

# Measurement of differential cross sections for Z bosons produced in association with charm jets in pp collisions at $\sqrt{s} = 13$ TeV



## The CMS collaboration

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**ABSTRACT:** Measurements are presented of differential cross sections for the production of Z bosons in association with at least one jet initiated by a charm quark in pp collisions at  $\sqrt{s} = 13$  TeV. The data recorded by the CMS experiment at the LHC correspond to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . The final states contain a pair of electrons or muons that are the decay products of a Z boson, and a jet consistent with being initiated by a charm quark produced in the hard interaction. Differential cross sections as a function of the transverse momentum  $p_T$  of the Z boson and  $p_T$  of the charm jet are compared with predictions from Monte Carlo event generators. The inclusive production cross section  $405.4 \pm 5.6$  (stat)  $\pm 24.3$  (exp)  $\pm 3.7$  (theo) pb, is measured in a fiducial region requiring both leptons to have pseudorapidity  $|\eta| < 2.4$  and  $p_T > 10$  GeV, at least one lepton with  $p_T > 26$  GeV, and a mass of the pair in the range 71–111 GeV, while the charm jet is required to have  $p_T > 30$  GeV and  $|\eta| < 2.4$ . These are the first measurements of these cross sections in proton-proton collisions at 13 TeV.

**KEYWORDS:** Hadron-Hadron scattering (experiments), QCD

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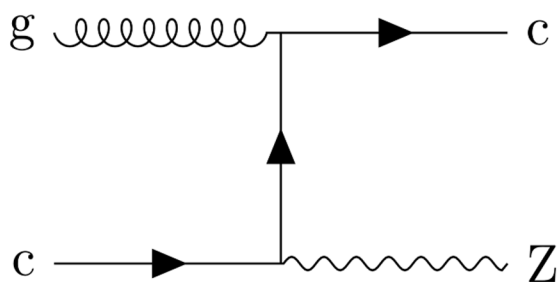
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## 1 Introduction

The CERN LHC produced a large number of events at  $\sqrt{s} = 13$  TeV in proton-proton (pp) collisions containing a Z boson accompanied by one or more jets initiated by charm quarks (c jets). The differential cross sections for inclusive Z+c jet production, as functions of the transverse momenta  $p_T$  of the Z boson and of the c jet, are used to verify quantum chromodynamics (QCD) models, provide information on the parton distribution function (PDF) of the charm quark, and investigate the possibility of observing the intrinsic charm quark (IC) component in the nucleon [1–3]. An IC component would enhance the rate of Z+c jet production, especially at large values of  $p_T$  of the Z boson and of the c jet.

Associated production of a Z boson and a c jet is an important background in searches for physics beyond the standard model (SM). For example, in supersymmetry models a top scalar quark ( $\tilde{t}$ ) could decay into a charm quark and an undetected lightest supersymmetric particle, providing thereby a large  $p_T$  imbalance [4]. One of the background sources for such a process is Z+c jet production with the Z boson decaying into neutrinos. Better modelling of Z+c jet production through studies of visible decay modes can enhance the sensitivity in searches for new physics. An example of a Feynman diagram corresponding to the Z+c jet process is shown in figure 1.

A previous measurement of the Z+c jet cross section at 8 TeV is reported in ref. [5]. In this paper the Z boson is formed from an identified electron or muon pair, and the c jet



**Figure 1.** Example Feynman diagram for the Z+c jet process.

is identified by applying charm tagging criteria [6] to reconstructed jets. This achieves a higher selection efficiency than in the 8 TeV measurement, where c jets were identified by reconstructed  $D^*(2010)$  mesons or low-momentum muons inside the jets.

Measurements of the fiducial total and differential cross sections of Z+c jet production are presented as functions of the  $p_T$  of the Z boson and of the c jet  $p_T$ . To provide a direct comparison with predictions from Monte Carlo (MC) event generators (generator level), we unfold the detector effects.

The data, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$ , were recorded by the CMS experiment during pp collisions in 2016. The minimum proton bunch spacing is 25 ns with 24 interactions on average per beam crossing.

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, covering a pseudorapidity region  $|\eta| < 2.5$ , a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, with each system composed of a barrel and two endcap sections, lie within the solenoid volume. Forward calorimeters, made of steel and quartz fibers, extend  $\eta$  coverage provided by the barrel and endcap detectors to  $|\eta| < 5$ . Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid that cover  $|\eta| < 2.4$ . Events of interest are selected using a two-tiered trigger system [7]. The first level, composed of specialized hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of  $\approx 100 \text{ kHz}$  within a fixed latency of about  $4 \mu\text{s}$ . The second level, known as the high-level trigger, consists of a farm of processors running full event reconstruction software optimized for fast processing, that reduces the event rate to  $\approx 1 \text{ kHz}$  before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in ref. [8].

## 3 Data and simulated events

Various MC generators are used to simulate the Z+jets background and the signal processes. The MADGRAPH5\_aMC@NLO version 2.2.2 [9] (MG5\_aMC) generator is used to

simulate Drell-Yan (DY) processes, including the  $Z+c$  jet signal, calculated at next-to-leading order (NLO). Background DY events include those with a  $Z$  boson and a jet initiated by a bottom quark (b jet), or a jet initiated by a light quark or a gluon (light jet). Samples are made for  $Z+n$  jet processes ( $n \leq 2$ ), calculated at NLO in perturbative QCD. A second signal model is provided by using MG5\_aMC to calculate leading order (LO) matrix elements for  $pp \rightarrow Z+n$  jets ( $n \leq 4$ ). For a third signal model, SHERPA v2.2 [10, 11] is used to generate  $pp \rightarrow Z+n$  jets events, with  $n \leq 2$  at NLO and  $n \leq 4$  at LO. All three signal models are normalized to the value of the inclusive  $Z$  + jets cross section calculated at next-to-next-to-leading order with FEWZ v3.1 [12]. These samples are generated using the NNPDF 3.0 [13] PDF set.

In addition to events with light and b jets, there are contributions to the background from processes producing top quark pairs [14, 15] and single top quarks [16, 17]. These samples are generated using NLO POWHEG v2.0 [18–20] or MG5\_aMC. There is also background from vector boson pair production, which is simulated using PYTHIA 8 v8.212 [21].

All samples, except SHERPA, use PYTHIA 8 to model the initial- and final-state parton showers and hadronization, with the CUETP8M1 [22] or CUETP8M2T4 [23] (top pair sample) tune that includes the NNPDF 2.3 [24] LO PDFs and the value of the strong coupling at the mass of the  $Z$  boson is  $\alpha_S(m_Z) = 0.119$ . Matching between the matrix element generators and the parton shower is done using the  $k_T$ -MLM [25, 26] scheme with the matching scale set at 19 GeV for the LO MG5\_aMC samples, and the FxFx [27] scheme with the matching scale set to 30 GeV for the NLO MG5\_aMC events.

GEANT4 [28] is used for CMS detector simulation. The simulation includes additional pp interactions (pileup) in the current and nearby bunch crossings.

The simulated events are reconstructed with the same algorithms used for the data.

