Electroweak and Top Physics at the Tevatron and Indirect Higgs Limits

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Abstract. We report a selection of the most recent CDF and D0 results on top quark and W and Z boson properties, based on Tevatron Run 2 data. The large datasets of W and Z bosons allow a very precise measurement of the W mass and detailed studies of vector boson production and asymmetries. Associated production of vector boson pairs has been observed and cross sections have been measured. The top quark is being studied in great detail, and a precision of 1.1\% in the measurement of its mass has been achieved. The precise knowledge of top and W masses are constraining the allowed mass range of a standard model Higgs in an unprecedented way.

PACS. 14.70.Fm W bosons – 14.70.Hp Z bosons – 14.65.Ha Top quarks – 14.80.Bn Standard-model Higgs bosons

1 Introduction

The CDF and D0 experiments are multipurpose detectors taking data at the Tevatron Collider. The Tevatron provides proton–antiproton collisions at a center-of-mass energy \(\sqrt{s} = 1.96\) TeV. In 2001 the Tevatron Run 2 began, after a five year period of significant upgrade of the accelerator itself and of the CDF and D0 experiments. Accelerator performances have kept improving since the start of Run 2. A peak luminosity of \(2.92 \times 10^{32}\) cm\(^{-2}\) s\(^{-1}\) has been recently achieved, and more than 3 fb\(^{-1}\) of integrated luminosity has been delivered so far to both experiments. The detectors collect data with an average efficiency of about 85\%. As of these proceedings, \(\approx 2.5\) fb\(^{-1}\) were written to tape by each experiment.

A description of the CDF and D0 upgraded detectors can be found in [1].

2 W and Z Cross Section Measurements

W and Z bosons are produced at the Tevatron through \(q\bar{q}\) annihilation and are identified by their leptonic decay into electrons, muons and taus. The signature is given by high energy charged leptons and high missing transverse energy for W candidates and two oppositely charged high energy leptons for Z candidates. W and Z identification is a key ingredient for top physics. W and Z boson decays are often components of background in searches for processes beyond the standard model (SM) and, being relatively well known processes, are used for calibrations and detector checks. The samples of W and Z boson decays collected by CDF and D0 now number in the millions of events, and have been used to produce excellent measurements of electroweak observables.

Inclusive cross sections of both W and Z production have been measured in all the three lepton decay channels [2]. All measurements are in agreement with the NNLO calculations [3]. The accuracy is limited by systematic effects (dominated by the luminosity uncertainty of 6\%).

The large statistics collected allows CDF to produce a \(d\sigma(Z)/dy\) measurement for \(Z^0/\gamma^* \rightarrow e^+e^-\) events obtained from 1.1 fb\(^{-1}\) of data. Figure 1 shows the \(d\sigma(Z)/dy\) distribution compared to theory prediction. The total cross section integrated over all di-electron rapidities is \(\sigma(Z) = 263.34 \pm 0.93\) (stat) \(\pm 3.79\) (syst) pb. This measurement, with increased statistics, can be used to constrain the parton distribution functions (PDFs).

Recently, CDF measured the ratio \(R\) of central-to-forward cross sections for \(p\bar{p} \rightarrow W \rightarrow e\nu\) and obtained \(R = 0.925 \pm 0.033\) [4]. The largest experimental uncertainty, due to luminosity, cancels in this ratio. The measurement can be compared to theoretical predictions obtained using different PDFs (see Fig. 2). This quantity is sensitive to the W rapidity distribution, and provides a novel way to constrain the PDFs.

3 W Mass Measurement

The W mass (\(M_W\)) is measured in the e\(\nu\) and \(\mu\nu\) channels from a maximum likelihood fit to the lepton transverse momentum and the transverse mass spectrum,
with the result: 

precision p to the highest possible precision and simulation of the p where the updated world average is: 

Fig. 1. The measured $d\sigma/dy$ (crosses) compared to theory prediction (solid line) for $Z \rightarrow e^+e^-$. 

