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# Event shape criteria for single-lepton top-quark signals

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Single-lepton plus jets signals from $t\bar{t}$ production at hadron colliders generally give more spherically symmetrical events than the principal backgrounds from $W$ production. We show that sphericity and aplanarity criteria, applied to lepton plus neutrino plus four-jet final states at the Fermilab Tevatron $p\bar{p}$ collider, help to discriminate; they can be used either to validate an eventual top-quark signal or simply to reduce background. An alternative circularity criterion in the transverse plane is less successful.

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The predicted top quark, an essential component of the standard model (SM), is apparently too heavy to have been discovered yet at high energy colliders; the present experimental limit is $m_t > 113$ GeV from the Collider Detector at Fermilab (CDF) [1] and independently $m_t > 103$ GeV from the D0 detector [2]. The consistency of radiative corrections to all electroweak data however indicates that $m_t = 150^{+19}_{-24}{}^{+15}_{-20}$ GeV [3], and hence that the top quark can probably be discovered at the Fermilab Tevatron $p\bar{p}$ collider sooner or later [4]. Here the SM predicts mainly $t\bar{t}$ pair production via QCD with $t \to bW$ decays; the smallest and cleanest signals are expected in two-lepton channels [5, 6], but larger single-lepton [7, 8] and all-jet [9] signals can also in principle be separated from backgrounds. Since the top-quark signals will initially (and perhaps for a considerable time) be based on a small number of events, it will be important to suppress the backgrounds as far as possible in ways that do not seriously reduce the signals. In this note we propose the use of event-shape criteria to distinguish the top signal and reduce backgrounds in the relatively copious single-lepton-plus-4-jet channel.

The underlying idea is that Tevatron $t\bar{t}$ production will be mainly near threshold in the c.m. frame of the lowest-order QCD subprocesses $q\bar{q} \to t\bar{t}$ or $gg \to t\bar{t}$, and hence will mostly lead to rather spherical event shapes in this frame. Phase-space factors favor spherical configurations; the $t\bar{t}$ spin correlations [10] and decay matrix elements introduce a substructure but do not drastically change this spherical tendency, which can help to distinguish the signal from backgrounds. This idea is very familiar in the context of heavy quark searches at $e^+e^-$ colliders and has recently been applied to 6-jet top-quark signals at the Tevatron [9]; we propose here to apply it to lepton-neutrino-4-jet signals from $t\bar{t} \to b\bar{b}WW \to b\bar{b}q\bar{q}'\ell\nu$ decays (where the neutrino is partially measured via transverse energy balance). Backgrounds in this channel from $b$- and $c$-quark semileptonic decays can be removed by lepton $p_T$ and isolation cuts [7]. The major background then comes from $W$ production plus 4 QCD jets, which remains comparable with the signal after all the usual cuts on transverse momenta $p_T$, pseudorapidities $\eta$, and missing transverse energy $\not{E}_T$ [7, 8]; we neglect contributions from $WW$ or $WZ$ plus 2 QCD jets [11] that are an order of magnitude smaller. This background can be further suppressed by requiring a $b$-jet-tag, costing the signal a tagging-efficiency factor of order 0.3 at present [4]. Alternatively, we may expect the inherent collinear singularities to cause spatial correlations of QCD jets with each other and with the beam axis, giving less spherical configurations and hence a discrimination between background and signal via an appropriate choice of event-shape variable as follows.

First we restrict ourselves to momenta in the transverse plane, in order to use the most direct neutrino information contained in its transverse momentum defined by $\mathbf{p}_T(\nu) = \not{\mathbf{E}}_T$. We consider the usual "circularity" event shape variable $C$ defined by

$$C = 2 \min \frac{\sum_i (\mathbf{p}_T^i \cdot \hat{\mathbf{n}})^2}{\sum_i (p_T^i)^2} , \tag{1}$$

summed over the lepton, neutrino, and 4-jet transverse momenta and minimized with respect to the choice of the unit vector $\hat{\mathbf{n}}$. This quadratic variable is unstable against the splitting or combining of jets; although $C$ is well defined for any given jet algorithm, it would be theoretically preferable to use a linearized variable such as

$$C' = \frac{\pi}{2} \min \frac{\sum_i |\mathbf{p}_T^i \cdot \hat{\mathbf{n}}|}{\sum_i |p_T^i|} . \tag{2}$$

Both $C$ and $C'$ are normalized to 1 for an ideal circular event and vanish for a linear configuration.

