SHARPENING UP THE $W \rightarrow t\bar{b}$ SIGNAL

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A B S T R A C T

We investigate distinguishing characteristics of lepton + jet events arising from $W \rightarrow t\bar{b}$ production with $t \rightarrow b\bar{\nu}$ decay at $p\bar{p}$ colliders. In two-jet events transverse masses have joint Jacobian peaks just below and above m_t associated with the t and $\bar{b}$ fragments and just below M_W associated with the $t\bar{b}$ cluster. The lepton + one-jet events of $W \rightarrow t\bar{b}$ origin also give distributions with striking features. Other useful diagnostics for t quark identification are presented, including those of $t\bar{t}$ hadroproduction.

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The search for the t-quark is currently focused on the process

$$\begin{array}{c}
 W \rightarrow t\bar{b} \\
 \quad \downarrow \\
 \quad b\bar{\ell}\nu
 \end{array}
 \tag{1}$$

with the UA1 collaboration reporting¹⁾ charged lepton + 2 jet events which may be of this origin. We have previously identified distinct characteristics of $W \rightarrow t\bar{b}$, such as a Jacobian peak in the transverse momentum of the $\bar{b}$ jet, which make this a particularly favourable configuration for finding the t-quark²⁾. All momenta in process (1) are measurable in the UA1 detector except for the longitudinal neutrino momentum ν_L . Transverse masses were introduced^{2,3)} to allow a model independent analysis which makes full use of the observed momenta (including the measured missing transverse momentum ν_T) and which are independent of the unknown ν_L . A further study is now in order to provide cross checks that can help establish the $W \rightarrow t\bar{b}$ mode and aid in the determination of the t-quark mass, m_t . In this letter we draw attention to a joint Jacobian peak structure which provides a crucial diagnostic for $W \rightarrow t\bar{b}$ candidate events. This test may help to distinguish $W \rightarrow t\bar{b}$ from $t\bar{t}$ hadroproduction³⁻⁹⁾ and other heavy quark backgrounds^{3,5,8)}. The sensitivity of transverse masses to measurement errors on $p_T(\nu)$ is discussed and other diagnostics of the $W \rightarrow t\bar{b}$ source are presented. Lepton + one jet events are an equally interesting $W \rightarrow t\bar{b}$ signal which we also study.

For the sake of clarity we begin with a qualitative discussion of the characteristics of $W \rightarrow t\bar{b}$ lepton + 2 jet events ignoring the W transverse motion and width. In our subsequent quantitative analysis we incorporate these transverse smearing effects and take into account

isolation and acceptance cuts.

A primary characteristic of the two body $W \rightarrow t\bar{b}$ decay is a Jacobian peak²⁾ in the transverse momentum distribution of the narrow $\bar{b}$ jet at

$$\bar{b}_T(\text{peak}) = \left[(M_W^2 + m_b^2 - m_t^2)^2 / (4M_W^2) - m_b^2 \right]^{\frac{1}{2}} \quad (2)$$

which also equals $t_T(\text{peak})$ if the transverse momentum, W_T , of the W boson is neglected. In events with an identified electron or muon this property of the recoil jet is in itself a useful $W \rightarrow t\bar{b}$ signature.

The t -quark produced in conjunction with the $\bar{b}$ also has a distinctive Jacobian peak in the cluster transverse mass³⁾

$$M_T^2(c, \nu) \equiv (c_T^0 + \nu_T)^2 - (\vec{c}_T + \vec{\nu}_T)^2 \quad (3)$$

where $c_T^0 = (\vec{c}_T^2 + m_c^2)^{\frac{1}{2}}$ and m_c is the invariant mass of the cluster; for $t \rightarrow (b\ell)\nu$ the cluster is $b\ell$ and $\vec{c}_T = (\vec{b} + \vec{\ell})_T$. This is an effective 2-body representation of the 3-particle decay, whose Jacobian peak occurs at $M_T(b\ell, \nu) \simeq m_t$. We subsequently use the notation

$$M_T(2) \equiv M_T(b\ell, \nu). \quad (4)$$

The information from the $M_T(2)$ and $\bar{b}_T$ distributions is complementary. To discuss both simultaneously it is advantageous to use, instead of $\bar{b}_T$, the variable $M_T(1)$ defined by

$$M_T^2(1) \equiv M_W^2 + m_b^2 - 2M_W \left[m_b^2 + \bar{b}_T^2 \right]^{\frac{1}{2}}. \quad (5)$$

The Jacobian peak of Eq. (2) thus becomes a peak at $M_T(1) = m_t$.

