Search for Anomalous $Wtb$ Couplings in Single Top Quark Production

V. M. Abazov  
*Joint Institute for Nuclear Research, Dubna, Russia*

Kenneth A. Bloom  
*University of Nebraska - Lincoln*, kbloom2@unl.edu

Gregory Snow  
*University of Nebraska - Lincoln*, gsnow1@unl.edu

D0 Collaboration

Follow this and additional works at: [http://digitalcommons.unl.edu/physicsbloom](http://digitalcommons.unl.edu/physicsbloom)

Part of the [Physics Commons](http://digitalcommons.unl.edu/physicsbloom)

[http://digitalcommons.unl.edu/physicsbloom/264](http://digitalcommons.unl.edu/physicsbloom/264)

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Kenneth Bloom Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

LAFEX, Centro Brasileiro de Pesquisas Fısıcas, Rio de Janeiro, Brazil

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

Universidade Federal do ABC, Santo André, Brazil

Instituto de Fısıca Teorica, Universidade Estadual Paulista, Sào Paulo, Brazil

University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada

University of Science and Technology of China, Hefei, People's Republic of China

Universidad de los Andes, Bogota, Colombia

Center for Particle Physics, Charles University, Prague, Czech Republic

Czech Technical University, Prague, Czech Republic

Universidad San Francisco de Quito, Quito, Ecuador

LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France

LPSC, Université Joseph Fourier Grenoble I, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France

CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France

LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France

CEA, Ifri, SPP, Saclay, France

IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France

IPNL, Université Lyon I, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany

Physikalisches Institut, Universität Bonn, Bonn, Germany

Physikalisches Institut, Universität Freiburg, Freiburg, Germany

Institut für Physik, Universität Mainz, Mainz, Germany

Ludwig-Maximilians-Universität München, München, Germany

Fachbereich Physik, Universität Wuppertal, Wuppertal, Germany

Panjab University, Chandigarh, India

Delhi University, Delhi, India

Tata Institute of Fundamental Research, Mumbai, India

University College Dublin, Dublin, Ireland

Korea Detector Laboratory, Korea University, Seoul, Korea

SungKyunKwan University, Suwon, Korea

CINVESTAV, Mexico City, Mexico

(D0 Collaboration)
In 0.9 fb$^{-1}$ of $p\bar{p}$ collisions, the D0 Collaboration presented evidence for single top quark production in events with an isolated lepton, missing transverse momentum, and two to four jets. We examine these data to study the Lorentz structure of the $Wtb$ coupling. The standard model predicts a left-handed vector coupling at the $Wtb$ vertex. The most general lowest dimension, CP-conserving Lagrangian admits right-handed vector and left- or right-handed tensor couplings as well. We find that the data prefer the left-handed vector coupling and set upper limits on the anomalous couplings. These are the first direct constraints on a general $Wtb$ interaction and the first direct limits on left- and right-handed tensor couplings.
Recently, we presented evidence for single top quark production in $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV [1] based on 0.9 fb$^{-1}$ of data collected using the D0 detector [2] at the Fermilab Tevatron collider. In this Letter, we report an extension of this analysis using the same data set and similar analysis tools to study the consistency of this excess with different hypotheses for the couplings involved in single top quark production. This is the first time such a test has been carried out.

The standard model (SM) has been extraordinarily successful in describing the data taken at the energies of present colliders. However, we know that the electroweak symmetry breaking sector of the SM gives rise to many unanswered questions, making a strong case for new physics beyond the SM. This new physics can manifest itself in the production of new particles or in corrections to SM processes that change the effective couplings of SM particles. The interactions between quarks and gauge bosons have been measured precisely at the CERN Large Electron Positron collider [3] except for the top quark, which was not kinematically accessible. The large mass of the top quark has prompted speculation that the top quark may play a special role in the mechanism of electroweak symmetry breaking and thus have nonstandard interactions with weak gauge bosons. We can probe the interactions of top quarks with W bosons via measurements of single top quark production and top quark decays in $t\bar{t}$ production, each yielding complementary information [4].

At the Tevatron, the dominant modes of single top quark production are $s$-channel and $t$-channel production. We use the notation “$tb$” for the sum of the $s$-channel processes $tb$ and $\bar{t}\bar{b}$ and “$tqb$” for the sum of the $t$-channel processes $tq\bar{b}$ and $t\bar{q}b$. We assume that single top quark production proceeds exclusively through $W$ boson exchange. Therefore, extensions of the SM in which single top quarks are produced via flavor-changing neutral current interactions [5] or the exchange of new massive scalar [6] or vector bosons [7] are not considered here. We further assume that $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$, i.e., the $Wtb$ vertex dominates top quark production and decay [8]. Finally, we assume that the $Wtb$ vertex is CP-conserving.

