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The study of $W' \rightarrow hH^{\pm}$ decay in $G(221)$ models

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Abstract. The existence of a heavy gauge boson W' is predicted by G(221) models, with $SU(2)_1 \times SU(2)_2 \times U(1)_X$ extended gauge groups. The doublet and bi-doublet Higgs sector of $G(221)$ models is assumed, and the breaking of the symmetry is produced in two stages. We study $W' \rightarrow hH^{\pm}$ production in p-p collisions at $\sqrt{s} = 8$ TeV. This analysis is dedicated to $W' \rightarrow hH^{\pm}$ decay channel, where h is neutral and $H^{\pm}$ is charged, and we calculate the partial width for $W' \rightarrow hH^{\pm}$ within $G(221)$ model. We further consider the final state consisting of two same-sign leptons, MET and four jets, from which two are b-jets, arising from the decays of $H^{\pm}$ and h and compare for this channel the predictions of $G(221)$ models with those of SUSY published by ATLAS Collaboration

1 Introduction

The recent discovery of a new boson with Higgs-like properties [1] enhanced the extended Higgs sector model building and searches. Several theories were considered, such as $G(221)$ models [2–21]. These models add one more $SU(2)$ gauge group to the Standard Model (SM) $SU(2)_L \times U(1)_Y$ gauge structure. An important feature is the emergence of new heavy Z' and W' gauge bosons, predicted also by other gauge extensions [22], such as the "sequential standard model"(SSM), where the couplings of the W' to fermions are assumed to be identical to those of the SM W. Another feature is the existence of heavy charged Higgs $H^{\pm}$ bosons. In $G(221)$ models the symmetry under $SU(2)_1 \times SU(2)_2 \times U(1)_X$ is spontaneously broken twice, to get masses for the W' and Z' bosons after the first symmetry breaking, and for W and Z bosons after the second one. As a consequence of the two symmetry breaking stages, an interaction of the form $W'hH$ can appear. h stands for a light boson wich can be identified with SM Higgs boson, due to the flexibility in the Yukawa sector of G(221) models.The coupling of W' with heavy Higgs bosons it is also possible, and has been calculated in a recent paper [23].

In the present work we investigate the decay of W' into a pair $hH^{\pm}$ in the general frame of $G(221)$ models. The interest in this exotic channel is that among its possible final states there are some considered to be specific to ATLAS SUSY searches [24–28]. In particular, one such state, consisting from two same-sign leptons, four jets and missing transverse energy (MET) has been investigated by ATLAS Collaboration in a search for supersymmetry (SUSY) in pp collisions . Here we study the production of this state by an alternative channel, specific to $G(221)$ models.

In these proceeding we present in section 2 the Higgs sector of the $G(221)$ models. In section 3 we briefly discuss the terms in the Lagrangian of interest for the present study and derive the form of the $W'hH^{\pm}$ interaction. In section 4 we calculate the width of the $W' \rightarrow hH^{\pm}$ rare decay, using recent phenomenological constraints on the $G(221)$ models [20]. We calculate also the cross section for the production of a $hH^{\pm}$ pair in pp collisions at 8 TeV via this channel. Section 5 is devoted to the study of the final state with 2 same-sign leptons, 4 jets and MET. We present then our results on the total cross-section and compare them with ATLAS results. The paper ends with our conclusions concerning the possibility of detecting he rare $W' \to hH^{\pm}$ decay at the present collider energies.

For more details in each section, please refer to our recent paper [29]. Where applying, we specify this explicitly.

2 Higgs sector of $G(221)$ models

We consider, for the first symmetry breaking stage, a simple doublet

$$\Phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix}, \tag{1}$$

which transforms as $(1, 2, \frac{1}{2})$ under the group action and gives masses to the heavy gauge bosons W' and Z'. For the second symmetry breaking stage we adopt a bi-doublet transforming as $(2, \bar{2}, 0)$ of the form:

$$\mathcal{H} = \begin{pmatrix} h_1^0 & h_1^+ \\ h_2^- & h_2^0 \end{pmatrix}. \tag{2}$$

The doublet and bi-doublet have nonzero vacuum expectation values (vevs):

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ u \end{pmatrix}, \tag{3}$$

and

$$\langle\mathcal{H}\rangle = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix}, \tag{4}$$

where u,k and k' are real values .

