Transport Study on Heavy Quarkonium production in Heavy Ion Collisions

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Based on : PRC89,054911(arXiv:1401.5845)
JPG: Nucl.Part.Phys.41,124006(arXiv:1409.5559)
NPA931,654(arXiv:1408.3900)

GOETHE

HIC for FAIR
Helmholtz International Center

SQM
DUBNA 2015

Outline

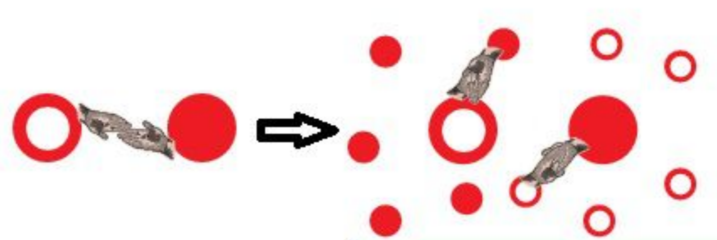
- Introduction
- Transport Model
- Numberical Results
- Summary

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**



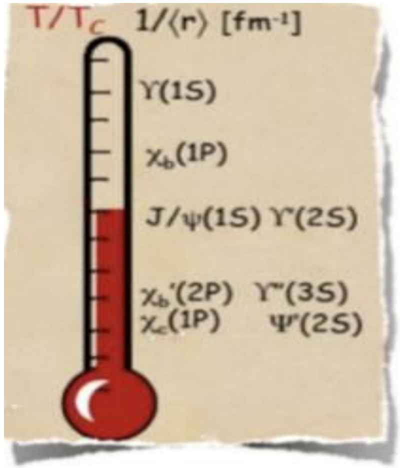
***Satz and Matsui: PLB178, 416(1986)*:**
J/Psi suppression as a probe of QGP in HIC

Introduction

- Thermometer

e.g for **V=U=F+TS** (H.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



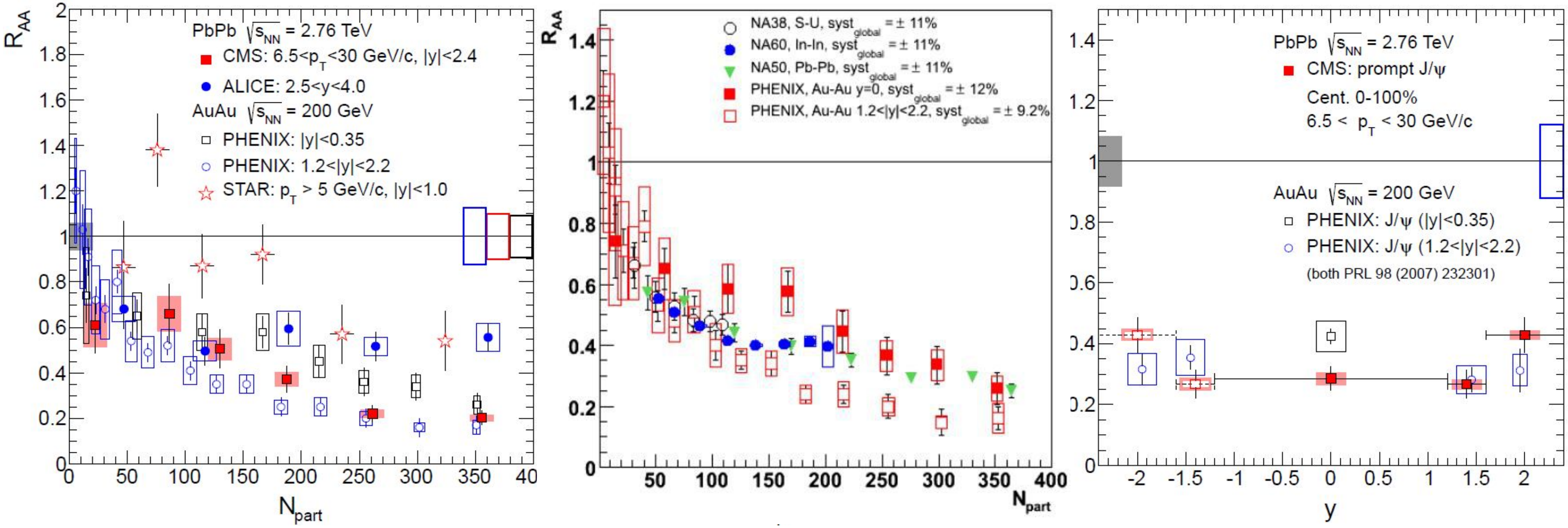
- Not so simple, many other effects affecting...
  - Cold matter effects, nuclear absorption (A.Capella et al), Cronin (J.W.Cronin et al), Shadowing (A.H.Mueller, R.Vogt, et al)
  - collisional break-up, gluo-diss.(G.Bhanot and M.H.Peskin) quasi-free diss.(R.Rapp)
  - Regeneration/Recombination (PBM, Thews, R.Rapp,et al)

- Observation

$$R_{AA}=\frac{N^{AA}_{J/\psi}}{N_{coll}N^{pp}_{J/\psi}}\sim\frac{\text{"}QCD_{medium}\text{"}}{\text{"}QCD_{vacuum}\text{"}}\begin{cases}=1 & \text{No effect}\\ <1 & \text{Suppression}\\ >1 & \text{Enhancement}\end{cases}$$

Introduction

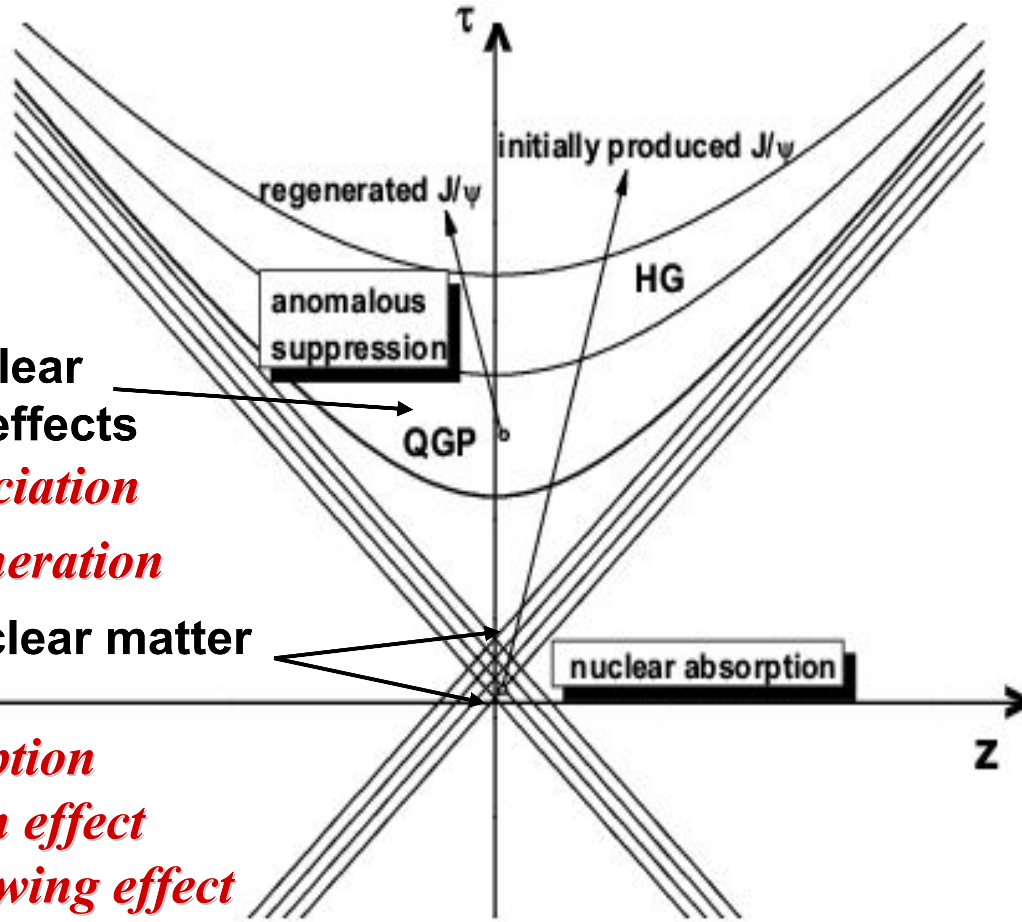
from SPS, to RHIC, Now, we are at LHC era



