Transport Study on Heavy Quarkonium production in HIC

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Outline

- Introduction
- Transport model
- Excitation analysis
- Thermal charm production
- Summary

Introduction

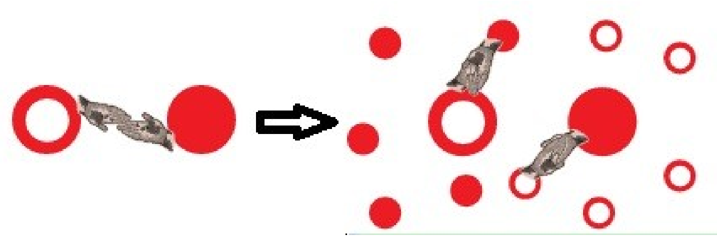
Large mass scale $m_Q >> \Lambda_{QCD}, T$

- 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**



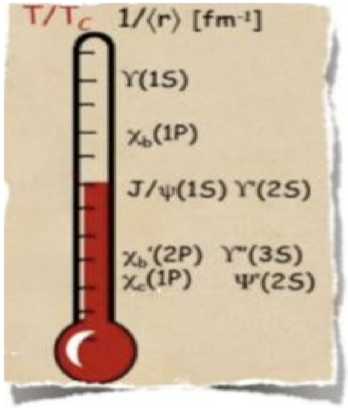
Satz and Matsui, PLB178, 416(1986):
J/Psi suppression as a probe of QGP in HIC

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...

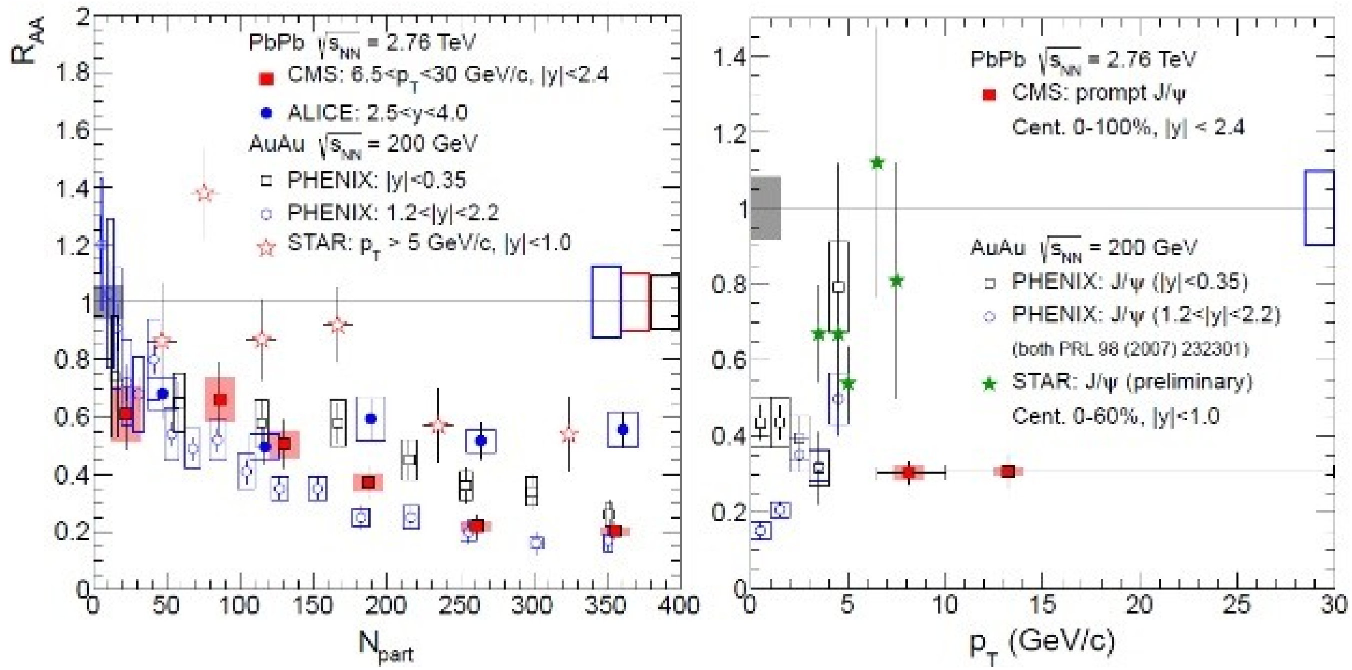
  - Cold matter effects: nuclear absorption, (A.Capella et al) Cronin, (J.W.Cronin et al) Shadowing (A.H.Mueller, R.Vogt, et al)
  - Collisional break-up: gluo-diss.(G.Bhanot and M.H.Peskin) quasi-free diss.(R.RAPP)
  - Regeneration/recombination: coalescence (PBM, Thews, R.Rapp, PF.Zhuang...)

- 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

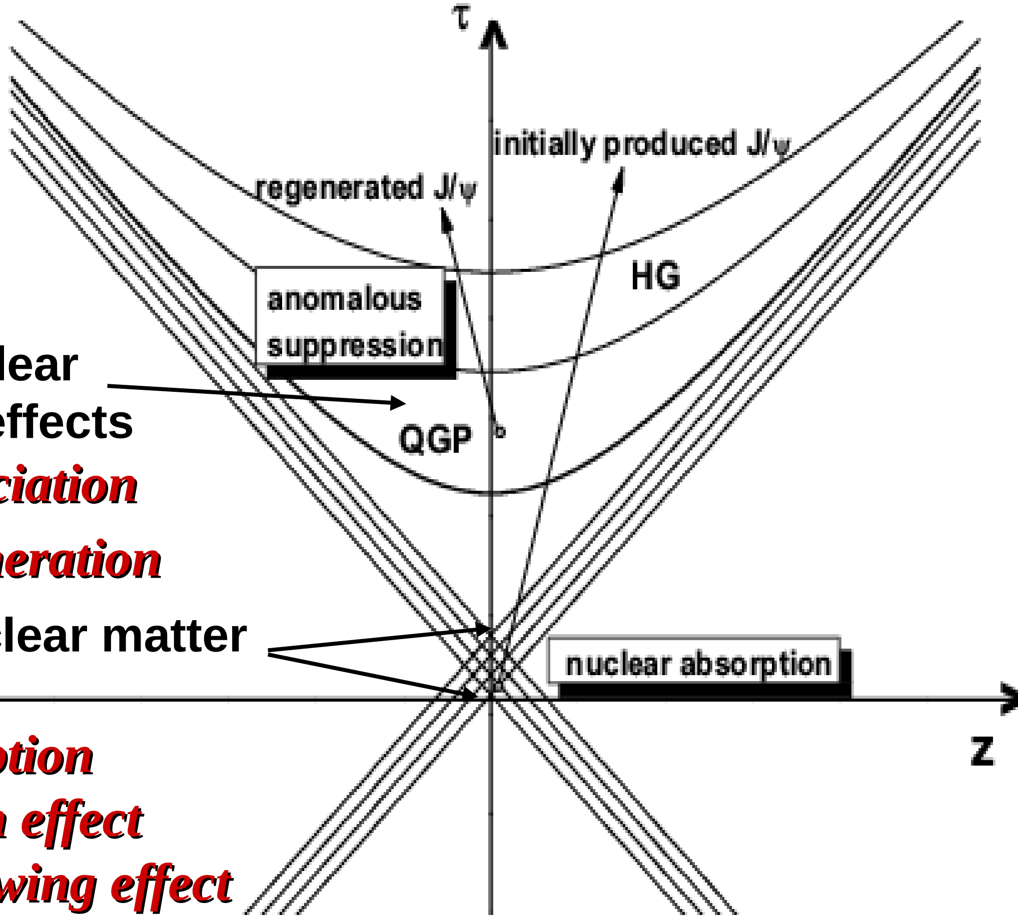
from SPS, to RHIC, Now, we are at LHC era



- ✓ Unifed model including interplay of Cold and Hot matter effects
- ✓ With increasing coll.energy, 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

Transport Equation

cold nuclear matter effects

1)Absorption

2)Cronin effect

3)Shadowing effect

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 $f_\Psi(\vec{x}, \vec{p}, t)$

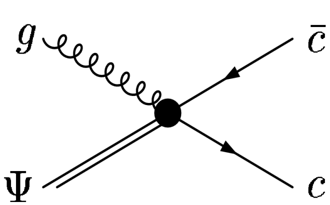
$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

$$g + \Psi \leftrightarrow Q + \overline{Q}$$
α → ← β

1) Gluon dissociation :

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

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



in Vacuum

↓

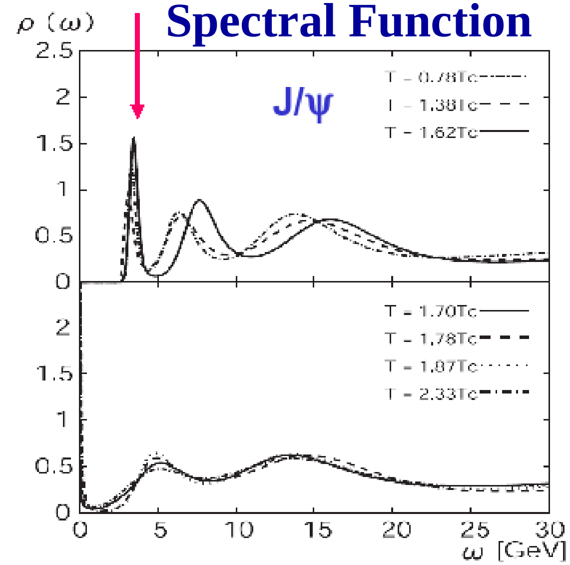
in Medium

OPE (Peskin,1979)

