Production measurements at LHCb

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Outline

• Introduction

• Production cross-sections

• Polarization ($J/\psi, \psi(2S)$)

• Associated production

• Future prospects

• Summary

Biased selection on quarkonia
Introduction

• Heavy flavor productions are tools to understand QCD
  ➢ Polarization measurements put further constraints to QCD-based models
  ➢ Better understanding of QCD is fundamental and essential for new physics searches

• LHCb is optimized for precision measurements in $b, c$ quark sectors
  ➢ Excellent tracking, vertexing, hadron and muon identification
  ➢ Kinematic coverage is unique: $2 < y < 4.5$, down to zero $p_T$

• Brief review of LHCb measurements
  ➢ Including comparisons with theories

List of LHCb measurements on quarkonia
Productions in pp collisions

- $J/\psi$ @ 2.76, 7, 8, 13 TeV
- $\psi(2S)$ @ 7 TeV
- $Y(nS)$ @ 7, 8 TeV
- $\chi_c$ @ 7 TeV
- $\chi_b$ @ 7/8 TeV

EPJC71 (2011) 1645
EPJC72 (2012) 2025
EPJC72 (2012) 2100
JHEP 02 (2013) 41
JHEP 06 (2013) 64
JHEP 11 (2015) 103
JHEP 10 (2015) 172
JHEP 11 (2012) 31
PLB718 (2012) 431
JHEP 10 (2013) 115
EPJC74 (2014) 3092
Quarkonia production at LHCb

- Measurements are mostly performed in $\mu^+ \mu^-$ final states, clean and easy to trigger
- Prompt $\psi$ and $\psi$ from $b$ decays are separated using pseudo decay time, $t_z$
  - Thanks to LHCb vertex detector
  - $\psi$ from $b$ is indirect probe of $b\bar{b}$ hadron production

$$t_z = \frac{(Z_{J/\psi} - Z_{PV}) \times M_{J/\psi}}{p_z}$$

JHEP 10 (2015) 172

LHCb

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

3 $< y < 3.5$

2 $< p_T < 3 \text{ GeV/c}$

Candidates per 5 MeV/c$^2$

Candidates per 0.2 ps

Data

Total fit

$J/\psi$-from-$b$

Prompt $J/\psi$

Wrong PV

Background
\( \sigma(J/\psi) \) as a function of \( \sqrt{s} \)

\[ \sigma(J/\psi, \text{prompt}) \text{ scales almost linearly with } \sqrt{s} \text{ in range 2.76-13 TeV} \]

\[ \sigma(J/\psi, \text{from b}) \text{ well described by FONLL prediction [JHEP05 (1998) 007]} \]
$p_T$ distributions: prompt $\psi$


- In good agreement with NLO NRQCD predictions
- NLO or NNLO* CSM calculations underestimates data
$p_T$ distributions: $\psi$ from $b$


Data consistent with FONLL calculations

See backup slide for $\psi(2S)$ from $b$
$p_T$ distributions: $\Upsilon @ 7$ TeV

- $p_T$ distributions consistent with NRQCD and CEM, but not with CSM
- NLO (NNLO*) CSM calculations underestimate $p_T$ differential cross-section
- Agreement with NRQCD and CEM are better
Ratio of $\sigma(J/\psi)$ at 13, 8 TeV

Uncertainties largely cancel

- Cross-section ratio between 13 and 8 TeV increases with $p_T$
- Ratio for prompt $J/\psi$ is consistent with NLO NRQCD predictions
- Agreement with FONLL also not bad
Ratio of $\sigma(\Upsilon)$ at 8, 7 TeV

- Cross-section increases by 30% from 7 to 8 TeV on average
- The ratio increases with $p_T$, magnitude not quite predicted by NRQCD
- The ratio has unexpected trend at small $y$
- Not compatible with COM calculations
Ratio of $\sigma(b)$ at $\sqrt{S} = 13/7(8)$

$b\bar{b}$ cross-section with semileptonic decays

$B^+$ cross-section using $B^+ \rightarrow J/\psi K^+$

Cross-section ratio measurements using semileptonic decays and exclusive decay are consistent. Behavior not predicted by FONLL.
Production for excited states

\[ \sigma(Y(nS))/\sigma(Y(1S)) \text{ at } 7 \text{ TeV} \]