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

Transport Model

Transport(cold&hot) + Hydrodynamic



Hydrodynamic Evolution

Transport Equation

hot nuclear matter effects

1)Dissociation

2)Regeneration

cold nuclear matter effects

1)Absorption

2)Cronin effect

3)Shadowing effect

Transport Model- transport equation & hot effects

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

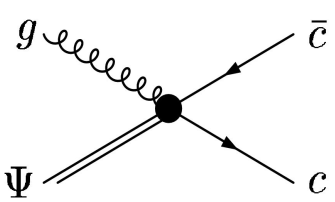
$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

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

1) Gluon dissociation :

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

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



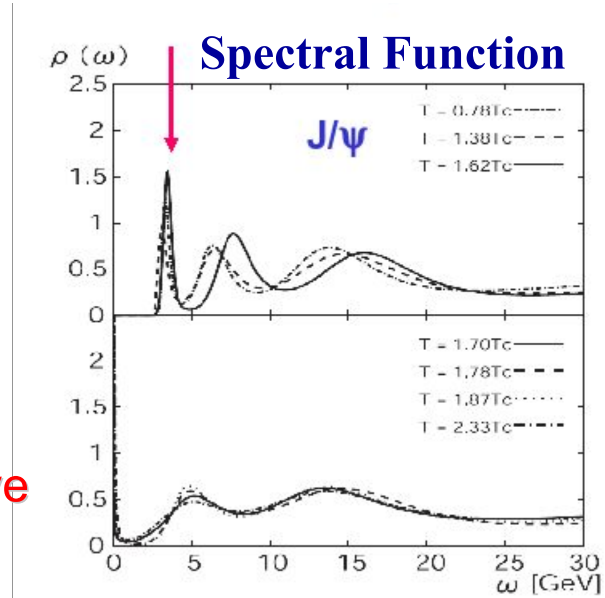
in Vacuum

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

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

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

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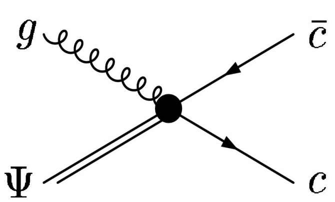

in Vacuum

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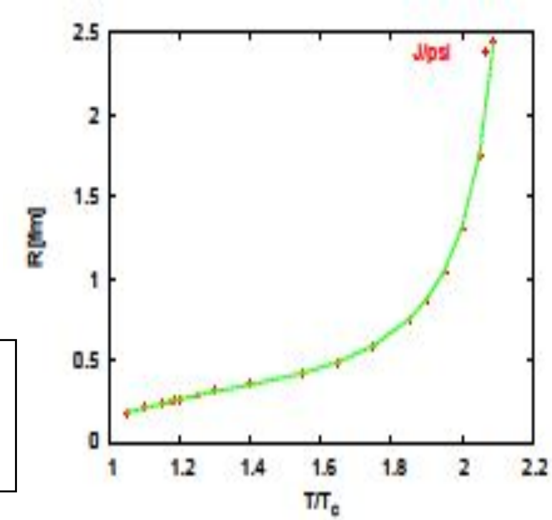
$$\sigma_g(\omega) = A_0 \cdot \frac{(\omega/\epsilon_\psi - 1)^{3/2}}{(\omega/\epsilon_\psi)^5}$$

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

in Medium

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



Transport Model- hot nuclear matter effects

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

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

$$g + \Psi \leftrightarrow Q + \overline{Q} \quad (\alpha \rightarrow,\ \beta \leftarrow)$$

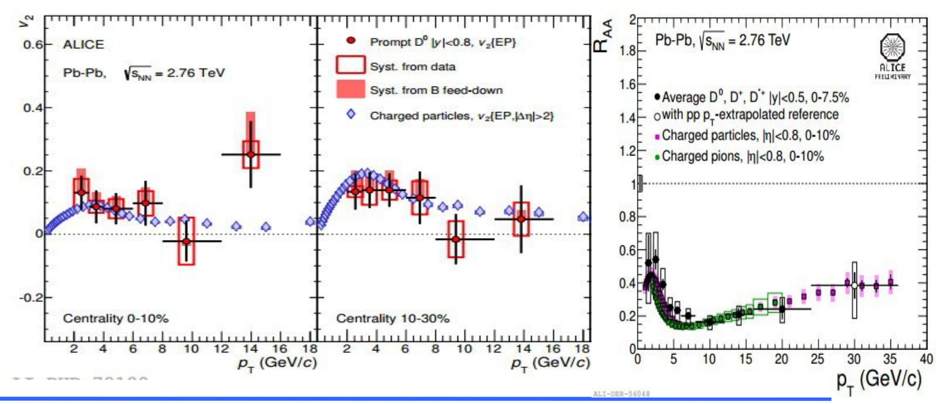
2) in-Medium Regeneration :

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

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

- Distribution for heavy quarks is assumed (strong interation limit) as:

$$f_Q(q,x) = N(x)\rho_Q(x)/(e^{u\cdot q/T}+1)$$



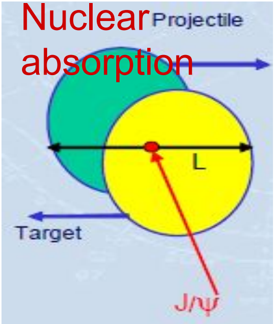
Transport Model- cold nuclear matter effects

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

Glauber superposition from pp collisions along with modification from CNMs:

Cold Effects

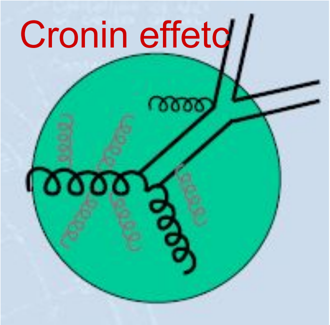
Absorption



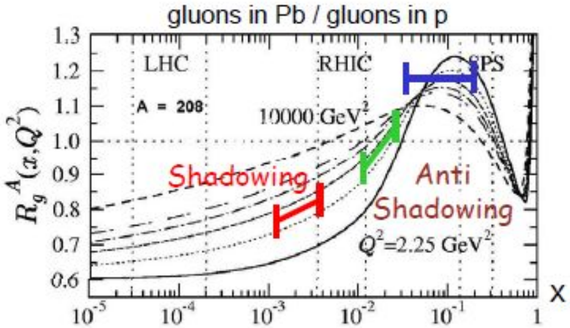
$t_{coll} << t_{\Psi}$ so it's neglected at LHC

