Exclusive Higgs Production in a Triplet Scenario

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In this talk, we discuss searching for the neutral Higgs boson of a triplet model in central exclusive production at the Large Hadron Collider. In a detailed Monte Carlo analysis, it is found that for appropriate values of the model parameters, an excellent Higgs mass measurement is possible, and that distinguishing the triplet model Higgs boson from the Higgs boson of the Standard Model is possible.

1 Introduction

It is well known that in the Standard Model (SM), there is one Higgs doublet responsible for the electroweak symmetry breaking, and consequently there is one physical Higgs boson in the model. The one physical Higgs boson can be considered as the minimal choice, since in addition for the mechanism providing masses for all the particles in the SM, it also takes care of the unitarity of the SM.

However, in most extensions of the SM more Higgs representations occur. In supersymmetric models one has necessarily at least two doublets. Singlets occur in many extensions of the SM. One motivation for including a singlet in a supersymmetric model is to include in a natural way the dimensionful coupling of the minimal supersymmetric standard model, the so-called μ-parameter. In left-right symmetric models, triplets are added to generate a small mass for the neutrinos. Although the new scalars do not always take part in the electroweak symmetry breaking, they affect the properties of the Higgs boson through mixing.

Models with an extended Higgs sector typically contain charged scalars. A large number of studies have previously investigated the possibility of studying the doubly or singly charged components of higher representations. However, the charged scalars may be considerably heavier than the light neutral bosons. Therefore, it would be instructive to study the properties of the light neutral Higgs particles in order to reveal the manifestation of new representations [1].

Higgs triplets are an especially attractive possibility [2]. A tiny neutrino mass may indicate that the mass is being generated by the seesaw mechanism containing the coupling of neutrinos to the triplet. In addition, composite Higgs models contain several multiplets, including the triplet ones. Triplets also occur in the little Higgs models.

Determining that a new detected state is indeed a Higgs boson and distinguishing it from the Higgs boson of the SM will be far from trivial. This task will require a comprehensive programme of precision Higgs measurements. In particular, it will be of utmost importance to determine the spin and CP properties of a new state and to measure precisely its mass, width and couplings.

Based on [3], we discuss here searching for the lightest neutral Higgs boson H_1^0 of a model containing triplets, and at the same time identifying the representation of the found H_1^0. For this it was found in [3] that the central exclusive production (CEP) mechanism (see, for example, [4]) is very beneficial, if forward proton detectors are installed at ATLAS and/or CMS (see [5]).

2 Models with General Higgs Representations

We start with the Standard Model gauge group $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ for the electroweak sector. The masses of the gauge bosons are then obtained from the kinetic part of Lagrangian,

$$L_{kin} = \sum_k (D^\mu \phi_k)^* (D_\mu \phi_k) + \frac{1}{2} \sum_i (D^\mu \xi_i)^T (D_\mu \xi_i), \tag{1}$$

where ϕ_k are complex representations and ξ_i are real ones. The covariant derivative is written as $D_\mu = \partial_\mu + igW_\mu^a T^a + \frac{Y}{2} g' B_\mu$, where T^a is the generator of SU(2) in the appropriate representation (with $\mathrm{Tr}(T^a T^b) = \frac{1}{2}\delta^{ab}$) and Y is the U(1) hypercharge. Here W^a and B are the SU(2) and U(1) gauge bosons respectively, and the mixing angle θ_W of the Z boson and photon is obtained by diagonalising the neutral sector. The W and Z boson masses are given by

$$m_Z^2 = (g^2 + g'^2) \sum_i T_{3i}^2 v_i^2, \quad m_W^2 = g^2 \sum_i T_{3i}^2 v_i^2, \tag{2}$$

where T_{3i} is the isospin third component and v_i is the VEV of particle i. It is clear from Eq. (2) that the doublet VEV decreases when several representations obtain non-vanishing VEVs. Furthermore, since the left-handed fermions are in doublets, the charged fermions can only get their masses through the Higgs doublet representation, $m_f = y_f v_{doublet}$, and the fermion Yukawa coupling, y_f, must increase to produce the fermion masses. This, for example, leads to an enhancement in the production cross section for Higgs production via gluon fusion, where the dominant contribution is due to the top quark loop. A further enhancement is present in the branching ratio to fermion anti-fermion pairs. The possibility arises, therefore, of observing a very different prediction to that of the Standard Model.