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

spectral peak dissapear above some tem. Td

Spectral Function



Transport Model- transport equation & ***hot effects***

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

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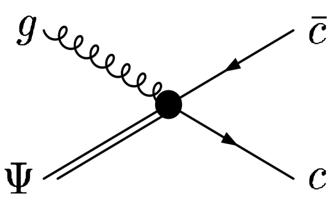
$\alpha \rightarrow$ $\quad$ $\leftarrow \beta$

1) Gluon dissociation :

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



in Vacuum

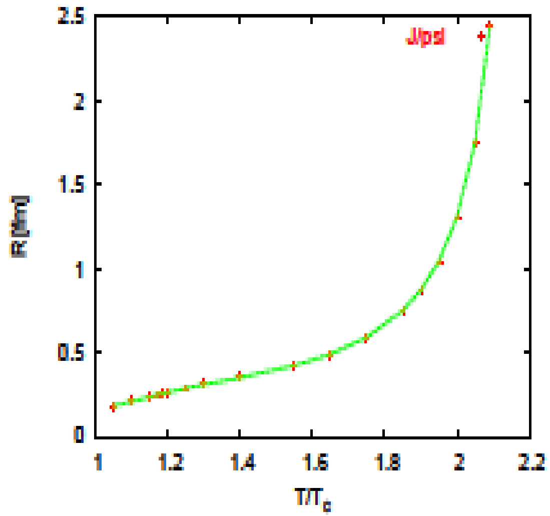
OPE (Peskin,1979)

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

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

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 $f_{\Psi}(\vec{x}, \vec{p}, t)$

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

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

$\alpha \rightarrow$ $\quad$ $\beta \leftarrow$

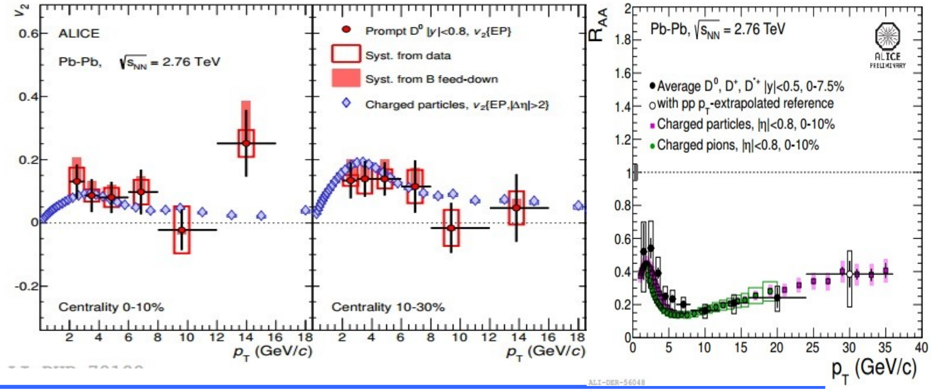
2) in-Medium Regeneration :

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

- 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- *solution* of transport equation

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

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

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

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

Both Initial production and Regeneration suffers Suppression

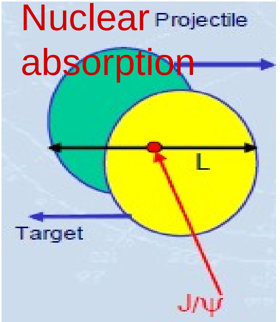
Transport Model- transport equation & *cold effects*

- Initial condition $f_\Psi(\vec{x}, \vec{p}, t)$ for transport eq.

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

Cold Effects

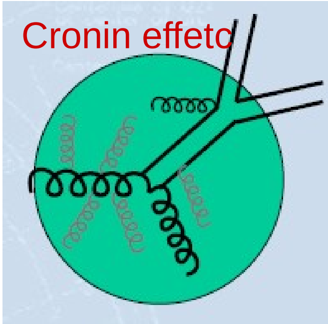
Absorption



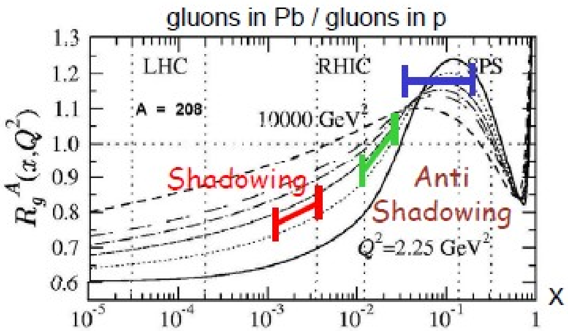
$t_{coll} << t_\Psi$ so it's neglected at LHC

