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Searches with Taus at the Tevatron

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We discuss tau identification techniques at hadron colliders, and present the measurements and the searches performed so far. We report on top quark pair production in the decay channel containing at least one tau lepton. Also, we present results dedicated to searches for new particles, with taus in the final state. We present a search for the charged Higgs boson in the tau decay channel, as well as for the leptoquark family containing tau leptons. Finally, we indicate the capabilities of detecting and triggering on tau leptons in the future collider run.

1. Introduction

Tau leptons are not only a precision measurement tool but also a sensitive probe for new physics. In this paper we review the importance of their contribution and the results obtained so far at the Tevatron Collider. Two experimental collaborations, CDF and D0, have collected data at a $p\bar{p}$ center of mass energy of $\sqrt{s} = 1.8$ TeV. There have been two major runs of the Tevatron, accumulating approximately 20 pb^{-1} of data in 1992–93, and 100 pb^{-1} in 1994–95. The next run starting starting early in the next millennium will provide 1000 pb^{-1} per year. Both the increased luminosity yield and the upgraded detector with improved detection capabilities will improve tau detection at both CDF and D0 experiments at the Tevatron.

At $p\bar{p}$ colliders various important processes involve the emission of high-p_T electron and muon leptons. Examples are W, Z° and top quark production. Collider detectors have specialized in detecting electrons and muons from these events. On the other hand, tau leptons decay predominantly into charged and neutral pions and suffer from large backgrounds from jet production, and are much more difficult to signal. However, abnormal rates of high p_T taus, with respect to the Standard Model (SM) predictions, can be an important manifestation of new physics in hadron

collider experiments. An example of this is the decay of top into a charged Higgs that would predominantly couple to taus. Understanding tau production at $p\bar{p}$ colliders is therefore important for several reasons:

- to check the universality of lepton couplings;
- the acceptance and sensitivity in search for processes with high-p_T leptons is increased;
- and, above all, to search for new physics.

2. Tau Identification

Tau leptons decay promptly either to lighter leptons or to hadronic jets. The hadronic and leptonic Branching Ratio (BR) are respectively BR($\tau \rightarrow h\nu_\tau$) $\simeq$ 64% [1] (50% one-prong and 14% three-prong decays) and BR($\tau \rightarrow l\nu_l\nu_\tau$) $\simeq$ 36%. Here, we only consider hadronic tau decays. At the moment, the case where the taus decay to leptons cannot be distinguished experimentally from prompt electrons or muons.

The identification of hadronically decaying τ's is difficult due to the background contributed by the much more numerous quark or gluon jets. This is especially true at a hadron collider, where the hadronic activity in the final state is very abundant.

During Run 1 (1992–1995), some forms of tau identification have been implemented at the trigger level in the CDF experiment at Fermilab.

These require that a cluster with a small number of calorimeter cells be found and correspond in direction to a track above a certain p_T threshold. However, this trigger is not very selective. One way to circumvent triggering on the hadronic tau decay itself is triggering on other event characteristics such as missing transverse energy ($\not{E}_T$), or on other specific event topologies. So far, this method of triggering has proved to be more effective than specifically triggering on the hadronic decay of the tau lepton. Although it is more effective than triggering on tau leptons themselves, the $\not{E}_T$ trigger is not fully efficient until $\not{E}_T$ reaches above 40 GeV. The low efficiency capabilities especially affects measurements which require large statistics, as the $W \to \tau\nu$ asymmetry and tau lepton universality [2], or production of events with low cross section, like searches for new signatures.

Hadronic tau decays have several characteristics that can be used to distinguish tau leptons from QCD quark or gluon jets. In general secondaries from a hadronic tau decay form a narrow collimated jet with only one charged particle track ($\approx 78\%$). Tau leptons also decay to three prongs ($\approx 22\%$). In addition, with the advent of solid state vertex detectors, large impact parameters and displaced vertices could eventually be used to enhance tau identification. The best set of variables to identify taus depends on the specific characteristics of the detector. In general both excellent tracking and calorimetry are essential. The CDF method to identify hadronic tau decays uses both tracking and calorimeter quantities. We look for isolated tracks with large transverse momentum ($p_T > 15$ GeV/c). We use primarily the tracking isolation in a cone $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ in (η, ϕ) space around the high-p_T track, as a powerful way to discriminate beween signal and background. Furthermore, using calorimeter information, we discriminate taus from electrons and muons by rejecting highly electromagnetic calorimeter clusters and minimum ionizing particles, respectively. We call this method a "track–based" τ algorithm.

