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Cross section predictions of the Z boson in association with jets at 14 TeV center-of-mass energy in proton–proton collisions

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Abstract: QCD predictions of the Z ($Z\to l^+l^-$) boson in association with jets (up to 2 jets) in proton–proton collisions are presented in this study. The results are predicted at LO and NLO accuracy using two most recent parton distribution functions, CT14 and MMHT2014. LO and NLO corrections are obtained with LO, NLO, and NNLO PDFs to find out the best PDF, which provides well compatible predictions with the experimental measurements. QCD predictions are performed at 13 and 14 TeV center-of-mass energies. To verify the obtained results, the predictions are compared with the measured results by ATLAS collaboration. NLO QCD predictions obtained by using NLO and NNLO PDFs show good agreement with the experimental data. The comparison of NLO predictions at 13 and 14 TeV center-of-mass energies shows that the Large Hadron Collider will provide approximately 9% more yield at 14 TeV center-of-mass energy than the yield at 13 TeV center-of-mass energy for the Z boson in association with 1 and 2 jets.

Key words: QCD predictions, cross section of Z boson, Large Hadron Collider, parton distribution functions, jets

1. Introduction

The Large Hadron Collider (LHC), the world's most powerful particle accelerator, was initiated to find solutions for particle physics questions and conduct research for physics beyond the standard model (BSM). Since the first proton beam was fired in the LHC, the center-of-mass energy has been increasing gradually. The current center-of-mass energy at the LHC is 13 TeV and it will reach its maximum collision energy of 14 TeV at the upcoming LHC run. More energy at the LHC means that it can produce heavier particles and as a result of this the chance of observing new particles increases. The higher energy at the LHC will provide more yields to study backgrounds for many physics processes. More information about the LHC can be found in Ref. [1].

One of the most important aspects of the LHC is the study of the Higgs boson and BSM studies. Understanding the nature of Z + jets events is very important in hadron colliders because they provide background for the Higgs boson search and lead to new ideas for physics BSM. These events also provide background for dark matter and SUSY particles in addition to resulting in extraction of gluon distribution functions and jet energy scale calibration [2]. Previous experiments such as CDF [3] and D0 [4] at Tevatron measured Z + jets cross section at $\sqrt{s} = 1.96$ TeV and in current LHC experiments CMS [5] and ATLAS [6] collaborations measured Z + jets cross section at $\sqrt{s} = 7$ TeV [6,7], 8 TeV [8,9], and 13 TeV [10].

The main goal of this study was to investigate QCD predictions of the Z boson in association with jets

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at $\sqrt{s}=14$ TeV for the upcoming LHC run. For the predictions, an MCFM MC generator [11] is used and the results obtained are compared with available experimental results, 13 TeV results by ATLAS collaboration. The predicted results are compared with the experimental outcomes to verify the code in MCFM. The results are predicted at leading order (LO) and next-to-leading order (NLO) accuracy by using LO, NLO, and next-to-next-to-leading order (NNLO) matrix elements of two most recent PDFs: CT14 and MMHT2014.

2. Cross section predictions of the Z boson in association with jets at LHC

The LHC is currently running at $\sqrt{s}=13$ TeV and the collision energy will be increased to 14 TeV in the near future. By considering this, we have generated Z events in association with 1 and 2 jets at $\sqrt{s}=13$ and 14 TeV. Since QCD predictions of single Z boson with no-associated jets were presented in our previous study [12], we will not go through Z boson QCD predictions with no-associated jets again. In this study, we begin with the verification of cross section predictions of inclusive Z boson in association with jets at NLO. Then the obtained results are compared with the published results by ATLAS collaboration at $\sqrt{s}=13$ TeV. The same selection criteria as shown in Table 1 are defined to be consistent with ATLAS results [10]. For this study, a factorization (μ_F) and renormalization (μ_R) scale of $\sqrt{m^2+\sum p_T^{jet}}$ is used. Here m is the invariant mass of the Z boson and p_T^{jet} is the transverse momentum of the associated jet.

