TOP QUARK PAIR PRODUCTION AND PROPERTIES MEASUREMENTS AT THE TEVATRON

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Abstract

The Tevatron proton-antiproton collider at Fermilab with its centre of mass energy of 1.96 TeV is currently the only source for the production of top quarks. This report reflects the current status of measurements of the top quark pair production cross section and properties performed by the CDF and DØ Collaborations. Utilising datasets of up to two fb^{-1}, these measurements allow unprecedented precision in probing the validity of the Standard Model.

1 Introduction

Since its discovery in 1995 at the Tevatron [1], the top quark remains the heaviest known fundamental particle to date. With a mass of 172.6 ± 1.4 GeV/c^2 [2], it is considered to be intimately connected with the mechanism of electroweak symmetry breaking in the Standard Model of elementary particle physics (SM) and also to be sensitive to physics beyond the framework of the SM.

This article reports recent measurements by the CDF and DØ Collaborations that probe the SM expectations for deviations both in the production and decay of the top quark. After a brief outline of the top quark properties within the SM framework in Section 2, the current status of measured top quark pair production rates is given Section 3, followed by a section on searches for top quark production beyond the SM. The subsequent three sections describe measurements probing the top quark decay in terms of branching fractions, search for flavour-changing neutral currents and the helicity of the W boson in the top quark decay, respectively. A conclusion is given in the final Section 8.

2 Top Quark Pair Production and Decay in the SM

Within the framework of the SM, top quark production at the Tevatron proceeds mainly in pairs: $p\bar{p} \rightarrow t\bar{t} + X$ via the strong interaction (85% $q\overline{q}$ annihilation and 15% gluon-gluon fusion).

The corresponding production cross section has been evaluated at next-to-leading order (NLO) QCD using two different approaches: One calculation considers soft gluon corrections up to next-to-next-to-next-to leading logarithmic (NNNLL) terms and some virtual terms in a truncated resummation, yielding 6.77 ± 0.42 pb for a top quark mass of 175 GeV/c^2 [3], while another calculation using the NLO calculation with LL and NLL resummation at all orders of perturbation theory gives $6.70^{+0.71}_{-0.88}$ pb for a top quark mass of 175 GeV/c^2 [4]. If a PDF uncertainty is combined linearly with the theoretical uncertainty for the first result – similar to what is done for the second result – both predictions exhibit not only similar central values but also similar relative uncertainties of ≈12-13%.

Due to its large mass, the top quark has an extremely short lifetime of approximately $5 \cdot 10^{-25}$ s, which makes it decay before it can form hadrons – a unique feature setting it apart from all other quarks. Since the top quark mass is well above the threshold for Wq decays with q being one of the down-type quarks d, s, b, this two-body decay dominates the top quark decay. As each quark flavour contributes to the total decay rate proportional to the square of the respective CKM matrix element V_{tq}, top decays into Ws and Wd are strongly suppressed with respect to the dominant decay $t \to Wb$.

Consequently, top quark pair events contain a b and a $\bar{b}$ quark from the $t\bar{t}$ decay, and depending on the decay modes of the two W bosons, the observed top quark pair final states can be divided into three event classes:

i) In *dilepton* events, both W bosons decay leptonically, resulting in a final state containing two isolated high-p_T leptons, missing transverse energy $\not{E}_T$ corresponding to the two neutrinos and two jets. This final state constitutes ≈5% of the $t\bar{t}$ events (not counting τ leptons) and gives the cleanest signal but suffers from low statistics.

ii) In *lepton+jets* events, one W boson decays leptonically, the other one hadronically, resulting in one isolated high-p_T lepton, $\not{E}_T$ and four jets. Events in the e+jets or μ+jets channels yield ≈29% of the branching fraction (≈34% when including leptonic τ decays) and provide the best compromise between sample purity and statistics.

iii) In *all-hadronic* events, both W bosons decay to $\overline{q}q'$ pairs, resulting in a six-jet final state. With a branching fraction of ≈46%, this final state represents the biggest fraction of $t\bar{t}$ events, but it is also difficult to separate from the large background of multijet production.

