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Differential QCD Predictions of the $W^{\pm}+1$ Jet for the Large Hadron Collider and Possible Future High Energy Colliders

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The differential quantum chromodynamics (QCD) predictions for the $W^{\pm}$ boson and a single jet as functions of the lepton pseudorapidity in proton-proton collisions are presented up next-to-leading order correction in QCD. The predictions are done by using the most modern parton distribution functions (PDFs). To check the reliability of the PDFs, we compared 7 TeV predictions with the available experimental results at the corresponding energy. Finally, the differential QCD predictions and the asymmetry between the $W^{+}+1$ jet and $W^{-}+1$ jet events at $\sqrt{s}=7$, 8, 13, 14 and 100 TeV are discussed in detail.

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I. INTRODUCTION

In high energy and particle physics, hadron colliders play an important role in testing the predictions of various theories. They both search for new particles and interactions predicted in the Standard Model (SM) and in the theories beyond the Standard Model (BSM). Discoveries of W and Z bosons [1], the top quark [2] and the Higgs boson [3,4] are the most significant examples of the discoveries that are made by hadron colliders. The most powerful hadron collider that is currently operating is the Large Hadron Collider (LHC). It started its operation in 2009 with a 7 TeV center-of-mass energy, and the energy was increased to 8 TeV in 2012. These two steps were called Run 1. The second step at the LHC is called Run 2, which operates at 13 and 14 TeV center-of-mass energies. $\sqrt{s}=13$ TeV proton-proton (pp) collisions have already started at the LHC, and it will finally reach its desired collision energy of 14 TeV [5] during the time frame from 2019 to 2021. Furthermore, the Future Circular Collider (FCC) is currently being designed for the post-LHC era with the goal of reaching a center-of-mass energy of 100 TeV in *pp* collision. The FCC will extend the searches for new physics on both the energy and the intensity frontiers of particle colliders. It will provide electron-positron and proton-electron collisions, as well as hadron collisions (proton-proton and heavy ion), at different energies [6].

In *pp* collisions, vector boson studies in association with jets are important because they provide background

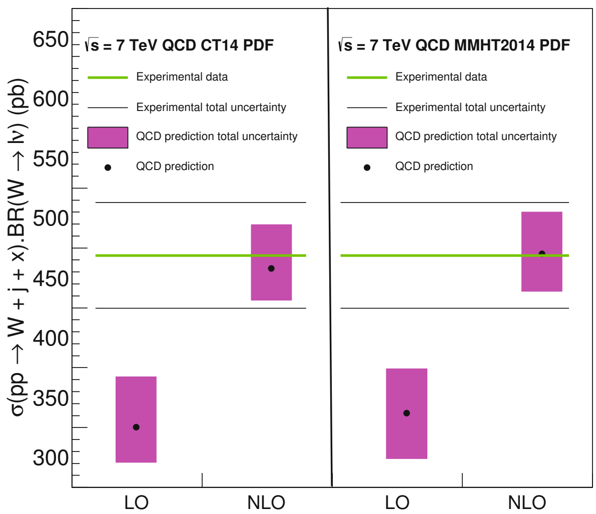

Fig. 1. (Color online) A comparison of 7 TeV ATLAS cross-section results and QCD predictions at the corresponding energy for the W boson in association with one inclusive jet in *pp* collisions. Both LO and NLO QCD predictions are obtained by using the two most recent PDFs, CT14 and MMHT2014.

for the top quark and for new physics searches, as well as for searches in the SM [7]. The associated jet production studies develop the calculations and Monte Carlo (MC) simulations in perturbative quantum chromodynamics (pQCD). Because of this, $W^{\pm}$ + jet events are very cirucial in pQCD [8]. Previous hadron collider experiments such as CDF and D0 at Tevatron reported W + jet production results at $\sqrt{s}=1.96$ TeV [9] in $p\bar{p}$ col-

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Table 1. NLO QCD predictions and total systematic uncertainties of $W^{+}+1$ jet and $W^{-}+1$ jet production at various center-of-mass energies in pp collisions. The total systematic uncertainties are calculated taking the quadratic sum of the PDF and scale uncertainties.

	$W^{+}+1$ Jet (pb)		$W^{-}+1$ Jet (pb)	
	CT14 PDF	MMHT2014 PDF	CT14 PDF	MMHT2014 PDF
7 TeV	$287.706^{+21.936}_{-15.985}$	$292.724^{+22.306}_{-17.457}$	$195.116^{+15.054}_{-13.451}$	$202.303^{+15.884}_{-13.227}$
8 TeV	$340.818^{+25.847}_{-16.273}$	$346.698^{+27.573}_{-17.751}$	$237.611^{+18.099}_{-15.351}$	$245.939^{+18.447}_{-15.399}$
13 TeV	$602.194^{+42.611}_{-27.129}$	$616.840^{+44.035}_{-33.580}$	$463.014^{+31.950}_{-25.254}$	$478.258^{+32.046}_{-27.213}$
14 TeV	$655.514^{+42.751}_{-29.741}$	$671.213^{+41.782}_{-33.345}$	$510.780^{+33.091}_{-26.242}$	$524.809^{+37.708}_{-25.264}$
100 TeV	$4849.761^{+91.285}_{-81.555}$	$4981.663^{+93.642}_{-88.285}$	$4589.529^{+85.299}_{-67.722}$	$4710.755^{+82.666}_{-63.549}$

Table 2. $W^{\pm}+1$ jet asymmetry (%) at various center-of-mass energies. The results are produced by using the two most recent PDFs, CT14 and MMHT2014.

