Production of the heaviest charged Higgs boson in 3-3-1 models

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We study the production cross section of the heaviest hypercharge-two Higgs boson ($H^{\pm}_{2}$) predicted by the 3-3-1 model. Taking into account intermediate vector bosons, including a new $Z'$ neutral boson, we calculate the cross section of $H^{\pm}_{2}$ pair production at CERN-LHC hadron collider. Considering $Z'$-mass of the order of 1 TeV, we found that the cross sections decreases from 100 fb to $1 \times 10^{-3}$ fb for the $H^{\pm}_{2}$-mass range 200 - 1000 GeV. We also found that for masses below the kinematic threshold (500 GeV), the cross section splits into three branches for $H^{\pm}_{2}$-boson, the hypercharge-one $H^{\pm}_{1}$-boson, and the $H^{\pm}_{2}HDM$-boson from a two Higgs doublet model.

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1. Introduction

An interesting alternative to extend the SM are the models with gauge symmetry $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$, also called 3-3-1 models, which introduce a family nonuniversal $U(1)$ symmetry [1, 2, 3]. These models have a number of phenomenological advantages. First of all, from the cancellation of chiral anomalies and asymptotic freedom in QCD, the 3-3-1 models can explain why there are three fermion families. Secondly, since the third family is treated under a different representation, the large mass difference between the heaviest quark family and the two lighter ones may be understood. Finally, these models contain a natural Peccei-Quinn symmetry, necessary to solve the strong-CP problem. In particular, these models extend the scalar sector of the SM into three $SU(3)_3$ scalar triplets. After the spontaneous breaking of the gauge symmetry and rotations into mass eigenstates, the model contains 4 massive charged Higgs ($H_1^\pm, H_2^\pm$), one neutral CP-odd Higgs ($A^0$), 3 neutral CP-even Higgs ($h^0, H_1^0, H_2^0$), and one complex neutral Higgs ($H_3^0$) bosons.

In this work we study the bosons which show couplings with the SM matter through mixing with non-SM particles. In particular, the charged sector is composed of two types of Higgs bosons: hypercharge-one Higgs bosons $H_1^\pm$ which exhibit tree-level couplings with the SM particles [4], and hypercharge-two Higgs $H_2^\pm$ bosons which show couplings with the SM matter through mixing with non-SM particles. In this work we study the $H_3^\pm$-boson production at CERN-LHC in $pp \rightarrow H_3^\pm H_3^\mp$ pair production. For comparison purposes, we include the $H_{2HDM}^\pm$-boson production from the two Higgs doublet model.

2. The 331 spectrum

We consider a 3-3-1 model where the electric charge is defined by:

$$Q = T_3 - \frac{1}{\sqrt{3}} T_8 + X,$$  \hspace{1cm} (2.1)

with $T_3 = \frac{1}{2} \text{Diag}(1, -1, 0)$ and $T_8 = \left( \frac{1}{2 \sqrt{3}} \right) \text{Diag}(1, 1, -2)$. In order to avoid chiral anomalies, the model introduces in the fermionic sector the following $(SU(3)_c, SU(3)_L, U(1)_X)$ left- and right-handed representations:

$$Q_L^1 = \begin{pmatrix} U^1 \\ D^1 \\ T^1 \end{pmatrix}_L : (3, 3, 1/3), \quad \begin{cases} U^1_R : (3^*, 1, 2/3) \\ D^1_R : (3^*, 1, -1/3) \\ T^1_R : (3^*, 1, 2/3) \end{cases}$$

$$Q_L^{2,3} = \begin{pmatrix} D^{2,3} \\ U^{2,3} \\ J^{2,3} \end{pmatrix}_L : (3, 3^*, 0), \quad \begin{cases} D^{2,3}_R : (3^*, 1, -1/3) \\ U^{2,3}_R : (3^*, 1, 2/3) \\ J^{2,3}_R : (3^*, 1, -1/3) \end{cases}$$

$$L_L^{1,2,3} = \begin{pmatrix} v^{1,2,3}_L \\ e^{1,2,3}_L \\ (v^{1,2,3}_L)^c \end{pmatrix}_L : (1, 3, -1/3), \quad \begin{cases} v^{1,2,3}_R : (1, 1, -1) \\ e^{1,2,3}_R : (1, 1, 0) \\ N^{1,2,3}_R : (1, 1, 0) \end{cases},$$  \hspace{1cm} (2.2)

