Heavy Flavour and Quarkonia production at LHCb

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Abstract. The LHCb detector, with its excellent momentum resolution and flexible trigger strategy, is ideally suited for measuring heavy quark and quarkonia production properties. Recent LHCb measurements of inclusive and differential cross-sections of the production of $J/\psi$ and $\Upsilon$ resonances, as well as charm, bottom and top quarks, in $pp$ collisions at different centre-of-mass energies are presented. Finally, results on the associated production of $\Upsilon$ and open charm hadrons and the exclusive production of charmonium are discussed.

1. Introduction
Heavy-flavour hadrons, containing open or hidden charm and beauty flavour, are among the most important tools for the study of Quantum Chromodynamics (QCD) in high-energy hadronic collisions. The heavy-quark mass acts as a long distance cut-off so that the partonic hard-scattering process can be calculated in the framework of perturbative QCD (pQCD) down to low transverse momenta ($p_T$). The (differential) cross section for open-heavy-flavour production is sensitive to the gluon and the heavy-quark content in the proton. Due to the forward geometry of the LHCb detector, the LHCb measurements provide valuable constraints on these parton-distribution functions (PDFs) at high and low values of Bjorken-$x$. When the heavy-quark pair forms a quarkonium bound state, this process is non-perturbative as it involves long distances and soft momentum scales. Therefore, the detailed study of heavy-flavour production and the comparison to predictions provide an important testing ground for both perturbative and non-perturbative aspects of QCD calculations. The dominant uncertainties for the theoretical predictions originate from higher order contributions. However, by measuring ratios of cross-sections at different centre-of-mass-energies, $\sqrt{s}$, the scale uncertainties almost cancel, while some sensitivity to the PDFs remains.

2. LHCb detector
The LHCb detector [1] is a single-arm forward spectrometer, fully instrumented in the pseudorapidity range $2 < \eta < 5$. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the $pp$ interaction region and tracking stations in front and behind of the dipole magnet. To increase the pseudorapidity coverage, forward shower counters consisting of five planes of scintillators (HeRSChEL) at -114, -19.7, -7.5, +20 and +114 m from the interaction point have been installed for Run II, which started in 2015. The combination of VELO and HeRSChEL has sensitivity to particles in the regions $-10 < \eta < -5$, $-3.5 < \eta < -1.5$, $1.5 < \eta < 10$. 

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The LHCb experiment is operated at a low number of interactions per beam crossing. The data used in the analyses presented below use data collected in \(pp\) collisions at \(\sqrt{s} = 5, 7, 8\) and 13 TeV.

3. Heavy quark production

3.1. Open charm production

Predictions of charm meson cross-sections are available in pQCD at next-to-leading order (NLO) using the general-mass variable-flavour-number scheme \([2]\) (GMVFNS) and at fixed order with next-to-leading-log resummation \([3]\) (FONLL). The cross-sections are calculated as a convolution of the PDFs, the partonic hard scattering cross-section, and a fragmentation function that parametrises the hadronisation of the charm quark into a given type of charm hadron. Since open charm production at LHCb is dominated by gluon-gluon scattering, the results have a sensitivity to the gluon distribution in the proton at high and low \(x\) (down to \(10^{-4}\)) \([4]\). In \(pp\) collisions, charmed mesons can be produced directly from hard collisions of partons, through the feed-down of excited states, or via decays of \(b\)-flavoured hadrons. The first two sources are referred to as prompt production, while the third process is referred to in the following as from-\(b\).

For this analysis the latter is treated as background.

Double differential cross-sections measurements for the prompt production of \(D^0, D^+, D_s^+\), and \(D^{*+}\) mesons at LHCb have been performed for \(\sqrt{s} = 5\) \([5]\), 7 \([6]\) and 13 TeV \([7]\) with respect to \(p_T\) and \(y\) of the charmed meson. Figure 1 shows a comparison of the double differential prompt \(D^0\) cross section at \(\sqrt{s} = 13\) TeV \([7]\) and the ratio of the cross sections between \(\sqrt{s} = 13\) and 5 TeV \([5]\) to the predictions. The individual cross sections and the ratio of the cross sections at 13 and 5 TeV are described by the predictions reasonably well, also for the other charm mesons.

As expected, the uncertainties of the predictions are significantly reduced for the ratio.

![Figure 1](image-url)

Figure 1. Measurements and predictions for (left) the double differential prompt \(D^0\) cross-section at \(\sqrt{s} = 13\) TeV (from \([7]\)) and (right) the prompt \(D^0\) cross-section ratios between \(\sqrt{s} = 13\) and 5 TeV (from \([5]\)).