Cronin

Gassian smearing treatment



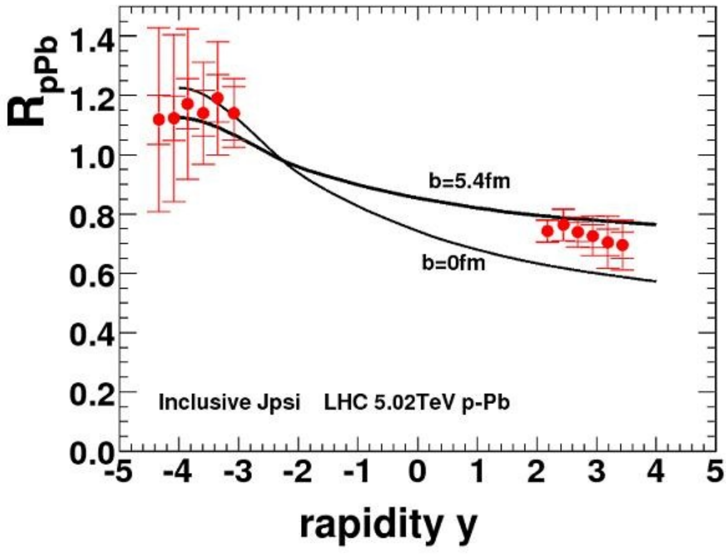
Shadowing

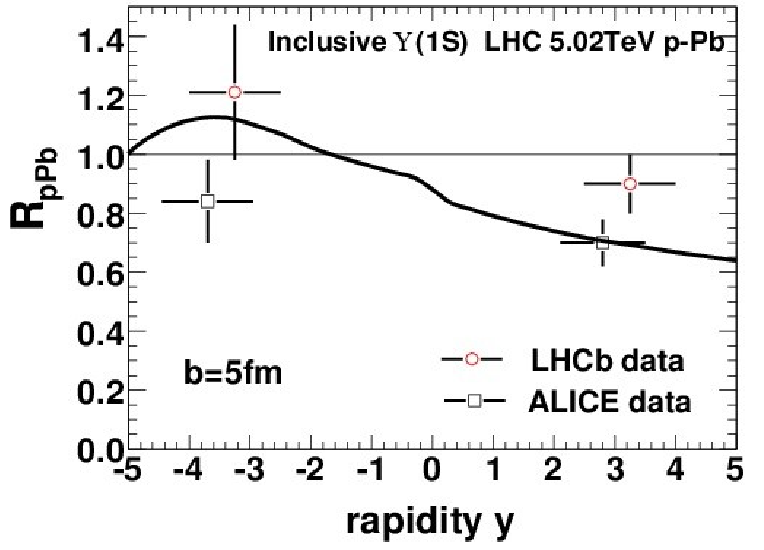


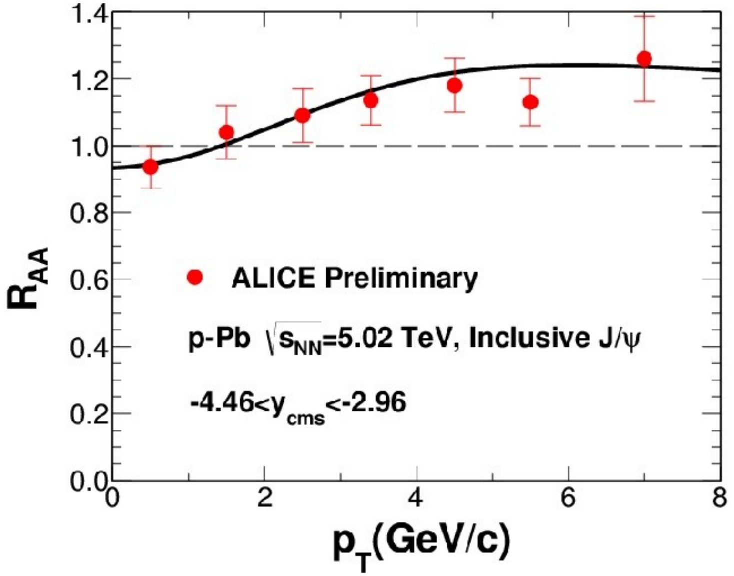
nPDF vs. free PDF

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

Transport Model- test of cold matter in *p-Pb*



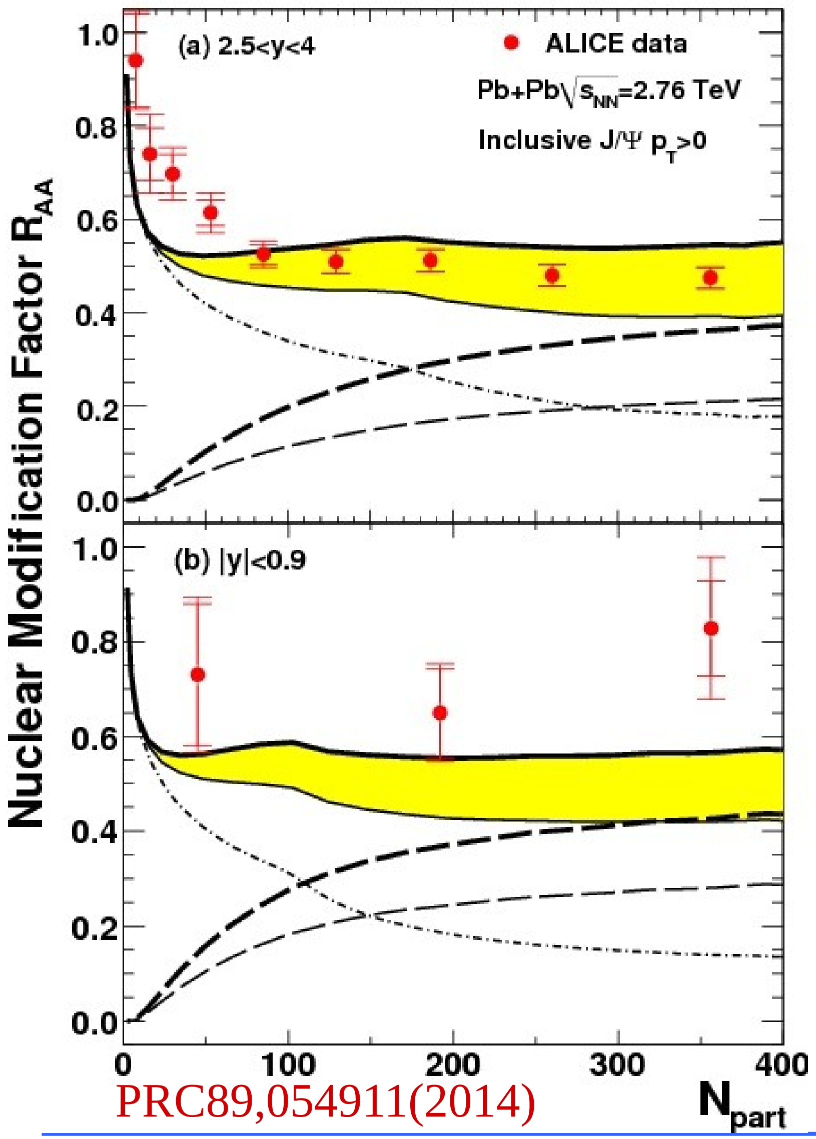




p-Pb 5.02 TeV

Cronin + Shadowing(EKS98)

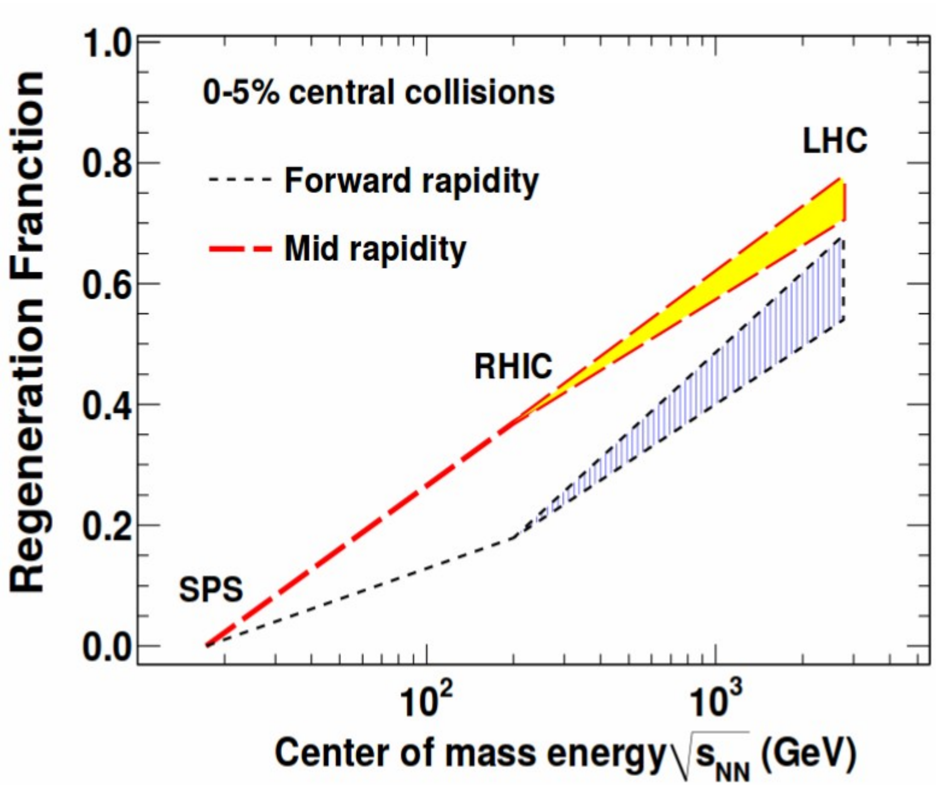
Results—Yield's *Centrality dependence*



PRC89,054911(2014)

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

Excitation—*Regeneration Fraction*

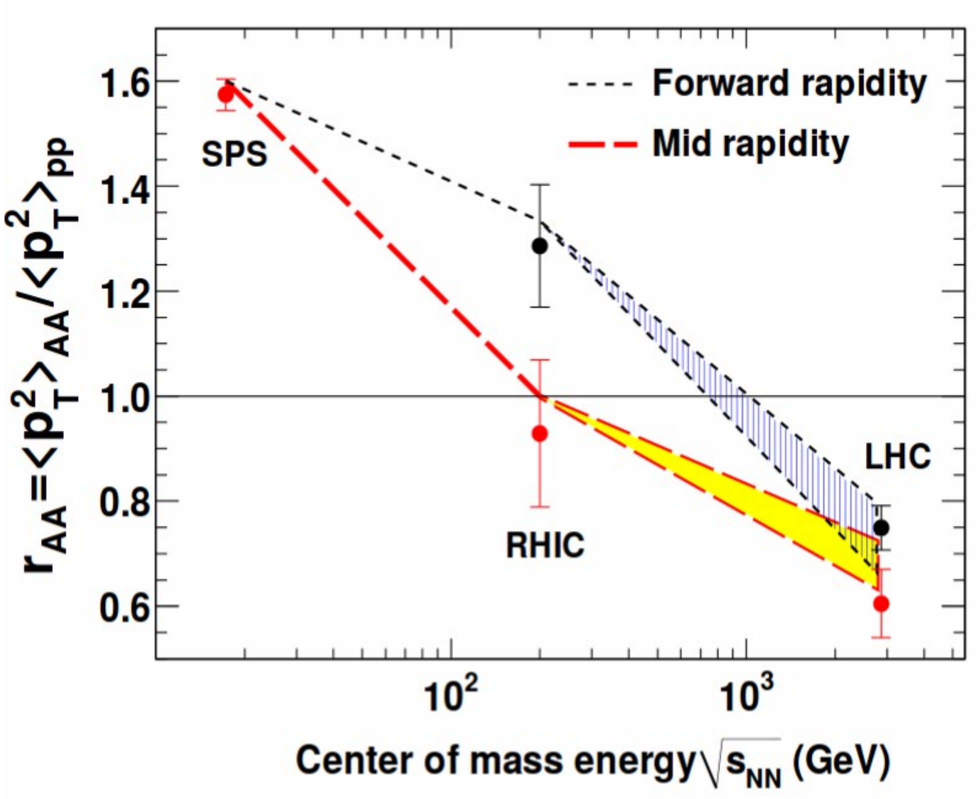


As the collision becomes more violent,

- **Medium becomes hotter:** ***stronger suppression for initial production***
- **More charm quark pairs:** ***larger regeneration***

The increasing trend for reg. fraction -----> regeneration gradually dominant *the charmonium final yield along with collision energy*

Excitation—*Momentum modificaiton*



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

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

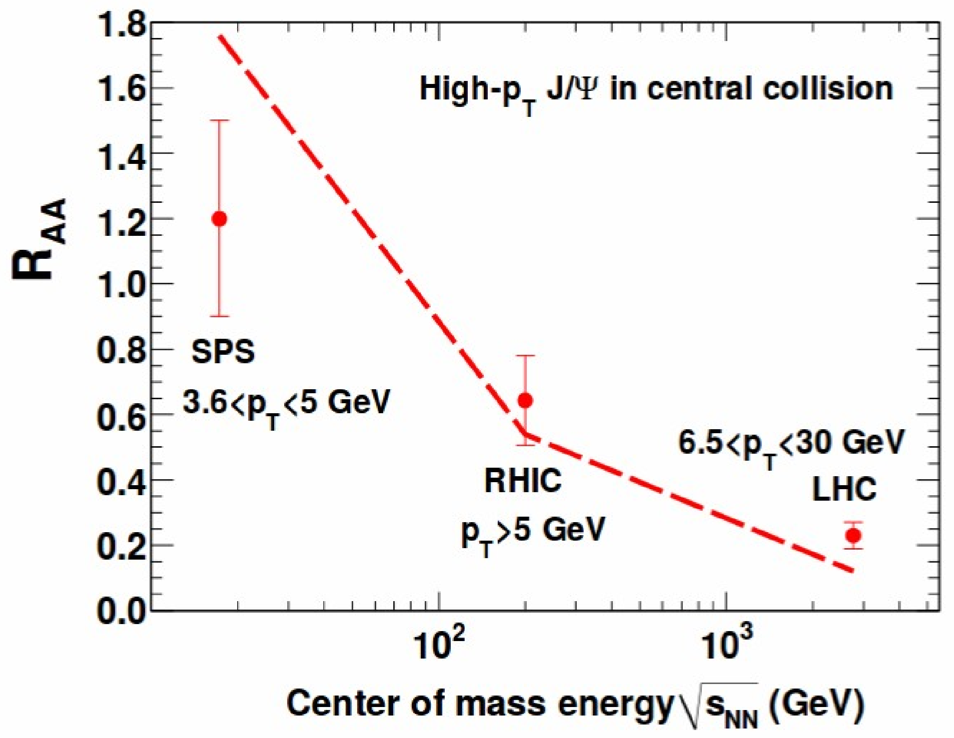
    ⇨ ***initial pt broadening***

- **Regeneration:**
  - **<u>coalescence</u> mechanism**
  - **<u>HQ energy loss</u> induced thermalization**

    ⇨ ***low pt regeneration***

The decreasing trend for rAA -----> *<u>much more hotter</u>* medium effects are working at LHC

Excitation—*High pT part*



As the collision becomes more violent,

Since energy loss, the charm's distribution becomes steeper, then the regeneration can hardly contribute to high-pT part.

