

Tau (or no) leptons in top quark decays at hadron colliders

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Measurements in the final states with taus or with no-leptons are among the most challenging as they are those with the smallest signal-to-background ratio. However, these final states are of particular interest as they can be important probes of new physics. Tau identification techniques and cross section measurements in top quark decays in these final states are discussed. The results, limited by systematical uncertainties, are consistent with standard model predictions, and are used to set stringent limits on new physics searches. The large data samples available at the Fermilab and at the Large Hadron Collider may help further improving the measurements.

1 Introduction

Many years after its discovery [1, 2], the top quark still plays a fundamental role in the program of particle physics. The study of its properties has been extensively carried out in high energy hadron collisions. The production cross section has been measured in many different final states. Deviation of the cross section from the predicted standard model (SM) value may indicate new physics processes. Top quarks are predominantly produced in pairs, and in each top quark pair event, there are two W bosons and two bottom quarks. From the experimental point of view, top quark pair events are classified according to the decay mode of the two W bosons: the all-hadronic final state, in which both W bosons decay into quarks, the “lepton+jet” final state, in which one W decays leptonically and the other to quarks, and the dilepton final state, in which both W bosons decay leptonically. The word “lepton” here refers to electrons and muons, whereas τ s are generally treated separately. When talking about τ s, we are referring to hadronic tau decays, τ_h . At the moment, the case where the τ s decay to leptons cannot be distinguished experimentally from prompt electrons or muons.

Cross section measurements have been performed both at the Tevatron and at the LHC and the accuracy of the experimental results rivals that of theory expectations [3]. After the first few years of proton-proton collisions for the first data-taking period at the LHC energies of 7 TeV (in 2010 and 2011) and 8 TeV (in 2012), thousands of top quark events have already been reconstructed and selected. Measurements of the inclusive top quark pair production cross section have been performed at the LHC in the dilepton and lepton+jet channels using electrons and muons and provide the most precise results; most of the results obtained are limited by systematic uncertainties.

Here, we will address the final states with τ s or with no leptons. Since the first measurement

using hadronic tau decays at a hadron collider [4], tau identification techniques have improved thanks to more sophisticated particle detectors, to advanced reconstruction algorithms, and to much increased data samples. The selection and the study of these final states continues to be challenging as they are those with the smallest signal-to-background ratio. However, these decay modes are potentially interesting on their own as their branching ratios are large and could signal the presence of new physics. As an example, the $t\bar{t}$ “tau dilepton” decay mode containing one τ (in which one W decays to an electron or a muon, and the other to a τ) has a similar branching fraction to the “standard” dilepton final states with electrons and muons. As the τ s are heavier than electrons or muons, their coupling to new physics processes could be enhanced. The case of the all-hadronic final state is more complicated, as the backgrounds are even larger. However, despite the large backgrounds, measurements have also been performed in this final state with reasonable precision. The measurement in the all-hadronic final state is complementary to other measurements and is interesting in its own right.

2 Tau and b -jet identification

Identification of τ s and b -jets is not only essential in providing the necessary tools to study the final states with τ s or no leptons, but also important because an efficient b -jet identification can suppress the large backgrounds and isolate the signal sought of these final states.

2.1 Tau identification

At hadron colliders various important processes involve the emission of high- p_T electrons and muons. Examples are W, Z, and top quark production. Collider detectors have specialized in detecting electrons and muons from these events. On the other hand, τ leptons decay predominantly into charged and neutral pions and suffer from large backgrounds from jet production, and are more difficult to signal. Hadronic tau decays produce narrow and more collimated jets when compared to quark or gluon jets. Since the first attempts to detect taus at a hadron collider [4], the performance of tau lepton reconstruction and identification algorithms have improved thanks more refined particle detectors, and to sophisticated techniques/algorithms yielding an improved understanding of the data. Overall, signal efficiencies and background rejection have improved.

Tau leptons decay promptly either to lighter leptons or to hadronic jets. The hadronic and leptonic branching fractions are $\mathcal{B}(\tau \rightarrow h\tau_\nu) \simeq 64\%$ (50% one-prong, and 14% three-prong decays) and $\mathcal{B}(\tau \rightarrow \ell\nu_\ell\nu_\tau) \simeq 36\%$, respectively. Tau leptons that decay into one or three charged hadrons are identified using final-state particles reconstructed in the tracker and in the calorimeters, both electromagnetic and hadronic. In order to reduce the contamination from quark and gluon jets, it is required that the τ candidate is isolated around the reconstructed τ momentum direction. Alternative identification methods are used to discriminate tau leptons from QCD jets or other backgrounds. Either cut-based discriminants, particle-flow (PF), or boosted decision tree (BDT) algorithms are used [5, 6]. As an example, the τ reconstruction is seeded by considering each jet as a tau candidate; a list of identification variable calculated from the tracking and calorimeter information are then combined into multivariate discriminants to reject misidentified QCD jets and electrons or muons. Finally, the number of τ leptons in the selected samples is extracted by fitting the distributions of BDT outputs to background and signal templates [6]. Alternatively, the algorithms use decay mode identification techniques and

