## Systematic procedures for identifying t quarks in $\overline{p}p$ collider events with a muon and jets

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Substantial rates are predicted for events containing a muon and jets resulting from  $W \rightarrow t\bar{b}$ ,  $Z \rightarrow t\bar{t}$ , and  $t\bar{t}$  hadroproduction, with  $t \rightarrow \mu\nu b$  decay. We investigate selective cuts to reject backgrounds from  $b\bar{b}$ ,  $c\bar{c}$ , and  $c\bar{s}$  production and to identify the *t*-quark events. For example, from a data sample containing 50  $W^{\pm} \rightarrow e^{\pm}\nu$  events, we expect that clean samples of approximately 4  $t\bar{b}$ -(or  $t\bar{b}$ -) and conservatively 4  $t\bar{t}$ -initiated  $\mu^{\pm}$ +jets events can be selected for a *t*-quark mass below 45 GeV. We suggest methods for distinguishing the contributions and for determining  $m_t$ .

We have recently argued<sup>1</sup> that lepton-plus-jet events at the CERN  $\bar{p}p$  collider could be used to identify the t quark and determine its mass. Our methodology there (and in some studies by others<sup>2</sup>) stressed the value of precise missing-transverse-momentum measurements and lepton isolation from the jets, not previously utilized.<sup>3</sup> In the present work we discuss and quantify supplementary techniques for reducing backgrounds due to other heavy quarks and establishing the presence of t-quark contributions, appropriate to the CERN experiments<sup>4</sup> where samples of lepton-plus-jet events have already been found. We shall emphasize muon events, since with present detectors they can be identified down to lower transverse momenta than electrons (e.g.,  $p_{\mu T} \geq 6$  GeV as compared to  $p_{eT} \geq 20$ GeV), allowing larger t-quark event rates.

The principal sources of t quarks are expected to be

$$q\bar{q} \rightarrow W^{\pm} \rightarrow t\bar{b}, b\bar{t}, \ q\bar{q} \rightarrow Z \rightarrow t\bar{t}, \ q\bar{q}, gg \rightarrow t\bar{t},$$
(1)

from which  $t \rightarrow b\mu\nu$  semileptonic decays lead to events with a muon plus jets. The main backgrounds to the signals are expected to come from the heavy-quark processes

$$q\bar{q} \rightarrow W^{\pm} \rightarrow c\bar{s}, s\bar{c}, \quad q\bar{q} \rightarrow Z \rightarrow b\bar{b}, c\bar{c} ,$$

$$q\bar{q}, gg \rightarrow b\bar{b}, c\bar{c} ,$$
(2)

with  $b \rightarrow c \mu v$  and/or  $c \rightarrow s \mu v$  decays.

The high mass of the t quark leads to a number of characteristic features of t decay into muons and jets that allow it to be distinguished from b or c decay. A t jet should be broad, with decay fragments appearing at high  $p_T$  to the jet axis and possibly forming several identifiable subjects; large energy release and high multiplicity are also expected. There are various ways of quantifying these features to select t-quark events. In the present work we use the fact that muons from t decay are on average less collimated with the parent jet axis and more isolated from

other decay jet fragments than muons of the same  $p_T$  from b or c decay.

Our criteria for isolating *t*-quark events at the  $\overline{p}p$  collider are the following: (i) single muon with  $p_T > 8$  GeV, (ii) two or more jets in addition to the muon, each of which has net transverse energy

$$E_T \simeq \sum_i |\vec{\mathbf{p}}_{iT}| > 8 \text{ GeV}$$

(for broad, overlapping jets we require their summed  $E_T$  to be greater than 16 GeV), and (iii) muon isolation in the following sense: in a cone of half-angle  $\theta_{\rm cone} = 30^\circ$  about the muon direction, the net accompanying  $p_T$  from other particles is bounded by