The higher Higgs representations are severely restricted by the electroweak ρ-parameter. The ρ-parameter in the Standard Model is defined by the ratio of the gauge boson masses,

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}, \tag{3}$$

which at tree level is exactly unity in the Standard Model. In a model with several scalar representations, whose neutral component develops a VEV, the ρ-parameter is given at tree level by [6]

$$\rho = \frac{\sum_i r_i \left(T_i(T_i+1) - T_{3i}^2) v_i^2 \right)}{\sum_i 2 T_{3i}^2 v_i^2}. \tag{4}$$

Here T_i is the weak isospin and $r_i = 1/2(1)$ for real (complex) representations. Finally, the ρ-parameter is experimentally constrained to be [7] (quoted errors are at 2σ),

$$\rho - 1 = 0.0002 \begin{array}{l} +0.0024 \\ -0.0009 \end{array}. \tag{5}$$

3 Higgs Bosons in a Triplet Model with $\rho = 1$

In order to fulfill the experimental constraint on the ρ-parameter in Eqn. (5), the triplet VEV has to be small. Using Eqs. (4) and (5), one finds that the upper limit for the triplet VEV is a few GeV. An alternative method to satisfy the experimental constraint at tree-level is to have representations which add up to $\rho = 1$.

We consider the model studied in [8] in which additional representations are chosen in such a way that the tree-level value of ρ remains unity. The ρ-parameter is fixed to one by choosing one complex scalar doublet ($\phi_{Y=1}$) and two triplets, one real ($\xi_{Y=0}$) and one complex ($\chi_{Y=2}$). These can be written as

$$\phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{0} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0*} \end{pmatrix}. \tag{6}$$

The VEVs of the neutral components of the Higgs fields are denoted by $\langle\chi^0\rangle = \langle\xi^0\rangle = b$ and $\langle\phi^0\rangle = a/\sqrt{2}$. For doublet-triplet mixing, the standard notation is employed:

$$c_H \equiv \frac{a}{\sqrt{a^2+8b^2}}, \quad s_H \equiv \frac{\sqrt{8}b}{\sqrt{a^2+8b^2}}, \quad v^2 \equiv a^2 + 8b^2. \tag{7}$$

As we are interested in this model mainly to illustrate the possibility of studying a neutral triplet Higgs sector, the tree-level results of this triplet model are sufficient for demonstrating the phenomenology of the higher representations. In this case, the neutral doublet and triplet do not mix and the neutral mass eigenstates are

$$H_1^0 = \phi^{0r}, \quad H_1^{0'} = \frac{1}{\sqrt{3}}(\sqrt{2}\chi^{0r} + \xi^0), \quad H_3^0 = c_H\chi^{0i} + s_H\phi^{0i}, \quad H_5^0 = \frac{1}{\sqrt{3}}(\sqrt{2}\xi^0 - \chi^{0r}), \tag{8}$$

where $\chi^0 = (\chi^{0r} + i\chi^{0i})/\sqrt{2}$. The mass of H_1^0 can be written as $m^2_{H_1^0} = 8c_H^2\lambda_1 v^2$, where λ_1 is the coupling between four doublets in the potential. Here we will assume H_1^0 is the lightest scalar, which can be the case if either c_H or λ_1 is small.

The couplings of this lightest neutral scalar to the fermions and the gauge bosons are

$$H_1^0 q\bar{q} : -\frac{g m_q}{2 m_W c_H}, \quad H_1^0 W^+W^- : g m_W c_H, \quad H_1^0 ZZ : \frac{g}{\cos^2\theta_W} m_W c_H. \tag{9}$$

It is clear that, at tree-level, the coupling of the H_1^0 to fermions is always enhanced by the factor of $1/c_H$. Importantly, the gauge boson couplings to H_1^0 are suppressed by a factor c_H with respect to the SM and the role of vector boson fusion mechanism for H_1^0 production is reduced if c_H is small.

The mass limits for H_1^0 can be deduced from the LEP results. If we assume that the number of b-quark pairs gives the Higgs boson mass limit, it must be heavier than 73 GeV (40 GeV) for $c_H = 0.5$ ($c_H = 0.2$). Unitarity further constrains most masses, requiring them to be less than of the order of 1 TeV. The Yukawa couplings are constrained by perturbativity, which limits the H_1^0 coupling to top,

$$\frac{g m_{top}}{2 m_W c_H} < \sqrt{4\pi}. \tag{10}$$

From this it follows that $c_H > 0.2$, which is the most stringent tree-level limit for c_H.

When calculating the branching ratios, it is necessary to consider also the loop induced decays of the Higgs bosons to gluons and photons. Taking these into account, the branching ratios of H_1^0 are presented in Fig. 1 for $m_{H_1^0} = 120$ GeV and 150 GeV.

