Thermal production of charms and charmonia in quark-gluon plasma

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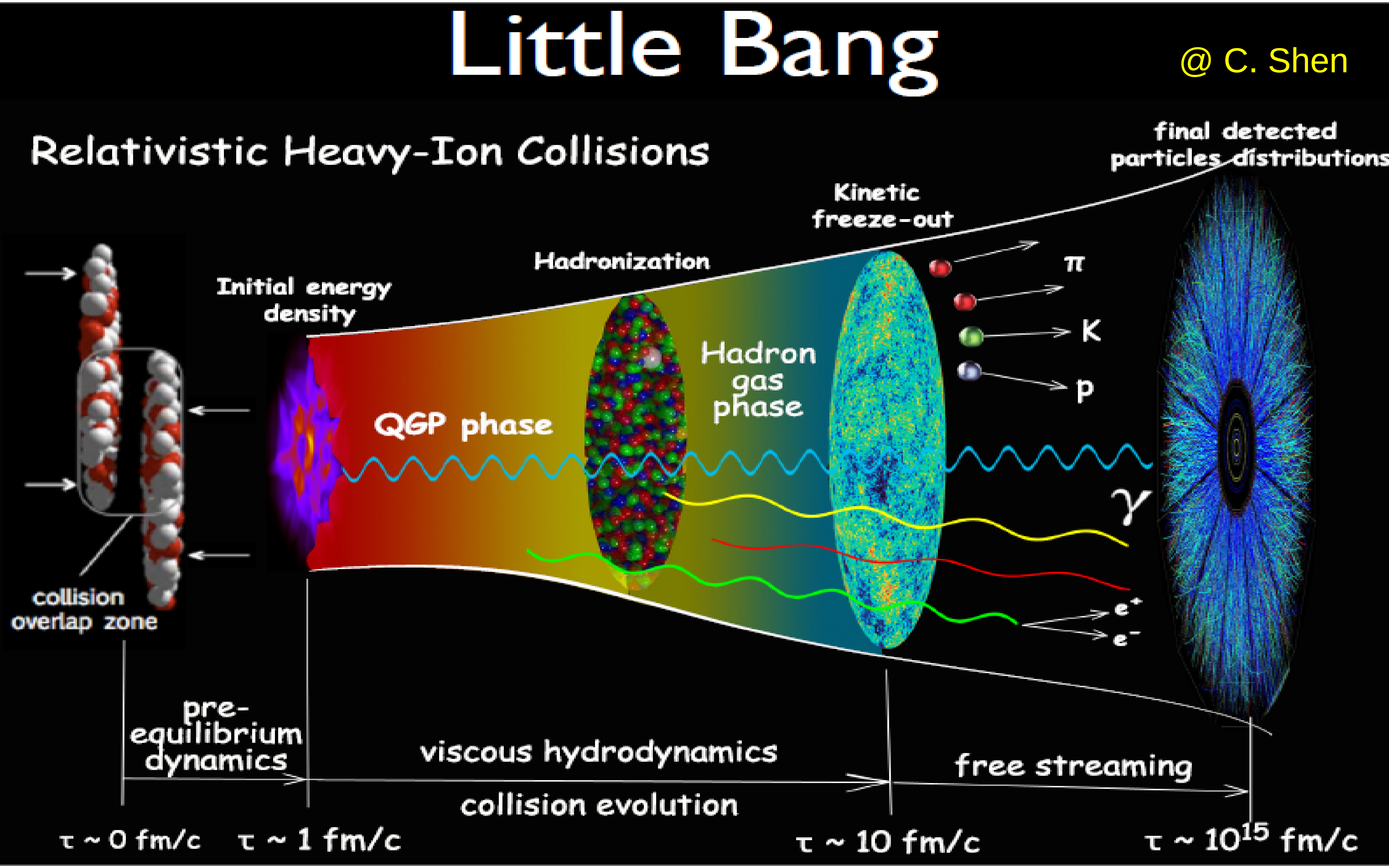
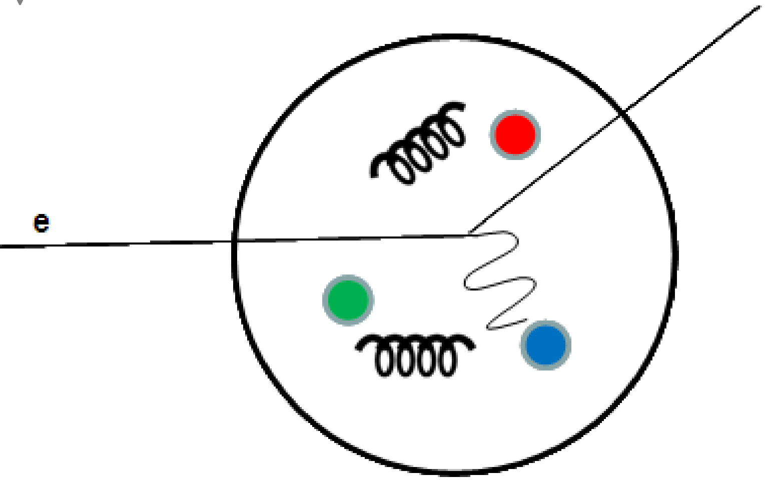
Outline