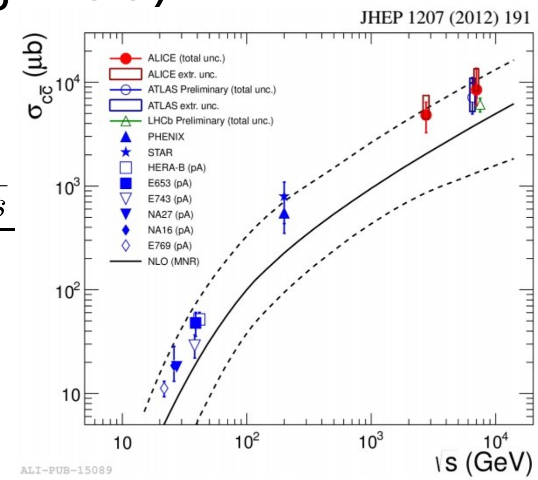
It's dominated by initial production, for which the controled by Debye screening and suppression.

The **decreasing trend** -----> stronger screening and suppression ---> hotter medium created at higher energy collisions

Thermal Charm Production--*Motivation*

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

the medium become much more hotter and denser



- hotter means thermal partons are more energetic ~ $\sqrt{s}$
- denser means a higher PDF in the medium

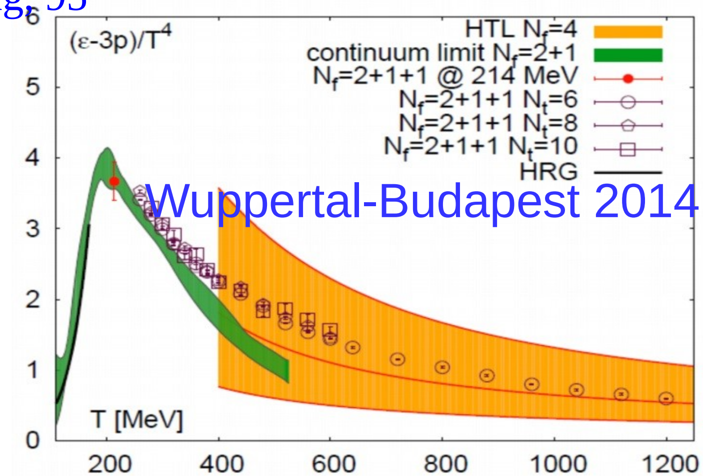
$$\sigma^{AB\to[c\bar{c}]}(s)=\sum_{i,j}\int dx_1 dx_2 \hat{\sigma}^{ij\to[c\bar{c}]}(x_1x_2s,m^2,\mu)\,f_i^A(x_1,\mu)\,f_j^B(x_2,\mu)$$

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

P.Levai, B.Muller and X.Wang, 95
B.Zhang and C.Ko, 08

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



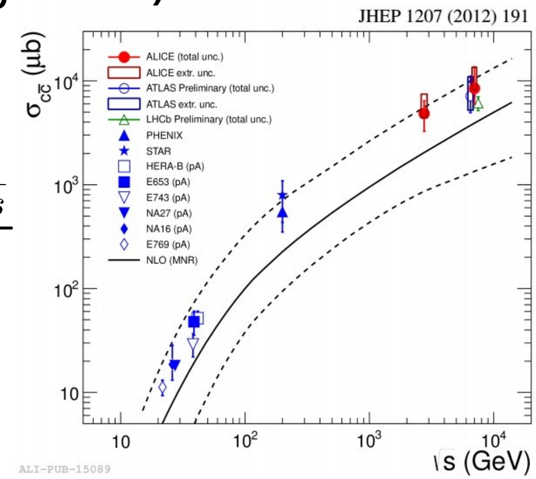
Thermal Charm Production--*Motivation*

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

the medium become much more hotter and denser

hotter means thermal partons are more energetic $\sim \sqrt{s}$

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***

P.Levai, B.Muller and X.Wang, 95
B.Zhang and C.Ko, 08

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

What's the effect on Charmonium production?

Charmonium Enhancement at FCC?

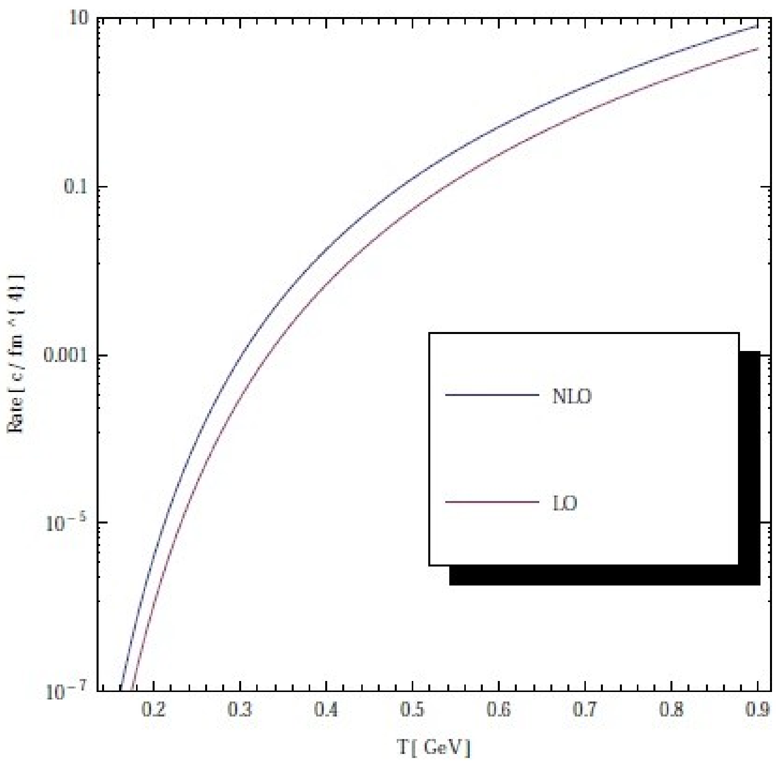
Future Circular Collider 39TeV!

Thermal Charm Production *Rate*

$$R_{12} = \frac{dN_{12}}{d^4x} = \frac{1}{\nu}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} 4F_{12}\sigma_{12}f_1 f_2$$

MNR-NLO cross section for charm production

P.Nason, S.Dawson, and R.Ellis, NPB 303, 607(1988); 327, 49(1989).
M.L.Mangano, P.Nason and G.Ridolfi, NPB373,295(1922)



B.Zhang, C.Ko and W.Liu, PRC77, 024901(2008)

Through detailed balance, the charm pair *annihilation rate* can be calculated, which depends on the charm fugacity.

Thermal Charm Production ***Rate***

$$R_{12} = \frac{dN_{12}}{d^4x} = \frac{1}{\nu}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} 4F_{12}\sigma_{12}f_1 f_2$$

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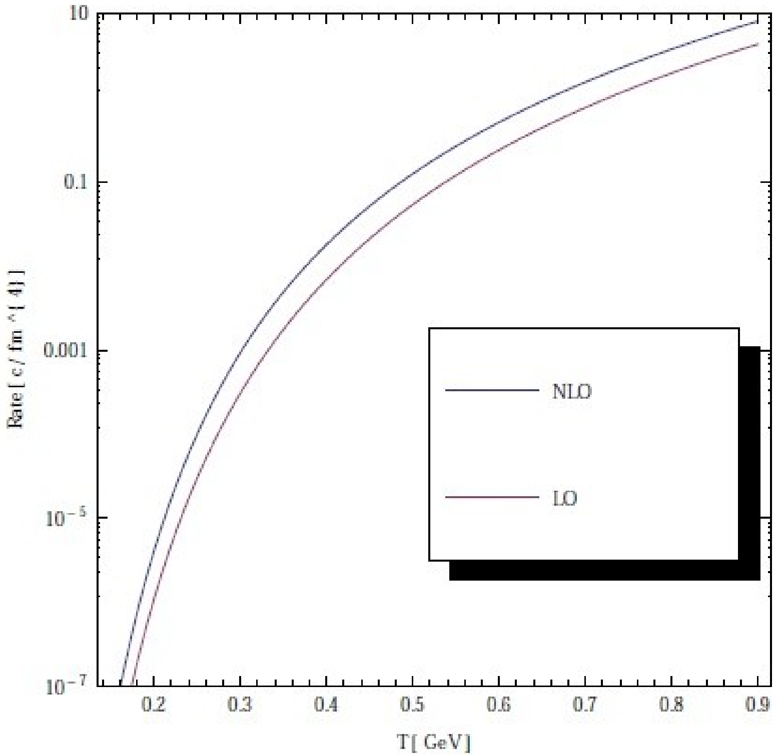


In D. Bodeker, M. Laine,JHEP 1207:130,2012, the thermal charm production rate or charm chemical equilibration rate is connected to the *2-point correlator* of HQ's Hamiltonian, and redefined to be a transport coefficiant which can be evaluated in Lattice QCD then.

