Detecting t-quark pairs at $\bar{p}p$ colliders using transverse dilepton masses and jets

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Hadronic $t\bar{t}$ production with semileptonic decays of either or both t and $\bar{t}$ quarks gives distinctive transverse-momentum correlations of electrons (or muons) and neutrinos. Multiple semileptonic modes of the $t \to b \to c \to s$ decay cascades are statistically quite probable, but explicit calculations show that they scarcely affect the $e\nu$ correlations. Opposite-sign dileptons, coming mainly from primary semileptonic decays of t and $\bar{t}$ together, have correlations that also reflect the t-quark mass, but less decisively than the $e\nu$ correlations. Events with large missing p_T and no identified leptons are also expected, at a rate comparable to high-p_T charged leptons. Distinctive broad jet signatures are also expected for all these events, with specific correlations of the trigger lepton and jet momenta.

We have pointed out[1] that high-p_T electron events with jets and missing transverse momentum, observed at the CERN $p\bar{p}$ collider,[2] suggest hadronic production of $t\bar{t}$ quark pairs with mass $m_t \sim 25$–40 GeV. Although the bulk of the UA1 "electron plus jet" events do not apparently contain the expected signature of a "wide" recoiling t jet (or indication of a b jet accompanying the electron),[3] this class of events is extremely promising for t-quark investigations and deserves the most careful consideration. Our previous analysis was based on a comparison of the transverse mass $M_T(e\nu)$ and missing p_T of these events with theoretical expectations for a single $t \to be\nu$ decay; the resulting $M_T(e\nu)$ distribution has a sharp end point at $M_T = m_t - m_b$.

In this paper we address the added complications from multiple semileptonic decays, involving $t \to b \to c \to s$ cascades with semileptonic possibilities at each stage, and from the semileptonic modes of the accompanying $\bar{t}$ quark. These complications would be absent if all charged leptons were identifiable in the collider experiments (so that multiple semileptonic decays could be eliminated). In practice, however, current experiments[2,4] do not generally identify electrons with transverse momentum less than 10 GeV or muons with transverse momentum less than 4 GeV, approximately. We show that a generalized transverse mass $M_T(e\nu)$, where ν now refers to the vector sum of all decay neutrino momenta, has a distribution similar to that of the primary $t \to be\nu$ decay, with a small tail extending above the previous end point $M_T = m_t - m_b$. We further explore other signatures of $t\bar{t}$ events, such as jets and e^+e^- pairs and large missing p_T without identified leptons.

An electron at high transverse momentum p_T, which is not within a narrow jet, is a tag for $t \to be\nu$ decay [or $W \to e\nu$, which can, however, be calibrated[1,5] through its distinctive Jacobian peak in $M_T(e\nu)$]. We use the term electron generically to denote both e^+ and e^-. Secondary electrons from $t \to b \to ce\nu$, etc., are much softer than the primary electrons and are largely eliminated by the experimental requirement of high p_T, typically[2,4] $p_{eT} > 15$ GeV. Electrons from hadronic $b\bar{b}$ production with $b \to ce\nu$, etc., must lie within a well-collimated b jet and can be so rejected; the angle θ between the electron and parent b momenta has the kinematic bound $\sin\theta < m_b/(p_e p_b)^{1/2}$. Accordingly, the existence of non-W events with isolated high-p_T electron and wide jets immediately signifies the possibility that t quarks are produced. Putting it another way, it is well established that heavy-quark contributions are likely to dominate in high-p_T electron production[6]; then the more isolated electrons signify heavier parents. Figure 1 illustrates some expected properties of heavy-quark production and decay at the CERN $p\bar{p}$ collider.[7] Our calcula-

