Spin Correlations in Top Quark Production and the Top Quark Mass

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ABSTRACT

Top-antitop quark pairs produced at the Tevatron have a sizeable spin correlation. That correlation feeds into the angular distribution of the decay products, particularly in the dilepton channel. Including the expected correlation in an overall analysis of a handful of actual dilepton events continues to favor a lower top mass (centered on 155 GeV) than the single lepton events.

In 1992 a phenomenological study of the top quark’s production and decay characteristics was presented[1], based on the observation that the contemporaneous lower limit on the mass allowed the top quark to decay into an on-shell W boson and bottom quark. The kinematics of this two-body decay constrain the subsequent final state kinematics, whether the W decays leptonically or into a quark-antiquark pair. In a pp collision the principal mechanism for producing a heavy pair of quarks is either through the light quark pair annihilation or gluon fusion. The decay chain 
t\to W^+ + b \text{ and } W^+ \to l^+ + \nu_l \text{ for the top and the charge conjugate chain for the antitop, leads to two energetic leptons and two missing neutrinos in the final state - the dilepton mode. For a given top mass the observed configuration can be assigned a probability, since we know a priori what the probability is for that configuration to be realized. Hence, a likelihood can be assigned to each event, as a function of the top mass, for that event to correspond to a bona fide top event.}

This method for determining the likelihood and most probable mass for a hypothetical top production via the dilepton or single, unilepton mode [1,2] (see also [3]) was applied to the meager published data from CDF. For simplicity, the possible spin correlation of the top pair was ignored in defining the likelihood. In Fig.1 the results for that analysis[4] are shown. The joint probability was computed for the dileptons and unileptons separately. The results of the analysis confirmed the CDF results for their seven published single lepton events and favor a mass near 175 GeV[5]. However, the three dilepton events, whose measured momenta were available, were analysed also (and the one D0 event, that the group had analysed[6], was included in the joint probability) and led to a lower mass of 156 ± 8 GeV. This lower value is consistent with results (using a modified Dalitz and Goldstein method) presented subsequently by the D0 group for 5 dilepton events[7].

Is this result significant? Because of lower backgrounds and fewer jets, the dilepton events should be more reliable indicators of top production. Can the mass determination for the dileptons be sharpened? This can be accomplished by including the spin correlations between the top and antitop in the likelihood function. A preliminary study was begun several years ago (with R.H. Dalitz and K. Sliwa) At
the tree level of QCD for light quark-antiquark annihilation into heavy quark pairs, the spins of the heavy quarks tend to be aligned, while for gluon fusion the heavy quark spins tend toward anti-alignment. It is known, however, that the gluon fusion mechanism is suppressed relative to light quark annihilation for the Tevatron energy and the expected range of top masses[8]. Hence, the alignment of spins is preferred.

The top spin correlations can be expressed as a double density matrix in a direct product form[9]. The resulting spin correlations are transmitted to the decay products. Ignoring the b-jets (whose polar angle relative to the lepton direction is fixed by kinematics), the correlations between the lepton directions and the parent top spin (in the top rest frame) produce correlations between the lepton directions, expressed here as a weighting factor:

\[ W(\theta, p, p_l, p_{l\bar{\ell}}) = \frac{1}{4} \left\{ 1 + \sin^2 \theta \left( p^2 + m^2 \right) (\hat{p}_{l\bar{\ell}})_x (\hat{p}_l)_x + \left( p^2 - m^2 \right) (\hat{p}_{l\bar{\ell}})_y (\hat{p}_l)_y \\
- 2 mp \cos \theta \sin \theta \left( (\hat{p}_{l\bar{\ell}})_x (\hat{p}_l)_z + (\hat{p}_{l\bar{\ell}})_z (\hat{p}_l)_x \right) + \left( p^2 - m^2 \right) \\
+ \left[ p^2 + m^2 \cos^2 \theta \right] (\hat{p}_{l\bar{\ell}})_z (\hat{p}_l)_z \left/ \left( \left( p^2 + m^2 \right) + \left( p^2 - m^2 \right) \cos^2 \theta \right) \right. \right\} \]

where \( \theta \) is the top quark production angle in the quark-antiquark CM frame, \( p \) is the quark CM momentum, \( \hat{p}_l \) is the \( l^+ \) momentum direction in the top rest frame and \( \hat{p}_{l\bar{\ell}} \) is the corresponding \( l^- \) direction in the antitop rest frame. For this \( q\bar{q} \) case the leptons will tend to be oppositely oriented in their respective top rest frames. When boosted back to the subprocess center-of-mass frame the same conclusion will hold, namely that \( q\bar{q} \) annihilation favors a large opening angle between the leptons. Finally, after the subprocess is folded back into the \( pp \) annihilation with the proton structure functions, the effect gets diluted, but not completely.

To study the importance of the spin correlation, a Monte Carlo generator of dilepton events with spin correlated top quark pairs was produced. The analysis procedure is altered to include the spin correlation weight in the determination of the overall Bayesian probability. When this is done for all the events, the resulting mass distribution is more sharply peaked than it is for the uncorrelated events as Fig.2 corroborates.

The new likelihood function, including the spin correlation weighting factor, is applied to the three published CDF events. The resulting probability distribution shifts the peaks from the previous analysis, but does not alter the conclusion that the dilepton events indicate a lower mass for the top quark. Fig.3 shows one of the events, illustrating that there is some gain in the sharpness of the distribution.

Without a larger sample of events it is not possible to draw any further conclusions, but the results here should encourage the application of the spin correlation weighting to the analyses of the existing dilepton data.

[1] R. H. Dalitz and Gary R. Goldstein, Phys. Lett. B287, 225 (1992); Phys. Rev. D45, 1531 (1992); Int. J. Mod. Phys. A9, 635 (1994).

[2] Gary R. Goldstein, K. Sliwa and R. H. Dalitz, Phys. Rev. D47, 967 (1993).
Figure Captions

Figure 1: The Log of the joint probabilities vs. $m_t$ given in Ref. [4].
Figure 2: Averaged probability distribution for Monte Carlo events with and without spin correlations.
Figure 3: One CDF dilepton event[5] probability distribution with spin correlations included. See Ref. [4] for uncorrelated case.
\log(\text{Product } P(mt))
