**W and Z Boson Production at Hadron Colliders**

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The electroweak theory has been tested to high precision, with measurements probing its predictions at the loop level. The current generation of particle accelerators will produce enough W and Z bosons through hadron collisions to significantly improve the accuracy of these measurements. I review the issues related to such production, with particular emphasis on associated uncertainties on the W boson mass, which has now been measured more precisely at the Tevatron than at the Large Electron Positron collider.

1. Introduction

The electroweak theory is highly overconstrained, with three fundamental parameters at tree level [1] and more than a dozen precise measurements of quantities derived from these parameters [2]. The experimental precision of these measurements, typically at the 0.1% level, is sufficient to probe for loop interactions of both observed and unobserved particles. Ongoing and future measurements at the Fermilab Tevatron and the Large Hadron Collider (LHC) will improve the accuracy of several quantities at the loop level. The mixing angle between the electromagnetic and weak symmetries, accessed through forward-backward lepton asymmetries, could have a reduced uncertainty from the full Tevatron data set [3]. The W boson mass and width have been measured most precisely by the DØ [4] and CDF [5] experiments, respectively, with accuracies that will significantly improve with the larger available data sets. The combined Tevatron top-quark mass measurement has a relative precision of 0.75% [6].

Of these measurements, the W boson mass has the greatest potential in the near term to significantly tighten constraints on unobserved particles [7]. The combination of existing measurements gives $m_W = 80.399 \pm 0.023 \text{GeV}$ [7], and future CDF and DØ measurements using data already collected will be at least this precise. Including predictions from the LHC, hadron-collider measurements expect [4,9] to +1σ shifts in several inputs to $m_W$. Of these measurements, the W boson mass has the greatest potential to improve the accuracy of several quantities at the loop level. The mixing angle between the electromagnetic and weak symmetries, accessed through forward-backward lepton asymmetries, could have a reduced uncertainty from the full Tevatron data set. The W boson mass and width have been measured most precisely by the DØ and CDF experiments, respectively, with accuracies that will significantly improve with the larger available data sets. The combined Tevatron top-quark mass measurement has a relative precision of 0.75%, or about a factor of three reduction of the current uncertainty.

A reduction of $m_W$ uncertainty will directly constrain the properties of new particles. The tree-level prediction $m_W = 79.964 \pm 0.005 \text{GeV}$ is more than 18σ from the measured value. An important loop correction arises from the top-bottom loop, due to the large mass difference $m_t - m_b$, with the correction proportional to $m_t^2$ [9]. The correction arising from Higgs boson loops is proportional to $\ln m_H$. Table I shows the shift in $m_W$ due to a doubling of $m_H$ and to +1σ shifts in several inputs to $m_W$ [5,10].

Given the ongoing and potential constraints from measurements of $m_W$, I focus on the status of experimental and theoretical uncertainties on this measurement at hadron colliders.

### Table I

| Parameter Shift | $m_W$ Shift (MeV/$c^2$) |
|-----------------|-------------------------|
| $\Delta \ln m_H = +0.693$ | -41.3 |
| $\Delta m_t = +1.3 \text{ GeV}/c^2$ | 7.9 |
| $\Delta \alpha_{EM}(Q = m_W c^2) = +0.00035$ | -6.2 |
| $\Delta m_Z = +2.1 \text{ MeV}/c^2$ | 2.6 |

2. W and Z Boson Production

There are many components of W and Z boson production at the Tevatron that enter into the $m_W$ measurement (Fig. 1 [5]). The interacting partons have a fraction $x$ of the (anti)proton’s momenta, with the relative fractions determining the boson’s longitudinal momentum. Initial-state radiation (ISR) of gluons or photons can give the boson a transverse boost $p_T^{W,Z}$. The boson decay is governed by the lepton electroweak interactions, or $+1\sigma$ shifts in several inputs to $m_W$. The boson decay is governed by the lepton electroweak interactions, or $+1\sigma$ shifts in several inputs to $m_W$.