Neglecting the W transverse motion and width, the kinematic limits of the above two M_T variables are

$$m_t < M_T(1) < M_W - m_b \quad (6)$$

$$0 < M_T(2) < m_t. \quad (7)$$

Thus the $M_T(1)$ distribution bounds m_t from above and the $M_T(2)$ distribution bounds the t-mass from below. On a $d\sigma/dM_T$ versus M_T plot, the Jacobian peaks of the two distributions appear back-to-back at $M_T = m_t$.

In addition we can construct a cluster transverse mass

$$M_T(3) \equiv M_T(\bar{b}b\ell;\nu) \quad (8)$$

which has a Jacobian peak at its upper bound M_W .

We now turn to realistic calculations for $p\bar{p}$ colliders at $\sqrt{s} = 540$ GeV, including effects of the transverse W-motion (using a parametric form which describes the observed W_T distribution¹⁰⁾), the W width (taken to be 2.9 GeV), and measurement uncertainties on the missing neutrino momentum¹⁰⁾. For definiteness we show predictions for $m_t = 40$ GeV throughout, which seems to be compatible with the UA1 t candidate events. We employ isolation and acceptance cuts which are intended to effectively approximate the corresponding requirements in the UA1 analysis¹⁾, along with their jet algorithm which combine jets with $((\Delta\eta)^2 + (\Delta\phi)^2)^{1/2} < 1$. Since the $t\bar{b}$ candidate events all have $\ell_T > 15$ GeV we take this as the p_T cut on the lepton, together with the isolation cut $\Sigma p_T(\text{hadrons}) < 3$ GeV within the cone $((\Delta\eta)^2 + (\Delta\phi)^2)^{1/2} < 0.7$ about the charged lepton direction. Since expected corrections increase by about 20% the detected E_T of the jets, we require in our calculations $j_T > 10$ GeV for all jets. The isolation and jet cuts effectively suppress the lepton + 2 jet backgrounds from $c\bar{c}$, $b\bar{b}$ and their higher order QCD contributions^{3,5,8)}.

In the following we denote the higher and lower p_T jets by j_1 and j_2 , respectively. At present the b and $\bar{b}$ jets are not identified through their quantum numbers, though this should be possible in the future using microvertex detectors. However for m_t not too large the p_T of the $\bar{b}$ recoil jet is almost always larger than that of the b -jet from t -decay (for example 92% of the time for $m_t = 40$ GeV); then the association of the fast jet with $\bar{b}$ is justified. Consequently $M_T(1)$ and $M_T(2)$ will be constructed using the momenta of jet 1 and jet 2 respectively.

For $W \rightarrow t\bar{b}$ events the three upper curves in Figure 1 show the smeared Jacobian peaks in the M_T distributions of Eqs. (4), (5) and (8). The (j_2, ℓ, ν) cluster mass, $M_T(2)$, is insensitive to the smearing effects; it is sharply peaked just below m_t . In the $M_T(1)$ distribution of the fast recoil jet the peak at $M_T(1) \approx m_t + 5$ GeV is less sharp. Thus events of $W \rightarrow t\bar{b}$ origin should dominantly populate the $M_T(2)$ region just below m_t and the $M_T(1)$ region just above m_t . In addition the $M_T(3) \equiv M_T(j_1 j_2 e; \nu)$ distribution should peak just below M_W for $W \rightarrow t\bar{b}$ events. These three Jacobian peaks characterize $W \rightarrow t\bar{b}$ decay.