Table 1. Selection criteria on leptons and jets. Selections are defined same as ATLAS selection criteria for Z boson in association with jets.

<table>
<tr><td rowspan="6">Z + jets</td><td rowspan="3">Leptons</td><td>$p_T > 25\,GeV$</td><td rowspan="6">$R\,(l-j) > 0.4$</td></tr>
<tr><td>$|\eta| < 2.5$</td></tr>
<tr><td>$71 < m_{ll} < 111\,GeV$</td></tr>
<tr><td rowspan="3">Jets</td><td>$p_T > 30\,GeV$</td></tr>
<tr><td>$|\eta| < 2.5$</td></tr>
<tr><td>anti-k_T R = 0.4</td></tr>
</table>

A comparison of the predicted results with ATLAS measurements is shown in the Figure. The green lines show experimental results, the blue dashed lines show the systematical uncertainty of experimental measurements, the red dotted lines show quadratic sum of the systematical and luminosity uncertainties of experimental data, and the black dots show the predicted results. In addition, CT14.LL, CT14.NL, and CT14.NN are respectively LO, NLO, and NNLO matrix elements of CT14 PDF. Similarly, MMHT_lo, MMHT_nl, and MMHT_nn are respectively LO, NLO, and NNLO matrix elements of MMHT2014 PDF. The process $\sigma^{Fid}_{pp\to Z+1(2)jet\,(s)}BR(Z\to l^+l^-)$ on the y-axis of this figure shows the fiducial cross section times branching ratio of the predicted and experimental results. In the figure, only NLO QCD predictions that are obtained using LO, NLO, and NNLO PDFs of CT14 and MMHT2014 are compared with experimental outcomes. As can be seen, NLO QCD predictions obtained with LO PDFs are not consistent with experimental results. However, NLO QCD predictions that are obtained using NLO and NNLO PDFs are closely consistent with experimental measurements. LO correction, the lowest order for a process to occur, uses tree level matrix element and it has low precision. However, the NLO correction uses one loop matrix element, has higher precision, and it reduces the scale uncertainty by lowering the dependency on the renormalization and factorization scales. In this regard, NLO QCD predictions provide more accurate calculations and they are in better agreement with experimental results. In this study, we choose Z + jets events only by applying tight cuts on p_T of leptons (>25 GeV), p_T of jets (>30 GeV), and R between leptons and associated jets (>0.4). By doing so, all the soft particles are filtered out.