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Figure 1: Leading-order production of W and Z bosons at the Tevatron [5]. Additional corrections from initial-state QCD or final-state QED radiation must be modelled accurately for the $m_W$ measurement.
2.1. Parton Distribution Functions

The momentum fraction $x$ of a given colliding parton is described by the parton distribution functions (PDFs). The PDFs are defined and fit to global data by independent groups \[11\, 12\] at a fixed momentum transfer $Q$, and extrapolated to higher $Q$ using the DGLAP equations \[13\]. Uncertainties on the input data are typically smaller than the deviations between the data for a given parton distribution function, resulting in poor global values of $\chi^2$ on the fits. Estimates of the PDF uncertainty on any given quantity follow an ad-hoc recipe defined by the fitters. The recipe typically gives a “90% confidence level (C.L.)” uncertainty, though this is based more on experience than on pure statistics. A significant challenge to the $m_W$ measurement is ensuring the accuracy of this uncertainty, and reducing it.

The uncertainty on $m_W$ due to PDFs arises from the detector acceptance to a charged lepton at a given pseudorapidity. Charged leptons decaying transverse to the beam carry the highest $p_T$ (half the boson mass, to first order). The smaller the decay angle with respect to the beam line, the smaller the $p_T$. At small angles, the charged lepton leaves the detector acceptance, and boosting the lepton along the beam axis affects the distribution of angles (and, correspondingly $p_T$) accepted by the detector. An uncertainty on the boost translates weakly into an uncertainty on $m_W$. The PDF uncertainty on the most recent DØ (CDF) $m_W$ measurement is 10 (13) MeV \[4\, 5\].

Tevatron data provide significant constraints on PDFs. For the $m_W$ measurement, the most relevant constraints come from measurements of the $Z$ boson rapidity distribution and the $W$ boson production charge asymmetry. Because $\sigma_W \times BR(W \rightarrow l\nu)/\sigma_Z \times BR(Z \rightarrow ll) \approx 10 \; 14\, 1$, the $W$ boson charge asymmetry has greater statistical power than the $Z$ boson rapidity. In addition, the charge asymmetry is a direct study of the $W$ boson production relevant to the $m_W$ measurement.

2.1.1. $W$ Boson Charge Asymmetry

On average, up quarks carry a higher fraction of the proton’s momentum than down quarks. Thus, the longitudinal momentum of the $W^+$ boson tends to be in the direction of the proton momentum. A measurement of the asymmetry between $W^+$ and $W^-$ production at a given boson rapidity gives information on the ratio of up- to down-quark momentum fraction. Historically, the asymmetry between the charged leptons from the $W$ boson decay have been measured, since the neutrino is not measured and the $W$-boson’s rapidity can not be fully reconstructed. The DØ Collaboration has recently performed such a measurement (Fig. 2 \[15\]), and incorporating its results into the PDF fits will improve their accuracy.

![Figure 2: The electron charge asymmetry as a function of pseudorapidity, as measured by the DØ Collaboration (points) and predicted by the CTEQ (solid line) and MRST (dashed line) PDF fits. Also shown is the CTEQ 90% C.L. uncertainty band.](image)

The CDF Collaboration has developed a novel method for directly measuring the $W$-boson charge asymmetry. The method solves for the boson rapidity using the $W$-boson mass as a constraint. The two solutions are given weights according to the expected boson kinematic and decay distributions. To remove any dependence on the input charge asymmetry, the procedure is iterated until a stable solution is reached. The CDF data (Fig. 3 \[16\]) will significantly improve predictions of the PDFs at high $W$ boson rapidity.

![Figure 3: The $W$ boson charge asymmetry as a function of rapidity, as measured by the CDF Collaboration (points) and predicted by the CTEQ (top) and MRST (bottom) fits (including the 90% C.L. uncertainty bands).](image)
2.1.2. Issues for the $m_W$ Measurement

With the overall precision on $m_W$ expected to approach 20 MeV in the next iteration of Tevatron measurements, it is useful to consider methods to produce a more robust estimate of the PDF uncertainty. Currently, both CDF and DØ rescale the 90% C.L. uncertainty obtained from the CTEQ recipe to produce a 68% C.L. uncertainty on $m_W$. This is motivated by the empirical observation that the spread of data for the valence $u$ and $d$ quarks are roughly Gaussian [17]. However, the gluon contribution to the $m_W$ uncertainty is non-negligible, and the 90% C.L. definition is not obtained strictly by statistics. There is thus some ambiguity as to whether the rescaling of uncertainties is appropriate.

