Invisible Higgs Boson Decay into Massive Neutrinos of 4th Generation

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Abstract

Results from several recent experiments provide indirect evidences in the favor of existence of a 4th generation neutrino. Such a neutrino of mass m about 50 GeV is compatible with current physical and astrophysical constraints and well motivated in the framework of superstring phenomenology. If sufficiently stable the existence of such a neutrino leads to the drastic change of Higgs boson physics: for a wide range of Higgs boson masses the dominant mode of Higgs boson decay is invisible and the branching ratios for the most promising modes of Higgs boson search are significantly reduced. The proper strategy of Higgs boson searches in such a framework is discussed. It is shown that in the same framework the absence of a signal in the search for invisible Higgs boson decay at LEP means either that the mass of the Higgs ($M_H$) is greater than 113.5 GeV or that the mass difference $|M_H - 2m|$ is small.
The existence of Higgs boson is the necessary consequence of Higgs mechanism of electroweak symmetry breaking. Proportionality of its Yukawa coupling constants to fermion mass is its important property. Such property is shared by wider class of models of electroweak symmetry breaking. For example, it is shared by technipion in Technicolor models. So the existence of scalar boson with Yukawa coupling constants proportional to fermion masses seems to be a general feature of electroweak symmetry breaking mechanisms in the standard model. The possibility for the existence of new heavy elusive fermions, dominating in Higgs boson decays, leads to drastic change in the strategy of Higgs boson searches. The idea on the dominant invisible modes of Higgs boson decays was discussed in the framework of Majoron, SUSY and low scale gravity models in \[1\] (and references therein), however the simplest possibility is the existence of massive neutrino of 4th generation. The measured Z-boson width excludes the existence of 4th neutrino with the mass below 45 GeV. However, the detailed analysis of 4th generation effects in the standard model parameters opens the window for its existence, provided that the mass of 4th neutrino is below around W-boson mass \[2\]. A fit \[2\] of the precision electroweak data is compatible with the 4th generation neutrino mass \(m \sim 50\) GeV. However, the allowed range for 4th neutrino masses may be wider, if the 4th neutrino is not accompanied by 4th generation quarks (as it can take place in Dp-brane phenomenology, naturally excluding quarks of 4th generation but leaving the room for the 4th generation of leptons \[3\]). It even can not be accompanied by a charged lepton, as it is assumed in some models of neutrino mass \[4\]. Provided that it is sufficiently metastable, or it has only invisible decay modes, 4th neutrino with the mass around 50 GeV could escape detection by products of its decay in LEP. The possibility \[5\] to analyze the LEP data on single gamma events, corresponding to a 4th neutrino pair production in the reaction \(e^+ e^- \rightarrow N \bar{N} \gamma\) for \(m > 50\) GeV is still not realized.

If 4th neutrino is sufficiently long-living or even absolutely stable its primordial gas from the early Universe can survive to the present time and concentrate in the Galaxy \[5,\] \[6\]. It was shown \[7\] that galactic fluxes of 4th neutrino can lead to the effect of indirect WIMP searches compatible with the DAMA data, and the effects of 4th neutrino-antineutrino annihilation in the Galaxy can explain \[8,\] \[9\] the galactic gamma background with energies above 1 GeV, observed by EGRET. The latter possibility is strengthened, provided that the 4th generation quarks and leptons possess the new strictly conserved gauge charge, as it can naturally follow from heterotic string phenomenology \[10\]. In that case 4th neutrino annihilation in Galaxy can explain the positron anomaly in electron component of cosmic rays \[10,\] \[11\].
It was shown [12] that the capture of 4th neutrinos by Earth can lead to the underground neutrino flux, accessible, in principle, to underground neutrino detectors.

In the present note we draw attention to the important role, 4th neutrino can play in the physics of Higgs boson. The probability of Higgs boson decay into $N\bar{N}$ pair is given by

$$
\Gamma(H \rightarrow N\bar{N}) = \frac{\sqrt{2}}{8\pi} Gm^2M_H \left(1 - \frac{4m^2}{M_H^2}\right)^{3/2},
$$  

(1)

where $G$ is the Fermi constant, $m$ and $M_H$ are the masses of the neutrino and Higgs boson respectively. This mode should be compared with the probabilities of the most important $b\bar{b}$ and $WW$ modes of Higgs boson decay.

