Top physics at the Tevatron

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Recent results on top quark physics, obtained at the Tevatron $p\bar{p}$ collider are presented. The measurements and searches were performed by the D0 and CDF collaborations, using between 3–5 fb^{-1} of Run II data at a center of mass energy of 1.96 TeV.

1 Introduction

15 years after the discovery of the top quark at the Fermilab Tevatron Collider [1, 2], CDF and D0 have collected thousands of top candidates at a center of mass energy of $\sqrt{s} = 1.96$ TeV, and have investigated top properties such as production cross sections of $t\bar{t}$ pairs and single top, top mass and decay mechanisms in detail. For example, the top quark mass has been measured with a precision less than 1%. In addition, it has become possible to perform sensitive searches for New Physics (NP) in the top sector. Many of the analysis techniques developed at the Tevatron will be of interest for the top physics program of the CMS and Atlas experiments. This paper describes only a selection of measurements and searches, done with 3–5 fb^{-1} of data, taken during Run II.

At the Tevatron, top quarks are produced predominantly in pairs, and, within the Standard Model (SM), the top quarks decay almost exclusively into a W boson and a b quark, resulting in one of the following three signatures: 'lepton+jets' (the final state includes one eletron or muon, at least 4 jets, and missing transverse energy from the undetected neutrino), 'dilepton' (two electrons or muons, at least two jets and missing transverse energy) and 'hadronic' (all jet signature). The production cross section has been measured in all three channels. The lepton+jets signature is considered the 'golden channel' because of its reasonable signal to noise ratio. The branching fraction is around 30%, and the backgrounds from QCD and W+jets can be reduced with the use of b-tagging, i.e. identification of jets originating from a b quark. This is done either through reconstruction of a secondary vertex clearly separated from the primary interaction vertex, or through association of a 'soft' lepton from semileptonic decay of a B hadron to the jet. Most results presented here use the lepton+jets signature with at least one jet tagged as coming from a b quark. In this particular channel, the dominant background is from W production with jets from heavy flavor ($b\bar{b}$ or $c\bar{c}$), which produces missing energy as well as a b tagged jets. The prediction of this background, which cannot be modeled reliably and needs correction factors extracted from the data, leads to one of the biggest systematic uncertainties.

2 Top quark pair production, and searches for new physics

The total top quark pair production cross section at $\sqrt{s} = 1.96$ TeV in $p\bar{p}$ collisions for a top quark mass of $m_t = 175$ GeV/c^2 can be calculated within the SM to be $6.7^{+0.7}_{-0.9}$ pb [3]. Deviations of the measurements from this value could indicate non-perturbative effects, or new production mechanisms beyond the SM. The recent measurements of the total top pair production cross section in all decay channels from CDF and D0 are in agreement with each other as well as the SM predictions. The combination of the CDF measurements yields a cross section of $7.50 \pm 0.31(stat.) \pm 0.34(syst.) \pm 0.15(lumi.)$ pb. The recent D0 measurements are shown in Figure 1. The top pair production cross section is now known with a relative uncertainty of less than 9% at the Tevatron center of mass energy, comparable to the theoretical uncertainty.

