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CDF and D0

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TEVATRON TOP QUARK STUDIES

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We present a summary of recent measurements utilizing top quark candidate events extracted from approximately 110pb^{-1} of $p\bar{p}$ data collected by the CDF and DØ experiments at the Tevatron collider. We report on a new combined Tevatron top quark mass of $174.3\pm 5.1\text{GeV}/c^2$ which takes into account five separate measurements made by the two experiments. We also demonstrate how the techniques developed for the mass analysis have been applied to further studies of the top quark and the $t\bar{t}$ system.

1 Introduction

Since the discovery of the top quark^{1,2}, a large amount of work has gone into the study of its properties. In particular, both CDF and DØ have made precision measurements of the top quark mass^{3,4,5,6} and the $t\bar{t}$ production cross section^{7,8,9} utilizing several candidate event samples associated with the different decay modes of the $t\bar{t}$ system. Now that these fundamental analyses have reached a mature state, the techniques developed to make these measurements are being applied to further studies of top quark properties and kinematics of the $t\bar{t}$ system. Here, we present the most recent combined Tevatron top quark mass measurement extracted from five separate analyses performed at CDF and DØ. We also report on four additional top quark studies which rely heavily on the analysis tools developed for these mass measurements. The topics chosen for presentation are a CDF measurement of W boson helicity in top quark decay, a DØ search for charged Higgs bosons in top quark decay, a CDF measurement of the CKM matrix value $|V_{tb}|$, and studies of the $t\bar{t}$ invariant mass spectrum at both CDF and DØ.

2 Combined Mass Measurement

Standard Model top quark decays are almost exclusively to Wb . We characterize decays of the $t\bar{t}$ system into three classes based on the decay modes of the two W bosons. The dilepton channel refers to events where both W bosons decay leptonically giving the final state $l^+\nu l^-\bar{\nu}b\bar{b}$ ($l = e$ or μ). The lepton + jets channel is composed of events in which one W boson decays leptonically while the other decays hadronically resulting in a final state of $l^+\nu q\bar{q}'b\bar{b}$ ($l = e$ or μ). All-hadronic events are those in which both W bosons decay hadronically giving the final state $q\bar{q}'q\bar{q}'b\bar{b}$. The new combined Tevatron top quark mass result takes into account CDF results based on each of the channels listed above and DØ measurements in the dilepton and lepton + jets channels. The relative contribution of the CDF and DØ results based on the lepton + jets channel to the combined central value is nearly 80%. The final result accounts for all correlated systematic

uncertainties between the different measurements. In order to “err” on the side of caution, the two experiments have assumed a 100% correlation on all systematic uncertainties related to the Monte Carlo models. The Tevatron average for m_t based on these results is $174.3 \pm 3.2(stat) \pm 4.0(syst) GeV/c^2$. Combining the statistical and systematic uncertainties gives $m_t = 174.3 \pm 5.1 GeV/c^2$. The details of these measurements have been reported elsewhere^{10 11}. It is possible, however, to identify a general set of analysis methods common to the five measurements which make up this final result. These techniques include event selection based on lepton identification, jet reconstruction of parton momenta, bottom quark tagging for reduction of background and parton combinatorics, and kinematic reconstruction via event fitting. In the subsequent sections, we will attempt to show how each of these analysis techniques are being applied to further studies of the top quark and the $t\bar{t}$ system.

