PHYSICAL REVIEW D **68**, 054027 (2003)

Invisible Higgs boson decay into massive neutrinos of fourth generation

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(Received 14 January 2003; published 30 September 2003)

Results from several recent experiments provide indirect evidence in favor of the existence of a fourth generation neutrino. Such a neutrino with a mass m of 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 a drastic change in 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 the CERN LEP means that the mass of the Higgs boson is greater than 113.5 GeV if the neutrino mass is about 50 GeV.

DOI: 10.1103/PhysRevD.68.054027 PACS number(s): 13.66.Fg, 14.60.Pq

The existence of the Higgs boson is a necessary consequence of the Higgs mechanism of electroweak symmetry breaking. The proportionality of its Yukawa coupling constants to the fermion mass is its important property. Such a property is shared by a wider class of models of electroweak symmetry breaking. For example, it is shared by technipion in technicolor models. So the existence of a scalar boson with Yukawa coupling constants proportional to fermion masses seems to be a general feature of the electroweak symmetry breaking mechanisms in the standard model. The possibility of the existence of new heavy elusive fermions, dominating in Higgs boson decays, leads to a drastic change in the strategy of Higgs boson searches. The idea of the dominant invisible modes of Higgs boson decays was discussed in the framework of the Majoron, supersymmetry (SUSY), and low scale gravity models in [1] (and references therein); however, the simplest possibility is the existence of massive neutrinos of the fourth generation. The measured Z boson width excludes the existence of a fourth neutrino with mass below 45 GeV. However, the detailed analysis of fourth generation effects in the standard model parameters [2,3] opens the window for its existence, provided that the mass of the fourth neutrino is below the W boson mass [2]. A fit [2] of the precision electroweak data is compatible with the fourth generation neutrino mass $m \sim 50$ GeV. However, the allowed range for fourth neutrino masses may be wider, if the fourth neutrino is not accompanied by fourth generation quarks (as can occur in Dp-brane phenomenology, naturally excluding quarks of the fourth generation but leaving room for a fourth generation of leptons [4]). The fourth neutrino cannot even be accompanied by a charged lepton, as is assumed in some models of neutrino mass [5]. Provided that it is sufficiently metastable or has only invisible decay modes, a fourth neutrino with a mass around 50 GeV could escape detection by products of its decay in the CERN e^+e^- collider LEP. The possibility [6] of analyzing the LEP data on single gamma events, corresponding to a fourth neutrino pair production in the reaction $e^+e^- \rightarrow N\bar{N}\gamma$ for $m > 50$ GeV, has still not been realized.

To be sufficiently long living or even absolutely stable, the fourth neutrino should possess some new approximately or strictly conserved charge. This possibility for the fourth generation quarks and leptons can naturally follow from heterotic string phenomenology [7] and is predicted in some models of family symmetry breaking [8]. If the fourth neutrino is sufficiently long living or absolutely stable, its primordial gas from the early Universe can survive to the present time and concentrate in the Galaxy [6,9]. According to experimental data [10] the neutrino mass range above 48 GeV is excluded if heavy Dirac neutrinos make up the dark matter in the galactic halo. However, the existence of heavy neutrinos is not inconsistent with the experiments [10] if heavy neutrinos form a nondominant component of dark matter population in the Galaxy. Although the predicted contribution of primordial fourth neutrinos to the total dark matter density is dynamically insignificant, it has been shown [11] that galactic fluxes of such a sparse component (fourth neutrinos) can lead to the effect of indirect weakly interacting massive particle (WIMP) searches compatible with the DAMA data, and the effects of fourth neutrino-antineutrino annihilation in the Galaxy can explain [12,13] the galactic gamma background with energies above 1 GeV, observed by EGRET. The latter possibility is strengthened, provided that the fourth generation quarks and leptons possess the new strictly conserved gauge charge. In that case fourth neutrino annihilation in the galaxy can explain the positron anomaly in the electron component of cosmic rays [7,14]. It was shown [15] that the capture of fourth neutrinos by the Earth can lead to the underground neutrino flux, accessible, in principle, to underground neutrino detectors. It should be noted that the estimated continuum flux of neutrinos from fourth neutrino annihilation inside the Earth turns out to be below

