Heavy Quarkonium Transport in Heavy-ion Collisions

Kai Zhou (周凯)

ITP/FIAS, Frankfurt U.

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FIAS Frankfurt Institute for Advanced Studies

SQM Berkeley 2016

zhou@th.physik.uni-frankfurt.de

Outline

- Introduction
- Theory Review
- Transport analysis (confronting data & Excitation)
- Thermal charm production
- Summary

Introduction

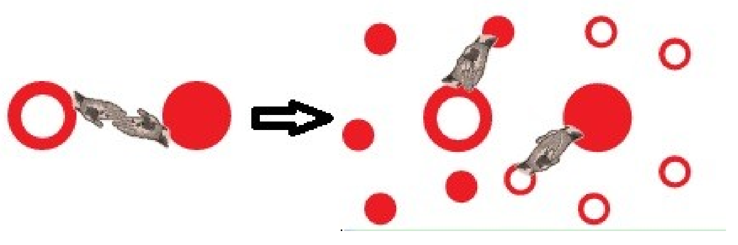
Large mass scale $m_Q >> \Lambda_{QCD}, T$

- Produced via Hard Processes from early stage

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

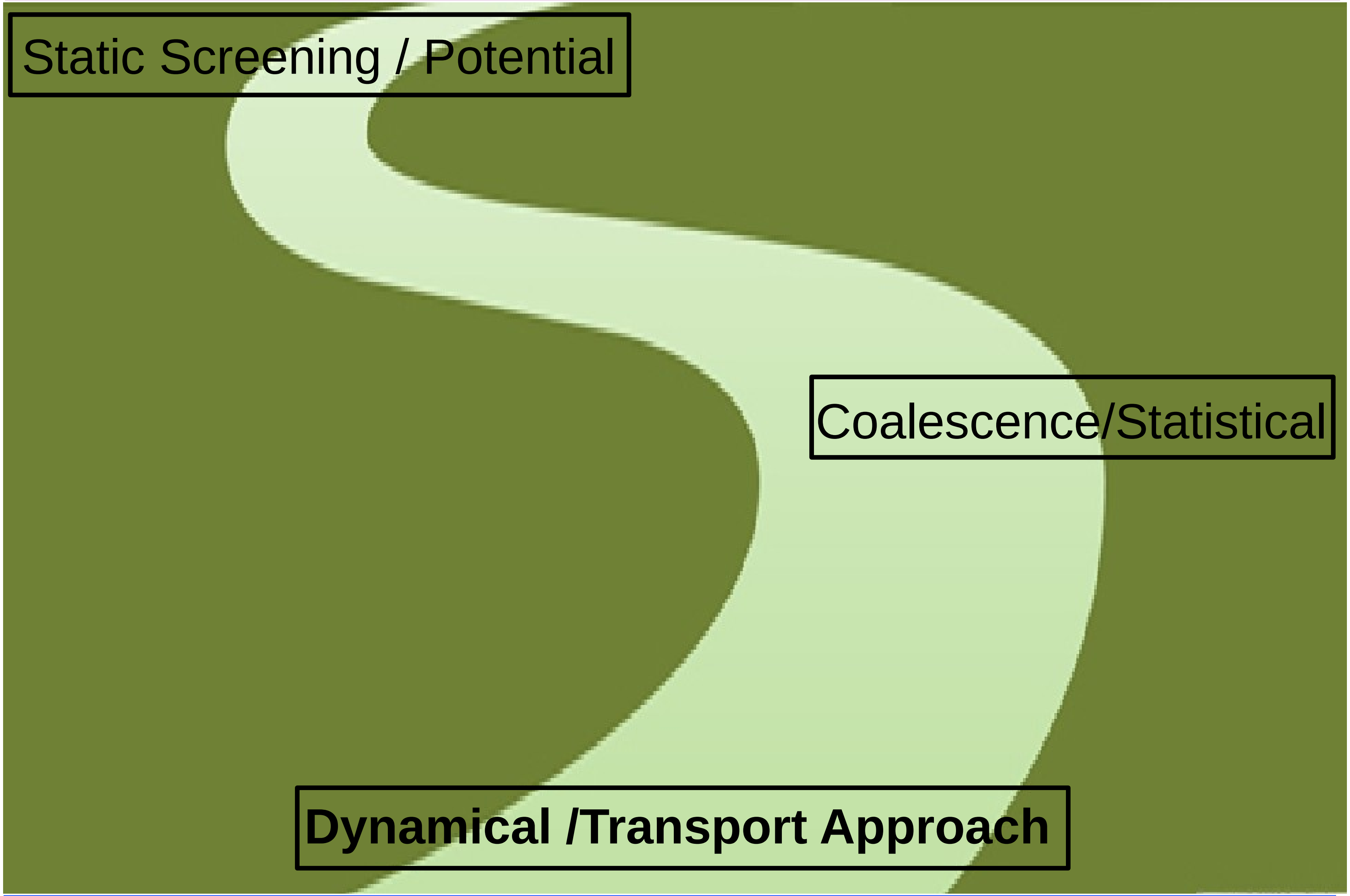
  - In vacuum **NR potential (or NRQCD)** e.g $V(r) = -\alpha_c / r + kr$
    ---spectroscopy well described

  - In medium **Color screening**



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

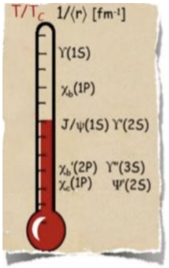
Theory Review - History



Theory Review – Static Screening / Potential

- Seminal work by **Matsui & Satz** - - - Color screening

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



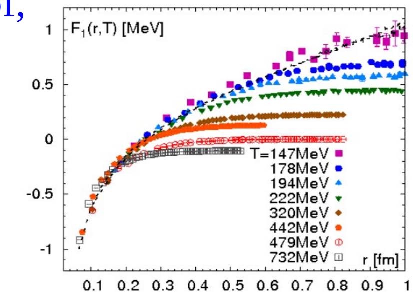
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

- Color screening at lQCD H.T.Ding, P. Petreczky, A.Rothkopf, F. Karsch,O.Kaczmarek ...

  - Ployakov loop correlator -- Color Singlet F

  - V=F or V=U? $U = F - T\partial F/\partial T$

  - With EFT(NRQCD), real-time Wilson loop



- Imaginary part (HTL, pNRQCD, lQCD) : dynamical nature

  thermal decay width

  M.Lain, J.Blaizot,N. Brambilla, A. Vairo, A.Rothkopf,

  - **Landau damping & Color Singlet-Octet transition (from EFT)**

- Entropic force repulsive, weaken the attractive energetic force D.E.Kharzeev,2014 H.Satz,2015

  $F_S = -T/\partial S/\partial r$ favor V=F huge number of excited states near Tc? adiabatically

- *T-matrix approach : real V in between F and U, close to U* S.Liu,R.Rapp,2015

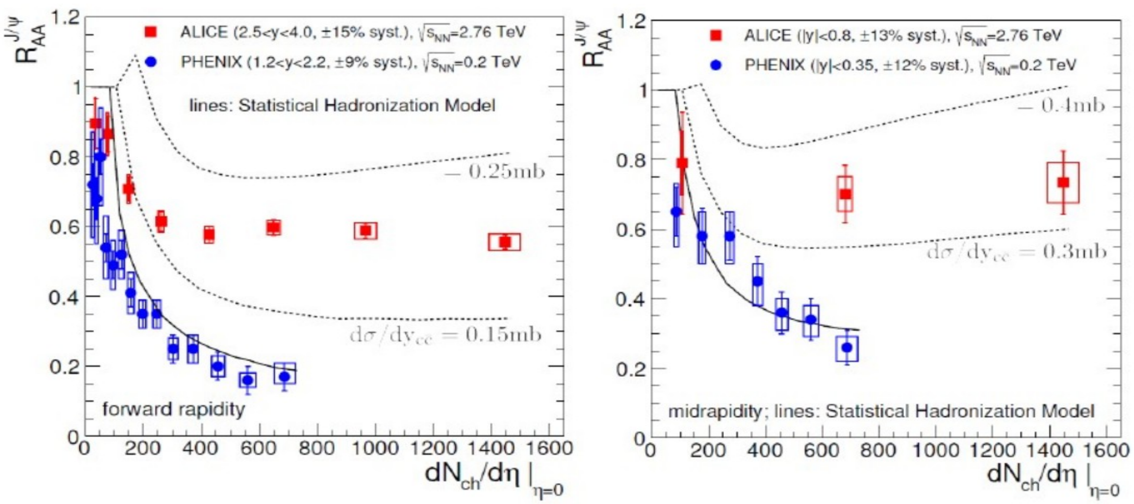
Theory Review – Statistical hadronization

Assuming HQ Hadrons are all produced thermally through **statistical hadronization** at the phase boundary.

HQ Balance equation : $N_{Q\bar{Q}} = \frac{1}{2} g_Q V n_o^{th} \frac{I_1(g_Q V n_o^{th})}{I_0(g_Q V n_o^{th})} + g_Q^2 V n_h^{th}$

PBM
Andronic,Braun-Munzinger,Stachel

- Inputs : $T, \mu_B, V = N_{ch}^{exp}/n_{ch}^{th}, N_{QQ}^{dir}(pQCD)$
- Outcome : $N_h = g_Q^2 V n_h^{th} = \frac{4 n_h^{th} N_{Q\bar{Q}}^2}{(n_o^{th})^2 V}(1 + \frac{1}{N_{Q\bar{Q}}})$



Hard to tackle the pT structure, since oium can hardly reach thermal equilibrium with the bath.

No dynamical information.

QGP screens all onium initial formation ?

