Measurements of the electron and muon inclusive cross-sections in proton-proton collisions at √s = 7 TeV with the ATLAS detector

Aad, G.; et al., [Unknown]; Bentvelsen, S.C.M.; Colijn, A.P.; de Jong, P.J.; de Nooij, L.; Doxiadis, A.; Garitaonandia, H.; Geerts, D.A.A.; Gosselink, M.; Kayl, M.S.; Koffeman, E.N.; Lee, H.C.; Linde, F.L.; Mechnich, J.; Mussche, I.; Ottersbach, J.P.; Rijpstra, M.; Ruckstuhl, N.M.; Tsiakiris, M.; van der Kraaĳ, E.E.; van der Leeuw, R.H.L.; van der Poel, E.F.; van Kesteren, Z.; van Vulpen, I.B.; Vermeulen, J.C.; Vreeswijk, M.

Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2011.12.054

Citation for published version (APA):
Aad, G., et al., U., Bentvelsen, S., Colijn, A. P., de Jong, P., de Nooij, L., ... Vreeswijk, M. (2012). Measurements of the electron and muon inclusive cross-sections in proton-proton collisions at √s = 7 TeV with the ATLAS detector. Physics Letters B, 707(5), 438-458. DOI: 10.1016/j.physletb.2011.12.054
Measurements of the electron and muon inclusive cross-sections in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

An understanding of electron and muon production in proton–proton ($pp$) collisions is a prerequisite for measurements and searches including these particles in the final state. Moreover, the inclusive production of these particles can be used to constrain theoretical predictions for heavy-flavour production, for which large uncertainties exist. At low transverse momentum ($p_T$) the inclusive electron and muon spectra are dominated by decays of charm and beauty hadrons. The contribution from $W$ and $Z/\gamma^*$ production, which dominates in the higher $p_T$ region, is well understood [1] and may be subtracted in order to obtain the heavy-flavour cross-section.

In measurements of $b$-quark production in $p\bar{p}$ collisions, an excess over the theoretical expectation was observed in earlier experiments [2–5]. This discrepancy was later resolved by improved experimental measurements [6] and the use of Next to Leading Order (NLO) with Next to Leading Log (NLL) resummation theory applied to LEP data to extract the $b$-quark fragmentation function [7,8]. The Tevatron data were, however, not sensitive to the $W$ contributions. These results are compared to the predictions of NLO + NLL and NLO calculations using the program FONLL [9,10]. Comparisons are also made to the NLO predictions from the POWHEG [11,12] program and the Leading Order (LO) expectations from PYTHIA [13].

2. Cross-section measurement and theoretical predictions

The measured differential cross-section within the kinematic acceptance of the charged lepton is defined by

$$\frac{\Delta \sigma_T}{\Delta p_T} = \frac{N_{sig}}{N_{bin} \cdot \int d\mathcal{L} \cdot dt} \cdot \epsilon_{(reco+PID)} \cdot \epsilon_{\text{trigger}}, \tag{1}$$

$\epsilon_{\text{trigger}}$ is the efficiency for triggering on the lepton candidate, $\epsilon_{(reco+PID)}$ is the combined efficiency for reconstruction and identification of the lepton candidate, and $\mathcal{L}$ is the integrated luminosity.

$\epsilon_{\text{trigger}}$ is the efficiency for triggering on the lepton candidate, $\epsilon_{(reco+PID)}$ is the combined efficiency for reconstruction and identification of the lepton candidate, and $\mathcal{L}$ is the integrated luminosity.

$\epsilon_{(reco+PID)}$ is the combined efficiency for reconstruction and identification of the lepton candidate, and $\mathcal{L}$ is the integrated luminosity.
where $N_{\text{sig}}$ is the number of signal electrons or muons with reconstructed $p_T$ in bin $i$ of width $\Delta p_T$, $\int L dt$ is the integrated luminosity, $\epsilon_{\text{trigger}}$ is the trigger efficiency and $\epsilon_{\text{reco+PID}}$ is the combined reconstruction and identification efficiency. $C_{\text{migration}}$ is the bin migration correction factor, defined as the ratio of the number of charged leptons in bin $i$ of true $p_T$ and the number in the same bin of reconstructed $p_T$ (transverse energy, $E_T$, in the electron case). The methods used to extract $N_{\text{sig}}$, from the total number of electron or muon candidates observed in each $p_T$ bin are explained in Sections 5.3 and 6.4. From the extracted signals, we subtract the contribution from hadrons produced in the MS and the decays of the heavy hadrons to leptons found in [14]. The ID provides precise track reconstruction within the precision chamber system covering the region $|\eta| < 2.7$ with three layers of Monitored Drift Tube (MDT) chambers. In the forward region, $2.0 < |\eta| < 2.7$, higher granularity Cathode Strip Chambers (CSCs) replace the first station of MDTs. The trigger chambers provide coverage within $|\eta| < 1.05$ using Resistive Plate Chambers (RPCs) and for $1.05 < |\eta| < 2.4$ using Thin Gap Chambers (TGCs). The MDT chambers measure the coordinate in the bending plane, while the RPCs and TGCs measure the coordinate in the non-bending plane ($\phi$) and provide a further hit in the bending plane.

Reconstruction of muon candidates begins with the reconstruction of track segments in the MS. Segment candidates formed from hits in the precision chambers are required to point loosely to the centre of ATLAS. A minimum of two track segments and one hit in each coordinate of the RPCs in the barrel and the TGCs in the end-caps are required to build an MS track. For $|\eta| < 2.5$ the track parameters are then back-extrapolated to the IP and matched to all tracks in the ID having hits in at least two ID sub-detectors. The ID track that best matches the MS track is retained, and the track parameters are computed by the statistical combination of back-extrapolated MS parameters and ID track parameters, the resulting track being referred to as a combined muon in the following.

