Quarkonium Production at LHCb

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Outline

1. Experiment
2. Exclusive production of $\psi$
3. Exclusive production of $\Upsilon$
4. Production of $\eta_c$
5. Forward production of $\Upsilon$
6. Forward production of $J/\psi$ at 13 TeV
7. Summary
- LHCb is a single-arm forward spectrometer at $2 < \eta < 5$ for a study of particles with $b$ or $c$ quarks
- 934 members, 65 Institutes from 17 countries
- Recorded luminosity: $1.0 \text{ fb}^{-1}$ at 7 TeV in 2010-2011, $2.0 \text{ fb}^{-1}$ at 8 TeV in 2012, $0.324/0.111 \text{ fb}^{-1}$ at 13 TeV in 2015/2016
- High-precision tracking (silicon strip, straw drift tubes), dipole magnet 4Tm
- Excellent PID based on two RICH detectors
- Muon system (alternating layers of Fe and MWPC)
- Versatile trigger
LHCb Experiment – II
Exclusive Quarkonium Production in $pp$ Collisions

A pomeron (color-singlet system)

(a) Exclusive and (b,c,d) inelastic quarkonium production
Exclusive \( J/\psi \) and \( \psi(2S) \) Production in \( pp \) Collisions at 7 TeV – I

930 pb\(^{-1} \) collected at \( \sqrt{s}=7 \) TeV in 2011, \( J/\psi(\psi(2S)) \) → \( \mu^+\mu^- \)

\[ p_T^2 < 0.8 \text{ GeV}^2/c^2, \quad |M(\mu^+\mu^-) - M_{J/\psi(\psi(2S))}| < 65 \text{ MeV}/c^2, \]

55985 \( J/\psi \) and 1565 \( \psi(2S) \) candidates found

R. Aaij et al., JPG 41, 055002 (2014)
Exclusive $J/\psi$ and $\psi(2S)$ Production in $pp$ Collisions at 7 TeV – II

3 BG sources: non-resonant (QED) $\mu^+\mu^-$, $0.8 \pm 0.1(17.0 \pm 0.3)$% of $J/\psi(\psi(2S))$, feed-down from $\chi_c \rightarrow J/\psi\gamma$ - $(7.6 \pm 0.9)$%, from $\psi(2S)$ - $(2.5 \pm 0.2)$%, inelastic interactions (proton dissociation/gluon radiation, higher $p_T$)

R. Aaij et al., JPG 41, 055002 (2014)
Exclusive $J/\psi$ and $\psi(2S)$ Production in $pp$ Collisions at 7 TeV – III

\begin{equation}
(291 \pm 7 \pm 19) \ (282) \ \text{pb}
\end{equation}

JMRT: S. Jones et al., JHEP 11 (2013) 085,
the photoproduction cross section extrapolated from HERA

LHCb: R. Aaij et al., JPG 41, 055002 (2014)
Exclusive $J/\psi$ and $\psi(2S)$ Production in $pp$ Collisions at 7 TeV – IV

Parton saturation effects accounted for at high energies:
R. Aaij et al., JPG 41, 055002 (2014)
2.9 fb$^{-1}$ at 7 and 8 TeV combined to increase statistics

$\Upsilon(nS) \rightarrow \mu^+\mu^-$ with $2 < \eta(\mu^\pm) < 4.5$, $2 < y(\Upsilon(nS)) < 4.5$

<table>
<thead>
<tr>
<th>$y(\Upsilon)$</th>
<th>$2 &lt; y &lt; 4.5$</th>
<th>$2 &lt; y &lt; 3$</th>
<th>$3 &lt; y &lt; 3.5$</th>
<th>$3.5 &lt; y &lt; 4.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(\Upsilon(1S, 2S, 3S))$</td>
<td>$382 \pm 26$</td>
<td>$146 \pm 16$</td>
<td>$133 \pm 16$</td>
<td>$94 \pm 14$</td>
</tr>
</tbody>
</table>

