Heavy flavour production at LHCb

Fabio Ferrari on behalf of the LHCb collaboration

1Università di Bologna, Dipartimento di Fisica ed Astronomia, via Irnerio 46, Bologna, Italy
2INFN - Sezione di Bologna, viale B. Pichat 6/2, Bologna, Italy
E-mail: fabio.ferrari@cern.ch

Abstract. The LHCb experiment is able to measure the production properties of heavy hadrons in a phase-space region that is complementary with respect to those of the ATLAS and CMS experiments. These measurements provide valuable information that allows to better understand quantum chromodynamics and to discriminate among several theoretical models.

The measurement of the production cross-section of $\Upsilon(1S), \Upsilon(2S)$ and $\Upsilon(3S)$ mesons at a centre-of-mass energy of 13 TeV is presented, along with the determination of the production cross-section of $B^+$ mesons at $\sqrt{s} = 7$ and 13 TeV. Finally, the measurement of the $D_s^+$ production asymmetry at centre-of-mass energies of 7 and 8 TeV is also presented.

1. Introduction

The determination of the production properties of heavy hadrons is crucial to probe quantum chromodynamics (QCD) effects. In particular, the $\Upsilon$ production measurements at the LHC are important since they can provide useful insights about the hadronic production of heavy quarkonia. Different models have been proposed to describe these processes, see for example [1, 2, 3], and several measurements of the production properties of $\Upsilon$ mesons have been performed at centre-of-mass energies of 2.76 [4], 7 [5, 6, 7, 8] and 8 TeV [6, 7, 8].

The measurement of the production cross-section of $B^+$ mesons also provides important tests for the QCD and in particular for the most recent theoretical calculations based on fixed next-to-leading order (NLO) QCD with next-to-leading logarithm (NLL) large transverse momentum resummation (FONLL) approach [9]. The measurement of the production properties of $B^+$ mesons has been performed by the ATLAS [10], CMS [11, 12] and LHCb [13, 14] collaborations at different centre-of-mass energies.

The production rates of $c$ and $\bar{c}$ mesons are not expected to be the same in $pp$ collisions and this phenomenon, commonly referred to as production asymmetry, represents a key ingredient to perform $CP$ violation measurements. A previous determination of the $D_s^+$ production asymmetry has been obtained by the LHCb collaboration [15] using data collected at a centre-of-mass energy of 7 TeV.

2. Measurement of $\Upsilon$ production at $\sqrt{s} = 13$ TeV

The data sample used corresponds to an integrated luminosity of 277 pb$^{-1}$ collected at a centre-of-mass energy of 13 TeV. The cross-section as a function of the transverse momentum ($p_T$) and rapidity ($y$) of the $\Upsilon$ candidates times the branching fraction of the decay $\Upsilon \rightarrow \mu^+\mu^-$,
Figure 1. Figure coloured online. Single differential cross-sections times $B(\Upsilon \rightarrow \mu^+\mu^-)$ as a function of (left) $p_T$ and (right) $y$ for (black squares) $\Upsilon(1S)$, (light gray upward triangles) $\Upsilon(2S)$ and (dark gray downward triangles) $\Upsilon(3S)$. The shaded areas in the left plot represent the predictions from NRQCD.

$B(\Upsilon \rightarrow \mu^+\mu^-)$, can be written as

$$\frac{d^2\sigma}{dp_Tdy} \times B(\Upsilon \rightarrow \mu^+\mu^-) = \frac{N_{\text{sig}}(p_T,y)}{\mathcal{L} \times \varepsilon_{\text{tot}}(p_T,y) \times \Delta y \times \Delta p_T},$$

(1)

where $N_{\text{sig}}(p_T,y)$ and $\varepsilon_{\text{tot}}(p_T,y)$ are the signal yield and total efficiency in a given $(p_T,y)$ bin, $\mathcal{L}$ is the integrated luminosity, and $\Delta p_T$ and $\Delta y$ are the bin widths.

Extended unbinned maximum-likelihood fits to the dimuon invariant mass are performed to extract the number of signal candidates. The total number of signal yields is $397\,841 \pm 381$ for $\Upsilon(1S)$, $99\,790 \pm 469$ for $\Upsilon(2S)$ and $50\,677 \pm 381$ for $\Upsilon(3S)$.

The detector acceptance, selection and trigger efficiencies are determined from simulated events, whereas the particle identification (PID) efficiency is obtained from large calibration samples of $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow \mu^+\mu^-$ decays. The tracking efficiency is obtained from simulation and then corrected by means of data-driven techniques.