4. Data and simulated samples used

The analysis is based on a data sample collected at $\sqrt{s} = 7$ TeV during April–August 2010. Requirements were made on the detector conditions (notably the ID plus either the EM calorimeter or the MS) and data quality, yielding total integrated luminosities of $1.28 \pm 0.04$ pb$^{-1}$ and $1.42 \pm 0.05$ pb$^{-1}$ for the electron and muon analyses, respectively, the integrated luminosity being measured with an uncertainty of 3.4% [16].

For the electron analysis events were selected using the hardware-based first-level (L1) calorimeter trigger, which identifies EM clusters within $|\eta| < 2.5$ above a given energy threshold. The data were recorded under four different trigger conditions, with a progressively higher minimum cluster transverse energy requirement applied as the instantaneous luminosity of the LHC increased. The bulk of the integrated luminosity (76%) was obtained with the L1 calorimeter trigger configured with an energy threshold of approximately 15 GeV, with the remaining 14%, 9% and 1% recorded with 11, 6 and 3 GeV thresholds, respectively. The integrated luminosity available for the electron analysis is limited to these early data, since the Higher Level Trigger algorithms used in later periods of higher instantaneous luminosity are designed to be efficient only for isolated electrons.

In the muon channel, events were selected by one of two L1 muon triggers. The first 3.5% of the data were recorded under the loosest requirement of at least three trigger hits in time coincidence with the collision (referred to as the lower threshold trigger), while the remaining data were obtained with the further requirement that the hit pattern be compatible with a track with $p_T > 10$ GeV. In the subsequent analysis it is required for muons with $p_T$ less than 16 GeV to be triggered by the lower threshold trigger, while the 10 GeV trigger is required for muons with $p_T$ in the range 16–100 GeV.

Simulated data samples have been generated in order to estimate backgrounds and correct for the trigger and reconstruction efficiencies and the resolution of the detector. PYTHIA 6.421 was used to simulate samples of electrons and muons from heavy-flavour and $W/Z/\gamma^*$ decays. PYTHIA was also used to simulate all sources of background electrons and muons.
samples of electrons from heavy-flavour decays were also generated with POWHEG-hvq v1.0 patch 4, interfaced to either PYTHIA or HERWIG v6.510 [17]. In conjunction with HERWIG, JIMMY v4.31 [18] was used to model the underlying event. The POWHEG samples use PHOTOS v2.15 [19] to model final state QED radiation. The PDF set was MRST LO* for the PYTHIA samples and CTEQ6.6 [21] for the POWHEG samples. All signal and background samples were generated at $\sqrt{s} = 7$ TeV using the ATLAS MC09 tune [22], and passed through the GEANT4 [23] simulation of the ATLAS detector.

5. Electron analysis

5.1. Electron candidate selection

Events from pp collisions are selected by requiring a collision vertex with more than two associated tracks. From these events, reconstructed electron candidates are required to pass a minimum cluster $E_T$ cut between 7 and 18 GeV depending on the trigger condition, to lie within the pseudorapidity coverage of the TRT, $|\eta| < 2.0$, and to be outside the transition region between the barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$. Candidate clusters with their energy-weighted centre close to problematic regions in the EM calorimeter are rejected, as are those with tracks passing through dead B-layer modules: the corresponding loss of acceptance varied by run period but amounted to no more than 7% and 3%, respectively.

Preselected candidates must be associated to tracks containing at least ten TRT and four silicon hits and are required to pass a minimum requirement on the fraction of the raw energy deposited in the strip layer of the EM calorimeter. Candidate electrons are then selected from those passing the preselection by imposing further identification criteria [15] designed to suppress electron-like (fake) signatures from hadrons. These identification criteria comprise $E_T$ and $|\eta|$ dependent cuts on the energy deposits in the strip and middle layers of the EM calorimeter as well as on the track quality and track-cluster matching.

The cluster transverse energy spectrum for the selected electron candidates in the data and simulation is shown in Fig. 1(a), in which data with $E_T < 18$ GeV have been rescaled to 1.3 pb$^{-1}$ from lower integrated luminosities. The discontinuities in the spectrum at 10, 20 and 30 GeV correspond to boundaries in the $E_T$-dependent identification cuts, which mainly affect the yield of hadronic fakes. The candidates in the simulation are sub-divided according to their dominant origins, which for $E_T < 26$ GeV are non-isolated signal electrons from semi-leptonic decays of charm and beauty hadrons ($\sim$10%), a background of secondary electrons, largely dominated by electrons from photon conversions ($\sim$20%) and the dominant background of misidentified hadronic fakes. The fraction of isolated signal electrons from $W/Z/\gamma^*$ production is also shown. For $E_T > 26$ GeV this contribution starts to become significant, with the efficiency of the identification cuts being higher for these isolated electrons, motivating the choice of the restricted 7–26 GeV analysis region.

The signal purity could be improved through the application of further cuts on the fraction, $f_{\text{HR}}$, of high-threshold (transition radiation) TRT hits out of all TRT hits measured on the track, the number of hits in the pixel B-layer, $n_{\text{BL}}$, and the ratio of the measured energy of the EM cluster to the track momentum, $E/p$. These variables offer excellent discriminating power against the hadronic fake ($f_{\text{HR}}$) and photon conversion ($n_{\text{BL}}$) backgrounds, as illustrated in Fig. 1(b)–(d). Applying tighter cuts on these variables would

![Fig. 1](https://example.com/fig1.png)
increase the signal fraction to 50% in the range \( 7 < E_T < 26 \text{ GeV} \) but leave no means of estimating the remaining background fraction from data. The cuts are therefore not applied, permitting the full distributions of the variables to be used in the fitting procedure described in Section 5.3.

