Published for SISSA by Springer

Received: *January 15, 2014*
Accepted: *March 5, 2014*
Published: *April 14, 2014*

Observation of associated production of a Z boson with a D meson in the forward region

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Abstract: A search for associated production of a Z boson with an open charm meson is presented using a data sample, corresponding to an integrated luminosity of $1.0\,\mathrm{fb}^{-1}$ of proton-proton collisions at a centre-of-mass energy of 7 TeV, collected by the LHCb experiment. Seven candidate events for associated production of a Z boson with a D^0 meson and four candidate events for a Z boson with a D^+ meson are observed with a combined significance of 5.1 standard deviations. The production cross-sections in the forward region are measured to be

$$\sigma_{Z\to\mu^+\mu^-,\,D^0} = 2.50 \pm 1.12 \pm 0.22\,\mathrm{pb}$$
$$\sigma_{Z\to\mu^+\mu^-,\,D^+} = 0.44 \pm 0.23 \pm 0.03\,\mathrm{pb},$$

where the first uncertainty is statistical and the second systematic.

Keywords: Hadron-Hadron Scattering, Heavy quark production, Forward physics, Particle and resonance production

ArXiv ePrint: 1401.3245

doi:10.1007/JHEP04(2014)091

Contents

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1 Introduction

The forward production cross-section for associated production of a Z boson[1] with an open charm meson in pp collisions provides information about the charm parton distribution inside the proton, the charm production mechanism, and double-parton scattering [1, 2]. A measurement of this cross-section is a complementary probe to previous measurements by LHCb of double charm production [3], inclusive $W^{\pm}$ and Z boson production [4–6] and Z production in association with jets [7]. Since the LHCb detector is fully instrumented in the forward region, measurements of electroweak boson production at LHCb have a unique sensitivity to both high and low Bjorken-x regions where parton distribution functions are not precisely determined by previous measurements [8].

The first observation of associated production of a Z boson with open charm hadrons is presented in this paper. The ATLAS and CMS collaborations have recently shown first results of W production in association with a charmed hadron [9, 10], a measurement that is directly sensitive to the s-quark content of the proton. The associative production of Z bosons with charmed jets has been reported by the D0 collaboration to be in disagreement with next-to-leading order pertubative QCD predictions [11].

In this paper the results are quoted as the product of the production cross-section and the branching fraction for the $Z \to \mu^+\mu^-$ decay. The selection of the Z candidates and the D mesons follows those of previous publications [3, 4, 7], allowing the analysis techniques and reconstruction efficiencies to be reused. The results are compared to predictions from two production mechanisms: single- (SPS) and double-parton scattering (DPS).

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[1] The contribution of the virtual γ^* and charge conjugated modes are always implied in this paper.

2 Detector and data sample

The LHCb detector [12] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV to 0.6% at 100 GeV, and impact parameter resolution of 20 μm for tracks with high transverse momentum.[2] Charged hadrons are identified using two ring-imaging Cherenkov detectors [13]. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [14]. The trigger [15] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

Candidate events are first required to pass a hardware trigger, which selects single muons with transverse momentum $p_{\mathrm{T}} > 1.48\,\mathrm{GeV}$. In the subsequent software trigger, at least one of the final state muons is required to have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. In order to avoid a few events with high hit multiplicity dominating the processing time in the software trigger, global event cuts are applied. The dominant global event cut requires the total hit multiplicity in the scintillating-pad detector to be fewer than 600 hits. This selects about 90% of the events that contain a Z boson.

The data sample consists of $1.0\,\mathrm{fb}^{-1}$ of integrated luminosity collected with the LHCb detector in 2011 using pp collisions at a centre-of-mass energy of 7 TeV.

