Measurement of color flow in $t\bar{t}$ events from $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV

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Color charge is conserved in quantum chromodynamics (QCD), the theory that describes strong interactions [1]. At leading order in the strong coupling constant $\alpha_s$, color can be traced from initial partons to final-state partons in high-energy hadron collisions. Two final-state partons on the same color-flow line are “color-connected” and attracted by the strong force. As these colored states shower, the potential energy of the strong force between them is released in the form of hadrons. Thus, knowledge of the color-connections between jets can serve as a powerful tool for separating processes that otherwise appear similar. For example, in the decay of a Higgs ($H$) boson to a pair of bottom ($b\bar{b}$) quarks, the two $b$ quarks are color connected to each other, since the $H$ is uncolored (color singlet), whereas in $g \rightarrow b\bar{b}$ background events, they are color-connected to beam remnants because the gluon carries a color and an anti-color (color-octet).

We present the first measurement of the color representation of the hadronically decaying $W$ boson in $t\bar{t}$ events, from 5.3 fb$^{-1}$ of integrated luminosity collected with the D0 experiment. A novel calorimeter-based vectorial variable, “jet pull,” is used, sensitive to the color-flow structure of the final state. We find that the fraction of uncolored $W$ bosons is $0.56 \pm 0.42$ (stat+syst), in agreement with the standard model.

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TABLE I: Yields of events passing selections with exactly 4 or ≥ 5 jets. At least two b-tagged jets are required in the analysis, but the numbers of events with zero or one b-tagged jet are also given. The number of \( t\bar{t} \) events decaying to \( \ell \nu bj \) shows the event yields for these selection criteria.

<table>
<thead>
<tr>
<th>channel</th>
<th>sample</th>
<th>0 b-tags</th>
<th>1 b-tag</th>
<th>≥ 2 b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \ell + 4 \text{jets} ) ( W + \text{jets} )</td>
<td>576 ± 75</td>
<td>229 ± 32</td>
<td>49 ± 8</td>
<td></td>
</tr>
<tr>
<td>Multijet</td>
<td>115 ± 16</td>
<td>46 ± 7</td>
<td>7 ± 2</td>
<td></td>
</tr>
<tr>
<td>Z+jets</td>
<td>42 ± 6</td>
<td>16 ± 3</td>
<td>4 ± 1</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>31 ± 4</td>
<td>19 ± 2</td>
<td>9 ± 1</td>
<td></td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>160 ± 22</td>
<td>417 ± 38</td>
<td>519 ± 51</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>923 ± 62</td>
<td>727 ± 24</td>
<td>589 ± 48</td>
<td></td>
</tr>
<tr>
<td>Observed</td>
<td>923</td>
<td>743</td>
<td>572</td>
<td></td>
</tr>
<tr>
<td>( \ell + \geq 5 \text{jets} ) ( W + \text{jets} )</td>
<td>60 ± 22</td>
<td>26 ± 11</td>
<td>7 ± 3</td>
<td></td>
</tr>
<tr>
<td>Multijet</td>
<td>17 ± 3</td>
<td>12 ± 2</td>
<td>3 ± 1</td>
<td></td>
</tr>
<tr>
<td>Z+jets</td>
<td>4 ± 1</td>
<td>2 ± 1</td>
<td>1 ± 1</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>3 ± 1</td>
<td>3 ± 1</td>
<td>2 ± 1</td>
<td></td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>34 ± 6</td>
<td>90 ± 13</td>
<td>132 ± 17</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>118 ± 19</td>
<td>132 ± 7</td>
<td>145 ± 15</td>
<td></td>
</tr>
<tr>
<td>Observed</td>
<td>112</td>
<td>127</td>
<td>156</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 1: (Color online) Diagram showing two jets in the \( \eta - \phi \) plane, and the reconstruction of the jet pull vectors (\( \vec{t} \)), jet pull angles (\( \theta_{\text{pull}} \)), and relative jet pull angles (\( \theta_{\text{rel}} \)).

A characteristic signature and contain two jets from the decay of a W boson, which is a color singlet. Each of the two b-jets coming from the top quark decays is color-connected to one of the beam remnants in a color-octet pattern.

In this Letter, we use data collected with the D0 detector [5] at the Fermilab Tevatron \( pp \) collider, corresponding to 5.3 fb\(^{-1}\) of integrated luminosity, to present the first experimental results on the study of jet pull, using \( tt \) events decaying to \( \ell + \text{jets} \) (\( t\bar{t} \rightarrow \ell WbW\bar{b} \rightarrow \ell p\bar{p}j\bar{j}b \), where \( \ell = e, \mu \)). The object identification, event selection, and simulated Monte Carlo (MC) events are the same as those used in the \( tt \) cross section analysis [6], except that looser criteria except for its color representation. The latter is simulated using the MADGRAPH (MG) [9] event generator interfaced to PYTHIA [10] for showering and hadronization. Simulated events are processed with a GEANT3-based [11] detector simulation, overlaid with random data to account for backgrounds, and reconstructed as data.

