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Next-to-leading order electroweak corrections to $\mathbf{pp} \to \mu^+\mu^-\mathbf{e}^+\mathbf{e}^- + \mathbf{X}$ at the LHC

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We present a calculation of next-to-leading-order electroweak corrections to off-shell ZZ production, i.e. $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$. All resonant and non-resonant contributions are included, with finite-width effects treated in the complex-mass scheme. The matrix elements are implemented into Monte Carlo programs allowing for the evaluation of arbitrary differential cross sections. We present integrated cross sections for the LHC at an energy of 13 TeV as well as differential distributions for realistic acceptance cuts applied to the final-state leptons.

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1. Introduction

After the discovery of the Higgs boson at the LHC Run I, one of the major tasks of LHC Run II is the precise measurement of the properties of the Higgs boson and the other particles of the Standard Model (SM). One class of processes particularly relevant to test the electroweak sector of the SM is gauge-boson pair production, in particular due to its sensitivity to the triple gauge-boson couplings. Moreover, this type of reactions constitutes a background to Higgs-boson production with subsequent decay into vector-boson pairs and to searches for new physics such as heavy vector bosons. In this proceedings contribution we focus on the production of Z-boson pairs with subsequent decays into four different charged leptons.

The $\mu^+\mu^-\mathrm{e}^+\mathrm{e}^-$ final state has also been used at Run I both by ATLAS and CMS to measure the cross section of Z-boson pair production [1, 2, 3] and to derive limits on anomalous triple gauge-boson couplings [4, 5]. So far, all these measurements are in agreement with the predictions of the SM.

The main focus of theoretical predictions for Z-boson-pair-production measurements in the past were QCD corrections which have been continuously improved over the last two decades. After increasing the complexity at next-to-leading order (NLO) from stable Z bosons to off-shell effects including leptonic decays [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16], there are meanwhile even NNLO QCD corrections available [17, 18]. A lot of progress has also been made matching the fixed-order predictions to a parton shower [19, 20, 21, 22, 23, 24].

At the required level of theoretical accuracy, the inclusion of electroweak (EW) corrections becomes crucial: It is well known that EW corrections may reach several tens of percent via the enhancement of Sudakov logarithms in high-energy tails of distributions [25, 26, 27, 28, 29, 30] or via radiative tails due to photon emission near resonances or thresholds. Logarithmic EW corrections to gauge-boson pair production at the LHC have been studied in Ref. [31]. Later, complete NLO EW corrections have been provided for all vector-boson-pair-production processes with stable gauge bosons [32, 33]. NLO EW corrections including leptonic decays, however, are so far only available for W-pair production in the double-pole approximation [34]. Here, we present a calculation of the complete NLO EW corrections to the process $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$, including all non-resonant contributions.

This proceedings contribution is organised as follows: Details of the calculational methods are given in Section 2, the numerical setup is presented in Section 3, and phenomenological results are discussed in Section 4. Our conclusions are given in Section 5.

2. Calculational methods

Initial states: Our definition of the leading-order (LO) contribution at $O(\alpha^4)$ includes the quark–anti-quark channels for $N_f = 5$ light flavours

$$q\bar{q} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-, \qquad q \in \{\mathrm{u},\mathrm{d},\mathrm{c},\mathrm{s},\mathrm{b}\}. \tag{2.1}$$

Sample diagrams for the quark–anti-quark annihilation channels are shown in Fig. 1. In general, the $\mu^+\mu^-\mathrm{e}^+\mathrm{e}^-$ production process receives contributions with two, one, or no potentially resonant Z-boson propagators. The NLO EW corrections at $O(\alpha^5)$ include the virtual corrections to the hard

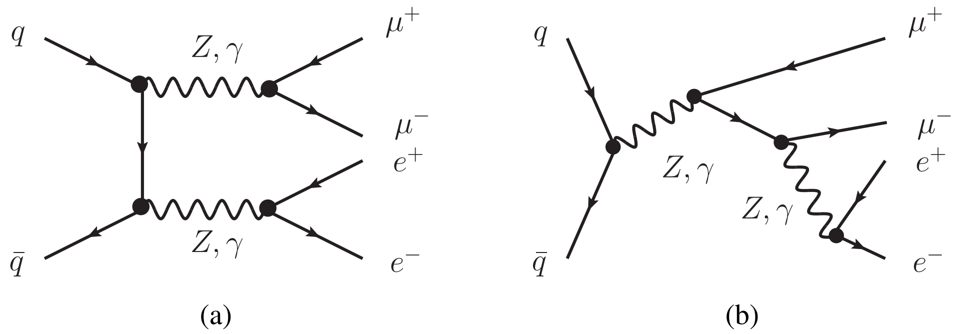


Figure 1: Sample tree-level diagrams contributing at $O(\alpha^4)$ to the quark–anti-quark annihilation channel.

process (2.1), and the corresponding real corrections with an additional photon in the final state. As we explain in Section 4, it is justified to exclude contributions with photons in the initial state.