Decays of τ leptons often produce neutral pions. We can thus use calorimeter informations to identify π°'s. We can add to the previous selection a search for the photons from the decay $\pi^\circ \to \gamma\gamma$ in the electromagnetic shower detector. Using this method we can also extend the search to three–prongs decays of τ leptons. We call this method a "calorimeter–based" τ algorithm.

The most abundant source of high–p_T leptons at hadron colliders is from W bosons decays. We check the tau identification method in a data sample which is enriched in $W \to \tau\nu$ decays. Typically, a $W \to \tau\nu_\tau \to hadrons + \nu_\tau\bar{\nu}_\tau$ decay has one jet from the τ, and $\not{E}_T$ due to the neutrinos. A monojet sample is selected by requiring one central jet with $15 < E_T < 40$ GeV, no other jet with $E_T > 7$ GeV in $|\eta| < 4.0$, and $20 < \not{E}_T < 40$ GeV. Figure 1a shows the track multiplicity in this sample and in a background sample of QCD jets. The latter is normalized to the monojet sample using the bins with ≥ 4 tracks where there is a very small contribution from $W \to \tau\nu_\tau$ events. The data show a clear excess in the one-prong and three-prong bins, as expected for a sample with significant τ fraction. Figure 1b shows the track multiplicity after applying all cuts from the τ selection. The background in all bins is greatly reduced and the data agree well with the expectation from a $W \to \tau\nu_\tau$ Pythia Monte Carlo.

3. Taus in Top Quark Decays

At the Tevatron Collider top quarks are expected to be produced primarily in pairs, $p\bar{p} \to t\bar{t}$. In the framework of the Standard Model each top quark decays into a W and a b quark. The final state of a $t\bar{t}$ decay therefore has two W bosons and two b quarks. The $t\bar{t}$ decays can be characterized by the decays of the two W bosons. The *dilepton* category is represented by the case in which both W bosons decay leptonically. Here we present the first evidence for top quark decays in the "tau dilepton" channel [3], where one W decays into $e\nu_e$ or $\mu\nu_\mu$ and the other into the third-generation leptons, τ and ν_τ. This channel is of particular interest because the existence of a charged Higgs boson $H^\pm$ with $m_{H\pm} < m_{top}$ could give rise to anomalous τ lepton production through the decay chain $t \to H^+ b \to \tau^+ \nu_\tau b$, which could be directly observable in this channel [4]. In the Standard
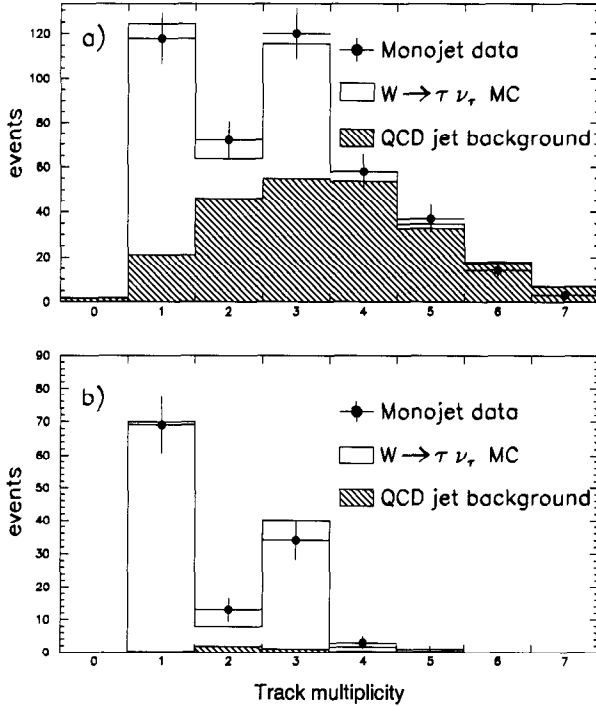
Figure 1. Track multiplicity in the monojet data sample. a) No τ ID cuts applied. b) After applying all τ ID cuts except track multiplicity.

