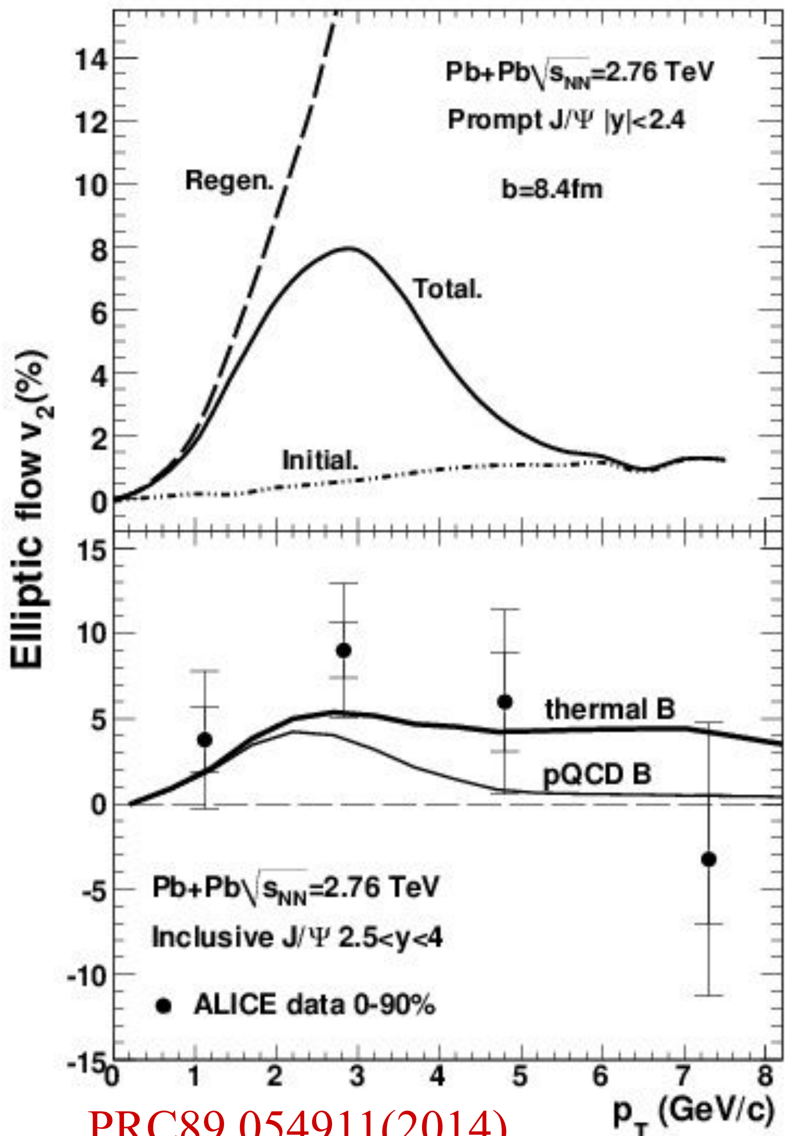




p-Pb 5.02 TeV

Cronin + Shadowing(EKS98) can describe the p-Pb(5.02 TeV) data well ！

Results—Eilliptic flow v2



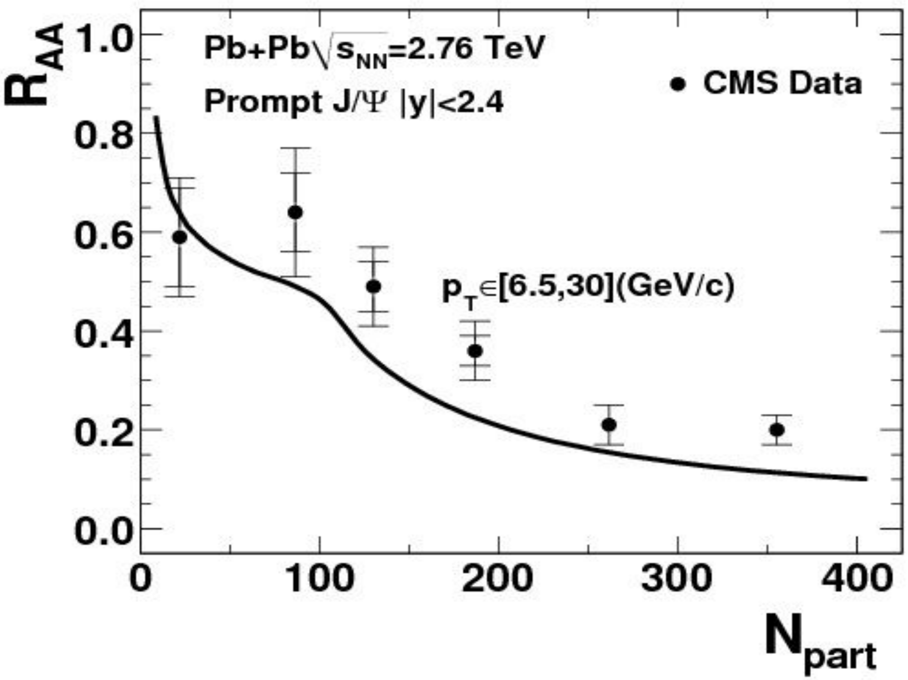
PRC89,054911(2014)

