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Tau Identification at Fermilab DØ and Higgs Searches Using Taus

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We describe the τ-lepton identification algorithms employed at the Fermilab DØ experiment. τ-lepton can significantly increase the sensitivity of many lepton analyses and especially searches for the Higgs boson. We point out several such searches for the Standard Model and beyond the Standard Model Higgs sector.

1. INTRODUCTION

An outstanding problem of the Standard Model (SM) of particle physics, the Electroweak Symmetry Breaking (EWSB), has been approached from many fronts, and the approach standing at the top of the line, the Higgs mechanism, is considered the most probable explanation. Although not devoid of shortcomings which also have a long list of solution propositions it quite simply describes the acquisition of mass by the Electroweak Bosons and also the SM quarks and leptons.

The Higgs boson couples to mass and therefore probing the EWSB is best in the channels where the Higgs boson decays into b-quarks, τ's, or EW bosons. The existing measurements of the SM parameters and cross sections push the limit of the hypothetical Higgs boson mass to 114 GeV [1]. Although for the Higgs mass above this limit the τ contribution to the sensitivity of the SM Higgs search is significantly reduced, the τ channel plays a substantial role in proving the overall consistency of the SM picture.

An intriguing opportunity exists for the τ channel when one considers a proposed solution to the hierarchy problem of the SM, the Minimal Supersymmetric Standard Model (MSSM), where the Higgs sector, now consisting of 5 Higgs bosons, couples differently to bottom quarks and τ's than to top quarks. The coupling to bottom-type fermions is thus enhanced by about the factor of $\tan\beta$, the parameter of the theory, and pushes the Higgs decay channels into b-quarks and τ's to the top of the list of the branching ratios.

The τ-lepton, by having a smaller mass, loses to the b-quark in the branching ratio but instead acquires an opportunity to be better distinguished from the enormous QCD backgrounds plaguing the b-quark channel. At the level where the reconstruction of the hypothetical Higgs boson mass can not play a significant role in distinguishing the Higgs signal from backgrounds the τ-lepton channel competes quite well with the b-quark channel and adds considerably to the Higgs search sensitivity despite the almost 9:1 ratio in the branching fraction.

1.1. Detector

The DØ experiment at Fermilab works with the proton anti-proton beams with the center-of-mass energy of 1.96 TeV. Its major components useful for the τ identification are the liquid argon calorimeter, silicon and scintillating fiber tracking system, and proportional drift tube (PDT) and scintillation counter muon system [3].

The DØ calorimeter consists of three separate cryostats divided into 4 layers of electromagnetic cells and several layers of fine hadronic and coarse hadronic cells. An Inter Cryostat Detector (ICD) made of scintillating tiles fills in the information gaps between the 3 parts of the calorimeter.

The tracking device consists of the Silicon Microstrip Tracker (SMT) and Central (Scintillating) Fiber Tracker (CFT) inserted into a 2 T superconducting solenoidal magnet.

The SMT is at the heart of the tracking sys-

tem being located right around the beam pipe and used for tracing the track origin and distinguishing between minimum bias, hard scattering events, and short lived particle decays. The SMT consists of 4 staggered layers of barrel sensors each comprised of two sublayers, and 14 disks to allow gapless coverage. In anticipation of the losses of innermost layer efficiency due to effects of radiation aging another layer, called Layer 0, has been installed inside the aging Layer 1.

The other indispensable part of the tracking system is the CFT which consists of 8 layers of scintillating fibers, each arranged in a combination of an axial and a stereo sublayer. Tracks that are formed by the SMT are propagated to the calorimeter through the Central Preshower (CPS) or Forward Preshower (FPS) using the CFT hit information.

A detailed study of the backgrounds masquerading as a tau-lepton requires knowledge of the Muon System response of the event. The Muon System consists of the Central Muon System with PDTs, toroidal magnets, and central scintillation counters, and the Forward Muon System with Mini Drift Tubes (MDT) and trigger scintillation counters.

1.2. Tau lepton

The τ-lepton is the heaviest, third generation lepton, which has a very short lifetime of about $3 \cdot 10^{-13}$ s. It decays before reaching any part of the DØ detector and therefore is only registrable through products of its decay [2]. The most significant τ decay channels relevant to the following are shown in Table 1.

