HZ associated production with decay in the Alternative Left-Right Model at CEPC and future linear colliders

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Abstract: Higgs and Z boson associated production with subsequent decay was studied in the framework of alternative left-right model, which is motivated by superstring-inspired $E_6$ model at CEPC and future linear colliders. We systematically analyze each decay channel of Higgs with constraints imposed by theory and latest experiment. Due to the mixing of scalars in the Higgs sector, charged Higgs bosons can also play essential roles in the phenomenological analysis of this process. The conclusion is that even though the predictions of this model for the signal strengths of this process are close to the standard model expectations, it can be differentiated in high luminosity.

Key words: new physics, Higgs, symmetry breaking, electron positron collider

PACS: 12.60.-i, 13.66.Fg

1 Introduction

With the discovery of Higgs boson by ATLAS [1] and CMS [2] at Large Hadron Collider (LHC) in 2012, the standard model(SM) has achieved great accomplishment. Higgs production with subsequent decay plays an essential role not only in the precision test of the Higgs property but provides a window to new physics beyond the SM(WSM). The study of Higgs and Z boson associated production and decay at Higgs factory such as Circular Electron Positron Collider(CEPC) and future linear colliders is significantly important in measuring gauge and Yukawa interactions, so more and more theorists and experimenters are motivated to investigate this process in new physics sceneries [3–6]. CEPC was proposed by Chinese scientists at about 240 GeV center-of-mass energy mainly for Higgs studies with two detectors situated in a very long tunnel more than twice the size of the LHC at CERN. A future linear collider, such as International Linear Collider(ILC) or Compact Linear Collider(CLIC), at center-of-mass energy $\sqrt{s} = 500$ GeV or even higher to TeV energy scale, will allow the Higgs sector to be probed with high precision significantly beyond that at High-Luminosity LHC [2–4]. CEPC and future linear colliders are $e^+ e^−$ colliders, and will be very important facilities for precision Higgs physics research, which may be an order of magnitude more precise that achievable at LHC. Such measurements may be necessary to reveal BSM effects in Higgs sector. Moreover, $e^+ e^−$-colliders provide the opportunity to measure Higgs couplings, rather than ratios with a cleaner background. In addition, an $e^+ e^−$ collider operating at 1TeV or above, for example CLIC or an upgraded ILC, will have the sensitivity to top quark Yukawa coupling and Higgs self-coupling parameters, thus will provide a direct probe of Higgs potential.

As for the discovery of neutrino masses and neutrino oscillations, it confirmed that SM is still incomplete. To provide a proper explanation for the measured neutrino masses, theorists have made many attempts to expand SM, such as supersymmetry, extra dimensions, Two Higgs Doublet Model(2HDM), Left-Right Model (LRM) and so on. The Alternative Left-Right Model(ALRM) [10–13], motivated by the superstring-inspired $E_6$ model, is one type of left-right model [14–17]. ALRM is based on $SU(3)_{C} \times SU(2)_{L} \times SU(2)_{R} \times U(1)_{B-L}/2 \times S$, where $SU(2)_{R} \times U(1)_{B-L}/2$ can break at TeV scale, so that allowing several interesting signatures at Large Hadron Collider(LHC). In ALRM all non-SM particles can couple with SM fermions and Higgs which will lead to low energy consequences. Due to the rich Higgs sector, there are four neutral CP-even and two CP-odd Higgs bosons, in addition to two charged Higgs bosons, which come from one bi-doublet and two left-handed and right-handed doublets and most of these Higgs bosons can be light, of order electroweak scale. As for the couplings of the SM-like Higgs with the fermions and gauge bosons, there are small changes compared to...
the corresponding ones in SM. In the literature, many studies have been done which primarily focus on dark matter or hadron production of ALRM [13, 18, 20].

In this paper we will mainly pay attention to the weak production of Z boson and Higgs. Firstly, each channel of Higgs decay modes has been analyzed in ALRM and compare them with the recent results reported by ATLAS and CMS experiments [21, 25]. There are possible discrepancies between their results of signal decay strengths in each channel. We analyze through five main Higgs decay channels: $H \rightarrow b\bar{b}$, $c\bar{c}$, $\tau\tau$, $ZZ$ and $WW$ in both ALRM and SM correspondingly. We find that the signal strength of Higgs decay channel $H \rightarrow ZZ$ is consistent with SM expectation. However the decay channel $H \rightarrow b\bar{b}$ is more sensitive to the mass of charged Higgs, where may exists discrepancy with SM. Secondly, $HZ$ and $Z\ell\ell$ associated production with decay in ALRM. Finally we study the subsequent decay of the final state Higgs into a pair of bottom quarks and $Z$ boson.

