Quarkonium results in heavy-ion collisions with CMS

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On behalf of the CMS collaboration

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Outline

- Introduction

- Charmonium
  - $J/\psi$ in PbPb and pPb
  - $\psi$ (2S) in PbPb

- Bottomonium
  - $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ in PbPb and pPb

- Conclusion
◆ Quarkonia as a probe of **deconfinement** via **colour screening**
  ◆ If $\lambda_D(T) < r$ → screening
    → melting of the bound state
    → yields suppressed
  → *Matsui and Satz, PLB 178 (1986) 416*

◆ **Sequential suppression** of the quarkonium states
  ◆ Screening at different $T$ for different states → sequential melting
  → *Digal, Petreczky, Satz, PRD 64 (2001) 0940150*

◆ **Enhancement** via **(re)generation** of quarkonia, due to the large heavy-quark multiplicity
  → *Andronic, Braun-Munzinger, Redlich, Stachel, PLB 571(2003) 36*

◆ Cold Nuclear Matter effects (**CNM effects**), such as nuclear absorption and gluon shadowing
Muon reconstruction: silicon tracker + muon subdetectors

- Tracker $p_T$ resolution: 1-2% up to $p_T \sim 100$ GeV/c:
  - separation of quarkonium states
  - displaced tracks for heavy-flavour measurements
**Y and J/ψ acceptance**

|               | 1.6<|y|<2.4 | 1.2<|y|<1.6 | |y|<1.2 |
|---------------|----------|-----------|----------|
| **ϒ** p<sub>T</sub> in pp |           | > 0 GeV/c |          |
| **J/ψ** p<sub>T</sub> in pp | > 0 GeV/c | > 2 GeV/c | > 6.5 GeV/c |
| **J/ψ** p<sub>T</sub> in PbPb | > 3 GeV/c | > 5.5 GeV/c | > 6.5 GeV/c |

- CMS can measure J/ψ down to ~ 0 p<sub>T</sub> in the forward region 1.6<|y|<2.4 (in pp collisions for now)
Charmonia
No significant dependence for $R_{AA}$ vs. rapidity and $p_T$

$R_{AA}$ vs. centrality:

- 0-5% factor $\sim 5$ suppression $\rightarrow R_{AA} = 0.20 \pm 0.03$ (stat.) $\pm 0.01$ (syst.)
- 60-100% factor $\sim 1.4$ suppression
**R_{AA} prompt J/ψ**

- **CMS Preliminary**
  - PbPb $\sqrt{s_{NN}} = 2.76$ TeV
  - PAS HIN-12-014

**Prompt J/ψ**

- $6.5 < p_T < 30$ GeV/c
  - no rapidity dependence

- $3 < p_T < 6.5$ GeV/c
  - slightly less suppressed than the ones with $6.5 < p_T < 30$ GeV/c

**R_{AA}**

- 50-100%
- 0-10%

**PAS HIN-12-014**

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Less suppression seen for low $p_T$ $J/\psi$ (ALICE) compared to high $p_T$ $J/\psi$ (CMS)

Sign of (re)generation for low $p_T$ $J/\psi$
Double ratio:

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

<table>
<thead>
<tr>
<th>R_{AA} (0-100%)</th>
<th>\psi(2S)</th>
<th>J/\psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 &lt; p_{T} &lt; 30 GeV/c, 1.6 &lt;</td>
<td>y</td>
<td>&lt; 2.4</td>
</tr>
<tr>
<td>6.5 &lt; p_{T} &lt; 30 GeV/c,</td>
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<td>&lt; 1.6</td>
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</table>

- At high-\(p_{T}\) (6.5<\(p_{T}\)<30 GeV/c, |y|<1.6): \(R_{AA}(\psi (2S)) < R_{AA}(J/\psi)\)
  - Consistent with a sequential melting scenario

- At intermediate-\(p_{T}\): \(R_{AA}(\psi(2S)) > R_{AA}(J/\psi)\)
  - Presence of sequential recombination (?)

