TOP PAIR PRODUCTION III: TESTING THE STANDARD MODEL IN TOP QUARK DECAYS

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With its discovery in 1995 by the CDF and DØ collaborations the top quark completed the set of quarks expected by the Standard Model. It is predicted to have the same quantum numbers and couplings as the other up-type quarks. Albeit, only very few of these properties have been verified so far. This article summarises the existing measurements of top quark properties in the pair production mode.

Keywords: Top Quark; Standard Model Tests; Properties.

1. Introduction

The set of quarks expected in the Standard Model (SM) of particle physics was fully observed in 1995 with the discovery of the top quark by the CDF and DØ collaborations[1,2]. All quantum numbers of the top quark except the mass are expected to be identical to those of the other two up-type quarks. Within the Standard Model these quantities fully define the production and decay properties of the top quark.

Only few of these predicted properties have been verified to date. These measurements were performed with the CDF and DØ experiments at the Tevatron, which is still the only accelerator available to study top quark physics.

This article summarises the current status of measurements of top pair decays which test the Standard Model predictions. Measurements of single top production are covered separately[3]. The selection of top pairs and the measurement of the top quark mass are covered in separate articles in these proceedings[4,5].

Further reports on top quark results[6,7,8] were given in the heavy quark session.

2. W-Helicity

Within the Standard Model top quarks decay into a W-boson and a b-quark. To check the expected $V-A$ structure of this weak decay the W-helicity was investigated. Only left-handed particles are expected to couple to the W-boson and thus the W can be either left handed $(-)$ or longitudinal (0). For the known b and t masses the fractions should be $f_- = 0.3$ and $f_0 = 0.7$, respectively. The right handed $(+)$ contribution is expected to be negligible.

Depending on the W-helicity $(-, 0, +)$ the charged lepton in the W decay prefers to align with the b direction, stay orthogonal or escape in the direction opposite to the b.

Several observables are sensitive to the helicity: the transverse momentum of the lepton, p_T^{lept}, the lepton-b-quark invariant mass, M_{lb} and the angle between the lepton and the b-quark direction. For best sensitivity at Tevatron energies this angle is measured in the W rest frame.

Currently the best results are obtained using M_{lb}^2 and the angle between lepton and b-quark, $\cos\theta^*$. Unless otherwise stated the results assume $f_0 = 0.7$ which remains unchanged for a $V+A$ admixture.

2.1. *Results using* M^2_{lb}

CDF has released an analysis[9] based on the lepton-b-quark invariant mass using both the lepton+jets channel with $\mathcal{L} = 695\,\mathrm{pb}^{-1}$ and the dilepton channel with $\mathcal{L} = 750\,\mathrm{pb}^{-1}$.

In the lepton+jets channel one measurement per event can be performed. b-tagging is required in the event selection. For events with only one identified b-jet the invariant mass of the identified jet with the identified lepton is used to create a M^2_{lb} distribution, see Fig. 1. For events with two identified b-jets M^2_{lb} is computed for both jets and used to create a 2 dimensional (2-d) distribution.

Dilepton events provide two simultaneous measurements. Both possible pairings of leptons to jets are used to create a 2-d M^2_{lb} distribution with two entries per event.

The obtained data distributions are compared to $V-A$ and $V+A$ templates obtained from simulation including signal and background processes.

A binned log-likelihood fit procedure is used to extract the fraction of $V+A$ in data in the three samples. The final left-handed W fraction is

$$f_+ = -0.02 \pm 0.07$$
$$f_+ < 0.09 \quad 95\%\mathrm{CL} \qquad (1)$$

in agreement with the SM expectation.

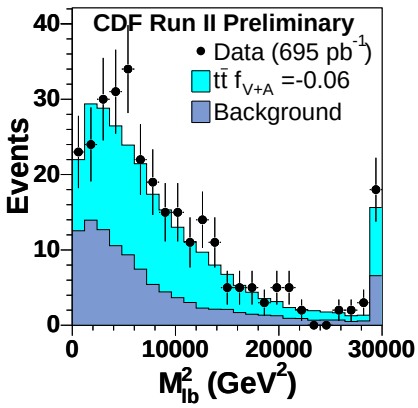

Fig. 1. M^2_{lb} distribution for lepton+jets data compared to simulation.

