Neutrino mass hierarchy and Majorana CP phases within the Higgs Triplet Model at LHC.

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In the Higgs Triplet Model neutrino masses are generated by the vacuum expectation value of an $SU(2)_L$ scalar triplet. We consider this model and we assume that the doubly charged component of the triplet has a mass in the range of several 100 GeV, such that it is accessible at LHC. Its decay into like-sign leptons provides a clean experimental signature, which allows for a direct test of the neutrino mass matrix. By exploring the branching ratios of this decay into leptons of various flavours, we explore the possibility of determining the type of neutrino mass hierarchy and measuring Majorana CP phases of the lepton mixing matrix.

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1. Introduction

We consider the Higgs Triplet Model, where neutrino masses are generated by the vacuum expectation value v_T of a scalar $SU(2)_L$ triplet $\Delta(H^{\pm\pm}, H^{\pm}, H^0)$ [1]:

$$\mathscr{L}_\Delta = f_{ab} L_a^T C^{-1} i\tau_2 \Delta L_b + \text{h.c.} \quad \rightarrow \quad \frac{1}{2} v_{La}^T C^{-1} M_{ab} v_{Lb} + \text{h.c.} \qquad \text{with} \qquad M_{ab} = \sqrt{2} v_T f_{ab}. \quad (1.1)$$

If the Higgs triplet is light enough, its doubly charged scalar component H^{++} could be produced at LHC via a Drell-Yan process [2]. The production cross section depends only on the mass of the scalar. For an integrated luminosity of 300 fb^{-1}, about 10^3 scalar pairs would be produced for a mass around 300 GeV. These scalars can decay into same-sign leptons $H^{++} \rightarrow l_a^+ l_b^+$. This decay provides a very spectacular signature, free from any Standard Model background. Moreover, the decay rate is proportional to the modulus of the corresponding element of the neutrino mass matrix:

$$\text{BR}_{ab} \equiv \text{BR}(H^{++} \rightarrow \ell_a^+ \ell_b^+) \equiv \frac{\Gamma(H^{++} \rightarrow \ell_a^+ \ell_b^+)}{\sum_{cd} \Gamma(H^{++} \rightarrow \ell_c^+ \ell_d^+)} = \frac{2}{(1+\delta_{ab})} \frac{|M_{ab}|^2}{\sum_{cd} |M_{cd}|^2}. \quad (1.2)$$

This opens a very interesting link between neutrino physics and collider physics: seeing this kind of events at LHC would be a direct test of the neutrino mass matrix.

In addition to the lepton channel the doubly charged Higgs can in principle decay also into charged Higgses and/or the W: $H^{++} \rightarrow H^+ H^+$, $H^{++} \rightarrow H^+ W^+$, $H^{++} \rightarrow W^+ W^+$. The first two decay modes depend on the mass splitting within the triplet, and we assume that they are kinematically suppressed. The branching ratio between $\ell^+ \ell^+$ and $W^+ W^+$ decays is controlled by the relative magnitude of the triplet Yukawas f_{ab} and the vacuum expectation value v_T.

In this model contributions to lepton flavour violating processes, $g_\mu - 2$, and to the electron electric dipole moment are expected. The strong experimental bounds on this type of processes put some constraints on the Yukawa couplings, the most stringent one coming from $\mu \rightarrow eee$.

We can obtain an estimate for the interesting range of the yukawa couplings: $4 \times 10^{-7} \lesssim f_{ab} \lesssim 5 \times 10^{-4}$, for $M_{H^{++}} = 100$ GeV. The upper bound comes from the decay $\mu \rightarrow eee$ and the lower one from the requirement that $\Gamma(H^{++} \rightarrow W^+ W^+) \lesssim \Gamma(H^{++} \rightarrow \ell_a^+ \ell_b^+)$, together with the constraint from cosmology on neutrino masses, $v_T f_{ab} \lesssim 10^{-10}$ GeV.

