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LEPTON PAIRS AS A SIGNAL FOR THE TOP QUARK

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ABSTRACT

Multilepton final states from the sequential decay of the top quark are studied. Lepton pairs with large invariant mass are proposed as a signal for the top quark. The background from different processes is estimated.

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1. INTRODUCTION

The decay of the top quark can lead to multilepton final states. The lepton pairs with some information about the associated jets provide a signal not relying heavily on the complicated event topology with moderate missing transverse energies. Unfortunately, the rates for the pairs are more than one order of magnitude below those for single leptons owing to the leptonic branching ratios and the fact that only a fraction of the second- and third-generation leptons are observable experimentally.

The multilepton signatures for the top quark have already been discussed on many occasions [1–5]. Especially the like-sign leptons in the process

$$W^+ \rightarrow t\bar{b} \begin{array}{l} \nearrow \ell^+ X \\ \searrow \ell^+ X \end{array} \quad (1)$$

have been proposed as a unique signal for the top quark [1,2]. However, a considerable background for this process is caused by the sequential decay of the b quark in the QCD process $p\bar{p} \rightarrow b\bar{b} + X$, which can be removed only by applying strong isolation criteria for the leptons [2]. Moreover, the correlations between the leptons in the like-sign pair are dominated by the two-body kinematics in the W decay and the hard process leading to an apparent similarity of all kinematical quantities in the signal and the background.

In this work we study the signal of opposite-sign dileptons for the top quark in the processes

$$p\bar{p} \rightarrow W^+ \rightarrow t\bar{b} \begin{array}{l} \searrow (\ell^+ \ell^-) X \end{array} \quad (2)$$

$$p\bar{p} \rightarrow Z^0 \rightarrow t\bar{t} + X \begin{array}{l} \nearrow (\ell^+ \ell^-) X \\ \searrow (\ell^+ \ell^-) X \end{array} \quad (3)$$

$$p\bar{p} \rightarrow t\bar{t} + X \begin{array}{l} \nearrow (\ell^+ \ell^-) X \\ \searrow (\ell^+ \ell^-) X \end{array} \quad (4)$$

The large mass of the top quark is reflected in the invariant mass of the lepton pair, with the exception of the pair coming from the b- and c-quark decay in the cascade. In the weak process $W^+ \rightarrow t\bar{b}$ the $\bar{b}$ jet is relatively hard, with the peaking of the transverse momenta well above 10 GeV (for the conventional expectations of the top-quark mass), and thus serves as an additional signature for this process. In the Z^0 decay and in the hard process the jet signal will be more obscure because many jets can appear with relatively low transverse energies.

The background sources for the dileptons of opposite signs are numerous. The heavy-flavour decays in the QCD processes, mainly $p\bar{p} \rightarrow b\bar{b} + X$, can lead to large rates for lepton pairs. In any hard process a ‘heavy’ bremsstrahlung gluon can convert to a heavy-quark pair and then create lepton pairs. The dileptons from the Drell–Yan continuum at the masses below the top-quark mass are an important source of background.

In Section 2 we briefly present the Monte Carlo calculation and study the top-quark signal in processes (2) to (4). The background processes are discussed in Section 3.

2. DILEPTON SIGNAL FOR THE TOP QUARK

We use simple Monte Carlo programs to simulate the events. In the programs, the W and the Z^0 are produced from the Drell–Yan subprocess and the $t\bar{t}$ production is calculated in the first-order QCD using only the $q\bar{q}$ and gg annihilation diagrams. The structure functions used are the non-scaling parametrizations of Glück, Hoffmann and Reya [6]. The heavy-quark decays are performed with the exact $V - A$ matrix elements, including the masses in all cases [7]. For simplicity the polarizations of the heavy quarks are summed over in the weak processes. We assume 40 GeV for the mass of the t quark and 0.1 for the semileptonic branching ratios in the heavy-quark decays. The initial bremsstrahlung, neglected here, would not quantitatively change our results, which are dominated by the large top-quark mass. Also the model-dependent effects, mainly the sharing of the momentum between the fragments in the cascade decay, as well as the effects due to the polarized production of the top quark in the weak processes, will mostly be compensated in the invariant mass of the fragments which we propose as a signature.

We find cross-sections of 990 pb, 77 pb, and 1.7 nb for the processes $W \rightarrow t\bar{b}(\bar{t}b)$, $Z^0 \rightarrow t\bar{t}$, and $p\bar{p} \rightarrow t\bar{t}$ respectively. In the weak processes we have used the K -factor of 1.6 suggested by the Collider data for $W \rightarrow e\nu$ [8].

