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Mixed QCD-Electroweak corrections to the Drell-Yan process in the high invariant mass region

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We report on the calculation of mixed QCD-electroweak corrections to the neutral-current-mediated production of a pair of massless leptons in the high invariant mass region. We find these corrections to be $O(-1\%)$ at relatively low values of the dilepton invariant mass, around 200 GeV. For invariant masses larger than 1 TeV, we observe that mixed corrections are larger, $O(-3\%)$, and are well reproduced by the product of next-to-leading order QCD and electroweak corrections. These results emphasise the importance of mixed QCD-electroweak corrections in Drell-Yan process studies, where percent-level precision is being targeted.

P3H-22-082, TTP22-051

Loops and Legs in Quantum Field Theory - LL2022,
25-30 April, 2022
Ettal, Germany

PoS(LL2022)069

1. Introduction

The Drell-Yan process offers an interesting opportunity to test the Standard Model (SM) and possibly reveal New Physics beyond it. Indeed, dilepton production at high invariant masses is sensitive to New Physics effects, which can be modelled using Standard Model Effective Field Theory (SMEFT) [1, 2]. In particular, the dilepton invariant mass distribution is affected by SMEFT-dimension-6 operators. Constraints on Wilson coefficients of such operators have been set using LEP data [3]. However, one may expect improvements on these constraints from LHC measurements, since higher energy of the LHC can compensate for its limited precision [4, 5]. To improve the bounds on the Wilson coefficients of SMEFT operators it is necessary to obtain percent-level predictions within the SM. Such precision requires the inclusion of both QCD corrections, which were found to be close to 1% at $O(\alpha_s^3)$ [6–11], and electroweak (EW) corrections. Indeed, even if the electroweak coupling constant is about a factor of ten smaller than the strong coupling constant, EW corrections are enhanced at large invariant masses because of the so-called Sudakov logarithms [12–15]. The potential interplay between this enhancement and the magnitude of NLO QCD corrections suggests that mixed QCD×EW corrections could impact predictions at the percent level. In this proceeding we report on the recent calculation of mixed QCD×EW corrections to the neutral-current-mediated production of a pair of massless leptons [16]. Qualitatively, our results are in agreement with the analysis of Ref. [17], although a direct comparison is not possible because of different set ups.
In section 2 we discuss the main technical aspects of the calculation of mixed corrections. In section 3 we present our results for the fiducial cross section, and study the impact of mixed corrections in different invariant mass regions. In section 4 we discuss some kinematic distributions. We conclude in section 5.

2. Technicalities

Before presenting our results, we notice that mixed QCD×EW corrections have already been studied for *resonant* production of Z and W bosons [18–23]. Despite the similarities between the resonant and the off-shell calculation, several complications arise when considering the full $q\bar{q}' \to \ell_1\bar{\ell}_2$ process. This is so because interactions between initial and final state are suppressed and thus negligible in the resonance region [24, 25], but they become important in the high invariant mass region.
Estimating mixed corrections requires three main ingredients: the double-virtual, the real-virtual and the double-real contributions. The double-virtual correction needs the full $q\bar{q}' \to \ell_1\bar{\ell}_2$ two-loop amplitude, and thus the computation of Feynman integrals that include various internal and external masses. The results are obtained starting from the two-loop amplitudes presented in Refs. [26, 27]. We have calculated the terms arising from closed fermionic loops that were not included in those references, and checked our analytic expressions against those in Refs. [28, 29]. After manipulating the results in Refs. [26, 27] to optimise the numerical efficiency, the evaluation time of the double-virtual contributions for a single phase-space point is close to 1 s on average.
Next, we require real-virtual contributions, which consist of one-loop corrections to lepton pair production with a single gluon or photon radiation. These corrections are of the NLO type.

