Electroweak and Top Physics at High Energies

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I present a summary of electroweak and top physics analyses from experiments at the Tevatron and HERA colliders, corresponding to the newest results acquired between Winter and Summer 2009. This includes progress in the precision measurement of the top quark and W boson masses and their constraint on the Higgs boson mass, establishing of processes with challenging signatures, measurements of top quark properties, as well as searches for new physics in data samples enriched with top quarks.

1 Introduction

This proceeding summarizes the latest results on electroweak and top quark physics. Most of the results included are from the Tevatron, while a few are from HERA. The Fermilab Tevatron has been colliding protons and antiprotons at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV since 2002. By summer 2009, it had delivered about 7 fb^{-1} of data to its experiments, CDF and D0. The results presented in this talk use up to 5 fb^{-1} of the collected data. The HERA collider at DESY operated from 1992 to 2007, colliding electron/positrons with protons at a center-of-mass energy of 319 GeV. The H1 and ZEUS detectors collected data corresponding to an integrated luminosity of about 900 pb^{-1}. In this talk I present combined results from both HERA experiments.

This proceeding is divided into three main parts. The first part focuses on the efforts to establish top and electroweak signatures, including the very precise understanding of W and Z boson physics and the new observed signatures which include diboson and single top production. The second part includes the precision measurement of the top quark and W boson mass and their constraint on the Higgs boson mass. The third part is about top quark physics, the analysis of its properties and searches beyond the standard model (SM) using top based samples.

2 Establishing Signatures

Electroweak and top quark measurements at hadron colliders span a wide range of cross sections. Figure 1 shows the measured cross sections for different processes by the CDF and D0 experiments. The Tevatron has measured all the predicted SM processes. Until recently these processes had only been measured in relatively clean samples, with signatures where there are no jets in the final state and a very small expected background contribution. The measurements of these physics processes demonstrate a good agreement with the SM prediction and among CDF and D0.

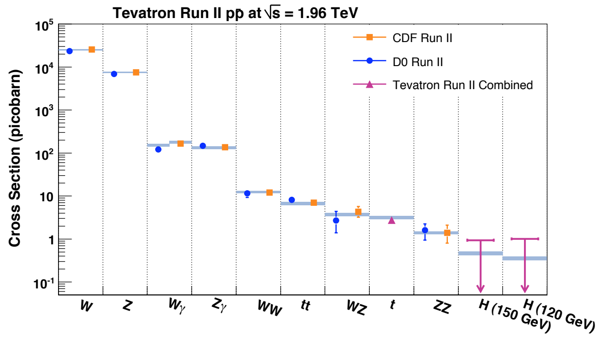

Figure 1: Measured cross sections by CDF and D0 experiments. Higgs boson limits are shown for m_{Higgs}=150 GeV and m_{Higgs}=120 GeV. Grey lines show the theory prediction.

In the past year the Tevatron experiments established these processes in more challenging environments, focusing on final states with jets, where the backgrounds are larger and topologically very similar. The main experimental reason why these difficult signatures are interesting is because they are a background to the unobserved Higgs boson. It is important to observe these processes to improve and establish analysis techniques. Moreover, establishing processes in different channels allows us to combine with the other channels to improve their precision, giving us confidence in their modeling and consistency between channels. Measuring cross sections could point to new physics through deviations from the SM.

In general, these processes have a large amount of background in comparison with signal. Moreover background are kinematically very similar. As these challenges arise the experiments introduce more sophisticated methods to analyze the data. Most of the results rely on multivariate techniques, either matrix-element or machine-learning based approaches. The matrix element technique is based on an event-per-event probability density by using the signal and background matrix elements. The inputs to the calculation are the 4-vectors of the final state particles. Machine learning techniques correspond to different computing algorithms such as Artificial Neural Networks or Boosted Decision Trees. Although they are different in their signal discrimination algorithm they use the same concept. These computing algorithms correlate kinematic and angular variables of simulated signal and background events in order to classify events into events with varying signal to background ratios.

The next sections describe the new measurements of challenging processes at the Tevatron and HERA.

2.1 W production at HERA

The H1 and ZEUS experiments searched for events containing high energy isolated leptons and missing transverse momentum produced in electron/positron collisions at HERA. These events are interesting as they may be a signature of physics beyond the SM. These experiments analyzed the full data set taken between 1994 and 2007 corresponding to an integrated luminosity of 0.98 fb^{-1}. In the SM, the production of single W bosons with subsequent leptonic decay gives rise to this topology (see Figure 2). An excess of electron and muon events with large missing transverse momentum containing a hadronic final state at high transverse momentum P_T^X was previously reported by H1. The observed event yield was found to be in agreement with the SM. The total single W boson production cross section is measured as 1.07±0.16(stat)±0.08(syst) pb. The differential single W production cross section is measured as a function of P_T^X, the results of which are displayed in Figure 2, and is in agreement with the SM prediction [1].

