Signature of heavy Charged Higgs Boson at LHC in the 1 and 3 prong Hadronic Tau Decay channels

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Abstract

We have done a fast simulation analysis of the $H^\pm$ signal at LHC in the 1 and 3 prong hadronic $\tau$-jet channels along with the $t\bar{t}$ background. The $\tau$ polarization was effectively used to suppress the background in both the channels. Combining this with appropriate cuts on the $p_T$ of the $\tau$-jet, the missing $E_T$ and the azimuthal angle between them reduces the background below the signal level. Consequently one gets a viable $H^\pm$ signal up to a mass range of 600-700 GeV at moderate to large $\tan \beta$. 
Introduction

The Minimal Supersymmetric Standard Model (MSSM) contains a pair of charged Higgs bosons $H^{\pm}$ along with three neutral ones. While it may be hard to distinguish any of the neutral Higgs bosons from that of the standard model, the $H^{\pm}$ carries the unambiguous hallmark of the MSSM Higgs sector. Therefore, it has an important role in the search of MSSM Higgs bosons at the Large Hadron collider (LHC). The leading order QCD process

$$ gb \rightarrow tH^{\pm} + h.c $$ (1)

gives a sizable production cross section for a heavy $H^{\pm}$ at LHC. However its dominant decay mode, $H^{\pm} \rightarrow t\bar{b}$, suffers from a large QCD background [1]. A more promising signature comes from its leading sub dominant decay mode,

$$ H^{\pm} \rightarrow \tau^{\pm}\nu_{\tau} $$ (2)

which accounts for a branching fraction of $\gtrsim10\%$ in the moderate to large $\tan\beta$ ($\gtrsim10$) region. Moreover one can enhance this signal over the SM background from

$$ W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau} $$ (3)

by exploiting the opposite polarizations of $\tau$ i.e. $P_{\tau} = +1$ and -1 from the signal(2) and background (3) respectively. This was shown to give a viable signature for a heavy $H^{\pm}$ boson at LHC in its 1-prong hadronic $\tau$ decay channel [2]. In particular the signal to background ratio was shown to be enhanced significantly by requiring the charged prong to carry $>80\%$ of the visible $\tau$ jet energy.

The work of ref [2] was based on a parton level Monte Carlo simulation for the $H^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$ signal(2) and the $W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$ background(3), followed by a simple hadronic $\tau$ decay code via

$$ \tau \rightarrow \pi^{\pm}\nu(12.5\%),\rho^{\pm}\nu(26\%),a_{1}^{\pm}\nu(15\%). $$ (4)

The $a_{1}^{\pm}$ mode contributes half and half to the 1-prong ($\pi^{\pm}\pi^{0}\pi^{0}$) and 3-prong ($\pi^{\pm}\pi^{\pm}\pi^{\mp}$) channels. So the three mesons of eq.(4) account for over 90\% of the 1-prong hadronic decay branching ratio(BR) of $\tau$ ($\simeq50\%$) [3]. A more exact analysis was done in [4] following the same procedure, where the signal(2) and background(3) were simulated using PYTHIA Monte Carlo(MC) event generator[6] along with the fast CMSJET package for detector simulation [7]. A similar analysis was also done by members of the ATLAS collaboration[8]. In this paper we have investigated the signal(2) and background(3) in both 1 and 3 prong hadronic decay channels of $\tau$ along the lines of ref.[4].

However, we have used the TAUOLA package[9] for hadronic $\tau$ decay unlike ref.[4], which had used the simple decay code of ref. [2] via eq.(4). The two $\tau$ decay programs give very similar results. But the TAUOLA package is more exact, since it includes the small non resonant contribution to hadronic $\tau$ decay. Besides this is the first investigation of this process including both 1 and 3 prong hadronic decay channels of $\tau$. 


