The hadronic $\tau$ decay of a heavy charged Higgs in models with singlet neutrino in large extra dimensions

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Abstract
We study the LHC sensitivity to the charged Higgs discovery in the channel $H^- \to \tau_L^- \nu$ in models with a singlet neutrino in large extra dimensions. The observation of such a signal would provide a distinctive evidence for these models since in the standard two Higgs doublet model type II, $H^- \to \tau_L^- \nu$ is completely suppressed.

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I. INTRODUCTION

The possibility that our world has more than four space–time dimensions has been considered long time ago [1]. More recently phenomenological studies based on simplified models have brought new insight on how extra dimensions may show up in present and future experimental setups. Localization of Standard Model (SM) degrees of freedom on a $(3+1)$-dimensional wall or 3–brane explains why low energy physics is effectively four dimensional [2]. In models where extra dimensions open up at the TeV scale, small neutrino masses can be generated without implementing the seesaw mechanism [3]. These models postulate the existence of $\delta$ additional spatial dimensions of size $R$ where gravity and perhaps other fields freely propagate while the SM degrees of freedom are confined to $(3+1)$-dimensional wall (4D) of the higher dimensional space. The idea that our world could be a topological defect of a higher–dimensional theory [4] finds a natural environment in string theory [5].

The true scale of gravity, or fundamental Planck scale $M_*$, of the $(4+\delta)D$ space time is related to the reduced 4D Planck scale $M_{Pl}$, as:

$$M_{Pl}^2 = R^\delta M_*^{\delta+2},$$  \hspace{1cm} (1)

where $M_{Pl} = 2.4 \times 10^{18}$ GeV is related to the usual Planck mass $1.2 \times 10^{19}$ GeV = $\sqrt{8\pi} M_{Pl}$. Since no experimental deviations from Newtonian gravity are observed at distances above 0.2 mm *6], the extra dimensions must be at the sub-millimeter level with $M_*$ as low as few TeV and $\delta \geq 2$.

The right handed neutrino can be interpreted as a singlet with no quantum numbers to constrain it to the SM brane and thus, it can propagate into the extra dimensions just like gravity [6]. Such singlet states in the bulk couple to the SM states on the brane as right handed neutrinos with small couplings – the Yukawa couplings of the bulk fields are suppressed by the volume of the extra dimensions. The interactions between the bulk neutrino and the wall fields generate Dirac mass terms between the wall fields and all the Kaluza-Klein modes of the bulk neutrino. As long as this mass is less than $1/R$, the Kaluza-Klein modes are unaffected while for the zero mode, the interaction generates a Dirac neutrino mass suppressed by the size of the extra dimensions:

$$m_D = \frac{\lambda}{\sqrt{2}} \frac{M_*}{v}$$  \hspace{1cm} (2)

where $\lambda$ is a dimensionless constant and $v$ the Higgs vacuum expectation value (VEV), $v \approx 246$ GeV. The mixing between the lightest neutrino with mass $m_D$ and the heavier neutrinos introduces a correction $N$ to the Dirac mass such that the physical neutrino mass $m_\nu$ is [3]:

$$m_\nu = \frac{m_D}{N},$$  \hspace{1cm} (3)

where

$$N \simeq 1 + \sum_{\vec{n}} \left( \frac{m_D R}{\vec{n}} \right)^2$$  \hspace{1cm} (4)

$\vec{n}$ is a vector with $\delta$ integer components counting the number of states and the summation is taken over the Kaluza-Klein states up the fundamental scale $M_*$. The sum over the different Kaluza-Klein states can be approximately replaced by a continuous integration. The following formula can be used:

$$\sum_{\vec{n}} f \left( \frac{\vec{n}^2}{R^2} \right) \rightarrow S_\delta R^\delta \int_0^{M_*} dx x^{\delta-1} f(x^2),$$  \hspace{1cm} (5)

where $f$ is a function of $\vec{n}^2/R^2$ and $S_\delta = 2\pi^{\delta/2}/\Gamma(\delta/2)$ is the surface of a unit radius sphere in $\delta$ dimensions. After
summing over Kaluza-Klein states up to the cut-off $M_*$, assuming $\delta \neq 2$:

$$N \simeq 1 + \left( \frac{m_D}{M_*} \right)^2 \left( \frac{M_{\psi}}{M_*} \right)^2 \frac{2\pi^{3/2}}{\Gamma(\delta/2)} \frac{1}{\delta - 2} .$$