Model the top BR to Wb is essentially 100% and the approximate BR of W to each of $e\nu_e$, $\mu\nu_\mu$, and $\tau\nu_\tau$ is 1/9, and to $q\bar{q}'$ is 6/9. Consequently, the total BR for $t\bar{t}$ into $e\tau$ and $\mu\tau$ events is 4/81, the same as for ee, $\mu\mu$, and $e\mu$ combined. In principle, the number of dilepton events could be doubled by including τ's. However, the 64% BR for τ decays into hadrons, decreased kinematic acceptance due to the undetected ν_τ, and a τ selection that is less efficient than the e or μ selection, result in a total tau dilepton acceptance about five times smaller than that for ee, $\mu\mu$, and $e\mu$ events. We report here on a search based on a $109\pm7\text{pb}^{-1}$ data sample collected with CDF during the Fermilab 1992–93 and 1994–95 Collider runs. The data sample used in this analysis requires high-p_T inclusive lepton events that contain an electron with $E_T > 20$ GeV or a muon with $p_T > 20$ GeV/c in the central region ($|\eta| < 1.0$).

Top events and background have different topologies. Dilepton events from $t\bar{t}$ decays are expected to contain two jets from b-decays and large missing transverse energy from the neutrinos. Due to large M_{top}, $t\bar{t}$ events exhibit large total transverse energy, H_T [5]. Finally, the leptons must have opposite charge. The dominant background is due to a real physics process, $Z/\gamma \rightarrow \tau^+\tau^- + jets$ events. We use kinematical variables to isolate $t\bar{t}$ events by requiring:

- $N_{jets} \geq 2$, where N_{jets} is the number of jets at $|\eta| < 2.0$ and $E_T > 10$ GeV;
- $H_T > 180$ GeV;
- $S_{\not{E}_T} > 3$ $(\text{GeV})^{1/2}$, where $S_{\not{E}_T} \equiv \frac{\not{E}_T}{\sqrt{\Sigma E_T}}$ is the significance of the missing transverse energy.

In addition, one high-p_T isolated track identifies the tau hadronic decay, using the method described in the previous Section. The final total acceptance is very small and amounts only to about 0.1%.

We observe 4 candidate events where we expect ~ 1 $t\bar{t}$ event and ~ 2 background events (see Table 3). In three of the events we identify jets from b quark decays, which supports the $t\bar{t}$ hypothesis. Two of the four candidate tau tracks show a significantly large impact parameter. Using the numbers of estimated background and observed events in Table 3 and the acceptances, we calculate the production cross section. For the calorimeter–based selection we find $\sigma_{t\bar{t}} = 10.2^{+16.3}_{-10.2}(\text{stat})\pm1.6(\text{syst})$ pb, and $29.1^{+26.3}_{-18.4}(\text{stat})\pm4.7(\text{syst})$ pb for the track–based selection, consistent with other measurements given the large statistical uncertainty.

Selection	Track–based	Cal–based
τ fakes	0.25±0.02	0.78±0.04
$Z/\gamma \rightarrow \tau^+\tau^-$	0.89±0.28	1.48±0.38
WW, WZ	0.14±0.08	0.24±0.10
Total Background	1.28±0.29	2.50±0.43
expected from $t\bar{t}$	0.7±0.3	1.1±0.4
Data (b-tagged)	4 (3)	4 (3)

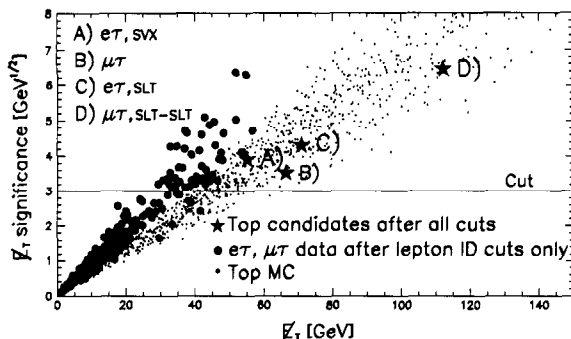Table 1: The expected number of background and $t\bar{t}$ events and the observed events.

Figure 2. The distribution of $S_{\not{E}_T}$ vs $\not{E}_T$ for events with a primary lepton and a tau candidate in the data. Three of the four final candidate events (stars) have b-tagged jets.

In the next collider run, CDF expects to detect about 20 of these "tau dilepton" events. Deviations from the SM predictions will possibly become statistically significant.