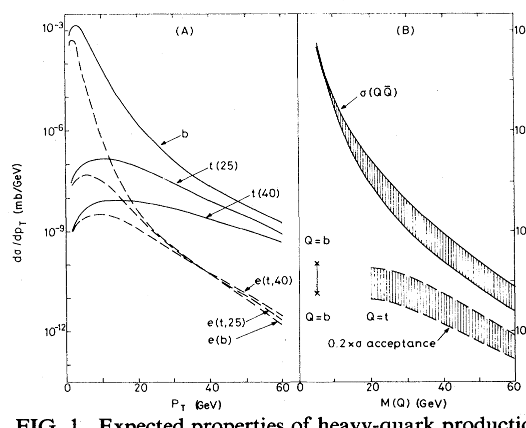

FIG. 1. Expected properties of heavy-quark production at the CERN $\bar{p}p$ collider, $\sqrt{s} = 540$ GeV. (A) p_T distributions of b and t quarks and their primary decay electrons, for $m_t = 25$ and 40 GeV. (B) Cross section for $b\bar{b}$ and $t\bar{t}$ production versus quark mass (solid curves) and the same multiplied by $e^{\pm}$ branching fraction 0.2 and acceptance factor for $p_T(e) > 15$ GeV (dashed curves and crosses). All curves in (A) and the lower curves in (B) are calculated with Q^2-dependent parton distributions as described in the text; the upper curves in (B) are calculated with a scaling gluon distribution, to suggest the scale of uncertainty.

tions use quark-antiquark plus gluon-gluon QCD fusion production with the Q^2-dependent parton distributions of Owens and Reya,[8] taking $Q^2=\hat{s}$ (the subprocess invariant energy square) and scale $\Lambda=0.5$ GeV. We assume hadronization of the heavy quarks through hard $\delta(1-z)$ fragmentation functions[9] to spinless or unpolarized hadrons and bare-quark $V-A$ matrix elements for decay. Flavor excitation diagrams[10,11] are hard to calculate reliably for heavy quarks and are omitted; in the c-quark case[11] they give similar p_T dependence to our treatment through the first two decades. Figure 1(A) shows the p_T spectra of parent quarks and decay electrons (these are broader than empirical forms used in Ref. 1). The width of the electron distribution is a measure of the quark mass, modulo uncertainties in the hadroproduction mechanism. Figure 1(B) gives the production cross section $\sigma(Q\bar{Q})$ versus heavy-quark mass (solid curves) and the effect of including $e^{\pm}$ branching fraction 0.2 and acceptance for $p_t(e)>15$ GeV (dashed curves and crosses). The lower curves are for our standard calculation above; the upper ones come from using scaling gluon distributions

$$G(x)=3(1-x)^5/x$$

and suggest the scale of uncertainty. This figure is to illustrate general trends; the absolute value of the cross section is not reliable, due to missing diagrams and various possible parameter adjustments.[12]

By the same token, large isolated missing p_T is also a tag for t decay; because of the $V-A$ matrix elements, the contributions from t decay are more important (relative to b decay) here than in the case of high-p_T electrons.

Given an isolated high-p_T trigger lepton (e^+ say), we accordingly attribute it to the primary decay $t\to be\nu$ of a hadronic $t\bar{t}$-production event (the contribution from $W\to t\bar{b}$ will differ in having a narrow away-side jet[13]). There is therefore at least one decay neutrino giving missing transverse momentum. For a more realistic assessment of the missing momentum, however, we must also take account of additional neutrinos associated with unidentified charged leptons in the various cascade-decay options:

$$t\to b(e\nu,\mu\nu,\tau\nu,c\bar{s},u\bar{d}),\quad b\to c(e\nu,\mu\nu,\bar{u}d)\ ,$$
$$c\to s(e\nu,\mu\nu,u\bar{d})\ ,\quad \tau\to\nu(e\nu,\mu\nu,u\bar{d})\ , \tag{1}$$

omitting for simplicity decay modes that are disfavored by quark mixing angles or by phase space. We have developed a Monte Carlo program to calculate the production of $t\bar{t}$ pairs by QCD fusion and their complete cascade decays, including all the options listed in Eq. (1). We assume 10% branching fractions for each semileptonic mode, except in τ decay where they are 20%. Bare-quark $V-A$ matrix elements are used, including the W propagator, with δ-function fragmentation at each step for the heavy quark. We assume a cut p_{eT}(trigger) >15 GeV following Refs. 2 and 4; we also assume that secondary charged leptons are identified if and only if p_{eT}(secondary) >10 GeV and $p_{\mu T}$(secondary) >4 GeV. Although the probability of neutrino emission in any single stage of the cascade decays is small, the net probability that one or more extra neutrinos are emitted (beyond the primary neutrino from the $t\to be\nu$ trigger process) is considerable. Without cuts, the probability that the trigger e^+ is accompanied by purely hadronic decays through the rest of the cascades is only 26%. With the charged lepton-identification cuts above, however, the probability of further semileptonic decays *without extra identified charged leptons* is 48–54 %, bringing the apparent single-e^+ rate up to 74–80 %, for $m_t=40$–25 GeV. Thus about two-thirds of these events have extra neutrinos in them. However, most of these extra neutrinos have low-p_T values, and in fact we find that a transverse-mass analysis based entirely[1] on the primary $t\to be\nu$ decay remains a reasonable first approximation.

