Measuring the W Boson Mass at Hadron Colliders

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Abstract

We discuss the prospects for measuring the W mass and width in Run II of the Tevatron and at the LHC. The basic techniques used to measure M_W are described and the statistical, theoretical and detector-related uncertainties are discussed in detail.

1 Introduction

Measuring the W mass, M_W, is an important objective for the Tevatron experiments in Run II. One hopes to measure M_W with a precision of ± 30 MeV per experiment per channel [1]. Together with the anticipated precision of 2 GeV for the top quark mass from Tevatron data [2], a determination of the W mass with an uncertainty of 30 MeV would make it possible to predict the Higgs boson mass, M_H, from one-loop electroweak corrections to M_W with an accuracy of approximately 30% [2, 3, 4]. With the best fit central value close to the LEP II direct search lower bound of $M_H > 114.4$ GeV [5], and the rather poor χ^2 which results from a fit of the current precision electroweak data to the Standard Model (SM) [6, 7], this would bring considerable additional pressure on the SM.

This document is structured as follows. The basic techniques used to measure the W mass and the expected statistical and overall uncertainties are briefly discussed in Sec. 2. The detector-related and theoretical uncertainties affecting the W mass and width measurements are described in more detail in Sec. 3 and Sec. 4, respectively. Alternative methods of measuring the W mass at the Tevatron are discussed in section 5. Section 6 concludes this document.

2 M_W Measurement from the M_T Lineshape

The determination of M_W depends on the two body nature of the W decay, $W \to \ell\nu_\ell$. The kinematical Jacobian peak and sharp edge at the value of $M_W/2$ is easily observed in the measurement of the transverse momentum (p_T) of either of the leptons. However, the Jacobian peak in the p_T distribution is smeared out by finite W width effects, detector

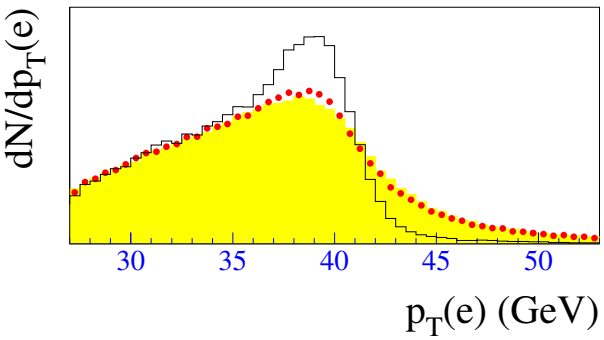

Figure 1: The effects of resolution and the finite p_T^W on $p_T(e)$ in W boson decay. The histogram shows p_T^W without detector smearing and for $p_T^W = 0$. The dots include the effects of adding finite p_T^W, while the shaded histogram includes the effects of detector resolutions. The effects are calculated for the DØ Run I detector resolutions.

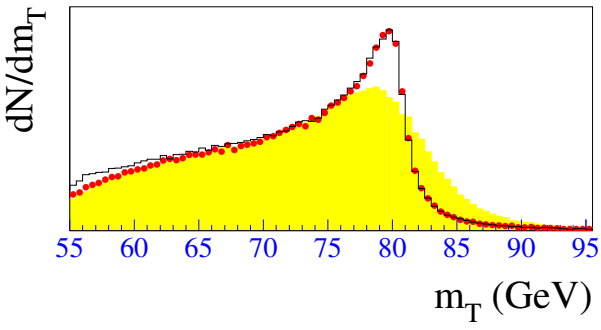

Figure 2: The effects of resolution and the finite p_T^W on M_T in $W \to e\nu$. The histogram shows M_T without detector smearing and for $p_T^W = 0$. The dots include the effects of adding finite p_T^W, while the shaded histogram includes the effects of detector resolutions. The effects are calculated for the DØ Run I detector resolutions.

resolution effects, and, in particular, the effect of the finite transverse momentum of the W boson, p_T^W. Figure 1 shows a calculation of the $p_T(e)$ distribution (unsmeared) with $p_T^W = 0$; the effect of finite p_T^W; and the inclusion of detector smearing effects. It is apparent that $p_T(e)$ is very sensitive to the transverse motion of the W boson.

Historically, precise understanding of p_T^W has been lacking, although it is currently modeled by measurable parameters through the resummation formalism of Collins, Soper, and Sterman [8]. For this reason, the transverse mass, M_T, was suggested [9] and has been the traditional measurable. It is defined by

$$M_T = \sqrt{2p_T(\ell)p_T(\nu)(1-\cos(\phi_{\ell,\nu}))}, \tag{2.1}$$

where $\phi_{\ell,\nu}$ is the angle between the charged lepton and the neutrino in the transverse plane. The observables are the lepton transverse energy or momentum $\vec{p}_T(\ell)$ and the non-lepton transverse energy $\vec{u}$ (recoil transverse energy against the W), from which the neutrino momentum $\vec{p}_T(\nu)$ and the transverse mass M_T are derived. M_T is invariant under transverse boosts to first order in the velocity of the W boson. Figure 2 shows that the sensitivity of M_T to p_T^W is indeed almost negligible. While considerably more stable to the phenomenology of the production model, the requirement that the neutrino direction be accurately measured leads to a set of experimental requirements which are difficult in practice to control.