Table 1
τ-lepton decay modes.

$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.9%
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.4%
$\tau^- \to h^- \nu_\tau$	11.6%
$\tau^- \to h^- \geq 1\pi_0 \nu_\tau$	36.5%
$\tau^- \to h^- h^- h^+ \geq 0$ neutrals ν_τ	15.2%

The experimental values are given in ref. [2].

A high transverse energy ($E_T > 10$ GeV) τ will be detected as a narrow jet (because of its low mass) with 1 or 3 tracks, often with clustered deposits in the electromagnetic part of the calorimeter at a small angle from the tracks, and with missing energy along the direction of the jet.

Particulars of the distribution of the energy deposition along the calorimeter cluster (see below) and ratio of the track transverse momentum (p_T) to the cluster transverse energy (E_T) can be also used to discriminate between the τ decaying hadronically or to an electron. Most muons can be distinguished from τ's because of low energy deposition in the calorimeter but a small percentage will have large brehmstrahlung or interact in the calorimeter depositing a substantial amount of their energy making it difficult to distinguish them from single charged pions.

2. TAU IDENTIFICATION

Two complementary algorithms are used to reconstruct τ's. Both algorithms use pre-clustered calorimeter towers. Calorimeter towers are sets of calorimeter cells organized geometrically with the E_T calculated with respect to the chosen hard scattering vertex. The first algorithm builds a τ-candidate object around a candidate track and the other one uses one of the pre-clusters as a seed.

1 to 3 tracks compatible with the τ decay inside the $\Delta R < 0.5$ are considered, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ is the pseudo-angular distance between the cluster axis antd the track. ϕ is the azimuthal angle and η is the pseudo-rapidity [3]. Track combined invariant mass is supposed to be smaller than the τ-lepton mass. The highest p_T track is supposed to satisfy $p_T > 1.5$ GeV cut.

Clustered electromagnetic calorimeter deposits are looked for starting from calorimeter layer 3 which has double the granularity of the rest of the electromagnetic calorimeter. These subclusters are formed by stitching together individual calorimeter cells. Up to 2 subclusters are found and their individual deposits into the layer 3 of the calorimeter are supposed to be greater than 800 MeV.

Different τ cluster and track variables are cal-

culated using the energy deposition distribution inside $\Delta R < 0.3$ and $\Delta R < 0.5$ cones around the cluster axis and track transverse momentum [4].

A neural network (NN) is trained using these variables as input. Signal sample is taken from the Monte Carlo simulated τ candidates coming from a Z boson decay, and the background is taken from data τ candidates recoiling against a muon, surrounded by large energy deposits in the calorimeter and tracks with high combined p_T within a $\Delta R < 0.5$ cone. Such muon candidate most probably belongs to a hadronic jet rather than a τ-lepton decay which means that the recoiling τ-candidate is also a jet mimicking a τ-lepton.

For the purposes of increasing the efficiency of the τ identification τ candidates are subdivided into 3 types according to the number of associated tracks and electromagnetic subclusters. Type 1 is characterized by having 1 track only and no electromagnetic subclusters. Type 2 also has 1 track and 1 or more reconstructed electromagnetic subclusters. And, finally, type 3 has 2 or more tracks and any numbers of subclusters. The NN is trained separately for each of the types. Figure 1 shows the resulting NN output for the τ type 2. By making a cut on the NN output one can reduce the amount of background in data.

The neural network significantly improves signal-to-background ratio of the τ identification as shown in the Table 2.

Table 2
Tau identification efficiencies (%).

$20 < E_T^\tau < 40$ GeV, $\lvert\eta\rvert < 2.5$				
τ type	1	2	3	all
jets	2	12	35	52
τ	11	60	24	95
$NN > 0.9$				
jets	0.06	0.24	0.8	1.1
τ	7	44	16	67

Using the calorimeter shower shape and track variables taus can also be discriminated from electrons. Those mainly concentrate in type 2. A separate neural network (NN_e) has been created for this purpose. The tau and electron efficiencies illustrating its effectiveness are shown in Table 3.