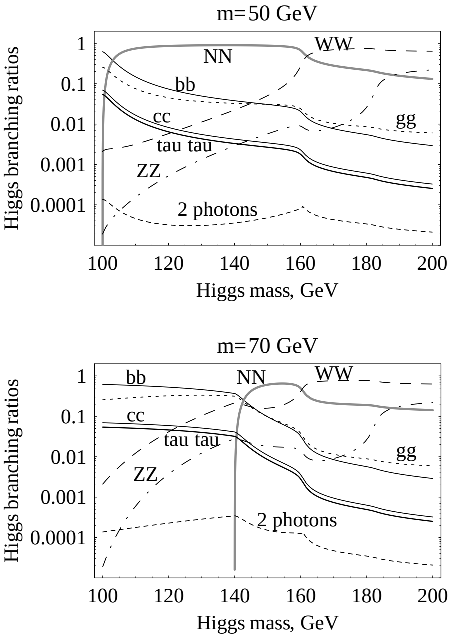

FIG. 1. Branching ratios of the Higgs boson decay modes $H \to N\bar{N}, b\bar{b}, WW, ZZ, c\bar{c}, \tau^+\tau^-, gg, \gamma\gamma$.

the atmospheric neutrino level. However, a monochromatic neutrino-antineutrino annihilation channel, being specific for fourth neutrinos in comparison with the other types of WIMPs (e.g., neutralinos), can lead to constraints on the model of stable fourth neutrino with mass 70–80 GeV in the refined analysis of underground muons detected by the MACRO Collaboration. We plan such analysis in the near future.

The absolute stability of fourth neutrinos is, evidently, not necessary for invisible Higgs boson decay dominance. However, the necessary condition for the metastable fourth neutrino—that it is either long living or decaying predominantly to invisible channels—implies rather specific physics for the fourth neutrinos. In the present note we draw attention to the important role the fourth neutrino can play in the physics of the Higgs boson [11,12,16]. The probability of Higgs boson decay into an $N\bar{N}$ pair is given by

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

where G is the Fermi constant, and 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 the Higgs boson mass for branching ratios for these decay modes and most other contributing modes is given for two values of the neutrino mass $m = 50$ GeV and $m = 70$ GeV. One easily finds that the dominance of the $N\bar{N}$ 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 larger by an order of magnitude than the mass of the b quark, taking into account also the number (three) of colored quark states in the b mode, a reduction factor ≈ 2 due to QCD corrections [17], and the phase volume difference for $N\bar{N}$ and $b\bar{b}$ channels. This leads to a branching ratio of the $N\bar{N}$ channel between 90% and 95% in the total Higgs boson width, if the mass of the Higgs boson is below the threshold for the WW mode. However, even at higher masses of the Higgs boson the fourth neutrino channel is significant. Note that, if the masses of the fourth leptons and fourth generation quarks are near the existing lower limits, the corresponding decay modes will be important for Higgs boson masses above 260 GeV. In the considered Higgs boson mass range the fourth generation fermions affect the Higgs boson decay modes $H \to gg, \gamma\gamma$ by the loop diagrams. Here their probabilities were estimated assuming a fourth charge lepton mass of $m_E = 100$ GeV and fourth up and down quark masses $m_U = m_D = 130$ GeV. This takes into account the difference in probabilities of these decays in comparison with previous analogous estimates for three fermion generations. The branching ratio of the process $H \to \gamma\gamma$ is small but in some mass ranges this mode can be the best choice in searches for Higgs bosons due to the clear signature of two isolated photons. The probability of the decay $H \to \gamma\gamma$ decreases due to the fourth fermion generation by a factor of 3–7 in dependence on the Higgs boson mass while the probability of $H \to gg$ increases by a factor of the order of 10 for the Higgs boson mass range under consideration. Both probabilities are almost independent of fourth generation fermion masses if these masses are relatively small.