	7 TeV (%)	8 TeV (%)	13 TeV (%)	14 TeV (%)	100 TeV (%)
CT14 PDF	$19.176\ ^{+0.936}_{-0.306}$	$17.843\ ^{+0.582}_{-0.963}$	$13.066\ ^{+0.160}_{-0.624}$	$12.410\ ^{+0.055}_{-0.373}$	$2.757\ ^{+0.456}_{-0.646}$
MMHT2014 PDF	$18.266\ ^{+0.918}_{-0.291}$	$17.002\ ^{+0.869}_{-0.683}$	$12.655\ ^{+0.429}_{-0.844}$	$12.241\ ^{+0.869}_{-0.429}$	$2.795\ ^{+0.077}_{-0.468}$

lisions, and current LHC experiments such as CMS and ATLAS reported W + jet production results at $\sqrt{s}=7$ [10] and 13 TeV [11,12] in pp collisions.

The LHC experiments showed that the numbers of W^{+} and W^{-} events in pp collisions are not same because the number of up (u) quarks is dominant in proton. However, the asymmetry between W^{+} and W^{-} decreases with the increasing center-of-mass energy at the LHC [13]. In this study, we produce next-to-leading order (NLO) QCD predictions for $W^{+}+1$ jet and $W^{-}+1$ jet by using MCFM [14] MC generator. The most recent PDFs that are used for QCD predictions are CT14 [15] and MMHT2014 [16]. Because of this, we used these two PDFs in the MCFM generator to find more precise results with the LHC data at $\sqrt{s}=7$, 8, 13, and 14 TeV and the FCC pp data at $\sqrt{s}=100$ TeV. Then, we study the charge asymmetry of simultaneous production of $W^{\pm}$ and one associated jet in pp collisions by using these NLO QCD results.

II. DIFFERENTIAL QCD PREDICTIONS OF $W^{\pm}+1$ JET PRODUCTION FOR FUTURE LHC RUNS AND THE POST LHC ERA

The production and cross-section studies of $W^{\pm}$ bosons in association with jets play an important role in particle physics because they provide background for possible new processes, such as the production of the SM Higgs boson and processes BSM. In this study, we first generate LO and NLO QCD predictions of $W^{+}+1$ jet and $W^{-}+1$ jet events at $\sqrt{s}=7$ TeV and compared the obtained results with available experimental results at the LHC. The purpose of this comparison is to confirm our selection criteria for the leptons from W boson decay and jets and to test the QCD correction and PDF that is consistent with experimental data. For the leptonic decay of the W boson ($W^{+}\to\ell^{+}\nu$ and $W^{-}\to\ell^{-}\bar{\nu}$, where $\ell^{\pm}$ is $e^{\pm}$ or $\mu^{\pm}$), we use $p_T^{\ell}>25$ GeV and $|\eta^{\ell}|<2.5$. Similarly, we use $p_T^{jet}>30$ GeV and $|\eta^{jet}|<4.4$. To constrain the cases where an extra one jet from the initial or the final state radiation exists, we select $\Delta R>0.5$, where ΔR is a cone between the lepton and the jet. We use the anti-k_t algorithm to reconstruct jets with a radius parameter $R=0.4$ [17]. In addition, $E_T^{miss}>25$ GeV and $m_T>40$ GeV are selected, where E_T^{miss} and m_T are respectively the missing transverse energy and the transverse mass. Finally, the renormalization (μ_R) and the factorization (μ_F) scales are selected as $\mu_R=\mu_F=\sqrt{m_W^2+\sum(p_T^{jet})^2}$. Here, m_W is the W boson mass, and p_T^{jet} is the jet's transverse momentum. To calculate the scale uncertainty, we take the difference between the cross sections for the value ($\mu_R=\mu_F=M_Z$) and the scaled value ($\mu_R=\mu_F=xM_Z$, where x is equal to $\frac{1}{2}$ or 2). Then, the total systematic uncertainty is calculated by taking the quadratic sum of the PDF and the scale uncertainties. A detailed calculation of the scale uncertainty can be found in our previous study [13].

A comparison of 7 TeV ATLAS results [10] to the QCD predictions at the corresponding energy is given in Fig. 1. As shown in the figure, NLO predictions for the CT14 and MMHT2014 PDFs at $\sqrt{s}=7$ TeV are consistent with experimental data, even though the LO predictions of the PDFs do not agree with the data. Additional quarks and gluons that have strong coupling factor (α_s) must be inserted into a LO process to obtain NLO QCD prediction of a process [18]. Because the LO correction is the born level at QCD, this level correction does not give a precise approximation for estimating the cross section of a particle. The LO correction results in a large scale uncertainty, but the dependences on the μ_R and μ_F scales are lower at the NLO correction [19]. For these

Table 3. $W^+ + 1$ jet NLO QCD predictions as a function of lepton η from 7 to 100 TeV center-of-mass energies. The results are produced by using the CT14 and the MMHT2014 PDFs, and the total systematic uncertainties are calculated taking the quadratic sum of the PDF and the scale uncertainties.