**τ Polarization**

It is easy to understand the effect of τ polarization($P_\tau$) on its 1-prong hadronic decay via the dominant contributions of eq.(4). The center of mass angular distributions of τ into $\pi$ or a vector meson $v(=\rho, a_1)$ is simply given in terms of its polarization as

$$\frac{1}{\Gamma_\pi} \frac{d\Gamma_\pi}{d\cos\theta} = \frac{1}{2} (1 + P_\tau \cos\theta)$$
$$\frac{1}{\Gamma_v} \frac{d\Gamma_{vL,T}}{d\cos\theta} = \frac{1}{2} m_\pi^2, m_v^2 \frac{1}{m_\tau^2 + 2m_v^2} (1 \pm P_\tau \cos\theta)$$  \hspace{1cm} (5)

where L, T denote the longitudinal and transverse polarization states of the vector meson. This angle is related to the fraction $x$ of the τ lab momentum carried by the meson, i.e the (visible) τ-jet momentum via

$$x = \frac{1}{2} (1 + \cos\theta) + \frac{m_{\pi,v}^2}{2m_\tau^2} (1 - \cos\theta).$$  \hspace{1cm} (6)

It is clear from eqs.(5) and (6) that the signal ($P_\tau = +1$) has a harder τ-jet than the background ($P_\tau = -1$) for the $\pi$, $\rho_L$ and $a_{1L}$ contributions; but it is the opposite for $\rho_T$ and $a_{1T}$ contributions. Now the transverse ρ and $a_1$ decays favor even sharing of the momentum among the decay pions, while the longitudinal ρ and $a_1$ decays favor uneven distributions, where the charged pion carries either very little or most of the momentum. Thus requiring the $\pi^\pm$ to carry $\geq 80\%$ of the τ jet momentum,

$$R_1 = \frac{p_{\pi^\pm}}{p_{\tau-jet}} \geq 0.8,$$  \hspace{1cm} (7)

retains about half the longitudinal ρ along with the pion but very little of the transverse contributions. This cut suppresses not only the $W \rightarrow \tau\nu$ background, but also the fake τ background to the 1-prong hadronic decay channel from QCD jets.

The 3-prong hadronic decay accounts for about 15% of τ−decay, of which 2/3rd (10%) comes from

$$\tau \rightarrow \pi^\pm \pi^\mp \pi^\mp \nu$$  \hspace{1cm} (8)

without any accompanying $\pi^0$. We shall consider only this 3-prong decay channel, which can be separated by either matching the tracker momentum of the τ-jet with the calorimetric energy deposit or by a veto on accompanying $\pi^0 \rightarrow 2\gamma$ in the electromagnetic calorimeter(EM). This effectively suppresses the fake τ background from QCD jets while retaining 2/3rd of the genuine τ events. As mentioned above 3/4th of the 3-prong decay(8) comes from the $a_{1L}$ contribution. Thus one can again enhance the $a_{1L}$ contribution by imposing a cut on the fractional τ-jet momentum carried by the like-sign pair, i.e

$$R_3 = \frac{p_{\pi^\pm \pi^\mp}}{p_{\tau-jet}} \neq 0.2 - 0.8.$$  \hspace{1cm} (9)
We shall see that this cut favors the \((P_\tau=+1)\) signal over the \((P_\tau = -1)\) background significantly even after including the non-resonant contribution to eq.(8). Note that the like sign pion pair in the 3-prong \((\pi^+\pi^+\pi^-)\) decay of \(a_1\) is analogous to the neutral pion pair in its 1-prong \((\pi^0\pi^0\pi^\pm)\) decay, i.e. \(R_3\) corresponds to \(1-R_1\) for the \(a_1\) channel.

**Signal and Background**

We have computed the \(H^\pm\) signal from the leading order QCD process\((1)\) using PYTHIA\([6]\). For simplicity we have used a common renormalization and factorization scale \(\mu_R = \mu_F = \hat{s}\). The resulting \(H^\pm\) cross section has been enhanced by a K-factor of 1.5 to account for the higher order corrections following ref \([10]\). Note that the \(H^\pm\) Yukawa coupling of the signal process\((1)\) is estimated using the running quark masses \(m_t(\mu_R)\) and \(m_b(\mu_R)\). Then it is followed by the hadronic decay of top, \(t \to bqq'\), along with the \(H^\pm \to \tau^\pm \nu\) decay of eq.(2). Finally the hadronic decay of \(\tau\) is simulated using TAUOLA \([9]\). Thus the final state consists of at least four hard jets, including the \(\tau\)-jet, along with a large missing-\(E_T\) (\(E_T\)). These events are expected to be triggered by a multi-jet trigger along with a higher level \(\tau\) trigger with high trigger efficiency of 90% at CMS \([4]\) \(^1\). The jets and the \(E_T\) are reconstructed with the fast CMS detector response simulation package CMSJET \([7]\). The program contains the detector resolution and the main cracks and inefficiencies.

