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Electroweak Results from the Tevatron Collider

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ELECTROWEAK RESULTS FROM THE TEVATRON COLLIDER

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We present the latest results on electroweak physics obtained from the analysis of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The large data samples collected with the CDF and D∅ detectors at the Tevatron collider allow measurements of the top quark mass to a 3% accuracy and of the W boson to a 0.1% accuracy. Many precision measurements that test the Standard Model and probe its possible extensions are also described.

1 Introduction

The Tevatron is the highest energy collider in the world. Protons and antiprotons are accelerated to an energy of 900 GeV each, and collide at a rate of $\sim 300 kHz$ in the core of the CDF and D∅ detectors. The machine was built with the primary goal of discovering the top quark, accomplished in 1995, but has achieved much more. In the four years of collider running from 1992 to 1996, for instance, more than 100,000 W bosons have been identified through their $e\nu$ and $\mu\nu$ decay modes. These data have allowed precise measurements of the W mass and many other electroweak measurements.

CDF and D∅ are multi-purpose detectors designed to identify electrons, muons, photons and jets by their tracking systems, calorimeters and muon chambers. Electron and photon energies are measured in the electromagnetic part of the calorimeter system; photons can be distinguished by the absence of a matching track. Muons are identified as minimum ionizing tracks matching signals in the outer muon chambers. Jets are reconstructed and measured in the calorimeters, that cover the pseudorapidity region $|\eta| < 4.2$; a determination of the transverse energy imbalance in the calorimeters, $\not{E}_T$, also allows one to measure the transverse momentum of energetic neutrinos. The data presented here amount to a total integrated luminosity of about $110\, pb^{-1}$ per experiment, corresponding to roughly $10^{13} p\bar{p}$ collisions. This enormous number is reduced by multi-level online trigger systems (hardware and software) to a size more amenable to data storage and analysis.

2 Constraining the Higgs Boson Mass

In the framework of Electroweak Symmetry Breaking within the Standard Model, weak radiative corrections tie the unknown mass of the Higgs boson to those of the top quark and the W boson. Therefore, after the precise electroweak measurements of the LEP and SLC experiments and the discovery of the top quark, a new race has begun, whose aim is to measure with the highest precision M_t and M_W. A big leap forward has been taken recently with the help of Tevatron data, and the Higgs boson is now expected to have a mass very close to the discovery reach of the LEP II experiments. In what follows we review these results.

2.1 The Mass of the Top Quark

The dominant production mode for top quarks at the Tevatron is $q\bar{q} \to t\bar{t}X$; each top quark decays to a b quark and a W boson. We classify the $t\bar{t}$ final states according to the number of electron or muon decays of the W pair: dilepton, single lepton, and all-hadronic modes involve respectively two, one, and zero such decays[a]. The best compromise between rate and background contamination is the single lepton decay: the most precise single determination of the top mass has been obtained by CDF using such events.

To reconstruct the top mass in the single lepton decay mode, both experiments use a kinematic fitting technique that receives as input the momentum of the charged lepton, the $\not{E}_T$ vector, and the momentum of the jets. Three constraints are implied by the $t\bar{t} \to l\nu q\bar{q}' b\bar{b}X$ decay hypothesis: the equality of $l\nu$ and $q\bar{q}'$ masses to M_W, and the equivalence of t and $\bar{t}$ masses. The fit chooses the most likely assignment of jets to the final state partons, taking into account the identification of a jet as a b quark product if the jet contains a secondary vertex or a soft lepton. Finally, the top mass distribution is fit with a likelihood technique to obtain M_t.

CDF starts from a dataset of 151 events selected with the following cuts: a $P_T > 20\,GeV$ central lepton, $\not{E}_T > 20\,GeV$, and four jets with $E_T^{1,2,3} > 15\,GeV$, $E_T^4 > 8\,GeV$, $|\eta_j| < 2.4$; of these, 34 events containing b jet candidates and 42 with four high-E_T central jets are selected. Monte Carlo optimization studies suggest a partition of the 76 events into four disjunct classes, depending on the presence and detection mode of b candidates, which affect the background contamination. The four measurements are then combined; the final result is $M_t = 175.9 \pm 4.8$ (stat) ± 4.9 (syst) GeV/c^2. The single lepton result is combined with the results obtained in the all-hadronic ($M_t = 186.0 \pm 10.0$

[a]Final states involving τ leptons are neglected here, since they are very difficult to identify.