The influence of fourth generation fermions on decay modes $H \to gg$ and $H \to \gamma\gamma$ differs because different sets of particles contributing to the loop diagrams for these processes. The crucial point is the presence of the W boson loop contributing to the amplitude of the process $H \to \gamma\gamma$. It prevails over fermion loop contributions and it has the opposite sign as compared to fermions. In the $H \to gg$ decay this is not the case; only heavy quarks contribute to the amplitude of this decay in the one-loop approximation. In the case of four generations the probability of $H \to \gamma\gamma$ decreases because the W boson loop contribution to the amplitude of this decay is partially canceled out by the effect of fourth generation fermions, adding their contributions to the loop diagrams of fermions of the known generations. The probability of $H \to gg$ is increased by about an order of magnitude due to virtual tripling of the number of heavy quarks that contribute to the process: from one type of quark (the top quark) to three types (top quarks and up and down quarks of the fourth generation). Also note that the W boson loop contribution to the amplitude of $H \to \gamma\gamma$ has a resonance at $M_H = 2M_W$ which accounts for a bumping behavior of this probability with variation of the Higgs boson mass. The most important fermion loop contributions to the considered processes are almost independent of the Higgs boson mass provided that the doubled fermion mass exceeds M_H at least by a few tens of percent of their difference but does not exceed the vacuum expectation value of the Higgs field, when the perturbative approach is not valid.

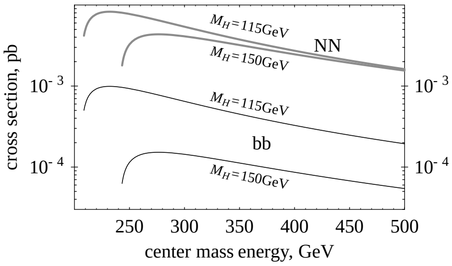

FIG. 2. Total cross sections of the processes $e^+e^-\to ZH \to l^+l^-b\bar{b}, l^+l^-N\bar{N}$ in dependence on the center-of-mass energy of colliding e^+e^- for $M_H=115$ GeV and $M_H=150$ GeV when $m=50$ GeV.

In the case when the $N\bar{N}$ decay mode dominates, the Higgs boson search can be effectively undertaken in the search for acoplanar lepton pairs or acoplanar jets, arising from the Higgs-struhlung reaction [11,12]

$$e^+e^-\to ZH \tag{2}$$

with successive Z boson decay into charged lepton pairs and elusive Higgs boson decay into a pair of $N\bar{N}$. The total cross section for this reaction is given by

$$\sigma(e^+e^-\to ZH)=\frac{(g_V^2+g_A^2)G^2M_Z^6}{6\pi\sqrt{s}}\,\frac{|\vec{q_1}|}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\times\left(1+\frac{1}{2}\,\frac{q_{10}^2}{M_Z^2}\right), \tag{3}$$

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 the squared center-of-mass energy and $|\vec{q_1}|=\sqrt{q_{10}^2-M_Z^2}$. The differential cross section for charged leptons from successive Z boson decays is given by

$$\frac{l_0d\sigma_\pm}{d^3l}=\frac{3}{2^5\pi^2}\beta_N\beta_l\frac{M_Z^4G^2D_Z}{C_V}\,\frac{1}{\sqrt{s}l_0}\{2l_0(q_{10}-l_0)C_V^2 \mp C_A^2M_Z^2\cos\theta+\cos^2\theta C_V^2[M_Z^2-2l_0(q_{10}-l_0)]\}, \tag{4}$$

where $C_V=g_V^2+g_A^2$, $C_A=2g_Vg_A$, $D_Z=1/[(s-M_Z^2)^2+M_Z^2\Gamma_Z^2]$, β_N and β_l are the $H\to NN$ and $Z\to l^+l^-$ branching ratios, respectively, θ is the angle between the momenta of the initial electron and the final negative lepton, and the kinematic limits of the considered process are $M_Z+M_H\leqslant\sqrt{s}$, $\frac{1}{2}[q_{10}-|\vec{q_1}|]\leqslant l_0\leqslant\frac{1}{2}[q_{10}+|\vec{q_1}|]$. The above formulas 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 two-jet events from quark-antiquark channels of Z boson decay (replacing C_V, C_A by appropriate values and taking into account three color degrees of freedom). In the case of the electron-positron mode of Z boson decay an interference diagram should be taken into account.