PDFs	Lepton $\|\eta\|$	7 TeV	8 TeV	13 TeV	14 TeV	100 TeV
CT14	0.00-0.20	$23.41^{+1.924}_{-0.911}$	$26.969^{+2.964}_{-1.151}$	$48.498^{+2.395}_{-3.347}$	$51.154^{+6.368}_{-1.410}$	$387.191^{+20.530}_{-11.931}$
	0.20-0.40	$22.793^{+2.297}_{-0.949}$	$26.744^{+1.706}_{-1.263}$	$46.166^{+7.818}_{-1.715}$	$51.036^{+2.890}_{-1.402}$	$405.272^{+41.830}_{-11.670}$
	0.40-0.60	$23.397^{+2.090}_{-1.624}$	$26.684^{+2.996}_{-1.751}$	$45.789^{+5.357}_{-2.009}$	$52.832^{+3.018}_{-4.102}$	$381.086^{+23.665}_{-21.606}$
	0.60-0.80	$23.945^{+2.489}_{-0.809}$	$28.918^{+1.837}_{-2.687}$	$47.780^{+4.123}_{-1.855}$	$52.480^{+2.257}_{-2.833}$	$405.391^{+19.774}_{-16.195}$
	0.80-1.00	$23.862^{+3.527}_{-1.474}$	$27.701^{+2.536}_{-1.097}$	$47.527^{+5.742}_{-2.583}$	$54.263^{+2.857}_{-3.802}$	$395.835^{+27.814}_{-17.710}$
	1.00-1.20	$24.376^{+1.238}_{-1.356}$	$28.040^{+1.636}_{-2.401}$	$47.726^{+4.890}_{-0.657}$	$54.276^{+1.271}_{-5.327}$	$391.228^{+11.746}_{-14.417}$
	1.20-1.40	$25.051^{+1.976}_{-2.395}$	$29.394^{+1.166}_{-2.239}$	$48.261^{+3.832}_{-1.088}$	$52.199^{+4.233}_{-2.501}$	$391.040^{+18.423}_{-34.661}$
	1.40-1.60	$23.15^{+1.751}_{-1.861}$	$27.858^{+2.256}_{-2.150}$	$50.160^{+3.146}_{-3.862}$	$51.308^{+5.081}_{-3.647}$	$394.460^{+13.159}_{-17.813}$
	1.60-1.85	$29.371^{+1.859}_{-0.898}$	$34.269^{+2.296}_{-1.734}$	$62.635^{+2.159}_{-3.564}$	$64.672^{+3.853}_{-3.687}$	$489.857^{+35.573}_{-22.348}$
	1.85-2.10	$27.977^{+2.576}_{-1.626}$	$33.955^{+2.428}_{-3.823}$	$57.967^{+8.860}_{-2.195}$	$65.692^{+6.914}_{-2.886}$	$482.778^{+18.894}_{-14.145}$
	2.10-2.40	$30.26^{+2.228}_{-1.938}$	$37.722^{+3.299}_{-3.074}$	$69.873^{+7.271}_{-4.155}$	$77.866^{+4.755}_{-7.826}$	$546.012^{+19.093}_{-10.470}$
MMHT2014	0.00-0.20	$23.925^{+1.614}_{-1.118}$	$28.640^{+2.221}_{-2.279}$	$48.099^{+2.807}_{-0.644}$	$53.937^{+2.827}_{-3.138}$	$376.509^{+32.291}_{-21.460}$
	0.20-0.40	$24.343^{+2.711}_{-1.029}$	$28.421^{+2.041}_{-2.044}$	$48.445^{+6.378}_{-3.877}$	$51.658^{+3.794}_{-2.850}$	$395.929^{+13.515}_{-14.219}$
	0.40-0.60	$24.096^{+1.989}_{-1.833}$	$28.185^{+2.827}_{-1.890}$	$49.850^{+4.065}_{-4.907}$	$53.705^{+3.038}_{-2.723}$	$403.266^{+45.914}_{-41.362}$
	0.60-0.80	$23.583^{+1.900}_{-1.292}$	$28.654^{+1.999}_{-1.028}$	$50.442^{+2.674}_{-3.121}$	$53.539^{+1.391}_{-1.341}$	$421.307^{+23.181}_{-17.184}$
	0.80-1.00	$24.603^{+3.043}_{-2.331}$	$28.026^{+2.794}_{-1.384}$	$49.321^{+5.440}_{-2.457}$	$55.629^{+3.872}_{-4.602}$	$423.454^{+37.316}_{-31.279}$
	1.00-1.20	$24.839^{+2.334}_{-1.519}$	$29.103^{+2.301}_{-2.635}$	$49.436^{+4.185}_{-2.605}$	$54.996^{+2.260}_{-3.755}$	$402.836^{+28.304}_{-6.749}$
	1.20-1.40	$24.322^{+1.776}_{-1.521}$	$29.213^{+1.686}_{-0.810}$	$48.129^{+4.120}_{-2.398}$	$53.164^{+3.097}_{-1.652}$	$408.025^{+24.130}_{-21.483}$
	1.40-1.60	$23.881^{+2.539}_{-1.174}$	$28.306^{+0.810}_{-0.811}$	$49.341^{+2.958}_{-5.013}$	$53.301^{+6.130}_{-3.853}$	$381.320^{+40.853}_{-11.572}$
	1.60-1.85	$29.204^{+2.777}_{-1.034}$	$35.819^{+2.272}_{-3.093}$	$64.038^{+3.914}_{-7.841}$	$67.800^{+5.325}_{-4.902}$	$493.092^{+21.668}_{-12.917}$
	1.85-2.10	$27.109^{+3.276}_{-1.193}$	$34.615^{+3.002}_{-2.207}$	$62.520^{+6.212}_{-5.129}$	$69.457^{+5.539}_{-7.231}$	$470.465^{+18.999}_{-43.683}$
	2.10-2.40	$30.294^{+2.418}_{-1.536}$	$38.084^{+2.237}_{-2.780}$	$70.769^{+3.771}_{-2.704}$	$76.446^{+7.771}_{-3.263}$	$552.663^{+18.037}_{-22.350}$

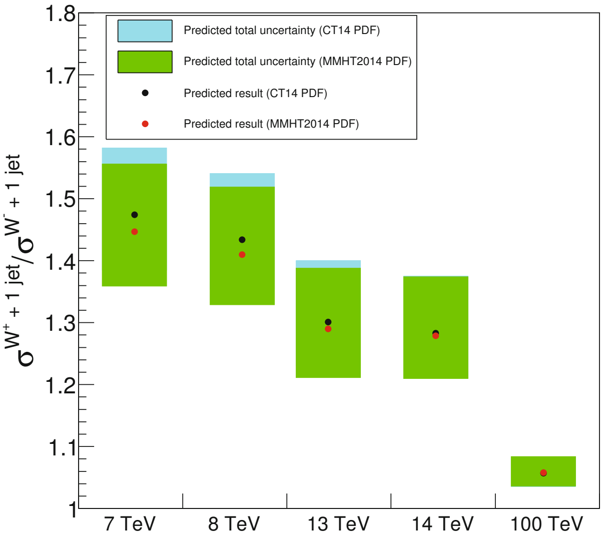


Fig. 2. (Color online) Ratio of $W^+ + 1$ jet to $W^- + 1$ jet NLO QCD predictions at various center-of-mass energies.

reasons, compared to the LO QCD correction, the NLO QCD correction is more consistent with the experimental data.

