SEARCH FOR SINGLE TOP QUARK PRODUCTION AND MEASUREMENTS OF TOP QUARK DECAY PROPERTIES AT THE TEVATRON

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We present preliminary results on the search for single top quark production and measurements of top quark decay properties by the CDF and DØ collaborations of the Fermilab Tevatron collider, using datasets of 108-164 pb$^{-1}$ of proton-antiproton collisions.

1 Introduction

After its discovery by the CDF and DØ collaborations$^1$ in Run I (1992-1996), the Fermilab Tevatron collider$^b$ remains the world’s only source of top quarks. The large top quark mass$^2$, $m_t = 178.0 \pm 4.3$ GeV, raises the tantalizing possibility that new physics beyond the Standard Model (SM), possibly related to the breaking of the electroweak symmetry, might lie just above the electroweak scale. In such case, its effects might be more apparent in the top quark sector than in any other sector of the SM. Therefore, interactions between the top quark and weak gauge bosons become extremely interesting. Within the SM, the top quark interaction to a $W$ boson is of the type $V-A$ and involves a $b$ quark almost 100% of the time, thus: \[ \Gamma_{Wtb}^\mu \propto |V_{tb}| \gamma^\mu (1 - \gamma_5), \]
with the CKM matrix element $|V_{tb}| \simeq 1$.

Charged current interactions define most of the top quark phenomenology: final state signature determined by $W$ boson decay modes, large top quark width, electroweak production of top quarks, $W$ helicity in top quark decays, $t\bar{t}$ spin correlations, etc. Despite their importance, the present direct experimental knowledge$^3$ is rather limited due to the low statistics available in Run I. In Run II, the anticipated large datasets (up to 4 fb$^{-1}$ according to baseline projections) and improved performance of the upgraded CDF and DØ detectors, will allow to perform incisive tests of the SM in the top quark sector. This paper summarizes the results from the first measurements on the $W$-$t$-$b$ interaction using Run II datasets of comparable or larger size than those available in Run I.

$^a$On behalf of the CDF and DØ collaborations.

$^b$The Tevatron is a proton-antiproton accelerator colliding beams in Run II at an increased center-of-mass energy of 1.96 TeV (from 1.8 TeV in Run I) and, as of beginning of 2004, instantaneous luminosities in excess of $6 \times 10^{31}$ cm$^{-2}$s$^{-1}$ (more than three times the Run I record).
2 Electroweak production of top quarks

The dominant production mechanisms for a single top quark at the Tevatron involve the exchange of a $W$ boson, either timelike (s-channel, $pp \rightarrow tb + X$) or spacelike (t-channel, $pp \rightarrow tqb + X$). The estimated cross sections at the Tevatron at $\sqrt{s} = 1.96$ TeV are $\sigma_s = 0.88^{+0.07}_{-0.06}$ pb and $\sigma_t = 1.98^{+0.23}_{-0.18}$ pb, respectively for the s- and t-channels. With a rate proportional to $|V_{tb}|^2$, single top quark production will allow to measure directly the CKM matrix element $|V_{tb}|$, thus providing direct experimental verification of the hypothesis of unitarity for the CKM matrix.

Despite the expected large rate ($\sim 40\%$ of $\sigma_H$), the electroweak production of top quarks has not been observed yet. Existing Run I limits at 95% Confidence Level (CL) are $\sigma_s < 18(17)$ pb, $\sigma_t < 13(22)$ pb and $\sigma_{s+t} < 14$ pb, as published by the CDF(DØ) collaborations. The experimental signature consists on one isolated high $p_T$ isolated electron or muon, high transverse missing energy and two or more jets, at least one of them being a $b$ jet. The dominant background processes are, in order of importance, $W+$jets, $t\bar{t}$ and multijets (where a jet is misidentified as an isolated lepton).

2.1 Search for single top quark production at CDF

The CDF Collaboration has performed a search for single top quark production in the lepton+jets channel using a sample of 162 pb$^{-1}$ collected in Run II.