Fig. 2. CDF experimental ratio of central-to-forward cross sections (solid triangles) compared to the CTEQ6.1 (upper plot) and MRST01E (lower plot) acceptance ratios (solid circles and squares). Dashed lines separate PDF eigenvectors. 

defined as:

$$M_T = \sqrt{2p_T^e p_T^\mu (1 - \cos \Delta \phi)},$$

where $p_T$ is the lepton transverse momentum and $\Delta \phi$ is the difference in azimuthal angle between the two leptons. There are two main components leading to a precise $M_W$ measurement: calibration of the detector to the highest possible precision and simulation of the $p_T$ ($M_T$) spectrum. CDF measured the $W$ mass using a sample of 200 pb$^{-1}$ of electron and muon data, with the result: $M_W = 80413 \pm 34$ (stat) $\pm 34$ (syst) MeV/c$^2$ = 80413 $\pm 48$ MeV/c$^2$ [7]. This is the most precise single measurement of the $W$ mass to date. The updated world average is $M_W = 80398 \pm 25$ MeV/c$^2$ [8]. In Table 1 the various contributions to the systematic uncertainty are shown. The dominant uncertainties are due to the $W$ boson statistics and to the lepton energy scale calibration. They will be reduced with increased statistics in the $W$ boson and calibration data samples. Since many simulation parameters are constrained by data control samples, their uncertainties are statistical and are expected to be reduced with more data as well. By the end of Run 2 the Tevatron experiments should be able to reduce the uncertainty on $M_W$ below 20 MeV/c$^2$. 

4 Direct $W$ Width Measurement

CDF and D0 measured directly the $W$ boson width $\Gamma_W$ using the high tail of the $M_T$ distribution. The width is determined by normalizing the predicted signal and background $M_T$ distribution in the region of $50 < M_T < 90$ GeV/c$^2$ and then fitting the predicted shape of the candidate events in the tail region $90 < M_T < 200$ GeV/c$^2$ which is most sensitive to the width. CDF has the most precise measurement of this quantity, based on 350 pb$^{-1}$ of data: $\Gamma_W = 2032 \pm 71$ MeV/c$^2$, in good agreement with SM predictions [7]. Figure 3 shows the $M_T$ distribution in the electron channel used for the $\Gamma_W$ measurement. The updated world average is: $\Gamma_W = 2106 \pm 50$ MeV/c$^2$ [7].

5 $W$ Charge Asymmetry

$W$ bosons at the Tevatron are primarily produced by annihilation of valence $u$ ($d$) and anti–$d$ (anti–$u$) quarks to $W^+(W^-)$. Since $u$ quarks carry, on average, a higher fraction of the proton momentum than $d$ quarks, a $W^+$ ($W^-$) tends to be boosted in the (anti–)proton direction. This results in a charge asymmetry defined as:

$$A_{gw} = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W},$$

where $y_W$ is the $W$ rapidity and $d\sigma(W^{\pm})/dy_W$ is the differential cross section for $W^{\pm}$ production. A measurement of the charge asymmetry is sensitive to the

Table 1. The uncertainties in MeV/c$^2$ on the $M_T$ fit for $M_W$ obtained from 200 pb$^{-1}$ of CDF Run 2 data.

| Uncertainty (MeV/c$^2$) | Electrons | Muons |
|--------------------------|-----------|-------|
| Lepton scale             | 30        | 17    |
| Lepton Resolution        | 9         | 3     |
| Recoil Scale             | 9         | 9     |
| Recoil Resolution        | 7         | 7     |
| u$\bar{u}$ Efficiency    | 3         | 1     |
| Lepton Removal           | 8         | 5     |
| Backgrounds              | 8         | 9     |
| $p_T(W)$                  | 3         | 3     |
| PDF                      | 11        | 11    |
| QED                      | 11        | 12    |
| Total systematic         | 39        | 27    |
| Statistical              | 48        | 54    |
| Total                    | 62        | 60    |
The longitudinal neutrino component can be partly reconstructed in events, using 1 fb\(^{-1}\) of data. D0 recently updated to 1 fb\(^{-1}\) of data. The observed distribution is consistent with the SM prediction and has a shape indicative of the radiation amplitude zero, although the result is statistically limited.

### 6.2 WZ Production

At \(\sqrt{s} = 1.96\) TeV, the SM predicts \(\sigma(WZ) = 2.7 \pm 0.25\) pb \[11\]. D0 recently updated on 1 fb\(^{-1}\) of data. Its previous evidence for WZ production in events with three charged leptons \[12\]. They measure \(\sigma(WZ) = 2.7^{+1.3}_{-1.2}\) pb. In winter 2007 CDF presented the observation of the WZ process based on 1.1 fb\(^{-1}\) of data \[13\]. In this analysis a significant improvement
was obtained by exploiting all the available detector information in defining leptons, therefore increasing the lepton acceptance. Recently CDF measurement was updated on 1.9 fb^{-1} of data. The measured cross section is \( \sigma(WZ) = 4.3 \pm 1.4 \) pb. Figure 6 shows the missing \( E_T \) distribution in the signal region.