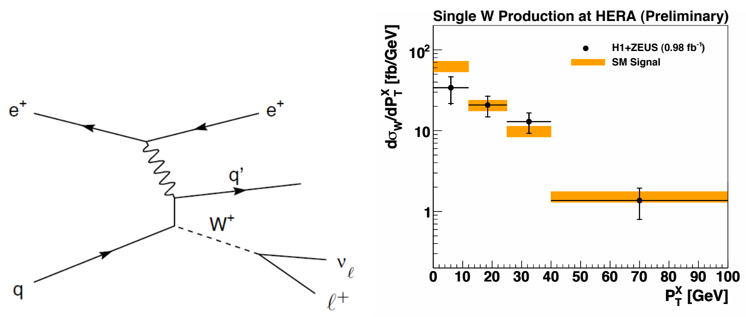

Figure 2: (left) W production at HERA. (right) The single W production cross section, measured by H1 and ZEUS in a common phase space as a function of the hadronic transverse momentum, P_T^X. The inner error bar represents the statistical error, which dominates, and the outer error bar indicates the statistical and systematic uncertainties added in quadrature. The shaded band represents the one standard deviation uncertainty in the SM prediction.

2.2 W and Z bosons at the Tevatron

At the Tevatron, the leptonic decays of W and Z bosons have been used extensively for precision measurements. Two of the more outstanding latest results in these samples are presented.

The W boson charge asymmetry has been measured using a new analysis method which directly reconstructs the W rapidity using an integrated luminosity of 1 fb^{-1} taken with the CDF detector. A precise measurement of the W asymmetry is a sensitive probe of the momentum fraction difference between u and d quarks in the $Q^2 \approx M_W^2$ region and is one of the best determinations of the proton d/u momentum ratio as a function of x. It also plays an important role in global fits. Figure 3 shows the measured asymmetry, A($|y_W|$), compared to an NLO prediction with CTEQ6.1M parton distribution functions (PDFs). Results are also compared to an NNLO prediction using MRST2006 PDFs and their corresponding error PDFs, and they were found to be in good agreement [2].

The forward backward charge asymmetry (A_{FB}) is also measured in Z→e^+e^- events using 1.1 fb^{-1} of data collected with the D0 detector. A_{FB} is measured as a function of the invariant mass of the electron-positron pair, and found to be consistent with the SM prediction (see Fig.3). The A_{FB} measurement is used to extract the effective weak mixing angle, $\sin^2\theta_W$ = 0.2326±0.0018(stat)±0.0006 (syst). The precision of this measurement is comparable to that obtained from LEP measurements of the inclusive hadronic charge asymmetry and that of

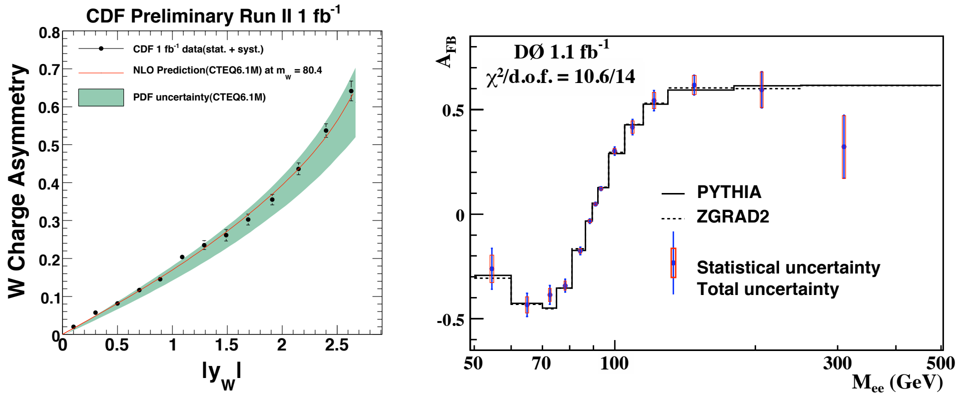

Figure 3: (left) The measured asymmetry, A($|y_W|$), compared to the NLO prediction with CTEQ6.1M PDFs. (right) Comparison between the unfolded AFB (points) and the Pythia (solid curve) and ZGRAD2 (dashed line) predictions. The inner (outer) vertical lines show the statistical (total) uncertainty.