 

Next we consider event shapes in three dimensions. The longitudinal neutrino momentum $p_L(\nu)$ is not measured; it can be inferred approximately by requiring that the lepton-neutrino invariant mass $m(\ell\nu) = M_W$, but this leaves a twofold ambiguity. We choose the solution that allows the most consistent $t\bar{t}$ reconstruction (details below) and form the conventional normalized $3 \times 3$ momentum tensor

$$M_{ab} = \frac{\sum_i p_a^i p_b^i}{\sum_i (p^i)^2} \tag{3}$$

from the lepton plus neutrino plus 4-jet momenta $p_a^i$ ($i = 1, \ldots 6; a = 1, 2, 3$), in the c.m. frame of these momenta. $M_{ab}$ has three eigenvalues $Q_i$ with $0 \le Q_1 \le Q_2 \le Q_3$ and $Q_1 + Q_2 + Q_3 = 1$; the sphericity $S$ and aplanarity $A$ are then defined by $S = \frac{3}{2}(Q_1 + Q_2)$ and $A = \frac{3}{2}Q_1$. (It would be theoretically preferable to use linearized variables such as thrust and acoplanarity, but for ease of computation we use $S$ and $A$ here.) Thus $S = 2A = 1$ for ideal spherical events, $S = \frac{3}{4}$ and $A = 0$ for plane circular events, and $S = A = 0$ for linear events. We therefore expect the Tevatron top signal to give typically larger $C$, $C'$, $S$, and $A$ than the $W +$ jets background, and have made quantitative parton-level calculations at $\sqrt{s} = 1.8$ TeV to confirm this.

For illustration we compute the $p\bar{p} \to t\bar{t}X$ production and decay distributions in lowest order with full spin correlation effects [10], using the Martin-Roberts-Stirling (MRS) set $S_0$ parton distributions of Ref. [12] evaluated at scale $Q = m_t$, neglecting possible additional QCD jets and taking $\ell + \nu +$ 4-jet final states. The total $t\bar{t}$ production rate is normalized conservatively to the central value of Ref. [13], although values about 20% higher have recently been proposed [14]. We calculate the $W +$ 4-jet background from the full tree-level matrix elements following Ref. [8], evaluating the parton distributions at scale $Q = \langle p_T \rangle$ in accord with Tevatron results [15]. We sum lepton flavors and charges $\ell = e^\pm, \mu^\pm$. We simulate calorimeter errors by Gaussian uncertainties on jet and lepton energies, following the CDF values tabulated in Ref. [16], and calculate the apparent neutrino $p_T$ from overall $E_T$ imbalance. We impose the following acceptance cuts on transverse momenta, pseudorapidities, and jet multiplicity $N_j$, selecting regions where the top-quark signal should be strong:

$$\begin{aligned} &p_T(j) > 20\ \text{GeV}, \quad &|\eta(j)| < 2, \quad &N_j = 4, \\ &p_T(\ell) > 20\ \text{GeV}, \quad &|\eta(\ell)| < 2, \quad &\not{E}_T > 20\ \text{GeV}. \end{aligned} \tag{4}$$

We also set minimum jet-jet and lepton-jet separations,

$$\Delta R(j,j) > 0.7, \qquad \Delta R(\ell, j) > 0.7, \tag{5}$$

where $(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$, to mimic some effects of jet-finding algorithms and lepton isolation cuts [15]. We note that these $\Delta R$ cuts already introduce some event-shape discrimination.

We first compare the shapes of the $C$, $C'$, $S$, and $A$ distributions for $t\bar{t}$ signal and $W+$ jets background, for the case $m_t = 150$ GeV. The means $\mu$ and standard deviations $\sigma$ for the signal (background) are

$$\begin{aligned} \mu(C) &= 0.51\ (0.48), & \sigma(C) &= 0.21\ (0.22), \\ \mu(C') &= 0.68\ (0.66), & \sigma(C') &= 0.14\ (0.15), \\ \mu(S) &= 0.50\ (0.41), & \sigma(S) &= 0.18\ (0.18), \\ \mu(A) &= 0.135\ (0.090), & \sigma(A) &= 0.079\ (0.066), \end{aligned} \tag{6}$$

from which we see that the circularity variables offer little discrimination in this case, whereas the $S$ and $A$ variables show appreciable displacements between signal and background. The $S$ and $A$ distributions are shown in Fig. 1. We see that the signal has significantly different distributions from the background, especially for $A$; this could help to validate an eventual top-quark signal (extracted by $b$ tagging say). Alternatively, cutting out events below a minimum value $S_{\min}$ or $A_{\min}$ would reduce the background more than the signal; integrated cross sections for $S > S_{\min}$ and $A > A_{\min}$ are shown in Fig. 2. We shall illustrate below the effects of a choice

