Status of the EW cross sections for the LHC

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1 Introduction

Charged and neutral current Drell-Yan (D-Y) processes, *i.e.* $p\overset{(-)}{p} \to W \to l\nu_l + X$, and $p\overset{(-)}{p} \to Z/\gamma \to l^+l^- + X$ play a very important role at hadron colliders, since they have huge cross sections, (*e.g.* $\sigma(pp \to W \to l\nu_l + X) \sim 20$ nb at LHC and about a factor of ten less for $\sigma(pp \to Z/\gamma \to l^+l^- + X)$) and are easily detected, given the presence of at least a high $p_\perp$ lepton, which to trigger on. Present analysis by ATLAS and CMS of early LHC data attained single-W cross section measurements with an accuracy of the order of few per cent. For these reasons and also because the physics around W and Z mass scale is presently known with high precision after the LEP and Tevatron experience, D-Y processes provide standard candles for detector calibration. Moreover, single-W as signal by itself will allow to perform a precise measurement of the W mass with a foreseen final uncertainty of the order of 15 MeV at LHC (20 MeV at Tevatron), a very important ingredient for precision tests of the Standard Model, when associated with a top mass uncertainty of the order of 1-2 GeV. Also, from the forward-backward asymmetry of the charged lepton pair in $pp \to Z/\gamma \to e^+e^-$ the mixing angle $\sin^2\vartheta_W$ could be extracted with a precision of 1×10^{-4}. Last, single-W and single-Z processes provide important observables for new physics searches: in fact the high tail of the l^+l^- invariant mass and of the W transverse mass is sensitive to the presence of extra gauge bosons predicted in many extension of the Standard Model, which could lie in the TeV energy scale detectable at LHC.

An important observation is that about 50% of the total present systematic error at LHC on the D-Y cross section measurement is due to theoretical uncertainties, in addition to the uncertainty due to PDF's knowledge. The sources of uncertainty in the theoretical predictions are essentially of perturbative and non-perturbative origin. The latter ones comprise the uncertainties related to the parton distribution functions and power corrections to resummed differential cross sections, which will not be discussed here.

In the following we review the current state-of-the-art on the calculation of higher order QCD and electroweak (EW) radiative corrections and their implementation in simulation tools, and we present some recent results about the combination of QCD and EW corrections to W production at the LHC.

2 Status of theoretical calculations and tools

In the present section, a sketchy summary of the main computational tools for EW gauge boson production at hadron colliders is presented. Concerning QCD calculations and tools, the present situation reveals quite a rich structure, that includes next-to-leading-order (NLO) and next-to-next-to-leading-order (NNLO) corrections to W/Z total production rate [1, 2], NLO calculations for $W, Z + 1, 2$ jets signatures (available in the codes DYRAD and MCFM) [3, 4], resummation of leading and next-to-leading logarithms due to soft gluon radiation (implemented in the Monte Carlo ResBos) [5, 6], NLO corrections merged with QCD Parton Shower (PS) evolution (in the event generators MC@NLO and POWHEG) [7, 8], NNLO corrections to W/Z production in fully differential form (available in the Monte Carlo programs FEWZ) [9] and DYNNLO [10]. Very recently the NNLL resummation of W/Z transverse momentum appeared in the literature [11].

As far as complete $\mathcal{O}(\alpha)$ EW corrections to D-Y processes are concerned, they have been computed independently by various authors in [12, 13, 14, 15, 16] for W production and in [17, 18, 19, 20, 21] for Z production. EW tools implementing exact NLO corrections to W/Z production are DK [12], WGRAD2 [13], ZGRAD2 [17], SANC [15] and HORACE [16], HORACE [19].

From the calculations above, it turns out that NLO EW corrections are dominated, in the resonant region, by final-state QED radiation containing large collinear logarithms of the form $\log(\hat{s}/m_l^2)$, where $\hat{s}$ is the squared partonic centre-of-mass (c.m.) energy and m_l is the lepton mass. Since these corrections amount to several per cents around the jacobian peak of the W transverse mass and lepton transverse momentum distributions and cause a significant shift (of the order of 100-200 MeV) in the extraction of the W mass M_W at the Tevatron, the contribution of higher-order corrections due to multiple photon radiation from the final-state leptons must be taken into account in the theoretical predictions, in view of the expected precision in the M_W measurement at the LHC. The contribution due to multiple photon radiation has been computed, by means of a QED PS approach [22] and implemented in the event generator HORACE. An independent approach is followed in WINHAC [23], where the multiple photon radiation is described with the YFS exponentiation formalism. The exact $\mathcal{O}(\alpha)$ contribution is obtained by means of an interface to the SANC system [25]. Higher-order QED contributions to W production have been calculated independently in [24] within the collinear structure functions approach

It is worth noting that, for what concerns the precision measurement of M_W, the shift induced by higher-order QED corrections is about 10% of that caused by one-photon emission and of opposite sign, as shown in [22]. Therefore, such an effect is non-negligible in view of the aimed accuracy in the M_W measurement at the LHC.

A further important phenomenological feature of EW corrections is that, in the region important for new physics searches (i.e. where the W transverse mass is much larger than the W mass or the invariant mass of the final state leptons is much larger than the Z mass), the NLO EW effects become large (of the order of 20-30%) and negative, due to the appearance of EW Sudakov logarithms $\propto -(\alpha/\pi)\log^2(\hat{s}/M_V^2)$, $V = W, Z$ [12, 13, 16, 17, 18, 19].