(6)

As shown in Table I, small neutrino masses, $m_\nu$, can be obtained consistent with atmospheric neutrino oscillations \[ [3]. \]

The framework of singlet neutrino in large extra dimensions must satisfy some phenomenological constraints: for $\delta = 2$, the mixing between the lightest state and the higher Kaluza-Klein excitations can be of $O(1)$ and therefore problematic since in such a case $m_D < 1/R$ is no longer valid. In addition, due to such a large mixing, this scenario might run into problem with nucleosynthesis \[ [4, 5, 6] \] (we consider $\delta > 2$ in this analysis). Finally, too much energy could be dissipated into the bulk neutrino modes, leading to an unacceptable expansion rate of the universe if $m_D^2 \geq 10^{-3}$ (eV)$^2$ and $1/R \leq 10 \text{ keV}$ \[ [3] \] (we confine this analysis to the parameter space where this constraint is satisfied).

The spectrum of many extensions of the SM includes a charged Higgs state. We consider as a prototype of these models the 2-Higgs Doublet Model of type II (2HDM-II), where the Higgs doublet with hypercharge $-1/2$ couples only to right–handed up–type quarks and neutrinos whereas the $+1/2$ doublet couples only to right–handed charged leptons and down–type quarks; an example is the Minimal Supersymmetric Standard Model (MSSM). In the following we will continue to use the VEV $v \simeq 246$ GeV as in formula (3). Its meaning in terms of $v_1$ (VEV of the $+1/2$ doublet) and $v_2$ (VEV of the $-1/2$ doublet) is the usual one:

$$\frac{v}{\sqrt{2}} = \sqrt{v_1^2 + v_2^2} \quad \tan \beta = \frac{v_2}{v_1} .$$

(7)

$H^-$ decays to the right handed $\tau^-$ through the $\tau$ Yukawa coupling:

$$H^- \to \tau^- \nu. \quad (8)$$

The $H^-$ decay to left handed $\tau^-$ is completely suppressed in MSSM. However, in the scenario of singlet neutrino in large extra dimensions, $H^-$ can decay to both right handed and left handed $\tau^-$ depending on the parameters $M_*, m_D, \delta, m_{H^\pm}$ and $\tan \beta$:

$$H^- \to \tau_R \bar{\nu} + \tau_L \psi, \quad (9)$$

where $\psi$ is a bulk neutrino and $\nu$ is dominantly a light neutrino with a small admixture of the Kaluza-Klein modes of the order $mR/|n|$. The measurement of the polarization asymmetry,

$$A = \frac{\Gamma(H^- \to \tau_L \psi) - \Gamma(H^- \to \tau_R \bar{\nu})}{\Gamma(H^- \to \tau_L \psi) + \Gamma(H^- \to \tau_R \bar{\nu})} .$$

(10)

can be used to distinguish between the ordinary 2HDM-II and the scenario of singlet neutrino in large extra dimensions – depending on the parameters – since in the 2HDM-II, the polarization asymmetry would be $-1.0$.

In this framework of large extra dimensions, the polarization asymmetry could also be $-1.0$ if the left handed $\tau$ component of the decay (3) is completely suppressed. In such a case, the decay of $H^-$ would be similar to the 2HDM-II case but possibly with a different phase space since the neutrino contains some admixture of the Kaluza-Klein modes.

The singlet neutrino may not necessarily propagate into the $\delta$-extra dimensional space. It is possible to postulate that the singlet neutrino propagate into a subset $\delta_\nu$ ($\delta_\nu \leq \delta$) of the $\delta$ additional spatial dimensions, in which case the formalism for the generation of small Dirac neutrino masses is merely a generalization of the case $\delta_\nu = \delta$ discussed above (4).

The charged Higgs decay to right handed $\tau$, $H^- \to \tau_R \bar{\nu}$ have been extensively studied for the LHC \[ [7, 8] \]. In this paper, we discuss the possibility to observe $H^- \to \tau_L \psi$ at the LHC above the top-quark mass. Table II shows the parameters selected for the current analysis. The cases where the asymmetry is $+1$ are discussed in details. We assume a heavy SUSY spectrum with maximal mixing. The present analysis is conducted in the framework of PYTHIA6.1 \[ [2] \] and ATLFAST \[ [3] \], and the Higgs masses and couplings are calculated to 1-loop with FeynHiggsFast \[ [4] \].