In section 3 we perform the numerical analysis for Higgs production of $Z$ boson and Higgs. Firstly, each channel of Higgs decay modes has been analyzed in ALRM and the required integrated luminosity when the masses of the fermions, which are quarks $u, d, d'$, the charged leptons $l$, and the addition singlet fermion $n$ called scotino:

$$m_u = \frac{1}{\sqrt{2}} Y_u v \sin \beta, \quad m_d = \frac{1}{\sqrt{2}} Y_d v \cos \beta,$$

$$m_d' = \frac{1}{\sqrt{2}} Y_{d'} v_R, \quad m_l = \frac{1}{\sqrt{2}} Y_l v \sin \beta,$$

$$m_n = \frac{1}{\sqrt{2}} Y_n v_R.$$

The mixing angle and the vacuum expectation are set as $\tan \beta = k/v_L$ and $\sqrt{v_L^2 + k^2} = v \equiv 246$ GeV. From Eq. (1), we also get the Yukawa couplings of the SM-like Higgs

$$Y_{H\phi} = \frac{m_\phi}{v} T_\phi, \quad Y_{Hd} = \frac{m_d}{v} T_{d},$$

$$Y_{Hd'} = \frac{m_{d'}}{v_R} T_{d'}, \quad Y_{H\ell} = \frac{m_\ell}{v} T_{\ell},$$

$$Y_{Hn} = \frac{m_n}{v_R} T_n,$$

where the $T_\phi, T_d, T_{d'}$ are the mixing parameters of the SM-like Higgs with the gauge eigenstates $\phi_{R}, \chi_{L}^{0R}, \chi_{R}^{0R}$ respectively. Similarly to the Yukawa coupling, the specific couplings of the SM-like Higgs with the massive EW gauge bosons can also be derived from the Lagrangian of the scale sector [19].

In the gauge sector, $W_L^\pm$ and $W_R^\pm$ can not be mixing with each other due to < $\phi_{R}^{0} >$ = 0. We get the mass eigenstates are $W_L^\pm = W_L^R$ which are the SM gauge bosons and the heavy charged bosons $W'^\pm = W_R^R$. The masses of these bosons are given by:

$$M_{W}^2 = \frac{1}{4} g^2 (k^2 + v_L^2),$$

$$M_{W'}^2 = \frac{1}{4} g^2 (k^2 + v_R^2).$$

At present, a lot of measurements focused on the heavy bosons have been done. Up to date a search for high-mass resonances using an integrated luminosity of 36.1 $fb^{-1}$ by the ATLAS collaboration offer a lower mass limit of $W'$ as $M_{W'} > 3.7$ TeV [26, 28]. This lower bounded on $M_{W'}$ is applicable in our following calculation in this paper.

For the neutral gauge bosons, the masses of two massive bosons can be calculated by

$$M_{Z,Z'}^2 = \frac{1}{2}(M_{LL}^2 + M_{RR}^2 + (M_{RR}^2 - M_{LL}^2) \times \sqrt{1 + \tan^2 2\theta}),$$

where mixing angle $\theta$ is defined as

$$\tan 2\theta = \frac{2M_{Z,R}^2}{M_{LL}^2 - M_{RR}^2},$$

where $Z,R$ are the duals of the bi-doublet $\Phi$ and the doublets $\chi_{L,R}$, which are defined as $\Phi = \tau_2 \Phi^* \tau_2$ and $\chi_{L,R} = i \tau_2 \chi_{L,R}^0$. From this Lagrangian, We can get

$$\mathcal{L}_Y = \overline{Q}_L Y^\nu \Phi Q_R + \overline{L}_L Y^d \chi L d_R + \overline{R}_L Y^u \chi R d'_L + \overline{\nu}_L Y^\nu \Phi \nu_R + \overline{L}_L Y^\ell \chi L \nu_R + \overline{R}_L Y^\ell \chi R \nu_R + \overline{n}_L Y^n \Phi n_R + \text{h.c.},$$