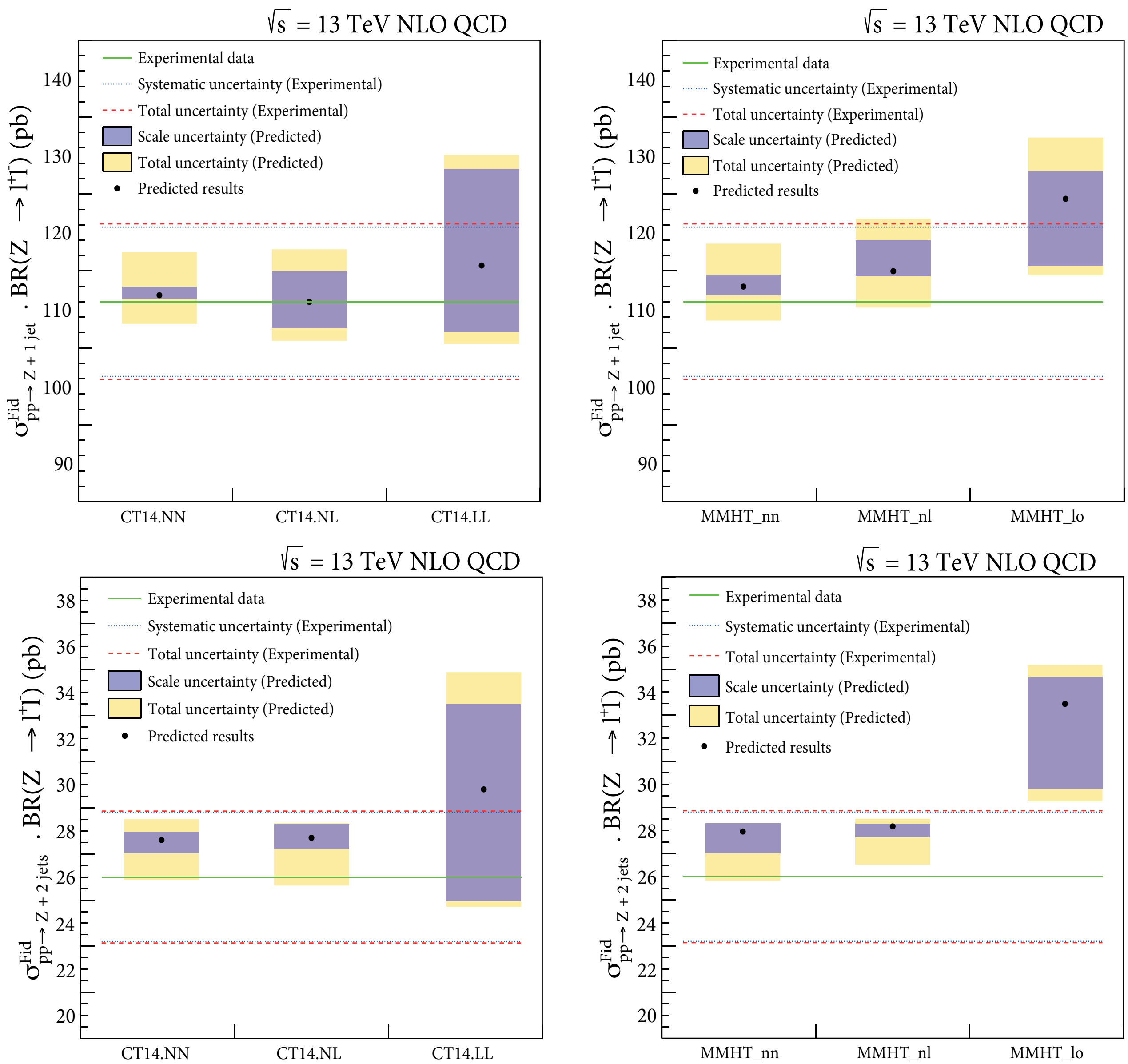

Figure. A comparison of the NLO QCD predictions that are obtained using LO, NLO, NNLO CT14, and MMHT2014 PDFs at 13 TeV center-of-mass energy with measured ATLAS results at the corresponding energy; Z + 1 jet events (top) and Z + 2 jets events (bottom).

The comparison of NLO predicted results with the experimental outcomes helps us to understand the order of correction with which PDF order will give more precise results at $\sqrt{s}$ = 14 TeV. Since NLO QCD predictions with NLO and NNLO PDFs give more consistent results with experimental outcomes at $\sqrt{s} = 13$ TeV, we will only focus on NLO QCD predictions that are obtained with NLO and NNLO PDFs at $\sqrt{s} = 14$ TeV. Thus, we can predict the expected yield increase for the next LHC run by comparing 13 and 14 TeV NLO

QCD predictions.

3. Results and discussion

QCD predictions of particle cross sections at hadron colliders are crucial to estimate the experimental measurements since these predictions are used to ensure the accuracy of the empirical analysis based on the experimental data. In this study, the two most recent PDF models (CT14 and MMHT2014) are used to obtain LO and NLO

Table 2. Z + jets QCD predictions at $\sqrt{s} = 13$ TeV and experimental results at the corresponding center-of-mass energy. The uncertainties for the predicted results are PDF and scale, respectively. For experimental results, the uncertainties are respectively statistical, systematical, and luminosity errors.