Folding in the acceptance cut for the trigger e^+, we calculate that 4–15 % of $t\bar{t}$-production events at $\sqrt{s}=540$ GeV will give a single $e^{\pm}$ with $p_T>15$ GeV and no other leptons above the assumed identification thresholds, for $m_t=25$–40 GeV.

The transverse mass $M_T(e\nu)$ of a primary electron and a collection of neutrinos ν_i with transverse momenta $\vec{p}_{iT}$ is defined by[1,2,5,14]

$$M_T{}^2(e\nu)=(\,|\,\vec{p}_{eT}\,|+|\,\Sigma\vec{p}_{iT}\,|\,)^2-|\,\vec{p}_{eT}+\Sigma\vec{p}_{iT}\,|^2\ . \tag{2}$$

M_T has the important property of being bounded by the invariant mass M_I of the $e\nu$ system considered; this in turn is bounded by the invariant mass of the parent $t\bar{t}$ system. In the $q\bar{q}\to t\bar{t}$ and $gg\to t\bar{t}$ QCD fusion processes, the

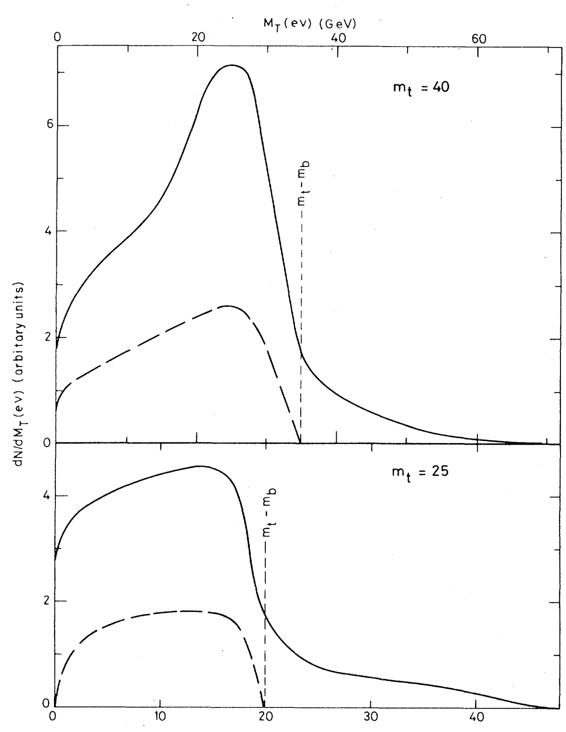

FIG. 2. Distributions of transverse mass $M_T(e\nu)$ in single-visible-electron events, where ν is the vector sum of all neutrino momenta, for $m_t=25$ and 40 GeV and $\sqrt{s}=540$ GeV. Solid curves are the full distributions including multiple semileptonic decays with unidentified extra charged leptons; dashed curves are the contributions from true single-electron events, with $p_T(e)>15$ GeV.