$$\Delta(\tau) \equiv \int_{\mathbf{x}} \Big\langle H(\tau,\mathbf{x}) H(0,\mathbf{0}) \Big\rangle_c \,, \quad 0 < \tau < \frac{1}{T} \,,$$

$$\Omega_{\rm chem} = \lim_{\Gamma_{\rm chem} \ll \omega \ll \omega_{\rm UV}} \omega^2 \big[1 + 2 f_{\rm B}(\omega)\big] \rho_\Delta(\omega) \,,$$

$$\Gamma_{\rm chem} = \Omega_{\rm chem}/(2\chi_f M^2)$$

Thermal Charm Production

rate equation for charm quark density:

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

$$\frac{1}{\cosh\eta}\partial_\tau n_c + \vec{\nabla}_T \cdot (n_c \vec{v}_T) + \frac{1}{\tau\cosh\eta} n_c = R_{gain} - R_{loss}$$

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

Couple the above Rate equation with the Hydro evolution we Can get the charm number's evolution ---->

Thermal Charm Production

- **Time evolution for charm number**

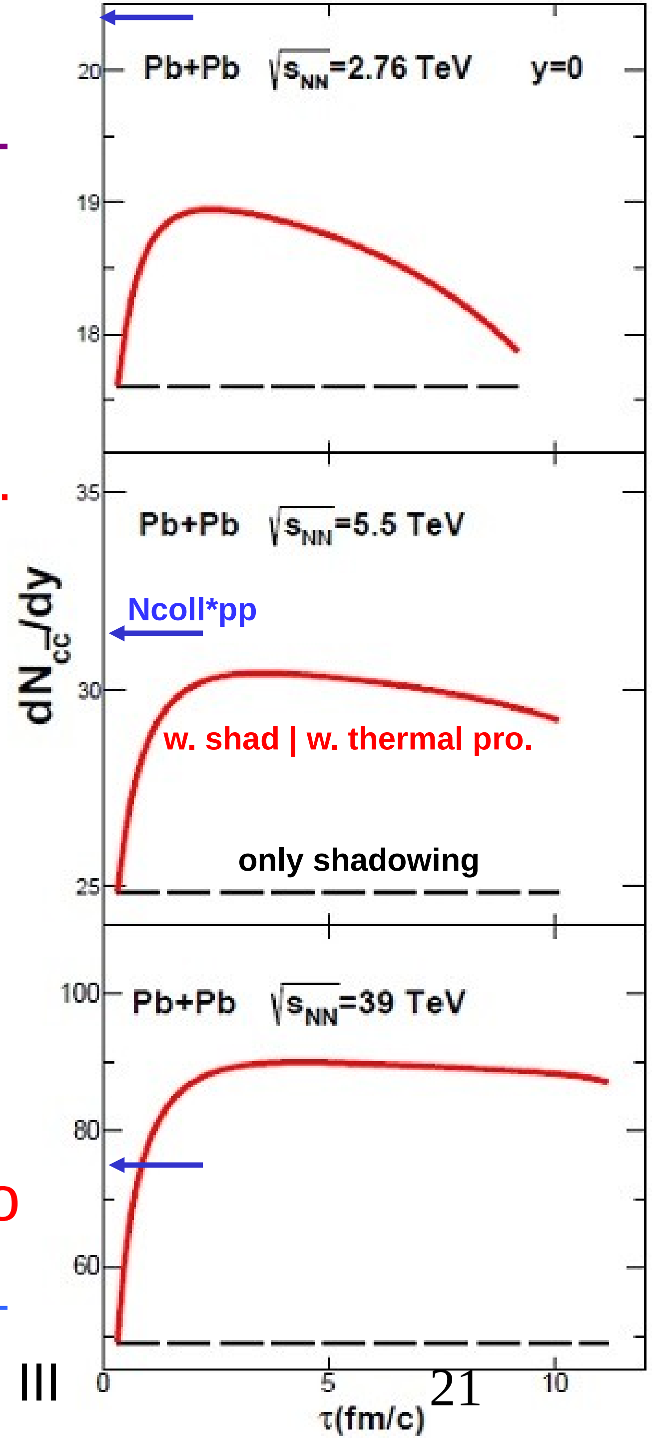
take central collision (b=0 fm) for example:

1) charm number first increase due to thermal pro. and then decrease due to annihilation in later

2) The larger flow will push out the charm and so attenuate their density and the annihilation.

thermal production in Pb+Pb becomes remarkable at 5 TeV and **39 TeV**.