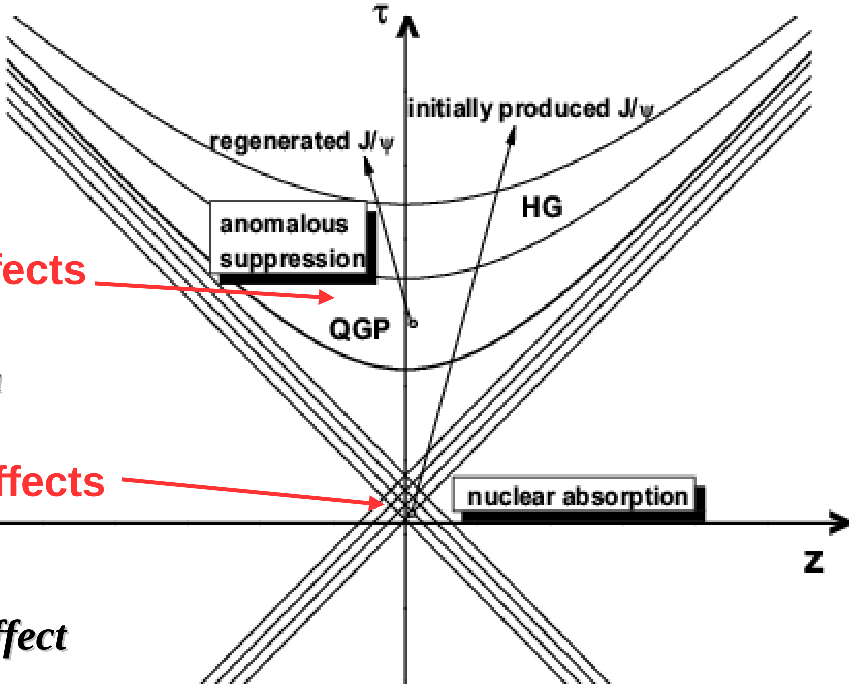
Theory Review – Dynamical / Transport approach

Classically, one focus on onia's phase space distribution function : $f(\mathbf{x}, \mathbf{p}, t)$

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

$$p(g, q, q) + \Psi \rightleftarrows Q + Q(+g)$$
$$\alpha \rightarrow \qquad \leftarrow \beta$$

General Ingredients :



Medium evolution + EoS

Transport equation

hot matter effects
1)Dissociation
2)Regeneration

cold matter effects
1)Absorption
2)Cronin effect
3)Shadowing effect

Theory Review – Dynamical / Transport approach

- Neglect the regeneration (for bottomonium)

Survival Prob $= e^{-\int_{\tau_F}^{\tau_{final}} d\tau \Gamma(T(\tau))}$

- Collisional damping + glue-dissociation

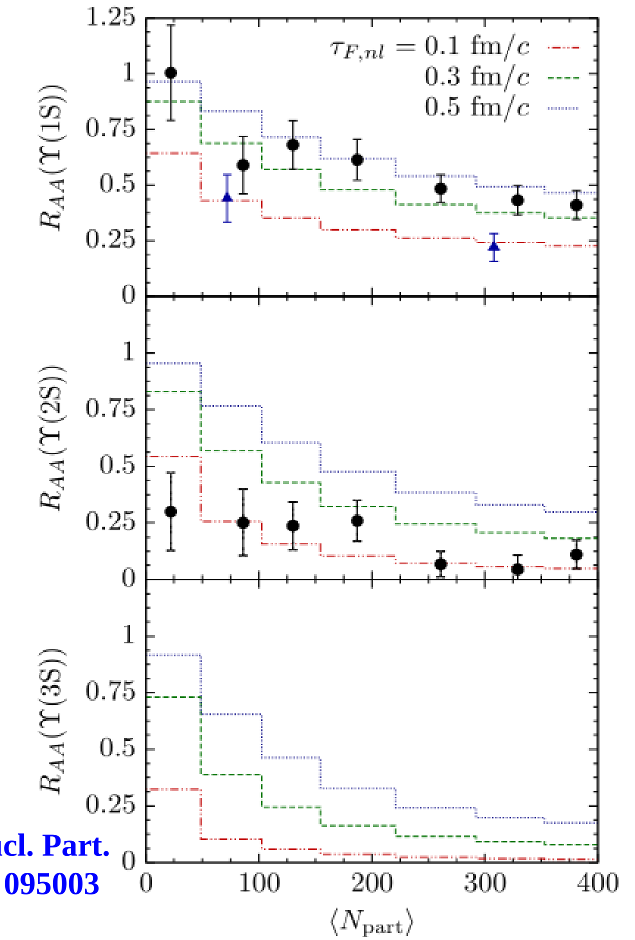
$$\Gamma_{tot} = \Gamma_{damp} + \Gamma_{gdiss}$$

Nendzig-Wolschin
F.Nendzig, G.Wolschin

$V = Re[V] + Im[V]$ (Screened Cornell + HTL Im[V])

$$\Gamma_{damp}(T) = \langle \Psi \; 2Im[V] \; \Psi \rangle$$

$$\Gamma_{gdiss} = \frac{g_d}{2\pi^2} \int \frac{dp_g p_g^2 \sigma_{diss}(E_g)}{e^{E_g/T} - 1}$$ (based on dipole inter.term in pNRQCD)



J. Phys. G: Nucl. Part. Phys.41(2014) 095003

Theory Review – Dynamical / Transport approach

- Neglect the regeneration (for bottomonium)

$$\text{Survival Prob} = e^{-\int_{\tau_F}^{\tau_{final}} d\tau \Gamma(T(\tau))}$$

- Collisional damping under Anisotropic Hydro

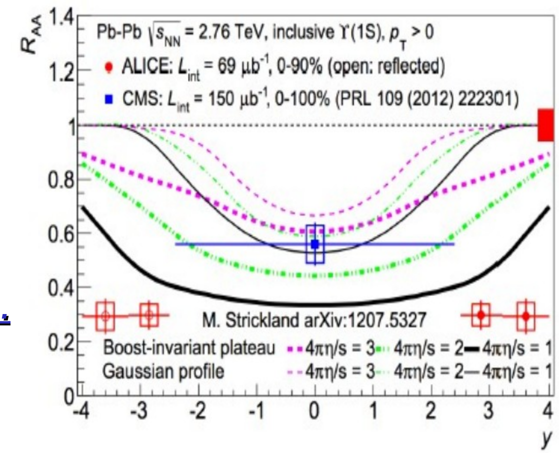
Strickland Group
Krouppa,Ryblewski,Strickland...

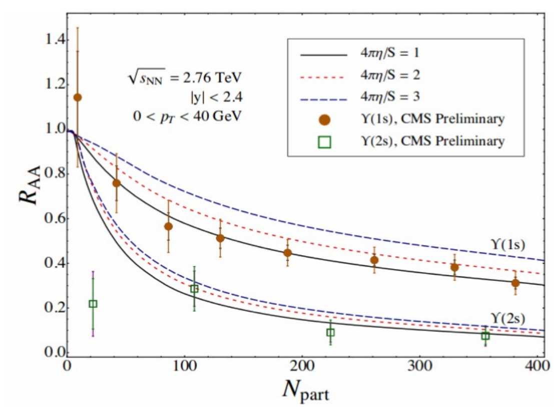
$$f(p,x) = f_{eq}(\sqrt{p_T^2 + [1+\xi(x)]p_z^2}/\Lambda(x))$$

$$Im[V] = -\alpha_s C_F T[\phi(r/m_D) - \xi(\Psi_1(r/m_D,\theta) + \Psi_2(r/m_D),\theta)]$$

$$\Gamma = 2Im[E_{bind}]/\theta(Re[E_{bind}])$$

- Tough for explaining the rapidity-dependence.





Phys. Rev. C 92, 061901 (2015)

Theory Review – Dynamical / Transport approach

- Assuming spatial homogeneity & HQ thermalization

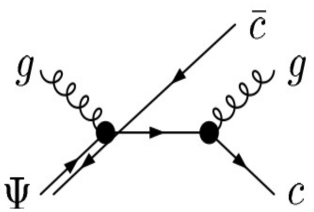
Rate equation : $dN_\Psi(t)/dt = -\Gamma_\Psi(t)(N_\Psi(t) - N_\Psi^{eq}(t))$ $\quad (\Gamma_\Psi = \int \frac{d^3k}{(2\pi)^3} f_p^{th}(k) v_{rel} \sigma(s))$

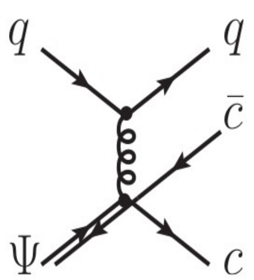
SHM for regeneration : $N_\Psi^{eq}(T) = \mathcal{R}(\tau)\gamma_Q^2(N_Q, T) V d_\Psi \int_{\mathbf{p}} f_\Psi^{eq}(\mathbf{p}, T)$ $\quad (R(\tau) = 1 - e^{-\tau/\tau_Q^{eq}})$

- "quasi-free" dissociation + blast-wave for regeneration

+ Fireball medium

TAMU Group
Zhao,Grandchamp,Rapp...





$\sigma_{p-\Psi} \sim 2\sigma_{p-Q}$

Neglect interference terms

Theory Review – Dynamical / Transport approach

- Assuming spatial homogeneity & HQ thermalization

Rate equation : $dN_\Psi(t)/dt = -\Gamma_\Psi(t)(N_\Psi(t) - N_\Psi^{eq}(t))$ $\quad (\Gamma_\Psi = \int \frac{d^3k}{(2\pi)^3} f_p^{th}(k) v_{rel}\sigma(s))$

SHM for regeneration : $N_\Psi^{eq}(T) = \mathcal{R}(\tau)\gamma_Q^2(N_Q, T) V d_\Psi \int_{\mathbf{p}} f_\Psi^{eq}(\mathbf{p}, T)$ $\quad (R(\tau) = 1 - e^{-\tau/\tau_Q^{eq}})$

- LO(g-diss) + NLO("quasi-free"+...) + Potential model(screened cornell) + Fireball medium

Song-Ko
Song,Han,Lee,Ko...