The symmetry breaking scale of the first stage is much higher than the electroweak one, therefore the parameter [20]

$$x \equiv \frac{u^2}{v^2} \tag{5}$$

is expected to be very large.

After the symmetry breaking stages, we are left with 12 real scalars. 6 of them are physical degrees of freedom: two neutral Higgs bosons, one beeing later identified to SM Higgs, one charged Higgs boson, and 2 pseudoscalar bosons. The other 6 zero-mass modes go into the longitudinal degrees of freedom for the heavy and light gauge bosons, giving them mass.

3 Lagrangian of $G(221)$ models and $W'hH^{\pm}$ interaction

The kinetic and potential terms of the Lagrangian:

$$\mathcal{L} \sim \left[(\mathcal{D}_\mu\mathcal{H})^\dagger Tr(\mathcal{D}^\mu\mathcal{H})\right] - V(\mathcal{H}, \widetilde{\mathcal{H}}, \Phi, \widetilde{\Phi}), \tag{6}$$

where

$$\mathcal{D}_\mu\mathcal{H} = \partial_\mu\mathcal{H} - i\,\frac{g_1}{2}\sum_{j=1}^{3}\tau_j W_j \mathcal{H} + i\,\frac{g_2}{2}\,\mathcal{H}^\dagger \sum_{j=1}^{3}\tau_j W'_j \tag{7}$$

is the covariant derivative that fixes the local gauge interaction, τ_j are the Pauli matrices, and g_1, g_2 are the coupling constants for the first and the second symmetry groups.

A general Higgs potential can have the form [9, 12]

$$\begin{aligned} V(\mathcal{H},\widetilde{\mathcal{H}},\Phi,\widetilde{\Phi}) = & - \mu_1^2 \mathrm{Tr}\mathcal{H}^\dagger\mathcal{H} + \lambda_1(\mathrm{Tr}\mathcal{H}^\dagger\mathcal{H})^2 + \lambda_2 \mathrm{Tr}\mathcal{H}^\dagger\mathcal{H}\mathcal{H}^\dagger\mathcal{H} \\ & + \tfrac{1}{2}\lambda_3(\mathrm{Tr}\mathcal{H}^\dagger\widetilde{\mathcal{H}} + \mathrm{Tr}\widetilde{\mathcal{H}}^\dagger\mathcal{H})^2 + \tfrac{1}{2}\lambda_4(\mathrm{Tr}\mathcal{H}^\dagger\widetilde{\mathcal{H}} - \mathrm{Tr}\widetilde{\mathcal{H}}^\dagger\mathcal{H})^2 \\ & + \lambda_5 \mathrm{Tr}\mathcal{H}^\dagger\mathcal{H}\widetilde{\mathcal{H}}^\dagger\widetilde{\mathcal{H}} + \tfrac{1}{2}\lambda_6\left(\mathrm{Tr}\mathcal{H}^\dagger\widetilde{\mathcal{H}}\mathcal{H}^\dagger\widetilde{\mathcal{H}} + \mathrm{Tr}\widetilde{\mathcal{H}}^\dagger\mathcal{H}\widetilde{\mathcal{H}}^\dagger\mathcal{H}\right) \\ & - \mu_2^2\Phi^\dagger\Phi + \rho_1(\Phi^\dagger\Phi)^2 \\ & + \alpha_1 \mathrm{Tr}\mathcal{H}^\dagger\mathcal{H}\Phi^\dagger\Phi + \alpha_2\Phi^\dagger\mathcal{H}^\dagger\mathcal{H}\Phi + \alpha_2'\Phi^\dagger\widetilde{\mathcal{H}}^\dagger\widetilde{\mathcal{H}}\Phi, \end{aligned} \tag{8}$$