NuTeV measurement. With about 8 fb^{-1} of data expected by the end of Run II, a combined measurement of A_{FB} by the CDF and D0 collaborations using electron and muon final states could lead to a measurement of $\sin^2\theta_W$ with a precision comparable to that of the current world average [3]

2.3 Dibosons

2.3.1 Z gamma

The first observation of the Z$\gamma \rightarrow \nu\bar{\nu}\gamma$ process at the Tevatron at 5.1 standard deviations significance was done using 3.6 fb^{-1} of integrated luminosity collected with the D0 detector. The measured Z cross section multiplied by the branching fraction of Z$\rightarrow \nu\bar{\nu}$ is 32$\pm$9(stat+syst)$\pm$2(lumi) fb for the photon E$_T$ > 90 GeV. This result is in agreement with the SM prediction of 39$\pm$4 fb. Limits on anomalous triple gauge couplings are set by comparing the photon E$_T$ spectrum in data with that from the sum of expected Z signal and background (see Fig.4). These are the most restrictive limits on anomalous trilinear Z$\gamma\gamma$ and ZZγ gauge boson couplings at a hadron collider to date [4].

2.3.2 WW

The direct production of WW pairs in proton-antiproton collisions is the primary background in searches for a high mass SM Higgs boson decaying to WW. A good understanding and modeling of WW production is thus essential to any Higgs to WW search. Studying WW production at the Tevatron also provides an opportunity to explore $\sqrt{s}$ energies higher than those available at the LEP collider. Both Tevatron experiments have measured the WW production cross section in the past, and the D0 experiment has recently released a new preliminary result. The most precise measurement to date of the WW production cross section using approximately 3.6 fb^{-1} of integrated luminosity collected by the CDF II detector is $12.1^{+1.8}_{-1.6}$ pb where the uncertainty

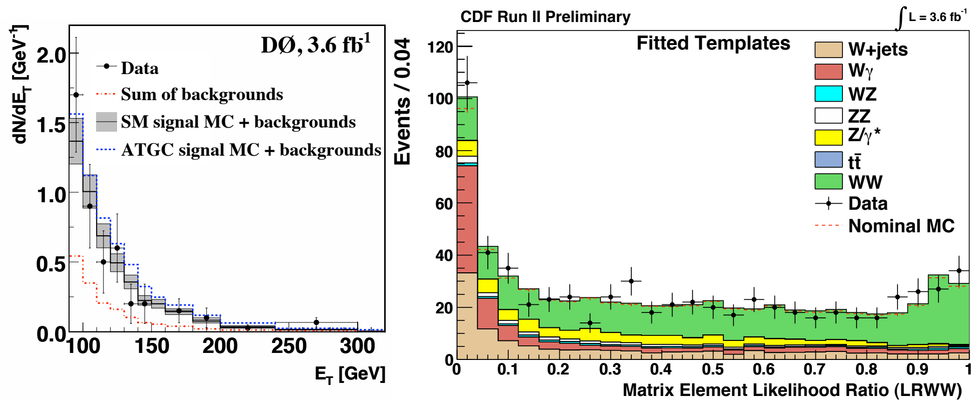

Figure 4: (right) Photon E_T spectrum in data (solid circles), sum of backgrounds (dash-dot line), and sum of MC signal and background for the SM prediction (solid line) and for the anomalous triple gauge coupling prediction with $h^{\gamma}_{30} = 0.09$ and $h^{\gamma}_{40}= 0.005$ (dashed line). The shaded band corresponds to the ± 1 s.d. total uncertainty on the predicted sum of SM signal and background. (left)

includes statistical, systematic, and luminosity uncertainties. This is in good agreement with the theoretical expectation of 11.66±0.66 pb. Figure 4 shows the matrix element likelihood ratio built from signal and background probability densities used to extract the number of WW events in data [5].

2.3.3 WW/WZ/ZZ with hadronic decays

The CDF experiment reported the first observation in hadronic collisions of the electroweak production of vector boson pairs (VV, V=W,Z) where one boson decays to a dijet final state using 3.5 fb^{-1} of integrated luminosity. The dijet mass is fitted using an unbinned maximum likelihood with the main systematic uncertainties treated as nuisance parameters and allowed to float in the fit within their predetermined uncertainties (see Fig. 5). The WW/WZ/ZZ cross section measured is 18±2.8(stat)±2.4(syst)±1.1(lumi) pb, in agreement with expectations from the SM. This results represents a 5.3 σ observation of the diboson production in the hadronic channel [6]. CDF has reached a similar observation in the WW/WZ production with an identified electron or muon, large missing transverse energy, and two jets in 2.7 fb^{-1} of integrated luminosity. The analysis employs a matrix element technique which calculates event probability densities for signal and background hypotheses. The probabilities are combined to form a discriminant variable which is evaluated for signal and background Monte Carlo events (se Fig.5). We measure a cross section of 17.7±3.9 pb which corresponds to a 5.4 σ significance [7]. The samples used on these results were shown to overlap by only 20%.

