PROCEEDINGS OF SCIENCE

Heavy flavour production at LHCb

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The LHCb experiment is able to measure the production properties of heavy hadrons in a region that is complementary with respect to those of the ATLAS and CMS experiments. These measurements provide useful information to better understand quantum chromodynamics and to discriminate between theoretical models. The determination of the production cross-sections of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ in pp collisions at a centre-of-mass energy of 13 TeV is presented, together with the measurement of the production cross-section of B^+ mesons in pp collisions at centre-of-mass energies of 7 and 13 TeV. Finally, the measurement of the D_s^+ production asymmetry at $\sqrt{s} = 7$ and 8 TeV is also reported.

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1. Introduction

Measurements of Υ production are a good probe of quantum chromodynamics (QCD) and can provide useful information about the hadronic production of heavy quarkonia. Several models have been proposed to discuss the underlying dynamics, such as the colour-singlet model (CSM) [1, 2, 3, 4, 5, 6, 7] and non-relativistic QCD (NRQCD) [8, 9, 10]. The production properties of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons have already been measured by LHCb at centre-of-mass energies of 2.76 [11], 7 [12, 13, 14, 15] and 8 TeV [13, 14, 15].

The B^+ production measurements provide an important test for the most recent calculations based on fixed next-to-leading order (NLO) QCD with next-to-leading logarithm (NLL) large transverse momentum resummation (FONLL) approach [16, 17]. The B^+ production cross-section has been measured at different centre-of-mass energies by the CMS [18, 19], ATLAS [20] and LHCb [21, 22] collaborations.

At LHC energies about one in ten collisions produces a charmed hadron. The production rates of hadrons containing c or $\bar{c}$ quarks (*e.g.* D_s^+ and D_s^- mesons) are not expected to be equal in pp collisions, as c and $\bar{c}$ quarks may combine with u and d valence quarks from the beam remnant, and production asymmetries may arise as a consequence of this fact. A previous measurement of the D_s^+ production asymmetry has been performed by the LHCb collaboration [23] using only data collected at a centre-of-mass energy of 7 TeV.

2. Υ production in pp collisions 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 [24]. The Υ candidates are built from two muons with large momentum and transverse momentum. The two particles are also required to form a good quality vertex and to have an invariant mass in the range $8.5 < M(\mu^+\mu^-) < 11.5$ GeV/c^2.

The double-differential production cross-section times dimuon branching fraction, $\mathscr{B}(\Upsilon \to \mu^+\mu^-)$, is defined as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \mathscr{B}(\Upsilon \to \mu^+\mu^-) = \frac{N_{\mathrm{sig}}(p_{\mathrm{T}}, y)}{\mathscr{L} \times \varepsilon_{\mathrm{tot}}(p_{\mathrm{T}}, y) \times \Delta y \times \Delta p_{\mathrm{T}}}, \quad (2.1)$$

where $N_{\mathrm{sig}}(p_{\mathrm{T}}, y)$ is the signal yield in a given (p_{T}, y) bin, $\mathscr{L}$ is the integrated luminosity, $\varepsilon_{\mathrm{tot}}(p_{\mathrm{T}}, y)$ is the total efficiency as a function of p_{T} and y and Δp_{T} and Δy are the bin widths.

In order to obtain the signal yields, extended unbinned maximum likelihood fits to the dimuon invariant-mass distribution are performed in each bin. The signal components are described by three Crystal Ball functions, one for each Υ, while the combinatorial background is modelled by an exponential function. The tail parameters of the Crystal Ball functions, the mass difference between the Υ states and the ratios of the resolution parameters are fixed to common values for all the fits. The dimuon invariant-mass distribution in the range $0 < p_{\mathrm{T}} < 30$ GeV/c and $2.0 < y < 4.5$ is shown in Fig. 1, with the results of the fit overlaid to the data points. The total number of signal events is $397\,841 \pm 796$ for $\Upsilon(1S)$, $99\,790 \pm 469$ for $\Upsilon(2S)$ and $50\,677 \pm 381$ for $\Upsilon(3S)$.

The total efficiency is the product of several components. The detector acceptance, selection and trigger efficiencies are obtained from simulation. The tracking efficiency is obtained from

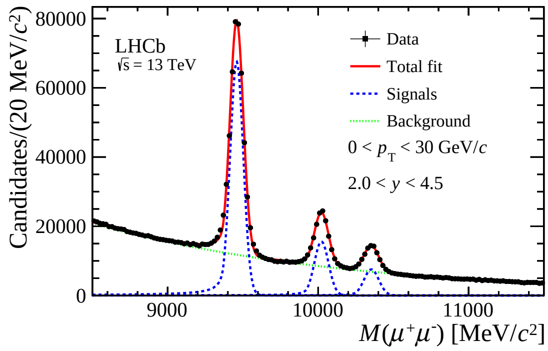

Figure 1: Dimuon invariant-mass distribution with the result of the fit overlaid to the data points.