### 5.2. Electron trigger efficiency measurement

The efficiency with which the signal electrons pass the L1 EM trigger is measured from the data in bins of cluster \( E_T \). For the 3 and 6 GeV threshold triggers, the efficiencies are measured using events selected by an alternative, very inclusive minimum bias trigger, based on hit information in the Minimum Bias Trigger Scintillator [24]. The efficiencies of the 11 and 15 GeV triggers are measured using events recorded by the 6 GeV trigger, which is fully efficient in the \( E_T \) region for which the higher threshold triggers are used. Since these data-derived measurements are performed on the selected electron candidates, dominated by the hadronic background, a systematic uncertainty is estimated by comparing the measured trigger efficiencies to those expected in the simulation for heavy-flavour electrons. The trigger efficiencies are measured to be between 92.1% and 100.0%, with a maximum uncertainty of 1.8%.

### 5.3. Electron signal extraction

In order to extract the heavy-flavour plus \( W/Z/\gamma^* \) signal electrons from the selected candidates, a binned maximum likelihood method is used, based on the distributions of \( f_{\text{TR}} \), \( n_{\text{BL}} \) and \( E/p \). From simulation, a twelve-bin three-dimensional probability density function (pdf) in these variables is constructed for the signal and conversion components. For the hadronic background, the shapes of the three template distributions are described by additional free parameters (as in [25]) and are fitted to the data: in doing so, the method assumes no correlations exist between the three discriminating variables in the hadronic component. A likelihood fit is performed in bins of \( \eta \) (on which the discriminating distributions depend) and in \( E_T \) in the range 7–26 GeV, allowing the fraction of signal, conversion and hadronic fake candidates to be found in each \( E_T \) bin.

The systematic uncertainty on the number of extracted signal electrons arising from the differences between the data and simulation in the discriminating variables for the signal and conversion components is estimated to be less than 4%, evaluated by repeating the signal extraction with the signal and conversion templates adjusted within their systematic uncertainties. For \( f_{\text{TR}} \) and \( E/p \), which have the largest effect, the differences were evaluated by comparing the distributions in data and simulation for a pure sample of photon conversions, selected by imposing the additional requirements of \( n_{\text{BL}} = 0 \) and either \( E/p > 0.8 \) or \( f_{\text{TR}} > 0.1 \), respectively. The impact of the finite statistics of the simulated samples (\(<2.5\%\)) and any possible bias in the method \((7.3\%)\) arising from the assumption that the template distributions for the hadron background are uncorrelated were studied using pseudo-experiment techniques. The uncertainty associated with the electron energy scale \((3.5\%)\) has been assessed by varying the electron candidate cluster energy by 1% for \(|\eta| < 1.4\) and by 3% for \(|\eta| > 1.4\), these systematic effects having been evaluated from \( Z \rightarrow e^+e^- \) events. Overall a statistical (systematic) uncertainty on the extracted signal component of approximately 3 (9\%) is obtained.

### 5.4. Determination of the electron efficiency and migration correction

The overall efficiency and migration correction factor, \( \epsilon_{\text{(rec+PID)}}/C_{\text{migration}} \), is determined from PYTHIA-simulated samples of heavy-flavour decays to electrons and varies between 0.6 and 0.7 as a function of the true electron \( p_T \). Efficiencies of individual cuts were cross-checked on data control samples where possible, and a systematic uncertainty of 5–10% is estimated by re-calculating \( \epsilon_{\text{(rec+PID)}}/C_{\text{migration}} \) from simulated samples produced with an increase in the amount of material inside the EM calorimeter, corresponding to the estimated uncertainty on the material budget (see [26] and references therein). The statistical uncertainty on \( \epsilon_{\text{(rec+PID)}}/C_{\text{migration}} \) is found to be between 0.4 and 3.5%.

Additionally, the efficiency of the electron identification cuts in the simulation is compared with a measurement made on data using a tag-and-probe (T&P) technique. The probe candidates, which must pass only the preselection cuts of Section 5.1, are taken from a sample of events enriched in heavy quark pair production where both heavy hadrons decay semi-leptonically. To select such events, the tag electron candidate is subject to more stringent identification cuts than those described in Section 5.1, including requirements on \( f_{\text{TR}} \) and \( n_{\text{BL}} \), and the T&P candidate pair must have opposite charge and an invariant mass below the \( Z \) mass window and outside of the \( J/\psi \) mass region. The signal purity remains low after the T&P selection, being 9 (31\%) for probe candidates before (after) applying the identification criteria. The signal component of the probe candidates before and after the identification cuts must therefore be extracted with a method similar to that described in Section 5.3. By comparing the measured identification efficiency of the extracted probe electrons to that expected in simulation as a function of \( E_T \), an uncertainty of 5% is obtained on the identification efficiency, with a further 7% systematic uncertainty coming from the T&P method itself.

Overall the uncertainty on \( \epsilon_{\text{(rec+PID)}}/C_{\text{migration}} \) is found to be 12–14%, depending on the true electron \( p_T \). Possible effects of the choice of heavy-flavour hadron decay model and the prompt \( J/\psi \) contamination are found to be negligible.

### 5.5. Electron production cross-section result

The differential cross-section for electrons from heavy-flavour production is found from Eq. (1) using a bin-by-bin unfolding method. Before applying the efficiency and migration correction factor, \( \epsilon_{\text{(rec+PID)}}/C_{\text{migration}} \), the theoretical prediction for the accepted electron cross-section from \( W/Z/\gamma^* \) decays, \( \sigma_{W/Z/\gamma^*}^{\text{accepted}} \), must first be subtracted.\(^2\) \( \sigma_{W/Z/\gamma^*}^{\text{accepted}} \) is obtained from PYTHIA, with the high-mass \( W/Z \) contribution normalised to the NNLO total cross-section [27,28].

