PRECISION PREDICTIONS AND TOOLS FOR WEAK BOSON PRODUCTION AT THE LHC*

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Precision studies of weak boson production at the LHC require that electroweak and QCD higher-order corrections are simultaneously taken into account in data analysis. After a review of the present status of higher-order calculations for single W and Z boson production at hadron colliders, we present some preliminary results on the combination of electroweak and QCD corrections to a sample of observables of the process $pp \to W^{\pm} \to \mu^{\pm} + X$ at the LHC. Our phenomenological analysis shows that a high-precision knowledge of QCD and a careful combination of electroweak and strong contributions is mandatory in view of the anticipated experimental accuracy.

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1. Introduction

The production of electroweak gauge bosons in hadronic collisions, with the weak boson decaying into a lepton pair, is a particularly clean process with a large cross section at the LHC. Electroweak Drell–Yan processes are of interest

1. to perform precision measurements of electroweak parameters, such as the W-boson mass and width from fits to the W transverse mass and lepton transverse momentum distributions in the charged-current (CC) channel, or the weak mixing angle from the forward–backward asymmetry in the neutral current (NC) channel;

2. as "standard candles", *i.e.* as means to understand the detector performances, as well as to monitor the collider luminosity with per cent precision and constrain the Parton Distribution Functions (PDFs), by using observables such as the W/Z rapidity and lepton pseudorapidity;

3. as important Standard Model (SM) backgrounds to new physics searches, such as the search for heavy W'/Z' gauge bosons predicted by various extensions of the SM. In this case, the relevant experimental observables are, for example, the invariant mass of the final state leptons (for the NC channel) and the transverse mass (for the CC channel) in the high tail, *i.e.* in the few TeV region at the LHC.

For all these measurements, precise theoretical predictions, including higher-order QCD and electroweak corrections, are needed [1, 2]. Furthermore, the implementation of such contributions in Monte Carlo generators is mandatory, in order to perform realistic studies of the impact of higher-order corrections on the observables of interest and to compare theory with data.

2. Higher-order QCD/electroweak calculations and tools

Concerning QCD calculations and tools for electroweak gauge boson production at hadron colliders, the present situation reveals a quite rich structure, that includes next-to-leading-order (NLO) and next-to-next-to-leading-order (NNLO) corrections to W/Z total production rate [3, 4], NLO calculations for $W, Z + 1, 2$ jets signatures [5, 6] (available in the codes DYRAD and MCFM), resummation of leading and next-to-leading logarithms due to soft gluon radiation [7, 8] (implemented in the Monte Carlo ResBos), NLO corrections merged with QCD Parton Shower (PS) evolution [9] (in the event generator MC@NLO), NNLO corrections to W/Z production in fully differential form [10–13] (available in the Monte Carlo program FEWZ), as well as leading-order multi-parton matrix elements generators matched with vetoed PS, such as, for instance, ALPGEN [14], MADEVENT [15] and SHERPA [16].

As far as complete $\mathcal{O}(\alpha)$ electroweak corrections to Drell–Yan processes are concerned, they have been computed independently by various authors in [17–21] for W production and in [22] for Z production. Electroweak tools implementing exact NLO corrections to W production are DK [17], WGRAD2 [18], SANC [20] and HORACE [21], while ZGRAD2 [22] includes the full set of $\mathcal{O}(\alpha)$ electroweak corrections to Z production. The predictions of a subset of such calculations have been recently compared, at the level of same input parameters and cuts, in the proceedings of the Les Houches [23] and TEV4LHC [24] workshops for W production, finding a very satisfactory agreement between the various, independent calculations. Work is in progress to perform similar comparisons for the Z production process.

From the calculations above, it turns out that NLO electroweak 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 center-of-mass 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 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 (at the level of 15–20 MeV) 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, in [25] for W production and in [26] for Z production, and implemented in the event generator HORACE. Higher-order QED contributions to W production have been calculated independently in [27] using the YFS exponentiation, and are available in the generator WINHAC. The treatment of multi-photon corrections has been recently improved in HERWIG (through the code SOPHTY [28], using the YFS formalism) and in the universal package PHOTOS [29], by means of a QED PS-like approach. Comparisons of such multi-photon calculations are documented in [28–30], showing good agreement, in spite of the quite different theoretical ingredients. 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 [25]. Therefore, such an effect is not negligible in view of the aimed accuracy in the M_W measurement at the LHC, especially for the W decays into muons.

A further important phenomenological feature of electroweak 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 electroweak effects become large (of the order of 20–30%) and negative, due to the appearance of electroweak Sudakov logarithms $\propto -(\alpha/\pi)\log^2(\hat{s}/M_V^2)$, $V = W, Z$ [17, 18, 21, 22]. Furthermore, in this region, weak boson emission processes (*e.g.* $pp \to e^+\nu_e V + X$), that contribute at the same order in perturbation theory, can partially cancel the large Sudakov corrections, when the weak boson V decays into unobserved $\nu\bar{\nu}$ or jet pairs, as recently shown in [31].