4. Search for Charged Higgs with Hadronic Tau Decays

The discovery of the top quark [6][7][8] at the Tevatron collider has generated a great interest in the search for new particles possibly emitted in its decay. Due to the large top quark mass a large range of mass of these daughter particles is also accessible.

Charged Higgs bosons are required by supersymmetric models. Their discovery would suggest that electroweak symmetry breaking occurs in a Higgs sector containing two doublets, rather than just one as required by the minimal Standard Model (SM). The two doublets imply physical fields which include two charged Higgs particles: H^+ and H^-. If the charged Higgs exists with a mass less than that of the top quark, the top quark can decay to a charged Higgs and a b quark. This would compete with the SM decay of the top quark to a W boson and a b quark. In particular, the top quark decay provides a promising signature for charged Higgs boson in the region where

$\tan\beta \geq m_t/m_b \approx 50$ (see Fig. 3), where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. The charged Higgs would decay almost exclusively to a tau lepton, unlike the W, which can decay to quarks and the other leptons. Thus, an enhancement in the tau lepton channel can provide a specific signature for the Higgs boson.
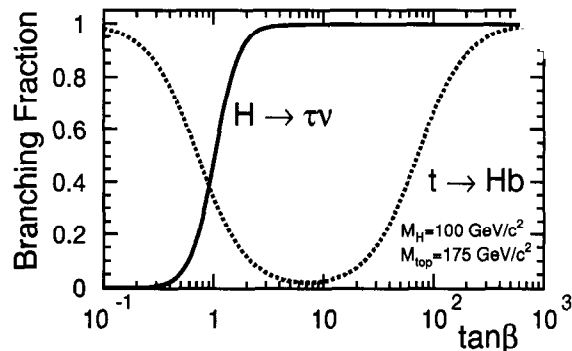

Figure 3. Branching fraction of $H \rightarrow \tau\nu$ and $t \rightarrow Hb$ as a function of $\tan\beta$.

At the Tevatron Collider, CDF has searched [9] for the charged Higgs boson assuming BR($H \rightarrow \tau\nu \simeq 100\%$).

CDF has used the results from the top analysis, in the final state with two jets, large transverse missing energy and two leptons, one of which is a hadronically decaying tau lepton [3] (see previous paragraph). Then, we apply the same selection to the top quark decays which contain the charged Higgs (i.e. $t\bar{t} \rightarrow WbH\bar{b}$ and $t\bar{t} \rightarrow HbH\bar{b}$), for different Higgs masses, and we calculate the total acceptances. Finally, we add the various contributions together as a function of $\tan\beta$. The total acceptance amounts to about 0.5% both in the WH$b\bar{b}$ and HH$b\bar{b}$ final states for different Higgs masses in the range 80–160 GeV/c^2. Only an exclusion region can be drawn, which excludes branching fractions BR($t \rightarrow Hb$)> 0.7.

CDF has also searched for charged Higgs in the inclusive channel final state where either one or

two taus can be present in the final state. CDF observes 7 events [9], with an expected background (mostly due to fakes from QCD jets) of 7.4 ± 2.0 events. If $\tan\beta \geq 50$, this analysis excludes charged Higgs boson with $M_{H^\pm} < 158$ GeV/c^2 for a top quark mass of 175 GeV/c^2 and $\sigma_{t\bar{t}} = 7.5$ pb. Figure 4 shows the excluded region.
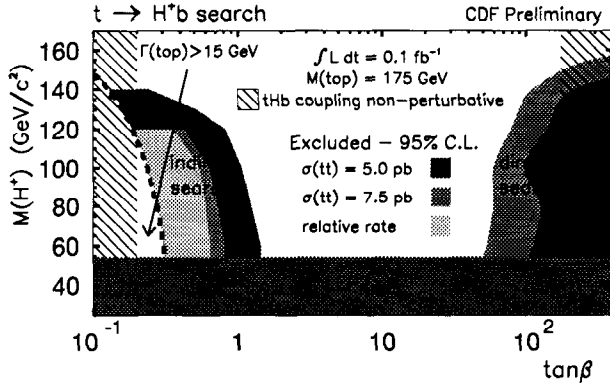

Figure 4. Shaded regions show the exclusion region for the charged Higgs boson as a function of $\tan\beta$.