A reasonable diagnostic of $W \rightarrow t\bar{b}$ events is that the peak regions of these three M_T distributions should be simultaneously populated. A consistency check for a $W \rightarrow t\bar{b}$ candidate data sample is that the peaks in the $M_T(1)$ and $M_T(2)$ distributions should not be separated by more than about 10 GeV. The vertical arrows at the top of Figure 1 indicate the central values for the three M_T distributions for the three electron + 2 jet and three muon + 2 jet UA1 $W \rightarrow t\bar{b}$ candidate events. The data values have substantial uncertainties comparable to those given for the masses quoted in Ref. 1.

With the jet defining algorithm, hadroproduced $t\bar{t}$ pairs also appear part of the time as lepton + 2 jet events. The following electron + n jet cross sections are obtained from $q\bar{q}, gg \rightarrow t\bar{t}$ and $q\bar{q}' \rightarrow W \rightarrow t\bar{b}$ fusion

calculations imposing the UA1 acceptance cuts detailed previously; we assume a semi-empirical enhancement factor $K = 2$ for both sources. The prediction for the $W \rightarrow t\bar{b}$ cross section is tied to the measured $W \rightarrow e\nu$ rate and thus should be reliable.

Table 1: Fusion cross section predictions for $m_t = 40$ GeV (and, for comparison, $m_t = 50$ GeV) with $e_T > 15$ GeV and $j_T > 10$ GeV.

source	$\sigma(\text{electron} + n \text{ jets})$ in pb				
	n=0	1	2	3	4
$t\bar{b}$	1(1)	27(12)	23(23)	-	-
$t\bar{t}$	1(0)	5(2)	20(9)	8(7)	0.5(0.5)

The corresponding number of events in each category can be estimated for the present UA1 data sample by multiplying these numbers by the integrated luminosity of 0.12 pb^{-1} and the lepton detection efficiency which is of order 0.5. The expectation for electron + 2 jet events is of order one event from $W \rightarrow t\bar{b}$ and one from $t\bar{t}$ fusion. The $M_T(2)$ and $M_T(3)$ distributions from $t\bar{t}$ are broad and undistinctive, see Fig. 1; cuts around the $t\bar{b}$ Jacobian peaks can suppress the $t\bar{t}$ contributions appreciably. For comparison purposes we still define $M_T(1)$ for $t\bar{t}$ by Eq. (5) using p_T of the fast jet. This distribution exhibits an enhancement near its upper endpoint due to the relatively lower j_{1T} values in $t\bar{t}$ events.

Accurate measurements of $\vec{v}_T$ are required for cluster transverse mass variables to be useful. To see the sensitivity of M_T to $\vec{v}_T$, we can recast Eq. (3) in the form

$$M_T^2(c, v) = m_c^2 + 2v_T(c_T^2 + m_c^2)^{1/2} - 2\vec{v}_T \cdot \vec{c}_T. \quad (9)$$

The value of the cluster invariant mass m_c is determined by the lepton and jet momenta which are fully measurable. The deviation of the cluster

M_T from m_c is proportional to v_T ; M_T can be larger than m_c only by virtue of non-zero v_T . Similar statements apply to the non-invariant mass variables

$$\begin{aligned} M^2(c v_T) &\equiv (c^0 + v_T)^2 - (\vec{c} + \vec{v}_T)^2 \\ &= m_c^2 + 2v_T(c_L^2 + c_T^2 + m_c^2)^{1/2} - 2\vec{v}_T \cdot \vec{c}_T \end{aligned} \quad (10)$$

used by the UA1 collaboration¹⁾ in their analysis of $W \rightarrow t\bar{b}$ candidate events. In a class of events where the measured $\vec{v}_T$ is consistent with zero within uncertainties, it may be preferable to test the m_c distributions directly, rather than the $M_T(c, v)$ or $M(c v_T)$ distributions.