which it is written in terms of the fields $\mathcal{H}$, $\widetilde{\mathcal{H}}$, Φ and $\widetilde{\Phi}$, where $\widetilde{\mathcal{H}} = \tau_2\mathcal{H}^*\tau_2$ and $\widetilde{\Phi} = i\tau_2\Phi^*$ ($\mathcal{H}^*$ and Φ^* denote the complex conjugates). The $\mu_1, \mu_2, \lambda_1, \ldots \lambda_6, \alpha_1, \alpha_2$ and α_2' are real parameters.

By minimizing the potential :

$$\frac{\partial V}{\partial u} = \frac{\partial V}{\partial k} = \frac{\partial V}{\partial k'} = 0 \tag{9}$$

we obtain a form of the charged sector of the Higgs mass matrix, which can be written as :

$$M_+^2 = \begin{pmatrix} \frac{\Delta\alpha k^2 u^2}{2\Delta k^2} & \frac{\Delta\alpha k u}{\sqrt{2}} & \frac{\Delta\alpha k'^2 u^2}{2\Delta k^2} \\ \frac{\Delta\alpha k u}{\sqrt{2}} & \Delta\alpha\Delta k^2 & \frac{\Delta\alpha k' u}{\sqrt{2}} \\ \frac{\Delta\alpha k'^2 u^2}{2\Delta k^2} & \frac{\Delta\alpha k' u}{\sqrt{2}} & \frac{\Delta\alpha k'^2 u^2}{2\Delta k^2} \end{pmatrix}, \tag{10}$$

After diagonalization of this mass matrix in the limit of $k' \to 0$, $k \to \frac{v}{\sqrt{2}}$ [11, 12] the physical charged Higgs boson can be written:

$$H^+ = \frac{1}{\sqrt{u^2+v^2}}(u h_1^+ + v\phi^+), \qquad m_{H^+}^2 = \frac{1}{2}\Delta\alpha(u^2+v^2). \tag{11}$$

where $\Delta\alpha = \alpha_2 - \alpha_2'$ and $\Delta k^2 = k^2 - k'^2$. If $u \gg v$, then $H^+ \approx h_1^+$. In the neutral sector one can define

$$h_{1,r}^0 = \frac{h}{\sqrt{2}}, \qquad m_h^2 = \frac{(\lambda_1+\lambda_2)v^2}{2}, \tag{12}$$

where h is the SM-like Higgs boson. The $H^\pm$ mass is different from the h SM mass, and little can be said about the mass of the charged Higgs, except that it is a heavy boson.

From the above kinetic part (7), after some tedious calculations, we obtain the $W'hH^\pm$ interaction:

$$\mathcal{L} \sim -\frac{1}{2}\, i g_2 W_\mu'^-(h\,\partial^\mu H^+ - H^+\,\partial^\mu h) + h.c. \tag{13}$$

As for the Yukawa and gauge interactions, very little is said about in the global analysis [20] of $G(221)$ models. Nevertheless we can derive useful observations by analyzing left-right symmetric models, where the coupling of the charged Higgs boson with a $q\bar{q}'$ pair is larger than that predicted by 2HDM [18, 19].

4 Decay width computation

Using Eq. (13) we have the tree level amplitude of the process

$$\mathcal{M} = \frac{i g_2}{2}\epsilon_\mu'(p_1 - p_2)^\mu, \tag{14}$$

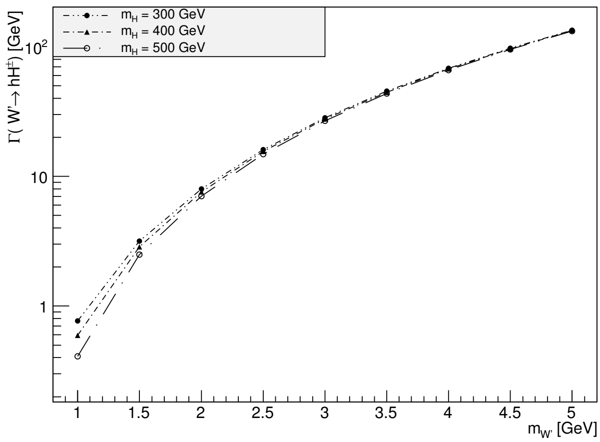

Figure 1. Partial width as a function of W' mass.

