PROCEEDINGS OF SCIENCE

Electroweak accuracy in V-pair production at the LHC

Anastasiya Bierweiler
Karlsruhe Institute of Technology (KIT), Institut für Theoretische Teilchenphysik, D-76128 Karlsruhe, Germany
E-mail: nastya@particle.uni-karlsruhe.de

Tobias Kasprzik*
Karlsruhe Institute of Technology (KIT), Institut für Theoretische Teilchenphysik, D-76128 Karlsruhe, Germany
E-mail: kasprzik@particle.uni-karlsruhe.de

Johann H. Kühn
Karlsruhe Institute of Technology (KIT), Institut für Theoretische Teilchenphysik, D-76128 Karlsruhe, Germany
E-mail: jk@particle.uni-karlsruhe.de

Vector-boson pair production is of great phenomenological importance at the LHC. These processes will help to validate the Standard Model at highest energies, and they may also open the door for the discovery of new physics potentially showing up in subtle modifications of the non-abelian structure of weak interactions. In this letter, we present the first full $\mathscr{O}(\alpha^3)$ analysis of on-shell $W^{\pm}Z$ and Z-pair production at the LHC with all mass effects consistently included. The resulting electroweak corrections are negative, strongly increase with increasing transverse momenta, and lead to significant modifications of rapidity and angular distributions. In view of the high energies accessible at the LHC, combined with considerable event rates, our results have to be included in a proper analysis of experimental data.

TTP12-028
LPN12-089
SFB/CPP-12-59

36th International Conference of High Energy Physics,
4-11 July 2012
Melbourne, Australia

*Speaker.

PoS(ICHEP2012)078

1. Introduction

A profound understanding of vector-boson pair production processes at the LHC is desirable for various reasons. Such processes not only contribute an important irreducible background to Standard-Model (SM) Higgs production at moderate energies, but will also provide deeper insight into the physics of the weak interaction at the high-energy frontier, possibly even allowing for the discovery of BSM physics. Consequently, great effort has been made during the last years to push the theory predictions for this process class to a new level, where, besides the dominating QCD corrections, also electroweak (EW) effects have been studied extensively (see, e.g., Ref. [1] and references therein).

Extending our work on the EW effects in W-pair production at the LHC [1], we present corresponding results for on-shell $W^{\pm}Z$ and ZZ pair production in the SM. We will restrict ourselves to pair production through quark–antiquark annihilation. Since Photon–photon collisions do not contribute to WZ production (in contrast to the case of W pairs) and are of higher order for Z-pair production, they will not be discussed further. Also gluon fusion is, evidently, irrelevant for WZ production. For the case of W-pair production we have demonstrated that gluon fusion amounts to order of 5% relative to the quark–antiquark annihilation with decreasing importance for increasing transverse momenta. Gluon fusion, furthermore, does not lead to a strong modification of the angular and rapidity distributions of the W bosons. A qualitatively similar behaviour is expected for ZZ production through gluon fusion, which therefore will not be discussed further. Also QCD corrections for WZ and ZZ production are expected to be similar to those for W pairs discussed in Ref. [1] and will not be analyzed in the present paper, which, instead, will be entirely devoted to genuine EW corrections. Earlier papers for gauge-boson pair production have emphasized the drastic influence of the EW corrections on cross sections and distributions in the high-energy region [2, 3, 4], neglecting at the same time terms of order $M_{\mathrm{W}}^2/\hat{s}$. In the present paper, the full mass dependence, namely terms proportional to powers of $M_V^2/\hat{s}$, is consistently accounted for to obtain results valid in the whole energy range probed by LHC experiments. Therefore, our results are complementary to those presented in Ref. [3], where only logarithmic corrections were considered, but the leptonic decays of the vector bosons and related off-shell effects were included in a double-pole approximation. Comparing both approaches, we try to estimate the remaining theoretical uncertainties related to EW corrections in this important process class.