Virtual corrections: The virtual corrections at $O(\alpha^5)$ to the quark–anti-quark annihilation channels are computed taking into account the full set of diagrams. As examples, two hexagon diagrams are shown in Fig. 2. We employ the complex-mass scheme [35, 36] for the proper handling of unstable internal particles.

Real corrections: The real corrections to the quark–anti-quark channels contain all tree-level contributions to the channels

$$q\bar{q} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + \gamma, \qquad q \in \{\mathrm{u},\mathrm{d},\mathrm{c},\mathrm{s},\mathrm{b}\}, \tag{2.2}$$

where the additional final-state photon is not necessarily resolved in the detector. The photon can be radiated off the initial-state quarks or off the final-state leptons, as schematically illustrated in Fig. 3. The Bremsstrahlung cross section diverges if the radiated photon becomes either soft or collinear to an external fermion. For soft- and collinear-safe observables, the collinear final-state singularities and the soft singularities cancel exactly the soft and collinear divergences appearing in the virtual corrections. The collinear initial-state singularities cancel after factorisation into redefined parton distribution functions. For our computation we use the DIS factorisation scheme

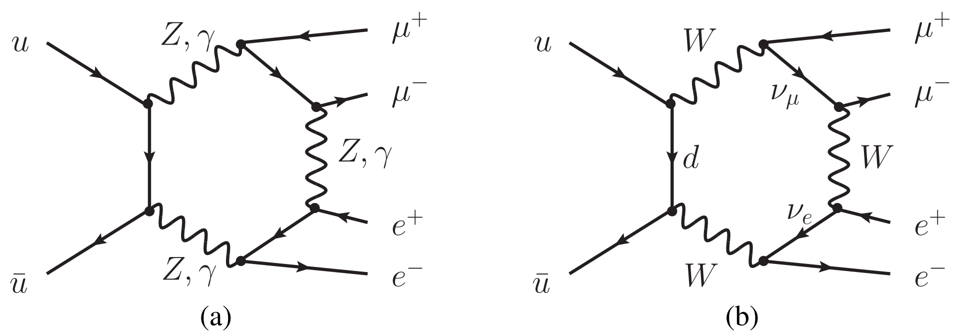


Figure 2: Sample diagrams for the virtual EW corrections.

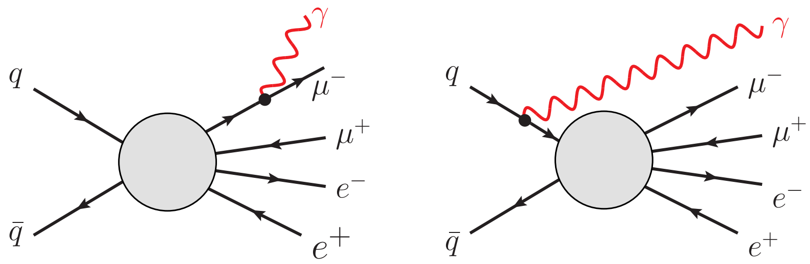


Figure 3: Real photon radiation from the final-state leptons and from the initial-state quarks

following Ref. [37]. In order to isolate the soft/collinear singularities in the phase-space integration, we have applied the dipole subtraction method. We have implemented both dimensional regularisation [38] and mass regularisation [39], and find excellent agreement between both approaches.

Phase-space integration and checks of the calculation: Two independent calculations have been performed using different methods and independent codes. One calculation is based on algebraic methods developed for four-fermion production in electron–positron collisions [35]. In the other calculation, all matrix elements are directly evaluated numerically with the matrix element generator RECOLA [40, 41]. The loop integrals are evaluated with the two independent branches of the tensor-integral library COLLIER [42] which is mainly based on the results of Refs. [43, 44, 45]. The phase-space integration is carried out with two different multi-channel Monte Carlo integrators, developed from the original implementations of Refs. [46, 47]. Additional checks have been performed employing the Mathematica package POLE [48].

