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Electroweak Physics at LHCb

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LHCb's unique forward acceptance allows for complementary measurements of electroweak boson production to those at the other Large Hadron Collider experiments. New high precision W and Z boson cross-section measurements, and their ratios, are presented. The unique phase-space available at LHCb means that these results allow new constraints to be placed on parton distribution functions. Forward vector boson production in association with forward jets is also discussed. These measurements probe parton distribution functions, but also provide important constraints on backgrounds when measuring other processes, such as top production in the forward region.

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1. Introduction

The LHCb experiment [1] at the Large Hadron Collider (LHC) is a fully-instrumented forward arm spectrometer in the forward region, initially proposed for studying decays of heavy flavour particles. However, the design and unique precision coverage of the LHCb detector in the forward region mean that LHCb is able to make complementary measurements of electroweak physics to the other LHC detectors.

Collisions that produce particles in the forward LHCb acceptance are typically between one parton at high Bjorken x and one parton at low x. The parton distribution functions (PDFs) that describe the partons at high x are largely constrained by previous measurements at fixed target experiments, HERA, and the Tevatron. The ATLAS and CMS detectors at the LHC also probe this region, and intermediate values of x. However, at the low-x values probed by the LHCb experiment the PDFs are less well constrained. Consequently, predictions of electroweak vector boson production in the forward region have a large uncertainty associated with the current state of PDF knowledge. Any measurements of vector boson production at the LHCb experiment will play an important role in constraining PDFs [2]. This article discusses these measurements. For a more detailed overview of the use of LHCb measurements, please see the discussion in Ref. [2].

Proton-proton collisions at LHCb typically contain fewer pile-up interactions than those at the other LHC detectors, with the average number of visible proton-proton interactions in each LHC bunch crossing typically between 1 and 2. This enables the positions of particle interactions and decays to be precisely determined. Cross-section measurements at LHCb also benefit from the precision determination of the LHC beam luminosities in collisions in LHCb [3]. The total integrated luminosity collected in collisions at LHCb in 2011, at a centre-of-mass energy of 7 TeV, is known to a precision of 1.71%, and the total integrated luminosity collected in collisions in 2012, at a centre-of-mass energy of 8 TeV, is known to an precision of 1.16%. This represents the most accurate luminosity determination at a bunched-beam hadron collider.

2. Measurements of Inclusive W and Z boson production at the LHCb experiment in Run I

LHCb measurements of inclusive W and Z boson production[1], where the bosons decay to leptons, are performed in a fiducial acceptance that is chosen to closely mirror the acceptance of the LHCb detector. For W and Z production, the charged lepton(s) produced by the boson decay are required to have $2.0 < \eta < 4.5$ and $p_{\mathrm{T}} > 20$ GeV. For measurements of Z boson production, the leptons are also required to have an invariant mass in the region $60 < M < 120$ GeV. No requirements are made on missing energy or related variables. As LHCb is not a hermetic detector, such variables are not reliably computed. The impact of this will be discussed below.

LHCb has measured the inclusive production of Z bosons in events where they decay to two electrons, for proton-proton collisions at centre-of-mass energies of 7 TeV [4] and at 8 TeV [5]. Events are selected with a purity greater than 90%. The dominant uncertainty on these measurements is due to the precision with which the reconstruction efficiencies of the electrons are determined. These efficiencies are measured from simulation, but the uncertainty is determined by

[1] Both γ^* production and Z/γ^* interference are implicitly included in this article when Z bosons are mentioned.

comparing the recorded data to this simulation sample. Cross-sections are measured differentially as functions of both the boson rapidity and the boson ϕ^*, an angular variable first introduced in Ref. [8] which is approximately the vector boson transverse momentum divided by its mass, but is easier to measure with high precision at hadron colliders. The measured differential cross-sections as a function of rapidity have been compared to next-to-next-to-leading order (NNLO) theoretical predictions determined using different PDF parameterisations, and have been found to be in agreement. The differential cross-sections as a function of ϕ^* also tend to agree reasonably with predictions which account for higher order perturbative terms which are particularly important at low transverse momentum.

LHCb has also measured the inclusive production of Z bosons, in events where the Z boson decays to two muons, in proton-proton collisions at a centre-of-mass energy of 7 TeV [6]. Events are selected with a purity of about 99.3%. All detection efficiencies are determined directly from data to high precision: the luminosity is the largest uncertainty on the total cross-section. Differential cross-sections are measured as a function of the boson rapidity (shown in Figure 1), transverse momentum, and ϕ^*, and again reasonable agreement is seen with the same theoretical predictions.