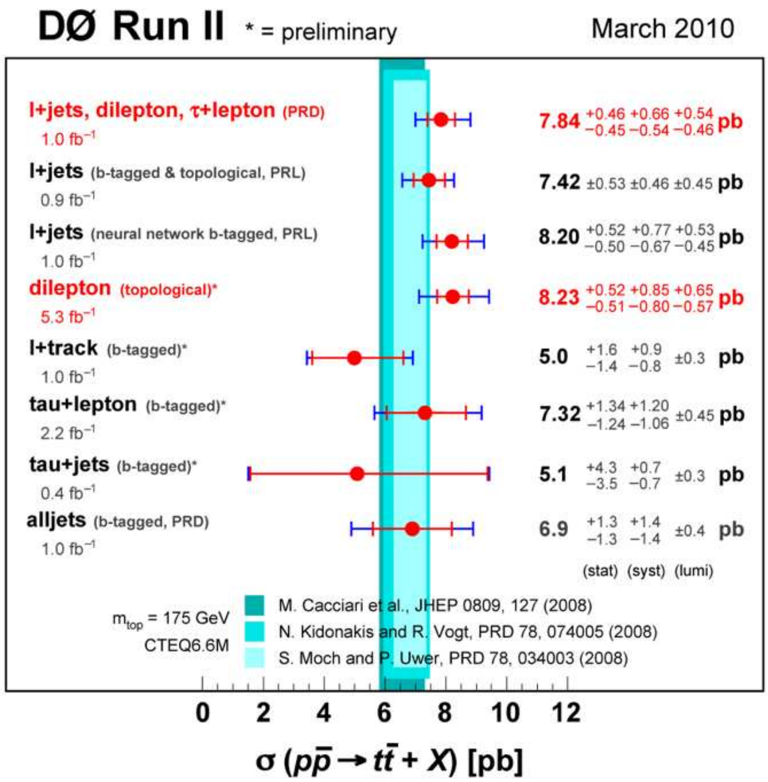

Figure 1: Recent measurements of the top quark pair production cross section at D0, in lepton+jets, dilepton and hadronic channels.

Many NP models predict the resonant production of $t\bar{t}$ pairs, and both Tevatron experiments performed searches for heavy massive resonances through the reconstruction of the invariant mass of the top quark pair. The observed spectrum is in good agreement with the SM expectation and no evidence of a resonance is found. D0, for example, has set a limit on the mass of a hypothetical massive leptophobic Z' at $m_{Z'} > 820$ GeV/c^2.

Another way that NP may be observed in $t\bar{t}$ production is through anomalies in the forward backward asymmetry. CDF has measured the asymmetry in the distribution of the top quark rapidity in the lab frame, using 3.2 fb^{-1} of data. $t\bar{t}$ events are reconstructed in the lepton+ jets channel, where one top decays semi-leptonically and the other hadronically. The lepton charge is used to tag top versus anti-top, and the hadronic side is used to reconstruct the rapidity of the top (or anti-top) system. There is a small lab frame charge asymmetry expected in QCD at NLO, $A_{fb} = 0.05 \pm 0.015$. In NP scenarios with a Z' or an axigluon this asymmetry can be as large as $\pm 30\%$. Figure 2 shows the raw A_{fb}, showing a noticeable shift from the predictions. In order to relate this to the true underlying asymmetry, corrections for background, acceptance and smearing effects have to be applied. CDF observes $A_{fb} = 0.193 \pm 0.065(stat.) \pm 0.024(syst.)$ in the lab frame. An earlier result from D0, uncorrected and using 0.9 fb^{-1} of data, yields $A_{fb} = 0.12 \pm 0.08(stat.) \pm 0.01(syst.)$ [4].

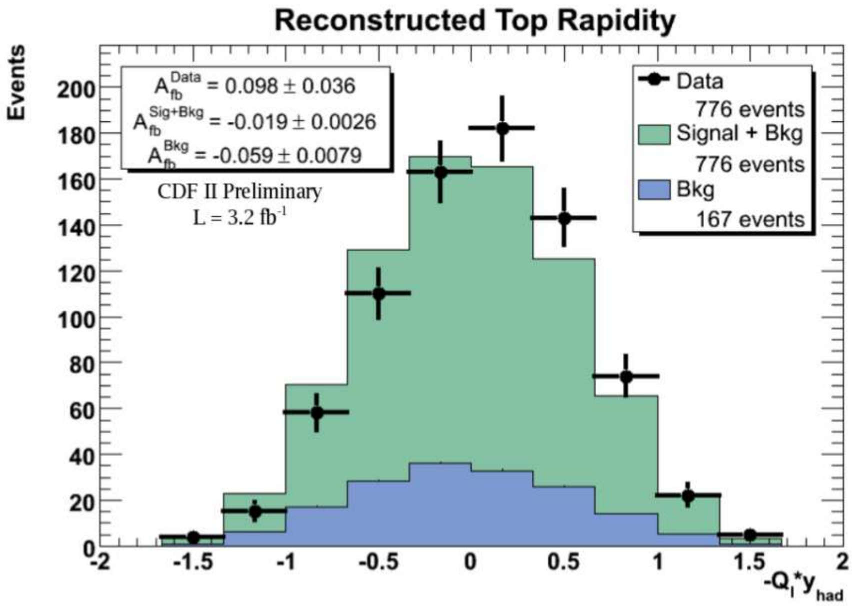

Figure 2: The reconstructed (raw) top rapidity in the lab frame, for data and simulation, as measured at CDF with 3.2 fb^{-1}.

