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Measurement of Properties of Electroweak Bosons with the DØ Detector

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This article reports three analyses of W and Z boson properties from the DØ experiment at the Fermilab Tevatron. The W boson mass measurement using 1 fb^{-1} DØ data is presented. This measurement reaches a 43 MeV precision on the W boson mass, which is currently the most precise result from a single experiment. It is used to place indirect constraint on the mass of the hypothetical Higgs boson. The W charge asymmetry analysis using 4.9 fb^{-1} DØ $W \rightarrow \mu\nu$ data to constrain the PDF uncertainty is reported. The measurement of effective electroweak mixing angle and the couplings of Z/γ^* to light quarks from the analysis of Z/γ^* forward-backward asymmetry based on 5 fb^{-1} DØ data is presented.

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1. Introduction

Measurements of the properties of the W and Z boson serve as precise examinations of the Standard Model and its predictions. Precise measurement of the W boson mass constrains the Standard Model prediction of the Higgs boson mass. Measurement of the W charge asymmetry improves the knowledge of the parton distribution functions (PDFs). The Z/γ^* forward-backward asymmetry analysis extracts the electroweak mixing angle based on Z/γ^* to light quark vertices, and directly probes the corresponding couplings.

The Tevatron at Fermilab is a proton-antiproton collider at 1.96 TeV with CP symmetric initial state. It can be called a factory of W and Z boson. The DØ experiment has recorded $\sim 10\ fb^{-1}$ data, in which there are about 7 M reconstructed $W \to e\nu$ events. Compared to LHC, at Tevatron, the W and Z boson are mainly produced by valence quarks. Therefore, Tevatron is ideal for asymmetry measurements to constrain the PDFs. And, the W and Z properties measurements benefit from the better knowledge of the PDFs of valence quarks.

2. W boson mass analysis

Knowledge of the W boson mass (M_W) is currently the limiting factor in our ability to tighten the constraints on new physics that couples to the electroweak sector. Improving the measurement of the M_W is an important contribution to our understanding of the electroweak interaction, and, potentially, of how the electroweak symmetry is broken.

The measurement of M_W using 1 fb^{-1} DØ data [1] is based on the $W \to e\nu$ decay mode with electrons inside the central calorimeter. The M_W is extracted from three kinematic variables measured in the plane transverse to the beam: the transverse mass m_T, the electron transverse momentum p_T^e, and the neutrino transverse momentum inferred from the event missing transverse momentum $\not\!\!E_T$. The transverse mass is defined as $m_T = \sqrt{2p_T^e \not\!\!E_T(1-\cos\Delta\phi)}$, where $\Delta\phi$ is the opening angle between the electron and neutrino momenta in the plane transverse to the beam.

The W and Z boson production and decay kinematics are simulated using the RESBOS [3] generator. The radiation of up to two photons is performed using the PHOTOS [4] program. The detector response is simulated using a fast parametric Monte Carlo simulation (PMCS) [1] developed for this analysis. The PMCS parameters are determined using a combination of detailed simulation and data control samples. The primary control sample used for both the electromagnetic and hadronic response tuning is $Z \to ee$ events. To determine the M_W, PMCS template distributions for m_T, p_T^e and $\not\!\!E_T$ are generated at a series of test M_W values. A binned likelihood between the data and each template is then computed. The minimal point of the log likelihood as a function of test M_W value defines the measured M_W value.

The M_W results from data are given in Table 1. The m_T, p_T^e, and $\not\!\!E_T$ distributions showing the data and PMCS template with background for the best fit M_W are shown in Fig. 1. The systematic uncertainties in the M_W measurement arise from a variety of sources and are summarized in Table 2. The results from the three methods are combined [5] to give the final result

$$\begin{aligned} M_W &= 80.401 \pm 0.021\ (\text{stat}) \pm 0.038\ (\text{syst})\ \text{GeV} && (2.1) \\ &= 80.401 \pm 0.043\ \text{GeV}. && (2.2) \end{aligned}$$

Table 1: Results [1] from the fits to data . The uncertainty is only the statistical component.

Variable	Fit Range (GeV)	M_W (GeV)	χ^2/dof
m_T	$65 < m_T < 90$	80.401 ± 0.023	48/49
p_T^e	$32 < p_T^e < 48$	80.400 ± 0.027	39/31
$\not{E}_T$	$32 < \not{E}_T < 48$	80.402 ± 0.023	32/31