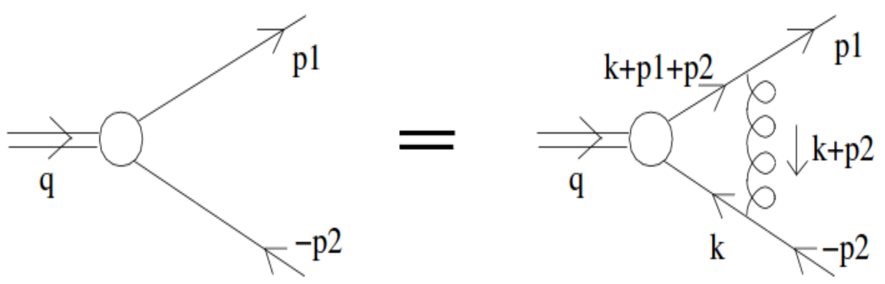


FIG. 1. The Bethe-Salpeter equation for quarkonium.

No pT information about regeneration is considered.

Theory Review – Dynamical / Transport approach

- Full transport : take detailed balance microscopically (easy for gluon-diss)

  - QGP evolution $\partial_\mu T^{\mu\nu} = 0,\ \partial_\mu n^\mu = 0$ + EOS
  - Onium motion
$$\cosh(y-\eta)\partial_\tau f + \mathbf{v}_T \cdot \nabla_T f + \frac{1}{\tau}\sinh(y-\eta)\partial_\eta f = -\frac{E}{E_T}\alpha \cdot f + \frac{E}{E_T}\beta$$

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

$$\sigma_{reg}(s) = \frac{4}{3}\frac{(s-m_\Psi^2)^2}{s(s-4m_Q^2)}\sigma_{g\Psi}(s)$$

$$\beta = \frac{1}{2E}\int \frac{d^3k}{(2\pi)^3 2E_g}\frac{d^3q_Q}{(2\pi)^3 2E_Q}\frac{d^3q_{\bar{Q}}}{(2\pi)^3 2E_{\bar{Q}}}(2\pi)^4\delta(p+k-q_Q-q_{\bar{Q}})W_{reg}(s) f_Q(q_Q,x) f_{\bar{Q}}(q_{\bar{Q}},x)$$

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

  - Initial condition : Glauber superposition with CNM effcts

Tsinghua Group
Zhou,Liu,Zhu,Yan,Zhuang...

Theory Review – Dynamical / Transport approach

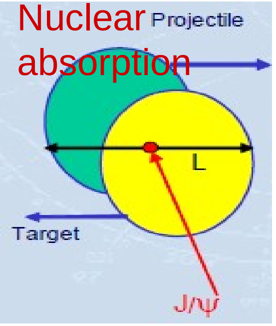
- Initial condition $f_\Psi(\vec{x}, \vec{p}, t)$ for transport eq.

  Glauber superposition along with Cold nuclear matter effects:

Cold Effects

Absorption

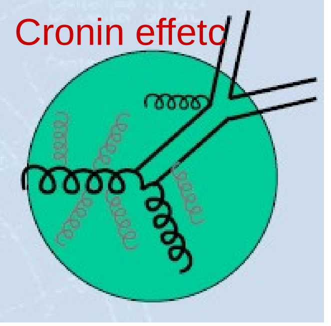
A.Capella, et al



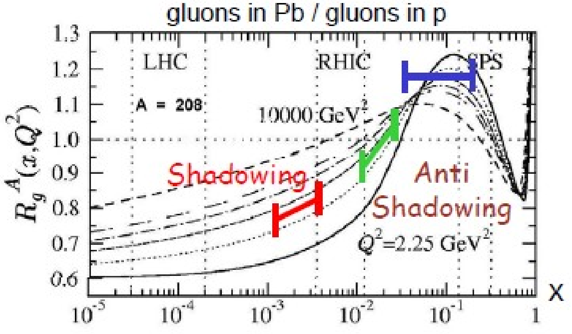
$t_{coll} << t_\Psi$ so it's neglected at LHC

Cronin Gassian smearing treatment

J.W.Cronin, et al



Shadowing



nPDF vs. free PDF

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

Theory Review – Dynamical / Transport approach

- (open) Quantum treatment : Onia not always lie in a fixed state...

- Langevin+potential approach + recombination — C.Young, E.Shuryak,09

$$\frac{d\mathbf{p}}{dt} = -\eta\mathbf{p} + \xi - \nabla U \qquad \frac{d\mathbf{r}}{dt} = \frac{\mathbf{p}}{m_c}$$

- Schroedinger-Langevin approach (no regeneration) see Talk at 30Jun, 12:00 — R.Katz, PB.Gossizux,15

Fluctuations — Dissipations

$$i\hbar\partial_t\Psi_{Q\bar{Q}}(\mathbf{r},t) = [H_0(\mathbf{r}) - \mathbf{F}_{\mathbf{R}}(t)\cdot\mathbf{r} + \hbar A(S(\mathbf{r},t) - (\mathbf{r},t)\rangle_{\mathbf{r}})]\Psi_{Q\bar{Q}}(\mathbf{r},t)$$

- J.P.Blaizot's generalized Langevin equation — J.P.Blaizot, D.D.Boni,15

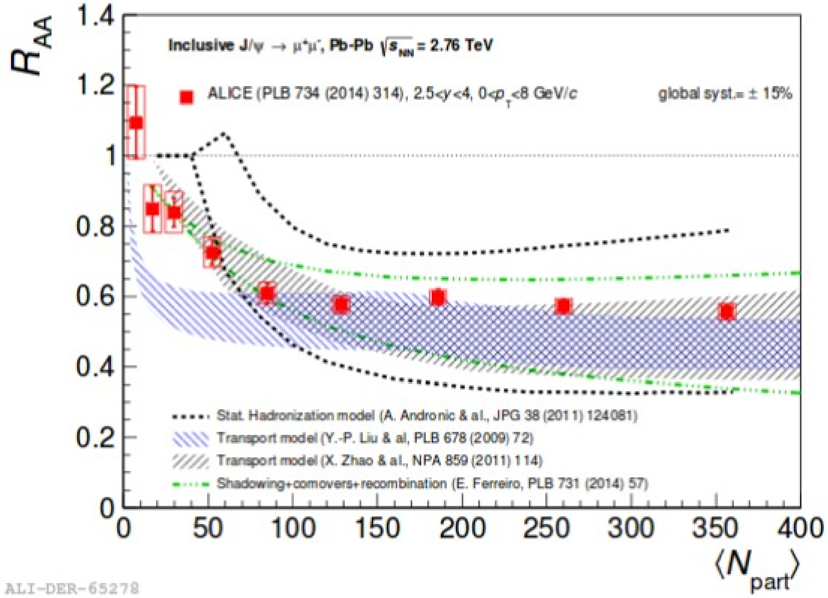
$$m_Q\ddot{\mathbf{R}} = m_Q\gamma(\mathbf{R})\cdot\dot{\mathbf{R}} + \mathbf{F}(\mathbf{R}) + \xi(\mathbf{R},t)$$

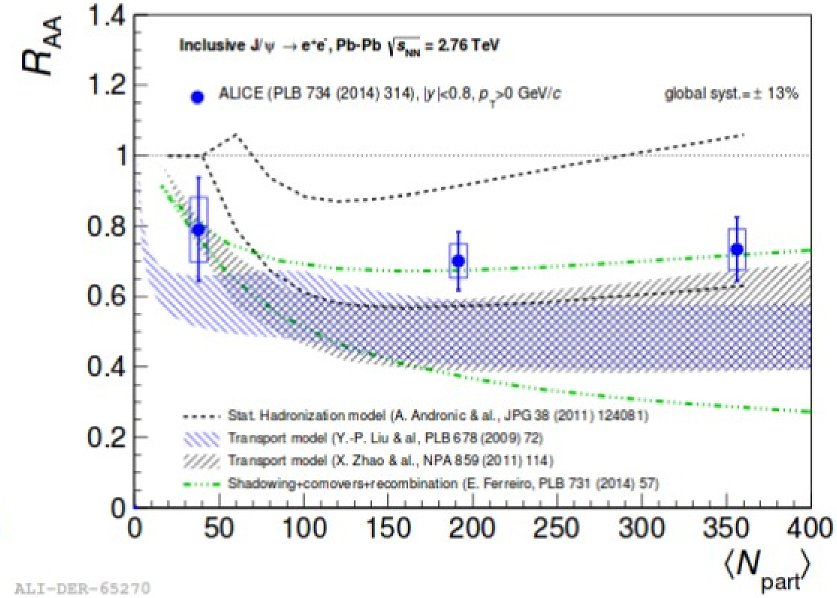
friction (and hence noise) depends explicitly on HQs configuration

- Quantum path-integral approach, Lindblad equation, ... — Y.Akamatsu, M.A.Escobedo, B.Z.Kopeliovich,...

… ...