## 4 Object reconstruction and event selection

The particle flow (PF) algorithm [29] is used to reconstruct and identify individual particle candidates (physics objects) in an event, through an optimized combination of information from the various elements of the CMS detector. Energy depositions are measured in the calorimeters, and charged particles are identified in the central tracking and muon systems.

Electrons are reconstructed from tracks, fitted with a Gaussian sum filter, matching energy deposits in the ECAL [30]. Identification requirements are applied based on the ECAL shower shape, matching between the track and the ECAL deposits, and observables characterizing the emission of bremsstrahlung radiation along the electron trajectory. Electrons are required to originate from the primary vertex, which is the vertex candidate with the largest value of summed physics-object  $p_T^2$ . Longitudinal and transverse impact parameters with respect to the primary vertex for barrel (endcap) are required to be  $<0.10$  ( $0.20$ ) and  $<0.05$  ( $0.10$ ) cm, respectively. The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with  $p_T \approx 45$  GeV from  $Z \rightarrow ee$  decays ranges from 1.7 to 4.5%. The dielectron mass resolution for  $Z \rightarrow ee$  decays when both

electrons are in the ECAL barrel is 1.9%, degrading to 2.9% when both electrons are in the endcaps.

Muons are reconstructed by combining signals from the inner tracker and the muon detector subsystems. They are required to satisfy standard identification criteria based on the number of hits in each detector, the track fit quality, and the consistency with the primary vertex by requiring the longitudinal and transverse impact parameters to be less than 0.5 and 0.2 cm, respectively. The efficiency to reconstruct and identify muons is greater than 96% [31]. Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution for muons with  $20 < p_T < 100$  GeV of 1% in the barrel and 3% in the endcaps.

To reduce the misidentification rate, electrons and muons are required to be isolated. The isolation of electron or muon is defined as the sum of the  $p_T$  of all additional PF candidates within a cone of radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$  (0.4) around the electron (muon) track, where  $\phi$  is the azimuthal angle in radians. After compensating for the contribution from pileup [32], the resultant sum is required to be less than 25% of the lepton  $p_T$ .

Jets are clustered from PF candidates using the infrared- and collinear-safe anti- $k_T$  algorithm with a distance parameter of 0.4, as implemented in the FASTJET package [33, 34]. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and, based on simulation, is within 5 to 10% of the true momentum over the entire  $p_T$  spectrum and detector acceptance. To mitigate the effects of pileup, charged particle candidates identified as originating from pileup vertices are discarded and a correction [32] is applied to remove remaining contributions. The reconstructed jet energy scale (JES) is corrected using a factorized model to compensate for the nonlinear and nonuniform response in the calorimeters. Corrections are derived from simulation to bring the measured response of jets to that of generator-level jets on average. In situ measurements of the momentum balance in dijet, multijet, photon+jet, and leptonically decaying Z+jet events are used to correct any residual differences between the JES in data and simulation [35]. The jet energy in simulation is degraded to match the resolution observed in data. The jet energy resolution (JER) amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. Additional selection criteria are applied to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [36]. Jets identified as likely coming from pileup [37] are also removed.

Events are selected online through a single electron trigger requiring at least one electron candidate with  $p_T > 27$  GeV (electron channel), or a single muon trigger requiring at least one muon candidate with  $p_T > 24$  GeV (muon channel). Offline, we require a pair of oppositely charged electrons or muons each satisfying identification and isolation criteria, with  $p_T > 10$  GeV and  $|\eta| < 2.4$ , and with an invariant mass close to the mass of the Z boson:  $71 < m_{ee \text{ or } \mu\mu} < 111$  GeV. To exceed the trigger threshold in the electron channel at least one electron must have  $p_T > 29$  GeV, and in the muon channel at least one muon must have  $p_T > 26$  GeV. Small residual differences in the trigger, identification, and isolation efficiencies between data and simulation are measured using tag-and-probe methods [38], and corrected by applying scale factors to simulated events.

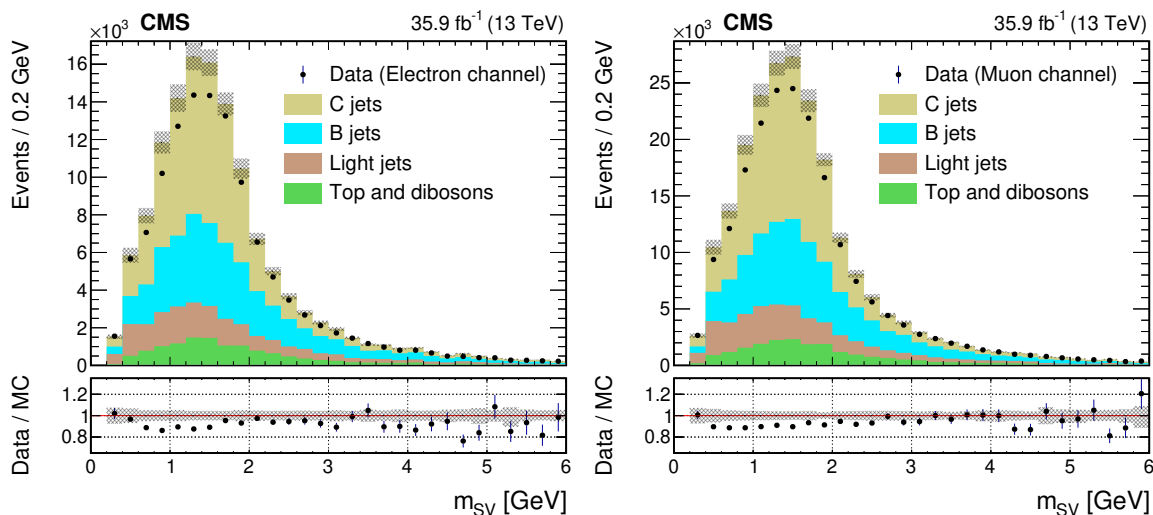
The event must contain at least one jet with  $p_T > 30$  GeV and  $|\eta| < 2.4$ , satisfying tight c tagging criteria using the deep combined secondary vertices algorithm [6]. This algorithm discriminates c jets from b and light jets based on jet properties such as the presence of displaced vertices (secondary vertices) and tracks with large impact parameter with respect to the primary vertex. Data from W+jets,  $t\bar{t}$ , and inclusive jet production are used to measure the c tagging efficiency for c jets, and mistag rates for b and light jets. These are compared with the simulation, where the reconstructed jet flavor is known from its hadron content. Small differences between data and simulation are corrected by applying scale factors to the simulation. The threshold applied in this analysis gives a c tagging efficiency of about 30%, and misidentification probabilities of 1.2% for light jets and 20% for b jets, with relative uncertainties between 5% and 15% depending on the  $p_T$  of the jet. If several c-tagged jets occur in the event, the one with the highest  $p_T$  is selected.