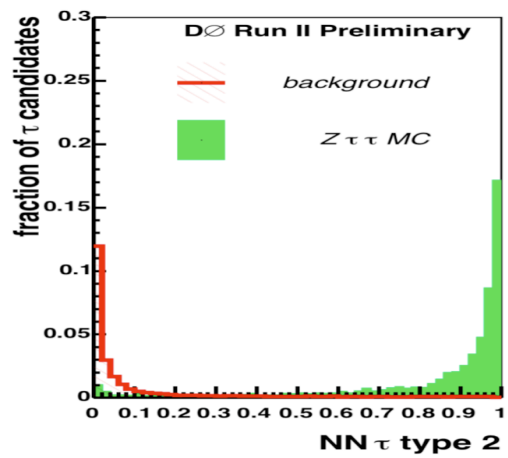

Figure 1. NN output for the τ type 2.

Table 3
Tau vs electron identification efficiencies when using NN elec (%).

$20 < E_T^\tau < 40$ GeV, $\lvert\eta\rvert < 2.5$		
	$NN(type2) > 0.9$	$NNe > 0.5$
electron	98	3.4
τ	44	38

A variable $E_T^\tau / P_T^{trk} \cdot (1 - CHF)$ can be used to reduce contamination from muons misidentified as taus. E_T^τ is the tau transverse energy, P_T^{trk} is the associated track transverse energy, and CHF is the fraction of the τ energy within the coarse hadronic part of the calorimeter. Table 4 shows the efficiencies corresponding to the misidentified muon rejection.

3. HIGGS SEARCHES

The hypothetical Higgs boson decay into the τ-leptons has the most significant branching ratio

Table 4
Efficiencies of cuts against the muon misidentified as τ (%).

$p_T^{\tau trk} > 10$ GeV, $\|\eta\| < 2.5$, $NN > 0.9$		
τ type	1	2
mis μ	2.5	3.1
elim mis μ	0.4	0.8
$E_T^\tau / P_T^{trk} \cdot (1 - CHF) > 0.4$	0.2	0.4
τ	5.5	35

at lower masses therefore its contribution plays an indispensable role in finding the evidence for the Higgs mechanism or excluding it. Some of the analyses briefly shown below also use DØ b-jet identification algorithms, described elsewhere [5].

3.1. Search for the SM Higgs boson in the $WH \to \tau\nu_\tau b\bar{b}$ channel in Run IIa

The analysis [6] studies the hypothetical Higgs boson production in association with a heavy electroweak boson W ($p\bar{p} \to HW$), where the Higgs decays into a pair of b-quarks ($H \to b\bar{b}$), and the W decays into a tau and a neutrino ($W \to \tau_h \nu_\tau$), where the τ is supposed to decay hadronically. The analysis is also sensitive to the $ZH \to \tau\tau b\bar{b}$ channel when one hadronic tau is mismeasured.

The analysis looks for events with high missing transverse energy ($\not\!\!E_T$) coming from the W decay and tau decay products. It uses 0.94 fb^{-1} of DØ Run IIa (2002-2006) data.

The hadronic tau candidate must satisfy $NN > 0.9$ cut, and several kinematic cuts. Two or three jets with $\Delta R(\tau, jet) > 0.5$ are required. Two of the jets with the highest p_T are required to satisfy asymmetric cuts on the b-tagging algorithm output function. Missing transverse energy and the angle between the $\not\!\!E_T$ and the τ ($\Delta\phi(\tau, \not\!\!E_T)$) are required to satisfy a cut in the $\not\!\!E_T$,$\Delta\phi(\tau, \not\!\!E_T)$ plane according to the formula $\Delta\phi(\tau, \not\!\!E_T) < 2 + (\pi - 2) \cdot (\not\!\!E_T - 30 \text{ GeV})/50 \text{ GeV}$. The di-jet invariant mass distribution after requiring the analysis cuts is shown in Figure 2.

In the absence of a significant signal a 95% confidence level (CL) limit is placed on the production cross section times the branching ratio into tau. It is shown in Figure 3. It is the first analysis trying to look for the SM Higgs boson in this channel at hadronic colliders and it reaches the level of 35 times the SM model cross section sensitivity.