- remarkable v2 from the regeneration ⇨ **reflect heavy quark thermalization.**
- "**ridge**" structure due to ***two component competition***:

{ ***hard***（initial、jet）
{ ***soft***（regeneration、bulk）

Backup—Yield's Centrality depen.（pT bin）

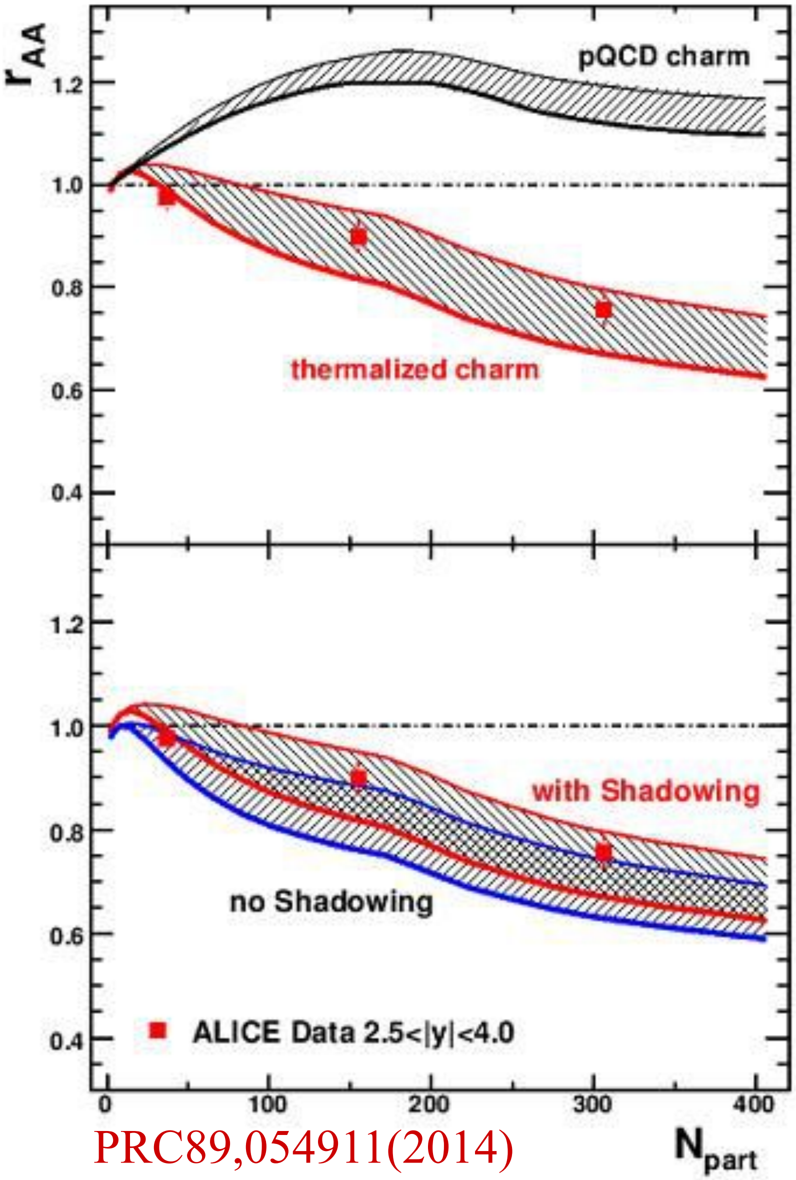
Mid-Rapidity



PRC89,054911(2014)

