J/psi and quarkonia as probes of deconfined matter

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J/psi Production with Detailed Rapidity Dependence at LHC (2014)

collaborate with: Yunpeng Liu, Kai Zhou, Pengfei Zhuang (advisor), Ulrich Heinz, Chun Shen
1. Introduction:
   **Deconfined matter** probed with **heavy quarkonia**

2. Nuclear matter effects on J/psi (charm flavor):
   - Cold nuclear matter effects
   - Hot nuclear matter effects

3. Excited charmonium state (2s) production mechanism

4. Prediction of Upsilon (bottom flavor) production

5. Summary
If we press nucleons into a tiny volume, to get extreme high density like in neutron star, what happens?

If we increase the temperature of nucleons, like in the early universe, what happens?

Lots of partons produced

Introduction

Press nucleon or nucleon heat

Quark-Gluon Plasma

Quarks and gluons are constrained in nucleons

Asymptotic freedom

How can we realize this new matter with extreme high temperature?

What can be a probe/signal of this deconfined matter existence?

What's the properties of this deconfined matter?

. . . .

Tsinghua University                Baoyi Chen         Ohio State University @ May 8, 2014
Introduction

Phase diagrams of matters produced in heavy ion collisions

**SPS**: ~ 10 GeV
Super Proton Synchrotron

**RHIC**: ~ 100 GeV
relativistic heavy ion collider

**LHC**: ~ 1000 GeV (1 TeV)
large hadron collider

Phase transition temperature:
\[ T_c \approx 170 \text{MeV} \approx 2.3 \times 10^{12} \text{K} \]
Introduction

Evidence of the deconfined matter

- Light hadron collective flow:
  - Collective flow of light hadrons are developed in parton level, not in hadron phase.

\[ \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]

\[ v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left( \frac{p_y}{p_x} \right) \]
Evidence of the deconfined matter

- Light hadron collective flow:
  - Collective flow of light hadrons are developed in parton level, not in hadron phase.

- Heavy quarkonium (J/psi, Upsilon) suppression:
  - For low T, potential between partons inside a hadron increase with distance constrained.
  - For T>Tc, confinement disappears.

Idea: Quarkonium may be dissolved when T is high enough (T>Tc)


Why heavy quarkonium important?

PRL 98, 162301

Jet quenching, ....
Heavy quark masses are mainly produced in initial hard scattering.

- **Charmonium** \((cc): J/\psi(1s), \chi_c(1p), \psi'(2s)\)
- **Bottonium** \((bb)\) \(\Upsilon(1s), \Upsilon(1p), \Upsilon(2s), \ldots\)

**Dissociation temperatures of charmonium** \(T_d\):

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

- **average radius** \(\langle r \rangle(T)\)
- **binding energy** \(\varepsilon(T)\)

**Why heavy quark important?**
- Heavy quark masses are mainly produced in initial hard scattering. 
  - *a clean probe of QGP*
- Produced via pQCD process. 
  - Rather solid
Introduction--quarkonium

In hot medium, J/psi binding energy keeps dropping to zero, at certain temperature.

J/psi radius keeps increasing to infinity, at a certain temperature.

Indicates a certain temperature, above which no J/psi can survive, "dissociation temperature Td"

J/psi suppression degree can be an evidence and also a "thermometer" of the produced parton matter

V=U (Satz, et al) :

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<th>ψ'(2S)</th>
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V=F(charmonia): Td(J/ψ)/Tc = 1.6
Td(1p,2s)/Tc = 1.0
Frame:
1. produce the deconfined matter (QGP), as a background
2. simulate J/psi evolution in QGP with Boltzmann-type transport equation.
3. Understand the charmonium (J/psi et.) production mechanisms & relations between J/psi suppression and QGP information
2+1 D ideal hydrodynamics:

\[
\begin{align*}
\partial_\mu T^{\mu\nu} &= 0 \\
\partial_\mu N^\mu &= 0
\end{align*}
\]

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

\[ N^\mu = nu^\mu \]

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


Heavy ion collisions:
- produce a deconfined matter.
- Find an evidence and study its properties

✓ Hydrodynamics already explain and predict light hadron pt-spectra and collective flow. (Heinz, et al)

✓ Transport model already explain and predict heavy quarkonium(J/psi,upsilon) data( Pengfei Zhuang, Ralf Rapp, et al)
Boltzmann-type transport equation used to describe $\psi$ evolution in the phase space

$$\partial_t f_\psi + v_\psi \cdot \nabla_x f_\psi = -\alpha_\psi f_\psi$$

With analytic solution,

$$f_\psi(p_t, y, x_t, \eta, \tau) = f_\psi(p_t, y, x_t, \eta, \tau_0) e^{-\int_0^\tau d\tau_1 \alpha_\psi(p_t, y, x_t, \eta, \tau_1)}$$