Cronin

Gassian smearing treatment



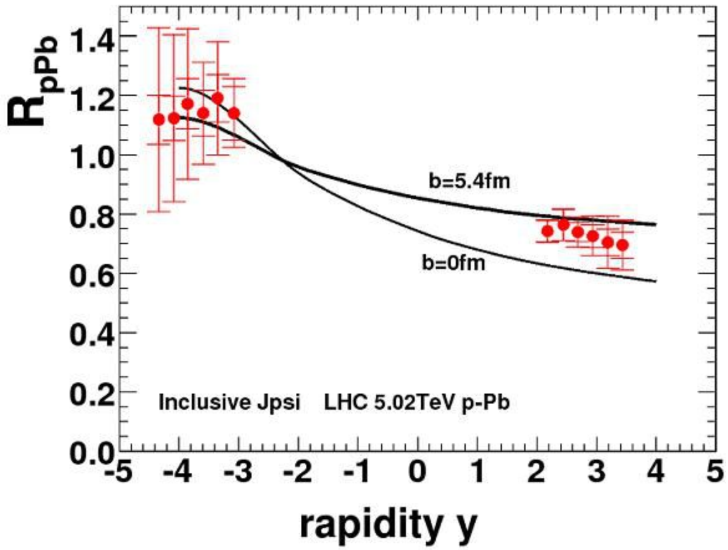
Shadowing

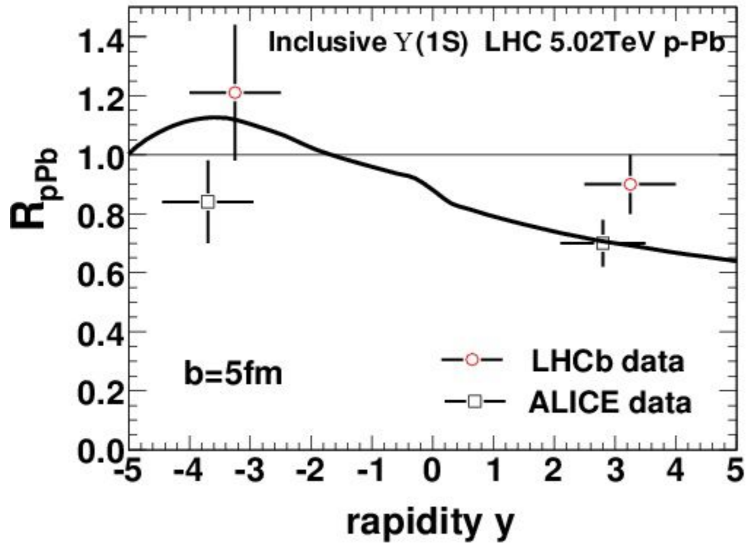


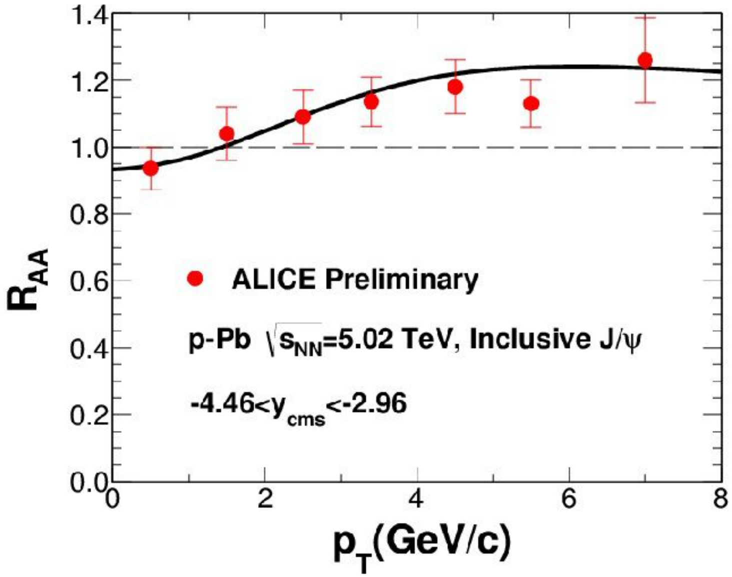
nPDF vs. free PDF

R.Vogt et al. PRL91 (2003) 142301.PRC71(2005) 05490

Transport Model- test of cold matter in p-Pb



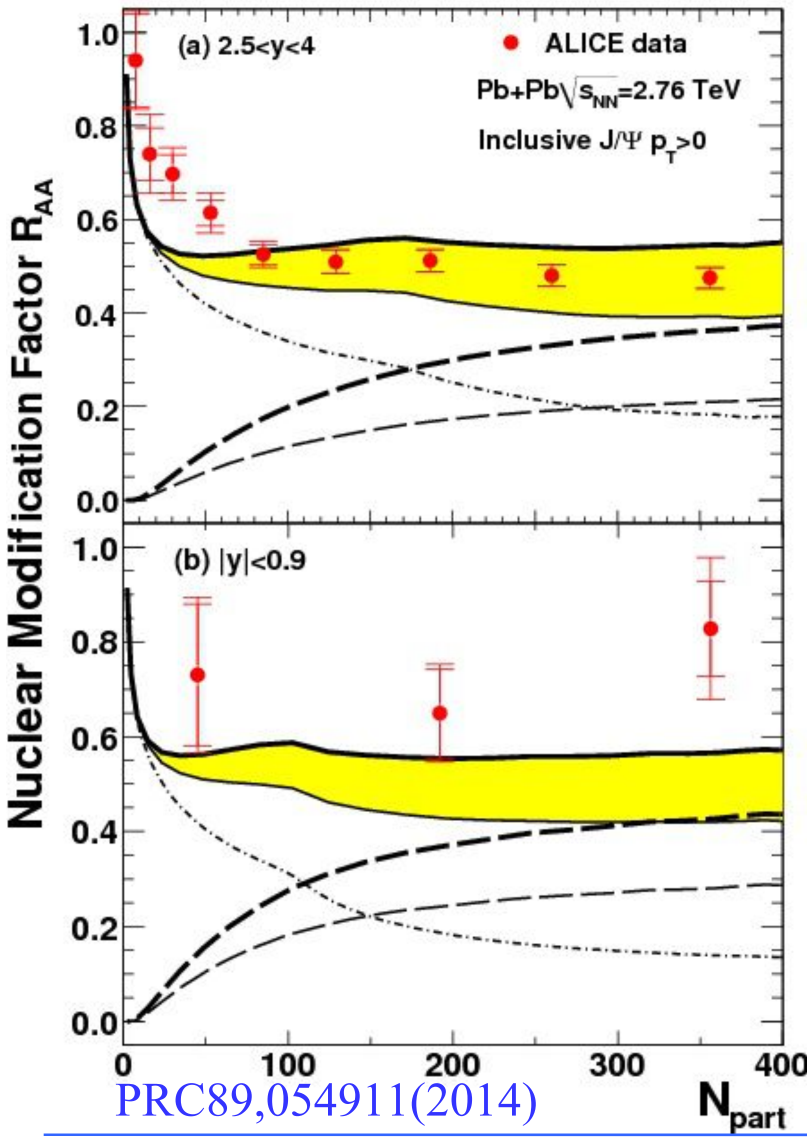




p-Pb 5.02 TeV

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

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

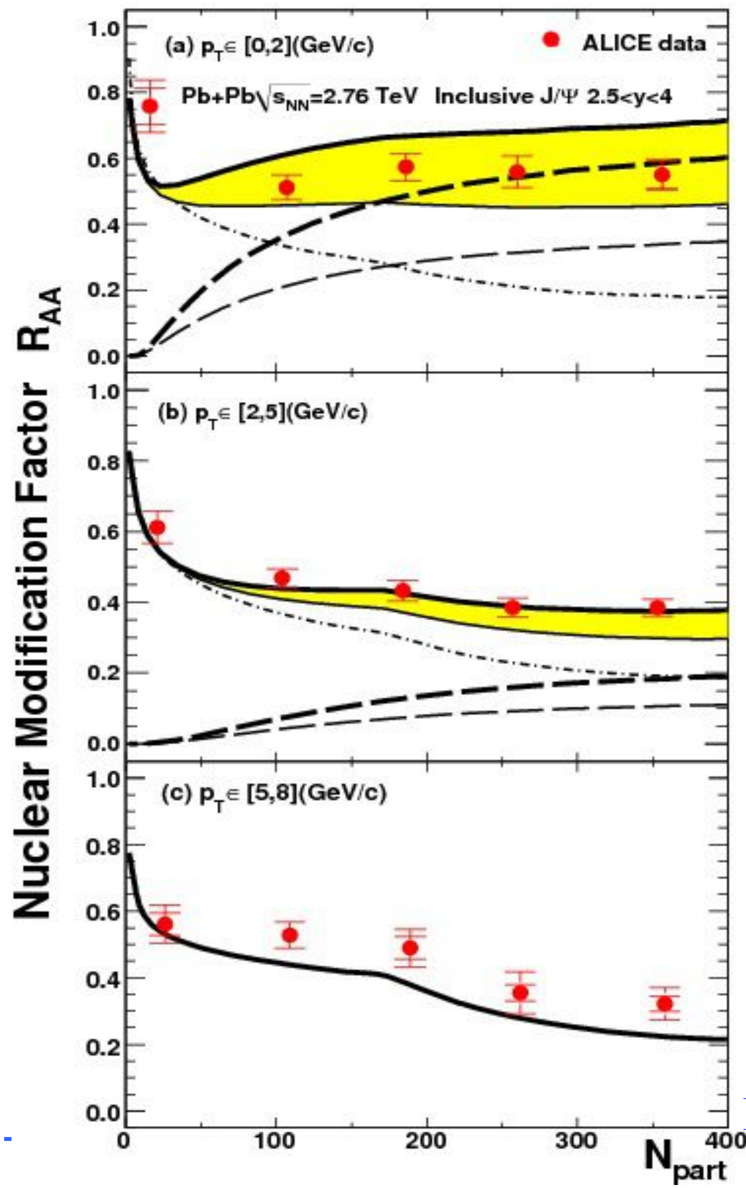


PRC89,054911(2014)