Note the "kink"----
Melting Tempereature from Color Screening

Results—Modification for Trans. pT: rAA



PRC89,054911(2014)

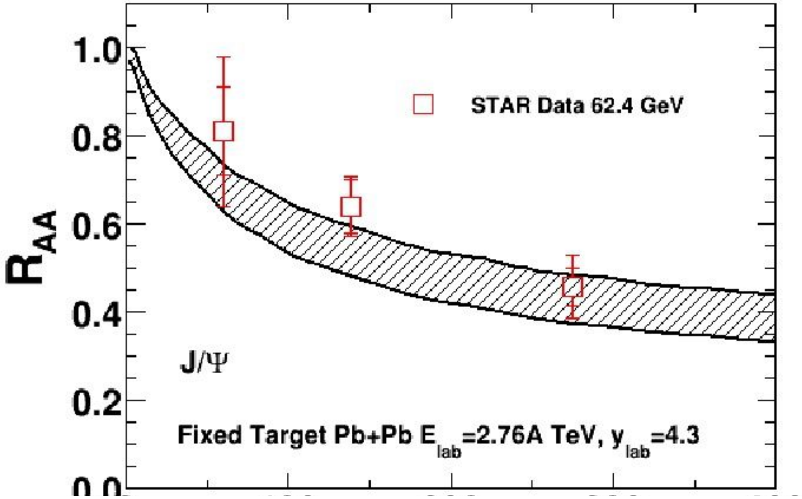
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

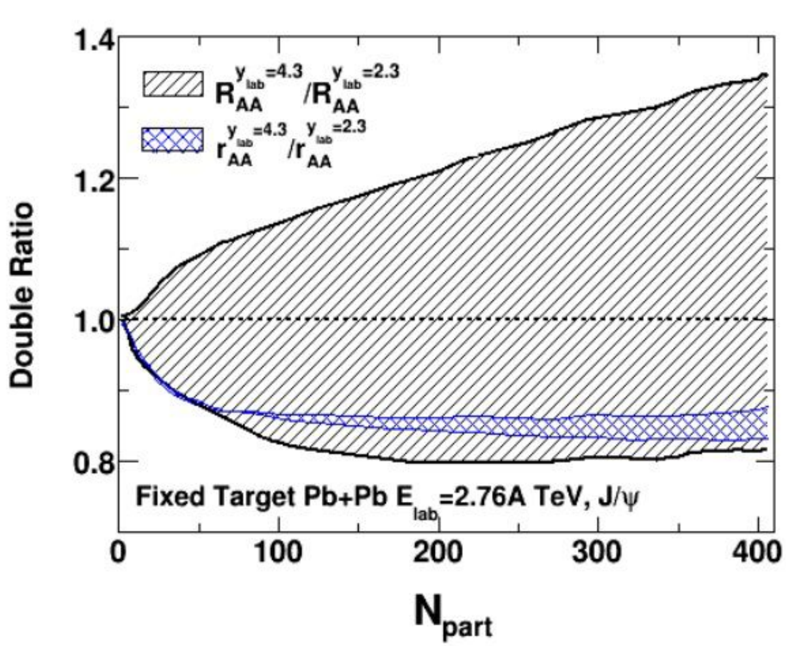
1, sensitive to the degree of heavy quark thermalization --energy loss.

2, not sesitive to the cold nuclear matter effect------ Shadowing effect.

clearly indicates QGP's medium effects

Fixed Target Pb+Pb 2.76A TeV (AFTER) $\sim \sqrt{s_{NN}} = 72GeV$





lower border : w/o Shadowing
upper border : with Shadowing

$$\Delta y = \tanh^{-1}\beta_{cms} = 4.3$$

mid-y (lab-y=4.3) : Anti-shadowing
for-y (lab-y=2.3) : Shadowing

Sensitive probe to gluon distribution

Transport Model- solution of transport equation

$$\left[\cosh(y-\eta)\frac{\partial}{\partial\tau}+\frac{1}{\tau}\sinh(y-\eta)\frac{\partial}{\partial\eta}+\vec{v}_t\cdot\vec{\nabla}_t\right]f=-\alpha f+\beta$$