Figure 2a shows the $M(j_2 \ell)$ and $M(j_1 j_2 \ell)$ distributions for $m_t = 40$ GeV. For $W \rightarrow t\bar{b}$ the peak values occur at

$$\begin{aligned} M(j_2 \ell; \text{peak}) &\approx \frac{3}{4} m_t \\ M(j_1 j_2 \ell; \text{peak}) &\approx \frac{7}{8} M_W. \end{aligned} \quad (11)$$

The $M(j_2 \ell)$ peak value is a useful measure of the t -mass. The $t\bar{t}$ distributions are somewhat broader than $t\bar{b}$, but have maxima at similar M values. For events of $W \rightarrow t\bar{b}$ origin a lower bound on the t -mass is

$$m_t > M(j_2 \ell). \quad (12)$$

If event D comes from W -decay we would infer that $m_t > 42 \pm 7$ GeV.

Another informative invariant mass is $M(j_1 e)$ which combines the t -decay electron with the $\bar{b}$ recoil jet. The $t\bar{b}$ distribution is more sharply peaked than the $t\bar{t}$ distribution as shown in Figure 2(b).

Comparisons with the UA1 events in Figs. 1 and 2 suggest that events B and M_4 are perhaps more likely to be of $t\bar{t}$ than $t\bar{b}$ origin, but of course this assessment does not take into account the experimental measurement uncertainties.

In the transverse plane the $\bar{b}$ recoil jet from $W \rightarrow t\bar{b}$ is preferentially back-to-back with the lepton from t -decay whereas no such correlation occurs in events of $t\bar{t}$ origin. Thus this distribution provides another useful $W \rightarrow t\bar{b}$ diagnostic. The azimuthal distributions $\Delta\phi(\ell j_1)$ are compared in Fig. 3, along with the UA1 $t\bar{b}$ candidate events.

With a large sample of $W \rightarrow t\bar{b}$ events it may be possible to solve $M_W^2 = (j_1 + j_2 + e + \nu)^2$ event-by-event and obtain two solutions for the unknown v_L . Assuming $t \rightarrow j_2 e \nu$ we can then determine two possible solutions for m_t . Moreover we can transform to the W rest frame and test the probability of the solutions against the predicted V-A form for the decay angular distribution,

$$\frac{d\sigma}{d\cos\theta} \propto (1 - v_t \cos\hat{\theta})(1 - v_{\bar{b}} \cos\hat{\theta}) \quad (13)$$

for $W \rightarrow t\bar{b}$, where v_q are the known velocities, $v_{\bar{b}} = 0.99$ and $v_t = 0.59$ for $m_t = 40$ GeV.

We note that lepton + 3 jet events should be dominantly associated with $t\bar{t}$ production although there will be some contribution from $Wg \rightarrow t\bar{b}g$ where the gluon has large p_T . The small rate of the lepton + 3 jet events from Wg has been ignored in table 1.

One observed¹⁾ electron + 3 jet event (5069/192) has a large missing p_T which makes the $e\nu$ transverse mass bound³⁾, $m_t > m_b + M_T(e\nu)$, particularly useful. The transverse mass value is $M_T(e\nu) = 36 \pm 7$ GeV, which implies $m_t > 41 \pm 7$ GeV if the e and ν come from a semileptonic

t decay. A $t\bar{t}$ interpretation of the overall kinematics of this event would seem to imply a t mass somewhat greater than 40 GeV.

As seen from table 1 a substantial fraction of the $W \rightarrow t\bar{b}$ signal occurs in lepton + 1 jet events for the UA1 jet algorithm and $j_T > 10$ GeV cut. The $t\bar{t}$ rate is considerably less in this channel and in addition a higher invariant mass of the single jet cluster would be expected in $t\bar{t}$ events. Backgrounds from $b\bar{b}$ and $c\bar{c}$ and their higher-order QCD corrections are severe at low ℓ_T but can be suppressed by lepton isolation cuts^{3,5,8}). Moreover the missing $\vec{p}_T$ from $b\bar{b}$ (and $c\bar{c}$) events will be aligned with $\vec{\ell}_T$ which is generally not the case for t decay events.