2.3.4 Top quark pairs

The top quark completes the third quark generation in the SM. Top quarks at the Tevatron are mainly produced in pairs via the QCD interaction about 3 times more often than singly via the

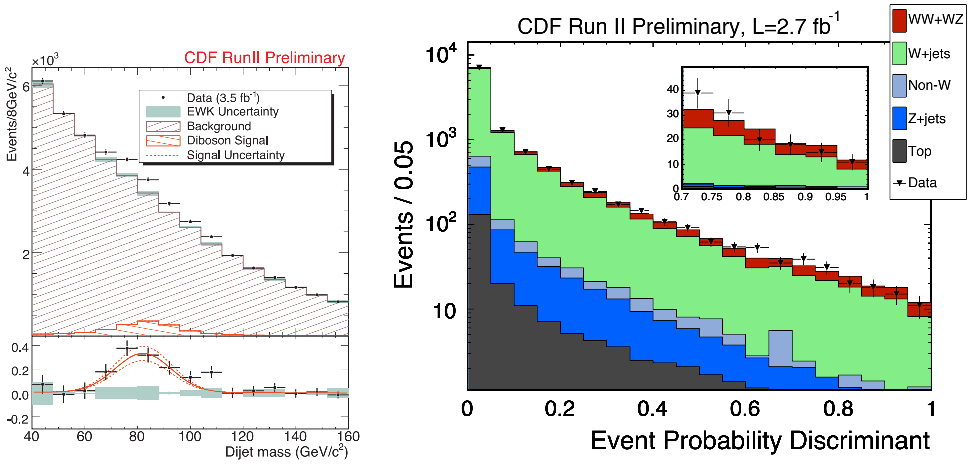

Figure 5: (left) Comparison of the diboson signal (solid line) with the background-subtracted data (points). The dashed lines represent the 1-σ statistical variations on the extracted signal. The gray band represents the systematic uncertainty due the EWK shape. (right) Observed event probability distribution distribution superimposed on distribution expected from simulated processes

electroweak interaction. Significant enhancements in the integrated luminosity and improvements to the sensitivity for detecting top quark decay products made the measurements of the $t\bar{t}$ production cross section no longer limited by statistical uncertainties. Current measurements have reached a comparable or better precision than of the theory.

The top quark decays predominantly to a W boson and a bottom quark. The decays of two W bosons define the final state topology which is referred to as "all-jets", "lepton+jets", and "dilepton" channels, respectively. In general, the lepton in the above processes refers to an electron or muon. The background composition in these three decay modes is very different. The dilepton channel has the best signal to background ratio, but the small branching ratio makes it statistically limited. On the contrary, the all-jets channel has a good branching ratio but large amount of background. The lepton+jets channel produces the most precise measurements since its background is smaller than in all-jets and has more signal than in dilepton modes.

Given that $t\bar{t}$ events have two b hadrons, whereas the backgrounds for each channel are dominated by jets of light flavor (u, d, s, g), top measurements rely on the use of techniques for the identification of b-jets, or b tagging which are based upon the fact that b hadrons have long lifetimes. If the b hadron decays to two or more charged stable particles, it can often be detected via a well-reconstructed vertex that is significantly displaced from the primary vertex.

In the dilepton channel there are two new measurements of the $t\bar{t}$ cross section, before and after b-tagging requirements are made. Candidate events are selected by requiring two leptons identified as electrons or muons. For the selection with b-jet identification we calculate background estimates using a parametrized tagging matrix prediction applied to normalized pretag samples. In a sample of about 4.47 fb^{-1} of data collected with the CDF detector the measurement before b-tagging is $\sigma_{t\bar{t}}$-pre= 6.56±0.65(stat)±0.41(syst)±0.38(lumi) pb and after requiring at least one b-tagged jet is $\sigma_{t\bar{t}}$-tag = 7.27±0.71(stat)±0.46(syst)±0.42(lumi) pb. Both results are in agreement. Since these samples have a large signal content and very different backgrounds they show a good modeling of the signal (see Fig.6) [8].

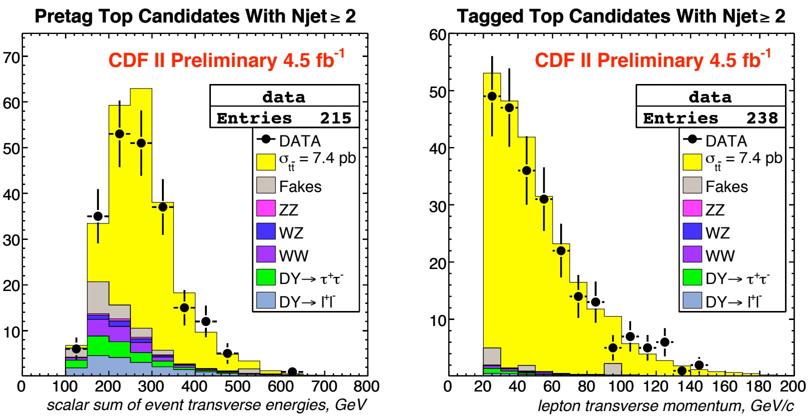

Figure 6: Data and simulation comparison of different variables before and after b-tagging in the dilepton channel.

