Heavy Quarkonium Transport in Heavy-ion Collisions

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27 Jun, Berkeley

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Outline

- Introduction
- Theory Review
- Transport analysis *(confronting data & Excitation)*
- 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**

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

Static Screening / Potential

Coalescence/Statistical

Dynamical / Transport Approach

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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

<table>
<thead>
<tr>
<th>state</th>
<th>$J/\psi(1S)$</th>
<th>$\chi_c(1P)$</th>
<th>$\psi'(2S)$</th>
<th>$\Upsilon(1S)$</th>
<th>$\chi_b(1P)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\chi_b(2P)$</th>
<th>$\Upsilon(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_d/T_c$</td>
<td>2.10</td>
<td>1.16</td>
<td>1.12</td>
<td>&gt; 4.0</td>
<td>1.76</td>
<td>1.60</td>
<td>1.19</td>
<td>1.17</td>
</tr>
</tbody>
</table>

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

• Entropic force repulsive, weaken the attractive energetic force
  \[ F_S = -T/\partial S/\partial r \]
  favor $V=F$ huge number of excited states near $T_c$? adiabatically

• $T$-matrix approach: real $V$ in between $F$ and $U$, close to $U$

M.Lain, J.Blaizot, N. Brambilla, A. Vairo, A. Rothkopf,
D.E.Kharzeev, 2014
H. Satz, 2015

S.Liu, R.Rapp, 2015

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

**HQ Balance equation:**

\[ N_{QQ} = \frac{1}{2} g_Q V n_o^{th} \frac{I_1(g_Q V n_o^{th})}{I_0(g_Q V n_o^{th})} + g_Q^2 V n_h^{th} \]

**Inputs:**

\[ T, \mu_B, V = N_{ch}^{exp} / n_{ch}^{th}, N_{QQ}^{dir}(pQCD) \]

**Outcome:**

\[ N_h = g_Q^2 V n_h^{th} = \frac{4 n_h^{th} N_{QQ}^2}{(n_o^{th})^2 V} (1 + \frac{1}{N_{QQ}}) \]

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?

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

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

\[
p(g, q, \bar{q}) + \Psi \rightleftarrows Q + Q(+g)
\]

\[\alpha \rightarrow \beta\]

**General Ingredients:**

- **Transport equation**
  - hot matter effects
    - 1) Dissociation
    - 2) Regeneration
  - cold matter effects
    - 1) Absorption
    - 2) Cronin effect
    - 3) Shadowing effect

**Medium evolution + EoS**
Neglect the regeneration (for bottomonium)

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

- **Collisional damping + glue-dissociation**

\[ \Gamma_{\text{tot}} = \Gamma_{\text{damp}} + \Gamma_{\text{diss}} \]

\[ V = Re[V] + Im[V] \quad (\text{Screened Cornell + HTL Im}[V]) \]

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

\[ \Gamma_{\text{diss}} = \frac{g_d}{2\pi^2} \int \frac{dp_g p_g^2 \sigma_{\text{diss}}(E_g)}{eE_g/T - 1} \quad (\text{based on dipole inter.term in pNRQCD}) \]

**Nendzig-Wolschin**

F. Nendzig, G. Wolschin


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Neglect the regeneration (for bottomonium)

\[
\text{Survival Prob} = e^{-\int_{r_F}^{r_{\text{final}}} d\tau \Gamma(T(\tau))}
\]

- Collisional **damping** under Anisotropic Hydro

Strickland Group
Krouppa, Ryblewski, Strickland...

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

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

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

- Tough for explaining the rapidity-dependence.
Assuming spatial homogeneity & HQ thermalization

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

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

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

**Neglect interference terms**

\( \sigma_p - \Psi \sim 2\sigma_p - Q \)

**TAMU Group**  
Zhao, Grandchamp, Rapp...
Assuming spatial homogeneity & HQ thermalization

Rate equation: \[ \frac{dN_{\Psi}(t)}{dt} = -\Gamma_{\Psi}(t)(N_{\Psi}(t) - N_{\Psi}^{eq}(t)) \]

SHM for regeneration: \[ N_{\Psi}^{eq}(T) = R(\tau)\gamma_Q^2(N_Q, T)V d_{\Psi} \int_p f_{\Psi}^{eq}(p, T) \]

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

No pT information about regeneration is considered.