3.2. Bottom production

The uncertainty in the knowledge of the \(b\) quark production cross section limits the sensitivity to searches for physics beyond the Standard Model (SM) as decays of hadrons containing a \(b\) quark are often dominant background processes. In addition, knowledge of the \(b\)-quark yield is essential for calculating the sensitivity of experiments testing the SM by measuring \(CP\)-violating and rare decay processes \([8]\).

The \(b\)-quark production cross-section is measured using semileptonic decays of \(b\) hadrons to charm hadrons \((D^0, D^+, D_s, \Lambda_c)\), where the vertex formed by the muon and the charm hadron is
detached from the PV. Prompt production of charm hadrons is treated as background. Figure 2 shows the differential cross-section as a function of $\eta$ for $\sigma(pp \rightarrow H_bX)$, where $H_b$ is a hadron that contains either a $b$ or a $\bar{b}$ quark, at $\sqrt{s} = 7$ TeV and 13 TeV along with the predictions from FONLL. The predictions describe the measurement at both centre-of-mass energies within uncertainties.

![Figure 2](image-url)  

**Figure 2.** Differential cross-section as a function of $\eta$ for $\sigma(pp \rightarrow H_bX)$, where $H_b$ is a hadron that contains either a $b$ or a $\bar{b}$ quark, at $\sqrt{s} = 7$ TeV (a) and 13 TeV (b) (from [9]). The measurements are compared to the predictions from FONLL.

### 3.3. **Top production in the forward region**

The production of top quarks ($t$) in the forward region is of considerable experimental and theoretical interest. Top quarks decay almost entirely via $t \rightarrow Wb$. The Standard Model (SM) predicts that about 75% of top production in the forward region is due to $tt$ pair production. The remaining 25% is mostly due to t-channel single-top production. In the forward region $tt$ production via $q\bar{q}$ and $gg$ scattering is enhanced relative to $gg$ fusion. This can result in larger charge asymmetries, which may be sensitive to physics beyond the SM. Forward $tt$ events can be used to constrain the gluon PDF at large and low $x$.

Events with a $t \rightarrow Wb$ candidate are selected by requiring one isolated muon and a $b$-tagged jet in the final state. The $W+$ jet yield is determined by performing a fit to the distribution of the isolation of the muon. Two boosted decision trees, trained on the characteristics of the secondary vertex and the jet, are used to separate heavy-flavour jets from light-parton jets, and to separate $b$ jets from $c$ jets [10]. The excess of the observed yield relative to the direct $W + b$ prediction is attributed to top quark production as shown in Fig. 3. The resulting inclusive top production cross-sections in the fiducial region of the measurement$^1$ are

$$\sigma(\text{top})[7 \text{ TeV}] = 239 \pm 53(\text{stat}) \pm 33(\text{syst}) \pm 24(\text{theory}) \text{ fb},$$

$$\sigma(\text{top})[8 \text{ TeV}] = 289 \pm 43(\text{stat}) \pm 40(\text{syst}) \pm 29(\text{theory}) \text{ fb},$$

in general agreement with the SM expectations at NLO from MCFM [11] of $180^{+51}_{-41}(312^{+83}_{-68})$ fb at $7(8)$ TeV [12].

Events with an isolated lepton plus two tagged jets have been used to measure $W + c\bar{c}$, $W + b\bar{b}$ and $tt$ production in the forward region. The yields are extracted from a multi-dimensional fit to the BDTs to separate $c$ from $b$ jets the di-jet mass and a multivariate discriminant to separate

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$^1$ defined by $p_T(\mu) > 25$ GeV, $2.0 < \eta(\mu) < 4.5$, $50 < p_T(b) < 100$ GeV, $2.2 < \eta(b) < 4.2$, $\Delta R(\mu, b) > 0.5$, and $p_T(\mu + b) > 20$ GeV
between \( W + c\bar{c} \) and \( W + b\bar{b} \) from \( t\bar{t} \). The measured cross-sections are in agreement with the SM predictions calculated at NLO using MCFM with large uncertainties due to the limited sample size [13] as shown in Fig. 3. With the full statistics at the end of Run II differential measurements can be performed and also other decay channels will be accessible.

4. Quarkonia production

4.1. \( J/\psi \) production at \( \sqrt{s} = 13 \) TeV

\( J/\psi \) mesons are reconstructed in the di-muon final state with \( p_T \) of the di-muon system restricted to \( p_T < 14 \) GeV/c. The excellent vertexing capability of LHCb allows a separation of prompt \( J/\psi \) mesons and \( J/\psi \)-from-\( b \). The number of prompt \( J/\psi \) and \( J/\psi \)-from-\( b \) candidates is determined by a combined fit to the di-muon invariant mass and the pseudo-proper time distribution, where the pseudo-proper time is defined as

\[
t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}.
\]

Here, \( z_{J/\psi} \) is the \( z \) position of the \( J/\psi \) decay vertex, \( z_{PV} \) that of the primary vertex, \( p_z \) the \( z \) component of the measured \( J/\psi \) momentum, and \( M_{J/\psi} \) the reconstructed mass of the \( J/\psi \) candidate.