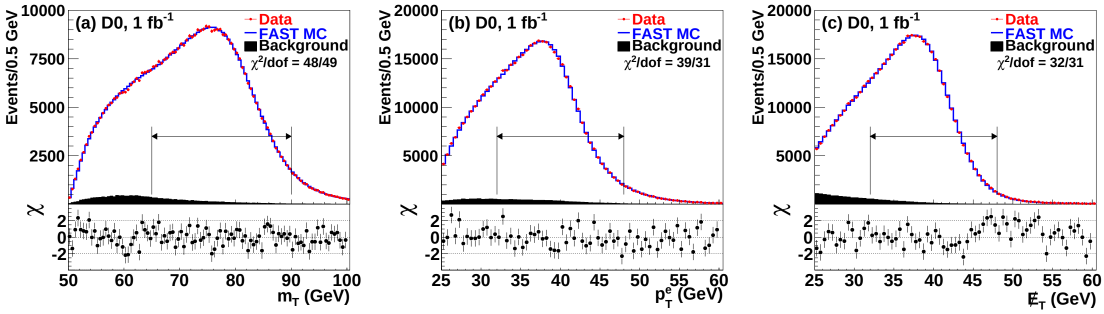

Figure 1: The (a) m_T, (b) p_T^e, and (c) $\not{E}_T$ distributions for data and PMCS simulation with backgrounds [1]. The χ values are shown below each distribution where $\chi_i = [N_i - (\text{PMCS}_i)]/\sigma_i$ for each point in the distribution, N_i is the data yield in bin i and only the statistical uncertainty is included. The fit ranges are indicated by the double-ended horizontal arrows.

This result is currently the most precise single experiment measurement of the M_W. The current world-average measured value with this result included is $M_W = 80.399 \pm 0.023$ GeV [2]. The measurement is on going using full DØ data set ($\sim 10 fb^{-1}$). With ten times more data, the statistical uncertainty, and experimental systematic uncertainties arising from limited Z statistics will decrease accordingly, and the theoretical uncertainty (especially the PDF uncertainty) will be a more important contribution to the uncertainties. Therefore, improving our knowledge of the PDFs

Table 2: Systematic uncertainties in the M_W measurement [1].

	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	35	37	41
PDF	10	11	11
QED	7	7	9
Boson p_T	2	5	2
Production Subtotal	12	14	14
Total	37	40	43

is highly motivated.

3. W charge asymmetry analysis

The measurement of W charge asymmetry to constrain the valence quark PDFs is highly motivated to reduce the W boson production model uncertainty for the M_W measurement.

At the Tevatron, W bosons are mostly produced by valence light quark pairs. For instance, a u quark from a proton with a $\bar{d}$ quark from antiproton produces a W^+ boson. Knowing that u ($\bar{u}$) quark carries more momentum than d ($\bar{d}$) quark, W^+ bosons are preferentially boosted along proton direction, while W^- is preferentially boosted along antiproton direction. W boson charge asymmetry as a function of W boson rapidity can be defined as:

$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W} \simeq \frac{u(x_1)/d(x_1) - u(x_2)/d(x_2)}{u(x_1)/d(x_1) - u(x_2)/d(x_2)} \tag{3.1}$$

where, y_W is W rapidity, $u(x)$ and $d(x)$ are the PDFs of the valence u and d quark in proton, x_1 and x_2 are the momentum fractions carried by an u or d quark in proton and antiproton, respectively.

Since the W charge asymmetry can be directly expressed in terms of PDFs (Equation 3.2), we can easily understand that the precision measurement of W charge asymmetry can directly constrain the PDFs. However, the W boson 4-momentum is not easy to be reconstructed, because the neutrino longitudinal momentum is not directly measurable at hadron colliders. An alternative observable is the charge asymmetry of the lepton from the W boson decay, which is defined as:

$$A(\eta_l) = \frac{d\sigma(l^+)/d\eta_l - d\sigma(l^-)/d\eta_l}{d\sigma(l^+)/d\eta_l + d\sigma(l^-)/d\eta_l} \tag{3.2}$$

The lepton charge asymmetry is directly observable but somewhat "dilutes" the W charge asymmetry due to the $V - A$ asymmetry and angular momentum conservation.

A measurement of the muon charge asymmetry from W boson decay using DØ $4.9 fb^{-1}$ data [6] is shown in Figure 3, along with the CTEQ6.6 prediction. A good agreement of the measured central values with theoretical prediction can be seen. The much smaller uncertainty (more than 5 times more precise for $\eta > 1$) from the DØ data than the theoretical prediction indicates the measurement largely improves our current knowledge of the PDFs.

4. Z/γ^* forward-backward asymmetry analysis

In the process $q\bar{q} \to Z/\gamma^* \to e^+e^-$, the coupling of fermions with γ^* contains only vector component ($g_v^f = I_3^f + 2Q_f \sin^2\theta_W$), while the coupling of Z with fermions contains both vector (g_v^f) and axial-vector ($g_a^f = I_3^f$) component. The differential cross-section can be expressed as

$$\frac{d\sigma(q\bar{q} \to e^+e^-)}{d\cos\theta^*} = A(1 - \cos^2\theta^*) + B\cos\theta^* \tag{4.1}$$

where, θ^* is azimuthal angle of e^- in the rest frame of Z/γ^*, A and B are functions of vector coupling (g_v^f), axial-vector coupling (g_a^f) and electroweak mixing angle ($\sin^2\theta_W$). This gives rise to a non-zero forward-backward asymmetry (A_{FB}) in the final states,

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}\frac{B}{A} = f(g_v^f,\ g_a^f,\ \sin^2\theta_W,\ \ldots) \tag{4.2}$$