3 Single top production

In the SM, single top quarks can be produced via electroweak interactions from the decay of an off-shell W boson ('s-channel'), or fusion of a virtual W boson with a b quark ('t-channel'). The SM prediction [5] is 0.98 ± 0.04 pb, and 2.16 ± 0.12 pb, respectively. The event selection is similar to that used in top pair production measurement, except that the final state contains two jets (instead of 4 or more). This makes the measurement of single top production extremely difficult: the background due to W+2 jet production, on the order of factor 20 over the single top production rate, is associated with large uncertainties.

The measurement of single top production is of importance as a direct probe of top weak coupling and V_{tb}, and presents a benchmark toward Higgs searches, which also have to face the difficulty of large backgrounds from W+jets. Both D0 and CDF have presented observation of single top in sophisticated measurements that combine many channels and measurement techniques. D0 presented first evidence for single top production in 2007, using 0.9 fb^{-1} [6], and CDF in 2009 with 2.3 fb^{-1} [7]. The summary of the recent results is shown in Figure 3 . For a top quark mass of m_t=170 GeV/c^2, the combined cross section is $2.76^{+0.58}_{-0.47}$ pb. Events with single top quarks have also been used by both collaborations to directly measure the absolute value of the CKM matrix element $|V_{tb}| = 0.88 \pm 0.07$ with a 95% C.L. lower limit of $|V_{tb}| > 0.77$.

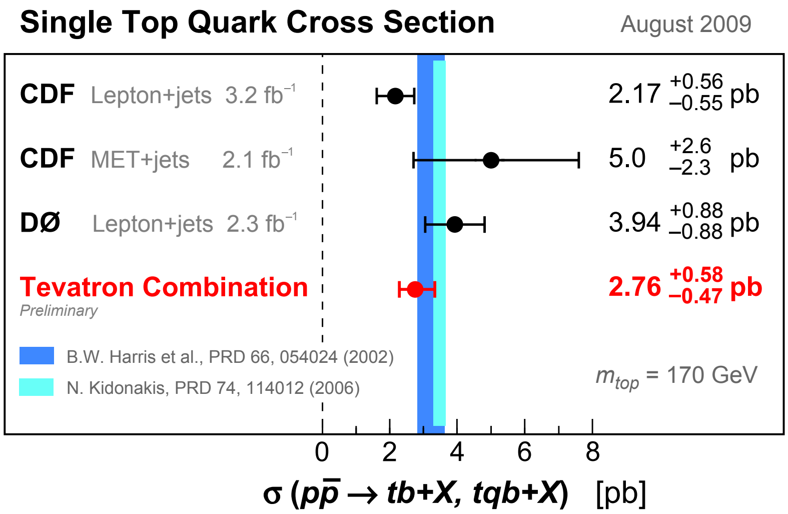

Figure 3: Tevatron combination of the single top quark cross section.

4 Top quark decay

Within the SM, the top quark decays via the $V-A$ charged-current interaction to a W boson and a b quark. New physics present in this decay could become evident in helicity measurements of the W boson originating from a top quark decay. For example, a different Lorentz structure of the Wtb interaction would alter the fractions of longitudinally (f0) and right-handed (f+) polarized W bosons from top-quark decay. The SM predicts values of 0.7 and 0, respectively. The CDF and D0 collaborations have measured these fractions using angular distributions of the charged lepton in the W rest frame measured with respect to the direction of motion of the W boson in the top quark rest-frame. CDF measured fractions of $f0 = 0.88 \pm 0.11(stat.) \pm 0.06(syst.)$ and $f+ = -0.15 \pm 0.07(stat.) \pm 0.06(syst.)$, using 2.7 fb^{-1} of data. D0 measured $f0 = 0.490 \pm 0.106(stat.) \pm 0.085(syst.)$ and $f+ = 0.110 \pm 0.059(stat.) \pm 0.052(syst.)$, using 1.2 fb^{-1} of data. All W-helicity measurements in top pair events performed at the Tevatron are compatible with the SM prediction within experimental uncertainties.

