



Measurement of the forward-backward production asymmetry of t and \bar{t} quarks in $p\bar{p} \rightarrow t\bar{t}$ events

The DØ Collaboration
URL <http://www-d0.fnal.gov>
(Dated: July 23, 2010)

We present a new measurement of the forward-backward production asymmetry (A_{fb}) of t and \bar{t} quarks in $p\bar{p} \rightarrow t\bar{t}$ events. We perform the measurement in lepton+jets final states, with events selected using a b -tagger based on a neural network, and $t\bar{t}$ candidates fully reconstructed using a kinematic fitter. In 4.3 fb^{-1} of data collected by the DØ experiment at the Fermilab Tevatron at $\sqrt{s} = 1.96 \text{ TeV}$, we find $A_{fb} = (8 \pm 4(\text{stat}) \pm 1(\text{syst}))\%$, integrated over acceptance.

Preliminary Results for Summer 2010 Conferences

I. INTRODUCTION

At leading order (LO) in quantum chromodynamics (QCD), the standard model (SM) predicts that top-pair production in $p\bar{p}$ interactions is color-charge symmetric. But this symmetry is accidental, as the initial $p\bar{p}$ state is not an eigenstate of charge symmetry. At the Tevatron, the color-charge asymmetry is observable as a forward-backward asymmetry. At next-to-leading order (NLO) in QCD, forward-backward asymmetries of five to ten percent appear [1, 2]. The asymmetries arise mainly from interference between contributions symmetric and anti-symmetric under the exchange $t \rightarrow \bar{t}$ [1], and depend strongly on the region of phase space being probed, as demonstrated in [2, 3]. A recent calculation shows that higher order corrections to the asymmetry in $t\bar{t}$ production are small [4]. The situation is less certain for $t\bar{t} + \text{jet}$ production, where [5] found large corrections at order α_s^4 . Some extensions of the standard model, such as $Z' \rightarrow t\bar{t}$ decays (analogous to $Z \rightarrow b\bar{b}$ and $Z \rightarrow c\bar{c}$) and warped extra dimensions, predict higher asymmetries [6]. Some, such as axiguons, predict lower asymmetries [7].

These asymmetries are most suited to be measured at the Tevatron, where in proton-antiproton collisions they can be directly observed in the lab frame, and contributions from gluon-gluon fusion processes, which are forward-backward symmetric, are small. At the LHC this measurement will be harder, as the asymmetry arising from proton-proton collisions will not be forward-backward and gluon-gluon fusion processes dominate the production. The difference between the reconstructed rapidities of the t and \bar{t} quarks, $\Delta y \equiv y_t - y_{\bar{t}}$, measures the asymmetry in $t\bar{t}$ (+ X) production. We define forward and backward events by the sign of Δy and then define the forward-backward asymmetry to be

$$A_{fb} = \frac{N^{\Delta y > 0} - N^{\Delta y < 0}}{N^{\Delta y > 0} + N^{\Delta y < 0}}. \quad (1)$$

This note describes an updated measurement of the forward-backward asymmetry in $t\bar{t}$ production in proton-antiproton collisions. A total of 4.3 fb^{-1} of data were collected at $\sqrt{s} = 1.96 \text{ TeV}$ from 2006 to 2009 using the D0 detector [8] with triggers that required an electron or muon and possibly one or more jets. The lepton+jets decay mode of the $t\bar{t}$ quark pair, where one of the two W bosons from the top or antitop quarks decays into hadronic jets and the other decays to leptons, is particularly suitable for this measurement. The lepton+jets channel combines a large branching fraction ($\approx 34\%$) with high purity of signal, as a consequence of requiring an isolated electron or muon of large transverse momentum (p_T). This channel offers accurate reconstruction of the $t\bar{t}$ directions in the collision rest frame, and the charge of the electron or muon provides an excellent tag for the t or \bar{t} quark.