1、**Regeneration plays an important roll in most of centralities, and can be dominant.**

2、**Competition leads to platform structure in most centralities.**

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



PRC89,054911(2014)

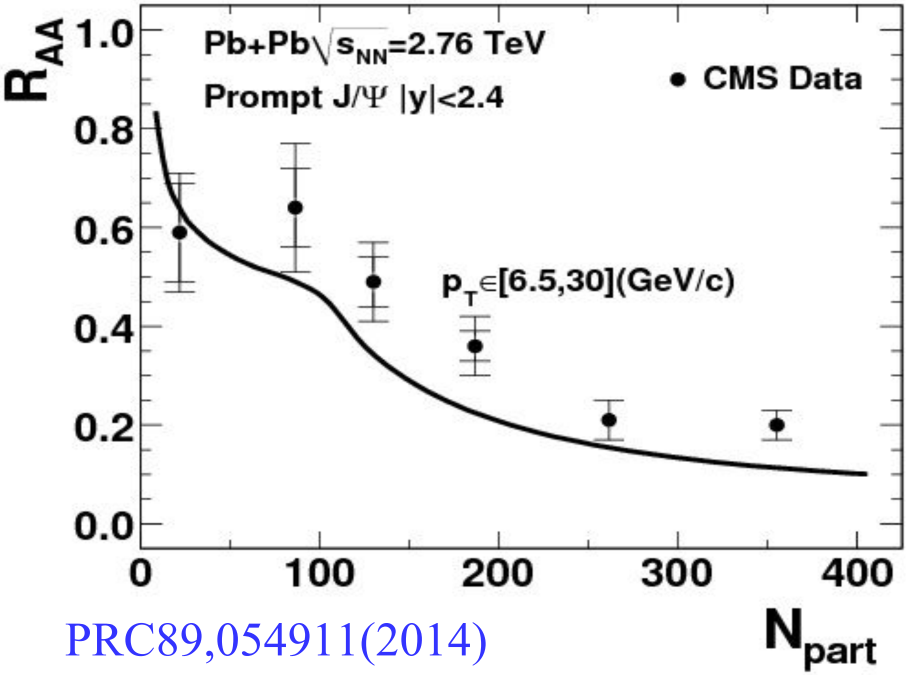
<u>Forward Rapidity</u>

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

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

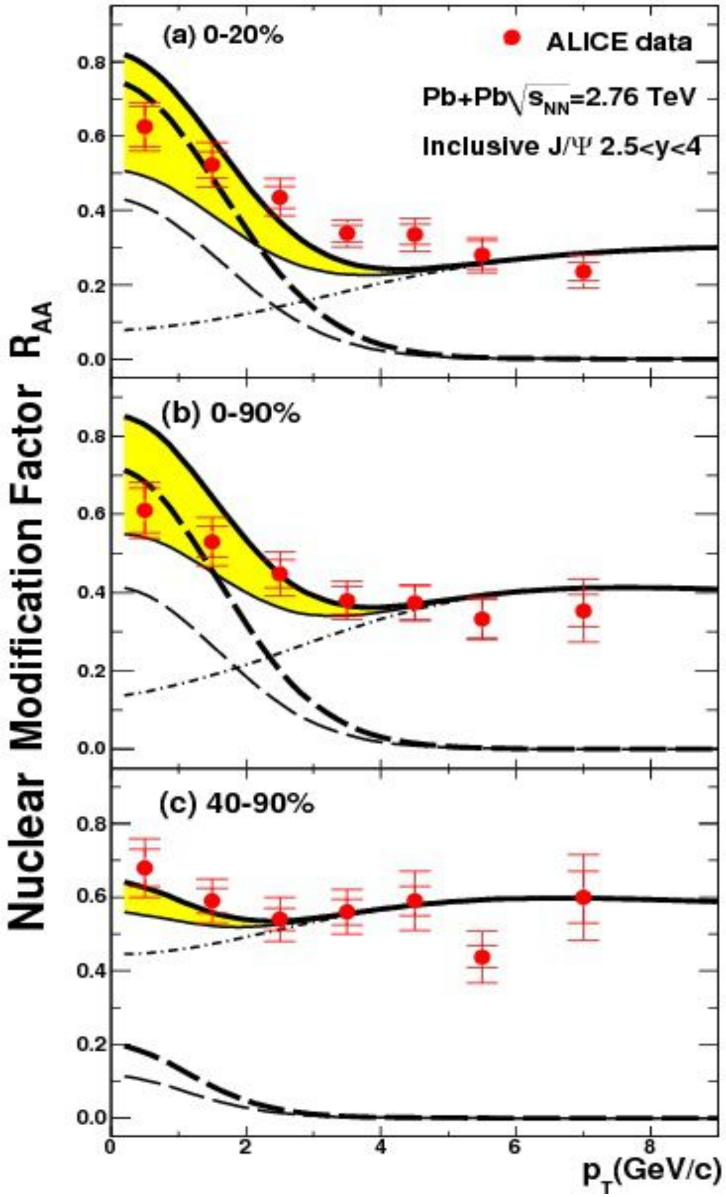


PRC89,054911(2014)

Mid-Rapidity

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

Results—RAA(pT)



Forward Rapidity

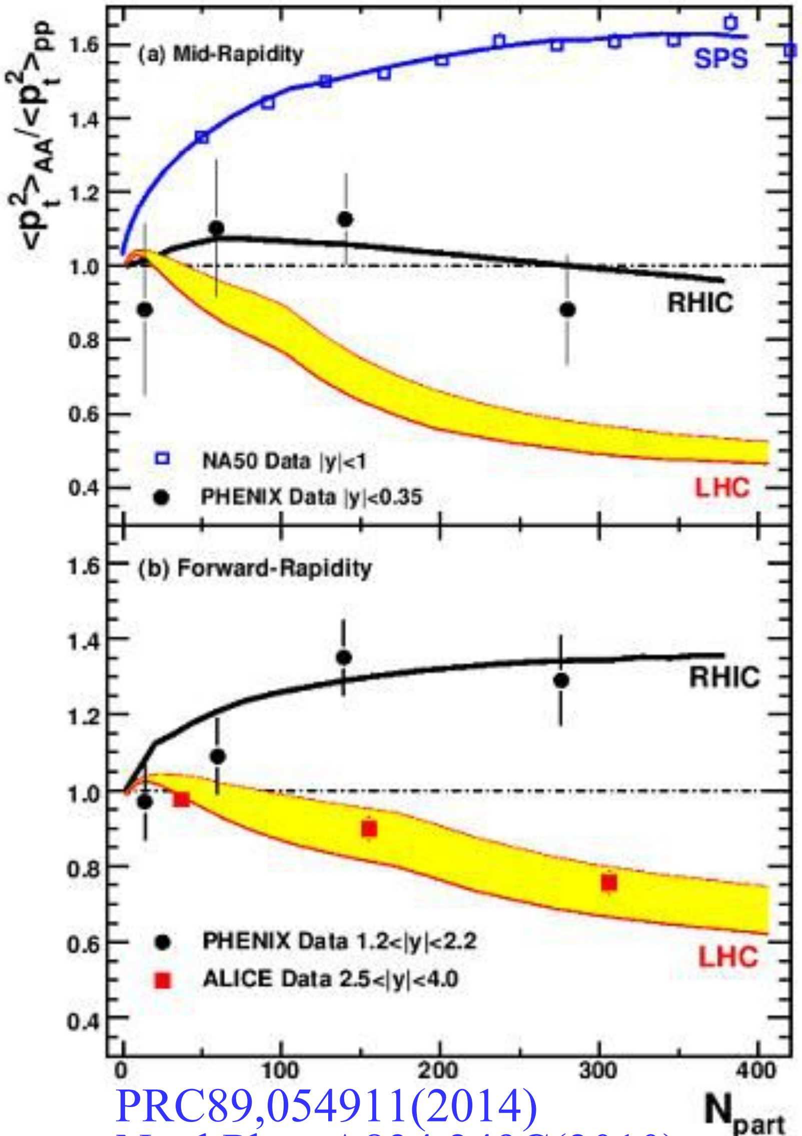
1、Regeneration -- low pT
Initial -- high pT.