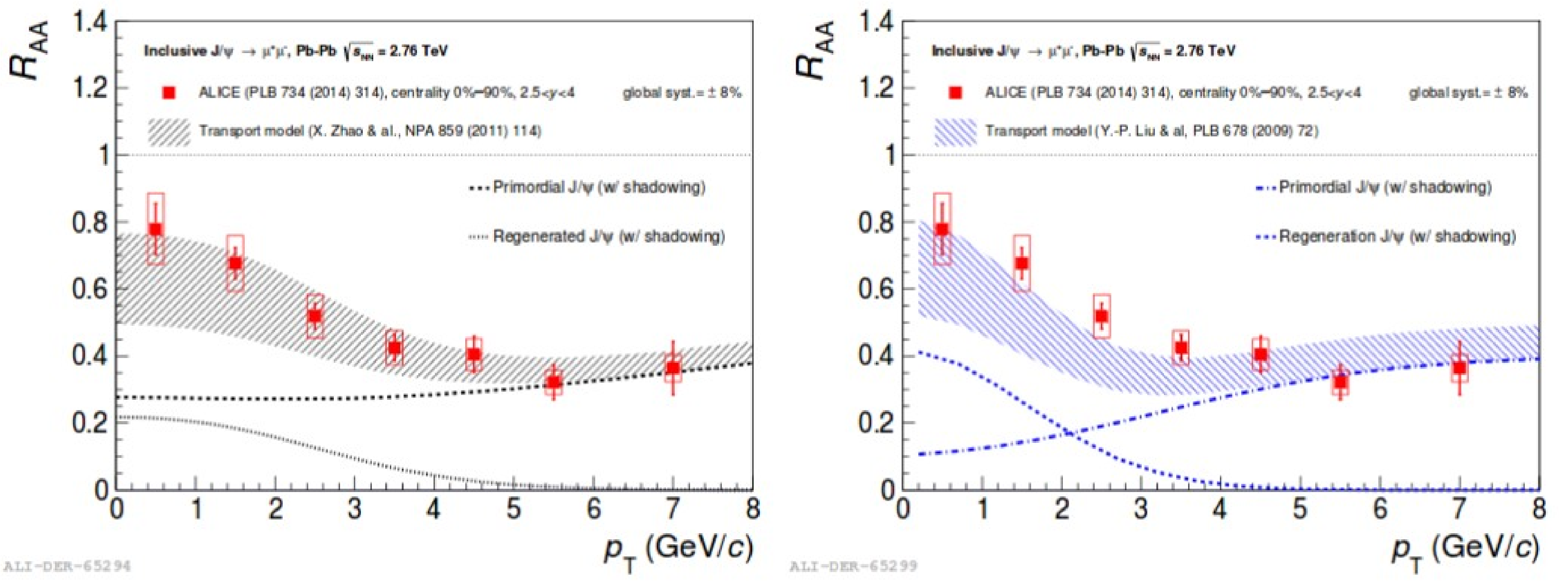
Transport Analysis





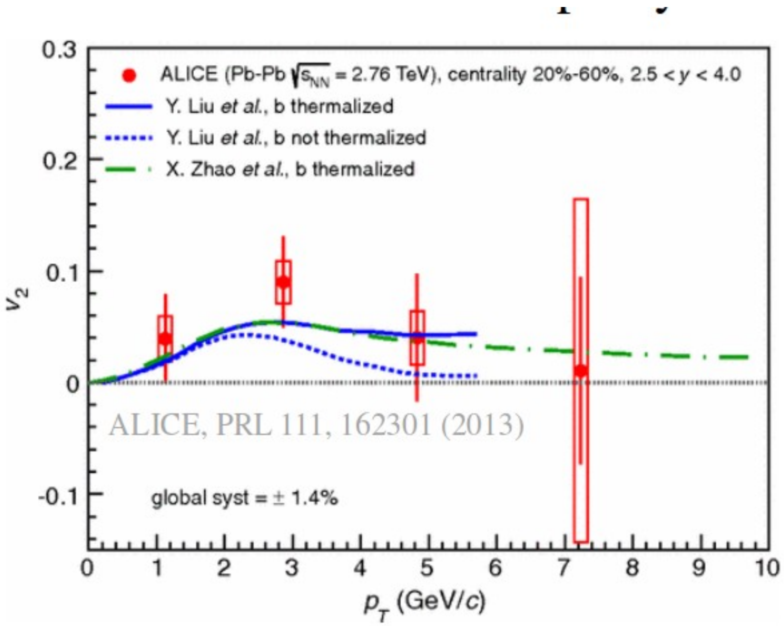
- Regeneration important in a wide centralities, and dominant in central / mid-rapidity.
- Competition between the two leads to platform structure for RAA in a wide centralities.

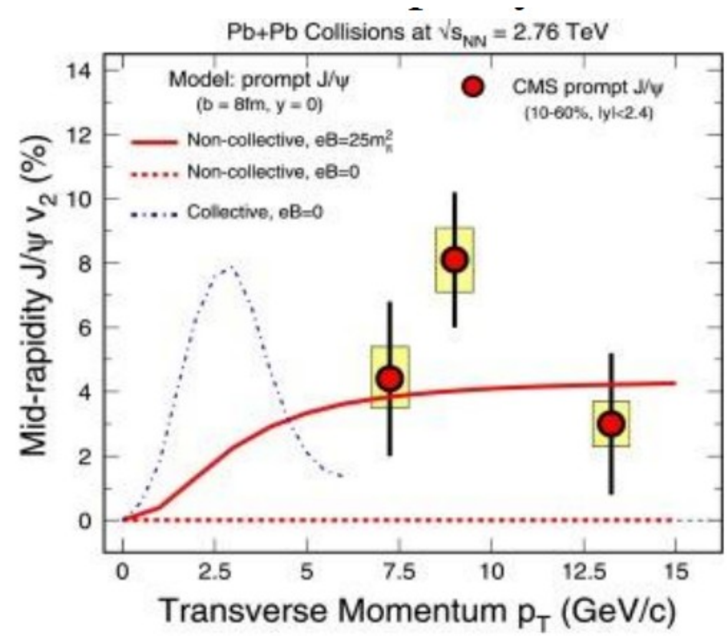
Transport Analysis



- Regeneration locates at soft –- decreasing trend at soft pT.
- Initial part suffers from cronin, leakage, screening / suppression

Transport Analysis

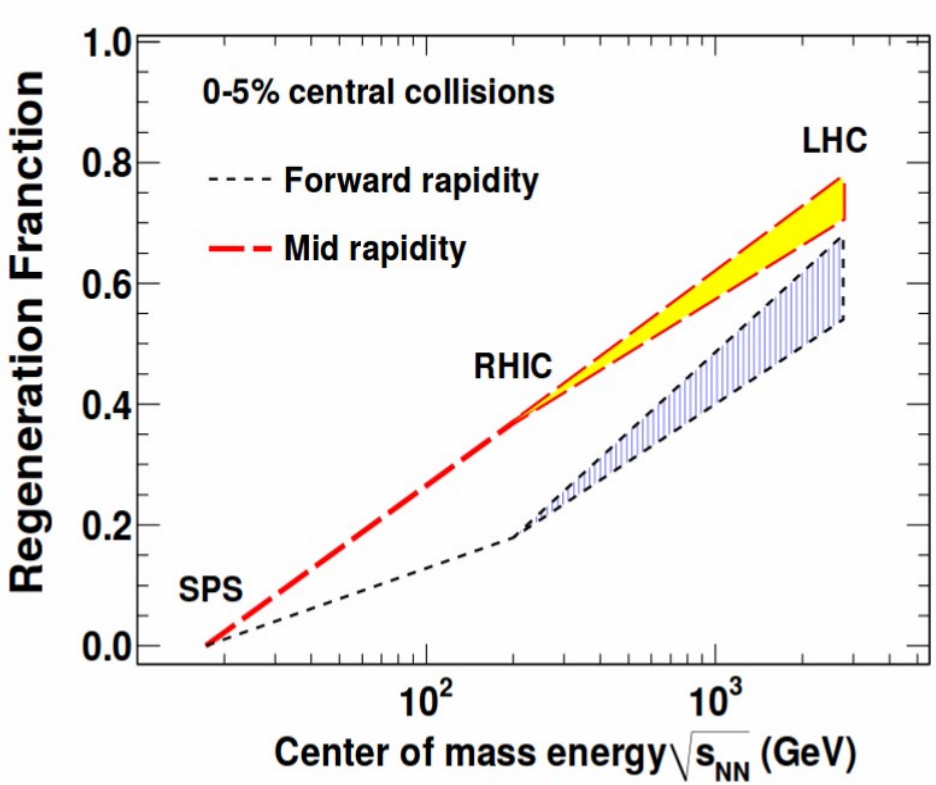




X.Y.Guo,S.Z.Shi,N.Xu,Z.Xu,P.F .Zhuang, PLB 2015

- Charmonium would flow, inherited from regeneration
- high-pT flow : a possible explain is the initial magnetic field induced non-collective flow