In Fig.1 the dependence on Higgs boson mass for branching ratios for these decay modes and other most contributing modes is given for two values of the neutrino mass, $m = 50$ GeV (Fig 1a) and $m = 70$ GeV (Fig 1b). One easily finds, that the dominance of $N\bar{N}$ mode in the Higgs boson width for Higgs boson masses up to 160 GeV naturally follows from the fact that the mass of $N$ is by the order of magnitude larger than the mass of b-quark also taking into account the number of colored quark states in the b-mode (3), a reduction factor $\approx 2$ due to QCD corrections [13] and the phase volume difference for $N\bar{N}$ and $b\bar{b}$ channels. It leads to the branching ratio of $N\bar{N}$ channel between 90 and 95 per cent in the total Higgs boson width, if the mass of Higgs boson is below the threshold for $WW$ mode. However, even at higher masses of Higgs boson the 4th neutrino channel is significant. Note that if the masses of 4th lepton and 4th generation quarks are near the existing lower limits, the respective decay modes would be important for the Higgs boson mass above 260 GeV. In the considered Higgs boson mass range the 4th generation fermions affect Higgs decay modes $H \rightarrow gg, \gamma\gamma$ by loop diagrams. Here their probabilities were estimated assuming 4th charge lepton mass $m_E = 100$ GeV, 4th up- and down- quark masses $m_U = m_D = 130$ GeV. It takes into account the difference in probabilities of these decays in comparison with previous analogous estimates for three fermion generations.

In the case, when the $N\bar{N}$ decay mode dominates, Higgs boson search can be effectively undertaken in the search for acoplanar lepton pairs or acoplanar jets, arising from the Higgs-struhlung reaction [7],[8]

$$
e^+e^- \rightarrow ZH
$$  

(2)

with successive Z-boson decay into charged lepton pair, and elusive Higgs boson decay into the pair of $N\bar{N}$. The total cross section for this reaction is
Figure 1: Branching ratios of the Higgs decay modes: $H \rightarrow NN, bb, WW, ZZ, c\bar{c}, \tau^+\tau^-, gg, \gamma\gamma$. a) $m = 50$ GeV, b) $m = 70$ GeV.
given by
\[ \sigma(e^+e^- \rightarrow ZH) = \frac{(g_V^2 + g_A^2) G^2 M_Z^6}{6\pi \sqrt{s}} \frac{\sqrt{q_1^2}}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \left( 1 + \frac{1}{2} \frac{q_{10}^2}{M_Z^2} \right), \quad (3) \]
where \( g_V = -1 + 4 \sin^2 \theta_W, g_A = -1, \) \( q_{10} = (s + M_Z^2 - M_H^2)/(2\sqrt{s}), \) \( s \) being squared center-mass energy, \( |q_1^2| = \sqrt{q_{10}^2 - M_Z^2}. \) The differential cross section for charged leptons from successive Z-boson decay is given by
\[ l_0 d\sigma^\pm d^3l = \frac{3}{2^5\pi^2} \beta_N \beta_l \frac{M_Z^4 G^2 D_Z}{C_V} \frac{1}{\sqrt{s} l_0} \left\{ 2l_0(q_{10} - l_0) C_V^2 \mp C_A^2 M_Z^2 \cos \theta + \cos^2 \theta C_V^2 [M_Z^2 - 2l_0(q_{10} - l_0)] \right\}, \quad (4) \]
where \( C_V = g_V^2 + g_A^2, \) \( C_A = 2g_V g_A, \) \( D_Z = \frac{1}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}, \) \( \beta_N \) and \( \beta_l \) are the \( H \rightarrow NN \) and \( Z \rightarrow l^+l^- \) branching ratios respectively, \( \theta \) is the angle between momenta of the initial electron and the final negative lepton, the kinematic limits of the considered process are \( M_Z + M_H \leq \sqrt{s}, \frac{1}{2} [q_{10} - |q_1^2|] \leq l_0 \leq \frac{1}{2} (q_{10} + |q_1^2|). \) The above formulae can be used for the case of visible modes of Z-boson decay to \( \mu\bar{\mu} \) and \( \tau\bar{\tau}, \) as well as for 2-jet events from quark antiquark channels of Z-boson decay (replacing \( C_V, C_A \) by appropriate values and taking into account 3 color degrees of freedom). In the case of electron-positron mode of Z-boson decay an interference diagram should be taken into account.

