Search for $t\bar{t}$ in the τ dilepton channels based on 350 pb^{-1} of CDF data

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Abstract. The search for the top pair production in the dilepton signature with one electron (or one muon) and one τ lepton decaying hadronically is discussed in this paper. The reported study is based on 359 pb-1 data recorded by the CDF experiment at the Tevatron (FNAL). The dominant backgrounds are due to the process $Z \to \tau_l \tau_{had}$, and to events with jets faking τ's, predominantly due to the production of $W \to l\nu + jets$ and the QCD backgrounds. A new method is developed to estimate the τ fake rate as given by these various processes. With the statistics available in this reported study, the probability for the 2.7 ± 0.4 expected background events to give rise to the observed number (5) or more is 15%.This is roughly equivalent to a one sigma excess over the expected background, and is in good agreement with the total number of events expected from the signal and the background, namely: 5.0 ± 0.5.The work is in progress on three times more data and should lead soon to a 3σ evidence and the first experimental observation of this signal. This paper also stress the importance of this signal as an entry point for New Physics, where decays into τ leptons are predicted to be predominant.

1. Introduction

The goal of this study is to extract the top pair events in which one top produces an electron or a muon, and the other top produces a τ lepton decaying into hadrons, from the mass of events produced by the 1.96 TeV $p\bar{p}$ collisions at Tevatron. With the increase of the luminosity and the upgrading of the CDF detector compared to the Run I period (1993-1994), it will be hopefully possible during the Run II to establish for the first time a clear evidence of this still poorly known top decay channel.

The signature of this process: $p\bar{p} \to t\bar{t}+X \to e,\mu+\nu_{e,\mu}+\tau_{had}+\nu_\tau+b\bar{b}+X$ is thus characterized by, one electron or one muon, a τ jet, two b-quark jets and the total missing transverse energy resulting from the ν's emitted in the decays of the W's into leptons and consequently in the decays of the τ('s) lepton(s). Therefore this analysis requires to master the identification of all the following fundamental objects: electrons, muons and hadronic decays of the τ lepton and eventually of the b-quark jets. A good measurement of the total missing transverse energy and of the transverse energy (Et) of the two b-jets is critical too. Understanding the most important backgrounds, i.e. the processes: $Z \to \tau_l \tau_{had}$, $W \to l\nu + jets$, QCD with jets faking a τ hadronic decay and diboson production, in a high jet multiplicity environment is a prerequisite.

In this document, the physics motivations of this analysis will be first presented. It will be followed by the description of the acceptance and of the event selection strategy, an overview of the lepton identification, and an explanation of the background estimation. Finally the results

Integrated Luminosity	$t\bar{t}$ $\rightarrow e+\tau_{had}$	passing geo and kine requirements	$t\bar{t}$ $\rightarrow \mu+\tau_{had}$	passing geo and kine requirements
350 $pb{-}1$	48	6.1	48	6.1
4 $fb{-}1$	551	69	551	69

Table 1. *MC estimates of the top pair events produced in the electron + τ and muon + τ dilepton channels with a total top pair production cross section of 7.3 pb [2]*

obtained on the measured top pair into τ dilepton cross-section, will be reported with the verification methods and an uncertainty estimate .

2. Physics motivations

2.1. Completing the study of all the possible top pair production into dilepton decays

In Run I, the analysis of the 109 pb^{-1} of 1.8 GeV $p\bar{p}$ collisions concluded on the observation of 4 $e\tau$ and $\mu\tau$ candidate events, where 2.5 ± 0.4 background events and 1.1 ± 0.4 top events were expected (assuming $\sigma_{t\bar{t}} = 7.7 \pm 2pb$, Run I combined result). Three of the 4 candidate events also had b-tagged jets, where 0.28 background events (and 0.63 top events) were expected. This was formally giving a 3σ significance for the presence of non background events, but because only 0.63 top events were expected, the nature of these 3 events was not clearly demonstrated [1].