II. $H^\pm$ PRODUCTION AND DECAYS

In this framework, no additional Higgs bosons are needed. As a result, the charged Higgs productions are the same as in the 2HDM-II, shown in Fig. [4]. We consider the $2 \to 2$ production process where the charged Higgs is produced with a top-quark, $gb \to tH^\pm$. Further, we re-
TABLE I: The parameters used in the current analysis of the signal with the corresponding polarization asymmetry. In general, $H^-$ would decay to $\tau_L^-$ and $\tau_R^-$, $H^+ \rightarrow \tau_R^+ \bar{\nu} + \tau_L^-$, depending on the asymmetry. For the decay $H^- \rightarrow \tau_R^+ \bar{\nu}$ (as in MSSM), the asymmetry is $-1$ and this case is already studied for the LHC [3, 4]. The signal to be studied is $H^+ \rightarrow \tau_L^+ \bar{\nu}$.

| Signal | $M_\tau$ (TeV) | $\delta_\nu$ | $\delta$ | $m_D$ (eV) | $m_{H^\pm}$ (GeV) | $\tan \beta$ | Asymmetry | $m_\nu$ (eV) |
|--------|---------------|--------------|--------|------------|-----------------|-----------|-----------|-----------|
| Signal-1 | 2 | 4 | 4 | 3.0 | 219.9 | 30 | $\sim -1$ | 0.5 $10^{-3}$ |
| Signal-2 | 20 | 3 | 3 | 145.0 | 365.4 | 45 | $\sim 1$ | 0.05 |
| Signal-3 | 1 | 5 | 5 | 5.0 | 506.2 | 4 | $\sim 1$ | 0.05 |
| Signal-4 | 100 | 6 | 6 | 0.005 | 250.2 | 35 | $\sim -1$ | 0.005 |
| Signal-5 | 10 | 4 | 5 | 0.1 | 350.0 | 20 | $\sim -1$ | 0.04 |
| Signal-6 | 50 | 5 | 5 | 0.04 | 450.0 | 25 | $\sim -1$ | 0.04 |

For the $H^-$ decay to the right handed $\tau$, we have [5]

$$\Gamma (H^- \rightarrow \tau_R^+ \bar{\nu}) \simeq \left[ \frac{\Gamma (H^- \rightarrow \tau_R^+ \bar{\nu})_{\text{MSSM}}}{N^2} \right] \left[ 1 + f(m_D, M_\tau, \delta) \right]$$

(14)

and the normalization factor $N$ is given by Equation (3) and the function $f(m_D, M_\tau, \delta)$ is (for $\delta \neq 2$):

$$f(m_D, M_\tau, \delta) = \frac{m_D^2 m_\nu^2}{M_\tau^2} \left( \frac{M_\nu}{M_\tau} \right)^2 2\pi^{\delta/2} \frac{\delta^2}{\Gamma (\delta/2)}$$

$$\times \left( \frac{1}{\delta - 2} - \frac{2}{\delta} + \frac{1}{\delta + 2} \right).$$

(15)

One can generalize these formulas for a singlet neutrino in a smaller number of extra dimensions $\delta < \delta_0$ than the extra dimensions available to gravity [6]. Assuming that all the extra dimensions are of the same size $R$, one has to replace in formulas (5) and (15):

$$\delta \rightarrow \delta_\nu = 2(\delta_\nu - \delta)$$

(16)

The more general case of a non–symmetric internal $\delta$–dimensional manifold is given in [6].

Depending on the parameters $M_\tau$, $m_D$, $\delta$, $m_{H^\pm}$ and $\tan \beta$, the $\tau \nu$ decay of the charged Higgs can be enhanced or suppressed compared to the MSSM case. In Fig. 2 and Fig. 3, we show few cases of how the other decays of the charged Higgs are affected in this framework; for the chosen values of $M_\tau$ and $\delta$, the decay branchings are similar to MSSM for small values of $m_D$ while at larger $m_D$, the $\tau \nu$ decay mode becomes strongly enhanced, especially at low $\tan \beta$. In Fig. 4, we show the polarization asymmetry as a function of the charged Higgs mass and for different values of $m_D$ and $\tan \beta$: for small $m_D$, right handed $\tau$'s are produced, except at low $\tan \beta$ while the asymmetry increases with $m_D$ (see Equation (11)). For very large values of $M_\tau$ and small $m_D$, we recover the MSSM case as shown in Fig. 3 irrespective of the values of $\delta$ considered.

