What is New in Quarkonium Production at RHIC and LHC?

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- Introduction
- A Full Transport Approach
- $P_t$ Distribution and $V_2$ Distribution
- $\Upsilon$ Production and Heavy Quark Potential
- Summary

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Introduction
SQM2011 experimental summary by K. Safarik: overall suppression of $J/\psi$ is nearly identical between SPS, RHIC & LHC!
However, the transverse momentum distribution is sensitive to the quarkonium production mechanism!
A Full Transport Approach
Cold nuclear matter effects:
1) nuclear absorption
2) Cronin effect
3) shadowing effect

Hot nuclear matter effects:
1) suppression in QGP and HG
2) regeneration in QGP and HG

Regeneration:
PBM, Stachel, Andronic et al; Thews, Mangano et al; Rapp, Zhao et al;

Quarkonium Production Picture

- initial production controls high pt region
- regeneration becomes important at low pt

screening only, screening + regeneration
A Full Transport Approach for Quarkonia in HIC
Yan, Zhu, Xu, Zhuang, 2005-2011

- **QGP hydrodynamics**
  \[
  \partial_t E + \nabla \cdot M = -(E + p)/\tau, \\
  \partial_t M_x + \nabla \cdot (M_x v) = -M_x/\tau - \partial_x p, \\
  \partial_t M_y + \nabla \cdot (M_y v) = -M_y/\tau - \partial_y p, \\
  \partial_t R + \nabla \cdot (R v) = -R/\tau.
  \]

+ equation of state (ideal gas or strongly coupled matter from lattice)

- **Quarkonium transport equations**
  \[
  (\Psi = J/\psi, \psi', \chi_c)
  \]

  \[
  \frac{\partial f_{\Psi}}{\partial \tau} + v_{\Psi} \cdot \nabla f_{\Psi} = -\alpha_{\Psi} f_{\Psi} + \beta_{\Psi}.
  \]

  \[
  \alpha_{\Psi}(p_t, x_t, \tau|b) = \frac{1}{2E_{\Psi}} \int \frac{d^3p_g}{(2\pi)^3 2\bar{E}_g} W_{g\bar{c}}(s) f_g(p_g, x_t, \tau) \Theta(T(x_t, \tau|b) - T_c),
  \]

  \[
  \beta_{\Psi}(p_t, x_t, \tau|b) = \frac{1}{2E_{\Psi}} \int \frac{d^3p_g}{(2\pi)^3 2\bar{E}_g} \frac{d^3p_c}{(2\pi)^3 2\bar{E}_c} \frac{d^3p_{\bar{c}}}{(2\pi)^3 2\bar{E}_{\bar{c}}} W_{c\bar{c}}(s) f_c(p_c, x_t, \tau|b) f_{\bar{c}}(p_{\bar{c}}, x_t, \tau|b)
  \times (2\pi)^4 \delta^{(4)}(p - p_g - p_c - p_{\bar{c}}) \Theta(T(x_t, \tau|b) - T_c),
  \]

- **Analytic solution**
  \[
  f_{\Psi}(p_t, x_t, \tau|b) = f_{\Psi}(p_t, x_t - v_{\Psi}(\tau - \tau_0), \tau_0|b) e^{-\int_{\tau_0}^{\tau} d\tau' \alpha_{\Psi}(p_t, x_t - v_{\Psi}(\tau - \tau'), \tau'|b)}
  + \int_{\tau_0}^{\tau} d\tau' \beta_{\Psi}(p_t, x_t - v_{\Psi}(\tau - \tau'), \tau'|b) e^{-\int_{\tau}^{\tau'} d\tau'' \alpha_{\Psi}(p_t, x_t - v_{\Psi}(\tau - \tau''), \tau''|b)}.
  \]

- **Initial production** \( f(\bar{p}, \bar{x}, t_0) \) including CNM, correlation between the cold and hot nuclear matter effect.
**Dissociation Cross Section**

\[ J/\psi \ (ϒ) + g \rightarrow Q + \bar{Q} \]

- gluon dissociation cross section described by OPE (Bhanot, Peskin, 1999):
  \[ \sigma(p_\psi, p_g) \]

- at finite temperature, we use the classical relation
  \[ \sigma(p_\psi, p_g, T) \frac{\langle r^2 \rangle(T)}{\langle r^2 \rangle(0)} \sigma(p_\psi, p_g) \]

  is calculated through the Schroedinger equation

- dissociation rate of \( ϒ \) at a fixed medium velocity \( v=0.5 \) and for \( V=U \):

1) \( T \)-dependence of the differential cross section is still an open problem;

2) we did not consider quasi-free processes which may play an important role at high \( T<T_d \).