FIG. 1. The Bethe-Salpeter equation for quarkonium.
Full transport: take detailed balance microscopically (easy for gluon-diss)

- **QGP evolution**
  \[ \partial_\mu T^{\mu\nu} = 0, \partial_\mu n^\mu = 0 + \text{EOS} \]

- **Onium motion**
  \[ \cosh(y - \eta) \partial_\tau f + \mathbf{v}_T \cdot \nabla_T f + \frac{1}{T} \sinh(y - \eta) \partial_\eta f = - \frac{E}{E_T} \alpha \cdot f + \frac{E}{E_T} \beta \]

\[ \alpha = \frac{1}{2E} \int \frac{d^3k}{(2\pi)^3 2E_g} \sigma_{g\Psi}(s) \cdot 4F_g \Psi f_g(k, x) \quad \sigma_{\text{reg}}(s) = \frac{4}{3} \frac{(s - m_\Psi^2)^2}{s(s - 4m_O^2)} \sigma_{g\Psi}(s) \]

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

- **Analytic solution**
  \[ f(\vec{p}_t, y, \vec{r}_t, \eta, \tau) \]
  \[ = f(\vec{p}_t, y, \vec{r}_t(\tau_0), Y(\tau_0), \tau_0) e^{-\int_{\tau_0}^{\tau} d\tau' A(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau')} \]
  \[ + \int_{\tau_0}^{\tau} d\tau' B(\vec{p}_t, y, \vec{r}_t(\tau'), Y(\tau'), \tau') e^{-\int_{\tau'}^{\tau} d\tau'' A(\vec{p}_t, y, \vec{r}_t(\tau''), Y(\tau''), \tau'')} \]

- **Initial condition**: Glauber superposition with CNM effects

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**:

  - **Absorption**
    - A. Capella, et al

  - **Cronin**
    - Gassian smearing treatment
    - J.W. Cronin, et al

  - **Shadowing**

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

  - **nPDF vs. free PDF**

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

- Langevin+potential approach + recombination

\[ \frac{dp}{dt} = -\eta p + \xi - \nabla U \]

\[ \frac{dr}{dt} = \frac{p}{m_c} \]

- Schroedinger-Langevin approach (no regeneration) see Talk at 30Jun, 12:00

J.P. Blaizot's generalized Langevin equation

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

- Quantum path-integral approach, Lindblad equation, ...

friction (and hence noise) depends explicitly on HQs configuration

References:
- C. Young, E. Shuryak, 09
- R. Katz, PB. Gossizux, 15
- 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

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


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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 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
  \[ \Rightarrow \text{initial pt broadening} \]

 ➤ Regeneration:
- Coalescence mechanism
- HQ energy loss induced thermalization
  \[ \Rightarrow \text{low pt regeneration} \]

The decreasing trend for rAA -----. much more hotter medium effects are working at LHC
Transport Analysis—Excitation of $high(\text{relatively}) \ p_T$

As the collision becomes more violent,
regeneration can hardly contribute to high-pT part.

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

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

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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 \}

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

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

What's its effect on Charmonium: Charmonium Enhancement?

$\frac{n_{J/\psi}}{n_c(v)} \sim n_c(v)$
Thermal Charm Production

Rate equation for charm quark density:
\[
\frac{1}{\cosh \eta} \partial_\tau n_c + \nabla_T \cdot (n_c v_T) + \frac{1}{\tau \cosh \eta} n_c = R_{gain} - R_{loss}
\]

- **loss and gain 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**
  P.Nason, S.Dawson, and R.Ellis, 88, 89.
  M.L.Mangano, P.Nason and G.Ridolfi, 92

- **detailed balance**

- **Shadowing through initial condition**

\[
n_c(\tau_0, x_T, b) = \frac{d\sigma_{c\bar{c}}/d\eta}{\tau_0} T_A(x_T) T_B(x_T - b) R^A_g(x_1, x_T) R^B_g(x_2, x_T - b)
\]

- **Hydrodynamic for QGP evolution**


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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
Summary

- Transport approach provides more clear physical picture.