where ϵ' is the W' polarization 4-vector and p_1, p_2 are the momenta of the two final Higgs bosons. From this, it can be shown (see [29]) that the decay rate is written as:

$$\Gamma(W'^{\pm} \to hH^{\pm}) = \frac{G_F}{24\sqrt{2}\pi(x+1)} \frac{\lambda^{3/2}(m_{W'}^2, m_{H^+}^2, m_h^2)}{m_{W'}^3}, \tag{15}$$

in terms of the known kinematical function λ.

The partial width can be calculated for various masses using the available phenomenological constraints on the parameter x. In our estimates, we adopt the lower bound $x \geq 100$ derived from recent phenomenological studies of $G(221)$ models [20]. From Fig. 1 it can be seen that for the most favourable case, $x = 100$ and $m_{H^{\pm}} = 300\,\mathrm{GeV}$, the branching ratio increases from 2% for $m_{W'} = 1000\,\mathrm{GeV}$ to 43% for $m_{W'} = 5000\,\mathrm{GeV}$.

5 Final state production cross sections in $G(221)$ models

In this section we discuss several final states that can arise in pp collisions at LHC from the decay $W'hH^{\pm}$ and compare the predictions of the $G(221)$ models with those of model independent searched.

The simulation and the analysis were based on a framework [30] that chains different software packages together: Monte Carlo generators, programs for the simulation of the events through the detector and program for data analysis.

The Monte Carlo generator chosen for simulating events in this study is PYTHIA 6.4 [31], a leading order (LO) generator. The data samples are used to model the final state which assumes 2 leptons, 4 jets and MET. The topology is generated using the parton distribution function (PDF) set to CTEQ 5L, the top mass fixed at 172.5 GeV, and the SM Higgs mass m_h = 126 GeV. The c.m. energy of the pp collisions is set at 8 TeV.

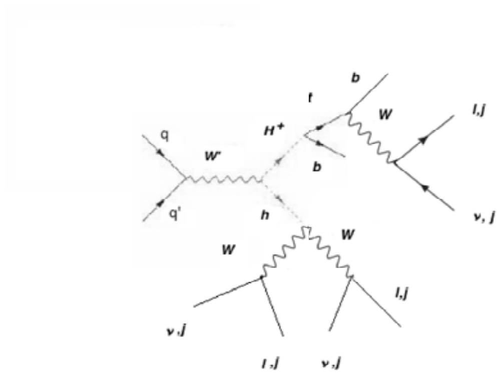

Figure 2. Production of the final state with 2 same-sign leptons, 4 jets and E_T^{miss} in pp collisions via the $W' \to hH^{\pm}$ decay.

In PYTHIA 6.4, the W' heavy gauge boson is produced according to the extended gauge model [32], where the couplings to the fermions are the same as the standard ones, and the coupling of W' to WZ is strongly supressed. As we mentioned above, the $G(221)$ models have enough flexibility to allow for such values. The coupling of W' to $hH^{\pm}$ is set according to the calculation of Sec. 4 based on $G(221)$ models. The decay width (15) and the branching ratio are functions of the masses and the large parameter x defined in (5).

The default option in PYTHIA 6.4 for the $H^{\pm} \to t\bar{b}$ decay is the 2HDM coupling with $\tan\beta = 5$. One can check that this choice underestimates by a large factor the coupling expected in $G(221)$ left-right symmetric models [18, 19]. In order to use a coupling closer to the expectations of such models, we performed the simulations in PYTHIA using 2HDM with $\tan\beta = 1$. For the other decays involved in the process shown in Fig. 2, we assumed SM couplings.