Figure 2 shows the total cross sections of $\mu^+\mu^-$ pair production for the Higgs-struhlung reaction [Eq. (2)] with the Higgs boson decaying invisibly into $N\bar{N}$ of mass 50 GeV. One can see that the total cross section is within the range of the LEP collider.

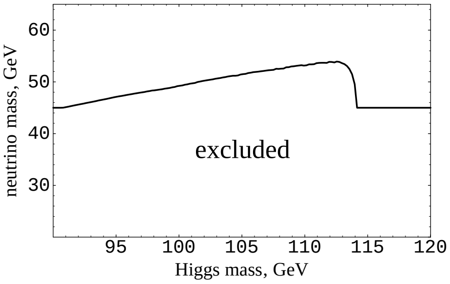

FIG. 3. Exclusion plot in neutrino mass and Higgs boson mass parameter space.

The LEP Working Group presented the results of a search for a Higgs boson, produced at the standard model rate, decaying into invisible particles [18,19]. No statistically significant excess was 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 the 95% C.L. of 114.4 GeV [18].

Figure 3 displays an exclusion plot in neutrino mass and Higgs boson mass parameter space. The region below $m=45$ GeV is excluded by the experimental data on Z boson decays [20]. There is no constraint on the neutrino mass above the line defined by the equation $M_H=2m$ because in this region Higgs boson decays into heavy neutrinos are prohibited by the phase space. The region between $m=45$ GeV and the solid line is excluded by the LEP data [18]. If a fourth generation neutrino of mass $m\approx50$ GeV exists, then taking into account the branching ratios one can infer from the LEP data [18] a lower limit on the Higgs boson mass ≈113.5 GeV (see Fig. 3).

Actually, the predicted effect of an elusive Higgs boson assumes the lifetime of the fourth neutrino to be greater than 10^{-7} s. If this lifetime exceeds the age of the Universe, an astrophysical search for fourth neutrino effects will be of special interest. It turns out that the inverse effect of the Higgs boson on the predicted astrophysical effects of fourth neutrinos is restricted by the very narrow interval of the fourth neutrino and Higgs boson mass ratio [21]. The mass difference between $2m$ and M_H should be negative and less than 3–4 GeV to significantly influence the primordial $N\bar{N}$ concentration owing to their annihilation in the Higgs boson channel in the period of their freezing out in the early Universe. So, for a mass of the neutrino 50 GeV and the Higgs boson mass of 114 GeV, the role of the Higgs boson is elusive in calculations of fourth neutrino freezing out in the early Universe, as well as in the effects of fourth neutrino annihilation in the Galaxy. A detailed discussion of the Higgs boson effect on the astrophysical signatures of fourth neutrinos will be given in a separate paper.

To conclude, the existence of scalar bosons with Yukawa coupling proportional to fermion mass is an important signature for the mechanism of electroweak symmetry breaking. The existence of massive fourth neutrinos makes elusive the dominant mode of decay of this boson, and the strategy for the Higgs boson search should take this possibility into account. In particular, the results presented mean that for the LHC in the mass region $M_H \simeq 115$–160 GeV the gluon fusion process $gg \to H$ is not dominant, and one has to search for a lepton or jet pair + missing energy from the reactions $qq \to qqH, WH, ZH, t\bar{t}H$ (prospects for observing the invisible Higgs boson in $qq \to t\bar{t}H$ were discussed in [22]). A positive result of such a search will not only prove one of the cornerstones of the standard model, but will also prove the existence of physics beyond the standard model, as well as making the hypothesis of the fourth neutrino deserving of serious attention. Experimental proof that the ratio of the elusive mode to the *b* quark mode of Higgs boson decay is as predicted for the fourth neutrino will strongly favor this hypothesis as compared with other possible models for the invisible Higgs boson. The set of astrophysical signatures provides a complete test of the hypothesis of the massive stable fourth neutrino.

The work was partially performed in the framework of Russian State contract 40.022.1.1.1106, with partial support from the Cosmion-ETHZ and AMS-Epcos Collaborations, from grant 00-15-96699 of support for Russian scientific schools, from RFBR grant 02-02-17490, and from a grant from Russian Universities 02.01.026.

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