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Review of precision calculations for the measurement of electroweak boson production and properties at hadron colliders

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Abstract. We review the present status of precision calculations and tools for the study of single electroweak gauge boson production at hadron colliders. The state-of-the-art of higher-order electroweak and QCD calculations, as well as their combination, is summarized, paying particular attention to the precision measurements of the W -boson parameters at the Fermilab Tevatron and CERN LHC.

1. Introduction

The production of electroweak (EW) gauge bosons W, Z in hadronic collisions, with the weak boson decaying into a lepton pair, is a particularly clean process with a large cross section at hadron colliders. Drell-Yan processes are of particular interest to perform precision measurements of EW parameters, such as the W -boson mass M_W and width Γ_W , as well as to monitor the collider luminosity with per cent precision and constrain the Parton Distribution Functions. They are also important backgrounds to new physics searches, such as the search for heavy gauge bosons predicted by Standard Model extensions.

As reported at the conference [1; 2], the first Run II measurements at the Tevatron of M_W and Γ_W have a total experimental uncertainty of 48 MeV and 71 MeV, respectively, which are the world's most precise single measurements to date. In the light of this situation and in view of the aimed accuracy at the LHC, precise theoretical predictions and Monte Carlo generators, including higher-order QCD and EW corrections, are definitely needed.

2. Higher-order QCD calculations and generators

Concerning QCD calculations and tools for EW gauge boson production at hadron colliders, 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 [3; 4], resummation of leading and next-to-leading logarithms due to soft-gluon radiation [5] (implemented in the Monte Carlo ResBos used at the Tevatron), NLO corrections merged with

QCD Parton Shower (PS) evolution [6] (in the event generator MC@NLO), NNLO corrections to W/Z production in fully differential form [7–9] (available in the Monte Carlo program FEWZ), as well as leading-order multi-parton matrix elements generators matched with vetoed PS, such as, for example, ALPGEN [10], MADEVENT [11] and SHERPA [12].

In particular, the possibilities offered by high-precision QCD calculations are exemplified by the NNLO predictions for the W/Z rapidity distributions, given in Ref. [7], where it is shown that NNLO corrections decrease the NLO result by about 2% and the scale dependence of the NNLO calculation is below the 1%, indicating a good convergence of the perturbative expansion. It must be emphasized that, at this precision level, NLO EW corrections are, a priori, of the same order of magnitude of $\mathcal{O}(\alpha_s^2)$ contributions and, therefore, they need to be included, for consistency, in the theoretical predictions, as demonstrated, for instance, in Ref. [13].

3. Electroweak corrections and tools

3.1. Next-to-leading-order corrections

Complete NLO EW calculations to both charged-current (CC) and neutral-current (NC) Drell-Yan processes are available today, as computed independently by various groups [13–18]. EW tools implementing exact NLO corrections to W production are DK [14], WGRAD2 [15], SANC [17] and HORACE [13], while ZGRAD2 [18] includes the full set of $\mathcal{O}(\alpha)$ EW corrections to Z production. In particular, WGRAD2 is an improved version of WGRAD [19], which is the code used at the Tevatron for the measurement of the W mass and is limited to the so-called pole approximation. The latter consists in evaluating the EW form factors at the partonic c.m. energy $\sqrt{\hat{s}} = M_W$ and in neglecting the W/Z box diagrams, that are not resonant contributions in the vicinity of the W resonance. On the other hand, ZGRAD2 is an improved version of ZGRAD [20], which is presently used at the Tevatron and includes the gauge-invariant subset of QED corrections to the NC Drell-Yan process.

From the above calculations, it turns out that NLO electroweak corrections to W and Z production are largely dominated, in the resonant region, by final-state QED radiation containing large collinear logarithms of the form $\log(\hat{s}/m_l^2)$, where m_l is the lepton mass. These corrections amount to several per cent, distort the shape of the distributions of interest and cause a significant shift (of the order of 100-200 MeV) in the extraction of the W mass at the Tevatron.