Let us note that in the minimal version of this model the baryon asymmetry of the universe cannot be generated by leptogenesis, and one has to invoke some other mechanism beyond the model. However, in this case lepton number violating decays of the doubly charged scalar of the model might destroy the pre-generated baryon asymmetry.[1] To avoid this to happen one has to require that these decays never come into equilibrium. This translates into a much stronger upper bound on the yukawas than the one given above: $2 \times 10^{-5} \lesssim f_{ab} \lesssim 5 \times 10^{-4}$, for $M_{H^{++}} = 100$ GeV.

2. Numerical Analysis and Results

In our analysis [3] we assume that a sufficient number of scalar pairs decaying into same sign leptons are observed. The decay $H^{++} \rightarrow l_a^+ l_b^+$ can occur in every flavour combination, including

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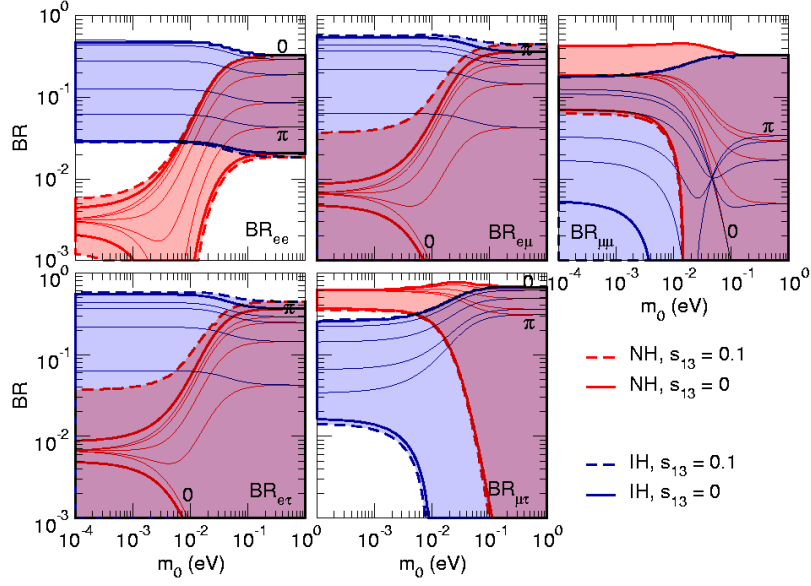[1] We thank Hitoshi Murayama for pointing out this problem to us.

Figure 1: Branching ratios BR($H \to \ell_a \ell_b$) as function of the lightest neutrino mass m_0 for NH (light-red) and IH (dark-blue). The thick solid lines are for $s_{13} = 0$, and the thick dashed lines for $s_{13} = 0.1$, where the dependence on phases as well as the uncertainty of solar and atmospheric oscillation parameters at 2σ are included. The thin solid lines show the branchings for oscillation parameters fixed at their best fit points and $s_{13} = 0$, $\alpha_{32} = \pi$, and $\alpha_{12} = 0, \pi/4, \pi/2, 3\pi/4, \pi$.

LFV ones. Events with τ are more difficult to reconstruct, so in our analysis we only consider events where at most one of the four leptons is a τ.

Our observables depend only on the neutrino mass matrix, Eq.(1.2). We parametrise it in terms of the PMNS matrix: $M = U \text{diag}(m_1, m_2, m_3) U^T$. We use as input parameters the two squared mass differences, and the mixing angles θ_{12} and θ_{23}. The parameters of our analysis are: the lightest neutrino mass m_0; $s_{13} = \sin \theta_{13}$; the Dirac phase δ; and the two physical Majorana phases α_{12} and α_{32}, defined as $\alpha_{ij} = \alpha_i - \alpha_j$ with α_i the phase associated to the i mass eigenstate.

In Fig. (1) we show the branching ratio into each channel as a function of the lightest neutrino mass. Colour red corresponds to normal hierarchy (NH) and blue to inverted hierarchy (IH). The solid line is for $s_{13} = 0$ and the dashed line for $s_{13} = 0.1$. For fixed m_0, the allowed interval arises due to the dependence on the phases and the uncertainty in neutrino parameters. The wide allowed region for IH and quasi degenerate (QD) neutrinos (in the limit of large values for m_0) suggest a strong dependence on the phases.

