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Measurements of spin correlation in top-quark production at the Tevatron

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Summary. — Since the discovery of the top quark in 1995 at the Fermilab Tevatron collider, top-quark properties have been measured with ever higher precision. The increase in data has provided the opportunity to probe many new aspects of the top-quark sector, one of these being the study of spin correlation in $t\bar{t}$ events. The first measurements performed by the CDF and DØ collaborations were based on templates of angular distributions. To achieve a significant improvement in sensitivity, the DØ collaboration pioneered a new approach based on matrix-element information, providing first evidence for non-vanishing spin correlation in $t\bar{t}$ events. A review of these measurements is presented below.

PACS `14.65.Ha` – Top quarks.
PACS `12.38.Qk` – Experimental tests.
PACS `13.85.Qk` – Inclusive production with identified leptons, photons, or other nonhadronic particles.

1. – Top-quark-pair production and decay

At the Tevatron $p\bar{p}$ collider with a center-of-mass energy of 1.96 TeV, 85% of the $t\bar{t}$ pairs are produced through quark-antiquark annihilation and 15% originate from gluon-gluon fusion. The SM predicts top quarks to decay almost exclusively to a W boson and a bottom quark, such that $t\bar{t}$ events can be classified into all-jets, lepton+jets and dilepton events, depending on the modes of the two W decays. The lepton+jets channel is characterized by four jets, one isolated, energetic charged lepton, and an imbalance in transverse momentum. The irreducible background comes mainly from W+jets events. Instrumental background arises from events in which a jet is misidentified as a lepton and from events with heavy quarks that decay into leptons that pass isolation requirements. The topology of the dilepton channel is given by two jets, two isolated, energetic charged leptons, and a significant imbalance in transverse momentum from the undetected neutrinos. Here, the main background processes are Z+jets and diboson events (WW, WZ and ZZ with associated jets), as well as the kind of instrumental background characterized above.

2. – Top-quark spin correlation in a nutshell

With the increased data recorded at the Tevatron experiments and the different nature of $t\bar{t}$ production compared to that at the LHC, measuring spin correlation in $t\bar{t}$ events has become one of the flagships of Tevatrons top-quark program. These measurements are of particular interest, as they test the full chain from the strong production to the electroweak decay of top quarks. Deviations from the SM prediction could arise from additional contributions in production, such as from stop-quark pairs, as well as from new decay modes of the top quark, such as to a charged Higgs boson ($t \rightarrow H^+b$). Moreover, if the lifetime of the top quark is much longer than expected, the spin could flip through final-state interactions before decay, resulting in a reduction of spin correlation [1].

The spin correlation strength A in production is defined as

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}\,, \tag{1}$$

where $N_{\uparrow\uparrow}, N_{\downarrow\downarrow}$ ($N_{\uparrow\downarrow}, N_{\downarrow\uparrow}$) reflects the number of events with spins pointing in the same (opposite) direction. The correlation strength A is different for $t\bar{t}$ events produced via quark-antiquark annihilation and via gluon-gluon fusion [2]. Its value depends on the choice of quantization axis. One possibility is the so-called beam basis, which is defined by the direction of the incoming proton and antiproton. It is best suited for studying top quarks produced at threshold, and in next-to-leading order quantum chromodynamics (NLO QCD) predicted to be 0.78 ± 0.04. For top quarks far away from threshold, the helicity basis, defined by the direction of flight of each of the top quarks, corresponds to the optimal choice. A third possibility, which interpolates between the beam and helicity basis, is the so-called off-diagonal basis. Here the angle between the top quark and the basis is given by $\tan(\omega) = \sqrt{(1-\beta^2)}\tan(\theta)$, with θ being the angle between the top quark and the beam line. At NLO, the correlation strength in the off-diagonal basis is expected to be $A_{\text{off}} = 0.78 \pm 0.04$ [1].

As the lifetime of the top quark is predicted to be less than $\frac{1}{\Lambda_{\text{QCD}}}$ [3, 4], its spin orientation is not expected to change before decaying, and A can be inferred from the angular distributions of the decay products. With θ being the angle between the beam axis and the final state particle in the $t(\bar{t})$ rest frame, the angular dependence has the form

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos(\theta)} = \frac{1}{2}(1 + \alpha\cos(\theta)), \tag{2}$$

where α is the so-called spin analyzing power. It is largest for charged leptons ($\alpha = 1.0$ in NLO QCD) and down-type quarks ($\alpha = 0.97$ in NLO QCD) [5].