The most general, lowest dimension, CP-conserving, Lagrangian for the $Wtb$ vertex is [9]

$$
\mathcal{L} = \frac{g}{\sqrt{2}} W^- \gamma^{\mu} (f_1^L P_L + f_2^R P_R) t
- \frac{g}{\sqrt{2}M_W} \partial_\mu W^- b \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + \text{H.c.},
$$

(1)

where $M_W$ is the mass of $W$ boson, $P_L = (1 - \gamma_5)/2$ is the left-handed projection operator, and $P_R = (1 + \gamma_5)/2$ is the right-handed projection operator. In the SM the values of the form factors are $f_1^L = 1$ and $f_2^L = f_2^R = f_2^R = 0$. In this case the predicted cross section for single top quark production is $2.9 \pm 0.3$ pb [10].

The presence of anomalous couplings can change angular distributions and event kinematics as demonstrated by the $p_T$ spectrum of the charged lepton from the decay of the top quark in Fig. 1. Such differences can be used to distinguish these couplings [11,12]. The magnitude of the right-handed vector coupling and tensor couplings can be indirectly constrained by the measurement of the $b \to s\gamma$ branching fraction [13]. Direct constraints on the combination of several couplings can be obtained from the measurement of the $W$ boson helicity in top quark decays [14]. The predicted single top quark production cross sections for the $s$ and $t$ channels combined are $2.7 \pm 0.3$ pb if $f_1^L = 1$ and $10.4 \pm 1.4$ pb if $f_2^L = 1$, and the other couplings vanish [11]. In these scenarios the ratio of the $s$- and $t$-channel cross section is approximately 1:2 and 6:1, respectively.

Ideally, we would like to set limits on all four couplings $f_1^L$, $f_1^R$, $f_2^R$, and $f_2^L$ simultaneously. This, however, requires more data than are currently available. We therefore look at two couplings at a time and assume that the other two are negligible. We consider three cases in which we allow the left-handed vector coupling $f_1^L$ and any one of the three nonstandard couplings to be nonzero. We refer to these as $(L_1, L_2)$, $(L_1, R_1)$, and $(L_1, R_2)$.

We look for events in which the top quark decays to a $W$ boson and a $b$ quark, followed by the decay of the $W$ boson to an electron or a muon and a neutrino. To enhance the signal content of the selected data sample, one or two of the jets are required to be $b$ tagged, i.e., identified as originat-

FIG. 1 (color online). Charged lepton $p_T$ spectrum from data and expectation for SM single top production plus background for events with two jets and one $b$-tagged jet. Superimposed are the distributions from single top quark production with different couplings (all other couplings set to zero) normalized to 10 times the SM single top quark cross section.
We model the single top quark signal using the COMPHEP-SINGLETOP Monte Carlo event generator [16], and the anomalous $Wtb$ couplings are considered in both production and decay in the generated signal samples. The event kinematics for both the $s$ channel and the $t$ channel reproduce distributions from next-to-leading-order calculations [10]. The decay of the top quark and the resulting $W$ boson are carried out in the SINGLETOP generator in order to preserve the information about the spin of the particles. PYTHIA [17] is used to add the underlying event, initial, and final-state radiation and for hadronization. The top quark mass is set to 175 GeV, and the CTEQ6L1 parton distribution functions [18] are used.

Background contributions from $W +$ jets and $t\bar{t}$ production are simulated using the ALPGEN leading-order Monte Carlo event generator [19] interfaced to PYTHIA. A parton-jet matching algorithm [20] is used to avoid double counting. The response of the D0 detector to the Monte Carlo events is simulated using GEANT [21]. Simulated events are processed through the same reconstruction software used for data, and efficiencies and resolutions are corrected to match the performance of the reconstruction for data. The $t\bar{t}$ background is normalized using the theoretical cross section [22]. The multijet background, which arises from events in which a jet is misidentified as an isolated electron or muon, is modeled using events from data containing lepton candidates failing the isolation requirements and that otherwise resemble the signal events.

