Electroweak Physics: Theoretical Overview

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Abstract. I give an overview of the theory status of predictions for single W and Z boson production at hadron colliders. I briefly report on work in progress for improvements necessary to match the anticipated high precision of electroweak measurements, such as the W mass and width, at the Fermilab Tevatron p¯p and the CERN LHC pp colliders.

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INTRODUCTION

Electroweak gauge boson production processes are one of the best, most precise probes of the Standard Model (SM). The electroweak physics program involving single W and Z boson production at hadron colliders has many facets:

• The comparison of direct measurements of the W boson mass (MW) and width (ΓW) in W pair production at LEP2 and single W production at the Tevatron, with indirect measurements from a global fit to electroweak precision data measured at LEP1/SLD, represents a powerful test of the SM. Any disagreement could be interpreted as a signal of physics beyond the SM. At present, direct and indirect measurements of MW and ΓW agree within their respective errors: MW(LEP2/Tevatron) = 80.392 ± 0.029 GeV versus MW(LEP1/SLD) = 80.363 ± 0.032 GeV and ΓW(LEP2/Tevatron) = 2.147 ± 0.060 GeV versus ΓW(LEP1/SLD) = 2.091 ± 0.003 GeV. Continued improvements in theory and experiment will further scrutinize the SM.

• The precise measurements of MW and the top quark mass (mt) provide an indirect measurement of the SM Higgs boson mass, Mh, and a window to physics beyond the SM, as illustrated in Figure 1. With the present knowledge of MW and mt, the SM Higgs boson mass can be indirectly constrained by a global fit to all electroweak precision data to be smaller than 199 GeV at 95% C.L. Future more precise measurements of MW and mt will considerably improve the present indirect bound on Mh: At the LHC, for instance, with anticipated experimental precisions of δMW = 15 MeV and δmt = 1 GeV, Mh can be predicted with an uncertainty of about δMh/Mh = 18%. In Figure 1 the predictions for MW(mt, Mh,...) within the SM and the minimal supersymmetric SM (MSSM) are confronted with their measurements today, at the LHC, and an International Linear Collider (ILC).

• The measurement of the mass and width of the Z boson and the total W and Z production cross sections can be used for detector calibration and as luminosity monitors, respectively.

• The W charge asymmetry and Z rapidity distributions severely constrain quark Parton Distribution Functions (PDFs).

• New, heavy gauge bosons may leave their footprints in forward-backward asymmetries, AFB, and the distribution of the invariant mass of the lepton pair, M(ll), produced in Z boson production at high M(ll). In Figure 2 the effects of a Z′ on AFB(M(ll)) at the LHC are shown, assuming a number of different models of extended gauge boson sectors, and compared with simulated data assuming a specific model. As can be seen, measurements of AFB at the LHC will be able to distinguish between different new physics scenarios provided, of course, the SM prediction is well under control.

In order to fully exploit the potential of the Tevatron and LHC for electroweak (EW) precision physics, the predictions have to be of the highest standards as well. The omission of EW radiative corrections in the comparison...
of predictions with data could result in fake signals of non-standard physics. For instance, in Ref. [7] it has been shown that the effects of weak non-resonant corrections on the tail of the transverse mass distribution of the lepton pair, $M_T(l\nu)$, produced in $p\bar{p} \rightarrow W \rightarrow l\nu$ at the Tevatron, from which $\Gamma_W$ can be extracted, are of the same order of magnitude as effects due to non-SM values of the $W$ width. Another example is $WZ$ production at the LHC, which is a sensitive probe of the non-abelian structure of the SM EW sector. As can be seen in Figure 3 [8], effects of non-standard weak gauge boson self-couplings can be similar in size and shape to the effects of EW corrections, and, thus, not including the latter could be mistaken as signals of new physics. Consequently, in recent years a lot of theoretical effort has gone into improving the predictions for $W$ and $Z$ production processes in order to match (or better exceed) the anticipated experimental accuracy. This not only requires the calculation of higher-order corrections but also their implementation in Monte Carlo (MC) integration programs for realistic studies of their effects on observables. In the following, I will first review some of the available theoretical tools and then provide a brief overview of the effects of EW radiative corrections on $W$ and $Z$ boson observables at hadron colliders. Finally, I will describe recent developments and work in progress in the context of the TeV4LHC workshop.