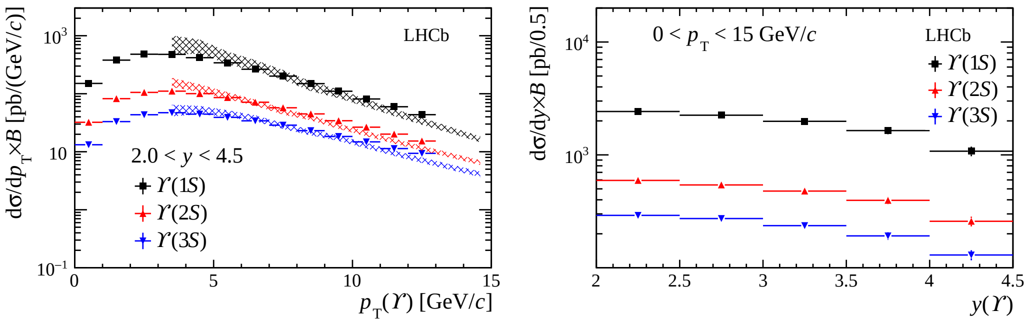

Figure 2: Single differential cross-sections times $\mathscr{B}(\Upsilon \to \mu^+\mu^-)$ as a function of (left) p_{T} and (right) y for (black squares) $\Upsilon(1S)$, (red upward triangles) $\Upsilon(2S)$ and (blue downward triangles) $\Upsilon(3S)$. The shaded areas in the left plot represent the predictions from NRQCD.

simulation and corrected by means of a data-driven technique, while the particle identification (PID) efficiency is obtained from control samples of $J/\psi \to \mu^+\mu^-$ and $\phi \to \mu^+\mu^-$ decays using a tag-and-probe approach.

Several sources of systematic uncertainties related to the choice of the fit model, the determination of the efficiencies and the measurement of the integrated luminosity have been investigated.

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

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

where the first uncertainties are statistical and the second systematic. Integrating the double-differential cross-section over p_{T} (y), the results as a function of y (p_{T}) are obtained and are shown in Fig 2. The experimental data at high p_{T} are described well by the predictions from NRQCD [25].

3. B^+ production in pp collisions at $\sqrt{s} = 7$ and 13 TeV

The data samples correspond to integrated luminosities of 1.0 fb^{-1} and 0.3 fb^{-1} at centre-of-mass

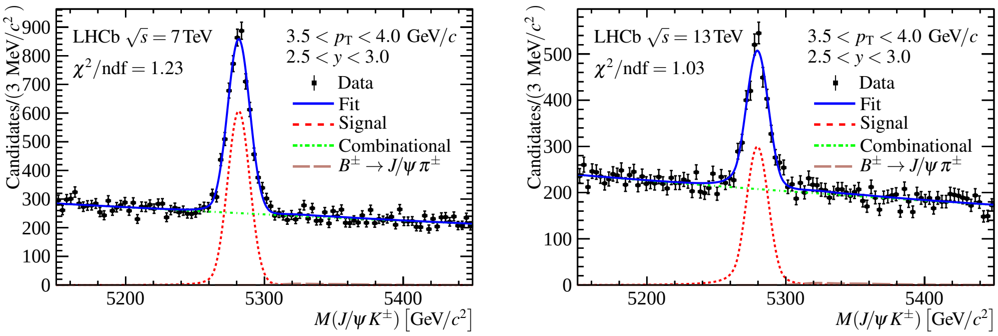

Figure 3: Invariant-mass distribution of $J/\psi K^+$ candidates with $3.5 < p_T < 4.0$ GeV/c and $2.5 < y < 3.0$ from data samples at the centre-of-mass energies of (left) 7 and (right) 13 TeV. The results of the fits to the $M(J/\psi K^+)$ distributions are overlaid to the data points.

energies of 7 and 13 TeV, respectively. Dimuon candidates are built from muons with large transverse momentum, satisfying track quality and PID requirements. The muon pair is also required to form a common vertex and its invariant mass needs to be consistent with the known J/ψ mass [26]. The B^+ candidates are formed by combining J/ψ and kaon candidates. The latter are required to have large transverse momenta (p_T) and to satisfy track quality criteria. No PID requirements are imposed on the kaons. The three tracks forming B^+ candidates need to form a common vertex and to have a lifetime larger than 0.3 ps, to suppress combinatorial background due to random association of tracks from the primary vertex (PV).