The background was computed from the leading order \(t\bar{t}\) production process using \(\mu_R = \mu_F = \hat{s}\) and multiplying the resulting cross-section with the appropriate K-factor 1.3\([11]\). This is followed by the hadronic decay of one top, \(t \to bqq'\), while the other decay via \(t \to bW \to b\tau\nu\). We do not consider the other contributions to the background of eq.(3) coming from \(W^{\pm}\)multijet production, since they can be effectively suppressed by the reconstructions of the hadronic top mass and b-tagging \([4]\). Note however that the same polarization cut suppresses this \(W^{\pm}\)multijet background as much as the \(t\bar{t}\) background.

The \(\tau\) identification is based on the narrowness of the \(\tau\) jet. To implement this we define a narrow signal cone of size \(\Delta R_S = 0.1\) and an isolation cone of size \(\Delta R_I = 0.4\) around the calorimetric jet axis, where \(\Delta R\) is defined via the azimuthal angle and the pseudo-rapidity as

\[
\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}
\]

We require 1 or 3 charged tracks inside the signal cone, with \(|\eta| < 2.5\) and \(p_T > 3\) GeV for the hardest track, the former corresponding to the pseudo-rapidity coverage of the tracker. We further require that there are no other charged tracks with \(p_T > 1\) GeV inside the isolation cone to ensure tracker isolation \([4]\). This was shown to be adequate to suppress the fake \(\tau\)-jet background to the \(W \to \tau\nu\) events of the CDF experiment in the 1-prong channel but not in

\(^1\)This trigger efficiency falls to 63-64% in full simulation\([5]\). We have not included it in this work, however, since it is based on fast simulation. Its effect will be to rescale the size of signal and background shown in the tables as well as figures 1-7 by 2/3rd. Correspondingly, the discovery limits of \(\tan \beta\) in fig.8 will increase by 25%.
the 3-prong channel [12]. In the latter case one has to combine the tracker isolation with the requirements of narrow width and small invariant mass(< 1.8 GeV) of the τ jet candidate using the calorimeter information to suppress the fake τ jet background[12, 13, 14], which is beyond the scope of the present work. Note however that in the high- \( p_T \) (\( \approx 100 \) GeV)range of our interest, the 3-prong τ-jet is expected to be tagged by the secondary vertex[14]. Moreover, we are interested in a sub sample of 3-prong τ-jets, without accompanying π⁰s, for which the fake background is relatively small, as we shall see below.

We ensure the absence of π⁰s by requiring the energy of the 3 charged tracks measured in the tracker to match with the calorimetric energy deposit of the τ-jet within the calorimetric energy resolution, i.e

\[
\Delta E = |E_{\text{tot}}^{\text{cal}} - E_{\text{tot}}^{\text{trk}}| < 10 \text{GeV}.
\]  

(11)

With this cut the τ-jet identified by the tracker matches well with the actual τ-jet of the event generator. Therefore, we shall use the tracker identification of τ-jet in both 1 and 3 prong channels.

In our simulation, as a basic sets of selection cuts for jet reconstruction, we apply

\[
p_T > 20 \text{ GeV}, |\eta| < 4.5
\]  

(12)

for all jets, the latter corresponding to the pseudo-rapidity coverage of the calorimeter. We require the minimum separation of

\[
\Delta R > 0.5
\]  

(13)

between jets. The missing-\( E_T \) arising mainly due to the presence of \( \nu_\tau \) accompanied with τ lepton, is reconstructed using the calorimetric informations, and we set a minimum cut

\[
E_T > 30 \text{ GeV}.
\]  

(14)

The \( E_T \) is expected to be large for signal as it originates mainly from the massive \( H^\pm \rightarrow \tau \nu \) decay, where as in the case of background it comes from a relatively light \( W \rightarrow \tau \nu \) decay.

In Fig.1 we show the distribution of \( p_T \) of τ-jet(\( p_T^{\tau-jet} \)) for signal in the upper panel along with the background from \( t\bar{t} \) in the lower panel. These distributions are subject to only the basic selection cuts of eqs.(11-14) and are normalized for integrated luminosity \( \mathcal{L} = 100 fb^{-1} \). The signals are shown for two masses of \( H^\pm \), \( m_{H^\pm} = 300 \text{ and } 600 \) GeV, for \( \tan \beta = 40 \). Evidently, the higher the mass of \( H^\pm \), the harder are the τ-jets. Notice that the signal cross section is several orders of magnitude less than the background even for \( p_T^{\tau-jet} > 100 \) GeV.