2. Details of the calculation

At the LHC, WW, $W^{\pm}Z$ and ZZ production is, at the lowest order $\mathcal{O}(\alpha^2)$, induced by the partonic processes

$$q\,\bar{q} \to \mathrm{W}^-\mathrm{W}^+ \quad (q = \mathrm{u,d,s,c,b})\,, \tag{2.1a}$$

$$\mathrm{u}_i\bar{\mathrm{d}}_j \to \mathrm{W}^+\mathrm{Z}\,, \quad \bar{\mathrm{u}}_i\mathrm{d}_j \to \mathrm{W}^-\mathrm{Z} \quad (i = 1,2;\ j = 1,2,3)\,, \tag{2.1b}$$

$$q\,\bar{q} \to \mathrm{ZZ}\,, \tag{2.1c}$$

where the hadronic results are obtained by convoluting the partonic cross sections with appropriately chosen PDFs and summing incoherently over all contributing channels. To allow for consistent predictions with full $\mathcal{O}(\alpha^3)$ accuracy, virtual EW corrections, as well as real corrections due to photon radiation have to be considered. The evaluation of the radiative corrections is based on the well-established `FeynArts/FormCalc/LoopTools` setup [5, 6, 7, 8, 9], the WW process has been independently cross-checked by a setup based on `QGraf` [10] and `Form` [11]. To considerably reduce the computational effort, light quark masses are neglected whenever possible. However, soft and collinear singularities occurring in intermediate steps of the calculation are regularized by small quark masses m_q and an infinitesimal photon mass λ, generating unphysical $\ln m_q$ and $\ln\lambda$ terms. To allow for a numerically-stable evaluation of those infrared-divergent parts of the cross sections related to real radiation, the phase-space slicing method is adopted. Finally, adding real and virtual contributions, the regulator-mass dependence drops out in any properly defined physical result. The input parameters to be specified in Section 3 are renormalized in a modified on-shell scheme [12], where the Fermi constant G_μ is used instead of $\alpha(0)$ to effectively account for universal corrections induced by the running of $\alpha(\mu)$ to the weak scale [13].

3. Input and setup

For the computation presented here the same setup as specified in Ref. [1] is applied. We use the following SM input parameters for the numerical analysis,

$$\begin{aligned} G_\mu &= 1.16637\times 10^{-5}\,\text{GeV}^{-2}, \\ M_\text{W} &= 80.398\,\text{GeV}, & M_\text{Z} &= 91.1876\,\text{GeV}, \\ M_\text{H} &= 125\,\text{GeV}, & m_\text{t} &= 173.4\,\text{GeV}, \end{aligned} \tag{3.1}$$

which are taken from Ref. [14]. In the on-shell scheme applied in our computation, the weak mixing angle $\cos^2\theta_\text{w} = M_\text{W}^2/M_\text{Z}^2$ is a derived quantity. For the computation of the processes (2.1) and the corresponding EW radiative corrections, we use the MSTW2008LO PDF set [15] in the LHAPDF setup [16]. In order to consistently include $\mathcal{O}(\alpha)$ corrections, in particular real radiation with the resulting collinear singularities, PDFs in principle should take these QED effects into account. Such a PDF analysis has been performed in Ref. [18], and the $\mathcal{O}(\alpha)$ effects are known to be small, as far as their effect on the quark distribution is concerned [17]. In addition, the currently available PDFs incorporating $\mathcal{O}(\alpha)$ corrections [18] include QCD effects at NLO, whereas our EW analysis is LO with respect to perturbative QCD only. For these reasons, the MSTW2008LO set is used as our default choice for the quark-induced processes. The renormalization and factorization scales are always identified, our default scale choice being the phase-space dependent average of the vector-boson transverse masses

$$\mu_\text{R} = \mu_\text{F} = \overline{m_\text{T}} = \frac{1}{2}\left(\sqrt{M_{V_1}^2 + p_{\text{T},V_1}^2} + \sqrt{M_{V_2}^2 + p_{\text{T},V_2}^2}\right). \tag{3.2}$$

A similar scale choice was taken in Ref. [3] for the computation of the EW corrections to four-lepton production at the LHC. In our default setup, we require a minimum transverse momentum and a maximum rapidity for the final-state vector bosons,

$$p_{\text{T},V_i} > 15\,\text{GeV}, \quad |y_{V_i}| < 2.5, \tag{3.3}$$

to exclude events where the bosons are emitted collinearly to the initial-state partons.