In addition to the question of uncertainty scaling, there is the issue of the functions used to parametrize the PDFs. There is considerable flexibility in the choice of functions, and there are various assumptions that are generally made to reduce the number of parameters in the fits. The existence of multiple PDF fits is extremely useful in this regard, and with respect to the definition of the uncertainty, since the various fits use different parametrizations. However, the existing fits are clearly not exhaustive, raising the possibility of an underestimated uncertainty due to a parametrization that poorly describes the distribution function.

There are several possible strategies for obtaining a more robust PDF uncertainty. One can measure $m_W$ using leptons at higher pseudorapidity, though this involves enormous effort to calibrate these detector regions. One can fit for $m_W$ in several lepton pseudorapidity bins to demonstrate that the PDFs accurately describe the distributions within the detector acceptance. Or one can apply an uncertainty obtained strictly (or dominantly) from Tevatron data, which would presumably provide a better $\chi^2$ but a larger uncertainty. At the LHC, the larger statistics and detector coverage will make some of these tests more feasible than at the Tevatron.

2.2. Boson $p_T$

A majority of $W$ and $Z$ bosons are produced with low $p_T$ (Fig. 4), where non-perturbative QCD must be used to describe the $p_T$ distribution. Both CDF and DØ model this distribution using the RESBOS generator [18], which is based on a differential calculation with parameters motivated by a resummation calculation in the non-perturbative regime. There are three parameters, $g_i$ ($i = 1, 2, 3$), whose values are constrained by fits to data. The most relevant parameter for the $m_W$ measurement is $g_2$, which determines the position of the distribution’s peak.

CDF obtains $g_2 = 0.685 \pm 0.048$ (stat) [3] using the $Z \rightarrow ll$ control samples for its $m_W$ measurement. This value of $g_2$, which uses CTEQ6M PDFs, is consistent with the value of $g_2 = 0.68^{+0.02}_{-0.04}$ obtained from a global fit using CTEQ3M PDFs. The other $g_i$ parameters are correlated and CDF found that varying $g_3$ has a negligible effect on $m_W$.

DØ has performed a dedicated measurement of $g_2$ for use in its $m_W$ measurement. To maximize sensitivity to $g_2$, DØ projects the $Z$ boson $p_T$ along the axis bisecting the charged leptons (Fig. 5). Fitting this distribution in the electron and muon decay channels gives $g_2 = 0.63 \pm 0.02$ using CTEQ6.6 PDFs. DØ has studied the PDF uncertainty on $g_2$, finding $\delta g_2 (PDF) = 0.04$.

The crucial step for the $m_W$ measurement is translating the $g_2$ value obtained by fitting the $Z$ boson $p_T$ into the appropriate value for $p_T^W$. The RESBOS parametrization provides this translation, but the uncertainty due to higher resummation orders has not been determined. In addition, variations in $\alpha_s$ affect the high end of the $p_T$ spectrum and could cause a small uncertainty on $m_W$. At the low end of the spectrum, small modifications could arise from QED initial-state radiation, which should be investigated. Other issues relevant to the $m_W$ measurement are including the full correlations with PDFs when determining the uncertainty, and including the diffractive production component that is not modelled by RESBOS.

Starting with the DØ Run 1B $m_W$ measurement [19], the Tevatron experiments have quoted measurements of $m_W$ based on fits to the charged-lepton and neutrino $p_T$ distributions. These fits are more sensitive to the modelling of $p_T^W$ than the traditional $m_T$ ($= \sqrt{2p_T^W p_{\ell}^W (1 - \cos \Delta \phi)}$) fit, providing an important test of the $p_T^W$ model.