2、Competition leads to slightly "Valley" struture

3、The decreasing behavior indicates regeneration

PRC89,054911(2014)

Results—Modification for Trans. pT: rAA



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

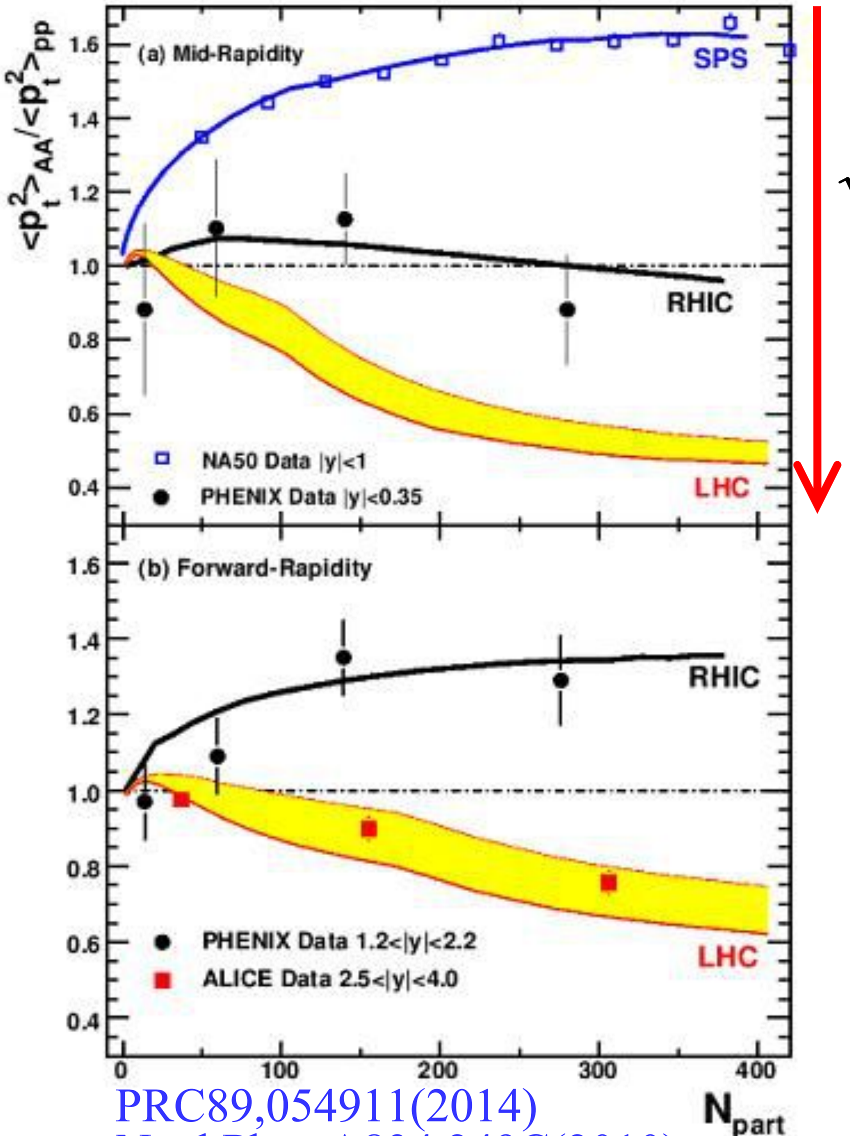
SPS: Cronin effect for ***initial***

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

LHC: dominan ***regeneration***

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

Results—Modification for Trans. pT: rAA



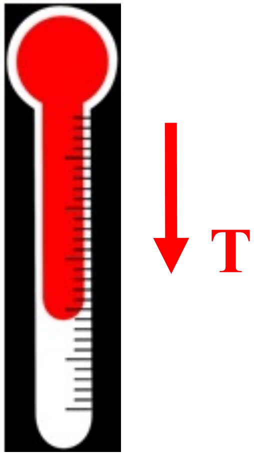
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

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

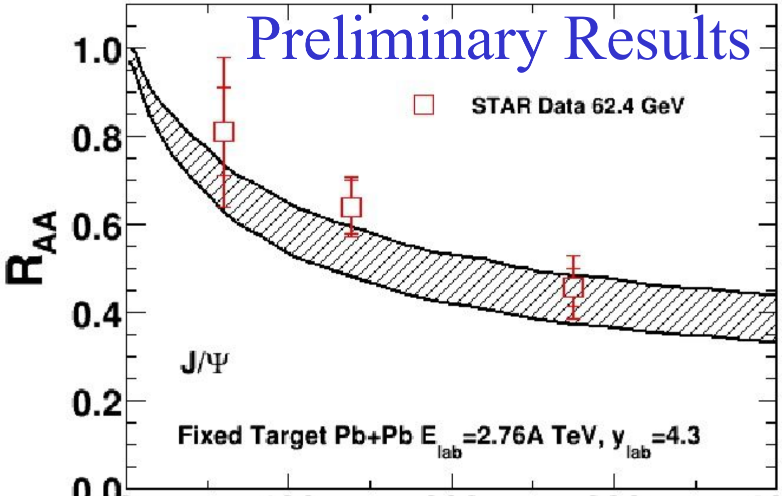
PRC89,054911(2014)

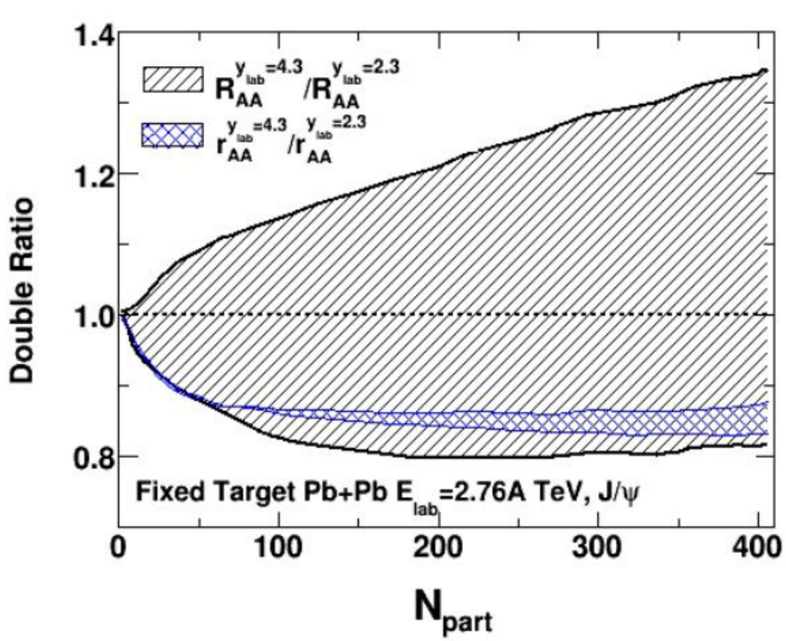
Nucl.Phys.A834,249C(2010)

Clearly showes a hotter medium been created at LHC !