The double-differential cross section is defined as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T \mathrm{d}y} = \frac{N_{\mathrm{sig}}(p_T, y)}{\mathscr{L} \times \varepsilon_{\mathrm{tot}}(p_T, y) \times \mathscr{B}(B^+ \to J/\psi K^+) \times \mathscr{B}(J/\psi \to \mu^+\mu^-) \times \Delta y \times \Delta p_T}, \tag{3.1}$$

where $N_{\mathrm{sig}}(p_T, y)$ is the number of signal candidates in a given (p_T, y) bin, $\mathscr{L}$ is the integrated luminosity, $\varepsilon(p_T, y)$ is the total efficiency as a function of the B^+ transverse momentum and rapidity, $\mathscr{B}(B^+ \to J/\psi K^+)$ is the branching ratio of B^+ decays to $J/\psi K^+$, $\mathscr{B}(J/\psi \to \mu^+\mu^-)$ is the branching ratio of J/ψ decays to $\mu^+\mu^-$ [26] and Δy and Δp_T are the bin widths. The value $\mathscr{B}(B^+ \to J/\psi K^+) = (1.044 \pm 0.040) \times 10^{-3}$ is obtained by combining previous determinations from Belle [28] and BaBar [29] collaborations.

The signal yield in each kinematic bin is obtained by means of extended unbinned maximum likelihood fits to the $J/\psi K^+$ invariant mass $(M(J/\psi K^+))$. The probability density function consists in a modified Crystal Ball (CB) function [27] describing the signal component, an exponential function modelling the combinatorial background and double CB function parameterising the contamination from the Cabibbo suppressed $B^+ \to J/\psi \pi^+$ decay mode. The $M(J/\psi K^+)$ distribution in one (p_T, y) bin at different centre-of-mass energies is shown in Fig. 3, with the result of the fits overlaid to the data points.

The total efficiency is the product of several components. The detector acceptance, particle reconstruction and selection efficiencies are determined from simulation, whereas the muons PID and tracking efficiencies are obtained from a control data sample of $J/\psi \to \mu^+\mu^-$ decays. The trigger efficiency is estimated with both data-driven techniques and simulation.

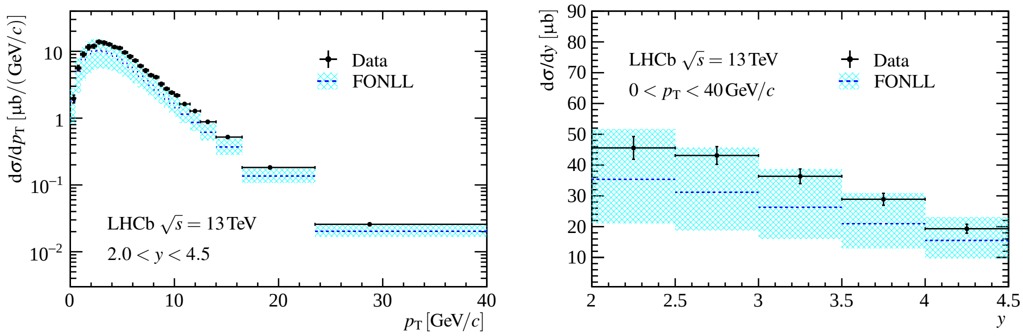

Figure 4: Differential production cross-section of B^+ candidates as a function of (left) p_T and (right) y for 13 TeV data. The shaded areas represent the FONLL predictions.

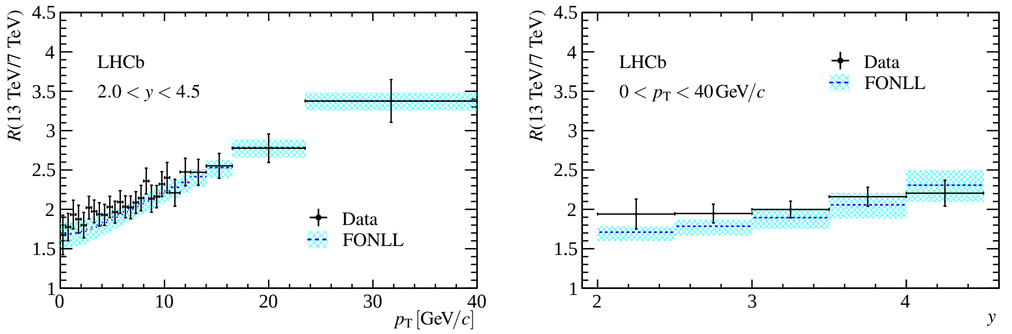

Figure 5: Cross-section ratio as a function of (left) p_T and (right) y. The shaded areas represent the FONLL predictions.