Both CDF and DØ have determined the W boson mass using the transverse mass approach. The combined $p\bar{p}$ collider result is [7]

$$M_W = 80.454 \pm 0.059 \text{ GeV}. \tag{2.2}$$

Presuming that Run II is to deliver an integrated luminosity of 2 fb^{-1}, the statistical precision on M_W can be estimated from the existing data. Figure 3 shows the statis-

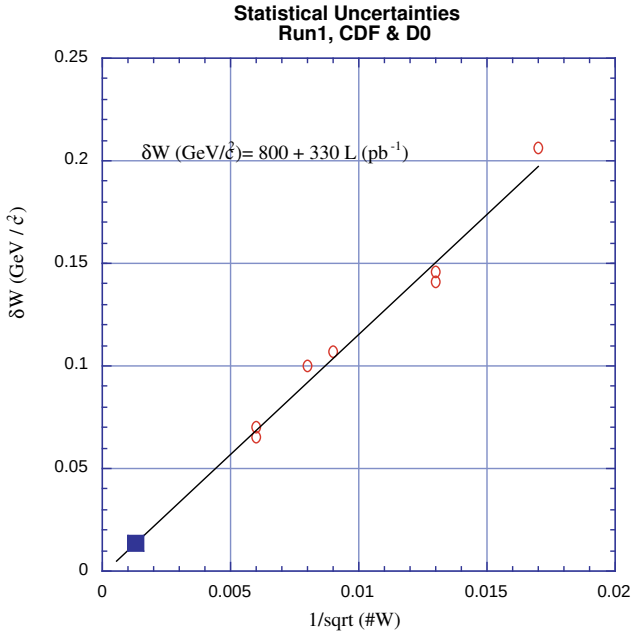

Figure 3: Statistical uncertainties in Run I M_W measurements. Each circle represents either a CDF or DØ measurement. The result of a straight line fit is shown. The shaded box is the approximate extrapolation to a 2 fb^{-1} Run II result.

tical uncertainties in these measurements as a function of $1/\sqrt{N_W}$ (N_W is the number of W boson events), demonstrating a predictable extrapolation to $N_W \simeq 700,000$ which corresponds to the expected Run II dataset per experiment per channel. The statistical uncertainty from this extrapolation is approximately 13 MeV. Taking into account the detector related and theoretical uncertainties discussed in more detail below, a total uncertainty of ± 30 MeV for M_W is projected. The current CDF and DØ Run II data samples are approximately 70 pb^{-1} [10].

For integrated luminosities larger than 2 fb^{-1}, the systematic errors rapidly become dominant. For 15 fb^{-1}, the goal for Run IIb, one hopes to achieve a precision of [11]

$$\delta M_W = \pm 17 \text{ MeV}. \tag{2.3}$$

For even larger data sets, the determination of the energy resolution will be systematically limited by the uncertainty in the width of the Z boson [11]. This will restrict the accuracy to about 15 MeV per channel per experiment.

At the LHC, for 10 fb^{-1}, one expects about 6×10^7 $W \to \ell\nu$ ($\ell = e,\ \mu$) events, resulting in a statistical error of < 2 MeV [12]. If the lepton energy and momentum scales can be determined with a precision of 0.02% or better, the W mass can be measured with a total uncertainty of ± 15 MeV [12].

3 Detector-specific Uncertainties

Much of the understanding of experimental systematics comes from a detailed study of Z bosons and hence as luminosity improves, systematic uncertainties should diminish

