Open and closed heavy-flavor suppression in heavy-ion collisions with CMS

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for the CMS Collaboration

Strangeness in Quark Matter, Birmingham, UK
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Quarkonia in hot and dense medium

- Heavy quarks are produced at early stage of collision
- Debye screening in Quark-Gluon Plasma leads to melting of quarkonia
- Quarkonia states have different binding energies
- Sequential melting of states is expected with increasing medium temperature

Matsui & Satz, PLB 178 (1986) 416

\[ R_{AA} = \frac{1}{N_{\text{coll}}} \frac{N_{\text{PbPb}}(J/\psi)}{N_{\text{pp}}(J/\psi)} \]

- J/\psi R_{AA} similar at SPS and RHIC energies
- More suppression at forward rapidity than at midrapidity
- Mix of shadowing, melting, and regeneration?
- What happens at the LHC with higher energy, luminosity?

Mocsy, EPJ C 61 (2009) 705

\[ T/T_c, \quad \langle r \rangle [\text{fm}^{-1}] \]


SPS from Scomparin @ QM06

Mihee Jo
Strangeness in Quark Matter 2013
Open heavy-flavor in hot and dense medium

- Quarks interact with medium and lose energy
- Inelastic scattering – radiative energy loss
- Elastic scattering – collisional energy loss
- Dead-cone effect
  - Small-angle gluon radiation is reduced for heavy quarks

- Open b mesons have not been measured separately at RHIC
- Would $R_{AA}$ be ordered as predicted by theory?

$R_{AA}(\text{light hadrons}) < R_{AA}(D) < R_{AA}(B)$


Non-photonic decays from D and B mesons
Muon reconstruction in CMS

- Excellent muon identification & triggering (DT, CSC, RPC)
- High mass/momentum resolution (Pixel & Strip silicon tracker)
Dimuon acceptance

- Due to the strong magnetic field and energy loss in the absorber, minimum momentum to reach the muon stations is 3~5 GeV/c

- $J/\psi$ acceptance
  - Mid-rapidity: $J/\psi$ $p_T > 6.5$ GeV/c
  - Forward rapidity: $J/\psi$ $p_T > 3$ GeV/c

- $\Upsilon$ acceptance
  - All rapidity: $\Upsilon$ $p_T > 0$ GeV/c
Dimuon spectrum in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV
$\Upsilon(1,2,3S)$

L$_{int}$ (PbPb) = 147 $\mu$b$^{-1}$

$p_T^{\mu} > 4$ GeV/c

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

$m_{\mu\mu}$ (GeV/c$^2$)
**J/ψ in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV**

- Reconstruction of $\mu^+\mu^-$ vertex
- 2D simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length $l_{j/ψ}$
- Extract the non-prompt $J/ψ$ fraction

$$l_{j/ψ} = L_{xy} \frac{m_{j/ψ}}{p_T}$$

2010 PbPb data 7.28 $\mu$b$^{-1}$: JHEP 05 (2012) 063
2011 PbPb data 150 $\mu$b$^{-1}$: CMS PAS HIN-12-014
Non-prompt J/ψ $R_{AA}$

- Non-prompt J/ψ from b-hadron decays is a probe to energy loss of b quarks in the medium.
- Centrality dependent suppression on $6.5 < p_T < 30$ GeV/c, $|y| < 2.4$ region
  - 0-5% centrality events shows suppression by a factor 2.5
- A hint of rapidity or $p_T$ dependent suppression

$$R_{AA} = \frac{L_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}(J/\psi)}{N_{pp}(J/\psi)} \frac{\epsilon_{pp}}{\epsilon_{PbPb}(Cent.)}$$
Non-prompt $J/\psi$ $R_{AA}$: Comparison to theory

- $R_{AA}$ of non-prompt $J/\psi$ as a function of $J/\psi$ $p_T$ is compared to theoretical calculations as a function of B $p_T$ (note: B $p_T > J/\psi$ $p_T$)
- Radiative energy loss is not enough to describe b-quark energy loss
- D meson $R_{AA} <$ Non-prompt $J/\psi$ $R_{AA}$ for most central collisions

CMS PAS HIN-12-014
ALICE: JHEP 09 (2012) 112
Centrality dependence is observed in all rapidity region.

At forward rapidity (1.6 < |y| < 2.4), lower $p_T$ (3 < $p_T$ < 6.5 GeV/c) is accessible.