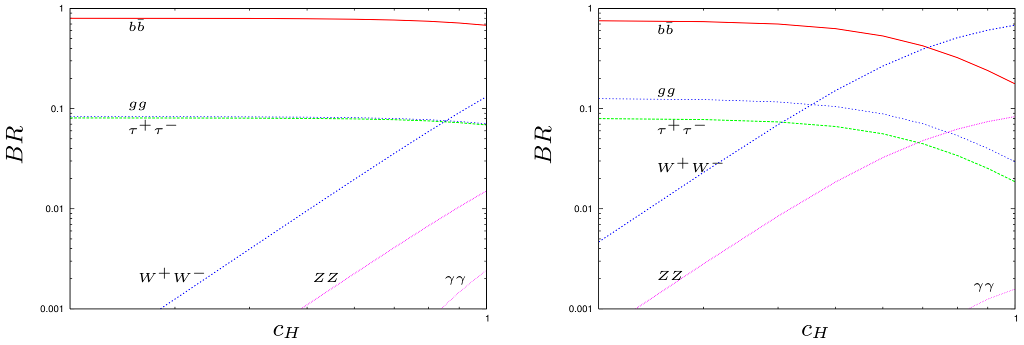

Figure 1: Branching ratios of H_1^0 to the Standard Model particles for $m_H = 120$ GeV (left) and $m_H = 150$ GeV (right).

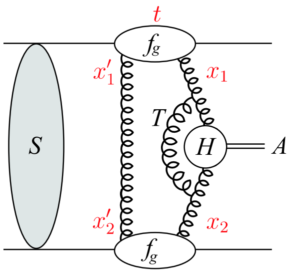

Figure 2: A symbolic diagram for the central exclusive production of a Higgs boson H.

4 Central Exclusive Diffractive Production of the Triplet Higgs Boson

The central exclusive production (CEP) of a Higgs boson is defined as $pp \to p \oplus H \oplus p$, where the $\oplus$ denote the presence of large rapidity gaps between the outgoing protons and the decay products of the central system. Schematically the process is shown in Fig. (2). It has been suggested in recent years that CEP offers a unique complimentary measurement to the conventional Higgs search channels. Firstly, if the outgoing protons scatter through small angles then, to a very good approximation, the primary active di-gluon system obeys a $J_z = 0$, CP-even selection rule [9]. The observation of the Higgs boson in the CEP channel therefore determines the Higgs quantum numbers to be $J^{PC} = 0^{++}$. Secondly, because the process is exclusive, all of the energy/momentum lost by the protons during the interaction goes into the production of the central system. Measuring the outgoing proton allows the central mass to be measured to just a few GeV, regardless of the decay products of the central system. A mass measurement of this type will require new forward proton detectors to be installed at ATLAS and/or CMS.

For a Standard Model Higgs boson, central exclusive diffraction could allow the main decay channels ($b\bar{b}$, WW and $\tau\tau$) to be observed in the same production channel, which provides the opportunity to study the Higgs coupling to b-quarks. This may be very difficult to access in other

$\sigma_{H\to b\bar{b}}$ (fb)	$m_H = 120$ GeV	$m_H = 150$ GeV
$c_H = 0.2$	113.5	55.2
$c_H = 0.5$	18.0	7.4
$c_H = 0.8$	6.6	1.5

Table 1: Generator level cross sections, $\sigma_{H\to b\bar{b}}$, for central exclusive Higgs boson production for $m_H = 120, 150$ GeV and $c_H = 0.2, 0.5, 0.8$.

search channels at the LHC, despite the fact that $H \to b\bar{b}$ is by far the dominant decay mode for a light SM Higgs boson. In [3], we propose that CEP is beneficial if higher representations of the Higgs sector are realised, in particular, in searches for the Higgs triplets discussed in Section 3. The CEP of the MSSM Higgs bosons is discussed, for instance, in Ref. [10]. The theoretical formalism [11] for central exclusive production contains distinct parts, as illustrated in Fig. 2.

5 Simulation of Higgs Production in the Triplet Model

We restrict our discussion and analysis to the ATLAS interaction point (IP), and note that a similar result would be obtained at CMS. There are three important aspects of forward proton tagging at the LHC that need to be considered for the purposes of this analysis; the acceptance and resolution of the proposed forward proton detectors and the ability of the detectors to measure the time-of-flight of each proton from the interaction point.

