ENHANCEMENT OF LOOP-INDUCED $H^\pm W^\mp Z^0$ VERTEX

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We discuss the non-decoupling effects on the loop-induced $H^\pm W^\mp Z^0$ vertex in the general two Higgs-doublet model. The decay process $H^\pm \to W^\pm Z^0$ is analyzed at one-loop level and possible enhancement of the decay width is explored. We find that a novel enhancement can be realized by the Higgs non-decoupling effects with large mass difference between charged and CP-odd Higgs bosons. The branching ratio of the process can be a few $\% \sim 10\%$. Therefore the decay mode may be detectable at LHC or future $e^+e^-$ linear colliders (LC’s).

1 Introduction

The Higgs sector remains unknown. Although the minimal model (with one Higgs doublet) does not contradict any current experimental data, various purely theoretical motivations often expect the extended Higgs sectors. The charged Higgs boson $H^\pm$ and CP-odd Higgs boson $A^0$ are always introduced in such the extension. Thus the detection of $H^\pm$ ( or $A^0$ ) is very important to confirm the extended Higgs sectors. If $H^\pm$ is light, it may be detectable through the mode $H^\pm \to \tau \nu$ and $cs$. However, heavy $H^\pm$ enough to open $tb$ as a main decay mode may be elusive because of large QCD background. In such the case, we have to investigate the possibility of alternative decay modes to prove $H^\pm$ with the branching ratio enough to yield substantial events. The possible modes may be $H^\pm \to \tau \nu$, $h^0 W^\pm$, $W^\pm Z^0$ and $W^\pm \gamma$. Unfortunately, it has been known that the latter two modes disappear at tree level in general Higgs models with multi-doublet structures, in which they can be induced only at loop levels. Thus these modes have been considered as a clear signal for exotic Higgs sectors (for example, including triplets).

In this talk, we discuss the loop-induced $H^\pm W^\mp Z^0$ vertex in the two Higgs-doublet model (2HDM) and MSSM. We examine the possible enhancement of the vertex at one-loop level. The decay width of $H^\pm \to W^\pm Z^0$ is then calculated at one-loop level and the branching ratio is estimated in order to see whether it can be enhanced enough to be detected at LHC or LC’s. We find that a novel enhancement can occur by the Higgs non-decoupling effects in 2HDM in the constraint from the present data. The branching ratio can be a few $\% \sim 10\%$ for $\tan \beta > 1$ at $m_{H^\pm} = 300$ GeV. In MSSM, the branching ratio is less than 0.01 $\%$ for $\tan \beta > 1$. Therefore, $H^\pm \to W^\pm Z^0$ may be useful as a probe of Higgs sectors between MSSM, 2HDM and exotic Higgs models.
2 Property of The Model

We here consider the model with a softly-broken discrete symmetry under \( \Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2 \). This Higgs potential is popular one and covers the MSSM Higgs potential as a special case. We assume the soft-breaking mass parameter \( \mu_2^3 \) to be real. This model includes the five massive physical scalar bosons; namely, the charged \( (H^\pm) \), CP-odd neutral \( (A^0) \) and two CP-even neutral ones \( (h^0 \text{ and } H^0) \). Three Nambu-Goldstone bosons \( w^\pm \text{ and } z^0 \) are absorbed into \( W^\pm_L \text{ and } Z^0_L \).

In 2HDM, whether the internal heavy Higgs bosons are decoupled or not is a model dependent problem. The masses of \( H^\pm, A^0 \text{ and } H^0 \) are naively expressed like \( M_i^2 = \lambda_i v^2 + O(\mu_2^3) \), where \( \lambda_i \) represent the linear combinations of the quartic-coupling constants. If large \( M_i \) are realized by \( \mu_2^3 \) with keeping \( \lambda_i \) to be small, the effects of heavy Higgs bosons then tend to be decoupled from low-energy observables as seen in MSSM. Alternatively, if \( M_i \) are large due to the growing \( \lambda_i \) with a small \( \mu_2^3 \), the decoupling theorem no longer work and the non-decoupling effects of the masses appear.