- Lower $p_T$ is less suppressed than higher $p_T$.
Prompt J/$\psi$ $R_{AA}$

- Prompt J/$\psi$ $R_{AA}$ with pp reference at 2.76 TeV, 231 nb$^{-1}$
  - $R_{AA}$ vs. $p_T$ and $y$ will be updated with more statistics. Stay tuned!
- Strong centrality dependence for $6.5 < p_T < 30$ GeV/c, $|y| < 2.4$ region
- 0-5% centrality events shows suppression by a factor almost 5
- No significant dependence on rapidity or $p_T$

CMS PAS HIN-12-014
Different rapidity regions have similar suppression magnitude and centrality dependence for $6.5 < p_T < 30$ GeV/c.

At forward rapidity ($1.6 < |y| < 2.4$), lower $p_T$ ($3 < p_T < 6.5$ GeV/c) is accessible.

- In most central case, lower $p_T$ is slightly less suppressed.
Prompt $J/\psi$ $R_{AA}$: Comparison to STAR

- **CMS: Prompt $J/\psi$**
  - $\sqrt{s_{NN}} = 2.76$ TeV
  - $6.5 < p_T < 30$ GeV/c, $|y| < 2.4$

- **STAR: Inclusive $J/\psi$**
  - $\sqrt{s_{NN}} = 200$ GeV
  - $p_T > 5$ GeV/c, $|y| < 1$

- Similar centrality trends but stronger suppression at CMS

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**CMS PAS HIN-12-014**
Prompt $J/\psi$ $R_{AA}$: Comparison to ALICE

- CMS: Prompt $J/\psi$
  - $6.5 < \pT < 30$ GeV/c, $|y| < 2.4$

- ALICE: Inclusive $J/\psi$
  - $p_T > 0$ GeV/c, $|y| < 0.9$
  - $p_T > 0$ GeV/c, $2.5 < |y| < 4$

- Stronger suppression at CMS for central events
  - Less suppression at low $p_T$ due to regeneration?

CMS PAS HIN-12-014
Prompt $J/\psi$ $R_{AA}$: Comparison to theory

- Prompt $J/\psi$ $R_{AA}$ at high $p_T$ is described well without recombination
- Collisional energy loss and CNM effects are not enough to describe prompt $J/\psi$ suppression
$\psi(2S)$ in pp & PbPb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

CMS Preliminary

<table>
<thead>
<tr>
<th>$\psi(2S)$ in pp $\sqrt{s} = 2.76$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{int}} = 231$ nb$^{-1}$</td>
</tr>
<tr>
<td>$N_{J/\psi} = 741 \pm 36$</td>
</tr>
<tr>
<td>$R_{\psi(2S)} = 0.049 \pm 0.010$</td>
</tr>
<tr>
<td>$\sigma = (32 \pm 1)$ MeV/c$^2$</td>
</tr>
</tbody>
</table>

CMS Preliminary

<table>
<thead>
<tr>
<th>$\psi(2S)$ in PbPb $\sqrt{s_{\text{NN}}} = 2.76$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{int}} = 150$ mb$^{-1}$</td>
</tr>
<tr>
<td>$N_{J/\psi} = 3211 \pm 65$</td>
</tr>
<tr>
<td>$R_{\psi(2S)} = 0.024 \pm 0.008$</td>
</tr>
<tr>
<td>$\sigma = (29 \pm 1)$ MeV/c$^2$</td>
</tr>
</tbody>
</table>

$R_{\psi(2S)} = \frac{\psi(2S)/J/\psi (PbPb)}{\psi(2S)/J/\psi (pp)}$

- $R_{\psi(2S)}$ in 0-20% PbPb is $\sim 2x$ smaller than in pp for $p_T > 6.5$ GeV/c, $|y| < 1.6$ region

CMS PAS HIN-12-007
\[ R_{AA}^{0-100\%}(\psi(2S)) = 1.54 \pm 0.32 \text{ (stat.)} \pm 0.22 \text{ (syst.)} \pm 0.76 \text{ (pp)} \]

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

- For \( p_T > 3 \text{ GeV/c}, 1.6 < |y| < 2.4 \), large uncertainties on pp
  - Indication that \( \psi(2S) \) is less suppressed than \( J/\psi \) but need more pp statistics
  - \( R_{AA} \) vs. \( p_T \) and \( y \) will be updated with more statistics. Stay tuned!
- \( \psi(2S) \) is more suppressed at \( p_T > 6.5 \text{ GeV/c}, |y| < 1.6 \)
\( \Upsilon(nS)/\Upsilon(1S) \) ratios