The consistency of the NLO correction shows that the NLO correction will provide a better estimate for future LHC and post-LHC runs. Because of this, we will not take the LO correction into account during the remainder. The numerical results for the NLO QCD predictions for $W^+ + 1$ jet and $W^- + 1$ jet production in a range of center-of-mass energy from 7 to 100 TeV are given in Table 1. Using the results in Table 1, we find the ratio of $\sigma_{W^+ +1jet}$ to $\sigma_{W^- +1jet}$, as shown in Fig. 2. In this figure, the ratios are obtained by using the CT14 and the MMHT2014 PDFs. As can be seen, the results for both PDFs are close to each other. The figure shows that the difference between $\sigma_{W^+ +1jet}$ and $\sigma_{W^- +1jet}$ decreases while the center-of-mass energy becomes larger. This shows that the probability of finding $W^+ + 1$ jet events will be close to the probability of finding $W^- + 1$ jet events at $\sqrt{s} = 14$ TeV, and it will be almost same at $\sqrt{s} = 100$ TeV. The correct method for calculating the charge asymmetry between $W^+ + 1$ jet and $W^- + 1$ jet events is not to take the ratio for these events. Because of this, we use the method that was previously used by the CMS collaboration to calculate the asymmetry between W^+ and W^- events [20]. We use Eq. (1) to calculate the asymmetry between $W^+ + 1$ jet and $W^- + 1$ jet events:

$$A = \frac{\sigma_{W^+ +1jet} - \sigma_{W^- +1jet}}{\sigma_{W^+ +1jet} + \sigma_{W^- +1jet}}. \quad (1)$$

In this equation, A is the asymmetry, and $\sigma_{W^\pm +1jet}$ is NLO QCD predictions for $W^+ + 1$ jet and $W^- + 1$ jet events.

Table 4. $W^{-}+1$ jet NLO QCD predictions as a function of lepton η from 7 to 100 TeV center-of-mass energies. The results are produced by using the CT14 and the MMHT2014 PDFs, and the total systematic uncertainties are calculated taking the quadratic sum of the PDF and the scale uncertainties.