LHCb: JHEP 06 (2013) 64, EPJC72 (2012) 2100

\[ \sigma(\psi(2S))/\sigma(J/\psi) \text{ at } 7 \text{ TeV} \]

Ratios increase with \( p_T \), constant as a function of \( y \)

Results are important to determine feed-down fractions
$\chi_c$ production

- $\frac{\sigma(\chi_c)}{\sigma(J/\psi)}$ increases with $p_T$
- $\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})}$ decreases with $p_T$ at low $p_T$ then becomes flat at mid $p_T$
- Data well predicted by NRQCD models

\( \chi_b \) production

- \( \chi_b(nP) \to Y(1S)\gamma \)
- \( \chi_b(3P) \to Y(3S)\gamma \)

**LHCb:** EPJC74 (2014) 3092

- \( Y(nS) \) has a large and similar fraction from decays of \( \chi_b(nP) \) states, 30-40%
- No evidence of dependence on pp colliding energy
Prospects

• Several analyses of quarkonia cross-section @ 13 TeV finalizing
• Cross-section measurements using 5 TeV pp special run data
• More will follow
Differential production cross-section of $B_c^+$ in pp collisions

PRL 114 (2015) 132001
$B_c^+$ production

- LHC is a factory of $B_c^+$ meson, decays extensively studied at LHCb
- $B_c^+$ differential cross-section precisely measured at LHCb

$$R(p_T, y) \equiv \frac{d\sigma_{B_c^+}(p_T, y)}{d\sigma_{B^+}(p_T, y)} \frac{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$$

Polarization of quarkonia in pp collisions

- $J/\psi$ and $\psi(2S)$ polarisation

EPJC73 (2013) 2631
EPJC74 (2014) 2872
Polarisation results


- Data consistent with no/small polarization
- No strong $p_T$ dependence
- Rule out NLO CSM predictions
- NLO NRQCD calculations also not satisfactory

NLO NRQCD
PRL 108 (2012) 172002
PRL 110 (2013) 042002
PRL 108 (2012) 242004
NLO CSM
PRL 108 (2012) 172002
Prospects

- Υ (nS) polarization measurement finalizing: preliminary results suggests tiny polarization, no evidence of $p_T$ dependence up to 20 GeV
Associated production

- $J/\psi$ + open charm
- $\Upsilon$ + open charm
- Double $J/\psi$

JHEP 06 (2012) 141
JHEP 07 (2016) 052
PLB707 (2012) 52
Double $J/\psi \oplus J/\psi$ @ 7 TeV

Measured with a small amount of data

\[
\sigma_{J/\psi J/\psi} = 5.1 \pm 1.5 \text{ nb}
\]

\[
\frac{\sigma_{J/\psi J/\psi}}{\sigma_{J/\psi}} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}
\]

- Data agree with theoretical calculations [PRD 84 (2001) 094023] within uncertainty
- Analyses with full 7 TeV dataset, and 13 TeV data @ 2015 are ongoing
$J/\psi + \text{open charm}$

- Correlation between $J/\psi$ and $D^0$ is small
- $J/\psi$ $p_T$ distribution is harder than inclusive

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sigma$ [nb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi D^0$</td>
<td>$161.0 \pm 3.7 \pm 12.2$</td>
</tr>
<tr>
<td>$J/\psi D^+$</td>
<td>$56.6 \pm 1.7 \pm 5.9$</td>
</tr>
<tr>
<td>$J/\psi D_s^+$</td>
<td>$30.5 \pm 2.6 \pm 3.4$</td>
</tr>
<tr>
<td>$J/\psi \Lambda_c^+$</td>
<td>$43.2 \pm 7.0 \pm 12.0$</td>
</tr>
</tbody>
</table>
\( \Upsilon + \text{open charm} \)

\[
\begin{align*}
\mathcal{B}_{\mu^+\mu^-} \times \sigma_{\Upsilon(1S)D^0}^{\sqrt{s}=7\text{ TeV}} &= 155 \pm 21 \text{ (stat)} \pm 7 \text{ (syst)} \text{ pb} \\
\mathcal{B}_{\mu^+\mu^-} \times \sigma_{\Upsilon(1S)D^+}^{\sqrt{s}=7\text{ TeV}} &= 82 \pm 19 \text{ (stat)} \pm 5 \text{ (syst)} \text{ pb} \\
\mathcal{B}_{\mu^+\mu^-} \times \sigma_{\Upsilon(1S)D^0}^{\sqrt{s}=8\text{ TeV}} &= 250 \pm 28 \text{ (stat)} \pm 11 \text{ (syst)} \text{ pb} \\
\mathcal{B}_{\mu^+\mu^-} \times \sigma_{\Upsilon(1S)D^+}^{\sqrt{s}=8\text{ TeV}} &= 80 \pm 16 \text{ (stat)} \pm 5 \text{ (syst)} \text{ pb}
\end{align*}
\]