THEORETICAL STATUS

Fully differential cross sections for single $W$ and $Z$ boson production at hadron colliders are known at next-to-next-to-leading order (NNLO) QCD [9, 10, 11, 12] (and references therein). Predictions for the $W$ transverse momentum distribution, $p_T(W)$, an important ingredient in the current $W$ mass measurement at the Tevatron, include an all-order

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The predictions for the $W$ mass in dependence of the top quark mass within the SM and MSSM in comparison with experimental $M_W$ and $m_t$ measurements at 68\% C.L.. The bands are obtained by varying the free parameters of the underlying model. Taken from Ref. [2].}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The forward-backward asymmetry, $A_{FB}(M(ll))$, of single $Z'$ production in $pp \rightarrow Z' \rightarrow l^+ l^-$ at the LHC for a number of models with heavy, non-standard gauge bosons. Taken from Ref. [6].}
\end{figure}
observables are strongly affected by EW corrections. Their main characteristics can be summarized as follows: more details see Ref. [8].

FIGURE 3. The maximal transverse momentum distribution of the charged leptons and the rapidity distribution of the reconstructed Z boson in WZ production at the LHC. Shown is the lowest order (Born) and the next-to-leading order (NLO) result including electroweak corrections. The labels $2a-4b$ denote different choices for anomalous triple gauge-boson couplings. For more details see Ref. [3].

TABLE 1. MC programs that provide precise predictions including QED and/or electroweak corrections for W and/or Z boson production at hadron colliders.

| Program   | Description                                                                              | Website                      |
|-----------|------------------------------------------------------------------------------------------|------------------------------|
| HORACE    | Multiple final-state photon radiation in W and Z production as solution of QED DGLAP evolution for lepton structure functions [19, 21], matched with exact EW $\mathcal{O}(\alpha)$ corrections to W production [17], [http://www.pv.infn.it/~hepcomplex/horace.html](http://www.pv.infn.it/~hepcomplex/horace.html) |
| RESBOS    | QCD corrections to W and Z production, soft gluon resummation, final-state QED $\mathcal{O}(\alpha)$ corrections [13, 22], [http://ubpheno.physics.buffalo.edu/~balazs/ResBos](http://ubpheno.physics.buffalo.edu/~balazs/ResBos) |
| SANC      | EW corrections to W and Z production: automatically generates Fortran code for one-loop corrections at parton level [16, 23], [http://sanc.jinr.ru](http://sanc.jinr.ru) |
| WGRAD2    | QED $\mathcal{O}(\alpha)$ and weak one-loop corrections to W production [7], [http://ubpheno.physics.buffalo.edu/~dow/wgrad.html](http://ubpheno.physics.buffalo.edu/~dow/wgrad.html) |
| WINHAC    | Multiple final-state photon radiation in W production via YFS exponentiation of soft photons [20], [http://placzek.home.cern.ch/placzek/winhac](http://placzek.home.cern.ch/placzek/winhac) |
| ZGRAD2    | QED $\mathcal{O}(\alpha)$ and weak one-loop corrections to Z production with proper treatment of higher-order terms around the Z resonance [18], [http://ubhhex.physics.buffalo.edu/~baur/zgrad2.tar.gz](http://ubhhex.physics.buffalo.edu/~baur/zgrad2.tar.gz) |

resummation of leading logarithms arising from soft gluon radiation [13, 14]. The complete EW $\mathcal{O}(\alpha)$ corrections to $pp, p\bar{p} \to W \to l\nu$ and $pp, p\bar{p} \to Z, \gamma \to l^+l^-$ have been calculated in Ref. [13, 7, 16, 17] and [18], respectively. Predictions including multiple final-state photon radiation have been presented in Ref. [13, 20, 21]. Most of these higher-order calculations have been implemented in MC programs and a list of some of the available codes providing precise prediction for W and Z boson observable at hadron colliders can be found in Table 1. W and Z boson observables are strongly affected by EW corrections. Their main characteristics can be summarized as follows:

- Photon radiation off the final-state charged lepton can considerably distort kinematic distributions and usually makes up the bulk of the effects of EW corrections. For instance, W and Z boson masses extracted respectively from the transverse mass and invariant mass distributions of the final-state lepton pair are shifted by $\mathcal{O}(100)$ MeV due to final-state photon radiation. This is due to the occurrence of mass singular logarithms of the form $\alpha \log(Q^2/m^2)$ that arise when the photon is emitted collinear to the charged lepton. In sufficiently inclusive observables these mass singularities completely cancel (KLN theorem). But in realistic experimental environments, depending on the experimental setup, large logarithms can survive. This is demonstrated in Figure 3 [24]: the more inclusive treatment of the photon emitted in $W^+ \to e^+\nu_e$ decays results in a significant reduction of the final-state QED effects when lepton identification cuts are applied whereas in the muon case large logarithms survive. Because of their numerical importance at one-loop, the higher-order effects of multiple final-state photon radiation have to be under good theoretical control as well [19, 20, 21].

- The impact of initial-state photon radiation is negligible after proper removal of the initial-state mass singularities by universal collinear counterterms to the quark PDFs. This mass factorization introduces a dependence on the
FIGURE 4. The ratio of the full $\mathcal{O}(\alpha^3)$ and Born transverse mass distribution of the final-state lepton pair, $M_T(l\bar{\nu})$, in $p\bar{p} \to W^+ \to l^+\nu$ ($l=e,\mu$) at the Tevatron with (dashed line) and without (solid line) lepton identification requirements. Shown are the results for the electron and muon case, which differ significantly in the treatment of the photon emitted collinear to the charged lepton. For more details see Ref. [24].

FIGURE 5. The ratio of the $\mathcal{O}(\alpha^3)$ $M_T(l\bar{\nu})$ distribution and an effective Born approximation (EBA) at the Tevatron and LHC, calculated in the pole approximation (dashed line) and including the complete EW $\mathcal{O}(\alpha)$ corrections (solid line). The difference between these two calculations is mainly due to the occurrence of large weak Sudakov-like logarithms: they are absent in the pole approximation where the weak corrections are calculated at $Q^2=M_Z^2$. For more details see Ref. [7].

QED factorization scheme: in complete analogy to QCD both the QED DIS and $\overline{\text{MS}}$ scheme have been introduced in the literature [24]. Recently, quark PDFs became available that also incorporate QED radiative corrections [25], which is important for a consistent treatment of initial-state photon radiation at hadron colliders.

- At high energies, i.e. in tails of kinematic distributions, for instance $M(ll) \gg M_Z$ and $M_T(l\bar{\nu}) \gg M_W$, Sudakov-like contributions of the form $\alpha \log^2(Q^2/M_V^2)$ ($M_V=M_W, Z$ and $Q$ is a typical energy of the scattering process) can significantly enhance the EW one-loop corrections. These corrections originate from remnants of UV singularities after renormalization and soft and collinear initial-state and final-state radiation of virtual and real weak gauge bosons. In contrast to QED and QCD the Bloch-Nordsiek theorem is violated, i.e. even in fully inclusive observables these large logarithms are present due to an incomplete cancellation between contributions from real and virtual weak gauge boson radiation [26]. Moreover, the $W$ and $Z$ boson masses serve as physical cut-off parameters and real $W$ and $Z$ boson radiation processes are usually not included, since they result in different initial and/or final states. The EW logarithmic corrections of the form $\alpha^L \log^N(Q^2/M_V^2), 1 \leq N \leq 2L$ ($L=1,2,\ldots$ for 1-loop, 2-loop, \ldots) to 4-fermion processes are known up to 2-loop $N^3LL$ order and are available in form of compact analytic formulae (see, e.g., Refs. [27, 28, 29] and references therein). Examples of the effects of these large weak corrections on $W$ and $Z$ boson observables at one-loop order are shown in Figure 5 ($M_T(l\bar{\nu})$ distribution) [7] and Figure 6 ($M(ll)$ and $A_{FB}(M_{ll})$ distributions) [18], respectively.