Figure 1 shows the transverse momentum p_T for the lepton (e or μ) from the t , b , or c quark in the top cascade for $W^+ \rightarrow t\bar{b}$. To guarantee the observability and to eliminate background processes we require $p_T > 5$ GeV for both of the leptons in the pair. It can be seen from Fig. 1 that a large fraction of the events will be lost by this cut. The decay of the c quark will not contribute essentially to these p_T values and to the large invariant masses. For the Z^0 decay $Z^0 \rightarrow t\bar{t}$ the lepton spectra from the top decay are almost identical with those for $W \rightarrow t\bar{b}$ in Fig 1.

Figure 2 shows the transverse energy E_T for the $\bar{b}$ jet and for the c -quark jet, which is accompanying one of the leptons in the pair in the process $W^+ \rightarrow t\bar{b}$. We require $E_T > 10$ GeV for at least one jet in the event to guarantee the jet signature necessary to eliminate background processes. Only a small fraction of the $t\bar{b}$ events are lost by this cut, as can be seen from the figure. The c -quark jet associated with one of the leptons is generally much softer than the $\bar{b}$ jet. Therefore, relatively ‘‘clean’’ events could be expected from the weak process with W decay.

Figure 3 shows the p_T spectra for the leptons in the strong process $p\bar{p} \rightarrow t\bar{t} + X$. The distributions are very similar to those in Fig. 1, except that they show a somewhat larger tail at high- p_T values. In Fig. 4 we show the transverse energies for the jets from the top decay and for the c jet in the top cascade accompanying one of the leptons. We assume that three jets are produced in the hadronic decay of the top quark, with some of them being measurable. However, no significant loss of events will occur when only one jet is required to have E_T larger than the threshold set for

$W \rightarrow t\bar{b}$. For the Z^0 decay the jet distributions are essentially the same as those for $p\bar{p} \rightarrow t\bar{t}$, except that a smaller spread of events can again be expected at large E_T values owing to the mass constraint of the weak process.

Because of the large mass of the top quark, the decay leptons are distributed almost spherically relative to the original quark. For the decay of the b quark, the relative angles are very limited, with the maximum given by $\sin^2 \theta/2 < m_b^2/4p_T^1 p_T^2$, where p_T^1 and p_T^2 are the transverse momenta of the fragments relative to the beam direction. For the minimum accepted p_T values, 5 GeV for the leptons and 10 GeV for the jet, the maximum angle has the value of 41° . Therefore, to define unambiguously the lepton pair from the top quark in the process $W^+ \rightarrow t\bar{b}$, we reject the leptons which are inside the cone of 41° relative to the $\bar{b}$ jet. This cut hardly reduces the signal in $W^+ \rightarrow t\bar{b}$, but it will eliminate the uncorrelated pairs especially in the background processes, which naturally can give large invariant masses.

The invariant mass for the lepton pair $m_{\ell\ell}$ from the top decay in the process $W^+ \rightarrow t\bar{b}$ is shown in Fig. 5 for $p_T > 5, 8$, and 10 GeV, for the leptons. The peaking of the mass spectrum around $m_t/3$ and the relatively sharp fall-off, especially for the low- p_T threshold, could be useful for the determination of the top-quark mass. The enhancement at the small invariant masses results from the semileptonic decays of the b and the c quark in the top cascade. Most of the events are retained when the low masses $m_{\ell\ell} < 5$ GeV are excluded to eliminate the b -quark background.

The mass spectra for the processes $Z^0 \rightarrow t\bar{t}$ and $p\bar{p} \rightarrow t\bar{t}$ are shown in Figs. 6 and 7, respectively, with the same conditions as those for $W^+ \rightarrow t\bar{b}$. We assume that it is not possible, in general, to separate the leptons and the jets from the decays of the two t quarks. Only at the high tail of the p_T spectrum, where the contributions from the cascade decays are negligible, could the first-generation leptons be identified by the charge argument. Because of the uncorrelated pairs the mass spectra for these processes are somewhat wider than those for $W^+ \rightarrow t\bar{b}$ and not bounded above by the top-quark mass. A careful study of the jet structure of the event is obviously the only practical way of distinguishing the lepton pairs from $t\bar{b}$ and from $t\bar{t}$ final states.