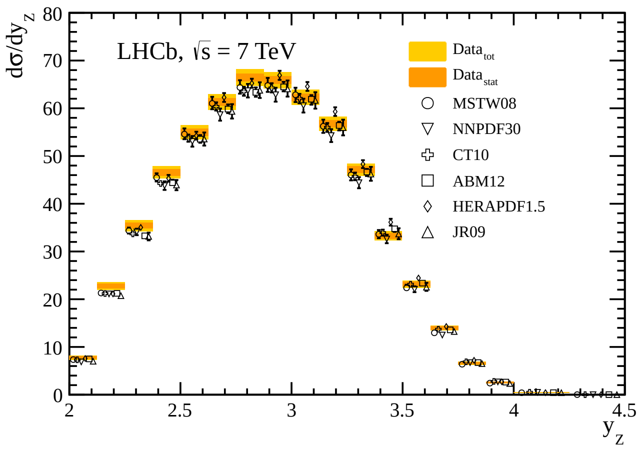

Figure 1: The differential cross-section for Z boson production in events where the Z boson decays to two muons. The LHCb measurement is shown by the bands: the inner band corresponds to the statistical uncertainty, and the outer band shows the total uncertainty. The points show theoretical predictions at NNLO using different PDF parameterisations. The uncertainties on the theoretical predictions correspond to both scale variations and PDF uncertainties. From Ref [6].

Inclusive W boson production has also been measured at LHCb, separately for both W boson charges, in events where the W boson decays directly to a muon and (anti-)neutrino [7]. Events are selected by requiring an isolated, prompt muon with high transverse momentum (above 20 GeV), in events where no other muon with transverse momentum above 2 GeV is identified. The purity is determined by fitting the muon transverse momentum in bins of the muon pseudorapidity. Templates for these fits are either taken from data or are constrained using data. The purities are around 80% for both the W^+ and W^- boson samples. The luminosity uncertainty dominates the total uncertainty in the total cross-section measurement. The cross-sections are measured as a function of the muon pseudorapidity, and are found to agree with NNLO predictions from different PDF parameterisations. The charge asymmetry (defined as the difference between the W^+ and W^- cross-sections divided by their sum) is also found as a function of the muon pseudorapidity. Many uncertainties cancel when this measurement is made (for example the luminosity), allowing a precise experimental determination. However, the PDF uncertainties on the theoretical predictions remain significant, because of the different initial state quarks required to produce W bosons of different charges. This asymmetry is shown in Figure 2. Again, the results are compared to predictions from different PDF parameterisations, and are found to be in agreement. The shape of the distribution reflects the V-A structure of the weak force and the quark content of the colliding protons.

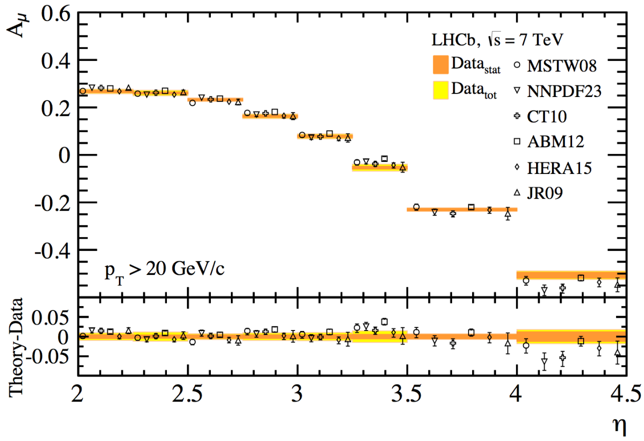

Figure 2: The charge asymmetry for leptons produced from W boson decays, measured in the LHCb acceptance. The LHCb data are shown by the orange bands (with the inner band showing the statistical uncertainty, and the outer band showing the overall uncertainty). The points show theoretical predictions at NNLO using different PDF parameterisations. The uncertainties on the theoretical predictions correspond to both scale variations and PDF uncertainties. From Ref [7].

In addition to determining the charge asymmetry, the W and Z boson production cross-sections can be considered together, accounting for the correlations in the measurements. The measured total cross-sections are shown in Figure 3, and are compared to predictions from different PDF parameterisations. Again, the results show good agreement with the theoretical predictions, but the size of the theoretical uncertainties show the potential for these measurements to constrain PDFs once correlations are accounted for. Indeed, many newer PDF fits to data already include LHCb results as an input [9, 10, 11, 12].

