Charmonium Production in pp, pPb and PbPb with CMS

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SQM2016
UC Berkeley, Berkeley, CA, United States
28th June 2016
Motivation

- **Quarkonia** - important probes in Heavy Ion collisions
  - Produced by gluon-gluon hard scattering in the early stage of collisions
  - Sensitive to gluon Parton Distribution Functions
  - Experience the full evolution of the medium

- **Cold Nuclear Matter effects (CNM)**
  - e.g.)
    - Modification of PDFs
    - Initial state energy loss
    - Nuclear absorption

- **Hot and Dense Medium effects (QGP)**
  - e.g.)
    - Debye screening - suppression
    - Recombination - enhancement
CMS Acceptance for Charmonia

- Charmonia reconstructed via $\mu^+\mu^-$ decay channel
  - Easy to detect with excellent momentum resolution
- Kinematic coverage of CMS
  - $|y| < 2.4$
  - $p_T$ down to 0 GeV/c at forward ($1.6 < |y| < 2.4$)
  - $p_T > 6.5$ GeV/c at mid-rapidity due to B field

![Muon Efficiency Diagram]

J/ψ cross sections in pp

![Cross Section Graph]

Lumi. uncertainty, 11%, not shown

0 GeV  6.5 GeV

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Outline

**Probe CNM effects**

- J/ψ in **Ultra Peripheral PbPb Collisions**
- J/ψ in pPb Collisions

![CMS-PAS HIN-14-009]

**Probe CNM + QGP effects**

- J/ψ in PbPb Collisions
- ψ(2S) in PbPb Collisions

![CMS-PAS HIN-12-014]

![PRL 113 (2014) 262301]

arXiv:1605.06966, submitted to PLB
Ultra Peripheral PbPb @ 2.76 TeV
CNM physics

- nuclear PDFs: $R_i^A(x, Q^2) = \frac{f_i^p/A(x, Q^2)}{f_i^p(x, Q^2)}$ ← proton PDF inside nucleus
  $\frac{f_i^p(x, Q^2)}{f_i^p(x, Q^2)}$ ← proton PDF

- CMS covers a broad range in Bjorken-x (gluon shadowing)
- Measurement in low x is crucial to understand the CNM effects and constrain various theoretical models
J/ψ in Ultra Peripheral PbPb

- Photon-induced reactions
  - b (impact parameter) > 2R (nucleus radius)
  - Cross sections $\propto$ (gluon density)$^2$
  - Clean probes with low background for gluon PDFs ($10^{-5} < x < 10^{-2}$)

- Event selection
  - UPC requirement
    - low activity in Hadron Forward Calorimeter
  - J/ψ - exactly two muon tracks
  - Forward Neutron
    - detection in Zero Degree Calorimeter
    - $(X_n0_o)$ break-up mode selected
      (neutrons on one side, nothing on the other side)

$\gamma + \text{Pb} \rightarrow \text{J/ψ} + \text{Pb}$

CMS

$\rho_{\gamma}(\mu^{+}\mu^{-}) < 1.0$ GeV

$1.8 < |y(\mu^{+}\mu^{-})| < 2.3$

down to $p_T \sim 0$ GeV

arXiv:1605.06996

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Different Interactions in UPC

- **Coherent J/ψ**
  - Photon couples to “a whole nucleus”
  - $p_T < 0.15$ GeV/c
- **Incoherent J/ψ**
  - Photon couples to “a single nucleon”
  - $0.15 < p_T < 1.05$ GeV/c
- **Two photon → Dimuon**
  - QED Background

- **MC(STARLIGHT) template fit to extract coherent contributions**
Coherent J/ψ cross sections

- **Impulse approximation** neglects all nuclear effects
- **Leading twist approximation** includes an effective gluon shadowing

- Results favor a model with shadowing effects
- Complementary to ALICE covering different rapidity range
pPb @ 5.02 TeV
Separation of prompt & non-prompt

- 2D fit to “dimuon mass” and “decay length”
  - Prompt: direct $J/\psi$ or feed down from $\psi'$ and $X_c$
  - Non-prompt: from B hadron decays

- Lifetime of B ~ O(500) $\mu$m/c
- IP resolution of CMS
  - transverse ~ 25-90 $\mu$m
  - longitudinal ~ 45-150 $\mu$m

\[
\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}
\]

- CMS Preliminary
  - $1.5 < y_{CM} < 1.93$
  - $3 < p_T < 4$ GeV/c

Counts / 20 MeV/c²

Counts / 80 $\mu$m
**J/ψ in pPb - cross section**

- Wide range in rapidity and \( p_T \) bins
  - \(-2.87 < y_{CM} < 1.93\) (\(-2.4 < y_{lab} < 2.4\))
  - \(2 < p_T < 30\) GeV/c (down to lower \( p_T \) at most forward)

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

**Prompt J/ψ**

Global uncertainty : 3.5%

- Forward (p-going)
- Backward (Pb-going)

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CMS-PAS HIN-14-009
\( R_{FB}(p_T, y) = \frac{\frac{d^2\sigma(p_T, y > 0)}{dp_T dy}}{\frac{d^2\sigma(p_T, y < 0)}{dp_T dy}} \)