3 Event selection

The selection of Z boson candidates and charmed mesons follows those of previous publications [3, 4, 7]. Candidate $\mathrm{Z} \to \mu^+\mu^-$ events are selected by requiring a pair of well reconstructed tracks identified as muons. The invariant mass of the two muons must be reconstructed in the range $60 < m_{\mu^+\mu^-} < 120\,\mathrm{GeV}$. Each muon track must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and lie in the pseudorapidity range $2.0 < \eta(\mu^\pm) < 4.5$. For the reconstruction of $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ and $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$ decays, well reconstructed and identified $\pi^\pm$ and $\mathrm{K}^\pm$ candidates are selected. To ensure a good particle identification separation, the kaons and pions are required to be in the momentum range $3.2 < p < 100\,\mathrm{GeV}$ and $p_{\mathrm{T}} > 250\,\mathrm{MeV}$. The selected hadrons are combined to form open charm meson candidates in the $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ and $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$ final states in the invariant mass range $1.82 < m_{\mathrm{K}^-\pi^+} < 1.92\,\mathrm{GeV}$ for D^0 and $1.82 < m_{\mathrm{K}^-\pi^+\pi^+} < 1.91\,\mathrm{GeV}$ for D^+. We require ct to be larger than 100 μm, where t is the decay time in the rest frame of the open charm mesons. All open charm mesons are required to have rapidity reconstructed in the range

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[2] In this paper units are chosen such that $c = 1$.

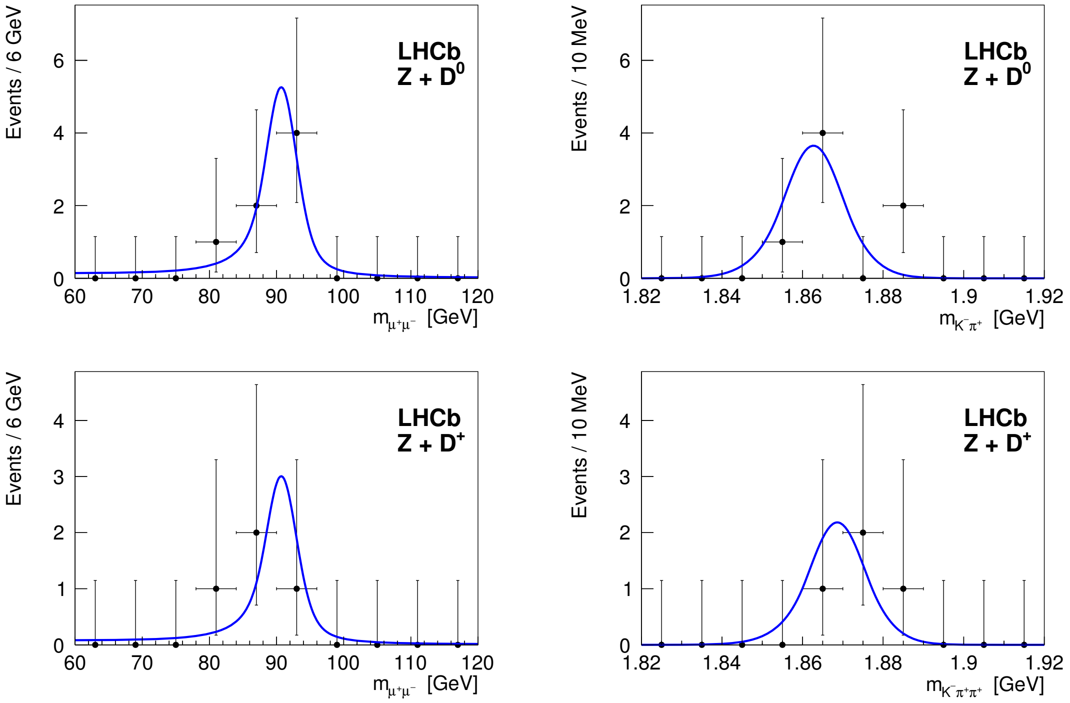

Figure 1. Invariant mass distribution for Z (left) and D (right) candidates for $\mathrm{Z + D^0}$ (top) and $\mathrm{Z + D^+}$ (bottom) events. The superimposed curves represent the projection of the fit described in section 4.

$2 < y(\mathrm{D}) < 4$ and $2 < p_{\mathrm{T}}(\mathrm{D}) < 12\,\mathrm{GeV}$. The kinematic selection criteria mentioned above, with the exception of the requirements on pions and kaons, define the fiducial region of this analysis.

The Z boson and charmed meson are required to be consistent with being produced at the same primary vertex. This is achieved by a requirement on the global χ^2 of this hypothesis, which itself is based on the χ^2 of the impact parameters of the muons and the D candidates and the vertex χ^2 of the reconstructed D meson candidates [16].

In total seven events with Z and $\mathrm{D^0}$ candidates and four events with Z and $\mathrm{D^+}$ candidates pass all selection criteria, no events with multiple candidates are observed. The invariant mass distributions for the D and the Z candidates are shown in figure 1.