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\text{LHCb: JHEP 07 (2016) 052}
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- \( \Upsilon \) \( p_T \) and \( y \) distributions compatible with inclusive productions (as DPS)
- Data are consistent with theoretical calculations [SPS from S. P. Barano: \( k_T \)-factorization and collinear approximation]

14/10/2016

LHCb Implication Workshop (Yanxi ZHANG)
\( \Upsilon + \) open charm

Assume \( \Upsilon \) and \( D \) produced independently (as DPS)

SPS: [S. P. Barano: \( k_T \)-factorization and collinear approximation]

Data suggest \( \Upsilon \) and \( D \) are not correlated, favor DPS production
Effective cross-section: $\sigma_{\text{eff}}$

- Assume associated production is purely from Double Parton Scattering:

$$\sigma_{\text{eff}} = \alpha \frac{\sigma_{c_1} \times \sigma_{c_2}}{\sigma_{\text{DPS=asso.}}_{c_1 c_2}}$$

<table>
<thead>
<tr>
<th>J/$\psi$ D$^0$</th>
<th>J/$\psi$ D$^+$</th>
<th>J/$\psi$ D$^+_s$</th>
<th>J/$\psi$ $\Lambda^+_c$</th>
</tr>
</thead>
</table>

$LHCb$: JHEP 06 (2012) 141
JHEP 07 (2016) 052

Consistent with Tevatron (jets): $\sigma_{\text{DPS}}^{\Upsilon(1S)D^0,+,\sqrt{s}=7\text{ TeV}} = 18.0 \pm 2.1 \text{ (stat)} \pm 1.2 \text{ (syst)} = 18.0 \pm 2.4 \text{ mb}$

$\sigma_{\text{eff}}^{\Upsilon(1S)D^0,+,\sqrt{s}=8\text{ TeV}} = 17.9 \pm 1.8 \text{ (stat)} \pm 1.2 \text{ (syst)} = 17.9 \pm 2.1 \text{ mb}$

Dominated by DPS? Or $\sigma_{\text{eff}}$ is not universal?
Prospects

Double $J/\psi$ @ 13 TeV

~1K signals in 0.3 fb$^{-1}$
Analysis to be public soon

Evidence of $\Upsilon + J/\psi$ in LHCb RunI data

$\Upsilon(1S) + J/\psi \sim 4 \sigma$
$\Upsilon(2S) + J/\psi \sim 3 \sigma$
Production prospects with $100 \times$ more data
Analyses with 300 fb$^{-1}$

- Inclusive productions already in good precision with RunI and early RunII data, however with many more data we make precise measurements of
  - $\chi_b(nP)$ production and decay
  - Associated production including bottom quark
    - $\psi + \psi$: $\sim 1M$ double $J/\psi$ and $\sim 1K \psi(2S) + \psi(2S)$
    - $\Upsilon(nS) + \psi$: $\sim 5K$ for $\Upsilon(1S) + J/\psi$
    - $\Upsilon(nS) + \Upsilon(nS)$: $\sim 50 \Upsilon(1S) + \Upsilon(1S)$
    - Double open $B$: expect $\sim 100$ double fully reconstructed $B^+ \rightarrow J/\psi K^+$ decays, many more if studying detached $J/\psi$
    - $\Upsilon(nS) + B$: could explore $\Upsilon(nS)$ + detached $J/\psi$ ($\sim 1000$), or $\Upsilon(nS)$+exclusive B decay ($\sim 100$)
Summary