where $U^i_L$ and $D^i_L$ for $i = 1, 2, 3$ are three up- and down-type quark components in the flavor basis, while $v^i_L$ and $e^i_L$ are the neutral and charged lepton families. The right-handed sector transforms
as singlets under $SU(3)_L$ with $U(1)_X$ quantum numbers equal to the electric charges. In addition, we see that the model introduces heavy fermions with the following properties: a single flavor quark $T^1$ with electric charge $2/3$, two flavor quarks $J^{2,3}$ with charge $-1/3$, three neutral Majorana leptons $(\nu^{1,2,3})_L^c$ and three right-handed Majorana leptons $N^1_{R,2,3}$. On the other hand, the scalar sector introduces one triplet field with VEV $\langle \chi \rangle_0 = v_\chi$, which provides the masses to the new heavy fermions, and two triplets with VEVs $\langle \rho \rangle_0 = v_\rho$ and $\langle \eta \rangle_0 = v_\eta$, which give masses to the SM fermions at the electroweak scale. The $(SU(3)_L, U(1)_X)$ group structure of the scalar fields are:

\[
\chi = \begin{pmatrix}
\chi_1^0 \\
\chi_2^0 \\
\frac{1}{\sqrt{2}}(v_\chi + \xi_\chi \pm i \zeta_\chi)
\end{pmatrix} : (3, -1/3)
\]

\[
\rho = \begin{pmatrix}
\rho_1^+ \\
\rho_2^+ \\
\frac{1}{\sqrt{2}}(v_\rho + \xi_\rho \pm i \zeta_\rho)
\end{pmatrix} : (3, 2/3)
\]

\[
\eta = \begin{pmatrix}
\eta_1^- \\
\eta_2^- \\
\eta_3^0
\end{pmatrix} : (3, -1/3).
\]

In particular, the $\rho$ and $\eta$ triplets contain hipercharge-one and hypercharge-two fields. After the symmetry breaking, the above weak eigenstates rotate into the following mass eigenstates \[5, 6\]:

\[
\text{Hipercharge-one Higgs: } H_1^\pm = -S_{\rho T} \rho_1^\pm + C_{\rho T} \eta_2^\pm
\]

\[
\text{Hipercharge-two Higgs: } H_2^\pm \approx \rho_3^\pm,
\]

where $T_{\rho T} = v_\eta / v_\rho$. The photon $A$, neutral weak boson $Z$ and a new neutral boson $Z'$ are \[7\]:

\[
A_\mu = S_W W_\mu^3 + C_W \left( \frac{1}{\sqrt{3}} T_W W_\mu^8 + \sqrt{1 - \frac{1}{3} (T_W)^2} B_\mu \right),
\]

\[
Z_\mu = C_W W_\mu^3 - S_W \left( \frac{1}{\sqrt{3}} T_W W_\mu^8 + \sqrt{1 - \frac{1}{3} (T_W)^2} B_\mu \right),
\]

\[
Z'_\mu = -\sqrt{1 - \frac{1}{3} (T_W)^2} W_\mu^8 + \frac{1}{\sqrt{3}} T_W B_\mu,
\]

where the Weinberg angle is defined as $S_W = \sqrt{3} g_X / \sqrt{3 g_L^2 + 4 g_X^2}$, with $g_L$ and $g_X$ the coupling constants of the groups $SU(3)_L$ and $U(1)_X$, respectively.

3. The couplings

For the interaction between the SM-quarks $q$ and neutral gauge bosons, we found \[7\]:

\[
\mathcal{L}^{NC} = e Q q \Phi \Phi q + \frac{g_L}{2 C_W} \Phi \left[ \gamma_\mu (g^q_{\nu} - g^q_{\nu} g^q_{\lambda}) Z^\mu + \gamma_{\nu} (g^q_{\mu} - g^q_{\mu} g^q_{\lambda}) Z'^\mu \right] q,
\]
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Table 1: Vector and Axial couplings of SM quarks and Neutral Gauge Bosons. The index \( m = 2,3 \) labels the 3\(^*\) multiplets.