The simulated events are classified according to generator-level information. Generator-level jets are made by clustering all stable particles resulting from hadronization using the anti- $k_T$  algorithm with a distance parameter of 0.4, and the jet flavor is defined by the flavor of the hadrons within the jet. If an event contains a generator-level jet with  $p_T > 10$  GeV containing a b hadron, the event is defined as a Z+b jet event. If there is no such generator-level b jet in the event and there is at least one generator-level jet with  $p_T > 10$  GeV containing a c hadron, the event is defined as a Z+c jet event. Other events in the DY sample are classified as Z+light jet events. The generator-level leptons are dressed by adding the momenta of all photons within  $\Delta R = 0.1$  around the lepton directions.

## 5 Signal determination and data unfolding

Measurement of the differential cross sections of Z+c jet production as a function of the  $p_T$  of the Z boson ( $p_T^Z$ ) and as a function of the c jet  $p_T$  ( $p_T^{c\text{ jet}}$ ) are performed in several steps. The first step is to select c jet-enriched samples of  $Z \rightarrow ee$  (electron channel) or  $Z \rightarrow \mu\mu$  (muon channel) candidate events. The second step is to split the sample into different bins according to the  $p_T$  of the Z boson or c-tagged jet ( $p_T^{c\text{-tagged jet}}$ ), and to measure the number of Z+c jet events in each bin. The third step is to unfold the data, using the simulation of the signal to construct response matrices to relate the observed distributions to those at the generator level. The final step is to combine the resulting unfolded electron and muon channel  $p_T$  distributions, and compare them with predictions from different MC event generators.

Charm hadrons can decay at points displaced from the primary vertex. This secondary vertex is reconstructed using the inclusive vertex finder algorithm [39]. The invariant mass of charged particles associated with the secondary vertex ( $m_{SV}$ ) in the c-tagged jet [6] is used to discriminate between signal and background. Figure 2 shows the observed distributions of  $m_{SV}$  in the electron and muon channels, compared with the different signal and background contributions predicted by the simulation. Although  $m_{SV}$  is an ingredient in the c tagging algorithm, there are sufficient differences remaining in the distributions for the c-tagged samples to provide information on the flavor composition. The normalized distributions of  $m_{SV}$  for Z+light jet, Z+c jet and Z+b jet components are compared in figure 3.



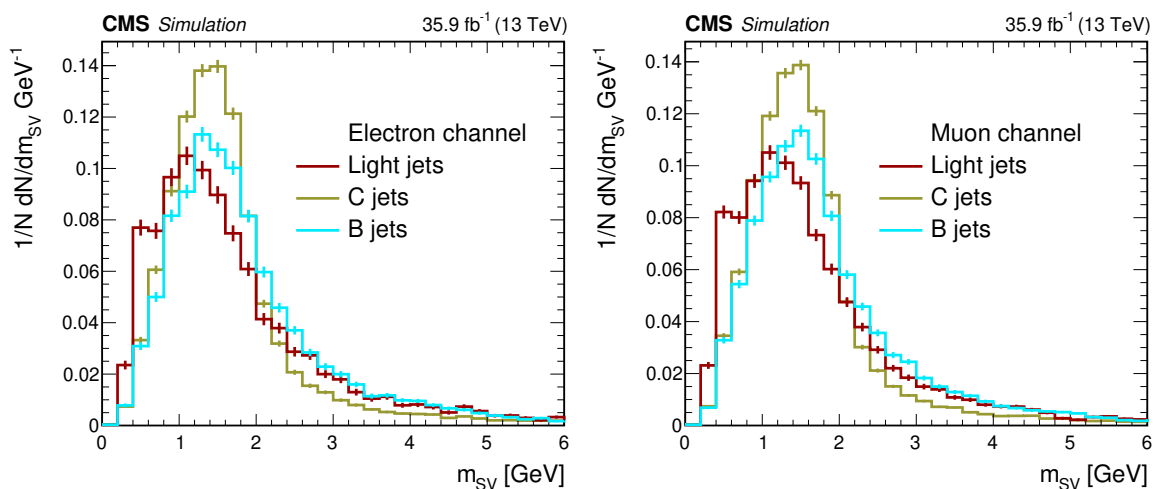
**Figure 2.** Distribution of the secondary vertex mass  $m_{SV}$  of the highest- $p_T$  c-tagged central jet, for electron (left) and muon (right) channels. The observed data is compared with the different signal and background components in simulation, before normalization scale factors are applied. Dashed area represents MC systematic uncertainties. The vertical bars on the data points represent statistical uncertainties. Bottom panels on each plot represent the data to MC ratio.

The top quark and diboson background predictions are taken directly from simulation. The normalizations for the Z+c jet, Z+b jet and Z+light jet components are then obtained by fitting templates of the  $m_{SV}$  distribution obtained from simulation to the observed data. A maximum likelihood template fit is performed separately in each bin of Z boson candidate or c-tagged jet  $p_T$ .

The values of the scale factors for the light ( $SF_l$ ), charm ( $SF_c$ ), and bottom ( $SF_b$ ) components, defined as the ratio of the fitted normalization to the prediction from simulation, are presented in tables 1–4 for each  $p_T$  bin for each Z+q jet process. The correlation coefficients between errors of different flavor SFs, found in the fit, are approximately equal to  $-0.8$ ,  $-0.35$  and  $-0.25$  for  $SF_c$  and  $SF_b$ ,  $SF_l$  and  $SF_b$ ,  $SF_c$  and  $SF_l$  respectively. Sources of systematic uncertainty are discussed in section 6. Figure 4 shows the distributions of the Z boson candidate and c-tagged jet  $p_T$  after applying these scale factors, assuming they are constant across the  $p_T$  range in which they are determined. The post-fit  $m_{SV}$  distributions are presented in appendix A. Good agreement is observed between simulation and data after applying these factors.

The generator-level signal is defined to be Z+c jet events with two oppositely charged generator-level electrons or muons with  $p_T > 10$  GeV (at least one with  $p_T > 26$  GeV),  $|\eta| < 2.4$ , and an invariant mass  $71 < m_{ee \text{ or } \mu\mu} < 111$  GeV. There must also be at least one generator-level c jet with  $p_T > 30$  GeV and  $|\eta| < 2.4$ . To avoid double counting, jets within  $\Delta R = 0.4$  of one of the two leptons from the Z candidate are removed.