When N-N collides

**Initial Production**

- $c\bar{c}$ resonance state evolves to $\psi$ from one pair
- most charm pair remains and tend to be thermalized in the hot medium

**Support Rate**

$$\alpha_\psi(p_t, x_t, \tau, b) = \frac{1}{2E_T} \int \frac{d^3k}{(2\pi)^3} \frac{2E_g}{2E_g} \sigma_{g\psi}(p, k, T) A F_{g\psi}(p, k) f_g(k, T)$$

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

(Peskin, Nucl.Phys.B156,365(1979))
Basic idea:

J/psi are produced in NN collisions, and then go through QGP, and suffer suppression by Dybe-screening of gluons ---- its suppression is signal of QGP

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

1. However, Suppression already exist in pA collisions, where QGP is absent.

Nuclear absorption

\[ J/\psi \] formation time \( \sim 0.5 \text{ fm}/c \)

At LHC, nuclei already pass through each before \( J/\psi \) formed. \( \sigma_{abs} \sim 0 \)

2. gluons multi-scattering with nucleons to gain extra energy before they fuse into a cc pair.

Cronin effect

\[ \langle p_t^2 \rangle^{pA} = \langle p_t^2 \rangle^{pp} + a_{gN}L \]

\[ (a_{gN} \text{ in } \text{GeV}^2/\text{fm} \text{, empirically extracted from pA data}) \]
3. parton distribution function (PDF) in a nucleus is different from a simple superposition (Glauber model) of the PDF in a free nucleon.

shadowing correction factor:

\[ R_i^A(x, \mu_F) = \frac{f_i^A(x, \mu_F)}{A f_i^{\text{nucleon}}(x, \mu_F)} , \quad f_i = q, \overline{q}, g . \]

\( x \): momentum fraction,  
\( \sqrt{\mu_F} \): transverse momentum

We take the results of EKS98 package as a correction of the initial charmonium distribution.

Cold Nuclear Matter Effects

Hot medium effect:
1) Gluon, hadron dissociations

Cold nuclear matter effects

We give the initial \( \psi \) distribution of A+A collision

\[ f_{\psi}(x, p, \tau_0, b) \propto \int d\tau_A d\tau_B \rho_A(x_t, z_A) \rho_B(x_t - b, z_B) \cdot R_g^A R_g^B \cdot \left( \frac{d\sigma_{J/\psi}}{p_t dp_t d\gamma_{13}} \right)_{aN} \]
J/psi suppression at RHIC seems similar with SPS data?

J/psi is less suppressed in central y (hotter medium) than in forward y?

R_{AA} (|y|<0.35) \sim R_{AA} (SPS)

R_{AA} (|y|<0.35) > R_{AA} (1.2<|y|<2.2)
At higher colliding energies, more and more charm pairs are produced.
New J/psi may be produced by following recombinations:

**In QGP:**
\[ c + \bar{c} \rightarrow J/\psi + g \]

**In hadron phase:**
\[ D + \bar{D} \rightarrow J/\psi + \text{mesons} \]

<table>
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<th></th>
<th>SPS</th>
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<tbody>
<tr>
<td>charm</td>
<td>0.2</td>
<td>10</td>
<td>130</td>
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<tr>
<td>bottom</td>
<td>---</td>
<td>0.05</td>
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\[
N_{cc}^{J/\psi} \propto \int \rho_c \rho_{cc} W_{cc}^{J/\psi} \cdot d^4x d^4p dt \\
N_{cc}^{J/\psi} \propto N_{cc}^2
\]

**Coalescence model:**
\[ T_{d(J/\psi)} \approx T_c \]
All J/psi are produced in phase transition \((T = T_d = T_c)\)

**Continuous regeneration:**
\[ T_{d(J/\psi)} \geq T_c \]
some J/psi are produced when \((T < T_d)\) by charm-pair recombination
some are from initial production (primary production)
Considering the charm pair regeneration contribution

\[ \partial_t f_\psi + \mathbf{v}_\psi \cdot \nabla_x f_\psi = -\alpha_\psi f_\psi + \beta_\psi \]

\[
\beta_\psi(p_t, x_t, T, b) = \frac{1}{4(2\pi)^9 E_T} \int \frac{d^3 k d^3 p_c d^3 p^-}{E_c E_c E^-} W_{gg}^{cc}(s) \cdot f_c(p_c, x, T) \cdot f_c^{-1} \\
\times (2\pi)^4 \delta(p + p_g - p_c - p^-)
\]