PDFs	Lepton $\|\eta\|$	7 TeV	8 TeV	13 TeV	14 TeV	100 TeV
CT14	0.00-0.20	$18.189^{+1.228}_{-1.282}$	$22.125^{+4.010}_{-3.095}$	$42.164^{+1.666}_{-4.890}$	$46.396^{+2.085}_{-4.090}$	$386.542^{+5.984}_{-7.863}$
	0.20-0.40	$18.044^{+1.350}_{-1.051}$	$21.133^{+4.083}_{-2.729}$	$41.486^{+2.349}_{-1.623}$	$42.342^{+6.426}_{-2.495}$	$388.724^{+34.975}_{-16.940}$
	0.40-0.60	$17.543^{+1.349}_{-0.779}$	$21.592^{+5.024}_{-3.921}$	$41.364^{+3.507}_{-2.837}$	$45.714^{+1.838}_{-3.827}$	$398.287^{+8.345}_{-14.265}$
	0.60-0.80	$17.244^{+1.346}_{-0.848}$	$20.951^{+4.141}_{-3.491}$	$39.247^{+3.987}_{-0.470}$	$44.646^{+3.486}_{-3.775}$	$385.029^{+25.873}_{-21.979}$
	0.80-1.00	$17.359^{+1.189}_{-1.253}$	$20.900^{+3.937}_{-3.373}$	$40.186^{+2.841}_{-4.155}$	$45.832^{+3.729}_{-3.173}$	$368.767^{+41.959}_{-13.894}$
	1.00-1.20	$17.461^{+1.054}_{-2.089}$	$20.405^{+3.781}_{-3.543}$	$38.879^{+4.031}_{-3.805}$	$40.702^{+5.194}_{-3.518}$	$379.185^{+36.271}_{-27.628}$
	1.20-1.40	$16.582^{+0.576}_{-1.379}$	$18.989^{+3.353}_{-2.216}$	$36.688^{5.596}_{-3.826}$	$43.399^{+3.227}_{-3.694}$	$351.746^{+47.737}_{-35.205}$
	1.40-1.60	$14.45^{+2.459}_{-0.927}$	$18.958^{+4.321}_{-3.900}$	$36.530^{+1.704}_{-2.397}$	$40.200^{+3.317}_{-4.031}$	$358.167^{+19.442}_{-16.757}$
	1.60-1.85	$18.131^{+1.787}_{-0.813}$	$21.256^{+4.137}_{-2.810}$	$44.899^{+4.222}_{-5.630}$	$46.285^{+5.984}_{-1.786}$	$466.031^{+32.640}_{-12.138}$
	1.85-2.10	$15.457^{+2.772}_{-1.765}$	$20.250^{+3.909}_{-3.206}$	$38.783^{+4.265}_{-7.385}$	$43.616^{+4.083}_{-1.997}$	$420.579^{+40.672}_{-24.586}$
	2.10-2.40	$17.04^{+2.607}_{-1.393}$	$21.864^{+5.198}_{-4.030}$	$44.745^{+5.668}_{-2.732}$	$49.966^{+2.284}_{-4.191}$	$485.074^{+39.780}_{-24.090}$
MMHT2014	0.00-0.20	$19.796^{+1.630}_{-2.216}$	$19.796^{+2.861}_{-4.019}$	$43.823^{+2.672}_{-2.878}$	$45.342^{+4.102}_{-0.688}$	$381.798^{+10.837}_{-7.706}$
	0.20-0.40	$18.540^{+1.435}_{-0.908}$	$18.540^{+4.088}_{-5.979}$	$43.808^{+2.723}_{-3.975}$	$45.609^{+4.511}_{-1.977}$	$423.582^{+40.219}_{-32.834}$
	0.40-0.60	$17.817^{+2.002}_{-0.970}$	$17.817^{+4.926}_{-6.050}$	$40.915^{+3.041}_{-1.285}$	$45.745^{+3.955}_{-1.836}$	$391.697^{+12.738}_{-18.202}$
	0.60-0.80	$17.673^{+1.610}_{-0.470}$	$17.673^{+4.837}_{-5.536}$	$40.465^{+3.052}_{-1.049}$	$45.314^{+3.281}_{-2.590}$	$406.960^{+31.075}_{-36.088}$
	0.80-1.00	$17.568^{+1.678}_{-0.985}$	$17.568^{+4.265}_{-5.581}$	$41.465^{+2.866}_{-2.152}$	$45.861^{+3.668}_{-4.758}$	$382.262^{+29.492}_{-25.539}$
	1.00-1.20	$17.656^{+1.336}_{-1.440}$	$17.656^{+3.540}_{-4.275}$	$41.429^{+3.025}_{-4.367}$	$44.111^{+4.715}_{-2.727}$	$352.295^{+37.220}_{-38.258}$
	1.20-1.40	$16.896^{+1.603}_{-0.961}$	$16.896^{+2.785}_{-4.598}$	$40.395^{+3.805}_{-4.576}$	$43.059^{+4.211}_{-2.098}$	$367.097^{+26.837}_{-29.381}$
	1.40-1.60	$15.692^{+1.915}_{-1.292}$	$15.692^{+3.888}_{-5.189}$	$36.933^{+3.118}_{-0.700}$	$41.998^{+2.463}_{-2.773}$	$375.596^{+18.533}_{-9.653}$
	1.60-1.85	$18.697^{+1.789}_{-0.894}$	$18.697^{+3.766}_{-5.455}$	$44.069^{+4.365}_{-1.117}$	$48.059^{+4.343}_{-2.353}$	$486.075^{+53.426}_{-49.430}$
	1.85-2.10	$17.709^{+2.299}_{-2.177}$	$17.709^{+3.371}_{-3.310}$	$42.851^{+4.286}_{-4.819}$	$46.526^{+4.504}_{-2.058}$	$451.967^{+31.650}_{-31.833}$
	2.10-2.40	$18.011^{+1.914}_{-2.041}$	$18.011^{+4.812}_{-6.515}$	$46.504^{+4.023}_{-2.810}$	$51.119^{+4.283}_{-1.564}$	$517.525^{+32.474}_{-26.687}$

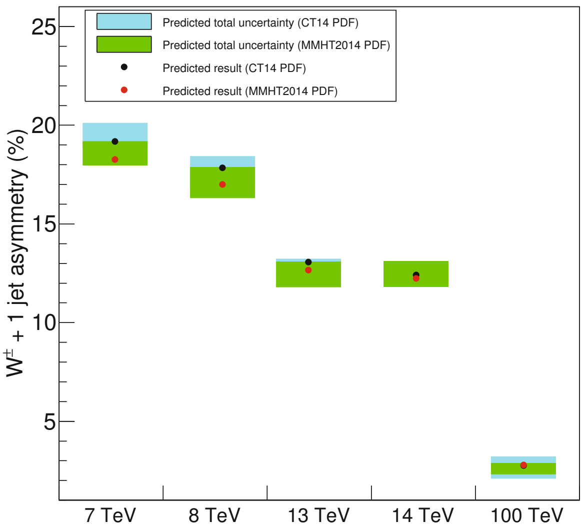


Fig. 3. (Color online) $W^{\pm}+1$ jet asymmetry at various center-of-mass energies.

We calculate the asymmetry between $W^{+}+1$ jet and $W^{-}+1$ jet events by using Eq. (1) with the NLO QCD predictions given in Table 1. Figure 3 shows the $W^{\pm}+1$ jet asymmetries at $\sqrt{s}$ = 7, 8, 13, 14 and 100 TeV. As can be seen, the asymmetry decreases when the center-of-mass energy increases. The numerical results for the $W^{\pm}+1$ jet asymmetry are given in Table 2. Using these results, we find that the asymmetry decreases by about 35% (CT14 PDF) and 32% (MMHT2014 PDF) from 7 TeV to 14 TeV. Similarly, it decreases by about 78% (CT14 PDF) and 77% (MMHT2014 PDF) from 14 TeV to 100 TeV. As shown in the Table, the asymmetry between the W^{+}+1 jet and the W^{-}+1 jet at $\sqrt{s}$ = 100 TeV is 2.8%, which is extremely low. This shows that numbers of W^{+}+1 jet and W^{-}+1 jet events at $\sqrt{s}$ = 100 TeV will be very close to each other.