In spite of this detailed knowledge of higher-order electroweak and QCD corrections, the combination of their effects is still at a very preliminary stage. There is only one attempt known in the literature [32], where the effects of QCD resummation are combined with NLO QED final-state corrections, leaving room for more detailed studies of the interplay between electroweak and QCD corrections to W/Z production at the LHC.

3. Combination of electroweak and QCD corrections

Starting from a factorized expression for the combination of electroweak and QCD corrections, it is possible to derive, after some simple manipulations, the following formula

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{QCD}\otimes\mathrm{EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\mathrm{QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{Born}}\right\}_{\mathrm{HERWIG\ PS}}, \quad (1)$$

where $d\sigma/d\mathcal{O}_{\mathrm{QCD}}$ stands for the prediction of the observable $d\sigma/d\mathcal{O}$, as obtained by means of one of the state-of-the-art generators available in the literature, $d\sigma/d\mathcal{O}_{\mathrm{EW}}$ is the HORACE prediction for the electroweak corrections to the $d\sigma/d\mathcal{O}$ observable, and $d\sigma/d\mathcal{O}_{\mathrm{Born}}$ 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 electroweak 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. Actually, since the QCD shower evolution generates partons in the soft/collinear approximation, the results obtained for $\mathcal{O}(\alpha\alpha_s)$ corrections according to such a procedure are expected to be unreliable when hard non-collinear QCD radiation turns out to be important. However, beyond this approximation, a full two-loop calculation of $\mathcal{O}(\alpha\alpha_s)$ corrections, which is presently unavailable, would be required.

4. Numerical results

The preliminary numerical results shown in the present Section have been obtained using the following values for the input parameters

$G_\mu = 1.16639\ 10^{-5}$ GeV^{-2}	$m_W = 80.419$ GeV	$m_Z = 91.188$ GeV
$g_W = 2.048$ GeV	$\sin^2\vartheta_W = 1 - {m_W}^2/{m_Z}^2$	$m_H = 120$ GeV
$m_e = 510.99892$ KeV	$m_\mu = 105.658369$ MeV	$m_\tau = 1.77699$ GeV
$m_u = 320$ MeV	$m_c = 1.2$ GeV	$m_t = 174.3$ GeV
$m_d = 320$ MeV	$m_s = 150$ MeV	$m_b = 4.7$ GeV
$V_{cd} = 0.22361$	$V_{cs} = 0.9747$	$V_{cb} = 0$
$V_{ud} = \sqrt{1 - V_{cd}^2}$	$V_{us} = 0.22361$	$V_{ub} = 0$
$V_{td} = 0$	$V_{ts} = 0$	$V_{tb} = 1$

using the G_μ input scheme for the calculation of electroweak corrections, where, in particular, the (effective) electromagnetic coupling constant is given in the tree-level approximation by

$$\alpha_{G_\mu}^{\rm tree} = \frac{\sqrt{2} G_\mu \sin^2\vartheta_W {m_W}^2}{\pi} \, . \tag{2}$$

However, for the coupling of external photons to charged particles needed for the evaluation of photonic corrections we use $\alpha(0) = 1/137.03599911$.

We study, for definiteness, the production process $pp \to W^\pm \to \mu^\pm + X$ at the LHC ($\sqrt{s} = 14$ TeV), imposing the cuts shown in Table I, where $p_\perp^\mu$ and η_μ are the transverse momentum and the pseudorapidity of the muon, $\not{E}_{\rm T}$ is the missing transverse energy, which we identify with the transverse momentum of the neutrino, as typically done in several phenomenological studies.

TABLE I

Selection criteria imposed for the numerical simulation of single-W production process at the LHC.

LHC
(a) $p_\perp^\mu \geq 25$ GeV $\not{E}_{\rm T} \geq 25$ GeV and $\lvert\eta_\mu\rvert < 2.5$
(b) the cuts as above $\oplus$ $M_\perp^W \geq 1$ TeV

For set up (b), a severe cut on the W transverse mass $M_\perp^W$ is superimposed to the cuts of set up (a), in order to isolate the region of the high tail of $M_{\rm T}^W$, which is interesting for new physics searches. The set of PDFs used in our study is MRST2004QED [33], in order to consistently incorporate electroweak corrections in association with QCD corrections. The QCD factorization/renormalization scale and the analogous QED scale (present in MRST2004QED) are chosen to be equal, as usually done in the literature [17,18,21], and fixed at $\mu_R = \mu_F = \sqrt{p_{\perp W}^2 + M_W^2}$, as done in previous LHC studies [34].

