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**D0**

## **A New Measurement of the W Boson Mass at D0**

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The D0 Collaboration

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# A New Measurement of the $W$ Boson Mass at DØ

The DØ Collaboration \*

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(July 15, 1999)

## Abstract

We present a new measurement of the  $W$  mass using the  $W \rightarrow e\nu$  data from the DØ forward detectors at the Fermilab Tevatron  $p\bar{p}$  Collider. This is the first measurement of the  $W$  mass with electron candidates in the range  $1.5 < |\eta| < 2.5$ . We present measurements of the  $W$  mass using the transverse mass, the electron transverse momentum and the neutrino transverse momentum, and the combined result using all three techniques. The combination of the forward detector measurement with the previous measurements using the central detector gives a new precise measurement of the  $W$  mass from DØ.

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In the standard model of the electroweak interactions (SM) [1], the mass of the  $W$  boson is predicted to be

$$M_W = \left( \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F} \right)^{\frac{1}{2}} \frac{1}{\sin\theta_w\sqrt{1-\Delta r_W}}. \quad (1)$$

In the “on-shell” scheme [2]  $\cos\theta_w = M_W/M_Z$ , where  $M_Z$  is the  $Z$  boson mass. A measurement of  $M_W$ , together with  $M_Z$ , the Fermi constant ( $G_F$ ), and the electromagnetic coupling constant ( $\alpha$ ), determines the electroweak radiative corrections  $\Delta r_W$  experimentally. Purely electromagnetic corrections are absorbed into the value of  $\alpha$  by evaluating it at  $Q^2 = M_Z^2$  [3]. The dominant contributions to  $\Delta r_W$  arise from loop diagrams that involve the top quark and the Higgs boson. If additional particles which couple to the  $W$  boson exist, they give rise to additional contributions to  $\Delta r_W$ . Therefore, a measurement of  $M_W$  is one of the most stringent experimental tests of SM predictions. Deviations from the predictions may indicate the existence of new physics. Within the SM, measurements of  $M_W$  and the mass of the top quark constrain the mass of the Higgs boson.

This paper reports a new measurement of the  $W$  boson mass using electrons detected in forward calorimeters. We used data recorded by the DØ detector [4] during the 1994–1995 run of the Fermilab Tevatron  $p\bar{p}$  collider. This forward electron measurement complements our previous measurement with central electrons [5] because the more complete rapidity coverage gives useful constraints on model parameters that permit reduction of the systematic error, in addition to increasing the statistical precision. Combining this measurement with our previously published measurements with central electrons using data taken in 1992–1993 and 1994–1995, determines the  $W$  boson mass to a precision of 93 MeV.

At the Tevatron,  $W$  bosons are produced mainly through  $q\bar{q}$  annihilation. We detect them by their decays into electron-neutrino pairs, characterized by an isolated electron [6] with large transverse momentum ( $p_T$ ) and significant transverse momentum imbalance ( $\cancel{p}_T$ ). The  $\cancel{p}_T$  is due to the neutrino which escapes detection. Many other particles of lower momenta, which recoil against the  $W$  boson, are produced in the breakup of the proton and antiproton. We refer to them collectively as the underlying event.

At the trigger level we require  $\cancel{p}_T > 15$  GeV and an energy cluster in the electromagnetic (EM) calorimeter with  $p_T > 20$  GeV. The cluster must be isolated and have a shape consistent with that of an electron shower.

During event reconstruction, electrons are identified as energy clusters in the EM calorimeter which satisfy isolation and shower shape cuts and have a drift chamber track pointing towards the cluster centroid. We determine forward electron energies by adding the energy depositions in the first  $\approx 40$  radiation lengths of the calorimeter in a cone of radius 20 cm, centered on the highest energy deposit in the cluster. Fiducial cuts reject electron candidates near calorimeter module edges and ensure a uniform calorimeter response for the selected electrons. The electron momentum ( $\vec{p}(e)$ ) is determined by combining its energy with its direction which is obtained from the shower centroid position and the drift chamber track. The trajectories of the electron and the proton beam define the position of the event vertex.