In the previous analysis, which used 0.9 fb^{-1} of data, A_{fb} was found to be $12\% \pm 8\%(\text{stat}) \pm 1\%(\text{syst})$ [3]. A set of measurements, performed by the CDF Collaboration on 1.9 fb^{-1} of data, using two slightly different techniques, found $A_{fb}^{p\bar{p}} = 17\% \pm 8\%$ and $A_{fb}^{t\bar{t}} = 24\% \pm 14\%$ [9]. Neither measurement by CDF is directly comparable to the method used in this analysis, as those measurements are corrected for reconstruction effects assuming SM production and for selection, assuming sufficient coverage of the entire phase space. Here, as in the previous D0 measurement, these assumptions are not made.

II. SELECTION AND RECONSTRUCTION

We select events with one electron or muon, missing transverse energy, \cancel{E}_T , and at least four jets. Events are required to have one isolated electron with $p_T > 20 \text{ GeV}$ and pseudorapidity (relative to the center of the detector) $|\eta| < 1.1$, or one isolated muon with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.0$. Events are required to have \cancel{E}_T above 20 GeV in the electron + jets channel and $25 \text{ GeV} < \cancel{E}_T < 250 \text{ GeV}$ in the muon + jets channel. Events from the multi-jet background are suppressed by requiring that the direction of the \cancel{E}_T is not aligned or anti-aligned with azimuthal component of the lepton momentum. The jets are reconstructed using a cone algorithm [10] with an angular radius $\mathcal{R} = 0.5$ (in pseudo-rapidity and azimuthal angle, ϕ) to cluster energy deposits in the calorimeter. All jets are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$, and the leading jet to have $p_T > 40 \text{ GeV}$. To reduce the impact from multiple interactions at high instantaneous luminosities, jets must contain at least two tracks matched to the primary vertex. More details on lepton and jet identification, and trigger requirements are given in Ref. [11].

To enhance the fraction of signal in the selected events, we require at least one of the four jets with the highest p_T to be identified as originating from long-lived b hadrons by a neural network b -jet tagging algorithm [12]. The variables used to identify such jets rely on the presence and characteristics of a secondary vertex and tracks with high impact parameters inside the jet. The b -tagging requirement used is 80% efficient for signal events.

The top pair is reconstructed from the decay products using a kinematic fitter [13]. The fitter varies the kinematics of the detected objects within their resolutions, and minimizes a χ^2 statistic with the constraints that both W boson masses are exactly 80.4 GeV and top and anti-top quark masses are exactly 172.5 GeV .

In each event the four jets with the highest p_T are considered in the fit. The b -tagging information is used to reduce the number of jet-parton assignments considered in the kinematic fitter. Only events in which the kinematic fit converges are used, and for each event only the solution with the lowest χ^2 is retained. The kinematic fitter converges for more than 99% of events passing selection.

III. PREDICTING THE ASYMMETRY

In the previous D0 measurement we found $A_{fb}^{pred} = (0.8 \pm 0.2 \text{ (stat)} \pm 1.0 \text{ (syst)})\%$ [3], using the MC@NLO simulation [14] and a parameterization of acceptance and reconstruction effects. Since then, the MC@NLO simulation has been integrated into the D0 software framework. We generate $t\bar{t}$ events with MC@NLO, pass them through a GEANT-based simulation [15] of the D0 detector and the same reconstruction chain that is used for data. We take the reconstructed A_{fb} from the simulated $t\bar{t}$ events using Equation 1 and find $A_{fb}^{pred} = (1_{-1}^{+2} \text{ (syst)})\%$ (see Section VI for a discussion of systematic uncertainty). The uncertainty from MC statistics for the current prediction is included in the systematic uncertainty.