A sample of our numerical results is shown in Fig. 1 for the W transverse mass $M_\perp^W$ and muon transverse momentum $p_\perp^\mu$ distributions according to set up (a) of Table I, and in Fig. 2 for the same distributions according to set up (b). In each figure, the upper panels show the predictions of the generators MC@NLO and MC@NLO + HORACE interfaced to HERWIG PS, in comparison with the leading-order result by HORACE convoluted with HERWIG shower evolution. The lower panels illustrate the relative effects of NLO QCD and electroweak corrections, as well as their sum, that can be obtained by appropriate combinations of the results shown in the upper panels. From Fig. 1 it can be seen that the NLO QCD corrections are positive around the Jacobian peak and tend to compensate the effect due to electroweak corrections. Therefore, their interplay is crucial for a precise M_W extraction at the LHC and their combined contribution can not be accounted for in terms of a pure QCD PS approach, as it can be inferred from the comparison of the predictions of MC@NLO versus the leading-order result by HORACE convoluted with HERWIG PS.

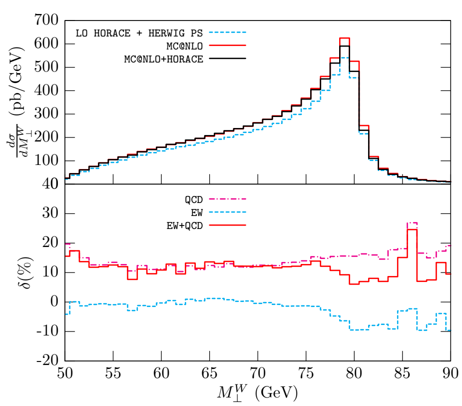

Fig. 1. Upper panel: predictions of MC@NLO, MC@NLO+HORACE and leading-order HORACE+HERWIG PS for the $M_\perp^W$ (left) and $p_\perp^\mu$ (right) distributions at the LHC, according to the cuts of set up (a). Lower panel: relative effect of QCD and electroweak corrections, and their sum, for the corresponding observables in the upper panel.

The interplay between QCD and electroweak corrections in the region interesting for new physics searches, *i.e.* in the high tail of $M_\perp^W$ and $p_\perp^\mu$ distributions, is shown in Fig. 2. For both $M_\perp^W$ and $p_\perp^\mu$ NLO QCD corrections are negative and sum up to negative electroweak Sudakov logarithms. Their sum is about $-40(-70)\%$ for $M_{\perp}^{W} \simeq 1.5(3)$ TeV and about $-30(-50)\%$ for $p_{\perp}^{\mu} \simeq 0.5(1)$ TeV. Therefore, a precise normalization of the SM background to new physics searches necessarily requires the simultaneous control of QCD and electroweak corrections, as well as the inclusion of two-loop electroweak Sudakov logarithms.

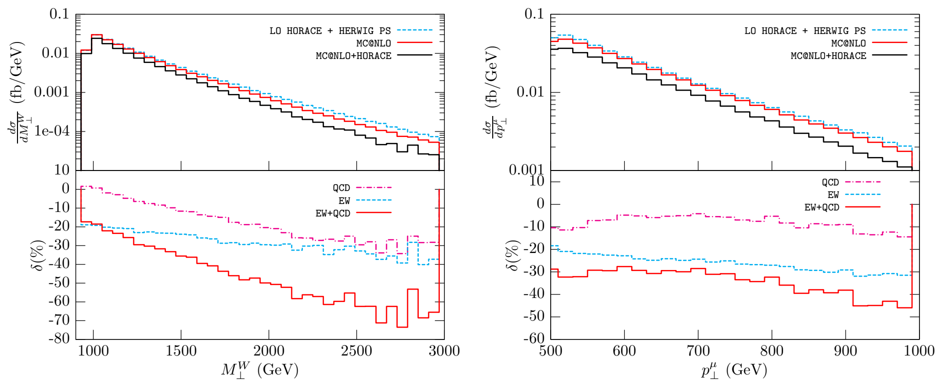

Fig. 2. The same as Fig. 1 according to the cuts of set up (b).

5. Conclusions

During the last few years, there has been a big effort towards high-precision predictions for Drell–Yan-like processes, addressing the calculation of higher-order QCD and electroweak corrections. Correspondingly, precision computational tools have been developed to keep under control theoretical systematics in view of the future measurements at the LHC.

We presented some preliminary results on the combination of electroweak and QCD corrections to a sample of observables of the process $pp \to W^{\pm} \to \mu^{\pm} + X$ at the LHC. Our preliminary investigation shows that a high-precision knowledge of QCD and a careful combination of electroweak and strong contributions is mandatory in view of the anticipated experimental accuracy. We plan, however, to perform a more complete and detailed phenomenological study, including the predictions of other QCD generators and considering further observables of interest for the many facets of the W/Z physics program at the LHC, with particular reference to the ratio of distributions of the so-called "scaled observables method" [35]. As a longer term project, we are interested to combine all the relevant QCD and electroweak corrections into a single, unified generator for complete and precise simulations of the Drell–Yan processes at the LHC.

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