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Vector-boson pair production at the LHC to $\mathcal{O}(\alpha^3)$ accuracy

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Abstract: Building on earlier work on electroweak corrections to W-pair production, the first calculation of the full electroweak one-loop corrections to on-shell ZZ, $\mathrm{W}^{\pm}\mathrm{Z}$ and $\gamma\gamma$ production at hadron colliders is presented, explicitly taking into account the full vector-boson mass dependence. As a consequence, our results are valid in the whole energy range probed by LHC experiments. Until now, the electroweak corrections have only been known in dedicated high-energy approximations limited to a specific kinematic regime, in particular requiring high boson transverse momenta. Therefore, our results comprise an important and so far missing ingredient to improve on the theory predictions for these fundamental Standard-Model benchmark processes also at intermediate energies and small scattering angles, where actually the bulk of events is located. In case of Z-pair production we have also included the leptonic decays and the associated weak corrections in our analysis. For this particular channel, corrections of about -4% are observed even close to the production threshold. For hard scattering processes with momentum transfers of several hundred GeV one finds large negative corrections which may amount to several tens of percent and lead to significant distortions of transverse-momentum and rapidity distributions.

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Contents

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. [**?**] and references therein).

Extending our work on EW effects in W-pair production at the LHC , we present[1] corresponding results for on-shell $W^{\pm}Z$, ZZ and $\gamma\gamma$ pair production in the SM. We will restrict ourselves to pair production through quark–antiquark annihilation. Photon–photon collisions do not contribute to WZ production (in contrast to the case of W pairs), are of higher order for Z-pair and γ-pair production and 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 and $\gamma\gamma$ production through gluon fusion, which therefore will not be discussed further. Also QCD corrections for WZ and ZZ/$\gamma\gamma$ production are expected to be similar to those for W pairs discussed in ref. [**?**] and will not be analyzed in the present paper, which, instead, will be entirely devoted to genuine EW corrections.

Earlier papers have emphasized the drastic influence of the EW corrections on cross sections and distributions in the high-p_{T} region. However, only pair-production channels with at least one massive gauge boson were considered [**? ? ?**] while a phenomenological analysis of the $\gamma\gamma$ channel is still missing. To close this gap, the first computation of the full EW corrections to photon-pair hadroproduction is presented in this work. Moreover, the above papers neglect terms of order $M_V^2/\hat{s}$. Also this issue will be addressed in the present paper. All the processes under consideration are affected by large corrections, amounting to several tens, sometimes up to fifty percent. (This fact has even triggered studies of next-to-next-to-leading logarithmic corrections for W-pair production at the LHC [**?**], which, however, where not extended to Z-pair or WZ production.) Nevertheless, significant differences are observed between the different final states, as far as the size of the corrections

[1] Preliminary results of this investigation have been presented in ref. [**?**].

is concerned. We, furthermore, investigate rapidity distributions, both for small and for large invariant masses of the diboson system and observe significant distortions that could be misinterpreted as anomalous triple-boson couplings. 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, in particular for V-pairs produced near threshold[2] or at low transverse momenta. Therefore, our results are complementary to those presented in refs. [? ?], 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.

To investigate this aspect in more detail, also the combined production and decay process for Z pairs is calculated, including NLO corrections. To simplify the discussion, only the four-lepton state $\mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$ is considered. Excellent agreement with the results of Accomando et al. is observed in the region where the high-energy approximation employed in ref. [?] is valid. We, furthermore, investigate the contributions from the different helicity configurations including NLO corrections and observe that the transverse polarization not only dominates completely at large p_{T}, it is also the most prominent configuration as far as the total cross section is concerned.

In addition, we also study the impact of real gauge-boson radiation leading to three-boson final states. In principle, these configurations might compensate some of the negative contributions from virtual corrections, in practice, however, real radiation is significantly smaller than virtual contributions.