(stat) ± 8.2 (syst) GeV/c^2) and dilepton channel ($M_t = 167.4 \pm 10.3$ (stat) ± 4.8 (syst) GeV/c^2), and the final CDF result is $M_t = 175.3 \pm 6.4\,GeV/c^2$.

The event selection of DØ is similar to that of CDF; DØ has a larger acceptance for the leptons and requires all jets to have $E_T > 15\,GeV$, but cannot identify secondary vertices from b decays. The M_t distribution of the 77 selected events (5 of which have a jet containing a soft lepton) is fit with a likelihood technique using two choices of an additional variable providing discrimination between signal and background events. The measured values are combined including systematic uncertainties to obtain $M_t = 173.3 \pm 5.6$ (stat) ± 5.5 (syst) GeV/c^2. This result is in turn combined with the result of the dilepton channel ($M_t = 168.4 \pm 12.3$ (stat) ± 3.6 (syst) GeV/c^2) to yield the final DØ measurement of $M_t = 172.1 \pm 7.1\,GeV/c^2$.

A combination of the CDF and DØ results, assuming a $2\,GeV/c^2$ correlated systematic uncertainty, yields $M_t = 173.8 \pm 5.0\,GeV/c^2$. The Tevatron data thus allow a measurement of the top quark mass with an accuracy of 3%.

2.2 The Mass of the W Boson

The W mass has been measured at the Tevatron with a 0.1% accuracy from its $e\nu$ and $\mu\nu$ decays. The most precise determination comes from the analysis of electron events at DØ; we describe it briefly here.

DØ measures M_W with a fit to the transverse mass distribution; the transverse mass $M_T^{e\nu} = \sqrt{2P_T^e P_T^\nu(1 - \cos\phi^{e\nu})}$ is insensitive, to first order, to the P_T boost of the W, which is difficult to model. The 28,323 candidate $W \to e\nu$ events collected in the 1994-95 run contain a central electron with $E_T > 25\,GeV$, $|\eta_e| < 1.0$, $\not{E}_T > 25\,GeV$, and have a small hadronic recoil against the W boson, $P_T^W < 15\,GeV/c$.

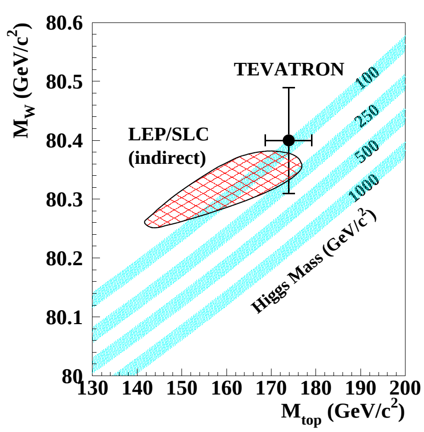

Figure 1: The W and top mass measurements performed by CDF and DØ suggest a small value for the Higgs boson mass.

The critical parameters in the extraction of M_W are the energy scale for the electron and for the hadronic recoil, that affect the measured value of the peak position, and the electron E_T and neutrino P_T resolutions, that determine the steepness of the peak. The e.m. scale in the calorimeter is set by studying $e^+e^-(\gamma)$ signals from

Z, J/ψ and Dalitz π^0 decays; the resulting uncertainty on M_W amounts to $65\,MeV/c^2$. The electron energy resolution is determined from the width of the M_Z distribution in a sample of $Z \to e^+e^-$ decays and from test beam data: the uncertainty on M_W due to this is $\sigma_{M_W} = 23\,MeV/c^2$. The uncertainty in the energy scale for the hadronic recoil and the neutrino P_T resolution give respectively 23 and $33\,MeV/c^2$ uncertainties in M_W. Finally, the dominant theoretical error comes from the knowledge of the parton distribution functions. The CTEQ3M set was used, which was determined using the highly constraining CDF W asymmetry 1992-93 data. A theoretical model [1] is used for the P_T^W distributions. The total uncertainty on M_W due to theoretical sources is estimated to be $21\,MeV/c^2$.