3. BACKGROUND PROCESSES

We have used the ISAJET Monte Carlo program [9] to study the background processes. To account for all uncorrelated phenomena we search for all possible lepton pairs in the events where at least one jet with $E_T > 10$ GeV is found, rejecting the leptons which are inside the cone of 41° relative to any jet above the E_T threshold.

The process $p\bar{p} \rightarrow b\bar{b} + X$ has a large cross-section, about 700 nb from the annihilation diagrams alone. However, the lepton pairs from the sequential decay of the b quark can contribute only to low invariant masses and can thus be eliminated by rejecting the pairs with invariant mass less than the mass of the b quark. The background from the events where a third jet is produced in addition to the $b\bar{b}$ pair, with the simultaneous semileptonic decay of both of the b quarks, will be small with the above conditions. A rough estimate for the upper limit of the contribution from this process can easily be obtained. Namely from the $p\bar{p}$ Collider data for hadronic jet production [10] we know that the fraction of the three-jet events is at the level of 10%. Combining this with the fact that the probability for producing a detectable lepton pair from the simultaneous decay of b and $\bar{b}$ quarks is about 10^{-5} [2] we find the cross-section to be about 1 pb. Using the ISAJET program, where the third jet can originate from the final-state QCD bremsstrahlung, we find no contribution from this kind of background. The same is true for the decays of the c quarks in the process

$p\bar{p} \rightarrow c\bar{c} + X$, for which the cross-section is larger but the fraction of detectable leptons is correspondingly smaller. The process $W^+ \rightarrow c\bar{s}$ will not contribute to the background owing to the long lifetime of the strange particles.

In any hard process a bremsstrahlung gluon can convert to a pair of heavy quarks, which in turn can decay semileptonically. However, the production of really heavy quarks is strongly suppressed by the factor m_Q^{-4} . Since the leptons from the conversions to lighter quarks ($c\bar{c}$, $s\bar{s}$) will obviously have very small transverse momenta, this background will be eliminated when the leptons with $p_T < 5$ GeV are rejected.

The dileptons from the Drell–Yan continuum at the masses between bottom- and top-quark mass are an important source of background. Most of these events will disappear with the requirement of a large- p_T jet in the event. From the remaining sample the electronic and muonic decays are easily eliminated because no significant missing transverse energy will be present. The absence of this kind of background is guaranteed by selecting $e\mu$ pairs instead of ee or $\mu\mu$ pairs. The background from $\tau^+\tau^-$ final states and the subsequent semileptonic decays of τ particles is very small, $\leq 10^{-2}$ pb. In this case large missing transverse energies can be generated by the requirement of a high- p_T jet in the event.

Tables 1 and 2 show the cross-sections for the lepton pairs in the weak, strong, and background processes, with different cuts in the transverse momentum of the leptons and the jet. A cut in the missing transverse energy, $E_T > 5$ GeV, is applied in Table 2. In the $t\bar{t}$ final state there are several possibilities for finding a lepton pair with large mass. Therefore, the rates for the pairs in the Z^0 decay are almost comparable and those in the strong process are several times above the rates for the process $W^+ \rightarrow t\bar{b}$. The background from the electronic or muonic Drell–Yan process is considerable, but disappears with the requirement of missing transverse energy. The remaining background from the $\tau^+\tau^-$ final states of the Drell–Yan events is almost negligible, but the isolation properties could still be used for eliminating it. Namely in the Drell–Yan process both of the final leptons are isolated, while in the decay of the top quark one of the leptons — that from the b-quark decay — is accompanied by a small jet. The rates for the strong process and the Z^0 decay would be reduced roughly by a factor of two if the pairs of isolated leptons were rejected.

4. CONCLUSIONS

An interesting signature for the top quark is provided by the dileptons with large invariant mass from the sequential decay of the top quark. We find cross-sections of about 3, 1, and 11 pb for the lepton pairs in the processes $W^+ \rightarrow t\bar{b}(\bar{t}b)$, $Z^0 \rightarrow t\bar{t}$, and $p\bar{p} \rightarrow t\bar{t}$, respectively, when the necessary cuts to eliminate background processes are applied.

The invariant mass of the lepton pairs separates neatly the dangerous background for the top-quark search, i.e. the copious production of the b quarks in the QCD process. The associated missing transverse energy in the semileptonic decay of the top quark is suitable for eliminating the background from the Drell–Yan continuum with electronic and muonic decays. The isolation conditions could be used to handle the remaining, although very small, background from the leptonic decays of the $\tau^+\tau^-$ final state in the Drell–Yan events.

