DTP/83/6
MAD/PH/99

Finding the t-quark in W boson decay debris

V. Barger^{*,†}, A.D. Martin[†] and R.J.N. Phillips[‡]

[†] Physics Department, University of Durham, South Road,
Durham DH1 3LE, U.K.

[‡] Rutherford Appleton Laboratory, Chilton, Didcot,
Oxon OX11 0QX, U.K.

^{*} Physics Department, University of Wisconsin, Madison,
Wisconsin 53706, U.S.A.

Abstract. We point out a spectacular jet plus electron signature of t-quark production at $\bar{p}p$ colliders via W boson decay $W \rightarrow \bar{t}b$ with subsequent $b \rightarrow \text{jet}$, and $\bar{t} \rightarrow b\bar{\nu}$ decays. The b jet momentum transverse to the beam has a Jacobian peak near $P_T(b) = (M_W^2 - m_t^2)/(2M_W)$; this jet is expected to be highly collimated. Electrons from $\bar{t}$ -decay occur with large momentum components normal to the b jet in the plane transverse to the beam. Both the b Jacobian peak and transverse momenta of the $\bar{t}$ -decay fragments can be used in making further determinations of m_t .

21st February 1983

Events with energetic isolated electrons and missing transverse momentum have been observed at the CERN $\bar{p}p$ collider^{1,2}. Most of these events have a transverse mass $M_T(\text{ev})$ that exceeds the kinematic maximum of 5 GeV for a single b or c decay³. This indicates that high mass particles are produced that decay leptonically or semileptonically. The events without jets are presumed to be due to $W \rightarrow e\nu$ decay^{1,2} giving a Jacobian peak⁴ in $M_T(\text{ev})$ at $M_W = 80 \text{ GeV}$. We have suggested³ that the other observed events (that is those accompanied by jets) are associated with the semileptonic decay $t \rightarrow e\nu b$ of a t-quark, and have estimated its mass to be in the range 25-40 GeV. The rate at which electron plus jet events occur relative to $W \rightarrow e\nu$ indicates a hadronic $t\bar{t}$ production cross section of order 10 nb.

Another source of t-quark events at $\bar{p}p$ colliders is the $W \rightarrow \bar{t}b$ decay, whose rate relative to $W \rightarrow e\nu$ can be reliably predicted given the mass, m_t , of the t-quark and which has a clean experimental signature. In this paper we address the detection of the $W \rightarrow \bar{t}b$ decay mode via the b-decay jet and the electron from the semi-leptonic decay $\bar{t} \rightarrow b\bar{\nu}$. We discuss further methods for determining the t-quark mass using this source.

In the free quark approximation, neglecting QCD corrections, the partial width for $W \rightarrow \bar{t}b$ is related to that for $W \rightarrow e\nu$ by

$$\Gamma(W \rightarrow \bar{t}b)/\Gamma(W \rightarrow e\nu) = 3|U_{tb}|^2(1-x)(1-\frac{1}{2}x-\frac{1}{4}x^2) \quad (1)$$

where $x = m_c^2/M_W^2$, small m_b^2/M_W^2 corrections are omitted. The quark mixing matrix element $|U_{tb}|$ is near unity. Hence for t masses of order 35 GeV, the $W \rightarrow \bar{t}b$ branching fraction is about twice that for $W \rightarrow e\nu$. The problem is to identify the $W \rightarrow \bar{t}b$ channel experimentally.

Two properties of W decay to a heavy quark are particularly promising in this regard, the Jacobian peak of the $W \rightarrow \bar{t}b$ transition and the distribution of fast leptons in semileptonic $\bar{t}$ decays. Since W bosons are produced approximately along the beam axis, by fusion of longitudinal quark-antiquark pairs, the $\bar{t}$ and b are nearly back-to-back in the plane transverse to the beam axis with (equal and opposite) transverse momentum P_T . Hence $d\sigma/dp_T^2$ has a Jacobian peak near the value

$$P_T(\text{peak}) = (M_W^2 - m_c^2)/(2M_W). \quad (2)$$

Accordingly the total momentum of the b -quark (which exceeds the transverse component) is much greater than the b -quark mass and the b decay fragments form a narrow jet.