In general, $H^- \rightarrow \tau_L^- \bar{\nu} + \tau_R^+ \bar{\nu}$ with the asymmetry between -1 and 1. However, the study of $H^- \rightarrow \tau_R^+ \bar{\nu}$ has been carried out in detail and reported elsewhere [3, 4]. Therefore, in the current study, we consider the parameters shown in Table 2 and Table 3 for which the asymmetry is one, i.e., $H^- \rightarrow \tau_L^- \bar{\nu}$.

The major backgrounds are the single top production $gb \rightarrow Wt$, and $t\bar{t}$ production with one $W^+ \rightarrow jj$ and the other $W^- \rightarrow \tau_L^- \bar{\nu}$. Depending on the polarization asymmetry (see Equation (1)), $H^- \rightarrow \tau_R^+ \bar{\nu}$ will contribute as an additional background. In Table 1, we list the rates for the signal and for the backgrounds. For the phenomenological analysis, it is convenient to express the partial widths in terms of inclusive formulas, where the contributions of the Kaluza–Klein modes are summed up to the kinematical limit $m_\nu \leq m_{H^\pm}$ as the $\tau$ mass can be neglected. The partial width of the Higgs decays to $\nu$ depends on the parameters $M_\tau$, $m_D$, $\delta$, $m_{H^\pm}$ and $\tan \beta$ [10, 11]:

$$\Gamma (H^- \rightarrow \tau_L^- \bar{\nu}) \simeq \frac{m_{H^\pm}}{8\pi} \left( \frac{m_D}{v} \right)^2 \frac{\chi_\delta}{\tan^2 \beta} (m_{H^\pm} R^-)^\delta,$$

(11)

where $(m_{H^\pm} R^-)^\delta$ is the number of Kaluza–Klein modes lighter than the charged Higgs mass and $\chi_\delta$ includes the phase space integral:

$$\chi_\delta \simeq \frac{2(\delta/2)}{\Gamma (\delta/2)} \left( \frac{1}{\delta - 2} - \frac{1}{\delta + 2} \right).$$

(12)

Using the relation [10],

$$(m_{H^\pm} R^-)^\delta = \left( \frac{m_{H^\pm}}{M_\tau} \right)^\delta \times (\frac{M_\nu}{M_\tau})^2.$$

(13)
TABLE II: The expected rates \((\sigma \times BR)\), for the signal \(gb \rightarrow tH^\pm \) with \(H^- \rightarrow \tau_R \bar{\nu} + \tau_L \psi\) and \(t \rightarrow jjb\), and for the backgrounds: \(Wt\) and \(tt\) with \(W^- \rightarrow \tau_L \bar{\nu}\) and \(W^+ \rightarrow jj\). We assume an inclusive \(tt\) production cross section of 590 pb. Other cross sections are taken from PYTHIA 6.1 with CTEQ5L parton distribution function. See Table I for the parameters used for Signal-1, Signal-2 and Signal-3. In the last columns, we compare the \(H^\pm \rightarrow \tau \nu\) branching ratios in this model to the corresponding MSSM branching ratios from HDECAY.  

| Process                  | \(\sigma \times BR\) (pb) | \(BR(H^\pm \rightarrow \tau \nu + \tau \psi)\) | MSSM: \(BR(H^\pm \rightarrow \tau \nu)\) |
|--------------------------|-----------------------------|---------------------------------|----------------------------------|
| Signal-1                 | 1.56                        | 0.73                            | 0.37                             |
| Signal-2                 | 0.15                        | 1.0                             | 0.15                             |
| Signal-3                 | 0.04                        | 1.0                             | 0.01                             |
| \(tt\)                   | 84.11                       |                                 |                                  |
| \(gb \rightarrow Wt\) \((p_T > 30 \text{ GeV})\) | 47.56                       |                                 |                                  |

FIG. 2: Charged Higgs decays in models with a singlet neutrino in large extra dimensions for \(M_* = 2 \times 10^4 \text{ GeV}, \delta = 3\) and \(\tan \beta = 1.5\). For small values of \(m_D\), we see similar decay branchings as in MSSM. As \(m_D\) gets larger, \(H^\pm \rightarrow \tau \nu\) becomes dominant below and above the top-quark mass.

