A Natural Nightmare for the LHC?

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A minimal lepton number conserving extension to the Standard Model is considered providing light Dirac neutrinos without resorting to tiny Yukawa couplings. Successful baryogenesis through leptogenesis is not only possible in this case, but even suggests an electroweak scale vacuum expectation value for a gauge singlet scalar in the model. The spectrum contains two massive Higgs bosons and a massless Nambu-Goldstone boson. The existence of the Nambu-Goldstone boson suppresses the Higgs to $b\bar{b}$ branching ratio and instead Higgs bosons will decay mainly into invisible Goldstone bosons. We consider the constraints on the potential and the implications for the LHC and ILC.

1 Introduction

It is (supposed to be) summer 2007. Physicists, the media and the general public are eagerly anticipating the start of LHC running. One of the primary aims of this immensely complex experiment is to uncover the mechanism underlying electroweak symmetry breaking – widely expected to be the Higgs mechanism. Central to this cause is the discovery of the Higgs boson, arguably the key to unravelling the reason why the $W^{\pm}$, the Z and indeed the other fundamental particles of the Standard Model have mass. But what if the LHC didn't see the Higgs? Not because it didn't exist, but because it decayed *invisibly* [1].

Nambu-Goldstone bosons, first considered in 1960 [2], have several special properties. In particular, they are massless and they couple to the divergence of the current j^{μ} associated with a spontaneously broken symmetry [3]. This coupling has a strength inversely proportional to the scale of the symmetry breaking F such that

$$\mathcal{L}_{\rm int} \;=\; \frac{1}{2\,F}\,\mathcal{J}\,\partial_{\mu} j^{\mu}\,, \tag{1}$$

where $\mathcal{J}$ is the Nambu-Goldstone boson (NGB) field. Suzuki and Shrock [4] first proposed that if the Standard Model Higgs boson were to mix with a new scalar field that was charged under a spontaneously broken global symmetry, then it would decay into a pair of NGBs if the scale F was close to the electroweak scale, $F \approx 100$ GeV. Interestingly, such an invisible Higgs decay could actually be searched for at colliders, and the relatively clean environment of e^+e^- machines makes them especially suited to this task [5].

This possibility seems less exotic when one considers that mixing between the SM Higgs H and a new complex scalar field Φ, $\mathcal{L}_{\rm int} = H^{\dagger}H\Phi^{\dagger}\Phi$, is one of very few renormalizable operators allowed which could link the SM to a new gauge singlet sector i.e. Φ is charged under a new global symmetry G_P but singlet under the SM gauge group. In this way the Higgs provides a portal into a hidden, or "phantom" sector [6].

Another example of such a portal is the neutrino Yukawa coupling which links SM fields with a gauge singlet right-handed neutrino. This interaction is so commonly invoked that it is now normally considered as part of the SM. In this way, the usual (Majorana) see-saw mechanism is a very simple "phantom sector". The Majorana see-saw mechanism even contains a broken global symmetry (lepton number) which in many extended models is spontaneously broken – leading to a NGB, the Majoron [7].

Stringent bounds can be placed on the coupling of massless particles to matter coming from considerations of energy loss in supernovae, stars and terrestrial collider experiments. For common NGBs such as Majorons, axions [8] and familions [9] these constraints generally mean that $F \gtrsim 10^9$ GeV. The underlying reason for such stringent bounds is that these NGBs couple to a current carried by quarks and/or charged leptons, e.g. lepton number in the case of the Majoron. If the NGB coupled to a current carried by gauge singlet matter (e.g. ν_R) then such stringent constraints on F would not apply.