Opposite the b jet, in the plane transverse to the beam, the fragments from $\bar{t}$ -decay form a much broader jet, since the $\bar{t}$ -quark rest mass is comparable to its total energy. Electrons from semileptonic $\bar{t}$ -decay will thus appear at wide angles to the axis defined by $\vec{p}_{bT}$, which is approximately $-\vec{p}_{eT}$. Such events with a narrow jet and an electron with a high transverse momentum component normal to the jet, as illustrated in Fig. 1, do not arise from other

known heavy quark sources. The measured transverse momenta of the $\bar{t}$ -decay fragments in these events can be used to independently determine the t -quark mass.

In semileptonic decay events for which the electron and neutrino transverse momenta are both measured, the $e\nu$ transverse mass defined by

$$M_T^2(e\nu) = (|\vec{p}_{eT}| + |\vec{p}_{\nu T}|)^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 \quad (3)$$

can alternatively be used to suppress backgrounds from either $W \rightarrow \bar{b}c$ or hadronic $\bar{b}b$ and $\bar{c}c$ production. The transverse mass from $b \rightarrow c e \nu$ decay has the kinematic upper bound

$$M_T(e\nu) \leq m_b - m_c. \quad (4)$$

Such events are thereby eliminated if we make a cut $M_T(e\nu) > 5$ GeV.

We now quantify the salient properties of $W \rightarrow \bar{t}b$ events. In the approximation of $\bar{q}q \rightarrow W$ production by collinear quarks, the Jacobian peak distribution of the b jet is given up to an overall normalization factor by⁴

$$\frac{d\sigma}{dp_T^2} = \int \frac{dM}{M_0} f(M^2) \left((M^2 - m_c^2)^2 - 2p_T^2 M^2 \right) \left((M^2 - m_c^2)^2 - 4p_T^2 M^2 \right)^{-\frac{1}{2}} \quad (5)$$

where $M_0 = p_T + (p_T^2 + m_c^2)^{\frac{1}{2}}$ and terms of order m_b^2/M_W^2 have been neglected. The factor $f(M^2)$ is the Breit-Wigner

resonance shape $f(M^2) = M_W \Gamma_W [(M^2 - M_W^2)^2 + (M_W \Gamma_W)^2]^{-1}$. Figure 2 illustrates the p_T spectrum for $m_c = 25$ and $m_t = 40$ GeV. The analysis of UA1 jet plus electron events suggests that m_t lies between these values.³

The b from $W \rightarrow tb$ first fragments to a B -hadron with momentum and mass close to those of the b quark ($m_B = 5$ GeV), and the primary b polarization is lost. The width of the b jet is determined largely by the kinematics of B decay, which we represent by a free-quark $b \rightarrow c\bar{u}d$ decay with $V-A$ couplings. The kinematical constraint $(p_b - p_1)^2 > (\sum_{j \neq 1} m_j)^2 \approx m_p^2$ where $i, j = c, \bar{u}, d$ etc, leads to the following upper limit on the opening angle of decay fragments relative to the b axis

$$\cos \theta_1 > (2E_b E_1 - m_b^2 - m_1^2 + m_p^2) / (2p_b p_1) > 1 - (m_b^2 + m_1^2) / (2p_b p_1). \quad (6)$$

Since p_b is large, this opening angle is small provided that p_1 is above some low minimum value. In the following we quantify more fully the characteristics of the decay jets.

The momentum distribution transverse to some axis of fragments $i = q, e, \nu$ originating in the decay $Q \rightarrow qe\nu$ of a quark Q is given by Eq. (B17) of ref. 5 to be

$$\frac{d\sigma}{d^2p_{iT}} = \int_{s_1}^{s_2} ds g_1(s) \left[(m_Q^2 + m_1^2 + 2\vec{p}_{iT} \cdot \vec{p}_{Q\bar{T}} - s)^2 - 4E_{iT}^2 E_{Q\bar{T}}^2 \right]^{-1/2} \quad (7)$$

where $g_1(s) = E_1 d\Gamma/d^3p_1$ is the invariant decay distribution and $E_{i\bar{T}} = (|\vec{p}_{iT}|^2 + m_i^2)^{1/2}$, $E_{Q\bar{T}} = (|\vec{p}_{Q\bar{T}}|^2 + m_Q^2)^{1/2}$. For the decay $t \rightarrow b\nu$ via $V-A$ interactions, the $g_i(s)$ are⁶

$$\begin{aligned} g_e(s) &= s^{-1} (m_t^2 - s) (s - m_b^2)^2 = g_1(s) \\ g_\nu(s) &= g_1(s) [2 + (m_t^2 + m_b^2)s^{-1} + 2m_t^2 m_b^2 s^{-2}] = g_2(s) \\ g_b(s) &= (m_t^2 - m_b^2)^2 + s(m_t^2 + m_b^2) - 2s^2 = g_3(s). \end{aligned} \quad (8)$$