We measure the sum of the transverse momenta of all the particles recoiling against the  $W$  boson,  $\vec{u}_T = \sum_i E_i \sin\theta_i \hat{u}_i$ , where  $E_i$  is the energy deposition in the  $i^{\text{th}}$  calorimeter cell

and  $\theta_i$  is the angle defined by the cell center, the event vertex, and the proton beam. The unit vector  $\hat{u}_i$  points perpendicularly from the beam to the cell center. The calculation of  $\vec{u}_T$  excludes the cells occupied by the electron. The sum of the momentum components along the beam is not well measured because of particles escaping through the beam pipe. From momentum conservation we infer the transverse neutrino momentum,  $\vec{p}_T(\nu) = -\vec{p}_T(e) - \vec{u}_T$ , and the transverse momentum of the  $W$  boson,  $\vec{p}_T(W) = -\vec{u}_T$ .

We select a  $W$  boson sample of 11,090 events by requiring  $p_T(\nu) > 30$  GeV,  $u_T < 15$  GeV, and an electron candidate with  $1.5 < |\eta| < 2.5$  and  $p_T(e) > 30$  GeV.

Since we do not measure the longitudinal momentum components of the neutrinos from  $W$  boson decays, we cannot reconstruct the  $e\nu$  invariant mass. Instead, we extract the  $W$  boson mass from the spectra of the electron  $p_T$  and the transverse mass,  $m_T = \sqrt{2p_T(e)p_T(\nu)(1 - \cos \Delta\phi)}$ , where  $\Delta\phi$  is the azimuthal separation between the two leptons. We perform a maximum likelihood fit to the data using probability density functions from a Monte Carlo program. Since neither  $m_T$  nor  $p_T(e)$  are Lorentz invariants, we have to model the production dynamics of  $W$  bosons to correctly predict the spectra. The  $m_T$  spectrum is insensitive to transverse boosts at leading order in  $p_T(W)/M_W$  and is therefore less sensitive to the  $W$  boson production model than the  $p_T(e)$  spectrum. On the other hand, the  $m_T$  spectrum depends strongly on the detector response to the underlying event and is therefore more sensitive to detector effects than the  $p_T(e)$  spectrum. The shape of the neutrino  $p_T(\nu)$  spectrum is sensitive to both the  $W$  boson production dynamics and the recoil momentum measurement. By performing the measurement using all three spectra we provide a powerful cross check with complementary systematics.

$Z$  bosons decaying to electrons provide an important control sample. We use them to calibrate the detector response to the underlying event and to the electrons, and to constrain the model for intermediate vector boson production used in the Monte Carlo simulations.

A  $Z \rightarrow ee$  event is characterized by two isolated high- $p_T$  electrons. We trigger on events with at least two EM clusters with  $p_T > 20$  GeV. We accept  $Z \rightarrow ee$  decays with at least one forward electron in the pseudorapidity range  $1.5 < |\eta| < 2.5$ , where  $\eta = -\ln(\tan \frac{\theta}{2})$ , and the other electron to be either forward or central with pseudorapidity  $|\eta| < 1.0$ . The central electron is required to have  $p_T > 25$  GeV but is allowed not to have a matching drift chamber track. The forward electron candidate is required to have  $p_T > 30$  GeV and a matching drift chamber track. This selection accepts 1,687 events.

For this measurement we used a fast Monte Carlo program developed for our central electron analysis [5], with some modifications in the simulation of forward electron events. The program generates  $W$  and  $Z$  bosons with the rapidity and  $p_T$  spectra given by a calculation using soft gluon resummation [7] and the MRSA [15] parton distribution functions. The line shape is a relativistic Breit-Wigner, skewed by the mass dependence of the parton luminosity. The measured intrinsic widths [9,10] are used. The angular distribution of the decay electrons includes a  $p_T(W)$ -dependent  $\mathcal{O}(\alpha_s)$  correction [11]. The program also generates  $W \rightarrow e\nu\gamma$  [12],  $Z \rightarrow ee\gamma$  [12], and  $W \rightarrow \tau\nu \rightarrow e\nu\bar{\nu}\nu$  decays.

The program smears the generated  $\vec{p}(e)$  and  $\vec{u}_T$  vectors using a parameterized detector response model and applies inefficiencies introduced by the trigger and event selection requirements. The model parameters are adjusted to match the data and are discussed below.

