ASSOCIATED Z BOSON PRODUCTION IN THE FORWARD REGION

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The Z plus jet and Z plus D production cross-sections in proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV and the inclusive Z boson production cross-section in proton-lead collisions at a centre-of-mass energy per proton-nucleon pair $\sqrt{s_{NN}} = 5$ TeV are measured by LHCb. These results are briefly presented here.

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1 Motivation

The LHCb detector [1] is a single-arm forward spectrometer designed for the study of particles containing b or c quarks. It is fully instrumented in the pseudorapidity range $2 < \eta < 5$. Its unique kinematic coverage allows to perform measurements that are sensitive to both low and high values of Bjorken x and hence are complementary to those performed at the general purpose detectors, ATLAS and CMS. At energy scales typical for Z boson production measurements at LHCb are sensitive to values of x as low as 1.7×10^{-4}, where they can provide a fundamental input to parton distribution functions (PDFs).

Here, cross-section measurements of Z plus jet ($Z+\text{jet}$) [2] and Z plus D ($Z+D$) [3] associative production are presented, together with first results on the inclusive Z boson production in proton-lead collisions at a centre-of-mass energy per proton-nucleon pair $\sqrt{s_{NN}} = 5$ TeV [4]. $Z+\text{jet}$ events are usually produced from a collision of a sea quark, or a gluon, with a valence quark and are thus sensitive to the gluon PDF [5]. The measurement of this cross-section can also be used to tune event generators. The $Z+D$ associative production is sensitive to the charm PDF, the charm production mechanism, and the double-parton scattering [7, 8].

2 Data sample and event selection

The measurements of the $Z+\text{jet}$ and $Z+D$ production cross-sections in proton-proton collisions at a centre-of-mass energy $\sqrt{s}=7$ TeV are based on a data sample corresponding to an integrated luminosity of 1 fb^{-1}. The measurement of the inclusive Z boson production cross-section in proton-lead collisions at a centre-of-mass energy per proton-nucleon pair $\sqrt{s_{NN}}=5$ TeV is based on a data sample corresponding to an integrated luminosity of 1.6 nb^{-1}.

The Z candidates are reconstructed from pairs of oppositely charged muons with transverse momentum $p_{\mathrm{T}}^{\mu}>20$ GeV and pseudorapidity $2<\eta^{\mu}<4.5$, combining into an invariant mass $60<M^{\mu\mu}<120$ GeV. These three criteria define the fiducial volume in which all the cross-sections are quoted. They guarantee very high purities, above 95%, with a small residual background mainly due to heavy flavour decays and misidentified hadrons.

For the measurement of the $Z+\text{jet}$ production cross-section, the jets are required to be within $2.0<\eta^{\text{jet}}<4.5$ and to be well-separated from the two muons to which the Z boson decays. They are reconstructed with the anti-k_{T} algorithm [6] with radius parameter $R=0.5$. The inputs to the jet finding are selected using the particle flow approach.

For the measurement of the $Z+D$ production cross-section, the D candidates are reconstructed using $D^0\to K^-\pi^+$ and $D^+\to K^-\pi^+\pi^+$ decay modes. The open charm mesons are reconstructed in a kinematic range of $2<\eta^D<4$ and $2<p_{\mathrm{T}}^D<12$ GeV, which also defines the fiducial volume of the measurement. Further kinematic and identification requirements are applied on the daughters of the open charm mesons.

3 $Z+\text{jet}$ production

The $Z+\text{jet}$ production cross-section is measured by LHCb for two different thresholds, corresponding to $p_{\mathrm{T}}^{\text{jet}}>10$ and 20 GeV, respectively.

Jets are corrected to hadron level and cross-sections are corrected for final state radiation. The Z+jet production cross-section is measured to be

$$\sigma = 16.0 \pm 0.2\ (\text{stat.}) \pm 1.2\ (\text{syst.}) \pm 0.6\ (\text{lumi.})\ \text{pb}$$

for $p_{\mathrm{T}}^{\text{jet}}>10$ GeV and

$$\sigma = 6.3 \pm 0.1\ (\text{stat.}) \pm 0.5\ (\text{syst.}) \pm 0.2\ (\text{lumi.})\ \text{pb}$$

for $p_T^{\rm jet} > 20$ GeV, where the first uncertainty is statistical, the second systematic, and the third due to luminosity. The cross-section ratio $\sigma(Z+{\rm jet})/\sigma(Z)$ for $p_T^{\rm jet} > 10$ GeV is