2 Details of the calculation

2.1 Contributions at leading order

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

$$
\begin{aligned}
q\bar{q} &\to \mathrm{W}^-\mathrm{W}^+ \quad (q=\mathrm{u},\mathrm{d},\mathrm{s},\mathrm{c},\mathrm{b})\,, && (2.1\mathrm{a})\\
\mathrm{u}_i\bar{\mathrm{d}}_j &\to \mathrm{W}^+\mathrm{Z}\,, \quad \bar{\mathrm{u}}_i\mathrm{d}_j \to \mathrm{W}^-\mathrm{Z} \quad (i=1,2;\ j=1,2,3)\,, && (2.1\mathrm{b})\\
q\bar{q} &\to \mathrm{ZZ}\,, && (2.1\mathrm{c})\\
q\bar{q} &\to \gamma\gamma\,. && (2.1\mathrm{d})
\end{aligned}
$$

where the corresponding LO partonic cross sections are evaluated according to

$$
\hat{\sigma}_{\mathrm{LO}}^{q\bar{q}'\to V_1V_2} = \frac{1}{2\hat{s}N_{q\bar{q}'}}\int \mathrm{d}\Phi(V_1V_2)\sum_{\mathrm{col}}\sum_{\mathrm{spin}}\sum_{\mathrm{pol}}|\mathcal{M}_0^{q\bar{q}'\to V_1V_2}|^2\,, \tag{2.2}
$$

with the tree-level helicity amplitudes $\mathcal{M}_0^{q\bar{q}'\to V_1V_2}$, the two-particle phase-space measure $\mathrm{d}\Phi(V_1V_2)$ and the averaging factor $N_{q\bar{q}'}=36$. It is understood that for ZZ and $\gamma\gamma$ produc-

[2] Although EW corrections are expected to be small at low energies, for Z-pair production a shift of about −4% is observed even close to threshold, whereas the corresponding corrections are below 1 percent in the remaining cases.

tion the cross sections receive an additional symmetry factor of 1/2. Note that one finds $\int \mathrm{d}\xi_V\,(\mathrm{d}\sigma^{\mathrm{pp}\to VV}/\mathrm{d}\xi_V) = 2\sigma^{\mathrm{pp}\to VV}$ for $\xi = p_{\mathrm{T}}$ or $\xi = y$ for these particular channels.

2.2 Electroweak radiative corrections

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 [? ? ? ? ?], and all processes have been independently cross-checked by a setup based on `QGraf` [?] and `Form` [?].

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(IR)-divergent parts of the cross sections related to real radiation, the phase-space slicing method is adopted as detailed in ref. [?] for mass regularization. Finally, adding real and virtual contributions, the regulator-mass dependence drops out in any properly defined physical result. However, in complete analogy to QCD, residual collinear singularities attributed to initial-state (IS) radiation survive and have to be absorbed in renormalized PDFs in a proper factorization procedure adding the collinear counterterm defined by eq. (3.16) of ref. [?]. In the present computation, we apply the $\overline{\mathrm{MS}}$ factorization scheme for the QED factorization.

The input parameters to be specified in Section 3.1 are renormalized in a modified on-shell scheme [?], 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 [?]. However, for the computation of the $\gamma\gamma$ channel, $\alpha(0)$ is used as input for the EW coupling, since the corresponding radiative corrections do not receive universal contributions related to the running of the coupling constant. According to the previous considerations, the partonic cross section at $\mathcal{O}(\alpha^3)$ accuracy may be written as

$$\hat{\sigma}_{\mathrm{NLO}}^{q\bar{q}'\to V_1V_2(\gamma)} = \hat{\sigma}_{\mathrm{LO}}^{q\bar{q}'\to V_1V_2} + \hat{\sigma}_{\mathrm{LO}}^{q\bar{q}'\to V_1V_2\gamma} + \hat{\sigma}_{\mathrm{virt}}^{q\bar{q}'\to V_1V_2}\,, \tag{2.3}$$

where the different NLO contributions are given by

$$\hat{\sigma}_{\mathrm{LO}}^{q\bar{q}'\to V_1V_2\gamma} = \frac{1}{2\hat{s}N_{q\bar{q}'}}\int \mathrm{d}\Phi(V_1V_2\gamma)\sum_{\mathrm{col}}\sum_{\mathrm{spin}}\sum_{\mathrm{pol}}|\mathcal{M}_0^{q\bar{q}'\to V_1V_2\gamma}|^2\,, \tag{2.4}$$