The electron energy resolution is described by sampling, noise, and constant terms. In

the Monte Carlo simulation of forward electrons we use a sampling term of  $15.7\%/\sqrt{p/\text{GeV}}$ , derived from beam tests. The noise term is determined by pedestal distributions derived from the  $W$  data sample. We constrain the constant term to  $c_{\text{EM}} = 1.0_{-1.0}^{+0.6}\%$  by requiring that the width of the dielectron invariant mass spectrum predicted by the Monte Carlo simulation is consistent with the  $Z$  data (Fig. 1).

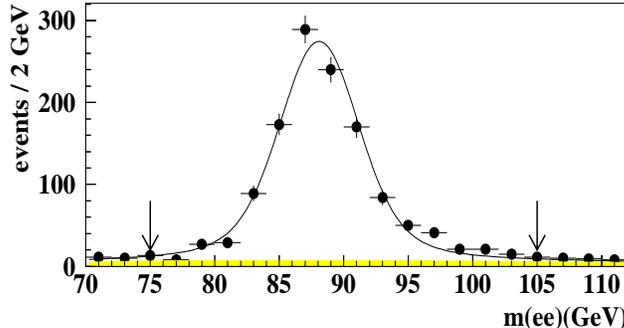


FIG. 1. The dielectron invariant mass distribution of the  $Z$  data ( $\bullet$ ). The solid line shows the fitted signal plus background shape and the small shaded area the background. The arrows indicate the fit window.

Beam tests show that the electron energy response of the calorimeter can be parameterized by a scale factor  $\alpha_{\text{EM}}$  and an offset  $\delta_{\text{EM}}$ . We determine these *in situ* using  $Z \rightarrow ee$  decays. We obtain for forward electrons  $\delta_{\text{EM}} = -0.1 \pm 0.7$  GeV and  $\alpha_{\text{EM}} = 0.95179 \pm 0.000187$  by fitting the observed mass spectra while constraining the resonance masses to the measured value of the  $Z$  boson mass [10,13]. The uncertainty in  $\alpha_{\text{EM}}$  is dominated by the finite size of the  $Z$  sample. Figure 1 shows the observed dielectron mass spectrum from the dielectron sample, and the line shape predicted by the Monte Carlo simulation for the fitted values of  $c_{\text{EM}}$ ,  $\alpha_{\text{EM}}$ , and  $\delta_{\text{EM}}$ .

We calibrate the response of the detector to the underlying event, relative to the EM response, using  $Z$  boson data sample. In  $Z \rightarrow ee$  decays, momentum conservation requires  $\vec{p}_T(ee) = -\vec{u}_T$ , where  $\vec{p}_T(ee)$  is the sum of the two electron  $p_T$  vectors. To minimize sensitivity to the electron energy resolution, we project  $\vec{u}_T$  and  $\vec{p}_T(ee)$  on the inner bisector of the two electron directions, called the  $\eta$ -axis (Fig. 2). We call the projections  $u_\eta$  and  $p_\eta(ee)$ .

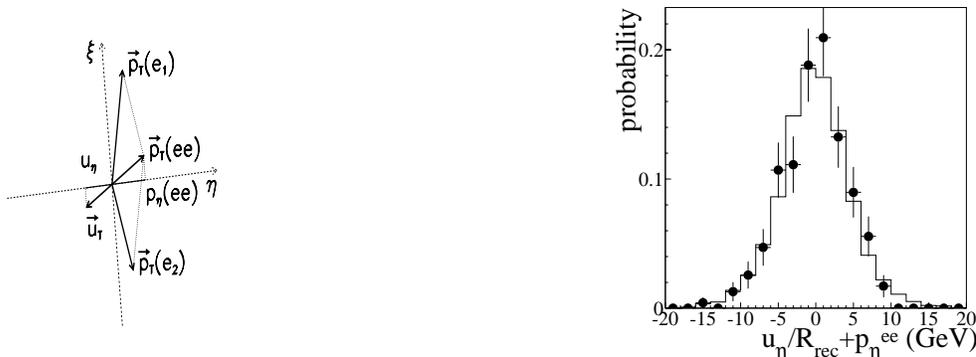


FIG. 2. The definition of the  $\eta$ -axis (left). The plot of  $u_\eta/R_{\text{rec}} + p_\eta(ee)$  (right) for the data ( $\bullet$ ) and simulation ( $-$ ).

