FULL NLO MASSIVE GAUGE BOSON PAIR PRODUCTION AT THE LHC

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Electroweak gauge boson pair production is a very important process at the LHC as it probes the non-abelian structure of electroweak interactions and is a background process for many searches. We present full next–to–leading order predictions for the production cross sections and distributions of on-shell massive gauge boson pair production in the Standard Model, including both QCD and electroweak corrections. The hierarchy between the $ZZ$, $WW$ and $WZ$ channels, observed in the transverse momentum distributions, will be analyzed. We will also present a comparison with experimental data for the total cross sections including a study of the theoretical uncertainties.

1 Introduction

Since the beginning of LHC operations in 2010, there have been numerous gauge boson pair measurements at 7 and 8 TeV, in particular looking for signs of new physics via anomalous couplings\textsuperscript{1,2}. It is indeed crucial to test the non-abelian structure of the electroweak (EW) sector of the Standard Model (SM) as new physics effects could modify this structure. When added to the fact that gauge boson pair production is an important background in the search for the Higgs boson, this triggers precise predictions on the theoretical side.

The QCD next–to–leading order (NLO) corrections have been known for decades\textsuperscript{3,4,5}. A full next–to–next–to–leading order (NNLO) QCD calculation is not yet available but some approximate results have been released in the past few months, for example in the $WW$ production\textsuperscript{6}. NLO EW corrections, known for a long time in the high energy approximation\textsuperscript{7,8,9}, have been fully calculated only recently\textsuperscript{10,11,12} including photon-quark induced processes\textsuperscript{12}.

We present full NLO predictions for the total cross sections and the differential distributions, including both QCD and EW effects. In particular the hierarchy that is observed in the $p_T$ distributions between the $ZZ$, $WW$ and $WZ$ channels is explained thanks to soft gauge boson approximation. A comparison with experimental data including theoretical uncertainties is also given. More details can be found in Ref.\textsuperscript{12}.

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that the QCD corrections are driven by the gluon-quark
is used to combine the virtual and real corrections. We also
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Overview of the calculation

The well-known QCD NLO corrections to $q\bar{q} \rightarrow VV'$ that were calculated a while ago\cite{3,4,5} have been recalculated as well as the gluon fusion channel that is formally a NNLO contribution. The NLO EW corrections include not only the virtual and real photon emission corrections to $q\bar{q}$ channels but also the photon–quark induced channels, the latter not being considered in Refs.\cite{10,11}. The NLO corrections to photon–photon initial state in the $WW$ channel were also incorporated. We used the MRST2004QED PDF set\cite{13} to account for the photon PDF. The relevant EW parameters are renormalized in the on–shell scheme.

In order to deal with infrared singularities we used dimensional regularization and mass regularization schemes. The two calculations are in excellent agreement. The Catani-Seymour dipole subtraction method\cite{14} is used to combine the virtual and real corrections. We also cross-checked the results with the phase-space slicing method\cite{15}. We performed independent calculations with the help of automated tools: the FeynArt/FormCalc\cite{16} suite to generate one-loop amplitudes. The one-loop integrals are calculated with the in-house library LoopInts, which agrees with the program LoopTools\cite{16,17}. MadGraph and HELAS routines are also used to calculate tree-level amplitudes. Further details about the calculation and the precise definitions of the various contributions discussed in the next section can be found in Ref.\cite{12}.

Hierarchy of radiative corrections

We present some selected results for the differential distributions at the LHC at 14 TeV, using the MRST2004QED PDF set and $\alpha_s(M_Z^2) = 0.1190$. The factorization and renormalization scales are both equal to $M_V + M_{VV'}$. We apply no cuts at the level of the on-shell $W^\pm$ and $Z$, since these will decay. It can be seen in Fig. 1 that the QCD corrections are driven by the gluon-quark induced processes (dotted blue lines) with a large correction at high $p_T$ driven by leading-logarithmic terms proportional to $\alpha_s \log^2(M^2_T/p_T^2)$. This is explained by the large gluon PDF and soft gauge boson emission and has been noticed for quite a while\cite{4,5} but the hierarchy

\[ \delta_{ZZ}^{\text{QCD}} \simeq \frac{1}{3} \delta_{WW}^{\text{QCD}} \simeq \frac{1}{6} \delta_{W-Z}^{\text{QCD}} \] 

with $\delta_{ZZ}^{\text{QCD}} \simeq 120\%$, clearly visible on Fig. 1, was not well understood.