The total cross-sections times $B(\Upsilon \rightarrow \mu^+\mu^-)$ in the range $0 < p_T < 15$ GeV/c and $2.0 < y < 4.5$ are determined to be

$$\sigma(\Upsilon(1S)) \times B(\Upsilon(1S) \rightarrow \mu^+\mu^-) = 4687 \pm 10 \pm 294 \text{ pb},$$
$$\sigma(\Upsilon(2S)) \times B(\Upsilon(2S) \rightarrow \mu^+\mu^-) = 1134 \pm 6 \pm 71 \text{ pb},$$
$$\sigma(\Upsilon(3S)) \times B(\Upsilon(3S) \rightarrow \mu^+\mu^-) = 561 \pm 4 \pm 36 \text{ pb},$$

where the first uncertainties are statistical and the second systematic. By integrating the double-differential cross-sections over the transverse momentum (rapidity) of the dimuon candidates, the cross-section as a function of the rapidity (transverse momentum) is obtained. The results are shown in Fig. 1, together with the predictions from non-relativistic QCD [3], that describe well the data in the high $p_T$ region.

3. Measurement of $B^+$ production at $\sqrt{s} = 7$ and 13 TeV

The data samples used correspond to integrated luminosities of 1.0 fb$^{-1}$ and 0.3 fb$^{-1}$ collected at centre-of-mass energies of 7 and 13 TeV, respectively. The double-differential cross-section can be expressed as

$$\frac{d^2\sigma}{dp_Tdy} = \frac{N_{\text{sig}}(p_T,y)}{\mathcal{L} \times \varepsilon_{\text{tot}}(p_T,y) \times B(B^+ \rightarrow J/\psi K^+) \times B(J/\psi \rightarrow \mu^+\mu^-) \times \Delta y \times \Delta p_T},$$

(2)
where $N_{\text{sig}}(p_T, y)$ and $\varepsilon(p_T, y)$ are the signal yield and total efficiency in a given $(p_T, y)$ bin, $\mathcal{L}$ is the integrated luminosity, $B(B^+ \rightarrow J/\psi K^+)$ is the branching ratio of $B^+$ decays to $J/\psi K^+$, $B(J/\psi \rightarrow \mu^+\mu^-)$ is the branching ratio of $J/\psi$ decays to $\mu^+\mu^-$ [16] and $\Delta y$ and $\Delta p_T$ are the bin widths. The value $B(B^+ \rightarrow J/\psi K^+) = (1.044 \pm 0.040) \times 10^{-3}$ is obtained by combining previous determinations from Belle [17] and BaBar [18] collaborations.

The signal yields are obtained by means of extended unbinned maximum-likelihood fits to the reconstructed $B^+$ invariant mass. The total efficiency is the product of several components. The detector acceptance, particle reconstruction and selection efficiencies are measured using simulated events, while the PID and tracking efficiencies are obtained from a large calibration sample of $J/\psi \rightarrow \mu^+\mu^-$ decays. The trigger efficiency is determined both with data-driven techniques and simulated events.

The production cross-sections of $B^+$ mesons integrated in the range $0 < p_T < 40$ GeV/$c$ and $2.0 < y < 4.5$ for 7 and 13 TeV data are found to be

$$\sigma(pp \rightarrow B^+X)_{\sqrt{s}=7\,\text{TeV}} = 43.0 \pm 0.2 \pm 2.5 \pm 1.7 \mu b,$$

$$\sigma(pp \rightarrow B^+X)_{\sqrt{s}=13\,\text{TeV}} = 86.6 \pm 0.5 \pm 5.4 \pm 3.4 \mu b,$$

where the first uncertainties are statistical, the second are systematic and the third are due to the limited knowledge of $B(B^+ \rightarrow J/\psi K^+)$. By integrating the results over the transverse momentum (rapidity) of the signal candidates, the cross-section as a function of the rapidity (transverse momentum) is obtained and it is shown in Fig. 2 for 13 TeV data. An interesting quantity to measure is the ratio between the cross-sections measured at $\sqrt{s} = 7$ and 13 TeV, since most of the systematic uncertainties cancel out. The obtained results as a function of $p_T$ and $y$ are shown in Fig. 3. Both the differential cross-sections and the ratios show a good agreement with the most recent FONLL predictions.