\( = \frac{\text{p-going (x} \sim 10^{-4}\text{)}}{\text{Pb-going (x} \sim 10^{-2}\text{)}} \)

- \( R_{FB} < 1 \) at low \( p_T \)
- Clue for other effects beyond presented nPDF predictions?
**J/ψ in pPb - event activity**

- Event activity characterized by $E_{T}^{HF|\eta|>4}$
- Transverse energy deposited in Hadron Forward Calorimeter (HF) at $4 < |\eta| < 5.2$
- Fraction of minimum bias events:

|  | $E_{T}^{HF|\eta|>4}$ | $\langle E_{T}^{HF|\eta|>4} \rangle$ | Frac |
|---|------------------|-----------------|------|
| pPb | 0–20 | 9.4 | 73% |
| min-bias | 20–30 | 24.3 | 18% |
| min-bias | 30–120 | 37.2 | 9% |

- $R_{FB}$ decreases with increasing event activity
- **Stay Tuned!** $R_{pPb}$ coming soon with 2015 pp at same $\sqrt{s_{NN}}$
PbPb @ 2.76 TeV
J/$\psi$ in PbPb

- Nuclear modification factor

\[ R_{AA} = \frac{1}{T_{AA}} \cdot \frac{dN_{AA}}{d\sigma_{pp}} = \frac{L_{int}^{pp}}{T_{AA}N_{MB}} \cdot \frac{N_{J/\psi}^{PbPb}}{N_{J/\psi}^{PP}} \cdot \frac{\epsilon_{pp}}{\epsilon_{PbPb}} \]

- More suppressed in more central collisions
- No significant $p_T$ and rapidity dependence
$\psi(2S)$ in PbPb

- Double Ratio:

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

- CMS PbPb & pp $\sqrt{s_{NN}} = 2.76$ TeV

- At high $p_T$ & mid-rapidity: consistent with sequential melting
- At low $p_T$ & forward: hint of recombination?

2015 PbPb @ 5.02 TeV
Stay Tuned!
Summary

• CNM effects probed by J/ψ in pPb
  • \( R_{FB} < 1 \) especially at low \( p_T \)
  • \( R_{FB} \) decreases with increasing event activity

• Coherent J/ψ photo-production in UPC PbPb
  • Evidence for gluon shadowing at low \( x \) region (at low \( Q^2 \))

• Suppression of J/ψ and \( ψ(2S) \) in PbPb
  • J/ψ is more suppressed in more central collisions
  • \( ψ(2S) \) is more suppressed than J/ψ at higher \( p_T \) & mid-y, and less suppressed at lower \( p_T \) & forward y
Backup
• Large coverage (muon & tracker $|\eta| < 2.4$)
• Highly selective trigger & muon ID in the muon system
• Excellent momentum and vertex resolution of the tracking system
two photon interaction
Centrality? Event activity?

- Centrality in PbPb
  - Related to the overlap fraction of the geometrical cross sections

- Event-activity variables in pPb
  - $E_T^{HF}$: raw transverse energy deposited in forward region HF ($4<|\eta|<5.2$)
In pPb, the correlation between the centrality variable and $N_{\text{coll}}$ is very loose.
QGP physics

• Debye screening (suppression)
  • 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>Υ(1S)</th>
<th>Υ(2S)</th>
<th>Υ(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>
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<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>

• Recombination (enhancement)
  • combination of quarks and antiquarks which are initially produced in “different” nucleon-nucleon collisions
Non-prompt J/ψ in pPb - $R_{FB}$

- **Forward-to-Backward Ratio** :
  \[
  R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/dp_Tdy}{d^2\sigma(p_T, y < 0)/dp_Tdy}
  \]

- **Forward (y>0)**: proton-going

- $p_T$ dependence less significant compared to prompt J/ψ

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CMS Preliminary 34.6 nb$^{-1}$ (pPb 5.02 TeV)
J/ψ in pPb - event activity

same $y_{CM}$
different $p_T$

CMS Preliminary 34.6 nb$^{-1}$ (pPb 5.02 TeV)

$R_{FB}$

$E_T^{\text{HF } |\eta|>4}$ [GeV]

1.5 < $|y_{CM}|$ < 1.93

5 < $p_T$ < 6.5 GeV/c

6.5 < $p_T$ < 30 GeV/c

same $p_T$
different $y_{CM}$

CMS Preliminary 34.6 nb$^{-1}$ (pPb 5.02 TeV)

$R_{FB}$

$E_T^{\text{HF } |\eta|>4}$ [GeV]

6.5 < $p_T$ < 30 GeV/c

0.0 < $|y_{CM}|$ < 0.9

0.9 < $|y_{CM}|$ < 1.5

1.5 < $|y_{CM}|$ < 1.93

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J/$\psi$ in pPb - event activity

**same $y_{CM}$ different $p_T$**

**same $p_T$ different $y_{CM}$**

**CMS Preliminary 34.6 nb$^{-1}$ (pPb 5.02 TeV)**

Non-prompt J/$\psi$

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\( Q_{pPb} \) vs centrality (ALICE)

