Turkish Journal of Physics

http://journals.tubitak.gov.tr/physics/

Research Article

Turk J Phys
(2018) 42: 737 – 741
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doi:10.3906/fiz-1808-7

A phenomenological calculation for W^+W^- diboson production for the Large Hadron Collider and Future Circular Collider

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Received: 03.08.2018 • **Accepted/Published Online:** 02.11.2018 • **Final Version:** 14.12.2018

Abstract: The Large Hadron Collider (LHC) at CERN has been designed to collide beams of protons at 7, 8, 13, and 14 TeV center-of-mass energies and a new hadron collider called the Future Circular Collider (FCC), which is larger and more energetic than the LHC, is being planned for the near future. The maximum planned energy for FCC is 100 TeV center-of-mass energy. In this regard, we present the leading order and next-to-leading order cross-section predictions of two simultaneously produced opposite-sign W bosons at 7, 8, 13, 14, and 100 TeV center-of-mass energies by using the MCFM MC generator. The results are obtained by CT14, MMHT2014, and MSTW2008 parton distribution functions. Finally, the advantage of increasing collision energy at hadron colliders is discussed by comparing the amount of data recorded at different center-of-mass energies for the $pp \to W^+W^-$ process.

Key words: W boson, cross-sections, QCD, Large Hadron Collider, Future Circular Collider

1. Introduction

Hadron colliders are large accelerators designed for the discovery of new particles and the observation of theoretically available particles. They become tools of discovery at the highest mass energy limit [1]. Since the best way for studying untested physics is to use higher collision energies, the high energy physics community has designed and is planning to design higher energy particle colliders.

Today's biggest and most powerful hadron collider, the Large Hadron Collider (LHC), is the prominent example of hadron colliders. Proton-proton (pp) collisions were successfully performed at 7 and 8 TeV center-of-mass energies by the LHC during 2010 and 2012. After successfully analyzing the recorded data, the LHC groups, CMS and ATLAS, reported the observation of the Higgs boson and the LHC opened a new era in particle physics with this discovery [2,3]. However, there are still many open questions that cannot be answered by the standard model (SM) [4] and the theories beyond the SM. Higher collision energies will lead to the discovery of new particles and answer many open questions in the field. Because of this, the center-of-mass energy at the LHC will be increased gradually, causing a more intense luminosity. The current data at the LHC are being taken at $\sqrt{s} = 13$ TeV and it will reach its maximum planned energy of $\sqrt{s} = 14$ TeV after being upgraded in 2019 [5]. A new and more energetic hadron collider, the Future Circular Collider (FCC), is under consideration for the post LHC-era with a center-of-mass energy of 100 TeV, which is almost one order of magnitude higher than the LHC's energy [6].

In higher energy hadron colliders, a larger cross-section is obtained with less data compared to lower

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energy colliders. In this study, we calculated how much data would be obtained with the predicted cross-sections from the 7 to 100 TeV energy range for the physical process $pp \rightarrow W^+W^-$. Because this channel provides an important test for $WW\gamma$ and WWZ channels, this study is very important for the SM of particle physics [7].

2. $\mathbf{W^+W^-}$ at $\sqrt{s}$= 14 and 100 TeV in pp collisions

Cross-section predictions of W^+W^- boson pairs are very important in particle physics due to their contribution to the testing of the SM. In this study, we only consider leading order (LO) and next-to-leading order (NLO) QCD predictions of W^+W^- boson pairs. Compared to LO QCD, NLO QCD provides better modeling for expected data at higher energies. We therefore generate LO and NLO QCD predictions of two simultaneously produced opposite-sign W bosons by using the MCFM MC program [8]. For these predictions, three commonly used PDFs, CT14 [9], MMHT2014 [10], and MSTW2008 [11], are used. The MSTW2008 PDF was previously shown to be a more advanced version of the previously used PDF sets such as MRST. Then, including various new data at the LHC, MMHT2014 PDFs were obtained from the same basic framework as MSTW2008. The CT14 PDF was designed as the next generation of the CT10 PDF, which was previously used by the HERA and Tevatron experiments. All three PDFs (MSTW2008, MMHT2014, and CT14) can be used in LHC analysis since they include various data processes at the LHC. In our previous studies, we confirmed the consistency of these PDFs with various LHC datasets [12,13]. The Table shows the obtained QCD results for the process $pp \rightarrow W^+W^-$ from 7 to 100 TeV for these different PDFs. Here, the LO correction is used with LO PDFs and NLO correction is used with LO, NLO, and next-to-next-to-leading (NNLO) PDFs. The systematic uncertainties in the Table are calculated by the sum of PDF and scale uncertainties in quadrature. As shown in the Table,

Table. LO and NLO QCD predictions for $pp \rightarrow W^+W^-$ from 7 to 100 TeV. The results are obtained by CT14, MMHT2014, and MSTW2008 PDFs.