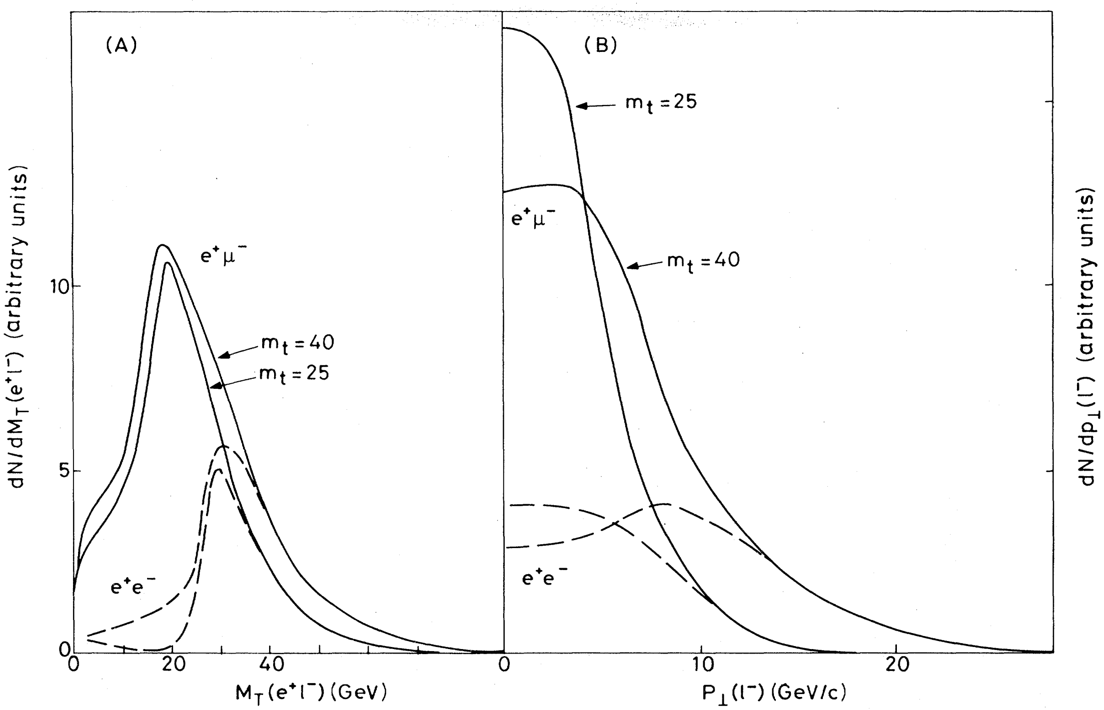

FIG. 3. (A) Distributions of transverse mass $M_T(e^+e^-)$ and $M_T(e^+\mu^-)$ for a trigger e^+ with $p_T > 15$ GeV and a second opposite-sign lepton above the identification threshold $p_T(e) > 10$ GeV, $p_T(\mu) > 4$ GeV. (B) Distributions of secondary e^-, μ^- lepton momentum components $p_\perp$ perpendicular to the trigger e^+ momentum in the transverse plane. We take $\sqrt{s} = 540$ GeV and $m_t = 25$ and 40 GeV.

$t\bar{t}$ invariant mass peaks close to threshold. Our calculations at $\sqrt{s} = 540$ GeV with $m_t = 25$–40 GeV indicate that 95–97% of the $t\bar{t}$ production occurs within $M_I(t\bar{t}) \le 4m_t$; hence the $M_T(e\nu)$ distribution is confined essentially within this range, but the precise shape is a matter for detailed calculations. The QCD fusion mechanisms are not expected to give a complete picture of $t\bar{t}$ hadroproduction; flavor excitation diagrams may affect the rate (though apparently not the p_T dependence); light-quark pickup and recombination during hadronization may also affect the longitudinal distributions of final hadrons containing t. However, for transverse quantities such as M_T which rely on p_T dependences only, the QCD fusion mechanisms provide a reasonable theoretical basis; the fact that the $t\bar{t}$ invariant mass is close to threshold confirms their relevance.[15]

Figure 2 shows the distributions of transverse mass $M_T(e\nu)$ calculated for $m_t = 25$ and 40 GeV. The solid curves resulting from the full (multineutrino) analysis are very similar in shape to the dashed curves, which correspond to the subset of events with a single semileptonic decay $t \to be\nu$ (all other decays being hadronic) and which are therefore bounded by $M_T \le m_t - m_b$. They are similar because the additional neutrinos are mostly rather soft and displace the value of M_T rather little. However, a component of more energetic neutrinos, coming mainly from the associated $\bar{t} \to \bar{b}e\nu$ decay, add a small tail to the distribution. Figure 2 demonstrates clearly that the $M_T(e\nu)$ distribution is a good way to determine the t-quark mass.