However, they involve several internal masses, and have to be computed in such a way that they remain numerically stable when the extra radiation becomes unresolved. We use OpenLoops [30–32] to obtain reliable and stable results for the relevant real-virtual amplitudes.
The last contribution is the tree-level, double-real correction, which involves the emission of a gluon and a photon in the final state. Real emission contributions are known to develop soft and collinear singularities and therefore they cannot be evaluated directly (see for instance Ref. [33] for a recent review on the topic). In our analysis we have exploited the nested soft-collinear subtraction scheme [34] to handle this issue and obtain fully differential results. Such procedure was originally designed for NNLO QCD calculations, but it turns out to be flexible enough to easily accomodate mixed QCD×EW corrections. In particular, it has recently been exploited to study resonant vector boson production [19, 21]. When considering off-shell production, radiation off initial and final states has to be accounted for simultaneously. This leads to a larger number of singular limits with respect to the on-shell case. Nevertheless, the overall structure of the subtraction scheme remains unaffected, since its building blocks are almost process-independent. We are then able to cope with the off-shell Z boson production by adapting NNLO QCD computations.

3. Phenomenological results: total cross section

We consider proton-proton collisions at 13.6 TeV center-of-mass energy. The results reported below are computed using the `NNPDF31_nnlo_as_0118_luxqed` [35] parton distribution functions, available through the `LHAPDF` [36] library. We use the strong coupling constant α_s as provided by the PDF set. We use the G_μ input scheme for the EW parameters. We also employ the complex-mass scheme [29, 37]. All the numerical values for the electroweak input parameters and further details on the set up can be found in Ref. [16]. We recombine photons and leptons into "lepton jets". We follow Refs. [38, 39] to cut on the invariant mass, the transverse momenta and the rapidities of these IR-safe objects, namely

$$m_{\ell\ell} > 200\,\text{GeV}\,, \quad p_{T,\ell^\pm} > 30\,\text{GeV}\,, \quad \sqrt{p_{T,\ell^-}p_{T,\ell^+}} > 35\,\text{GeV}\,, \quad |y_{\ell^\pm}| < 2.5\,. \tag{1}$$

As the central value we take the renormalization scale μ_R and the factorization scale μ_F to be equal to half of the invariant mass of the (dressed) dilepton system, i.e. $\mu_F = \mu_R = \mu = m_{\ell\ell}/2$ as the central value. To estimate theoretical uncertainties we take the envelop of scale uncertainties and EW input scheme uncertainties. The former are estimated by increasing or decreasing the scale μ by a factor of two. For the latter we consider the $\alpha(m_Z)$-scheme, where $\alpha(m_Z) = 1/128$ is an input parameter, and keep the other parameters fixed.
To present our findings we introduce the following notation

$$d\sigma = \sum_{i,j=0} d\sigma^{(i,j)}\,, \qquad \delta\sigma^{(i,j)} = \int d\sigma^{(i,j)} \quad \text{with} \quad \sigma^{(0,0)} \equiv \delta\sigma^{(0,0)}\,, \tag{2}$$

where $d\sigma^{(0,0)}$ and $\sigma^{(0,0)}$ represent the LO cross sections, while $d\sigma^{(i,j)}$ and $\delta\sigma^{(i,j)}$ with $i,j > 0$ correspond to cross sections at order $O(\alpha_s^i\alpha^j)$. Using the set up described above, we obtain the following result

$$\sigma^{(0,0)} + \delta\sigma^{(1,0)} + \delta\sigma^{(0,1)} + \delta\sigma^{(2,0)} = 1928.3^{+1.8\%}_{-0.15\%}\ \text{fb}\,, \tag{3}$$