### 6.3 ZZ Production

The ZZ production cross section predicted by the SM at the Tevatron is \( \sigma(ZZ) = 1.4\pm 0.1 \) pb at NLO. D0 observed 1 candidate event and put an upper limit on the production cross section of \( \sigma(ZZ) < 4.3 \) pb at 95% C.L.. CDF combined the final states with 4 charged leptons and 2 charged leptons plus 2 neutrinos, and did a measurement of the ZZ production cross section \( \sigma(ZZ) = 0.75^{+0.41}_{-0.34} \) based on 1.5 fb^{-1} of data. The observed signal has a significance of 3\( \sigma \). This is the smallest cross section measured at the Tevatron. Figure 7 shows the likelihood ratio distribution for ll\nu\nu candidate events.

### 7 Top Quark Physics

The top quark, discovered in 1995 at the Tevatron [14], has proven to be a very interesting particle. It is unique among known fermions because of its large mass, of the order of the electroweak symmetry breaking scale. Its properties allow to perform stringent tests of the SM and to search for new physics through a deviation from SM predictions.

At the Tevatron center of mass energy top quarks are produced primarily in \( t\bar{t} \) pairs via the strong process \( pp \rightarrow t\bar{t} \). In the SM each top quark decays through charged current weak interaction almost exclusively into a real W and a b quark \((t \rightarrow Wb)\). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. The \( t\bar{t} \rightarrow W^+bW^-\bar{b} \) events can thus be identified by means of different combinations of energetic leptons and jets. The branching ratio for both W’s from a \( t\bar{t} \) pair to decay leptonically is: 2/81 for e\mu, e\tau, \mu\tau and 1/81 for ee, \( \mu\mu, \tau\tau \) (dilepton channels). Decay modes of \( t\bar{t} \) pairs in which one W boson decays hadronically and the other leptonically into an e or a \( \mu \) (single lepton + jets channel) have a branching ratio of 24/81. When both W’s decay hadronically (all hadronic channel) the branching ratio is 36/81. CDF and D0 identified top quark candidate events using most of these signatures.

### 8 Top Pair Cross Section Measurement

By measuring the \( t\bar{t} \) production cross section \( \sigma_{t\bar{t}} \) in many channels and comparing it to perturbative QCD calculations, we can test the SM predictions in great detail. The experimental uncertainty on the top quark pair production cross section has become comparable to the theoretical one \((\approx 12\%)[15]\). Figure 8 shows a summary of the top pair cross section measurements in the various channels at D0 (left plot) and CDF (right plot). All the measurements are consistent with each other and with the theoretical expectations, which are indicated by the vertical band.

D0 recently performed a simultaneous measurement of the \( t\bar{t} \) production cross section and ratio \( R = B(t \rightarrow Wb)/B(t \rightarrow W\ell) \), counting the number of events with 0, 1 and at least 2 reconstructed b-quark jets (shown in figure 9). Figure 10 shows a summary of \( R \) measurements at the Tevatron. The measured \( R = 0.991^{+0.094}_{-0.085} \) (stat+syst) can be translated into a lower limit on the V_{tb} Cabibbo-Kobayashi-Maskawa (CKM) matrix element of |V_{tb}| > 0.901 at 95% C.L. and assuming CKM unitarity.
The precision of the jet energy scale is crucial in this respect. The assignment of jets to partons usually has many possible permutations. Finally, there are background processes which mimic $t\bar{t}$ events.

CDF and D0 performed many determinations of $M_{top}$, using different techniques and all the top decay final states. In the single lepton + jets and all hadronic channels the uncertainty from jet energy scale (JES) can be reduced by using the reconstructed invariant dijet mass of the hadronically decaying $W$ boson in top candidate events as an internal constraint (see Figure 11). This method converts the dominant systematic uncertainty into a statistical uncertainty, which will improve with more data.
At the time of this writing, CDF obtained the most precise determination of the top mass in the single lepton + jets channel, using a matrix element integration method for the signal and a neural network discriminant to identify background events. CDF finds $M_{\text{top}} = 172.7 \pm 1.3$ (stat.) $\pm 1.2$ (JES) $\pm 2.1$ (total) GeV/$c^2$, using 1.7 fb$^{-1}$ of data. The precision of this single measurement is already better than the last combined CDF top mass result obtained using up to 1 fb$^{-1}$ of data: $M_{\text{top}} = 170.5 \pm 2.2$ (total) GeV/$c^2$.

D0 obtains its most precise top quark mass measurement by combining measurements performed in the dilepton, single lepton + jets and all hadronic channels. D0 finds: $M_{\text{top}} = 172.1 \pm 1.5$ (stat.) $\pm 1.9$ (syst) GeV/$c^2 = 172.1 \pm 2.4$ (total) GeV/$c^2$, based on up to 1 fb$^{-1}$ of data.