CDF is also investigating the effect of the width of the distribution of the top quark mass (effective at small values of $\tan\beta$) and the non perturbative $t{\to}Hb$ coupling which is important both at low and large values of $\tan\beta$. The Yukawa couplings of $H^\pm$ to fermions can become arbitrarily large in the limits where $\tan\beta \to 0$ and $\tan\beta \to \infty$. As an example, if $M_{H^\pm} = 100$ GeV/c^2, then at $\tan\beta = 0.2$, $\Gamma_{top} \approx 20$ GeV, and at $\tan\beta = 175$, $\Gamma_{top} \approx 8$ GeV and $\Gamma_{H^\pm} \approx 6$ GeV. Therefore, the perturbative coupling of $t - H - b$ limits our search to the region $0.2 < \tan\beta < 175$. Outside this range, our Monte Carlo simulations and branching fraction equations become invalid.
Limits from the CDF 'indirect search' for $H^\pm \to c\bar{s}$ are not discussed here. A combined analysis for Run 1 data is underway to set limits on charged Higgs production.

5. Neutral Higgs boson

Neutral Higgs (H^0) can also be produced at the Tevatron. The production cross section can be substantially large [10], especially if the production goes through the process $gg \to H$, with σ_{gg} of the order of few picobarns. The neutral Higgs decays with higher branching ratio to b quark and tau lepton pairs. In a region where the Higgs mass is in the region $80 \leq M_H \leq 130$ GeV/c^2, the contribution from the decay $H^0 \to \tau^+\tau^-$ becomes non negligible, as the branching ratio $\mathrm{BR}(H_{SM} \to \tau^+\tau^-) \approx 8\%$. This signature could become significant in Run 2, and discrepancies from the SM could be measured if present.
Analogously, the associated hadroproduction of a neutral Higgs boson with a $\tau\bar{\tau}$ pair ($p\bar{p} \to b\bar{b}H^0 \to b\bar{b}\tau^+\tau^-$) could manifest as an excess in tau production. According to some non-SM models, the coupling can be as large as $(g)^2 \approx \tan\beta$. For values of $\tan\beta \approx m_t/m_b = 35$, the enhancement in the cross section could potentially become significantly large.
The experimental signature is a final state with two jets possibly coming from b jets and two τ leptons. At the present, due to a small cross section and the findings in the data, only limits can be drawn [11].

6. Search for the Third Family Leptoquark

Leptoquarks belong to a class of particles carrying both color and lepton quantum numbers which mediate transitions between quarks and leptons. Leptoquarks do not exist within the SM but appear in many SM extensions which predict a symmetry between quarks and leptons. The Tevatron with the currently highest center of mass energy in the world is in a unique position to search directly for the existence of the leptoquarks.
Assuming pair production, CDF has searched for the third generation Leptoquark (LQ3) [12] ($LQ_3\overline{LQ_3} \to \tau^+\tau^-jj$). The selection requires one of the τ leptons to decay to e or μ with $P_T > 20$ GeV/c^2. The other τ decays hadronically. In addition, the selection requires two jets with $E_T > 20$ GeV. CDF observes 1 event in 110 pb^{-1} of data which survives all cuts,

with an estimated background of $2.4^{+1.2}_{-0.6}$ events (mostly from $Z \to \tau\tau$ +*jets*). For scalar leptoquarks we set a limit at $M_{LQ3} >99$ GeV/c^2. We also consider vector leptoquarks with "anomalous chromomagnetic moments" parametrized by k [13]. CDF sets a limit $M_{LQ3} >170$ GeV/c^2 and $M_{LQ3} >225$ GeV/c^2, for $k=0$ and $k=1$ respectively (see also [12]).

We use the third generation leptoquark search to constrain technicolor models containing a technifamily. In technicolor models containing a technifamily, color–octet technirhos (ρ_T) enhance the pair production of color–triplet technipions (π_{LQ}), which behave as third generation leptoquarks. We can set constraints [14] on the production of technipions and technirhos as a function of their masses. Comparing to the theoretical expectations for technipion pair production, we place bounds in the $M(\pi_{LQ})$–$M(\rho_T)$, for three values of the mass splitting, 0, 50 GeV/c^2 and infinity (see Figure 5). For $\Delta M=0$ and $M(\pi_{LQ})<$ $M(\rho_T)/2$, we exclude color octet technirhos with mass less than 465 GeV/c^2 at 95% confidence level.