The central exclusive signal and background events are simulated with full parton showering and hadronisation effects using the ExHuME v1.3.4 event generator [12]. ExHuME contains a direct implementation of the KMR calculation [11, 4] of central exclusive diffraction given in Sec. 4. The CTEQ6M [13] parton distribution functions are used to calculate the generalised gluon distributions, f_g. The generator level cross sections for central exclusive $H \to b\bar{b}$ production in the triplet model are presented in Table 1 for $m_H = 120, 150$ GeV and $c_H = 0.2, 0.5, 0.8$.

The backgrounds to $H \to b\bar{b}$ can be broken down into three broad categories; central exclusive, double pomeron exchange and overlap. See the discussion on backgrounds in [3]. To enhance the signal, we follow the experimental method used in a previous study of $H \to b\bar{b}$ in the SM and the MSSM [14], which imposes a number of exclusivity cuts. These include a cut on di-jet mass fraction, comparison of rapidity of the system found from different input, back-to-back structure of di-jets, and number of charged tracks in signal and background.

A major experimental challenge for central exclusive jet analyses is developing a trigger strategy to retain enough events. As discussed in [3], several different triggering strategies are needed.

We estimate the significance of observing a neutral Higgs boson in the triplet model for the mentioned parameter choices. As the overlap background is luminosity dependent we must specify how the data was collected. For example, we examine the significance for an integrated luminosity of 60 fb^{-1}, which corresponds to between three and four years of data acquisition given a peak luminosity of 2×10^{33} cm^{-2} s^{-1}. We also present in [3] results for 300 fb^{-1} of data, which corresponds to between three and four years of data acquisition given a peak luminosity of 10^{34} cm^{-2} s^{-1}.

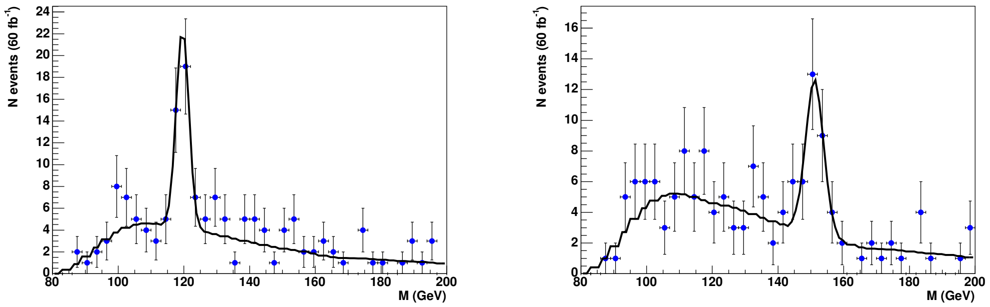

Figure 3: Expected mass distributions given 60 fb^{-1} of data, collected at $2{\times}10^{33}$ cm^{-2} s^{-1} using a JR25+MU6 trigger, for the following parameter choices: (left) $m_H = 120$ GeV and $c_H = 0.5$, significance is 4.5σ. (right) $m_H = 150$ GeV and $c_H = 0.5$, significance is 3.9σ.

6 Conclusions

Searches for the manifestation of the extended Higgs sector at the LHC may allow new insight in the nature of electroweak symmetry breaking. The central exclusive production mechanism would provide a very powerful tool to complement the standard strategies at the LHC for studying Higgs particles. Here we focus on the production of the neutral Higgs boson of the triplet model in the forward proton mode. We assume a model with the tree-level value of the electroweak ρ-parameter consistent with experiment, $\rho = 1$. Although this model is used as a benchmark model for the triplets, our results are more general. An extra contribution from other representations enhances the doublet Yukawa couplings resulting in a different experimental signature to that of the SM. We show that a factor of two enhancement of the fermion couplings due to the higher representations implies a significant difference to the doublet case. Let us emphasise that in the case of the current model, all the fermion couplings to the Higgs boson, which is responsible for the fermion masses, increase. This is in contrast with, for instance, the MSSM, where couplings of up-type and down-type fermions change from the Standard Model differently, due to the fact that there are only doublets in the model. It is a common feature of higher Higgs representations that the doublet couplings are enhanced, which thus indicates that higher representations are involved.

We present a detailed Monte Carlo analysis of the central exclusive production of a triplet model Higgs boson for a number of parameter choices. For $c_H \leq 0.5$, we have shown that a light H_1^0 Higgs boson (of mass 120-150 GeV) can be observed with a 4σ (or better) significance if a fixed rate trigger is used. The expected error in the Higgs mass measurement using forward proton detectors is small. Regardless of the parameter choice, the mass measurement can always be made to better than 2 GeV if a fixed rate single jet trigger is used to retain events in which both protons are tagged at 420 m from the IP.

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