The Higgs sector, in general, does not have the custodial \( SU(2)_V \) symmetry in 2HDM. In terms of \( 2 \times 2 \) matrices \( M_i = (i \tau_2 \Phi_i^*, \Phi_i), (i = 1, 2) \), the Higgs sector includes the term \( \sim \lambda' \{ \text{tr}(M_2^2 \tau_3 M_1^\dagger) \}^2 \). Such the term is not invariant under the transformation \( M_i \to g_L^\dagger M_1 g_R \) \( (g_L, R \in SU(2)_L, R) \). Namely, the term breaks \( SU(2)_R \) and thus the custodial \( SU(2)_V \) symmetry explicitly. The coupling constant of this term is expressed as \( \lambda' = (m_{H^\pm}^2 - m_{A^0}^2)/v^2 \). The explicit breaking of \( SU(2)_V \) in the Higgs sector is measured by the mass difference between \( A^0 \) and \( H^\pm \).

3 Loop-Induced \( H^\pm W^\mp Z^0 \) Vertex

We observe the absence of the tree \( H^\pm W^\mp Z^0 \) coupling in 2HDM (and MSSM). The coupling is expected to be generated in the kinetic part of the Higgs sector: \( \mathcal{L}_{\text{THDM}}^{\text{kin}} = (D_\mu \Phi)^\dagger D^\mu \Phi + (D_\mu \Psi)^\dagger D^\mu \Psi \), where \( \Phi \) and \( \Psi \) are the Higgs doublets in the basis of the gauge-eigenstates:

\[
\Phi = \left( \begin{array}{c}
\frac{1}{\sqrt{2}}(\phi^0 + v + i z^0) \\
\frac{1}{\sqrt{2}}(h^0 + i A^0)
\end{array} \right), \quad \Psi = \left( \begin{array}{c}
\frac{1}{\sqrt{2}}(H^+ + i H^0)
\end{array} \right).
\]

\( \phi^0 \) and \( \psi^0 \) are the linear combinations of \( h^0 \) and \( H^0 \). Since \( \Psi \) does not have any vacuum expectation value, we can see the absence of the tree \( H^\pm W^\mp Z^0 \) coupling. It can be induced through the mixing between \( \Phi \) and \( \Psi \) at loop-levels.
We next discuss the non-decoupling effects of heavy particles on the $H^\pm W^\mp Z^0$ vertex. The effective Lagrangian is

$$L_{\text{eff}} = f_{H^+W^-Z^0} H^+ W^- Z^0 + h.c. + g_{H^+W^-Z^0} H^+ F_{Z^0}^{\mu\nu} F_{\mu\nu} + h.c. + h_{H^+W^-Z^0} i\epsilon_{\mu\nu\rho\sigma} H^+ F_{Z^0}^{\mu\nu} F_{W}^{\rho\sigma} + h.c..$$  (2)

The coefficient $f_{H^+W^-Z^0}$ is mass-dimension 1 and the others are dimension $-1$. The contributions of the heavy particles of the masses $M_i$ to the coefficients can be estimated at one-loop level as

$$f_{H^+W^-Z^0} \sim g \times \frac{M^2}{\cos\theta_W} (\times \ln M_i) \sim \frac{m_W m_Z}{v^3} \times M_i^2 (\ln M_i),$$

$$g_{H^+W^-Z^0}, h_{H^+W^-Z^0} \sim \frac{m_W m_Z}{v^3} \times \ln M_i.$$  (3)

Therefore the naive power-counting shows that there may be substantial non-decoupling effects of the heavy Higgs bosons as well as heavy fermions on the one-loop induced $H^\pm W^\mp Z^0$ vertex.

The vertex is, however, strongly constrained by the custodial $SU(2)_V$ symmetry. Each term in the Lagrangian (2) comes from the following each operator;

$$\text{tr} [\gamma_3 (D_\mu M)^\dagger (D^\mu N)] \text{ or } \text{tr} [\gamma_3 M^\dagger N F_{Z^0}^{\mu\nu} F_{W}^{\mu\nu}] \text{ or } i\epsilon_{\mu\nu\rho\sigma} \text{tr} [\gamma_3 M^\dagger N F_{Z^0}^{\mu\nu} F_{W}^{\rho\sigma}],$$  (4)

where $2 \times 2$ matrices $M$ and $N$ are defined by $M = (i\tau_2 \Phi^*, \Phi)$ and $N = (i\tau_2 \Psi^*, \Psi)$. All the operators (4) are not invariant under $SU(2)_R$ and thus $SU(2)_V$, the vertex is induced according to the $SU(2)_V$ breaking in the model.