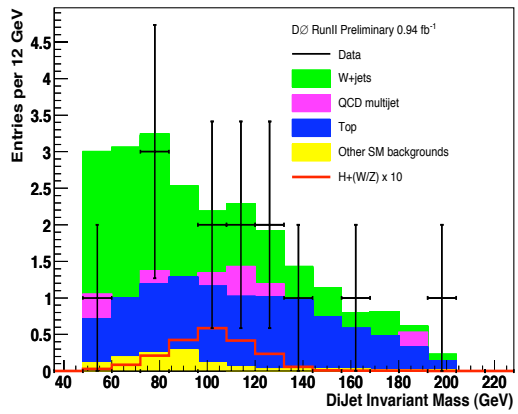

Figure 2. Di-jet invariant mass after applying the analysis cuts.

3.2. Search for MSSM Higgs Boson Production in Di-tau Final States with L=2.2 fb^{-1} at the DØ Detector

Another analysis searches for the Higgs boson decaying into a pair of taus. This channel is not very sensitive to the SM Higgs but is very important in searches for the MSSM [7]. Tau decays considered in the Run IIa [8] are to $\tau_e\tau_\mu$, $\tau_h\tau_\mu$, $\tau_h\tau_e$, and $\tau_h\tau_\mu$ in the Run IIb (2006-2007), where τ_h is the hadronic decay and τ_μ, τ_e are the decays to a muon or an electron, respectively.

Major sources of background include QCD, $Z \to ll$ and $W \to l\nu$, where l is any lepton including τ. Purity of the taus in data reaches very high level (around 90%). Visible mass (invariant mass of the τ-pair and $\not\!\!E_T$ is shown in Figure 4.

In the absence of a signal a 95% CL limit is set on the production of the MSSM Neutral Higgs bosons times branching ratio into $\tau\tau$ and

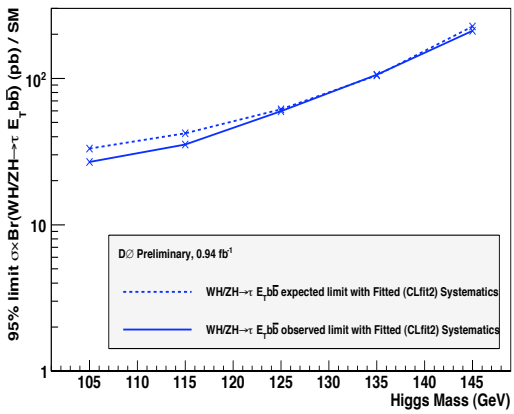

Figure 3. 95% CL limit on the Higgs production cross section times branching ratio of the Higgs into tau.

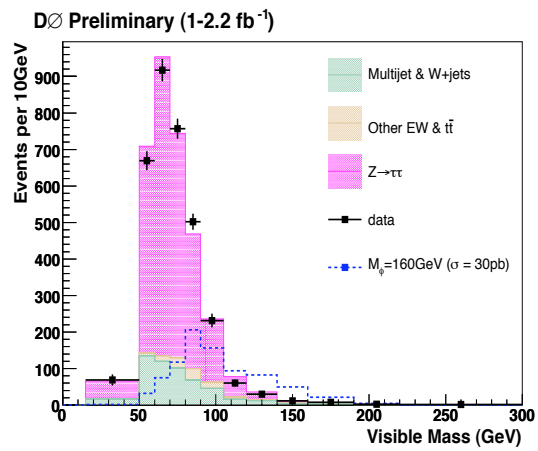

Figure 4. Visible mass of the τ-pair.

constrains the MSSM parameter space, in the $\tan\beta, M_A$ plane, where M_A is the mass of the pseudo-scalar Higgs boson [1]. The excluded MSSM parameter space is shown in Figure 5 for the maximal mixing scenario.

3.3. A search for neutral higgs bosons at high $\tan\beta$ in the mode $\phi b \rightarrow \tau_\mu \tau_h b$ in Run IIb

A different analysis looks for the associated production of the MSSM Higgs boson with the b-quark. The coupling of the neutral Higgs to the b-quark is enhanced in the MSSM, see Section 1. This analysis uses 1.2 fb^{-1} data of the Run IIb [9].