The same hierarchy is also observed in the EW corrections as displayed in Fig. 2 (left-handed and middle figures). This hierarchy is much more pronounced than for the QCD case, with

\[ \delta_{ZZ}^{\text{EW}} \simeq \frac{1}{90} \delta_{WW}^{\text{EW}} \simeq \frac{1}{190} \delta_{W-Z}^{\text{EW}} \] 

and $\delta_{ZZ}^{\text{EW}} \simeq 0.3\%$. The virtual Sudakov effect in the $q\bar{q} \rightarrow VV'$ is clearly visible (dashed red lines) and has been also discussed in Ref.\cite{10,11}.

The hierarchies between the $ZZ$, $WW$ and $WZ$ channels in both QCD and EW radiative corrections share some common features. They are effects of the dominant double-logarithmic terms in the gluon-quark and photon-quark induced processes, in which the non-abelian structure of the theory, the different couplings strengths and PDF effects play a role. The analytical approximations using soft gauge boson emission from a quark-gauge boson final state, presented in Ref.\cite{12}, reproduce this hierarchy even if they are off by a factor of two at $p_T \simeq 700$ GeV. It

![Figure 1: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

2 Overview of the calculation

3 Hierarchy of radiative corrections

![Figure 2: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 3: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 4: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 5: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 6: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 7: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 8: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 9: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 10: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 11: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 12: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 13: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 14: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 15: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 16: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 17: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 18: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 19: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

![Figure 20: $Z$ (left), $W^+$ (middle) and $W^-$ (right) transverse momentum distributions (in GeV) of the NLO QCD corrections (in %) in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.
Figure 2: $Z$ (left) and $W^+$ (middle) transverse momentum as well as $M_{WW}$ invariant mass (right) distributions (in GeV) of the NLO EW corrections (in %), in $\sigma(pp \rightarrow ZZ, WW, W^-Z)$, respectively.

has been checked that they coincide with the full result at much higher $p_T$, thereby validating the approximation. In the case of the EW corrections, the $\gamma q$ processes are further enhanced by a $t$-channel massive gauge boson exchange, explaining the huge enhancement of the EW corrections in the $WW$ and $WZ$ channels compared to the $ZZ$ channel. It compensates or even overcompensates the virtual Sudakov effect in the $WW$ and $WZ$ channels, making the photon-quark induced processes absolutely necessary for the full NLO EW calculation. The right-handed side of Fig. 2 shows the importance of the diphoton subprocess in the $WW$ invariant mass distribution where it is the leading EW effect.

4 Total cross sections and comparison with experimental data

We have calculated the total cross sections fully at NLO and compared with the most up-to-date ATLAS and CMS results from HEP-EPS 2013 Conference. This is an update of our previous results. In order to account for the EW corrections using modern PDFs such as the MSTw set, we rescaled our NLO QCD predictions calculated with modern sets by a factor $\delta_{\text{EW}}$ calculated with MRST2004QED including the photon PDF: $\delta_{\text{EW}} = \frac{\sigma_{\text{NLO QCD+EW}}}{\sigma_{\text{NLO QCD}}}$. Recently the NNPDF Collaboration has released a new set including also a photon PDF and we have checked at the level of the total cross section that the ratio $\delta_{\text{EW}}$ does not change significantly by trading MRST2004QED with NNPDF2.3QED.