(1)
and

\[
M^2_{LL} = \frac{g^2 v^2}{4 \cos^2 \theta_w}, \\
M^2_{LR} = \frac{g^2 (v^2 \sin^2 \theta_w - k^2 \cos^2 \theta_w)}{4 \cos^2 \theta_w \sqrt{\cos 2 \theta_w}}, \\
M^2_{RR} = \frac{g^2 (2v^2 \sin^2 \theta_w + 2(k^2 + v^2) \cos^2 \theta_w - k^2 \sin^2 2 \theta_w)}{8 \cos^2 \theta_w \cos 2 \theta_w}.
\]

From Eqs. (6-7), we know that mixing angle \( \theta \) are strongly influenced masses of \( Z \) and \( Z' \), and when \( \theta \to 0 \), \( Z \simeq Z_L \) and \( Z' \simeq Z_R \). The latest LHC experiments using a data sample corresponding to an integrated luminosity of 36.1 fb\(^{-1} \) from proton-proton collisions give a limitation for the \( Z' \) gauge boson as \( M_{Z'} \gtrsim 2.42 \) TeV \cite{28, 30}, and we use the constraint in our numerical calculation.

Ref. \cite{17} gives the most general Higgs potential with the symmetry invariance,

\[
V(\Phi, \chi_{L,R}) = -\mu^2_T T_r[\Phi^\dagger \Phi] + \lambda_1 T_r[\Phi^\dagger \Phi]^2 + \lambda_2 T_r[\Phi^\dagger \Phi] T_r[\Phi^\dagger \Phi] - \mu^2_b (\chi^\dagger_{L} \chi_{L} + \chi^\dagger_{R} \chi_{R}) + \lambda_3 [(\chi^\dagger_{L} \chi_{L})^2 + (\chi^\dagger_{R} \chi_{R})^2] + 2\lambda_4 (\chi^\dagger_{L} \chi_{L})(\chi^\dagger_{R} \chi_{R}) + 2\lambda_5 T_r[\Phi^\dagger \Phi](\chi^\dagger_{L} \chi_{L} + \chi^\dagger_{R} \chi_{R}) + 2\lambda_6 (\chi^\dagger_{L} \Phi^\dagger \Phi^\dagger \chi_{L} + \chi^\dagger_{R} \Phi^\dagger \Phi^\dagger \chi_{R}) + \mu_3 (\chi^\dagger_{L} \Phi^\dagger \Phi^\dagger \chi_{L} + \chi^\dagger_{R} \Phi^\dagger \Phi^\dagger \chi_{R}).
\]

We follow the theorems \cite{31, 32} to ensure that the matrix of the quartic terms, which are dominant at higher values of the fields, is copositive. The ref. \cite{19} present a detailed study for the conditions which keep the potential Eq. (5) bounded from below. After symmetry breaking there are ten scalars remained as physical Higgs bosons in ALRM, four charged Higgs bosons (\( M_{H^\pm}, M_{H^0^+} \)), two pseudo-scalar Higgs bosons (\( M_{A^0_1}, M_{A^0_2} \)) and the remaining four CP-even neutral Higgs bosons (\( M_{H_1^0}, M_{H_2^0}, M_{H_{1-2}^0} \)).

The lightest neutral eigenstate \( H_1^0 \) is the SM-like Higgs, whose mass is fixed to be 125.09 GeV. For charged Higgs \( H^\pm_1 \), the diagonalizable matrix is related to angle \( \beta \) with \( \tan \beta = k/v_\tau \). However for \( H^\pm_2 \), the diagonalizable matrix is related to angle \( \zeta \) with \( \tan \zeta = k/v_\tau \). The vevs of \( v_\tau \) is much larger than \( v_\lambda \). From this point, \( H^\pm_2 \) couples to the SM particles stronger than \( H^\pm_1 \). The LEP experiments have searched for charged bosons via pair charged Higgs production. The data statistically combined by four experiments (ALEPH, DELPHI, L3 and OPAL) \cite{23} showed that the mass of charged Higgs boson must be greater than 80 GeV. This lower limit will be used as a reference in our calculations. Recently, ATLAS and CMS have also search the charged boson masses ranging from 200 to 2000 GeV \cite{34, 35}, and constrains for some models such as hMSSM are given.