In Run II, the increase from 1.8 to 1.96 GeV in the center of mass energy has yielded an increase in the cross section for the top pair production estimated by the theoretical calculations to grow from 5 pb to 6.5 pb, i.e. by of the order of 20-25% . Furthermore, the higher luminosity produced by the Tevatron at Run II allowed CDF to collect about $350pb^{-1}$ data, by September 2004 , and about $1fb^{-1}$ data by the end of 2005, data that are available for this analysis. A total of at least $4fb^{-1}$ data are expected to be recorded by 2008, if the machine continues to run as presently. There are good expectation for getting up to $6fb^{-1}$ or even $8fb^{-1}$ by 2009, i.e. before the LHC is running at full speed. The Table 1 gathers the number of signal events that are expected to be produced in the τ dilepton channels both in the electron and muon cases, taking 7.3 pb as the total top pair production cross section [2], for the total luminosity taken into account for this report (i.e. $350pb^{-1}$) and extrapolating directly these numbers to the case of $4fb^{-1}$ total integrated luminosity.

The results from a preliminary search in CDF, based on the first $195pb^{-1}$ recorded data of Run II, achieved an upper limit on the ratio R of top decays into τ leptons as compared to top decays into electrons or muons of 5.2 with 95% C.L. [3]. A clear 3 σ observation of the top in τ dilepton channels should be possible soon with an optimization of $S/\sqrt{B}$.

2.2. A key-tool for beyond the Standard Model searches

Apart from the observation of this top decay channel into dileptons with at least one τ lepton, this study aims to the measurement of the cross section of this decay process. This will not really help improving the precision of the overall top pair production cross section, as the studied decay process cannot add significantly to the precision. The main point here is to check if as expected from the Standard Model (SM) the top decays only into Wb or if there is room for other decay channels as in particular, the decay of the top into a charged Higgs plus a bottom quark. This charged Higgs would then decay into a τ lepton and its corresponding neutrino, leading to an enhancement of the ratio, $R = \frac{t \rightarrow \tau\nu_\tau b}{t \rightarrow l\nu_l b}$ (l = e or μ), in contradiction with the value of 1 predicted by the Standard Model. The optimization of the R value should be done using $\frac{S}{\sqrt{S+B}}$.

Indeed any value greater than 1 would thus be an indication of physics beyond the Standard Model. For instance if there is a charged Higgs of mass lower than the top mass, it would preferently coupled with the top quark because of its high mass. For the same reason, it would couple much more to the τ lepton than to lighter leptons. The decay chain: $t \rightarrow bH^+ \rightarrow b\tau\nu_\tau$ would yield to values of R greater than 1. A total integrated luminosity of at least $4fb^{-1}$ or more is needed to establish a value of R different from 1. While waiting for more data, at least one can improve the first upper limit of 5.2 achieved with $195pb^{-1}$ of data as quoted before [3]. Moreover a crucial aspect of this study is that understanding Physics signatures that involve missing energy, several jets, 2 or 3 leptons and especially τ leptons is instrumental for the search of New Physics. Indeed, these are typical SUSY signatures, and if $tan\beta$ is high enough, the rate of decays into τ leptons as compared to other processes are predicted to become predominant. Therefore, being able to handle high multiplicity signatures including τ leptons is a new important achievement in $p\bar{p}$ colliders.

3. Event selection strategy and acceptance

The analysis presented in this document makes uses of $350pb^{-1}$ of data collected at CDF in Run II until September 2004.

The data used for the signal measurement was triggered by the inclusive high P_t electron (or muon) trigger that requires an electron or a muon with a transverse energy greater that 18 GeV.