- Natural outcome from picture in classical transport approach:

  "quarkonia cat" cold? hot?

  What's sensitive probe: flow and $p_T$-
  from $p_T$ broadening
  To $p_T$ suppression

- 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**

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

for open & hidden heavy mesons

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

**Color Evaporation Model**

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

\[ f_0(\vec{p}, x_T) = \frac{(2\pi)^3}{E_T^\Psi \cosh y_\Psi} \frac{d\sigma_{pp}^\Psi}{dy} \int d\zeta_A d\zeta_B \rho_A(\vec{x}_T, z_A) \cdot \rho_B(\vec{x}_T - \vec{b}, z_b) R_g(\vec{x}_T, x_1, \mu_f) \cdot R_g(\vec{x}_T - \vec{b}, x_2, \mu_f) f_{pp}(\vec{p}_T, \vec{x}_T, z_A, z_B) \]

Results—Elliptic flow $v_2$

- remarkable $v_2$ from the regeneration $\iff$ 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

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

PRC89,054911(2014)
Results—$p_T$ dependence: $RAA(p_T)$

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

- **Regeneration:**
  - Coalescence mechanism
  - Energy loss induced thermalization
    $\Rightarrow$ *low $p_T$ regeneration*

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

SPS: Cronin effect for initial production

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

RHIC: competition betw. initial Vs. regeneration

LHC: dominant regeneration

PRC89,054911(2014)
Results—Bottomonium differs $V=U$ or $V=F$
Full transport: take detailed balance microscopically (easy for gluon-diss)

\[ \sigma_g \Psi(s) \]

\[ \Psi \rightarrow g \rightarrow \bar{c} \rightarrow c \]

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

Spectral Function

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

\[ \sigma_g \Psi(T) = \sigma_g \Psi(0) \cdot \frac{\langle r_{\Psi}^2(T) \rangle}{\langle r_{\Psi}^2(0) \rangle} \]

The divergence of size defines the melting Td

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Transport Model- solution of transport equation

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

\[
f(\vec{p}_t, y, \vec{v}_t, \eta, \tau) = f(\vec{p}_t, y, \vec{v}_t(\tau_0), Y(\tau_0), \tau_0) e^{-\int_{\tau_0}^{\tau} d\tau' A(\vec{p}_t, y, \vec{v}_t(\tau'), Y(\tau'), \tau')} + \int_{\tau_0}^{\tau} d\tau' B(\vec{p}_t, y, \vec{v}_t(\tau'), Y(\tau'), \tau') e^{-\int_{\tau'}^{\tau} d\tau'' A(\vec{p}_t, y, \vec{v}_t(\tau''), Y(\tau''), \tau'')}
\]

\[
\vec{v}_t = \frac{p_t}{E_t}
\]

\[
\vec{v}_t(\tau') = \vec{v}_t - \vec{v}_t \left[ \tau \cosh(y - \eta) - \tau' \cosh(\Delta(y - \eta)) \right]
\]

\[
Y(\tau') = y - \Delta(y - \eta)
\]

\[
A(\vec{p}_t, y, \vec{v}_t(\tau'), Y(\tau'), \tau') = \frac{\alpha(\vec{p}_t, y, \vec{v}_t(\tau'), Y(\tau'), \tau')}{\cosh(\Delta(y - \eta))}
\]

\[
B(\vec{p}_t, y, \vec{v}_t(\tau'), Y(\tau'), \tau') = \frac{\beta(\vec{p}_t, y, \vec{v}_t(\tau'), Y(\tau'), \tau')}{\cosh(\Delta(y - \eta))}
\]

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

Both Initial production and Regeneration suffers Suppression