hadronic τ decays are reconstructed starting with the clustering of all PF particles into jets [5]. For each jet, a charged hadron is combined with other nearby charged hadrons or photons to identify the decay modes. The identification of π^0 mesons is enhanced by clustering electrons and photons in “strips” along the bending plane to take into account possible broadening of calorimeter signatures by early showering photons. Then, strips and charged hadrons are combined to reconstruct the following combinations: single hadron, hadron plus a strip, hadron plus two strips and three hadrons. Tau energy scale is derived using *in situ* calibration based on the $Z \rightarrow \tau\tau$ peak position. Overall, the τ identification algorithms efficiently discriminate against potentially large backgrounds from quarks and gluons that occasionally hadronize into jets of low particle multiplicity. The reconstruction efficiency of the algorithms is measured using tau leptons produced in Z-boson decays. The tau lepton misidentification rates for jets and electrons are also determined from multijet data samples. Tau identification efficiencies of 60–70% are obtained with a few percent ($\simeq 1$ –2%) background contamination due to “fakes”, i.e. where a jet is misidentified as a tau.

Some forms of tau identification have been implemented at the trigger level. However, requiring one tau alone may not be sufficient to reduce the trigger rates or to collect a tau-enriched sample of events to study a given final state and, wherever possible, the tau trigger is used in combination with other objects, such as electrons or muons, or jets, or other specific event topologies. Alternatively, inclusive electron or muon or multi jet triggers are used, and the tau lepton is only selected “offline”.

2.2 b -jet identification

Top quark pair events contain at least two jets from the hadronization of b -quarks from the $t \rightarrow Wb$ decays. In order to select top quark events, b -jet identification is therefore important, as it can be used as an additional suppression of non- $t\bar{t}$ backgrounds. All experiments use multivariate techniques combining information from lifetime (displaced tracks and/or vertices), mass (associated to the secondary vertex), decay chain reconstruction, in order to discriminate b -jets from c - and light-flavor (i.e. u, d, s, g) jets. Several alternative algorithms have been developed. The efficiency of the algorithms is measured in multijet events where a muon is reconstructed inside a jet, or are calibrated in other data samples. For jets originating from the hadronization of light-flavor jets, the misidentification efficiency is estimated using the distribution of the negative tags in jet samples, i.e. those resulting from tracks produced upstream with respect to the primary interaction vertex. A typical performance is obtained with a b -tagging efficiency of approximately 70%, and a fake rate from light-flavor jets of $\simeq 1\%$ [7].

3 Taus in top quark decays

Besides the final states with electrons and muons in the “dilepton” or “lepton+jet” final states, measurements are also performed in the final states containing at least one tau, i.e. “tau+lepton” and “tau+jets”. The interest of determining the cross section in these channels is mainly to check the consistency of the measurements with the results from the other final states. Abnormal rates of taus with respect to the SM predictions can be an important manifestation of new physics. For example, the existence of a charged Higgs with a mass smaller than the top quark mass $m_H < m_t$ could give rise to anomalous tau lepton production directly observable in these decay channels, via $t \rightarrow H^+b$. A $t\bar{t}$ cross section measurement in the final

state with taus makes it possible to probe flavor-dependent effects in top quark decays. Other possible non-SM processes that can enhance the top-quark-to- τ -lepton branching fraction are R-parity violating decays of the top quark in supersymmetric models [8] and new Z' bosons with non-universal couplings [9]. Furthermore, the $t \rightarrow (\tau\nu_\tau)b$ decay exclusively involves third generation leptons and quarks, and directly probes interactions between members of the third generation family.