The allowed regions for NH and IH in the *ee* channel are very well separated because in the case of NH this channel is suppressed. The reason is that, contrary to the case of IH and QD, for NH in the limit of vanishing m_0, BR_{ee} is suppressed by $r = \Delta m_{21}^2 / |\Delta m_{31}^2|$ or by powers of s_{13}:

$$\text{BR}_{ee}^{\text{NH},m_0=0} \approx s_{12}^4 r + 2 s_{12}^2 s_{13}^2 \sqrt{r} \cos(\alpha_{32} - 2\delta), \tag{2.1}$$

$$\text{BR}_{ee}^{\text{IH},m_0=0} = \frac{1}{2} \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\alpha_{12}}{2} \right) = \frac{3}{2} \text{BR}_{ee}^{\text{QD}}, \tag{2.2}$$

Therefore, seeing a suppression in the channel to two electrons would be a clear signature of a hierarchical spectrum with normal order.

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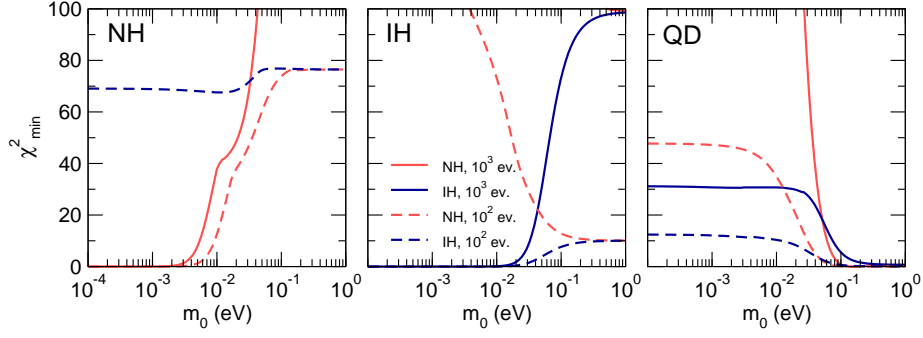**Figure 2:** $\chi^2_{\min}$ vs m_0 assuming a true NH (left), IH (middle), and QD spectrum (right). The χ^2 is shown for 10^2 (dashed) and 10^3 (solid) events. In the fit we assume either NH (light-red) or IH (dark-blue). We adopt the following true parameter values. Left: $m_0 = 0$, NH, $\alpha_{32} = \pi$; middle: $m_0 = 0$, IH, $\alpha_{12} = 0$; right: $m_0 = 0.15$ eV, $\alpha_{12} = 0.1\pi$, $\alpha_{32} = 1.6\pi$; and always $s_{13} = 0$.
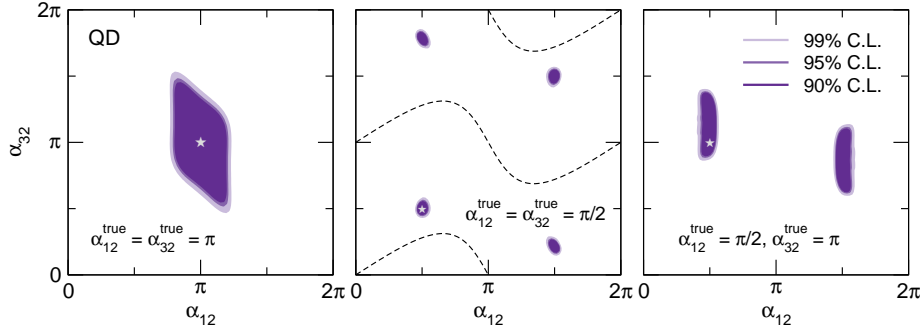

Figure 3: Determination of the Majorana phases for QD spectrum ($m_0 = 0.15$ eV) from 10^3 events. We assume $s_{13}^{\text{true}} = 0$ and three example points for the true values of the Majorana phases. The dashed lines in the middle panel correspond to the true values of the phases for which the degenerate solution appears at a CP conserving value of α_{32}.