A fraction of Z+c jet events that are outside the signal phase space will migrate into the reconstructed signal region, primarily events with c jets with generated  $p_T < 30$  GeV but reconstructed  $p_T > 30$  GeV due to the finite detector resolution. The fraction of Z+c



**Figure 3.** Distribution of the secondary vertex mass of the highest- $p_T$  c-tagged central jet, for electron (left) and muon (right) channels for Z+light jet, Z+c jet and Z+b jet components, normalized to 1. Vertical bars represent statistical uncertainties.

c-tagged jet $p_T$ (GeV)	$SF_l$	$SF_c$	$SF_b$
30–37	$1.16 \pm 0.05^{+0.29}_{-0.21}$	$0.70 \pm 0.04^{+0.09}_{-0.11}$	$1.06 \pm 0.05^{+0.16}_{-0.12}$
37–45	$0.79 \pm 0.06^{+0.26}_{-0.18}$	$0.89 \pm 0.03^{+0.10}_{-0.08}$	$0.92 \pm 0.05^{+0.16}_{-0.16}$
45–60	$0.97 \pm 0.06^{+0.23}_{-0.19}$	$0.74 \pm 0.03^{+0.08}_{-0.06}$	$1.07 \pm 0.06^{+0.09}_{-0.09}$
60–90	$0.99 \pm 0.07^{+0.24}_{-0.18}$	$0.87 \pm 0.04^{+0.08}_{-0.08}$	$0.95 \pm 0.07^{+0.09}_{-0.12}$
90–250	$0.92 \pm 0.07^{+0.27}_{-0.19}$	$0.98 \pm 0.05^{+0.11}_{-0.10}$	$1.04 \pm 0.07^{+0.08}_{-0.08}$

**Table 1.** Values of Z+light jet  $SF_l$ , Z+c jet  $SF_c$ , and Z+b jet  $SF_b$  scale factors measured in the electron channel, as a function of c-tagged jet  $p_T$ . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.

Z candidate $p_T$ (GeV)	$SF_l$	$SF_c$	$SF_b$
0–30	$0.86 \pm 0.05^{+0.24}_{-0.18}$	$0.76 \pm 0.04^{+0.11}_{-0.09}$	$1.25 \pm 0.07^{+0.17}_{-0.18}$
30–50	$0.98 \pm 0.05^{+0.23}_{-0.17}$	$0.80 \pm 0.03^{+0.08}_{-0.08}$	$0.91 \pm 0.05^{+0.10}_{-0.08}$
50–65	$0.85 \pm 0.07^{+0.21}_{-0.16}$	$0.78 \pm 0.04^{+0.15}_{-0.11}$	$1.04 \pm 0.06^{+0.17}_{-0.17}$
65–95	$1.14 \pm 0.08^{+0.30}_{-0.22}$	$0.97 \pm 0.04^{+0.08}_{-0.07}$	$0.76 \pm 0.06^{+0.09}_{-0.11}$
95–300	$1.01 \pm 0.07^{+0.26}_{-0.20}$	$0.83 \pm 0.05^{+0.07}_{-0.07}$	$1.13 \pm 0.07^{+0.08}_{-0.08}$

**Table 2.** Values of Z+light jet  $SF_l$ , Z+c jet  $SF_c$ , and Z+b jet  $SF_b$  scale factors measured in the electron channel, as a function of Z candidate  $p_T$ . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.



c-tagged jet $p_T$ (GeV)	$SF_1$	$SF_c$	$SF_b$
30–37	$0.95 \pm 0.04^{+0.24}_{-0.17}$	$0.82 \pm 0.03^{+0.12}_{-0.07}$	$1.04 \pm 0.05^{+0.11}_{-0.19}$
37–45	$0.93 \pm 0.05^{+0.26}_{-0.23}$	$0.82 \pm 0.03^{+0.06}_{-0.06}$	$0.96 \pm 0.05^{+0.12}_{-0.09}$
45–60	$0.81 \pm 0.04^{+0.20}_{-0.15}$	$0.79 \pm 0.03^{+0.09}_{-0.06}$	$1.10 \pm 0.04^{+0.08}_{-0.07}$
60–90	$0.88 \pm 0.04^{+0.23}_{-0.17}$	$0.80 \pm 0.03^{+0.06}_{-0.08}$	$1.25 \pm 0.05^{+0.12}_{-0.10}$
90–250	$0.92 \pm 0.05^{+0.24}_{-0.17}$	$0.79 \pm 0.04^{+0.07}_{-0.06}$	$1.16 \pm 0.06^{+0.12}_{-0.12}$

**Table 3.** Values of Z+light jet  $SF_1$ , Z+c jet  $SF_c$ , and Z+b jet  $SF_b$  scale factors measured in the muon channel, as a function of c-tagged jet  $p_T$ . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.

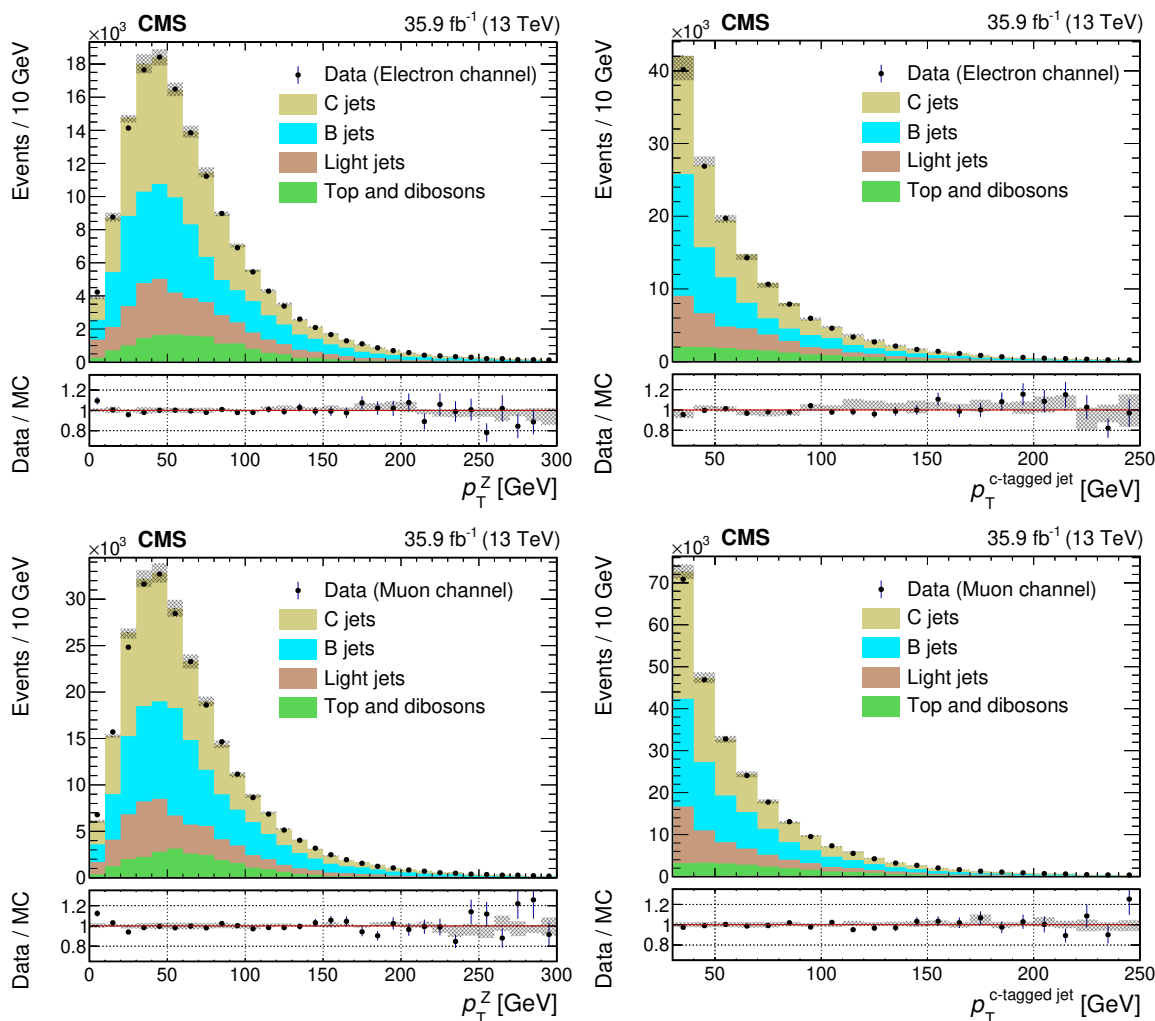
Z candidate $p_T$ (GeV)	$SF_1$	$SF_c$	$SF_b$
0–30	$0.97 \pm 0.04^{+0.24}_{-0.20}$	$0.82 \pm 0.03^{+0.09}_{-0.08}$	$1.09 \pm 0.05^{+0.11}_{-0.10}$
30–50	$0.91 \pm 0.04^{+0.21}_{-0.16}$	$0.80 \pm 0.02^{+0.07}_{-0.06}$	$0.99 \pm 0.04^{+0.05}_{-0.06}$
50–65	$0.63 \pm 0.06^{+0.17}_{-0.13}$	$0.73 \pm 0.03^{+0.09}_{-0.06}$	$1.24 \pm 0.05^{+0.09}_{-0.10}$
65–95	$0.96 \pm 0.05^{+0.25}_{-0.18}$	$0.85 \pm 0.03^{+0.09}_{-0.06}$	$1.04 \pm 0.05^{+0.13}_{-0.14}$
95–300	$0.89 \pm 0.05^{+0.23}_{-0.17}$	$0.78 \pm 0.04^{+0.07}_{-0.07}$	$1.33 \pm 0.06^{+0.08}_{-0.08}$