By fitting its transverse distribution, the mass is measured to be $M_W = 80.43 \pm 0.11\,GeV/c^2$. This result can be combined with the average of the CDF results ($M_W = 80.375 \pm 0.120\,GeV/c^2$) to obtain $M_W = 80.40 \pm 0.09\,GeV/c^2$.

The top mass and the W boson mass can then be used in conjunction with the other electroweak parameters measured at e^+e^- machines to constrain the Higgs boson mass. As fig.1 shows, the preferred value of M_H inferred from the radiative corrections is possibly within reach of the LEP II experiments and the next Tevatron run.

3 Studies of W and Z Boson Production

3.1 Production Cross Sections

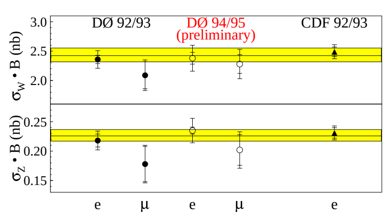

Figure 2: The theoretical predictions for the cross section of $p\bar{p} \to WX \to l\nu X$ and $p\bar{p} \to ZX \to l^+l^-X$ (shaded bands) are in agreement with the experimental results with electrons and muons.

The production rates for gauge bosons provide a fundamental test of the Standard Model. To measure their cross sections and related quantities, W and Z events are collected by CDF and DØ via their leptonic decays involving electrons and muons: for W bosons, a high P_T lepton and $\not{E}_T > 25\,GeV$ are required; the Z selections collect events with pairs of high P_T electrons or muons. Fig.2 shows the good agreement between the measured cross sections and the theoretical predictions [2] at order $\mathcal{O}(\alpha_s^2)$. The main uncertainties arise from the determination of of the integrated luminosity and the choice of the parton distribution functions.

3.2 Measurements of the W Boson Width

From a measurement[3] of the ratio $R = \frac{\sigma_W B(W \to l\nu)}{\sigma_Z B(Z \to ll)} = 10.32 \pm 0.43$ an indirect measurement of Γ_W is possible. The SM prediction for σ_W/σ_Z and the LEP measurement of $B(Z \to ll)$ allow to compute $B(W \to l\nu) = R \times B(Z \to ll) \times \frac{\sigma_Z}{\sigma_W} = 0.1043 \pm 0.0044$, and the theoretical calculation of $\Gamma(W \to l\nu)$ allows to obtain $\Gamma_W = \frac{\Gamma(W \to l\nu)}{B(W \to l\nu)} = 2.159 \pm 0.092\, GeV$, in good agreement with the Standard Model prediction ($\Gamma_W = 2.077 \pm 0.014\, GeV$).

A direct measurement of the width of the W boson is difficult to extract from the W peak, whose shape is dominated by the experimental resolution; however, the high mass tail contains useful information on the width, since in this region the Breit-Wigner tail takes over the gaussian resolution. CDF has exploited this feature with the $W \to e\nu$ candidates collected in the 1994-1995 run. A likelihood fit to the line-shape in the transverse mass region $110 < M_W^T < 200\, GeV/c^2$ yields $\Gamma_W = 2.19^{+0.17}_{-0.16}$ (stat) ± 0.09 (syst) GeV: although this is a less precise determination than the indirect result, it is also less sensitive to theoretical assumptions.

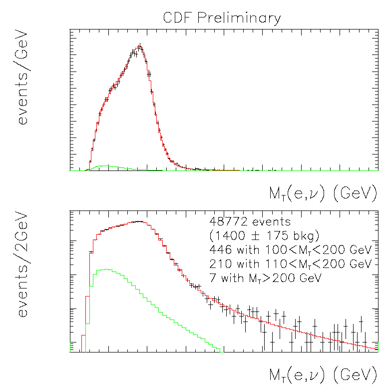

Figure 3: Determination of the W width from the transverse mass line-shape.

3.3 The W Charge Asymmetry

W production at the Tevatron shows an asymmetry due to the momentum fractions carried by the originating partons: W^+ (W^-) bosons tend to be produced in the (anti-)proton direction, due to the higher momentum carried on average by u ($\bar{u}$) quarks w.r.t. $\bar{d}$ (d) ones; the cross section is therefore a function of W rapidity. The W rapidity is not measurable due to the two-fold ambiguity in ν longitudinal momentum; what is measured is instead the lepton asymmetry $A(y_l) = \frac{dN^+(y_l)/dy - DN^-(y_l)/dy}{dN^+(y_l)/dy + DN^-(y_l)/dy}$, which receives a $V-A$ contribution from the full polarization of the produced boson.