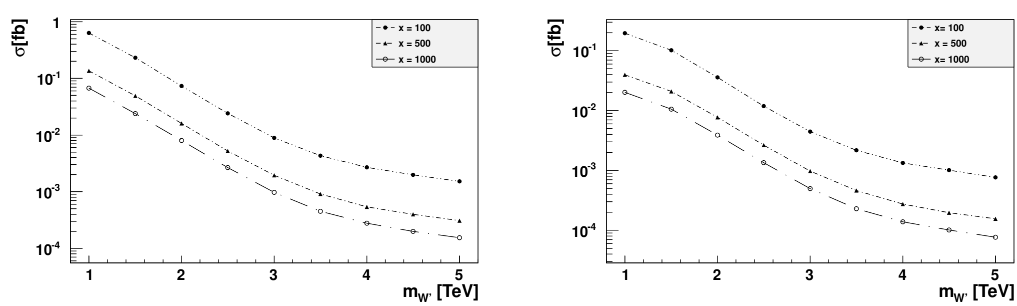

Figure 3. Cross section σ for the production of 2 electrons, 4 jets and E_T^{miss} in pp collisions via the channel $W' \to hH^{\pm}$, as a function of $m_{W'}$, for $m_{H^{\pm}} = 300$ GeV (left) and $m_{H^{\pm}} = 500$ GeV (right), for $x = 100$, 500 and 1000.

We used Delphes [33] framework to perform realistic fast simulations of the ATLAS detector and to acquire reconstructed physics objects (jets,leptons,pthotons and MET). The analysis was performed with ROOT [34]. A first result can be seen in Fig. 3: the cross-section of 2 leptons, 4 jets and MET in the final state, as a function of W' mass, charged Higgs mass and x parameter.

In [29] we compared the predictions of $G(221)$ models with SUSY results [24–27]. There were considered events with no leptons, six jets and MET [24], one lepton, six jets and MET [25], two opposite sign leptons , four jets and MET [26], and four b-jets, one lepton and MET [27]. These states can also be produced in the context of $W' \to hH^{\pm}$ $G(221)$ models, with h decaying to a pair of W bosons, and $H^{\pm}$ decaying to top and bottom quarks. The presented results shows the ATLAS model independent upper limits for visible cross-sections, for SUSY searches, and the fiducial $G(221)$ models cross-sections. Although we applied only a part of ATLAS SUSY phase space cuts, the values suggest the smallness of the $G(221)$ predictions with respect to the ATLAS results. However, we note that the $G(221)$ fiducial cross-sections are considerably higher than those predicted by 2HDM $pp \to W \to hH^{\pm}$ decay with default PYTHIA 6.4 parameters.

6 Summary and Conclusions

The study aimed to compare $W'hH^{\pm}$ decay predicted by $G(221)$ models finalized with 2 leptons, 4 jets and MET topology with upper limits on visible cross-sections obtained by several ATLAS SUSY searches [24–27].

A two-stage symmetry breaking with the Higgs sector consisting of a Higgs doublet in the first symmetry breaking stage, and of a Higgs bi-doublet in the second one was considered [20]. The coupling between the new W' boson arising in this model, the SM-like Higgs boson and a charged non-standard Higgs boson was derived, and the partial width of the rare decay $W'hH^{\pm}$ was calculated. Then we obtained the cross-sections of 2 leptons, 4 jets and MET with PYTHIA 6.4 calculations, as a function of W' and charged Higgs boson masses.

By considering different final states and assuming specific kinematical cuts that were obptimized for SUSY searches, fiducial cross-sections for the $G(221)$ $W' \to hH^{\pm}$ decay were computed. Comparing them with ATLAS upper limits on visible cross-section, it can be concluded that the $G(221)$ models are below ATLAS current sensitivity.

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