3. Numerical setup

Input parameters: For the values of the on-shell masses and widths of the gauge bosons we use

$$M_\mathrm{Z}^\mathrm{os} = 91.1876\,\mathrm{GeV}\,, \quad \Gamma_\mathrm{Z}^\mathrm{os} = 2.4952\,\mathrm{GeV}\,, \quad M_\mathrm{W}^\mathrm{os} = 80.385\,\mathrm{GeV}\,, \quad \Gamma_\mathrm{W}^\mathrm{os} = 2.085\,\mathrm{GeV}\,. \tag{3.1}$$

In the complex-mass scheme, the on-shell masses need to be converted to pole masses according to

$$M_i = \frac{M_i^\mathrm{os}}{\sqrt{1+(\Gamma_i^\mathrm{os}/M_i^\mathrm{os})^2}}, \qquad \Gamma_i = \frac{\Gamma_i^\mathrm{os}}{\sqrt{1+(\Gamma_i^\mathrm{os}/M_i^\mathrm{os})^2}}, \qquad i = \mathrm{W,Z}. \tag{3.2}$$

Since we do not encounter resonant Higgs or top propagators in our calculation, we can safely neglect their widths and use

$$M_\mathrm{H} = 125\,\mathrm{GeV}, \qquad m_\mathrm{t} = 173\,\mathrm{GeV}. \tag{3.3}$$

All charged leptons $\mathrm{e}^\pm$, $\mu^\pm$, $\tau^\pm$ and the light quarks u, d, c, s, b are treated as massless throughout the calculation. For the electromagnetic coupling α, we use the G_μ-scheme where the coupling is defined from the muon decay constant, $G_\mu = 1.16637 \times 10^{-5}\,\mathrm{GeV}^{-2}$, and the pole masses of the W and Z bosons according to

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_\mathrm{W}^2 \left(1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right). \tag{3.4}$$

This definition absorbs the running of α up to the electroweak scale and some universal constants which depend on the top-quark mass. Both the renormalisation scale μ_R and the factorisation scale μ_F are set to the Z-boson mass, $\mu_\mathrm{R} = \mu_\mathrm{F} = M_\mathrm{Z}$. For the parton distribution functions (PDFs) we use the `NNPDF23_nlo_as_0118_qed` parameterisation [49].

Acceptance cuts: For our analysis, we have chosen an inclusive setup inspired by the ATLAS collaboration [1]. For each charged lepton, we require a minimum transverse momentum and a maximum rapidity,

$$p_\mathrm{T}(\ell_i) > 15\,\mathrm{GeV}, \qquad |y(\ell_i)| < 2.5. \tag{3.5}$$

Furthermore, for each pair of charged leptons we demand a minimum separation in the rapidity–azimuthal-angle plane,

$$\Delta R(\ell_i, \ell_j) = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} > 0.2\,. \tag{3.6}$$

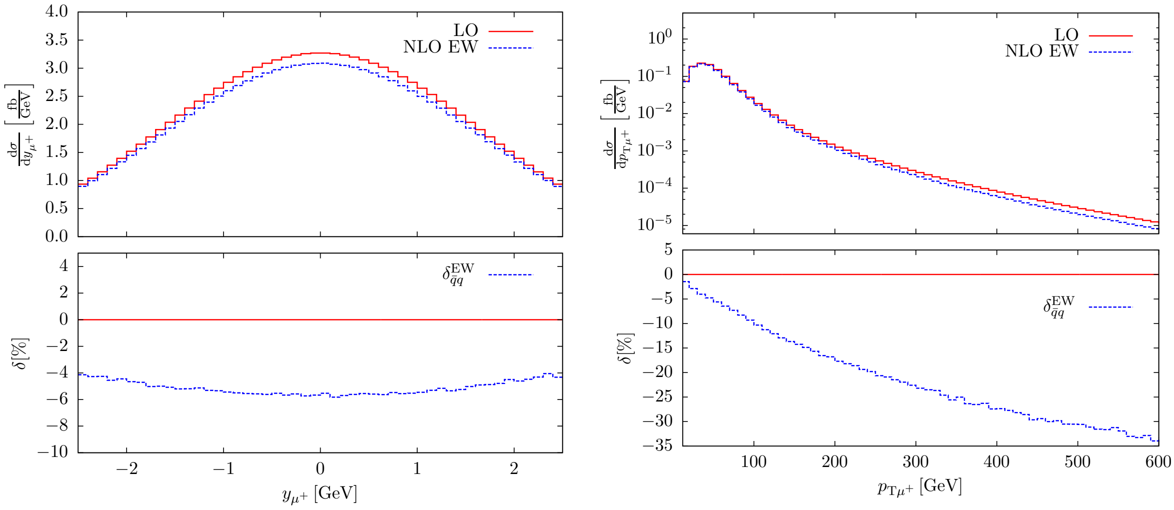
In the real corrections, photons are recombined with the closest charged lepton if the separation of the photon–lepton system, $\Delta R(\gamma, \ell_i)$, is less than 0.2.