If the b jet from $t \to be\nu$ decay can be identified and measured experimentally, it is possible to construct and study a three-body transverse mass $M_T(e,\nu,b)$ and a "cluster" transverse mass $M_T(eb,\nu)$ where the eb system is treated as a single entity, as described in Ref. 1. These quantities have the advantage of peaking sharply at their upper end point $M_T = m_t$, giving a clean indication of the t-quark mass, in the case of a single semileptonic decay. Our Monte Carlo analysis shows that these crucial features are little changed in the general case when multiple semileptonic possibilities are included. These M_T distributions (shown in Ref. 1 and not repeated here) suffer only a slight broadening of the peaks and the addition of small tails beyond the previous end point.

The events discussed so far have only one identified $e^\pm$ (or $\mu^\pm$); any other charged leptons are below their identification thresholds. Another important and interesting class of events is those with several identified charged leptons.[6,16–18] In our calculations, assuming a trigger e^+ with $p_T > 15$ GeV the probabilities for observing an additional e^+, e^-, μ^+, and μ^- are 0.6–0.8%, 4–6%, 3.3–3.7%, and 10–14%, respectively, for $m_t = 25$–40 GeV; the probability that three or more charged leptons are present and identified is 1–2%. Leptons of opposite sign to the trigger electron have a broader p_T distribution and hence a greater chance of being identified, thanks to the primary semileptonic decay of the associated $\bar{t}$ quark.

Figure 3(a) shows the transverse-mass distribution of opposite-sign pairs $e^+\mu^-$, e^+e^-. These distributions are strongly dependent on the trigger cut $p_T(e^+) > 15$ and identification thresholds $p_T(\mu^-) > 4$ GeV, $p_T(e^-) > 10$ GeV that are used in our calculations, as can be seen by comparing the $e^+\mu^-$, e^+e^- cases which differ simply by