Because we consider leptonic decays of $W^{\pm}$ bosons, the energy may be carried away by neutrinos. Because of this, differential QCD predictions for the $W^{\pm}+1$ jet give a better estimate and a more realistic result for the future hadron colliders. Due to this, we calculated the differential NLO QCD predictions for the W^{+}+1 jet and the W^{-}+1 jet as functions of the lepton η. The predicted results for the $W^{\pm}+1$ jet as a function of the lepton η are given in Tables 3 and 4. Using the results in these Tables, we plot NLO QCD predictions for the $W^{\pm}+1$ jet at various center-of-mass energies in Fig. 4. As can be seen in the figure, the differential NLO QCD predictions increase when the energy increases from 7 TeV to 100 TeV. Using the NLO QCD predictions that are given in Tables 3 and 4 in Eq. (1), we calculate the asymmetry between the $W^{+}+1$ jet and the $W^{-}+1$ jet as a function of the lepton η. The numerical results for this

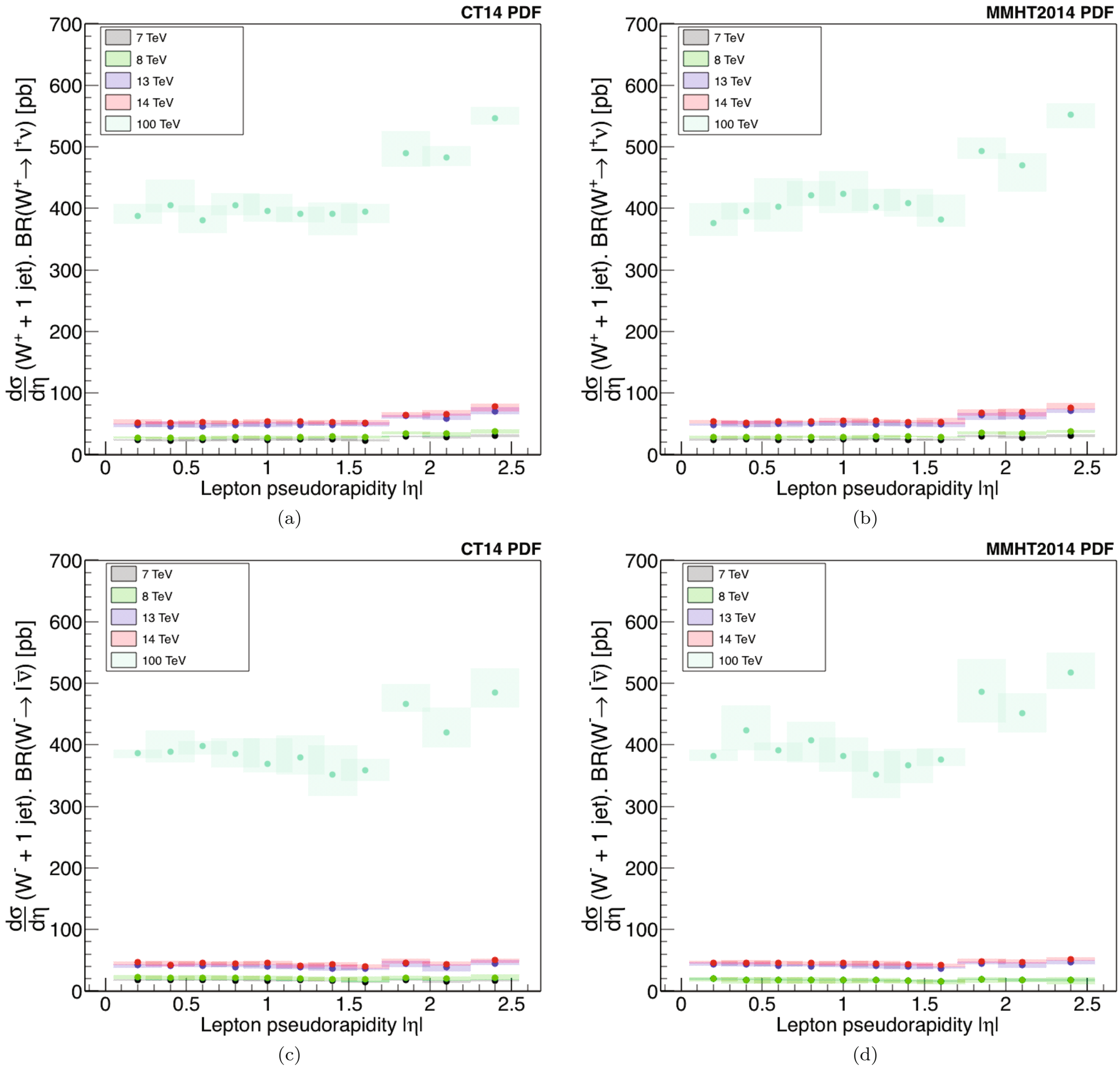


Fig. 4. (Color online) $W^+ + 1$ jet and $W^- + 1$ jet differential NLO QCD predictions as functions of the lepton pseudorapidity at various center-of-mass energies. Colored dots show the results, and shaded colors in the y direction show total systematic uncertainties.