$$\hat{\sigma}_{\mathrm{virt}}^{q\bar{q}'\to V_1V_2} = \frac{1}{2\hat{s}N_{q\bar{q}'}}\int \mathrm{d}\Phi(V_1V_2)\sum_{\mathrm{col}}\sum_{\mathrm{spin}}\sum_{\mathrm{pol}}2\,\mathrm{Re}\left\{(\mathcal{M}_0^{q\bar{q}'\to V_1V_2})^*\,\mathcal{M}_1^{q\bar{q}'\to V_1V_2}\right\}\,, \tag{2.5}$$

with the properly renormalized one-loop amplitudes $\mathcal{M}_1^{q\bar{q}'\to V_1V_2}$. The hadronic results at the LHC are then obtained by convoluting the partonic cross sections with appropriately chosen PDFs and summing incoherently over all contributing channels,

$$\sigma_{\mathrm{NLO}}^{\mathrm{pp}\to V_1V_2(\gamma)} = \int_{\tau_0}^1 \mathrm{d}\tau\int_\tau^1\frac{\mathrm{d}x_b}{x_b}\sum_{q,\bar{q}'} f_{q/\mathrm{p}}(x_a,\mu_{\mathrm{F}}^2)f_{\bar{q}'/\mathrm{p}}(x_b,\mu_{\mathrm{F}}^2)\,\hat{\sigma}_{\mathrm{NLO}}^{q\bar{q}'\to V_1V_2(\gamma)}(\tau s,\mu_{\mathrm{F}}^2)\,, \tag{2.6}$$

where the hadronic CM energy s is related to $\hat{s}$ via $\hat{s} = \tau s$, with $\tau = x_a x_b$. The kinematic production threshold of a vector-boson pair in the final state is reflected by the choice of the lower integration boundary $\tau_0 = (M_{V_1} + M_{V_2})^2/s$, corresponding to a minimal partonic CM energy of $\hat{s}_0 = \tau_0 s$. The factorization scale μ_F enters the partonic cross section through the redefinition of the PDFs in the QED factorization procedure described above.

2.3 Radiation of massive gauge bosons

As in ref. [**?**] we study the effect of massive boson radiation on the massive vector-boson pair production cross section, where the additional massive boson is treated fully exclusively in the event selection to allow for a robust estimate of the corresponding phenomenological effects. This is motivated by the possibility that the logarithmically enhanced positive contributions from the radiation of an additional soft or collinear massive gauge boson might compensate the negative virtual corrections, as has been argued recently for Z+jet production [**?**].

To be specific, we take into account the following partonic channels, where the corresponding partonic cross sections have to be computed according to

$$\hat{\sigma}_\mathrm{LO}^{q\bar{q}'\to V_1V_2V_3} = \frac{1}{2\hat{s}N_{q\bar{q}'}} \int \mathrm{d}\Phi(V_1V_2V_3) \sum_\mathrm{col}\sum_\mathrm{spin}\sum_\mathrm{pol} |\mathcal{M}_0^{q\bar{q}'\to V_1V_2V_3}|^2 \,. \tag{2.7}$$

In case of ZZ pair production, the contributions from the processes

$$\begin{aligned} q\bar{q} &\to \mathrm{ZZZ}\,, \\ q\bar{q}' &\to \mathrm{ZZW}^\pm \end{aligned} \tag{2.8}$$

have to be considered, where the two Zs with highest p_T have to fulfill the LO cuts to be specified in section 3.1, while the third massive particle is treated inclusively. To assess the real-radiation effects in $\mathrm{W}^\pm\mathrm{Z}$ production, we compute the cross sections for

$$\begin{aligned} q\bar{q} &\to \mathrm{W}^\pm Z\mathrm{W}^\mp\,, \\ q\bar{q}' &\to \mathrm{W}^\pm\mathrm{ZZ}\,. \end{aligned} \tag{2.9}$$