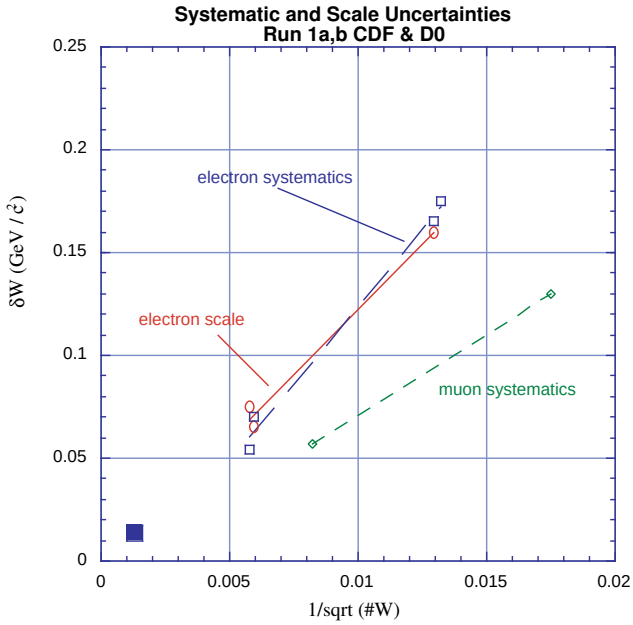

Figure 4: Systematic uncertainties for each Run I M_W measurement. The open squares are the four electron measurements from CDF and DØ, the circles are the scale uncertainties from two DØ electron measurements and the Run Ib CDF measurement, and the diamonds are the systematic uncertainties (excluding scale) for the CDF muon measurements. The large box is the position of the extrapolated statistical uncertainties to the Run II luminosity. The lines are linear fits to each set of points.

in kind. Certainly, the scale and resolution of the recoil energy against the W come from measurements of the Z system. Likewise, background determination, underlying event studies, and selection biases depend critically, but not exclusively, on Z boson data. Most importantly, the lepton energy and momentum scales depend solely on the Z boson datasets. In the Run I W mass measurement, the largest systematic uncertainties originated from the lepton energy and momentum scales, and the modeling of the W recoil. Non-Z related recoil systematics were estimated to enter at the 10 MeV level.

Figure 4 shows the CDF and DØ systematic uncertainties for both electrons and muons as a function of $1/\sqrt{N_W}$. The calorimeter scale uncertainties for electrons is currently tied to the determination of fiducial di-lepton decay resonances, notably the Z boson, but also the J/ψ, Υ and the E/p dependence on the energy E, using electrons from W and Z decays. As the statistical precision improves, the dominant feature of the scale determination becomes its value in the region of M_W, so offsets and any low energy nonlinearities become relatively less important and hence reliance on the low mass resonances is reduced. On the other hand, for the muon momentum scale determination, where the observable is the curvature, low mass resonances are also important. Figure 4 suggests that this uncertainty is truly statistical in nature and extrapolates to approximately the 15 MeV level. The ability to bound non-linearities using collider data may become a limiting source of error in Run II.

Figure 4 also shows the non-scale systematic uncertainties from both the CDF and DØ electron measurements of M_W and the CDF muon measurement. Here the extrapo-

lation is not as straightforward, but there is clearly a distinct statistical nature to these errors. That they appear to extrapolate to negative values suggests that the systematic uncertainties may contain a statistically independent component for both the muon and the electron analyses.

$Z \to \ell^+\ell^-$ data constrain both the lepton scales and resolutions and an empirical model of the hadronic recoil measurement. The determination of the lepton scales and resolutions requires a measurement of the Z boson mass, M_Z and width, Γ_Z, and calibration of these observables using the available LEP data. In order to do this, it is necessary to use exactly the same theoretical input which has been used to extract M_Z and Γ_Z at LEP, ie. to include the reducible and irreducible $\mathcal{O}(g^4 m_t^2/M_W^2)$ corrections to the effective leptonic weak mixing parameter, $\sin^2\theta^l_{\rm eff}$, and the W mass [13], in the calculation. A calculation of the complete $\mathcal{O}(\alpha)$ corrections to $p\overset{(-)}{p} \to \gamma,\ Z \to \ell^+\ell^-$ which also takes into account the $\mathcal{O}(g^4 m_t^2/M_W^2)$ corrections has recently been completed [14].

4 Theoretical Uncertainties

The M_T lineshape simulation requires a theoretical model, as a function of the W mass and width, of the differential cross section. The W mass is extracted by comparing data with templates of the M_T distribution for different values of M_W. The theoretical model must take into account both QCD corrections and electroweak corrections.

QCD provides an understanding of the p_T^W distribution and thus of the hadronic recoil in W events. For a quantitative understanding of the W (and Z) boson p_T distribution it is necessary to resum soft gluon radiation. In the low p_T region, the perturbative calculation must be augmented by a non-perturbative contribution which depends on three parameters which are tuned to fit the $Z \to \ell^+\ell^-$ data. Electroweak radiative corrections, in particular final-state QED radiation is important, because bremsstrahlung shifts the W mass to smaller values and affects the isolation variables needed to select a clean W sample.