**Table 4.** Values of Z+light jet  $SF_1$ , Z+c jet  $SF_c$ , and Z+b jet  $SF_b$  scale factors measured in the muon channel, as a function of Z candidate  $p_T$ . The first uncertainty is the statistical uncertainty from the fit, the second is the systematic uncertainty.

jet events that are inside the signal phase space is estimated from the number of selected events in which the c-tagged jet and lepton pair match within  $\Delta R < 0.3$  to a generator-level highest- $p_T$  c jet and lepton pair satisfying the phase space requirements. Figure 5 shows this fraction as functions of Z boson and c-tagged jet  $p_T$ , for electron and muon channels, calculated using MADGRAPH5\_aMC@NLO sample.

Response matrices are constructed using the Z+c jet events in the DY sample that is simulated using the MG5\_aMC (NLO) generator, and cross-checked using the MG5\_aMC (LO) generator. Each matrix entry represents the probability for an event generated in the signal phase space within a certain c jet (or Z boson)  $p_T$  range to end up within a certain reconstructed c jet (or Z boson candidate)  $p_T$  range. The unfolding was done with 5 detector-level  $p_T$  bins and 4 generator-level  $p_T$  bins. The TUNFOLD package v17.5 [40], which is based on a least-squares fit, is then used to invert the response matrices and unfold the distribution of the measured number of Z+c jet events.

Figure 6 shows the efficiency (defined as the fraction of signal events generated in the fiducial phase space that pass all selection criteria after reconstruction) as a function of the generator-level Z boson or c jet  $p_T$  for electron and muon channels, calculated using the MG5\_aMC (NLO) sample. The dominant losses are due to the c tagging and lepton selection efficiencies.

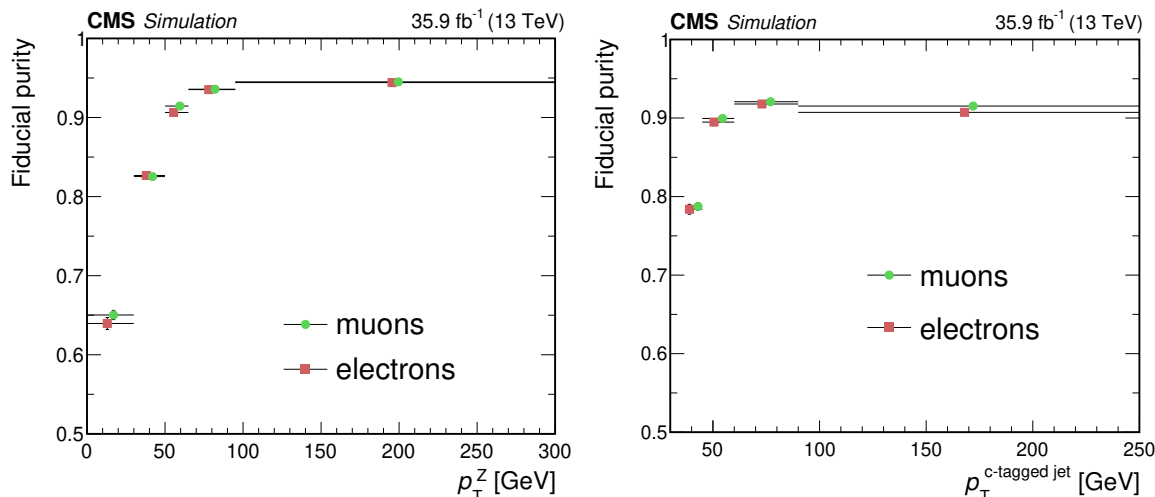


**Figure 4.** The distributions of  $p_T$  in data and corrected simulation, after applying the fitted scale factors to the Drell-Yan components. The upper plots show distributions for the electron channel, with the  $p_T$  of the electron pair (left) and  $c$ -tagged jet (right). The lower plots show distributions for the muon channel with the  $p_T$  of the muon pair (left) and  $c$ -tagged jet (right). Dashed area represents MC systematic uncertainties. The vertical bars on the data points represent statistical uncertainties. Bottom panels on each plot represent the data to MC ratio.

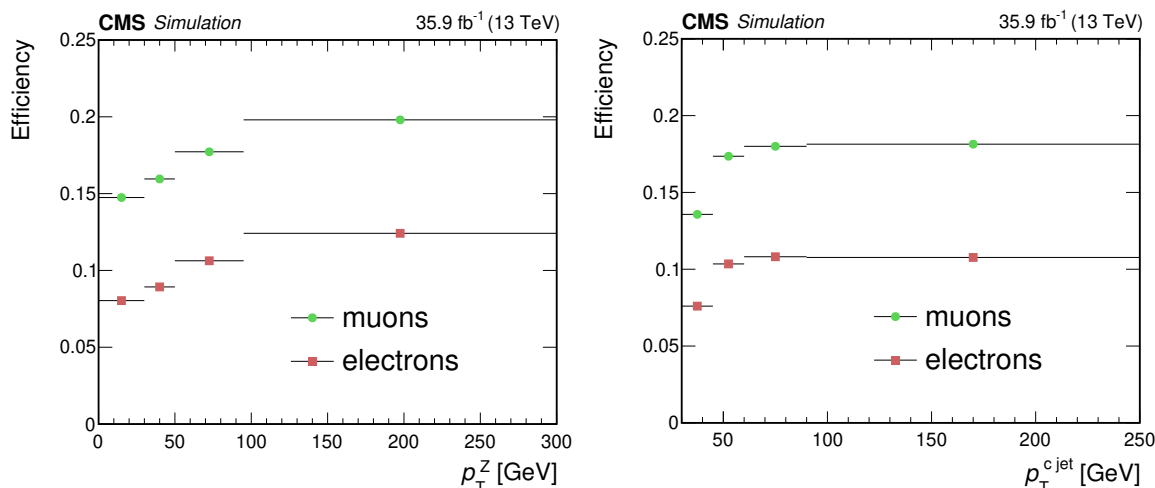
## 6 Systematic uncertainties

The systematic uncertainties are estimated by varying relevant parameters and then repeating the unfolding procedure, recalculating the values of the efficiency, response matrix, and number of  $Z+c$  jet and background events in each case. The differences observed between the unfolded distributions are assumed as the uncertainties. The following uncertainties are included:

- *QCD renormalization and factorization scales.* The ambiguity in the choice of QCD renormalization scale ( $\mu_R$ ) and factorization scale ( $\mu_F$ ) leads to uncertainty in the theoretical predictions for the DY process. This uncertainty is estimated by chang-



**Figure 5.** Fraction of selected Z+c jet events originating within the fiducial phase space as a function of  $p_T$ . The plots show distributions for electron and muons channels as a function of  $p_T^Z$  (left) and  $p_T^{c\text{-tagged jet}}$  (right).



**Figure 6.** Efficiency as a function of  $p_T$ . The plots show distributions for the electron and muon channels, as a function of  $p_T^Z$  (left) and  $p_T^{c\text{ jet}}$  (right).

ing the values of  $\mu_R$  and  $\mu_F$  by factors of 0.5 and 2 relative to the default values,  $\mu_F = \mu_R = m_Z$ , excluding the  $(0.5\mu_F, 2\mu_R)$  and  $(0.5\mu_R, 2\mu_F)$  combinations. Largest deviations from the central values were used as uncertainty.

- *PDF.* The unfolding is performed with different PDF replicas and compared with the nominal distribution.
- *c tagging efficiency.* The effect of uncertainties in the c tagging rates is estimated by varying tagging and mistagging scale factors for the different jet flavors. Scale factors for tagging c jets, and mistagging b jets and light jets are varied up and down by one standard deviation. The combined c tagging uncertainty is then calculated

Channel	QCD (%)	PDF (%)	c tag/mistag (%)	JER (%)	JES (%)	Pileup (%)	Top Pair (%)	ID\Iso (%)	$\mathcal{L}$ (%)	MC stat. (%)
$\mu\mu, p_T^{c, \text{jet}}$	5.5	0.5	4.2	3.9	4.8	1.5	0.6	1.0	2.5	4.2
$\mu\mu, p_T^Z$	1.9	0.5	4.2	1.1	3.9	1.6	0.8	1.0	2.5	3.1
$ee, p_T^{c, \text{jet}}$	6.4	0.6	4.2	3.1	6.4	3.0	0.7	2.6	2.5	6.3
$ee, p_T^Z$	2.6	0.5	4.1	1.1	4.8	1.8	0.6	2.6	2.5	3.8

**Table 5.** Summary of the systematic uncertainties in the integral fiducial cross section arising from the various sources for electron (ee) and muon ( $\mu\mu$ ) channels, calculated by integrating over  $p_T^{c, \text{jet}}$  or  $p_T^Z$ .

as the sum in quadrature of these variations. The variation of scale factors is  $\approx 15\%$  for light jets, and  $\approx 5\%$  for charm and bottom jets.

- *Jet energy resolution and scale.* Both the JES and JER corrections can affect jet  $p_T$  and the  $m_{SV}$  distributions used in the  $SF_b$  and  $SF_l$  measurements. The uncertainty resulting from JES corrections is estimated by varying the  $p_T$ - and  $\eta$ -dependent scale factors within their uncertainty (up to  $\approx 4\%$ ). The JER uncertainty is estimated by varying the amount of jet  $p_T$  resolution degradation applied to the simulation up and down by one standard deviation ( $\approx 10\%$ ).
- *Pileup.* The corresponding uncertainty is estimated by changing the total inelastic cross section by  $\pm 4.6\%$  [41].
- *Lepton identification and isolation.* Uncertainties resulting from the modeling of the identification and isolation of muons and electrons are estimated by varying the corresponding scale factors within their uncertainties. For electrons the uncertainty is less than 3%, while for muons uncertainties in identification and isolation are less than 2%.
- *Top pair production cross section.* The uncertainty because of the cross section used for the modeling of top quark pair production is estimated by varying the normalization of the top pair component of the background by  $\pm 10\%$  [42].
- *Luminosity.* The uncertainty is obtained by changing the luminosity value used to normalize the unfolded distributions by  $\pm 2.5\%$  [43].
- *Statistical uncertainties in  $m_{SV}$  templates.* The uncertainty is obtained by taking into account statistical fluctuations in each bin of the simulated  $m_{SV}$  distributions, used in the fit of  $SF_l$ ,  $SF_c$  and  $SF_b$ .

The uncertainties in the integral fiducial cross section from the considered sources are listed in table 5.

## 7 Results

The total fiducial cross section is measured as

$$\sigma_{\text{fid}} = \frac{N_{\text{charm}} P_{\text{fid}}}{\varepsilon \mathcal{L} \mathcal{B}(Z \rightarrow \ell\ell)}, \quad (7.1)$$

where  $N_{\text{charm}}$  is the integral number of measured charm events,  $P_{\text{fid}}$  is the integral fiducial purity,  $\varepsilon$  is the integral fiducial selection efficiency,  $\mathcal{L}$  is the integrated luminosity, and  $\mathcal{B}(Z \rightarrow \ell\ell) = 3.36\%$  is the branching fraction of the  $Z$  boson to  $\ell\ell$  with  $\ell = e$  or  $\mu$ .

The fiducial differential cross sections are obtained from the unfolded distributions as

$$\frac{d\sigma}{dp_{\text{T}}} = \frac{N_i}{\mathcal{L} \Delta_i \mathcal{B}(Z \rightarrow \ell\ell)}, \quad (7.2)$$

where  $N_i$  is the number of events in  $p_{\text{T}}$  bin  $i$  of the unfolded distribution and  $\Delta_i$  is the width of the bin.

The results of the measurement of total and differential fiducial cross sections from the electron and muon channels are combined by a fit using the CONVINO tool [44], which includes statistical and systematic uncertainties. The uncertainties related to the  $c$  tag and mistag rates, JER, JES, pileup, luminosity, and top quark pair cross section are assumed fully correlated between the channels, whereas uncertainties from other sources are assumed to be uncorrelated. The experimental systematic uncertainties are those related to  $c$  tag and mistag rates, JER, JES, identification and isolation, pileup, and luminosity. The rest are designated as theoretical systematic uncertainties.

