Charmonium production in Pb-Pb collisions at 5.02 TeV with CMS

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**Quantum Chromo-Dynamics**

QCD is the theory of strong nuclear force, which describes the interactions between quarks and gluons.

**Hadrons**

- **Baryon**
  - Lifetime: $>10^{34}$ years (proton)
  - 15 minutes (neutron)
  - $<10^{-8}$ seconds (others)

- **Meson**
  - Lifetime: $<10^{-8}$ seconds

**Confinement**

**Coupling Strength vs Energy**

- **Nonperturbative QCD** (Quark confinement)
- **Transition scale $Q_0$**
- **Perturbative QCD** (Quark asymptotic freedom)

**Quark-Gluon Plasma**

**Asymptotic Freedom**
Quark-Gluon Plasma

State of matter where quarks and gluons are deconfined

Formed at high temperature and low density

At LHC the QGP is formed in HI collisions

Big Bang

Quark-Gluon Plasma

Nuclear Matter

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Pheniics Fest 2017

05/30/17
Quark-Gluon Plasma

Nuclear collisions and the QGP expansion

- collision evolution
- expansion and cooling
- particle detectors
- kinetic freeze-out
- distributions and correlations of produced particles

lumpy initial energy density

QGP phase quark and gluon degrees of freedom

collision overlap zone

quantum fluctuations

Charmonia

Probe of QGP formation

$\tau \sim 0 \text{ fm}/c$

$\tau_0 \sim 1 \text{ fm}/c$

$\tau \sim 10 \text{ fm}/c$

$\tau \sim 10^{15} \text{ fm}/c$
Charmonium in Heavy-Ion collisions

- **SPS**
  - NA38
  - NA50
  - NA60
  - 1986

- **RHIC**
  - PHENIX
  - STAR
  - 2000

- **LHC**
  - ALICE
  - ATLAS
  - CMS
  - LHCb
  - 2009

- **LHC**
  - 2017

Graph shows the evolution of charmonium production in heavy-ion collisions over time at different energy scales. The vertical axis represents the square root of the center-of-mass energy between nucleons ($\sqrt{s_{NN}}$) in TeV. The horizontal axis represents the year of the experiments.
Charmonium Suppression

Suppression: Production suppressed via color screening in the QGP

Proposed by T. Matsui and H. Satz in 1986

Quarks confined

$T < T_{\text{diss}}$

$\Lambda_D (\text{fm})$

$T_{\text{diss}}$

$T$

$\Lambda_D$

$Q$

$\bar{Q}$

$r$

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Charmonium Suppression

Suppression: Production suppressed via color screening in the QGP

Proposed by T. Matsui and H. Satz in 1986

\[ T > T_{\text{diss}} \]

\[ \Lambda_D \text{ (fm)} \]

\[ T_{\text{diss}} \]

Quarks free

\[ r \]

\[ \Lambda_D \]
Charmonium Suppression

Suppression: Production suppressed via color screening in the QGP

Sequential Melting: Differences in binding energies lead to sequential melting with temperature

\[ \psi^{(2S)} \quad J/\psi \]

\[ T < T_c \]

PHENIX, Phys.Rev C91, 024913
Charmonium Suppression

→ Suppression: Production suppressed via color screening in the QGP

→ Sequential Melting: Differences in binding energies lead to sequential melting with temperature

\[ \psi(2S) \quad \text{and} \quad J/\psi \]

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Charmonium Suppression

Suppression: Production suppressed via color screening in the QGP

Sequential Melting: Differences in binding energies lead to sequential melting with temperature

$\psi(2S)$, $J/\psi$

$T > T_c$

PHENIX, Phys.Rev C91, 024913
Charmonium Regeneration

→ **Recombination:** Number of $c\bar{c}$ pairs increase with collision energy

<table>
<thead>
<tr>
<th>Central AA collisions</th>
<th>$N_{c\bar{c}}$ event</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS, 20 GeV</td>
<td>~0.2</td>
</tr>
<tr>
<td>RHIC, 200GeV</td>
<td>~10</td>
</tr>
<tr>
<td>LHC, 2.76TeV</td>
<td>~85</td>
</tr>
<tr>
<td>LHC, 5.02 TeV</td>
<td>~115</td>
</tr>
</tbody>
</table>

→ **Regeneration:** Charmonium production enhanced via recombination at hadronization phase

![Graph showing J/ψ Production Probability vs. Energy Density](image)
Charmonium in p-p and Pb-Pb

Reference:
No QGP expected

Hot Matter Effects:
Suppression vs Regeneration
Large Hadron Collider

CMS Detector

LHC Collider
### LHC Runs: Recorded by CMS

#### Run 1 (2011-2013)

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-p, √s&lt;sub&gt;NN&lt;/sub&gt; = 2.76 TeV</td>
<td>L = 5 pb&lt;sup&gt;-1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Pb-Pb, √s&lt;sub&gt;NN&lt;/sub&gt; = 2.76 TeV</td>
<td>L = 150 μb&lt;sup&gt;-1&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

#### Run 2 (2015)

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-p, √s&lt;sub&gt;NN&lt;/sub&gt; = 5.02 TeV</td>
<td>L = 28 pb&lt;sup&gt;-1&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Pb-Pb, √s&lt;sub&gt;NN&lt;/sub&gt; = 5.02 TeV</td>
<td>L = 460 μb&lt;sup&gt;-1&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

- ~2x increase in Energy
- ~3x increase in Pb-Pb Luminosity (~information stored)
**J/ψ Reconstruction**

- **Channel:** \( \text{J/ψ} \xrightarrow{\text{μ}^+, \text{μ}^-} \text{Inv Mass} \)

- **J/ψ production can be classified as:**
  - **Prompt:** Direct or by feed-down
    - Beam → Collision → Beam
  - **Non-Prompt:** From B-meson decays
    - Beam → Collision → Beam

**Decay Length:** Distance between Primary and secondary vertex

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[Image of CMS plots showing mass distributions and decay length distributions for J/ψ production in PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \).]
Main Observables

Nuclear Modification Factor $R_{AA}$

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA}\sigma_{pp}^{J/\psi} \rangle}$$

Medium effects quantified comparing the Pb-Pb charmonium yield with the p-p cross section, scaled by a geometrical factor (from Glauber model)

- No medium effects $\rightarrow R_{AA} = 1$
- Hot matter effects $\rightarrow R_{AA} \neq 1$

Centrality

Participants

Spectators

Can be estimated experimentally by measuring the number of charge tracks produced or the energy deposited in the transverse plane.

Experimental access to different medium densities and geometries
Stronger suppression seen in central events
Charmonia in Run 2


Sequential Melting:
Ratio of $R_{AA}$
$\Psi(2S)/J_{psi} < 1$

$\Psi(2S)$ more suppressed than $J/\Psi$ at 5.02 TeV

$\Psi(2S)$ slightly less suppressed compared to $J/\Psi$ at 2.76 TeV central events
Suppression of $J/\Psi$ mesons observed in Pb-Pb collisions at 2.76 TeV

Suppression of $\Psi(2S)$ with respect to $J/\Psi$ mesons observed in Pb-Pb collisions at 5.02 TeV

$J/\Psi \ R_{AA} \ @ \ 5.02 \ TeV$ results coming soon!