IV. ESTIMATION OF BACKGROUND

The main background is from W +jets production. To estimate it, we define a likelihood discriminant \mathcal{L} using variables that are well-described in our simulation, provide separation between signal and W +jets background, and do not bias $|\Delta y|$ for the selected signal. Discrimination is based on: the p_T of the leading b -tagged jet (p_T^{lb}); the χ^2 statistic from the kinematic fit (χ^2); the invariant mass of the jets assigned to the hadronic W boson decay (M_{jj}); and $k_T^{\min} = p_T^{\min} R^{\min}$, where R^{\min} is the smallest angular distance between any two jets used in the kinematic fit, and p_T^{\min} is the smaller of the corresponding jets' transverse momenta. All four variables are presented in Figure 1.

The next largest background after W +jets is from multijet production, where a jet mimics an isolated electron or muon. Following the procedure described in Ref. [11], the distributions in likelihood discriminant, shown in Figure 2, and reconstructed asymmetry for this background are derived from samples of data that fail lepton identification. The normalization of this background is estimated from the size of those samples and the large difference in efficiencies of lepton isolation for true and false leptons [16]. The effects of additional background sources are not considered explicitly in extracting A_{fb} ; namely Z +jets, single top quark, and diboson production, as they were found to be negligible in the previous measurement [3].

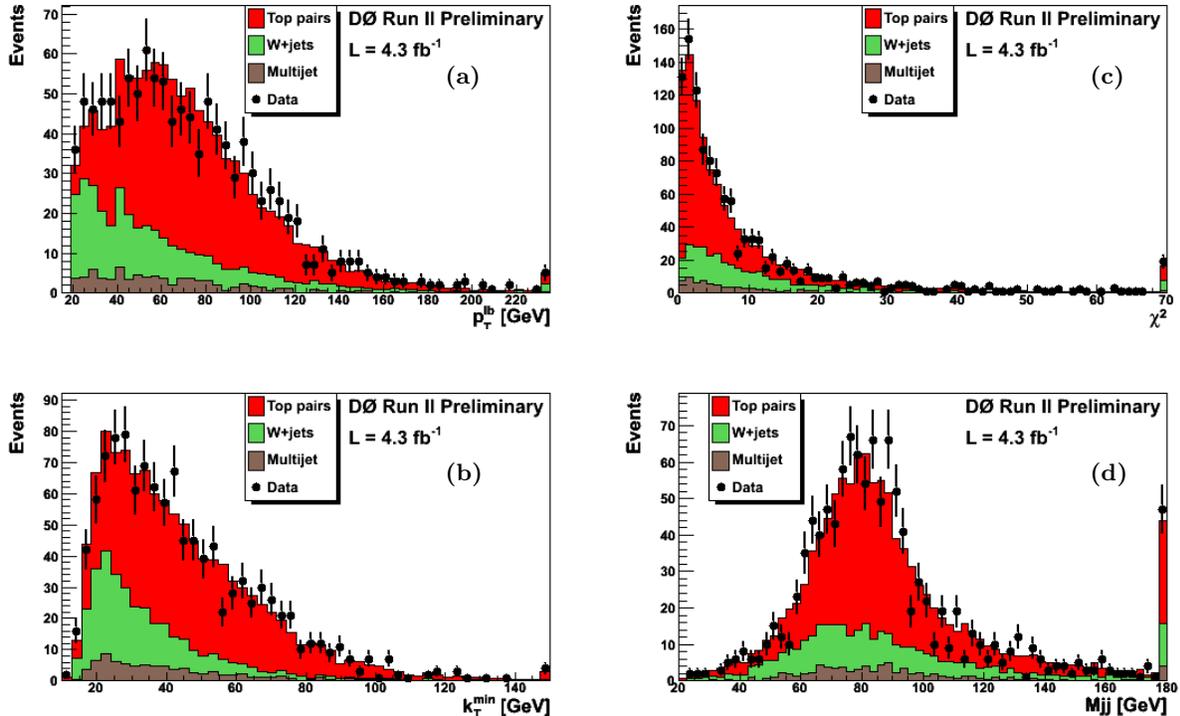


FIG. 1: Distributions of the transverse momentum of the leading b -tagged jet (a), the χ^2 statistic from the kinematic fit (b), k_T^{\min} (c) and the invariant mass of the jets assigned to the hadronic W by the kinematic fitter (d). Overflows are included in the highest bins of each distribution.