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





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

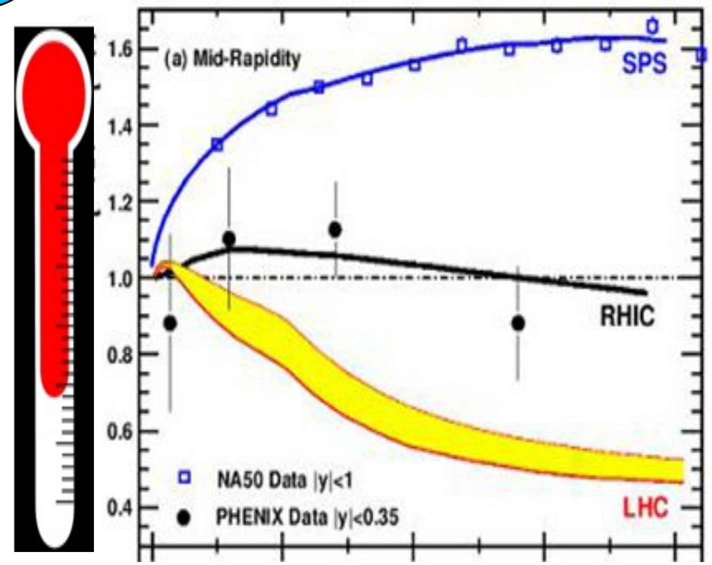
$$\Delta y = \tanh^{-1} \beta_{cms} = 4.3$$

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

Sensitive probe to gluon distribution

Summary

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



not that hot

a little hot

very hot !

- Finite chemical potential 's effects, which is relavent for lower energy case : FAIR
- Event-by-event simulation for both open and hiden heavy mesons

Thank You !

Transport Model- ideal Hydro dynamics

● **2+1D hydrodynamics**

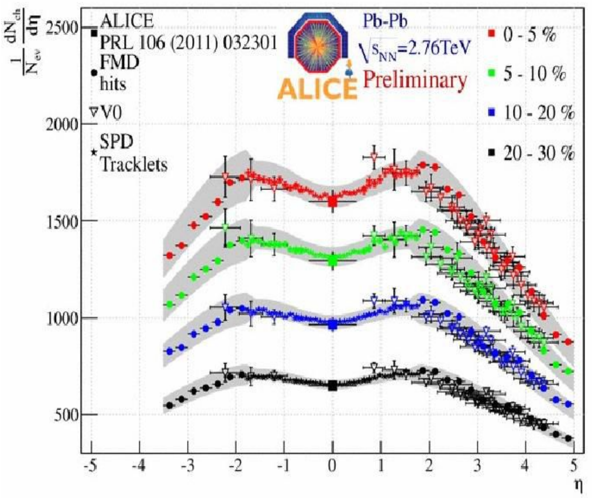
$$\begin{cases} \partial_\mu T^{\mu\nu} = 0 \\ \partial_\mu j^\mu = 0 \end{cases} \qquad T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - g^{\mu\nu} p \qquad j^\mu = n u^\mu$$

● **Equation Of State:**

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

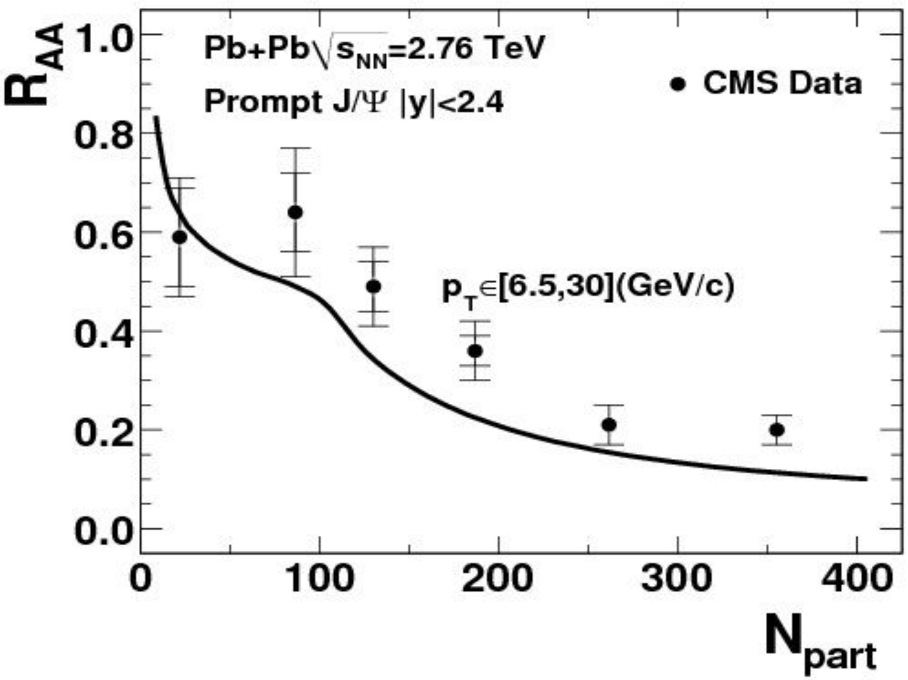
● **Initialization:**

Glauber model & constrained by fitting Charged Multiplicities



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

Mid-Rapidity



PRC89,054911(2014)

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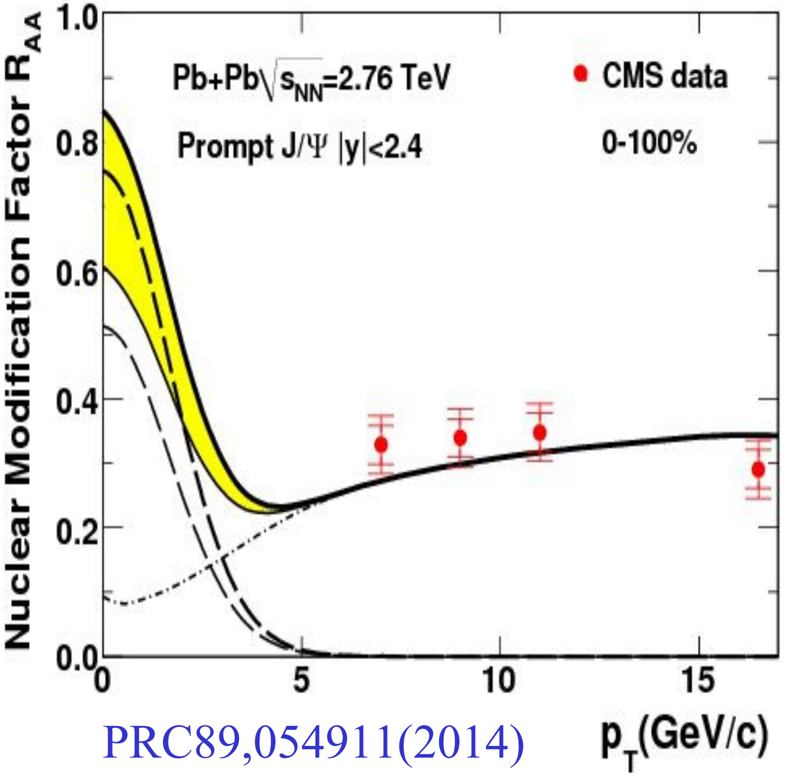
Color Screening

Backup—RAA(pT)