Subsequently, the offline selection requires:

- an identified isolated lepton (electron or muon) with $E_t > 20$ GeV, and pseudorapidities $|\eta| < 1$ to benefit from the whole traking system performance
- an identified central isolated τ decaying into hadrons with $E_t > 15$ GeV. The identification is driven by the reconstruction of the one or three charged pions inside a narrow cone
- a missing transverse energy ($\not{E}_T$) greater than 20 GeV to account for the three neutrinos in the signal events
- two jets, one with $E_t > 25$ GeV, and the other with $E_t > 15$ GeV
- a high activity in the event to account for the high top mass : the sum H_t of the transverse energies of the four identified objects and of $\not{E}_T$is greater than 205 GeV
- passes a veto against $Z \rightarrow \tau\tau + jets$ background

4. Signal and background estimation

4.1. The signal

The top signal is simulated with Pythia [4]. The τ lepton decay is handled by the Tauola package [5]. The $t\bar{t}$ cross-section taken here is the one obtained by the CDF II collaboration [2]. It combines six measurements of the top quark pair production cross-section, using a data sample with an integrated luminosity of up to 760 pb^{-1}, collected by the CDF II detector. The combined result is: $\sigma_{t\bar{t}} = 7.32 \pm 0.47(stat) \pm 0.57(syst) \pm 0.42$ (luminosity) pb, assuming a top mass of 175 GeV/c^2 .

4.2. The irreducible background

The irreducible background is due to physics processes that give a signature very similar to the signal, in terms of the total transverse missing energy ($\not{E}_T$), the leptons with one electron or muon and one τ lepton decaying hadronically, plus at least two jets. The main contribution is given by $Z \rightarrow \tau\tau$ + 2 $jets$ events where one τ lepton is decaying leptonically and the other one hadronically. Smaller contributions are due to diboson events, mainly due to WW + 2 jets events.

These background estimates are based on Pythia and AlpGen [6] Monte Carlo packages. The appropriate scale factors are extracted from the $Z \rightarrow \mu\mu + 2\ jets$ sample in order to ensure that the predicted number of extra jets is compatible with the observations.

4.3. The reducible background

Events with fake τ lepton but with jets or leptons misidentified as τ hadronic decays can end up into the final signal selection sample. These are largely dominated by events with jets faking τ's, and a relatively small contribution from events where one electron fakes a τ lepton ($Z \rightarrow ee$ + 2 jets). Events where one muon fakes a τ lepton are neglected.
In order to estimate the background where an electron fakes a τ, an electron to τ fake rate is measured from the $Z \rightarrow ee$ data events. The number of events with τ candidates that fail the electron rejection requirement but pass all the other analysis requirements is then scaled by the electron to τ fake rate.

The background where a jet fakes a τ is the dominant background in this analysis but also the trickiest to precisely estimate. W bosons with one or more than one jet produced in association are the main source of this background, but top pairs where one W decays leptonically and the other one decays into two quarks or QCD events with two or more than two jets contribute also significantly to this background as shown in Table 2.
A method was developed to estimate the probability for a central jet to be identified as a τ jet and found to be of the order of 1% in the W+jets samples [7]. The jet to τ fake rate function is parametrized with the jet transverse energy, the number of jets in the event and the sum of transverse energies deposited in the detector. The fake rate from QCD events with 2, 3 and 4 jets was found to be compatible with the fake rate from the $W \rightarrow l\nu + 1,\ 2,\ and\ 3\ jets$ samples respectively[7].

5. Control regions

Before looking at the number of observed events in the signal region, one must ensure that the prediction for the background is trustworthy. To do this, control regions are defined as the subsamples of events containing one identified lepton (electron or muon), one identified τ, missing transverse energy, and none or at least one extra jet. These control samples are dominated by the contribution from $W \rightarrow l\nu + jets$ events. The number of events as well as several kinematical distributions are checked. Figure 1 shows distributions of the product of the electron charge and the τ lepton charge and of the parameter H_t (i.e. the sum of all the transverse energies comprised within a pseudorapidity range of ± 2) in the muon case. The high probabilities of consistency between the observed and predicted distributions ensure that the background estimation is well under control.