D0 uses three liquid-argon/uranium calorimeters to measure the energies of particles: a central section (CC) covering \( |\eta| \) up to ≈ 1.1 and two end calorimeters (EC) that extend coverage to \( |\eta| \approx 4.2 \) [3], housed in separate cryostats [12]. In addition, scintillators between the CC and EC cryostats provide sampling of developing showers for 1.1 < |\( \eta \)| < 1.4. There are approximately ten layers in the radial direction (depending on \( \eta \)), generally composed of cells spanning 0.1 x 0.1 in \( \eta \times \phi \). The energy resolution is about 15%/\( \sqrt{E} \) + 0.3% (in GeV) for electrons and 50%/\( \sqrt{E} \) + 5% for hadrons. Pileup energy from overlapping pp interactions results in about 0.5% of cells having energy above the noise-limited energy threshold (≈ 50 – 500 MeV, depending on layer and \( \eta \)). This energy is roughly exponentially distributed, with a mean of ≈ 350 MeV.

The pull is determined for each jet of a pair of reconstructed jets, using the measured energies of the calorimeter cells. Each cell within \( \Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} < 0.7 \) of the \( E_T \)-weighted center of one of the jets of the pair (\( \eta_{d}^{\text{jet}}, \phi_{d}^{\text{jet}} \)) is assigned to the jet nearer in \( \Delta R \). The contribution of each selected cell to the jet pull is \( t_{\text{cell}}^{E_T} = E_T^{\text{cell}}/|r_{\text{cell}}| \), where \( r_{\text{cell}} = (\eta_{d}^{\text{cell}} - \eta_{d}^{\text{jet}}, \phi_{d}^{\text{cell}} - \phi_{d}^{\text{jet}}) \), and \( E_T^{\text{cell}} \) is the cell’s transverse energy with respect to the nominal center of the detector. The jet pull is \( t = \sum t_{\text{cell}}^{E_T} \). The polar angle of the jet pull, \( \theta_{\text{pull}} \), is defined to be zero when pointing in the positive \( \eta \) direction along the beamline. A small correction to the jet pull is made to account for the energy response and noise in the calorimeters as a function of \( \eta_{d} \), particularly in regions between the central and forward cryostats. The angle of the jet pull direction relative to the line defined by the centers of the jet pair (\( \theta_{\text{rel}} \)) is of primary interest, as we expect color-connected jets to have pulls pointing towards each other. The \( \theta_{\text{rel}} \) quan-
there are detector and reconstruction effects on jet events. A direct interpretation of the effects from color-flow differences, separation in the detector, and flavor. We expect the initial or final state leads to possible additional color data as shown in Fig. 2, with smaller pointing away from each other. This tendency is seen in an anti-proton beam, thus the jet pulls should be generally color-connected to the proton beam and the other to the hadronic jet pairs from hadronic $W$ boson decay within $\Delta R < 0.7$ cone gives a slightly improved singlet-octet separation. The relative jet pulls $\theta_{\text{rel}}^{\text{pull}}$ in data are also found to be well-modeled by simulation for other jet pairings, such as a random $w$-pair jet and a random $b$-pair jet. In control samples consisting of events with a leptonic $W$ boson decay, and two, three, or four jets, none identified as $b$-jets, various jet pairings also have jet pulls that agree with simulations. Figure 3 shows the $\theta_{\text{rel}}^{\text{pull}}$ distributions for jets in a control sample with a leptonic $W$ boson decay and two not-$b$-tagged jets.

To quantify the method’s sensitivity to the color-flow structure (color-singlet versus color-octet) for the hadronic $W$ boson decay, we fit the data to two hypotheses; (i) standard model $tt$ with a color-singlet hadronically decaying $W$ boson (singlet MC) and (ii) $tt$ with a hypothetical color-octet “$W’$” boson (octet MC). We determine the fraction of events coming from color-singlet $W$ boson decay ($f_{\text{Singlet}}$) using the fitting procedure from the D0 combined $tt$ cross section analysis [6]. We simultaneously measure the $tt$ cross section to avoid any possible influence of the $tt$ signal normalization on the $f_{\text{Singlet}}$ measurement. The discriminating variable used for the fit is derived from the $\theta_{\text{rel}}^{\text{pull}}$ angles of the $w$-pair jets and depends on the $\Delta R$ between the two jets and their $\eta_d$. We define the following subdivisions for the data sample, which were optimized by studying the $tt$ singlet and octet MC. For events failing the $W$ mass requirement, we do not split the regions further; for other events we split the data sample according to the $\eta_d$ and $\Delta R$ between the jets. For events where the two jets are highly separated ($\Delta R > 2$), we use the $\theta_{\text{rel}}^{\text{pull}}$ of the leading-$p_T$ jet. Little discrimination is possible for these events, since the additional color radiation is distributed over a large area of the calorimeter. When the two jets are close ($\Delta R < 2$) and $|\eta_d| < 1.0$ for both jets, we use the minimum $\theta_{\text{rel}}^{\text{pull}}$ of the two jets. This is the most sensitive region, and the jet pull is accurately reconstructed in the central calorimeter due to less pileup energy and uniformity of response. Otherwise, if $|\eta_d|$ of the leading-$p_T$ jet is the $\theta_{\text{rel}}^{\text{pull}}$ of the leading-$p_T$ (second-leading $p_T$) jet is used.