4. Phenomenological results

At the LHC with centre of mass energy 13 TeV, the cross section for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ for the setup described above amounts to $\sigma^{\mathrm{LO}}_{\bar{q}q} = 11.4959(5)\,\mathrm{fb}$ at LO, with a relative NLO EW correction of $\delta_{\bar{q}q} = \sigma^{\mathrm{NLO}}_{\bar{q}q}/\sigma^{\mathrm{LO}}_{\bar{q}q} = -5.3\%$. This correction reduces the LO cross section by a non-negligible amount. In addition to the $\bar{q}q$ contributions, photon-induced contributions of the form $\gamma\gamma \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-$ emerge at the same order in the electroweak coupling. However, because of the strong suppression of the photon density in the proton and the lack of doubly-resonant contributions in the hard process, this channel contributes to the full cross section only about one permille. Contributions with one photon and one (anti-)quark in the initial state at $O(\alpha^5)$ are even smaller in size. Since the same pattern is also observed for differential distributions, we neglect all photon-induced channels in this proceedings contribution, restricting our results to the dominant $\bar{q}q$-induced channels both at LO and NLO EW.

In addition to integrated cross sections, we have investigated the impact of the EW corrections on differential distributions at 13 TeV. Figure 4a shows the distribution in the rapidity of the anti-muon at LO and NLO EW. For this observable, the EW corrections are rather smooth in the entire range considered. They tend to slightly increase at central rapidities, where the bulk of the cross section resides and decrease towards larger rapidities. Their relative size of -4% to -6% reflects the impact of the EW corrections on the inclusive cross section.

In Fig. 4b, the transverse-momentum distribution of the anti-muon is shown. This observable illustrates one of the main features of EW corrections: The relative size of the correction grows

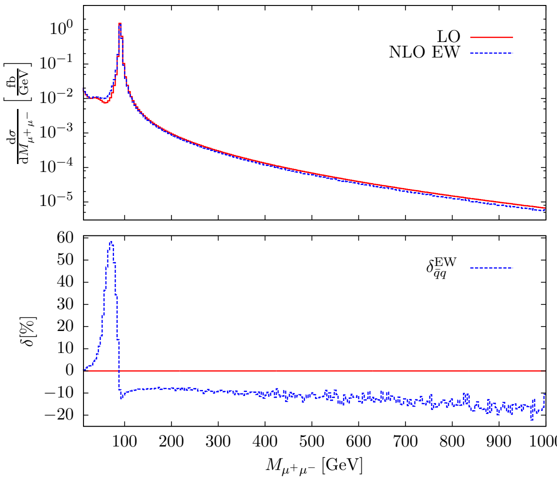


(4a) (4b)

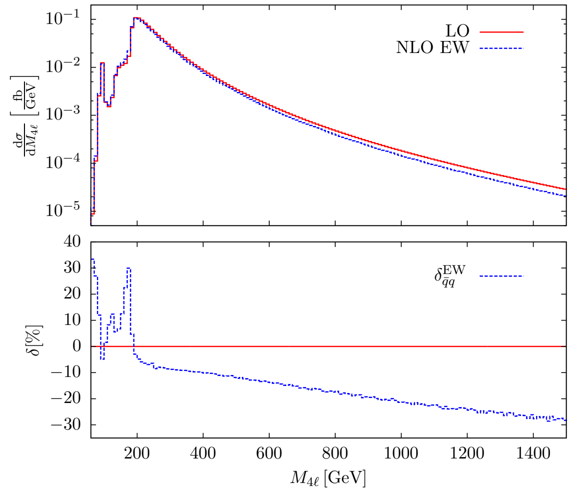
Figure 4: Rapidity distribution (a) and transverse-momentum distribution (b) of the anti-muon in pp $\rightarrow \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ at LO (solid red line) and NLO EW accuracy (dashed blue line) [upper panels], and the relative impact of the NLO EW corrections, normalized to the LO result [lower panels].