To increase the search sensitivity, we divide our data into 12 independent analysis channels based on the lepton ($e$ or $\mu$), jet multiplicity (2, 3, or 4), and number of $b$ tagged jets (1 or 2). The $W +$ jets background is normalized such that the number of events predicted by the simulation agrees with the number of events observed in each analysis channel before $b$ tagging is applied. After all cuts, we select 1398 $b$ tagged lepton + jets events, which we expect to contain $62 \pm 13$ single top quark events, $348 \pm 80$ $t\bar{t}$ events, $849 \pm 222$ $W +$ jets events, and $202 \pm 48$ multijet events. A detailed breakdown of the sample composition in each channel is given in Ref. [1]. Within each channel, the signal efficiency of the complete selection does not depend strongly on the assumed $Wtb$ coupling. The selection efficiencies for signal with different $Wtb$ couplings vary between $(1.07 \pm 0.15)\%$ and $(1.52 \pm 0.16)\%$ for $tb$ events with 1 $b$ tag, between $(0.86 \pm 0.13)\%$ and $(1.14 \pm 0.14)\%$ for $tqb$ events with 1 $b$ tag, between $(0.40 \pm 0.08)\%$ and $(0.60 \pm 0.10)\%$ for $tb$ events with 2 $b$ tags, and between $(0.07 \pm 0.01)\%$ and $(0.10 \pm 0.02)\%$ for $tqb$ events with 2 $b$ tags.

Systematic uncertainties in the signal and background models are described in detail in Ref. [1]. The dominant contributions to the uncertainties in the background estimate come from: the normalization of the $t\bar{t}$ background (18%), which includes the top quark mass uncertainty; the normalization of the $W +$ jets and multijets backgrounds to data (17%–27%), which includes the uncertainty in the fraction of events with heavy flavor production; and the $b$-tagging efficiencies (12%–17% for double-tagged events). The uncertainties from the jet energy scale corrections (1%–20%) and the $b$ tagging probabilities affect both the shape and normalization of the simulated distributions. All other components contribute at the level of a few percent.

We use boosted decision trees [23,24] to discriminate between the single top quark signal and background. For training, we divide our data into only four independent analysis channels defined by lepton flavor and $b$ tag multiplicity. Each channel contains events with 2, 3, or 4 jets. For each of the three coupling scenarios, the signal samples consist of a sample of events generated with left-handed vector coupling set to one, i.e., with SM coupling, and a sample of events generated with the nonstandard coupling set to one and all other couplings set to zero. The background sample consists of events from all background sources in proportions according to the background model described above.

We use 50 variables in the training: the 49 variables that were used in Ref. [1] plus the lepton $p_T$ which helps distinguish the signals with different couplings, as can be
we use a superposition of three signal samples: one with left-handed vector couplings, one with the left-handed tensor coupling only set to one, and one with both couplings set to one to take into account the effect of the interference. We then compute a likelihood as a product over all bins and channels. Here we use 12 channels defined by lepton flavor, $b$ tag multiplicity, and jet multiplicity (2, 3, or 4). We assume Poisson distributions for the observed counts and flat non-negative prior probabilities for the signal cross sections. The prior for the combined signal acceptance and background yields is modeled with a multivariate Gaussian describing the effect of systematic uncertainties, including correlations.

A two-dimensional posterior probability density is computed as a function of $|f_T|^2$ and $|f_X|^2$, where $f_X$ is any of the other three nonstandard couplings, in each channel. These probability distributions are shown in Fig. 3. We quote the values of the couplings that maximize the two-dimensional likelihood as our measurements. In all three scenarios we measure zero for the right-handed vector and left- and right-handed tensor couplings. We compute 95% C.L. upper limits on these couplings by integrating out the left-handed vector coupling to get a one-dimensional posterior probability density. The measured values are given in Table I. The data favor the left-handed vector hypothesis over the alternative hypotheses.

In summary, we have studied the excess observed in 0.9 fb$^{-1}$ of D0 data in the search for single top quark production. We attribute this excess to single top quark production and study its consistency with different hypotheses for the structure of the $Wtb$ coupling and find that the data prefer the left-handed vector coupling over the alternative hypotheses studied. These are the first direct constraints on a general $Wtb$ interaction and the first direct limits on left- and right-handed tensor couplings.

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); 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); STFC (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC, and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); and the Alexander von Humboldt Foundation (Germany).

*Visitor from Augustana College, Sioux Falls, SD, USA.
†Visitor from The University of Liverpool, Liverpool, United Kingdom.
‡Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.
§Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
‖Visitor from Helsinki Institute of Physics, Helsinki, Finland.
¶Visitor from Universität Zürich, Zürich, Switzerland.
**Deceased.