Trileptons from the top quark

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The cascade decays of $t\bar{t}$, $t\bar{b}$, $b\bar{t}$, and $b\bar{b}$ systems produced in $p\bar{p}$ collisions by strong or electroweak mechanisms lead to trilepton events, which offer top-quark signatures free from $c\bar{c}$ and Drell-Yan backgrounds. Even a few events could be valuable. Since at least two of the leptons must have a common parent, same-sign trileptons or events with opposite-sign pair masses greater than m_b must have top origins, and the minimum pair invariant mass in such events gives a lower bound on the top mass. Alternative $t\bar{t}$ and $t\bar{b}$ ($b\bar{t}$) origins can be distinguished by topology and/or lepton isolation.

Heavy-quark decays give charged leptons that help to signal the presence of heavy flavor, as recognized in many proposals[1–3] to search for top quarks in the CERN $p\bar{p}$ collider experiments.[4] Although most emphasis has been placed on single-lepton production, the interest of multilepton signatures has long been known and there have recently been fresh studies of the dileptons[5,6] expected from t and b production in $p\bar{p}$ collisions. In the present work we discuss and evaluate the trilepton signals expected from the strong and electroweak production of $t\bar{t}$, $t\bar{b}$, and $b\bar{t}$ pairs at $p\bar{p}$ colliders plus the backgrounds from $b\bar{b}$ production. The predicted trilepton event rates are smaller than single- or double-lepton rates for typical momentum cuts $p_T > 5$ GeV, but such events are particularly interesting for the following reasons:

(a) Even one or two events can be instructive and revealing.

(b) At least two of the leptons must come from the same heavy-quark parent.

(c) There is no background from $c\bar{c}$ or Drell-Yan pair production; for same-sign trileptons there is no $b\bar{b}$ background either.

(d) For mixed-sign trileptons, a simple invariant-mass cut separates most of the t-quark signal cleanly from $b\bar{b}$ background.

(e) Trileptons are necessarily present when there is b or t production; they provide an additional constraint on the possible origins of lepton events.

Our analysis includes both electroweak t production and $t\bar{t}$ hadroproduction, all stages of cascade decay, the effect of a p_T cut, and possible B^0-$\bar{B}^0$ mixing; in these and some other respects it goes beyond the earlier trilepton discussion of Chau, Keung, and Ting.[1] Since our aim is to assess the expected size of multilepton signals and the separation of different sources, we assume for simplicity a common p_T cut for electrons and muons. Present experimental acceptance cuts for electrons and muons (typically $p_T > 15$ GeV for electrons and $p_T > 5$ GeV for muons) differ, but it is expected that lower electron p_T acceptance cuts will be possible in the future.

Our present calculations begin with the strong and electroweak production of heavy quarks $Q = b,t$ from $p\bar{p}$ via the lowest-order gluon and light-quark subprocesses

$$\begin{aligned} &gg, q\bar{q} \to Q\bar{Q} \,, \\ &q\bar{q} \to Z^0 \to Q\bar{Q} \,, \\ &q\bar{q}\,' \to W^{\pm} \to Q\bar{Q}\,' \,, \end{aligned} \tag{1}$$

using the patron distributions of Ref. 7 and QCD-motivated enhancement factors $K=2$ in all cases, with quark masses $m_b = 4.6$ GeV, $m_t = 35$ GeV (for illustration). With $K=2$ the cross section for $W^{\pm}$ production and $e^{\pm}\nu$ decay agrees with the observed cross section; thus this choice properly normalizes all W and Z contributions. Since higher-order QCD corrections may be ex-

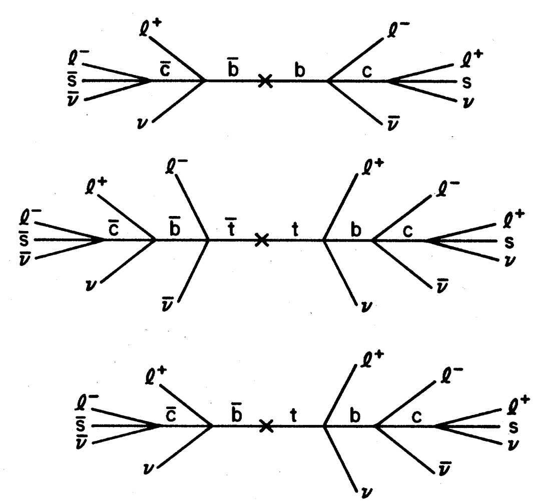

FIG. 1. Diagrams indicating principal lepton origins in $b\bar{b}$, $t\bar{t}$, $t\bar{b}$ cascade decays. Each lepton vertex $l\bar{\nu}$ may be replaced by a quark vertex $q\bar{q}\,'$.