Several sources of systematic uncertainties related to the luminosity determination, branching fractions, signal yields and efficiencies have been investigated.

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

$$\sigma(pp \to B^+X)_{\sqrt{s}=7\text{ TeV}} = 43.0 \pm 0.2 \pm 2.5 \pm 1.7\ \mu\text{b},$$
$$\sigma(pp \to B^+X)_{\sqrt{s}=13\text{ TeV}} = 86.6 \pm 0.5 \pm 5.4 \pm 3.4\ \mu\text{b},$$

where the first uncertainties are statistical, the second are systematic and the third are due to the limited knowledge of $\mathcal{B}(B^+ \to J/\psi K^+)$.

Integrating the double-differential cross-sections over p_T (y), the cross-section as a function of y (p_T) is obtained. The distributions obtained from 13 TeV data are shown in Fig. 4. Taking the ratio between the results obtained at the two different centre-of-mass energies, most of the systematic uncertainties cancel out. The obtained ratios as a function of p_T and y are shown in Fig. 5. All results show good agreement with FONLL predictions [30] over the measured range.

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

The data sample corresponds to integrated luminosities of 1.0 fb^{-1} and 2.0 fb^{-1} at centre-of-mass

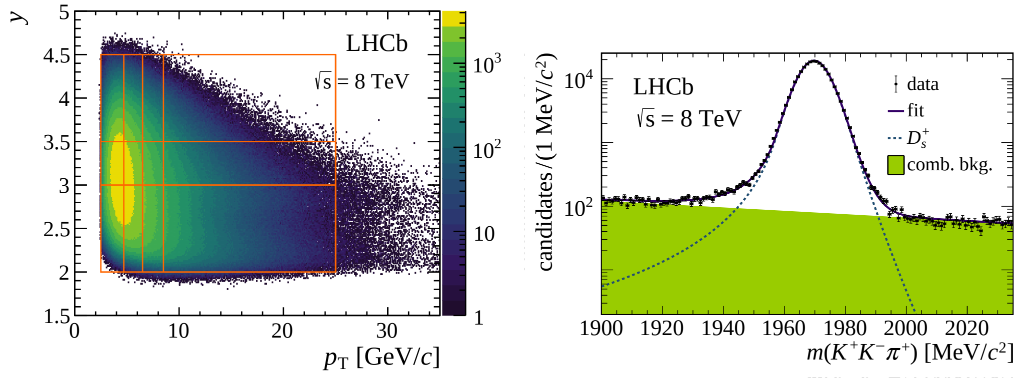

Figure 6: (left) Distribution of rapidity versus transverse momentum for $D_s^\pm$ candidates. The binning scheme used to measure the production asymmetry in different phase-space regions is also shown. (right) Invariant-mass distribution of $K^+K^-\pi^+$ candidates in the range $2.5 < p_{\mathrm{T}} < 4.7$ GeV/c and $2.0 < y < 3.0$. The results of the fit are overlaid to the data points.

energies of 7 and 8 TeV, respectively. The D_s^+ candidates are reconstructed in the $\phi(\to K^+K^-)\pi^+$ final state. The three tracks forming the D_s^+ meson are required not to point back to any PV and to have high momenta and transverse momenta. The D_s^+ candidates need to point to the PV and their decay vertices have to be significantly displaced from any PV. Kaons and pions are selected using PID criteria and the invariant mass of the kaon pair is required to be within 20 MeV/c^2 of the known ϕ mass [26].

Assuming that *CP* violation in the Cabibbo favoured $D_s^+ \to \phi(\to K^+K^-)\pi^+$ decay is negligible at the level of precision of this measurement, the production asymmetry can be obtained as

$$A_{\mathrm{P}} = \frac{1}{1-f_{\mathrm{bkg}}}(A_{\mathrm{raw}} - A_{\mathrm{D}} - f_{\mathrm{bkg}}A_{\mathrm{sec}}), \tag{4.1}$$

where f_{bkg} is the fraction of D_s^+ mesons produced from a b-hadron decay, A_{raw} is the raw asymmetry, A_{D} is the sum of various detection and instrumental asymmetries and A_{sec} is the production asymmetry of b-hadrons decaying to D_s^+ mesons. The raw asymmetry is defined as

$$A_{\mathrm{raw}} = \frac{N(D_s^+) - N(D_s^-)}{N(D_s^+) + N(D_s^-)}, \tag{4.2}$$

where $N(D_s^+)$ ($N(D_s^-)$) is the observed number of D_s^+ (D_s^-) signal candidates. The production asymmetry is measured in two-dimensional bins of transverse momentum and rapidity to check if it exhibits any dependence on these quantities. The (p_{T}, η) distribution of D_s^+ candidates for 8 TeV data is shown in the left part of Fig. 6, with the chosen binning scheme overlaid.