The integration limits for Eq. (7) are $s_1 = m_b^2$ and $s_2 = m_t^2 + m_1^2 + 2\vec{p}_{iT} \cdot \vec{p}_{t\bar{T}} - 2E_{iT} E_{t\bar{T}}$. The reality of the square root in Eq. (7) implies limits on $\vec{p}_{iT}$. For $b \rightarrow c\nu$ decay the above formula applies using $g_e(s) = g_2(s)$, $g_\nu(s) = g_1(s)$ and $g_b(s) = g_3(s)$ with the replacements $m_t \rightarrow m_b$ and $m_b \rightarrow m_c$.

The width of the decay jet about its axis is determined by Eq. (7) with $\vec{p}_{Q\bar{T}} = 0$. Figure 3a shows the distribution in the transverse momenta of the decay fragments with respect to the jet axis for $\bar{t}$ or b decays with $m_t = 35$ GeV and $m_b = 5$ GeV. The transverse momenta of the decay fragments i, j, k are bounded by $p_{iT} < \lambda^{1/2} (m_Q^2, m_1^2, (m_j + m_k)^2) / (2m_Q) < m_Q/2$ where $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc$. Hence the b jet is much narrower than that of the $\bar{t}$. It may even be possible to identify some high momentum jets through their widths.

In the transverse half-plane opposite the b , the direction of the electron from $\bar{t}$ -decay provides an additional tag for identification of $W \rightarrow tb$ events. In the

approximation that the $\bar{t}$ and b are back-to-back in the transverse plane, the b jet direction defines the direction of the $\bar{t}$ quark. An important observable is the transverse momentum components of the electron relative to this b -axis which can also be calculated from Eq.(7), for given $\vec{p}_{bT} = -\vec{p}_{tT}$. We define components $[p_N, p_{\parallel}]$ of $\vec{p}_{eT}$ which are normal and antiparallel respectively to the b jet axis $\hat{p}_{bT}$ in the transverse plane. The distributions in each of these components can be found by integration of Eq.(7) over the following ranges. For given p_N in the allowed interval $|p_N| \leq D/m_e$, where $D = \frac{1}{2}(m_t^2 - m_b^2)$, the integration limits on the parallel component are $p_{\parallel} = [D|\vec{p}_{tT}| \pm E_{tT}(D^2 - m_e^2 p_N^2)^{1/2}]/m_t^2$. An acceptance cut $p_{eT} > p_{cut}$ excludes the integration interval $|p_{\parallel}| \leq (p_{cut}^2 - p_N^2)^{1/2}$. For given $p_{\parallel}$ in the allowed interval $-D(E_{tT} + |\vec{p}_{tT}|)^{-1} \leq p_{\parallel} \leq D(E_t - |\vec{p}_{tT}|)^{-1}$ the integration limits on the normal component are $p_N = \pm (D^2 + 2D|\vec{p}_{tT}|p_{\parallel} - m_e^2 p_{\parallel}^2)^{1/2}/E_{tT}$. A p_{eT} acceptance cut excludes the integration interval $|p_N| \leq (p_{cut}^2 - p_{\parallel}^2)^{1/2}$.

Figures 3b and 3c show the predicted distributions of the normal and antiparallel components of $\vec{p}_{eT}$ relative to the $\vec{p}_{bT}$ axis. The effect of a cut $p_{eT} > 10$ GeV is also shown. It can be seen that electrons with normal component $p_N > m_b/2 = 2.5$ GeV are a second tag for $W \rightarrow \bar{t}b$ events. We have also calculated the smearing of these distributions due to W transverse momenta as expected⁷ in QCD and found the effects to be scarcely perceptible. The secondary electrons from $t \rightarrow b \rightarrow e$ and $t \rightarrow b \rightarrow c \rightarrow e$ cascades have been ignored

since they would largely fall below a realistic $p_{eT} > 10$ GeV acceptance cut.