with increasing energy. For the considered observable, the relative correction is about -35% of the LO cross section at a transverse-momentum scale of 600 GeV. The reason for this behaviour is that in this so-called Sudakov regime [50] the cross section is dominated by single and double logarithms of the form $\alpha\log(Q^2/M_Z^2)$ and $\alpha\log^2(Q^2/M_Z^2)$, where Q denotes a typical momentum scale associated with the considered process [30]. For massless gauge bosons (like photons), such logarithms occur only at intermediate steps of the calculation for inclusive observables. The masses in such a case do serve only as unphysical regulators, and the entire logarithmic contribution drops out when the virtual corrections and the real-photon-radiation contributions are combined properly. However, W and Z bosons can be experimentally reconstructed and do have a measurable, non-vanishing mass that may be interpreted as a physical regulator. It is thus not necessary to explicitly include contributions due to the radiation of massive external vector bosons. The logarithms emerging from the virtual corrections therefore remain in the full result and enhance the relative size of the correction for large ratios of Q^2/M_Z^2.

A similar Sudakov enhancement can also be observed in the invariant-mass distribution of the $\mu^+\mu^-$ system, shown in Fig. 5a. In this particular observable, the impact of the EW corrections amounts to about -20% at 1 TeV, being slightly less significant than in the transverse-momentum distribution discussed above. Above 1 TeV, however, the cross-section contribution becomes so small that only very few events are expected to be detected in this phase-space region. A larger Sudakov enhancement can be observed at higher values of the invariant masses. Even though the statistical accuracy that can be achieved experimentally in LHC Run II is limited, this kinematic regime is of particular relevance, as one expects signatures of new physics mostly to emerge in tails of invariant-mass and transverse-momentum distributions, should physics beyond the SM become relevant in the few-TeV range. Another typical feature of the invariant-mass distribution is



(5a)



(5b)

Figure 5: Invariant-mass distributions for the $(\mu^+\mu^-)$-system (a) and for the for four-lepton system (b) in pp $\to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ at LO (solid red line) and NLO EW accuracy (dashed blue line) [upper panels], and the relative impact of the NLO EW corrections, normalized to the LO result [lower panels].

the radiative tail and the corresponding sign change of the correction near the Z resonance: The dominant contribution of the hard process comes from the Z peak, while above and below the peak the cross section falls off rapidly. However, real photon emission from the final state may shift events to smaller values of $M_{\mu^+\mu^-}$. Since the LO cross section is small in this phase-space region, the relative EW correction is large and amounts to nearly $+60\%$.

Figure 5b shows the invariant-mass distribution of the four-lepton system that falls off less steeply than the $M_{\mu^+\mu^-}$ distribution. The EW corrections reach roughly -30% at an invariant mass of 1.5 TeV. The plot is characteristic for Z-pair production: The first peak around M_Z results from a single-resonant s-channel configuration (c.f. Fig. 1b) and the threshold at $2M_\mathrm{Z}$ from a double-resonant t-channel configuration (c.f. Fig. 1a). The knee in between the two peaks at around $M_\mathrm{Z} + 2p_{\mathrm{T,min}}$ corresponds to the threshold where in t-channel configurations one Z boson may be produced on-shell. This explains the three radiative tails observed in the relative EW corrections below the resonances and thresholds via the same mechanism explained at the invariant $\mu^+\mu^-$ mass.

5. Conclusion

In this proceedings contribution, the first calculation of the NLO EW corrections to the process pp $\to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ has been presented. In the considered setup, the corrections to the inclusive cross section are negative and reduce the LO result by about -5%, which is clearly non-negligible in the confrontation of data with theory. Observables like invariant-mass and transverse-momentum distributions show the expected Sudakov behaviour that enhances the magnitude of the relative EW corrections up to -30% in the high-energy tails of distributions. Below resonances or thresholds, radiation effects increase the size of the relative EW corrections up to $+60\%$. Electroweak corrections, thus, lead to significant distortions of differential distributions and need to be included in future precision analyses of LHC data.

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