PDF	TeV	LO QCD LO PDF	NLO QCD LO PDF	NLO QCD NLO PDF	NLO QCD NNLO PDF
CT14	7	$30.234^{+1.958}_{-1.890}$	$44.948^{+2.502}_{-2.710}$	$46.294^{+2.350}_{-1.200}$	$47.048^{+2.408}_{-1.198}$
	8	$36.310^{+2.572}_{-2.429}$	$54.626^{+3.448}_{-2.603}$	$56.889^{+1.755}_{-1.639}$	$57.966^{+1.731}_{-1.547}$
	13	$67.702^{+6.701}_{-5.215}$	$108.037^{+5.508}_{-4.831}$	$111.312^{+3.660}_{-2.872}$	$113.906^{+4.532}_{-2.732}$
	14	$74.464^{+6.466}_{-6.676}$	$119.524^{+6.371}_{-4.458}$	$123.459^{+2.717}_{-2.764}$	$126.147^{+4.043}_{-3.491}$
	100	$662.362^{+133.800}_{-124.589}$	$1354.556^{+21.523}_{-27.707}$	$1265.142^{+51.202}_{-31.738}$	$1284.262^{+60.551}_{-33.612}$
MMHT2014	7	$28.504^{+3.703}_{-1.952}$	$43.244^{+3.603}_{-2.649}$	$46.934^{+2.050}_{-1.767}$	$47.692^{+2.939}_{-1.643}$
	8	$34.328^{+2.192}_{-1.946}$	$52.970^{+4.685}_{-2.736}$	$57.427^{+1.929}_{-1.729}$	$58.390^{+3.010}_{-1.642}$
	13	$64.654^{+4.840}_{-5.965}$	$105.534^{+8.154}_{-6.712}$	$112.594^{+3.744}_{-3.039}$	$115.072^{+3.312}_{-3.283}$
	14	$70.595^{+6.498}_{-6.907}$	$117.688^{+7.457}_{-7.027}$	$124.592^{+3.864}_{-2.682}$	$126.856^{+5.002}_{-1.859}$
	100	$679.909^{+132.084}_{-136.385}$	$1417.300^{+22.248}_{-19.755}$	$1290.867^{+56.101}_{-39.437}$	$1281.029^{+58.038}_{-38.953}$
MSTW2008	7	$29.673^{+2.770}_{-1.224}$	$45.021^{+3.363}_{-2.330}$	$46.924^{+2.685}_{-1.514}$	$47.530^{+2.760}_{-1.433}$
	8	$35.653^{+3.427}_{-1.526}$	$54.478^{+4.462}_{-2.154}$	$57.511^{+2.523}_{-1.828}$	$58.146^{+2.473}_{-1.944}$
	13	$67.807^{+6.344}_{-5.451}$	$111.110^{+7.920}_{-5.805}$	$112.521^{+3.821}_{-2.811}$	$113.897^{+4.781}_{-2.621}$
	14	$74.666^{+6.436}_{-6.844}$	$123.209^{+8.354}_{-6.977}$	$124.574^{+4.204}_{-2.363}$	$126.729^{+4.934}_{-3.277}$
	100	$752.927^{+140.789}_{-145.573}$	$1555.823^{+22.392}_{-27.494}$	$1273.022^{+38.363}_{-48.906}$	$1275.741^{+20.878}_{-61.273}$

the obtained QCD predictions by CT14, MMHT2014, and MSTW2008 PDFs are consistent with each other between the error limits. Because of this, any of these PDFs can be selected as a reference PDF for the rest of this study.

We first select the MMHT2104 PDF as a reference PDF and compare LO, NLO, and NNLO PDF results at a range from 7 to 100 TeV, as shown in Figure 1. As can be seen in the figure, the cross-section increases when the center-of-mass energy increases. From 7 to 14 TeV, (NLO QCD + NNLO PDF) > (NLO QCD + NLO PDF) > (NLO QCD + LO PDF). However, from 14 to 100 TeV, it is exactly the opposite. We further compare NLO QCD results that are obtained by NNLO of CT14, MMHT2014, and MSTW2008 PDFs as shown in Figure 2. As can be seen in the figure, the results for three different PDFs are consistent with each other both for LHC level energies (from 7 to 14 TeV) and FCC pp collision energy (100 TeV).