Major sources of background for this search are also QCD, $Z + jets(b,c) \rightarrow ll + jets(b,c)$, $W + jets(b,c)$ and top pairs ($t\bar{t}$). Right now the sensitivity of the analysis is limited by a 30% systematic error on the NLO scale factor applied to the $Z + (b,c) \rightarrow ll + (b,c)$ background estimate modeled with the help of ALPGEN [11] and PYTHIA [10] Monte Carlo generators at low Higgs masses and a 11% uncertainty associated with the $t\bar{t}$ cross section at higher Higgs masses.

There are two extra multivariate methods used in addition to the tau neural net. These are a neural net utilizing some kinematic differences between $t\bar{t}$ background and the Higgs signal model (KNN), and a likelihood which includes a visible mass of the τ pair to additionally discriminate signal from the QCD background (LHood). A square cut in the two dimensional plane, see Figure 6, is optimized to reach a maximum sensitivity of the search.

In the absence of a significant signal the search also puts a constraint on the MSSM $\tan\beta, M_A$ parameter space which is shown in Figure 7 for the maximal mixing scenario.

4. CONCLUSIONS

DØ maintains a highly efficient τ-lepton identification algorithm which allows high τ purity ($> 90\%$) to be reached along with the high level of jet background rejection ($< 1\%$). It is very important in expanding the sensitivity of lepton analyses and is indispensable by itself in searches for EWSB.

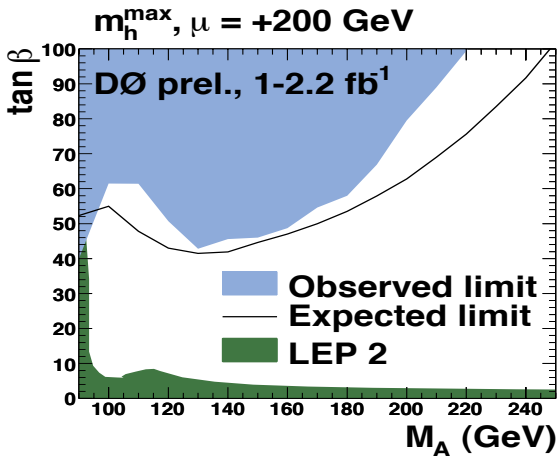

Figure 5. Constraints on the $\tan\beta, M_A$ MSSM parameter space for the maximal mixing scenario.

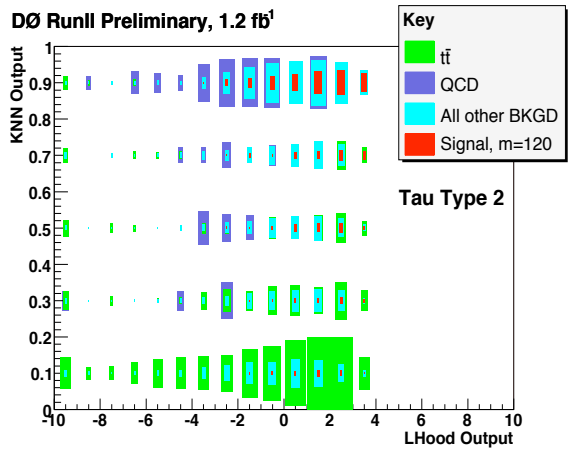

Figure 6. Two dimensional plane of the kinematic neural net and QCD likelihood.

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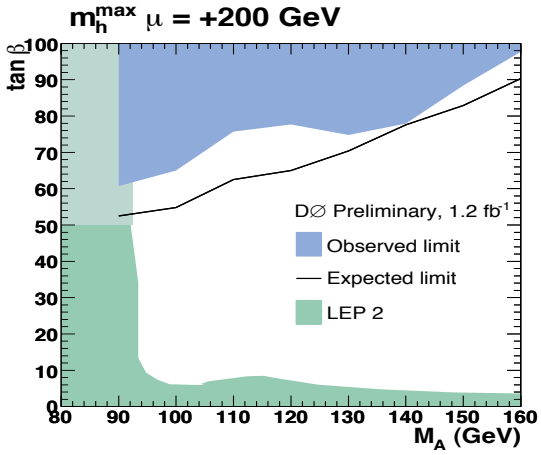

Figure 7. Constraints on the $\tan\beta, M_A$ MSSM parameter space for the maximal mixing scenario.