- More statistics will reduce uncertainties and allow stronger statements
In pA collisions at 5 TeV, CMS is probing small x-regions

- CMS coverage
  - $-2.87 < y_{CM} < 1.93$
  - $2 < p_T < 30$ GeV/c

- $x_{1,2} = \sqrt{m_{j/\psi}^2 + p_T^{j/\psi}^2} \cdot e^{\pm y}$
- $x \sim 10^{-4} - 10^{-2}$

Will be presented:
- Forward, backward cross section
- Nuclear effects in J/$\psi$ production, $R_{FB}$
- $p_T$-dependent $R_{FB}$
- Event-activity dependent $R_{FB}$

**J/$\psi$ in pPb**
Cross sections measured as a function of rapidity and $p_T$

Modification of nPDF can be probed by comparing the corrected yields of the $p$-going direction and the Pb-going direction
$R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/dp_Tdy}{d^2\sigma(p_T, y < 0)/dp_Tdy}$

- $R_{FB}$ vs. $p_T$: strong dependence
  - increasing with $p_T$ consistently for 3 rapidity bins

- $R_{FB}$ vs. rapidity:
  - at this high $p_T$, no strong rapidity dependence

CMS Preliminary

34.6 nb\(^{-1}\) (pPb 5.02 TeV)

CMS HIN-14-009
At large $J/\psi$ rapidities in two $p_T$ bins:

- Decreasing $R_{FB}$ with increasing event activity
- More pronounced at low $p_T$
Looking at high-$p_T$ only:

- Event activity dependence still clear
- No significant rapidity dependence for the $R_{FB}$ at high $p_T$
A good agreement between the 4 LHC experiments for the $R_{FB}$ vs. $p_T$ and rapidity
Bottomonia
◆ Y states are suppressed in PbPb collisions
◆ Centrality dependent, stronger suppression for excited states
◆ Ordered with assumed binding energies

◆ With a larger reference at the same energy collisions
  ◆ A precise mapping of the kinematics of the suppression in Y is possible
Improvements:

- pp reference x 20
- Bigger, more precise PbPb sample
- Reduced stat. uncertainties

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}}{N_{pp}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$
Questioning since the last CMS results:

- Is the $\Upsilon$ suppression dependent on $p_T$ and rapidity?
- No suppression at high-$p_T$?
- At forward rapidities, ALICE sees $R_{AA} \approx 0.30$ (in $2.5 < y < 4$)
- Responses with ~20 times more pp data and an improved PbPb reconstruction
The suppression is constant over the analysis range.

Will help to constrain theoretical models.
$\Upsilon(nS)/\Upsilon(1S)$ event activity dependence

$\Upsilon(nS)/\Upsilon(1S)$ decrease with increase of charged-particle multiplicity in both pp and pPb: reflect an influence of the particles on the $\Upsilon$ and/or reflect a different multiplicity associated with the $\Upsilon$ states production
No significant dependence for PbPb results as function of $N_{\text{tracks}}$ and $E_T|\eta|>4$, but we have large uncertainties (more PbPb data needed)
Different $<E_T>$: 3.5 (pp), 14.7 (pPb), 760 GeV(PbPb)

$N_{\text{Track}}$: less coherent behaviour

$\text{pp}$: multi-parton interaction?
Similar trend measured by ALICE for $J/\psi$ in pp at 7 TeV

Activity-dependent analysis of the copious pp data at 7 TeV may give a better understanding of the $\Upsilon$ states
Summary

- **PbPb**
  - J/ψ more suppressed in central compared to peripheral events
  - low $p_T$ J/ψ less suppressed than high $p_T$ J/ψ
  - There is a sequential suppression for $\Upsilon$ states in order of binding energies
  - No $p_T$ dependence for relatively high $p_T$ $\Upsilon$, as well as no rapidity dependence