All of these final states contain two b-jets from the hadronisation of the (anti-) b quarks, and additional jets can arise from initial and final state radiation.

3 Measurement of the Top Quark Pair Production Cross Section

Top quark pair production cross section measurements provide a unique test of the predictions from perturbative QCD calculations at high transverse momenta. Analysing all three event classes allows both the improvement of statistics of top events and studies of properties and important checks for physics beyond the SM that might result in enhancement/depletion in some particular channel via novel production mechanisms or decay modes.

The following subsections give an overview of the cross section measurements pursued at the Tevatron rather than quoting single cross section results, with the exception of the most precise single measurement to date, obtained by DØ in the lepton+jets channel. All current measurements are summarised in Figure 2.

3.1 Dilepton Final State

A typical selection of dilepton events requires two isolated high p_T leptons, $\not\!\!E_T$ and at least two central energetic jets in an event. The most important physics background processes containing both real leptons and $\not\!\!E_T$ are Z/γ^*+jets production with $Z/\gamma^* \to \tau^+\tau^-, \tau \to e, \mu$ and the production of dibosons (WW, ZZ, WZ). Instrumental backgrounds are to be considered as well, arising from misreconstructed $\not\!\!E_T$ due to resolution effects in Z/γ^*+jets production with $Z/\gamma^* \to e^+e^-/\mu^+\mu^-$, and also from W+jets and QCD multijet production where one or more jets fake the isolated lepton signature. To ensure proper description of the instrumental backgrounds, these are usually modelled using collider data, while for the physics backgrounds typically Monte Carlo simulation is used.

A further enhancement of the signal fraction in the selected data samples is possible by requiring additional kinematical event properties like the scalar sum of the jet p_Ts H_T to be above a certain threshold or rejecting events where both selected leptons have like-sign electric charge. The obtained purities in such selected samples are usually quite good with a signal to background ratio (S/B) better than 2 at least, although signal statistics are low. The acceptance for dilepton final states can be enhanced by loosening the selection to require only one fully reconstructed isolated lepton (e, μ) in addition to an isolated track ("ℓ+track analysis"). In particular, such a selection allows the inclusion of "1 prong" hadronic τ decays.

The top quark production cross section was recently measured for the first time also in the lepton+tau final state by DØ [5)], using events with hadronically decaying isolated taus and one isolated high p_T electron or muon. To separate real taus from jets, a neural network was used, and the sample purity was enhanced by requiring b-jet identification (see Section 3.2) in the selected events. The result is shown together with the other measurements in Figure 2.

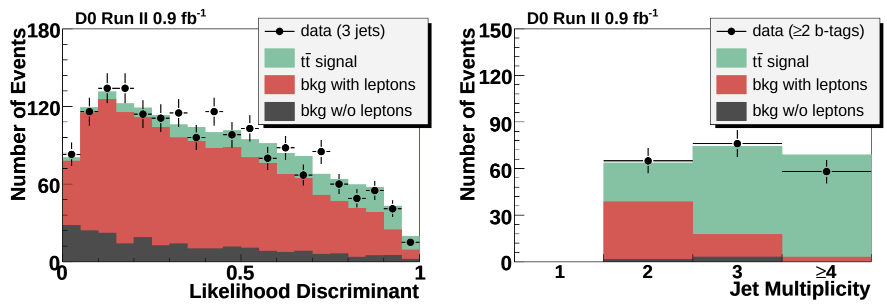

Figure 1: *Sample composition in a lepton+jets sample, requiring three jets (left) or at least two b-tagged jets (right)* [6].

3.2 Lepton+Jets Final State

A typical lepton+jets selection requires one isolated high p_T lepton (e or μ which includes $\tau \to e\nu\bar{\nu}$, $\tau \to \mu\nu\bar{\nu}$), $\not\!\!E_T$ and at least 4 jets, yielding samples with a S/B around 1/2. The dominant physics background to be considered here comes from W+jets production while the main instrumental background arises from QCD multijet production where a jet fakes the isolated lepton signature.