4. Measurement of $D_s^+$ production asymmetry at $\sqrt{s} = 7$ and 8 TeV

The data samples used correspond to integrated luminosities of 1.0 fb$^{-1}$ and 2.0 fb$^{-1}$ collected at centre-of-mass energies of 7 and 8 TeV, respectively. Assuming that the CP violation in the Cabibbo favour $D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\pi^+$ decay is negligible, the production asymmetry can be written as the sum of various components

$$A_P = \frac{1}{1 - f_{\text{bkg}}} (A_{\text{raw}} - A_D - f_{\text{bkg}}A_{\text{sec}}),$$

(3)
The fraction of samples of charm mesons decays and includes the tracking, PID and trigger asymmetries. The detection asymmetry is determined by means of data-driven techniques using large calibration is di
where the first uncertainty is statistical and the second systematic. The production asymmetry is measured in different \((p_T, y)\) bins to check any dependence on such quantities.

The raw asymmetry is defined as \(A_{\text{raw}} \equiv \frac{[N(D_s^+)] - [N(D_s^-)]}{[N(D_s^+) + N(D_s^-)]}\), where \(N(D_s^+)\) (\(N(D_s^-)\)) is the observed number of \(D_s^+\) (\(D_s^-\)) signal candidates, obtained by means of binned maximum-likelihood fits to the \(K^+K^-\pi^+\) (\(K^+K^-\pi^-\)) invariant-mass spectra. The detection asymmetry is determined by means of data-driven techniques using large calibration samples of charm mesons decays and includes the tracking, PID and trigger asymmetries. The fraction of \(D_s^+\) mesons produced from a \(b\)-hadron decay is obtained from simulation and measurements of cross-sections [14, 19] and branching fractions [16]. Finally, the \(b\)-hadron production asymmetries are taken from previous LHCb measurements [20, 21, 22].

The \(D_s^+\) production asymmetry integrated in the range \(2.5 < p_T < 25\ \text{GeV}/c\) and \(2.0 < y < 4.5\) is found to be

\[
A_P = (-0.52 \pm 0.13 \pm 0.10)\%,
\]
where the first uncertainty is statistical and the second systematic. The production asymmetry is different from zero at the 3.3\(\sigma\) level.

The results as a function of the transverse momentum of \(D_s^+\) candidates in different rapidity bins are shown in Fig. 4, together with the prediction obtained from the PYTHIA 8.1 event
generator. The strong dependence of the production asymmetry on the transverse momentum in simulated events is not observed in data.

5. Conclusions
The measurement of heavy hadron-production properties is important to better understand QCD. Thanks to its unique forward geometry, the LHCb experiment is able to measure heavy-hadron production in a kinematic region complementary to those of the ATLAS and CMS experiments. The results shown here can be utilized to discriminate between several theoretical models and to tune the production mechanisms present in the event generators.

References
[1] Fritzsch H 1977 Phys. Lett. B 67 217
[2] Baier R and Ruckl R 1981 Phys. Lett. B 102 364
[3] Bodwin G T, Braaten E and Lepage G P 1995 Phys. Rev. D 51 1125
[4] Aaij R et al. (LHCb collaboration) 2014 Eur. Phys. J. C 74 no.4 2835
[5] Aaij R et al. (LHCb collaboration) 2012 Eur. Phys. J. C 72 2025
[6] Aaij R et al. (LHCb collaboration) 2015 JHEP 09 084
[7] Aaij R et al. (LHCb collaboration) 2015 JHEP 11 103
[8] Aaij R et al. (LHCb collaboration) 2017 JHEP 12 110
[9] Cacciari M, Frixione S and Nason P 2001 JHEP 03 006
[10] Aalld G et al. (ATLAS collaboration) 2013 JHEP 10 042
[11] Khachatryan V et al. (CMS collaboration) 2011 Phys. Rev. Lett. 106 112001
[12] Khachatryan V et al. (CMS collaboration) 2017 Phys. Lett. B 771 435
[13] Aaij R et al. (LHCb collaboration) 2012 JHEP 04 093
[14] Aaij R et al. (LHCb collaboration) 2013 JHEP 08 117
[15] Aaij R et al. (LHCb collaboration) 2012 Phys. Lett. B 713 186
[16] Tanabashi M et al. (Particle Data Group) Review of particle physics, Phys. Rev. D 98 (2018) 030001
[17] Abe K et al. (Belle collaboration) 2003 Phys. Rev. D 67 032003
[18] Aubert B et al. (BaBar collaboration) 2005 Phys. Rev. Lett. 94 141801
[19] Aaij R et al. (LHCb collaboration) 2014 JHEP 08 143
[20] Aaij R et al. (LHCb collaboration) 2017 Phys. Rev. D 95 no.5 052005
[21] Aaij R et al. (LHCb collaboration) 2017 Phys. Lett. B 774 139
[22] Aaij R et al. (LHCb collaboration) 2015 Phys. Rev. Lett. 114 041601