Proposal for Detecting Top Spin Correlation Effects at the Fermilab Tevatron

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We propose to observe the top spin correlation effect at the Fermilab Tevatron through the measurement of the correlated asymmetries of the charged lepton momenta using the dilepton decay events of top and antitop quark pairs. The possibility of reconstructing the events and observing the asymmetries at 3σ level with projected luminosity of the Fermilab Tevatron for run II is demonstrated by simulation. The effect can provide the first direct measurement of the spin of a quark. [S0031-9007(96)00834-4]

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Both CDF and D0 have recently announced the observation of the top quark [1]. The published central value of the top quark mass is well above twice the W boson mass. The heaviness of the top quark offers a unique chance to observe the $t\bar{t}$ spin correlation effects through their decay products because the top quark is expected to decay before it has time to hadronize [2,3]. Despite many studies in the literature [3,4], the possibility of observing the top spin correlation at the Fermilab Tevatron with the projected luminosity for run II is yet to be demonstrated.

In this Letter, we propose to measure the charged lepton correlated asymmetries in the top dilepton events. We shall demonstrate that it is possible to observe such asymmetries at 3σ level with Tevatron II. The lepton correlated asymmetry, A_P, with respect to a plane P passing through the interaction point is defined as follows. Let $\vec{l}_1$ be the momentum of the charged lepton associated with top decay evaluated in the top rest frame. Similarly, let $\vec{l}_2$ be that associated with antitop decay evaluated also in its own rest frame. Then, define $A_P = (N_+ - N_-)/(N_+ + N_-)$ where N_+ is the number of events in which both $\vec{l}_1$ and $\vec{l}_2$ lie on the same side of P while N_- is the number of events with both $\vec{l}_1$ and $\vec{l}_2$ lying on the opposite side of P. By choosing different P, one can construct different asymmetries. These asymmetries vanish when the effects of both top spin and W spin are ignored (or averaged over), and they remain small even when the W spin effects are included. This property makes them the ideal candidates for the observation of the $t\bar{t}$ spin correlation effects.

In order to measure the lepton correlated asymmetries it is essential to make full reconstruction of the top dilepton events. We assume that the top mass will be well measured in Tevatron run I and run II. For dilepton candidate events, we further assume that the missing transverse momentum measured is equal to the sum of the missing transverse momenta of the two neutrinos associated with the dilepton. Contribution to the missing transverse momentum from other neutrinos in the event reduces the efficiency of the reconstruction and lowers the signal-to-noise ratio but does not spoil the observability of the asymmetries we consider here.

The analysis of the productions and the decays of $t\bar{t}$ in a hadronic collider with and without spin correlation effect can be found in the literature [3,4] with various degrees of sophistications. We shall use the simple analytic differential cross sections for $q\bar{q}$ and $gg \to t\bar{t} \to bW^+\bar{b}W^- \to b\bar{l}\bar{\nu}_l\bar{b}l'\nu_{l'}$ provided in Ref. [3]. Using these formulas, we simulated the $t\bar{t}$ production and decay employing the event generator PYTHIA 5.7.

The algorithm of our reconstruction of the top dilepton events proceeds as follows. We choose two arbitrary directions in the transverse plane as the candidate directions of the transverse momenta for the two neutrinos. The momenta of the two neutrinos are then fixed by the four on-shell conditions of the top quarks and the W bosons. In general, four candidate solutions are obtained this way. One then computes the absolute value of the difference, $\Delta E_\perp$, between the sum of the transverse momenta of the two neutrinos and the measured missing transverse momentum of the event. Varying the two candidate directions in the transverse plane, we can choose as our best solution the one with minimum $|\Delta E_\perp|$. Once the neutrinos are reconstructed, top momenta can be calculated. Invariably, our reconstruction does not always produce fully the true kinematics of the collision; however, for our purpose, it is sufficient that the reconstruction produces the true top direction with enough efficiency. We checked that the reconstructed top direction highly peaked around the true top direction.

In principle, one can also look for the W correlated asymmetries for the two W's from $t\bar{t}$ decays in the reconstructed top dilepton, lepton-jet, and jet-jet events. The predicted W asymmetries can be easily obtained from Ref. [3]. They are no more than a few percent and about an order of magnitude smaller than some of the lepton correlated asymmetries. The enhancement of the lepton correlated asymmetries over the W correlated asymmetries [5] is one feature that favors the observation of top spin correlation effects through the dilepton channel.