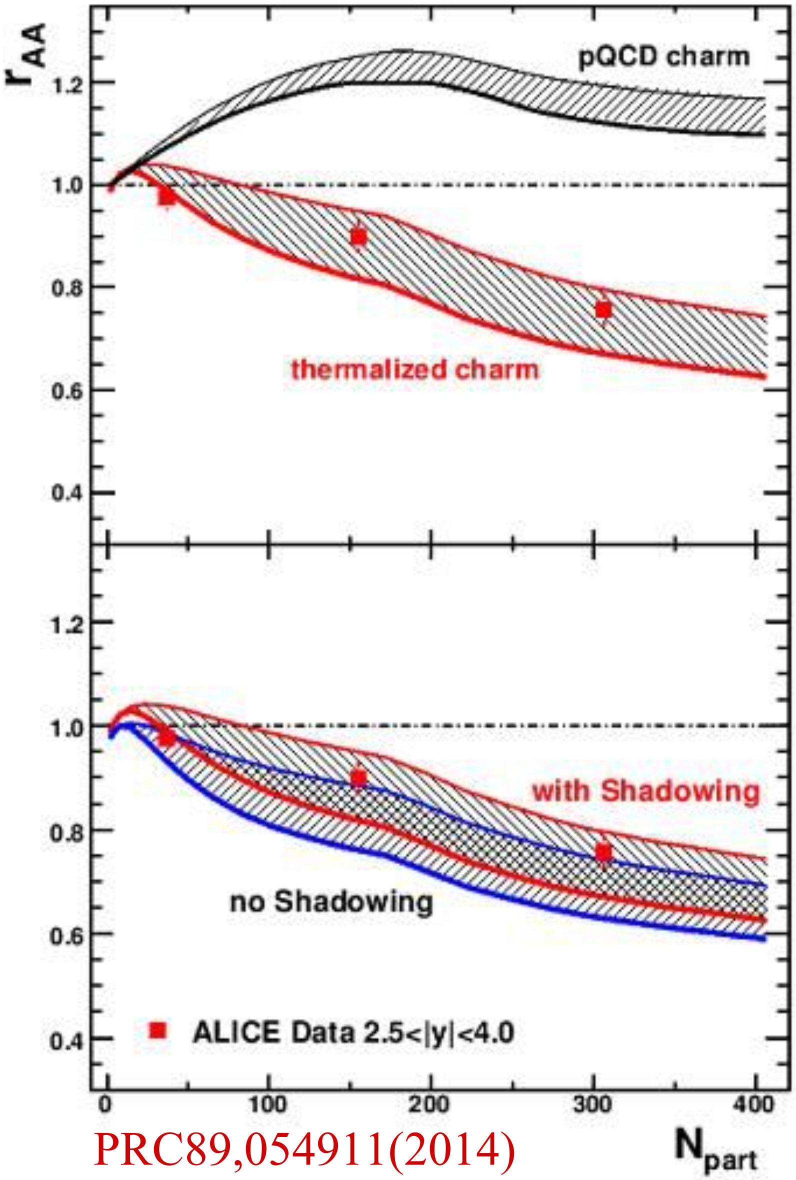


PRC89,054911(2014)

Mid-Rapidity

"Valley" struture more clearly

Backup-- Trans. pT: rAA



PRC89,054911(2014)

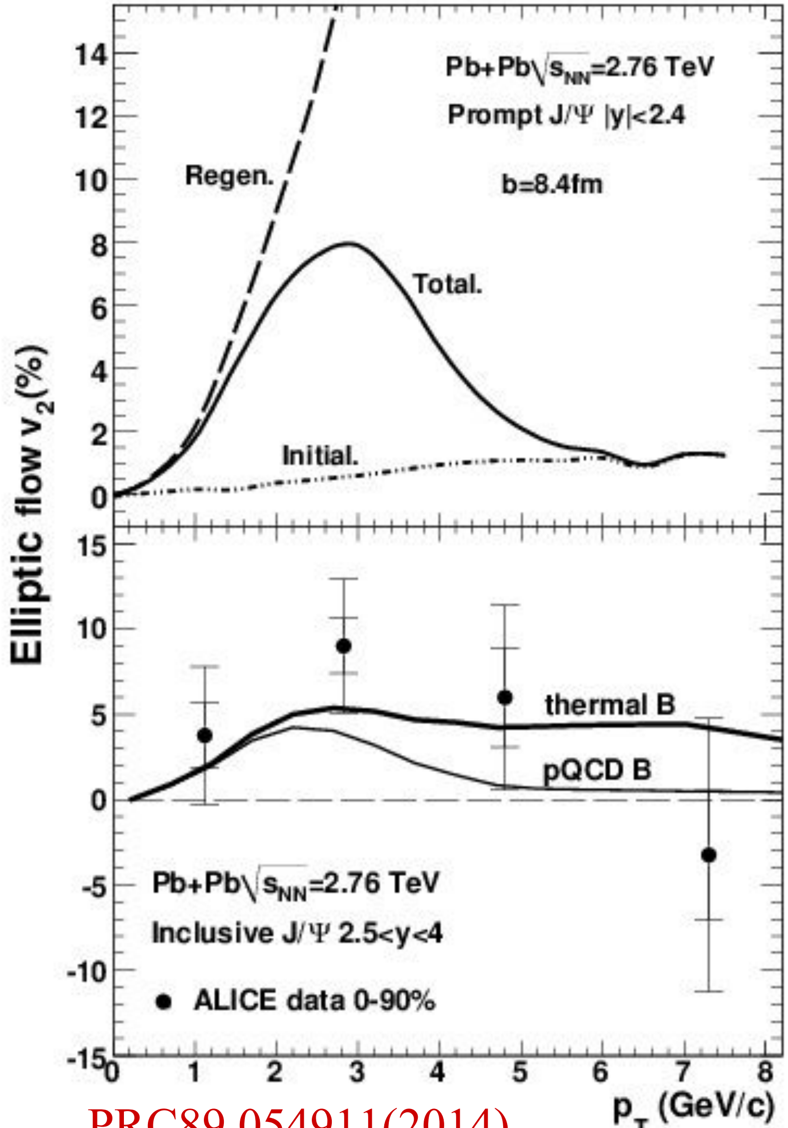
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

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

Results—Eilliptic flow v2



PRC89,054911(2014)

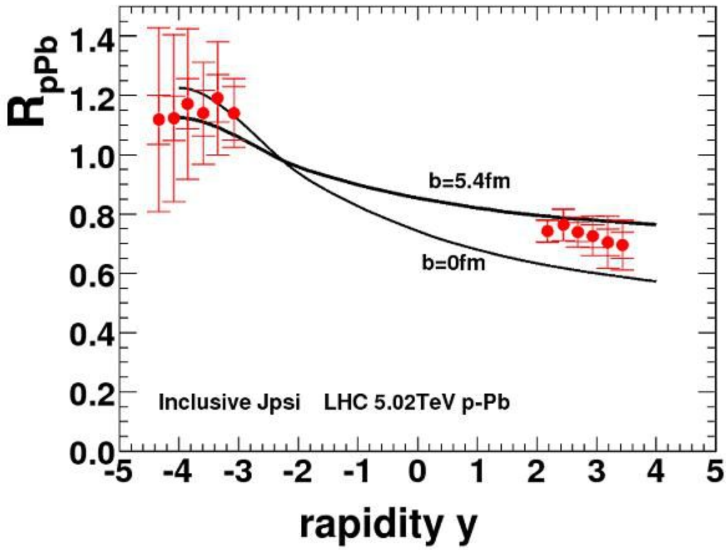
1, remarkable v2 due to important regeneration !
-->Refletc energy loss of heavy quark.

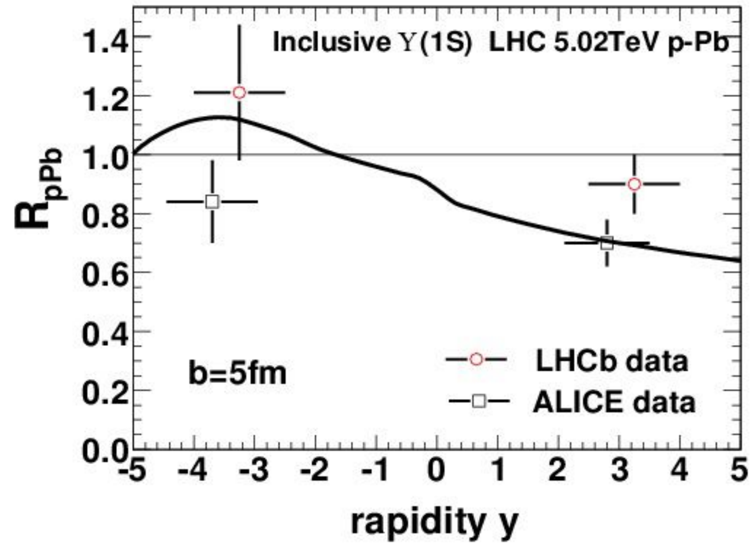
2, "Ridge"struture from two-component:

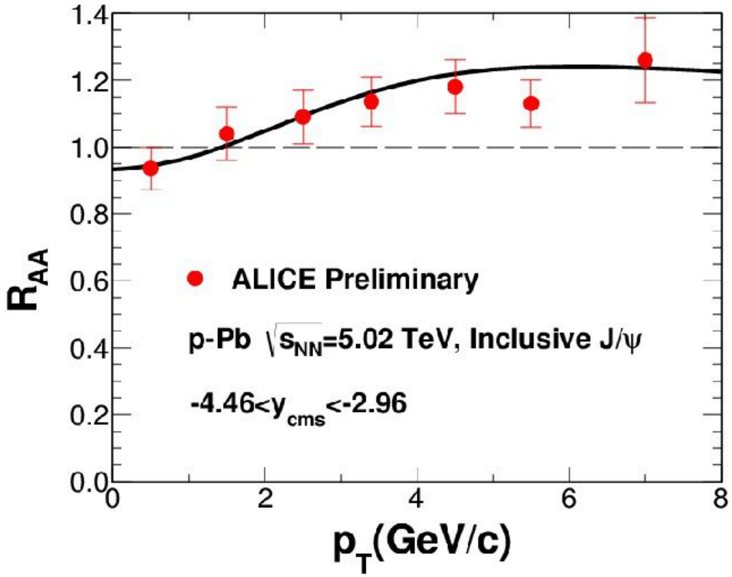
- **hard（initial、jet）**
- **soft（regeneration、hydro）**

3， v2 for high pT indicates B meson's thermalization

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 !