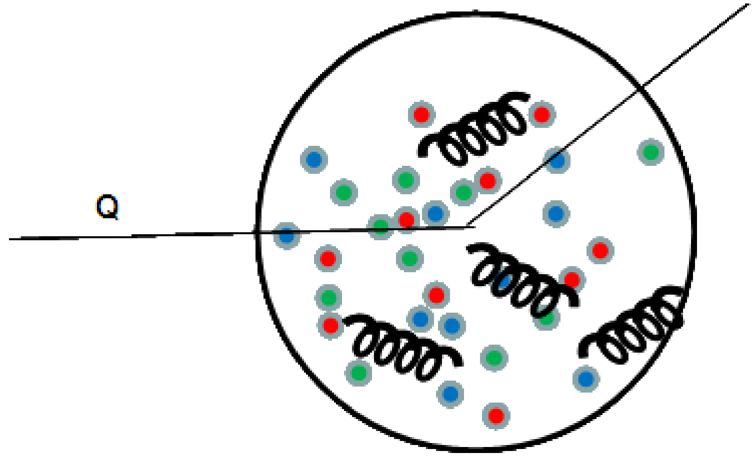
- Introduction
- Thermal production of charms
- Thermal production of charmonia
- Numerical results
- Summary

Introduction

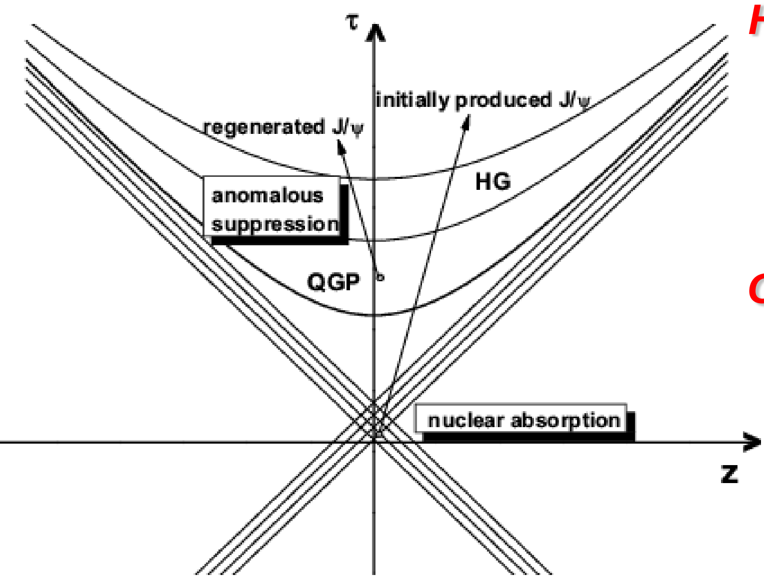


Matsui and Satz: PLB178, 416(1986):
J/Psi suppression as a probe of QGP in HIC





Electrons are usually used to probe the electro-magnetic structure of nucleons



Hot Nuclear Matter effects:

1)suppression in QGP and HG (Masui, Satz et al.)

2)regeneration in QGP and HG (PBM, Thews, R.Rapp et al.)

Cold Nuclear Matter effects:

1)nuclear absorption (J.Huefner, A.Capella et al.)

2)Cronin effect (J.W.Cronin, J.Huefner et al.)