- \( Q_{pPb} \) decreases with increasing centrality at forward
- \( Q_{pPb} \) is rather flat or slightly increasing at backward
- Both in experimental data, and in CNM theoretical predictions
Comparison with other experiments

• Prompt J/ψ:

• Non-prompt J/ψ:

• Trends vs. $p_T$ and $y$ are similar for all 4 experiments

ALICE: JHEP 1402 (2014) 073
ATLAS: arXiv.1505.08141
LHCb: JHEP 1402 (2014) 072
Comparison with other experiments

- Points are plotted in the middle of the bin

**ATLAS** : arXiv.1505.08141

**LHCb** : JHEP 1402 (2014) 07
Comparison with other experiments

- Points are plotted in the middle of the bin

**ATLAS** : arXiv.1505.08141

**LHCb** : JHEP 1402 (2014) 07
Non-prompt $J/\psi$ in PbPb

- Nuclear modification factor

$$R_{AA} = \frac{1}{T_{AA}} \cdot \frac{dN_{AA}}{d\sigma_{pp}} = \frac{L_{int}^{pp}}{T_{AA} N_{MB}} \cdot \frac{N_{PbPb}^{J/\psi}}{N_{pp}^{J/\psi}} \cdot \frac{\epsilon_{pp}}{\epsilon_{PbPb}}$$

- $R_{AA} < 1$: suppression
- $R_{AA} = 1$: no modification compared to pp
- $R_{AA} > 1$: enhancement

- More suppressed with increasing centrality (less than prompt)
- No significant $p_T$ and rapidity dependence
prompt J/psi (differential)

- No strong dependence on rapidity at high $p_T$
- At forward, lower $p_T$ J/ψ is slightly less suppressed in most central
Non-prompt J/psi (differential)

- Rapidity dependence
  - CMS Preliminary
  - PbPb $\sqrt{s_{NN}} = 2.76$ TeV
  - Non-prompt J/$\psi$
  - $|y|<1.2$
  - $1.2<|y|<1.6$
  - $1.6<|y|<2.4$
  - $6.5<p_T<30$ GeV/c
  - $3<p_T<6.5$ GeV/c

- $p_T$ dependence
  - CMS Preliminary
  - PbPb $\sqrt{s_{NN}} = 2.76$ TeV
  - Non-prompt J/$\psi$
  - $|y|<1.2$
  - $1.2<|y|<1.6$
  - $1.6<|y|<2.4$
  - $6.5<p_T<30$ GeV/c
  - $3<p_T<6.5$ GeV/c

- No strong dependence on rapidity at high $p_T$
- At forward, lower $p_T$ J/$\psi$ has strong dependence and less suppressed than higher $p_T$ J/$\psi$

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Comparison with other exp.

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

- CMS: prompt $J/\psi$
  - $|y| < 2.4$
  - $6.5 < p_T < 30$ GeV/c

- ALICE: inclusive $J/\psi$
  - $2.5 < y < 4.0$

AuAu $\sqrt{s_{NN}} = 200$ GeV

- STAR: $J/\psi$ (arXiv:1208.2736)
  - $|y| < 1.0$
  - $p_T > 5$ GeV/c

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Comparison with theory

CMS Preliminary

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

- Vitev: 0-10%, y~0
  - Rad E loss+CNM
  - Rad E loss+CNM+Dissoc

- WHDG: 0-80%, y~0
  - Rad+Coll E loss

- Buzatti: 0-100%, y~0
  - CUJET preliminary

- He,Fries,Rapp: 0-100%, y~0
  - HF transport

- Uphoff et al: b=5 fm,|y|<2.4
  - BAMPS

- MC@sHQ+EPOS2: 0-100%, y~0
  - col, col+rad LPM

- b-quarks: 0-100% |$\eta$|<2.4
  (via secondary $J/\psi(\mu^+\mu^-)$)

$p_T$ (GeV/c) vs $R_{AA}$
### J/ψ azimuthal anisotropy

- **Elliptic flow ($v_2$)**
  - Important to understand the dynamics of heavy-ion collision

- **In non-central collisions**
  - Asymmetry in the collective expansion
  - Path-length dependent absorption

- **Reflected in the azimuthal distribution of particle yields**

\[
\frac{1}{N_{\text{total}}} \cdot \frac{d^2 N}{d\phi} \propto 1 + 2v_2 \cos(2\Delta \phi)
\]
J/ψ v2 in PbPb

- J/ψ has a non-zero v2: \(0.054 \pm 0.01\text{(stat.)} \pm 0.006\text{(syst.)}\)
- No strong centrality, \(p_\text{T}\) and rapidity dependence
Non-prompt J/ψ in PbPb

- J/ψ has a non-zero $v2$ : $0.054 \pm 0.01$ (stat.) $\pm 0.006$ (syst.)
- No strong centrality, $p_T$ and rapidity dependence
Non-prompt J/$\psi$ in PbPb

- J/$\psi$ v$_2$ at low p$_T$ is much smaller than hadron v$_2$ while higher p$_T$ shows similar v$_2$
- D$_0$ v2 has similar trend to hadron rather than J/$\psi$