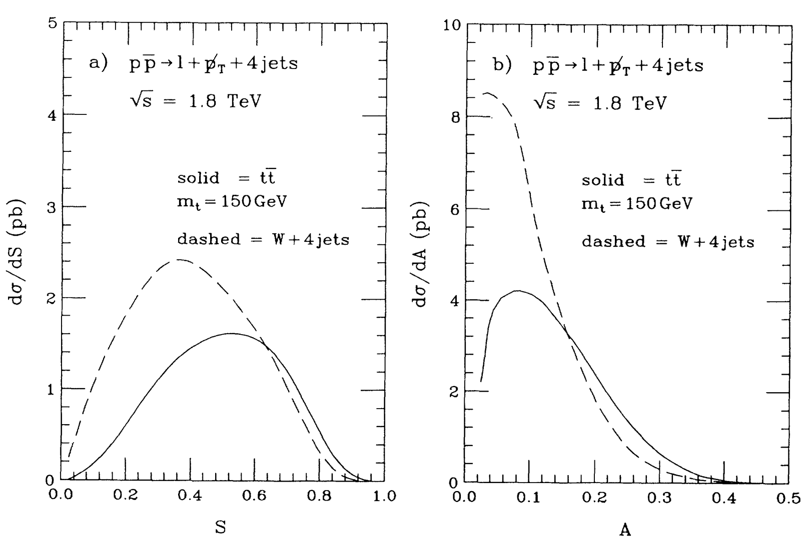


FIG. 1. Sphericity $S$ and aplanarity $A$ distributions for $t\bar{t}$ signal ($m_t = 150$ GeV) and $W +$ jets background, for $\ell + \nu +$ 4-jet events at the Tevatron.

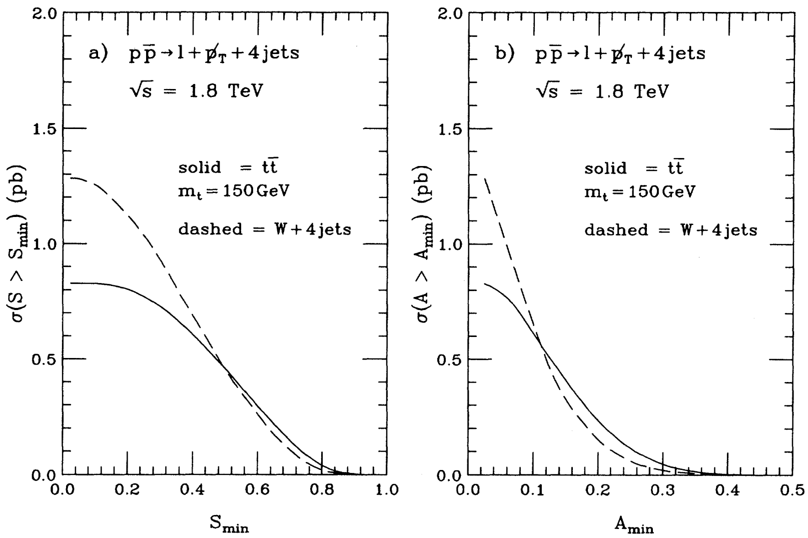


FIG. 2. Integrated signal and background cross sections for (a) $S > S_{\min}$ and (b) $A > A_{\min}$, versus $S_{\min}$ and $A_{\min}$, respectively.

$S_{\min} = 0.20$, $A_{\min} = 0.05$ (not specifically optimized), similar to cuts suggested for all-jet signals [9]; this reduces the signal (background) by 15% (36%), giving a cleaner result and an increase in its statistical significance (signal)/$\sqrt{(\text{background})}$.

To extract a top-quark mass peak, we introduce a constrained event parameterization as follows. We first compute the two solutions for $p_L(\nu)$ by requiring $m(\ell\nu) = M_W$; if they are formally complex, we set the imaginary parts to zero, getting the single nearest-to-on-shell solution. We then select the pair of jets with invariant mass closest to $M_W$, and identify them as the $W \to jj$ decay candidates. The remaining two jets are candidates for $b$ and $\bar{b}$ jets, if this is a $t\bar{t}$ event. From the four possible ways of pairing the latter two jets with our unique $W \to jj$ choice and the two-fold $W \to \ell\nu$ solution, we select whichever pairing gives the closest agreement between the resultant $b+W$ invariant masses. The mean of these two closest $m(bW)$ values is defined as the reconstructed top mass $\tilde{m}_t$ (following the notation of Ref. [5]); taking the mean gives a narrower signal peak than either the semileptonic or the hadronic $m(bW)$ value separately. Our $\tilde{m}_t$ variable differs from those proposed in Refs. [7, 8]. Figure 3 presents the calculated $\tilde{m}_t$ distribution for signal and background, for $m_t$ = 130, 150, and 170 GeV, first with the standard acceptance cuts of Eqs. (4) and (5) (upper curves), and also with the additional event-shape cuts $S > 0.20$, $A > 0.05$ (lower curves). Hadronization effects have not been included, except in their contributions to calorimeter resolution; we expect they will somewhat further smear the $\tilde{m}_t$ peak.