3)shadowing effect (A.H.Mueller, M.Gyulassy, R.Vogt, E.Ferreiro et al.)

$$g + J/\psi \leftrightarrow c + \bar{c}$$

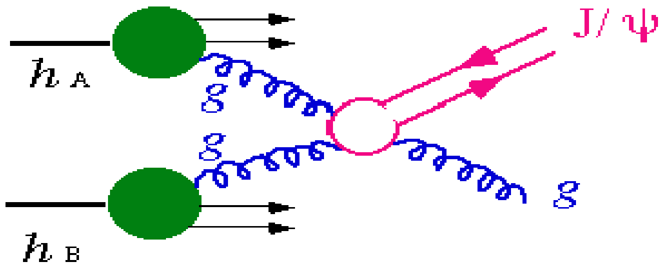
$$\xrightarrow{\alpha} \qquad \xleftarrow{\beta}$$

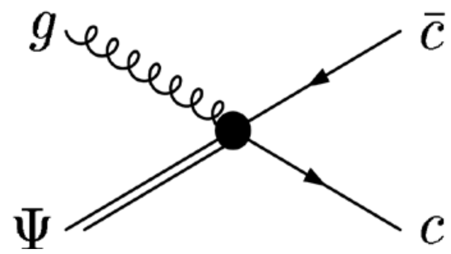
- **_Initial production_**

  initial production controls high pt region

- **_Regeneration_**

  important at low pt due to heavy quark energy loss





Nuclear modification factor:

characterize the differences of J/Psi production between A+A and simple superposition of p+p collisions

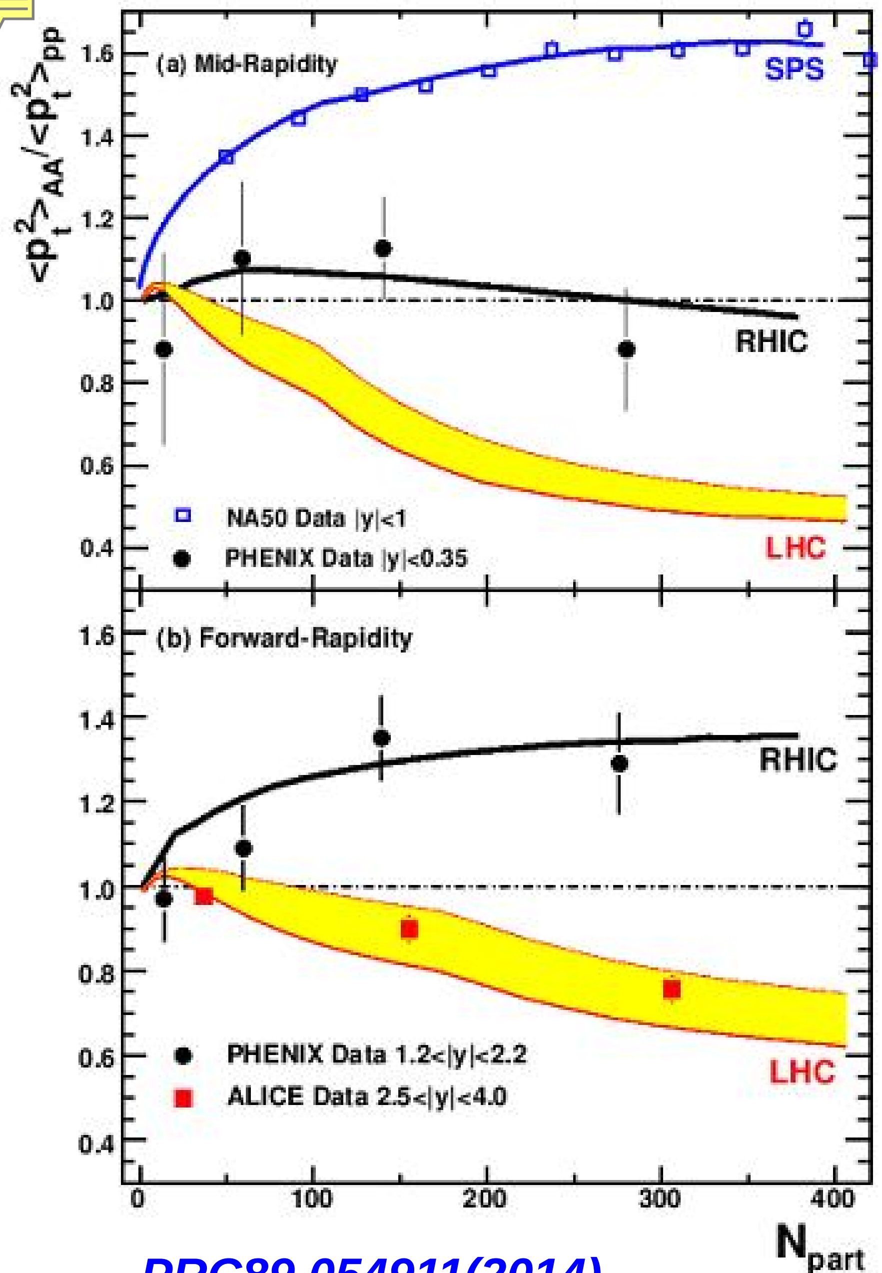
$$R_{AA} = \frac{N_{J/\psi}^{AA}}{N_{coll} N_{J/\psi}^{pp}} \sim \frac{"QCD_{medium}"}{"QCD_{vacuum}"}$$