7. Trilepton Searches

Supersymmetry (SUSY) [15] is a new symmetry which provides a well motivated extension of the SM. Supersymmetric transformations relate fermionic and bosonic degrees of freedom. Each left–handed and right–handed fermion of the SM is postulated to have its own bosonic superpartner with equal mass and coupling strengths. Similarly each SM boson would have its own fermionic superpartner, again with equal mass and couplings. No superparticles have been observed so far.

In SUGRA models, the light neutralinos and charginos are much lighter than the gluino or squarks, and may be the only sparticles directly accessible at the Tevatron. Chargino and neutralino pairs would be produced directly at hadron colliders. The production of $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$, followed by the decays $\tilde{\chi}^{\pm}_1 \to \chi^0_1 l\nu$ and $\chi^0_2 \to$ $l^+l^-\tilde{\chi}^0_1$, is a source of three charged leptons (e or μ) and $\not{E}_T$, called trilepton events. The trilepton signal has a small SM backgrounds, and is
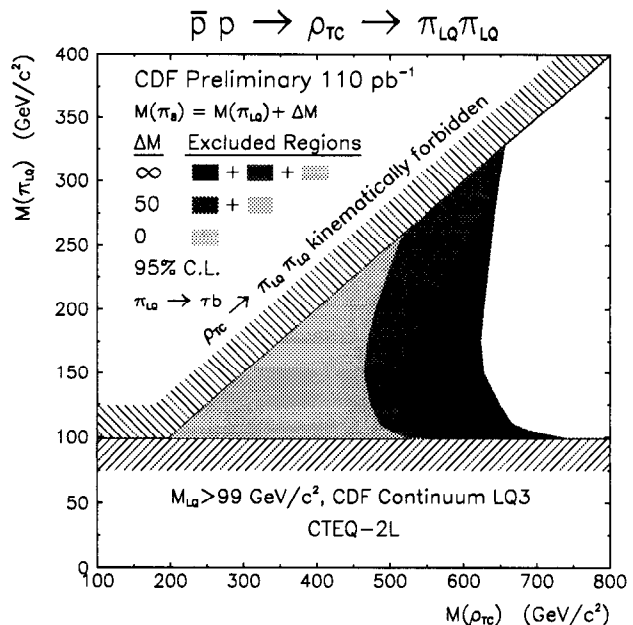

Figure 5. The 95%C.L. exclusion regions in the $M(\pi_{LQ})$–$M(\rho_T)$ plane. The three shaded areas correspond (from left to right) to technipion mass splitting values of 0, 50 GeV/c^2 and ∞, respectively.

consequently one of the "golden" SUSY signatures. The branching fractions also depend on tanβ and, for large tanβ, gauginos tend to decay to τ's . So far, the results of the CDF and D0 experiments only include searches for electrons and muons [16]. Both experiments are currently studying a development for triggering (please see Section 8) in Run 2 on trilepton signatures also with taus.

8. Tau Trigger in Run 2

At the beginning of the new millennium, the Tevatron will start delivering high–energy colliding proton and antiproton beams for both collider experiments at Fermilab. Both D0 and CDF have started the upgrade of their detectors in preparation for the new data taking. Triggering will be the ultimate challenge in order to select the

most useful events and to record data on disk at a high rate. For Run 2, the CDF experiment is implementing a new tau trigger which combines the information of specific physics signatures with tracking requirements for the tau lepton. The experience gained during Run 1 and Monte Carlo simulations have taught that tracking information is more efficient than calorimetry, especially for low p_T taus. Track isolation can be used to further reduce the acquisition rate. Track isolation is implemented by requiring no track with $p_T >1.5$ GeV/c in a cone around the seed track, in the region where $10° \leq \Delta\phi \leq 30°$. The tau lepton selection is still not enough by itself to reduce the QCD background. Therefore, we have to use a specific signature which combines a lepton with a track in the same event. The trigger rate is reduced by a factor of 10 when the tau–tagging tracking requirement is used with the 8 GeV inclusive electron sample (see Figure 6). The Level 2 trigger rate is about 10 nb when we require an electron ($E_T > 8$ GeV) and one isolated track with $p_T > 5$ GeV/c. When using this selection, it is possible to include taus in the trigger and still mantain a good rejection over background. To further reduce the electron or track momentum thresholds, one would need additional requirements.