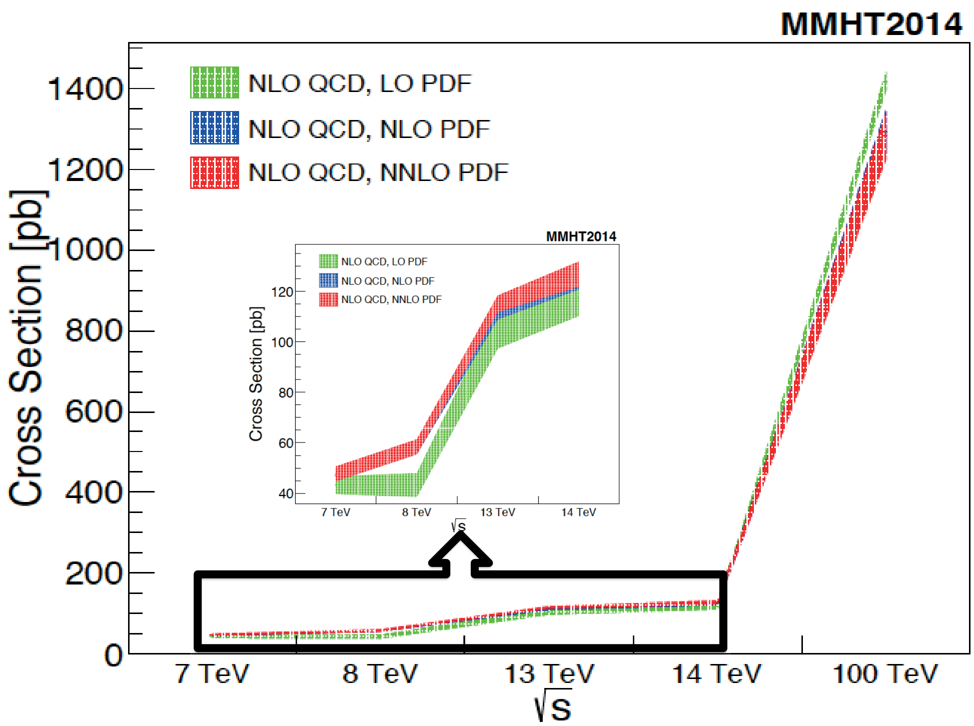

Figure 1. The comparison of LO, NLO, and NNLO MMHT2014 PDFs at NLO QCD.

Once the collision energy of protons is increased, the obtained number of events from the data increases. In other words, if we have an equal amount of 7 and 8 TeV data, the number of W^+W^- events at $\sqrt{s}$ = 8 TeV will be greater than at $\sqrt{s}$ = 7 TeV. The reason why this situation occurs is that the cross-section of particles increases with the increase of the collision energy. The mathematical statement of this fact can be given as follows:

$$\text{Number of events} = \text{Cross-section} \times \text{luminosity}$$

Luminosity (L) is the ratio of the number of events detected (N) in a certain time to the interaction cross-section (σ). If we take this one further step, we can set the following equation:

$$\sigma_{7\,TeV} L_{7\,TeV} = \sigma_{8\,TeV} L_{8\,TeV} \rightarrow L_{8\,TeV} = \frac{\sigma_{7\,TeV}}{\sigma_{8\,TeV}} L_{7\,TeV}$$