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It is interesting to note that the predicted correlated asymmetries for the neutrinos vanish [5]. This lack of symmetry between the properties of charged lepton and neutrino reflects exactly the $V - A$ coupling of the weak charged current interaction. Therefore, the observation of a nontrivial lepton correlated asymmetry and vanishing neutrino correlated asymmetries can by itself constitute a check on the $V - A$ coupling of the charged weak current between t and b. Unfortunately, as we shall demonstrate, the typical trigger for missing $E_\perp$ used to select $t\bar{t}$ candidate events introduces bias so that the neutrino correlated asymmetries are no longer vanishing when the trigger is turned on. However, one may still hope that by understanding this trigger-induced effect better one can derive some direct experimental constraint on g_A/g_V coupling of the top quark.

The lack of symmetry between the charged lepton and neutrino in their asymmetries also implies that, in order to look for lepton-quark correlated asymmetries in the top lepton-jet events, one should distinguish between the up-type and the down-type jets in the W decay. This is difficult, if not impossible. Since the lepton-jet events are much more abundant than the dilepton events, the possibility of observing the lepton-quark asymmetries may still deserve further study.

In hadron colliders, $t\bar{t}$ are produced either by quark-antiquark ($q\bar{q}$) annihilation or by gluon-gluon (gg) fusion. The lepton correlated asymmetries for these two cases typically have opposite signs and different magnitudes [5]. At the Fermilab Tevatron energy, the number of $q\bar{q}$ produced top events are roughly 8 times that of the gg produced events. This ratio decreases with energy and, at Large Hadron Collider (LHC) energy, the number of gg produced top events are roughly 4 times that of the $q\bar{q}$ produced events. For the asymmetries we considered, we found that the substantial asymmetries that can be observed at the Fermilab Tevatron become much smaller at the expected LHC collider energy. This is the result of accidental cancellation between the contribution of the $q\bar{q}$ production channel and that of the gg production channel. We have checked that the contribution due to the $q\bar{q}$ channel alone is indeed not so small. This cancellation could be a generic feature which may make LHC an unfavorable machine to look for the top spin correlation effect. For the same reason, the next linear collider should be an ideal machine for observing such correlation due to the absence of such cancellation.

In this Letter we shall only discuss the asymmetries with respect to the following planes defined in the $t\bar{t}$ center of mass frame: (1) $t\bar{t}$ production plane (defines asymmetry A_1), (2) the plane perpendicular to the production plane and contains the top (asymmetry A_2), (3) the plane perpendicular to the two previous planes (asymmetry A_3), and (4) the plane normal to the beam direction (asymmetry A_4). These planes are chosen as samples to demonstrate the possibilities only. The optimal choice will depend on the details of the detectors and clearly need further study [5].

The typical trigger for top dilepton events [1], namely, $p_T \geq 20$ GeV for leptons, $p_T \geq 10$ GeV for b jet, missing transverse energy $\not{E}_\perp \geq 25$ GeV, and rapidity $|\eta| \leq 2$, was applied. Afterwards, the reconstruction algorithm we described earlier was carried out. A typical hadron calorimeter energy resolution of $70\%/\sqrt{E}$ was used as b-jet energy smearing, and the missing transverse energy was Gaussian smeared with a 15% standard deviation. The effect of including the contribution of other neutrinos in an event to the missing transverse energy was investigated [5]. To isolate the effect of the bias originated from reconstruction algorithm to the asymmetries, we also studied the case with the event reconstruction turned on but with the trigger turned off. Similarly we also studied the case with the event reconstruction turned off but with the trigger turned on. The effect of energy smearing is also investigated. In each case, we computed the lepton correlated asymmetries, the neutrino correlated asymmetries, and the W correlated asymmetries with respect to the planes described earlier. In Table I, we present the measured correlated asymmetries A_1, A_2, A_3, and A_4 for the four cases: (I) trigger off, reconstruction off; (II) trigger on, reconstruction off; (III) trigger off, reconstruction on; (IV) trigger on, reconstruction on; and (V) trigger on, reconstruction on and with energy smearing included. The corresponding asymmetries when the top spins were "uncorrelated" (that is, their spins are summed over in their productions and averaged over in their decays) are given in brackets. The average values and the standard deviations of the asymmetries were extracted directly from the simulated data. When both top and W spins were uncorrelated, as in most standard event generator packages, we verified that all the asymmetries vanish if the trigger and event reconstruction were turned off. As one can see in the table, the asymmetries measured by charged leptons are generally larger than the asymmetries measured by neutrinos and W bosons. The systematic effects of trigger and reconstruction are quite obvious in the case of neutrino asymmetries as one would expect from the large missing $E_\perp$ cut as well as the contributions from other neutrinos in the event. Because of space limitations, a detailed discussion of the various effects and their origins will be given elsewhere.