2 Dirac neutrino masses and baryogenesis

Neutrinos are not necessarily Majorana particles. As yet, we have no firm evidence of neutrinoless double beta decay, a characteristic signature of the lepton number violation associated with Majorana neutrinos. Along the same lines as the Majorana see-saw mechanism, an operator generating naturally small, Dirac, neutrino masses is

$$\mathcal{L}_\nu \;=\; \frac{(\overline{L}\cdot\tilde{H})\,(\Phi\cdot\nu_R)}{\Lambda}\;, \tag{2}$$

where L is the usual $\mathrm{SU}(2)_L$ lepton doublet, $\tilde{H} \equiv i\,\sigma_2\,H$ is the SM Higgs doublet, ν_R is a gauge singlet right-handed neutrino and Φ is a new gauge singlet, complex scalar field.

In a model generating eq. (2), some global symmetry G_P carried by only by the gauge singlets Φ and ν_R prevents the neutrinos from acquiring masses via a $\overline{L}\cdot\tilde{H}\nu_R$ term in the Lagrangian. After the spontaneous breakdown of G_P and the electroweak symmetry, eq. (2) results in naturally small Dirac neutrino masses if the vacuum expectation values (VEVs) $\langle\Phi\rangle \approx \langle H\rangle \approx 100$ GeV provided that $\Lambda \sim 10^{16}$ GeV. A model generating the operator (2) was first considered by Roncadelli and Wyler [10].

Although lepton number is conserved in this model, it was recently shown [11] that the model could lead to successful baryogenesis via (Dirac) leptogenesis [12]. This is possible because the model of [10] contains heavy Dirac states, S and $\bar{S}$ much like the heavy, but Majorana, right-handed neutrinos of the usual see-saw. In the early Universe the S particles decay into neutrinos and Higgs scalars. Significantly, CP can be violated in this decay process. After the S have decayed, no reaction can take place quickly enough to bring the left and right-handed neutrinos into equilibrium – this is related to the smallness of the light neutrino masses. Matter/antimatter asymmetries in the left and right-handed neutrino sectors, produced during the CP-violating decays of the S, cannot equilibrate and a net lepton asymmetry remains amongst the left-handed $\mathrm{SU}(2)_L$ doublet leptons. Rapid $B+L$ violating processes in the early Universe, which are insensitive to asymmetries in the gauge singlet ν_R, convert this lepton asymmetry into a baryon asymmetry.

Under reasonable assumptions, one can derive approximate limits on the VEV of the singlet scalar field Φ [11], $0.1\ \mathrm{GeV} \lesssim \langle\Phi\rangle \lesssim \frac{2\ \mathrm{TeV}}{T_{RH}}$, where T_{RH} is the reheating temperature of the Universe after inflation.

3 Higgs phenomenology

In models containing a singlet scalar Φ charged under a new global symmetry, e.g. $G_P = U(1)_P$, nothing prevents the term, $\mathcal{L}_{\mathrm{link}} \;=\; \eta\, H^\dagger\, H\, \Phi^*\, \Phi$, from appearing in the Lagrangian, where η is a new dimensionless coupling. After the spontaneous breakdown of $\mathrm{U}(1)_P$ and electroweak symmetry the two massive Higgs bosons in the model mix. The spectrum also contains a massless NGB $\mathcal{J}$ associated with the breakdown of $\mathrm{U}(1)_P$. The Higgs bosons will couple to this NGB [4] as

$$\mathcal{L}_{\rm int} \;=\; \frac{1}{2\,\langle\Phi\rangle}\,\mathcal{J}\,\partial_\mu j^\mu \;\;\rightarrow\;\; -\frac{m_{H_i}}{\langle\Phi\rangle}\,O_{2i}\,H_i\,\mathcal{J}\mathcal{J}\,, \tag{3}$$

where O_{2i} is a mixing matrix element parameterizing the mixing of the massive H_i. Hence, the massive Higgs bosons H_i will decay into the massless and invisible $\mathcal{J}$ [13]. For Higgs masses $m_{H_i} \lesssim 130$ GeV the dominant decay mode of the Standard Model Higgs is $H \to b\bar{b}$. Comparing the rates $\Gamma(H_1 \to b\bar{b})$ and $\Gamma(H_1 \to \mathcal{J}\mathcal{J})$ it can be shown that for 20 GeV $\lesssim m_{H_1} \lesssim 130$ GeV the Higgs will dominantly decay into invisible $\mathcal{J}\mathcal{J}$.