A combined (both s- and t-channels) search and a dedicated t-channel search have been carried out. Both analyses start with a preselection requiring one isolated electron or muon with $p_T > 20$ GeV and $|\eta_{det}| < 1.1$, $E_T > 20$ GeV, exactly 2 jets with $p_T > 15$ GeV and $|\eta_{det}| < 2.8$, at least one of which is required to be $b$-tagged using a secondary vertex algorithm, followed by a topological selection requiring $140 \text{ GeV} \leq M_{tb} \leq 210 \text{ GeV}$. In addition, in case of the t-channel search, the leading jet is required to have $p_T > 30$ GeV. Good agreement is found between observation and expectation, with a total of 28 (25) events observed versus $27.8 \pm 4.3$ (24.3 ± 3.5) expected in the combined (t-channel) search.

In order to increase the statistical sensitivity to the signal, a maximum likelihood fit to a discriminant variable in data is performed, using a sum of templates determined from Monte Carlo. In case of the combined search, the variable chosen is $H_T$, defined as the sum of the lepton $p_T$, $E_T$ and jet $p_T$, which shows a similar distribution for both s- and t-channel processes. In case of the t-channel search, the fit is performed to $Q \times \eta$, with $Q$ being the lepton charge and $\eta$ the pseudorapidity of the untagged jet, which shows a distinct asymmetry for single top t-channel production. In the fit, the background is allowed to float but is constrained to the expectation. The actual fit parameters are the deviations with respect to the SM cross-sections, i.e. $\beta_i = \sigma_i/\sigma_i^{SM}$, with $i=$single top, $t\bar{t}$ and non-top. The fitted signal content in data (see Fig. II) are found to be consistent with zero in both searches: $\hat{\beta}_{s+t} = 0.64 \pm 1.55$ (combined) and $\hat{\beta}_t = 0.00 \pm 1.39$ (t-channel). An upper limit on the single top cross-section is determined from a Bayesian approach using the likelihood and a flat prior on $\beta$. Systematic uncertainties have been taken into account via a convolution procedure. The single top cross-section limits at 95% CL observed in data are $\sigma_{s+t} < 13.7$ pb and $\sigma_t < 8.5$ pb, in good agreement with the expected limits of $\sigma_{s+t} < 14.1$ pb and $\sigma_t < 11.3$ pb, respectively.

2.2 Search for single top quark production at DØ

The DØ Collaboration has also performed a search for single top quark production in the lepton+jets channel using a sample of 164 pb$^{-1}$ collected in Run II.

In order to maximize the acceptance for signal, a rather loose event preselection is applied: one electron (muon) with $p_T > 15$ GeV and $|\eta_{det}| < 1.1 (|\eta| < 2.0)$, $E_T > 15$ GeV, between 2 and 4 jets with $p_T > 15$ GeV and $|\eta_{det}| < 3.4$, with the leading jet having $p_T > 25$ GeV and $|\eta_{det}| < 2.5$. Providing direct experimental verification of the hypothesis of unitarity for the CKM matrix.
In addition, at least one jet is required to be \( b \)-tagged, where two classes of algorithms, secondary vertex (SVT) and soft-muon (SLT) tagging, are considered. Therefore, four orthogonal analysis channels are defined: \( e+\)jets/SVT, \( \mu+\)jets/SVT, \( e+\)jets/SLT and \( \mu+\)jets/SLT. In case of the \( e+\)jets channel, a jet lifetime probability algorithm has also been used as a cross-check. Good agreement is found between expectation and observation for each separate analysis channel, both in terms of normalization and shape of kinematic distributions.

This analysis has not applied a final selection yet and therefore no observed limit in the data has been reported at this conference. The expected limits at the preselection level, from the combination of all four orthogonal analysis channels, are \( \sigma_{s+t} < 15.8 \) pb, \( \sigma_s < 13.8 \) pb and \( \sigma_t < 19.8 \) pb. The above limits, which are already better than in DØ Run I \(^5\), have been obtained using the Modified Frequentist method\(^7\) and include systematic uncertainties. The expected limits without systematic uncertainties are about a factor of two smaller. The main systematic uncertainties arise from the determination of \( b \) tagging efficiency in data, jet energy scale, trigger efficiency modeling and assumptions on the flavor composition of the W+jets background. Significant improvements to the sensitivity are expected from a reduction in the systematic uncertainties as well as the addition of a final election to the analysis.