A more stringent test of $W \rightarrow t\bar{b}$ single jet events are the characteristic features of the transverse and invariant mass distributions given in Fig. 4. A large value of $M_T(\ell\nu)$ just below $m_t - m_b$ and a value of $M_T(j\ell;\nu)$ just below M_W would be evidence for a $W \rightarrow t\bar{b}$ event. The $M_T(1)$ distribution of the jet is similar to that shown in Fig. 1 for $W \rightarrow t\bar{b}$ two-jet events. A possible event of this nature was observed by UA1 in their 1982 data sample¹¹⁾; the M and M_T values for this event are indicated on Fig. 4. Taken at face value the j_T and mass values suggest an event of $W \rightarrow t\bar{b}$ origin with a t mass of at least 40 GeV, though the kinematics of the event are statistically unfavoured.

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Figure Captions

- Fig. 1 Transverse mass distributions in lepton + 2 jet events calculated for $W \rightarrow t\bar{b}$ (solid curves) and $t\bar{t}$ fusion (dashed curves) with $t \rightarrow b\ell\nu$ decay, taking $m_t = 40$ GeV. $M_T(1)$ is determined by the p_T of the fast jet (j_1) through Eq. (5). $M_T(2)$ and $M_T(3)$ are the $(j_2\ell; \nu)$ and $(j_1j_2\ell; \nu)$ cluster transverse masses, respectively. For $W \rightarrow t\bar{b}$ the fast jet is almost always the $\bar{b}$ jet and the transverse masses have Jacobian peaks just below m_t for $M_T(1)$, just above m_t for $M_T(2)$, and just below M_W for $M_T(3)$. In contrast $t\bar{t}$ gives broad $M_T(2)$ and $M_T(3)$ distributions. Acceptance cuts of $p_{\ell T} > 15$ GeV and $p_{jT} > 10$ GeV are used in the calculations. The lepton + 2 jet event rates from $t\bar{b}$ and $t\bar{t}$ are taken to have equal normalisation as is about the case for our fusion calculations. The central values of the UA1 $W \rightarrow t\bar{b}$ candidate events are denoted by vertical arrows at the top of the figure; these values have substantial uncertainties: see ref. 1. The UA1 run/event identification numbers for the electron + 2 jet events are B(6301/716), D(7443/509), E(8578/983) and for the muon + 2 jet events are M₁(6639/118), M₃(7935/232), M₄(7658/947).
- Fig. 2 Invariant mass distributions (a) $M(j_2\ell)$ and $M(j_1j_2\ell)$, (b) $M(j_1\ell)$, resulting from $W \rightarrow t\bar{b}$ (solid curves) and $t\bar{t}$ fusion (dashed curves) with $t \rightarrow b\ell\nu$ decay for $m_t = 40$ GeV. The $W \rightarrow t\bar{b}$ mass distributions in (a) peak at approximately $3/4 m_t$ and $7/8 M_W$ respectively. In (b) the distribution from $t\bar{t}$ is concentrated at considerably lower mass values than $t\bar{b}$. The normalisations and data are as in Fig. 1.
- Fig. 3 Distributions in the azimuthal angle $\Delta\phi(j_1\ell)$ between the fast jet and the lepton in $t\bar{b}$ and $t\bar{t}$ lepton + 2 jet events (solid curves) and $t\bar{b}$ lepton + 1 jet events (dashed curve). The angles from the UA1 lepton + 2 jet events are indicated.

Fig. 4 Transverse and invariant mass distributions for lepton +
1 jet events of $W \rightarrow t\bar{b}$ origin. Standard acceptance cuts are
imposed. The mass values corresponding to a $W \rightarrow t\bar{b}$ candidate
event (2282/338) from the 1982 UA1 data sample (ref. 11)
occur at the upper end of the distributions as indicated in
the lower part of the figure.

FIG. 1

INVARIANT MASS DISTRIBUTIONS FOR LEPTON + 2 JET EVENTS

FIG. 3

FIG. 4