

STANDARD MODEL PRECISION TESTS AT  
HADRON COLLIDERS: THEORETICAL CONTROL  
ON DRELL–YAN PROCESSES\*

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After discussing the relevance of single- $W$  and single- $Z$  production processes at hadron colliders, we review the theoretical knowledge of Drell–Yan physics and present some preliminary results on the combination of electroweak and QCD corrections to a sample of observables of the process  $pp \rightarrow W^\pm \rightarrow \mu^\pm + X$  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 LHC experimental accuracy.

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## 1. Introduction

Charged and neutral current Drell–Yan (D–Y) processes, *i.e.*  $pp^{(-)} \rightarrow W \rightarrow l\nu_l + X$ , and  $pp^{(-)} \rightarrow Z/\gamma \rightarrow l^+l^- + X$  play a very important role at hadron colliders, since they have huge cross sections (*e.g.*  $\sigma(pp \rightarrow W \rightarrow l\nu_l + X) \sim 20$  nb at LHC and about a factor of ten less for  $\sigma(pp \rightarrow Z/\gamma \rightarrow l^+l^- + X)$ ) and are easily detected, given the presence of at least a high  $p_\perp$  lepton, which to trigger on. For these reasons and also because the physics around  $W$  and  $Z$  mass scale is now known with high precision after the LEP and Tevatron experience, D–Y processes will provide standard candles for detector calibration during the first stage of LHC running. 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  $pp \rightarrow Z/\gamma \rightarrow e^+e^-$  the mixing angle  $\sin^2 \vartheta_W$  could be extracted with a precision of  $1 \times 10^{-4}$ . Useful observables for the measurement of the  $W$  mass are the transverse mass distribution and the charged lepton transverse momentum distribution. While the latter is in principle experimentally cleaner, the former is less sensitive to the effects of higher order radiative corrections affecting the theoretical predictions. Another promising observable for the precision measurement of the  $W$  mass is the ratio  $(d\sigma/dM_W^T)/(d\sigma/dM_Z^T)$ , where the systematic effects of radiative corrections tend to partially cancel between numerator and denominator. Even if at Tevatron the method is limited by the large statistical error associated with the small  $Z$  production cross section, it will become very important at LHC, where the statistics is not a limiting factor.

The few per cent level precision in principle achievable in the cross sections motivated a proposal to use these observables as luminosity monitor for the LHC. Last, single- $W$  and single- $Z$  processes will 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.

For the above reasons, it is of utmost importance to predict the  $W$  and  $Z$  observables with as high as possible theoretical precision. 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 radiative corrections and their implementation in simulation tools.

## 2. Status of theoretical predictions

### 2.1. 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 [1, 2], NLO calculations for  $W, Z + 1, 2$  jets signatures [3, 4] (available in the codes DYRAD and MCFM), resummation of leading and next-to-leading logarithms due to soft gluon radiation [5, 6] (implemented in the Monte Carlo ResBos), NLO corrections merged with QCD Parton Shower (PS) evolution [7] (in the event generator MC@NLO), NNLO corrections to  $W/Z$  production in fully differential form [8, 9] (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 [10], MADEVENT [11], HELAC [12] and SHERPA [13].

As far as complete  $\mathcal{O}(\alpha)$  electroweak corrections to Drell–Yan processes are concerned, they have been computed independently by various authors in [14–18] for  $W$  production and in [19] for  $Z$  production. Electroweak tools implementing exact NLO corrections to  $W$  production are DK [14], WGRAD2 [15], SANC [17] and HORACE [18], while ZGRAD2 [19] 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 the same input parameters and cuts, in the proceedings of the Les Houches [20] and TEV4LHC [21] 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 [22] for  $W$  production and in [23] for  $Z$  production, and implemented in the event generator HORACE. Higher-order QED contributions to  $W$  production have been calculated independently in [24] using the YFS exponentiation, and are available in the generator WINHAC.

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 not negligible in view of the aimed accuracy in the  $M_W$  measurement at the LHC.

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  $\propto -(\alpha/\pi) \log^2(\hat{s}/M_V^2)$ ,  $V = W, Z$  [14, 15, 18, 19]. Furthermore, in this region, weak boson emission processes (*e.g.*  $pp \rightarrow e^+ \nu_e V + X$ ), 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 [25].

## 2.2. Combination of electroweak and QCD corrections

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 [26], 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.

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

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

where  $d\sigma/d\mathcal{O}_{\text{QCD}}$  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,  $d\sigma/d\mathcal{O}_{\text{EW}}$  is the HORACE prediction for the electroweak 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 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.