3 W Boson Helicity in Top Quark Decays

The Standard Model predicts that the top quark decays only to longitudinally polarized ($h_w = 0$) and left-handed ($h_w = -1$) W bosons. A leading order Standard Model calculation predicts the fraction of longitudinally polarized W bosons produced in top decay to be roughly 70% in the case of $m_t = 175 GeV/c^2$. Unusual top couplings such as anomalous static moments could produce a departure from the above expectation. The relevant information on W boson polarization can be extracted from the decay angular distributions of the charged lepton in the rest frame of the top quark. However, this technique requires full event reconstruction and the associated uncertainties due to neutrino reconstruction and parton combinatorics. In contrast, the CDF measurement relies solely on the reconstructed P_T spectrum of the charged leptons produced in the decays of the W bosons, a parameter highly correlated with W helicity. An unbinned maximum likelihood fit of the lepton P_T spectrum to the sum of the expectations from the decay of longitudinal and left-handed W bosons plus the expected background is performed based on the assumption of zero contribution from right-handed W bosons. The background contribution (shape and magnitude) is estimated from Monte Carlo and data and subjected to a gaussian constraint in the fit. The final fit result for the longitudinal fraction is found to be $0.97 \pm 0.37 \pm 0.12$, consistent with the Standard Model prediction.

4 Search for Charged Higgs Bosons in Top Decay

Charged Higgs bosons appear in the simplest extensions of the Standard Model Higgs sector, an integral feature of SUSY. A two-Higgs doublet model results in five Higgs bosons and two additional parameters in the electroweak sector (e.g. $\tan \beta$ and m_{H^+}). If a charged Higgs turns out to be lighter than the top quark, it could potentially be seen in top quark decays at the Tevatron. A closer examination of the parameter space reveals that the decay channel $t \rightarrow H^+ b$ can compete with the Standard Model Decay of $t \rightarrow W^+ b$ in cases where m_{H^+} is small and $\tan \beta$ is either small or large. A low $\tan \beta$ implies that the Higgs will decay predominantly to $\bar{s}c$, while a high $\tan \beta$ implies a majority of decays to $\tau^+ \nu$. A direct search for the charged Higgs decay modes is difficult due to the strong dependence of signal characteristics on the parameters. Instead, DØ chooses to perform a “disappearance” search based on the selection criteria of the top cross section analysis. In general, $t\bar{t}$ events in which one of the top quarks decays via a charged Higgs have characteristics which make the events less likely to pass the top cross section analysis selection criteria. In particular, jet reconstruction plays a critical role in this analysis. In the case where $t \rightarrow H^+ b \rightarrow \tau^+ \nu b$, for example, we should nominally expect to reconstruct one or more less jets than in the case of the standard model decay chain $t \rightarrow W^+ b \rightarrow q\bar{q}b$ which greatly reduces chances of the event passing the selection criteria of the standard cross section analysis. Based on fixed values of $\sigma(t\bar{t})$ and m_t , Monte Carlo experiments including signal and background

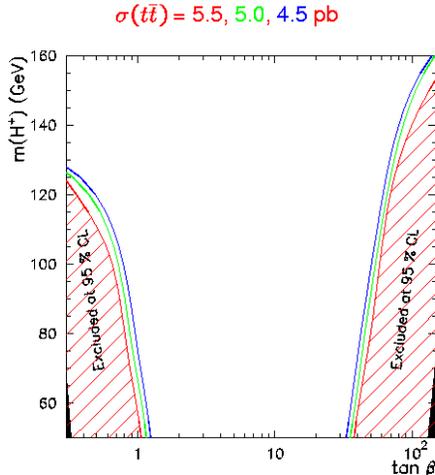


Figure 1: $D\Phi$ Charged Higgs exclusion curves in the $\tan\beta, m_{H^+}$ parameter space.

are performed for each bin in the $[\tan\beta, m_{H^+}]$ parameter space. The number of events in each simulated experiment which pass the selection criteria are compared with the actual number of events observed. A point in the parameter space is included in the exclusion region if 95% of the Monte Carlo experiments performed at that point give fewer events than the actual number observed. Both $\sigma(t\bar{t})$ and m_t must be treated as input values due to the fact that their measured values are based on the assumption $B(t \rightarrow W^+b) = 1$. The $D\Phi$ exclusion curves are shown in Figure 1 for $\sigma(t\bar{t}) = 4.5pb^{-1}, 5.0pb^{-1}$, and $5.5pb^{-1}$. Smaller input values of $\sigma(t\bar{t})$ lead to larger exclusion regions.