### 4 Enhancement of Decay Process $H^\pm \to W^\pm Z^0$

We proceed to examine the decay process $H^\pm \to W^\pm Z^0$. The decay width in 2HDM (with Type II Yukawa coupling) with large $\Delta m = m_{H^0} - m_{H^\pm}$ and also that in MSSM with heavy sparticles are shown in Fig 1. In MSSM, in addition to the Higgs decoupling property, $m_{H^0}$ is approximately degenerated with $m_{H^\pm}$. Thus the Higgs effects are small and the heavy fermion effects are dominant. Since the $H^\pm tb$ coupling constant consists of $m_t \cot \beta$ and $m_b \tan \beta$, the top-quark contributions are rapidly reduced for larger $\tan \beta$. On the other hand, in 2HDM with large $\Delta m$, a novel enhancement of the width is realized for large $\tan \beta$ because of the non-decoupling effects of Higgs bosons.

Let us consider the branching ratio of this decay mode in 2HDM next. The other decay modes included here are $H^\pm \to t\bar{b}, \tau\nu$ and $h^0 W^\pm$. The parameters are fixed as $m_{h^0} = 140$ GeV, $m_{H^0} = 310$ GeV and $\alpha = \beta - \pi/2$. We also assume
that $m_t = 175$ GeV and $m_b(m_{H^\pm}) = 3$ GeV. We can see in Fig 2 that the branching ratio become larger than 1 % if $\Delta m$ is greater than 200 GeV for $\tan \beta > 5 \sim 8$. The maximal value can amount to near 10 % for very large $m_A^0$ and $\tan \beta > 20$. In the nearly $SU(2)_V$ symmetric cases in the Higgs sector ($m_A^0 \sim m_{H^\pm} = 300$ GeV), the Higgs non-decoupling effects are canceled out and only the fermion effects remain, so that the branching ratio becomes less than 0.01 %. As mentioned before, the non-zero $\mu_3^2$ reduces the non-decoupling Higgs effects. So far we have tried to extract the Higgs non-decoupling effects as large as possible, assuming the soft-breaking parameter $\mu_3^2$ to be zero. However, $\mu_3^2$ is often very important in various aspects of physics. The reduction of the branching ratio by $m_3 = \mu_3/\sqrt{\sin \beta \cos \beta}$ is shown in Fig 3.

5 Summary and Discussion

We have discussed the loop induced $H^\pm W^\mp Z^0$ vertex. The possibility of its enhancement has been explored. The conditions for the enhancement is summarized as 1) Non-decoupling properties of Higgs sector with small $\mu_3^2$, and 2) Large SU(2) breaking in the Higgs sector by the mass difference between $A^0$ and $H^\pm$. Although such conditions are not satisfied in the framework of MSSM, it is possible for 2HDM to satisfy them within the arrowed region from the current experimental data and also from the perturbative unitarity. As a result, the branching ratio of $H^\pm \to W^\pm Z^0$ can be a few % $\sim 10$ %. Such the enhancement may make it possible to detect the decay mode at LHC and also
LC’s. At LHC, the charged Higgs boson is mainly produced through the subprocess $gb \rightarrow tH^\pm$, where over one hundred production of $H^\pm \rightarrow W^\pm Z^0 \rightarrow ll\nu\nu$ can be expected per a year for $Br(H^+ \rightarrow W^+ Z^0) > 1\%$. Since the background (mainly $ud \rightarrow WZ$) is naively estimated to be such that a few % of the branching ratio are required to see a signal, we can expect to detect the decay mode with the enhancement above. We also expect that it can be detectable at LC’s ($\sqrt{s} = 1$ TeV, $L = 160$ fb$^{-1}$/year), where over a few dozen events of $H^\pm \rightarrow W^\pm Z^0 \rightarrow ll\nu\nu, lljj, lvjj$ and $v\nu jj$ are produced per a year for $Br(H^+ \rightarrow W^+ Z^0) > 1\%$ with less background.

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