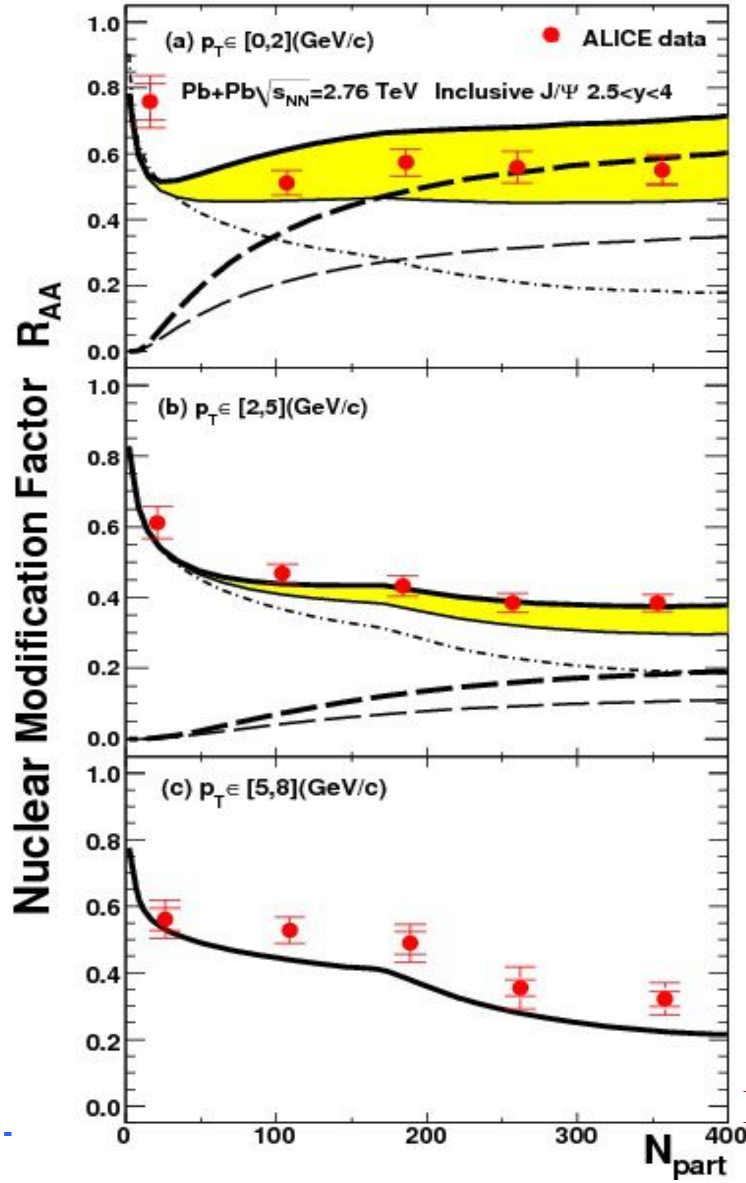
$$\begin{aligned}
& f(\vec{p}_t, y, \vec{x}_t, \eta, \tau) \\
= \; & f(\vec{p}_t, y, \vec{r}_t(\tau_0), Y(\tau_0), \tau_0) e^{-\int_{\tau_0}^{\tau} d\tau' A(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau')} \\
& + \int_{\tau_0}^{\tau} d\tau' B(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau') e^{-\int_{\tau'}^{\tau} d\tau'' A(\vec{p}_t, y, \vec{r}_t(\tau''), Y(\tau''), \tau'')}
\end{aligned}$$

$$\begin{aligned}
\vec{v}_t &= \frac{\vec{p}_t}{E_t} \\
\vec{r}_t(\tau') &= \vec{x}_t - \vec{v}_t\left[\tau\cosh(y-\eta) - \tau'\cosh(\Delta(y-\eta))\right] \\
Y(\tau') &= y - \Delta(y-\eta) \\
A(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau') &= \frac{\alpha(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau')}{\cosh(\Delta(y-\eta))} \\
B(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau') &= \frac{\beta(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau')}{\cosh(\Delta(y-\eta))}
\end{aligned}$$

$$\Delta(y-\eta) \equiv \operatorname{arcsinh}\left(\frac{\tau}{\tau'}\sinh(y-\eta)\right)$$

Both Initial production and Regeneration suffers Suppression

Results—Yield's Centrality depen.（pT bin）



Forward Rapidity

1、flat structure gradually dissappears with pT.---->

Regeneration is mostly contributed in low pT part.

