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 $m_Q \gg \Lambda_{QCD}, T$

- 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 IQCD:

  \[
  \begin{array}{|c|c|c|c|c|c|c|c|}
  \hline
  \text{state} & \text{J/\( \psi \)(1S)} & \chi_c(1P) & \psi(2S) & \Upsilon(1S) & \chi_b(1P) & \Upsilon(2S) & \chi_b(2P) & \Upsilon(3S) \\
  \hline
  T_d/T_e & 2.10 & 1.16 & 1.12 & > 4.0 & 1.76 & 1.60 & 1.19 & 1.17 \\
  \hline
  \end{array}
  \]

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


  - Cold matter effects: nuclear absorption, Cronin, Shadowing
  - Collisional break-up: gluo-diss. (G.Bhanot and M.H.Peskin) quasi-free diss. (R.Rapp)
  - Regeneration/recombination: coalescence (PBM, Thews, R.Rapp...)

- Observation

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

  \[=egin{cases}
  1 & \text{No effect} \\
  < 1 & \text{Suppression} \\
  > 1 & \text{Enhancement}
  \end{cases}\]

Kai Zhou        Trento       ECT* Quarkonium 2016 3
Introduction

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

- Unified 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

Hydrodynamic Evolution

\[ \left\{ \begin{array}{l}
\partial_{\mu} T^{\mu\nu} = 0 \\
\partial_{\mu} j_{\mu} = 0 \\
\end{array} \right\} + \text{EoS} \]

Transport Equation

- hot nuclear matter effects
  - 1) Dissociation
  - 2) Regeneration
- cold nuclear matter effects
  - 1) Absorption
  - 2) Cronin effect
  - 3) Shadowing effect

Kai Zhou        Trento        ECT* Quarkonium 2016
Transport Model- transport equation & **hot effects**

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

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

1) Gluon dissociation:

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

\[N_g/(e^{p_{g\mu}/T} - 1)\]

<table>
<thead>
<tr>
<th>Spectral Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ</td>
</tr>
</tbody>
</table>

**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

Kai Zhou     Trento     ECT* Quarkonium 2016
Transport Model- transport equation & hot effects

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

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

1) Gluon dissociation :

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

$$N_g / (e^{p^\mu u_\mu/T} - 1)$$

Gluon dissociation:

- in Vacuum
- OPE (Peskin, 1979)

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

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

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

Kai Zhou        Trento        ECT* Quarkonium 2016 7
Transport Model - transport equation & hot effects

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

\[
\partial_t f + \vec{v}_T \cdot \nabla_T f + \nu_z \partial_z f = -\alpha f + \beta
\]

2) in-Medium Regeneration :

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

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

- 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:

Absorption

Cronin Gassian smearing treatment

Shadowing

Cold Effects

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

nPDF vs. free PDF

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

Competition leads to platform structure in most centralities.
Results—$p_T$ dependence: RAA($p_T$)

- **Initial production:**
  - Cronin effect in initial stage
  - strong low pt suppression and high pt leakage effect
  - $\Rightarrow$ initial pt broadening

- **Regeneration:**
  - coalescence mechanism
  - energy loss induced thermalization
  - $\Rightarrow$ low pt regeneration

Kai Zhou        Trento

PRC89,054911(2014)
Results—Modification for Trans. $p_T : r_{AA}$

SPS: Cronin effect for initial production

RHIC: competition betw. initial Vs. regeneration

LHC: dominant regeneration

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

PRC89,054911(2014)
Clearly showes a hotter medium been created at LHC!

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

\[ \sqrt{S_{NN}} \uparrow \quad QGP \uparrow \]

hotter

PRC89,054911(2014)

Results—Bottomonium differs $V=U$ or $V=F$
When we go to higher and higher energy collisions (e.g. 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

\[ \sigma^{AB \rightarrow [c\bar{c}]}(s) = \sum_{i,j} \int dx_1 dx_2 \hat{\sigma}^{ij \rightarrow [c\bar{c}]}(x_1, x_2, s, m^2, \mu) f^A_i(x_1, \mu) f^B_j(x_2, \mu) \]

\[ \rightarrow \text{secondary in-medium thermal charm production rate can be large} \]

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

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

- the medium become much more hotter and denser

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

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

\[\Rightarrow \text{secondary in-medium thermal charm production rate can be large}\]

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

**Charmonium Enhancement?**

Future Circular Collider

39TeV!
**Thermal Charm Production**

Rate equation for charm quark density:

\[ \partial_\mu n_\mu^c = R_{\text{gain}} - R_{\text{loss}} \]

\[ R_{\text{gain}} = R_{gg \rightarrow c\bar{c}(g)} + R_{q\bar{q} \rightarrow c\bar{c}(g)} \quad \text{(Nason, Dawson & Ellis, 1988)} \]

\[ R_{\text{loss}} : \text{from detailed balance with } R_{\text{gain}} \]

\[ n_c(\tau_0, \vec{x}_T|\vec{b}) = \frac{d\sigma_{c\bar{c}}}{d\eta} \frac{1}{\tau_0} T_A(\vec{x}_T) T_B(\vec{x}_T - \vec{b}) R_g^A(x_1, \vec{x}_T) R_g^B(x_2, \vec{x}_T - \vec{b}) \]

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

Kai Zhou        Trento         ECT* Quarkonium 2016
NEW Results—RAA(Npart)

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

upper dotted-lines: without shadowing

@2.76TeV
- weak thermal charm production

@5.5TeV
- regeneration enhanced $\sim 40\%$ (quadratic in $c$)

@39TeV
- wide plateau $\rightarrow$ clearly increasing trend
- central coll. $0.2 \rightarrow 0.75$ (3 times!)
- production sourced directly from thermal medium but not initial produced charm
Results—RAA(pT)

Initial production dominate high pT, regeneration 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

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

cold? hot?