Detector simulations based on the GEANT program [14] predict a detector response to

the recoil particle momentum of the form  $R_{\text{rec}} = \alpha_{\text{rec}} + \beta_{\text{rec}} \ln(p_T/\text{GeV})$ . We constrain  $\alpha_{\text{rec}}$  and  $\beta_{\text{rec}}$  by comparing the mean value of  $u_\eta + p_\eta(ee)$  with Monte Carlo predictions for different values of the parameters. We use  $\alpha_{\text{rec}} = 0.693 \pm 0.060$  and  $\beta_{\text{rec}} = 0.040 \pm 0.021$  with a correlation coefficient of  $-0.98$  obtained in central electron analysis [5]. We check that  $Z$  events with both electrons in the end calorimeter give a recoil response measurement statistically consistent with the above (Figure 2).

The recoil momentum resolution has two components. We smear the magnitude of the recoil momentum with a resolution of  $s_{\text{rec}}/\sqrt{p_T/\text{GeV}}$ . We describe the detector noise and pile-up, which are independent of the boson  $p_T$  and azimuthally symmetric, by adding the  $\cancel{p}_T$  from a random  $p\bar{p}$  interaction, scaled by a factor  $\alpha_{\text{mb}}$ , to the smeared boson  $p_T$ . To model the luminosity dependence of this resolution component correctly, the sample of  $p\bar{p}$  interactions was chosen to have the same luminosity spectrum as the  $W$  sample. We constrain the parameters by comparing the observed rms of  $u_\eta/R_{\text{rec}} + p_\eta(ee)$  with Monte Carlo predictions. We use  $s_{\text{rec}} = 0.49 \pm 0.14$  and  $\alpha_{\text{mb}} = 1.032 \pm 0.028$  with a correlation coefficient of  $-0.60$  measured in central electron analysis [5]. Since we exclude the cells occupied by the electrons, the average transverse energy flow,  $S_T = \sum_i E_i \sin \theta_i$ , is higher for the  $W$  sample than for the  $Z$  sample. This bias is caused by requiring the identification of two electrons in the  $Z$  sample versus one in the  $W$  sample. The larger energy flow translates into a slightly broader recoil momentum resolution in the  $W$  sample.  $\alpha_{\text{mb}}$  is corrected by a factor  $1.03 \pm 0.01$  to account for this effect in the  $W$  boson model. The  $p_\eta$  balance width is in good agreement between data and Monte Carlo for our  $Z$  event sample. Hence we use the same recoil resolution for forward electron  $W$  events as for the central  $W$  events [5]. Figure 2 shows a plot of  $u_\eta/R_{\text{rec}} + p_\eta(ee)$  when both electrons are in the forward calorimeters.

Backgrounds in the  $W$  sample are  $W \rightarrow \tau\nu \rightarrow e\nu\bar{\nu}\nu$  decays (1.0%, which is included into the Monte Carlo simulation), hadrons misidentified as electrons ( $3.64\% \pm 0.78\%$ , determined from the data), and  $Z \rightarrow ee$  decays ( $0.26\% \pm 0.02\%$ , determined from HERWIG/GEANT simulations). Their shapes are included in the probability density functions used in the fits.

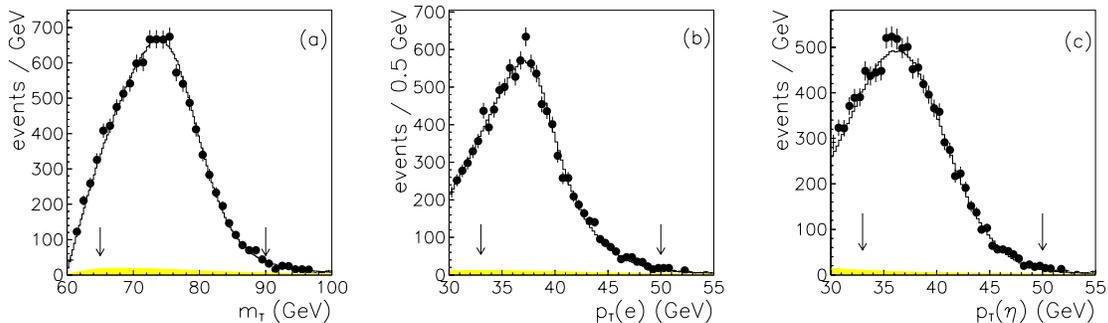


FIG. 3. Spectra of (a)  $m_T$ , (b)  $p_T(e)$  and (c)  $p_T(\nu)$  from the data ( $\bullet$ ), the fit ( $—$ ), and the backgrounds (shaded). The arrows indicate the fit windows.