The cross section can be extracted from such a selected sample either purely based on topological and kinematical event properties combined in a multivariate discriminant to separate the $t\bar{t}$ signal from background or by adding identification of b-jets. Since topological analyses do not depend on the assumption of 100% branching of $t \to Wb$, they are less model-dependent than tagging analyses. On the other hand, requiring b-jet identification is a very powerful tool in suppressing the background processes, which typically exhibit little heavy flavour content. With b-jet identification, the top signal can also be easily extracted from lower jet multiplicities, where topological analyses need to impose additional selection criteria like cutting on H_T to be able to extract the signal. In addition, b-tagged analyses can provide very pure signal samples, easily exceeding a S/B > 10 in selections requiring at least four jets with two identified b-jets (see for example Figure 1).

The identification of b-jets can be based on the long *lifetime* of B hadrons resulting in significantly displaced secondary vertices with respect to the primary event vertex or large significant impact parameters of the corresponding tracks. A combination of this type of information in a neural network tagging algorithm yields b-tagging efficiencies of about 54% while only about 1% of light quark jets are misidentified as b-jets – hence the improved S/B in tagged analyses. Another way to identify b-jets is to reconstruct *soft leptons* inside a jet originating from semileptonic B decays. So far only soft-μ tagging has been deployed in $t\bar{t}$ analyses.

The most precise $t\bar{t}$ production cross section measurement to date with a relative uncertainty of 11% has been performed by DØ on 0.9 fb^{-1} of data in the lepton+jets channel [6]. For this measurement, two complementary analyses based on a kinematic likelihood discriminant and on b-tagging (see Figure 1) were combined and yield $\sigma_{t\bar{t}} = 7.42 \pm 0.53(\text{stat}) \pm 0.46(\text{syst}) \pm 0.45(\text{lumi})$ pb for a top quark mass of 175 GeV/c^2. Comparing this measurement with the theory prediction, the top quark mass can be extracted as well, yielding 170 ± 7 GeV/c^2 in good agreement with the world average.

A first τ+jets cross section analysis using events with hadronically decaying isolated taus and lifetime b-tagging was performed as well by DØ – the result is shown together with other measurements in Figure 2.

3.3 All-Hadronic Final State

The all-hadronic final state is studied by requiring events with at least six central energetic jets and no isolated high p_T leptons. Due to the overwhelming background from QCD multijet production with a cross section orders of magnitude above that of the signal process, b-jet identification is mandatory for this final state. Further separation of signal and background is achieved by using multivariate discriminants based on topological and kinematical event properties.

3.4 Summary of the Top Quark Pair Production Cross Section Measurements

Figure 2 provides an overview of recent cross section measurements performed by CDF and DØ. All measurements show good agreement with the SM prediction and with each other. The single best measurements are approaching a relative precision of $\Delta\sigma/\sigma = 10\%$ that should be achievable for the datasets of 2 fb^{-1} already at hand and provide stringent tests to theory predictions.With increasing datasets, these measurements naturally start to become limited by

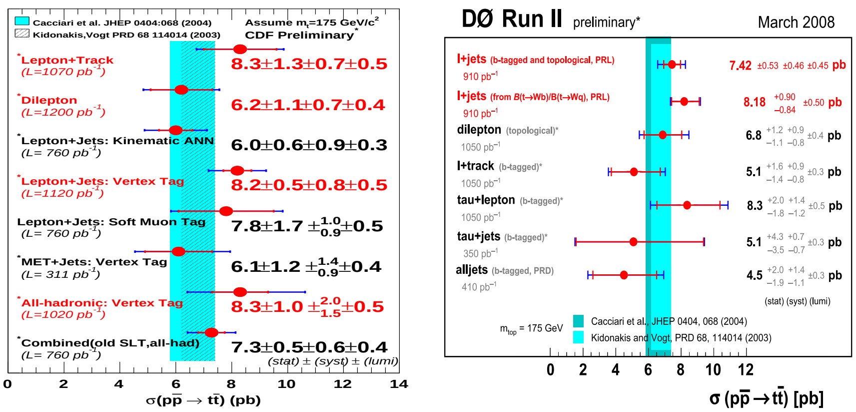

Figure 2: *Top quark pair production cross section measurements performed by CDF and DØ.*

systematic uncertainties rather than statistical ones, but it will be possible to further constrain the systematic uncertainties as well using additional data.