$$\sum_i |\vec{\mathbf{p}}_{iT}| < 3 \text{ GeV} .$$

(This cone covers 7% of the total solid angle.) The muon and the jets serve as a tag for heavy-quark decays. The muon isolation cuts plus the minimum  $p_T$  requirements on the jets effectively eliminate the backgrounds from *b* and *c* quarks, as we shall establish quantitatively. In *b* or *c* decay, it is impossible for a high- $p_T$  muon to have large angular separation from another high- $p_T$  decay fragment *f*; there is a kinematic bound

$$\sin^2 \frac{1}{2}\theta < m_b^2 / (4p_\mu p_f) < m_b^2 / (4p_{\mu T} p_{fT})$$
(3)

on the angle  $\theta$  between  $\mu$  and f. With  $\mu$  and decay fragment transverse momenta above 8 GeV, this bound is about  $\theta < 35^{\circ}$ . Our particular choice of  $p_T$  and angular cuts are sufficient to reject the backgrounds, but other choices could be entertained. The *t* signals are not sensitive to moderate increases in  $\theta_{\rm cone}$  up to 45° (15% of the total solid angle).

We calculate heavy-quark hadroproduction from the lowest-order QCD processes  $q\bar{q}, gg \rightarrow Q\bar{Q}$  (ignoring the

possibility of flavor excitation<sup>5</sup> and nonperturbative effects). For parton distributions we use the  $Q^2$ -dependent fits of Owens and Reya<sup>6</sup> evaluated at  $Q^2 = \hat{s}$ , the invariant mass squared of the  $Q\bar{Q}$  system, with  $\Lambda = 0.3$  GeV and five active flavors in the formula for  $\alpha_s(Q^2)$ . Closely similar results were obtained with the parton distributions of Ref. 7. For the quark masses we take  $m_c = 1.5$  GeV,  $m_b = 4.6$  GeV,  $m_t = 25-45$  GeV. To simulate the effects of multiple gluon bremsstrahlung from the incident quarks, we impose an empirical  $p_T$  distribution on the  $Q\bar{Q}$  system according to

$$dN/dp_T^2(Q\bar{Q}) \propto \exp(-25p_T/\sqrt{\hat{s}})$$
(4)

which approximately represents the content of the formulas of Ref. 8. However, we find that this  $p_T$  smearing has little effect on the results after the above cuts are applied, because the  $b\bar{b}$  and  $c\bar{c}$  contributions are eliminated and the  $t\bar{t}$  contributions are already broad in  $p_T$ . The heavy quarks are presumed to fragment into heavy spinless or unpolarized hadrons, of the same masses as the quarks. Fragmentation is implemented by the model of Peterson, Schlatter, Schmitt, and Zerwas,<sup>9</sup> with probability distribution

$$D(z) = (\text{constant}) / \{ z [1 - 1/z - \epsilon/(1 - z)]^2 \}, \quad (5)$$

where z is the hadron/quark c.m. momentum fraction and  $\epsilon$  is a parameter proportional to  $1/m_Q^2$ ; data on c and b production are consistent with  $\epsilon = 0.15 (m_c^2/m_Q^2)$ , which we adopt.

The heavy-hadron decay is represented by the spin average of the corresponding free-quark V - A decay, for both semileptonic and hadronic modes. We take account of all the branches of the  $t \rightarrow b \rightarrow c \rightarrow s$  cascade decay sequences that are unsuppressed by mixing angles or phase space, as previously described in the third paper of Ref. 1. Any heavy quark produced in a decay stage is taken to fragment into a corresponding heavy hadron which in turn decays as above; the semileptonic  $Q \rightarrow Q' \mu v$  branching fraction is taken to be 10% at each stage, consistent with data and the standard model. We find that the high- $p_T$ "trigger muon" that characterizes the events of interest comes dominantly from primary  $Q \rightarrow Q' \mu v$  decays rather than from subsequent cascades.

