Measurement of the Forward-Backward Charge Asymmetry in Top-Quark Pair Production in Proton-Antiproton Collisions at DØ

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Abstract. A measurement of the forward-backward charge asymmetry in top-antitop ($t\bar{t}$) pair production in proton-antiproton ($p\bar{p}$) collisions is presented. The asymmetry is measured for different jet multiplicities in the lepton+jets final state on 0.9 fb$^{-1}$ of data collected by the DØ experiment at the Fermilab Tevatron Collider. The result is sensitive to new physics, which is demonstrated by setting an upper limit on $t\bar{t}$ production via heavy neutral gauge bosons ($Z'$).

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INTRODUCTION

At the Tevatron, top quarks are mainly produced in top-antitop-quark ($t\bar{t}$) pairs. Since the initial proton-antiproton ($p\bar{p}$) state is not a charge conjugation ($C$) eigenstate, the final state is not expected to be symmetric under $C$ either.

The charge asymmetry is therefore not expected to vanish and can be translated to a forward-backward asymmetry. Because of limited statistics, instead of a differential measurement this analysis [1] measures the integrated forward-backward asymmetry:

$$A_{fb} = \frac{N_f - N_b}{N_f + N_b},$$

(1)

where $N_f$ ($N_b$) is the number of forward (backward) events, meaning events, where the rapidity difference $\Delta y = y_t - y_{\bar{t}}$ between top quark and antitop quark is positive (negative).

At leading-order (LO) $t\bar{t}$ production is charge symmetric. However, starting at next-to-leading-order (NLO), an asymmetry arises from the inferences between production diagrams. A total asymmetry of 4–5% is expected [2]. The contributions to $A_{fb}$ differ depending on which processes interfere. They are positive (6.4% NLO) for 2 $\rightarrow$ 2 processes while they are negative (-7–8)% NLO, -(3–0)% NNLO for 2 $\rightarrow$ 3 processes, which result in at least one more jet in the final state [3, 4]. By measuring the asymmetry for different jet multiplicities, this analysis attempts to verify this behavior.

MEASUREMENT OF THE FORWARD-BACKWARD CHARGE ASYMMETRY

The presented analysis uses approximately 900 pb$^{-1}$ of data collected by the DØ experiment [5] at Fermilab and proceeds with the following steps. First a sample enriched in $t\bar{t}$ events is selected, then each event is fully reconstructed using a kinematic fitter. After that, the sample is fitted for sample composition and asymmetry simultaneously. To suppress model-dependent effects, the result is not corrected for acceptance, instead a simple description of the accepted phase space is given. Likewise, it is not corrected for reconstruction effects, but a dilution is given to be used with any model.

Event Selection

Each the top and the antitop quark decays to a $W$ boson and a $b$ quark. The subsequent decay of the $W$ boson determines the event topology. For this analysis, we consider the decay channel with one $W$ boson decaying to hadrons and the other one to leptons. The resulting final state consists of one high-$p_T$ lepton, missing transverse energy $E_T$ from the neutrino, two jets originating from a long-lived $b$ hadron ($b$ jet), and two light quark jets. This will be referred to as the lepton+jets channel.

Based on the final state, events with $\geq 4$ reconstructed jets are selected. The jets have to have transverse momentum $p_T > 20$ GeV (35 GeV for the leading jet) and pseudorapidity $|\eta| < 2.5$. At least one of the jets has to be identified as a $b$ jet by a neural network tagging algo-
W+jets and multijet production. The size and asymmetry of the W boson masses are exactly 80.4 GeV and the top quark mass is 170 GeV. The event has to have a primary vertex, which fulfills certain quality requirements, and $E_T > 15$ GeV.

After the selection, each event is reconstructed to a $t\bar{t}$ hypothesis by a kinematic fitter [7]. It varies the four-momenta of each object within their resolutions and minimizes a $\chi^2$ statistic under the constraint that the W boson masses are exactly 80.4 GeV and the top quark masses exactly 170 GeV. The $b$-tagging information is used to reduce the jet combinatorics.

Although it is also possible to determine the asymmetry using only the lepton charge and direction, reconstructing the whole event doubles the sensitivity.