The differential cross-section for electrons from heavy-flavour production within \(|\eta| < 2.0\) (excluding \(1.37 < |\eta| < 1.52\)) and \(7 < p_T < 26 \text{ GeV}\) is plotted in Fig. 4 (left) and reported in Table 3. The statistical uncertainty originates from the signal extraction procedure (Section 5.3), and the sources of systematic uncertainty, as discussed in the preceding sub-sections, are summarised in Table 1. Correlations between the systematic uncertainties common to the signal extraction and the T&P efficiency measurement, such as discrepancies between the data and simulation in the signal and conversion pdfs and the energy scale uncertainty, are taken into account in the evaluation of the overall systematic uncertainty on the cross-section. To account for possible biases due to the \( p_T \) distribution of the signal, the predictions of simulated heavy-flavour samples from different programs (PYTHIA, POWHEG+PYTHIA and POWHEG+HERWIG) are compared and found to yield consistent results.

\(^2\) The uncertainty on the heavy flavour cross-section arising from the overall uncertainty on \( \sigma_{W/Z/\gamma^*}^{\text{accepted}} \) is negligible, reaching at most 1% in the highest \( p_T \) bin where the \( W/Z/\gamma^* \) contribution to the signal reaches its maximum of 13%.
We obtain a fiducial heavy-flavour electron cross-section in the range $7 < p_T < 26$ GeV and within $|\eta| < 2.0$, excluding $1.37 < |\eta| < 1.52$, of
\[
\sigma_{HF}^e = 0.946 \pm 0.020 \text{(stat.)} + 0.146 \text{(syst.)} \pm 0.032 \text{(lumi.)} \text{mb.}
\]

6. Muon analysis

6.1. Muon candidate selection

Muon candidates within a pseudorapidity of $|\eta| < 2.5$ are selected if they have at least two MDT segments and an ID track with hits in two different sub-detectors. In addition to signal muons from charm, beauty and $W/\gamma$ decays, the selected candidates comprise a significant fraction of background muons from pion and kaon decays in flight ($\pi/K$) and misidentified muons from hadronic showers in the calorimeter that reach the MS and are wrongly matched to a reconstructed ID track (fakes). The $\pi/K$ background is subdivided into those that decay close enough to the IP such that the majority of hits on the ID track come from the decay muon (early-$\pi/K$) and those that do not (late-$\pi/K$). The signal purity of the sample, determined using the method discussed in Section 6.4, ranges from 45% at $p_T = 4$ GeV to 90% at 40 GeV in the region of the $W/Z$ Jacobian peak.

6.2. Muon trigger efficiency measurement

The trigger efficiency for the muon candidates is evaluated using events recorded by an independent trigger based on calorimeter information alone. The efficiency for the lower threshold trigger is found to be 68% at $p_T = 4$ GeV and to reach a plateau of 84% at 9 GeV. The 10 GeV threshold trigger efficiency is constant for $p_T > 16$ GeV with a value of 74%. (The muon trigger efficiency is dominated by the limited acceptance of the muon trigger chambers.) The data samples used to compute the efficiency contain background muons. In order to obtain the efficiencies for signal muons, correction factors of 1.04 for the low threshold trigger and 1.08 for the 10 GeV trigger are estimated from simulation. Systematic uncertainties on these correction factors come from the simulation statistics (0.5% and 0.7% for the lower threshold and 10 GeV triggers, respectively) and from the mis-modelling of the signal fraction by the simulation (0.7% and 0.2% for the two triggers), the latter being assessed by reweighting the simulated sample according to the measured signal fraction. Other sources of systematic uncertainty arise from the statistical fluctuations in the independent trigger sample (from 0.4% to 0.9% for the low threshold trigger, and 0.5% for the 10 GeV trigger) and from the bias introduced by the independent trigger (evaluated to be 2.3% for the 10 GeV trigger by comparing to events triggered by the low threshold trigger).

6.3. Muon reconstruction efficiency measurement

The combined muon reconstruction efficiency has three components: the ID efficiency ($\epsilon_{ID}$), the MS efficiency ($\epsilon_{MS}$) and the matching efficiency ($\epsilon_{Match}$). The overall efficiency has been determined from high-statistics simulated muon samples from heavy-flavour hadron and $W/Z/\gamma^*$ decays, with correction factors for each component of the reconstruction, $\alpha_x = \epsilon_{x-data} / \epsilon_{x-simulation}$ ($x = ID, MS, Match$), being determined by comparing the simulation-derived efficiencies with those observed in data. The overall reconstruction efficiency is found to be 85% at $p_T = 4$ GeV, reaching 95% at 7 GeV. The plateau value of 95% is the same for both isolated and non-isolated muons.

The ID correction factor $\alpha_{ID}$ is evaluated with a T&P method on $J/\psi$ and $Z$ events, using a combined muon track as a tag and an MS track as a probe. The fraction of ID tracks found over the number of probes has been computed and compared to the expectation in simulation, giving a value of $\alpha_{ID} = 1.00 \pm 0.005$, where the quoted uncertainty includes both the statistical and systematic contributions.