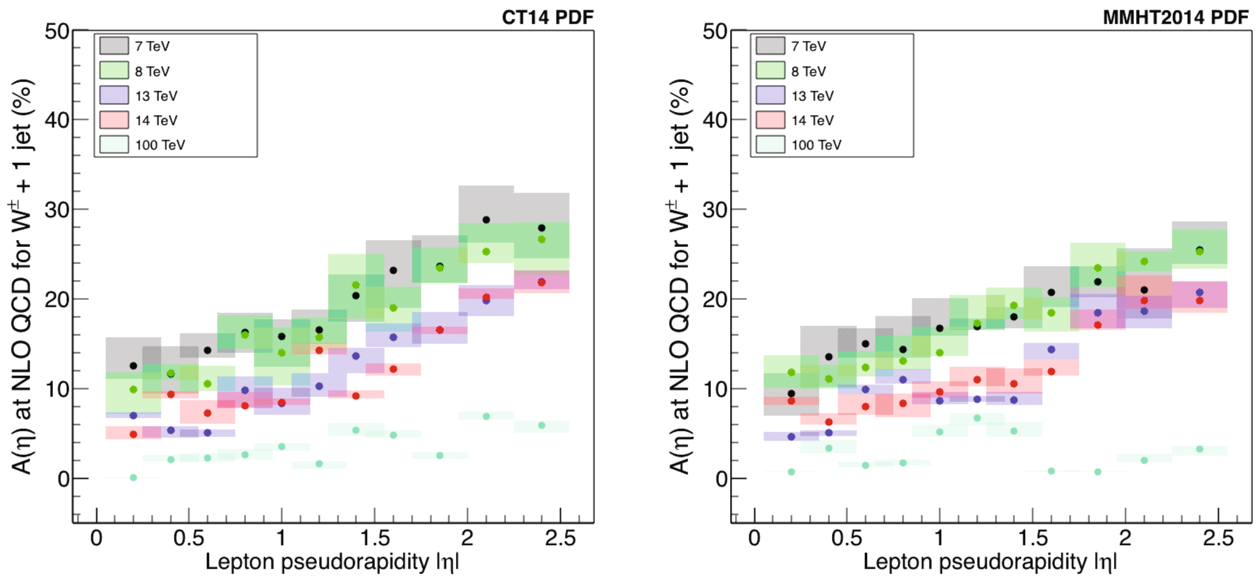
asymmetry are given in Table 5. Using the results in the Table, we plot the $W^\pm + 1$ jet lepton charge asymmetry at various center-of-mass energies as shown in Fig. 5. As can be seen in the figure, the asymmetry as a function of the lepton η decreases when the center-of-mass energy increases. The results in Table 5 show that the asymmetry between the $W^+ + 1$ jet and the $W^- + 1$ jet will range between 4.877% and 21.826% (6.219% and 19.854%) at $\sqrt{s} = 14$ TeV and between 0.083% and 6.885% (0.697% and 6.693%) at $\sqrt{s} = 100$ TeV for CT14 (MMHT2014) PDFs in the region $0.0 \leq \eta \leq 2.4$. This shows that the numbers of $W^+ + 1$ jet and $W^- + 1$ jet events will be close to each other at the next LHC run and that the probability of finding $W^+ + 1$ jet events will be almost the same as the probability of finding $W^- + 1$ jet events when the FCC will start to run at $\sqrt{s} = 100$ TeV.

III. CONCLUSIONS

In this study, the production cross section of $W^\pm$ bosons in association with one jet is presented. To obtain the results, we used the two most recent PDFs (CT14 and MMHT2014) and we compared the results

Table 5. Numerical results for $W^{\pm}+1$ jet lepton charge asymmetry (%) at various center-of-mass energies. The results are produced by using the CT14 and the MMHT2014 PDFs, and the total systematic uncertainties are calculated taking the quadratic sum of the PDF and the scale uncertainties.