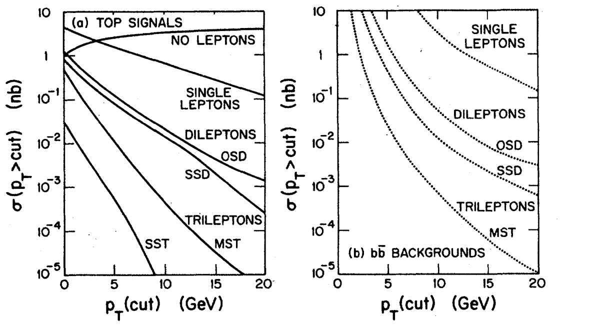

FIG. 2. Inclusive multilepton cross sections from heavy-quark production in $p\bar{p}$ collisions at $\sqrt{s}=620$ GeV, vs minimum p_T acceptance cut: (a) Sum of contributions from $t\bar{t}$, $t\bar{b}$, $b\bar{t}$ production, (b) principal background contributions from $b\bar{b}$ production. Shown separately are the nonleptonic, single lepton, same-sign dilepton (SSD), opposite-sign dilepton (OSD), same-sign trilepton (SST), and mixed-sign trilepton (MST) signals, summed over both lepton flavors and charges ($e^{\pm},\mu^{\pm}$).

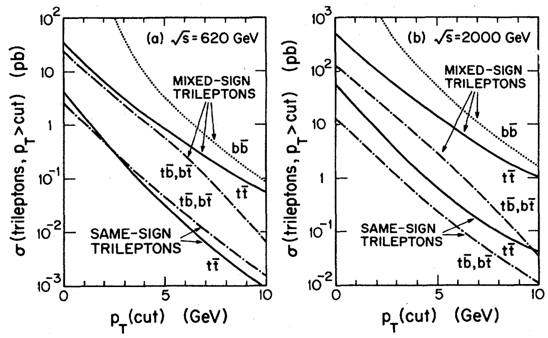

FIG. 3. Inclusive trilepton cross sections versus p_T cut in $p\bar{p}$ collisions: (a) $\sqrt{s}=620$ GeV, (b) $\sqrt{s}=2000$ GeV. The $b\bar{b}$, $t\bar{t}$, and $t\bar{b}$ ($b\bar{t}$) contributions are shown separately for mixed-sign trileptons and same-sign trileptons, for a single-lepton flavor as defined in Eqs. (2) and (3).

pected to be of similar significance for hadroproduction, we choose the same value $K=2$ for the fusion subprocesses as well.

Higher-order processes such as $gg\to gQ\bar{Q}$ are not included explicitly, since they should not greatly alter the distributions considered here. The produced heavy quarks are taken to fragment into spinless or unpolarized heavy hadrons according to the model of Ref. 8. These hadrons decay by V-A matrix elements along the chain $t\to b\to c\to s$; at each stage the heavy-quark decay product again hadronizes according to Ref. 8. Exceptionally, for c products of b decay, δ-function c fragmentation is used to agree with CESR data;[9] this is not inconsistent with the softer fragmentation observed for hadroproduced c quarks, since the environment of b decay has relatively little energy release and an asymptotic fragmentation picture is not necessarily applicable here, where final-state interactions may play a larger role.

We concentrate attention on leptons produced along the primary cascade axis; e.g., at the $t\to b$ we select leptons from $t\to b\bar{l}\nu$ and neglect the side branches $t\to b\bar{s}c$, $c\to s\bar{l}\nu$ or $t\to b\bar{\tau}\nu$, $\bar{\tau}\to\bar{\nu}\bar{l}\nu$ which yield fewer and softer leptons. Monte Carlo techniques are used with typically 2×10^5 shots in a given sample, giving statistical accuracy better than 10% in trilepton rates with $p_T>5$ GeV—considerably smaller than the corresponding theoretical uncertainties and model dependence. Results are illustrated for $p\bar{p}$ c.m. energies $\sqrt{s}=620$ GeV and in some cases for $\sqrt{s}=2000$ GeV, corresponding to the expected 1984 running of the CERN collider and future operation of the Fermilab collider, respectively.