Cross section measurements form the foundation for all further property analyses like the ones described in the subsequent sections of this article by characterising the datasets enriched in top quark pairs and providing the necessary understanding of object identification, background modelling and sample composition.

4 Search for Top Quark Pair Production beyond the SM

4.1 Search for a Narrow-Width Resonance decaying into $t\bar{t}$

Various beyond the SM theories predict the existence of a massive Z-like boson that could decay into $t\bar{t}$ and hence add a resonant production mode to the SM process. Any such additional production would be visible in the $t\bar{t}$ invariant mass distribution provided the resonance X decaying to $t\bar{t}$ is sufficiently heavy and narrow.

Both CDF and DØ perform a search for a generic heavy resonance X of narrow width ($\Gamma_X = 0.012 M_X$) compared to the detector mass resolution in b-tagged lepton+jets datasets. The $t\bar{t}$ invariant mass spectrum is recon-

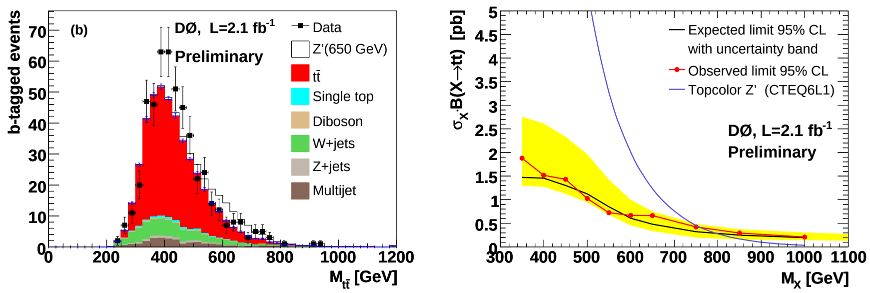

Figure 3: *Left: Expected and observed $t\bar{t}$ invariant mass distribution in lepton+jets data with four or more jets. Right: Expected and observed 95% C.L. upper limits on $\sigma_X \cdot \mathcal{B}(X \to t\bar{t})$* [8].

structed using either a kinematic fit to the $t\bar{t}$ production hypothesis (CDF) or directly from the four-momenta of the up to four leading jets, the lepton and the neutrino momentum (DØ). The latter approach was shown to provide better sensitivity for large resonance masses than the previously used constrained kinematic fit and also allows the inclusion of data with fewer than four jets in case that jets merged. As both experiments observe no significant deviation from the SM expectation, 95% C.L. upper limits on $\sigma_X \cdot \mathcal{B}(X \to t\bar{t})$ are given for values of M_X between 450 and 900 GeV/c^2 (CDF) respectively 350 and 1000 GeV/c^2 (DØ, see Figure 3).

Both experiments provide 95% C.L. mass limits for a leptophobic topcolour-assisted technicolour Z' boson as a benchmark model. Using 955 pb^{-1}, CDF finds $M_{Z'} > 720$ GeV/c^2 (expected limit: 710 GeV/c^2) [7] while DØ finds $M_{Z'} > 760$ GeV/c^2 (expected limit: 795 GeV/c^2) [8] using 2.1 fb^{-1} of data.

4.2 Search for $t\bar{t}$ Production via a Massive Gluon

Instead of a new colour singlet particle decaying into $t\bar{t}$ as described in the previous subsection, there could also be a new massive colour octet particle G contributing to $t\bar{t}$ production. Such a "massive gluon" production mode would interfere with the corresponding SM production process.