In spite of this detailed knowledge of higher-order EW and QCD corrections, the combination of their effects is presently under investigation. Some attempts have been explored in the literature [26, 27, 28]. Many analysis at the resonance peak rely on the LL factorized approach where a QCD Parton Shower is interfaced to PHOTOS [29] (or SOPHTY [30] as in the case of HERWIG++) for the simulation of final state QED radiation. Preliminary tests of the level of precision for this kind of approach has been discussed at the W/Z peak, for LHC energies of 7, 10 and 14 TeV [31].

Recent activity is devoted to the inclusion of NLO EW corrections in the framework of a QCD generator, with possible inclusion of higher order QED corrections [32, 33]. Here our approach is discussed in some detail [33].

A first strategy for the combination of EW and QCD corrections consists in the following formula

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD\&EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\text{MC@NLO}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{Born}}\right\}_{\text{HERWIG PS}} \tag{1}$$

where $d\sigma/d\mathcal{O}_{\text{MC@NLO}}$ stands for the prediction of the observable $d\sigma/d\mathcal{O}$ as obtained by means of MC@NLO, $d\sigma/d\mathcal{O}_{\text{EW}}$ is the HORACE prediction for the EW corrections to the $d\sigma/d\mathcal{O}$ observable, and $d\sigma/d\mathcal{O}_{\text{Born}}$ is the lowest-order result for the observable of interest. The label HERWIG PS in the second term in r.h.s. of Eq. (1) means that EW corrections are convoluted with QCD PS evolution through the HERWIG event generator, in order to (approximately) include mixed $\mathcal{O}(\alpha\alpha_s)$ corrections and to obtain a more realistic description of the observables under study. In Eq. (1) the infrared part of QCD corrections is factorized, whereas the infrared-safe matrix element residue is included in an additive form. It is otherwise possible to implement a fully factorized combination (valid for infrared safe observables) as follows:

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1+\frac{[d\sigma/d\mathcal{O}]_{\text{MC@NLO}}-[d\sigma/d\mathcal{O}]_{\text{HERWIG PS}}}{[d\sigma/d\mathcal{O}]_{\text{LO/NLO}}}\right)\times$$
$$\times\left\{\frac{d\sigma}{d\mathcal{O}_{\text{EW}}}\right\}_{\text{HERWIG PS}}, \tag{2}$$

where the ingredients are the same as in Eq. (1) but also the QCD matrix element residue is now factorized. It is worth noticing that the QCD correction factor in front of $\{d\sigma/d\mathcal{O}_{\text{EW}}\}_{\text{HERWIG PS}}$ is defined in terms of two different normalization cross sections, namely the LO or the NLO one, respectively. The two prescriptions differ at order α_s^2 by non-leading contributions. Nevertheless, Eq. (2) normalized in terms of the LO cross section can give rise to pathologically large order α_s^2 corrections in the presence of huge NLO effects. On the other hand, when NLO matrix element effects do not introduce particularly relevant corrections, the two prescriptions are substantially equivalent. Eqs. (1) and (2) have the very same $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ content, differing by terms at the order $\alpha\alpha_s$. Their relative difference can be taken as an estimate of the uncertainty of QCD & EW combination. In [33] a complete numerical study has been performed on the various approximations of the radiative corrections to D-Y and for several physical observables, for two standard event selections at Tevatron on peak (Tevatron) and LHC on peak (LHC a) and far off peak (LHC b). We summarize in Table 1 the relative effects of the different sources of corrections to the integrated cross section. NLO QCD is the complete $O(\alpha_s)$ correction, NLL QCD is the matrix element contribution of the NLO QCD correction, NLO EW is the full $O(\alpha)$ correction, Shower QCD stands for the $O(\alpha_s^n), n \geq 2$ correction and $O(\alpha\alpha_s)$ represents the mixed EW-QCD corrections estimated by properly combining the additive and factorized cross sections. It is worth noticing in particular that the latter corrections remain below the 1% level for typical event selections at the Tevatron and the LHC, while they can amount to some per cent in the region important for new physics searches at the LHC.

$\delta(\%)$	NLO QCD	NLL QCD	NLO EW	Shower QCD	$O(\alpha\alpha_s)$
Tevatron	8	16.8	-2.6	-1.3	~ 0.5
LHC a	-2	12.4	-2.6	1.4	~ 0.5
LHC b	21.8	20.9	-21.9	-0.6	~ 5

Table 1: Relative effect of the main sources of QCD, EW and mixed radiative corrections to the integrated cross sections for the Tevatron, LHC a and LHC b.

3 Conclusions

After reviewing the currently available theoretical calculations and tools, we discussed a strategy to estimate the missing higher order corrections to D-Y processes. In general, for the LHC we remarked that available calculations and tools do not currently allow to reach a theoretical accuracy better than some per cent level, when excluding PDF uncertainties. Future measurements at the LHC would require the consistent inclusion of NLO EW matched with multiphoton radiation within a unified NLO QCD generator. In a longer run probably require the calculation of complete $\mathcal{O}(\alpha\alpha_s)$ corrections. Recent work in this direction is the calculation of the two-loop $\mathcal{O}(\alpha\alpha_s)$ virtual corrections to D-Y production [34] and of the one loop $\mathcal{O}(\alpha)$ corrections to the signature $W + 1$ jet [35].

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