- **= 1** No medium effect
- **< 1** Suppression
- **> 1** Enhancement

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

Transverse momentum modification factor:

Sensitive to the hot nuclear matter effects but affected weakly by the cold nuclear matter effects.



PRC89,054911(2014)

Nucl.Phys.A834,249C(2010)

@SPS:

Almost all the finally observed charmonia are from primordially produced one

@RHIC:

Regeneration only plays a partial role

@LHC:

Regeneration becomes equally important in forward rapidity, and even dominant in mid-rapidity

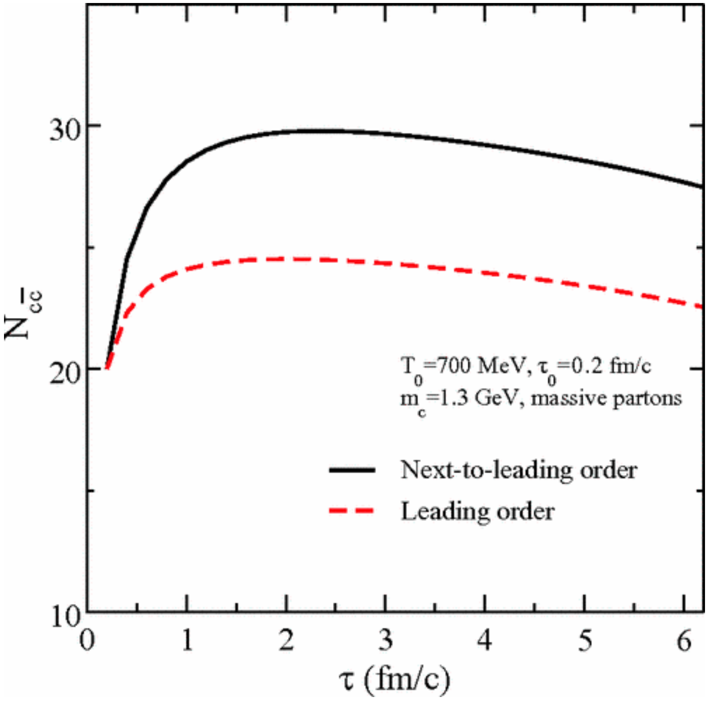
Future Circular Collider

39TeV!

All the heavy quarks are initially produced!

$$\partial_\mu N^\mu = 0$$

How about the thermal charm production and its contribution to charmonia ?



thermal production can appreciably enhance the yield of charm quarks

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

Thermal production of charms

- ***charm production processes***

Leading Order:

$$q+\bar{q}\rightarrow c+\bar{c} \qquad g+g\rightarrow c+\bar{c}$$

Next-to-leading Order:

$$q+\bar{q}\rightarrow c+\bar{c}+g \qquad g+g\rightarrow c+\bar{c}+g$$

- ***rate equation***

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

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

σ_{12} ***charm pair production cross section(P. Nason et al. 1988)***

R_{loss} ***determined by detailed balance***

- **Ideal hydrodynamic equations**

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

$$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - g^{\mu\nu} p$$
$$j^\mu = nu^\mu$$