III. ANALYSIS

The polarization of the \(\tau\)-lepton is included in this analysis through TAUOLA. We consider the hadronic one-prong decays of the \(\tau\)-lepton since these are believed to carry a better imprint of the \(\tau\)-polarization:

\[
\begin{align*}
\tau^- &\rightarrow \pi^- \nu \quad (11.1\%) \quad (17) \\
\tau^- &\rightarrow \rho^- (\rightarrow \pi^- \pi^0) \nu \quad (25.2\%) \quad (18) \\
\tau^- &\rightarrow a_1^- (\rightarrow \pi^- \pi^0 \pi^0) \nu \quad (9.0\%) \quad (19)
\end{align*}
\]

In Fig. 3, we show the effects of the \(\tau\) polarization in the signal and the backgrounds in the case of one-prong \(\tau^- \rightarrow \pi^- \nu\). For the signal in MSSM, right handed \(\tau_R\)'s come from the charged Higgs decay, \(H^- \rightarrow \tau_R \bar{\nu}\), while in the backgrounds, left handed \(\tau_L\)'s come from the decay of the \(W^- (\rightarrow \tau_L \bar{\nu})\). Since the charged Higgs is a scalar and the \(W^-\) a vector, the polarization of the \(\tau\) results in a stronger \(\tau\)-jet in the MSSM signal than in the backgrounds for \(\tau^- \rightarrow \pi^- \nu\) and longitudinal \(\rho\) and \(a_1\). The studies reported in [9, 10] take advantage of this polarization effect in suppressing the backgrounds further by demanding that the charged track carries a significant part of the \(\tau\)-jet energy:

\[
p_{\tau}/E^{-\text{jet}} > 80\%.
\]

For the signal in MSSM, this requirement would retain only the \(\pi\) and half of the longitudinal \(\rho\) and \(a_1\) contributions while eliminating the transverse components along with the other half of the longitudinal contribu-
FIG. 4: The polarization asymmetry as a function of $m_{H^\pm}$, for various values of $\tan\beta$ and $m_D$. For small values of $m_D$, the decay $\tau^-$ are right handed (except for small $\tan\beta$ values) while left handed $\tau^-$'s are produced as $m_D$ gets larger.

FIG. 5: The polarization asymmetry and the $H^\pm \rightarrow \tau\nu$ branching ratio for two values of ($M_\ast$, $m_D$) and $\delta = 4$, 5 and 6. For very large $M_\ast$ and small $m_D$, we recovery the MSSM case, i.e., an asymmetry of $-1$ (right handed $\tau^-$) and MSSM branching ratios (bottom plots).

FIG. 6: Polarization of the decay $\tau$ from $H^\pm$ in MSSM and in models with a singlet neutrino in large extra dimensions. In the latter case, both left and right handed $\tau$'s can be produced with some polarization asymmetry. In the backgrounds, the $\tau$ comes from the decay of the $W^\pm$. The signal to be studied is in the box — the polarization of the decay $\tau$ in this signal is the same as in the background. Thus, $\tau$ polarization effects would not help in suppressing the backgrounds but they may help distinguish between the 2HDM and other models.

tions as can be seen from Fig. 7. However, this requirement would suppress much of the backgrounds, shown in Fig. 8. In the framework of large extra dimensions, we are interested in $H^- \rightarrow \tau^- \nu$ where, as shown in Fig. 6, the polarization of the $\tau$-lepton would be identical to the background case but opposite to the MSSM case. Therefore, the requirement (20) would not help in suppressing the backgrounds, as can be seen from Fig. 8 and Fig. 9. Nevertheless, there are still some differences in the kinematics which can help reduce the background level, and we discuss the details of the analysis as follow:

(a) Search for one-prong hadronic $\tau$ decays with one $\tau$-jet, $p_T^\tau > 30$ GeV and $|\eta^\tau| \leq 2.5$, at least three non $\tau$ jets with $p_T^jet > 30$ GeV. One of these jets must be a b-tagged jet with $|\eta^b| < 2.5$. Further, we apply a b-jet veto by requiring only a single b-jet with $|\eta^b| \leq 2.0$ and $p_T > 50$ GeV. We assume a $\tau$-jet identification efficiency of 30% and a b-tagging efficiency of 50%, for an integrated luminosity of 100 fb$^{-1}$. We further assume a multi-jet trigger with a high level $\tau$ trigger.

