Top Quark Mass and Properties at the Tevatron

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Abstract. We present recent analyses of top quark properties performed at Run II of the Tevatron. Measurements of the top quark mass, branching ratios and W boson helicity inside top quark decays are covered.

Keywords: Particle physics; hadron colliders; top quark; electroweak physics; heavy quark
PACS: 12.15.Ff; 12.15.Lk; 14.65.Ha

TOP PHENOMENOLOGY AT THE TEVATRON

The top quark has been discovered only recently [1] due to its very large mass: $M_{top} \approx 175$ GeV$/c^2$. Indeed, the top quark is easily the heaviest particle in the Standard Model (SM). This peculiar property brings several reasons to study it. First, the Yukawa coupling of the top quark is nearly one which could be a sign that it plays a special role in the origin of mass beyond the Standard Model. Second, radiative corrections due to top quark loops are often dominant in the prediction of precision observables like the W or Higgs boson mass. Finally, its large mass implies it has a very short lifetime ($\sim 10^{-25}$s), about an order of magnitude smaller than the hadronization time, which provides a unique opportunity to study a bare quark.

The top quarks are produced by the Tevatron, a $p\bar{p}$ collider operating at a center-of-mass energy of 1.96 TeV for the current period of data-taking (Run II). They are produced predominantly in pairs ($t\bar{t}$) via the strong interaction with a predicted cross-section of $6.7^{+0.7}_{-0.9}$ pb [2]. Because the V_{tb} CKM matrix element is nearly one under the 3 families SM assumption, the top quarks are predicted to decay $> 99.8\%$ of the time to a real W boson and a b-quark. The two resulting W bosons in turn decay either hadronically or leptonically, defining the three channels of $t\bar{t}$ events (with branching ratios in parenthesis): “all-hadronic” for two hadronic decays (46%), “lepton+jets” for one leptonic and hadronic decays (29%) and “dilepton” for two leptonic decays (5%). By “leptons” we refer only to electrons and muons, taus being generally too difficult to identify to be usually considered in top quark properties measurements.

The $t\bar{t}$ events reconstruction are performed by the CDF and DØ detectors that are described in detail elsewhere [3]. Typical event selections include identification of isolated leptons with high transverse momentum (p_T), large transverse missing energy ($\not{E}_T$) due to the undetected neutrino(s) from W boson decays, several high-p_T jets and identification of b-jets (b-tagging) generally using secondary vertex tagging. The integrated luminosity ($\int \mathscr{L} dt$) used for the measurements presented here vary from $\approx$ 200–350 pb^{-1}.

MASS MEASUREMENTS

The current information on M_{top} comes from measurements performed during Run I of the Tevatron (with a luminosity of $\approx$ 100 pb^{-1}). The world average is $M_{top} = 178.0 \pm 4.3$ GeV$/c^2$ [4]. The final goal in Run II is to collect between 4-8 fb^{-1} and reduce the uncertainty on M_{top} to ≈ 2 GeV$/c^2$.

A precise measurement of M_{top} is strongly motivated in the SM because the radiative corrections to many precision observables are dominated by top quark loops. A famous example is the indirect constraint on the Higgs boson mass (M_H). The current constraint is $M_H = 126^{+73}_{-48}$ GeV$/c^2$ [5]. More detailed discussions on the precision electroweak observables can be found in these proceedings (see contribution from P. Renton).

Before describing specific analyses, we first discuss general considerations. One challenge of the M_{top} measurement is to solve the combinatorics problem in the event reconstruction. For example there are four jets in the final state in the lepton+jets channel ($t\bar{t} \to l\nu q\bar{q}'bb$), resulting in 12 possible jet-parton assignments (since the two W daughter jets are interchangeable in the reconstruction). The problem is simplified by tagging b-jets as described above. Another limitation of the measurement is the large uncertainty in the modeling of the jet energy response, referred to as the jet energy scale uncertainty (JES). This is generally the dominant systematic uncertainty, and is currently about 3 GeV$/c^2$ for CDF and 5–6 GeV$/c^2$ for DØ[1].