where we have included all the contributions up NNLO QCD, but neglected mixed QCD×EW corrections. We find that NLO QCD corrections, $\delta\sigma^{(1,0)}$, impact the LO cross section by about 20%, and the NLO EW corrections $\sim$ 3%, compatible with the expectations ($\delta^{\text{EW}} \sim \alpha/\sin^2\theta_W \sim 0.03$, where θ_W is the weak mixing angle). We also obtain NNLO QCD corrections of order 0.9%. Such value is smaller than naive power counting predictions due to a strong cancellation between the $q\bar{q}$ and the gq channels. After including mixed QCD×EW corrections, the LO cross section decreases by about 1%. This value exceeds by one order of magnitude the expectations based on power counting expectations, since $O(\alpha\alpha_s) \sim 0.1\%$. In fact, these corrections are *larger* than the NNLO QCD ones, they receive the dominant contribution from the $q\bar{q}$ partonic channel. The central value of the fiducial cross section in Eq. (3) and its uncertainty become

$$\sigma_{\text{QCD}\times\text{EW}} \equiv \sigma^{(0,0)} + \delta\sigma^{(1,0)} + \delta\sigma^{(0,1)} + \delta\sigma^{(2,0)} + \delta\sigma^{(1,1)} = 1912.6^{+0.65\%}_{-0.04\%}\ \text{fb}. \tag{4}$$

We notice that the inclusion of mixed corrections reduces the theoretical uncertainties below percent level. This is due to the fact that these corrections ameliorate the input-scheme dependence of the NLO QCD ones.

To estimate the impact of universal Sudakov logarithms on EW corrections we consider different invariant mass windows

$$\begin{aligned} &\Phi^{(1)}:\ 200\ \text{GeV} < m_{\ell\ell} < 300\ \text{GeV}, \qquad &&\Phi^{(2)}:\ 300\ \text{GeV} < m_{\ell\ell} < 500\ \text{GeV}, \\ &\Phi^{(3)}:\ 500\ \text{GeV} < m_{\ell\ell} < 1.5\ \text{TeV}, \qquad &&\Phi^{(4)}:\ 1.5\ \text{TeV} < m_{\ell\ell} < \infty, \end{aligned} \tag{5}$$

and compare the exact result for mixed contributions with the corresponding factorised approximation. The latter consists of the product of QCD and electroweak corrections and can be defined as

$$\delta\sigma^{(1,1)}_{\text{fact}} = \delta^{(1,0)}_{\text{NLO}}\,\delta^{(0,1)}_{\text{NLO}}\,\sigma^{(0,0)}, \qquad \text{with} \qquad \delta^{(1,0)}_{\text{NLO}} = \frac{\delta\sigma^{(1,0)}}{\sigma^{(0,0)}}, \qquad \delta^{(0,1)}_{\text{NLO}} = \frac{\delta\sigma^{(0,1)}}{\sigma^{(0,0)}}. \tag{6}$$

Such approximation is expected to capture the leading Sudakov logarithms that should provide the dominant contribution, at least for high values of $m_{\ell\ell}$. Indeed, from Table 1 it is clear that the full result is well approximated by $\delta\sigma^{(1,1)}_{\text{fact}}$ for $m_{\ell\ell} > 1$ TeV. In contrast, the factorised approximation underestimates the mixed corrections for lower invariant masses. From Table 1 we observe that results including NLO QCD, NLO EW, NNLO QCD and mixed QCD×EW corrections feature s sub-percent theoretical uncertainties in all the invariant mass windows.

4. Kinematic distributions

We now present the effects of the different corrections to the dilepton invariant mass distribution. Our best prediction for the fiducial cross section is defined as

$$d\sigma_{\text{QCD}\times\text{EW}} = d\sigma^{(0,0)} + d\sigma^{(1,0)} + d\sigma^{(0,1)} + d\sigma^{(2,0)} + d\sigma^{(1,1)}\,. \tag{7}$$

We study the relative impact of NLO EW and QCD×EW corrections on the results computed through NLO QCD

$$R^{(0,1)}_{\text{QCD}} = \frac{d\sigma^{(0,0)} + d\sigma^{(1,0)} + d\sigma^{(0,1)}}{d\sigma^{(0,0)} + d\sigma^{(1,0)}}, \qquad R^{(1,1)}_{\text{QCD}} = \frac{d\sigma^{(0,0)} + d\sigma^{(1,0)} + d\sigma^{(0,1)} + d\sigma^{(1,1)}}{d\sigma^{(0,0)} + d\sigma^{(1,0)}}, \tag{8}$$