Similarly, we calculate W and Z contributions via the lowest-order processes  $q\bar{q}' \rightarrow W$ ,  $Z \rightarrow Q\bar{Q}'$ , adding the same  $p_T$  smearing for multiple gluon bremsstrahlung and including fragmentation and cascade decays for the heavy quarks as before. We calculate the W,Z decay branching fractions assuming just three generations of quarks and leptons and normalizing to a cross section  $\sigma(p\bar{p}\rightarrow W^{\pm}$  $\rightarrow e^{\pm}v)=0.56$  nb at  $\sqrt{s}=540$  GeV compatible with present data;<sup>4</sup> this normalization corresponds to a K factor of 2 in the fusion subprocess.

For each cross-section contribution we apply the muon isolation cut to the light quarks and leptons at the end of the cascade process; the effects of the further angular smearing in the light-quark hadronization should be unimportant for the large value of  $\theta_{\rm cone}$  that we use.

One further source of background not specifically addressed above, which deserves more theoretical attention, is  $b\overline{b}$  production accompanied by the radiation of a hard gluon. With this process, b decay to a hard muon and soft hadrons may not be rejected by the isolation cuts (ii) and (iii), if  $\overline{b}$  and the gluon are the recognized jets. However, calculations based on Eq. (4) indicate that this background is negligible for our choice of cuts, which were partly motivated by this consideration.

The assumptions and approximations above are realistic and reasonable for an initial approach. Our calculations are intended to estimate the *t* signals and *b,c* backgrounds well enough to show that they can be separated. Table I summarizes the cross sections for heavy-quark production via the various mechanisms and the resulting  $\mu^{\pm}$  rates after heavy-quark decays with our acceptance cuts.

Figure 1 shows the calculated  $p_T$  distributions for  $\mu^{\pm}$ from heavy-quark production and decay, with and without the acceptance cuts described above. The muon spectrum from direct  $W^{\pm} \rightarrow \mu^{\pm} \nu$  decay is also given for comparison. Without cuts, it can be seen that the  $t\bar{t}$  and  $t\bar{b}$ signals are liable to be swamped by backgrounds from  $b\bar{b}$ (and  $c\bar{c}$  which is similar). With our proposed cuts, however, the backgrounds are suppressed to a negligible level for  $p_{\mu T} > 8$  GeV (which is also one of our cut criteria) while the t-decay signals are not greatly reduced. We note that the  $W \rightarrow t\overline{b} \ (\overline{tb})$  contribution with  $\overline{b} \ (b)$  semileptonic decay is suppressed as well. Thus, using our methodology a clean t signal of appreciable size can be separated: see Table I. To quantify, in a data sample containing 50  $W^{\pm} \rightarrow \mu^{\pm} v$  events, there should be of order 4  $t\overline{b}, b\overline{t}$  and 4  $t\overline{t}$ events with an isolated identified muon, if  $m_t = 35$  GeV.

Once a clean t signal has been experimentally established in the above manner, the next step is the separation of  $t\overline{t}$ - and  $t\overline{b}$ -initiated events; the former should be characterized by two broad, possibly overlapping jets while the latter should contain an energetic, relatively narrow b jet. Beside broadness, multiplicity and other characteristics can also help to distinguish between t and b jets. One quantitative measure of the broadness of a jet, that may

TABLE I. Estimated cross sections for heavy-quark production in  $\overline{p}p$  collisions at  $\sqrt{s} = 540$  GeV, and for the heavy-quark decays into muons with acceptance cuts described in the text. Blank entries have values below  $10^{-3}$  nb.