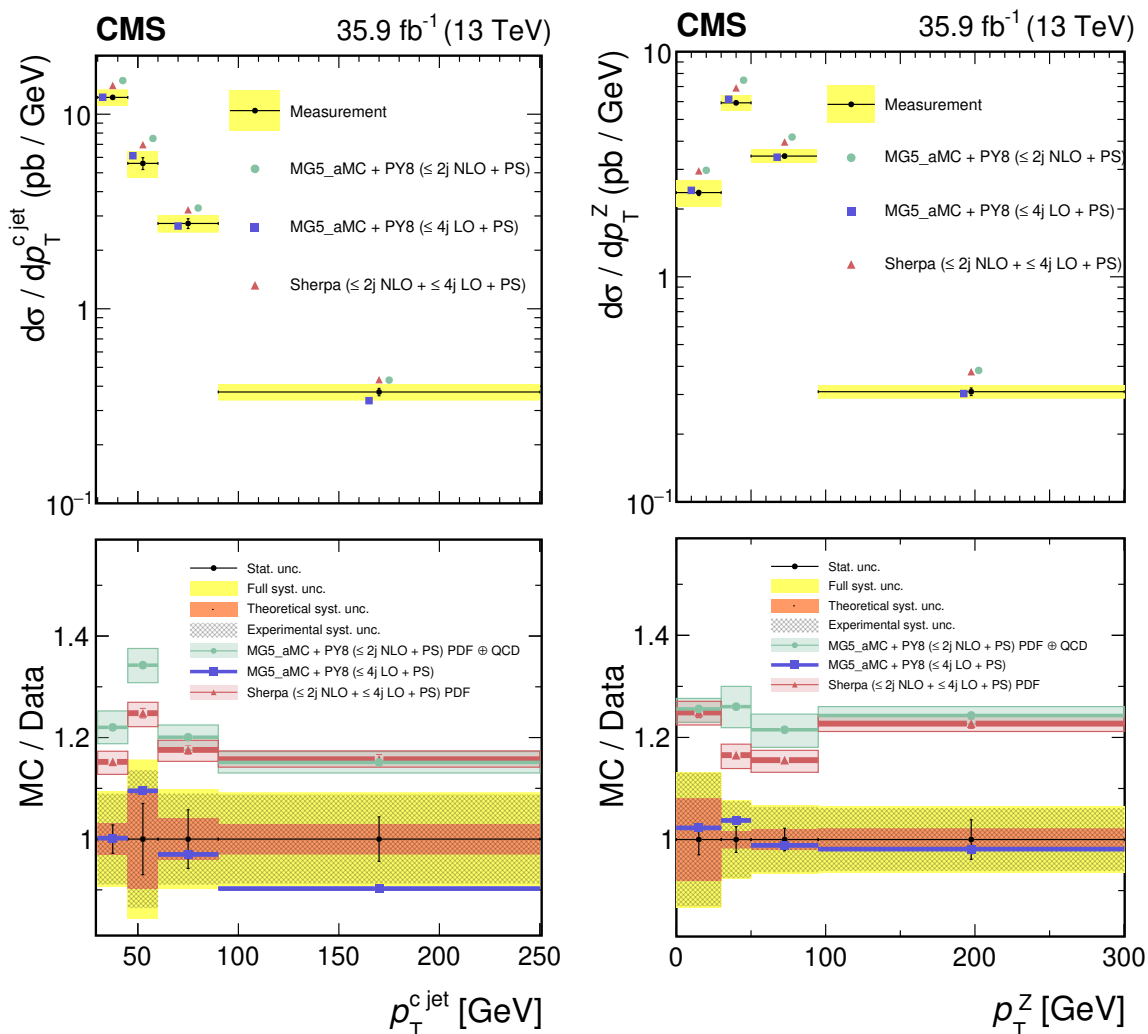
The total fiducial cross section value for  $Z$  boson  $p_{\text{T}} < 300$  GeV equals  $405.4 \pm 5.6$  (stat)  $\pm 24.3$  (exp)  $\pm 3.7$  (theo) pb, where (exp) and (theo) denote experimental and theoretical systematic uncertainties, respectively. This value is significantly lower than the MG5\_aMC (NLO) predicted value of  $524.9 \pm 11.7$  (theo) pb. The theoretical systematic uncertainty includes uncertainties in QCD scale and PDF.

The values of the cross sections as a function of  $p_{\text{T}}$  of the  $Z$  boson and  $c$  jet after combining are shown in figure 7. This also shows a comparison of the measured fiducial cross sections with predictions from the generators MG5\_aMC (NLO), MG5\_aMC (LO), and SHERPA. The prediction from MG5\_aMC at leading order shows good agreement with data, while both MG5\_aMC and SHERPA at next-to-leading order tend to overestimate the cross section.

The values of the measured differential cross sections are presented in tables 6 and 7.

## 8 Summary

The first differential cross sections for inclusive  $Z+c$  jet production as functions of transverse momenta  $p_{\text{T}}$  of the  $Z$  boson and of the associated  $c$  jet are presented for collisions at  $\sqrt{s} = 13$  TeV using  $35.9 \text{ fb}^{-1}$  of data collected by the CMS experiment at the CERN LHC. The measurements pertain to a fiducial space defined as containing a  $c$  jet with  $p_{\text{T}} > 30$  GeV and pseudorapidity  $|\eta| < 2.4$ , and a pair of leptons with each lepton having  $p_{\text{T}} > 10$  GeV,  $|\eta| < 2.4$ , and at least one with  $p_{\text{T}} > 26$  GeV, and a dilepton mass between



**Figure 7.** Measured fiducial differential cross sections for inclusive  $Z+c$  jet production,  $d\sigma/dp_T^{c,jet}$  (left) and  $d\sigma/dp_T^Z$  (right). Yellow band shows total systematic uncertainties. Predictions from MG5\_aMC (LO) are shown with statistical uncertainties only. The vertical bars on the data points represent statistical uncertainties.

$p_T^{c,jet}$ (GeV)	electrons (pb/GeV)	muons (pb/GeV)	combined (pb/GeV)
30–45	$11.91 \pm 0.54 \pm 1.50$	$12.34 \pm 0.44 \pm 1.05$	$12.20 \pm 0.34 \pm 1.15$
45–60	$5.30 \pm 0.63 \pm 0.92$	$5.73 \pm 0.49 \pm 0.66$	$5.59 \pm 0.39 \pm 0.87$
60–90	$3.10 \pm 0.25 \pm 0.51$	$2.66 \pm 0.19 \pm 0.41$	$2.74 \pm 0.16 \pm 0.27$
90–250	$0.43 \pm 0.03 \pm 0.06$	$0.34 \pm 0.02 \pm 0.03$	$0.37 \pm 0.02 \pm 0.03$

**Table 6.** Measured differential cross section as a function of  $p_T^{c,jet}$  for electron and muon channels and combined value. The first and second uncertainty values correspond to the statistical and systematic contributions, respectively.