5 Measurement of $|V_{tb}|$

The Standard Model predicts that the top quark decays almost exclusively via the $t \rightarrow W^+b$ channel. The branching fraction for this decay is dependent on the magnitude of the CKM matrix element $|V_{tb}|$ which is itself constrained to a value extremely close to one by a global fit based on experimental measurements of other CKM matrix elements. The fit itself is based, however, on the assumptions of CKM matrix unitarity and three generations in the Standard Model. Non-Standard model physics and/or additional generations could in fact result in deviations from this predicted value. The CDF measurement of $|V_{tb}|$ is based on the assumption that top quark decay proceeds exclusively via real W bosons. Using the bottom quark tagging techniques developed in the mass and cross section analyses, CDF is able to measure the ratio R_b defined as $\Gamma(t \rightarrow Wb)/\Gamma(t \rightarrow Wq)$. Top quark candidate events are divided into four non-overlapping bins based on the number and type of tagged bottom quark jets in the event. The number of events in each category is necessarily dependent on the fraction of bottom quarks present in the top quark decays. An estimation of the background in each bin along with studies of acceptance and tagging efficiency are used to construct a likelihood function for the number of events in each bin as a function of R_b . A minimization of this likelihood function gives a value for $R_b = 0.93^{+0.31}_{-0.23}$. With the added assumption of unitarity, CDF also calculates a value for $|V_{tb}| = 0.96^{+0.16}_{-0.12}$ and sets a lower limit of 0.74 at the 95% confidence limit. Since the calculation of $|V_{tb}|$ from R_b is based on the Standard Model with three generations, the result for $|V_{tb}|$ serves solely as a check of the Standard Model prediction.

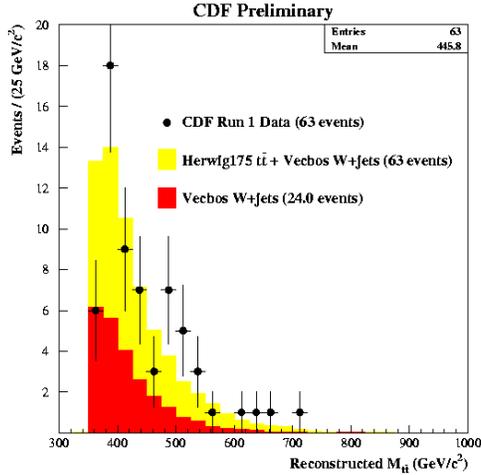


Figure 2: CDF $t\bar{t}$ Invariant Mass Distribution.

6 $t\bar{t}$ Invariant Mass Spectrum

Several proposed extensions of the Standard Model such as Topcolor Assisted Technicolor¹² can produce enhancements and/or resonances in the $t\bar{t}$ invariant mass spectrum. Both CDF and DØ have studied $t\bar{t}$ invariant mass distributions in candidate event samples utilizing the sophisticated kinematic event fitters developed for the top quark mass measurements. For these studies, the event fitters are modified to include the additional kinematic constraint of the measured top quark mass. Monte Carlo studies show that utilizing the top mass constraint in the event fitting routines allows for better precision measurements of other kinematic variables in the fitted events due primarily to the increased likelihood of correct parton assignments for all reconstructed jets. Figure 2 shows the $t\bar{t}$ invariant mass distribution for the 63 candidate events in the CDF lepton + jets channel. The data is in good agreement with the Standard Model prediction for the combined signal and background shown as the light-shaded region in the figure. While not shown here, the DØ $t\bar{t}$ invariant mass spectrum is also in good agreement with Standard Model predictions. From the above comparison, CDF can set lower limits on the mass of a heavy particle decaying to a narrow $t\bar{t}$ resonance based on a given theory. For the Topcolor Assisted Technicolor theory of Hill and Parke¹², for example, CDF sets a lower mass limit on the Z' on the order of $600\text{GeV}/c^2$.

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