The D0 experiment extracted a new measurement of the $t\bar{t}$ production cross section in the all-jets channel using 1 fb^{-1} of integrated luminosity. The cross section was extracted using high-multiplicity jet events, specifically selected with at least six jets, two of them b-tagged. To improve the signal purity a neural network b-tagger is used with inputs variables related to the characteristics of secondary vertices and tracks associated with b hadron decays. A model of the multijet background was created from lower jet-multiplicity data. The cross section was obtained from a likelihood fit to the discriminant distribution and the measurement is 7.9±2.2 pb assuming M_{top}= 170 GeV/c^2, and 6.9±2.0 pb assuming M_{top}= 175 GeV/c^2 [9].

The CDF experiment updated the measurement of the $t\bar{t}$ production cross section in the all-jets channel using about 2.9 fb^{-1} of data. Assuming M_{top}=172.5 GeV/^{2} and δJES=0 (the reference values for a CDF average over all channels) obtains a measurement of 7.2±1.3 pb. Both results are shown in Fig.7 and agree with theoretical expectations [10].

The most precise $t\bar{t}$ measurements are extracted in the lepton+jets channel. CDF updated a result using two complementary methods, one based on b-tagging, and the other a topological approach, which uses event kinematics to distinguish $t\bar{t}$ events from backgrounds. These analyses use datasets corresponding to an integrated luminosity of up to 4.6 fb^{-1}. By measuring the cross section ratio between $t\bar{t}$ and Z production and normalizing to the well-known theoretical Z cross section predicted by the SM, the extracted $t\bar{t}$ cross sections are effectively insensitive to the uncertainty on luminosity. The luminosity systematic uncertainty for both measurements has been replaced by a small uncertainty from the theoretical Z→ll cross section. The Best Linear Unbiased Estimate (BLUE) technique is used to combine both measurements with the result $\sigma_{t\bar{t}}$= 7.70±0.52 pb, for a top-quark mass of 172.5 GeV/c^2. Figure 8 shows a comparison of data and simulation in both measurements [11].

Figure 9 shows the combination of all the CDF results assuming M_{top}=172.5 GeV/c^2. For

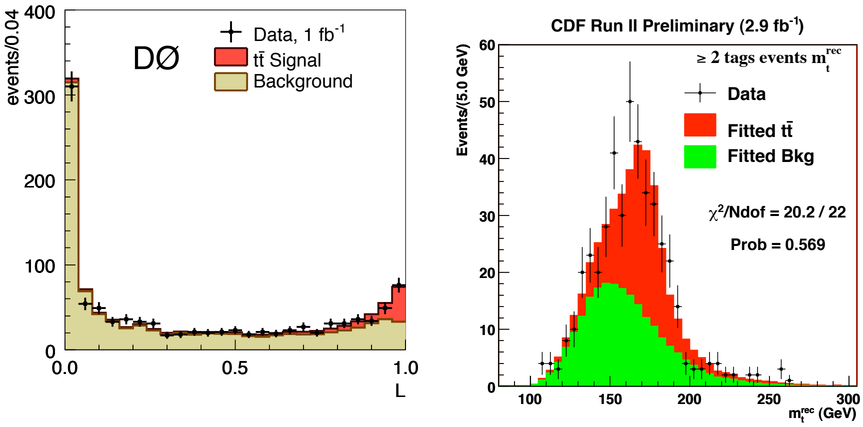

Figure 7: (left) Data and simulation comparison of the likelihood discriminant used all-jets channel $t\bar{t}$ cross section measurement. (right) Data and simulation comparison with events with 2 b-tagged jets in the all-jets channel.

each measurement, the statistical uncertainty is shown by the magenta line, which is superimposed on the black line which is the total uncertainty additionally including systematic and luminosity uncertainties. The four measurements carry the following weights in the combination: the lepton+jets channel with artificial neural network discriminant with a weight of 70%, the lepton+jets channel with secondary vertex b-tagging with 18%, the dilepton channel with 18%, and the all-jets channel with -6%. The combined measurement is $\sigma_{t\bar{t}}$ = 7.50±0.31(stat)±0.33(syst)±0.13(Z-theory)±0.06(lumi) pb. The result is in good agreement with the theoretical prediction.