CDF recently reported the most precise measurement of M_{top} to date. It has been performed in the lepton+jets channel using $\int \mathscr{L} dt$ = 318 pb^{-1} of data. One novelty of this analysis is the usage of the hadronic W boson decays ($W \to jj$) to improve the jet energy scale uncertainty. Templates of reconstructed top quark and W boson mass are created in MC events as a function of the true top quark mass and the jet energy scale and compared with the data. The fit to the data yields $M_{top} = 173.5\ ^{+3.7}_{-3.6}$ (stat. + JES) GeV$/c^2$ where both the statistical and JES uncertainties are included. The systematic uncertainties not including the JES are small (1.7 GeV$/c^2$). The final result is $M_{top} = 173.5\ ^{+4.1}_{-4.0}$ GeV$/c^2$. Figure 1 shows the reconstructed top quark mass in the data with the best fits from the MC templates overlaid. Analyses using the template method in the lepton+jets channel have also been performed by the DØ collaboration. The best measurement so far corresponds to a luminosity of 230 pb^{-1} and yields $M_{top} = 170.0 \pm 4.2$ (stat.) ± 6.0 (syst.) GeV/c^2.

A different class of analyses uses a matrix-element method that consists of computing a probability for each event to be signal with a given top quark mass. The probability is computed using the full SM production and decay matrix-elements. This method has been shown to be very powerful statistically, as demonstrated by the best measurement in Run I [6]. The CDF collaboration has recently reported a measurement using this method: $M_{top} = 173.8\ ^{+2.7}_{-2.6}$ (stat.) ± 3.3 (syst.) GeV/c^2. The result is in very good agreement with the template analysis above. A similar measurement is expected to be released by the DØ collaboration very soon.

The top quark mass can also be measured in the dilepton channel but with larger

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[1] The DØ JES uncertainty is expected to go down near the CDF level in the next few months.

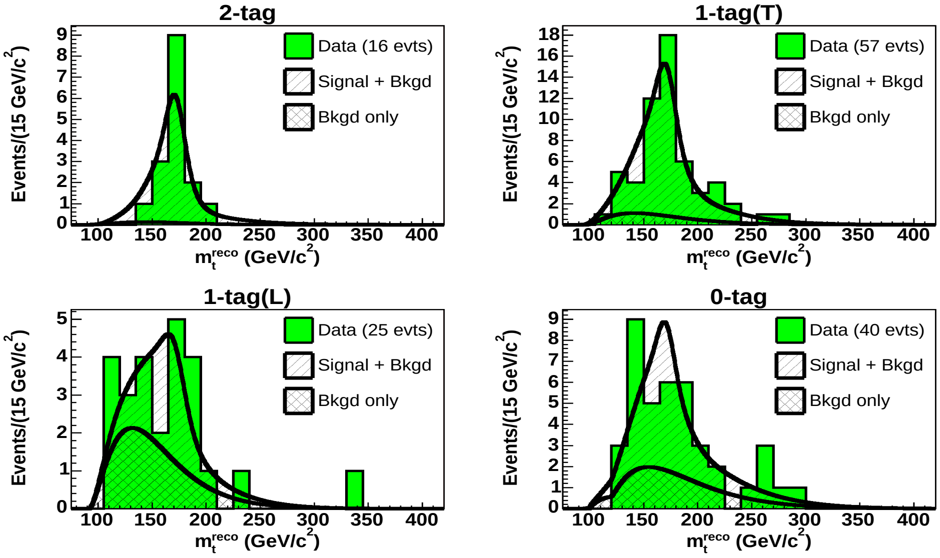

FIGURE 1. The reconstructed top quark mass for various subsamples of the lepton+jets sample collected by CDF ($\sim$ 318 pb^{-1}). Overlaid are the best fit from signal and background templates.

statistical uncertainties due to the smaller branching ratio and the two neutrinos in the final state that complicate the event reconstruction. The CDF collaboration has recently reported the best measurement in this channel to date using the matrix-element method: $M_{top} = 165.3\ \pm 6.3$ (stat.) ± 3.6 (syst.) GeV/c^2 (340 pb^{-1}). The best measurement at DØ so far is: $M_{top} = 155\ ^{+14}_{-13}$ (stat.) ± 7 (syst.) GeV/c^2 (230 pb^{-1}).