Assuming a SM top decay, CDF has performed a search for a corresponding contribution by comparing the $t\bar{t}$ invariant mass distribution in a 1.9 fb^{-1}

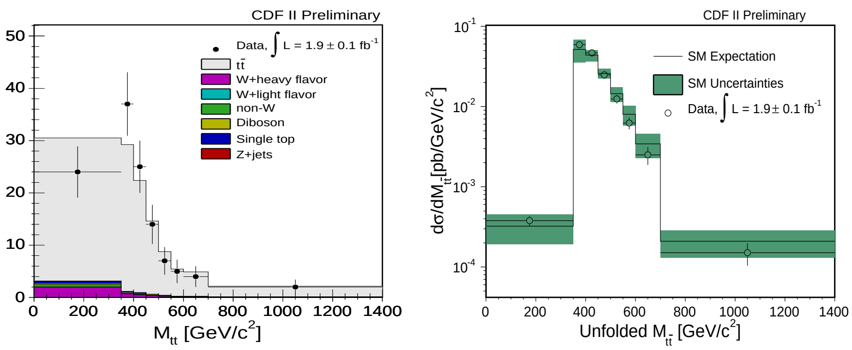

Figure 4: *Left: Reconstructed $t\bar{t}$ invariant mass distribution in lepton+jets data with at least four jets. Right: Corresponding observed $t\bar{t}$ differential cross section, compared to the SM expectation* [10].

b-tagged lepton+jets dataset with the SM expectation. As the largest discrepancy with respect to the SM observed is 1.7σ for the explored mass and width range 400 GeV/c^2 $\leq M_G \leq$ 800 GeV/c^2, $0.05 \leq \Gamma_G/M_G \leq 0.5$, upper and lower limits are provided on the corresponding coupling strengths of the massive gluon [9].

4.3 Measurement of the $t\bar{t}$ Differential Cross Section $d\sigma/dM_{t\bar{t}}$

Contributions beyond the SM in $t\bar{t}$ production could manifest themselves in either resonances, broad enhancements or more general shape distortions of the $t\bar{t}$ invariant mass spectrum. A very generic way to search for such effects is to measure the $t\bar{t}$ differential cross section $d\sigma/dM_{t\bar{t}}$ and compare the shape with the SM expectation.

CDF reconstructs the $t\bar{t}$ invariant mass spectrum in a 1.9 fb^{-1} b-tagged lepton+jets dataset (see Figure 4) by combining the four-vectors of the four leading jets, lepton and missing transverse energy. After subtracting the background processes, the distortions in the reconstructed distribution due to detector effects, object resolutions and geometric/kinematic acceptance are corrected for by the application of a regularised unfolding technique. From the unfolded distribution, the $t\bar{t}$ differential cross section $d\sigma/dM_{t\bar{t}}$ is extracted and its shape is compared with the SM expectation. The shape comparison yields

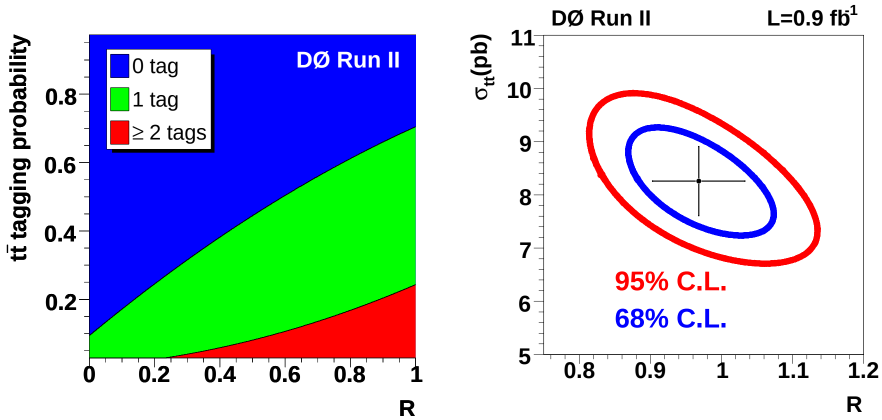

Figure 5: *Left: Fractions of events with 0, 1 and* ≥ 2 *b-tags for* $t\bar{t}$ *events with* ≥ 4 *jets as a function of* R*. Right: 68% and 95% C.L. statistical uncertainty contours in the* R *vs.* $\sigma_{t\bar{t}}$ *plane* [12].

good agreement with the SM, yielding an Anderson-Darling p-value of 0.45 [10].

