Quarkonia production in heavy–ion collisions in CMS

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Outline

- **Introduction**
  - Motivation, CMS Detector

- **Charmonia in PbPb collisions**
  - Prompt J/ψ: $R_{AA}$
  - Prompt J/ψ: azimuthal anisotropy

- **Bottomonia in PbPb & pPb collisions**
  - $\Upsilon$(1S), $\Upsilon$(2S) and $\Upsilon$(3S)

- **Summary**
Motivation

**Quarkonia**
- Bound states of heavy quark and antiquark
- Large mass requires a large momentum transfer only during the *early stage* of the collisions.
  ⇒ Powerful tool to probe QGP

**Debye screening**
- Loosely bound states (with smaller binding energies) melt at lower temperature.
- Sequential melting of the quarkonia
  ⇒ Thermometer of QGP

<table>
<thead>
<tr>
<th>Resonance</th>
<th>J/ψ</th>
<th>ψ'</th>
<th>γ(1S)</th>
<th>γ(2S)</th>
<th>γ(3S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [GeV]</td>
<td>3.10</td>
<td>3.68</td>
<td>9.46</td>
<td>10.02</td>
<td>10.36</td>
</tr>
<tr>
<td>ΔE [GeV]</td>
<td>0.64</td>
<td>0.05</td>
<td>1.10</td>
<td>0.54</td>
<td>0.20</td>
</tr>
<tr>
<td>Radius [fm]</td>
<td>0.25</td>
<td>0.45</td>
<td>0.14</td>
<td>0.28</td>
<td>0.39</td>
</tr>
</tbody>
</table>

T. Matsui & H. Satz, PLB 178 (1986) 416
Mocsy, EPJC 61 (2009) 705
CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING
SOLENOID
Niobium-titanium coil
carrying ~18000 A

Silicon Tracker
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~3.6M channels

Crystal Electromagnetic Calorimeter (ECAL)
~76k scintillating PbWO₄ crystals

Preshower
Silicon strips
~16m² ~137k channels

Hadron Calorimeter (HCAL)
Brass + plastic scintillator
~7k channels

Forward Calorimeter
Steel + quartz fibres
9k channels

Muon Chambers
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
Muon Reconstruction

- Excellent muon Identification and triggering in **the muon system**
- Outstanding momentum and vertex resolution of **the tracking system**
Dimuons in PbPb @ 2.76 TeV

CMS Preliminary

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

$p_T^\mu > 4$ GeV/c

$\int L_{\text{int}} (\text{PbPb}) = 147 \mu b^{-1}$

$\rho, \omega, \phi$

$\psi(2S)$

$\Upsilon(1,2,3S)$

$\text{Events/(GeV/c}^2\text{)}$

$m_{\mu\mu}$ (GeV/c$^2$)
Separation of prompt $J/\psi$ and non-prompt $J/\psi$

- 2-Dimensional simultaneous fit for $m_{\mu\mu}$ & $\ell_{J/\psi}$

Direct $J/\psi$

Prompt $J/\psi$

Feed-down from $\psi'$ and $\chi_c$

Inclusive $J/\psi$

Non-prompt $J/\psi$ from B-decays

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

- \( N_{J/\psi} = 2619 \pm 60 \)
- \( \alpha = 47 \pm 1 \) MeV/c²
- \( l_{J/\psi} = 150 \mu b^{-1} \)
- \( 6.5 < p_t < 8 \text{ GeV/c} \)
- Cent. 10-60%
- \( 0 < \beta < \beta_{\psi/\gamma} \)
- \( \psi/\gamma < \frac{\beta}{2} \)

Counts / (0.02 GeV/c²)

Counts / (0.03 mm)

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

- \( l_{J/\psi} < 2.4 \)
- \( 6.5 < p_t < 8 \text{ GeV/c} \)
- Cent. 10-60%
- \( 0 < \beta < \beta_{\psi/\gamma} \)
- \( \psi/\gamma < \frac{\beta}{2} \)

Lifetime of the b hadrons \( \mathcal{O}(500) \mu \text{m/c} \)

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Prompt $J/\psi R_{AA}$

- Nuclear modification factor

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA}N_{MB}} \frac{N_{PbPb}}{N_{pp}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}} : R_{AA} = 1 \text{ No modification compared to pp collisions}$$

- Suppressed by factor $\sim 5$ in the most central bin
- No $p_T$ and $y$ dependent suppression is observed.
Elliptic flow \((v_2)\)
- Important to understand the dynamics of heavy-ion collision

- Asymmetry in the collective expansion
- Path-length dependent absorption

Reflected in the azimuthal distribution of particle yields

\[
\frac{1}{N_{total}} \cdot \frac{d^2 N}{d\phi} \propto 1 + 2v_2 \cos(2\Delta\phi)
\]
No strong centrality, $p_T$, and rapidity dependence

Integrated $v_2$ value (10–60%, $6.5 < p_T < 30$ GeV/c, $|y| < 2.4$)

\[ v_2 = 0.054 \pm 0.013\text{(stat.)} \pm 0.006\text{(syst.)} \]

‘First’ significant measurement of prompt J/$\psi$ $v_2$
Comparison with other hadrons

- J/ψ $v_2$ at lower $p_T$ region is much smaller than hadron $v_2$ while higher $p_T$ region shows similar $v_2$ values.
- D meson $v_2$ has similar trend to hadron rather than J/ψ.
Y(nS) in PbPb

In PbPb, Excited states are suppressed relative to the ground state.