2.3.5 Single Top

Observation of top quarks produced via the electroweak interaction was achieved by both Tevatron experiments in 2008. Each experiment used different multivariate techniques to separate signal from background. Following this discovery the two experiments report here a combination of the CDF and D0 measurements of the inclusive single top quark production cross section. The total integrated luminosity included in CDF's analysis is 3.2 fb^{-1} and D0's analysis is 2.3 fb^{-1}. A Bayesian analysis is used to extract the cross section from the distributions of multivariate discriminants provided by the collaborations. For a top quark mass M_{top}=170 GeV/c^2, the measured cross section is 2.76 $^{+0.58}_{-0.47}$ pb (see Figure 10). The extracted CKM matrix element is $|V_{tb}|$=0.88±0.07 with a 95% C.L. lower limit of $|V_{tb}|$ >0.77 [12].

Using the same data, the D0 collaboration reports direct evidence for electroweak production of single top quarks through the t-channel exchange of a virtual W boson. This is the first analysis to isolate an individual single top quark production channel. Three multivariate techniques optimized for the t-channel process to measure the t- and s-channel cross sections simultaneously are combined and measure a cross sections of $3.14^{+0.94}_{-0.80}$ pb for the t-channel and 1.05±0.81 pb for the s-channel. The measured t-channel result is found to have a significance

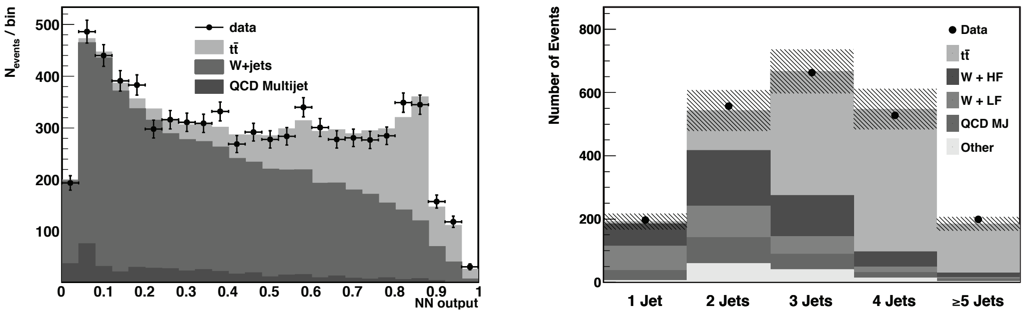

Figure 8: (left) The output of an artificial neural network (ANN), trained to distinguish $t\bar{t}$ events in the lepton+jets channel from background without using b-tagging, for simulated $t\bar{t}$ and background events, and data. The $t\bar{t}$ cross section is extracted from a fit of templates to the data. (right) Number of data and predicted background events as a function of jet multiplicity, with the number of $t\bar{t}$ events normalized to the measured cross section. The hashed lines represent the uncertainty on the predicted number of events.

of 4.8 standard deviations and is consistent with the SM prediction. Figure 10 shows these measurements [13].

2.4 Precision Measurements

The precision measurement of the W boson mass and top quark mass helps to tighten the constraints on the mass of the Higgs boson as determined from internal consistency of the SM. Improving the measurement of M_W and M_{top} is an important contribution to our understanding of the electroweak interaction, and, potentially, of how the electroweak symmetry is broken.

2.4.1 W-boson

The D0 experiment has measured the W boson mass in W→eν decays using 1 fb^{-1}. To determine M_W, fast simulation (FASTMC) template distributions for m_T (W boson transverse mass, shown in Fig.11), p_T^e(electron P_T), and MET (missing transverse energy) are fitted using a binned likelihood between data and each template. The results are combined to give the final result M_W =

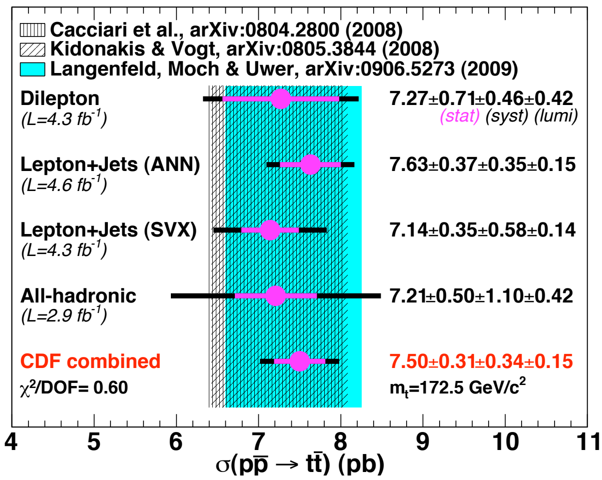

Figure 9: Combination of CDF $t\bar{t}$ cross section measurements assuming M_{top}=172.5 GeV/c^2.