CDF obtained the best top mass measurement in the dilepton channel using the matrix element method and analyzing 1.8 fb$^{-1}$ of data: $M_{\text{top}} = 170.4 \pm 3.1$ (stat.) $\pm 3.0$ (syst) GeV/$c^2$.

D0 recently presented a new top mass measurement in the dilepton channel based on 1 fb$^{-1}$ of data, using two different weighting methods: $M_{\text{top}} = 173.7 \pm 5.4$ (stat.) $\pm 3.4$ (syst) GeV/$c^2$. Figure [12] shows a comparison between data and Monte Carlo of the peak mass for the 57 D0 dilepton top candidate events found in 1 fb$^{-1}$ of data.

Figure [12] summarizes the most recent CDF and D0 top mass measurements and the Tevatron combined top mass result: $M_{\text{top}} = 170.9 \pm 1.1$ (stat) $\pm 1.5$ (syst) GeV/$c^2 = 170.9 \pm 1.8$ (total) GeV/$c^2$, based on data sets including up to 1 fb$^{-1}$ of data [15]. The top quark mass is known with a precision that was thought to be unreachable at the Tevatron only a few years ago: $\Delta M_{\text{top}}/M_{\text{top}} \approx 1.1\%$, of the order of the top natural width. Therefore, both experiments are now addressing a number of effects that, too small to have an impact on the previous measurements, could now become important. At the same time, they are figuring out which theoretical aspects are relevant, at the 1 GeV/$c^2$ level, and whether they are sufficiently well under control. Before the end of Run 2 the Tevatron experiments are likely to reach a 1 GeV/$c^2$ precision on the top quark mass.
After the top discovery phase, CDF and D0 moved to detailed studies of its properties. Both experiments investigated the top candidate events kinematic properties and the decay vertex. Among the many performed studies, here we show a very recent result on the $W$ helicity in top decays. More results on top quark properties can be found in [17].

### 10.1 $W$ Helicity in Top Decays

$W$ helicity in top decays is fixed by the $V-A$ structure of the $tWb$ vertex and it is reflected in the kinematics of $W$ decay products. SM predicts that the fraction of left-handed $W$s is $F_- \approx 30\%$, the fraction of longitudinally polarized $W$s is $F_0 \approx 70\%$, while the right handed fraction $F_+^*$ is suppressed. Both experiments measures the angular distribution of charged leptons in the $W$ rest frame measured with respect to the direction of motion of the $W$ boson in the top-quark rest-frame (cos$\theta^*$). Figures 14 and 15 show the cos$\theta^*$ distributions observed in D0 dilepton and CDF single lepton + jets candidate events respectively.

Using 1 fb$^{-1}$ of single lepton + jets and dilepton candidate events D0 measures $F_+ = 0.017 \pm 0.048$ (stat) $\pm 0.047$ (syst) ($F_+ < 0.14$ at 95% C.L.), with $F_0$ fixed to the SM value.

Using 1.7 fb$^{-1}$ of single lepton + jets + di-lepton candidate events CDF measures $F_+ = 0.01 \pm 0.05$ (stat) $\pm 0.03$ (syst) ($F_+ < 0.12$ at 95% C.L.). CDF attempted also a 2 parameters fit, obtaining simultaneously both fractions: $F_0 = 0.38 \pm 0.22$ (stat) $\pm 0.07$ (syst) and $F_+ = 0.15 \pm 0.10$ (stat) $\pm 0.04$ (syst). Recently CDF presented a new analysis which measures $F_+ = -0.04 \pm 0.04$ (stat) $\pm 0.03$ and therefore extracts a more stringent upper limit: $F_+ < 0.07$ at 95% C.L. All results are consistent with SM predictions within the uncertainties.

### 11 Evidence for Single Top Production

The single top production mechanism involves electroweak production of a top quark via the $Wtb$ vertex ($t$ and $s$ channel exchange of a virtual $W$ boson). The experimental signature consists of the $W$ decay products plus two or three jets, including one $b$ quark jet from the decay of the top quark. In $s$-channel events a second $b$ quark jet comes from the $Wtb$ vertex. In $t$-channel events a second jet originates from the recoiling light-quark and a third low-$E_T$ jet is produced at larger $\eta$ through the splitting of the initial state gluon into a $b\bar{b}$ pair.