Figure 6. Level 2 cross section for Run 2: electron ($E_T >8$ GeV) plus tau ($p_T >5$GeV/c) trigger.

9. Prospects for Run 2

The analyses are limited by the luminosity and the reach of the searches is just entering the interesting regions. In Run 2, two upgraded detectors at the Tevatron will collect more data at a higher energy of 2 TeV. The nominal integrated luminosity is 2 fb^{-1}, with a possible extension to 10 or even 30 fb^{-1}. The production cross section for heavy sparticles for example will increase significantly with the higher energy. Chargino and neutralino searches, as well as squarks and gluino searches, will cover a wide range of SUSY parameter space in Run 2. Most importantly, by extending Run 2 up to an integrated luminosity of about 20 fb^{-1} and combining search channels, the Tevatron can perform a crucial test of the MSSM Higgs boson sector. The W and top quark mass measurements performed by CDF and D0, and in-
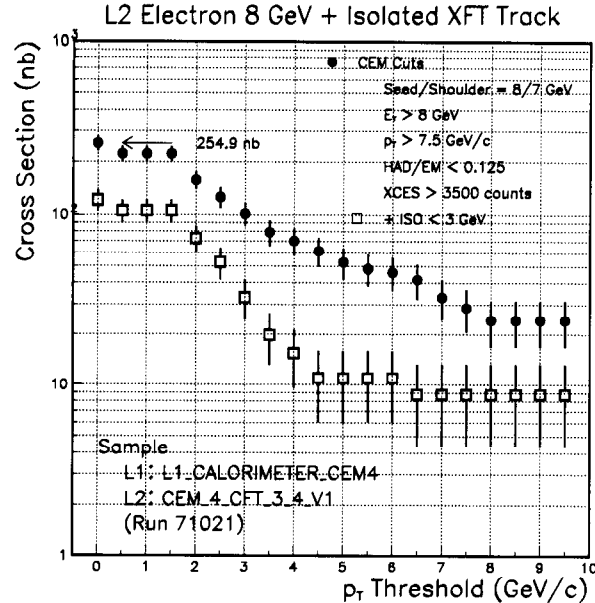
direct measurement of the Z^0 line shape from experiments at LEP and SLC, suggest a small value for the Higgs boson mass (see Figure 7). Also, most SUSY theories predict a Higgs mass which is comprised between 130 and 150 GeV/c^2. When combining these data together, the picture looks promising for the Higgs searches at the Tevatron during Run 2.

The experience gained from Run 1 analyses will greatly increase the quality of the Run 2 searches. New triggering capabilities will open up previously inaccessible channels, particularly those involving τ's and heavy flavors. A factor of 20 of more data, combined with improved detector capabilities, makes the next Run at the Tevatron an exciting prospect.
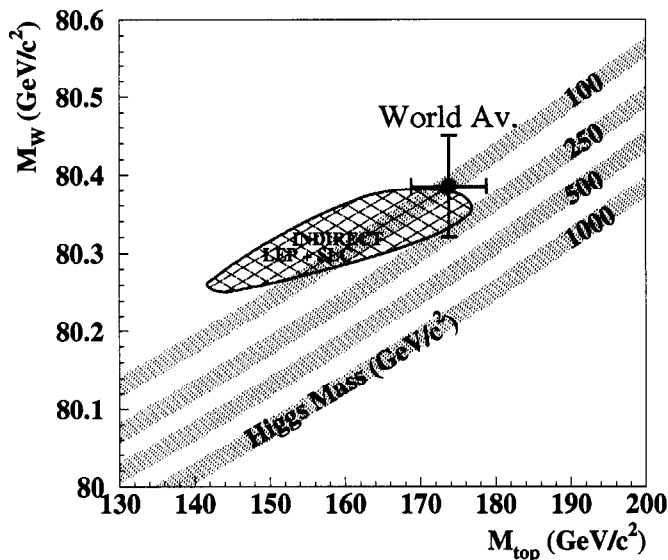
Figure 7. The measurements of the top quark and W boson masses performed by CDF and D0 superimpose on different predictions for the value of the Higgs mass.

10. Conclusions

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, both present and future, 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 a serious matter. Vertex detectors can also help tau identification, and more experience in tau detection can still be gained at the Tevatron, to be of great interest for future collider experiments.

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