# DRELL YAN PROCESSES AT LHC

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**Abstract**

The relevance of single-$W$ and single-$Z$ production processes at hadron colliders is well known: in the present paper the status of theoretical calculations of Drell-Yan processes is summarized and some 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 are discussed. The 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 LHC experimental accuracy.

## 1 Introduction

Precision measurements of electroweak (EW) gauge boson production and properties will be a crucial goal of the physics program of proton-proton collisions at the LHC. $W$ and $Z$ bosons will be produced copiously and careful measurements of their observables will be important in testing the Standard Model (SM) and uncovering signs of new physics [1].

Thanks to the high luminosity achievable at the LHC, the systematic errors will play a dominant role in determining the accuracy of the measurements, implying, in particular, that the theoretical predictions will have to be of the highest standard as possible. For Drell-Yan (D-Y) processes, this amounts to make available calculations of $W$ and $Z$ production processes including simultaneously higher-order corrections coming from the EW and QCD sector of the SM. Actually, in spite of a detailed knowledge of EW and QCD corrections separately, the combination of their effects have been addressed only recently [2, 3, 4] and need to be deeply scrutinized in view of the anticipated experimental accuracy.

In this contribution, after a review of existing calculations and codes, we present the results of a study aiming at combining EW and QCD radiative corrections to D-Y processes consistently. We do not include in our analysis uncertainties due to factorization/renormalization scale variations, as well as uncertainties in the Parton Distribution Functions arising from diverse experimental and theoretical sources, which are left to a future publication. Some results already available in this direction can be found in [5].

## 2 Status of theoretical predictions and codes

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 [6, 7], NLO calculations for $W, Z+1, 2$ jets signatures [8, 9] (available in the codes DYRAD and MCFM), resummation of leading and next-to-leading logarithms due to soft gluon radiation [10, 11] (implemented in the Monte Carlo ResBos), NLO corrections merged with QCD Parton Shower (PS) evolution (in the event generators MC@NLO [12] and POWHEG [13]), NNLO corrections to $W/Z$ production in fully differential form [14, 15] (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 [16], MADE-

VENT [17], HELAC [18] and SHERPA [19].

As far as complete $\mathcal{O}(\alpha)$ EW corrections to D-Y processes are concerned, they have been computed independently by various authors in [20, 21, 22, 23, 24] for $W$ production and in [25, 26, 27, 28] for $Z$ production. Electroweak tools implementing exact NLO corrections to $W$ production are DK [20], WGRAD2 [21], SANC [23] and HORACE [24], while ZGRAD2 [25], HORACE [27] and SANC [28] include the full set of $\mathcal{O}(\alpha)$ EW corrections to $Z$ production. The predictions of a subset of such calculations have been compared, at the level of same input parameters and cuts, in the proceedings of the Les Houches 2005 [29] and TEV4LHC [30] workshops for $W$ production, finding a very satisfactory agreement between the various, independent calculations. A first set of tuned comparisons for the $Z$ production process has been recently performed and is available in [31].

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 (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 [32] for $W$ production and in [33] for $Z$ production, and implemented in the event generator HORACE. Higher-order QED contributions to $W$ production have been calculated independently in [34] using the YFS exponentiation, and are available in the generator WINHAC. They have been also computed in the collinear approximation, within the structure functions approach, in [35].

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 $\propto -(\alpha/\pi)\log^2(\hat{s}/M_V^2)$, $V = W, Z$ [20, 21, 24, 25, 26, 27]. 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 [36].

## 3 Theoretical approach

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

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

where $d\sigma/d\mathcal{O}_{\rm MC@NLO}$ stands for the prediction of the observable $d\sigma/d\mathcal{O}$ as obtained by means of MC@NLO, $d\sigma/d\mathcal{O}_{\rm EW}$ is the HORACE prediction for the EW corrections to the $d\sigma/d\mathcal{O}$ observable, and $d\sigma/d\mathcal{O}_{\rm Born}$ 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. However, it is worth noting that the convolution of NLO EW corrections with QCD PS implies that the contributions of the order of $\alpha\alpha_s$ are not reliable when hard non-collinear QCD radiation turns out to be relevant, e.g. for the lepton and vector boson transverse momentum distributions in the absence of severe cuts able to exclude resonant $W/Z$ production. In this case, a full $\mathcal{O}(\alpha\alpha_s)$ calculation would be needed for a sound evaluation of mixed EW and QCD corrections. Full $\mathcal{O}(\alpha)$ EW corrections to the exclusive process $pp \to W + j$ (where $j$ stands for jet) have been recently computed, in the approximation of real $W$ bosons, in [37, 38], while one-loop weak corrections to $Z$ hadro-production have been computed, for on-shell $Z$ bosons, in [39]. It is also worth stressing that 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 infra-red safe observables) as follows:

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

where the ingredients are the same as in eq. (1) but also the QCD matrix element residue in now factorized. Eqs. (1) and (2) have the very same $\mathcal{O}(\alpha)$ and

$\mathcal{O}(\alpha_s)$ content, differing by terms of the order of $\alpha\alpha_s$. Their relative difference has been checked to be of the order of a few per cent in the resonance region around the $W/Z$ mass, and can be taken as an estimate of the uncertainty of QCD and EW combination.