Bjorken expansion

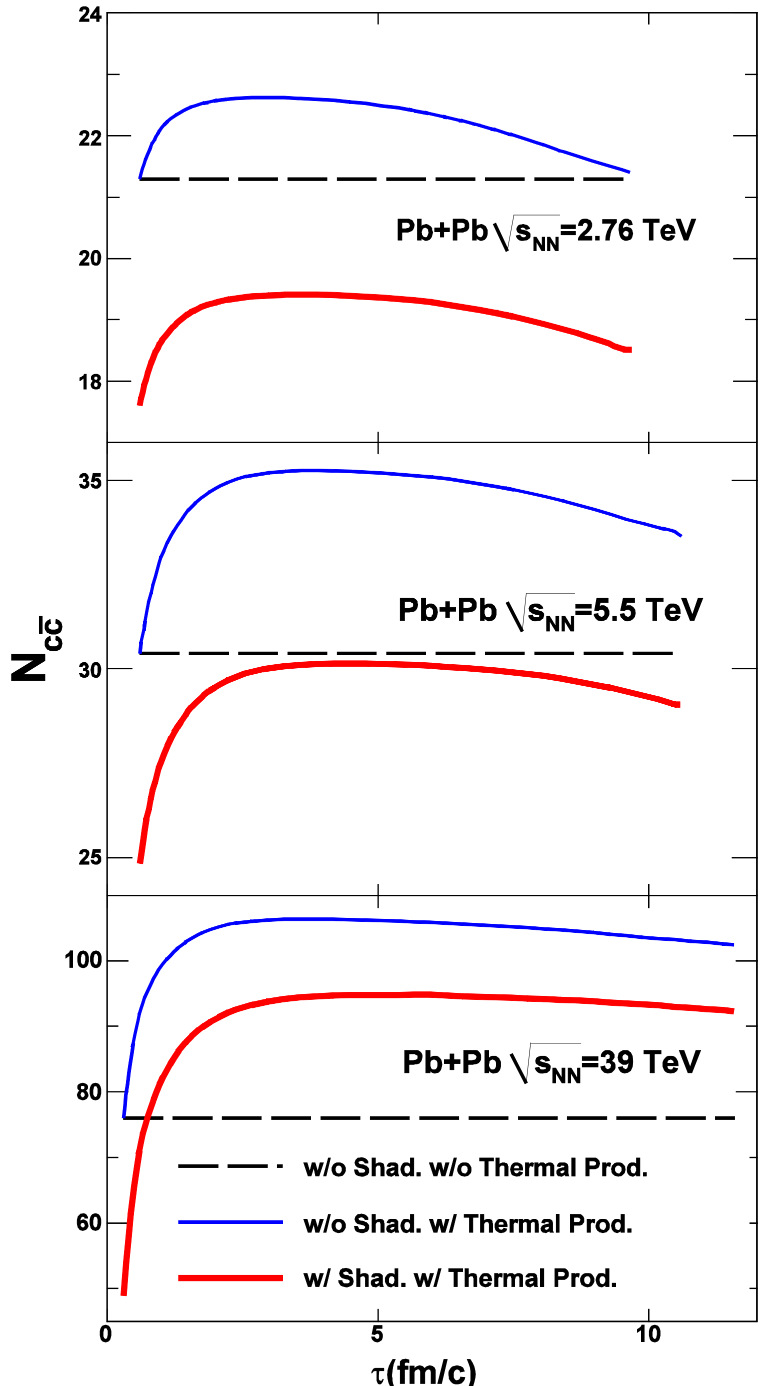
- **QGP hydrodynamic equations**

$$\begin{cases} \partial_\tau E + \nabla \cdot \mathrm{M} = -(E+p)/\tau \ , \\ \partial_\tau M_x + \nabla \cdot (M_x \mathbf{v}) = -M_x/\tau - \partial_x p \ , \\ \partial_\tau M_y + \nabla \cdot (M_y \mathbf{v}) = -M_y/\tau - \partial_y p \ , \\ \partial_\tau R + \nabla \cdot (R\mathbf{v}) = -R/\tau \end{cases}$$

+ Equation Of State (ideal gas or strongly coupled matter from lattice)

- **The final charged multiplicity is used to determine the initial entropy density as input for hydrodynamics**

charm number evolution



@ 2.76TeV thermal charm production is cancelled by shadowing.

@ 5.5 TeV thermal charm production comparable with shadowing.