3 Measurement of B(\( t \to Wb \)/B(\( t \to Wq \)) at CDF

The CDF Collaboration has performed a measurement of the ratio \( b=B(t \to Wb)/B(t \to Wq) \) using a sample of \( 108 \) pb\(^{-1} \) collected in Run II. This measurement allows to test the SM prediction of \( B(t \to Wb) \approx 1 \). The analysis closely follows the approach used in Run I \(^8\), based on the examination of the \( b \)-tagging rates in the lepton+jets channel.

The preselected sample is split into four separate subsamples: \( 3 \)-jet and \( \geq 4 \)-jet, each of them with single and double \( b \)-tags. In each of the subsamples, the average event tagging probability for \( t\bar{t} \) can be expressed as a function of \( b\epsilon \), where \( \epsilon \) represents the single-\( b \) tagging efficiency. Additional effects such as the limited acceptance for \( b \)-tagging, non-\( b \) quark tag rates, non-\( t\bar{t} \) tagged backgrounds, etc, are taken into account. A likelihood fit is performed to the four subsamples simultaneously to determine the value of \( b\epsilon \) most consistent with the observation. The total number of \( t\bar{t} \) events is also fitted. The most likely value for \( b\epsilon \) found is \( 0.25^{+0.22}_{-0.18} \).

Using a single-\( b \) tag efficiency of \( \epsilon = 0.45 \pm 0.05 \), as measured in calibration samples, one can infer \( b = 0.54^{+0.49}_{-0.39} \), consistent with the SM value of 1. This analysis can also be used to set a lower limit of \( b > 0.15 \) at 95% CL. The same analysis, extrapolated to \( 500 \) pb\(^{-1} \), is expected to yield a lower limit in \( b \) of about 0.7 at 95% CL.
4 Measurement of the W helicity in top quark decays at DØ

The chiral structure of the $W$-$t$-$b$ vertex in the SM results in $\simeq 70\%(30\%)$ of $W$ bosons in top quark decays being longitudinally (left-hand) polarized.

The DØ Collaboration has performed a measurement of the longitudinal helicity fraction, $F_0$, using a sample of 125 pb$^{-1}$ collected in Run I. This analysis starts from a preselected lepton+jets sample and makes additional requirements: exactly four jets and a cut on the background probability (see below) of less than $10^{-11}$, resulting in a total of 22 events, with an expected signal-to-background of 1:1. The extraction of $F_0$ is based on a likelihood fit to the full event topology, where the event probability is defined as the normalized 12-fold differential cross-section, computed from the signal ($t\bar{t}$) and background ($W + 4j$) leading order matrix elements, and taking into account the per-event resolution effects. Optimal treatment of the combinatorial background is achieved by summing over all 12 possible jet-parton assignments. This method had been successfully applied to the top quark mass extraction yielding the world’s single most precise measurement. The result obtained is $F_0 = 0.56 \pm 0.31 \text{ (stat + } m_t) \pm 0.07 \text{ (syst)}$, in good agreement with the SM expectation $F_0^{SM} \simeq 0.7$.

5 Summary

The Tevatron collider experiments, CDF and DØ, are in a unique position to provide incisive tests of the SM as well as to search for new physics in the top quark sector. Their extended capabilities as a result of the detector upgrades, together with the $\geq 20$-fold increase in integrated luminosity with respect to Run I expected by the end of Run II, open an extremely rich program of measurements of top quark properties. Here we have shown preliminary results on the search for electroweak production of top quarks and measurements of top quark decay properties such as $B(t \to Wb)/B(t \to Wq)$ and $F_0$ using datasets of 108-164 pb$^{-1}$.

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