4 Cross-section determination and significance

Signal events are those for which the Z boson and charmed meson are produced directly in the same pp interaction. Charmed hadrons produced from the decay of a beauty hadron are considered as background. In addition two other background sources are considered: combinatorial background and background from multiple pp interactions (pile-up).

Both the SPD and DPS mechanisms can lead to the associated production of a Z boson and a beauty hadron. Contamination from feed-down from beauty hadrons decaying to D mesons, where the beauty hadron has been produced in DPS, is estimated from simulation to be 1.7% (1.3%) for $D^0(D^+)$ [3] of the DPS contribution for a Z boson and a charmed meson. The SPS contribution to the feed-down is determined with MCFM [17], which predicts the associated production of a Z boson with a b quark to be 20% smaller than the associated production of a Z with a c quark. This estimate is likely to be conservative, since, according to the recent measurements by the D0 collaboration [11], the production of Z + c-jets is larger by a factor four with respect to Z + b-jets for the region with jet $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, with only a small dependence on the jet p_{T} [11]. Taking into account the branching fractions, the beauty feed-down contribution in SPS is estimated to be 9.4% (3.7%) for $D^0(D^+)$ mesons of the SPS contribution for a Z boson and a charmed meson. This estimate takes into account the suppression due to the requirement on the D to originate from the same vertex as the Z candidate. Since the individual contributions to feed-down from Z plus a b quark from DPS and SPS are unknown, we assume that the contamination from b-quark decays is dominated by DPS. This assumption is in line with the theoretical predictions for Z plus charm quark production shown in table 2. An uncertainty is assigned that corresponds to the assumption that the SPS contribution is at most 50%. This leads to an uncertainty of half the difference between DPS and SPS of 3.9% (1.1%) for the $D^0(D^+)$ meson sample.

Combinatorial background is estimated by performing a two-dimensional fit to the mass distributions of the Z boson and the D meson candidates. Probability density functions (PDFs) describing the signal and backgrounds are used for the fit: the signal consists of a Z boson with a D meson; the background consists of a signal Z boson with a random combination of charged hadrons as well as combinatorial background where all measured stable particles are randomly combined. Since the combinatorial background for Z bosons is known to be small $(0.31 \pm 0.06)\%$ [7], it is not considered explicitly in the fit model. The PDF for the Z invariant mass is calculated using FEWZ [18] with the Z mass as the renormalisation and factorisation scale and using the MSTW08 [19] parametrisation for the parton density functions of the proton. Final-state radiation and detector resolution are included by convolving the resulting Z lineshape with a resolution function, obtained using the inclusive Z sample of the same data taking period. The PDF for the charmed hadron candidates is a modified Novosibirsk function [20] with the parameters taken from ref. [3]. The combinatorial background components are modelled with exponential distributions for the purity determination and a uniform distribution for the significance calculation. Using a uniform distribution for the combinatorial background in the significance calculation is a conservative approximation: it improves the stability of the fit and tends to assign more events to the signal region and therefore leads to a lower significance. The fit to the two-dimensional mass distributions of the Z boson and the open charm candidates is shown in figure 2.

Following refs. [3, 16], the contribution from pile-up is assessed using a fit to the χ^2 distribution of the hypothesis that the Z boson and the D mesons originate from the same primary vertex. It is estimated from a higher statistics sample with a looser selection to be $(2.8 \pm 0.6)\%$. The total purity, defined as the signal fraction, amounts to $(95.3 \pm 3.8)\%$ and $(95.6 \pm 1.2)\%$ for the Z boson plus D^0 and D^+ meson samples, respectively.