The peak for Υ(3S) is hardly visible.
$R_{AA}$ for $\Upsilon(nS)$

**Centrality integrated results**

- $R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$
- $R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$
- $R_{AA}(\Upsilon(3S)) = 0.03 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$
  
  ($< 0.10 \text{ at } 95\% \text{ CL}$)

**$\Upsilon$ states are suppressed sequentially.**

$$R_{AA}[\Upsilon(1S)] > R_{AA}[\Upsilon(2S)] > R_{AA}[\Upsilon(3S)]$$
**Cold nuclear matter effects in pPb**
- Initial state energy loss, comover break up, shadowing, etc.
- Provide a better understanding of the effects from QGP
- CNM itself is an interesting matter.

**1st pPb run @ LHC in Jan.–Feb. 2013**
- $\sqrt{S_{NN}} = 5.02$ TeV
- Recorded luminosity by CMS: 31.7 nb$^{-1}$
Y(nS) in pPb from 2013

2013 pp
X20 more statistics than 2011 pp data

CMS Preliminary
pp $\sqrt{s} = 2.76$ TeV
L_{int} = 5.1 pb$^{-1}$

2013 pp
Events / (0.05 GeV/c$^2$)

m_{\mu^+\mu^-} (GeV/c$^2$)

CMS Preliminary
pp $\sqrt{s} = 2.76$ TeV
L_{int} = 5.1 pb$^{-1}$

pPb
Events / (0.05 GeV/c$^2$)

m_{\mu^+\mu^-} (GeV/c$^2$)

CMS Preliminary
pPb $\sqrt{s_{NN}} = 5.02$ TeV
L_{int} = 31 nb$^{-1}$

- Limited kinematic range(|$y_{CM}$| < 1.93) due to the rapidity shift in the asymmetric p+Pb collisions
- Fitting procedure is same in pp, pPb, and PbPb analysis.
Double & Single ratios

**Single Ratio**

- **pPb vs pp**: Excited states are suppressed more than the ground state in pPb compared to pp.

**Double Ratio**

- **PbPb vs pPb**: Additional final state effects in PbPb that affect the excited states more than the ground state.
Event activity variables

- Single ratios in all cases show the weaker dependence on $E_T$.
- In pp and pPb, the significant decreasing dependence on $N_{\text{tracks}}$.
  - $\Upsilon$ would affect the multiplicity?
  - Multiplicity would affect the $\Upsilon$?

raw transverse energy measured in HF

corrected $N_{\text{tracks}}$ in inner tracker
**Summary**

**Charmonia in PbPb collisions**
- Prompt $J/\psi$ is suppressed by factor 5 in the most central bin.
- Significant anisotropy of prompt $J/\psi$ in $10-60\%$, $6.5 < p_T < 30$ GeV/c, $|y| < 2.4$

**Bottomonia in PbPb & pPb collisions**
- Sequential melting of $\Upsilon(nS)$ is observed in PbPb.
- Indication for the cold nuclear matter effect in pPb.
1st PbPb run @ $\sqrt{s_{NN}} = 2.76$ TeV
- Nov. – Dec. 2010
- Recorded luminosity by CMS : 7.28 $\mu$b$^{-1}$

1st pp run @ $\sqrt{s_{NN}} = 2.76$ TeV
- March 2011
- Recorded luminosity by CMS : 225 nb$^{-1}$

2nd PbPb run @ $\sqrt{s_{NN}} = 2.76$ TeV
- Nov. – Dec. 2011
- Recorded luminosity by CMS : 150 $\mu$b$^{-1}$

pPb run @ $\sqrt{s_{NN}} = 5.02$ TeV
- Jan. – Feb. 2013
- Recorded luminosity by CMS : 31.7 nb$^{-1}$

2nd pp run @ $\sqrt{s_{NN}} = 2.76$ TeV
- Feb. 2013 (3 days)
- Recorded luminosity by CMS : 5.41 pb$^{-1}$

CMS ION LUMINOSITY 2011 and 2010

CMS Integrated Luminosity, pPb, 2013, $\sqrt{s} = 5.02$ TeV/nucleon
Data included from 2013-01-20 14:08 to 2013-02-10 05:05 UTC
Sequential melting scenario