In Fig.2 we demonstrate the distribution in \( R_1 \) (7) for 1-prong decay channel of τ-jet for both signal and background with \( p_T^{\tau-jet} > 100 \) GeV. The spillover of the distribution to the \( R_1 > 1 \) region reflects the 15-20% uncertainty in the calorimetric energy measurement of the τ-jet. As discussed above, for the signal process where \( P_\tau = +1 \), peaks occur at the two ends because of the uneven sharing of energy between pions while in the case of background,
for which $P_\tau = -1$, a peak occurs at the middle due to the almost equal sharing of energy between pions. Note that at the large $R_1$ end of the distributions the dominant contribution comes from $\rho_L$ and $\pi$ channels. Therefore a cut like $R_1 > 0.8$ leads to a very large suppression of the background while retaining almost half of the signal events. Note that one would in any case require a reasonably hard charged track, corresponding to $R_1 \approx 0.3$, for effective $\tau$ identification and rejection of the QCD jet background [13]. So extending this cut to $R_1 > 0.8$ costs very little to the signal, while it effectively suppresses the $P_\tau = -1$ background. For 3-prong decay of $\tau$-jets we present the $R_3$ distribution in Fig.3 for both signal and background, where $R_3$ is defined by eq.(9). We have shown the distribution for two values of $H^\pm$ mass as before. As mentioned above, the like sign pair of $\pi$s plays the same role as the $\pi^0$ pair in the case of 1-prong decay channel of $\tau$-jet via a $a_1$, i.e., the $\pi^0\pi^0\pi^\pm$ channel. Hence, the like sign pion pair carries either very little or most of the $\tau$-jet energy for the signal($P_\tau = +1$), while it carries roughly 2/3rd of the $\tau$-jet energy for the background($P_\tau = -1$). Consequently selecting events in the region $R_3 < 0.2$ and $R_3 > 0.8$ helps to suppress the background. We found the efficiency due to this selection cut is about 55% for signal and 35% for background. Note that there is no constraint on $R_3$ for $\tau$-identification unlike the 1-prong channel.

Since the $H^\pm$ production(1) is accompanied by a top quark, it is useful to reconstruct top quark mass. We perform the $W$ and top mass reconstructions from hadronic decay modes by requiring at least three reconstructed jets in addition to a single $\tau$ jet. For the $W$ mass reconstruction we require the invariant mass of two jets out of them to be

$$m_{jj}^{rec} = m_W \pm 15 \text{ GeV}$$

(15)
and the corresponding $W$ momenta are obtained out of these jet momenta. In case of several pairs satisfying this mass band, the pair having invariant mass closest to $m_W$ is chosen. The top mass reconstruction is performed using this pair and one of the remaining jets and demanding

$$m_{Wj}^{rec} = m_t \pm 30 \text{ GeV}.$$  \hspace{1cm} (16)

Notice here that we have not done any kind of b-tagging. However to take care of b-tagging we multiply the signal and background cross section by a b-tagging efficiency($\epsilon_b$) factor 0.5 [4]. This includes the loss of efficiency due to the reduced coverage of $|\eta| < 2.5$ for this jet. Though the $t\bar{t}$ background has 2 b jets, one still gets efficiency factor $2\times0.5\times(1-0.5)=0.5$ by requiring only one b-tag.

We have also investigated the relative azimuthal opening angle in the transverse plane between $\tau$ jet and the $E_T$ vector, which is also connected with the transverse mass via,

$$m_T = \sqrt{2p_{\tau-jet}^T.E_T(1-\cos \Delta \phi(\tau-jet, E_T))}.$$ \hspace{1cm} (17)