Setup: Inspired by D meson collective flows, we take charm distribution as thermalization.
Considering the charm pair regeneration contribution

\[
\partial_t f_\psi + v_\psi \cdot \nabla_x f_\psi = -\alpha_\psi f_\psi + \beta_\psi
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\[
\beta_\psi(p_t, x_t, T, b) = \frac{1}{4(2\pi)^9 E_T} \int \frac{d^3k d^3p_c d^3p_{\bar{c}}}{E_{g} E_c E_{\bar{c}}} W_{cc}^{g\psi} (\tau) \times (2\pi)^4 \delta(p + p_c)
\]

With charm pair recombination, both calculations from our model and ralf rapp can explain RHIC data:

\[
N_{J/\psi} = N_{J/\psi}^{dic} + N_{J/\psi}^{th}
\]

R. Rapp et al  Y. Liu et
Higher T (~450 MeV) in \( y = 0 \) than T (~ 410 MeV) in \( y = 3 \)

- Strong decreasing RAA with rapidity is caused by disappearance of J/\( \psi \) regeneration in forward \( y \) (or \( \eta \)).

Strong evidence of J/\( \psi \) regeneration:

\[
\sigma_{cc}^{\text{tot}} = 4.8 \pm 4.66 \text{ mb}
\]

(3+1 D hydro is from Hirano.)

Charm pair production in pp collisions

\[
\sigma_{pp}^{cc} / d\eta (\eta)
\]
Strong evidence of J/psi regeneration:

- More $N_{c\bar{c}}$, (coordinate space distri.), more regenerated J/psi.
- Charm quarks tend to be thermalized (momentum space), regenerated J/psi dominates total yield at low $p_t$ region.
Strong evidence of J/ψ regeneration:

- Charm quarks tend to be thermalized (momentum space), regenerated J/ψ dominates total yield at low $p_T$ region.

More, (coordinate space distribution), more regenerated J/ψ.

RAA

$\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb
Inclusive J/ψ $2.5<\gamma<4$

Far below 1

$<p_T^2>_{AA}/<p_T^2>_{pp}$

More regenerated J/ψ. (momentum space), regenerated J/ψ.
Elastic Collisions on J/psi

- J/psi can be dissociated by Deybe-screening of partons in QGP (inelastic collision);
- elastic collision effect is believed to be neglectable, but to what degree?

Ingredients: elastic collisions changes J/psi mass in the medium. Mean field method to consider this effect in (PRD 79, 011501)

\[
\partial_\tau f_\psi + \nabla_x \cdot \nabla_p f_\psi = -\alpha_\psi f_\psi + \beta_\psi
\]

QCD sum rules

Second-order stark effect

Point to center of fireball

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● reduced threshold of J/psi makes regeneration more easily;
● mean field force $F$ induced by inhomogeneous property of the medium pulls J/psi to the center of the fireball
- **Reduced threshold of J/psi** makes regeneration more easily;
- Mean field force $F$ induced by inhomogeneous property of the medium pulls J/psi to the center of the fireball.

---

**Regenerated J/psi more sensitive to this effect**, initial J/psi already produced before this effect appears. (based on the assumption that primary charmonium are formed before medium expansion)

**Total J/psi yield** (init + rege) changes less than 10%, with elastic collision effect.

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Elastic Collisions on J/psi
Excited charmonium state

So many experimental data and theoretical calculations about charmonium bound state (J/psi); few data about its excited state (1p, 2s, ...)

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\[ V = U \] (upper lim.)

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New puzzles about \( \psi(2s) \):
1. RAA(\( \psi(2s) \)) seems more larger than RAA(J/ψ)
2. With Np increasing, Temperature of the fireball increases, \( \psi(2s) \) easier to survive ? ? (even it's a loosely bound state ?)