3.1 Tau+lepton channel

Among the final states including taus is the $t\bar{t}$ “tau dilepton” channel, i.e. where one W boson decays into $e\nu$ or $\mu\nu$ and the other into the hadronically decaying τ lepton and ν_τ , in the final state $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$, where $\ell = e, \mu$. The expected fraction of events of the τ dilepton channel is approximately 5% (4/81) of all $t\bar{t}$ decays, i.e. similar to the fraction of the “light” dilepton channels ($ee, \mu\mu, e\mu$) which is equal to 4/81 of all $t\bar{t}$ decays. Events are selected with one W decaying to a charged lepton (either an electron or a muon, either prompt or from a τ leptonic decay) and a neutrino, and the other W decaying to a τ lepton and a neutrino with the τ lepton in turn decaying hadronically, τ_h . In addition, at least one jet is tagged (b -tag) as originating from a b quark (b -jet) by means of an algorithm that can identify b -jets with “high” efficiency while maintaining a good rejection of light-quark jets. Missing transverse momentum is also required, signaling the presence of energetic neutrinos. After the final event selection, the largest background contributions come from events where one W boson is produced in association with jets, and from $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow (\ell\nu_\ell b)(qq'\bar{b})$ events, where one jet is misidentified as the τ_h . This large background is estimated using control data samples by determining the τ misidentification probabilities in jet-dominated samples (these are orthogonal to the samples of selected events and are used to determine the “per-jet” τ misidentification probability); the misidentification rates are then applied to every jet in the $W + \geq 3$ jet sample of selected events [10]; alternatively, in order to determine the background contribution it can be exploited the fact that events with lepton and τ candidates with electric charge of opposite sign (OS) contain real τ leptons while those with same sign (SS) charge are pure background [11]. The top quark pair production cross section is measured in dilepton events with one electron or muon, and one hadronically decaying τ lepton from the decay $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$, (with $\ell = e, \mu$) [10, 11]. The measured cross section in this channel is consistent with the value measured in the other final states, and the total uncertainty of approximately 13-18% is dominated by systematics. The limiting sources of uncertainty come from the determination of the τ -fake determination and from the b -tagging efficiency uncertainties. These results are used to set stringent limits on charged Higgs production [12, 13, 14].

The top quark pair production and decay into leptons with at least one hadronically decaying τ lepton is also studied at the Tevatron proton-antiproton collider at Fermilab. The top quark pair production cross section at 1.96 TeV is measured together with the top branching ratio into τ lepton, $\mathcal{B}(t \rightarrow \tau\nu_\tau b)$ [15]. Furthermore, in order to discriminate the signature of the tau+lepton decay from the di-tau processes and perform a measurement of the branching ratio of top quark decay in tau, a second log-likelihood ratio discriminant method is implemented to separate the two processes. Measurements are in good agreement with the expectations of the SM (and with lepton universality) within the experimental uncertainties, and with the results obtained using other decay channels of the top quark at the Tevatron. Due to the smaller production cross section at the Tevatron, the results are limited by statistical uncertainties, and the total uncertainty is approximately 30%.

3.2 Tau+jets channel

The top quark pair production cross section in the final state with one hadronically decaying tau lepton together with additional jets is also measured. The tau+jets final state, i.e. $t\bar{t} \rightarrow (\tau_h \nu_\tau b)(q\bar{q}'\bar{b})$ is expected to be the largest ($\simeq 15\%$) among those with τ leptons in the final state, but it also has large background contributions. At the LHC, data for this measurement are collected either with a dedicated b -jet or with a multijet trigger, depending on the analysis. The trigger efficiencies have been measured in data, determining separately the efficiency of a single jet and a single τ_h to pass the trigger requirements. Events with at least four (or five) jets are selected, where one (or two) of the jets are identified as having originated from b quarks. One hadronically decaying tau is selected, exploiting tight identification criteria to best suppress the large multijet backgrounds. The presence of any additional lepton is vetoed. Given the small expected signal over the background ratio, a neural network has been developed to separate the top quark pair signal from the W +jets and multijet backgrounds. The multijet background is estimated from data by using the same selection as the preselected sample except that a veto is applied on the presence of a b -tagged jet. A set of different variables is used to build the neural network discriminator. In order to reduce the uncertainties, the full discriminator output is fit with a likelihood in order to extract the signal and background yields [16]. Alternatively, the τ_h contribution is separated from quark- or gluon-initiated jets with a one-dimensional fit to the distribution of the number of tracks (n_{tracks}) associated with the τ_h candidate. Since the τ_h decays preferentially to one or three charged particles (and other neutral decay products), this variable provides good separation between hadronically decaying tau leptons and jets, as the latter typically produce a large number of charged particles. To extract the signal from the n_{tracks} distribution, the data sample is fitted with three probability density functions (templates): a tau/electron template, a gluon-jet template and a quark-jet template. The electron and τ_h templates are combined into a single tau/electron template, using Monte Carlo predictions to determine their relative contributions. The tau/electron template is obtained from simulated $t\bar{t}$ events. The remaining significant contributions come from mis-identified jets, and are separated into two templates: the gluon-jet template describes the QCD multijet processes which are dominated by gluon-initiated jets, and the quark-jet template describes the remaining processes ($t\bar{t}$, single-top quark and W + jets) that are enriched in quark-initiated jets. They are both determined from data, from a control region of the multijet sample (gluon-jet template) and from a $t\bar{t}$ control sample (for the quark-jet template). A binned likelihood is used to extract the different contributions from the n_{tracks} distribution [17]. The main backgrounds come from multijet events, $t\bar{t}$ events with a different final state or signal events where the wrong jet is chosen as the τ_h candidate. A small contribution from single-top, and W + jets events is also present. Dominant sources of systematic uncertainties are due to tau identification, jet energy scale, and initial- and final-state radiation jets. The cross section measurements are consistent with SM predictions, and the total uncertainty (dominated by systematics) is approximately 21% [16] and 25% [17].