![Figure 4: The measured dimuon $p_T$ in 200 pb$^{-1}$ of CDF data, for muon pairs with invariant mass between 66 and 116 GeV.](image-url)
Final-state photon radiation (FSR) off a charged lepton from the $W$ boson decay reduces the charged lepton momentum, and thus the inferred boson mass. Modelling this effect results in an $O(150 \text{ MeV})$ correction to the measured $m_W$. DØ models FSR with PHOTOS [20], a resummed calculation focused exclusively on FSR, and compares with WGRAD [21], a next-to-leading order (NLO) calculation. CDF uses a histogram of photons extracted from WGRAD to apply FSR at the end of event generation.

To determine the uncertainty on $m_W$ due to the FSR model, DØ takes the difference between fits using PHOTOS and WGRAD. This is almost certainly an overestimate, since PHOTOS includes higher-order terms (through resummation) that WGRAD does not. The uncertainty is nonetheless small due to the electron energy calibration using the $Z$ boson mass, which largely corrects for mismodelling of photon radiation.

CDF models higher-order QED radiation by scaling the photon energy by 10%, taking half the scaling correction as an uncertainty. Other uncertainties due to the infrared cutoff in WGRAD and a comparison of full $O(\alpha)$ and FSR-only WGRAD are also quoted. CDF is undertaking a thorough investigation of higher-order QED effects using the HORACE generator [22].

HORACE calculates the leading logarithm QED corrections, and reweights them to model the full $\alpha''$ calculation. The procedure assumes that the reweighting needed to model $O(\alpha)$ is the same for all orders of $\alpha$. A CDF study has found that the reweighting produces a $4.5 \pm 1.4 \text{ MeV}$ shift in the $m_W$ fit, when compared to the leading log calculation. A comparison of the reweighted logs with the $O(\alpha)$ calculation shows an $\approx 10 \text{ (20) MeV}$ shift for electrons (muons). The mass shift is lower in the reweighted log simulation, since the higher orders suppress soft QED radiation. Variations in the truncation of the perturbative series in HORACE have less than a 1 MeV effect on $m_W$.

The HORACE generator improves our understanding of QED radiation, though there is no clear recipe for determining the residual uncertainty on $m_W$. A full $O(\alpha^2)$ calculation would be useful in order to validate the HORACE reweighting procedure, but this requires significant effort. Such a calculation could address the question of whether there are uncertainties due to additional diagrams not accounted for in the HORACE reweighting scheme (e.g., final-state radiation of electron-positron pairs). Alternative generators could also be useful; for example, the WINHAC [23] generator incorporates higher orders through exponentiation rather than showering and could provide a cross-check, but not a measure of uncertainty.

Another issue is the potential correlation between initial-state QCD and final-state QED radiation. Currently, CDF and DØ factorize the two, generating QED FSR after RESBOS, or boosting bosons produced by HORACE. Recently, unified generators have become available: the HORACE authors have added MC@NLO [24] for QCD ISR, and the RESBOS authors have added QED FSR in the generator RESBOSA. However, these are still factorized approaches and do not include interference between QCD and QED radiation.

Uncertainties on QED FSR can be mitigated by calibrating the lepton momentum using the $Z$ boson mass in $Z \rightarrow ll$ events. DØ uses this technique for its calibration, though CDF does not because doing so would inflate the overall uncertainty due to the relatively small $Z \rightarrow ll$ statistics.
2.4. Boson Decay

The left-handed coupling of the $W$ boson to the quarks and leptons produces a decay angular distribution proportional to $(1 + \cos^2 \theta)$ for production by valence quarks at leading order, where $\theta$ is the angle between the (anti)quark and (anti)lepton momenta. Higher-order QCD corrections modify the angular distributions, and have been calculated at NLO and implemented in RESBOS. A comparison of RESBOS to the dedicated NLO generator DYRAD [25] shows consistency in the region of high $W$ boson $p_T$ $(p_T^W > 15$ GeV). At lower $p_T$ the distributions are more accurately described by a resummation procedure, which for RESBOS involves an averaging over helicities. Resummation calculations separated by helicity are in progress, but until they are complete there is some ambiguity of the uncertainty on $m_W$ from the RESBOS decay model.