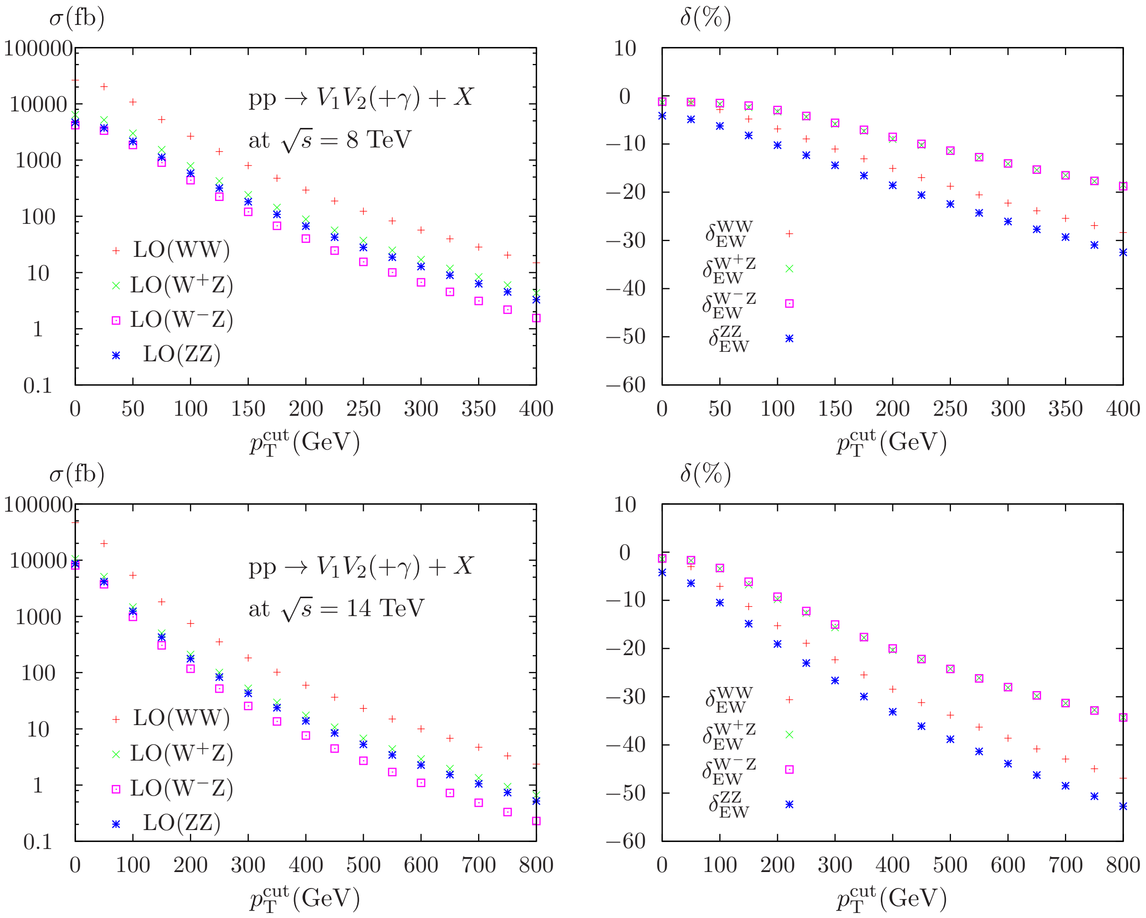

Figure 1: Leading-order cross sections (left) and corresponding relative EW corrections (right) to WW, $W^{\pm}Z$ and ZZ production at the LHC for different cuts on the vector-boson p_T.

4. Numerical results

In this section we present integrated cross sections for WW, $W^{\pm}Z$ and ZZ production at the CERN LHC with center-of-mass (CM) energies of $\sqrt{s} = 8$ TeV (LHC8) and $\sqrt{s} = 14$ TeV (LHC14), respectively. Results for the corresponding full EW corrections to the processes $pp \to W^{\pm}Z + X$ and $pp \to ZZ + X$ are shown for the first time, while the contributions for W-pair production have already been presented in Ref. [1] and are listed only for comparison. In the following, relative corrections δ are defined through $\sigma_{NLO} = (1+\delta) \times \sigma_{LO}$.

Figure 1 shows integrated cross sections and the respective EW corrections for different cut values on the boson transverse momenta at LHC8 and LHC14, respectively, where the plot range has been adapted to the CM energy available. The p_T-dependent relative EW corrections are largest for ZZ production and similar to those in WW production, for WZ production they are significantly smaller. At LHC8, for ZZ production corrections of -30% are observed for $p_T^{cut} = 400$ GeV, rising to -50% at $p_T^{cut} = 800$ GeV for $\sqrt{s} = 14$ TeV. As expected, the relative corrections to W^+Z production coincide with those to W^-Z production at the percent level as a consequence of the identical corresponding unpolarized partonic cross sections.