Putting all this together, the spin correlation strength can be measured by studying the double differential cross section

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos(\theta_1)\mathrm{d}\cos(\theta_2)} = \frac{1}{4}(1 - C\cos(\theta_1)\cos(\theta_2)), \tag{3}$$

where $C = A\alpha_1\alpha_2$. Despite the small branching fraction of the $W \rightarrow \ell\nu_\ell$ decays, the dilepton channel is best suited for measuring spin correlation in $t\bar{t}$ decays because unlike down-type quarks, charged leptons can be easily identified. In addition, the momentum of leptons is measured better than that of jets, and the contamination from background in this final state is very small.

3. – Measuring spin correlation from angular distributions

As the first measurement of spin correlation performed at the DØ experiment [6], the second one is based on templates of angular distributions [7]. To extract the parameter C from eq. (3), templates are formed for the products of $\cos(\theta_{l1})\cos(\theta_{l2})$ which requires a full reconstruction of the angles of the charged leptons in the t and $\bar{t}$ rest frame. Using the neutrino-weighting method, both neutrino pseudorapidities are sampled from expected Monte Carlo (MC) distributions, and for each point in phase space, all solutions are weighted according to the degree of agreement of the reconstructed neutrino momenta with the measured imbalance in transverse momentum. The weighted mean of all kinematic solutions is used to estimate $\cos(\theta_{l1})\cos(\theta_{l2})$ in each event.

The spin correlation strength C_{beam} is extracted from a binned maximum likelihood fit, where templates for signal, both with and without spin correlation, are mixed together as a function of C_{beam}, including contributions from background. Systematic uncertainties are incorporated into the fit as free parameters, and the ordering principle for ratios of likelihoods [8] is used to set limits or extract a central value for the data.

Based on an integrated luminosity of $5.4\,\mathrm{fb}^{-1}$ corresponding to a total of 441 dilepton candidate events with an expected signal purity of 74%, the spin correlation strength C_{beam} is found to be

$$C_{\mathrm{beam}} = 0.10 \pm 0.45(\mathrm{stat} + \mathrm{syst}).$$

This is consistent within two standard deviations with the NLO prediction of $C_{\mathrm{beam}} = 0.78 \pm 0.04$. The measurement is dominated by a statistical uncertainty of about 0.4, with the largest systematic uncertainty of 0.07 resulting from limited statistics of the MC samples used to form templates.

A similar measurement based on $2.8\,\mathrm{fb}^{-1}$ of dilepton events is carried out by the CDF collaboration [9]. Different from the DØ measurement, the off-diagonal basis is chosen. In addition, instead of a one-dimensional template of $\cos(\theta_{l1})\cos(\theta_{l2})$, the correlation strength is extracted using two two-dimensional templates of $\cos(\theta_{l1})$ *vs.* $\cos(\theta_{l2})$ of the two leptons and $\cos(\theta_{b1})$ *vs.* $\cos(\theta_{b2})$ of the two jets from the b quarks. The event kinematics is reconstructed through a kinematic fit based on priors of the $t\bar{t}$ mass, longitudinal and transverse momentum, as well as resolution functions for the jet energies and the missing transverse momentum.

From a total of 195 $t\bar{t}$ candidate events with a predicted purity of about 65%, the spin correlation strength C_{off} is measured to be

$$C_{\mathrm{off}} = 0.32^{+0.55}_{-0.78}(\mathrm{stat} + \mathrm{syst}),$$

which is well consistent with the SM prediction of $C_{\mathrm{off}} = 0.78 \pm 0.04$. The largest systematic uncertainty of 0.28 is from the uncertainty on the yields of signal and background, followed by 0.2 from the dependence on the choice of parton distribution functions.

The first study of the spin correlation strength C_{beam} in the lepton+jets final state is accomplished by the CDF collaboration using $5.3\,\mathrm{fb}^{-1}$ of data [10]. To increase the signal purity, at least one jet is required to arise from a b quark. Only the best kinematic solution to the $t\bar{t}$ fit hypothesis is retained. The measurement makes use of two templates of $\cos(\theta_l)\cos(\theta_d)$ and $\cos(\theta_l)\cos(\theta_b)$, where the jet closest to the b jet in the rest frame of the W boson is considered to come from the the down-type quark.