The production cross section is predicted to be 0.88 and 1.98 pb in the $s$ and $t$ channels respectively [18] for $M_{top} = 175$ GeV/$c^2$, about half as large as the pair production and with a much larger background. On the other hand, this mechanism allows a direct access to the $Vtb$ CKM matrix element, and can be used to test the $V-A$ structure of the top charged current interaction.

In order to extract the single top signal from the challenging background dominated dataset, both experiments use various multi variate techniques. D0 presented the first evidence of single top quark production using 0.9 fb$^{-1}$ of data [19]. D0 searched for single top with three analysis methods: decision trees (DT), matrix element (ME) and a neural network (NN). Discriminants are constructed with a large number of kinematic observables (DT, NN) or by evaluating the differential probability of signal using the single top ME. Combining the three analyses D0 finds a 3.6$\sigma$ signal and measures a production cross section of 4.7 $\pm$ 1.3 pb. This can be translated into the first direct measurement of the $Vtb$ CKM matrix element: $V_{tb} = 1.3 \pm 0.2$ (or $V_{tb}$: 0.68 < $|V_{tb}|$ < 1 at 95% C.L.). Figure 16 shows the D0 results obtained with the three methods.

Recently CDF confirmed the evidence for single top production in 1.5 fb$^{-1}$ of data, using a multivariate likelihood function technique (giving a $2.7\sigma$ excess over
the SM background) and a matrix element discriminant technique (giving a 3.1σ excess). CDF measures: $V_{tb} = 1.02 \pm 0.18$ (exp) ± 0.07 (theory).

### 12 Indirect Limits on Higgs Mass

The Higgs boson is the last remaining SM particle to be observed, and the one responsible for generating the $W$ and $Z$ boson masses. Direct searches at LEP experiments have excluded a Higgs boson with mass less than 114.4 GeV/$c^2$ at 95% C.L. in the production mode $e^+e^- \rightarrow ZH$ [20]. The mass of the $W$ depends on the top quark and Higgs masses through radiative effects. Since the Higgs mass is unknown, experimental measurements of the top and $W$ boson masses provide the strongest indirect constraints on the Higgs mass, based on its contribution to the radiative correction which grows logarithmically with the Higgs mass at the one loop level. Figure 17 shows the SM prediction of $M_W$ as a function of $M_{top}$ for Higgs masses ranging from 114 to 1000 GeV/$c^2$. Figure 18 shows the $\Delta \chi^2$ curve derived from a global fit to precision electroweak measurements as a function of the Higgs-boson mass, assuming the SM to be the correct theory of nature. The preferred value for the Higgs mass, corresponding to the minimum of the curve, is $M_H = 76^{+33}_{-24}$ GeV/$c^2$, well below the lower experimental limit set by the LEP 2 experiments. The upper limit on $M_H$ has been set at 144 GeV/$c^2$, at 95% C.L., and rises to 182 GeV/$c^2$ if one takes into account the LEP 2 direct limit.

In the context of the minimal supersymmetric models (MSSM) the overall agreement of all observables appears very good for a wide region of the parameter space [21]. Figure 19 shows the $M_W - M_{top}$ plane prediction of the SM and the MSSM compared to the experimental result. The predictions within the two models consist of two bands with a small overlap region. The latter corresponds in the SM to a light Higgs boson and in the MSSM to the parameters region where all superpartners are heavy. The current experimental measurements of $M_W$ and $M_{top}$ prefer a relatively light Higgs mass. Only by the end of Run 2 one might gather indirect information on the Higgs SUSY sector from the $M_W$ and $M_{top}$ measurements [21].

### 13 Conclusions

The Run 2 of the Tevatron is well underway. Tevatron experiments have in their hands a gold mine of more than 2 fb$^{-1}$ of data. Both CDF and D0 are producing...
Fig. 19. Prediction for $M_W$ in the SM and the MSSM as a function of $M_{top}$. The allowed MSSM band is obtained scanning over the SUSY mass parameters. The allowed SM band is obtained varying the $M_H$ in SM. The two ellipses correspond to the present experimental situation at 95% C.L. and to the extrapolation assuming 8 fb$^{-1}$ of data at the Tevatron.

interesting results in the electroweak sector, bringing SM tests to a level of precision which meets or exceed that of electron-positron colliders. The top quark mass is known with a 1.1% precision, the $W$ boson mass with a 0.04% precision. They together limit the mass of the SM Higgs to be smaller than 144 GeV/$c^2$ at 95% C.L.. CDF and D0 will continue to collect data (6-8 fb$^{-1}$ are expected by the end of Run 2) and to improve the precision on top and $W$ masses over the next few years.

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