		$\sigma$ (nb)	$B(\mu^{\pm})\sigma$ (nb) after cuts
$\overline{p}p \rightarrow W^{\pm}$	$t \to t \overline{b}, b \overline{t}$ (25)	1.4	0.034
	$\rightarrow t\overline{b}, b\overline{t}$ (35)	1.2	0.038
	$\rightarrow t\overline{b}, b\overline{t}$ (45)	0.9	0.045
	$\rightarrow c\overline{s}, s\overline{c}$	1.7	
<i>p̄p→Z</i>	$\rightarrow t\bar{t}$ (25)	0.13	0.006
	$\rightarrow t\bar{t}$ (35)	0.08	0.005
	$\rightarrow t\bar{t}$ (45)	0.02	0.001
	$\rightarrow b\overline{b}$	0.22	
	$\rightarrow c\overline{c}$	0.18	
<i>₱</i> ₽→ <i>qq</i> ,	$gg \rightarrow t\bar{t}$ (25)	2.9	0.052
	$\rightarrow t\bar{t}$ (35)	0.57	0.036
	$\rightarrow t\bar{t}$ (45)	0.16	0.018
	$\rightarrow b\overline{b}$	6×10 <sup>3</sup>	0.001
	$\rightarrow c\overline{c}$	3×10 <sup>5</sup>	



FIG. 1. Calculated muon  $p_T$  distributions from heavy-quark production and decays in  $\overline{p}p$  collisions at  $\sqrt{s} = 540$  GeV, with  $m_t = 35$  GeV: (a) without cuts, (b) with the acceptance cuts described in the text. The  $t\bar{t}$  and  $b\bar{b}$  curves include both fusion and Z sources;  $c\bar{c}$  results are similar to  $b\bar{b}$  in the  $p_T$  range shown. The  $W^{\pm} \rightarrow t\bar{b}$ ,  $b\bar{t}$  contributions (denoted in the figure by tb) are separated into two parts, according to whether the muon comes from t or b decay. All rates are summed over  $\mu^+$  and  $\mu^-$ . For comparison the  $\mu^{\pm}$  spectrum from direct  $W^{\pm} \rightarrow \mu^{\pm} \nu$  decay is also shown. The cross-hatched region  $p_{\mu T} < 8$  GeV is excluded by our experimental identification requirements.



FIG. 2. Calculated  $p_T$  distribution of the higher- $p_T$  jet in  $t\overline{b}$  and  $t\overline{t}$  events with  $t \rightarrow b\mu\nu$  decay, for  $m_t=35$  GeV, with full acceptance cuts.

apply event by event, is the sum of the moduli of the transverse momenta  $p_{\perp}$  of the constituents relative to the jet axis. A lower bound can be estimated, based on the energy release in heavy-quark Q decay, by assuming that the ultimate light particle decay configurations are distributed isotropically in the Q rest frame; then the particle momenta  $|\vec{p}_i|$  sum to  $m_Q$  and integrating the Jacobian factor gives

$$\left\langle \sum_{i} | \vec{\mathbf{p}}_{i\perp} | \right\rangle = \pi m_{\mathcal{Q}} / 4 , \qquad (6)$$

which is indeed reproduced by our cascade decay calculations. An additional fragmentation contribution of order 5 GeV (as seen in high- $p_T$  jets at the  $\bar{p}p$  collider<sup>10</sup>) must be folded in, but this is small compared to the above contribution of about  $0.8m_t$  from t-quark energy release. The t jet may sometimes be resolvable into subjects bud,  $bv\bar{\tau}$ ,  $bv\bar{e}$ , etc., which could also aid in the  $t\bar{t}, t\bar{b}$  separation.

Kinematic characteristics provide further means of distinguishing between  $t\bar{t}$  and  $t\bar{b}$  events. For  $W \rightarrow t\bar{b}$  with  $t \rightarrow b\mu\nu$  decay, the muon is accompanied by narrow b and  $\bar{b}$  jets, of which  $\bar{b}$  usually has high  $p_T$  with a Jacobian peak<sup>1</sup> near

$$p_T(\bar{b} \text{ jet}) \simeq (M_W^2 - m_t^2)/2M_W$$
 (7)

In practice it may not be possible to recognize which jet is  $\overline{b}$ ; however, this Jacobian peak remains evident in the  $p_T$ 



