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Dominant mixed QCD-electroweak $\mathcal{O}(\alpha_s\alpha)$ corrections to Drell–Yan processes in the resonance region

Stefan Dittmaier [a], Alexander Huss [b,c,*], Christian Schwinn [a,d]

[a] *Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, D-79104 Freiburg, Germany*
[b] *Institute for Theoretical Physics, ETH, CH-8093 Zürich, Switzerland*
[c] *Department of Physics, University of Zürich, CH-8057 Zürich, Switzerland*
[d] *Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, D-52056 Aachen, Germany*

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Abstract

A precise theoretical description of W- and Z-boson production in the resonance region is essential for the correct interpretation of high-precision measurements of the W-boson mass and the effective weak mixing angle. Currently, the largest unknown fixed-order contribution is given by the mixed QCD-electroweak corrections of $\mathcal{O}(\alpha_s\alpha)$. We argue, using the framework of the pole expansion for the NNLO QCD-electroweak corrections established in a previous paper, that the numerically dominant corrections arise from the combination of large QCD corrections to the production with the large electroweak corrections to the decay of the W/Z boson. We calculate these so-called factorizable corrections of "initial–final" type and estimate the impact on the W-boson mass extraction. We compare our results to simpler approximate combinations of electroweak and QCD corrections in terms of naive products of NLO QCD and electroweak correction factors and using leading-logarithmic approximations for QED final-state radiation as provided by the structure-function approach or QED parton-shower programs. We also compute corrections of "final–final" type, which are given by finite counterterms to the leptonic vector-boson decays and are found to be numerically negligible.

* Corresponding author.
E-mail address: ahuss@phys.ethz.ch (A. Huss).

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1. Introduction

The class of Drell–Yan-like processes is one of the most prominent types of particle reactions at hadron colliders and describes the production of a lepton pair through an intermediate gauge-boson decay,

$$\mathrm{pp}/\mathrm{p}\bar{\mathrm{p}} \to V \to \ell_1\bar{\ell}_2 + X.$$

Depending on the electric charge of the colour-neutral gauge boson V, the process can be further classified into the neutral-current ($V = \mathrm{Z}/\gamma$) and the charged-current ($V = \mathrm{W}^{\pm}$) processes. The large production rate in combination with the clean experimental signature of the leptonic vector-boson decay allows this process to be measured with great precision. Moreover, the Dell–Yan-like production of W or Z bosons is one of the theoretically best understood and most precisely predicted processes. As a consequence, electroweak (EW) gauge-boson production is among the most important "standard-candle" processes at the LHC (see, e.g. Refs. [1,2]). Its cross section can be used as a luminosity monitor, and the measurement of the mass and width of the Z boson represents a powerful tool for detector calibration. Furthermore, the W charge asymmetry and the rapidity distribution of the Z boson deliver important constraints in the fit of the parton distribution functions (PDFs) [3], which represent crucial ingredients for almost all predictions at the LHC.

Of particular relevance for precision tests of the Standard Model is the potential of the Drell–Yan process at the LHC for high-precision measurements in the resonance regions, where the effective weak mixing angle, quantified by $\sin^2\theta^{\ell}_{\mathrm{eff}}$, might be extracted from data with LEP precision [4]. The W-boson mass can be determined from a fit to the distributions of the lepton transverse momentum ($p_{\mathrm{T},\ell}$) and the transverse mass of the lepton pair ($M_{\mathrm{T},\ell\nu}$) which exhibit Jacobian peaks around M_{W} and $M_{\mathrm{W}}/2$, respectively, and allow for a precise extraction of the mass with a sensitivity below 10 MeV [5,6] provided that PDF uncertainties can be reduced [7–10].

To fully exploit the potential of the extraordinary experimental precision that is achievable for the Drell–Yan process, it is necessary to have theoretical predictions that match or even surpass the expected accuracy. The current state of the art includes QCD corrections at next-to-next-to-leading-order (NNLO) accuracy [11–18] supplemented by leading higher-order soft-gluon effects [19–22] and soft-gluon resummation for small transverse momenta [23–29]. For event generation, next-to-leading-order (NLO) calculations have been matched to parton showers [30–32], with a recent effort to include NNLO corrections in a parton-shower framework [33–35]. Concerning EW effects, the NLO corrections [36–47] as well as leading higher-order effects from multiple photon emission and universal weak effects [46–50] are known. The sensitivity to the photon PDF through photon-induced production channels has been studied in Refs. [44,47,51,52].

In addition to the N^{3}LO QCD corrections, the next frontier in theoretical fixed-order computations is given by the calculation of the mixed QCD–EW corrections of $\mathcal{O}(\alpha_{\mathrm{s}}\alpha)$ [53]. These corrections can affect observables relevant for the M_{W} determination at the percent level [54] and therefore must be under theoretical control. Up to now, QCD and EW corrections have been combined in various approximations [55–60]. However, a full NNLO calculation at $\mathcal{O}(\alpha_{\mathrm{s}}\alpha)$ is necessary for a proper combination of QCD and EW corrections without ambiguities. Here some partial results for two-loop amplitudes [61–63] as well as the full $\mathcal{O}(\alpha_{\mathrm{s}}\alpha)$ corrections to the W and Z decay widths [64,65] are known. A complete calculation of the $\mathcal{O}(\alpha_{\mathrm{s}}\alpha)$ corrections requires to combine the double-virtual corrections with the $\mathcal{O}(\alpha)$ EW corrections to W/Z + jet