LEP, LHC and ILC Higgs phenomenology is influenced by the number of visible Higgs decay events seen as compared to the SM expected value. This is quantified by the parameter $\mathcal{R}^2$ defined as

$$\mathcal{R}_i^2 \equiv \frac{\sigma(pp \to H_i\,X)\,\mathrm{Br}(H_i \to YY)}{\sigma(pp \to h_{\rm SM}\,X)\,\mathrm{Br}(h_{\rm SM} \to YY)}\,,\;\; \mathcal{T}_i^2 \equiv \frac{\sigma(pp \to H_i\,X)}{\sigma(pp \to h_{\rm SM}\,X)}\,\mathrm{Br}(H_i \to \mathcal{J}\mathcal{J})\,, \tag{4}$$

where YY is a visible final state such as $b\bar{b}$ or $\gamma\gamma$, and $\mathcal{T}^2$ is the analogous parameter for invisible decays.

Looking to the future, both the ATLAS and CMS experiments have performed detailed studies exploring the discovery potential of their detectors in cases where Higgs bosons decay to visible final states [14] and also invisible final states [15]. Considering $\mathcal{L} = 30$ fb^{-1} of LHC integrated luminosity, it can be estimated that it would be difficult to discover a visibly decaying Higgs if $\mathcal{R}_i \lesssim 0.2$. Furthermore, ATLAS studies [15] indicate that with the same amount of integrated luminosity, invisible Higgs bosons with $m_{H_i} \lesssim 200$ GeV could be excluded only if $\mathcal{T}_i^2 \gtrsim 0.3$.

Figure 1 (left) shows the areas where either $\mathcal{R}_i^2 \geq 0.3$ or $\mathcal{T}_i^2 \geq 0.3$ in the m_{H_1} vs. $m_{H_2} - m_{H_1}$ plane. The plot assumes maximal mixing and $\langle\Phi\rangle = \langle H\rangle$. It is clear that a "nightmare" region remains where no Higgs bosons are accessible to the LHC if experiments do not have the sensitivity to see into areas where $\mathcal{R}_i^2 \leq 0.3$ and $\mathcal{T}_i^2 \leq 0.3$.

4 Triviality and vacuum stability

The potential of the model being considered reads

$$V \;=\; \mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger\Phi + \lambda_H (H^\dagger H)^2 + \lambda_\Phi (\Phi^*\Phi)^2 - \eta H^\dagger H \Phi^*\Phi\,. \tag{5}$$

There are two classic constraints regarding this potential; triviality and vacuum stability. The triviality constraint is essentially the requirement that the couplings λ_H, λ_Φ and η stay perturbative up to a certain scale $\Lambda_T \gg \langle H\rangle$. Demanding the vacuum is stable leads to the requirement that the potential is bounded from below, at least up to a scale $\Lambda_V \gg \langle H\rangle$. The vacuum stability bound can be reduced to the requirement that $4\,\lambda_H(Q)\;\lambda_\Phi(Q) > \eta(Q)^2$, at all scales $Q \lesssim \Lambda_V$.