To date, *ad hoc* event generators have been used in the W mass measurement. In Run II, this measurement will reach a precision of tens of MeV, requiring much more attention to detail in Monte Carlo calculations. Precision electroweak measurements in Run II should strive to use Monte Carlo programs that are common to both collider experiments and include state-of-the-art QCD and electroweak calculations. Currently, simulations are largely based on two programs: `RESBOS` [15] which includes resummed QCD corrections but ignores electroweak radiative corrections, and `WGRAD` [16] which includes $\mathcal{O}(\alpha)$ electroweak corrections, but ignores QCD corrections. A merging of the two programs would be highly desirable in order to achieve the goal of a unified program which includes both QCD and electroweak radiative corrections.

The current W production model has a number of shortcomings which lead to systematic uncertainties in the W mass measurement. These uncertainties are discussed in the following.

4.1 Parton Distribution Functions

The transverse mass distribution is invariant under the longitudinal boost of the W boson. However, the incomplete rapidity coverage of the detectors introduces a depen-

dence of the measured M_T distribution on the longitudinal momentum distribution of the produced W's, determined by the parton distribution functions (PDF's). Therefore, quantifying the uncertainties in the PDFs and the resulting uncertainties in the W mass measurement is crucial.

The measurement of the W charge asymmetry at the Tevatron, which is sensitive to the ratio of d to u quark densities in the proton, is of direct benefit in constraining PDF effects in the W mass measurement. This has been demonstrated by the CDF experiment. From the variation among the six reference PDFs, an uncertainty of 15 MeV was taken which is common to the electron and muon analyses. Since the Run Ib charge asymmetry data is dominated by statistical uncertainties, a smaller uncertainty is expected for the Run II measurement. Measurements of Drell-Yan production at the Tevatron can be used to get further constraints on PDFs.

Since the PDF uncertainty originates from the finite rapidity coverage of the detectors, it is expected to decrease with the more complete rapidity coverage of the Run II detectors. The advantage of a larger rapidity coverage has been demonstrated by the DØ experiment [17]: the uncertainty on the W mass measurement using their central calorimeter was 11 MeV, while that using both the central and end calorimeter was 7 MeV. With the upgraded calorimeters and trackers for the rapidity range $|\eta| > 1$, the CDF experiment can measure the W mass over a larger rapidity range in Run II.

There has been a systematic effort to map out the uncertainties allowed by available experimental constraints, both on the PDFs themselves and on physical observables derived from them [18, 19]. This approach will provide a more reliable estimate and may be the best course of action for precision measurements such as the W mass or the W production cross section.

4.2 *W* Boson Transverse Momentum

The neutrino transverse momentum is estimated by combining the measured lepton transverse momentum and the W recoil: $\vec{p}_T(\nu) = -(\vec{p}_T(\ell) + \vec{u})$. It is clear therefore that an understanding of both the underlying W boson transverse momentum distribution and the corresponding detector response, usually called the recoil model, is crucial for a precision W mass measurement. For the CDF Run Ib W mass measurement, the systematic uncertainties from these two sources were estimated to be $15 - 20$ MeV and $35 - 40$ MeV, respectively, in each channel [20].

The strategy employed in Run I, which is expected to be used also in Run II, is to extract the underlying p_T^W distribution from the measured p_T^Z distribution (Y is the weak boson rapidity):

$$\frac{d^2\sigma}{dp_T^W dY} = \frac{d^2\sigma}{dp_T^Z dY} \times \frac{d^2\sigma/dp_T^W dY}{d^2\sigma/dp_T^Z dY} \,, \tag{4.1}$$

where the ratio of the W and Z differential distributions is obtained from theory. This method relies on the fact that the observed p_T^Z distribution suffers relatively little from detector smearing effects, allowing fits to be performed for the true distribution. The experimental uncertainties, as in many aspects of the W mass measurement, are dominated by the available $Z \to \ell^+\ell^-$ statistics and should scale correspondingly with the delivered luminosity in Run II. Theoretical uncertainties in the ratio of W to Z transverse

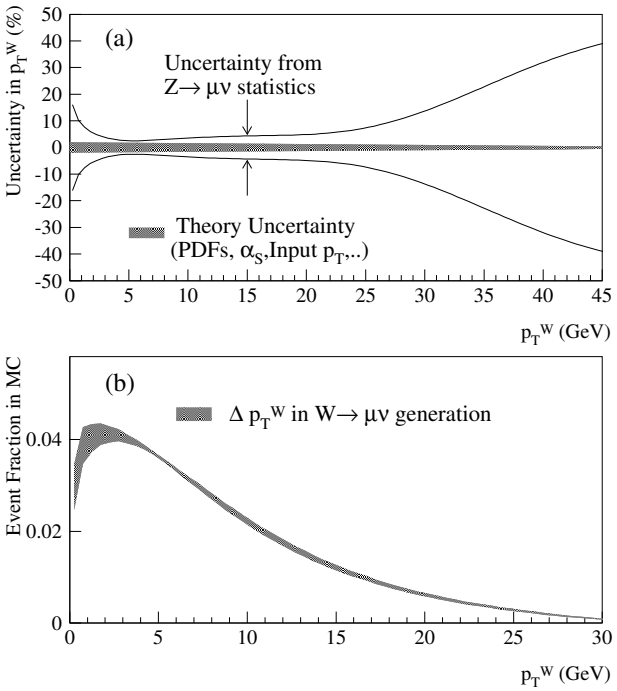

Figure 5: (a) A comparison of the two sources of uncertainty on the derived p_T^W distribution. (b) The p_T^W distribution extracted for the CDF Run Ib $W \to \mu\nu$ mass measurement.