3. Tevatron $m_W$ Measurements

The CDF and DØ experiments use independent procedures to calibrate the detector response to charged leptons and to hadrons from the underlying event. CDF utilizes its precision tracker to measure $m_W$ in both $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ decays, while the DØ measurement relies on its hermetic calorimeter to focus on the electron decay channel.

3.1. Charged Lepton Calibration

The CDF lepton momentum calibration begins with the tracker. Charged-track momentum is calibrated using $J/\psi \rightarrow \mu\mu$, $\Upsilon \rightarrow \mu\mu$, and $Z \rightarrow \mu\mu$ events. Fits to the invariant mass of muon pairs in these samples set the momentum scale, and are sensitive to modelling of the ionization energy loss. CDF models the energy loss using the mean from the Bethe-Bloch equation [26] for each traversed layer of material. In the $J/\psi$ sample, which contains more than 600,000 events, the calibration uncertainty is dominated by the energy loss model. Modelling the energy loss as a Landau distribution could improve the quality of the calibration fit, resulting in a smaller overall uncertainty. However, some care is required to preserve the Bethe-Bloch mean when using the Landau distribution.

CDF calibrates the average muon energy loss by fitting the momentum scale as a function of mean inverse $p_T$ of muon pairs from $J/\psi$ decays, and fit to a line where the slope equals the residual energy loss and the intercept equals the momentum scale. The CDF electron momentum calibration transfers the track calibration to the calorimeter using electrons from $W$ boson decays. CDF fits the ratio of calorimeter energy to track momentum ($E/p$) using the peak region (Fig. 7). The position of the peak is sensitive to the radiation of low-momentum photons in the tracker. The rate of this radiation is in turn sensitive to the amount of tracker material, which is tuned using the high end of the $E/p$ $(1.19 - 1.85)$ distribution. This tuning empirically corrects the rate of high-momentum radiation, and relies on the theoretical radiation spectrum to model the region near the peak. For very low momentum radiation ($< 50$ MeV), the model includes quantum-mechanical interference effects that suppress the radiation.

![Figure 6: The momentum scale required in the simulation to obtain the world-average $J/\psi$ mass. The scale is plotted as a function of mean inverse $p_T$ of muon pairs from $J/\psi$ decays, and fit to a line where the slope equals the residual energy loss and the intercept equals the momentum scale.](image)

![Figure 7: The ratio of calorimeter energy to track momentum for electrons from $W$ boson decays. The region between the arrows is used to fit for the calorimeter energy scale.](image)
CDF tests its lepton momentum calibration by fitting for the Z boson mass using $Z \rightarrow ll$ events. The consistency of the fit $m_Z$ with the LEP measurements \(^2\) in both the electron and muon decay channels provides a stringent test of the detector response and modelling of radiative corrections from first principles. CDF adds the $m_Z$ fit to its momentum calibration, though the relatively low Z boson statistics results in a negligible contribution to the muon calibration, and a 30% contribution to the electron calibration. Since the muon calibration uncertainties are dominantly systematic, it is expected that future measurements will rely more on the Z boson mass fit.

The DØ electron momentum calibration is based solely on fits to the Z boson mass, as a function of detector region. The calibration determines both the energy scale and an offset. The offset corrects for any inaccuracies in the modelling of detector noise and underlying event in the electron energy measurement. After calibration, the Z boson mass distribution is well described by the simulation (Fig. 8).

The use of $Z \rightarrow ll$ events for calibration cancels a number of systematic uncertainties when applied to the $W \rightarrow ll$ mass sample. However, there is no independent test of the calibration, making the measurement less robust and ultimately increasing the overall uncertainty. In addition, extra care must be taken to understand and account for uncertainties that do not cancel when the calibration is applied to the W boson sample. For example, the electron $p_T$ measurement relies on a measurement of the track angle with respect to the beam line. A global scale of this angle brings the track closer to the beam line can bias the $m_Z$ fit up or down, depending on the topology. However, the $m_W$ fit is always biased to lower values.

**3.2. Neutrino Calibration**

Since the neutrino momentum is inferred from the measured momentum imbalance of the event, the neutrino calibration is effectively a calibration of all the particles in the event. Excluding the charged lepton from the W boson decay, these particles are known as the recoil. The recoil momentum is the vector sum of diffuse contributions that are not as well measured as the charged lepton (Fig. 9). The detector response to these particles uses an empirical model with parameters determined from $Z \rightarrow ll$ events.