Figure 4 shows the single differential production cross-sections for prompt \( J/\psi \) and \( J/\psi \)-from-\( b \) as a function of \( p_T \) in the forward region at \( \sqrt{s} = 13 \) TeV [14]. The cross-section for \( J/\psi \)-from-\( b \) is about a factor of ten smaller than for prompt \( J/\psi \) with a \( p_T \) and \( y \) dependence similar to what was observed by LHCb at lower \( \sqrt{s} \). The measurements are described by non-relativistic QCD (NRQCD) [15] for prompt \( J/\psi \) and FONLL for \( J/\psi \)-from-\( b \).

4.2. \( \Upsilon \) production at \( \sqrt{s} = 7 \) and 8 TeV

The production of \( \Upsilon \) mesons in \( pp \) collisions can occur either directly or via feed down from the decay of heavier bottomonium states. The cross-section for \( \Upsilon \) is measured differentially in \( p_T \) and \( y \) in the di-muon final state in the fiducial volume \( 1 < p < 30 \) GeV/c, \( 2 < \eta < 4.5 \) at \( \sqrt{s} = 7 \) and 8 TeV. The signal yields in each \( (p_T, \eta) \) bin are determined from an unbinned extended maximum likelihood fit to the di-muon mass spectrum of the selected candidates. Fig. 5 a) shows the differential cross-section for \( \Upsilon(1S), \Upsilon(2S) \) and \( \Upsilon(3S) \) at \( \sqrt{s} = 8 \) TeV [16]. The shape of all three states are well described by predictions based on the CO model [17].
Figure 4. Differential cross-sections as a function of $p_T$, (left) compared with the NRQCD calculation for prompt $J/\psi$ and (right) with the FONLL calculation for $J/\psi$-from-$b$ meson (from [14]).

The ratio of the cross-sections at $\sqrt{s} = 8$ and 7 TeV as a function of rapidity, integrated over the region $p_T < 30 \text{ GeV}/c$ is shown in Fig. 5b). They are compared with the expectations from the CO mechanism with normalisation factors fixed from the fits to the differential cross-sections. The shape observed in data does not agree with the pure CO model.

Figure 5. Left: differential cross-sections in bins of $y$ for $\Upsilon(1S)$(red), $\Upsilon(2S)$(blue) and $\Upsilon(3S)$(green) at $\sqrt{s} = 8$ TeV. Right: ratio of differential cross-sections at $\sqrt{s} = 8$ and 7 TeV (from [16]). Lines in both plots show fit results with the CO model predictions.

4.3. $\Upsilon$ plus open charm

Production of multiple heavy quark pairs in $pp$ collisions receives contributions from single parton (SPS) as well as double parton scattering (DPS). Within the DPS mechanism, the $\Upsilon$ meson and $c\bar{c}$ ($C$ hadron) pair are produced independently in different partonic interactions. Neglecting the parton correlations in the proton, the contribution is estimated according to the
formula
\[ \sigma^{\Upsilon \times \sigma} = \frac{\sigma^{\Upsilon} \times \sigma^{\sigma}}{\sigma_{\text{eff}}}, \]
where \( \sigma^{\Upsilon} \) and \( \sigma^{\sigma} \) are the inclusive \( \Upsilon \) and charm cross-sections, and \( \sigma_{\text{eff}} \) is an effective cross-section.

The associated production of \( \Upsilon \) mesons with open charm hadrons (\( D^0 \), \( D^+ \), \( D_s^+ \) and \( \Lambda_c^+ \)) was measured by LHCb using the data collected at \( \sqrt{s} = 7 \) and 8 TeV [18]. The selected \( \Upsilon \) and \( C \) candidates are paired to form \( \Upsilon C \) candidates. A global fit to the \( \Upsilon C \) candidates is performed, which requires both hadrons to be consistent with originating from a common vertex. A cut on the quality of the fit reduces the background from the pile-up of two independent \( pp \) interactions producing separately a \( \Upsilon \) and \( C \) hadron to a negligible level. The event yields are determined using unbinned extended maximum likelihood fits to the two-dimensional \( \Upsilon C \) mass distributions of the selected candidates\(^2\). For \( \Upsilon(1S)D^0 \), \( \Upsilon(2S)D^0 \), \( \Upsilon(1S)D^+ \), \( \Upsilon(2S)D^+ \) and \( \Upsilon(1S)D_s^+ \) a signal is observed with significances exceeding five standard deviations. Cross-sections are measured for \( \Upsilon(1S)D^0 \) and \( \Upsilon(1S)D^+ \). They are in agreement with DPS expectations and significantly exceed the expectations from SPS. Assuming only DPS production, the measured cross-sections are used to determine \( \sigma_{\text{eff}} \) to be \( \sigma_{\text{eff}} = 18.0 \pm 1.8 \) nb, in agreement with most previous measurements as shown in Fig. 6. This supports the assumption of \( \sigma_{\text{eff}} \) being process and energy independent.