Since, in the signal process(2) both $\tau$-jet and $E_T$ are originating from a comparatively massive $H^\pm$ particle, leading to harder $\tau$-jet and missing momentum, it is expected that the signal distributions in $m_T$ and $\Delta \phi(\tau-jet, E_T)$ will be much broader than the background(3),
which can distinguish the signal and background events. In Fig.4 we show the distribution in \( \Delta \phi(\tau - \text{jet}, E_T^\tau) \) for the signal for two values of \( m_H^\pm = 300 \) GeV and 600 GeV and \( \tan \beta = 40 \) along with background. These distributions are for 1-prong \( \tau \)-jet events passed by the selection cuts: \( E_T^{\tau-\text{jet}} > 100 \) GeV, \( R_1 > 0.8 \), \( E_T^\tau > 100 \) GeV. In Fig.5 we show the same distribution in \( \Delta \phi(\tau - \text{jet}, E_T^\tau) \) for \( \tau \)-jets decaying via 3-prong decay modes. In Fig.6 and Fig.7 we present the distributions in \( m_T \) for 1-prong and 3-prong channels of \( \tau \)-jet respectively. Evidently, as expected the background is concentrated at small azimuthal opening angle \( \Delta \phi \approx 0 \), while the signal is peaked at the largest opening angle \( \Delta \phi \approx 180^\circ \). Likewise the background distribution in \( m_T \) is restricted to \( m_T < m_W \), while the signal distribution is peaked at much larger \( m_T \) and extends all the way up to \( m_H \), which can also be used to estimate the \( H^\pm \) mass. Thus either a cut on \( \Delta \phi \) or \( m_T \) can suppress the background by enormous amount without practically any loss of signal events. We will see later that a \( \Delta \phi > 60^\circ \) cut brings down the background level to less than the signal.

In our simulation we have generated \( 10^6 \) events each for signal and background processes in the \( \tau + \) multijet channel. In Table 1 we demonstrate the cumulative effect of our selection cuts for 1-prong decay channel of \( \tau \) jet, while Table.2 shows the same for 3-prong decay channel of \( \tau \) jet. We present the number of events surviving out of \( 10^6 \) generated events after each cut. In both the tables we present the results for signal for two sets of values of \( m_{H^\pm}, \tan \beta = (300 \) GeV,40) and (600 GeV,40) as well as for \( t\bar{t} \) background. First row shows the number of hadronically decaying \( \tau \) particles which come from \( H^\pm \) decay of eq.(2) and W decay background of eq.(3). It reflects the hadronic \( \tau \) decay branching ratio of \( \sim 65\% \). The second row shows the number of events having an identified \( \tau \)-jet, which are subject to the basic cuts of eqs.(12-14) and where \( \tau \)-identification is performed using tracker informations as discussed above. As expected the corresponding efficiencies for signal are higher than the background because of harder \( \tau \)-jet from \( H^\pm \) decay. For the same reason the efficiency after the \( p_T^{\tau-\text{jet}} > 100 \) GeV cut, shown in the third row, is about 2.8\% for the background where as for signal it is 33\%(58\%) for \( m_H = 300(600) \) GeV. In the signal events about 3/4 contribution comes from the 1-prong decay channel and 1/4 contribution is from 3-prong decay channel of \( \tau \), where as for the background it is 60\% from 1-prong channel and 40\% from 3-prong decay channel of \( \tau \). The ratio of signal events in the 1 and 3 prong channels agree with the respective \( \tau \) branching fractions of 50 and 15\%. This shows that the \( \tau \) identification via the tracker as described above works quite well for the signal events. On the other hand there is a clear excess of 3-prong events in the \( t\bar{t} \) background, showing a large contamination of fake \( \tau \) from hadronic jets in this channel, as mentioned earlier. However, they are removed after the removal of accompanying \( \pi^0 \)'s via the \( \Delta E \) cut of eq.(11). After this cut the 3-prong events are about 1/5th of the 1-prong events for both the signal and background in agreement with the respective \( \tau \) branching fractions of 50 and 10\%.

The next rows show the effects of \( \tau \) polarizations on the signal and background. The \( R_1 > 0.8 \) cut retains about 40\% of the signal against only 10\% of the background. In fact the effective loss to the signal is quite small, since the low \( R_1 \) peak of Fig.2 would be lost anyway due to the requirement of a hard charged track for \( \tau \) identification as mentioned earlier. The corresponding cuts of \( R_3 > 0.8 \) or \( < 0.2 \) retains about 55\% of the signal against...
35% of the background. It shows the efficacy of $\tau$ polarization in the extraction of the $H^\pm$ signal in the 1-prong as well as 3-prong $\tau$-jet channels. Note also that the measurement of the polarization variables $R_1$ and $R_3$ is quite simple, since it only requires measuring the momenta of the charged tracks in the tracker.

The $p_T > 100$ GeV cut has an efficiency of 60(90)% for a $m_{H^\pm} = 300(600)$ GeV Higgs signal and 40% for the $t\bar{t}$ background. This is followed by the $W$ and top mass cuts which have a combined efficiency 20% for the signal as well as background. Its main utility is in suppressing the $W$+multijet background, as mentioned earlier. Finally, the $\Delta \phi > 60^\circ$ cut suppresses the background by a factor of 50, with very little loss to the signal.