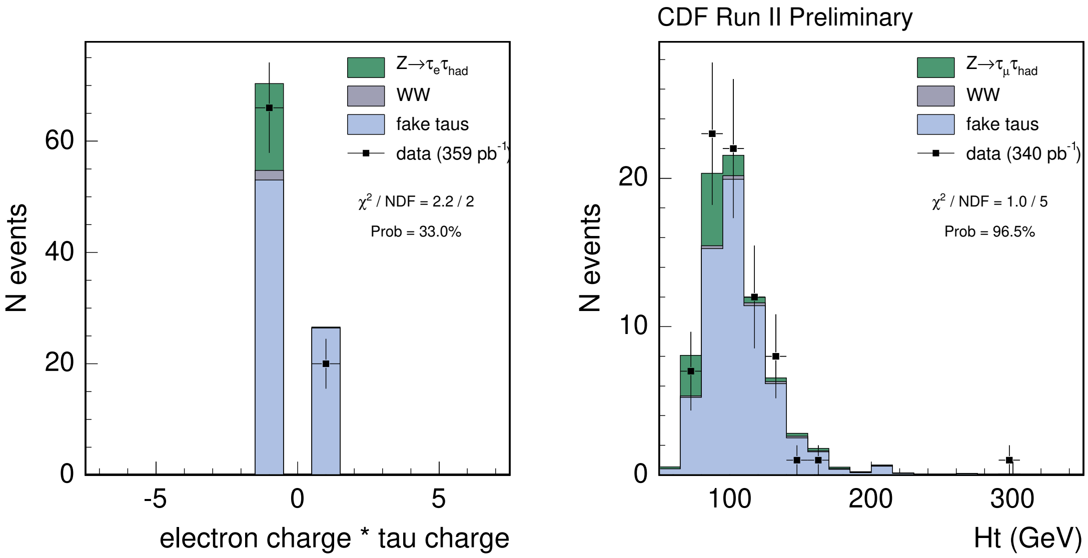
6. Results

The Table 2 summarizes the number of predicted signal and background events in the electron plus τ and the muon plus τ decay channels for a luminosity of $359pb^{-1}$ and $344pb^{-1}$ respectively. The knowledge of the error on the signal yield is not needed to achieve the first goal of this analysis, which is a clear observation of the top into the τ decay channel.

Five events compatible with τ dilepton events are observed. Two of them have one electron plus one τ lepton, the other three have one muon plus one τ lepton.This is in agreement with the signal+background expectations and so well inside the sensitivity of this analysis.

Some of the kinematical characteristics of these events are reported in Table 3. One can note that one out of the five events have a track multiplicity of one whereas the other four have 3 tracks multiplicity; all five events have an invariant mass compatible with the τ lepton mass.

The result is given in terms of the probability for the five observed events to be due to background only. This probability is estimated by folding a Poisson distribution of mean 2.8



(a) Charge product of the electron and the tau (b) Event activity distribution in the $\mu + \tau$ channel

Figure 1. *Two control distributions for events having 1 lepton, 1 τ, $\not\!\!E_T$>20 GeV*

	Electron + tau 359 pb^{-1}	Muon + tau 344 pb^{-1}
jet$\rightarrow$ τ fakes	0.91 ± 0.29	0.92 ± 0.29
e$\rightarrow$ τ fakes	0.10 ± 0.025	0.05 ± 0.012
$Z \rightarrow \tau_{\rightarrow l}\tau_{\rightarrow had}$+jets	0.39 ± 0.13	0.32 ± 0.10
$WW \rightarrow l\tau + jets$	0.034 ± 0.011	0.027 ± 0.008
Total Background	**1.4±0.3**	**1.3±0.3**
	2.8±0.4	
SIGNAL ($t\bar{t} \rightarrow l + \tau$) (assuming $\sigma(t\bar{t}) = 7.3$ pb and $m_{top} = 175$ GeV)	$1.32 \pm 0.05_{stat.only}$	$0.92 \pm 0.05_{stat.only}$
	$2.2 \pm 0.1_{stat.only}$	

Total non Higgs standard model expectations	5.0±0.5
N events observed in 350 pb^{-1}	**5**

Table 2. *Summary of predicted signal and backgrounds vs observations*

with a gaussian distribution of standard deviation 0.4 and found to be **15%** probability value (p-value). This constitutes a 1σ (68%) evidence for this attempt to observe the τ dilepton channel in the $t\bar{t}$ production, as shown in Figure 2. This analysis is not yet sensitive to a 3σ evidence of this process. However the work is now underway with three times more statistics and a refinment of the selection tools. This should hopefully lead to the first clear observation of the decay of the top into the τ lepton [8].