momentum distributions contribute a further $\mathcal{O}(5)$ MeV to the overall error. The two sources of uncertainty are compared for the CDF Run Ib $W \to \mu\nu$ analysis in Fig. 5.

4.3 QCD Higher Order Effects

The charged leptons in $W \to \ell\nu$ are produced with an angular distribution determined by the $\mathcal{O}(\alpha_s^2)$ calculation of Ref. [21] which, for W^+ bosons with a helicity of -1 with respect to the proton direction, has the form:

$$\frac{d\sigma}{d\cos\theta_{\rm CS}} \propto 1 + a_1(p_T^W)\cos\theta_{\rm CS} + a_2(p_T^W)\cos^2\theta_{\rm CS}. \tag{4.2}$$

Here, $\theta_{\rm CS}$ is the polar direction of the charged lepton with respect to the proton direction in the Collins-Soper frame [22]. a_1 and a_2 are p_T dependent parameters. For $p_T^W = 0$, $a_1 = 2$ and $a_2 = 1$, providing the angular distribution of a W boson fully polarized along the proton direction. For the p_T^W values relevant to the W mass analysis ($p_T^W < 30$ GeV), the change in W polarization as p_T^W increases only causes a modest change in the angular distribution of the decay leptons [21].

While the uncertainty associated with the change in the angular distribution of the W decay lepton due to higher order QCD corrections (a few MeV) has been negligible for the Run I measurements, it can not be ignored for the Run II measurements.

4.4 Electroweak Radiative Corrections

The understanding of electroweak radiative corrections is crucial for precision W mass measurements at the Tevatron. The dominant process is final state photon radiation

(FSR) from the charged lepton, the effect of which strongly depends on the lepton identification criteria and the energy or momentum measurement methods employed. Calorimetric energy measurements, such as those employed in the electron channel, are more inclusive than track based momentum measurements used in the muon channel and the effect of FSR is consequently reduced. In the CDF Run Ib W mass measurement the mass shifts due to radiative effects were estimated to be -65 ± 20 MeV and -168 ± 10 MeV for the electron and muon channels, respectively [20]. These effects will be larger in Run II due to increase in tracker material in CDF and magnetic tracking in DØ.

The Monte Carlo program used for the Run I W mass measurement incorporated a calculation of QED corrections by Berends and Kleiss [23]. This treatment, however, does not include initial state radiation (ISR), or soft and virtual corrections. Furthermore, multi-photon radiation effects are ignored in Ref. [23]. The systematic uncertainties of the missing radiative corrections were estimated to be 20 MeV and 10 MeV in the electron and muon channels, respectively [20]. Clearly these systematic uncertainties become much more significant in the context of statistical uncertainties of $\mathcal{O}(10)$ MeV expected for 2 fb^{-1} in Run II.

In the last few years two independent calculations of the full $\mathcal{O}(\alpha)$ electroweak (EW) corrections to W production in Monte Carlo form have been carried out [16, 24, 25]. Calculating the EW radiative corrections to resonant W boson production, the problem arises how an unstable charged gauge boson can be treated consistently in the framework of perturbation theory. This problem has been studied in Ref. [26] with particular emphasis on finding a gauge invariant decomposition of the EW $\mathcal{O}(\alpha)$ corrections into a QED-like and a modified weak part. In Ref. [26], it was demonstrated how gauge invariant contributions that contain the infrared (IR) singular terms can be extracted from the virtual photonic corrections. These contributions can be combined with the also IR-singular real photon corrections in the soft photon region to form IR-finite gauge invariant QED-like contributions corresponding to initial state, final state and interference corrections. The collinear singularities associated with initial state photon radiation can be removed by universal collinear counter terms generated by "renormalizing" the parton distribution functions, in complete analogy to gluon emission in QCD.

The various individual contributions to the electroweak $\mathcal{O}(\alpha)$ corrections on the M_T distribution are shown in Fig. 6. The initial state QED-like contribution uniformly increases the cross section by about 1% for electron (Fig. 6a) and muon (Fig. 6b) final states. It is largely canceled by the modified weak initial state contribution. The interference contribution is very small. The final state QED-like contribution significantly changes the shape of the transverse mass distribution and reaches its maximum effect in the region of the Jacobian peak, $M_T \approx M_W$.