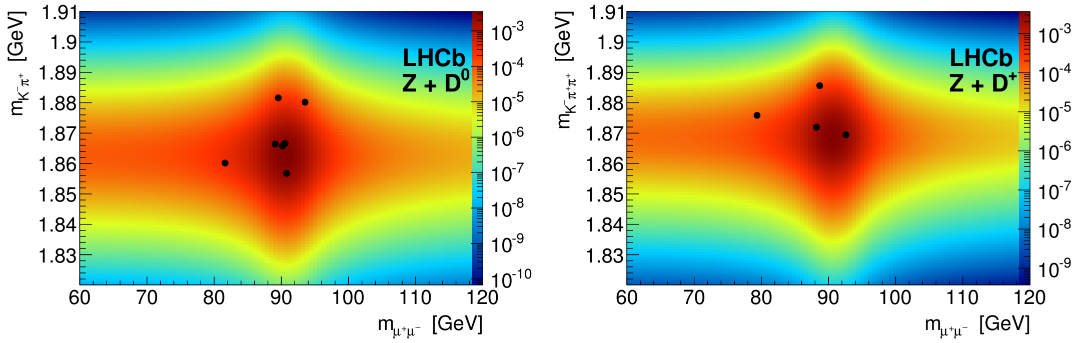

Figure 2. Invariant mass of the Z and D^0 (left) and Z and D$^+$ (right) candidates (shown as black dots) compared to the fit (see text) that was used to extract the combinatorial background. The fit shown includes the signal and the background components. The colour scale shows the PDF value at any given point.

The cross-sections are then calculated as

$$\sigma_{\mathrm{Z}\to\mu^+\mu^-,\mathrm{D}} = \frac{\rho}{\mathcal{L}\,\mathcal{B}_{\mathrm{D}}\,\varepsilon_{\mathrm{GEC}}}\,N^{\mathrm{corr}}_{\mathrm{Z}\to\mu^+\mu^-,\mathrm{D}} = \frac{\rho}{\mathcal{L}\,\mathcal{B}_{\mathrm{D}}}\sum_{\mathrm{candidates}}\varepsilon^{-1}, \tag{4.1}$$

where $N^{\mathrm{corr}}_{\mathrm{Z}\to\mu^+\mu^-,\mathrm{D}}$ is the efficiency-corrected event yield, ε is the single event efficiency, $\varepsilon_{\mathrm{GEC}}$ the efficiency of the global event cuts used in the trigger, ρ the purity, $\mathcal{L}$ the integrated luminosity and $\mathcal{B}_{\mathrm{D}}$ the branching fraction of an open charm hadron into the reconstructed final state [21].

The single event efficiencies are computed according to refs. [3, 4, 6, 7] as

$$\varepsilon = \varepsilon^{\mathrm{trg}}_{\mathrm{Z}\to\mu^+\mu^-} \times \varepsilon_{\mathrm{Z}\to\mu^+\mu^-} \times \varepsilon_{\mathrm{D}},$$

where $\varepsilon_{\mathrm{Z}\to\mu^+\mu^-}$ and ε_{D} are the $\mathrm{Z}\to\mu^+\mu^-$ and D reconstruction efficiencies, respectively, and $\varepsilon^{\mathrm{trg}}_{\mathrm{Z}\to\mu^+\mu^-}$ is the trigger efficiency. The efficiencies $\varepsilon_{\mathrm{Z}\to\mu^+\mu^-}$ and ε_{D} are taken from refs. [7] and [3], respectively. The trigger efficiency $\varepsilon^{\mathrm{trg}}_{\mathrm{Z}\to\mu^+\mu^-}$ is calculated as

$$\varepsilon^{\mathrm{trg}}_{\mathrm{Z}\to\mu^+\mu^-} = 1 - \left(1 - \varepsilon^{\mathrm{trg}}_{1\mu}(\mu^+)\right) \times \left(1 - \varepsilon^{\mathrm{trg}}_{1\mu}(\mu^-)\right),$$

where $\varepsilon^{\mathrm{trg}}_{1\mu}$ is the efficiency of the single muon trigger, that in turn has been measured using a tag-and-probe method on the inclusive $\mathrm{Z}\to\mu^+\mu^-$ sample [4]. All efficiencies have been validated using data-driven techniques and the appropriate correction factors have been applied [13–15, 22–25]. The efficiencies have been further corrected for the inefficiency introduced by the global event cuts used in trigger. Finally, the efficiency corrected yields are found to be $N^{\mathrm{corr}}_{\mathrm{Z}\to\mu^+\mu^-,\mathrm{D}^0} = 99 \pm 45$ and $N^{\mathrm{corr}}_{\mathrm{Z}\to\mu^+\mu^-,\mathrm{D}^+} = 41 \pm 21$, where the uncertainties are statistical only.