	PDFs	Predicted results (pb)		Experimental results (pb)
		LO	NLO	
Z + 1 jet	CT14.NN	$85.14^{+0.57\,+2.49}_{-0.23\,-3.16}$	$116.85^{+1.12\,+5.46}_{-0.42\,-3.70}$	$116 \pm 0.3 \pm 9.7 \pm 2.5$
	CT14.NL	$84.14^{+2.18\,+2.51}_{-1.96\,-3.23}$	$115.98^{+3.99\,+5.56}_{-3.37\,-3.78}$	
	CT14.LL	$85.16^{+7.12\,+3.52}_{-4.71\,-3.91}$	$120.71^{+12.52\,+7.04}_{-8.67\,-5.37}$	
	MMHT_nn	$85.71^{+0.80\,+2.51}_{-0.57\,-3.24}$	$117.97^{+1.54\,+5.37}_{-1.12\,-4.28}$	
	MMHT_nl	$86.62^{+2.18\,+2.55}_{-0.22\,-3.31}$	$119.97^{+3.99\,+5.52}_{-0.62\,-4.68}$	
	MMHT_lo	$89.87^{+2.41\,+3.70}_{-4.71\,-4.27}$	$129.38^{+3.65\,+7.07}_{-8.67\,-4.68}$	
Z +2 jets	CT14.NN	$25.26^{+0.67\,+4.94}_{-0.25\,-4.69}$	$28.60^{+0.36\,+0.84}_{-0.58\,-1.62}$	$27 \pm 0.1 \pm 2.8 \pm 0.6$
	CT14.NL	$24.99^{+1.00\,+5.24}_{-0.85\,-4.38}$	$28.70^{+0.59\,+0.21}_{-0.48\,-2.01}$	
	CT14.LL	$27.19^{+2.49\,+5.86}_{-3.60\,-4.92}$	$30.80^{+3.69\,+1.04}_{-4.86\,-1.52}$	
	MMHT_nn	$25.31^{+0.42\,+5.24}_{-3.40\,-4.37}$	$28.96^{+0.36\,+0.04}_{-0.94\,-1.91}$	
	MMHT_nl	$25.99^{+0.15\,+5.63}_{-4.19\,-4.55}$	$29.18^{+0.11\,+0.31}_{-0.48\,-1.59}$	
	MMHT_lo	$29.68^{+1.11\,+6.88}_{-7.30\,-5.54}$	$34.49^{+1.17\,+1.22}_{-3.69\,-1.99}$	

Table 3. LO and NLO QCD predictions obtained using CT14 and MMHT2014 PDFs at $\sqrt{s} = 14$ TeV. Both PDFs are used with their LO (CT14.LL, MMHT_lo), NLO (CT14.NL, MMHT_nl), and NNLO (CT14.NN, MMHT_nn) matrix elements. The uncertainties for the predicted results are PDF and scale, respectively.