Since final state photon radiation has a significant impact on the W mass extracted from data, one has to worry about the effects of multi-photon radiation. A first attempt towards the inclusion of the $\mathcal{O}(\alpha^2)$ real photon corrections in $q\bar{q}' \to W \to \ell\nu\gamma\gamma$ and $q\bar{q} \to Z \to \ell^+\ell^-\gamma\gamma$ was made in Ref. [27]. More recently, two calculations of higher order QED corrections to $W \to \ell\nu$ decays have been performed which include both real and virtual corrections. Ref. [28] uses Yennie-Frautschi-Suura exclusive exponentiation to calculate multi-photon radiation effects whereas a QED parton shower approach is employed in Ref. [29]. Using a simplified detector model, multi-photon radiation in W

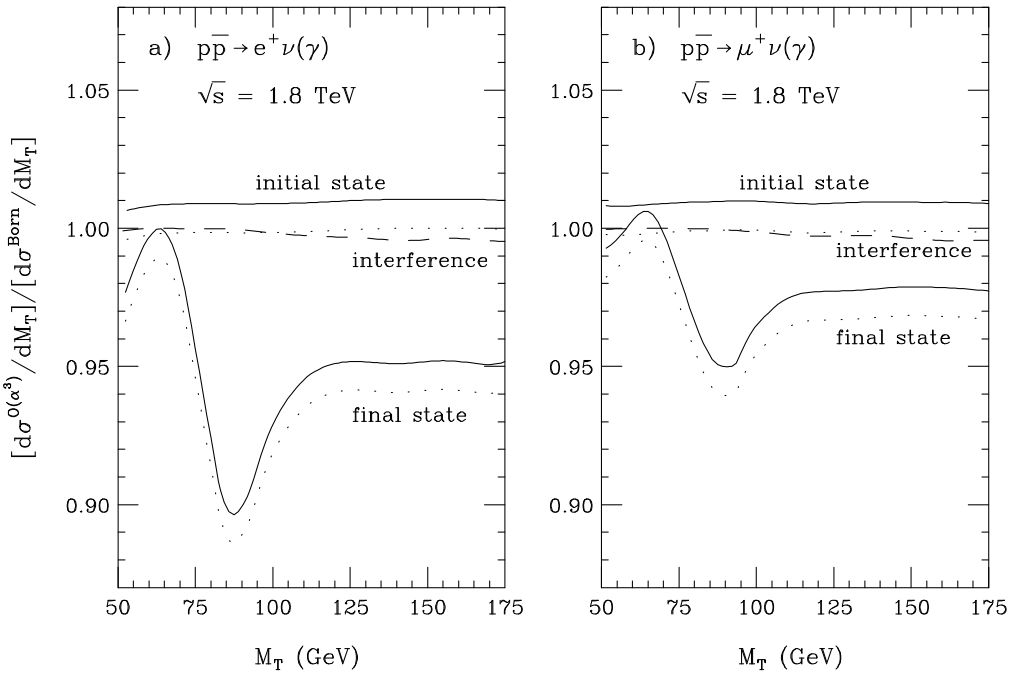

Figure 6: Ratio of the $\mathcal{O}(\alpha^3)$ and lowest order cross sections as a function of the transverse mass for a) $p\bar{p} \to e^+\nu(\gamma)$ and b) $p\bar{p} \to \mu^+\nu(\gamma)$ at $\sqrt{s} = 1.8$ TeV for various individual contributions. The upper (lower) solid lines show the result for the QED-like initial (final) state corrections. The upper (lower) dotted lines give the cross section ratios if both the QED-like and modified weak initial (final) state corrections are included. The dashed lines display the result if only the initial – final state interference contributions are included. Lepton identification requirements are not taken into account here.

decays was found [29] to shift the W mass by a few MeV in the electron channel, and by about $10-15$ MeV in the muon channel. In view of the expected precision of $15-30$ MeV for M_W in Run II and at the LHC, it will be important to take multi-photon radiation effects into account when extracting the W mass from data.

So far, no calculation exists which includes multi-photon radiation effects in hadronic Z boson production. In $Z \to \ell^+\ell^-$, both final state leptons couple to photons, in contrast to $W \to \ell\nu$ where only one of the final state particles carries electric charge. As a result, one expects that multi-photon radiation affects the Z boson mass and width more strongly than the corresponding W observables. Since M_Z and Γ_Z are crucial in determining the lepton energy and momentum scales, a calculation of Z boson production in hadronic collisions which takes into account higher order QED corrections is needed.