2.1 Determination of the neutrino mass spectrum

In Fig.(2) we try to quantify the ability of the data to determine the neutrino mass spectrum by performing a χ^2 analysis. We assume some true values for the parameters, which are specified in the caption. Then these data are fitted with both possibilities of NH (red) and IH (blue), and a given value of m_0. We show the results for 10^3 and 10^2 events. A true NH (left panel) can be identified with high significance, due to the distinctive signature provided by BR_{ee}. A true IH or QD spectrum (middle and right panels) are more difficult to identify, but good sensitivity is obtained depending on the number of events. We have found that it is possible to decide whether the lightest neutrino mass is smaller or larger than roughly 0.01 eV, which marks the transition between hierarchical and quasi-degenerate spectra. If it is smaller the mass ordering (normal vs inverted) can be identified.

2.2 Determination of Majorana phases

We have also explored the possibility of measuring CP phases within this neutrino mass model at LHC. There is no explicit CP violation in the decay of the doubly charged scalar, but it depends in a CP conserving way on the Majorana phases. In Fig.(3) we assume a QD spectrum and some
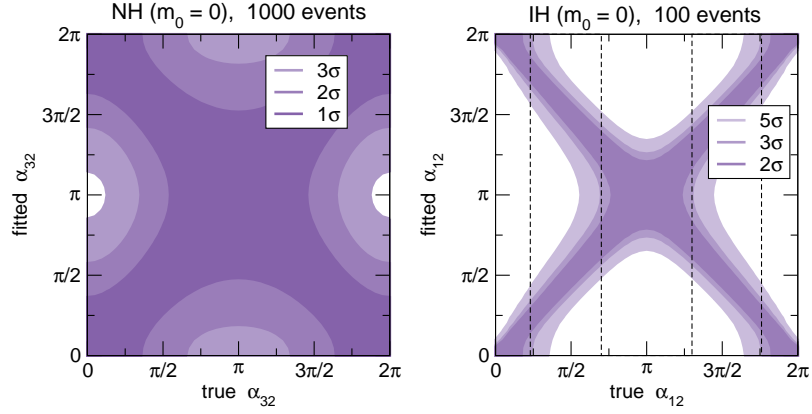
Figure 4: Determination of the Majorana phase for vanishing lightest neutrino mass. We assume $s_{13}^{\text{true}} = 0$. Left: 1, 2, 3σ ranges for α_{32} as a function of its true value for NH assuming 10^3 events. Right: 2, 3, 5σ ranges for α_{12} as a function of its true value for IH assuming 10^2 events. The dashed vertical lines indicate the region where CP violating values of α_{12} can be established at 3σ.

true values for the Majorana phases. We find that the accuracy to reconstruct the value of the true phases depends on the true values that we assume. As can be seen from the plots, some degenerate solutions appear. There are two kinds of degeneracies. First, as a consequence of CP invariance, the branching ratios are invariant under the simultaneous change of $\alpha_{ij} \to 2\pi - \alpha_{ij}, \delta \to 2\pi - \delta$. The second degeneracy appears due to the fact that the phases α_{12} and α_{32} always appear in the same particular combination in the limit $s_{13} = 0$.

In Fig.(4) we show the allowed regions for the physical phase as a function of the true value for the phase. In the case of NH the sensitivity to α_{32} is very bad, even if we consider 10^3 events. In the case of IH, the determination is very efficient already with 10^2 events, apart from the degeneracy $\alpha_{12} \to 2\pi - \alpha_{12}$.

3. Conclusions

A Higgs triplet in the TeV scale offers an appealing mechanism to provide mass to neutrinos which can be directly tested at the LHC. Such a scenario opens the possibility to measure the Majorana phases of the lepton mixing matrix, which in general is a very difficult task.

The observation of a doubly charged scalar at LHC would be a great discovery of physics beyond the Standard Model, but it does not confirm the Higgs triplet mechanism for neutrino masses, since doubly charged particles decaying into leptons are predicted in many models. In case such a particle is indeed found at LHC, various consistency checks will have to be performed.

References

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[2] A. Hektor, M. Kadastik, M. Muntel, M. Raidal and L. Rebane, Nucl. Phys. B **787**, 198 (2007). T. Han, B. Mukhopadhyaya, Z. Si and K. Wang, Phys. Rev. D **76**, 075013 (2007).

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