2.2. *Results using* $\cos\theta^*$

Both CDF and DØ used $\cos\theta^*$ to measure the W-helicity.

2.2.1. *DØ*

DØ investigated about $370\,\mathrm{pb}^{-1}$ in both the dilepton and the lepton+jets channel[10].

In the lepton+jets channel $\cos\theta^*$ is reconstructed from the measured objects after improving the resolution with a constraint fit using the W and top masses. Only the jet assignment of the best fit is considered.

In the dilepton channel the same constraints are used to reconstruct the neutrino momenta with a fourfold ambiguity. In order to account for detector resolution the recontruction is repeated 100 times with object momenta smeared according to the experimental resolution. Both possible assignments of the leading 2 jets to the leptons are considered. The result from the repetitions and assignments are averaged to obtain two $\cos\theta^*$ measurements per event (Fig. 2).

The resulting $\cos\theta^*$ distributions are compared to $V+A$ and $V-A$ templates from simulation that include background contributions. To obtain the final result a maximum likelihood fit is used. DØ obtains:

$$f_+ = 0.056 \pm 0.080 \pm 0.057$$
$$f_+ < 0.23 \quad 95\%\mathrm{CL}. \qquad (2)$$

consitent with the SM prediction.

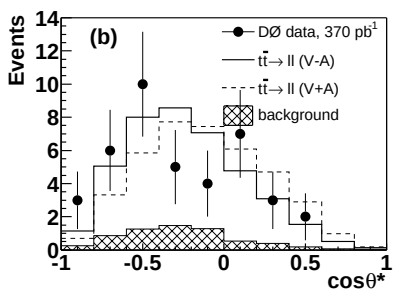

Fig. 2. $\cos\theta^*$ measured in dilepton events.

2.2.2. *CDF*

CDF has performed two different analyses in the lepton+jets channel using $\mathcal{L} = 1\,\mathrm{fb}^{-1}$.

The template based method[11] is very similar to the DØ analysis described in Sect. 2.2.1. Fig. 3 shows the data distribution and the fitted template curves which result in:

$$f_+ = -0.05 \pm 0.06 \pm 0.03$$
$$f_+ < 0.11 \quad 95\%\mathrm{CL}. \tag{3}$$

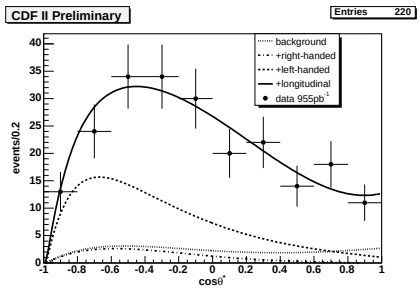

Fig. 3. Distribution of $\cos\theta^*$ measured by CDF compared to template predictions.

The second analysis[12] uses migration matrices to transfer the theory prediction to the level of measured quantities. It also uses all possible jet assignment weighted according to their signal probability based on kinematic properties. It obtains

$$f_+ = -0.03 \pm 0.03 \pm 0.04$$
$$f_+ < 0.10 \quad 95\%\mathrm{CL}. \tag{4}$$

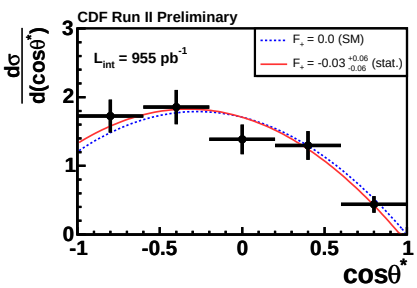

Fig. 4. Unfolded $\cos\theta^*$ distribution by CDF compared to Standard Model and best fit theory.

Both CDF measurements are also reinterpreted as measurements of f_0 assuming the SM contribution of f_+. Both results are compatible with the SM of $f_0 \simeq 70\%$ within their 20% uncertainty.