The product $\alpha_{MS} \cdot \alpha_{Match}$ is obtained with two methods. The first method identifies single muon tracks in jets from energy deposits corresponding to minimum-ionising particles in calorimeter cells matched to extrapolated ID tracks. In order to reject the background from pions and kaons from the primary vertex, a cut on the impact parameter ($d$) to the primary vertex in the transverse plane is applied: $|d|/\sigma_d > 3$, where $\sigma_d$ is the error on $d$ from the tracking algorithm. According to simulation this cut selects muons from beauty decays with a purity of 99%. The factor $\epsilon_{MS} \cdot \epsilon_{Match}$ is then computed by evaluating the fraction of these tracks that are reconstructed in the MS and matched to the ID track. The second method identifies muons by matching ID tracks with hits in the MS trigger chambers. The trigger bias of this method has been evaluated with simulated data to be 2% for $p_T < 6$ GeV and less than 0.2% at higher momenta. Overall a value of $\alpha_{MS} \cdot \alpha_{Match} = 0.986 \pm 0.003 \text{(stat.)} \pm 0.001 \text{(syst.)}$ is obtained, the central value being the average of the results from the two methods and the systematic uncertainty coming from the difference between the two. Both methods are sensitive up to $p_T = 30$ GeV, in the region where the control sample is dominated by the non-isolated muons. To take into account isolated muons and muons with $p_T > 30$ GeV, the result has been compared with $\alpha_{MS} \cdot \alpha_{Match}$ computed from two other T&P techniques, using muons from $J/\psi$ and $Z$ decays. The T&P technique used here is the same as that used in the determination of $\epsilon_{ID}$ but with the probe muon selected among the ID tracks, and a full combined track being required in the numerator. The $\alpha_{MS} \cdot \alpha_{Match}$ Scale factors obtained with the T&P methods are fully compatible with those obtained using the single muon track methods.

Overall the systematic uncertainty on the muon reconstruction efficiency is dominated by the uncertainties on the scale factors reported above and evaluates to 1.2%.

6.4. Muon signal extraction

The muon reconstruction provides independent information on the $p_T$ of the track reconstructed in the ID and in the MS. The difference in $p_T$: $\Delta p_T = p_T^{\text{ID}} - p_T^{\text{MS}}$, where both momenta are extrapolated to the IP, is sensitive to the origin of the muons: signal,
early-\(\pi/K\), and late-\(\pi/K\) or fakes, as illustrated in Fig. 2 for three \(p_T\) intervals. A fit to the data distribution is performed to extract the signal component using templates from the simulation. The early-\(\pi/K\) component template, like the signal, has a \(\Delta p_T\) distribution peaked around zero, since the \(p_T\) reconstructed in the ID for a \(\pi/K\) that decays close to the IP is dominated by hits from the decay muon. The late-\(\pi/K\) component and the fake component may be described by a single template with a broader \(\Delta p_T\) distribution shifted towards higher values. Since the early-\(\pi/K\) component is significant only for \(p_T < 10\) GeV and cannot be strongly discriminated from the signal, we fix the ratio of the early-\(\pi/K\) component to the late-\(\pi/K\) plus fakes component to its expectation in the simulation and use only a single background template in the fit. A systematic uncertainty is assigned to cover the possible difference in the (early-\(\pi/K\))/(late-\(\pi/K\) + fakes) ratio between data and simulation as explained below.

The fit is performed in \(p_T\) bins over the whole range. For \(p_T \leq 52\) GeV the template distributions are taken from a \textsc{pythia} dijet sample with \(p_T > 15\) GeV (where \(p_T\) is the \(p_T\) of the primary parton) with the additional requirement that at least one set of particles crossed a surface of \(\Delta \eta \times \Delta \phi = 0.12 \times 0.12\) with a total energy greater than 17 GeV. For \(p_T > 52\) GeV a dijet sample with \(p_T > 280\) GeV is used.

The systematic uncertainty on the extracted signal fraction arising from the difference in the \(\Delta p_T\) distributions between the simulated template samples and the expected data distributions is evaluated on simulated samples of QCD jets (light and heavy-flavour) and W/Z inclusive events that reproduce the expected composition of data. The maximum possible bias is found to be 3%. The effect of any mis-modelling of the background \(\Delta p_T\) template is also checked by comparing the extracted signal fraction to that obtained when using a background template taken from a simulated sample whose \(p_T\) spectrum is weighted to reproduce the spectrum observed in data before the signal extraction. A difference of 1.5% is found, within the bias mentioned above. Therefore we quote an overall 3% systematic uncertainty for the template modellisation. The systematic uncertainty on the signal fraction due to the finite statistics of the simulated samples used for the template distributions is found to be between 1% and 8%.

The accuracy of the assumption that the ratio of the early-\(\pi/K\) component to the combined late-\(\pi/K\) plus fakes component, \(r\), is reproduced correctly by the simulation is tested by comparing the \(\Delta p_T\) distributions in data and simulation as a function of the early-\(\pi/K\) fraction. A correction factor \(r_{\text{data}}/r_{\text{simulation}}\) is determined as 1.1 ± 0.1. This 10% uncertainty on \(r\) corresponds to an uncertainty on the signal of 2% at \(p_T = 4\) GeV, rapidly falling to zero for \(p_T > 10\) GeV.

The muon momentum resolution has been studied using tracks from the decays \(Z \rightarrow \mu^+\mu^-\) and \(J/\psi \rightarrow \mu^+\mu^-\). With an iterative procedure, the simulated muon track momenta are smeared and scaled as a function of pseudorapidity to reproduce the \(J/\psi\) and the \(Z\) invariant mass shapes measured in data [31]. A full set of smearing parameters for the MS and ID are obtained, and the corresponding effect on the combined muon derived. The corrected sample is used to obtain the unfolding coefficients \(c_{\text{migration}}\), in Eq. (1). The uncertainty on the unfolding coefficients is determined by varying independently the cross-section values of the heavy-flavour and W/Z components by 30% and 10% respectively. The associated systematic uncertainty is at the level of 0.1% over almost the whole spectrum with a maximum value of 1.2% around the W/Z Jacobian peak.