## 4 Numerical results: $W$ and $Z$ production

In order to assess the phenomenological relevance of the combination of QCD and EW corrections, we study, for definiteness, the charged-current process $pp \to W^\pm \to \mu^\pm + X$ at the LHC, imposing the following selection criteria

$$\begin{aligned} &\text{a.} \quad p_\perp^\mu \geq \ 25 \text{ GeV}, \quad \not{E}_T \geq \ 25 \text{ GeV}, \quad |\eta_\mu| < 2.5, \\ &\text{b.} \quad \text{the cuts as above } \oplus \ M_\perp^W \geq 1 \text{ TeV}, \end{aligned} \tag{3}$$

where $p_\perp^\mu$ and $\eta_\mu$ are the transverse momentum and the pseudorapidity of the muon, $\not{E}_T$ is the missing transverse energy, which we identify with the transverse momentum of the neutrino, as typically done in several phenomenological studies. 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 $M_T^W$, which is interesting for new physics searches. We also consider the neutral-current reaction $pp \to \gamma, Z \to e^+e^- + X$, selecting the events according to the cuts

$$p_\perp^{e^\pm} \geq 25 \text{ GeV}, \quad |\eta^{e^\pm}| < 2.5, \quad M_{e^+e^-} \geq 200 \text{ GeV}. \tag{4}$$

The granularity of the detectors and the size of the electromagnetic showers in the calorimeter make it difficult to discriminate between electrons and photons with a small opening angle. We adopt the following procedure to select the event: we recombine the four-momentum vectors of the electron and photon into an effective electron four-momentum vector if, defining

$$\Delta R(e,\gamma) = \sqrt{\Delta\eta(e,\gamma)^2 + \Delta\phi(e,\gamma)^2}, \tag{5}$$

$\Delta R(e,\gamma) < 0.1$ (with $\Delta\eta, \Delta\phi$ the distances of electrons and photons along the longitudinal and azimuthal directions). We do not recombine electrons and photons if $\eta_\gamma > 2.5$ (with $\eta_\gamma$ the photon pseudo-rapidity). We apply the event selection cuts as in Eq. (4) only after the recombination procedure.

The parton distribution function (PDF) set MRST2004QED [40] has been used to describe the proton partonic content. The QCD factorization / renormalization scale and the analogous QED scale (present in the PDF set MRST2004QED) are chosen to be equal, as usually done in the literature [20, 21, 24, 25, 27], and fixed at $\mu_R = \mu_F = \sqrt{\left(p_\perp^W\right)^2 + M^2_{\mu\nu_\mu}}$ (for the charged-current case), where $M_{\mu\nu_\mu}$ is the $\mu\nu_\mu$ invariant mass, and at $\mu_R = \mu_F = \sqrt{\left(p_\perp^Z\right)^2 + M^2_{e^+e^-}}$ (for the neutral-current case), where $M_{e^+e^-}$ is the invariant mass of the lepton pair.

In order to avoid systematics theoretical effects, all the generators used in our study have been properly tuned at the level of input parameters, PDF set and scale to give the same LO/NLO results. The tuning procedure validates the interpretation of the various relative effects as due to the radiative corrections and not to a mismatch in the setups of the codes under consideration.

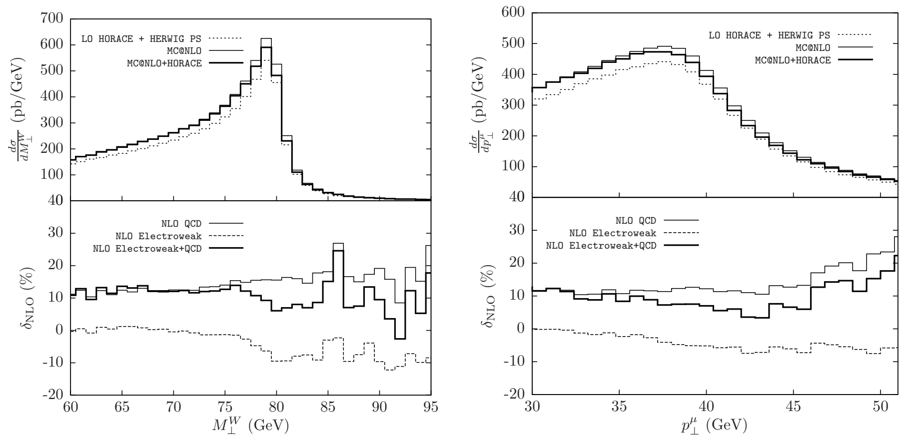


Figure 1: *Upper panel: predictions of MC@NLO, MC@NLO+HORACE and leading-order HORACE+HERWIG PS for the $M_\perp^W$ (left) and $p_\perp^\mu$ (right) distributions at the LHC, according to the cuts of set up a. of Eq. (3). Lower panel: relative effect of QCD and EW corrections, and their sum, for the corresponding observables in the upper panel.*