PDFs	Lepton $\|\eta\|$	7 TeV (%)	8 TeV (%)	13 TeV (%)	14 TeV (%)	100 TeV (%)
CT14	0.00-0.20	$12.551^{+3.207}_{-1.462}$	$9.867^{+1.966}_{-2.744}$	$6.986^{+0.347}_{-0.250}$	$4.877^{+0.954}_{-0.508}$	$0.083^{+0.008}_{-0.003}$
	0.20-0.40	$11.629^{+3.111}_{-2.173}$	$11.720^{+1.026}_{-0.774}$	$5.339^{+0.474}_{-0.846}$	$9.311^{+0.393}_{-0.465}$	$2.084^{+0.548}_{-0.240}$
	0.40-0.60	$14.299^{+1.837}_{-0.897}$	$10.548^{+1.960}_{-0.815}$	$5.077^{+0.375}_{-0.489}$	$7.223^{+1.473}_{-1.133}$	$2.207^{+0.594}_{-0.432}$
	0.60-0.80	$16.269^{+2.146}_{-2.290}$	$15.976^{+2.186}_{-1.545}$	$9.805^{+1.499}_{-1.956}$	$8.066^{+1.573}_{-0.231}$	$2.576^{+0.663}_{-0.519}$
	0.80-1.00	$15.776^{+1.903}_{-3.299}$	$13.994^{+2.824}_{-3.688}$	$8.369^{+1.721}_{-1.265}$	$8.423^{+0.462}_{-0.272}$	$3.540^{+0.320}_{-0.475}$
	1.00-1.20	$16.528^{+2.246}_{-1.578}$	$15.760^{+2.167}_{-1.523}$	$10.215^{+1.460}_{-1.141}$	$14.292^{+0.822}_{-0.448}$	$1.563^{+0.300}_{-0.531}$
	1.20-1.40	$20.342^{+2.421}_{-2.891}$	$21.505^{+3.488}_{-3.716}$	$13.623^{+0.870}_{-1.920}$	$9.205^{+0.616}_{-0.274}$	$5.290^{+0.899}_{-0.575}$
	1.40-1.60	$23.138^{+3.379}_{-4.104}$	$19.011^{+2.319}_{-2.672}$	$15.723^{+1.510}_{-1.064}$	$12.139^{+0.630}_{-0.704}$	$4.822^{+0.543}_{-0.305}$
	1.60-1.85	$23.662^{+3.393}_{-1.812}$	$23.436^{+2.283}_{-1.698}$	$16.493^{+2.014}_{-1.543}$	$16.571^{+0.367}_{-0.518}$	$2.493^{+0.383}_{-0.331}$
	1.85-2.10	$28.825^{+3.861}_{-2.510}$	$25.281^{+3.224}_{-1.250}$	$19.828^{+1.696}_{-1.713}$	$20.196^{+0.985}_{-0.166}$	$6.885^{+0.532}_{-0.363}$
	2.10-2.40	$27.949^{+3.911}_{-3.423}$	$26.614^{+1.897}_{-3.946}$	$21.923^{+1.245}_{-0.843}$	$21.826^{+1.325}_{-1.226}$	$5.910^{+0.492}_{-0.862}$
MMHT2014	0.00-0.20	$9.444^{+2.229}_{-2.512}$	$11.807^{+1.940}_{-1.743}$	$4.652^{+0.496}_{-0.515}$	$8.657^{+0.408}_{-0.470}$	$0.697^{+0.043}_{-0.026}$
	0.20-0.40	$13.532^{+3.499}_{-3.370}$	$11.087^{+1.569}_{-1.073}$	$5.026^{+0.336}_{-0.357}$	$6.219^{+1.005}_{-0.282}$	$3.374^{+0.865}_{-0.575}$
	0.40-0.60	$14.981^{+1.762}_{-1.565}$	$12.342^{+1.805}_{-1.001}$	$9.844^{+0.619}_{-0.503}$	$8.004^{+1.358}_{-0.957}$	$1.455^{+0.329}_{-0.234}$
	0.60-0.80	$14.325^{+3.736}_{-0.841}$	$13.067^{+2.804}_{-1.031}$	$10.975^{+1.201}_{-0.433}$	$8.320^{+1.131}_{-1.549}$	$1.732^{+0.367}_{-0.288}$
	0.80-1.00	$16.682^{+3.419}_{-0.760}$	$14.031^{+2.861}_{-0.378}$	$8.653^{+0.974}_{-0.380}$	$9.625^{+1.158}_{-0.635}$	$5.112^{+0.823}_{-0.489}$
	1.00-1.20	$16.903^{+0.936}_{-0.402}$	$17.270^{+3.217}_{-0.630}$	$8.812^{+0.335}_{-0.266}$	$10.983^{+1.487}_{-0.762}$	$6.693^{+0.552}_{-0.802}$
	1.20-1.40	$18.016^{+1.062}_{-1.262}$	$19.307^{+1.934}_{-1.600}$	$8.737^{+0.856}_{-0.583}$	$10.502^{+1.790}_{-1.098}$	$5.280^{+0.939}_{-0.646}$
	1.40-1.60	$20.693^{+2.971}_{-1.601}$	$18.492^{+1.666}_{-2.096}$	$14.382^{+0.653}_{-1.108}$	$11.861^{+1.366}_{-0.419}$	$0.756^{+0.087}_{-0.048}$
	1.60-1.85	$21.935^{+1.730}_{-1.724}$	$23.427^{+2.875}_{-2.055}$	$18.472^{+2.051}_{-1.757}$	$17.039^{+1.782}_{-0.522}$	$0.717^{+0.093}_{-0.050}$
	1.85-2.10	$20.974^{+4.623}_{-3.180}$	$24.197^{+1.105}_{-1.101}$	$18.666^{+1.665}_{-1.982}$	$19.771^{+2.877}_{-0.892}$	$2.005^{+0.687}_{-0.223}$
	2.10-2.40	$25.428^{+3.176}_{-1.476}$	$25.274^{+2.451}_{-1.926}$	$20.691^{+1.350}_{-1.674}$	$19.854^{+2.080}_{-1.380}$	$3.283^{+0.323}_{-0.765}$



(a) (b)

Fig. 5. (Color online) $W^{\pm}+1$ jet lepton charge asymmetry at various center-of-mass energies. Colored dots show the results, and shaded colors in the y direction show total systematic uncertainties. A(η) on the y axis is the lepton charge asymmetry as a function of the lepton η.

at $\sqrt{s}$ = 7 TeV with the available experimental data to check the consistency of the PDFs and the selection criteria that are used for the leptons. In addition, we confirmed the consistency of NLO QCD corrections with the experimental data by this comparison. After this comparison, we obtain NLO QCD predictions for the

$W^+ + 1$ jet and the $W^- + 1$ jet at $\sqrt{s} = 7$, 8, 13, 14 and 100 TeV. By using these predictions, we calculate the ratio and the asymmetry between $W^+ + 1$ jet and $W^- + 1$ jet events. The results show that the asymmetry is decreasing when the center-of-mass energy is increasing. That means the difference between $W^+ + 1$ jet and $W^- + 1$ jet events will decrease for higher energy collisions. Because we only consider the leptonic decay of $W^\pm$ bosons for the physical process of this study, the energy may be carried away by the neutrinos. Because of this, we take differential QCD predictions for $W^\pm + 1$ jet events as a function of the lepton η into account. Then, we calculate the lepton charge asymmetry for $W^+ + 1$ jet and $W^- + 1$ jet events as a function of lepton η for the region $0.0 \leq |\eta| \leq 2.4$. The results show that NLO QCD predictions for the $W^\pm + 1$ jet as a function of lepton η are increasing from 7 to 100 TeV center-of-mass energies for each η region. However, the asymmetry between the $W^+ + 1$ jet and the $W^- + 1$ jet is decreasing when the center-of-mass energy is increasing. For LHC level energies (7 to 14 TeV), a notable asymmetry exists between $W^+ + 1$ jet and $W^- + 1$ jet events. However, the asymmetry between $W^+ + 1$ jet and $W^- + 1$ jet events is negligable for the FCC pp collision energy, $\sqrt{s} = 100$ TeV. This shows that the probability of finding $W^+ + 1$ jet events is higher than the probability of finding $W^- + 1$ jet events at LHC-level energies even though the difference between them is decreasing at energies from 7 to 14 TeV. However, they will be very close to each other at FCC pp collision energy.

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