Double Ratio = \[ \frac{R_{\text{inclu}}(\psi(2S))}{R_{\text{inclu}}(J/\psi)} \]

a) > 1 ?
b) Increase with Np (or T) ?

arXiv:1209.1084

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Excited charmonium state

**Prompt**: from Charm flavor. (initially produced + regenerated later)

**Non-prompt**: from bottom flavor. (from B decay)

For inclusive yield in certain pt-bin, we add B-decay contribution by

\[
R^{\text{incl}}_{AA}(\Psi) = \frac{N^{\text{prompt}}_{AA}(\Psi) + N^{B \rightarrow \Psi}_{pp^{*}\text{coll}} \times Q}{N^{\text{prompt}}_{pp^{*}\text{coll}}(\Psi) + N^{B \rightarrow \Psi}_{pp^{*}\text{coll}}} 
\]

---

**Fitting non-prompt fraction in pp collisions**

- CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV ($|y|<2.4$)
- CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV ($1.6<|y|<2.4$)
- CMS pp $\sqrt{s} = 2.76$ TeV ($|y|<2.4$)
- CMS pp $\sqrt{s} = 2.76$ TeV ($1.6<|y|<2.4$)
- CMS pp $\sqrt{s} = 7$ TeV ($1.2<|y|<2.4$)
- CMS pp $\sqrt{s} = 7$ TeV ($|y|<1.2$)
- CMS pp $\sqrt{s} = 1.96$ TeV ($|y|<0.8$)

Data: 1.96 TeV pp

$\Psi(2S)$

$\pm 15\%$

$J/\psi$

$\pm 15\%$

$\Psi(p_T)$ = non-prompt/inclusive

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b-quark quenched factor $Q$

Hot-medium effect:

- **low Pt** (taken as $\sim 1.4$)
- **middle Pt** (taken as $\sim 1.0$)
- **high Pt** (experimental data, $\sim 0.35$)

Limit: $0.28 \sim 0.45$
Excited charmonium state

For this high pt-bin, no regenerated J/psi (from thermal charm quark) contribution.

With V=U
(satz. et al)

\[ \frac{T_d^{J/\psi}}{T_c} \approx 2.1 \]

\[ \frac{T_d^{\Psi^*}}{T_c} \approx 1.1 \]

• For inclusive J/psi, ~10% from B decay
• For inclusive Psi(2s), ~90% from B decay

With B-decay contribution, double ratio increase with centrality.

\[ DR = \frac{R_{AA}^{J/\psi}(N_p) + R_{AA}^{B \rightarrow \psi}}{R_{AA}^{\Psi^*}(N_p) + R_{AA}^{B \rightarrow J/\psi}} \]

Const.

decrease

For inclusive J/psi, 10% from B decay
For inclusive Psi(2s), 90% from B decay
Excited charmonium state

**middle Pt**

Inclusive Prompt

B decay contribution explain experimental data well at **high, middle, low Pt region**.
Excited charmonium state

middle Pt

2.76 TeV Pb+Pb
3<p_t<8 GeV/c
2.5<v<4

Q: 0.5~1.5
Q=1 (black line)

96% CL

ALICE Data

low Pt

LHC 2.76 TeV Pb+Pb
P_T: 0-3 GeV/c
Rapidity: 2.5-4

ALICE

Inclusive

Prompt

B decay contribution explain experimental data well at high, middle, low Pt region.
Totally fails. Only this experimental data is far above 1.

Large enhancement of $\psi'$ can't be explained by B decay contribution.
Different from
\[ R_{AA} = \frac{N_{\psi}^{AA}}{N_{\psi}^{pp*coll}} \]
\[ r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}} \]
more sensitive to the final charmonium production mechanisms.

Source of final charmonia

- initial production at the colliding time
- Recombination from thermalized charm
- Contribution from B decay

large \[ \langle p_t^2 \rangle \]
small \[ \langle p_t^2 \rangle \]
competition cause decreasing with \( N_p \)
Upsilon suppression in QGP

- Setup: inspired by the lattice simulation on J/psi spectral function at finite temperature, the shape of the spectral function changes only a little for $T < T_d(J/\text{psi})$, but suddenly collapses around the $T_d$.

So, we use

$$\sigma_{gY}(T, p_g, p_Y) = \sigma_{gY}(0, p_g, p_Y) / \Theta(T_d - T)$$

- Vacuum value $(T<T_d)$
- Infinity $(T>T_d)$

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V=U: 4.0  1.8  1.6
V=F: 3.0  1.1  1.0
Upsilon suppression in QGP

\[
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\text{state} & J/\psi(1S) & \chi_c(1P) & \psi'(2S) & \Upsilon(1S) & \chi_b(1P) & \Upsilon(2S) & \chi_b(2P) & \Upsilon(3S) \\
T_d/T_c & 2.10 & 1.16 & 1.12 & > 4.0 & 1.76 & 1.60 & 1.19 & 1.17 \\
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\]