σ[fb]	$\sigma^{(0,0)}$	$\delta\sigma^{(1,0)}$	$\delta\sigma^{(0,1)}$	$\delta\sigma^{(2,0)}$	$\delta\sigma^{(1,1)}$	$\delta\sigma^{(1,1)}_{\text{fact.}}$	$\sigma_{\text{QCD}\times\text{EW}}$
$\Phi^{(1)}$	1169.8	254.3	−30.98	10.18	−10.74	−6.734	$1392.6^{+0.75\%}_{-0\%}$
$\Phi^{(2)}$	368.29	71.91	−11.891	2.85	−4.05	−2.321	$427.1^{+0.41\%}_{-0.02\%}$
$\Phi^{(3)}$	82.08	14.31	−4.094	0.691	−1.01	−0.7137	$91.98^{+0.22\%}_{-0.14\%}$
$\Phi^{(4)} \times 10$	9.107	1.577	−1.124	0.146	−0.206	−0.1946	$9.500^{+0\%}_{-0.97\%}$

Table 1: Fiducial cross section in the invariant mass windows given in Eq. (5). The factorised approximation is reported in the second to last column. Results for the complete cross section according to the definition in Eq. (4) are presented in the last column with the corresponding uncertainties. See Ref. [16] for details.

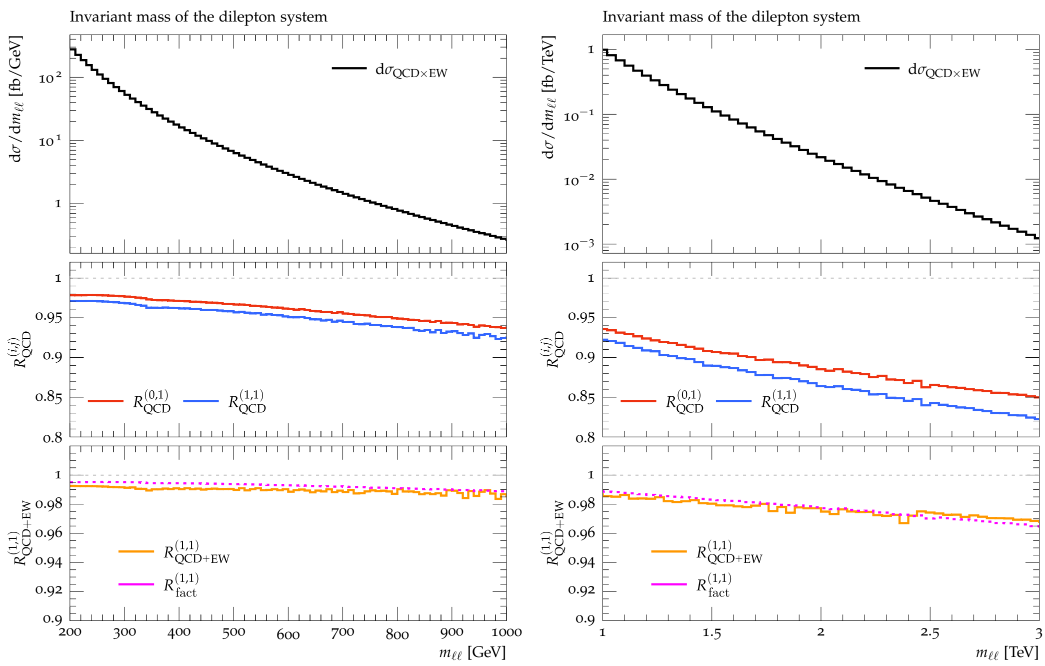

Figure 1: Distribution of the dilepton invariant mass for the Drell-Yan process at the 13.6 TeV LHC. The left plot presents results in the range 200 GeV $< m_{\ell\ell} <$ 1 TeV, the right plot shows results in the range 1 TeV $< m_{\ell\ell} <$ 3 TeV. The upper panel shows predictions for the cross section (see Eq.(4)). The middle panel shows the ratio of the NLO EW and mixed QCD×EW corrections to the full NLO QCD result. The lower pane shows the ratio of mixed QCD×EW corrections to the NLO result, including both EW and QCD corrections (orange line), and the factorised approximation (pink line). See Ref. [16] and the text for details.