2、Jpsi naturally provide two probes:

a） Hard Probe：high pT，Color Screening

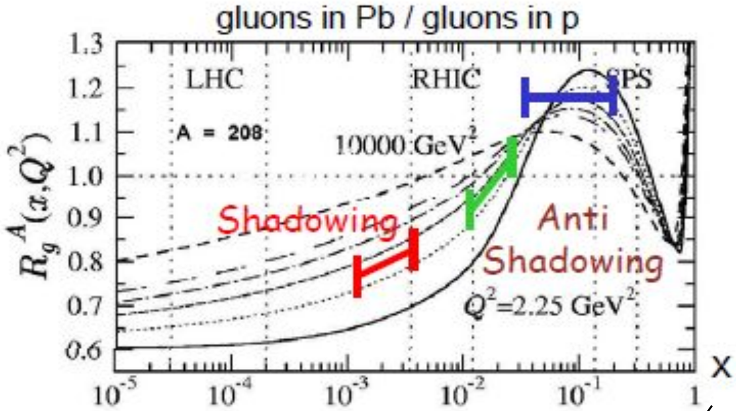
b） Soft Probe：low pT，Thermalization

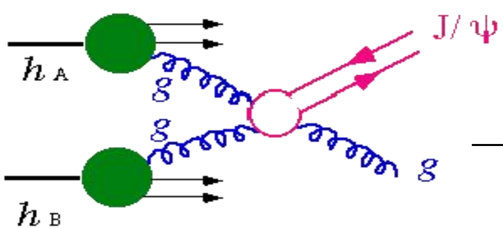
PRC89,054911(2014)

Transport Model- cold nuclear matter effects

Shadowing $R_g^A(x,\mu_F) = \dfrac{f_g^A(x,\mu_F)}{A f_g^{Nucleon}(x,\mu_F)}$

for open & hiden heavy mesons





$$\xrightarrow[\text{Color Evaporation Model}]{\text{(2->1)process}} \quad x_{1,2}^g = \frac{\sqrt{m_{c\bar{c}}^2 + p_T^2}}{\sqrt{s_{NN}}} e^{\pm y}$$

pp

$$\frac{d\sigma_{pp}^{\psi}}{dp_T^{\psi} dy_{\psi}} = \int dy_g x_1 x_2 \cdot f_g(x_1,\mu_F) f_g(x_2,\mu_F) \frac{d\sigma_{gg\to\psi g}}{dt}$$

AA

$$f_0(\vec{p},\vec{x}_T) = \frac{(2\pi)^3}{E_T^{\Psi}\cosh y_{\Psi}} \frac{d\sigma_{pp}^{\Psi}}{dy} \int dz_A dz_B \rho_A(\vec{x}_T, z_A) \cdot \rho_B(\vec{x}_T - \vec{b}, z_b) \mathcal{R}_g(\vec{x}_T, x_1, \mu_f) \cdot \mathcal{R}_g(\vec{x}_T - \vec{b}, x_2, \mu_f) \bar{f}_{pp}(\vec{p}_T, \vec{x}_T, z_A, z_B)$$

$$\mathcal{R}_g(\vec{x}_T, x, \mu_f) = 1 + N_{A,\rho}[R_g^A(x,\mu_f) - 1] \frac{T_A(\vec{x}_T)}{T_A(0)}$$

R.Vogt et al. PRL91 (2003) 142301.
PRC71(2005) 054902

Transport Model- ideal Hydro dynamics

- **2+1D hydrodynamics($\mu_B = 0$)**

$$\begin{cases} \partial_\tau \rho_T + \nabla_T \cdot (\rho_T \vec{v}_T) = 0 \quad (\rho_T(\vec{x}_T, \tau) = \tau \cdot n_{c\bar{c}}^{Lab}) \\ \partial_\tau E + \nabla_T \cdot \vec{M}_T = -(E+p)/\tau \\ \partial_\tau M_x + \nabla_T \cdot (M_x \vec{v}_T) = -M_x/\tau - \partial_x p \\ \partial_\tau M_y + \nabla_T \cdot (M_y \vec{v}_T) = -M_y/\tau - \partial_y p \end{cases}$$

kinetic thermalization for HQ

$$\begin{cases} \partial_\mu T^{\mu\nu} = 0 \\ \text{Boost Invariance in z-direction} \end{cases}$$

$$E = (\varepsilon + p)\gamma^2 - p \qquad \vec{M} = (\varepsilon + p)\gamma^2 \vec{v}$$

- **Equation Of State:**

Ideal Gas with quarks and gluons for QGP
& HRG for Hadronic phase

- **Initialization:**

Glauber model & constrained by
fitting Charged Multiplicities