Angular distributions at the Tevatron

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Abstract. We review measurements of angular distributions in top pair events by the CDF and D0 collaborations. The helicity of $W$ bosons produced in top decays was measured, as was the correlation between the top quark and antiquark spins in $p\bar{p} \rightarrow t\bar{t}$ production. We also review the information available on top quark polarization in $p\bar{p} \rightarrow t\bar{t}$ production.

1. Introduction
As the heaviest of the known elementary quanta of the standard model of particle physics (SM), the top quark offers many opportunities to search for new phenomena beyond the SM. Given the precise SM predictions for polarizations in the process $p\bar{p} \rightarrow t\bar{t} \rightarrow (W^+ b)(W^- \bar{b})$, we seek to identify such new phenomena by measuring these polarizations.

Details on event selection, the estimation of sample composition, and the modeling of signal and background processes can be found in other proceedings from this conference. In the spirit of the papers being reviewed here, we concentrate on the unique aspects of the measurements of angular distributions.

2. Measurements of $W$ helicity in top decays
Data supports the SM prediction of $B(t \rightarrow Wb) \approx 100\%$ [1]. The SM further predicts the fractions of decay into each of the $W$ boson helicity states: $f_- = 30\%$ for left handed helicity, $f_0 = 69.6\%$ for longitudinally polarized $W$ bosons, and $f_+ = 0.1\%$ for right handed helicity, whose production is suppressed by the $V-A$ structure of the weak force [2]. The uncertainties on these predictions are smaller than the experimental uncertainties. Nevertheless, data may indicate new physics, for example, with an observation of sizable $f_+$.

We select events in the “lepton+jets” channel, which corresponds to $t\bar{t} \rightarrow (W^+ b)(W^- \bar{b})$ decays where one $W$ boson decays hadronically and the other decays leptonically into an electron or a muon and one or more neutrinos, possibly through an intermediate $\tau$ lepton. We also select events in the “dilepton” channel which corresponds to decays where both $W$ bosons decay leptonically. Leptons are required to be well isolated in the detector, and to have transverse momentum $p_T > 20\, \text{GeV}$. We use only events where at least one of the selected jets is tagged as arising from $b$ decay. The tagging is based primarily on tracks and secondary vertices that are displaced from the primary collision vertex. Transverse momentum imbalance is also used to suppress background, as it is expected for signal events due to the undetected neutrino(s).

We distinguish between helicity states by reconstructing the angle between the up-type decay product and the incoming top quark in the $W$ boson’s rest frame, $\theta^*$ (see figure [1]). In the lepton+jets channel we perform a kinematic fit that varies the four-momenta of the detected
objects within their experimental resolutions and minimizes a $\chi^2$ statistic within the constraints $M_W = 80.4$ GeV and $m_t = 172.5$ GeV; the $\chi^2$ statistic is used to assign the observed jets to the final state quarks from top decay. $\cos \theta^*$ is reconstructed both for the leptonic decay and for the hadronic decay. For the latter, the up-type quark is not identified, and due to this ambiguity we only measure $|\cos \theta^*|$, which is useful to constrain $f_0$. In the dilepton channels D0 [3] accounts for the resolutions using a statistical procedure that considers both possible jet-quark assignments.

The preliminary CDF dilepton measurement [4] uses a different technique, calculating the likelihood of the helicity fractions given the data without choosing a particular reconstruction. Assuming a certain set of helicity fractions, the probabilities of the four-vectors of the final state partons are predicted according to the SM matrix elements and the proton’s parton distribution functions. The probabilities for the observed final state four-vectors are then calculated according to the experimental resolutions, taking into account all jet-quark assignments. Background contributions are similarly included using the $W$+jets matrix elements from VECBOS [5]. Unlike previous CDF measurements, this “matrix element” technique uses the hadronic decay and all of the jet kinematics to constrain the helicity fractions, thus improving the precision by $\approx 20\%$. Due to effects that are not modeled by the likelihood, such as higher order diagrams, events without a correct jet-quark assignment, and other backgrounds, we expect the fitted fractions to be biased. The fits are calibrated using fully simulated events. We find that the measured fractions depend linearly on the simulated fractions, which simplifies the interpretation of the fit results.

The CDF and D0 collaborations released a preliminary combined measurement of $W$ helicity in top decays [7]. The combined measurement found $f_0 = 0.722 \pm 0.081$ and $f_\perp = -0.033 \pm 0.046$. Preliminary CDF lepton+jets results [6] supersede earlier work included in the combination. They are $f_0 = 0.726 \pm 0.066 \pm 0.067$ and $f_\perp = -0.045 \pm 0.043 \pm 0.058$, where the first quoted uncertainty is statistical and the second one systematic. These results are shown in figures [2 and 3]. Taken together, these results are in excellent agreement with the SM.

3. Top quark polarization

The lifetime of the top quark is much shorter than the time scale for its spin flip [8], so its production and decay polarizations are almost the same. The production mechanisms at the Large Hadron Collider and the Fermilab Tevatron Collider differ significantly, and so, there is interest in measuring the top quark polarization at both accelerators. Unfortunately, no dedicated measurements of top quark polarization in $p\bar{p} \rightarrow t\bar{t}$ production were published by the Tevatron collaborations. However, several relevant data distributions were published, and these will be reviewed here.
Figure 2. Combined measurement of $W$ helicity fractions and its inputs.

Figure 3. Updated CDF lepton+jets measurement of $W$ helicity fractions.