"heavy quarkonia cat"

not that hot

not that hot

ea little hot

very hot!

since \( N_{\text{regeneration}} \sim N_{cc}^2 \), 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

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

Kai Zhou  Trento  ECT* Quarkonium 2016
Results—Elliptic flow $v_2$

- remarkable $v_2$ from the regeneration $\rightleftharpoons$ reflect heavy quark thermalization.
- "ridge" structure due to two component competition:
  - hard (initial, jet)
  - soft (regeneration, bulk)

PRC89,054911(2014)
Backup—Yield's Centrality depen. (pT bin)

Mid-Rapidity

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

PRC89,054911(2014)
Results—Modification for Trans. pT: rAA

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

2. not sensitive to the cold nuclear matter effect------Shadowing effect.

Clearly indicates QGP's medium effects

PRC89,054911(2014)
Fixed Target Pb+Pb 2.76A TeV (AFTER) \( \sim \sqrt{s_{NN}} = 72\text{GeV} \)

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

\[ \Delta y = \tanh^{-1} \beta_{\text{cms}} = 4.3 \]

\{ 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

\[
\begin{align*}
\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 \\

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')} \\
&\quad + \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{align*}
\]

\[
\begin{align*}
\vec{v}_t &= \frac{p_t}{E_t} \\
\vec{r}_t(\tau') &= \vec{x}_t - \vec{v}_t [\tau \cosh(y - \eta) - \tau' \cosh(\Delta(y - \eta))]
\end{align*}
\]

\[
\begin{align*}
A(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau') &= \frac{\alpha(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau')}{\cosh(\Delta(y - \eta))} \\
B(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau') &= \frac{\beta(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau')}{\cosh(\Delta(y - \eta))}
\end{align*}
\]

\[
\Delta(y - \eta) \equiv \text{arcsinh} \left( \frac{\tau}{\tau'} \sinh(y - \eta) \right)
\]

Both Initial production and Regeneration suffers Suppression
Results—Yield's Centrality depen. (pT bin)

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

Kai Zhou        Trento
ECT* Quarkonium 2016

PRC89,054911(2014)
**Shadowing**

\[ R_g^A(x, \mu_F) = \frac{f_g^A(x, \mu_F)}{A f_{g{\text{Nucleon}}}(x, \mu_F)} \]

for open & hidden heavy mesons

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

**Color Evaporation Model**

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

\[ f_0(\bar{p}, x_T^T) = \frac{(2\pi)^3}{E_T^\psi \cosh y_\psi} \frac{d\sigma_{pp}^{\psi}}{dy} \int dz_A dz_B \rho_A(x_T^T, z_A) \cdot \]

\[ \rho_B(x_T^T - \bar{b}, z_b) \cdot R_g(x_T^T, x_1, \mu_f) \cdot \]

\[ R_g(x_T^T - \bar{b}, x_2, \mu_f) \cdot f_{pp}(p_T^T, x_T^T, z_A, z_B) \]

---

Kai Zhou        Trento        ECT* Quarkonium 2016
Transport Model- ideal Hydro dynamics

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

\[
\begin{align*}
\partial_\tau \rho_T + \nabla_T \cdot (\rho_T \bar{v}_T) &= 0 \quad (\rho_T (\bar{x}_T, \tau) = \tau \cdot n_{\text{c}\text{c}}^{\text{Lab}}) \\
\partial_\tau E + \nabla_T \cdot \bar{\mathbf{M}}_T &= -(E + p) / \tau \\
\partial_\tau M_x + \nabla_T \cdot (M_x \bar{v}_T) &= -M_x / \tau - \partial_x p \\
\partial_\tau M_y + \nabla_T \cdot (M_y \bar{v}_T) &= -M_y / \tau - \partial_y p
\end{align*}
\]

\[\text{kinetic thermalization for HQ}\]

\[\partial \mu T^{\mu\nu} = 0\]

\[\text{Boost Invariance in z-direction}\]

\[E = (\varepsilon + p)\gamma^2 - p \quad \bar{\mathbf{M}} = (\varepsilon + p)\gamma^2 \bar{v}\]

- **Equation Of State:**
  Ideal Gas with quarks and gluons for QGP & HRG for Hadronic phase

- **Initialization:**
  Glauber model & constrained by fitting Charged Multiplicities

---

Kai Zhou        Trento
ECT* Quarkonium 2016