<table>
<thead>
<tr>
<th>Fermion</th>
<th>( g_{V}^{u} )</th>
<th>( g_{A}^{u} )</th>
<th>( g_{V}^{d} )</th>
<th>( g_{A}^{d} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^{1} )</td>
<td>(-\frac{1}{2} + \frac{2}{5} g_{W}^{2} )</td>
<td>(-\frac{1}{2} )</td>
<td>(-\frac{1}{6} \sqrt{3 - 4 g_{W}^{2}} )</td>
<td>(-\frac{1}{2} \sqrt{3 - 4 g_{W}^{2}} )</td>
</tr>
<tr>
<td>( D^{m} )</td>
<td>(-\frac{1}{2} + \frac{2}{5} g_{W}^{2} )</td>
<td>(-\frac{1}{2} )</td>
<td>(\frac{3 - 2 g_{W}^{2}}{6 \sqrt{3 - 4 g_{W}^{2}}} )</td>
<td>(\frac{1 - 2 g_{W}^{2}}{2 \sqrt{3 - 4 g_{W}^{2}}} )</td>
</tr>
<tr>
<td>( U^{1} )</td>
<td>(\frac{1}{2} - \frac{4}{5} g_{W}^{2} )</td>
<td>(\frac{1}{2} )</td>
<td>(\frac{3 - 2 g_{W}^{2}}{6 \sqrt{3 - 4 g_{W}^{2}}} )</td>
<td>(\frac{1 - 2 g_{W}^{2}}{2 \sqrt{3 - 4 g_{W}^{2}}} )</td>
</tr>
<tr>
<td>( U^{m} )</td>
<td>(\frac{1}{2} - \frac{4}{5} g_{W}^{2} )</td>
<td>(\frac{1}{2} )</td>
<td>(\frac{3 - 8 g_{W}^{2}}{6 \sqrt{3 - 4 g_{W}^{2}}} )</td>
<td>(\frac{1}{2 \sqrt{3 - 4 g_{W}^{2}}} )</td>
</tr>
</tbody>
</table>

Figure 1: Charged Higgs boson pair production in \( pp \) collisions

where \( q \) is \( U = (U^{1}, U^{2}, U^{3}) \) or \( D = (D^{1}, D^{2}, D^{3}) \) for up- and down-type quarks, respectively, and \( Q_{q} \) the electric charge in units of the positron charge \( e \). The vector and axial-vector couplings of the \( Z \) and \( Z' \) bosons are written in table 1 for each SM quark.

On the other hand, from the kinetic term of the Higgs Lagrangian, we obtain the following Higgs-Higgs-Vector interaction associated with the charged Higgs sector:

\[
i: \mathcal{L}^{HHV} = -ie \left[ H_{1}^{+} H_{1}^{-} + H_{2}^{+} H_{2}^{-} \right] (p - q)^{\mu} A_{\mu} - \frac{i g_{L}}{2 g_{W}} \left[ C_{2W} H_{1}^{+} H_{1}^{-} + 2 S_{2W} H_{2}^{+} H_{2}^{-} \right] (p - q)^{\mu} Z_{\mu} + \frac{i g_{X}}{2 \sqrt{3} g_{W}} \left[ (C_{2W} + T_{W}^{3}) H_{1}^{+} H_{1}^{-} + 2 (1 + T_{W}^{3}) H_{2}^{+} H_{2}^{-} \right] (p - q)^{\mu} Z_{\mu}^{\prime}\]  

4. Results

For the pair production from figure 1, we use the couplings in (3.2). Figure 2 show the cross section for Higgs boson pair production \( H_{1}^{\pm} \) for \( M_{Z}^{\prime} = 1 \) TeV and \( pp \) collisions at CM energy of 14 GeV. For comparison purposes, we include the charged Higgs boson \( H_{1}^{\pm} \) and \( H_{2}^{\pm}_{\text{HDM}} \) from a two
Higgs doublet model (2HDM). We observe the following behaviour:

- Below the kinematic threshold $M_H < 500$ GeV, the cross sections split into three branches, where $\sigma(H_2) > \sigma(H_1) > \sigma(H_{2HDM})$.

- The $H^\pm_2$ bosons exhibit larger contributions than $H^\pm_1$. This splits is due to the different contributions exhibits by the $H^\pm_1$ and $H^\pm_2$ bosons with the gauge bosons in Eqn. (3.2).

- For 2HDM model, we obtain smaller production ratios due to the fact that in this model the $Z'$ contribution does not exist.

- For $M_H > 500$ GeV, the $Z'$ contribution is suppressed by kinematic conditions ($M_{Z'}^2 < 2M_H$). Thus, the cross section decreases, as shown.

- The $H^\pm_1$-$Z'$ coupling is $\beta_T$-dependent as shown in Eq. (5). For numerical purposes we fix $T_{\beta_T} = 9$.

5. Acknowledgements

This work was supported by Colciencias

References