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 Eq. (3), and in Fig. 2 for the same distributions according to set up b. In Fig. 1 and Fig. 2, the upper panels show the predictions of the generators MC@NLO and MC@NLO + HORACE interfaced to HERWIG PS (according to eq. (1)), in comparison with the leading-order result by HORACE convoluted with HERWIG shower evolution. The lower panels illustrate the relative effects of the matrix element residue of NLO QCD and of full EW corrections, as well as their sum, that can be obtained by appropriate combinations of the results shown in the upper panels. More precisely, the percentage corrections shown have been defined as $\delta = (\sigma_{\rm NLO} - \sigma_{\rm Born+HERWIG\,PS})/\sigma_{\rm Born+HERWIG\,PS}$, where $\sigma_{\rm NLO}$ stands for the predictions of the generators including exact NLO corrections matched with QCD PS.

From Fig. 1 it can be seen that the QCD corrections are positive around the $W$ jacobian peak, of about 10-20%, and tend to compensate the negative effect due to EW 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. It is also worth noting that the convolution of NLO corrections with the QCD PS broadens the sharply peaked shape of the fixed-order NLO QCD and EW effects.

The interplay between QCD and EW corrections to $W$ production 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 $p_\perp^\mu$, the QCD corrections are positive and largely cancel the negative EW Sudakov logarithms. Therefore, a precise normalization of the SM background to new physics searches necessarily requires the simultaneous control of QCD and EW corrections.

Results about the combination of QCD and EW corrections for the di-lepton invariant mass in the neutral-current D-Y process $pp \to \gamma, Z \to e^+e^- + X$, according to the cuts of Eq. (4) can be found in [41]. The QCD corrections are quite flat and positive with a value of about 15% over the mass range 200–1500 GeV. The EW corrections are negative and vary from about $-5\%$ to $-10\%$ and thus partially cancel the QCD contribution. Therefore, as for the charged-current channel, the search for new physics in di-lepton final states needs a careful combination of EW and QCD effects.

## 5 Conclusions

During the last few years, there has been a big effort towards high-precision predictions for D-Y-like processes, addressing the calculation of higher-order QCD and EW corrections. Correspondingly, precision computational tools

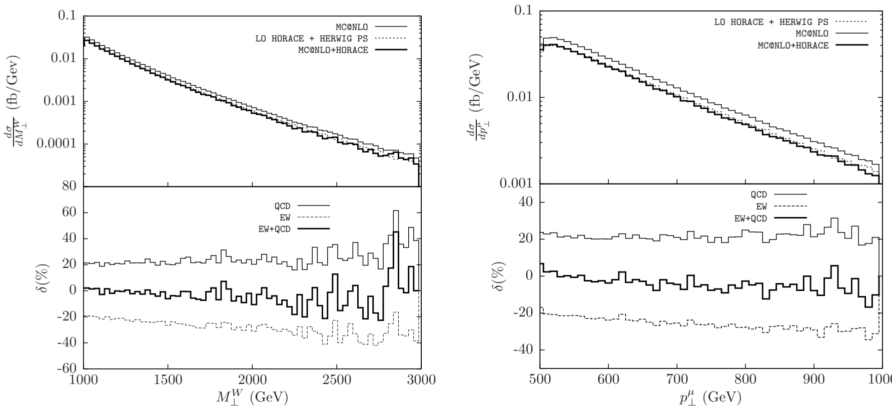


Figure 2: *Upper panel: predictions of MC@NLO, MC@NLO+HORACE and leading-order HORACE+HERWIG PS for the* $M_\perp^W$ *(left) and* $p_\perp^\mu$ *(right) distributions at the LHC, according to the cuts of set up a. of Eq. (3). Lower panel: relative effect of QCD and EW corrections, and their sum, for the corresponding observables in the upper panel.*

have been developed to keep under control theoretical systematics in view of the future measurements at the LHC.

We presented some original results about the combination of EW and QCD corrections to a sample of observables of $W$ and $Z$ production processes at the LHC. Our investigation shows that a high-precision knowledge of QCD and a careful combination of EW 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.

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