V. EXTRACTION OF ASYMMETRY

We extract the sample composition and the asymmetry simultaneously using a maximum likelihood fit to the distribution of events. The distribution of the likelihood discriminant and the distribution of $\text{sign}(\Delta y)$ are fitted simultaneously to the sum of four templates: a forward ($\Delta y > 0$) signal template, a backward ($\Delta y < 0$) signal template, a W +jets template, and a multijet template. Both signal templates contain the same likelihood discriminant distribution, and differ only in having all events either forward or backward. The measured asymmetry is taken from the relative fraction of events fitted to the forward and backward signal templates. The W +jets template contains the simulated reconstructed asymmetry. The signal templates are derived from events generated with MC@NLO, and the W +jets template from events generated with ALPGEN, with the jet showering performed by PYTHIA [17]. The multijet template contains an asymmetry from data, corrected for the contribution of other sources (e.g. $t\bar{t}$) in that sample.

The fitted parameters are shown in Table I and distributions of the discriminant, normalized to data, are shown in Figure 2. The plot of Δy for the data and simulation is shown in Figure 3. The fitted asymmetry is $(8 \pm 4)\%$. The cross section for $t\bar{t}$ production found using this fit is 8.2 ± 0.4 (stat) pb, which is in agreement with the D0 lepton+jets cross section measurement of $\sigma_{t\bar{t}} = 7.70^{+0.79}_{-0.70}$ (stat+syst+lumi) pb [11].

TABLE I: Sample sizes and fit results. The first line lists the size of the selected data sample, N_{sel} , broken up into forward and backward portions in lines two and three, and the fourth line the size of an auxiliary sample, N_{aux} used to derive the multijet background. Lines five to seven list the fitted number of events for $t\bar{t}$ signal, W +jets background, and multijet background events in the selected sample. The last line gives the fitted asymmetry with the statistical uncertainty included. The first column gives the results of the nominal fit. The second and third columns show the results of the same fit procedure done separately for each lepton channel. The fourth and fifth columns show the results for events with four jets and five or more jets. The sixth and seventh columns show the results for events with one b -tag and more than one b -tag.

	Both Channels	e +jets	μ +jets	4 jets	≥ 5 jets	1 b -tag	≥ 2 b -tag
N_{sel}	1137	619	518	956	181	583	554
$N_{sel} (\Delta y > 0)$	604	327	277	513	91	317	287
$N_{sel} (\Delta y < 0)$	533	292	241	443	90	266	267
N_{aux}	465	385	80	395	70	319	146
$N_{t\bar{t}}$	808 ± 37	433 ± 27	370 ± 25	658 ± 34	145 ± 14	298 ± 29	490 ± 25
N_W	280 ± 34	135 ± 25	148 ± 23	256 ± 31	29 ± 13	244 ± 29	55 ± 20
N_{MJ}	49 ± 4	51 ± 4	0 ± 1	42 ± 4	7 ± 2	40 ± 3	9 ± 2
$A_{fb} (\%)$	8 ± 4	8 ± 6	7 ± 6	9 ± 5	0 ± 10	14 ± 8	4 ± 5