and define the ratio of the two quantities in Eq.(8) as

$$R^{(1,1)}_{\text{QCD+EW}} = R^{(1,1)}_{\text{QCD}}/R^{(0,1)}_{\text{QCD}} = \frac{d\sigma^{(0,0)} + d\sigma^{(1,0)} + d\sigma^{(0,1)} + d\sigma^{(1,1)}}{d\sigma^{(0,0)} + d\sigma^{(1,0)} + d\sigma^{(0,1)}}. \tag{9}$$

The corresponding distributions are shown in Fig. 1. It follows from the figure that NLO EW corrections grow by a factor of ten when $m_{\ell\ell}$ increases from 200 GeV to 3 TeV. Mixed corrections exhibit a similar shape and increase from $O(-3\%)$ to $O(-18\%)$ in the same invariant mass range.

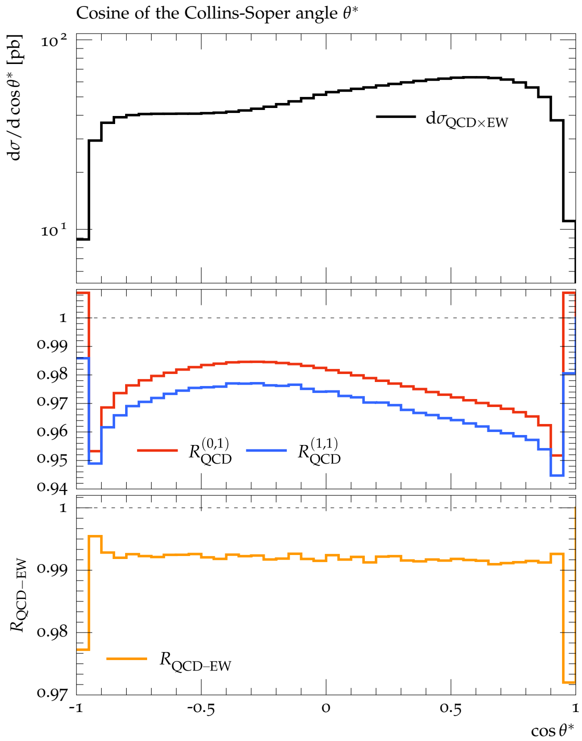

Figure 2: Distributions of the cosine of the Collins-Soper angle. See Ref. [16] and the text for details.

We further notice that the ratio $R_{\rm QCD+EW}$ is not constant and grows by about a factor of 4 when moving from $m_{\ell\ell} = 200$ GeV to $m_{\ell\ell} = 3$ TeV. In the lower panel of Fig. 1 we also present the invariant mass distribution for the factorised approximation. In agreement with the discussion in the previous section, the plots show that such an approximation is consistently above $R^{(1,1)}_{\rm QCD+EW}$ for $m_{\ell\ell}$ below 1 TeV, and becomes more accurate for higher invariant mass values.

Interestingly, mixed QCD-electroweak corrections seem to be enhanced with respect to naive expectations at low values of $m_{\ell\ell}$ (see also Table 1). In fact we observe these corrections to be only three times smaller than the EW corrections, and we do not expect large Sudakov logarithms at such energy scales. On the other hand, we point out that NLO QCD corrections are 20% of the LO cross section whereas the mixed QCD×EW corrections are 30% of the NLO EW contribution. Since such difference is not too large, the enhancement at low invariant masses can be an effect of the numerical interplay of different contributions.