The results of the two-dimensional mass fits described above allow the significance of the observation of the associated production of a Z boson with an open charm meson to be estimated. The significance is assessed using pseudo-experiments. For each pseudo-experiment the events are sampled according to the observed number of events using the background-only hypothesis. The distributions obtained are fitted using the function described above. The p-value obtained from the pseudo-experiments for the associated production of Z with D mesons corresponds to a significance of 3.7 and 3.3 standard deviations for the D^0 and D^+ cases, respectively. The combined significance for the associated production of a Z boson with an open charm meson corresponds to a significance of 5.1 standard deviations.

5 Systematic uncertainties

The largest systematic uncertainties are summarised in table 1. The total systematic uncertainties are 8.7% (6.6%) for the $D^0(D^+)$ samples and are therefore small with respect to the statistical uncertainties.

Systematic uncertainties on the trigger, reconstruction and selection efficiencies are computed in a similar manner to refs. [3, 4]. They are dominated by the statistical uncertainty of the tag and probe samples for all efficiencies related to the Z and differences in the track reconstruction efficiency between data and simulation as well as uncertainties in the particle identification efficiency in case of the D reconstruction. The uncertainties are propagated by varying the efficiencies ten thousand times within their uncertainties and taking the standard deviation of the resulting yields as the uncertainty on the event yield. In total the estimated uncertainty due to the efficiencies corresponds to 6.8% (5.0%) for the $D^0(D^+)$ samples.

An uncertainty on the pile-up contamination of 0.6% is assigned as a systematic uncertainty. The feed-down from beauty hadron decays was estimated with precision of 3.9% (1.1%) for Z and $D^0(D^+)$, and is assigned as a systematic uncertainty. The uncertainties in the branching fractions of an open charm hadron into the reconstructed final state of 1.3% for D^0 and 2.1% for D^+ are taken from ref. [21].

The absolute luminosity scale was measured with a precision of 3.5 % at specific periods during the data taking, using both van der Meer scans [26] where colliding beams are moved transversely across each other to determine the beam profile, and a beam-gas imaging method [27, 28].

Other systematic uncertainties, including those related to the purity estimation are found to be negligible.

6 Results and discussion

The cross-sections for associated production of a Z boson and a D meson are measured to be

$$\begin{aligned}\sigma_{Z\to\mu^+\mu^-,D^0} &= 2.50 \pm 1.12 \pm 0.22\,\mathrm{pb}\\ \sigma_{Z\to\mu^+\mu^-,D^+} &= 0.44 \pm 0.23 \pm 0.03\,\mathrm{pb},\end{aligned}$$

where the first uncertainty is statistical and the second systematic. These cross-sections correspond to the following fiducial region: $60 < m_{\mu^+\mu^-} < 120\,\mathrm{GeV}$, $p_T(\mu^\pm) > 20\,\mathrm{GeV}$, $2 < \eta(\mu^\pm) < 4.5$, $2 < p_T(D) < 12\,\mathrm{GeV}$ and $2 < y(D) < 4$.

	$Z+D^0$	$Z+D^+$
Efficiencies	6.8	5.0
Pile-up	0.6	0.6
Feed down	3.9	1.1
$\mathcal{B}_D$	1.3	2.1
Luminosity	3.5	3.5
Total	8.7	6.6

Table 1. Relative systematic uncertainties for the production cross-section of a Z boson with an open charm meson [%].

The measured cross-section is expected to be the sum of the SPS and DPS predictions. The prediction of the SPS for the $Zc\bar{c}$ production cross-section is calculated with MCFM [17] at leading order and, using the massless approximation, at next-to-leading order [1]. The contributions from Zc production [29] are calculated in both cases at next-to-leading order. The renormalisation and factorisation scales are set to the Z boson mass and varied by a factor of two to assess the theory uncertainty. The MSTW08 [19] parton distribution functions with their uncertainties at 68% confidence level are used. For the parton level predictions the fiducial region requirements on the D mesons are applied to the c quarks. The cross-sections are corrected for the fragmentation fractions as in ref. [30]. These hadronisation factors do not take into account the change in momentum in the $c \to D$ transition, but only the total probability that a charm quark hadronises into a given charm meson. Reference [31] suggests that the hadronisation of charm quarks may lead to an enhancement of charm hadrons in the LHCb acceptance.