Transport Analysis—Excitation of *Regeneration Fraction*



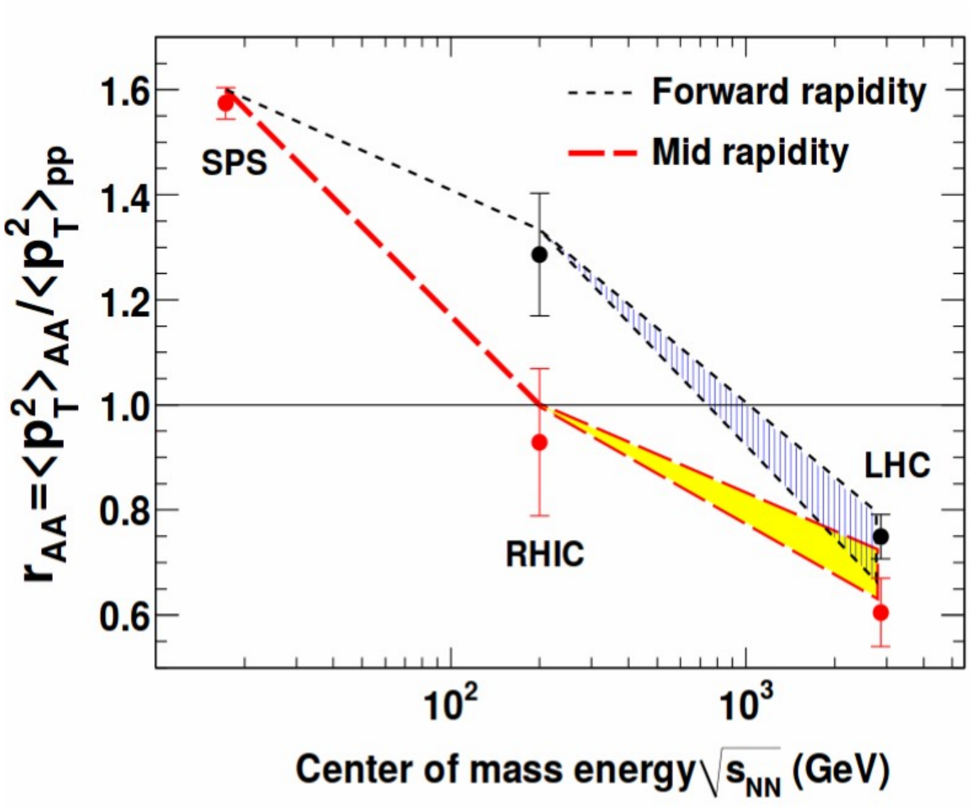
As the collision becomes more violent,

- **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*

Transport Analysis—Excitation of *momentum modification*

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



➢ Initial production:

- Cronin in initial stage
- strong low pt suppression and high pt leakage effect

⇨ **initial pt broadening**

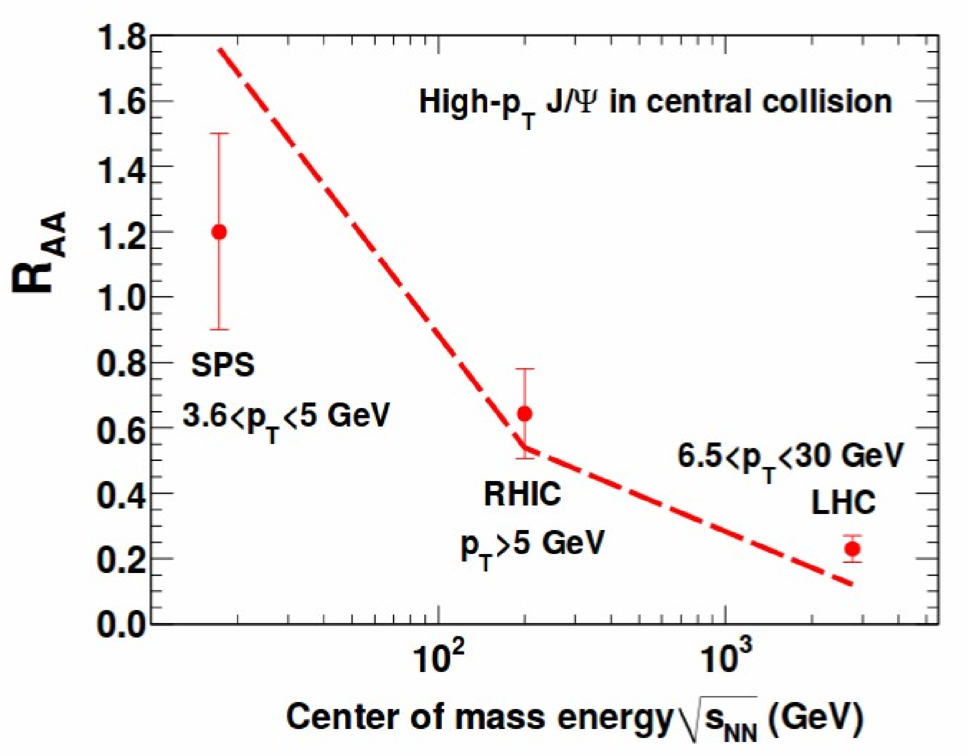
➢ Regeneration:

- Coalescence mechanism
- HQ energy loss induced thermalization

⇨ **low pt regeneration**

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

Transport Analysis—Excitation of *high(relatively) pT*



As the collision becomes more violent,

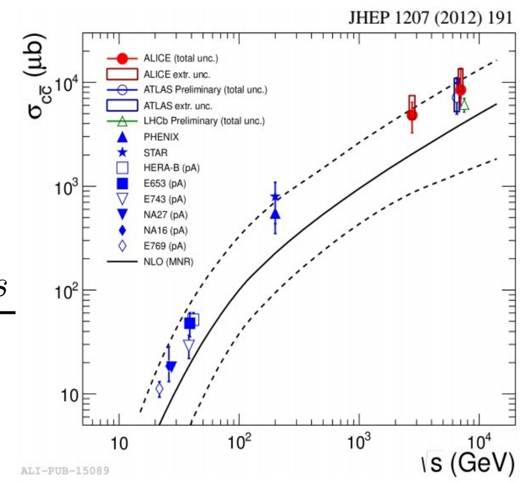
regeneration can hardly contribute to high-pT part.

It's dominated by initial production, thus controled by Debye screening and suppression.

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

Thermal Charm Production--Motivation

Go to higher and higher energy collisions (eg. FCC) :



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

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

In-medium **thermal charm production rate** can be large

P.Levai, B.Muller and X.Wang, 95, B.Kaempfer,O.Pavlenko,97
J.Uphoff, O.Fochler, Z.Xu,C.Greiner, 2010 , B.Zhang and C.Ko, 08

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

What's its effect on Charmonium:
Charmonium Enhancement ?

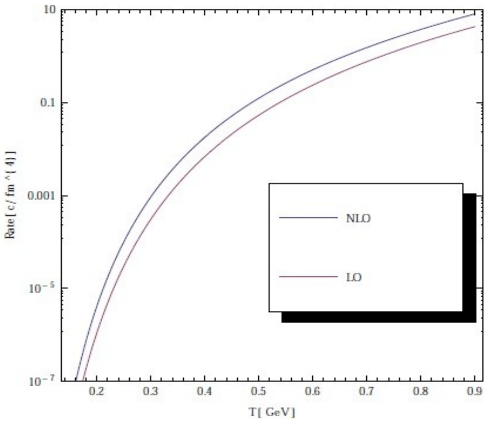
Thermal Charm Production

Rate equation for charm quark density:

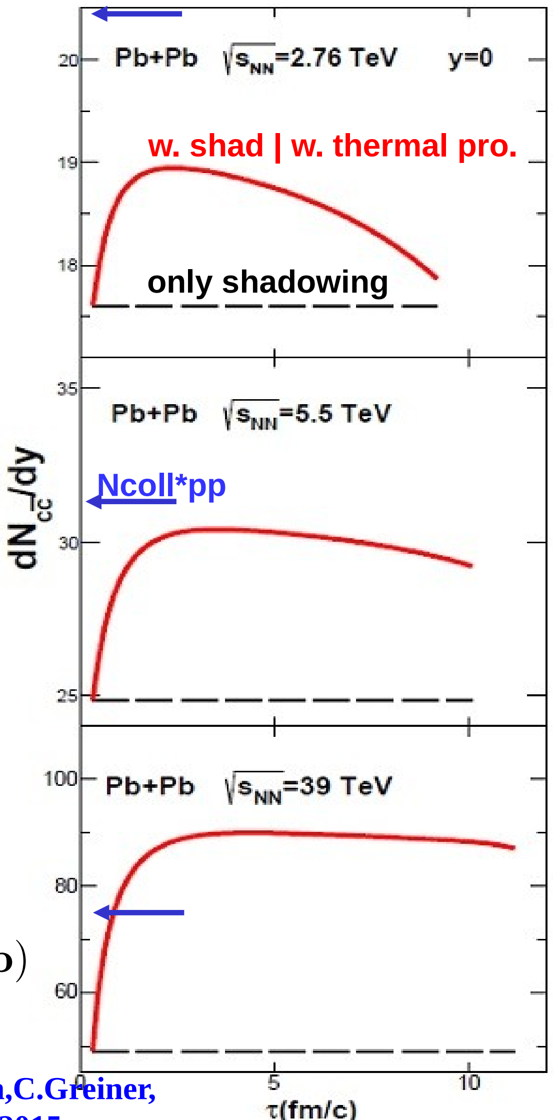
$$\frac{1}{\cosh\eta}\partial_\tau n_c + \nabla_T \cdot (n_c \mathbf{v}_T) + \frac{1}{\tau\cosh\eta} n_c = R_{gain} - R_{loss}$$

- loss and gain rate

$$R_{12} = \frac{d_{N12}}{d^4x} = \frac{1}{\nu}\int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} 4F_{12}\sigma_{12} f_1 f_2$$



- MNR-NLO
  P.Nason, S.Dawson, and R.Ellis, 88, 89.
  M.L.Mangano, P.Nason and G.Ridolfi, 92
- detailed balance
- Same with Zhang-Ko
  B.Zhang, C.Ko and W.Liu, 08