In the first case the $\mathrm{W}^\mp$ is treated inclusively, in the second case the Z with lowest p_T. In section **??**, numerical results will be presented for massive boson radiation normalized to the LO $q\bar{q}$-induced pair-production channels,

$$\delta_{V_1V_2V_3} = \sigma_\mathrm{LO}^{\mathrm{pp}\to V_1V_2V_3}/\sigma_\mathrm{LO}^{\mathrm{pp}\to V_1V_2} - 1\,, \tag{2.10}$$

as well as for hard photon radiation (i.e. $p_{\mathrm{T},\gamma} > 15$ GeV, $|y_\gamma| < 2.5$),

$$\delta_{V_1V_2\gamma} = \sigma_\mathrm{LO}^{\mathrm{pp}\to V_1V_2\gamma}/\sigma_\mathrm{LO}^{\mathrm{pp}\to V_1V_2} - 1\,. \tag{2.11}$$

3 Numerical results

In this section, for the first time the full EW corrections to Z- and γ-pair production as well as $\mathrm{W}^\pm\mathrm{Z}$ production are presented. Most of the discussion is focussed on LHC8 and

LHC14. For completeness, we also show cross sections for these processes at the Tevatron with a CM energy of $\sqrt{s} = 1.96$ TeV. The corresponding results for W-pair production originally presented in ref. [?] are given for comparison. In the following, the relative effects $\delta_{\rm EW}$ of the EW corrections are defined as

$$\delta_{\rm EW} = \frac{\sigma_{\rm NLO}^{\rm pp\to V_1V_2(\gamma)}}{\sigma_{\rm LO}^{\rm pp\to V_1V_2}} - 1\,. \tag{3.1}$$

3.1 Input and setup

For the computation presented here the same setup as specified in ref. [?] is applied. To be specific, we use the following SM input parameters for the numerical analysis,

$$\begin{aligned} G_\mu &= 1.16637\times 10^{-5}\ {\rm GeV}^{-2}, & & \\ M_{\rm W} &= 80.398\ {\rm GeV}, & M_{\rm Z} &= 91.1876\ {\rm GeV}, \\ M_{\rm H} &= 125\ {\rm GeV}, & M_{\rm t} &= 173.4\ {\rm GeV}\,. \end{aligned} \tag{3.2}$$

For the evaluation of all tree-level contributions we assume a block-diagonal CKM matrix with

$$|V_{\rm ud}| = |V_{\rm cs}| = 0.974\,, \quad |V_{\rm us}| = |V_{\rm cd}| = \sqrt{1-|V_{\rm ud}|^2}\,. \tag{3.3}$$

Ignoring, furthermore, quark masses within the first two families, both tree-level and one-loop predictions for ZZ and $\gamma\gamma$ are equivalent to those without quark mixing. As a consequence of the smallness of the bottom-quark PDF the tree-level contribution from $\rm b\bar{b}$ annihilation to ZZ or $\gamma\gamma$ is small to start with. In addition, the non-diagonal CKM elements involving b quarks are small, and the ansatz (3.3) is well justified. As a consequence, $\rm b\bar{b}\to ZZ$ or $\gamma\gamma$ can safely be handled within the third family.[3] The situation is different for the WZ channel. In this case, the interplay between CKM angles and PDFs leads to a shift of the tree-level prediction of about one percent. For the radiative corrections the CKM matrix can, therefore, still be set to unity.

In the on-shell scheme applied in our computation, the weak mixing angle $\cos^2\theta_{\rm w} = M_{\rm W}^2/M_{\rm Z}^2$ is a derived quantity. For the computation of the processes (2.1) and the corresponding EW radiative corrections, we use the MSTW2008LO PDF set [?] in the LHAPDF setup [?]. 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. [?], and the $\mathcal{O}(\alpha)$ effects are known to be small, as far as their effect on the quark distribution is concerned [?]. In addition, the currently available PDFs incorporating $\mathcal{O}(\alpha)$ corrections [?] 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. Our default choice for the factorization scale is the average of the vector-boson transverse masses

$$\mu_{\rm F} = \overline{m_{\rm T}} = \frac{1}{2}\left(\sqrt{M_{V_1}^2 + p_{{\rm T},V_1}^2} + \sqrt{M_{V_2}^2 + p_{{\rm T},V_2}^2}\right)\,. \tag{3.4}$$

[3] We point out that a non-vanishing top-quark mass is consistently included in the computation of the one-loop contributions discussed in this paper.