FIG. 3. Calculated invariant-mass distribution of muon plus jets in (a)  $t\bar{t}$  events and (b)  $t\bar{b}$  events, with  $t \rightarrow b\mu\nu$  decay, including muon and jet acceptance cuts. If  $m_t$  is above (below) about 35 GeV, there are more (less)  $t\bar{b}$ - than  $t\bar{t}$ -initiated events.

distribution of the higher- $p_T$  jet in these events, as shown in Fig. 2. This provides one means of determining  $m_t$ . For comparison, Fig. 2 also shows the  $p_T$  distribution of the higher- $p_T$  jet in  $t\bar{t}$  events, which shows no such Jacobian enhancement. Complications from additional gluon bremsstrahlung jets will be absent in most events, due to our jet acceptance cut.

Assuming that the above considerations largely separate  $t\bar{t}$  from  $t\bar{b}$  events, we investigate further distributions to ascertain the t mass. Figure 3 shows the invariant-mass distribution of the muon + jets, where the jets are defined as the light quark and lepton by-products of the cascade decays. For  $t\bar{t}$  events, the position of the maximum increases with  $m_t$ . For  $t\bar{b}$  events, on the other hand, the maximum occurs 10–20 GeV below  $M_W$  and is rather insensitive to  $m_T$ .

We have previously advocated<sup>1</sup> the use of transverse masses, incorporating the missing neutrino transverse momentum, as a powerful means of determining  $m_t$  from collider data. With our  $b\bar{b}$  veto cuts described earlier, there need be no concern about backgrounds<sup>2</sup> from  $b\bar{b}$ events with poorly measured missing  $p_T$ . Figure 4(a) illustrates the expected distributions for the  $\mu\nu$  transverse mass, where  $\nu$  denotes the total missing  $p_T$  from the primary and cascade neutrinos, which can be measured. The  $M_T(\mu\nu)$  distribution falls sharply off just below  $m_t - m_b$ ; the small tail above this drop-off is of multiple neutrino origin.<sup>1</sup>

For  $t\overline{b}$  events in which the recoil  $\overline{b}$  jet and the b jet from semileptonic t decay are experimentally distinguished, it is also useful to form a cluster<sup>1</sup> transverse mass  $M_T(b\mu;\nu)$ where b denotes the system of visible decay particles from



FIG. 4. Expected transverse- and invariant-mass distributions for  $m_t=35$  GeV. (a)  $\mu\nu$  transverse mass; (b) cluster  $(b\mu)\nu$  transverse mass; (c) invariant mass of visible particles from t decay.

the  $t \rightarrow b\mu\nu$  cascade. This quantity has a sharp Jacobian peak at  $m_t$  with a small tail due to neutrinos from the recoil  $\overline{b}$  cascade. Figure 4(b) shows this distribution. Similarly for  $t\overline{t}$  events in which the recoil  $\overline{t}$  jet is experimentally separated from the b jet of the t decay, we can construct  $M_T(b\mu;\nu)$  whose distribution is also shown in Fig. 4(b). For this class of events, we can also form the invariant mass of the recoiling  $\overline{t}$  jet, as given in Fig. 4(c); approximately half the events, with fully hadronic decay cascades, occur in a sharp peak (within 1 GeV of  $m_t$ ) that will, however, be broadened by fragmentation effects and experimental resolution; events with missing neutrinos in the recoil  $\overline{t}$  jet provide the tail below  $m_t$ .

In summary, the prospects for identifying and studying the t quark at the CERN  $\overline{p}p$  collider appear to be excellent. The high- $p_T$  muon-plus-jets topology is especially promising. By imposing the appropriate cuts it is possible to retain a large fraction of the t-quark decay events while essentially eliminating the background from b- and c-

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quark decays. In a data sample containing 50  $W^{\pm} \rightarrow e^{\pm} v$ events, a total of about 8  $t\bar{b}$ ,  $t\bar{b}$ , and  $t\bar{t}$  events should survive our acceptance cuts if the mass  $m_t$  is below 45 GeV. Our suggested systematic procedures should therefore be a viable means to establish the existence of the t quark and to estimate its mass.

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