- regeneration rate is determined by the detailed balance
**Dissociation Length** $\langle r^2 \rangle(T)$ **in Potential Model**

**Lattice calculated free energy** $F$ **for a pair of** $Q\bar{Q}$

**two limits of the potential:**

$$V(r,T) = \begin{cases} F, & \text{slow dissociation} \\ U = F + TS, & \text{rapid dissociation} \end{cases}$$

**Schrödinger equation at finite** $T$:

average distance $\langle r \rangle(T)$

binding energy $\epsilon(T)$

**dissociation temperature**:

$\langle r \rangle(T_D) \rightarrow \infty, \quad \epsilon(T_D) \rightarrow 0$

**for** $V=U$ (**Satz et al**)
$P_t$ Distribution and $V_2$ Distribution
the competition between initial production and regeneration leads to a minimum, a signature for the coexistence of both production mechanisms.

\[ \tau_0 = 0.6 \text{ fm}, \quad T_0 = 344 \text{ MeV}, \]

\[ \sigma_{pp}^{J/\psi} = 0.74 \mu b, \quad \sigma_{pp}^{cc} = 0.12 nb \] (PHENIX pp data) at mid rapidity
J/$\psi$ Rapidity Dependence at RHIC

Less regeneration in forward rapidity explains the two puzzles naturally.

$\sigma_{pp}^{J/\psi} = 0.42 \mu b, \quad \sigma_{pp}^{c\bar{c}} = 0.04 nb$ at forward rapidity
$J/\psi R_{AA}(N_p)$ at high pt at RHIC

STAR data, QM2011

high pt particles can survive in hot medium.
centrality dependence of $J/\psi R_{AA}(p_t)$ at RHIC

STAR data, QM2011

more suppression in central collisions
$J/\psi R_{AA}(N_p)$ at LHC

more regeneration at LHC $\rightarrow R_{AA}^{\text{ALICE}} > R_{AA}^{\text{PHENIX}}$

$\tau_0 = 0.6 \text{ fm}, \quad T_0 = 430 \text{ MeV}$ (Hirano, Heinz),

$\sigma_{pp}^{J/\psi} = 2.33 \mu b$ (arXiv:1107.0137), $\quad \sigma_{pp}^{c\bar{c}} = 3.45 nb$ (total, QM2011 talk by Dainese)
**$J/\psi R_{AA}$ ($N_p$) at high pt at LHC**

$LHC$ Pb-Pb 2.76TeV

$6.5 < p_T < 30$ GeV/c

$0 < |y| < 2.4$

$T_0 = 484$ MeV

CMS QM2011

**more regeneration at low pt** $\rightarrow R_{AA}^{ALICE} > R_{AA}^{CMS}$

$t_0 = 0.6$ fm, $T_0 = 484$ MeV (Hirano, Heinz),

$d\sigma_{pp}^{J/\psi} / dy = 3.5$ $\mu$b (arXiv:1107.0137)
Averaged Transverse Momentum

SPS: Cronin effect

RHIC: competition between the two sources

LHC: dominant regeneration

Data from NA50 2000
Data from PHENIX 2007
SPS Pb-Pb 17.3GeV
RHIC Au-Au 200GeV
LHC Pb-Pb 2.76TeV

Averaged Transverse Momentum

\[ \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}} \]
**J/psi elliptic flow at RHIC**

STAR data, QM2011

our prediction: Yan, Xu, Zhuang: nucl-th/0608010,PRL2006

impact parameter $b=7.8$ fm

no J/psi V2 at RHIC, but remarkable v2 at LHC!
**J/psi elliptic flow at LHC**

**our prediction at \( \sqrt{s} = 5.5 \text{ TeV}, b=7.8 \text{ fm} \) (NPA2010) :**

**remarkable v2 at LHC !**
Production and Heavy Quark Potential
**J/ψ:**
the production and suppression mechanisms are complicated: there are primordial production and nuclear absorption in the initial state and regeneration and anomalous suppression during the evolution of the hot medium.