OTHER PROPERTIES

It is very important to study in detail the properties of the top quark since it might be more closely related to new physics than other SM particles due to its large mass. For instance, one can study the polarization of the W boson inside the top decays. In the SM, 70%, 30% and 0% of W bosons are predicted to have a longitudinal, left-handed and right-handed helicity, respectively. The W helicity is sensitive to the angle between the charged lepton in W rest frame and the b-jet angle, denoted as $\cos\theta^*$. The DØ collaboration measured the fraction of right-handed W bosons in top decays: $f^+ < 0.25$ at 95% confidence level (C.L.) [7]. Figure 2 shows the distribution $\cos\theta^*$ in data. The W helicity is also sensitive to the charged lepton p_T spectrum from W boson decays that has been used at CDF to measure the fraction of longitudinal W bosons: $f^0 = 0.27^{+0.35}_{-0.21}$.

The assumption that the top quark decays nearly 100% of the time to $t \to Wb$ is checked by measuring $R = B(t \to Wb)/B(t \to Wq)$. This is done by counting the number of b-tags in the sample. Such a measurement was performed at DØ and yielded $R > 0.64$ at 95% C.L.. A consistent result has been obtained by CDF: $R > 0.61$ at 95% C.L. [8].

Other properties of the top quark will be measured in Run II as more data is accumulated like the electric charge, $t\bar{t}$ spin correlation and rare decays.

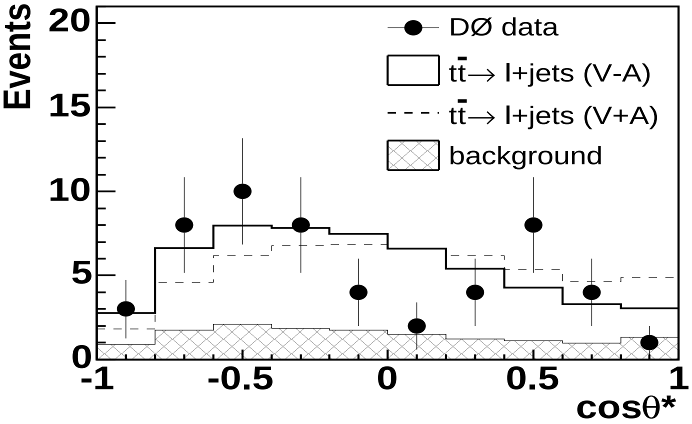

FIGURE 2. Distribution of $\cos\theta^*$ for data (points), signal assuming pure V-A interaction (full line), pure V+A interaction (dashed line) and background for events with *b*-tag (DØ experiment [7]).

CONCLUSION

The precise determination of top quark properties is already well underway in Run II at the Tevatron. The best measurement of the top quark mass to date has been performed at CDF: $M_{top} = 173.5\,^{+4.1}_{-4.0}\ \mathrm{GeV}/c^2$. A very competitive measurement is expected to be released by DØ very soon. Measurements of other properties of top quarks show a good agreement with the SM using only the small $t\bar{t}$ samples collected so far ($\mathscr{O}(100)$ events per experiment). We can expect these datasets to grow by a factor of ten or so by the end of Run II, which will greatly improve our knowledge of the peculiar particle that is the top quark.

We note that there was no time to present all analyses of top quark properties performed at the Tevatron. More details can be found on the public web pages of the CDF [9] and DØ [10] experiments.

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