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Measurements of the electron and muon inclusive cross-sections in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

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ABSTRACT

This Letter presents measurements of the differential cross-sections for inclusive electron and muon production in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV, using data collected by the ATLAS detector at the LHC. The muon cross-section is measured as a function of p_T in the range $4 < p_T < 100$ GeV and within pseudorapidity $|\eta| < 2.5$. In addition the electron and muon cross-sections are measured in the range $7 < p_T < 26$ GeV and within $|\eta| < 2.0$, excluding $1.37 < |\eta| < 1.52$. Integrated luminosities of 1.3 pb^{-1} and 1.4 pb^{-1} are used for the electron and muon measurements, respectively. After subtraction of the $W/Z/\gamma^*$ contribution, the differential cross-sections are found to be in good agreement with theoretical predictions for heavy-flavour production obtained from Fixed Order NLO calculations with NLL high-p_T resummation, and to be sensitive to the effects of NLL resummation.
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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/γ^* 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 p_T region where the deviation between the NLO and the NLO + NLL perturbative QCD (pQCD) calculations becomes apparent. At the LHC, NLL resummation can be probed directly in the pQCD prediction for heavy-flavour production in hadron collisions for the first time.

In the analyses reported in this Letter the p_T spectra of inclusive electrons and muons are measured using an integrated luminosity of 1.3 pb^{-1} and 1.4 pb^{-1}, respectively. A kinematic acceptance of $7 < p_T < 26$ GeV and pseudorapidity[1] $|\eta| < 2.0$ excluding $1.37 < |\eta| < 1.52$ is considered for electrons, and $4 < p_T < 100$ GeV and $|\eta| < 2.5$ for muons.

This Letter is organised as follows. The experimental and theoretical methodology is outlined in Section 2. A short description of electron and muon reconstruction in the ATLAS detector is provided in Section 3, with the recorded and simulated data samples used in the analyses being discussed in Section 4. Sections 5 and 6 describe the cross-section measurements in the electron and muon channels respectively. For the muon analysis, the inclusive cross-section is compared to the most recent theoretical predictions in Section 6.6. Finally in Section 7, the electron and muon cross-sections from heavy-flavour hadron production are determined by subtracting the $W/Z/\gamma^*$ 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

$$\frac{\Delta\sigma_i}{\Delta p_{T_i}} = \frac{N_{\mathrm{sig}_i}}{\Gamma_{\mathrm{bin}_i} \cdot \int \mathcal{L}\,dt} \cdot \frac{C_{\mathrm{migration}_i}}{\epsilon_{(\mathrm{reco+PID})_i} \cdot \epsilon_{\mathrm{trigger}_i}}, \qquad (1)$$

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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where N_{sig_i} is the number of signal electrons or muons with reconstructed p_T in bin i of width Γ_{bin_i}, $\int \mathcal{L} dt$ is the integrated luminosity, $\epsilon_{\text{trigger}_i}$ is the trigger efficiency and $\epsilon_{(\text{reco+PID})_i}$ is the combined reconstruction and identification efficiency. $C_{\text{migration}_i}$ 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_{sig_i} 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 $W/Z/\gamma^*$ production in order to obtain a cross-section corresponding to the decays of heavy-flavour hadrons produced in the pp collisions to electrons or muons. In the electron analysis, the $W/Z/\gamma^*$ accepted cross-section, $\sigma^{W/Z/\gamma^*}_{\text{accepted}_i}$, is subtracted before applying the efficiency and migration correction factor, $\epsilon_{(\text{reco+PID})_i}/C_{\text{migration}_i}$, which is specific to heavy-flavour electrons due to the dependence of the identification efficiency on isolation. In the muon analysis, the same correction factor applies for muons originating from both heavy-flavour and $W/Z/\gamma^*$ decays, allowing the subtraction to be performed at the cross-section level.

The spectrum of charged leptons from heavy-flavour decays is calculated in a theoretical framework, FONLL, permitting direct comparison with the data. FONLL is based on three main components: the heavy quark production cross-section calculated in pQCD by matching the Fixed Order NLO terms with NLL high-p_T resummation, the non-perturbative heavy-flavour fragmentation functions determined from e^+e^- collisions and extracted in the same framework, and the decays of the heavy hadrons to leptons using decay tables and form factors from B-factories. The theoretical uncertainties associated with the FONLL prediction will be discussed in Section 7 when the comparisons to the measured cross-sections are made.

3. Electron and muon reconstruction in the ATLAS detector

The ATLAS detector consists of three main components: an Inner Detector (ID) tracking system immersed in a 2 T magnetic field, surrounded by electromagnetic (EM) and hadronic calorimeters and an outer muon spectrometer (MS). A full description can be found in [14]. The ID provides precise track reconstruction within $|\eta| < 2.5$, employing pixel detectors close to the beam-pipe, silicon microstrip detectors (SCT) at intermediate radii and a Transition Radiation Tracker (TRT) at outer radii. Within $|\eta| < 2.0$ the TRT provides substantial discriminating power between electrons and pions over a wide energy range. The inner-most pixel layer (the B-layer) is located at a radius of 50 mm and provides precision vertexing and significant rejection of tracks produced by photon conversions.

Within $|\eta| < 2.5$, EM calorimetry is provided by the barrel and end-cap lead/Liquid-Argon (LAr) EM sampling calorimeters, and hadronic calorimetry by the three-part steel/scintillating tile barrel calorimeter plus the two copper/LAr end-caps. The EM calorimeter is segmented in the longitudinal and transverse directions, with fine granularity along the η direction in the first (strip) layer. The identification of electron candidates is seeded by a preliminary set of clusters in the EM calorimeter using a sliding window algorithm, with those clusters having a match to a suitable ID track being reconstructed [15]. In the transition region between the barrel and end-cap calorimeters at $1.37 < |\eta| < 1.52$ the electron identification and energy resolution is degraded by the large amount of material in front of the first active layers, prompting the exclusion of this region from the electron analysis.

The MS comprises separate trigger and high-precision tracking chambers which measure the deflection of muons in a magnetic field generated by three super-conducting air-core toroids. The precision chamber system covers 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 (ϕ) 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 ± 0.04 pb^{-1} and 1.42 ± 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. Further

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