5 Measurement of $\mathcal{B}(\mathbf{t} \to \mathbf{Wb})/\mathcal{B}(\mathbf{t} \to \mathbf{Wq})$

Assuming the validity of the SM, specifically the existence of three fermion generations, unitarity of the CKM matrix and insignificance of non-W boson decays of the top quark (see Section 6), the ratio of branching fractions $R = \mathcal{B}(t \to Wb)/\Sigma_{q=d,s,b}\mathcal{B}(t \to Wq)$ simplifies to $|V_{tb}|^2$, and hence is strongly constrained: $0.9980 < R < 0.9984$ at 90% C.L. [11]. Deviations of R from unity could for example be caused by the existence of a fourth heavy quark generation.

The most precise measurement of R thus far has been performed by DØ in the lepton+jets channel using data corresponding to an integrated luminosity of 900 pb^{-1}. By comparing the event yields with 0, 1 and 2 or more b-tagged jets and using a topological discriminant to separate the $t\bar{t}$ signal from background in events with 0 b-tags, R can be extracted together with the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ simultaneously (see Figure 5). This measurement allows the extraction of $\sigma_{t\bar{t}}$ without assuming $\mathcal{B}(t \to Wb) = 100\%$, yielding

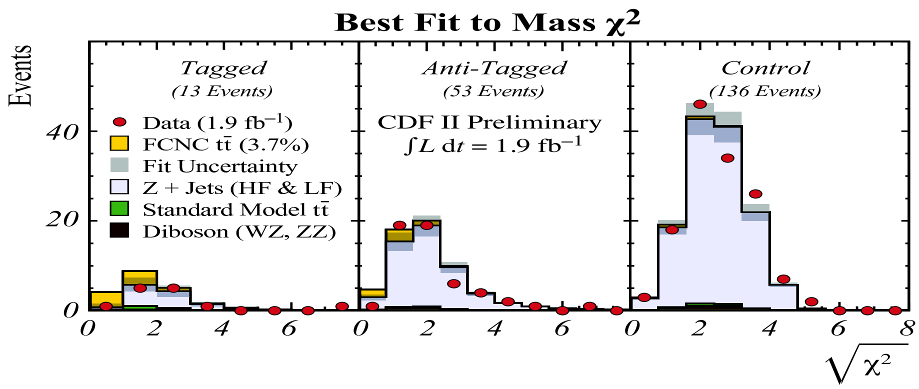

Figure 6: *Expected and observed mass χ^2 distributions of $Z+\geq 4$ jets events in signal samples with $\geq$1 and 0 b-tags and a background enriched sample to control uncertainties of the background shape and normalisation* [13].

$R = 0.97^{+0.09}_{-0.08}$ (stat+syst) and $\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84}$ (stat+syst) $\pm$ 0.50 (lumi) pb for a top quark mass of 175 GeV/c^2 in agreement with the SM prediction [12].

6 Search for Flavour Changing Neutral Currents in Top Decays

The occurrence of flavour changing neutral currents (FCNC) – a decay of type $t \to Vq$ with $V = Z, \gamma, g$ and $q = u, c$ – is strongly suppressed in the SM and expected to occur at a rate below $\mathcal{O}(10^{-10})$, well out of reach of being observed at the Tevatron. Consequently, any observation of FCNC decays would signal physics beyond the SM.

CDF has performed a search for $t \to Zq$ in a 1.9 fb^{-1} dataset of $Z+\geq 4$ jets events with $Z \to e^+e^-$or $\mu^+\mu^-$, assuming a SM decay of the second top quark $t \to \overline{q}q'b$. Since the event signature does not contain any neutrinos, the events can be fully reconstructed. The best discriminant found to separate signal from background processes is a mass χ^2 variable that combines the kinematic constraints present in FCNC decays. The signal fraction in the selected dataset is determined via a template fit in signal samples with 0 or $\geq$1 b-tags and a background-enriched control sample to constrain uncertainties on the background shape and normalisation (see Figure 6).