R. Aaij et al., JHEP 1509, 084 (2015)
Exclusive $\Upsilon$ Production in $pp$ Collisions at 7 and 8 TeV – II

3 BG sources: non-resonant $\mu^+\mu^-$, feed-down from $\chi_b \rightarrow \Upsilon\gamma$, inelastic interactions

After feed-down subtraction inelastic BG from the $p_T^2$

$$\sigma(pp \rightarrow p\Upsilon p) \; (\text{pb}) = 9.0 \pm 2.1 \pm 1.7, \; 1.3 \pm 0.8 \pm 0.3, < 3.4 \text{ at } 95\% \text{CL}$$

R. Aaij et al., JHEP 1509, 084 (2015)
Good agreement of the differential $\sigma$ with the NLO prediction

The photoproduction cross section discriminates between the LO and NLO, agrees with NLO and other models accounting for $t$ dependence

R. Aaij et al., JHEP 1509, 084 (2015)


\[ \eta_c(1S) \] Production at 7 and 8 TeV via the Decay $\eta_c(1S) \rightarrow p\bar{p} - I$

LHCb used 0.7 fb\(^{-1}\) at 7 TeV and 2.0 fb\(^{-1}\) at 8 TeV

The yields from the fit for the $\eta_c(1S)$ from $b$-hadron decays (data at 7 and 8 TeV combined) are $2020 \pm 230 \, \eta_c(1S)$ and $6110 \pm 116 \, J/\psi$ mesons.

The signal is fitted with a BW $\otimes$ double Gaussian, $J/\psi \rightarrow p\bar{p}\pi^0$ is small.

The yields from the fit of $\eta_c(1S)$ for the prompt sample

<table>
<thead>
<tr>
<th>$\sqrt{s}$, TeV</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(1S)$</td>
<td>$13370 \pm 2260$</td>
<td>$22416 \pm 4072$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$11052 \pm 1004$</td>
<td>$20217 \pm 1403$</td>
</tr>
</tbody>
</table>

$\eta_c(1S)$ Production at 7 and 8 TeV via the Decay $\eta_c(1S) \rightarrow p\bar{p} – III$

$\rho_T$ dependence of the $\eta_c(1S)$ is similar to that of the $J/\psi$

(In conflict with the NLO prediction in the HQ spin-symmetry relation?)

Excellent tracking and use of the $p\bar{p}$ for both the $\eta_c(1S)$ and $J/\psi$ allow a precise measurement of their mass difference

Momentum scale calibration is applied and validated with the $J/\psi$ mass measurement

The fit of $M_{p\bar{p}}$ in the sample of $b$-hadron decays gives $M_{J/\psi}$ and $\Delta M_{J/\psi,\eta_c(1S)} = 114.7 \pm 1.5 \pm 0.1$ MeV

<table>
<thead>
<tr>
<th>State</th>
<th>Mass, MeV</th>
<th>Width, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(1S)$</td>
<td>$2982.0 \pm 1.5 \pm 0.1$</td>
<td>$25.8 \pm 5.2 \pm 1.9$</td>
</tr>
<tr>
<td>PDG</td>
<td>2983.6 $\pm 0.6$</td>
<td>31.8 $\pm 0.8$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>3096.66 $\pm 0.19 \pm 0.02$</td>
<td>$-$</td>
</tr>
<tr>
<td>PDG</td>
<td>3096.900 $\pm 0.006$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

For the first time the inclusive branching of $\eta_c(1S)$ production in $b$-hadron decays at $p_T > 6.5$ GeV/$c$ is obtained:

$B(b \to \eta_c(1S)X)/B(b \to J/\psi X) = 0.421 \pm 0.055 \pm 0.025 \pm 0.045_B$, 

$B(b \to \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.29 \pm 0.67_B) \times 10^{-3}$.