**Y:**
1) the regeneration can be safely neglected;
2) there is almost no feed-down for Y;
3) weaker CNM effect
from the comparison with data, \( V \) is close to \( U \).
Yat LHC: $R_{AA}(N_p)$

\[ R_{AA}^Y(1S) \]

\[ V=U \]

\[ V=F \]

Scheme (B)

CMS $\sqrt{s_{NN}}=2.76$ TeV

\[ \sigma_{pp}^Y = 14 \mu b, \quad \sigma_{pp}^{\bar{b}b} = 43 nb \]

*again, V is close to U.*
Conclusions:

- *pt dependence is more sensitive to the production and suppression mechanism.*
- *regeneration is important at RHIC and LHC.*
- *competition between initial production and regeneration can explain systematically the data from SPS to LHC.*
- *Upsilon production at RHIC and LHC supports V=U.*

Uncertainty analysis:

*pp collision, shadowing effect, EoS, time scales, ……*

Suggestions:


- *measure J/psi-D correlation at LHC* (since both are from the same source)

- *measure quarkonium v2 at LHC* (which is very sensitive to the production and suppression mechanisms).
## Quarkonium in Vacuum

<table>
<thead>
<tr>
<th>State</th>
<th>$\Upsilon$ (1S)</th>
<th>$\chi_c$ (1P)</th>
<th>$\psi'$ (2S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$ (GeV/c$^2$)</td>
<td>3.10</td>
<td>3.53</td>
<td>3.68</td>
</tr>
<tr>
<td>$r_0$ (fm)</td>
<td>0.50</td>
<td>0.72</td>
<td>0.90</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>State</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>$m$ (GeV/c$^2$)</td>
<td>9.46</td>
<td>10.02</td>
<td>9.99</td>
<td>10.26</td>
<td>10.36</td>
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<tr>
<td>$r_0$ (fm)</td>
<td>0.28</td>
<td>0.56</td>
<td>0.44</td>
<td>0.68</td>
<td>0.78</td>
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</tbody>
</table>

**Contribution to the observed ground state $\Upsilon$(1S)***

<table>
<thead>
<tr>
<th>$\Upsilon$(1S)</th>
<th>$\Upsilon$(1P)</th>
<th>$\Upsilon$(2S)</th>
<th>$\Upsilon$(2P)</th>
<th>$\Upsilon$(3S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51%</td>
<td>27%</td>
<td>11%</td>
<td>10%</td>
<td>1%</td>
</tr>
</tbody>
</table>

**Contribution to the observed ground state $J/\psi$***

<table>
<thead>
<tr>
<th>$J/\psi$</th>
<th>$\chi_c$</th>
<th>$\psi'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>30%</td>
<td>10%</td>
</tr>
</tbody>
</table>
**Dependence on EoS**

**J/Psi Pt distribution at LHC where EoS plays an essential role!**

![Graph showing the relationship between \( p_t \) (GeV) and \( R_{AA} \) for wQGP and sQGP.](image)
Only Cold Nuclear Matter Effect?
**D D Correlation**

**NN collisions:** back-to-back correlation

**RHIC:** almost no correlation

**LHC:** near-side correlation

![Diagram](image_url)

![Graphs](image_url)
**Yat RHIC:**  $R_{AA}(p_t)$


- strong Cronin effect for survived ground state
- no $p_t$ dependence for disappeared excited states

central Au+Au at $\sqrt{s} = 200$ GeV
\[ \Delta \left( p_t^2 \right)^{\gamma} = \left( p_t^2 \right)_{AA} - \left( p_t^2 \right)_{pp} = a_{gN} L \]

\[ \Delta \left( p_t^2 \right)^{\gamma} = \frac{a_{gN}^{RHIC}}{a_{gN}^{SPS}} R_{Au} \Delta \left( p_t^2 \right)_{J/\psi}^{SPS} = 2.4 \Delta \left( p_t^2 \right)_{J/\psi}^{SPS} \]

\[ \Delta \left( p_t^2 \right)^{\gamma} = \Delta \left( p_t^2 \right)^{J/\psi} \]


Au+Au at \( \sqrt{s}=200 \) GeV
Measuring RHIC Temperature by Excited $\Upsilon$ States

Initial temperature dependence of $R_{AA}$

*central Au+Au at $\sqrt{s}=200$ GeV*


Suppression of excited $\Upsilon$ states is sensitive to the fireball temperature!
Yat LHC: \( R_{AA}(p_T) \)

CMS Preliminary

\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

\[ \gamma(1S) \]

**high pt is controlled by initial production!**