- **Cartoon for Debye screening**
  - The larger the binding energy, the higher the dissociation temperature $T_d$.
  - As temperature goes up, Debye length $r_\lambda(T)$ decreases.

\[ r_0 > r_\lambda(T) \]
Non-prompt $J/\psi$ $R_{AA}$

- Suppressed by factor $\sim 3$ in the most central bin
- Hints of smaller suppression at lower $p_T$ region, mid-rapidity region

Information on the $b$–quark energy loss in medium
Prompt J/$\psi$ $R_{AA}$

**Rapidity dependence**

CMS Preliminary
PbPb $\sqrt{s_{_{NN}}} = 2.76$ TeV

Prompt $J/\psi$

- $|y|<1.2$
- $1.2<|y|<1.6$
- $1.6<|y|<2.4$

| $p_T$ dependence |

- 6.5 $< p_T < 30$ GeV/c
- 3 $< p_T < 6.5$ GeV/c

**Left :** No strong dependence on rapidity at high $p_T$ region

**Right :** At forward rapidity region, lower $p_T$ $J/\psi$ is slightly less suppressed in the most central bins.
**Non-prompt J/ψ R_{AA}**

**Rapidity dependence**

- **Left**: In all rapidity bins at high $p_T$ region, centrality dependent suppression is shown.
- **Right**: In the forward region, lower $p_T$ J/ψ has strong centrality dependence and less suppressed than high $p_T$ J/ψ.

**p_T dependence**
ψ(2S) Single ratio

- Single ratio: \( R_{\psi(2S)} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \)

- \( 6.5 < p_T < 30 \text{ GeV/c} \)

- \(|y| < 1.6\)

- \( R_{\psi(2S)} \) in 0–20% PbPb
  ~ 2 times smaller than in pp

- \( 3 < p_T < 30 \text{ GeV/c} \)

- \( 1.6 < |y| < 2.4 \)

- \( R_{\psi(2S)} \) in 0–20% PbPb
  ~ 5 times larger than in pp

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**ψ(2S) Double ratio & \(R_{AA}\)**

**Double ratio:**

\[
\frac{(N_{\psi(2S)}/N_{J/\psi})_{PbPb}}{(N_{\psi(2S)}/N_{J/\psi})_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}
\]

**Centrality integrated results**

\[
R_{0-100\%}^{AA}(\psi(2S)) = 1.54 \pm 0.32 \text{(stat)} \pm 0.22 \text{(syst)} \pm 0.76 \text{(pp)}
\]

\[
R_{0-100\%}^{AA}(\psi(2S)) = 0.11 \pm 0.03 \text{(stat)} \pm 0.02 \text{(syst)} \pm 0.02 \text{(pp)}
\]

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**CMS-PAS HIN-12-007**

**Lower p\(_{T}\) forward region**

\(3<p_{T}<30 \text{ GeV/c}\)

\(1.6<|y|<2.4\)

**High p\(_{T}\) mid rapidity region**

\(6.5<p_{T}<30 \text{ GeV/c}\)

\(|y|<1.6\)
**Y(nS) Double ratio in PbPb**

- **Y(2S) double ratio vs centrality**
  - No strong centrality dependence
  - Suppressed even in the most peripheral bin

\[
\begin{align*}
\frac{N_{Y(2S)/N_{Y(1S)|PbPb}}}{N_{Y(2S)/N_{Y(1S)|pp}}} & = 0.21 \pm 0.07[{\text{stat.}}] \pm 0.02[{\text{syst.}}] \\
\end{align*}
\]

- **Y(3S) double ratio vs centrality**
  - Peak at PbPb is hard to distinguish.
  - Set the upper limit

\[
\begin{align*}
\frac{N_{Y(3S)/N_{Y(1S)|PbPb}}}{N_{Y(3S)/N_{Y(1S)|pp}}} & = 0.06 \pm 0.06[{\text{stat.}}] \pm 0.06[{\text{syst.}}] \\
& \leq 0.17 \text{ at 95\% C.L.}
\end{align*}
\]
Remark for pPb Y analysis

- Since the beam energy of proton and Pb nucleus is asymmetric, C.M frame is boosted by $\Delta y \sim 0.47$ w.r.t. lab frame.

- Symmetric range in C.M.frame $[-1.93, 1.93]$ is selected for muon’s $\eta$ and dimuon’s rapidity.
  - for the 1st run (proton going to $-$) : $[-2.4, 1.47]$
  - for the 2nd run (proton going to $+$) : $[-1.47, 2.4]$

- Binning in 2 event activity variables
  - corrected $N_{\text{tracks}}$ in inner tracker ($|\eta|<2.4, p_T>0.4$ GeV/c)
  - raw transverse energy($E_T$) measured in HF ($4<|\eta|<5.2$)