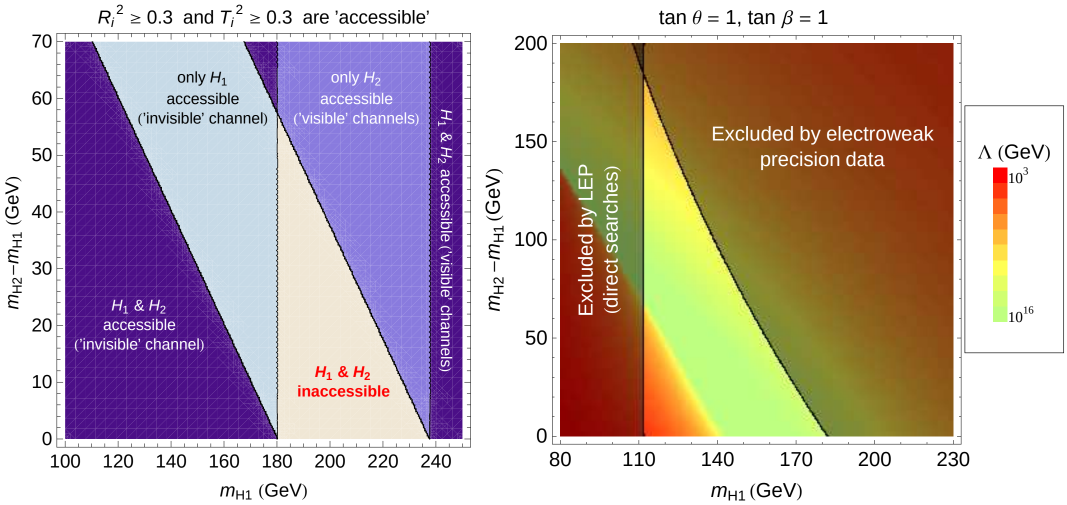

Figure 1: *The m_{H_1} vs. $m_{H_2} - m_{H_1}$ plane for $\tan\beta = 1$ and $\tan\theta = 1$. The left panel shows where different Higgs bosons are accessible. We define that a given H_i is accessible if either $\mathcal{R}_i^2 \geq 0.3$ or $\mathcal{T}_i^2 \geq 0.3$. In the dark (blue) regions both Higgs bosons are accessible. In the white (beige) region no Higgs bosons are accessible. The right panel shows the expected cut-off Λ, of the effective theory taking the triviality and positivity of the potential into account (the lower of either Λ_T or Λ_V is shown). The curved line shows the 95% C.L. upper limit on the Higgs masses coming from precision electroweak data (see [11]).*

The running parameters, defined at a scale $Q_0 = M_Z$ can be evolved up to higher scales with 1-loop renormalization group equations [16]

$$\begin{aligned}
16\pi^2 \frac{d\lambda_H}{dt} &= \eta^2 + 24\,\lambda_H^2 + 12\,\lambda\,Y_t^2 - 6\,Y_t^4 - 3\,\lambda(3\,g_2^2 + g'^2) + \frac{3}{8}\Big[2\,g_2^4 + (g_2^2 + g'^2)^2\Big]\,, \\
16\pi^2 \frac{d\eta}{dt} &= \eta\Big[12\,\lambda_H + 8\,\lambda_\Phi - 4\,\eta + 6\,Y_t - \frac{3}{2}(3\,g_2^2 + g'^2)\Big]\,, \\
16\pi^2 \frac{d\lambda_\Phi}{dt} &= 2\,\eta^2 + 20\,\lambda_\Phi^2\,,
\end{aligned} \tag{6}$$

where $t \equiv \ln Q/Q_0$, g' and g_2 are respectively the $\mathrm{U}(1)_Y$ and $\mathrm{SU}(2)_L$ gauge couplings and Y_t is the top quark Yukawa coupling.

Figure 1 (right) shows the m_{H1} vs. $m_{H2} - m_{H1}$ plane assuming $\langle\Phi\rangle = \langle H\rangle$ and maximal mixing, where the background colours show the scale of new physics Λ required either by positivity of the potential or triviality (whichever is lower). The plots can be compared to see that a region which is difficult to access at the LHC does in fact coincide with a potentially high effective theory cut-off. Furthermore, this region is compatible with constraints from LEP (using visible, invisible and model-independent Higgs searches [17]) and precision electroweak data (see ref. [11]).

Further investigation into the prospects for finding both potentially invisible Higgs bosons in this minimal model are currently underway, making use of the SHERPA event generator [18].

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