### 3. Numerical results

We study, for definiteness, the production process  $pp \rightarrow W^\pm \rightarrow \mu^\pm + X$  at the LHC ( $\sqrt{s} = 14$  TeV), imposing the cuts shown in Table I, where  $p_\perp^\mu$  and  $\eta_\mu$  are the transverse momentum and the pseudorapidity of the muon,  $E_T$  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  $M_\perp^W$ , which is interesting for new physics searches. The set of PDFs used in our study is MRST2004QED [27], 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 [14, 15, 18], and fixed at  $\mu_R = \mu_F = \sqrt{p_{\perp W}^2 + M_W^2}$ , as done in previous LHC studies [28].

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 $E_T \geq 25$ GeV and $ \eta_\mu  < 2.5$ |
| (b) | the cuts as above $\oplus$ $M_\perp^W \geq 1$ TeV                  |

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.

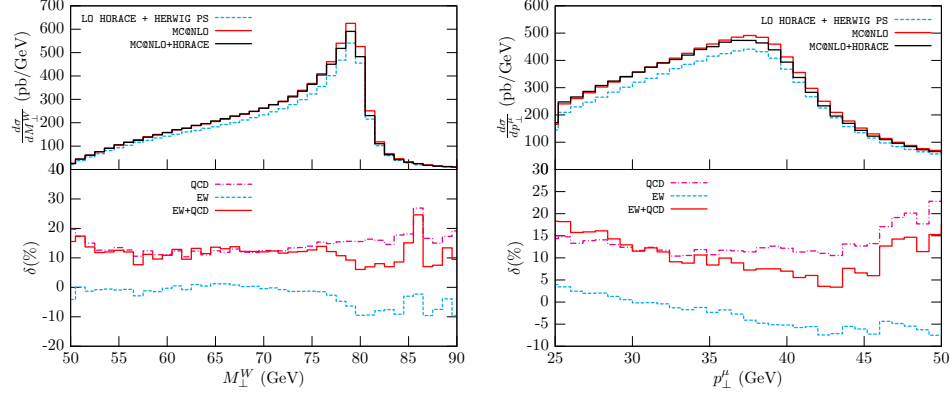


Fig. 1. Upper panel: predictions of MC@NLO, MC@NLO+HORACE and leading-order HORACE+HERWIG PS for the  $M_W^\perp$  (left) and  $p_\perp^\mu$  (right) distributions at the LHC, according to the cuts of set up (a). Lower panel: relative effect of QCD and electroweak corrections, and their sum, for the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

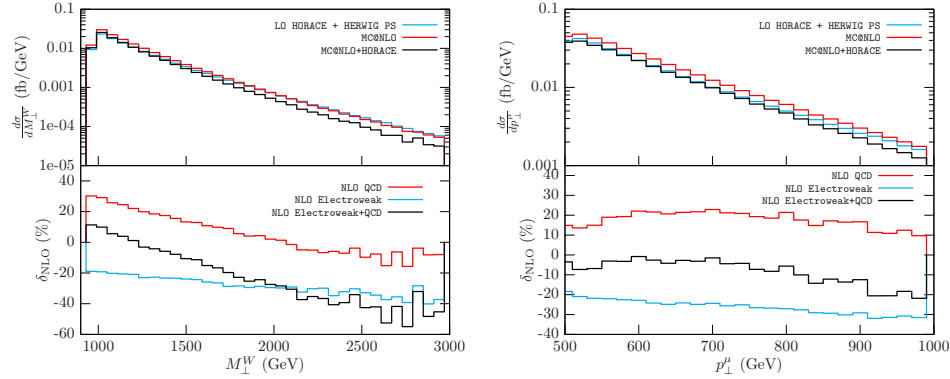


Fig. 2. The same as Fig. 1 according to the cuts of set up (b).

The interplay between QCD and electroweak corrections in the region interesting for new physics searches, *i.e.* in the high tail of  $M_W^\perp$  and  $p_\perp^\mu$  distributions, is shown in Fig. 2. For both  $M_W^\perp$  and  $p_\perp^\mu$  NLO QCD cor-

rections are positive and partially cancel the negative electroweak Sudakov logarithms. Their sum is about  $-10(-40)\%$  for  $M_{\perp}^W \simeq 1.5(3)$  TeV and about  $-5(-20)\%$  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.

#### 4. 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  $pp \rightarrow W^{\pm} \rightarrow \mu^{\pm} + X$  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” [29]. 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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