The cross sections of prompt $\eta_c(1S)$ production at $p_T > 6.5$ GeV/$c$ and $2.0 < y < 4.5$ are determined assuming unpolarized $J/\psi$ production:

$\left(\frac{\sigma_{\eta_c(1S)}}{\sqrt{s}=7\text{TeV}}\right) = 0.52 \pm 0.09 \pm 0.08 \pm 0.06\sigma_{J/\psi}, B \mu b,$

$\left(\frac{\sigma_{\eta_c(1S)}}{\sqrt{s}=8\text{TeV}}\right) = 0.59 \pm 0.11 \pm 0.09 \pm 0.08\sigma_{J/\psi}, B \mu b,$

The prompt $\sigma_{\eta_c(1S)}$ agrees with the LO colour-singlet prediction and is by 2 orders smaller than that in the LO colour-octet model.

Efficiency-corrected dimuon mass distributions for $3 < p_T < 4$ GeV/c, $3.0 < y < 3.5$

<table>
<thead>
<tr>
<th>$\sqrt{s}$, TeV</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(1S) \rightarrow \mu^+ \mu^-$, $10^3$</td>
<td>$2639.8 \pm 3.7$</td>
<td>$6563.1 \pm 6.3$</td>
</tr>
<tr>
<td>$\Upsilon(2S) \rightarrow \mu^+ \mu^-$, $10^3$</td>
<td>$667.3 \pm 2.2$</td>
<td>$1674.3 \pm 3.5$</td>
</tr>
<tr>
<td>$\Upsilon(3S) \rightarrow \mu^+ \mu^-$, $10^3$</td>
<td>$328.8 \pm 1.5$</td>
<td>$786.6 \pm 2.6$</td>
</tr>
</tbody>
</table>

R. Aaij et al., JHEP 1511, 103 (2015)
Production at 7 and 8 TeV – II

Differential cross sections \( \frac{d\sigma}{dp_T} (\Upsilon \rightarrow \mu^+ \mu^-) \) at 7 and 8 TeV

The curves - the fit results with the Tsallis function at 6 < \( p_T \) < 30 GeV/c,

\[ \frac{d\sigma}{dp_T} \propto \left( 1 + \frac{E_{\text{kin}}}{nT} \right)^{-n} \quad \text{and} \quad \propto p_T^{-n} \] at high \( p_T \)

R. Aaij et al., JHEP 1511, 103 (2015)
Differential cross sections $\frac{d}{dy} \sigma(\Upsilon \rightarrow \mu^+ \mu^-)$ at 7 and 8 TeV at $p_T < 30$ GeV/c

Thick lines - fit results with the CO model at $2.5 < y < 4.0$, dashed - full $2.0 < y < 4.5$

R. Aaij et al., JHEP 1511, 103 (2015)
Ratios of differential cross sections $\frac{d}{dp_T} \sigma(\Upsilon \rightarrow \mu^+\mu^-)$ at 8 and 7 TeV

Left - linear fit and NRQCD (thick), right - CO model predictions

R. Aaij et al., JHEP 1511, 103 (2015)
The production ratios integrated over $2.0 < y < 4.5$ and $p_T < 30 \text{ GeV}/c$

$R_{ij}$: little dependence on rapidity, increase with $p_T$

$R_{21}$ agrees with 0.27, $R_{31}$ exceeds 0.04 in the same model, but agrees with 0.14-0.22 for hybrid $\Upsilon(3S)$,


R. Aaij et al., JHEP 1511, 103 (2015)
Forward $J/\psi$ Production at 13 TeV – I

LHCb used 3.05 pb$^{-1}$ collected at 13 TeV

$\sqrt{s} = 13$ TeV, $L_{int} = 3.05$ pb$^{-1}$

$3 < y < 3.5$

$2 < p_T < 3$ GeV/c

Invariant mass (left) and pseudodecay time (right)

$t_z = (z_{J/\psi} - z_{PV}) M_{J/\psi}/p_z$ separates prompt $J/\psi$ and $J/\psi$ from $b$ hadrons

R. Aaij et al., JHEP 1510, 172 (2015)
Forward $J/\psi$ Production at 13 TeV – II

LHCb used 3.05 pb$^{-1}$ collected at 13 TeV

Double differential cross section for prompt $J/\psi$ and $J/\psi$ from $b$-hadron decays

R. Aaij et al., JHEP 1510, 172 (2015)
Forward $J/\psi$ Production at 13 TeV – III

Ratios of differential cross sections between 13 and 8 TeV for (left) prompt $J/\psi$ and (right) $J/\psi$ from $b$ hadron decays