Using a total of 725 $t\bar{t}$ candidate events, the spin correlation strength is extracted from a fit to a binned likelihood to be

$$C_{\text{beam}} = 0.72 \pm 0.69(\text{stat} + \text{syst}).$$

The result is dominated by a large statistical uncertainty of 0.64, with the leading systematic uncertainty of 0.2 coming from the choice of the Monte Carlo generator. As the jet from the down-type quark is identified with an efficiency of only about 60%, this measurement is about 30% less sensitive relative to the corresponding measurement in the dilepton channel.

4. – Application of matrix-element information

To increase the sensitivity, the DØ collaboration pioneered a new way of measuring spin correlation employing a matrix-element approach [11].

For each observed final state x, the probability that it arises from $q\bar{q} \to t\bar{t}$ production with spins correlated according to the SM ($H = c$), or uncorrelated spins ($H = u$) is given by

$$P_{sgn}(x;H) \propto \int \mathrm{d}\epsilon_1 \mathrm{d}\epsilon_2 f_{PDF}(\epsilon_1) f_{PDF}(\epsilon_2) \frac{|M(y;H)|^2}{\epsilon_1\epsilon_2 s} W(x,y)\mathrm{d}\Phi_6, \tag{4}$$

where ϵ_1, ϵ_2 are the energy fractions of the incoming partons, f_{PDF} are the leading-order parton distribution functions CTEQ6L1 [12], $M(y;H)$ is the leading-order matrix element for production and decay [2] and $\mathrm{d}\Phi_6$ is an element of the six-body production phase space. The transfer functions $W(x,y)$ reflect the probability for a partonic object y to be reconstructed as an observed object x. Based on these probabilities, a variable

$$R = \frac{P_{sgn}(H = c)}{P_{sgn}(H = c) + P_{sgn}(H = u)} \tag{5}$$

can be defined to discriminate between $t\bar{t}$ events with (c) and without (u) SM spin correlation [13]. As in the measurement based on $\cos(\theta_{l1})\cos(\theta_{l2})$ templates, C is extracted from a binned maximum-likelihood fit using signal templates in R generated from MC@NLO with and without spin correlations, as well as contributions from background. Systematic uncertainties are again incorporated as free parameters in the fit.

Using $5.4\,\text{fb}^{-1}$ of dilepton $t\bar{t}$ events, the spin correlation strength C is measured to be

$$C = 0.57 \pm 0.31(\text{stat} + \text{syst}),$$

which is consistent with the NLO prediction of $C = 0.78 \pm 0.04$. Relative to the previous measurements based on templates, this improves the sensitivity by about 30%. The largest systematic uncertainty of 0.07 is from limited statistics in forming the templates.

In addition, the DØ collaboration also applies this approach to $5.3\,\text{fb}^{-1}$ of lepton+jets events [14]. Requiring at least two jets to be identified as coming from a b quark, the signal purity is increased to about 90%. As in the case of dilepton events, the ME is calculated with and without spin correlation and templates in the ratio R are formed. To increase the sensitivity and to reduce the dilution from initial and final state radiation, events are split into four subsamples, by dividing the data into two groups of events, one with four jets and the other with more than four jets. To reduce the contamination from events in which a b jet is mistakenly taken to arise from W boson decay, these two groups are again separated according to whether the invariant mass of the two light-flavor jets is within $\pm 25\,\text{GeV}$ of the W boson mass.

Using a total of 729 $t\bar{t}$ candidate events, the spin correlation is extracted to be

$$C_{\text{beam}} = 0.89 \pm 0.33(\text{stat} + \text{syst}).$$

Combining this measurement, with the one in the dilepton channel, $C_{\text{beam}}$is determined to be

$$\begin{aligned} &C_{\text{beam}} = 0.69 \pm 0.23(\text{stat} + \text{syst}),\\ &C_{\text{beam}} > 0.05 \text{ at } 99.7\% \text{ C.L.}, \end{aligned}$$

providing first evidence for non-vanishing spin correlation in $t\bar{t}$ events.

5. – Summary

Different Tevatron measurements of spin correlation in $t\bar{t}$ events have been presented. Exploring both, the dilepton and the lepton+jets channels and moving from templates based on angular distributions to templates using matrix-element information, the sensitivity of the measurements is improved significantly, and evidence attained for non-vanishing spin correlation in $t\bar{t}$ events. Thus far, only half of the full Tevatron data has been analyzed, and making use of all available data, is likely to provide an even more definitive statement on the observation of spin correlation in these events.

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