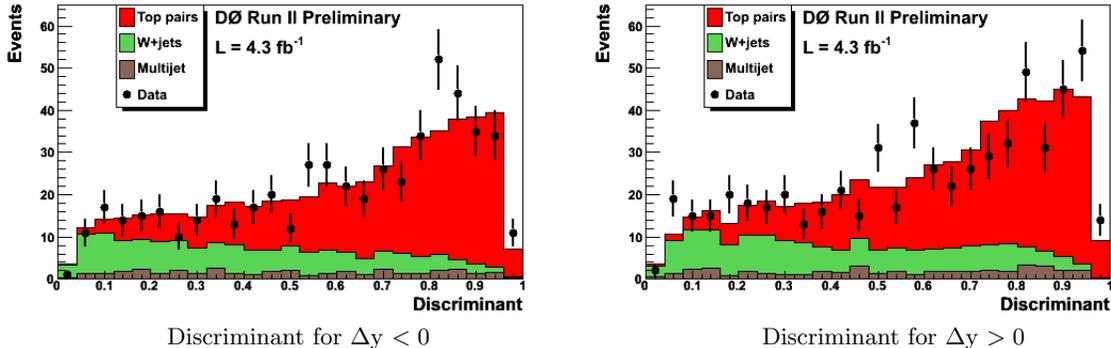


FIG. 2: The normalizations from the fit to the discriminant of the signal and background templates and the data.

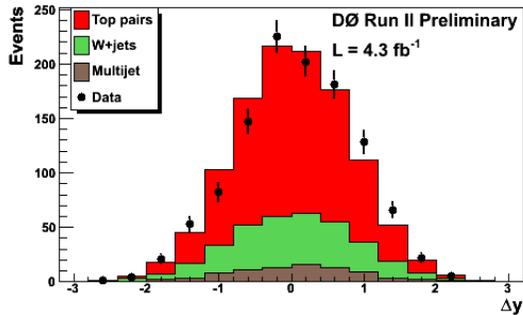


FIG. 3: Comparison of data and signal plus background for Δy with fractions fit to the discriminant. The difference between the shapes of the distributions in simulation and data is the visual representation of the difference between the prediction and measurement of A_{fb} .

VI. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties on A_{fb} and on A_{fb}^{pred} are shown in Table II. The total uncertainty listed in the table is derived assuming no correlations between the various sources. Because the methods to predict the expected asymmetry and to measure the asymmetry from data are different, some of the systematics used for the measurement and the prediction are not the same.

Jet identification efficiency, jet energy scale and jet energy resolution are varied within their uncertainties. The efficiency of jets to pass vertex requirements is varied within its uncertainty. In the nominal analysis, additional $p\bar{p}$ collisions are modeled by re-weighting the MC to match the distribution of instantaneous luminosity in data. To estimate the uncertainty on this modeling, we repeat the measurement without this re-weighting.

To understand the effect of the signal model, we perform the measurement with ALPGEN+PYTHIA instead of MC@NLO+HERWIG. The top mass used in the signal simulation is varied by ± 1 GeV. The uncertainty for the predicted asymmetry due to the limited MC statistics of the $t\bar{t}$ signal sample is taken into account.

The observed and simulated distributions of the reconstructed transverse momentum of the top pair system ($p_T^{t\bar{t}}$) do not agree. To evaluate the possible effect on the measured asymmetry, we re-weight the signal simulation to match $p_T^{t\bar{t}}$ in background-subtracted data. We repeat the measurement of A_{fb} using the re-weighted signal templates, instead of the nominal signal templates and take the difference as an additional uncertainty. The distribution of Δy after re-weighting is used to recalculate A_{fb}^{pred} , and the difference is taken as an additional uncertainty on the prediction.

The asymmetry from the W +jets is varied within the uncertainty due to limited Monte Carlo statistics. The fraction of Wcc and Wbb events making up the W +jets simulation is varied by 15%. Uncertainties on the fake lepton selection rate and true lepton selection rate used to evaluate multijet background are propagated to the multijet background yield [16]. Efficiencies for b -, c - and light jets to be tagged are varied within their uncertainties.

The total systematic uncertainty for the measured asymmetry is $\pm 1\%$. For the predicted asymmetry, the total systematic uncertainty is $+2\%/ -1\%$.