3. Top Charge

The top quarks electrical properties are fixed by its charge. However, in reconstructing top quarks the charges of the objects usually aren't checked. Thus an exotic charge value of $|q_t| = 4e/3$ isn't excluded by standard analyses.

DØ performed a reconstruction of the top charge in the lepton+jets channel[13] using $\mathcal{L} = 370\,\mathrm{pb}^{-1}$. Two or more identified b-jets are required. The assigment of b-jets to the leptonic or hadronic event side is based on the quality of a fit to the $t\bar{t}$ hypothesis, which uses the W and top masses as constraints.

The charge is then reconstructed for both top quarks in the event as

$$Q_{\mathrm{lep}} = |q_l + q_{b_\mathrm{l}}|$$
$$Q_{\mathrm{had}} = |-q_l + q_{b_\mathrm{h}}|\,, \tag{5}$$

where the charge of the b-jets in the leptonic and hadronic side, q_{b_l} and q_{b_h}, are obtain using the charged tracks assigned to the b-jets.

The reconstructed top charge distribution are compared to templates from simulation of the two cases and judged with unbinned likelihoods. From the likelihood ratio DØ excludes the $4e/3$ case at 92% CL and limits its fraction in the current data sample to less than 80% at 90% CL.

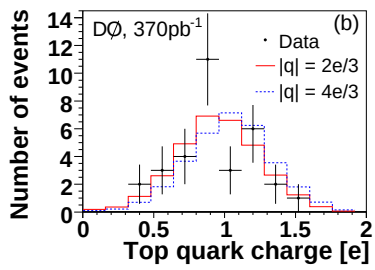

Fig. 5. Top charge in DØ data and simulation.

4. Top Branching Ratio

In top quark decays any down-type quark can be produced in association with the W-boson. The relative strength of these modes is governed by the CKM matrix. With an expected $|V_{tb}| \simeq 0.999$ the decay into b-quarks is by far dominating in the Standard Model. Various extension of the Standard Model allow for deviations from these expectations.

In top pair production only the branching ratio

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \quad (6)$$

is experimentally accessible. CDF and DØ have performed analyses that determine R from the ratio of $t\bar{t}$ events with two, one or no b-tags[14,15]:

$$\begin{array}{ll} \text{DØ } (230\,\text{pb}^{-1}) & \text{CDF } (162\,\text{pb}^{-1}) \\ R = 1.03^{+0.19}_{-0.17} & R = 1.12^{+0.27}_{-0.23} \\ R > 0.64 & R > 0.62 \quad 95\%\ \text{CL.} \end{array} \quad (7)$$

These results are regularly converted to limits on the CKM matrix element

$$|V_{tb}| > 0.80 \qquad |V_{tb}| > 0.78 \quad 95\%\ \text{CL.} \quad (8)$$

It is important to note that in these analyses a sensitivity to deviations from the expected $|V_{tb}| \simeq 1$ would only be reached if the fraction of top quarks that decays to b-quarks was comparable to the light quark fractions.

5. Searches for New Particles

Further results are obtained by checking the presence of new particles in $t\bar{t}$ decays.

CDF has searched for H^+ in top decays by checking the cross-sections of various Standard Model modes including one τ channel and looking for modes that are expected in H^+ decays. Limits on the branching fraction $B(t \to bH^+)$ are set for various H^+ decay modes and masses[16].

From the reconstructed top mass distribution CDF infers the possible mass of a t' particle to be $M_{t'} > 258\,\text{GeV}$ at 95% CL[17].

CDF and DØ have investigated the distribution of the invariant mass of $t\bar{t}$ pairs and checked for resonances. Cross-section limits for narrow resonances are obtained and presented as mass limits in a Z' model[18,19].

6. Summary

Several properties of the top quark are investigated in $t\bar{t}$ events by the CDF and DØ collaborations.

Measurements of the W-Helicity can probe 10% $V+A$ contributions, the excotic charge value of the top quark can be excluded at 92% CL and measurements of the decay flavour have reached 20% precision. More analyses including searches for unknown particles in $t\bar{t}$ events have been performed.

No significant deviation from the Standard Model has been observed (yet).

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