The raw asymmetry is measured by means of binned maximum-likelihood fits to the invariant mass of the $K^+K^-\pi^+$ final state. The signal component is modelled using an Hypathia function [31], while the combinatorial background is described by an exponential function. The distribution of the $K^+K^-\pi^+$ invariant mass in the range $2.5 < p_{\mathrm{T}} < 4.7$ GeV/c and $2.0 < y < 3.0$ is shown in the right part of Fig. 6, with the result of the fit overlaid to the data points.

The detection asymmetry is the sum of various components as tracking, PID and trigger asymmetries. All of these are obtained by means of data-driven techniques. The fraction of secondary

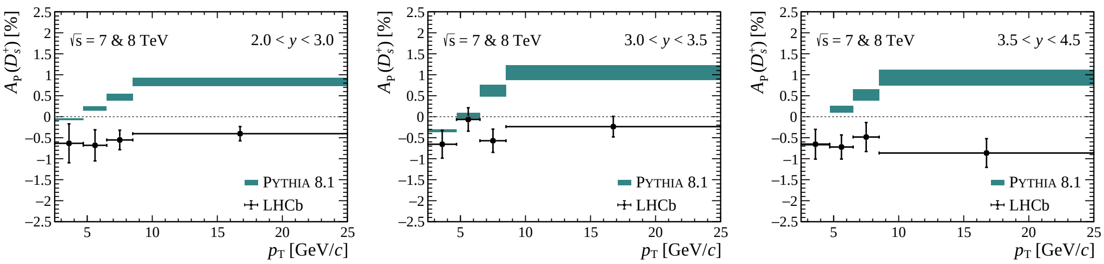

Figure 7: Production asymmetry of D_s^+ candidates as a function of the transverse momentum in the range (left) $2.0 < y < 3.0$, (middle) $3.0 < y < 3.5$ and (right) $3.5 < y < 4.5$. The shaded areas represent the production asymmetry obtained from the PYTHIA 8.1 event generator.

D_s^+ decays is obtained from simulation, cross-sections [22, 32] and branching fractions [26] measurements and it is found to be $f_{\rm bkg} = (4.12 \pm 1.23)\%$. The production asymmetries of b-hadrons are taken from external inputs [33, 34, 35].

Several sources of systematic uncertainties related to the choice of the fit model and to the determination of the detection asymmetries have been investigated.

The D_s^+ production asymmetry integrated in the range $2.5 < p_{\rm T} < 25$ GeV/c and $2.0 < y < 4.5$ is found to be

$$A_{\rm P} = (-0.52 \pm 0.13 \pm 0.10)\%,$$

where the first uncertainty is statistical and the second systematic. A deviation of 3.3 σ from the hypothesis of no production asymmetry is found.

The production asymmetry is also measured as a function of the transverse momentum and rapidity of the D_s^+ candidates. The results are shown in Fig. 7, together with the prediction obtained from the PYTHIA 8.1 event generator [36, 37]. The simulated events show a strong dependence on the D_s^+ transverse momentum that is not observed in data.

5. Conclusions

Thanks to its unique forward geometry, the LHCb experiment is able to measure heavy-hadron production in a kinematic region that is complementary to those of ATLAS and CMS. The determination of the production cross-section of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons at $\sqrt{s} = 13$ TeV is reported and found to be in agreement with the prediction from NRQCD in the high $p_{\rm T}$ region. The measurement of the production cross-section of B^+ mesons collected at centre-of-mass energies of 7 and 13 TeV is also presented and the results obtained are in agreement with FONLL predictions. Finally, a measurement of the D_s^+ production asymmetry with 7 and 8 TeV data is reported and a deviation of 3.3 σ from the hypothesis of no production asymmetry is found. No dependence of the production asymmetry on the candidates transverse momentum is observed, in contrast with the predictions of the PYTHIA 8.1 event generator.

The LHCb experiment is playing a key role in the quest for a better knowledge of heavy flavour production mechanisms. The results here presented can be utilised to discriminate between several theoretical models and can provide useful inputs to tune the production mechanisms in event generators.

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