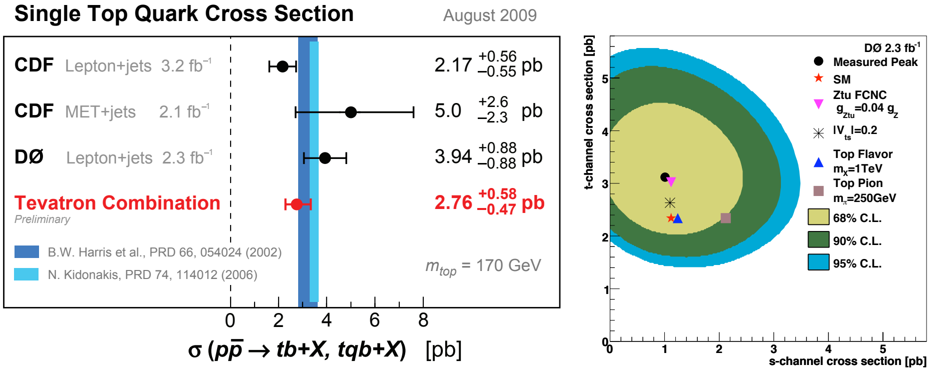

Figure 10: (left) Tevatron single top cross section measurements and their combination. (right) Posterior probability density for t-channel and s-channel single top quark production in contours of equal probability density. Also shown are the measured cross section, SM expectation, and several representative new physics scenarios.

80.401±0.043 GeV. This is the most precise measurement from a single experiment to date [14].

The dominant uncertainties arise from the available statistics of the W→eν and Z→ee samples. Thus, this measurement can still be expected to improve as more data are analyzed. The M_W measurement reported here agrees with other individual measurements. This result is combined with all the previous direct measurements of M_W boson in data collected by the Tevatron experiments, including the CDF 200 pb^{-1} published results from the first period of Run-II (2001-2004) (see Fig. 11). The resulting Tevatron average for the mass of the W boson is M_W = 80.420±31 MeV [15]

2.4.2 Top quark mass

A new update of the most precise measurement of the top quark mass has been done by the CDF experiment using 4.3 fb^{-1} of integrated luminosity. The measurement is done in the lepton+jets channel using a matrix element integration method with a Quasi-Monte Carlo integration to take into account finite detector resolution and quark mass effects. The events are required to have at least one b-tagged jet. The extracted measurement is M_{top} = 172.6±0.9 (stat)±0.7 (JES)±1.1 (syst) GeV/c^2 [16]. Results from the five published Run I measurements and six preliminary Run II measurements in different channels are combined. Taking into account the statistical and systematic uncertainties and their correlations, the preliminary world-average result is: M_{top} = 173.1±1.3 GeV/c^2, where the total uncertainty is obtained assuming Gaussian systematic uncertainties and adding them plus the statistical uncertainty in quadrature. The mass of the top quark is now known with a relative precision of 0.75%, limited by the systematic uncertainties, which are dominated by the jet energy scale uncertainty. It can be reasonably expected that with the full Run II data set the top-quark mass will be known to better than 0.75%. To reach this level of precision further work is required to determine more accurately the various correlations present, and to understand more precisely the b-jet modeling, signal, and background uncertainties which may limit the sensitivity at larger data sets [17].

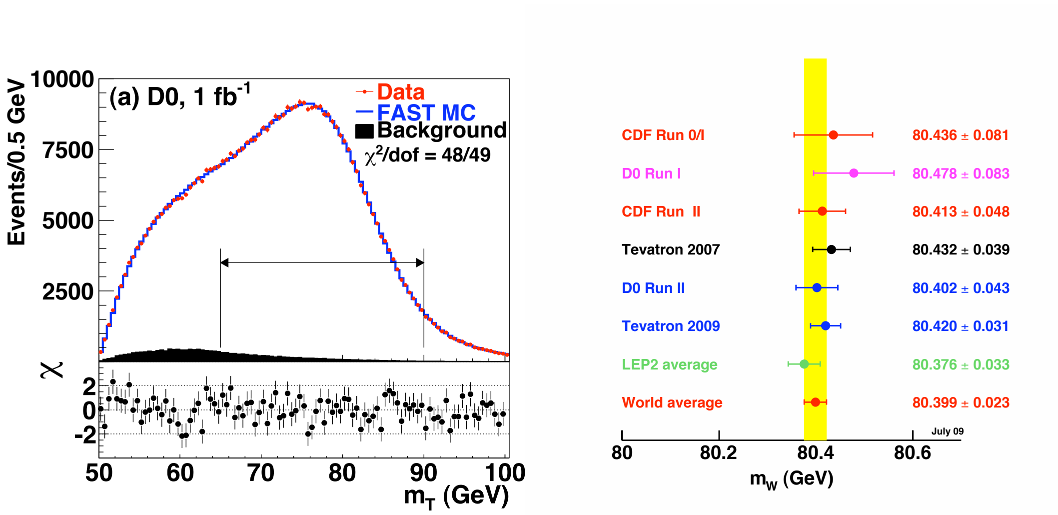

Figure 11: (left)The m_T distributions for data and FASTMC simulation with backgrounds. (right) Summary of the measurements of the W boson mass and their average as of July 2009. The result from the Tevatron corresponds to the values which include corrections to the same W boson width and PDFs. An estimate of the world average of the Tevatron and LEP results assuming no correlations between the Tevatron and LEP is included.