Now put the above charm information into Charmonium calculation ----->



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

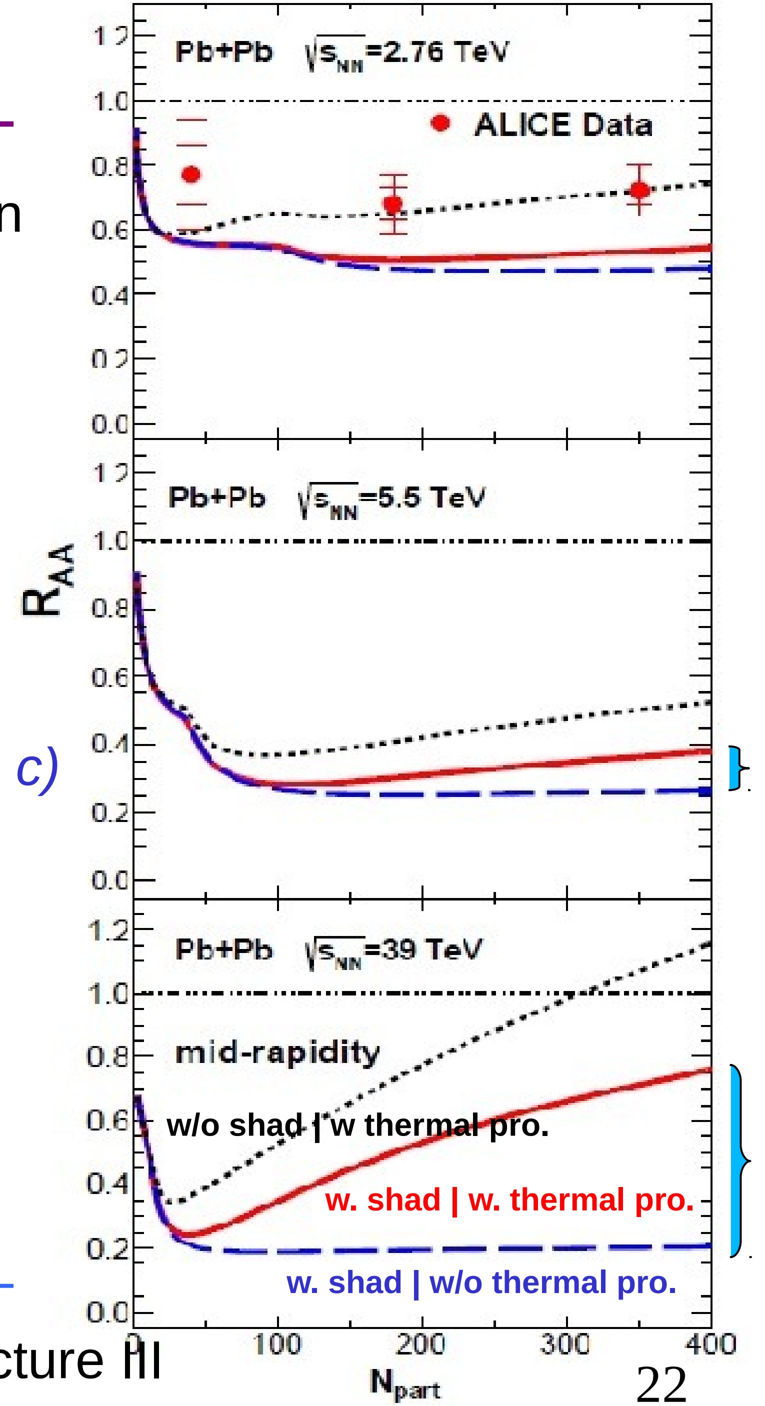
- *weak thermal charm production*

@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

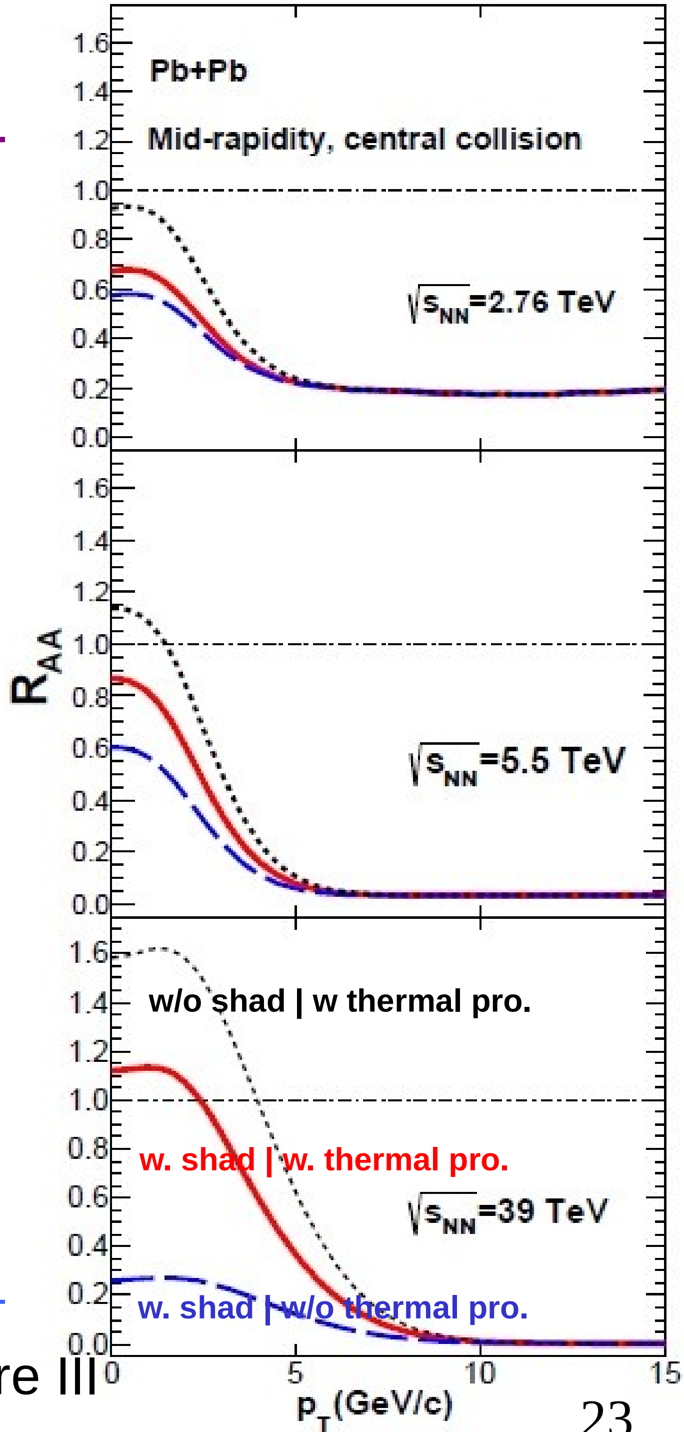
- *regeneration mostly from initial charm*

@5.5TeV

- *sizeable enhancement ~ 40% at low pT*

@39TeV

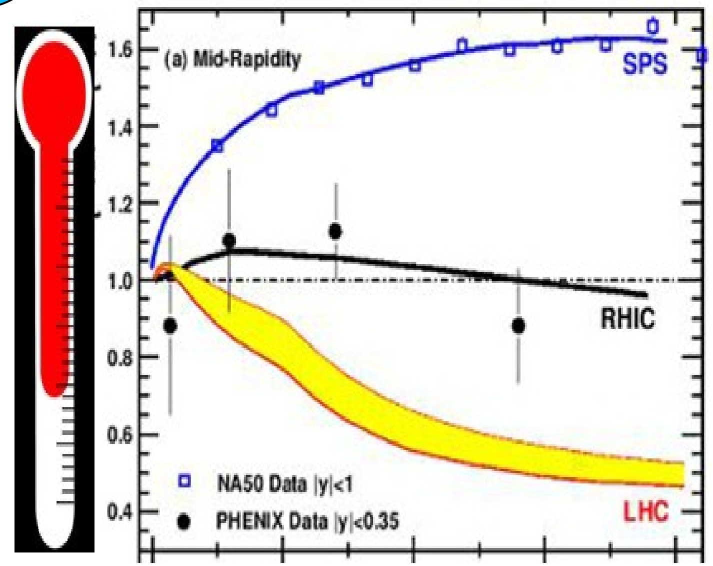
- *RAA >1 at low pT~enhancement*
- *slight bump impling thermalization (flow)*



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**

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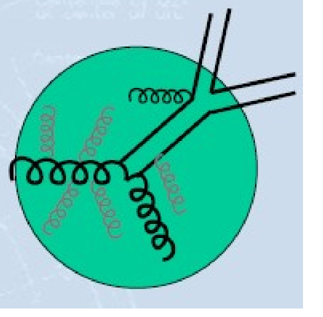
Thank You !

Transport Model- transport equation & *cold effects*

Absorption $\times \quad e^{-\sigma_{abs}\left(T_A(\vec{x}_t, z_A, +\infty)+T_B(\vec{x}_t-\vec{b}, -\infty, z_B)\right)}$

$t_{coll} << t_{\Psi}$ (so at LHC can safly be neglected)

Cronin pT broadening



Gassian smearing :

$$\bar{f}_{pp}(\vec{p}_T, \vec{x}_T, z_A, z_B) = \frac{1}{\pi a_{gN} \cdot l(\vec{x}_T, z_A, z_B)} \int d^2\vec{p'}_T e^{-\frac{{p'_T}^2}{a_{gN} \cdot l(\vec{x}_T, z_A, z_B)}} f_{pp}(|\vec{p}_T - \vec{p'}_T|)$$

$$a_{gN} = \Delta^2(\mu)\sigma_{pp}^{inelasitic}\rho_0$$

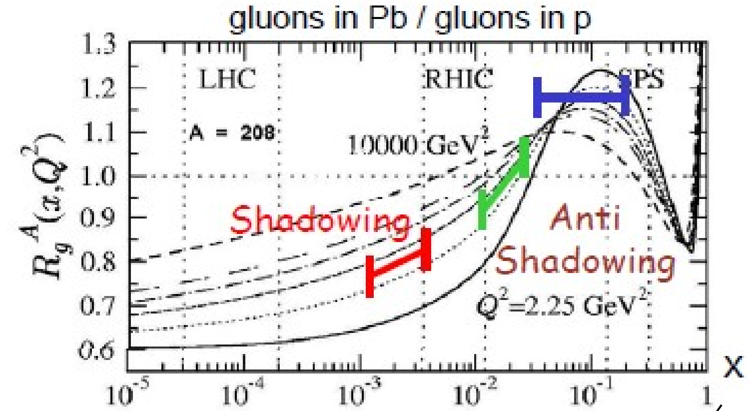
Init.J.Mod.Phys.E.12,211(2003)
Phys.Rev. C 73, 014904(2006)

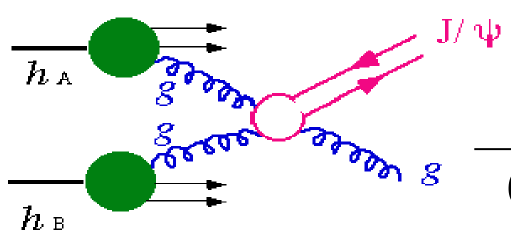
Transport Model- cold nuclear matter effects

Shadowing

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

for open & hiden heavy mesons





(2->1)process

Color Evaporation Model

$$x_{1,2}^g = \frac{\sqrt{m_{c\bar{c}}^2 + p_T^2}}{\sqrt{s_{NN}}} e^{\pm y}$$

pp

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

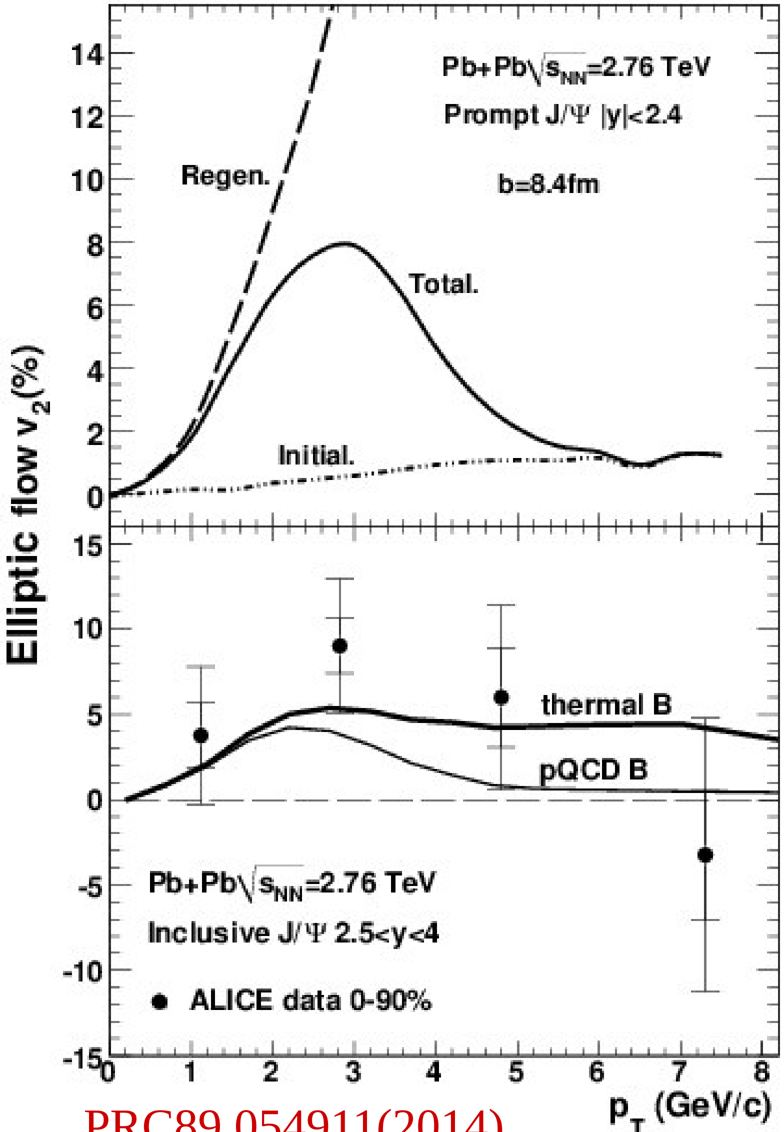
AA

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

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

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

Results—Eilliptic flow v2



PRC89,054911(2014)