R. Aaij et al., JHEP 1510, 172 (2015)
Ratios of differential cross sections between 13 and 8 TeV integrated over $p_T$ for (left) prompt $J/\psi$ and (right) $J/\psi$ from $b$ hadrons. The FONLL prediction: M. Cacciari et al., JHEP 05, 007 (1998) R. Aaij et al., JHEP 1510, 172 (2015)
Forward $J/\psi$ Production at 13 TeV – V

Ratios of differential cross sections between 13 and 8 TeV integrated over $y$ for (left) prompt $J/\psi$ and (right) $J/\psi$ from $b$ hadrons

Data are compared to NRQCD and FONLL predictions

R. Aaij et al., JHEP 1510, 172 (2015)
The $J/\psi$ production cross section for (left) prompt $J/\psi$ and (right) $J/\psi$ from $b$ hadrons compared to FONLL

R. Aaij et al., JHEP 1510, 172 (2015)
Differential cross sections integrated over $y$, (left) compared to NRQCD for prompt $J/\psi$ and (right) to FONLL for $J/\psi$ from $b$ hadrons

R. Aaij et al., JHEP 1510, 172 (2015)
Summary

- Exclusive $J/\psi / \psi(2S)$ production at 7 TeV: good agreement with NLO and the models including saturation

- The first measurement of exclusive $\Upsilon(nS)$ production at 7/8 GeV: LO and NLO separated, agreement with NLO and refined models

- $\eta_c(1S)$ production at 7/8 TeV: first $B(b \rightarrow \eta_c(1S) + X)$, $\sigma_{\text{prompt}}$ agrees with CS LO, CO LO is too high, precise $\Delta M_{J/\psi, \eta_c(1S)}$

- Forward production of $\Upsilon$ at 7/8 TeV: the double differential $\sigma_{\text{prod}}$ measured as a function of $p_T$ and $y$, the measured increase in $\sigma_{\text{prod}}$ between 8 and 7 TeV significantly exceeds theory expectations, for $p_T < 15$ GeV/c the results agree with the previous and supersede them

- Forward production of $J/\psi$ at 13 TeV: the measured $\sigma_{\text{prompt}}(p_T)$ agrees with NRQCD, FONLL describes well the cross section for $J/\psi$ from $b$ hadrons and its $\sqrt{s}$ dependence, but the prediction is below $\sigma(13)/\sigma(8)$
Double differential cross sections $\frac{d^2\sigma}{dp_T dy}(\Upsilon \to \mu^+ \mu^-)$ at 8 TeV

R. Aaij et al., JHEP 1511, 103 (2015)
Double differential cross sections $\frac{d^2}{dp_T dy} \sigma(\Upsilon \rightarrow \mu^+ \mu^-)$ at 7 TeV

R. Aaij et al., JHEP 1511, 103 (2015)
The production ratios for $\Upsilon(2S) \rightarrow \Upsilon(1S)$, $\Upsilon(3S) \rightarrow \Upsilon(1S)$, $\Upsilon(3S) \rightarrow \Upsilon(2S)$ at 7 TeV

R. Aaij et al., JHEP 1511, 103 (2015)
Forward $J/\psi$ Production at 13 TeV – III

Fractions of $J/\psi$ mesons from $b$-hadron decays

R. Aaij et al., JHEP 1510, 172 (2015)

$F_b = \frac{\text{Number of } J/\psi \text{ from } b\text{-hadron decays}}{\text{Total number of } J/\psi}$
Forward $J/\psi$ Production at 13 TeV – III

Differential cross section integrated over $y$
for (left) prompt $J/\psi$ and (right) $J/\psi$ from $b$-hadron decays

R. Aaij et al., JHEP 1510 (2015) 172
Forward $J/\psi$ Production at 13 TeV – V

Differential cross section integrated over $p_T$
for (left) prompt $J/\psi$ and (right) $J/\psi$ from $b$-hadron decays

R. Aaij et al., JHEP 1510, 172 (2015)