@ 39 TeV thermal charm production overcomes shadowing.

Thermal production enhances J/Psi regeneration, but shadowing effect suppress J/Psi regeneration, the final result is controlled by the competition of the two.

Thermal production of charmonia

- ***transport approach***

  L. Yan et al. (2006), Y. Liu et al. (2009), K. Zhou et al. (2014)

- ***quarkonium transport equations***

$$\partial_\tau f_\Psi + \mathbf{V}_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi$$

$$(\Psi = J/\psi,\ \chi_c,\ \psi')$$

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

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

Including thermal charm production

Analytic solution

$$f_\psi(\vec{p},\vec{x},\tau) = f_\psi(\vec{p},\vec{x}_0,\tau_0)e^{-\int_{\tau_0}^{\tau} d\tau_1 \alpha_\psi(\vec{p},\vec{x}_1,\tau_1)} + \int_{\tau_0}^{\tau} d\tau_1 \beta_\psi(\vec{p},\vec{x}_1,\tau_1) e^{-\int_{\tau_1}^{\tau} d\tau_2 \alpha_\psi(\vec{p},\vec{x}_2,\tau_2)}$$

- **For the in-vacuum dissociation cross section, one can use results from the OPE method with a perturbative Coulomb interaction (Bhanot, Peskin,1999):**

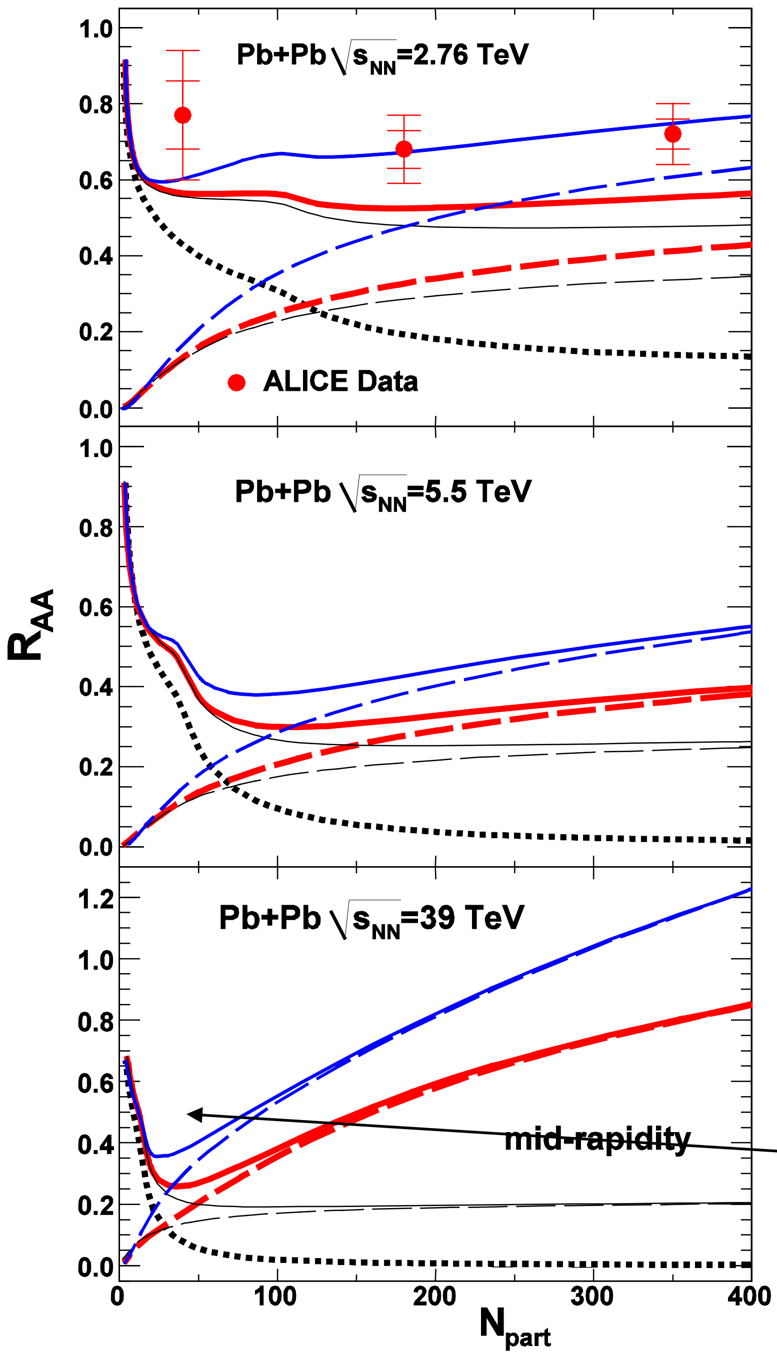
$$\sigma(p_\psi, p_g)$$

- **When going to high temperature medium, we estimate the temperature effect on gluon dissociation by taking the geometrical relation**