### 6.5. Muon resolution and unfolding

The muon momentum resolution has been studied using tracks from the decays \(Z \rightarrow \mu^+\mu^-\) and \(J/\psi \rightarrow \mu^+\mu^-\). With an iterative procedure, the simulated muon track momenta are smeared and scaled as a function of pseudorapidity to reproduce the \(J/\psi\) and the \(Z\) invariant mass shapes measured in data [31]. A full set of smearing parameters for the MS and ID are obtained, and the corresponding effect on the combined muon derived. The corrected sample is used to obtain the unfolding coefficients \(c_{\text{migration}}\), in Eq. (1). The uncertainty on the unfolding coefficients is determined by varying independently the cross-section values of the heavy-flavour and W/Z components by 30% and 10% respectively. The associated systematic uncertainty is at the level of 0.1% over almost the whole spectrum with a maximum value of 1.2% around the W/Z Jacobian peak.

### 6.6. Muon production cross-section result

The signal fraction of the muon transverse momentum spectrum has been corrected for the trigger and reconstruction efficiencies and unfolded from the detector response. Fig. 3 shows the resulting inclusive muon differential cross-section for muons within \(|\eta| < 2.5\) as a function of \(p_T\), compared to the overall theoretical expectation. The expected W/Z component comes from \textsc{mc@nlo} [32,33] using the CT106.6 PDFs, normalised to the

---

**Fig. 2.** The \(\Delta p_T\) distribution in the \(p_T\) bins 4–5 GeV (a), 10–11 GeV (b) and 18–20 GeV (c) for muon combined track candidates. The signal, early-\(\pi/K\) and late-\(\pi/K\) plus fakes components from simulation are shown. The early-\(\pi/K\)s are defined as those that decay close enough to the IP that the majority of hits on the ID track come from the decay muon.

**Fig. 3.** Muon differential cross-section as a function of the muon transverse momentum for \(|\eta| < 2.5\) compared to theoretical predictions. The Drell–Yan component corresponds to the Z/\(\gamma^*\) for \(M_{\mu^+\mu^-} < 60\) GeV.
The measured heavy-flavour cross-sections are compared to the FONLL calculations, with a rigorous evaluation of the associated uncertainty shown as a band in Fig. 4. The theoretical uncertainties originate from several different sources. The dominant contribution comes from the renormalisation and factorisation scales (up to 35% at low $p_T$)\textsuperscript{5}. The uncertainty on the heavy quark masses contributes up to 9% at low $p_T$\textsuperscript{6} and the PDF-related uncertainty (taken from the CTEQ6.6 error set) is below 8% over

\begin{table}[h!]
\centering
\begin{tabular}{|c|c|}
\hline
Source of systematic uncertainty & Cross-section uncertainty (\%) \\
\hline
Possible bias in signal extraction & 3 \\
Early-$\ ETA$ fraction & $<2$ \\
Stat. uncertainty on signal extraction templates & 1-8 \\
Efficiency scale factor & 1.2 \\
Trigger efficiency control sample & 0.4-0.9 \\
Statistics & \\
Trigger efficiency control sample bias & $<2.3$ \\
Trigger efficiency background bias & 0.2-0.7 \\
Trigger efficiency mis-modelling & 0.5-0.7 \\
Signal fraction & \\
Unfolding procedure & 0.1-1.2 \\
Integrated luminosity & 3.4 \\
Total & 5-8 \\
\hline
\end{tabular}
\caption{Summary of systematic uncertainties on the muon cross-section measurement. The uncertainties apply in the $p_T$ bins of the measurement; an interval or upper limit is given where the uncertainty varies as a function of $p_T$.}
\end{table}

\begin{table}[h!]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
$p_T$ interval [GeV] & $\frac{d\sigma}{dp_T}$ (stat. syst.) & $\frac{d\sigma}{dp_T}$ & $\frac{d\sigma}{dp_T}$ (stat. syst.) \\
\hline
7-8 & 315.5 $\pm$ 57 & 302 $\pm$ 17 & 308 $\pm$ 25 \\
8-10 & 167 $\pm$ 27 & 142 $\pm$ 8 & 146 $\pm$ 9 \\
10-12 & 67 $\pm$ 11 & 58.0 $\pm$ 6.0 & 60 $\pm$ 9 \\
12-14 & 30.3 $\pm$ 4.7 & 26.1 $\pm$ 4.1 & 28 $\pm$ 6 \\
14-16 & 15.3 $\pm$ 4.2 & 11.3 $\pm$ 3.8 & 14 $\pm$ 4 \\
16-18 & 8.0 $\pm$ 3.1 & 7.92 $\pm$ 0.41 & 7.8 $\pm$ 1.0 \\
18-20 & 4.58 $\pm$ 0.15 & 7.2 & 4.5 $\pm$ 0.24 \\
20-22 & 2.75 $\pm$ 0.09 & 2.78 $\pm$ 0.03 & 2.7 $\pm$ 0.6 \\
22-26 & 1.29 $\pm$ 0.05 & 1.37 $\pm$ 0.02 & 1.4 $\pm$ 0.2 \\
\hline
\end{tabular}
\caption{Differential cross-sections $d\sigma/dp_T$ in (nb/GeV) for electron (muon) heavy-flavour production in the pseudorapidity region $|\eta| < 2$ (excluding $1.37 < |\eta| < 1.52$), with statistical (stat.) and systematic (syst.) uncertainties. The 3.4% luminoosity uncertainty is included in the latter. The predictions of FONLL are also given.}
\end{table}