From the results of these simulations, we conclude that the asymmetry A_4 should be a potent observable for probing the correlation. The standard deviation of A_4 distribution in the ideal case, (I) of Table I, is about $\sigma = 1.14$ which implies that one needs about $n = (3\sigma/A)^2 = 285$ events to observe the asymmetry at 3σ level, where A is the averaged asymmetry given in the table for A_4. For the most realistic case of (V), σ is about 1.25 and A_4 is -0.133, which requires about 794 events to observe the effect at 3σ level. This is reachable with the projected luminosity of the Fermilab Tevatron for run II, with improved detector resolution and acceptance

TABLE I. The measured correlated asymmetries $A_i(l)$'s, $A_i(\nu)$'s, and $A_i(W)$'s for the four cases: (I) trigger off, reconstruction off; (II) trigger on, reconstruction off; (III) trigger off, reconstruction on; (IV) trigger on, reconstruction on; and (V) trigger on, reconstruction on with energy smearing. The corresponding asymmetries when the top spins were "uncorrelated" are given in brackets. All the values are in units of percentage. The total number of simulated events is 100 000.

	I	II	III	IV	V
$A_1(l)$	3.99(−0.11)	5.90(0.58)	4.16(0.68)	6.42(1.94)	5.50(1.14)
$A_2(l)$	−11.78(0.41)	−11.18(−0.55)	−10.30(−0.30)	−7.98(0.12)	−7.58(−0.06)
$A_3(l)$	−9.65(−0.09)	−8.68(−1.34)	−8.00(−1.22)	−6.80(−1.4)	−6.64(−1.26)
$A_4(l)$	−20.34(0.18)	−17.64(−0.13)	−16.68(−1.86)	−13.72(−1.66)	−13.30(−2.00)
$A_1(\nu)$	0.54(−0.68)	9.50(8.86)	5.44(4.70)	12.24(11.80)	9.02(8.48)
$A_2(\nu)$	−1.95(−0.06)	0.60(1.68)	1.80(2.20)	2.16(2.42)	2.56(2.52)
$A_3(\nu)$	−1.45(−0.09)	3.62(4.30)	−1.94(−1.54)	2.64(2.82)	0.74(1.22)
$A_4(\nu)$	−3.41(−0.37)	−1.84(−0.13)	0.33(0.27)	−0.02(0.24)	0.84(1.02)
$A_1(W)$	0.79(0.16)	3.24(2.32)	1.92(1.34)	3.94(3.18)	3.70(2.92)
$A_2(W)$	−1.98(−0.51)	−0.48(0.33)	−3.34(−0.12)	−3.14(0.58)	−2.96(0.58)
$A_3(W)$	−2.70(−1.46)	0.56(0.42)	−3.70(−1.44)	−3.64(−1.32)	−4.60(−2.34)
$A_4(W)$	−3.66(−0.91)	−3.32(−0.04)	−7.12(−1.68)	−6.58(−0.72)	−7.57(−1.62)

expected for both CDF and D0 detectors upgrades and perhaps with improved algorithms for identifying the top dilepton events.

The dilepton background of $t\bar{t}$ production events was estimated in many references [6,7]. In recent CDF publications [7], it was estimated that, for the 10 candidate events observed so far, the contributions from the main sources of background give a total of about 2 ± 0.4 events from Drell-Yan productions of dilepton, $Z \rightarrow \tau\tau$, WW productions, or lepton misidentification. That is, the background is about 20% without using b tagging. With b tagging, the background can be reduced to below 1% (see Ref. [1]). The direct $b\bar{b}$ production background, which may be harder to remove by b tagging, is only about 0.5%. Assuming that the b tagging efficiency in CDF run II is 80%, the required number of events for observation of asymmetry at the 3σ level is about 1000 with b tagging.