The CDF recoil calibration defines a physics-motivated model for the scale and resolution of the recoil. The scale is a logarithmic function of boson $p_T$. As $p_T$ increases, the particles in the recoil have higher $p_T$ and are contained in a smaller jet cone. The resolution improves with increasing $p_T$, with the expected dependence of a sampling calorimeter. The resolution due to underlying event uses the same dependence, with parameters determined from data collected with an unbiased trigger. With a few parameters CDF has demonstrated quantitative agreement between data and simulation for the important recoil distributions in the W boson samples. For example, the projection of the recoil vector along the direction of the muon in $W \rightarrow \mu\nu$ events is shown Fig. 10.

The DØ recoil calibration uses a detector-response library as a function of true recoil momentum, derived using $Z \rightarrow ll$ events and an unbiased trigger to model the effects of the underlying event \(^2\). The use of a library removes any assumptions on the form of the response functions, though the properties of these functions must be checked to ensure that they are re-
3.3. $W$ Boson Mass Fits

Fits for $m_W$ are performed using the charged-lepton and neutrino $p_T$ spectra, and the reconstructed $m_T$ distribution. The latter provides the most precise measurement of $m_W$, with the combination of the fits improving the total precision by a few percent. The results of the $m_T$ fits in the muon channel at CDF and the electron channel at DØ are shown in Figs. 12 and 13 respectively.

The CDF and DØ $m_W$ measurements are:

$$m_W = 80.413 \pm 0.034\text{(stat)} \pm 0.034\text{(sys)} \text{ GeV} \ (CDF),$$

$$m_W = 80.401 \pm 0.021\text{(stat)} \pm 0.038\text{(sys)} \text{ GeV} \ (DØ).$$

These are the two most precise measurements from individual experiments. The systematic uncertainties on the measurements are shown in Tables III and IV. In both cases the dominant uncertainty is on the lepton momentum scale calibration, which is performed in situ. Thus, this uncertainty is expected to reduce with increased statistics.

Combining all Tevatron measurements gives [7]:

$$m_W = 80.420 \pm 0.031 \text{ GeV} \ (\text{Tevatron}),$$ (1)

which is more precise than the combined LEP measurement of $m_W = 80.376 \pm 0.033 \text{ GeV}$. The current world-average value of $m_W$ is [7]

$$m_W = 80.399 \pm 0.023 \text{ GeV} \ (\text{World average}).$$ (2)
4. Global Electroweak Fits

Several groups have updated their fits to the global electroweak data using the latest $m_W$ measurements. The Gfitter group has obtained a best-fit Higgs boson mass $m_H = 83^{+30}_{-23}$ GeV [29], more than $1\sigma$ below the LEP direct exclusion $m_H > 114$ GeV [30]. There is thus tension between the electroweak fits and $m_H$, and this tension increases if one only considers the predictions from $m_W$ alone. The Gfitter group has fit for $m_H$ using only one sensitive variable at a time, and obtains $m_H = 42^{+56}_{-22}$ GeV when using only $m_W$ (Fig. 14). In fact, all measurements prefer a low-mass Higgs, except the forward-backward asymmetry measurement in polarized electron-positron collisions. The Gfitter group has determined the probability of such a deviant measurement to be 1.4%, if due to measurement uncertainties alone.

Given the tension between the electroweak fits and the direct limit on $m_H$, it is natural to consider possible new-physics contributions to $m_H$. One possibility is the presence of supersymmetric-particle loops in the $W$ boson propagator. Such loops in the minimal supersymmetric standard model increase the $W$-boson mass and reduce this tension. Figure 15 shows the range of top-quark and $W$-boson masses preferred by the MSSM and by the SM [31]. However, there are other constraints on supersymmetry that create a different set of tensions.

| Source                  | Uncertainty (MeV) |
|-------------------------|-------------------|
| Lepton Scale            | 23.1              |
| Lepton Resolution       | 4.4               |
| Lepton Efficiency       | 1.7               |
| Lepton Tower Removal    | 6.3               |
| Recoil Energy Scale     | 8.3               |
| Recoil Energy Resolution| 9.6               |
| Backgrounds             | 6.4               |
| PDFs                    | 12.6              |
| $W$ Boson $p_T$         | 3.9               |
| Photon Radiation        | 11.6              |

Table III Systematic uncertainties on the combination of the six fits in the electron and muon channels for the CDF $m_W$ measurement [3].
Given the large uncertainties on the PDFs at the moment, this projection appears optimistic.