The DPS cross-section is calculated using the factorisation approximation as [32]

$$\sigma^{\mathrm{DPS}}_{Z \to \mu^+\mu^-, D} = \frac{\sigma_{Z\to\mu^+\mu^-}\,\sigma_D}{\sigma_{\mathrm{eff}}}, \tag{6.1}$$

where $\sigma_{Z\to\mu^+\mu^-}$ and σ_D are the inclusive production cross-sections of $Z \to \mu^+\mu^-$ and D mesons, respectively, and σ_{eff} is the effective DPS cross-section. The production cross-sections of Z bosons and prompt D mesons are taken from refs. [4, 30] and extrapolated to the fiducial region of this analysis. The effective DPS cross-section has been measured by several experiments at the ISR [33], SPS [34], Tevatron [35, 36] and LHC [3, 37, 38]. The measured value is energy and process independent within the experimental precision [39] and the value of $\sigma_{\mathrm{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb is taken from ref. [35]. The factorisation ansatz used to derive eq. (6.1) has been criticised as being too naïve [40]. The corresponding uncertainty is not assessed here but could be large in this region of phase space [32]. The contribution of the non-factorisable component is estimated in ref. [41] to be 30 % for $x \leq 0.1$ and up to 90 % for $x \sim 0.2 - 0.4$.

The measured cross-sections are presented in table 2 together with three theoretical predictions discussed above: a DPS prediction and two SPS predictions from fixed order calculations using MCFM [1, 17]. For the associative production of Z bosons and D^0 mesons

	Measured	MCFM massless [1]	MCFM massive [17]	DPS (Eq. (6.1))
$\mathrm{Z}+\mathrm{D}^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07}\,{}^{+0.11}_{-0.17} \pm 0.05$	$0.64^{+0.01}_{-0.01}\,{}^{+0.08}_{-0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
$\mathrm{Z}+\mathrm{D}^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03}\,{}^{+0.05}_{-0.07} \pm 0.03$	$0.28^{+0.01}_{-0.01}\,{}^{+0.04}_{-0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

Table 2. Comparison of the measured cross-sections [pb] and the theoretical predictions for the associated production of a Z boson with an open charm meson. For the measured cross-section the first uncertainty is statistical and the second systematic. For the MCFM-based calculations the first uncertainty is related to the uncertainties of the parton distribution functions, the second is the scale uncertainty and the third due to uncertainties associated with c-quark hadronisation as discussed in the text. The DPS predictions are calculated using eq. (6.1).

the sum of DPS and SPS contributions is consistent with the measured cross-section within the large uncertainties from both theory and experiment, while for $\mathrm{Z}+\mathrm{D}^+$ case, the measured cross-section lies below the expectations.

7 Conclusion

Associated production of a Z boson with an open charm hadron is observed by LHCb for the first time in pp collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 1.0 fb^{-1}.

Eleven signal candidates are observed, consisting of seven $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ candidates and four $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$ candidates, all associated with a $\mathrm{Z} \to \mu^+\mu^-$ decay. The cross-sections for the associated production of Z bosons and D mesons in the fiducial region are found to be

$$\begin{aligned}\sigma_{\mathrm{Z}\to\mu^+\mu^-,\mathrm{D}^0} &= 2.50 \pm 1.12 \pm 0.22\,\mathrm{pb}\\ \sigma_{\mathrm{Z}\to\mu^+\mu^-,\mathrm{D}^+} &= 0.44 \pm 0.23 \pm 0.03\,\mathrm{pb},\end{aligned}$$

where the first uncertainty is statistical and the second systematic. The results are quoted as the product of the production cross-section and the branching fraction of the $\mathrm{Z} \to \mu^+\mu^-$ decay. These cross-sections correspond to the fiducial region $60 < m_{\mu^+\mu^-} < 120\,\mathrm{GeV}$, $p_\mathrm{T}(\mu^\pm) > 20\,\mathrm{GeV}$, $2 < \eta(\mu^\pm) < 4.5$ $2 < p_\mathrm{T}(\mathrm{D}) < 12\,\mathrm{GeV}$ and $2 < y(\mathrm{D}) < 4$. The results are consistent with the theoretical predictions for $\mathrm{Z}+\mathrm{D}^0$ production, and lie below expectations for $\mathrm{Z}+\mathrm{D}^+$ case. With more data a measurement of the differential distributions will be possible, which could allow to disentangle the SPS and DPS contributions.

Acknowledgments

We thank John M. Campbell for help in obtaining the MCFM predictions. We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 and Region Auvergne

(France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); NSF (USA). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

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