It is also worth noting that, as discussed in Ref. [2], the measurement of the W width at the Tevatron relies on the inclusion of final-state QED radiation only, according to the calculation of Ref. [21]. However, if one considers the relevant regions for the direct measurement of the W width, *i.e.* $100 \text{ GeV} \leq M_T^W \leq 200 \text{ GeV}$ and $60 \text{ GeV} \leq p_T^l \leq 100 \text{ GeV}$, it can be seen from Fig. 1 and Fig. 2 (for the W decay into muons) that the theoretical predictions including only final-state QED radiation differ from the complete NLO EW calculation at the level of some per cent, when considering standard selection criteria and realistic muon identification requirements. This could have some impact on the precision measurement of the W width and it would be interesting to quantify the impact of such a difference on the determination of the Γ_W value, when performing fits to experimental data.

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 electroweak Sudakov logarithms $\propto -(\alpha/\pi) \log^2(\hat{s}/M_V^2)$, $V = W, Z$ [13–18]. 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 Ref. [22].

Concerning the level of agreement between the predictions of the different codes implementing exact EW calculations, detailed tuned comparisons, using the set of same input parameters and

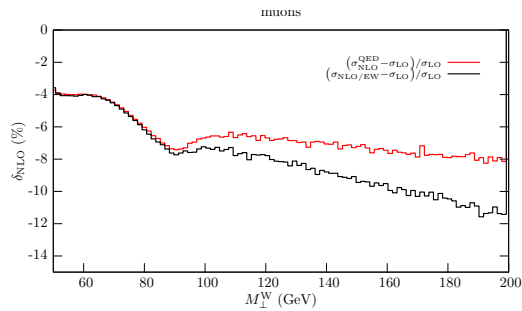


Figure 1. Relative effect of final-state QED radiation only in comparison with the one due to complete NLO EW corrections, as a function of the W transverse mass, at the Tevatron.

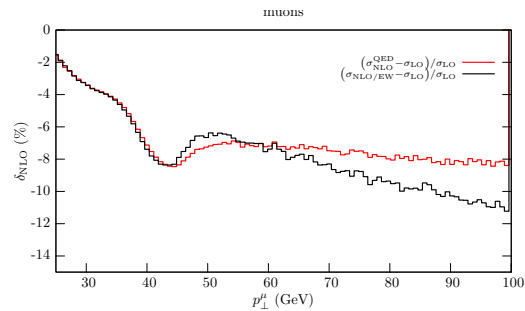


Figure 2. Relative effect of final-state QED radiation only in comparison with the one due to complete NLO EW corrections, as a function of the lepton transverse momentum, at the Tevatron.

cuts, have been recently reported in the proceedings of the Les Houches [23] and TEV4LHC [24] workshops. A very satisfactory agreement between the various, independent calculations has been found, showing that NLO EW corrections to W production are under control. Work is in progress to perform similar comparisons for the Z production process.

3.2. Multiple photon corrections

Since, as already remarked, $\mathcal{O}(\alpha)$ final-state radiation causes a significant shift in M_W , it is necessary to worry about the contribution of higher-order QED corrections beyond $\mathcal{O}(\alpha)$. The leading logarithmic corrections due to multiple photon radiation from the final-state leptons have been computed, by means of a QED PS approach, in Ref. [25] for W production and in Ref. [26] for Z production, and implemented in the event generator HORACE. Higher-order QED contributions to W production have been calculated independently in Ref. [27] using the YFS exponentiation, and are available in the generator WINHAC. Comparisons of such multi-photon calculations are documented in Ref. [28], 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 [25]. Therefore, such an effect is not negligible in view of the aimed accuracy in the M_W measurement at hadron colliders. In Ref. [26] it has been also proved that multiple photon corrections are relevant for Z production too, because important sources of systematic error in the W mass determination, such as the error coming from momentum and energy scale calibrations, are directly related to the extraction of the Z -boson mass. Again, the shift in M_Z due to higher-order contributions was found to be about 10% and of opposite sign of that due to one-photon radiation. This shift is of the same order of the statistical uncertainty presently reached in Z mass fits at the Tevatron and constitutes a further motivation to take care of multiple photon radiation in the experimental analysis.