7. Conclusion

This work has developed a new way to estimate the most difficult element in the analysis involving τ lepton decaying hadronically, i.e. the amount of τ *fake rate*. Indeed identifying τ's decaying hadronically in a high luminosity $p\bar{p}$ collider is one of the difficult tagging task. Jets as provided by several Standard Model processes with rather high cross sections are making life even harder.

channel	$l\ E_t$ (GeV)	$\tau\ E_t$	1^{st} jet E_t	2^{nd} jet E_t	$\not{E}_T$	H_t	N jets
$e+\tau$	68	20	35	33	72	228	2
$e+\tau$	42	40	69	40	53	244	3
$\mu+\tau$	42	44	62	55	100	302	2
$\mu+\tau$	29	44	102	96	29	301	4
$\mu+\tau$	53	31	49	48	36	216	2

Table 3. *kinematical characteristics of the 5 observed events. Energy unit is GeV.*

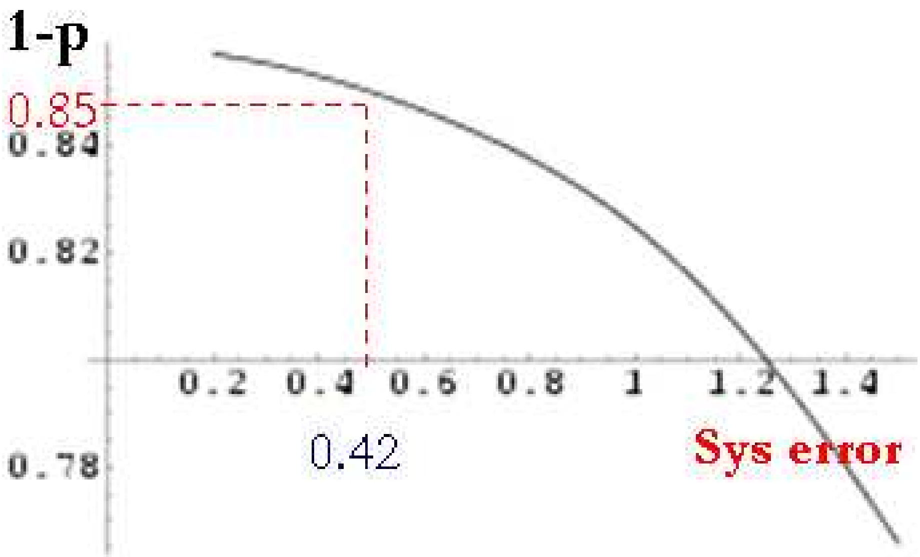


Figure 2. Dependence with the systematic error on the background of the probability for the background alone to fluctuate to 5 or more, with an expected mean number of 2.7 background events.

Moreover due to the still low statistics at disposal, not all the available detecting and tagging tools can be used to identify the top into τ dilepton events, as for instance requiring at least one b-tagged jet. The proposed analysis does not make use of this additional requirement. This is the reason why it is even more crucial to have a reliable estimate of the τ fake rate as performed here.

The work is ongoing on extracting the signal with three times more luminosity and on refining the selection tools by making use of more sophisticated statistical identification of the τ events based on maximum likelyhood or neuralnet. It is hoped this way to reach a 3σ observation of the top into τ dilepton signal and to further improve the estimate of the ratio R with the already available $1fb^{-1}$ data [9]

The longer term expectation is to obtain an accurate enough estimate of the ratio R in order to get or not an indication of New Physics. This could occur still with the Tevatron data or later on at LHC, depending how New Physics will happen to be.

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