- \( \Upsilon(2S)/\Upsilon(1S) \) and \( \Upsilon(3S)/\Upsilon(1S) \) ratios on minimum-bias

\[
\frac{N_{\Upsilon(2S)}}{N_{\Upsilon(1S)}}(PbPb) \frac{N_{\Upsilon(1S)}}{N_{\Upsilon(2S)}}(pp) = 0.21 \pm 0.07 \pm 0.02
\]

\[
\frac{N_{\Upsilon(3S)}}{N_{\Upsilon(1S)}}(PbPb) \frac{N_{\Upsilon(1S)}}{N_{\Upsilon(3S)}}(pp) < 0.17 \text{ (95\% C.L.)}
\]

\( \Upsilon(nS) \) \( R_{AA} \)

- \( \Upsilon(2S) \) is clearly suppressed
- \( \Upsilon(1S) \) suppression is consistent with excited state suppression (~50% feed down)

\begin{align*}
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)) &< 0.1 \text{ (95\% C.L.)}
\end{align*}

- Sequential suppression of \( \Upsilon(nS) \) in order of binding energy

LHCb: JHEP 11 (2012) 031

\( \Upsilon(nS) R_{AA} \): Comparison to theory

- 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
Summary

- Charmonia at lower $p_T$
  - $\psi(2S)$ suppression has too large uncertainties to draw a conclusion
  - New pp data from 2013 will help to solve this question!
- Charmonia at higher $p_T$
  - $J/\psi$ are more suppressed than RHIC energy
  - $\psi(2S)$ is more suppressed than $J/\psi$
- Bottomonia
  - Clear ordering of the suppression of the $\Upsilon(nS)$
- Measured quarkonia family shows sequential melting as a function of binding energy
Dimuon spectrum in pPb at $\sqrt{s_{NN}} = 5.02$ TeV

CMS Preliminary 2013

$pPb \sqrt{s_{NN}} = 5$ TeV

$L_{int} = 31$ nb$^{-1}$

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

$\rho, \omega, \phi$

$\psi(2S)$

$\eta$

Events/(GeV/c$^2$)

$m_{\mu\mu}$ (GeV/c$^2$)
BACK UP
\(\psi(2S) / J/\psi\) Double ratio : CMS and ALICE

- CMS has a hint of less suppression of the \(\psi(2S)\) compare to \(J/\psi\) at lower \(p_T\)
  - pp reference at \(\sqrt{s} = 2.76 TeV\)
- ALICE does not see same effect
  - pp reference at \(\sqrt{s} = 7 TeV\)
- Given the large uncertainties on the results
  - No discrepancy

CMS PAS HIN-12-007
ALICE: preliminary results from QM2012 by Scomparin, Arnaldi
\( \Upsilon(nS)/\Upsilon(1S) \) ratios

- Fit curve of pp is superimposed onto PbPb data by fixing the \( \Upsilon(1S) \) yields and background and mass peak components to PbPb.
- \( \Upsilon(2S)/\Upsilon(1S) \) and \( \Upsilon(3S)/\Upsilon(1S) \) ratio come from fit curve of pp.
- Double ratios on minimum-bias:
  
  \[
  \frac{N_{\Upsilon(2S)}}{N_{\Upsilon(1S)}} \left( \frac{PbPb}{pp} \right) = 0.21 \pm 0.07 \pm 0.02
  \]
  
  \[
  \frac{N_{\Upsilon(3S)}}{N_{\Upsilon(1S)}} \left( \frac{PbPb}{pp} \right) < 0.17 \ (95\% \text{ C.L.})
  \]

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https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011
\( \Upsilon(nS) \) signal extraction in pp and PbPb

- Much smaller number of higher order states in PbPb compare to pp

![Graph showing signal extraction](chart.png)

- CMS PbPb \( \sqrt{s_{NN}} = 2.76 \) TeV
- Cent. 0-100\%, \( |y| < 2.4 \)
- \( L_{\text{int}} = 150 \mu\text{b}^{-1} \)
- \( p_T > 4 \text{ GeV/c} \)
\( \Upsilon(2S)/\Upsilon(1S) \) Double ratios

- \( \Upsilon(2S)/\Upsilon(1S) \) double ratio of differential centrality bin is measured

- No strong centrality dependence is observed on \( \Upsilon(2S)/\Upsilon(1S) \) double ratio

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011