(b) The W from the associated top-quark is reconstructed and the candidates satisfying $|m_{jj} - m_W| \leq 25$ GeV are retained (and their four-momenta are renormalized to the W mass) for the
and $\rho$ be reversed and it is for the backgrounds: $W^+ \rightarrow \tau_R \bar{\nu}$. We plot the ratio of the momentum carried by the charged track to the $\tau$-jet energy. This ratio should peak near 0; the peak near 1 comes from the backgrounds but opposite to signal in MSSM.

For transverse $\rho$ and $a_1$, these criteria would select charged pions with this ratio near 1.

FIG. 9: The one prong decays of the $\tau$-lepton from the signal in models with a singlet neutrino in large extra dimensions with a polarization asymmetry of 1: $H^- \rightarrow \tau_R \bar{\psi}$. (The $\tau^-$ from $H^-$ decays are 100% left handed). The situation is thus similar to the backgrounds but opposite to signal in MSSM.

reconstruction of the top-quark: this is done by minimizing the variable $\chi^2 = (m_{jjb} - m_t)^2$. We take $m_W = 80.14$ GeV and $m_t = 175$ GeV. Subsequently, the events satisfying $|m_{jjb} - m_t| < 25$ GeV are retained for further analysis.

(c) We raise the cut on $p_T^\tau$, i.e., $p_T^\tau > 100$ GeV. To satisfy this $p_T^\tau$ cut, the $\tau$ jet from the backgrounds needs a large $p_T$ boost from the W boson. This will result in a smaller opening angle, $\Delta \phi$, between the decay products $\tau \nu$. $\Delta \phi$ is the azimuthal opening angle between the $\tau$ jet and the missing transverse momentum. In the signal $H^- \rightarrow \tau^- \bar{\nu}$, the $\tau$ jet will require little or no boost at all to satisfy this high $p_T^\tau$ cut. This explains the backward peak in the $\Delta \phi$ distribution for the signal as shown in Figures 10 and 11. Because of the neutrino in the final state, only the transverse mass

\[ m_T = \sqrt{2p_T^\tau p_T [1 - \cos(\Delta \phi)]} \]

(21)
can be reconstructed. In the backgrounds, the transverse mass has an upper bound at the $W^-$ mass ($W^- \rightarrow \tau^- \nu$) while in the signal, it is constrained by the charged Higgs mass ($H^- \rightarrow \tau^- \nu$). However, due to the experimental resolution of

FIG. 7: The one prong decays of the $\tau$-lepton from the signal in MSSM: $H^- \rightarrow \tau_R \bar{\nu}$. We plot the ratio of the momentum carried by the charged track to the $\tau$-jet energy. This ratio peaks near 1 for $\tau \rightarrow \pi \nu$ and near 0 and 1 for longitudinal $\rho$ and $a_1$. For transverse $\rho$ and $a_1$, this ratio peaks in the middle.

FIG. 8: The one prong decays of the $\tau$-lepton from the $t\bar{t}$ and $Wt$ backgrounds: $W^- \rightarrow \tau_R \bar{\nu}$. Here the situation should be reversed and it is for the $\rho$ and $a_1$. For $\tau \rightarrow \pi \nu$, the ratio should peak near 0; the peak near 1 comes from the $\tau$-jet labeling criteria in ATLAST: a jet is labeled a $\tau$-jet by requiring the hadronic decay products to carry a significant fraction (>0.9) of the $\tau$-jet energy within a jet cone ($\Delta R < 0.3$). For $\tau \rightarrow \pi \nu$, these criteria would select charged pions with this ratio near 1.
The main effects responsible for the suppression of the backgrounds are: the azimuthal opening angle — between the τ-jet and the missing transverse momentum — which peaks forward in the backgrounds (W± → τν) and backward in the signal (H± → τψ); and the difference in the kinematic bounds on the transverse mass — this bound is at the W-mass in the backgrounds whereas in the signal, the bound is at the charged Higgs mass. The overall efficiencies of the kinematic cuts (c), (d), and (e) might change as a result of the event by event difference in the neutrino mass mψ leading to an overall change in the signal-to-background ratios and signal significances of Table II but the results of Figures 12, 13 and 14 would not be affected because these results rely on the differences in the τ-polarization and in the kinematic bounds on the transverse mass, irrespective of the neutrino mass mψ. In Table II, we present results for 3 different values of the number of extra dimensions. With different mass distributions of mψ depending on the number of extra dimensions, the overall efficiencies for the cuts (c), (d) and (e) might change differently for each of the cases presented in Table II.
TABLE III: The expected signal-to-background ratios and significances calculated after cut (e) for an integrated luminosity of 100 fb$^{-1}$ (one experiment). See Table I for the parameters used for Signal-1, Signal-2 and Signal-3. In all the cases considered, the signal can be observed at the LHC with significances in excess of 5-σ at high luminosity.