In principle, if the acceptance for the  $W \rightarrow e\nu$  decays were complete, the transverse mass distribution or the lepton  $p_T$  distribution would be independent of the  $W$  rapidity. However, cuts on the electron angle in the laboratory frame cause the observed distributions of the transverse momenta to depend on the  $W$  rapidity. Hence a constraint on the  $W$  rapidity

distribution is useful in constraining the production model uncertainty on the  $W$  mass. We introduce in the Monte Carlo a scale factor  $k_\eta$  for the  $W$  boson rapidity as  $\eta_W \rightarrow k_\eta \eta_W$  and extract it by fitting Monte Carlo electron rapidity distribution simulated with different value of  $k_\eta$  to the data. The scale factor is found to be consistent, within errors, with unity with uncertainty 1.6%.

The fit to the  $m_T$  distribution (Fig. 3(a)) yields  $M_W = 80.766$  GeV with a statistical uncertainty of 108 MeV. A  $\chi^2$  test gives  $\chi^2 = 17$  for 25 bins which corresponds to a confidence level of 81%. The fit to the  $p_T(e)$  distribution (Fig. 3(b)) yields  $M_W = 80.587$  GeV with a statistical uncertainty of 125 MeV. The confidence level of the  $\chi^2$  test is 5%. The fit to the  $p_T(\nu)$  distribution (Fig. 3(c)) yields  $M_W = 80.726$  GeV with a statistical uncertainty of 163 MeV and confidence level 33%.

We estimate systematic uncertainties in  $M_W$  from the Monte Carlo parameters by varying them within their uncertainties (Table I). In addition to the parameters described above, the calibration of the electron polar angle measurement contributes a significant uncertainty. We use muons from  $p\bar{p}$  collisions and cosmic rays to calibrate the drift chamber measurements and  $Z \rightarrow ee$  decays to align the calorimeter with the drift chambers. Smaller uncertainties are due to the removal of the cells occupied by the electron from the computation of  $\vec{u}_T$ , the uniformity of the calorimeter response, and the modeling of trigger and selection biases.

TABLE I. Uncertainties in the  $W$  boson mass measurement in MeV.

Source	Forward	Forward + Central
$W$ boson statistics	107	61
$Z$ boson statistics	181	59
Calorimeter linearity	52	25
Calorimeter uniformity	–	8
Electron resolution	42	19
Electron angle calibration	20	10
Recoil response	17	25
Recoil resolution	42	25
Electron removal	2	12
Selection bias	5	3
Backgrounds	20	9
Parton distribution functions	35	15
Parton luminosity	2	4
$p_T(W)$ spectrum	25	15
$W$ boson width	10	10
radiative decays	1	12

The uncertainty due to the model for  $W$  boson production and decay consists of several components (Table I). We assign an uncertainty that characterizes the range of variations in  $M_W$  obtained when employing several recent parton distribution functions: MRST [8], MRSA [15], MRSR2 [16], CTEQ5M [17], and CTEQ4M [18]. We allow the  $p_T(W)$  spectrum to vary within constraints derived from the  $p_T(ee)$  spectrum of the  $Z$  data and from  $\Lambda_{QCD}$  [13]. The uncertainty due to radiative decays contains an estimate of the effect of

neglecting double photon emission in the Monte Carlo simulation [19].

The fit to the  $m_T$  spectrum results in a  $W$  boson mass of  $80.766 \pm 0.108(\text{stat}) \pm 0.208(\text{syst})$  GeV, the fit to the  $p_T(e)$  spectrum results in  $80.587 \pm 0.125(\text{stat}) \pm 0.217(\text{syst})$  GeV, and the fit to the  $p_T(\nu)$  spectrum results in  $80.726 \pm 0.163(\text{stat}) \pm 0.307(\text{syst})$  GeV. The good agreement of the three fits shows that our simulation models the  $W$  boson production dynamics and the detector response well. Fits to the data in bins of luminosity,  $\phi(e)$ ,  $\eta(e)$ , and  $u_T$  do not show evidence for any systematic biases.