Fig. 2 shows the total cross sections of \( \mu^+\mu^- \) pair production for the Higgsstruhlung reaction (Eq.2) with the Higgs boson decaying invisibly into \( N\overline{N} \) of mass 50 GeV. One can see that the total cross section is within the range of LEP collider. The LEP working group presented results of a search for a Higgs boson, produced at the Standard Model rate, decaying into invisible particles [14,15]. No statistically significant excess has been observed when compared to a background prediction. Assuming that the Higgs boson decays only into invisible states a lower bound has been set on its mass at 95% CL of 114.4 GeV [14]. In the case of 4th generation neutrino of \( m \approx 50 \) GeV taking into account the branching ratios one can infer from the LEP data [14] the lower limit on Higgs mass \( \approx 113.5 \) GeV. If a 4th generation neutrino of mass \( m \approx 50 \) GeV exists then the absence of the signal at LEP means either that the mass of the Higgs \( M_H \) is greater than 113.5 GeV or that the mass difference \( |2m - M_H| \) is small leading to a significant phase space suppression of the invisible Higgs decays.

Actually, the predicted effect of elusive Higgs boson assumes the lifetime of 4th neutrino to be \( > 10^{-7} \) sec. If this lifetime exceeds the age of the Universe, astrophysical search for 4th neutrino effects will be of special interest. It turns out that the inverse effect of Higgs boson on the predicted
Figure 2: Total cross sections of the processes $e^+e^- \rightarrow ZH \rightarrow t^+t^- b\bar{b}$, $t^+t^- N\bar{N}$ in dependence on center mass energy of colliding $e^+e^-$ for $M_H = 115$ GeV and $M_H = 150$ GeV when $m = 50$ GeV.

astrophysical effects of 4th neutrinos is restricted by the very narrow interval of 4th neutrino and Higgs mass ratio [13]. The mass difference between 2$m$ and $M_H$ should be negative and less than 3-4 GeV to influence significantly the primordial $N\bar{N}$ concentration owing to the Higgs boson channel of their annihilation in the period of their freezing out in early Universe. So, for the mass of neutrino 50 GeV and the Higgs boson mass 114 GeV the role of Higgs boson is elusive in the calculations of 4th neutrino freezing out in the early Universe, as well as in the effects of 4th neutrino annihilation in the Galaxy. The detailed discussion of Higgs boson effect on the astrophysical signatures of 4th neutrinos will be given in a separate paper.

To conclude, the existence of scalar boson with Yukava coupling proportional to fermion mass is the important signature for the mechanism of electroweak symmetry breaking. The existence of massive 4th neutrino makes elusive the dominant mode of decay of this boson, and the strategy of Higgs boson search should take into account this possibility. In particular, the presented results mean that for LHC in the mass region $M_H \simeq 115 - 160$ GeV the gluon fusion process $gg \rightarrow H$ is not dominating and one has to search for lepton or jet pair + missing energy from reactions $qq \rightarrow qqH, WH, ZH$. The positive result of such search will not only prove one of the corner stones
of the standard model, but it will also prove the existence of physics beyond
the standard model, as well as it will make the hypothesis of 4th neutrino
deserving serious attention. The experimental proof that the ratio of the
evasive mode to b-quark one of Higgs boson decay is as it is predicted for 4th
neutrino will strongly favor this hypothesis as compared with other possible
models for invisible Higgs boson. The set of astrophysical signatures provides
the complete test of the hypothesis on massive stable 4th neutrino.

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