5 Other Methods of Determining M_W at Hadron Colliders

While the traditional transverse mass determination has been the optimal technique for the extraction of M_W in previous hadron collider experiments, other techniques may be employed in the future. These methods may shuffle or cancel some of the systematic and statistical uncertainties resulting in more precise measurements.

5.1 Transverse Momentum Fitting

As noted in Sec. 2, the most obvious extensions of the traditional transverse mass approach to determining M_W are fits of the Jacobian kinematical edge from the transverse momentum of both leptons. DØ has measured M_W using all three distributions and the uncertainties are indeed ordered as one would expect: The fractional uncertainties on M_W from the DØ Run I measurements for the three methods of fitting are: 0.12% (M_T), 0.15% ($p_T(e)$), and 0.21% ($p_T(\nu)$). As expected, the $p_T(e)$ method is slightly less precise than the measurement using the transverse mass. However, for a central electron ($|\eta| \lessapprox 1$), the uncertainty in the $p_T(e)$ measurement due to the p_T^W model is 5 times that in the M_T measurement. This is nearly balanced by effects from electron and hadron response and resolutions which are relatively worse for M_T. Accordingly, when there are sufficient statistics to enable cuts on the measured hadronic recoil, the measurement uncertainty from the p_T^W model might be better controlled and enable the $p_T(e)$ measurement to compete favorably with the M_T measurement which relies so heavily on modeling of the hadronic recoil. In order to optimize the advantages of all three measurements, the DØ final Run I determination of M_W combined the separate results [30].

The resolution sensitivity for muon measurements is even less than that for electrons so that has the benefit of slightly favoring a transverse mass measurement with muons over that for electrons.

5.2 Ratio Method

The W mass can also be determined from the ratio of the transverse mass distributions of the W and Z boson [31, 32, 33]. The advantage of the method is that one can cancel common scale factors in ratios and directly determine the quantity $r^{meas} \equiv \frac{M_W}{M_Z}$, which can be compared with the precise value of M_Z from the LEP experiments. The downside of the ratio method is that the statistical precision of the Z sample is directly propagated into the resultant overall δM_W.

DØ has carried out a "proof of principle" analysis, determining M_W from the ratio of the transverse mass distributions of the W and Z boson [31, 32, 33]. Since the W and Z boson mass are different, the Z boson data are rescaled to fit the W boson data. The preliminary DØ result for M_W from Run Ib data using the transverse mass ratio method is [33]

$$M_W = 80.115 \pm 0.211 \text{ (stat.)} \pm 0.050 \text{ (syst.) GeV}. \tag{5.1}$$

For comparison, the result from the fit to the M_T distribution is [30]

$$M_W = 80.440 \pm 0.070 \text{ (stat.)} \pm 0.096 \text{ (syst.) GeV}. \tag{5.2}$$

As expected, the transverse mass ratio method results in a much improved systematic uncertainty. The statistical uncertainty, however, is significantly larger than for the fit to the M_T distribution.

As mentioned in Sec. 2, systematic uncertainties begin to limit the precision for M_W which can be achieved from the fit to the transverse mass distribution at the Tevatron for integrated luminosities of 15 fb^{-1} or more. Such high luminosities may be achievable in Run IIb. Up to 30 fb^{-1} are conceivable if additional upgrades are made to the accelerator

Table 1: Projected uncertainties of the W boson mass measurement using the transverse mass fit and the transverse mass ratio method for $W \to e\nu$.

$\int \mathcal{L}dt$ (fb^{-1})	2	15	30	$\int \mathcal{L}dt$ (fb^{-1})	2	15	30
M_T fit				ratio method			
stat. uncert. (MeV)	19	7	5	stat. uncert. (MeV)	44	16	11
syst. uncert. (MeV)	19	16	15	syst. uncert. (MeV)	10	4	3
total uncert. (MeV)	27	17	16	total uncert. (MeV)	45	16	11

complex [11]. Table 1 shows the expected precision of the W mass measurement from the transverse mass fit and the W to Z transverse mass ratio, extrapolated from the Run Ib measurement by DØ [30]. For integrated luminosities larger than about 15 fb^{-1} the transverse mass ratio method gives an uncertainty for M_W which is smaller than that obtained with the traditional method of fitting the M_T distribution.

6 Conclusions

The measurements of the W mass in Run I of the Tevatron contribute significantly to the world average of M_W. Close inspection of the various systematic error sources leads us to believe that a W mass measurement in Run II at the 30 MeV level per experiment is achievable. Alternative methods for determining M_W at the Tevatron have been discussed and may turn out to be more appropriate in the Run IIb operating environment than the traditional transverse mass fitting approach. Determination of the W mass at the LHC will be extremely challenging, using detectors that are not optimized for this measurement. Clearly, the W mass measurement at the Tevatron in Run II will contribute significantly to a reduction of the overall uncertainty of M_W, and thus to a precise indirect determination of the Higgs boson mass.