The last but one rows show the signal and background cross-sections in the $\tau$+multijet channel, representing the $10^6$ generated events. It corresponds to $\sigma_{tH^\pm} \times \text{Br}(H^\pm \rightarrow \tau \nu) \times 2/3$ for the signal and $2 \sigma_{tH} \times 1/9 \times 2/3$ for the background. The last rows show the signal and background cross-sections remaining after all the cuts, which includes a b-tagging efficiency factor of 0.5. We see that at this stage the background is reduced to less than the signal size. It can be still further suppressed via the transverse mass distribution without any loss of signal. The $m_T$ distribution can also be used to estimate $m_H$, as mentioned earlier. Thus the discovery limit is primarily controlled by the size of the signal shown in the last row. Fig. 8 shows the discovery limit corresponding to 25 signal events for 1-prong and (1+3)-prong channel of $\tau$-jet. This is shown separately for $\mathcal{L} = 30 fb^{-1}$ and $100 fb^{-1}$ expected from the low and high luminosity runs of LHC separately. It shows a promising discovery potential for $H^\pm$ over the mass range up to 600-700 GeV at moderate to large tan $\beta$. However it should be noted here that a full simulation for the high luminosity run has not been completed yet[14]. It would require higher trigger threshold of $\tau$-jets, which would move up the discovery limits at low $m_H$ to slightly higher values of tan $\beta$.

**Summary**

We have investigated the $H^\pm$ signal at LHC in the 1 and 3 prong hadronic $\tau$-jet channels along with the $t\bar{t}$ background. The signal and background processes were generated using the PYTHIA event generator interfaced with TAUOLA for the 1 and 3 prong hadronic $\tau$ decays. The detector response was simulated using the fast simulation packages CMSJET. We have shown that the opposite polarization of $\tau$ from the signal ($H^\pm \rightarrow \tau \nu$) and background ($W^\pm \rightarrow \tau \nu$) processes can be effectively used to suppress the background with respect to the signal in both 1 and 3-prong $\tau$-jet channels. The signal was also found to have much harder distributions than the background in the azimuthal opening angle ($\Delta \phi$) between the $\tau$-jet and the missing $E_T$ as well as in the transverse mass ($m_T$) of the two. Combining these distinctive features with those of $\tau$ polarization we could effectively suppress the background to below the signal size. Thus the $H^\pm$ discovery potential of LHC in the 1 and 3 prong $\tau$-jet channels is primarily determined by the signal cross section in these channels. We find a promising $H^\pm$ signal at LHC over the mass range of several hundred GeV at moderate to large tan $\beta$. 

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Table 1: Number of events after each set of cuts for two sets of \((M_H, \tan\beta)\) values for the signal and the \(t\bar{t}\) background process. Number of \(\tau+\)multijet events generated in each case is \(10^6\). Last two rows show the production cross sections in the \(\tau+\)multijet channel and cross section after multiplying with efficiency factors including the b-tagging efficiency for the 1-prong hadronic \(\tau\) decay channel.

| Cuts                  | \(m_H, \tan\beta\) \((300, 40)\) | \(m_H, \tan\beta\) \((600, 40)\) | Bg \(t\bar{t}\) |
|-----------------------|-----------------------------------|-----------------------------------|----------------|
| No. of had.\(\tau\) decay event | 640531                           | 641346                           | 641009         |
| Identified \(\tau\) jets | 448288                           | 465556                           | 229622         |
| \(E_T^{\tau-jet} > 100\) GeV | 212491                           | 370562                           | 17875          |
| 1 prong decay         | 158865                           | 281428                           | 10182          |
| \(R_{1\pi} > 0.8\)     | 57240                            | 103470                           | 1046           |
| \(E_T > 100\) GeV      | 32441                            | 89587                            | 410            |
| Number of jets \(\geq 3\) | 15083                            | 41783                            | 308            |
| W mass rec, \(m_{jj} = m_W \pm 15\) GeV | 9861                             | 27091                            | 147            |
| Top mass rec, \(m_{jW} = m_t \pm 30\) GeV | 6376                             | 17339                            | 87             |
| \(\Delta \phi(\tau-jets, E_T) > 60^\circ\) | 5154                             | 16394                            | 2              |
| \(\sigma \times \text{BR (pb)}\) | 0.431                            | 0.045                            | 73             |
| Cross section \(\times\) efficiency \(\times \epsilon_b\) \(\text{(fb)}\) | 1.1                              | 0.37                             | 0.15           |