|                    | Signal-1 | Signal-2 | Signal-3 |
|--------------------|----------|----------|----------|
| Signal events      | 41       | 215      | 16       |
| $t\bar{t}$         | 7        | 7        | 7        |
| $Wt$               | 3        | 3        | 3        |
| Total background   | 10       | 10       | 10       |
| $S/B$              | 4.1      | 21.5     | 1.6      |
| $S/\sqrt{B}$       | 13.0     | 68.0     | 5.1      |

IV. CONCLUSIONS

Large extra dimensions models with TeV scale quantum gravity assume the existence of additional dimensions where gravity – and possibly other fields – propagate. The size of the extra dimensions are constrained to the sub-millimeter level since no experimental deviations from the Newtonian gravity has been observed at distances larger than $\sim 0.2$ millimeter.

In these models, the right handed neutrino can freely propagate into the extra dimensions because it has no quantum numbers to constrain it to the SM brane. The interactions between the bulk neutrino and the SM fields on the brane can generate Dirac neutrino masses consistent with the atmospheric neutrino oscillations without implementing the seesaw mechanism. There are no additional Higgs bosons required in these models. The charged Higgs productions are therefore the same as in the 2HDM.

The charged Higgs can decay to both the right and the
FIG. 14: The distribution of the ratio of the charged pion track momentum in one prong τ decay to the τ-jet energy for $m_A = 350$ GeV, $\tan \beta = 45$, $M_\tau = 20$ TeV, $\delta = 3$ and $m_\nu = 0.05$ eV. In the 2HDM-II, this ratio would peak near 0 and 1 as shown while in other models, the actual distribution of this ratio would depend on the polarization asymmetry since both left and right handed τ’s would contribute. In the case shown, the asymmetry is $\sim 1$ and the ratio peaks near the center of the distribution.

left handed τ-leptons, $H^- \rightarrow \bar{\tau}_R \bar{\nu} + \tau_L \psi$ whereas in the 2HDM-II such as MSSM, only the right handed τ decay of the $H^-$ is possible through the τ Yukawa coupling: $H^- \rightarrow \tau_\nu \bar{\nu}$. The τ decay of the charged Higgs has been studied in details for ATLAS and CMS. In the current study, we focus on the observability of $H^- \rightarrow \tau_\nu \psi$ at the LHC for Higgs masses larger than the top-quark mass.

The charged Higgs is generated through the $2 \rightarrow 2$ process, $gb \rightarrow tH^\pm$ — where $H^\pm \rightarrow \tau_\nu \bar{\nu} + \tau_L \psi$ — and we require the hadronic decay of the associated top-quark: $t \rightarrow jjb$. The major backgrounds considered are the single top-quark production, $gb \rightarrow tW^\pm$ and the $t \bar{t}$ production with one $W^+ \rightarrow jj$ and the other $W^- \rightarrow \tau_\nu \bar{\nu}$. We include the τ polarization in the analysis and select one-prong hadronic τ decays since these events carry a better imprint of the τ polarization. Due to the neutrino in the final state, only the transverse mass can be reconstructed. In the backgrounds, the transverse mass has an upper bound at the W mass while in the signal, the bound is at the charged Higgs mass. As a result, above the W threshold, the background is relatively very small. Thus, the discovery reach of the charged Higgs in the $\tau\nu$ channel is limited by the signal size itself.

The mass of the neutrino $\psi$ would be different on event by event basis. Consequently, the efficiencies of the kinematic cuts would somewhat be different. However, main results of the current analysis derive from the differences in the polarizations of the $\tau$-lepton and in the transverse mass bounds, and would not be significantly affected by the neutrino mass effect.

Although the observation of a signal in the transverse mass distribution can be used to claim discovery of the charged Higgs, it is insufficient to pin down the scenario that is realized. Additionally, by reconstructing the fraction of the energy carried by the charged track in the one-prong τ decay, it is possible to claim whether the scenario is the ordinary 2HDM or not. The further measurement of the polarization asymmetry might provide a distinctive evidence for models with singlet neutrino in large extra dimensions.

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