Transport Model- solution of transport equation

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

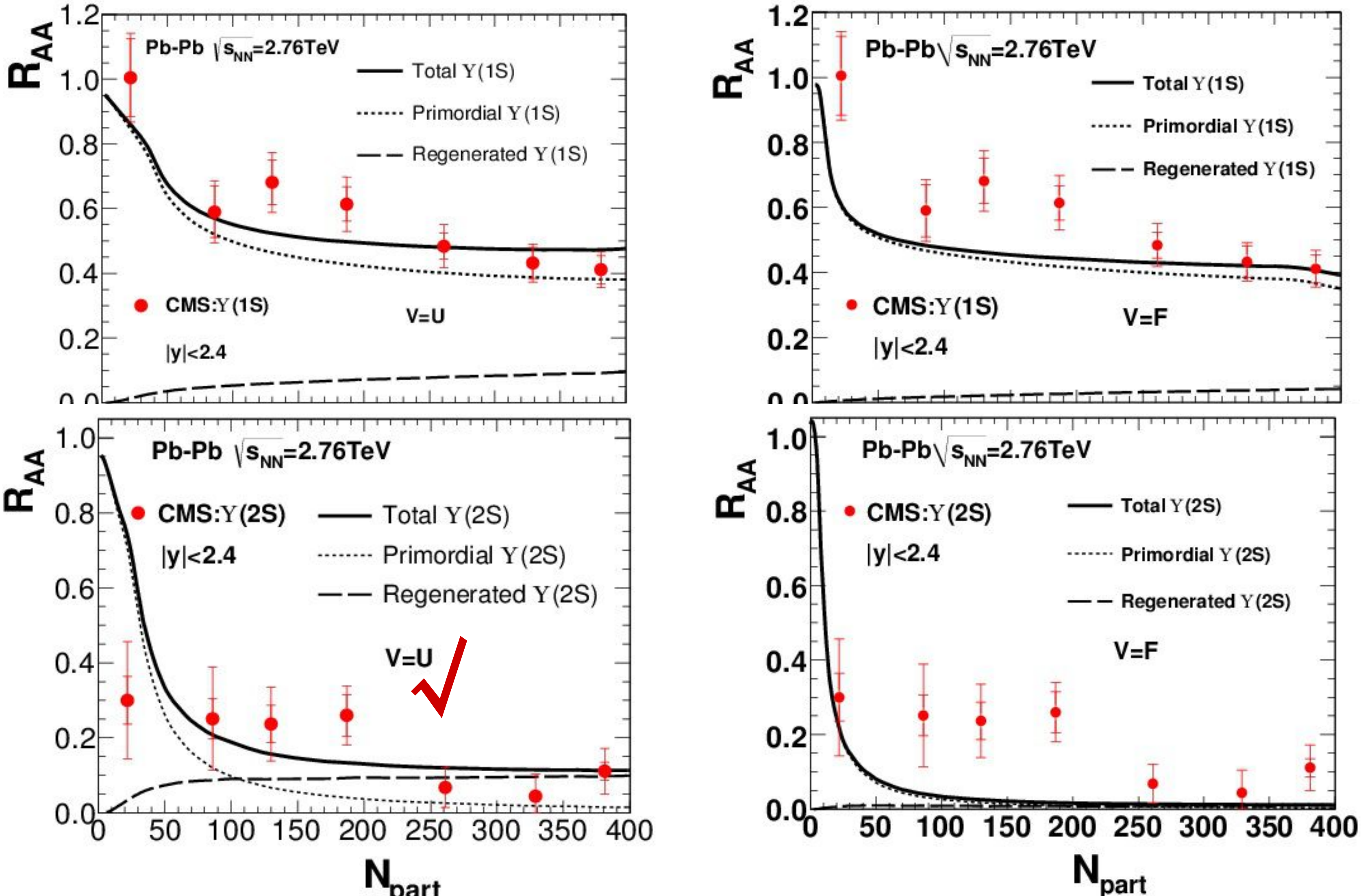
$$\begin{aligned}
& f(\vec{p}_t, y, \vec{x}_t, \eta, \tau) \\
= \; & f(\vec{p}_t, y, \vec{r}_t(\tau_0), Y(\tau_0), \tau_0) e^{-\int_{\tau_0}^{\tau} d\tau' A(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau')} \\
& + \int_{\tau_0}^{\tau} d\tau' B(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau') e^{-\int_{\tau'}^{\tau}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

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

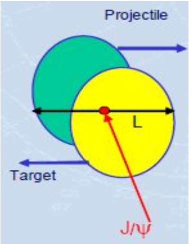
$$\Delta(y-\eta) \equiv \operatorname{arcsinh}\left(\frac{\tau}{\tau'}\sinh(y-\eta)\right)$$

Both Initial production and Regeneration suffers Suppression

Results—Bottomonium differs V=U or V=F

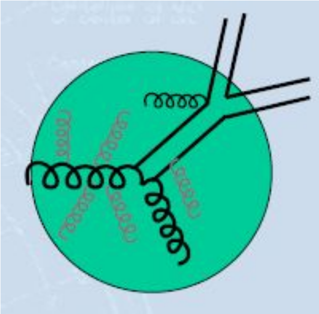


Transport Model- cold nuclear matter effects



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 (use Gaussian smearing)

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

$a_{gN} = \Delta^2(\mu)\sigma_{pp}^{inelasitic}\rho_0$ $\quad a_{gN} = 0.15 GeV^2/c^2$ @ LHC Pb-Pb 2.76TeV

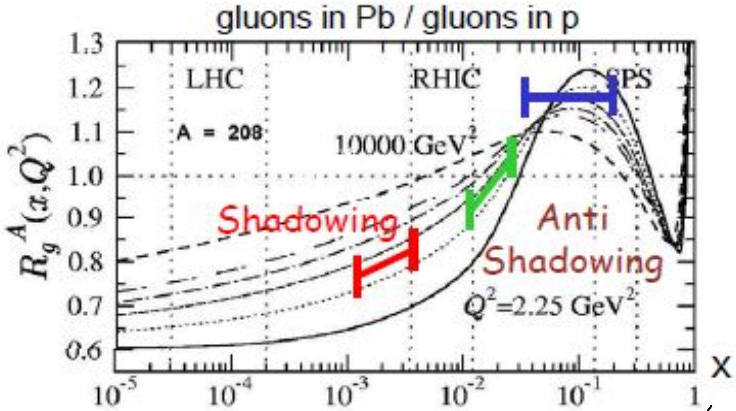
Init.J.Mod.Phys.E.12,211(2003)
Phys.Rev. C 73, 014904(2006)

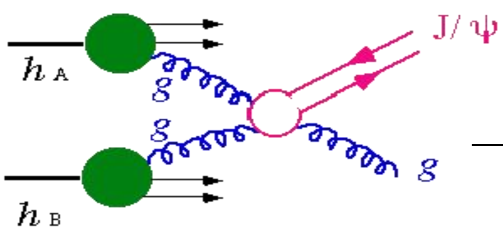
Transport Model- cold nuclear matter effects

Shadowing

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

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

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