A detailed study of the theoretical uncertainties affecting the predictions has been performed. We calculated the scale uncertainty with the factorization and renormalization scales varied in the interval $\frac{1}{2} \mu_0 \leq \mu_R = \mu_F \leq 2 \mu_0$ where the central scale is $\mu_0 = M_V + M_V$. We used the MSTw2008 90%CL set to calculate the correlated PDF+$\alpha_s$ uncertainty. The parametric uncertainties coming from the experimental errors on $M_W$ and $M_Z$ are negligible. The results are presented in Fig. 3 and are similar in the three different channels. We obtain $\delta_{\text{EW}} \approx 0.97, 1.00, 1.01$ for the $ZZ, WZ, WW$ channels respectively. The scale uncertainty amounts to $\sim +3\%/-2\%$ at 7 TeV, two times less at 33 TeV. The PDF+$\alpha_s$ uncertainty is of the order of $\pm 4\%$.

We have combined the scale and PDF+$\alpha_s$ into the overall theoretical uncertainty of the total cross section and compared with experimental data, as displayed in Fig. 4. We found a total uncertainty $\sim +7\%/-6\%$ at 7 and 8 TeV, slightly less at 33 TeV, in all three channels. The comparison with ATLAS and CMS results is good, in particular in the $ZZ$ and $WZ$ channels. In the $WW$ channel, there is a $1\sigma$ excess at 7 TeV and a $1.8\sigma$ excess at 8 TeV. As estimated in Ref. and confirmed by the results in Ref. a full NNLO calculation is not expected to account for this deviation.

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Figure 3: The scale uncertainty in $\sigma(pp \rightarrow ZZ)$ at the LHC (left) and the PDF/PDF+$\alpha_s$ uncertainty in $\sigma(pp \rightarrow WW)$ (right), in pb, as a function of the center-of-mass energy (in TeV). In the inserts deviations from the central predictions are shown.

Figure 4: The NLO QCD+EW total cross section (in pb) of the processes $pp \rightarrow ZZ$ (left), $pp \rightarrow W^+Z + W^-Z$ (middle) and $pp \rightarrow WW$ (right) at the LHC as a function of the center-of-mass energy (in TeV) including the total theoretical uncertainty. The insert shows the relative deviation from the central cross sections, and the experimental data points are also displayed on the main figures.

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1. ATLAS Collaboration, G. Aad et al., (2012), arXiv:1210.2979.
2. CMS Collaboration, S. Chatrchyan et al., Phys.Lett. B721, 190 (2013), arXiv:1301.4698.
3. J. Ohnemus, Phys.Rev. D44, 3477 (1991).
4. S. Frixione, Nucl.Phys. B410, 280 (1993).
5. J. Ohnemus, Phys.Rev. D50, 1931 (1994), hep-ph/9403331.
6. S. Dawson, I. M. Lewis, and M. Zeng, (2013), arXiv:1307.3249.
7. E. Accomando, A. Denner, and S. Pozzorini, Phys.Rev. D65, 073003 (2002), hep-ph/0110114.
8. E. Accomando, A. Denner, and A. Kaiser, Nucl.Phys. B706, 325 (2005), hep-ph/0409247.
9. E. Accomando, A. Denner, and C. Meier, Eur.Phys.J. C47, 125 (2006), hep-ph/0509234.
10. A. Bierweiler, T. Kasprzik, H. Kühn, and S. Uccirati, JHEP 1211, 093 (2012), arXiv:1208.3147.
11. A. Bierweiler, T. Kasprzik, and J. H. Kühn, (2013), arXiv:1305.5402.
12. J. Baglio, L. D. Ninh, and M. M. Weber, (2013), arXiv:1307.4331.
13. A. Martin, R. Roberts, W. Stirling, and R. Thorne, Eur.Phys.J. C39, 155 (2005), hep-ph/0411040.
14. S. Catani and M. Seymour, Nucl.Phys. B485, 291 (1997), hep-ph/9605323.
15. U. Baur, S. Keller, and D. Wackeroth, Phys.Rev. D59, 013002 (1998), hep-ph/9807417.
16. T. Hahn and M. Perez-Victoria, Comput. Phys. Commun. 118, 153 (1999).
17. G. van Oldenborgh, Comput.Phys.Commun. 66, 1 (1991).
18. A. Martin, W. Stirling, R. Thorne, and G. Watt, Eur.Phys.J. C63, 189 (2009), arXiv:0901.0002.
19. The NNPDF Collaboration, R. D. Ball et al., (2013), arXiv:1308.0598.