Sample Composition and Asymmetry

The largest background processes to $t\bar{t}$ production are $W+\text{jets}$ and multijet production. The size and asymmetry of the multijet background is estimated from data, using a sample with non-isolated leptons. To be able to discriminate from the $W+\text{jets}$ background, a likelihood discriminant $\mathcal{L}$ is defined, which is based on variables which are well-modeled by Monte Carlo, provide good separation between $t\bar{t}$ and $W+\text{jets}$, and do not bias the rapidity difference $|\Delta y|$. The asymmetry of the $W+\text{jets}$ background is suppressed by the kinematic fit, and the remaining asymmetry is estimated by simulation. The other small sources of background are taken into account in the systematic uncertainties. The likelihood distributions are fitted simultaneously for sample composition and sign of $\Delta y$ using a maximum likelihood method. Figure 1 shows the outcome of the fit for events with $\geq 4$ jets in data and Monte Carlo.

The resulting asymmetry is $A_{fb} = [12 \pm 8\text{(stat.)} \pm 1\text{(sys.)}]\%$ for events with $\geq 4$ jets. Table 1 shows the asymmetry as it was measured on data and as predicted by the generator MC@NLO [8] for different jet multiplicities.

| $N_{\text{jet}}$ | DØ data | MC@NLO |
|-----------------|---------|--------|
| $\geq 4$        | $12 \pm 1\text{(stat.)}\pm 1\text{(sys.)}$ | $0.8\pm0.2\text{(stat.)}\pm1.0\text{(acc)}$ |
| $= 4$           | $19\pm9\text{(stat.)}\pm2\text{(sys.)}$ | $2.3\pm0.2\text{(stat.)}\pm1.0\text{(acc)}$ |
| $\geq 5$        | $-16^{+15}_{-12}\text{(stat.)}\pm3\text{(sys.)}$ | $-4.9\pm0.4\text{(stat.)}\pm1.0\text{(acc)}$ |

Acceptance and Reconstruction Effects

The integrated asymmetry strongly depends on the region of phase space probed. The largest effect stems from requiring $\geq 4$ jets above a certain $p_T$ threshold, which is strongly correlated to the 4th highest particle jet $p_T$. Figure 2 shows how the generated asymmetry depends on that variable.

![Figure 2](image-url)
that the selection can be described by simple particle-level cuts. This description has been shown to yield an accuracy of 2% (absolute).

Misreconstruction of the sign of $\Delta y$ dilutes the observed asymmetry. It can occur by misidentifying the lepton charge, a negligible effect, and by misreconstructing the event geometry. If $p$ is the probability to measure the sign of $\Delta y$ correctly, the fraction of visible asymmetry, which is called the dilution factor, is $D = 2p - 1$.

Since corrections for the reconstruction effects are highly model-dependent, the parametrization of the dilution for different jet multiplicities is provided instead. It is shown for events with $\geq 4$ jets in Figure 3.

To compare a predicted asymmetry from any model with the observed one, the generated $A_{fb}$ has to be folded with the acceptance and reconstruction effects. This was done with the MC@NLO prediction to obtain the numbers in Table 1.

Sensitivity to New Physics

Resonance production of $t\bar{t}$ can change the forward-backward charge asymmetry. Axigluons are predicted to give negative asymmetries [9]. Production via heavy neutral gauge bosons ($Z'$), however, can give large positive contributions to the asymmetry, and this example was studied in this work. By measuring the asymmetry one is in principle sensitive to narrow and wide resonances. The distribution for $A_{fb}$, as a function of the fraction $f$ of $t\bar{t}$ events produced via a leptoophobic $Z'$ with $Z$-like coupling to quarks, was predicted for several $Z'$ masses using ensembles of simulated datasets. Employing the Feldman-Cousins method [10] limits at 95% confidence are derived and displayed in Figure 4.

![Figure 3](image3.png)

**Figure 3.** The dilution and its uncertainty as a function of generated $|\Delta y|$ for $t\bar{t}$ events with $\geq 4$ jets.

![Figure 4](image4.png)

**Figure 4.** 95% C.L. limits on the fraction of $t\bar{t}$ produced via a $Z'$ resonance as a function of the $Z'$ mass. The dashed curve indicates the expected limit with the shaded bands at one and two standard deviations. The solid curve represents the observed limit.

Summary

A first measurement of the integrated forward-backward charge asymmetry in top quark pair production was presented. The measured asymmetries are consistent with the MC@NLO predictions, and the expected behavior for events with $=4$ jets and $\geq 5$ jets is indicated by the data. Parametrizations of the acceptance and dilution allow comparisons with any model. Limits on $t\bar{t}$ production via heavy neutral gauge bosons can be determined.

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