Another interesting measurement testing SM predictions associated with top quark decay is top spin determination. Top and anti-top spins are correlated, if top lifetime is short enough. The spin correlation can be measured through the angle of decay products, such as leptons and jets, in the top rest frame with respect to a chosen quantization axis. Commonly, a spin correlation parameter C is measured, where $t\bar{t}$ is decaying with the following differential cross section and decay rate:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\Theta_+ d\cos\Theta_-} = \frac{1 + C\cos\Theta_+\cos\Theta_-}{4}\,.$$

$\Theta_+(\Theta_-)$ denotes the angle of flight direction of $l^+(l^-)$ with respect to the quantization axis of the top (anti-top) quark. At D0, a dilepton sample is used, and the angles are measured with respect to the beam axis. The SM prediction at NLO is 0.78, and the measurement yields $C = -0.17^{+0.64}_{-0.53}(stat.+syst.)$. At CDF, the helicity basis is chosen, where the SM prediction for C at NLO is 0.4. The measured correlation parameter is $C = 0.6 \pm 0.5(stat.) \pm 0.16(syst.)$. The measurements are statistics limited and, within errors, in agreement with the SM prediction.

5 Top quark mass

The mass of the top quark is an important SM parameter, and precise top and W mass measurements are used to constrain the mass of the SM Higgs. Figure 4 shows the current constraints and their effect on the global electroweak fit and the SM Higgs mass, suggesting a light SM Higgs.

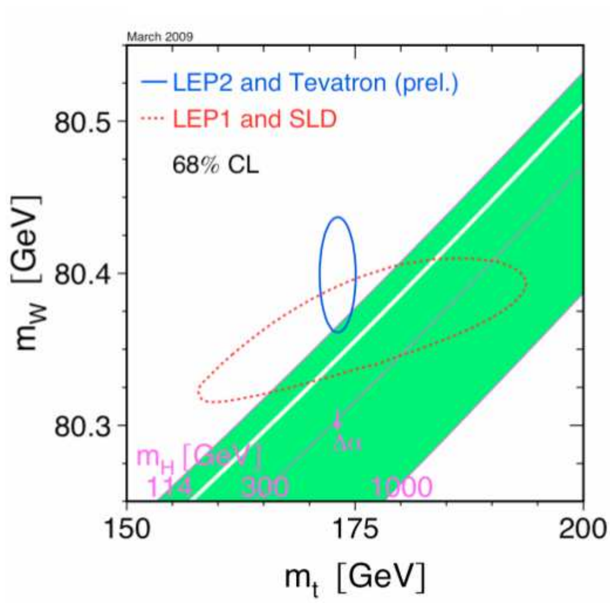

Figure 4: Current m_{top} and m_W measurements and their effect on the global electroweak fit and SM Higgs Boson.

One of the advances of Run II has been the reduction of the experimental uncertainty on the mass measurement due to the jet energy scale by an in situ calibration measurement, using hadronically decaying W bosons in the lepton+jets and the hadronic channel. The result of the combination of all decay channels from both CDF and D0 yields a top mass of $m_{top} =$

$173.1 \pm 0.6(stat.) \pm 1.1(syst.)$ GeV/c^2. Currently the most precise single top quark measurement is carried out at CDF in the lepton+jets channel, using 4.8 fb^{-1} of data, and yields a top mass of $172.8 \pm 1.3(tot.)$ GeV/c^2 [9]

6 Summary

The Tevatron has entered a new era of top quark precision measurement, and a broad program of measurements of top quark properties is underway. Already, more than twice the data presented here has been written to tape and will provide a large enough dataset to provide sensitive searches for NP in the top sector. Much of the work on background calibration can provide guidance and focus to the LHC top program and beyond.

7 Acknowledgments

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