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References

[1] R. Brock *et al.*, arXiv:hep-ex/0011009.

[2] D. Amidei *et al.* [TeV-2000 Study Group Collaboration], FERMILAB-PUB-96-082.

[3] U. Baur and M. Demarteau, arXiv:hep-ph/9611334.

[4] J. Erler and P. Langacker, arXiv:hep-ph/9809352.

[5] The LEP Electroweak Working Group, arXiv:hep-ex/0212036 and LEPEWWG/2003-01.

[6] M. Chanowitz, these proceedings and arXiv:hep-ph/0304199.

[7] M. Grünewald, these proceedings and arXiv:hep-ex/0304023.

[8] J. C. Collins, D. E. Soper and G. Sterman, Nucl. Phys. B **250** (1985) 199.

[9] J. Smith, W. L. van Neerven and J. A. Vermaseren, Phys. Rev. Lett. **50** (1983) 1738.

[10] A. Kotwal, talk given at DPF2003, Philadelphia, April 5 – 8, 2003.

[11] U. Baur *et al.* [The Snowmass Working Group on Precision Electroweak Measurements Collaboration], in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. N. Graf, eConf **C010630** (2001) P1WG1 [arXiv:hep-ph/0202001].

[12] S. Haywood *et al.*, arXiv:hep-ph/0003275.

[13] G. Degrassi, P. Gambino and A. Vicini, Phys. Lett. B **383** (1996) 219 [arXiv:hep-ph/9603374]; G. Degrassi, P. Gambino and A. Sirlin, Phys. Lett. B **394** (1997) 188 [arXiv:hep-ph/9611363].

[14] U. Baur, O. Brein, W. Hollik, C. Schappacher and D. Wackeroth, Phys. Rev. D **65** (2002) 033007 [arXiv:hep-ph/0108274].

[15] C. Balazs and C. P. Yuan, Phys. Rev. D **56** (1997) 5558 [arXiv:hep-ph/9704258].

[16] U. Baur, S. Keller and D. Wackeroth, Phys. Rev. D **59** (1999) 013002 [arXiv:hep-ph/9807417].

[17] B. Abbott *et al.* [D0 Collaboration], Phys. Rev. Lett. **84** (2000) 222 [arXiv:hep-ex/9909030] and Phys. Rev. D **62** (2000) 092006 [arXiv:hep-ex/9908057].

[18] W. T. Giele, S. A. Keller and D. A. Kosower, arXiv:hep-ph/0104052.

[19] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207** (2002) 012 [arXiv:hep-ph/0201195].

[20] T. Affolder *et al.* [CDF Collaboration], Phys. Rev. D **64** (2001) 052001 [arXiv:hep-ex/0007044].

[21] E. Mirkes, Nucl. Phys. B **387** (1992) 3.

[22] J. C. Collins and D. E. Soper, Phys. Rev. D **16** (1977) 2219.

[23] F. A. Berends and R. Kleiss, Z. Phys. C **27** (1985) 365.

[24] S. Dittmaier and M. Krämer, Phys. Rev. D **65** (2002) 073007 [arXiv:hep-ph/0109062].

[25] U. Baur and D. Wackeroth, Nucl. Phys. B (Proc. Suppl.) **116** (2003) 159 [arXiv:hep-ph/0211089].

[26] D. Wackeroth and W. Hollik, Phys. Rev. D **55** (1997) 6788 [arXiv:hep-ph/9606398].

[27] U. Baur and T. Stelzer, Phys. Rev. D **61** (2000) 073007 [arXiv:hep-ph/9910206].

[28] W. Placzek and S. Jadach, arXiv:hep-ph/0302065.

[29] C. M. Carloni Calame, G. Montagna, O. Nicrosini and M. Treccani, arXiv:hep-ph/0303102.

[30] B. Abbott *et al.* [D0 Collaboration], Phys. Rev. Lett. **84** (2000) 222 [arXiv:hep-ex/9909030] and Phys. Rev. D **62** (2000) 092006 [arXiv:hep-ex/9908057].

[31] S. Rajagopalan and M. Rijssenbeek, "Measurement of the W Mass Using the Transverse Mass Ratio of the W and Z", DØ Note 3000, June, 1996; S. Rajagopalan, "Measurement of the W Mass Using the Transverse Mass Ratio of the W and Z", Division of Particles and Fields Conference, 1996.

[32] W. T. Giele and S. Keller, Phys. Rev. D **57** (1998) 4433 [arXiv:hep-ph/9704419].

[33] D. Shpakov, "A W Boson Mass Measurement Using the Transverse Mass Ratio of the W and Z Bosons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV", Ph.D. Thesis, Stony Brook, August 2000.