In the top quark’s rest frame we define the angle $\theta$ between the direction of flight of a certain decay product and the chosen polarization axis. The differential cross section is then:

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta} = \frac{1}{2} \left( 1 + |\vec{P}| \, \alpha \cos \theta \right),$$

where $\vec{P}$ is the polarization vector and $\alpha$ is the analyzing strength for that decay product. We analyze the spin of the top quark by looking at the direction of its decay lepton, as for this decay $\alpha$ is essentially one \footnote{9} and the lepton is easily identified.

Figure 4, from reference \footnote{10}, shows distributions of the cosine of the angle between the flight directions of the lepton and its progenitor top quark, $\cos \theta_{l,t}$. This angle measures the top quark polarization in the helicity basis. From CP invariance we expect the distributions for positive and for negative leptons to be the same, and they are combined to increase statistical strength. The SM prediction is contrasted with production through a heavy $Z$-like boson whose couplings are identical to those of the $Z$ boson, resulting in highly polarized top quark production. The reconstruction in the dilepton channel of reference \footnote{10} uses the “neutrino-weighting” method, which samples possible neutrino pseudorapidity ($\eta$) values, weighting each set by its compatibility with the measured momentum imbalance given the experimental resolutions. For each set of neutrino $\eta$s, the full decay chain is derived analytically using $M_W$ and $m_t$ constraints.

Figure 5, from reference \footnote{11}, shows distributions of the cosine of the angle between the flight directions of the lepton and of the same-sign colliding proton, $\cos \theta_{\pm}$. Again, CP invariance predicts identical distributions for positive and negative leptons, which are combined in the plot. To conclude, the published Tevatron data hints at SM-like, unpolarized top pair production.

4. Measurements of spin correlations in top pair production

The spins of the top quark-antiquark pair produced by the SM process $p\bar{p} \rightarrow t\bar{t}$ are highly correlated. This correlation leads to the doubly differential cross section:

$$\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} \left( 1 - A_{\alpha_1 \alpha_2} \cos \theta_1 \cos \theta_2 \right),$$

$$,$
where the $\theta$s are leptonic decay angles along some axis, and $A$ is the strength of the corresponding spin correlation. In the beam axis, the SM prediction is $A_{\text{SM}}^{\text{beam}} = 0.78$, calculated to next-to-leading order in quantum chromodynamics. Only one lepton, with $\alpha \approx 1$, is available in the lepton+jets channel. The spin of the other top must be inferred from the angle of one of the jets arising from its decay products. For the $b$-jet, $\alpha = -0.41$, and for the jet arising from the down-type quark, $\alpha = 0.97$. Identifying the latter jet is difficult, making the dilepton channel particularly attractive for this measurement.

A preliminary measurement of spin correlations by the CDF collaboration in the lepton+jets channel [11] was reported in the previous workshop. Here we report on a new measurement in the dilepton channel [12].

To reconstruct $t\bar{t}$ events in the dilepton channel, we perform a fit for the energies of the $b$-jets, the transverse momentum imbalance ($\not{E}_T$) due to the neutrinos, and the best jet-quark assignment. For each set of values assumed in the fit, the six unknown neutrino momentum components are solved for analytically from the four mass constraints and the two neutrino-$\not{E}_T$ values. The fit maximizes a likelihood with $\chi^2$ terms for each parameter and with a-priori probability density functions for $p_T^t$, $p_T^{\bar{t}}$, and $m_{t\bar{t}}$. These density functions are simulated by the PYTHIA event generator.

The spin correlation coefficient, $\kappa = -A_1 \alpha_2$, is measured for the beam axis, defined here using both proton and anti-proton directions which results in the minus sign. It is extracted from a template fit to the observed two-dimensional distributions of $(\cos \theta_+ , \cos \theta_-)$ and of $(\cos \theta_b , \cos \theta_{\bar{b}})$. The expected sample composition is assumed during this fit. The templates are produced by reweighting $t\bar{t}$ events generated by PYTHIA without spin correlations. To model a
given correlation strength, $\kappa \in (-1, -0.8, \ldots, 1)$, we use weights of $1 + \kappa \cos \theta_+ \cos \theta_-$, where the $\theta$s are the generator-level decay angles of the down-type fermion. Templates for the diboson and Drell-Yan background processes were simulated using PYTHIA and ALPGEN (respectively). Templates for the multijet background were derived from control data.

The fit procedure was checked for biases using ensembles of simulated pseudo datasets. No calibration is needed, and the measured value is $\kappa = 0.042^{+0.563}_{-0.562}$.

In references [13] and [14], the D0 Collaboration reports measurements of spin correlations in the dilepton channel and lepton+jets channels, respectively. Both analyses measure the fraction $f$ of $t\bar{t}$ events whose spins are correlated as in the SM predictions (while the rest have uncorrelated spins) using a discriminant that summarizes efficiently all event kinematics:

$$R(x) = \frac{P_c(x)}{P_c(x) + P_u(x)},$$

where $x$ is the observed event, $P_c$ is its probability assuming SM production, and $P_u$ is its probability assuming uncorrelated spins. The $P$s are calculated as in the matrix element technique described above. This discriminant was suggested in reference [15].

The observed distributions of $R$ in the dilepton channel, and in the best of the four sub-channels of the lepton+jets analysis, are shown in figure 6. In the dilepton channel we measure $f = 0.74 \pm 0.41$, in the lepton+jets channel $f = 1.15 \pm 0.43$, and combined $f = 0.85 \pm 0.29$. Deriving frequentist limits on the physical value of $f$ with a C.L. of 99.7%, we find it is positive. This is the first evidence for spin correlations in top pair production.

Figure 6. $R$ distributions from the dilepton (left) and lepton+jets (right) channels.