Figure 1 shows schematically the various origins of leptons in cascade decay of $b\bar{b}$, $t\bar{t}$, and $t\bar{b}$ systems; clearly there are many multilepton possibilities. Indeed, it is interesting to note that truly nonleptonic final states (containing no $e^{\pm}$ or $\mu^{\pm}$) are relatively unlikely. Since the nonleptonic fractions of $t\to b$, $b\to c$, and $c\to s$ decays are about 0.75, 0.75, and 0.80, respectively, the probability that the full double-cascade-decay process yields no leptons is only 0.36 for $b\bar{b}$, 0.27 for $t\bar{b}$, and 0.20 for $t\bar{t}$ systems. However, when a minimum p_T cut is introduced (necessary for lepton recognition in present experiments), the multilepton signals are progressively reduced. Figure 2 illustrates this behavior for inclusive multilepton signals, summing over both lepton flavors and signs. Here the no-lepton rate includes both nonleptonic decays and semileptonic decays with charged leptons below the p_T cut; the latter accounts for the rise of this rate as the charged-lepton identification cut is raised. As noted earlier, a common electron and muon p_T acceptance cut has been assumed for simplicity.

Figure 3 shows the predicted inclusive cross sections for same-sign trileptons (SST) and mixed-sign trileptons (MST) of a single flavor versus the p_T acceptance cut, assuming all leptons satisfy the same cut. The precise relationships to mixed-flavor cross sections are as follows:

$$\begin{aligned}\sigma(\mathrm{SST})&=\sigma(\mu^+\mu^+\mu^+)+\sigma(\mu^-\mu^-\mu^-)=\sigma(e^+e^+e^+)+\sigma(e^-e^-e^-)\\&=\tfrac{1}{3}[\sigma(\mu^+\mu^+e^+)+\sigma(\mu^-\mu^-e^-)]=\tfrac{1}{3}[\sigma(\mu^+e^+e^+)+\sigma(\mu^-e^-e^-)]\ ,\end{aligned}\tag{2}$$

$$\begin{aligned}\sigma(\mathrm{MST})&=\sigma(\mu^+\mu^+\mu^-)+\sigma(\mu^-\mu^-\mu^+)=\sigma(e^+e^+e^-)+\sigma(e^-e^-e^+)\\&=\sigma(\mu^+\mu^+e^-)+\sigma(\mu^-\mu^-e^+)=\sigma(e^+e^+\mu^-)+\sigma(e^-e^-\mu^+)\\&=\tfrac{1}{2}[\sigma(\mu^+e^+\mu^-)+\sigma(\mu^-e^-\mu^+)]=\tfrac{1}{2}\sigma[(e^+\mu^+e^-)+\sigma(e^-\mu^-e^+)]\ .\end{aligned}\tag{3}$$

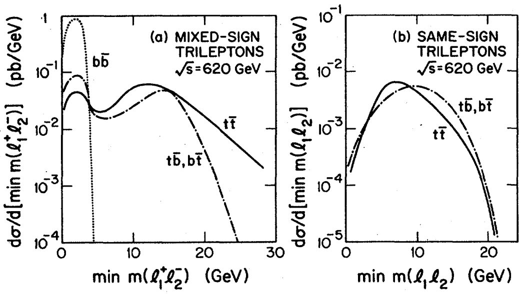

FIG. 4. Trilepton cross sections and lepton pair masses at $\sqrt{s}=620$ GeV: (a) Mixed-sign trileptons versus minimum opposite-sign pair mass; (b) same-sign trileptons versus minimum pair mass. Dotted, solid, and dashed-dotted curves denote $b\bar{b}$, $t\bar{t}$, and $t\bar{b}$ ($b\bar{t}$) contributions, respectively, for a single-lepton flavor.