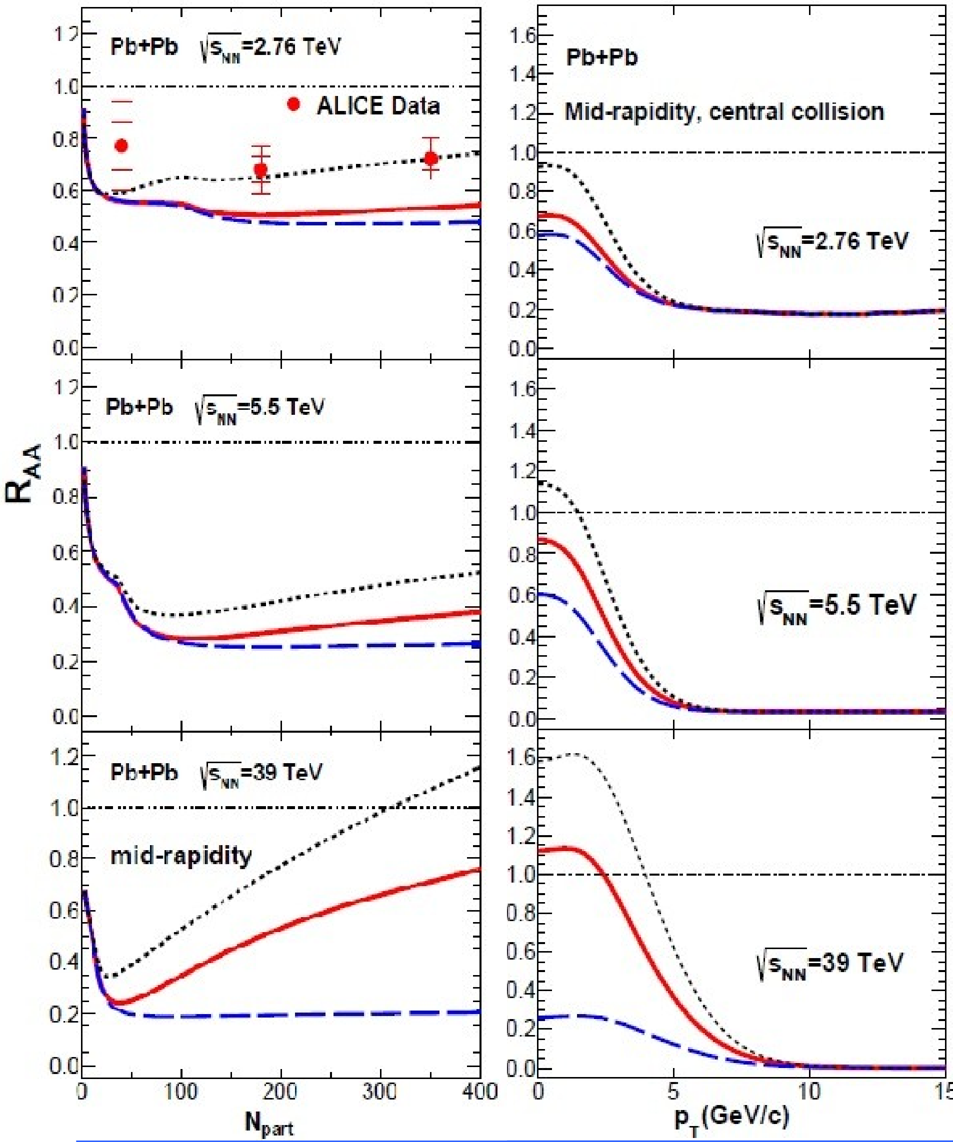
- Shadowing through initial condition

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

- Hydrodynamic for QGP evolution

K.Zhou,Z.Chen,C.Greiner, P.Zhuang, PLB2015

Thermal Charm Production



- thermal c + no shad.
- thermal c + shad
- no thermal c + shad

Thermal charm production enhances charmonium regeneration at FCC :

- Deep valley in RAA(Np)
- Enhancement, bump at soft pt
- Source from initial charm to in-medium charm

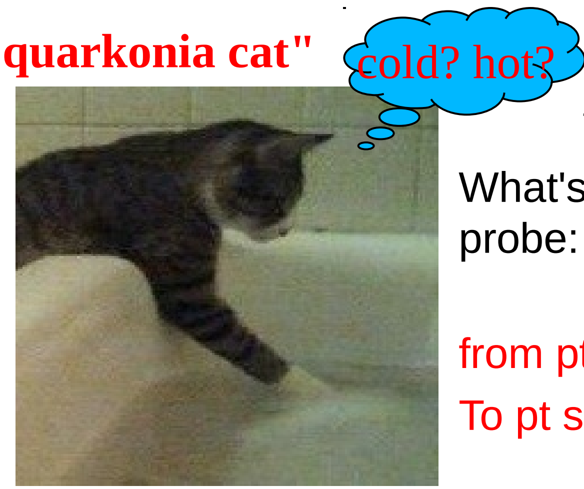
K.Zhou,Z.Chen,C.Greiner, P.Zhuang, PLB2015

Summary

- Transport approach provides more clear physical picture.

- Natural outcome from picture in classical transport approach :

"quarkonia cat"

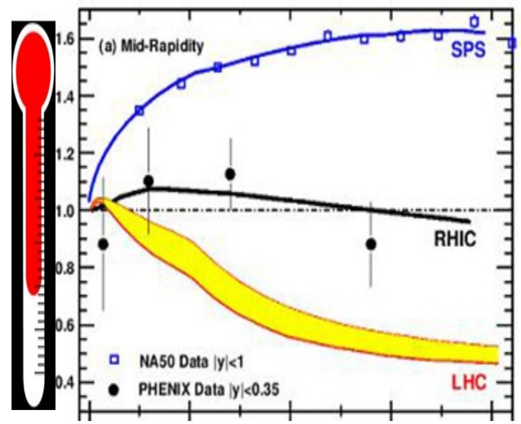


What's sensetive probe: flow and pT-

from pt broadening

To pt suppression

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



not that hot

a little hot

very hot !

- For higher energy collisions, thermal charm production can lead to onium enhancement at FCC.

- –--- Treat open and hidden flavor production on the same footing ?

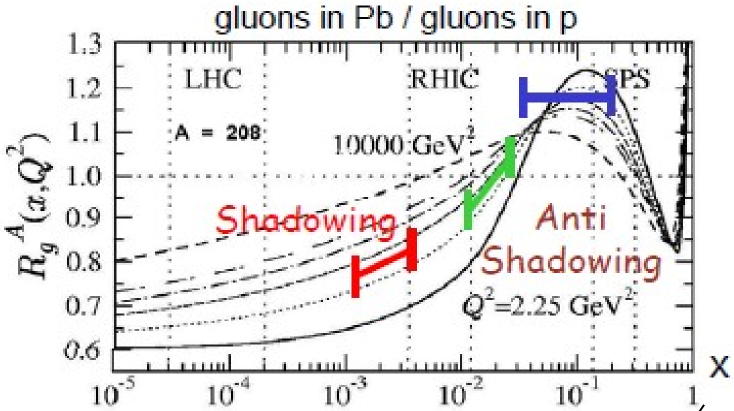
Thank You !

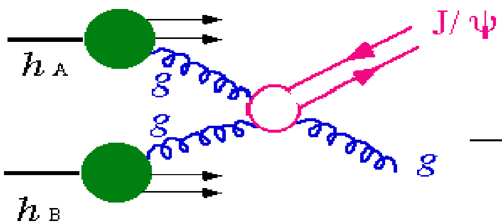
Many Thanks to : **Y.P. Liu, B.Y. Chen,**
Z. Xu, N. Xu, H. Stoecker,
C. Greiner, P.F. Zhuang
for fruitful collaborations and discussions.

Transport Model- cold nuclear matter effects

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

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

$$\frac{d\sigma_{pp}^{\psi}}{dp_T^{\psi}dy_{\psi}}=\int dy_g x_1x_2\cdot f_g(x_1,\mu_F)f_g(x_2,\mu_F)\frac{d\sigma_{gg\to\psi g}}{dt}$$

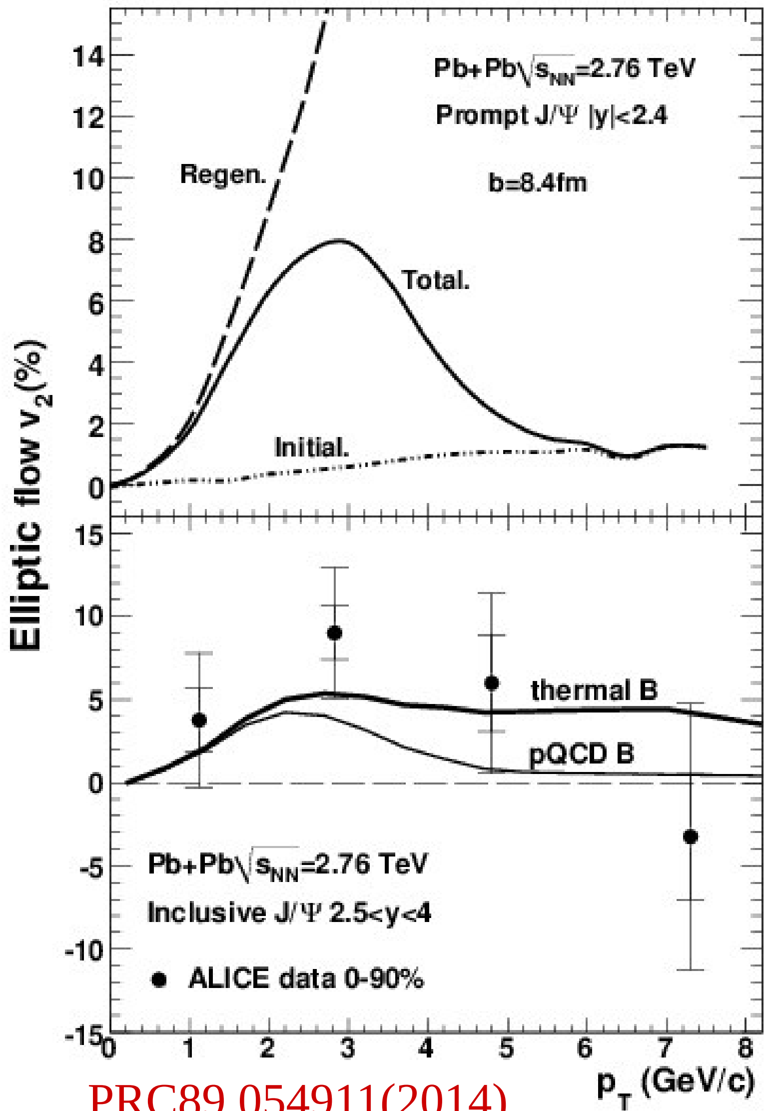
AA

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

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

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

Results—Eilliptic flow v2



PRC89,054911(2014)