Table II lists the contribution of each non-negligible source of systematic uncertainty on $f_{\text{Singlet}}$. For all but the theoretical cross sections, MC statistics, and normalization of the $W+\text{heavy flavor jets}$ background uncertainties, we apply the systematic uncertainties just to the $tt$ signal sample and ignore the effect on background, as the purity of the $tt$ sample is high. To estimate the possible systematic shift of the $\theta_{\text{rel}}^{\text{pull}}$ distribution due to the different energy scale and noise of the calorimeter cells between...
TABLE II: The one standard deviation ($\sigma$) variation of $f_{\text{Singlet}}$ from main systematic uncertainties. The total systematic uncertainty includes all uncertainties, summed in quadrature.

<table>
<thead>
<tr>
<th>Source</th>
<th>+1$\sigma$</th>
<th>−1$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet/octet MC shapes</td>
<td>0.188</td>
<td>−0.188</td>
</tr>
<tr>
<td>Jet pull reconstruction</td>
<td>0.100</td>
<td>−0.093</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.033</td>
<td>−0.013</td>
</tr>
<tr>
<td>Vertex confirmation</td>
<td>0.028</td>
<td>−0.029</td>
</tr>
<tr>
<td>PYTHIA tunes</td>
<td>0.023</td>
<td>−0.025</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.024</td>
<td>−0.009</td>
</tr>
<tr>
<td>Jet reconstruction and identification</td>
<td>0.017</td>
<td>−0.017</td>
</tr>
<tr>
<td>$t\bar{t}$ modeling</td>
<td>0.014</td>
<td>−0.033</td>
</tr>
<tr>
<td>Event statistics for matrix method</td>
<td>0.009</td>
<td>−0.010</td>
</tr>
<tr>
<td>Other Monte Carlo statistics</td>
<td>0.009</td>
<td>−0.007</td>
</tr>
<tr>
<td>Multijet background</td>
<td>0.006</td>
<td>−0.007</td>
</tr>
<tr>
<td><strong>Total systematic</strong></td>
<td>0.222</td>
<td>−0.218</td>
</tr>
</tbody>
</table>

We use the nuisance parameters method where the expectation is fit to the data, for a variation of the initial prediction within the systematic uncertainties, allowing also the central result to change [6]. Other methods give compatible results.

We measure $f_{\text{Singlet}} = 0.56 \pm 0.42$ (stat) ± 0.22(syst) and $\sigma_{\bar{t}t} = 8.50^{+0.87}_{-0.75}$ pb, consistent with our dedicated cross section measurement [6]. Figure 4 shows the distribution for one of the regions of the discriminating color-flow variable, using the measured $t\bar{t}$ cross section and measured $f_{\text{Singlet}}$. The expected constraints on the discriminant color-flow variable, using the measured $t\bar{t}$ cross section and measured $f_{\text{Singlet}}$. The expected 99% C.L. and 95% C.L. limits are $f_{\text{Singlet}}>0.011$ and $f_{\text{Singlet}}>0.277$ respectively, corresponding to an expected sensitivity to exclude $f_{\text{Singlet}}=0$ of about three standard deviations, based on pseudo-experiments. The 68% C.L. allowed region from data is 0.179 < $f_{\text{Singlet}}$ < 0.879. Figure 5 shows the expected 68%, 95%, and 99% C.L. bands for $f_{\text{Singlet}}$.

In summary, we have presented the first study of color flow in $t\bar{t}$ events, with the method of jet pull, using 5.3 fb$^{-1}$ of D0 integrated luminosity. The standard model MC predictions are found to be in good agreement with data, for both the jets from the hadronically decaying $W$ boson, which should be in a color-singlet configuration, and the $b$-tagged jets from the top quark decays, which should be in a color-octet configuration. To quantify our ability to separate singlet from octet color-flow, we measured the color representation of the hadronically decaying $W$ boson and found $f_{\text{Singlet}} = 0.56 \pm 0.42$ (stat+syst), while the expected 95% C.L. limit was $f_{\text{Singlet}}>0.277$. The ability to use color flow information experimentally will benefit a wide range of measurements and searches for new physics.

We thank Jason Gallicchio, Matthew Schwartz, Steven Mrenna, Peter Skands, and Jay Wacker for discussions and guidance. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3.
FIG. 5: (Color online) Expected C.L. bands for $f_{\text{Singlet}}$. The measured value is shown on the horizontal axis, and the input value on the vertical axis. The wide-dashed line shows the expected value and the black-white fine-dashed line indicates the measured value of $f_{\text{Singlet}}$. 

[3] D0 uses a right-handed coordinate system, with the $z$-axis pointing in the direction of the proton beam and the $y$-axis pointing upwards. The azimuthal angle $\phi$ is defined in the $xy$ plane and is measured from the $x$-axis. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where $\theta$ is the polar angle. Detector $\eta$ ($\eta_d$) is the $\eta$ of an object measured from the nominal detector center. 