Our results show that (a) $S$ and $A$ distributions of top-quark signals differ significantly from background in the lepton + neutrino + 4-jets channel, (b) these differences could help to validate an eventual top signal or alternatively reduce background and improve significance, and (c) the signal would peak in our reconstructed top mass variable $\tilde{m}_t$.

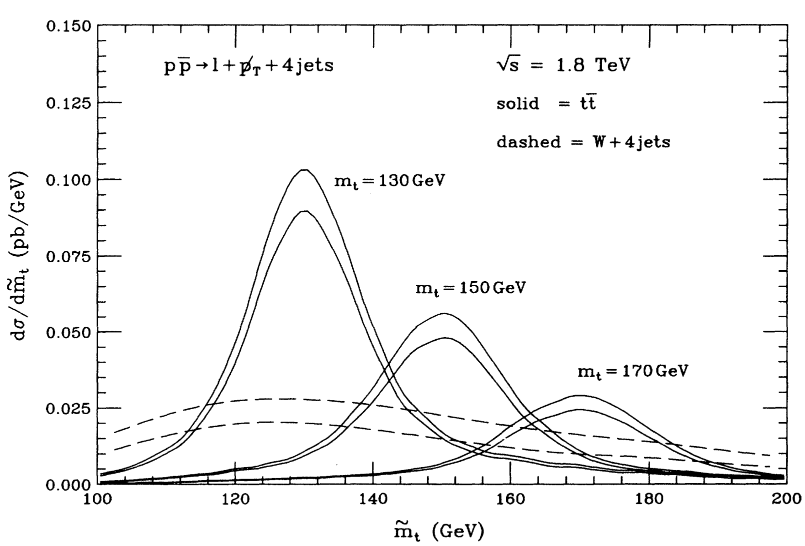


FIG. 3. Reconstructed top-quark mass $\tilde{m}_t$ distributions for Tevatron $t\bar{t}$ signals with $m_t$ = 130, 150, 170 GeV, and $W$+4-jets background. Upper curves are for $S > 0$, $A > 0$; lower curves are for $S > 0.20$, $A > 0.05$.

Event-shape criteria have previously proved promising in the 6-jet channel [9]; they may also have value in lepton-plus-3-jet and dilepton channels.

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[1] CDF Collaboration, A. Barbaro-Galtieri, presented at the International Europhysics Conference on High Energy Physics, Marseille, France, 1993 (unpublished).
[2] D0 Collaboration, M. Narain, in Proceedings of the XXVIIth Rencontres de Moriond, 1993 (unpublished).
[3] P. Langacker, Pennsylvania Report No. UPR-0555-T, 1993 (unpublished).
[4] S. Protopopescu and G.P. Yeh, presented at the Top Physics Symposium, Madison, Wisconsin, 1992 (unpublished).
[5] H. Baer, V. Barger, J. Ohnemus, and R.J.N. Phillips, Phys. Rev. D **42**, 54 (1990), and references therein.
[6] T. Han and S. Parke, Phys. Rev. Lett. **71**, 1494 (1993).
[7] H. Baer, V. Barger, and R.J.N. Phillips, Phys. Rev. D **39**, 3310 (1989).
[8] F.A. Berends, H. Kuif, B. Tausk, and W.T. Giele, Nucl. Phys. **B357**, 32 (1991); F.A. Berends, J.B. Tausk, and W.T. Giele, Phys. Rev. D **47**, 2746 (1993).
[9] J.M. Benlloch, N. Wainer, and W.T. Giele, Phys. Rev. D (to be published).
[10] V. Barger, J. Ohnemus, and R.J.N. Phillips, Int. J. Mod. Phys. A **4**, 617 (1989).
[11] V. Barger, T. Han, J. Ohnemus, and D. Zeppenfeld, Phys. Rev. D **41**, 2782 (1990).
[12] A.D. Martin, R.G. Roberts, and W.J. Stirling, Phys. Rev. D **47**, 867 (1993).
[13] R.K. Ellis, Phys. Lett. B **259**, 492 (1991).
[14] E. Laenen, Report No. FERMILAB-PUB-93/155-T (unpublished).
[15] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **70**, 4042 (1993).
[16] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **45**, 3921 (1992).