\[\begin{align*}
V=U: & \quad 4.0 \quad 1.8 \quad 1.6 \\
V=F: & \quad 3.0 \quad 1.1 \quad 1.0 \\
\end{align*}\]

\[0.1 \times Y(1s) \quad T=200\,\text{MeV} \quad 0.1 \times Y(2s) \quad T=250\,\text{MeV} \]

\[0.1 \times Y(1p) \quad T=250\,\text{MeV} \quad Y(1s) \quad Y(2s) \quad Y(1p) \]

\[\alpha \, (\text{fm}^{-1}) \quad p_t \, (\text{GeV}/c) \quad p_t \, (\text{GeV}/c) \]

\[\text{Y}(1s): \text{width} \sim 0.02 \, \text{fm}^{-1} = 4 \, \text{MeV} \quad \text{J/psi: width} \sim 60 \, \text{MeV} \]

- **1S state not sensitive to medium, (1p,2s) states suffer medium dissociation**


51%, 37%, 12% of \((1s, 1p+2p, 2s+3s)\) contributes to the final upsilon(1s) yield.
Upsilon suppression in QGP

\( \Upsilon \) at RHIC: \( R_{AA}(N_p) \)

\( \Upsilon \) at LHC: \( R_{AA}(N_p) \)

Y.Liu, B.Chen, N.Xu, PZ,PLB2011

For minimum bias events:

PHENIX data: \( R_{AA} < 0.64 \) (NPA2009)

Our result: \( R_{AA} = 0.63 \) for \( V=U \)

\( R_{AA} = 0.53 \) for \( V=F \)

Both RHIC and LHC upsilon data, support \( V=U \)

(just like J/psi)
With Boltzmann-type transport model, we consider charmonium ground state (J/psi), excited state (psi(2s)) production and yield suppression by both cold and hot nuclear matter effects.

- **Regeneration** from charm pair recombination becomes more important for J/psi in higher colliding energies (LHC). Its contribution is mainly at low pt region.

- **Excited state psi(2s)** inclusive yield in nucleus-nucleus collisions is dominated by B hadron decay, which is different from J/psi.

- Elastic collision effect can be neglected for bound state charmonium (J/psi).

- Both charmonium and upsilon calculations with our model indicates that heavy quarkonium potential inside quarkonium is close to its internal energy \( V=U \).

In order to understand heavy quarkonium suppression in hot medium, both quarkonium properties (dissociation temperature, heavy quark production cross section, etc) and more realistic QGP evolution are needed.
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Thank you very much!
(3+1) dimensional hydro from hirano (ref. )

Plus Boltzmann-type Transport Model for heavy flavor

1. Only cold nuclear matter effect. Shows weak rapidity dependence.

2. Hot + Cold nuclear matter effect. Also weak rapidity dependence. (consistent with boost-invariance in central rapidity)
- Regeneration absence in forward rapidity can’t cause the decreasing tendency of the data.
- Non-thermal charm distribution improvement still can’t explain the data.
Introduction

**Time scale of heavy ion collisions:**

1. *local thermalization time of QGP:*
   - SPS ~ 1.0 fm/c
   - RHIC ~ 0.6 fm/c
   - LHC ~ 0.6 fm/c (or smaller)

2. *Charm-pair formation time:*
   \[ t_{cc} \approx \frac{1}{2m_c} \approx 0.08 \text{fm/c} \]
   \[ (m_c = 1.3 \text{GeV}) \]

3. *J/psi formation time:*
   \[ t_{cc} \approx 0.35 \text{fm/c} \]

Formed J/psi may collide with other nucleons, and be dissociated at SPS. This effect can be neglected at RHIC and LHC (higher energies).
1. Local thermalization time of QGP:
   - SPS: \( \sim 1.0 \text{ fm/c} \)
   - RHIC: \( \sim 0.6 \text{ fm/c} \)
   - LHC: \( \sim 0.6 \text{ fm/c} \) (or smaller)

2. Charm-pair formation time:
   \[ 0.08 \text{ fm/c} \]

3. J/psi formation time:
   \[ 0.35 \text{ fm/c} \]

Su Hong Li, et al, PRD 82, 054008)
Upsilon suppression in QGP

$\Upsilon$ at RHIC: $R_{AA}(N_p)$

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$R_{AA} = 0.53$ for $V=F$

51%, 37%, 12% of (1s, 1p, 2s) contributes to the final upsilon(1s) yield.

$\sigma_{pp}^\Upsilon = 14 \mu b, \quad \sigma_{pp}^{bb} = 43 nb$