The differential kinematic distributions for \( \Upsilon D^0 \) and \( \Upsilon D^+ \) are studied and all are found to be in good agreement with the DPS expectations as the main production mechanism. As an example Fig. 6 shows the azimuthal angular separation of \( \Upsilon(1S) \) and \( D^0 \) which is consistent with a flat distribution as expected for uncorrelated scattering processes (DPS).

### 4.4. Central exclusive \( J/\psi \) and \( \psi(2S) \) production at \( \sqrt{s} = 13 \) TeV

Central exclusive production (CEP), \( pp \rightarrow pXp \), in which the protons remain intact and the system \( X \) is produced with a rapidity gap on either side, proceeds via the exchange of colourless, neutral particles, either photons or combinations of gluons, for example pomerons. Experimentally, this leads to a unique signature with a small number of particles in the detector, either produced directly or as decay products, and two rapidity gaps that extend to the outgoing protons. The outgoing protons are not detected but escape through the beam-pipe. CEP is attractive to study QCD and the role of the pomeron, particularly when the mass of the central system is high enough to allow perturbative calculations. Furthermore, it allows searches for exotic states in a low-background experimental environment and probes of the gluon distribution of the proton.

CEP charmonia candidates are selected through their characteristic signature, which is only the charmonium meson that is reconstructed from its decay to two muons. The addition of HeRSChE-L extends the pseudorapidity region in which charged particles can be vetoed and roughly halves the inelastic background contribution compared to the previous measurements at lower energies [21]. The largest background is due to inelastic production of \( J/\psi \) and \( \psi(2S) \) mesons with additional gluon radiation or proton dissociation where the additional particles are not detected in LHCb. Since the inelastic background has a higher \( p_T \) than the signal the background contribution is determined by a fit to the \( p_T^2 \) distribution of the meson. The inelastic background accounts for approximately 20% of the selected candidates. The differential cross-sections for \( J/\psi \) and \( \psi(2S) \) mesons at \( \sqrt{s} = 13 \) TeV as functions of the rapidity of the mesons are shown in Fig. 7 [22]. Both measurements are better described by NLO than by LO predictions [23, 24].

\(^2\) The fit model is a sum of several components, each of which is the product of a di-muon mass distribution, corresponding to an individual \( \Upsilon \) state or combinatorial background, and a \( C \) candidate mass distribution,
Figure 6. Left: effective cross-section as determined from the associated production of Υ and open charm together with results from other experiments; right: corrected distribution of $|\Delta \phi|/\pi$ for Υ(1S)D$^0$ events (from [18]). The blue line shows the result of the fit with a constant function as a model for uncorrelated scattering processes (DPS). The SPS predictions are shown with dashed (orange) and longdash-dashed (magenta) curves for calculations based on the $k_T$-factorization [19] and the collinear approximation [20], respectively.

Figure 7. Differential cross-section for central exclusive $J/\psi$ (left) and $\psi(2S)$ (right) production compared to LO and NLO predictions (from [22]).

5. Conclusions
Differential cross section measurements and ratios of cross sections at different centre-of-mass energies have been presented for heavy flavour (charm and beauty) and quarkonia ($J/\psi$ and Υ) production. In general the differential cross-sections and the ratio of cross-sections at different corresponding to a $C$ signal or combinatorial background component.
\( \sqrt{s} \) are described by the predictions within uncertainties. Uncertainties for the predictions are significantly reduced by taking the ratios and also many experimental uncertainties cancel.

Top production has been observed in agreement with NLO predictions in the forward region with low statistics. The full Run II dataset will allow to perform differential measurements and to access different decay channels.

Measurements of the associated production of \( \Upsilon \) and open charm have been presented. The cross-sections and the differential distributions indicate the dominance of double parton scattering as the main production mechanism.

Measurements of differential cross-sections for central exclusive \( J/\psi \) and \( \psi(2S) \) have been discussed. They agree with the shapes predicted by NLO calculations. The additional instrumentation of the LHCb detector with forward shower counters for Run II significantly improved the background evaluation for central exclusive processes.

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