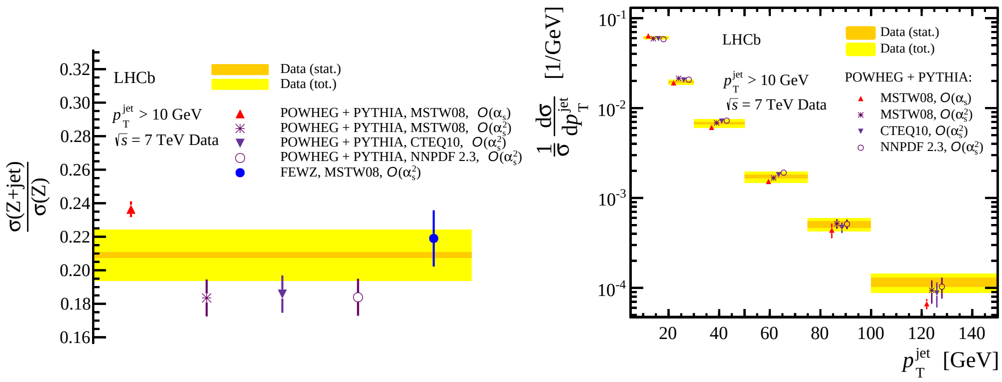

Figure 1: Experimental results and theoretical predictions for the cross-section ratio $\sigma(Z+{\rm jet})/\sigma(Z)$ (left) and for the differential Z+jet production cross-section as a function of $p_T^{\rm jet}$ (right), both for $p_T^{\rm jet} > 10$ GeV.

shown in Fig. 1, together with predictions at different orders in perturbative QCD, using different PDF sets, and including or not the effect of hadronisation and underlying event. The cross-section ratio is found to be 20% for $p_T^{\rm jet} > 10$ GeV and 8% for $p_T^{\rm jet} > 20$ GeV and is in general agreement with the predictions. Several differential cross-sections are also measured and compared to predictions at $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$. The differential $Z+$jet production cross-section as a function of $p_T^{\rm jet}$ is shown in Fig. 1. Measurements are in good agreement with the predictions at $\mathcal{O}(\alpha_s^2)$.

4 $Z + D$ production

After applying the requirements described in Sec. 2, 7 and 4 candidates are found in the $Z + D^0$ and $Z + D^+$ channels, respectively, corresponding to a combined significance of 5.1 σ. This is the first observation of $Z + D$ production in proton-proton collisions. Three different sources of background are taken into account: D originating from beauty hadrons decays, which are found to be the dominant contribution, background due to multiple proton-proton interactions, and combinatorial background, which is evaluated by fitting the two-dimensional invariant mass distribution of the muon pair and of the $K^-\pi^+$ ($K^-\pi^+\pi^+$) pair for the $Z+D^0$ ($Z+D^+$) channel.

The $Z+D$ production cross-section is measured to be

$$\sigma_{Z\to\mu^+\mu^-,D^0} = 2.50 \pm 1.12\ (\text{stat.}) \pm 0.22\ (\text{syst.})\ \text{pb}$$

in the $Z+D^0$ final state and

$$\sigma_{Z\to\mu^+\mu^-,D^+} = 0.44 \pm 0.23\ (\text{stat.}) \pm 0.03\ (\text{syst.})\ \text{pb}$$

in the $Z+D^+$ final state, where the first uncertainty is statistical and the second systematic.

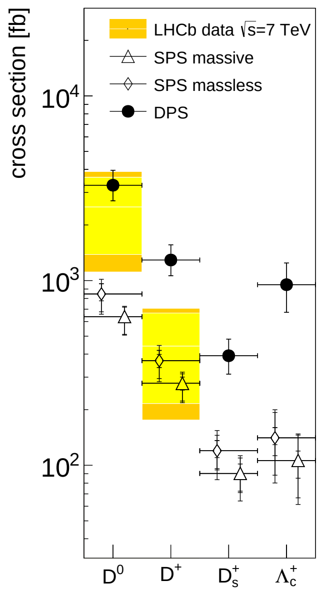

Figure 2: Experimental results and theoretical predictions for the $Z+D$ production cross-section.