3. Z+jet and W+jet measurements at the LHCb experiment in Run I

LHCb has also studied events where a forward W or Z boson is produced in association with a forward jet. Jet reconstruction at LHCb [13] uses a particle flow approach, clustering particles

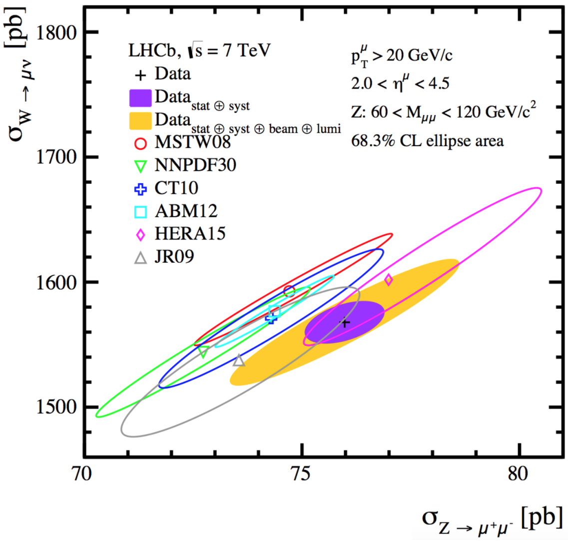

Figure 3: LHCb measurements of W and Z production compared to NNLO predictions using different PDF parameterisations. Uncertainties on the theoretical predictions are due to the PDFs. From Ref [6].

with the anti-$k_{\rm T}$ algorithm [14]. The radius parameter is set to $R = 0.5$.

The Z+jet production cross-section has been measured at LHCb for two different transverse momentum thresholds (20 and 10 GeV) in proton-proton collisions at a centre-of-mass energy of 7 TeV [13]. In addition, differential distributions with respect to both the Z boson and the jet kinematic variables have been measured, as has the ratio of Z+jet production to inclusive Z boson production. The dominant uncertainty comes from the jet energy scale. All these measurements show good agreement with NLO theoretical predictions for a variety of different PDF parameterisations.

The ratio of the W+jet production cross-section to the Z+jet production cross-section has also been measured in both 7 and 8 TeV collisions [15]. The dominant uncertainty comes from estimating the sample purity, here determined using a fit to a variable that describes the isolation of the muon(s) from the boson decay. These measurements agree with the Standard Model predictions, but, in addition to allowing different PDFs to be compared, they also enable a precise constraint of the W+b-jet background when measuring top production at LHCb [16].

4. Conclusions

LHCb measurements of W and Z boson production in Run I constitute some of the most precise measurements at the LHC thanks to LHCb's excellent knowledge of the recorded integrated luminosity. The LHCb results are all consistent with Standard Model predictions, but are also sensitive to different PDF parameterisations, and are already used to constrain new PDF fits. Boson production in association with jets has also been measured at LHCb, enabling further tests of PDFs, but also providing key inputs to other studies, such as top production in the forward region.

Proton-proton collisions are already being recorded at a centre-of-mass energy of 13 TeV: the LHCb invariant dimuon mass distribution from the first collisions at this new energy is shown in Figure 4, where a clear peak associated with the Z boson is visible. The results that these and subsequent data will yield will play an important role in understanding QCD and electroweak physics in the coming years.

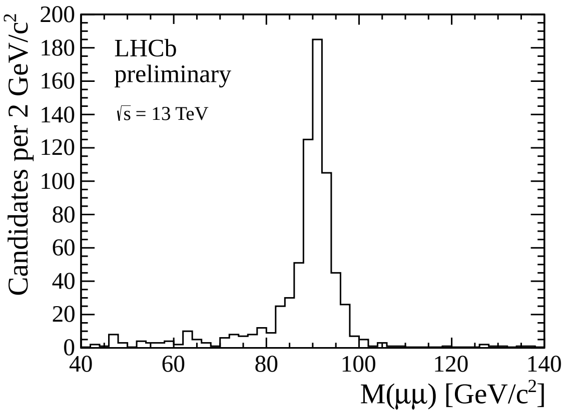

Figure 4: The dimuon invariant mass distribution seen in the first proton-proton collisions recorded by the LHCb experiment in 2015 at a centre-of-mass energy of 13 TeV.

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