$$\sigma(p_\psi, p_g, T) \approx \frac{\langle r^2\rangle(T)}{\langle r^2\rangle(0)} \sigma(p_\psi, p_g)$$

$\langle r^2\rangle(T)$ **calculate using potential model with lattice simulated heavy quark potential at finite temperature**

Numerical results



@2.76TeV

Thermal production increase R_{AA} 0.48→0.55 (with shadowing);
Thermal production increase R_{AA} 0.48→0.77 (without shadowing).

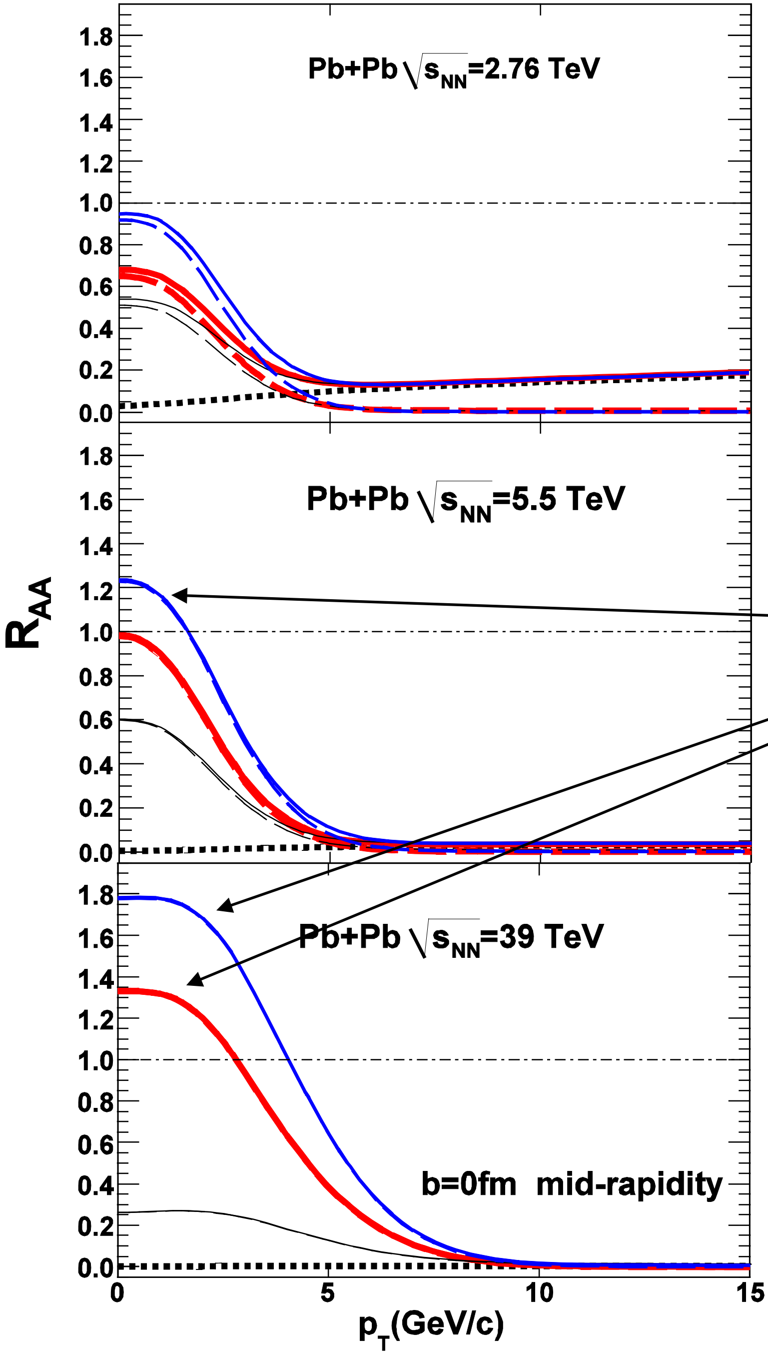
@5.5TeV

With thermal production, R_{AA} shows a slightly increasing trend; Without thermal production, R_{AA} appears a flat structure.