The cross-sections are quoted in the fiducial volume defined in Sec. 2, with the two additional requirements on p_{T}^{D} and η^{D}. A comparison between experimental results and theoretical predictions is shown in Fig. 2.

The measured cross-section is expected to be the sum of the single parton scattering (SPS) and double-parton scattering (DPS) predictions. The $Z+D^0$ measurement is in agreement with the predictions, while the $Z+D^+$ measurement is below the expectation. The SPS prediction is calculated with MCFM [9] using the MSTW08 PDF set [10], while the DPS prediction is calculated with the factorisation approximation [11] as:

$$\sigma^{\text{DPS}}_{Z\to\mu^+\mu^-,D} = \sigma_{Z\to\mu^+\mu^-}\sigma_D/\sigma_{\text{eff}},$$

where $\sigma_{Z\to\mu^+\mu^-}$, σ_D, and σ_{eff} are taken from [12, 13, 14]. More statistics is needed in order to measure differential cross-sections and disentangle the SPS and DPS contributions.

5 Inclusive Z boson production in proton-lead collisions

Measurements in proton-lead collisions can serve as reference for future lead-lead collisions but can also provide a significant constraining power for nuclear PDFs in unprobed regions of the phase space, at both low and high x_A values, where x_A is the Bjorken variable of the parton in the nucleon [15].

The analysis presented here is based on two data samples of proton-lead collisions at a centre-of-mass energy per proton-nucleon pair $\sqrt{s_{NN}} = 5$ TeV. The energy of the proton beam is $E_p = 4$ TeV, the energy of the lead beam per nucleon is $E_N = 1.58$ TeV. Due to the asymmetry in the beam energies, there is a shift in rapidity $\Delta y = 0.47$ between the laboratory and the centre-of-mass frames. The two data samples correspond to two different beam configurations, referred to as *forward* and *backward*, respectively. The cross-section is measured in the direction of the proton beam in the forward configuration, thus accessing low x_A values, and in the direction of the lead beam in the backward configuration, thus accessing high x_A values. The Z candidates are reconstructed in the $Z \to \mu^+\mu^-$ final state by appling the requirements discussed in Sec. 2. In total, 11 and 4 candidates are observed in the forward and backward configurations, respectively.

The inclusive Z boson production cross-section is measured to be

$$\sigma^{\text{fwd}}_{Z\to\mu^+\mu^-} = 13.5^{+5.4}_{-4.0}\ (\text{stat.}) \pm 1.2\ (\text{syst.})\ \text{nb}$$

in the direction of the proton beam and

$$\sigma^{\text{bwd}}_{Z\to\mu^+\mu^-} = 10.7^{+8.4}_{-5.1}\ (\text{stat.}) \pm 1.0\ (\text{syst.})\ \text{nb}$$

in the direction of the lead beam, where the first uncertainty is statistical and the second systematic.

This is the first observation of inclusive Z boson production in proton-lead collisions, corresponding to a significance of 10.4 σ for the forward and 6.8 σ for the backward measurements. A comparison between experimental results and theoretical predictions calculated at NNLO using FEWZ [16] and the MSTW08 PDF set, with and without nuclear effects, is shown in Fig. 3. Nuclear effects are parametrised by the EPS09 nuclear PDF set at NLO [17]. The measurements are in agreement with the predictions and are dominated by the statistical uncertainties. More statistics is needed in order to investigate the presence of nuclear effects. The first observation of inclusive Z boson production in proton-lead collisions demonstrate, however, the excellent potential of the study of electroweak physics in proton-lead collisions in LHCb and may thus support future proton-lead runs.

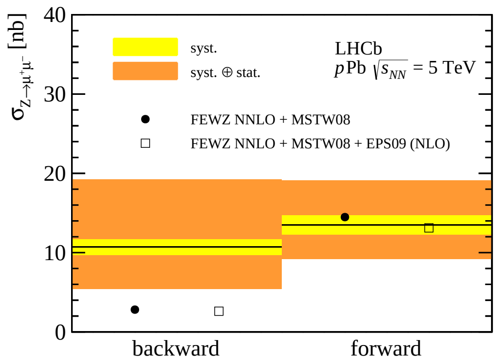

Figure 3: Experimental results and theoretical predictions for the inclusive Z boson production cross-section. Uncertainties on theoretical predictions are negligible compared to those on experimental results.

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