We combine all the six measurements ( fits to central electron [5] and forward electron  $W$  boson events using three techniques ). We obtain the combined 1994-1995 measurement  $M_W = 80.487 \pm 0.096$  GeV. The  $\chi^2$  is 4.6/5 dof, with a probability of 46%. Combining with the measurement from the 1992-93 data gives the 1992-95 data measurement of  $M_W = 80.474 \pm 0.093$  GeV.

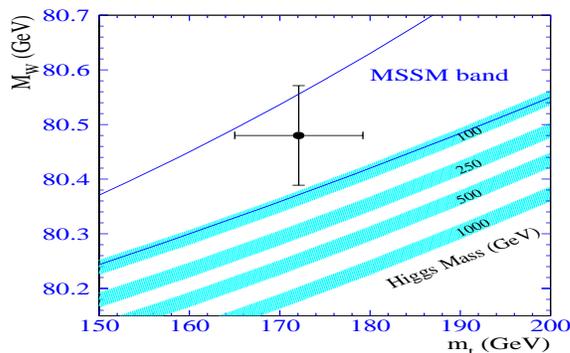


FIG. 4. Direct  $W$  boson and top quark mass measurements by the DØ [20] experiment. The bands show SM predictions for the indicated Higgs masses [21].

Using Eq. 1 we find  $\Delta r_W = -0.0317 \pm 0.0061$ , which establishes the existence of electroweak corrections to  $M_W$  at the level of five standard deviations. Figure 4 compares the direct measurements of the  $W$  boson and top quark masses to SM predictions.

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## REFERENCES

- [1] S.L. Glashow, Nucl. Phys. **22**, 579 (1961); S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967); A. Salam, *Proceedings of the 8<sup>th</sup> Nobel Symposium*, edited by N. Svartholm (Almqvist and Wiksells, Stockholm 1968), p. 367.
- [2] A. Sirlin, Phys. Rev. D **22**, 971 (1980); W. Marciano and A. Sirlin, Phys. Rev. D **22**, 2695 (1980) and erratum-*ibid.* **31**, 213 (1985).
- [3] S. Eidelmann and F. Jegerlehner, Z. Phys. C **67**, 585 (1995).
- [4] S. Abachi *et al.* (DØ), Nucl. Instrum. Methods in Phys. Res. A **338**, 185 (1994).
- [5] B. Abbott *et al.* (DØ), Phys. Rev. D **58**, 092003 (1998); B. Abbott *et al.* (DØ), Phys. Rev. Lett. **80**, 3008 (1998).
- [6] We generically refer to electrons and positrons as electrons.
- [7] G.A. Ladinsky and C.-P. Yuan, Phys. Rev. D **50**, 4239 (1994).
- [8] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. **C4**, 463-496 (1998).
- [9] S. Abachi *et al.* (DØ), Phys. Rev. Lett. **75**, 1456 (1995).
- [10] The LEP Collaborations, the LEP Electroweak Working Group, and the SLD Heavy Flavour Group, CERN-PPE/97-154 (unpublished).
- [11] E. Mirkes, Nucl. Phys. **B387**, 3 (1992).
- [12] F.A. Berends and R. Kleiss, Z. Phys. C **27**, 365 (1985).
- [13] R.M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1998).
- [14] F. Carminati *et al.*, *GEANT Users Guide*, CERN Program Library W5013, 1991 (unpublished).
- [15] A.D. Martin, W.J. Stirling, and R.G. Roberts, Phys. Rev. D **50**, 6734 (1994) and Phys. Rev. D **51**, 4756 (1995).
- [16] A.D. Martin, R.G. Roberts and W.J. Stirling, Phys. Lett. B **387**, 419 (1996).
- [17] H.L. Lai *et al.* (CTEQ collaboration), hep-ph/9903282 (unpublished).
- [18] H.L. Lai *et al.*, Phys. Rev. D **55**, 1280 (1997).
- [19] U. Baur *et al.*, Phys. Rev. D **56**, 140 (1997) and references therein.
- [20] B. Abbott *et al.* (DØ), FERMILAB-PUB-98/031-E, submitted to Phys. Rev. D.
- [21] G. Degrossi *et al.* Phys. Lett. B **418**, 209 (1998); G. Degrossi, P. Gambino, and A. Sirlin, Phys. Lett. B **394**, 188 (1997).