• LHCb studied productions using RunI data for
  ➢ Charmonia: $J/\psi$ (also RunII), $\psi(2S)$, $\chi_c(1P)$, $\eta_c$ …
  ➢ Bottomonia: $\Upsilon(nS)$, $\chi_b(nP)$, …
  ➢ $B_{c}^{+}$ state
  ➢ $J/\psi + D$, $\Upsilon + D$, $J/\psi + J/\psi$, …
• Also measured the polarization for
  ➢ $J/\psi$ and $\psi(2S)$
• More measurements using RunI and early RunII data will come out soon
  ➢ $\psi(2S)$ and $\Upsilon(nS)$ productions at 5 and 13 TeV
  ➢ $\Upsilon(nS)$ polarization measurements
• With 300/fb data, we could explore more (precise) associated production, especially $\Upsilon(nS)$+…

Thank you for your attention
Backups
$p_T$ distributions (prompt $J/\psi$ @ 7 TeV)

LO/NLO NRQCD

[Pos ICHEP 2010 192]
[PRL 106(2011)022301]

NLO/NNLO CSM

[PLB653,60]
[PRL98,252002]
[PRL101,152001]
[EPJC61,693]

NLO NRQCD With feed-down

[PRL106,042002]

CEM [PR462,125]
$p_T$ distributions ($\psi(2S)$ from $b$)
$p_T$ distributions ($\Upsilon@7$ TeV)

Left:

- LHCb data ($2.0<y<4.5$)
- direct NNLO* CSM ($2.0<y<4.5$)
- direct NLO CSM ($2.0<y<4.5$)

Right:

- LHCb data ($2.0<y<4.5$)
- direct NNLO* CSM ($2.0<y<4.5$)
- direct NLO CSM ($2.0<y<4.5$)

NLO/NNLO* CSM

[PRL101,152001,PRL98,252002]
$p_T$ distributions for $\Upsilon(nS)$

**Description of Graphs:**

- **Graph (a):** $\Upsilon(1S)$ data compared to direct NNLO* CSM and direct NLO CSM predictions. The data is shown as black dots, while the predictions are indicated by colored bands.
  - **Y(1S) LHCb $\sqrt{s} = 8$ TeV**
  - **Note:** Direct NNLO* CSM and direct NLO CSM underestimates $\Upsilon$ data and $p_T$ distributions not predicted.

- **Graph (b):** $\Upsilon(2S)$ data compared to direct NNLO* CSM and direct NLO CSM predictions.
  - **Y(2S) LHCb $\sqrt{s} = 8$ TeV**

- **Graph (c):** $\Upsilon(3S)$ data compared to direct NNLO* CSM and direct NLO CSM predictions.
  - **Y(3S) LHCb $\sqrt{s} = 8$ TeV**

**References:**

- Direct NNLO* CSM: [EPJC61, 693]
- Direct NLO CSM: [PRL98,252002]
Ratio of $\sigma(b)$ at $\sqrt{S} = 13/7(8)$

$B^+ \text{ cross-section using } B^+ \to J/\psi K^+$

$\bar{b}\bar{b}$ cross-section with semileptonic decays

Cross-section ratio measurements using semileptonic decays and exclusive decay are consistent. Behavior not predicted by FONLL.
$\chi_c$ reconstruction

- Converted photon v.s. CALO photon
$\eta_c$ production

- Prompt and secondary $\eta_c$ production
$\chi_b(1P)$ production

(a) $JHEP$ 10 (2014) 088

(b) $JHEP$ 10 (2014) 088

LHCb $\chi_b$
LHCb $\chi_c$ scaled
LO NRQCD

2.0 < $y$ < 4.5

Fraction of $J^{(1S)}$ from $\chi_b(1P)$ (%)

JHEP 11 (2012) 31
Polarization analysis

\[ \lambda_0 \]

LHCb $\sqrt{s} = 7 \text{ TeV}$

\[ p_T(J/\psi) \text{ [GeV/c]} \]

LHCb $\sqrt{s} = 7 \text{ TeV}$

\[ p_T(J/\psi) \text{ [GeV/c]} \]

pp $\sqrt{s} = 7 \text{ TeV}$

LHCb

ALICE

$2.5 < y < 4.0$

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$J/\psi + \text{open charm mass}$

- 2D mass plots
$J/\psi$ + open charm

- Invariant mass and charm $p_T$

Charm $p_T$ distributions similar to inclusive ones
$pPb$ data taking (2013)

- $pPb$ x