There is also plenty of room for improvement on our analysis of the correlated asymmetries. Even though trigger and reconstruction show little systematic effects for the lepton asymmetry, they do shift the neutrino and the W asymmetries by non-negligible amounts. A quantitative understanding of these effects may allow us to tune the trigger selection and reconstruction algorithm for the observation of the asymmetries. It is well known that discrete ambiguities exist in general in the reconstruction of top dilepton events. A detailed quantitative study of its effect on the asymmetries could precipitate an improvement on reconstruction algorithm for better efficiency and better signal-to-noise ratio. We have been quite casual in choosing the planes to define the asymmetries and in choosing the combinations of these asymmetries to measure. One may wonder if there is an optimal choice of plane or combinations of planes that can maximize the observability of the correlation effect. One may also wonder if there are choices that will enhance or suppress the contribution of $q\bar{q}$ annihilation channel relative to the gg fusion channel.

Before we conclude, we wish to point out still another way of measuring the asymmetry. The asymmetries are functions of the orientations of the defining plane P passing through the collision point. Hence each asymmetry (charged leptons, neutrinos, or W's) can be considered as a function on a sphere and analyzed by multipole expansion. As an illustration, in Fig. 1 we plot the charged lepton asymmetry without trigger and reconstruction effects as a function of the plane P for

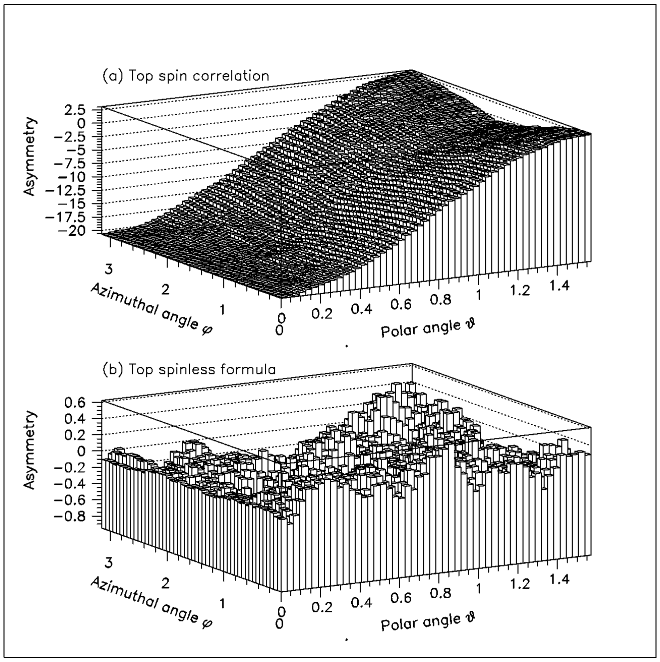

FIG. 1. (a) Charged lepton asymmetry $A_P(l)$ as a function of the orientation of the defining plane P for the case with top spin correlation. Here, $\theta = 0$ represents the plane perpendicular to the beam direction while $\theta = \pi/2$, $\phi = 0$ represents the production plane. (b) Same as (a) but for the case when top spins are "uncorrelated."

both the case with top spin correlation [Fig. 1(a)] and the case without [Fig. 1(b)]. With improved reconstruction algorithm and detector resolution, this can potentially be a very effective way of searching for the top spin correlation effects [5].

In conclusion, top spin correlation is certainly one of the most interesting top physics to be uncovered. It can provide a direct observation of the spin $1/2$ character of the top quark (which we have not been able to do for the lighter quarks) and can potentially test the $V - A$ character of the weak charged current associated with top. We have clearly demonstrated the possibility of observing this effect at the Fermilab Tevatron run II. The fact that this effect may be even harder for LHC to measure should make the task more important for Tevatron. A detailed account of our study will be presented elsewhere [5].

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Note added.—While this paper was being finalized, we came across two papers dealing with a similar subject (T. Stelzer and S. Willenbrock, Report No. hep-ph/9512292, and G. Mahlon and S. Parkes [8]). They proposed one of the asymmetries, A_3, we discussed in this Letter. This asymmetry can be obtained analytically without referring to the off-diagonal terms of the polarization density matrices of $t\bar{t}$ production [3]. From our results, it is clear that A_3 is not the best observable to detect the top spin correlations.

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