Source	Effect on Measured A_{fb}	Effect on Predicted A_{fb}
Jet identification efficiency	± 0.1	± 0.3
Jet energy scale	$+0.0/-0.2$	$+0.6/-0.0$
Jet energy resolution	$+0.0/-0.6$	$+0.3/-0.1$
Vertex requirements of jets	± 0.1	± 0.2
Additional collisions	± 0.3	± 0.3
Alternative signal model	± 0.1	not applicable
Top mass uncertainty	± 0.0	not applicable
Top pair p_T model	$+0.1/-0.0$	$+1.0/-0.0$
Monte Carlo statistics of $t\bar{t}$ signal	not applicable	± 0.9
W +jets heavy flavor fraction	± 0.0	not applicable
W +jets asymmetry	± 0.6	not applicable
Fake lepton selection rate	± 0.1	not applicable
True lepton selection rate	± 0.0	not applicable
b -tagging efficiency for heavy flavor	$+0.0/-0.1$	± 0.1
b -tagging efficiency for light flavor	$+0.0/-0.1$	± 0.0
Total	$+0.8/-1.0$	$+1.6/-1.2$

TABLE II: Absolute systematic uncertainties on the fitted and predicted asymmetries.

VII. CONCLUSIONS

We have presented an updated measurement of the integrated forward-backward asymmetry in top-quark pair production. We observe an asymmetry of

$$A_{fb} = (8 \pm 4(\text{stat}) \pm 1(\text{syst}))\% \quad (2)$$

for top-pair events that satisfy the experimental acceptance, uncorrected for effects from reconstruction or selection. The MC@NLO-based prediction for this measurement is $A_{fb}^{pred} = (1_{-1}^{+2}(\text{syst}))\%$. Further work is needed to evaluate the compatibility of data with the standard model.

Acknowledgements

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); PPARC (United Kingdom); MSMT (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); Research Corporation, Alexander von Humboldt Foundation, and the Marie Curie Program.

-
- [1] J. H. Kuhn and G. Rodrigo, Phys. Rev. D **59**, 054017 (1999).
 - [2] M. T. Bowen, S. D. Ellis and D. Rainwater, Phys. Rev. D **73**, 014008 (2006).
 - [3] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **100**, 142002 (2008).
See EPAPS Document No. E-PRLTAO-100-059814 for plots. For more information on EPAPS, see <http://www.aip.org/pubservs/epaps.html>.
 - [4] L. G. Almeida, G. F. Sterman and W. Vogelsang, Phys. Rev. D **78**, 014008 (2008).
 - [5] S. Dittmaier, P. Uwer and S. Weinzierl, “NLO QCD corrections to t anti- t + jet production at hadron colliders,” Phys. Rev. Lett. **98**, 262002 (2007) [arXiv:hep-ph/0703120].
 - [6] A. Djouadi, G. Moreau, F. Richard and R. K. Singh, arXiv:0906.0604 [hep-ph].
 - [7] O. Antunano, J. H. Kuhn and G. Rodrigo, Phys. Rev. D **77**, 014003 (2008).
 - [8] V. Abazov *et al.* [D0 Collaboration], Nucl. Instrum. Methods Phys. Res., Sect. A **565**, 463 (2006).
 - [9] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **101**, 202001 (2008).
 - [10] G.C. Blazey *et al.*, in U. Baur, R. K. Ellis and D. Zeppenfeld, FERMILAB-PUB-00-297.
 - [11] V. M. Abazov *et al.* [D0 Collaboration], D0 Note 6037-CONF (2010).
 - [12] V. M. Abazov *et al.* [The D0 Collaboration], Nucl. Instrum. Methods in Phys. Res., Sect. A **620**, 400 (2010).
 - [13] S. S. Snyder, FERMILAB-THESIS-1995-27.
 - [14] S. Frixione and B. R. Webber, JHEP **0206**, 029 (2002).
S. Frixione, P. Nason and B. R. Webber, JHEP **0308**, 007 (2003).
 - [15] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).
 - [16] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **74**, 112004 (2006).
 - [17] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, JHEP **0307**, 001 (2003).
S. Höche *et al.*, [hep-ph/0602031].