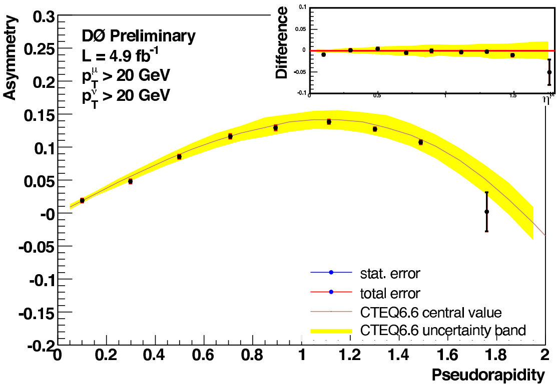

Figure 2: Comparison [6] of muon charge asymmetry as a function of pseudorapidity (η) for $p_T > 20$ GeV measured from DØ 4.9fb^{-1} data with CTEQ6.6 prediction.

where, F and B stand for “forward” ($\cos\theta^* > 0$) and “backward” ($\cos\theta^* < 0$), respectively.

At the same time, Z/γ^* is mostly produced by light valence quark pair $u\bar{u}$ and $d\bar{d}$ at Tevatron. Therefore, from the observable A_{FB} we can precisely measure electroweak mixing angle $\sin^2\theta_W$ based on Z/γ^* to light quark vertices, and directly probe the corresponding couplings. Also, at Z-pole A_{FB} is dominated by interference of vector and axial-vector couplings of Z/γ^* to quarks, while far away above Z-pole A_{FB} is dominated by Z/γ^* interference, which is sensitive to new physics.

The A_{FB} distribution as a function of electron pair invariant mass (M_{ee}) unfolded from DØ $\sim 5\ fb^{-1}$ data [7] comparing with theoretical predictions is shown in Figure 4. The A_{FB} from DØ data is in good agreement with theoretical predictions and there is no evidence for new physics at high mass.

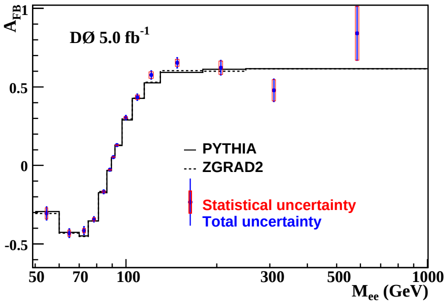

Figure 3: Comparison [7] between the unfolded A_{FB} from DØ data and theoretical predictions.

The electroweak mixing angle extracted from the A_{FB} distribution of the $\sim 5\ fb^{-1}$ DØ data is

$$\sin^2\theta_W \ = \ 0.23091 \pm 0.0008\ (stat.) \pm 0.0006\ (syst.). \tag{4.3}$$

It is currently the most precise measurement based on Z/γ^* to light quark vertices. The systematic uncertainty is dominated by PDF uncertainty ($\pm$0.00048), which will become a more important contribution in future analysis using all DØ ($\sim 10\ fb^{-1}$) data.

The vector and axial-vector couplings of Z/γ^* with u and d quark extracted from the A_{FB} distribution of the $\sim 5\ fb^{-1}$ DØ data [7] are shown in Figure 4 with 68% C.L. contours comparing with other experiments. It is currently the most precise direct measurement of the couplings of Z/γ^* to light quarks u and d.

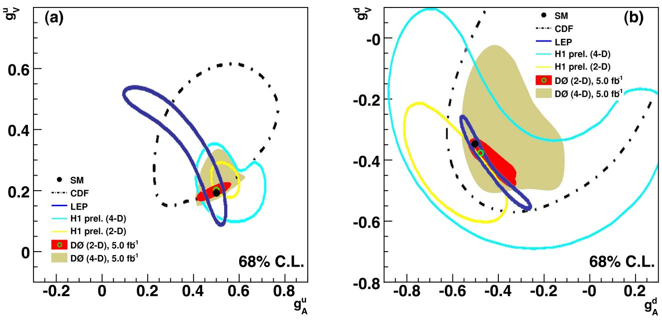

Figure 4: The 68% C.L. contours [7] of (a) g_v^u and g_a^u, and (b) g_v^d and g_a^d measured from A_{FB} distribution of DØ data, comparing with other experiments.

5. Conclusion

Measurements of electroweak boson properties are precise examinations of the Standard Model and its predictions. The Tevatron accelerator providing a CP symmetric initial state is ideal for asymmetry measurements. The properties measurements of electroweak bosons at Tevatron benefit from lower PDF uncertainties compared to LHC. The W boson mass measurement constrains the Higgs boson mass. The W boson mass measured from DØ 1 fb^{-1} data is currently the most precise result from a single experiment. The W charge asymmetry measurement constrain further the PDF uncertainties. The muon charge asymmetry from $W \to \mu\nu$ events of DØ 4.9 fb^{-1} data is much more precise than predicted from current knowledge of the PDFs. The Z/γ^* forward-backward asymmetry analysis using DØ 5 fb^{-1} data gives currently the most precise measurement of the electroweak mixing angle based on Z/γ^* to light quark coupling. It also gives currently the most direct measurement of the coupling of Z/γ^* to light quarks u and d.

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