The importance of fully understanding and controlling EW radiative corrections to precision $W$ and $Z$ boson observables at hadron colliders is illustrated in Table 2 on the example of a precise $W$ mass and width measurement. It demonstrates how theoretical progress is driven by improvements in the experimental precision.
FIGURE 6. Comparison of predictions for the $M_{ll}$ ($l = e, \mu$) distribution and $A_{FB}(M_{ll})$ that include either only QED or the complete EW $\mathcal{O}(\alpha)$ corrections to Z boson production at the LHC. The increasing difference between these two calculations with $M_{ll}$ is due to the occurrence of large weak Sudakov-like logarithms. The effects differ for muons and electrons in the final state due the differences in the applied lepton identification cuts. For more details see Ref. [18].

TABLE 2. Impact of EW radiative corrections on W boson observables, in particular $M_W$ and $\Gamma_W$ extracted from the $M_T(l\nu)$ distribution, confronted with present and anticipated experimental accuracies [4, 32, 33, 34, 35].

| Theory includes:                                      | Effects on observable:                                      | Experimental precision:                                      |
|------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| final-state QED (approximation) [30]                  | shift in $M_W$: -65 ± 20 (-168 ± 20 ) MeV in the $e(\mu)$ case | Tevatron RUN I: $\delta M_W^{\text{QED}} = 59$ MeV $\delta \Gamma_W^{\text{QED}} = 87$ MeV |
| full EW $\mathcal{O}(\alpha)$ contribution to resonant W production (pole approx.) [31, 24] | shift in $M_W$: ≈ 10 MeV                                     | Tevatron RUN II: $\delta M_W^{\text{QED}} = 27$ MeV          |
| full EW $\mathcal{O}(\alpha)$ corrections             | affects distributions at high $Q^2$ and direct $\Gamma_W$ measurement, shift in $\Gamma_W$: ≈ 7 MeV [7] | Tevatron RUN II: $\delta \Gamma_W^{\text{QED}} = 25 - 30$ MeV |
| real two-photon radiation [36]                        | significantly changes shape of $M_T$                        | LHC: $\delta M_W^{\text{QED}} = 15$ MeV                     |
| multiple final-state photon radiation                 | shift in $M_W$: 2(10) MeV in the $e(\mu)$ case [19]        |                                                             |

WORK IN PROGRESS

The EW working group of the TeV4LHC workshop is presently addressing the following questions: What is the residual theoretical uncertainty of the best, presently available predictions for W and Z boson production at hadron colliders? Do we need more theoretical improvements to be able to fully exploit the EW physics potential of the Tevatron and the LHC? As a first step, the EW working group will perform a tuned numerical comparison of available codes that provide precise predictions for W and Z observables (see Table 1) in the spirit of the LEPI/II CERN yellow books. First results of a tuned comparison of W and Z production cross sections and kinematic distributions can be found in Ref. [37]. First studies of effects of combined EW and QCD corrections, higher-order EW Sudakov-like logarithms and multiple final-state photon radiation suggest that for the anticipated precision at the LHC these effects need to be included in the data analysis. Moreover, the model for non-perturbative QCD contributions, small $x$ effects and the impact of heavy-quark masses need to be well understood for a detailed description of the $p_T(W)$ distribution. Several groups are presently working on the combination of EW and QCD radiative corrections in one MC program, the interface of higher-order EW calculations, i.e. multiple photon radiation from final-state leptons and EW Sudakov logarithms, with fixed $\mathcal{O}(\alpha)$ calculations, and the calculation of mixed QED/QCD two-loop corrections of $\mathcal{O}(\alpha\alpha_s)$, which are not yet available. The ultimate goal is to provide one unified MC program that includes all relevant QED, EW and QCD radiative corrections to W and Z boson production that matches the anticipated experimental capabilities of the Tevatron and LHC for EW precision physics.

3 See http://conferences.fnal.gov/tev4lhc for more information.
CONCLUSIONS

Electroweak gauge boson physics offers plentiful and unique opportunities to test the SM and search for signals of physics beyond the SM. Impressive progress has been made in providing precise predictions at NLO, NNLO QCD and NLO EW and higher (in leading logarithmic approximation), and a number of MC programs have been made available to study their effects on observables. In the context of the TeV4LHC workshop, these tools are used to determine if they are sufficient in view of the anticipated experimental capabilities for EW precision physics at the Tevatron and the LHC. There is ongoing work on further improving the predictions for W and Z boson observables and on providing one MC program, including all relevant QED, EW and QCD corrections, which will meet the high standards of W and Z boson measurements at the Tevatron and the LHC.

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