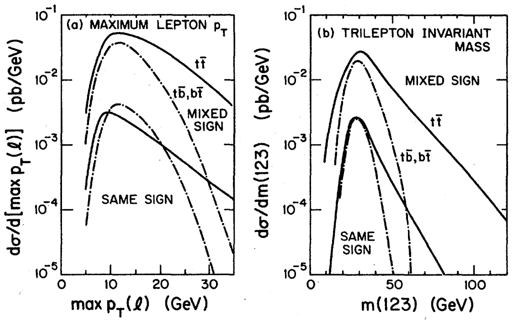

FIG. 5. Distributions of top trileptons with $p_T > 5$ GeV and opposite-sign pair masses > 4 GeV at $\sqrt{s}=620$ GeV; (a) cross sections vs maximum lepton p_T; (b) cross sections vs trilepton invariant mass. The contributions from $t\bar{t}$ (solid curves) and $t\bar{b}, b\bar{t}$ (dashed-dotted curves) are shown separately.

Thus mixed-flavor configurations are three times as common as single flavor, and summing over all flavor configurations gives total trilepton cross sections eight times as large as those of Fig. 3. This figure also shows that $b\bar{b}$ backgrounds exceed the MST top signals for all p_T cuts up to 10 GeV. There is no such background for SST, but the signals here are smaller.

The $b\bar{b}$ MST background can be separated, however, since it necessarily contains opposite-sign $l_1^+ l_2^-$ lepton pairs from a common parent, with invariant mass consequently less than m_B-m_K. This fact is illustrated in Fig. 4, which shows the distributions with respect to the lowest pair mass (SST) and lowest opposite-sign pair mass (MST). We see that requiring the opposite-sign pair masses to exceed 4 GeV essentially removes the $b\bar{b}$ background while leaving 80% ($t\bar{t}$) or 60% ($t\bar{b}, b\bar{t}$) of the top signals intact.

Figure 5 displays two more properties of top trileptons (after requiring $p_T > 5$ GeV and opposite-sign pair masses >4 GeV). Figure 5(a) shows that the maximum lepton p_T can be large: for $t\bar{t}$ events, 30% of events have $\max(p_T) > 30$ GeV. Figure 5(b) shows the distributions with respect to total trilepton invariant mass, which peak near 30 GeV, but have a small tail extending beyond 100 GeV from $t\bar{t}$ contributions (the $t\bar{b}$ contributions are obviously bounded by $M_W = 81$ GeV).

Can we distinguish between $t\bar{t}$ and $t\bar{b}$ ($b\bar{t}$) trilepton origins? Their distributions illustrated above differ little in the ranges where most events lie. However, it should be possible to distinguish origins in many cases from the event topology and jet structure, especially if some b and/or c decays are identified by a microvertex detector. Apart from this, we can use jet-isolation criteria (as discussed, e.g., in Ref. 3). Among MST events satisfying the p_T and pair-mass criteria of Fig. 5, about 75% of the $t\bar{t}$ events contain two primary $t \to bl\nu$ decay leptons, whereas 100% of the $t\bar{b}$ events contain just one. Each primary lepton has a good change to be well separated in angle from accompanying particles. Depending on the precise choice of isolation criterion, a large fraction of $t\bar{t}$ MST events will have two isolated leptons, whereas most $t\bar{b}$ events will not. This approach does not work for SST, since none of them have two primary leptons, but these are only a small fraction of trilepton events.

Finally, we mention the possibility of B^0-$\bar{B}^0$ decay mixing, especially for $B^0(b\bar{s})$ states, that can effectively give wrong-sign $b \to \bar{c}\, l\, \bar{\nu}$ in place of $b \to c\bar{l}\nu$ for a fraction ϵ of b decays (see Ref. 5 for a discussion of the large effects on $b\bar{b}$ dileptons). This can turn some MST into SST and vice versa, the total number of trileptons, remaining unchanged. For a mean wrong-sign decay fraction $\epsilon = 0.15$, a plausible upper limit,[5] the SST rates increase by about 20% for both $t\bar{t}$ and $t\bar{b}$ components, while the MST percentage correction is an order of magnitude smaller for $p_T > 5$ GeV and $\sqrt{s}=620$ GeV. Effects of this order will be very difficult to detect.

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