We then consider angular distributions, which are potentially sensitive to the nature of quark-lepton currents. In particular, we present the results for the forward-backward asymmetry that has been recently measured by the CMS collaboration [40] in order to set limits on BSM four-fermion interactions. We define

$$A_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \tag{10}$$

	$\tilde{A}_{\rm FB}$	$A_{\rm FB}$
$\Phi^{(1)}$	$0.1442^{+0.05\%}_{-0.31\%}$	$0.1440^{+0.11\%}_{-0.09\%}$
$\Phi^{(2)}$	$0.1852^{+0.08\%}_{-0.40\%}$	$0.1847^{+0.10\%}_{-0.19\%}$
$\Phi^{(3)}$	$0.2401^{+0.13\%}_{-0.64\%}$	$0.2388^{+0.06\%}_{-0.47\%}$
$\Phi^{(4)}$	$0.3070^{+0.49\%}_{-1.5\%}$	$0.3031^{+0.19\%}_{-1.2\%}$

Table 2: Values of the forward-backward asymmetry in the invariant mass windows defined in Eq. (5). $\tilde{A}_{\rm FB}$ includes the LO, NLO-QCD, NLO-EW and NNLO-QCD contributions, whereas $A_{\rm FB}$ further includes the mixed QCD×EW correction computed in Ref. [16].

where

$$\sigma_F = \int_0^1 {\rm d}\cos\theta^* \, \frac{{\rm d}\sigma(pp \to \ell^-\ell^+)}{{\rm d}\cos\theta^*}, \qquad \sigma_B = \int_{-1}^0 {\rm d}\cos\theta^* \, \frac{{\rm d}\sigma(pp \to \ell^-\ell^+)}{{\rm d}\cos\theta^*}, \tag{11}$$

and θ^* is the Collins-Soper angle [41]; it can be found in Eq. (4.11) of Ref.[16]. Since the distribution of θ^* is non symmetric (see Fig. 2), $A_{\rm FB}$ is non-zero. After including all the corrections up to NNLO QCD and QCD×EW we find

$$A_{\rm FB} = 0.1580^{+0.15\%}_{-0.07\%} \,. \tag{12}$$

Omitting the mixed QCD×EW corrections changes the prediction in Eq. (12) by about 2 per mille which is comparable with the uncertainty of $A_{\rm FB}$ in Eq.(12). However, considering different invariant mass windows (see Table 2) we notice that the impact of mixed QCD×EW corrections reach -1.3% at high $m_{\ell\ell}$. Such shifts should become observable at the high-luminosity (HL) LHC.

5. Conclusions

We reported on the calculation of mixed QCD-electroweak correction to the production of a massless dilepton pair at the LHC. We investigated the high invariant mass region, $m_{\ell\ell} > 200$ GeV, and found mixed corrections to the fiducial cross section to be about -1% of the LO contribution. The impact of mixed corrections exceed by about an order of magnitude the expectation based the magnitude of strong and EW couplings. For invariant masses above 1 TeV, mixed corrections become even larger, and reach $\mathcal{O}(-3\%)$ at $m_{\ell\ell} \sim 3$ TeV. Their behaviour is compatible with the growth of Sudakov logarithms, and can be well approximated by the production of NLO QCD and EW contributions. For $m_{\ell\ell} > 1.5$ TeV this factorised approximation is indeed able to capture more than 90% of the exact result. The inclusion of mixed corrections drastically reduces the theoretical uncertainties due to input-scheme variations. The residual uncertainty on the fiducial cross section is estimated to be below a percent. We also studied the impact of mixed QCD×EW corrections on the forward-backward asymmetry and found a percent level effect for dilepton invariant masses above a TeV. We believe these results to be of interest for New Physics searches at the HL-LHC.

Acknowledgments

This research was partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under grant 396021762-TRR 257 .

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PoS(LL2022)069