Since the observed distributions are consistent with the SM background

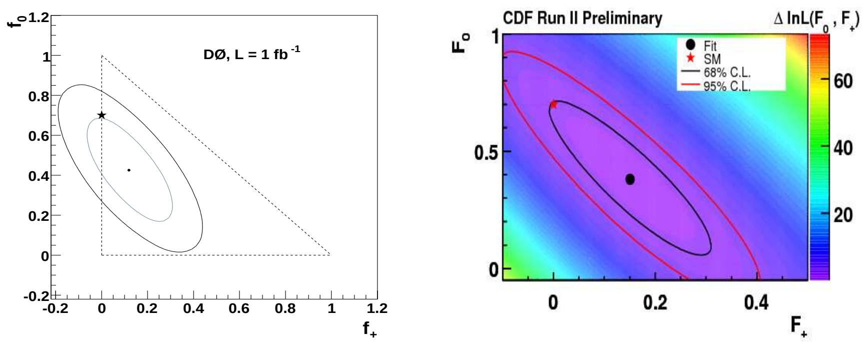

Figure 7: *Results of the W boson helicity fits (left: DØ* [15]*, right: CDF* [14]*). The ellipses show the 68% and 95% C.L. contours around the measured data points. The stars show the SM expectation; the triangle denotes the physically allowed region where f_0 and f_+ sum to one or less.*

processes, a 95% C.L. upper limit on the branching fraction $\mathcal{B}(t \to Zq)$ of 3.7% is derived [13]. This is the best limit on $\mathcal{B}(t \to Zq)$ to date.

7 Measurement of the W Boson Helicity in Top Quark Decays

Assuming a massless b-quark, the top quark decay in the V−A charged current weak interaction proceeds only via a left-handed ($f^- \approx 30\%$) and a longitudinal ($f^0 \approx 70\%$) fraction of W boson helicities. The helicity of the W boson is reflected in the angular distribution $\cos\theta^*$ of its decay products, with θ^* being the angle of the down-type decay products of the W boson (charged lepton respectively d- or s-quark) in the W boson rest frame with respect to the top quark direction. Any observed right-handed fraction $f^+ > \mathcal{O}(10^{-3})$ would indicate physics beyond the SM.

CDF has measured the W boson helicity fractions in 1.9 fb^{-1} of b-tagged lepton+jets data comparing the $\cos\theta^*$ distribution of leptons in data to templates for longitudinal, right- and left-handed signal plus background templates. When fitting both f^0 and f^+ simultaneously, the result is $f^0 = 0.38 \pm 0.21\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})$ and $f^+ = 0.15 \pm 0.10\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$ [14].

DØ has measured the W boson helicity fractions using the $\cos\theta^*$ distributions in dilepton and lepton+jets events including their hadronic W boson decays in 1 fb^{-1} of data, yielding $f_0 = 0.425 \pm 0.166$ (stat.) ± 0.102 (syst.) and $f_+ = 0.119 \pm 0.090$ (stat.) ± 0.053 (syst.) [15].

Both measurements agree with the SM at the 1σ level (see Figure 7).

8 Conclusion

A wealth of top quark analyses is being pursued at the Tevatron, probing the validity of the SM with unprecedented precision. The measured top quark pair production rates are found to be consistent with the SM expectation across the decay channels, with the most precise measurements surpassing the precision of theory predictions. There is no evidence thus far for contributions beyond the SM in either top quark production or top quark decay. However, with some measurements still being statistically limited, there is still room for surprises. More detailed descriptions of the analyses presented here and many more interesting top quark physics results can be found online [16].

Continuously improving analysis methods and using the increasing integrated luminosity from a smoothly running Tevatron that is expected to deliver more than 6 fb^{-1} by the end of Run II, we are moving towards more precision measurements and hopefully discoveries within and outside the SM.

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