### 3 NUMERICAL RESULTS AND DISCUSSION

#### 3.1 ALRM effects in Higgs decay

Each channel of discovered Higgs has already been detected by CMS and ATLAS experimental groups. The decay signal strengths of Higgs to ZZ bosons and \( bb \) pair are given in Table 1 independently by CMS \cite{21, 22}, ATLAS \cite{23, 24}.

| \( \mu_{XX} \) | CMS     | ATLAS  |
|-------------|---------|--------|
| \( \mu_{ZZ} \) | \( 1.05 \pm 0.19 \) | \( 1.29 \pm 0.20 \) |
| \( \mu_{bb} \) | \( 0.81 \pm 0.45 \) | \( 0.90 \pm 0.18 \) |

Table 1. The decay signal strengths of Higgs to ZZ bosons and \( bb \) pair given by CMS and ATLAS collaborations. \( \mu_{XX} \) stands for \( \mu(H \to XX) \).

Due to the detectors’ limits and the defects of hadron collider, the data in Table 1 may deviate from the real results, especially in \( H \to bb \). The Higgs signal strength in a particular final state \( XX \) \( \mu_{XX} \) is defined as

\[
\mu_{XX} = \frac{\sigma}{\sigma_{SM}} \frac{BR(H \to XX)}{BR(H \to XX)_{SM}} = \frac{\Gamma(H \to gg)}{\Gamma_{tot}(H \to XX)} \frac{\Gamma(H \to XX)_{SM}}{\Gamma_{tot} \Gamma(H \to XX)_{SM}} = \kappa_{gg} \kappa_{tot}^{-1} \kappa_{XX},
\]

where \( \sigma \) stands for the total Higgs production cross section at LHC and \( BR(H \to XX) \) is the corresponding branching ratio. The total decay width of Higgs can be considered as the sum of some dominant Higgs partial decay widths. In Eq. (23), we can see the Yukawa couplings \( Y_{\mu H_1} \) and \( Y_{\mu h_0} \) in ALRM may be changed by adding a factor of \( \frac{T_\alpha}{\sin \beta} \) and \( \frac{T_\beta}{\cos \beta} \) respectively from the SM values.
In Fig. 1 the effect of these two factors are plotted to show that both of them tend to be 1 while \( \frac{T_{L}}{\cos \beta} \) of \( Y_{Hd\bar{d}} \) is bigger than 1 particularly in the region of small \( M_{H^{\pm}} \) with large \( \tan \beta \). \( Y_{Hd\bar{d}} \) strongly depends on the mass of \( H^{\pm} \). However, the total decay width of Higgs boson remains very close to the SM result, \( \kappa_{\text{tot}} \simeq 1 \), when the mass of \( H^{\pm} \) is big enough.

As for \( \kappa_{gg} \), this channel is mainly propagated through the top quark triangle loop diagram and the extra quark \( d' \) can be neglected due to the suppression of its coupling with SM-like Higgs. From Fig. 1 we can see that the adding factor to top Yukawa coupling can be almost 1 and make the top Yukawa coupling unchanged from the SM result. Therefore, the ratio \( \kappa_{gg} = \frac{\Gamma(H \rightarrow gg)}{\Gamma(H \rightarrow gg)^{\text{SM}}} \) can be considered as 1.

Now we turn to the SM-like Higgs decay into ZZ in ALRM. For the kinematics forbidden, we compute \( H \rightarrow ZZ \) via \( H \rightarrow ZZ' \rightarrow Zff \), where \( f = e, \mu, \tau \) and \( u, d, c, s, b \) quark.

It is worth mentioning that the parameters \( \lambda_{3}, \alpha_{12} \) and \( M_{H^{\pm}} \) is not sensitive in the numerical results, only \( 0 < \lambda_{3} < \sqrt{4\pi} \) and \( \alpha_{12} > 0 \), to be consistent with the perturbative unitarity and the minimization and boundedness from below conditions Eqs. (21-24) in ref. \( \text{[19]} \). The relevant input parameters are chosen as \( \text{[28]} \):

\[
\alpha(0) = 137.035999, \ m_{W} = 80.385 \text{ GeV}, \\
m_{Z} = 91.1876 \text{ GeV}, \ m_{t} = 125.09 \text{ GeV}, \\
M_{H} = 150 \text{ GeV}, \ M_{H^{+}} = 4000 \text{ GeV}, \\
\alpha_{1} = \alpha_{2} = 1, \ \lambda_{3} = 1.5 .
\]  