- **pPb**
  - For the J/ψ
    - Nuclear effects seen in pPb prompt J/ψ production ($R_{FB} < 1$)
    - $R_{FB}$ is clearly dependent on J/ψ transverse momentum
    - Large event activity affects more the forward-backward ratio
  - For the $\Upsilon$
    - $\Upsilon(nS)/<\Upsilon(nS)>$: increase with increasing event activity in pp, pPb and PbPb
    - Detailed understanding of $\Upsilon$ states requires more PbPb data, and activity-dependent analysis of pp data at 7 TeV

- All our public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
Back-up
Strickland: some tension to describe $\Upsilon(1S)$ and $\Upsilon(2S)$ simultaneously with the same $\eta/S$ value

Rapp: regeneration and nuclear absorption could be significant also for bottomonia

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J/$\psi$ separation

Inclusive J/$\psi$

prompt J/$\psi$

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

Direct J/$\psi$

Feed-down from
$\psi(2S)$ and $\chi_c$

CMS Preliminary
CMS PAS HIN-12-014

$|y| < 2.4$
$6.5 < p_T < 30$ GeV/c
Cent. 0-10%

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$6.5 < p_T < 30$ GeV/c
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$\ell J/\psi = L_{xy} \frac{m_{J/\psi}}{p_T}$

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Non zero $v_2$ for prompt $J/\psi$ vs. centrality and vs. rapidity

In [10-60%] and for $6.5 < p_T < 30$ GeV/c: $v_2 = 0.054 \pm 0.013 \pm 0.006$ with a 3.8$\sigma$ significance
Non zero $v_2$ for prompt $J/\psi$ vs. $p_T$
v_2 of prompt J/ψ measured by CMS at 2.76 TeV is complementary to ALICE results (p_T < 10 GeV/c and 2.5 < |y| < 4)

STAR results at 0.2 TeV are consistent with zero in 2 < p_T < 10 GeV/c
J/\psi separation

Inclusive J/\psi

prompt J/\psi

Direct J/\psi

Feed-down from \psi(2S) and \chi_c

Non-prompt J/\psi form B decays
Y(1S), Y(2S), Y(3S) in PbPb

- PbPb vs. pp: $R_{AA}$

- Clear suppression of $Y(2S)$

- $Y(1S)$ suppression consistent with excited state suppression (~50% feed down)

- [0-100%]:
  
  $R_{AA}(Y(1S)) = 0.56 \pm 0.08 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$
  
  $R_{AA}(Y(2S)) = 0.12 \pm 0.04 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$
  
  $R_{AA}(Y(3S)) < 0.1 \text{ (at 95\% C.L.)}$

- Sequential suppression of the three states in order of their binding energy
pPb collisions

- pPb collisions: understand Cold Nuclear Matter (CNM) effect from QGP
- pPb asymmetric collisions (~0.47 rapidity boost)
  - analysis window $|y_{CM}|<1.93$

<table>
<thead>
<tr>
<th>System</th>
<th>Pb p</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAB</td>
<td>-2.4</td>
</tr>
<tr>
<td>Collision (CM)</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

- Binning in 2 event-activity variables:
  - $N_{\text{track}}|\eta|<2.4$ corrected, $p_T>400$ MeV/c
  - $E_T|\eta|>4$ raw transverse energy measured in HF
Signal extraction same procedure in pp, pPb and PbPb:

- Unbinned maximum log likelihood with 1S, 2S/1S, 3S/1S variables in the fit
  - Signal: 3 Crystal-Ball functions
  - Background: erfFunction x exponential (all background parameters free)
promp t J/ψ: $v_2$ vs. $p_T$

- At low $p_T$: $v_2$ prompt J/ψ < $v_2$ charged hadrons and $v_2$ D mesons (ALICE)
- At high $p_T$ 8 < $p_T$ < 10 GeV/c: similar $v_2$ for prompt J/ψ and charged hadrons

→ Path-length dependence of partonic energy loss in a deconfined medium?
pPb vs. PbPb: additional final-state effects in PbPb that affect the excited states more than the ground state
pPb vs. pp: excited states suppressed more than the ground state in pPb compared to pp collisions (significance < 3 \sigma)