4. Combining electroweak and QCD corrections

In spite of the detailed knowledge of higher-order EW and QCD corrections, the combination of their effects is still at a very preliminary stage. There is only one attempt known in the literature [29], where the effects of QCD resummation are combined with NLO QED final-state corrections, leaving room for more detailed studies of the interplay between EW and QCD corrections to W/Z production in hadronic collisions.

Starting from a factorized expression for the combination of EW 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 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, more importantly, to obtain a more realistic description of the observables under study.

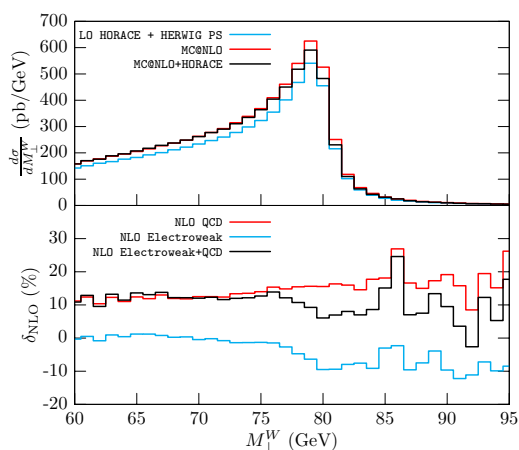


Figure 3. W transverse mass distribution at the LHC and relative effect of NLO EW and QCD corrections, together with their combination.

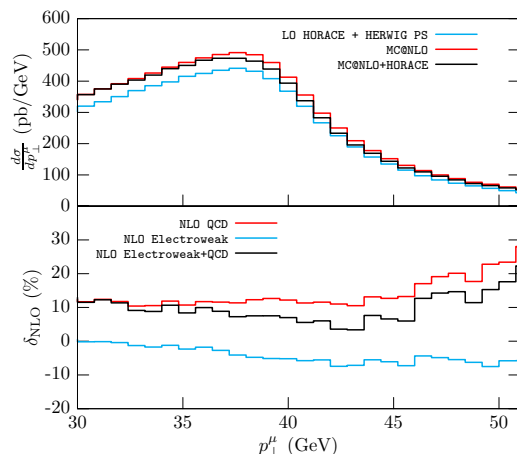


Figure 4. Lepton transverse momentum distribution at the LHC and relative effect of NLO EW and QCD corrections, together with their combination.

A sample of our numerical results is shown in Fig. 3 and in Fig. 4 for the W transverse mass M_{\perp}^W and muon transverse momentum p_{\perp}^{μ} distributions, respectively, according to standard selection cuts at the LHC. 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 EW corrections, as well as their sum, that can be obtained by appropriate combinations of the results shown in the upper panels. It can be seen that the NLO QCD corrections are positive around the jacobian peak and tend to compensate the effect due to EW corrections, showing that their interplay is crucial for a precise M_W extraction at the LHC. Moreover, it is worth noting how the well-known peaked shape of EW corrections around the W peak [13; 14; 19] is significantly broadened by the convolution with QCD PS.

5. Conclusions

The calculations of higher-order QCD and EW corrections to single gauge boson production at hadron colliders, as well as the corresponding computational tools, are essential ingredients for precision studies of Drell-Yan processes at the Tevatron Run II and LHC. In particular,

exact NLO EW corrections and multiple photon corrections are reducible sources of systematic uncertainty in the measurement of W -boson parameters and should be included in future analysis, beyond the present theoretical approximations adopted on the experimental side. A careful combination of QCD and EW contributions is also mandatory.

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