Once $W \rightarrow \bar{t}b$ events have been identified by the above signatures, they can be used to determine the t -quark mass. One method is to use the Jacobian peak of the b jet, as presented in Figure 2. However, for $m_t \sim 35$ GeV $\ll M_W$, it may be difficult to obtain a precise value in this way. A second method to determine m_t is to measure the width and endpoint of the electron p_N distribution.

If the missing transverse momentum carried by the neutrino is also measured, then the transverse mass studies³ offer a third valuable independent determination of m_t , largely insensitive to the transverse motion of the W and t . The transverse mass of a system of particles is defined as $M_T = (\sum_{iT} E_{iT})^2 - (\sum_{iT} \vec{p}_{iT})^2$ where $E_{iT} = (p_{iT}^2 + m_i^2)^{1/2}$. From the electron and neutrino parameters alone we can form the two-body transverse mass $M_T(e\nu)$ with a predictable distribution bounded by $0 \leq M_T(e\nu) \leq m_t - m_b$. If the b jet momentum is also measured, a three-body transverse mass can be defined with $m_b \leq M_T(eb, \nu) \leq m_t$ but now with a very sharp Jacobian peak at the upper end-point $M_T = m_t$. Predicted shapes for these distributions are shown in ref.3.

Finally we briefly address the expected event rate for detecting $\bar{t}$ quarks from $W \rightarrow \bar{t}b$ production with $m_t = 35$ GeV. From eq.(1) and a $t \rightarrow b$ branching fraction of 10%, the rate uncorrected for acceptance is 0.2 times the $W \rightarrow e\nu$ rate. If only events with $p_{eT} > 10$ GeV are accepted, this

rate is reduced by 50%. Even if other acceptance criteria are introduced, it seems quite feasible to study t quarks by this method.

In summary, events in $\bar{p}p$ collider experiments with an electron at high transverse momentum component normal to a narrow jet provide a striking signature of the $W \rightarrow \bar{t}b$ decay mode with $\bar{t} \rightarrow e$ and $b \rightarrow \text{jet}$, which can be usefully employed in making further determinations of the t -quark mass.

We thank David Scott for discussion. We also thank St. Mary's College, Durham for kind hospitality while this work was being carried out. This research was supported in part by the SERC of Great Britain and in part by the University of Wisconsin Alumni Research Foundation, and in part by the United States Department of Energy under contract DE-AC02-76ER00881.

References

1. UA1 Collaboration, Phys. Letters 122B, 103 (1983).
2. UA2 Collaboration, submitted to Phys. Letters B.
3. V. Barger, A.D. Martin and R.J.N. Phillips, Phys. Letters (to be published).
4. V. Barger, A.D. Martin and R.J.N. Phillips, Durham report DTP/83/2.
5. V. Barger, T. Gottschalk and R.J.N. Phillips, Phys. Rev. D16, 764 (1977).
6. V. Barger and R.J.N. Phillips, Phys. Rev. D14, 80 (1976).
7. F. Halzen, A.D. Martin and D.M. Scott, Phys. Rev. D25, 754 (1982); Phys. Letters 112B, 160 (1982).

Figure Captions

Fig. 1. Type of events proposed for detecting t-quarks from $W \rightarrow \bar{t}b$ decay, with b giving a jet and $\bar{t}$ decaying semileptonically.

Fig. 2. The Jacobian peak in the transverse momentum of the b jet from $W \rightarrow \bar{t}b$, with $m_t = 25$ and 40 GeV, taking $M_W = 80$ GeV and $\Gamma_W = 2.9$ GeV.

Fig. 3. Momentum distributions of primary decay fragments of heavy quarks from $W \rightarrow \bar{t}b$ calculated for $m_t = 35$ GeV: (a) b or $\bar{t}$ decay fragment momenta perpendicular to the jet axis defined by the parent quark momentum; (b) $\bar{t}$ decay electron momentum component normal to both the beam axis and the axis of the recoil b-jet from $W \rightarrow \bar{t}b$; (c) $\bar{t}$ -decay electron component antiparallel to the b-jet direction, in the plane transverse to the beam axis. In parts (b) and (c) the solid curves are full distributions and the dashed curves represent the effect of a $P_{\text{ET}} > 10$ GeV acceptance cut, the full distributions scale approximately with m_t , which is the only large mass scale in t-quark decays. Figure (c) has been calculated from eq.(7) with the Jacobian peak value of P_{ET} .

FIG. 1