At the Tevatron the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$, and the top quark mass m_{top} are also measured in this final state. A neural network is used to reduce the large QCD multijet background contribution. A binned likelihood fit based on the predicted and observed number of events is used to measure $\sigma_{t\bar{t}}$ [18, 19]. Then, to extract the top quark mass m_{top} , a likelihood function built from signal and background probabilities is used [18]. The cross section measurement is combined using all measured $t\bar{t}$ channels with leptons in the final state (τ_h +jets, e/μ +jets, “light” dileptons), and repeat the negative log-likelihood fit for the number of $t\bar{t}$ signal and

multijet background events by fixing the $t\bar{t}$ branching fractions to their SM values, but this time fit for all $t\bar{t}$ channels simultaneously [19]. Furthermore, the cross section times the branching fraction, $\sigma_{t\bar{t}} \times \mathcal{B}_{t\bar{t} \rightarrow \tau_h + \text{jets}}$, is also measured. The cross section measurements are limited by statistical uncertainties, as only a handful of events are selected at the Tevatron.

4 All hadronic final state

The all-hadronic final state ($t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow 6 \text{ jets}$) is the most common with a branching fraction $\mathcal{B}_{t\bar{t} \rightarrow \text{all-hadronic}} \simeq 46\%$, but it competes with very high backgrounds from QCD multijet events. This final state, where both W bosons decay hadronically, is characterized by a six-jet topology. As an example, the cross sections for this QCD process at the Tevatron is higher than the top cross section by approximately three orders of magnitude. Despite the extremely high background levels, it is possible to isolate a top quark signal in this mode after applying further kinematical cuts and identifying the b quark(s) in the final state. Furthermore, it does not suffer from the presence of neutrinos of large transverse momentum p_T that escape detection. Events are selected with a multijet trigger and are required to have two reconstructed jets tagged as b -jets to identify $t\bar{t}$ event candidates. In addition, kinematical and topological characteristics are also exploited. The all-hadronic $t\bar{t}$ channel nominally has six jets and does not contain intrinsic missing transverse momentum (E_T^{miss}) or isolated leptons in the final state. Therefore, a veto against the presence of isolated leptons and significant E_T^{miss} is applied. After the event selection, a kinematic fit is performed to compute the top quark mass in the selected events. The kinematic fit is based on a likelihood approach to find the correct association of jets with the final state partons of the fully hadronic $t\bar{t}$ decays. The requirement of b -jets in the event selection reduces the combinatorics in the jet-parton assignment. In the mass distribution, the number of $t\bar{t}$ events remaining after the final selection is determined through an unbinned maximum likelihood fit of contributions from $t\bar{t}$ signal and multijet background. The results correspond to a signal fraction of approximately 31% [21] and 35% [20]. The cross section measurements in this channel are consistent with the other measurements in dilepton and lepton+jets final states, as well as with the predictions of the SM. The measurements have a total uncertainty of 20% [20] and 37% [21]. Dominant sources of uncertainty are the jet energy scale, and the b -tagging and mistagging rates on the efficiency of the event selection.

5 Summary

Measurements in the final states with taus or no leptons are some of the most challenging to be performed in top quark physics but are certainly possible. Since the first measurements, the much larger number of selected events has allowed for an improved understanding of these final states. Some of the latest and most relevant measurements have been presented and discussed. The precision of the measurements achieved both at the Tevatron and in the first few years of operation at the Large Hadron Collider have demonstrated a good understanding of the data, and have shown good consistency with expectations. Results are limited by systematical uncertainties and, with some optimism, it is natural to expect in the years to come further improvements in the understanding of these final states.

In conclusion, we have learned that, however difficult, tau detection is possible at hadron collider experiments. Taus can extend the sensitivity in searches for both known and “new” physics. Hadron colliders have an enormous discovery potential and new physics can show up

as an excess of tau production. It is essential that detector upgrades and new detector designs consider tau detection as an additional handle to new physics searches.



Figure 1: A day without rain in the vineyard.

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