$p_T^Z$ (GeV)	electrons (pb/GeV)	muons (pb/GeV)	combined (pb/GeV)
0–30	$2.28 \pm 0.13 \pm 0.28$	$2.40 \pm 0.08 \pm 0.24$	$2.37 \pm 0.07 \pm 0.31$
30–50	$5.91 \pm 0.23 \pm 0.54$	$5.90 \pm 0.19 \pm 0.46$	$5.93 \pm 0.15 \pm 0.45$
50–95	$3.69 \pm 0.13 \pm 0.27$	$3.32 \pm 0.09 \pm 0.22$	$3.44 \pm 0.08 \pm 0.23$
95–300	$0.32 \pm 0.02 \pm 0.03$	$0.30 \pm 0.02 \pm 0.02$	$0.31 \pm 0.01 \pm 0.02$

**Table 7.** Measured differential cross section as a function of  $p_T^Z$  for electron and muon channels and combined value. The first and second uncertainty values correspond to the statistical and systematic contributions, respectively.

71 and 111 GeV. The main background sources correspond to Z+light jet, Z+b jet, top quark pair, and diboson (ZZ, ZW, or WW) production. To provide a direct comparison with predictions from Monte Carlo (MC) event generators, we unfold detector effects from our measurements.

The total fiducial cross section for the Z boson with  $p_T < 300$  GeV is measured to be  $405.4 \pm 5.6$  (stat)  $\pm 24.3$  (exp)  $\pm 3.7$  (theo) pb, while the MADGRAPH5\_aMC@NLO generator at next-to-leading order predicts  $524.9 \pm 11.7$ (theo) pb for the same fiducial region. The theoretical uncertainties include QCD scale variation and parton distribution function uncertainties. The predictions from MC event generators were compared with measurements, which are in good agreement with MADGRAPH5\_aMC@NLO at leading order, while both MADGRAPH5\_aMC@NLO and SHERPA at next-to-leading order tend to overestimate the cross section. Predictions from all three generators were normalized to the cross section calculated with FEWZ at next-to-next-to-leading order. The prediction of inclusive Z+jets production at next-to-leading order is in better agreement with data than that at leading order [45]. This could be an indication that the parton distribution functions overestimate the charm content. These results can be used to improve existing constraints on the charm quark content in the proton.

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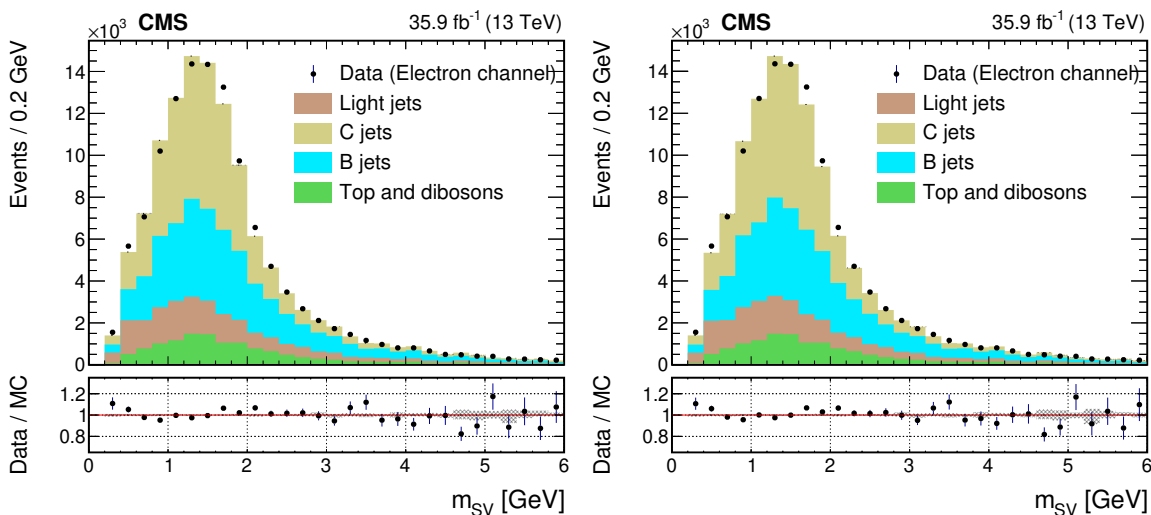
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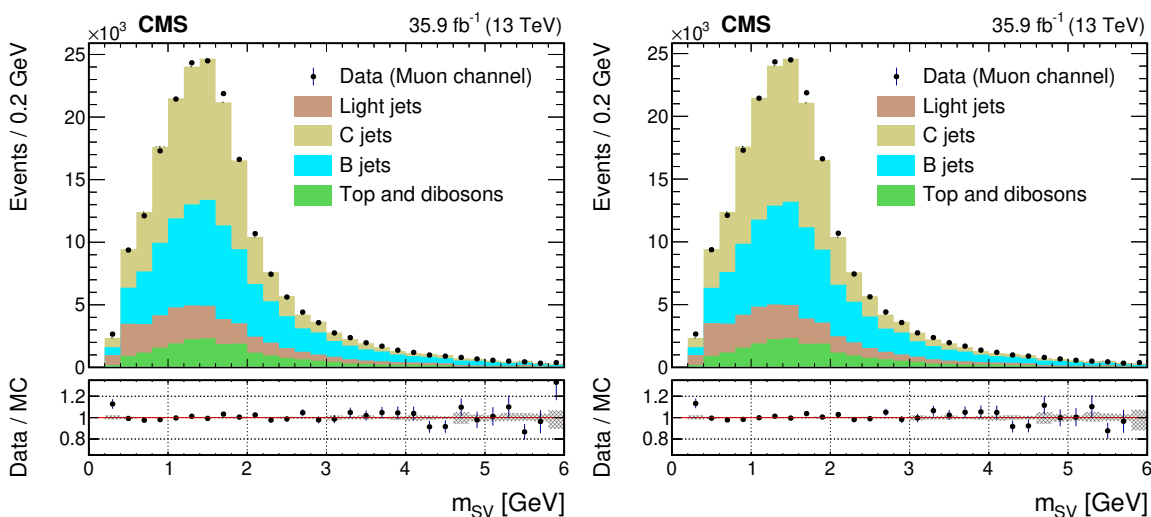


## A Post-fit secondary vertex mass distributions

Figures 8 and 9 show post-fit secondary vertex mass distributions for electron and muon channels. The normalization scale factors from the fit of  $m_{SV}$  were applied as a function of Z or c-tagged central jet  $p_T$ .



**Figure 8.** Distribution of the secondary vertex mass  $m_{SV}$  of the highest- $p_T$  c-tagged central jet, for electron channel. The observed data is compared to the different signal and background components in simulation, after normalization scale factors as function of Z  $p_T$  (left) and c-tagged central jet  $p_T$  (right) are applied. Bottom panels on each plot represent the data to MC ratio.



**Figure 9.** Distribution of the secondary vertex mass  $m_{SV}$  of the highest- $p_T$  c-tagged central jet, for muon channel. The observed data is compared to the different signal and background components in simulation, after normalization scale factors as function of Z  $p_T$  (left) and c-tagged central jet  $p_T$  (right) are applied. Bottom panels on each plot represent the data to MC ratio.

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