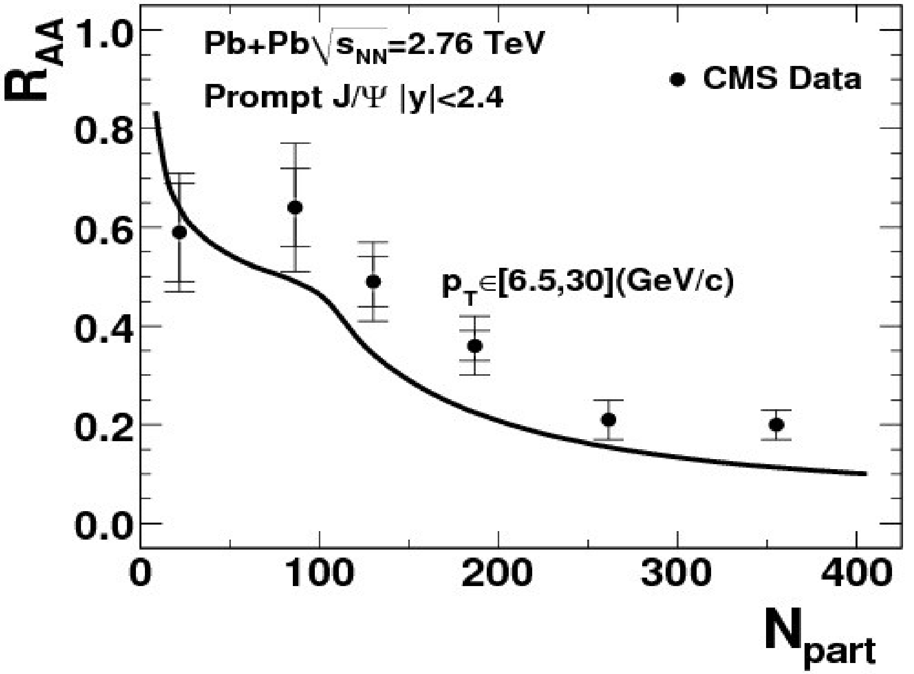
- remarkable v2 from the regeneration ⇨ reflect heavy quark thermalization.

- "ridge" structure due to ***two component competition***:

  - ***hard (*** initial, jet)
  - ***soft (*** regeneration,bulk)

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

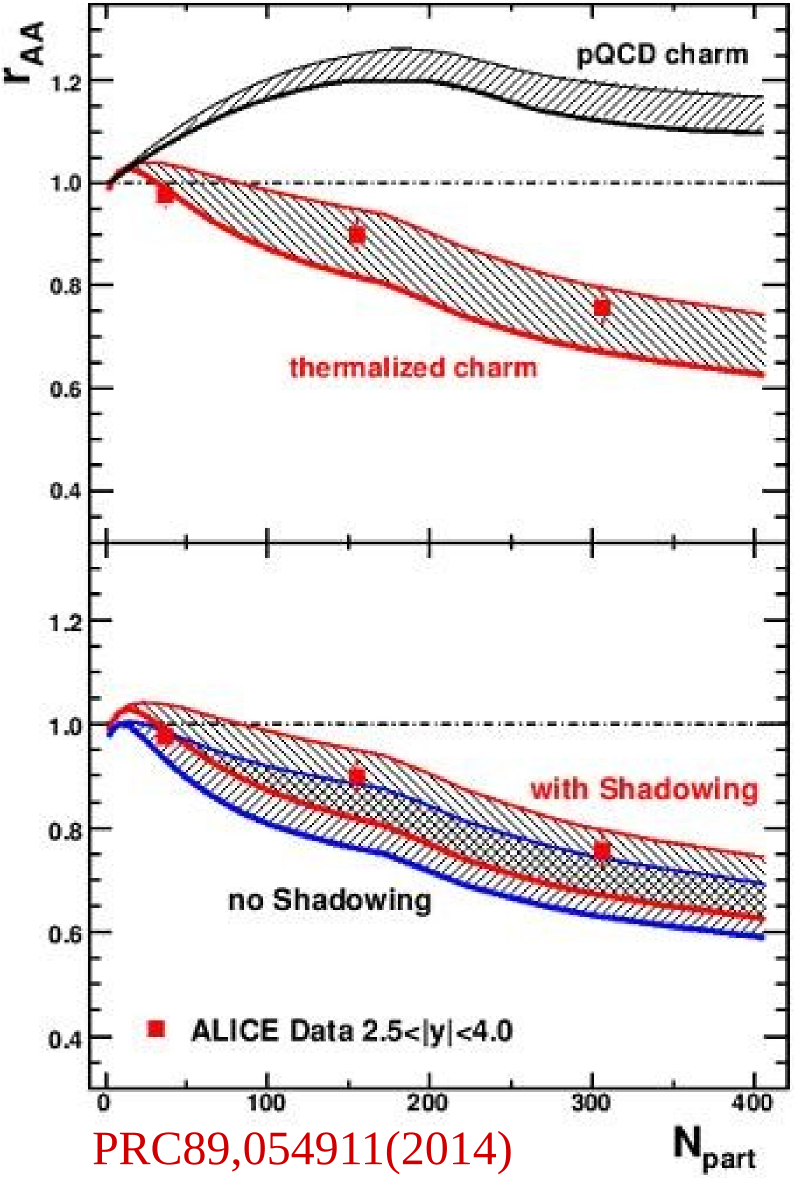
Mid-Rapidity



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

PRC89,054911(2014)

Results—Modification for Trans. pT: rAA



PRC89,054911(2014)

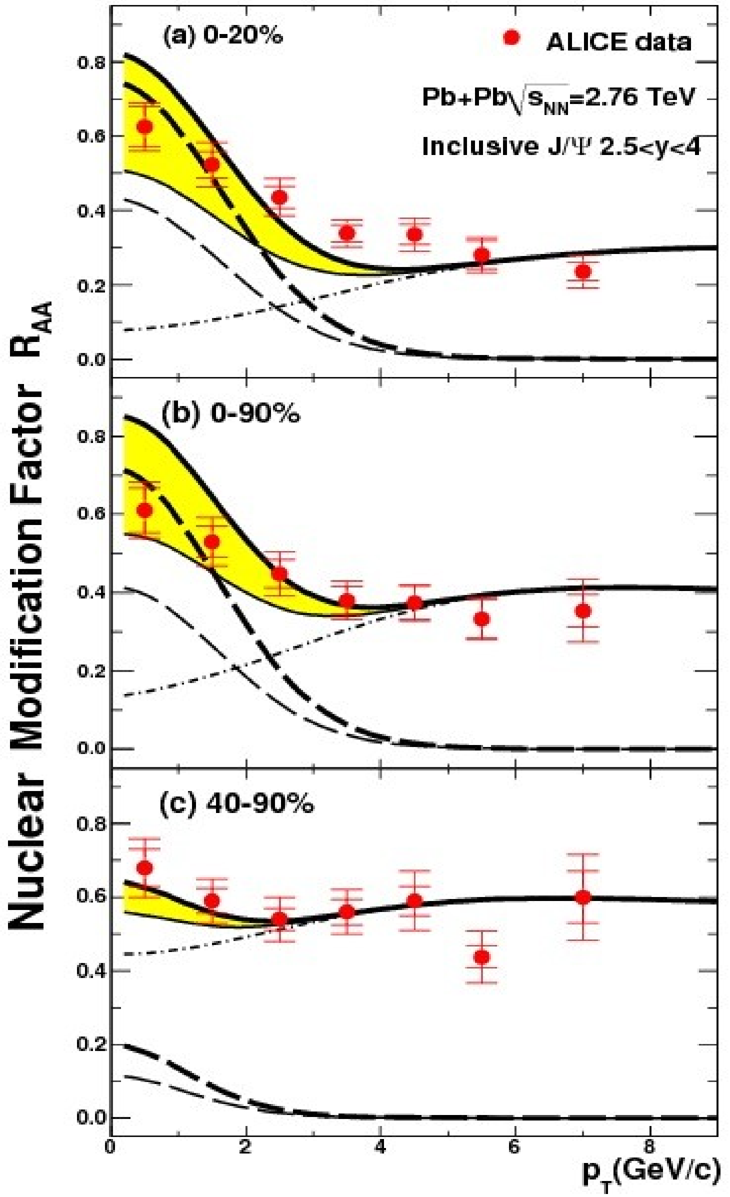
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

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—*pT dependence* : RAA(pT)



➢ Initial production:

- Cronin effect in initial stage
- strong low pt suppression and high pt leakage effect