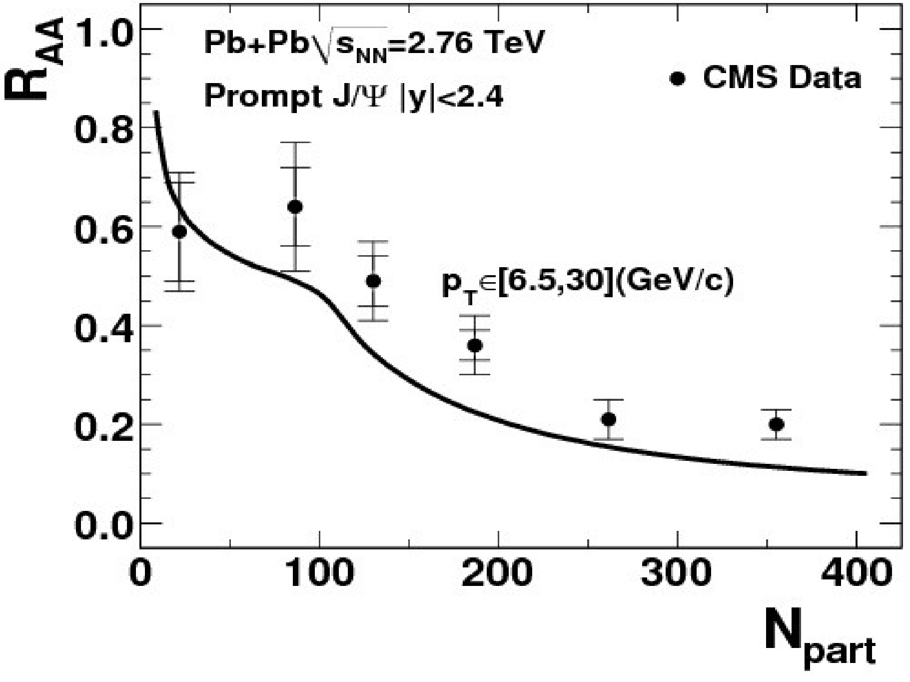
- **remarkable v2 from the regeneration ⇨ reflect heavy quark thermalization.**
- **"ridge" structure due to *two component competition*:**

{ *hard* （ initial 、 jet ）

***soft* （ regeneration 、 bulk ）**

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

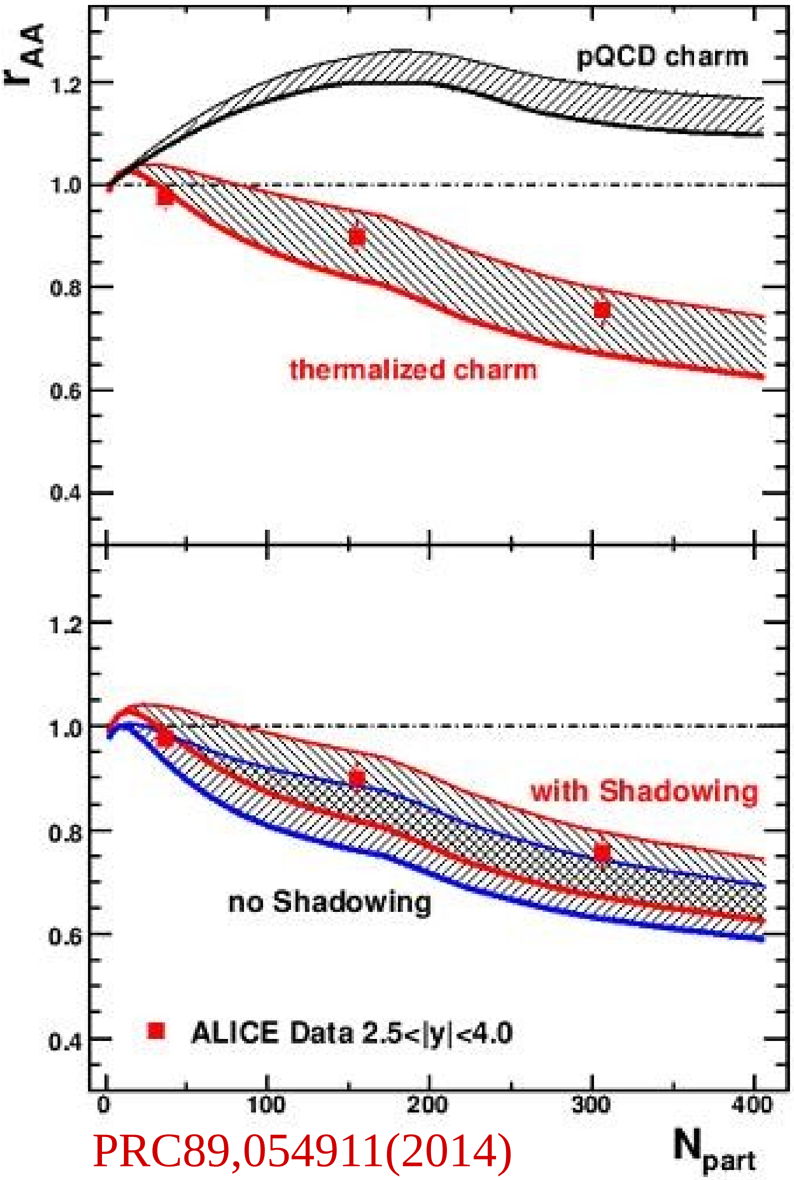
Mid-Rapidity



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

PRC89,054911(2014)

Results—Modification for Trans. pT: rAA



PRC89,054911(2014)

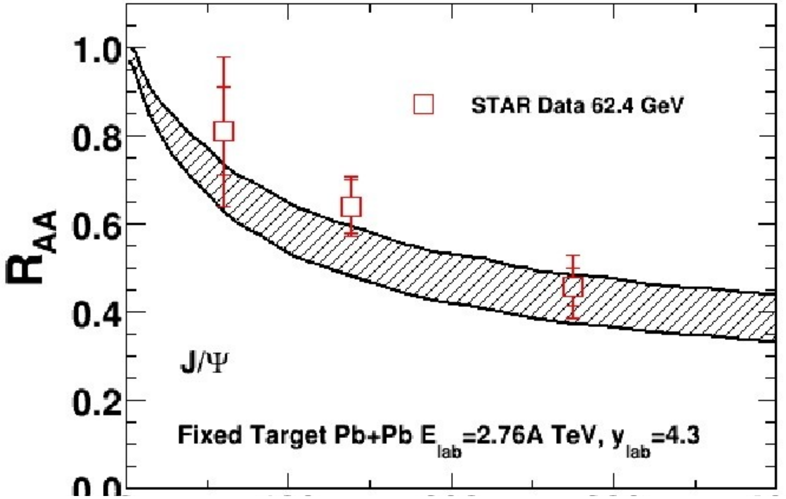
$$r_{AA} = \frac{\left\langle p_T^2 \right\rangle_{AA}}{\left\langle p_T^2 \right\rangle_{pp}}$$

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

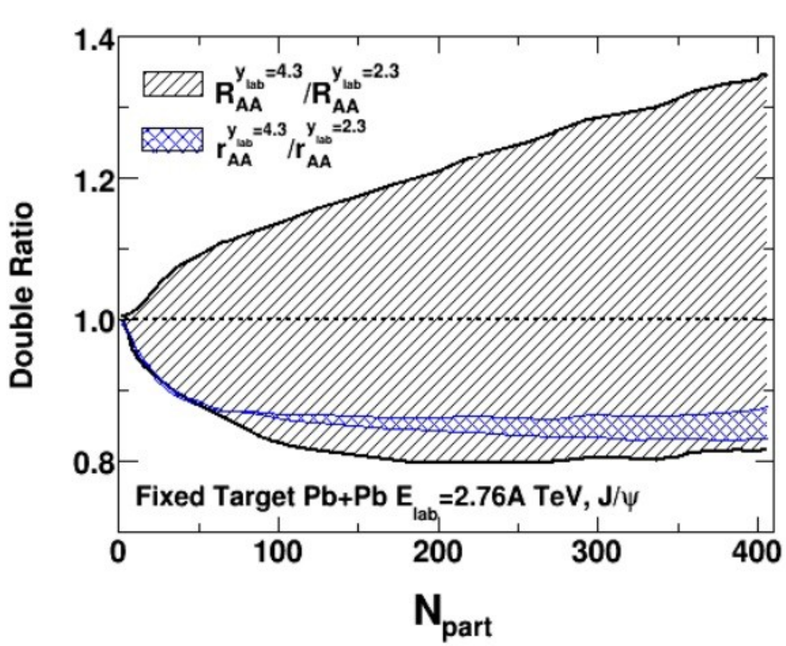
Fixed Target Pb+Pb 2.76A TeV (AFTER) $\sim \sqrt{s_{NN}} = 72GeV$