In addition to the expected improvement in \(m_W\) precision from analysis of the complete Tevatron datasets, even greater precision is predicted by the ATLAS experiment at the LHC. With 10 fb\(^{-1}\) of \(\sqrt{s} = 14\) TeV data (one year of running at design luminosity), the ATLAS experiment expects to have a precision of 7 MeV on its measurement of \(m_W\) \cite{3}. However, there are significant challenges to achieving this goal. For example, the ATLAS projection is based on the charged-lepton \(p_T\) fit for a single decay channel and assumes the recoil uncertainty is negligible. However, both the CDF and DØ measurements find a larger recoil uncertainty on this mass fit than on the fit to the \(m_T\) distribution, due to the tight cut on the recoil momentum in the event selection. Thus, one would expect a non-negligible recoil uncertainty for the ATLAS measurement. In addition, ATLAS expects the \(p_T^W\) uncertainty to dominate the production model uncertainty, with a negligible PDF uncertainty. Given the large uncertainties on the PDFs at the momentum fraction relevant for \(W\) boson production at the LHC, this projection appears optimistic.

Even though there will be significant challenges to overcome for measuring \(m_W\) at ATLAS and CMS, there will be \(O(10^8)\) \(W\)- and \(O(10^7)\) \(Z\)-boson events to calibrate the detector response to leptons and recoil, and to measure the \(Z\) boson rapidity and \(p_T\) distributions to constrain the PDFs and \(p_T^W\). In addition, there is a \(W\) boson charge asymmetry at the LHC which is similar to that of the Tevatron, providing further possible PDF constraints. Given these large statistics and calibration tools, it is realistic to expect a measurement with precision better than 10 MeV from the LHC experiments.

Finally, there is potential for a precision measurement of the weak mixing angle from the forward-backward asymmetry of leptons in Drell-Yan production at the Tevatron. The distribution of the angle \(\theta\) between the negative-lepton and proton momenta has the form \cite{32}:

\[
d\sigma/d\cos\theta \propto 3/(1 + \cos^2\theta) + A_{FB} \cos\theta,
\]

where \(A_{FB}\) is the asymmetry between negative leptons produced in the forward (\(\cos\theta > 0\)) and backward (\(\cos\theta < 0\)) directions, and is a function of the vector and axial couplings of the fermions to the \(Z\) and \(\gamma\) bosons. Since the vector coupling is equal to \(I_3^L - 2e\sin^2\theta_W\), where \(I_3^L\) is the weak charge, the measurement provides sensitivity to the weak mixing angle.

CDF and DØ have performed measurements of \(A_{FB}\) in the electron decay channel with 72 fb\(^{-1}\) \cite{32} and 1.1 fb\(^{-1}\) \cite{3} of data, respectively. Assuming statistical scaling of the uncertainties on the DØ measurement, the combined Tevatron precision using electron and muon channels in \(O(10)\) fb\(^{-1}\) of data could approach 0.0003, which would contribute to the world-average value of \(\sin^2\theta_W = 0.23149 \pm 0.00013\).
Another possibility for improving electroweak constraints is the determination of $\sin^2 \theta_W$ through the measurement of the forward-backward asymmetry of Drell-Yan at the Tevatron. However, much work is required to demonstrate the scaling of uncertainties with an order of magnitude more data, and to achieve sensitivity in the muon decay channel.

Overall, there is significant ongoing progress in precision electroweak measurements at hadron colliders. The constraints on the Higgs boson mass are quickly tightening, and if there is no SM Higgs there is a reasonable possibility that it will be first excluded by the $W$ boson mass measurement.

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