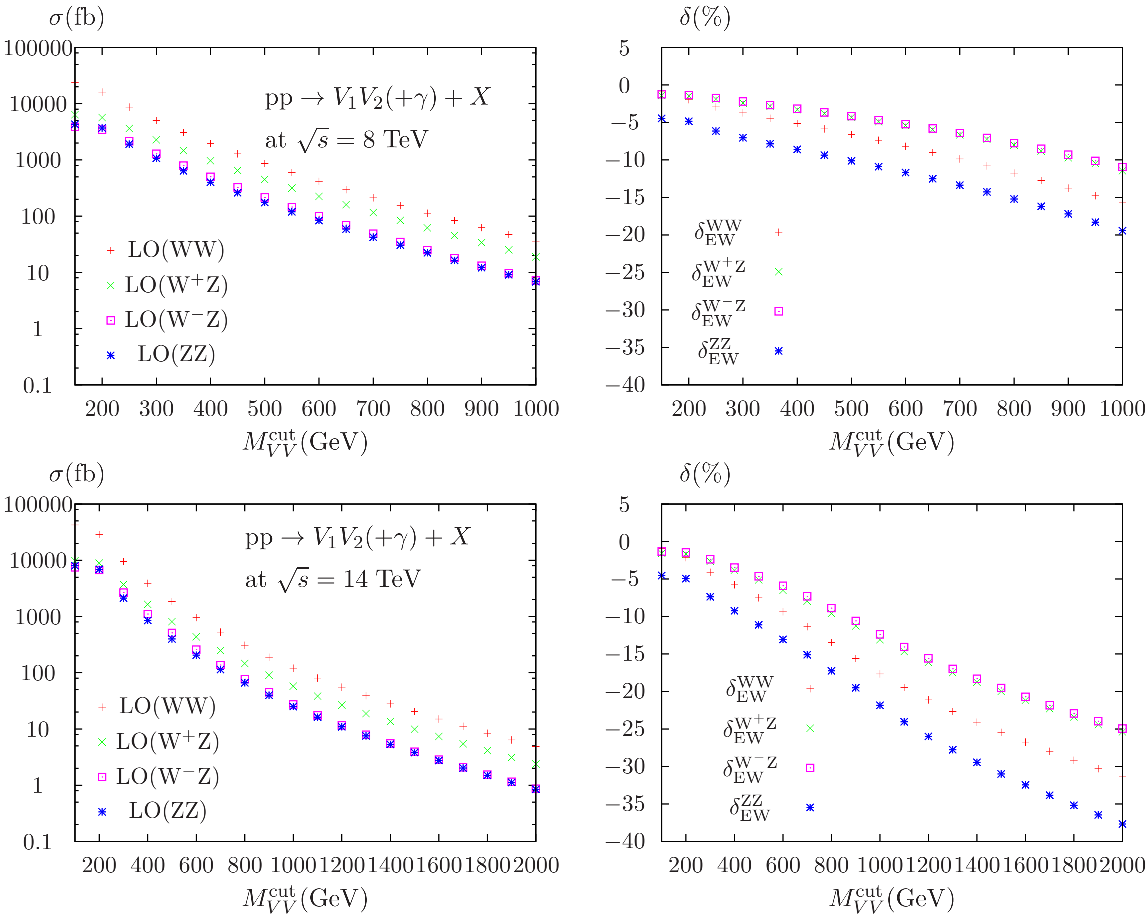

Figure 2: Leading-order cross sections (left) and corresponding relative EW corrections (right) to WW, $W^{\pm}Z$ and ZZ production at the LHC for different cuts on the vector-boson invariant mass.

In Figure 2, integrated cross sections are presented for different values of the minimal invariant masses of the final-state boson pair at LHC8 and LHC14, respectively. Again, one observes negative EW corrections rising with the energy. However, the relative corrections are smaller than in the $p_{\mathrm{T}}^{\mathrm{cut}}$ scenario, since vector-boson pair production at high invariant masses is dominated by collinear emission at low p_{T} (corresponding to small $\hat{t}$) which is not affected by large negative Sudakov logarithms.