2.4.3 Electroweak Fit

The new measurements of the top quark mass and W boson mass allow to check the validity of the SM and, within its framework, to infer valuable information about its fundamental parameters. The accuracy of the W- and Z-boson measurements makes them sensitive to the mass of the top quark, and to the mass of the Higgs boson m_H through loop corrections. While the leading M_{top} dependence is quadratic, the leading m_H dependence is logarithmic. Therefore, the inferred constraints on M_{top} are much stronger than those on m_H. Figure 12 shows the most probable value of m_H using these measurements [18].

2.5 Top Quark Properties and Searches

Since the top quark has the strongerst coupling to the Higgs boson of all other fermions, it makes the study of top quark properties very interesting. It is an ideal place to study the interactions and to search for new physics related to electroweak symmetry breaking. In the past years the Tevatron has made huge progress in the measurements of many of these properties and also in searches for new physics contaminating the top quark sample. Due to length restrictions, these proceedings do not include details of these analyses. All of these results can be found in the CDF and D0 experiments public webpages at `http://www-cdf.fnal.gov/physics/new/top/top.html` and `http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html`.

3 Conclusions

The Tevatron is making precision measurements to help constrain the SM. Measurements like the W charge asymmetry and $\sin^2\theta_W$ are good examples. In teh past year, the Tevatron expanded its experimental reach on signatures. These processes give confidence in the experimental tools while establishing challenging processes on the way to the Higgs boson. The top quark cross section is now known to 6.5% (better than theory). The top quark mass known to 0.7%. The Tevatron should be able to reach 1 GeV/c^2. The new W boson mass Tevatron combination is now better than LEP2 average. The Tevatron is expected to reach 20 MeV precision. Top quark physics is beginning to have sensitivity to unexpected in particle properties and in the data samples In the near future.

The LHC will rediscover top and use it as most likely the most important stepping stone to find new physics

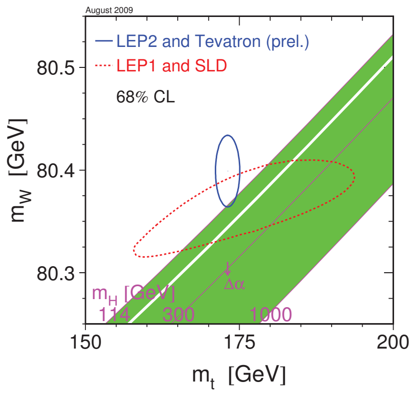

Figure 12: $\Delta\chi^2 = \chi - \chi_{min}$ vs. m_H curve. The vertical band shows the 95% C.L. exclusion limit on m_H from the direct searches at LEP-II (up to 114 GeV/c^2) and the Tevatron (160 GeV to 170 GeV/c^2).

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Discussion

Tobias Haas (DESY): Could you please explain on the details of the systematic error on the W mass measurement. It seems to be dominated by the electron energy scale. If so, can it profit from a combination of the D0 and CDF results in the spirit if the HERA combinations?
Answer: The energy scale is treated differently in each experiment, experimentsdo not use a common energy scale.D0 uses the Z sample for scale and linearity. For CDFthe Z is a relatively minor scale determinant. The fact that they are different helps for decoupling in the combination.
Majid Hashemi (University of Antwerp): Related to anomalous top peak at HERA could the shape center shift related to MC shape be related to JES of b-jets
Answer: The position of the peak near 80 GeV is due to kinematic cuts applied in the analysis. Within statistical uncertainties, the position and shape of this peak are in agreement between data and prediction. This gives us confidence that the jet energy scale is well understood.he jet energy scale is known at a level of 1.5this analysis, controlled by independent high statistics neutral current event samples. The expected shape of single top is shown with arbitrary normalization. Masses above 150 GeVare interpreted as statistical fluctuation, not as a top mass peak.
Bennie Ward (Baylor University): If I understand correctly, you have an error of 1.2 GeV on m_t, which seems to imply that your statistical error is less than $1.2/173 = 4.94x10^-3$, which means $N > 20.8x10^4$. Do you have $20.8x10^4$ tops ?
Answer: The uncertainty on the top quark mass measurement comes from the uncertainty on the mean of the top mass distribution.Our resolution on the mass is more than 20 GeV. The uncertaintyon the mean decreases as $\sqrt{(Nevents)}$. Note that this number could be smaller than 1.2 GeV (top mass width).No, we don't have$20.8x10^4$ tops but we don't need this amount to achieve the current precision.