	PDFs	Predicted results (pb)	
		LO	NLO
Z + 1 jet	CT14.NN	$92.95^{+0.61\,+2.21}_{-0.28\,-3.02}$	$127.74^{+1.07\,+5.54}_{-0.65\,-3.89}$
	CT14.NL	$92.21^{+2.39\,+2.22}_{-2.11\,-3.06}$	$126.93^{+3.81\,+5.74}_{-3.62\,-4.21}$
	CT14.LL	$93.28^{+7.98\,+3.34}_{-5.25\,-3.92}$	$132.33^{+14.03\,+7.21}_{-8.56\,-5.13}$
	MMHT_nn	$93.57^{+0.90\,+2.27}_{-0.62\,-3.07}$	$128.81^{+1.72\,+5.84}_{-1.07\,-4.06}$
	MMHT_nl	$94.60^{+2.39\,+2.23}_{-0.28\,-3.15}$	$130.55^{+0.19\,+6.03}_{-3.62\,-4.00}$
	MMHT_lo	$98.53^{+2.73\,+3.52}_{-5.25\,-4.23}$	$140.89^{+5.47\,+8.54}_{-8.56\,-5.80}$
Z + 2 jets	CT14.NN	$28.18^{+0.03\,+5.47}_{-0.61\,-4.93}$	$30.62^{+0.82\,+0.68}_{-0.11\,-0.71}$
	CT14.NL	$27.72^{+1.60\,+5.76}_{-1.10\,-4.67}$	$31.39^{+1.21\,+1.83}_{-0.95\,-1.91}$
	CT14.LL	$29.92^{+4.44\,+6.53}_{-2.95\,-4.91}$	$34.19^{+5.80\,+0.92}_{-4.17\,-1.84}$
	MMHT_nn	$28.21^{+0.59\,+5.48}_{-0.64\,-4.89}$	$31.44^{+0.82\,+0.68}_{-0.93\,-1.57}$
	MMHT_nl	$29.32^{+0.50\,+5.42}_{-1.60\,-5.18}$	$32.34^{+0.26\,+1.83}_{-0.95\,-1.82}$
	MMHT_lo	$32.87^{+1.49\,+7.64}_{-2.95\,-5.99}$	$38.36^{+1.63\,+0.92}_{-4.17\,-2.58}$

QCD predictions of Z + 1 and 2 jets at $\sqrt{s} = 13$ and 14 TeV. Numerical values of LO and NLO QCD predictions and ATLAS measurements are given in Table 2. We find that NLO QCD predictions that are obtained using LO, NLO, and NNLO CT14 PDFs respectively give 4%, 0.02%, and 0.75% discrepancy with the data for Z + 1 jet events and 14%, 6.3%, and 6% discrepancy with the data for Z + 2 jets events. Moreover, NLO QCD predictions that are obtained using LO, NLO, and NNLO MMHT2014 PDFs give 12%, 3.4%, and 1.7% discrepancy with the data for Z + 1 jet and 28%, 8%, and 7% discrepancy with the data for Z + 2 jets events. This shows that the results are acceptable and they are in agreement with the experimental data. However, NLO QCD predictions give better agreement with the experimental data for Z + 1 jet events compared to Z + 2 jets events. The MCFM-8.0 program has NLO accuracy for $Z+ \leq 2$ jets and so we have only studied up to Z+2 jets. Previously, CDF collaboration compared $9.64\, fb^{-1}$ collected data with NLO QCD calculations for $Z+ \geq 1$ jets by using BLACKHAT+SHERPA and they found more discrepancy between predicted and experimental results for $Z+ \geq 3$ jets [13]. However, Z + jets measurements with the ATLAS detector using the anti-k$_T$ algorithm do not show any discrepancy at high jet multiplicities [6]. The reason for this was that the anti-k$_T$ algorithm has different angular reach and approach to the additional radiation between two hard particles [14]. Our results show that NLO predictions that are obtained using NLO and NNLO PDFs are almost the same as experimental measurements and the results are acceptable when the uncertainties are taken into account.

LO and NLO QCD predictions that are obtained using LO, NLO, and NNLO CT14 and MMHT2014 PDFs at $\sqrt{s} = 14$ TeV are given in Table 3. As expected, the results show that the probability of finding Z + jets events decreases when the number of jets is increasing. However, the probability of observing Z + jets events increases as the center-of-mass energy increases. The comparison of NLO QCD predictions in Tables 2 and 3 obtained using NLO and NNLO PDFs shows an increase in the signal yield ($\sim$9%) for Z + 1(2) jet(s) events from $\sqrt{s} = 13$ and 14 TeV. As the center-of-mass energy increases multiple interactions can take place and particles are more likely to be involved in hard scattering [15]. This could be an explanation for the higher total cross sections of Z + jets events at $\sqrt{s} = 14$ TeV.

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