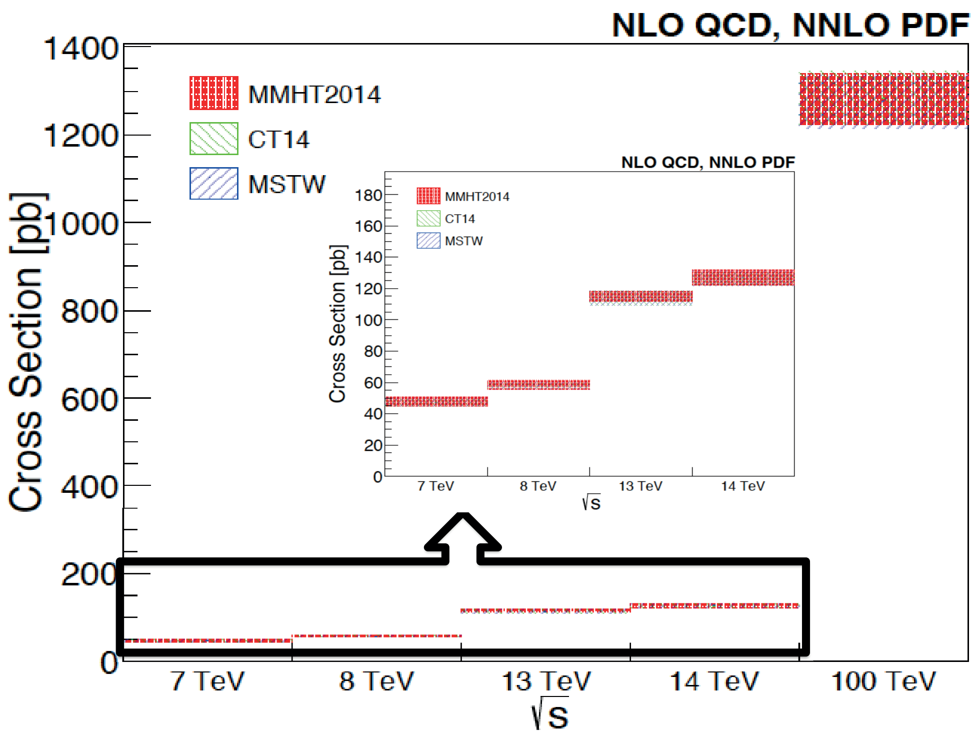

Figure 2. The comparison of MMHT2014, CT14, and MSTW2008 PDF models for LHC energies (from $\sqrt{s}=$ 7 to 14 TeV) and FCC pp collision energy ($\sqrt{s}=$ 100 TeV).

Based on this statement, we calculate the required data amount at $\sqrt{s}=$ 8, 13, 14, and 100 TeV to satisfy 7 TeV statistics.

$$L_{8\,TeV}=\frac{\sigma_{7\,TeV}}{\sigma_{8\,TeV}}L_{7\,TeV}=\frac{47.692}{58.390}5.55=4.53fb^{-1}$$

$$L_{13\,TeV}=\frac{\sigma_{7\,TeV}}{\sigma_{13\,TeV}}L_{7\,TeV}=\frac{47.692}{115.072}5.55=2.3fb^{-1}$$

$$L_{14\,TeV}=\frac{\sigma_{7\,TeV}}{\sigma_{14\,TeV}}L_{7\,TeV}=\frac{47.692}{126.856}5.55=2.08fb^{-1}$$

$$L_{100\,TeV}=\frac{\sigma_{7\,TeV}}{\sigma_{100\,TeV}}L_{7\,TeV}=\frac{47.692}{1281.029}5.55=0.21fb^{-1}$$

Here, the cross-section numbers are used from MMHT2014 NNLO PDF NLO QCD predictions as given in the Table and the data amount recorded at CMS is 5.55 fb^{-1}. Figure 3 illustrates the numbers of required data at $\sqrt{s}=$ 8, 13, 14, and 100 TeV to reach the same statistics with 7 TeV data. As can be clearly seen, the required data amount decreases with the increase of the collision energy for W^+W^- events.

3. Conclusion

This study presents LO and NLO QCD predictions of two simultaneous and opposite-sign W bosons (W^+W^-). The LO QCD predictions are obtained by LO PDFs of CT14, MMHT2014, and MSTW2008 PDF models and NLO QCD corrections are obtained by LO, NLO, and NNLO PDFs of CT14, MMHT2014, and MSTW2008

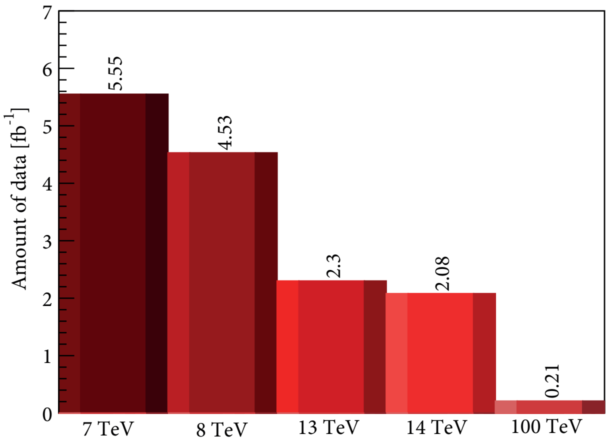

Figure 3. Required data at $\sqrt{s} =$ 8, 13, 14, and 100 TeV to reach the same statistics with $\sqrt{s} = 7$ TeV data.

PDF models. First, we showed the consistency of the PDFs (CT14, MMHT2014, and MSTW2008), comparing the cross-section results that are obtained by these PDFs at a range from 7 to 100 TeV. Then MMHT2014 PDF was taken as a reference PDF model and LO, NLO, and NNLO corrections of the PDF were compared for LHC energies (from 7 to 14 TeV) and FCC pp collision energy (100 TeV). The results showed that the cross-section of W^+W^- events increases at all corrections when the collision energy increases. With this result, we understand that the higher center-of-mass energies will provide larger amounts of data with the same statistics compared to lower center-of-mass energies. Because of this, we calculated the amount of required data at $\sqrt{s} =$ 8, 13, 14, and 100 TeV to obtain the same statistics with 7 TeV data. The results show that the required amount of data is 2.08 fb^{-1} at $\sqrt{s} =$ 14 TeV and 0.21 fb^{-1} at $\sqrt{s} =$ 100 TeV to reach same the statistics with $\sqrt{s} =$ 7 TeV data.

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