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

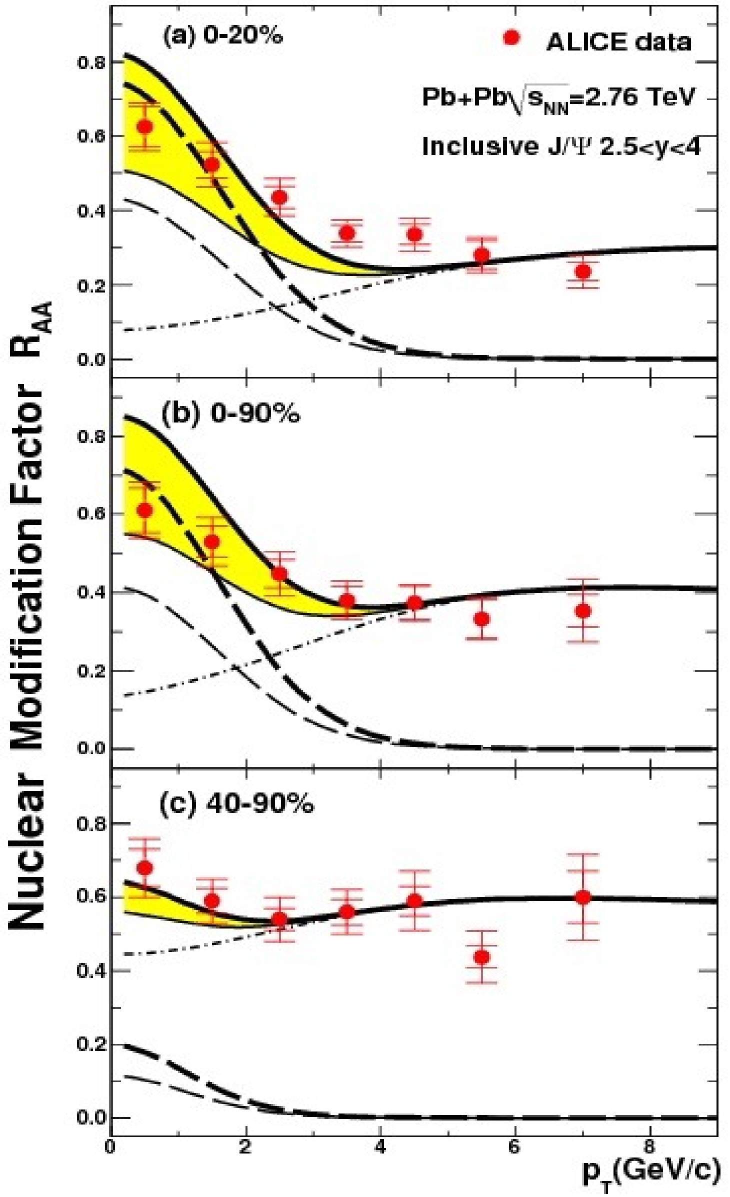
$$\Delta y = \tanh^{-1} \beta_{cms} = 4.3$$

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



Sensitive probe to gluon distribution

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**

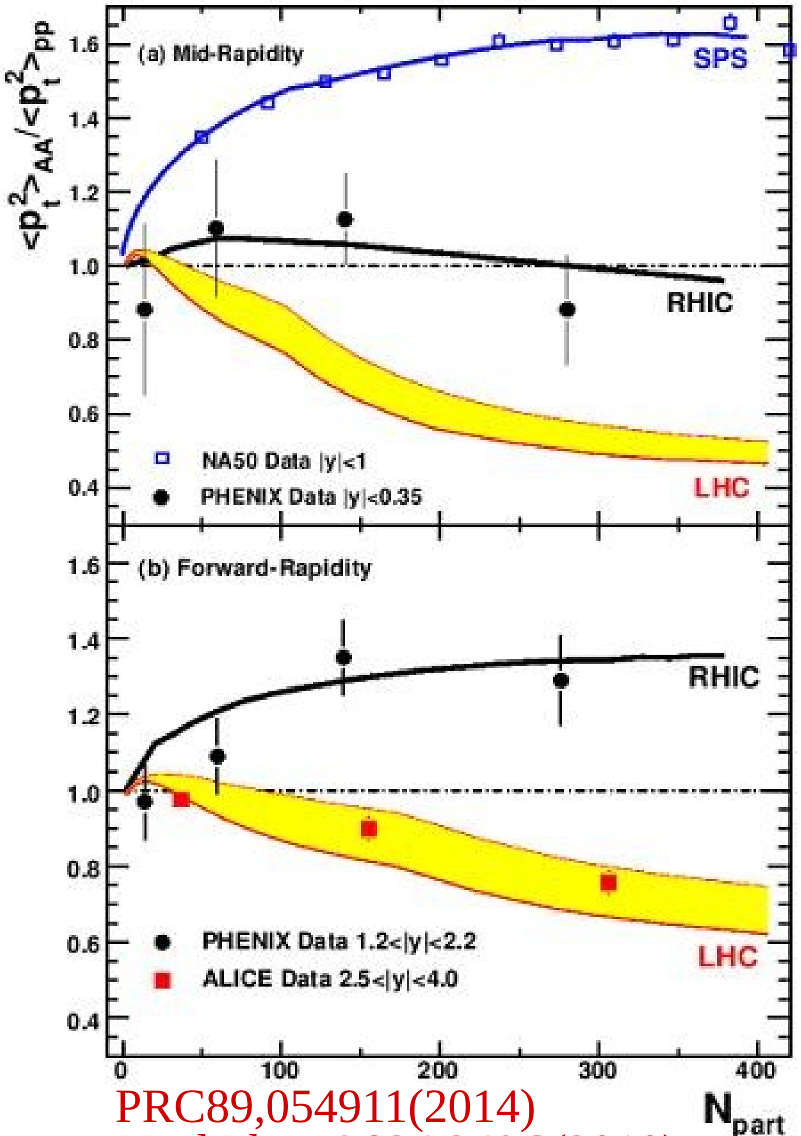
    ⇨ ***initial pt broadening***

- **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)

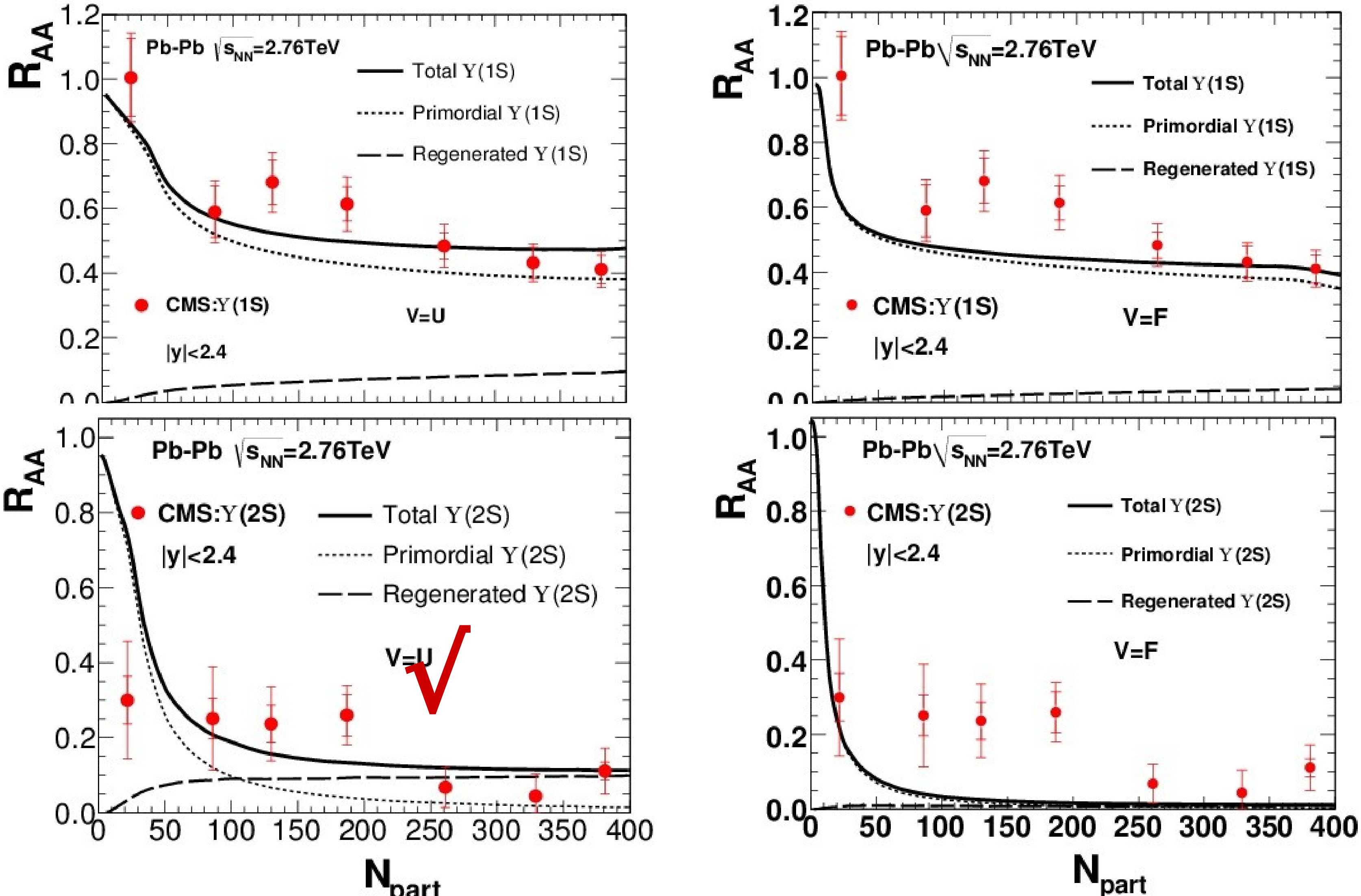
SPS: Cronin effect for
initial production

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

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

LHC: dominant ***regeneration***

Results—Bottomonium differs V=U or V=F



Transport Model- ideal Hydro dynamics

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

$$\partial_\tau \rho_T + \nabla_T \cdot (\rho_T v_T) = 0 \quad (\rho_T(x_T,\tau) = \tau \cdot n_{c\bar{c}}^{Lab})$$

← *kinetic thermalization for HQ*

$$\begin{cases} \partial_\tau E + \nabla_T \cdot M_T = -(E+p)/\tau \\ \partial_\tau M_x + \nabla_T \cdot (M_x v_T) = -M_x/\tau - \partial_x p \\ \partial_\tau M_y + \nabla_T \cdot (M_y v_T) = -M_y/\tau - \partial_y p \end{cases}$$

← $\partial_\mu T^{\mu\nu} = 0$, *Boost Invariance in z-direction*

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

- **Equation Of State:**

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

- **Initialization:**

Glauber model & constrained by fitting Charged Multiplicities