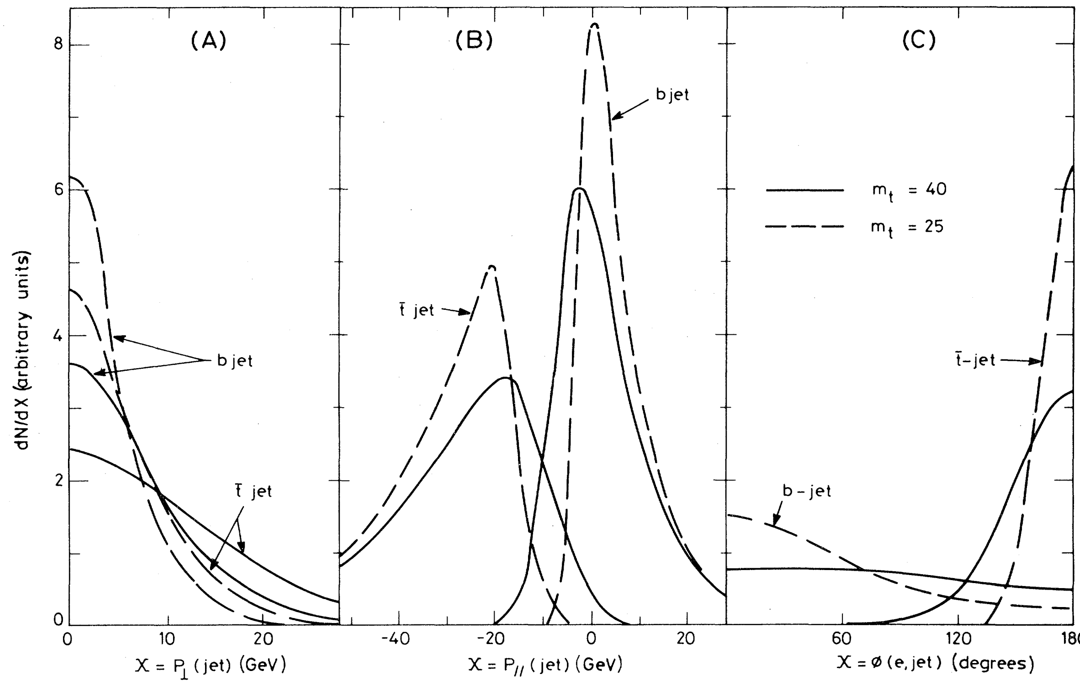

FIG. 4. Correlation of b and associated $\bar{t}$ jets from $t \to be\nu$, in the transverse plane with the direction of a trigger e^+ having $p_T(e^+) > 15$ GeV. Distributions are shown with respect to (A) $p_\perp$(jet), the jet-momentum component perpendicular to e^+, (B) $p_{||}$(jet), the component parallel to e^+, (C) $\phi(e, \text{jet})$, the angle between the electron and jet directions. Solid and dashed curves denote results for $m_t = 40$ and 25 GeV, respectively; $\sqrt{s} = 540$ GeV.

the secondary-lepton identification criterion. In fact, the position of the peak is essentially determined by these cuts and the mass m_t is manifested only in smaller details. Figure 3(b) shows the distribution of the component $p_\perp(l^-)$ of the secondary-lepton momentum perpendicular to the trigger e^+ momentum in the transverse plane. These distributions too are strongly dependent on the experimental cuts, but the mass m_t is more clearly manifested in the width and tail of the distribution than in Fig. 3(a). It appears to be possible to extract m_t from such charged dilepton correlations, though less decisively than in the case of $e\nu$ (or $\mu\nu$) correlations.

The full invariant masses of lepton pairs are also measurable. However, theoretical predictions for these distributions rely on knowing the longitudinal-momentum correlations of the heavy hadrons containing t and $\bar{t}$ quarks, which are subject to much more uncertainty due to possible leading-particle effects. We do not display them here.

Another interesting class of events arising from $t\bar{t}$ decays is characterized by large missing p_T but no visible leptons (some possible events like this are mentioned in Ref. 2). These can come from decays like $t \to b\tau\nu$ with $\tau \to \nu q\bar{q}$ and also from semileptonic modes where the final e or μ escape identification. In our model calculations at $\sqrt{s} = 540$ GeV, with lepton-identification thresholds as before, we find missing $p_T > 15$ GeV with no identified charged leptons in 4% (10%) of $t\bar{t}$ events with $m_t = 25$ GeV (40 GeV); about half of these arises through τ channels. Such events must be present if $t\bar{t}$ production takes place; they are comparable in number to the high-p_T single-lepton events discussed earlier.

Finally, we stress that in addition to the various lepton correlations analyzed above, important signatures from the jet structure of t and $\bar{t}$ decays may be expected. Because of trigger bias, the b-quark emitted with the trigger electron has relatively small average p_T of order 7 GeV, biased toward the electron hemisphere (more so the lighter the t-quark mass). The b jet should be somewhat broader than light-quark jets; light decay fragments obey the kinematic bound given above for decay electrons. Trigger bias gives the associated $\bar{t}$ considerable mean p_T of order 25 GeV, mostly opposite to the electron. This $\bar{t}$ jet should be very broad; light decay fragments f obey the kinematic bound $\sin\theta < m_t/(p_f p_t)^{1/2}$. This jet may in some cases be resolvable into three components from $\bar{t} \to \bar{b}q\bar{q}$, etc.

Figure 4 shows the calculated correlations of the b jet and associated $\bar{t}$-jet momenta with the trigger e^+ direction. We illustrate distributions in the following variables, all defined in the transverse plane: (a) $p_\perp$(jet) the momentum component perpendicular to e^+, (b) $p_{||}$(jet) the momentum component parallel to e^+, (c) $\phi(e,\text{jet})$ the azimuthal angle between the jet and e^+ momenta. Solid (dashed) lines represent results for $m_t = 40$ GeV (25 GeV), with $\sqrt{s} = 540$ GeV and $p_{eT} > 15$ as before. The results show considerable dependence on m_t; it appears feasible to make a t-quark mass determination from lepton-jet correlations of this kind.

For events with large missing p_T and no identified leptons, there are very similar correlations between the missing p_T and the jet momenta. Since $V-A$ decay favors fast neutrinos more than fast electrons, the trigger bias is less severe here; the correlations are slightly weaker, the distributions analogous to those in Fig. 4 are slightly flatter. (To suppress $b\bar{b}$ and $c\bar{c}$ backgrounds, the missing p_T should be isolated, not collinear with a jet.)

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