The measurement of the W asymmetry allows one to put very tight constraints on the parton distribution functions at high $Q^2 = M_W^2$ in the Bjorken-x region $0.006 < x < 0.34$. The measurement obtained by CDF with the 1992-93 data, whose uncertainty was dominated by statistics, demonstrated that $p\bar{p}$ collider data had a better sensitivity to the (d/u) parton distribution function than the deep inelastic scattering data. New sets of PDF were obtained using these results.

The inclusion of the 1994-95 data, with forward muons added and a new method for determining the charge of high rapidity tracks, allowed both a 5-fold increase in statistics and an extension of the probed x range. As can be seen in fig.4, the data shows that a further tuning of the d/u ratio at small x (high y_l) is necessary. By restricting the shape of the parton distribution functions, the W asymmetry measurement has significantly reduced the systematic uncertainties in all $p\bar{p}$ W mass determinations. At CDF the 1992-93 asymmetry data allowed σ_W^{syst} to decrease from 75 to $50\,MeV/c^2$. The new measurement will reduce this uncertainty to about $20\,MeV/c^2$.

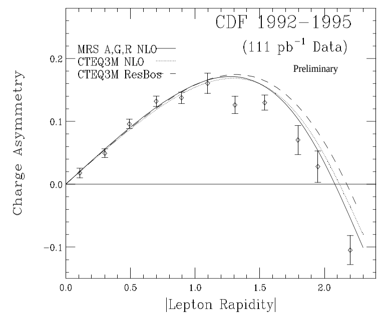

Figure 4: The lepton charge asymmetry distribution obtained by CDF is shown here compared with the predictions of various PDF.

3.4 Rare W Decays

While tens of rare Z decay modes have been studied, almost nothing is known of rare W decays. CDF has searched its whole dataset for the radiative process $W^{\pm} \to \pi^{\pm}\gamma$, whose expected branching ratio is 3×10^{-8}: no such events are expected in $110\,pb^{-1}$, consequently a signal would be evidence of physics outside the Standard Model. Events were collected by a trigger requiring a photon with $E_T > 23\,GeV$; candidate $\pi\gamma$ events were then required to have a $E_T > 15\,GeV$ jet consistent with a single charged track, no other jets, and invariant mass $|M_{\pi\gamma} - M_W| < 8.7\,GeV/c^2$ (a 3σ window).

3 events survive the selection, with an expected background of 5.2 ± 1.5 events; a lower limit can thus be set on the relative branching ratio: $\Gamma(W \to \pi^{\pm}\gamma)/\Gamma(W \to e^{\pm}\nu) \leq 7 \times 10^{-4}$ at 95% C.L..

4 Search for New Physics in Electroweak Processes

4.1 Anomalous Gauge Boson Couplings

The self-interaction of gauge bosons preserves unitarity by virtue of interference effects, and their couplings are determined uniquely in the Standard Model. The most general effective Lagrangian for the self-interactions can be written with 8 couplings (4 CP-conserving and 4 CP-violating); the CP-conserving ones in the SM at tree level are given by $k_V = 1$, $\lambda_V = 0$, where V stands for a γ or a Z boson: new physics would be indicated by a deviation from these values. The cross sections for diboson production at the Tevatron are typically in the picobarn range. However, an anomalous coupling would destroy the gauge cancellations, and produce large increases in cross section.

A WWV interaction with constant anomalous couplings violates unitarity at high $\sqrt{s}$, and a form factor Λ is needed: $\Delta\kappa(\hat{s}) = \frac{\Delta\kappa}{1+\hat{s}/\Lambda^2}$, $\lambda(\hat{s}) = \frac{\lambda}{1+\hat{s}/\Lambda^2}$. Λ is the scale at which the Standard Model predictions are probed. D$\emptyset$ has studied the WW, WZ and $W\gamma$ final states to put limits on $\Delta\kappa$ and λ. Fits to the P_T distributions of leptons and photons are used to get the best sensitivity. The combined limits from the three channels are: $-0.30 < \Delta\kappa < 0.43$ (for $\lambda =$ 0), $-0.20 < \lambda < 0.20$ (for $\Delta\kappa$ =0).