@39TeV

Without thermal production, R_{AA} is around 0.2 in most of centralities. Considering thermal production, R_{AA} can reach to 0.85 (1.25 if without shadowing) in most central collisions.

valley structure due to the thermal production



@LHC

The thermal charm production enhances the charmonium regeneration further, which strengthens the decreasing trend.

exceed unit due to the thermal production

@FCC

Due to the higher temperature, the QGP becomes a rich source for charm pair thermal production, and this overcome the stronger suppression through regeneration mechanism.

Summary

- ***The thermal charm production can dramatically enhance the charm quark pairs yield at extremely high energies such as collisions at FCC.***

- ***At FCC , RAA presents a clearly valley structure due to the competition between the strong suppression and strong regeneration.***

- ***At FCC , differential RAA as a function of pT can exceed 1 with thermal charm production.***

Thank You!

Primary *rate equation*

$$\partial_\mu N^\mu = \partial_\mu\left(n^{LR}_{c\bar{c}} u^\mu\right) = R_{gain} - R_{loss}$$

- ***Writing*** $n_{c\bar{c}} = \gamma n^{LR}_{c\bar{c}}$ ***,it turns to be***

$$\partial_\mu N^\mu = \partial_\mu\left(n^{LR}_{c\bar{c}} u^\mu\right) = R_{gain} - R_{loss}$$

$$\eta = (1/2)\ln\left((t+z)/(t-z)\right), \tau = \sqrt{t^2 - z^2}$$

$$\frac{1}{\cosh\eta}\partial_\tau n_{c\bar{c}} + \nabla_T \cdot \left(n_{c\bar{c}} \cdot \mathbf{V}_T\right) + \frac{1}{\tau\cosh\eta} n_{c\bar{c}} = R_{gain} - R_{loss}$$

- ***Setting*** $n_{c\bar{c}} = \rho_T/\tau$ ***,*** $\rho_T\left(\tau, \mathbf{X}_T\right)$ ***being charm pair number density, it can be expressed as***

$$\partial_\tau \rho_T + \nabla_T \cdot \left(\rho_T \cdot \mathbf{V}_T\right) = \tau\left(R_{gain} - R_{loss}\right)$$

- ***The Lorentz-invariant form for rate***

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

$$F_{12} = \sqrt{\left(p_1 \cdot p_2\right)^2 - m_1^2 m_2^2}$$

- ***Setting*** $R_{loss} = \left(n^{LR}_{c\bar{c}} / n^{eq}_{c\bar{c}}\right)^2 r_{loss}$

$$r_{c\bar{c}\to ij} = \int \frac{d^3p_c}{(2\pi)^3 2E_c}\frac{d^3p_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} 4F_{c\bar{c}}\sigma_{c\bar{c}} f_c^{eq} f_{\bar{c}}^{eq}$$

$$f^{eq}_{c(\bar{c})} = 1/\left(e^{p\cdot u(x)/T(x)} + 1\right)$$

Simplified *rate equation*

$$\partial_\tau \rho_T + \nabla_T \cdot \left(\rho_T \cdot \mathbf{V}_T\right) = \tau R_{gain} - \frac{\rho_T^2}{\gamma^2\tau} r_{loss}$$

$$\frac{dN_{ch}}{d\eta} = -232.7 - 189.6\sqrt{S_{NN}} + 598.2\left(\sqrt{S_{NN}}\right)^{0.217}$$

$$\frac{ds\left(\tau_0, \mathbf{X}_T\right)}{d\eta} = \kappa \frac{\rho_{sr}\left(\mathbf{X}_T\right)}{\rho_{sr}\left(0\right)} \frac{dN_{ch}}{d\eta}$$

$$\rho_{sr}\left(\mathbf{X}_T\right) = \frac{1-\alpha}{2} n_{part}\left(\mathbf{X}_T\right) + \alpha n_{coll}\left(\mathbf{X}_T\right)$$