Table 2: Same as in Table 1, but for \(\tau\) jets in 3-prong decay channel.

| Cuts                  | \(m_H, \tan\beta\) \((300, 40)\) | \(m_H, \tan\beta\) \((600, 40)\) | Bg \(t\bar{t}\) |
|-----------------------|-----------------------------------|-----------------------------------|----------------|
| No. of had.\(\tau\) decay event | 640531                           | 641346                           | 641009         |
| Identified \(\tau\) jets | 448288                           | 465556                           | 229622         |
| \(E_T^{\tau-jet} > 100\) GeV | 212491                           | 370562                           | 17875          |
| 3 prong decay         | 53626                            | 89134                            | 7683           |
| \(\Delta E < 10\) GeV | 32886                            | 54901                            | 2610           |
| \(R_{3\pi} < 0.4\) or \(> 0.8\) | 18159                            | 29714                            | 858            |
| \(E_T > 100\) GeV      | 10456                            | 26173                            | 269            |
| Number of jets \(\geq 3\) | 4854                             | 12161                            | 206            |
| W mass rec, \(m_{jj} = m_W \pm 15\) GeV | 3138                              | 7886                             | 110            |
| Top mass rec, \(m_{jW} = m_t \pm 30\) GeV | 2010                             | 5073                             | 60             |
| \(\Delta \phi(\tau-jets, E_T) > 60^\circ\) | 1676                             | 4881                             | 1              |
| \(\sigma \times \text{BR (pb)}\) | 0.431                            | 0.045                            | 73             |
| Cross section \(\times\) efficiency \(\times \epsilon_b\) \(\text{(fb)}\) | 0.36                             | 0.11                             | 0.07           |
Figure 1: The number of events are shown against $p_T$ of $\tau$-jets for signal and background processes for integrated luminosity $\mathcal{L} = 100 fb^{-1}$ and are subject to $p_T^{\tau-jet} > 20$ GeV and $|\eta_{\tau-jet}| < 2.5$ cuts. The mass of charged Higgs and $\tan\beta$ are set to $m_{H^\pm} = 300$ and 600 GeV and $\tan\beta = 40$. 

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Figure 2: The number of events are plotted against the fraction of $\tau$-jet momentum carried by the charged prong $R_1$ for the 1-prong decay channel of $\tau$-jet for signal and background processes. Both the distributions are subject to $p_{T-jet}^{\tau} > 100$ GeV and $|\eta_{\tau-jet}| < 2.5$ cuts. The masses of charged Higgs and tan $\beta$ are same as in Fig.1.
Figure 3: Same as in Fig.2, but against the fraction of $\tau$-jet momentum carried by the like sign pair ($R_3$) for the 3-prong $\tau$-jet channel.
Figure 4: The number of events are shown against the opening azimuthal angle $\Delta \phi(\tau-jets, E_T)$ for signal and background for 1-prong decay channel of $\tau$-jets. These are subject to $p_{T\tau-jet} > 100$ GeV, $R_1 > 0.8$ and $E_T > 100$ GeV cuts.
Figure 5: Same as in Fig.4, but for 3-prong decay channel of $\tau$-jets.
Figure 6: The number of events are shown against transeverse mass $m_T$ for signal and background for 1-prong decay channel of $\tau$-jets. These are subject to $p_T^{\tau-jet} > 100$ GeV, $R_1 > 0.8$ and $E_T > 100$ GeV. The masses of charged Higgs and tan $\beta$ are same as in previous figures.
Figure 7: Same as in Fig.5, but for 3-prong decay channel of $\tau$ jets.
Figure 8: Discovery limits of charged Higgs are shown as functions of $\tan \beta$ for integrated luminosity $\mathcal{L} = 30 \text{ fb}^{-1}$ (solid lines) and $\mathcal{L} = 100 \text{ fb}^{-1}$ (dashed lines) for $H^\pm \rightarrow \tau \nu$ where $\tau$ decays hadronically in both 1-prong and 3-prong channels. In each case the contribution from 1-prong channel only are shown by upper lines where as contribution from the combined 1 and 3-prong channels are shown by lower lines.