The $ZV\gamma$ vertex is absent in the SM, but is predicted by some new theoretical models [4]. The vertex can be described by four couplings regulated by Λ, $h_i^V(\hat{s}) = \frac{h_i^V}{(1+\hat{s}/\Lambda^2)^n}$ (i=1,..,4, $V = Z,\gamma$); the choice $n = 3$ (i=1,3) and $n = 4$ (i=2,4) gives the same energy dependence for the couplings [5]. D$\emptyset$ has extracted limits on the anomalous couplings from the $ee\gamma$, $\mu\mu\gamma$ and $\nu\bar{\nu}\gamma$ final states of the produced $Z\gamma$ pairs; the limits depend on the choice of Λ and on assumptions about the correlations between the two couplings. The results are: $|h_3^{Z,\gamma}| < 0.36, 0.37$; $|h_4^{Z,\gamma}| < 0.05, 0.05$ (95% C.L., $\Lambda = 750\,GeV$).

4.2 Searches for New Gauge Bosons

New gauge bosons are predicted by many extensions of the Standard Model; however, W' bosons with mass below $\sim 1\,TeV/c^2$ have been indirectly excluded by a number of different observations: a limit $M_{W'} > 1.3\,TeV/c^2$ comes from particle physics studies of the weak interaction [6]; cosmological nucleosynthesis studies [7] set a limit $M_{W'} > 1\,TeV/c^2$; analyses [8] of the SN1987A exclude a W' mass below $16\,TeV/c^2$. However one study [9], comparing various experimental results, suggests the possibility of a W' boson with mass $M_{W'} \sim 230\,GeV/c^2$. CDF and D$\emptyset$ have both obtained direct limits for the mass of a W'. CDF excludes masses below $652\,GeV/c^2$, D$\emptyset$ excludes masses below $610\,GeV/c^2$. Both assume Standard Model couplings.

For a new neutral Z' boson things are different. Some recent predictions [10] state that in Super String and Super Gravity models it is "natural" to expect the lightest Z' bosons to have masses below $1\,TeV/c^2$. Experimentally, a reference model is considered where the new bosons have couplings to quarks and leptons equal to those of the Z, with a width scaled with its mass from Γ_Z at $M_{Z'} = M_Z$. Limits on Z' production are extracted by comparing the observed dilepton mass distribution to a superposition of the predicted Z' signal for various masses with the Drell-Yan spectrum. A Z' with mass lower than 690 GeV/c^2 is excluded by CDF at 95% C.L. (fig.5); similarly, the DØ collaboration excludes a SM-like Z' boson with mass lower than 670 GeV/c^2.

5 Concluding Remarks

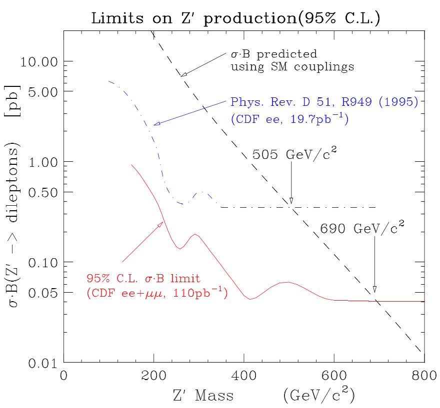

Figure 5: The cross section limit for Z' bosons from the full CDF dataset (lower curve) intersects the theoretical prediction at $M_{Z'} = 690\,GeV/c^2$.

The CDF and DØ experiments have measured the W mass with a 0.1% accuracy and the top mass with a 3% accuracy; these determinations start to indirectly constrain the Higgs boson mass. Various properties of W bosons have been investigated; in particular, a very precise measurement of the W boson asymmetry by CDF challenges theory to devise a more accurate description of the data with new sets of parton distribution functions, and has proven a decisive factor in reducing the W mass uncertainty at $p\bar{p}$ colliders. Detailed studies of anomalous gauge boson couplings have been performed which produced improved limits on these quantities, and limits have been put to the existence of new W' and Z' bosons.

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