Finally, we compare our results ($\delta_{\mathrm{EW}}^{\mathrm{ZZ}}$) to those given in Table 3 of Ref. [3] ($\delta_{\mathrm{EW}}^{\mathrm{ZZ,ADK}}$), which were obtained in the high-energy limit. We observe very good agreement in the whole energy range considered if we employ the additional constraint $|\Delta y_{\mathrm{ZZ}}| < 3$ on the rapidity gap of the Z bosons to explicitly enforce Sudakov kinematics (i.e. $\hat{s}, \hat{t}, \hat{u} \gg M_{\mathrm{Z}}^2$). For instance, we find $\delta_{\mathrm{EW}}^{\mathrm{ZZ}} = -28.5\%$, to be compared with $\delta_{\mathrm{EW}}^{\mathrm{ZZ,ADK}} = -28.1\%$ for $M_{\mathrm{ZZ}} > 1000$ GeV. As expected, EW corrections to ZZ production in the Sudakov regime are exhaustively described by logarithmic weak corrections, and mass effects do not play a significant role. Surprisingly, also off-shell effects and final-state photon radiation, both included in Ref. [3], as well as LHC acceptance cuts, do not seem to noticeably affect the relative EW corrections after the Z reconstruction has been performed.

5. Conclusions

Extending our work on W-pair production at hadron colliders, we have computed the full EW corrections to on-shell $W^{\pm}Z$ and ZZ production at the LHC. At high transverse momenta, the relative corrections are found to be largest in the ZZ case and moderate for WZ production. in case of ZZ production at the LHC we find perfect agreement with older results obtained in the high-energy approximation. In the future, a more detailed discussion of the presented results will follow [19], including predictions for differential cross sections.

Acknowledgements

This work has been supported by "Strukturiertes Promotionskolleg Elementarteilchen- und Astroteilchenphysik", SFB TR9 "Computational and Particle Physics" and BMBF Contract 05HT4VKATI3.

References

[1] A. Bierweiler, T. Kasprzik, J.H. Kühn, S. Uccirati, arXiv:1208.3147 [hep-ph].

[2] E. Accomando, A. Denner and S. Pozzorini, Phys. Rev. D **65** (2002) 073003 [hep-ph/0110114].

[3] E. Accomando, A. Denner and A. Kaiser, Nucl. Phys. B **706** (2005) 325 [hep-ph/0409247].

[4] E. Accomando, A. Denner, C. Meier, Eur. Phys. J. **C47** (2006) 125-146. [hep-ph/0509234].

[5] J. Küblbeck, M. Böhm and A. Denner, Comput. Phys. Commun. **60** (1990) 165;
H. Eck and J. Küblbeck, *Guide to FeynArts 1.0*, University of Würzburg, 1992.

[6] T. Hahn, Comput. Phys. Commun. **140** (2001) 418 [hep-ph/0012260].

[7] T. Hahn and M. Pérez-Victoria, Comput. Phys. Commun. **118** (1999) 153 [hep-ph/9807565].

[8] T. Hahn, C. Schappacher, Comput. Phys. Commun. **143** (2002) 54-68. [hep-ph/0105349].

[9] G. J. van Oldenborgh, J. A. M. Vermaseren, Z. Phys. **C46** (1990) 425-438.

[10] Nogueira, P. Automatic Feynman graph generation. J. Comput. Phys., **vol. 105 (1993)** pp. 279–289.

[11] J. A. M. Vermaseren, math-ph/0010025.

[12] A. Denner, Fortsch. Phys. **41** (1993) 307-420. [arXiv:0709.1075 [hep-ph]].

[13] S. Dittmaier, M. Krämer, 1, Phys. Rev. **D65** (2002) 073007. [hep-ph/0109062].

[14] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667** (2008) 1.

[15] A. D. Martin *et al.*, Eur. Phys. J. **C63**, (2009) 189-285. [arXiv:0901.0002 [hep-ph]].

[16] M. R. Whalley, D. Bourilkov and R. C. Group, in *HERA and the LHC*, eds. A. de Roeck and H. Jung (CERN-2005-014, Geneva, 2005), p. 575, hep-ph/0508110.

[17] M. Roth and S. Weinzierl, Phys. Lett. B **590** (2004) 190 [hep-ph/0403200].

[18] A. D. Martin, R. G. Roberts, W. J. Stirling, R. S. Thorne, Eur. Phys. J. **C39** (2005) 155-161. [hep-ph/0411040].

[19] A. Bierweiler, T. Kasprzik, J.H. Kühn, in preparation.