\begin{table}[h!]
\centering
\begin{tabular}{|c|c|c|}
\hline
$p_T$ interval [GeV] & $\sigma_{\mu}$ & $\sigma_{\mu}$ (W/Z/\gamma*) sub. \\
\hline
4-5 & 3490 & 3490 & 7 & 230 \\
5-6 & 1390 & 1390 & 4 & 90 \\
6-7 & 680 & 680 & 3 & 40 \\
7-8 & 364 & 364 & 2 & 23 \\
8-9 & 210 & 210 & 1 & 3 \\
9-10 & 130 & 130 & 1 & 8 \\
10-11 & 84 & 84 & 1 & 5 \\
11-12 & 53 & 53 & 0.9 & 3 \\
12-14 & 31 & 31 & 0.5 & 2 \\
14-16 & 16.3 & 16.1 & 0.4 & 1.1 \\
16-18 & 9.4 & 9.2 & 0.06 & 0.6 \\
18-20 & 5.5 & 5.3 & 0.04 & 0.3 \\
20-22 & 3.4 & 3.2 & 0.03 & 0.2 \\
22-24 & 2.11 & 1.87 & 0.03 & 0.13 \\
24-26 & 1.46 & 1.20 & 0.02 & 0.10 \\
26-28 & 1.11 & 0.84 & 0.02 & 0.07 \\
28-30 & 0.88 & 0.60 & 0.02 & 0.06 \\
30-32 & 0.73 & 0.43 & 0.02 & 0.05 \\
32-34 & 0.58 & 0.26 & 0.02 & 0.04 \\
34-36 & 0.54 & 0.20 & 0.02 & 0.03 \\
36-38 & 0.48 & 0.13 & 0.01 & 0.03 \\
38-40 & 0.428 & 0.088 & 0.014 & 0.029 \\
40-44 & 0.311 & 0.074 & 0.009 & 0.020 \\
44-48 & 0.176 & 0.056 & 0.007 & 0.011 \\
48-52 & 0.085 & 0.025 & 0.005 & 0.007 \\
52-60 & 0.042 & 0.015 & 0.002 & 0.003 \\
60-70 & 0.0197 & 0.0083 & 0.0013 & 0.0013 \\
70-80 & 0.0081 & 0.0029 & 0.0008 & 0.0006 \\
80-90 & 0.0048 & 0.0021 & 0.0006 & 0.0004 \\
90-100 & 0.0024 & 0.0009 & 0.0005 & 0.0002 \\
\hline
\end{tabular}
\caption{Differential cross-sections $d\sigma/p_T$ (in nb/GeV) in the pseudorapidity region $|\eta| < 2.5$, before and after subtraction of the W/Z/\gamma* component, with statistical (stat.) and systematic (syst.) uncertainties. The 3.4% luminosity uncertainty is included in the latter. The uncertainty on the W/Z/\gamma* component is not included and amounts to 4% of the subtraction, increasing the systematic error by 5-10% for $p_T > 32$ GeV.}
\end{table}
the whole $p_T$ range. Uncertainties arising from the value of $\alpha_s$ and on the non-perturbative fragmentation function are found to be small, approximately 1% and less than 5% [9] respectively. The total uncertainty, dominated by the renormalisation and factorisation scales, is in the approximate range 20–40%, decreasing with $p_T$. The electron and muon results are seen to be fully compatible with the overall FONLL uncertainty bands.

The results are also compared to the NLO predictions of the POWHEG program, interfaced to either PYTHIA or HERWIG for the parton shower simulation, and to the LO plus parton shower predictions of PYTHIA. Whereas POWHEG+PYTHIA agrees well with the FONLL predictions, POWHEG+HERWIG predicts a significantly lower total cross-section. Less than half of this difference may be accounted for by different heavy-flavour hadron decay models, checked by implementing a common decay simulation, EVTGEN [36], for both showering and hadronisation programs. PYTHIA (LO) describes the $p_T$-dependence well but predicts approximately a factor two higher total cross-section.

Comparisons are also made to the NLO central value expectation obtained from the FONLL program by excluding the NLL resummation term of the pQCD calculation. As shown in Fig. 4 (right), the data deviate significantly from the NLO prediction, showing sensitivity to the NLL resummation term in the pQCD calculation for the first time in heavy-flavor production at hadron colliders.

8. Conclusions

The differential cross-sections of electrons and muons arising from heavy-flavour production have been measured and found to be in good agreement in the transverse momentum range $7 < p_T < 26$ GeV and pseudorapidity region $|\eta| < 2.0$ (excluding $1.37 < |\eta| < 1.52$). The inclusive differential cross-section of muon production has also been measured in the extended $p_T$ range $4 < p_T < 100$ GeV within $|\eta| < 2.5$.

The theoretical predictions for heavy-flavour production from the FONLL computation are in good agreement with the electron and muon measurements. Good agreement is also seen with the predictions of POWHEG+PYTHIA, although POWHEG+HERWIG predicts a significantly lower total cross-section. PYTHIA describes the $p_T$-dependence well but predicts approximately a factor two higher total cross-section. For muons with $p_T > 25$ GeV a deviation from the NLO central prediction is seen, indicating sensitivity of the heavy-flavour production data to the NLL high-$p_T$ resummation terms.

Acknowledgements

We thank Matteo Cacciari for supplying the theoretical predictions from FONLL, within our acceptance cuts, and for many useful discussions.