⇨ ***initial pt broadening***

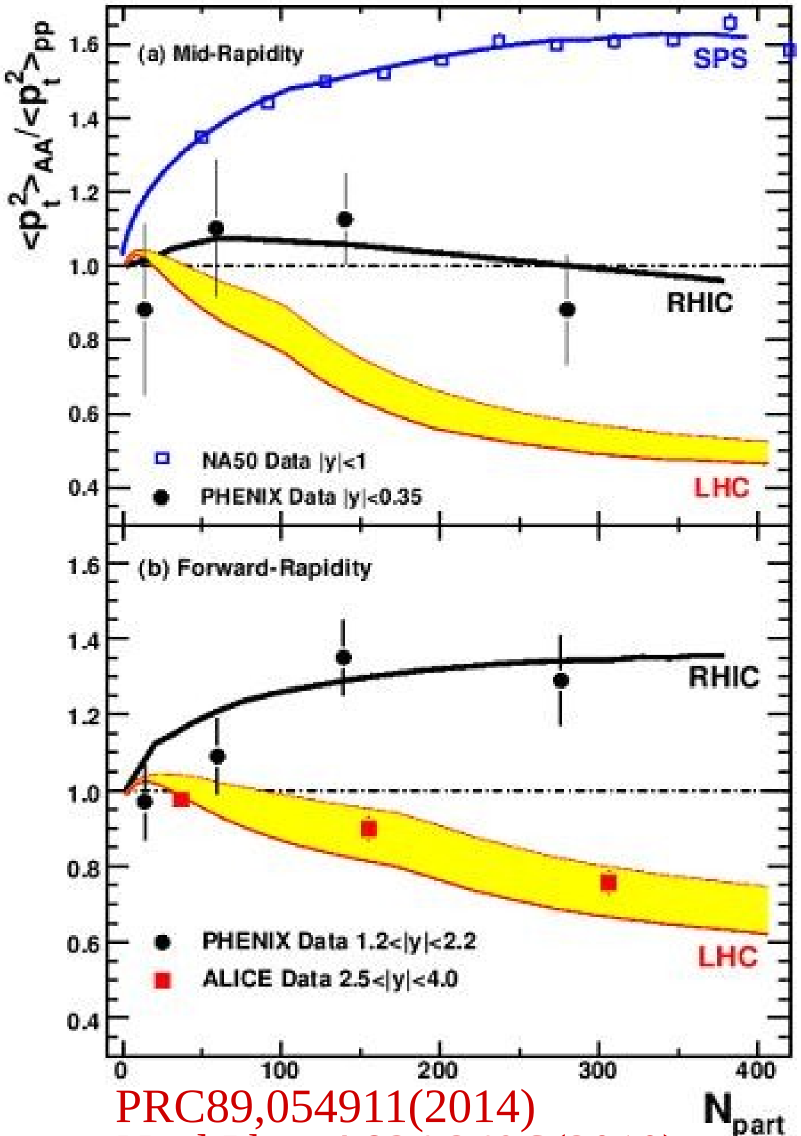
➢ Regeneration:

- 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)

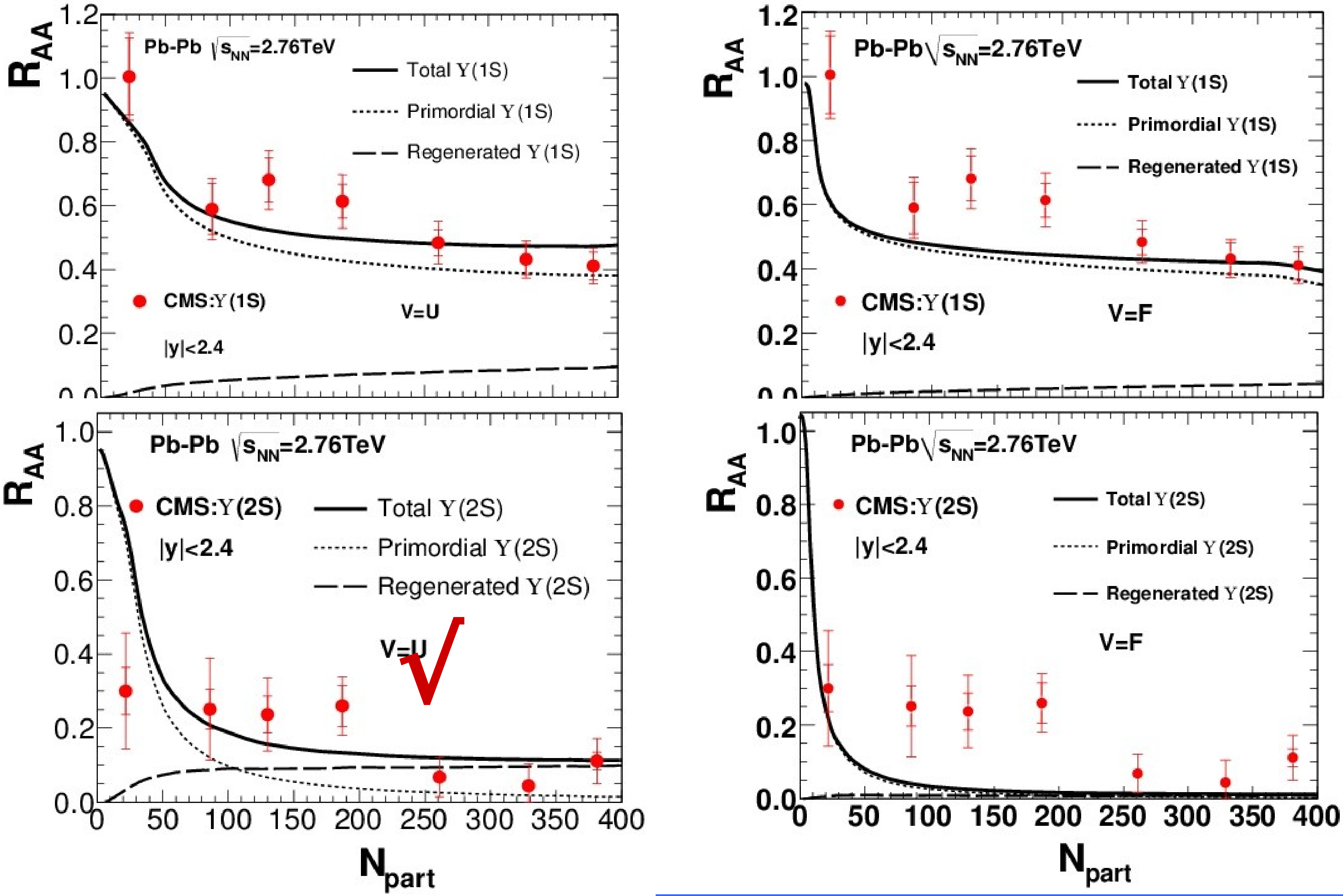
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

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

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

LHC: dominant ***regeneration***

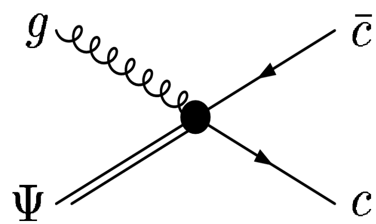
Results—Bottomonium differs V=U or V=F



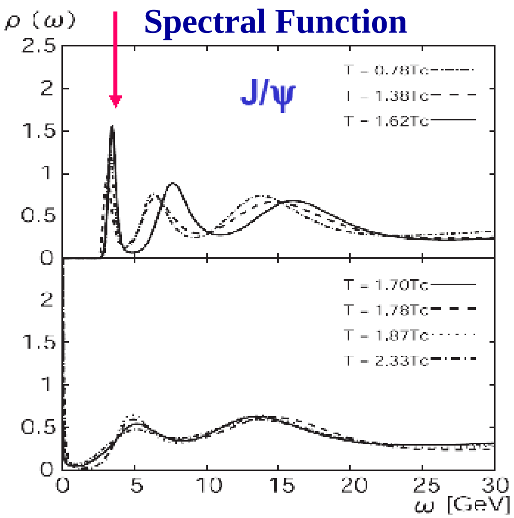
Theory Review – Dynamical / Transport approach

- Full transport : take detailed balance microscopically (easy for gluon-diss)

$\sigma_{g\Psi}(s)$



Tsinghua Group
Zhou,Liu,Zhu,Yan,Zhuang...



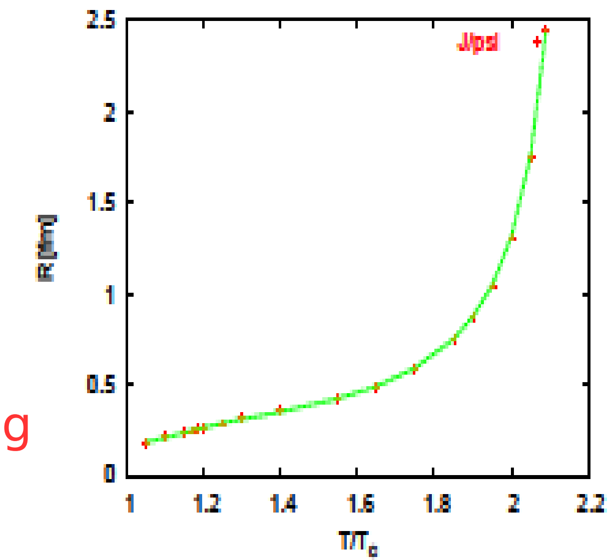
Spectral peak disapear above Td

in Vacuum : OPE / pNRQCD

$$\sigma_{g\Psi} = A_0 \cdot \frac{(\omega/\epsilon_\Psi - 1)^{3/2}}{(\omega/\epsilon_\Psi)^5}$$

in Medium : geometric scaling

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



The divergence of size defines the melting Td

Transport Model- *solution* of transport equation

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

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

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

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

Both Initial production and Regeneration suffers Suppression