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Table 1Cross-sections (pb) for lepton pairs with $m_{\ell^+\ell^-} > 5 \text{ GeV}$

Cuts	$W \rightarrow t\bar{b}(\bar{t}b)$	$Z^0 \rightarrow t\bar{t}$	$p\bar{p} \rightarrow t\bar{t} + X$	$p\bar{p} \rightarrow \ell^+\ell^- + X$
$E_T^j > 10 \text{ GeV}, p_T^\ell > 5 \text{ GeV}$	2.79	0.68	11.32	8.01
$E_T^j > 10 \text{ GeV}, p_T^\ell > 8 \text{ GeV}$	1.04	0.30	5.32	2.71
$E_T^j > 10 \text{ GeV}, p_T^\ell > 10 \text{ GeV}$	0.45	0.16	3.27	1.28
$E_T^j > 15 \text{ GeV}, p_T^\ell > 5 \text{ GeV}$	2.21	0.51	8.67	3.43
$E_T^j > 15 \text{ GeV}, p_T^\ell > 8 \text{ GeV}$	0.99	0.22	4.34	1.59
$E_T^j > 15 \text{ GeV}, p_T^\ell > 10 \text{ GeV}$	0.43	0.12	2.57	0.78

Table 2Cross-sections (pb) for lepton pairs with $m_{\ell^+\ell^-} > 5 \text{ GeV}$
and missing transverse energy larger than 5 GeV

Cuts	$W \rightarrow t\bar{b}(\bar{t}b)$	$Z^0 \rightarrow t\bar{t}$	$p\bar{p} \rightarrow t\bar{t} + X$
$E_T^j > 10 \text{ GeV}, p_T^\ell > 5 \text{ GeV}$	0.91	0.26	6.00
$E_T^j > 10 \text{ GeV}, p_T^\ell > 8 \text{ GeV}$	0.23	0.13	2.95
$E_T^j > 10 \text{ GeV}, p_T^\ell > 10 \text{ GeV}$	0.07	0.06	1.70
$E_T^j > 15 \text{ GeV}, p_T^\ell > 5 \text{ GeV}$	0.83	0.19	4.48
$E_T^j > 15 \text{ GeV}, p_T^\ell > 8 \text{ GeV}$	0.22	0.09	2.15
$E_T^j > 15 \text{ GeV}, p_T^\ell > 10 \text{ GeV}$	0.07	0.05	1.18

Figure captions

- Fig. 1 : Transverse momentum for the lepton (electron or muon) from the t quark (solid curve), from the b quark (dashed curve), and from the c quark (dash-dotted curve), in the top-quark cascade in the process $W^+ \rightarrow t\bar{b}(\bar{t}b)$.
- Fig. 2 : Transverse energy for the $\bar{b}$ jet and for the c-quark jet in the top cascade in the process $W^+ \rightarrow t\bar{b}(\bar{t}b)$.
- Fig. 3 : Transverse momentum for the lepton from the t quark (solid curve), from the b quark (dashed curve), and from the c quark (dash-dotted curve) in the top-quark cascade in the process $p\bar{p} \rightarrow t\bar{t} + X$.
- Fig. 4 : Transverse energy for the fragments in the hadronic decay of the top quark and the transverse energy for the c-quark jet in the top cascade in the process $p\bar{p} \rightarrow t\bar{t} + X$.
- Fig. 5 : Invariant mass for the lepton pair (e^+e^- or $\mu^+\mu^-$), with $p_T > 5$ GeV (solid curve), $p_T > 8$ GeV (dashed curve), and $p_T > 10$ GeV (dash-dotted curve), for the lepton from the top-quark decay in the process $W \rightarrow t\bar{b}(\bar{t}b)$.
- Fig. 6 : Invariant mass for the lepton pair with $p_T > 5$ GeV (solid curve), $p_T > 8$ GeV (dashed curve), and $p_T > 10$ GeV (dash-dotted curve), for the leptons from the top-quark decay in the process $p\bar{p} \rightarrow t\bar{t} + X$.
- Fig. 7 : Invariant mass for the lepton pair with $p_T > 5$ GeV (solid curve), $p_T > 8$ GeV (dashed curve), and $p_T > 10$ GeV (dash-dotted curve), for the leptons from the top-quark decay in the process $Z^0 \rightarrow t\bar{t}$.

Fig. 1

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