We also thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNESW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF...
Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References

[1] ATLAS Collaboration, JHEP 1012 (2010) 060.
[2] C. Albajar, et al., Phys. Lett. B 256 (1991) 121.
[3] D0 Collaboration, Phys. Rev. Lett. B 487 (2000) 264.
[4] CDF Collaboration, Phys. Rev. Lett. 71 (1993) 2396.
[5] CDF Collaboration, Phys. Rev. Lett. 71 (1993) 500.
[6] D. Acosta, et al., Phys. Rev. D 71 (2005) 032001.
[7] M. Cacciari, P. Nason, Phys. Rev. Lett. 89 (2002) 122003.
[8] M. Mangano, AIP Conf. Proc. 753 (2005) 247.
[9] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007.
[10] M. Cacciari, S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi, JHEP 4007 (2004) 033.
[11] S. Frixione, P. Nason, C. Oleari, JHEP 0711 (2007) 070.
[12] S. Alioli, P. Nason, C. Oleari, E. Re, JHEP 1006 (2010) 043, arXiv:1002.2581.

ATLAS Collaboration

G. Aad 48, B. Abbott 111, J. Abdallah 11, A.A. Abdelalim 49, A. Abdesselam 118, O. Abdinov 10, B. Abi 112, M. Abolins 88, H. Abramowicz 153, H. Abreu 115, E. Acerbi 89a,89b, B.S. Acharya 164a,164b, D.L. Adams 24, T.N. Addy 56, J. Adelman 175, M. Aderholz 99, S. Adomeit 98, P. Adragna 75, T. Adye 129, S. Afksse 22, J.A. Aguilar-Saavedra 124b, a, M. Ahn 21, S.P. Ahlen 21, F. Ahles 48, A. Ahmad 148, M. Ahsan 40, G. Aielli 133a,133b, T. Akdogan 18a, T.P.A. Akesson 79, G. Akimoto 155, A.V. Akimov 94, A. Akiyama 67, M.S. Alam 1, M.A. Alam 76, J. Albert 169, S. Albrand 55, M. Aleksandriv 65, F. Alessandrini 89a, G. Alexa 25a, G. Alexander 153, G. Alexandre 49, T. Alexopoulos 9, M. Alhroob 20, M. Aliev 15, G. Alimonti 89a, J. Alisio 120, M. Aliyev 10, P.P. Alport 73, S.E. Allwood-Spiers 53, J. Almond 82, A. Aloisio 102a,102b, R. Alon 171, A. Alonso 79, M.G. Alviggi 102a,102b, K. Amako 66, P. Amaral 29, C. Amelung 22, V.V. Ammosov 128, A. Amorim 124a,8, G. Amaros 167, N. Amram 153, C. Anastopoulos 29, N. Andari 115, T. Andeen 34, C.F. Anders 20, K.J. Anderson 30, A. Andreazza 89a,89b, V. Andrei 58a, M.-L. Andrieux 55, X.S. Anduaga 70, A. Angerami 34, F. Anghinolfi 29, N. Anjos 124a, A. Annovi 47, M. Antonacci 47, A. Antonov 96, J. Antos 144b, F. Anulli 132a, S. Arai 66, A.T.H. Arce 44, J.P. Archambault 28, S. Arfaoui 29d, J.-F. Arguin 14, E. Ariki 18a, M. Arik 18a, A. Armbruster 87, O. Arnaez 81, C. Arnaut 115, A. Artamonov 95, G. Artong 132a,132b, D. Arutinov 20, S. Asai 155, R. Asfandiyarov 172, S. Ask 27, B. Ásman 146a,146b, L. Asquith 5, K. Assamagan 24, A. Astbury 169, A. Astvatsatourian 52, A. Atoian 75c, B. Aubert 4, B. Auerbach 175, E. Aug 115, K. Augsten 127, M. Auerousseau 145a, N. Austin 73, G. Avolio 163, R. Avramidou 9, D. Axen 168, C. Ay 54, G. Azuelos 93e, Y. Azuma 155, M.A. Baak 29, G. Baccaglioni 89a, C. Bacci 134a,134b, A.M. Bach 14, H. Bachacou 136, K. Bachas 29, G. Bachy 29, M. Backes 29, M. Backhaus 20, E. Badescu 25a, P. Bagnaia 132a,132b, S. Bahinipati 2, Y. Bai 32a, D.C. Bailey 158, T. Bain 158, J.T. Barnes 129, O.K. Baker 175, M.D. Baker 24, S. Baker 77, F. Baltasar Dos Santos Pedrosa 29, E. Banas 38, P. Banerjee 93, Sw. Banerjee 172, D. Banfi 29, A. Bangert 137, V. Bansal 169, H.S. Bansi 17, L. Barak 171, S.P. Baranov 94, A. Barashkou 65, A. Barbaro Galtieri 14, T. Barber 27, E.L. Barberio 86, D. Barberis 30a,50b, M. Barbero 20, D.Y. Bardin 65, T. Barillari 99, M. Barisonzi 174, T. Barklow 143c, N. Barlow 27, B.M. Barnett 129, R.M. Barnett 14, A. Barone 134a, G. Barone 49, A.J. Barn 118, F. Barreiro 80, J. Barreiro Guimarães da Costa 57, P. Barrillon 115, R. Bartoldus 143, A.E. Barton 71, D. Bartsch 20, V. Bartsch 149, R.L. Bates 53, L. Batkova 144a, J.R. Batley 27, A. Battaglia 16, M. Battistin 29, G. Battistoni 89a, F. Bauer 136, H.S. Bawa 143f, B. Beare 158, T. Beau 78, P.H. Beauchemin 118, R. Beccherle 50a, P. Bechtle 41, H.P. Beck 16, M. Beckingham 48, K.H. Becks 174, A.J. Beddall 18c, A. Beddall 18c, S. Bedikian 175, V.A. Bednyakov 65, C.P. Bee 83, M. Begel 24, S. Behar Harpaz 152, P.K. Behera 63, M. Beimforde 99, C. Belanger-Champagne 85, P. Bell 49, W.H. Bell 49, G. Bella 153,