(10)

We have used Feynrules \( \text{[36, 37]} \) to generate the model files and MadGraph \( \text{[38]} \) to calculate the numerical values of cross sections. In Fig. 2 we display the results of \( \kappa_{zz} = \frac{\Gamma(H \rightarrow zz)}{\Gamma(H \rightarrow zz)^{\text{SM}}} \) as functions of tan\( \beta \) and \( M_{H^{\pm}} \). This Figure confirms our theoretical expectation and shows that \( \kappa_{zz} \) can slightly deviate from 1. In Fig. (a) \( \kappa_{zz} \) is calculated by MadGraph and the relevant couplings \( \kappa_{zz} = g^{(HZZ)}_{\text{ALRM}}/g^{(HZZ)}_{\text{SM}} \) respectively. Obviously the results are the same by that two ways. In Fig. (b) with the increasing of \( M_{H^{\pm}} \), the trend is rapidly increasing and then stable while \( M_{H^{\pm}} \gtrsim 200 \text{ GeV} \). So in the following calculation \( M_{H^{\pm}} \) is equal to 200 GeV, unless otherwise stated. In this case, it is clear that the signal strength \( \mu_{zz} \) is also close to the SM expectation and can be consistent with CMS experimental results. It is remarkable that all signal strengths of Higgs decay channels in ALRM are close to SM results with MadWidth \( \text{[39]} \) automatically computing decay widths.

In Fig. 3(a), \( \kappa_{bb} \) is plotted as a function of \( M_{H^{\pm}} \). This figure shows that the decay channel \( H \rightarrow b\bar{b} \) is more sensitive to \( M_{H^{\pm}} \) than that in \( H \rightarrow ZZ \). In addition, it is remarkable that the decay width of this channel in ALRM is slightly larger than that in SM. In Fig. 3(b), \( \kappa_{bb} \) is plotted as a function of tan\( \beta \), it is clearly that tan\( \beta \) has little impact on \( \kappa_{bb} \). From Fig. 3 we find that the decay channel \( H \rightarrow b\bar{b} \) is more sensitive to \( M_{H^{\pm}} \) than tan\( \beta \). And \( \kappa_{bb} \) decreases significantly with the increasing of \( M_{H^{\pm}} \). Cause for the constraints on \( M_{H^{\pm}} \) from the decay channel \( H \rightarrow b\bar{b} \), \( M_{H^{\pm}} \) can be varied in a larger
parameter space than $M_{H_1^\pm}$.

\[ \text{(a)} \]

\[ \begin{array}{c}
\text{(b)} \\
\end{array} \]

Fig. 3. (a)$\kappa_{\tilde{b}\tilde{b}}$ as a function of $M_{H_1^\pm}$ for the parameter $\tan \beta = 50$; (b)$\kappa_{\tilde{b}\tilde{b}}$ as a function of $\tan \beta$ for the parameter $M_{H_1^\pm} = 600\text{GeV}$.

3.2 ALRM effects in $e^+e^- \rightarrow HZ$

In this subsection the production of $e^+e^- \rightarrow HZ$ at CEPC and future $e^+ e^-$ colliders has been studied and Feynman diagrams of this process are displayed in Fig. 4. Due to the contributions from $t$ channel are negligible small, we only give the Feynman diagrams in $s$ channel. As can be seen from Fig. 4, a new scalar $A_2$ and a heavy boson $Z'$ are added in the propagators. The relevant input parameter are chosen as above.

\[ \begin{array}{c}
\text{(1)} \\
\text{(2)} \\
\text{(3)} \\
\end{array} \]

Fig. 4. Feynman diagrams for the process $e^+e^- \rightarrow HZ$ with a new scalar $A_2$, a heavy boson $Z'$ propagator and some new couplings.

The cross section as a function of $\tan \beta$ with the mass of heavy boson $W'$ varying from 4 TeV to 5 TeV and charged boson $H_1^\pm$ varying from 150 GeV to 300 GeV is shown in Fig. 5 at $\sqrt{s} = 240$ GeV. Obviously the total cross sections are all less than SM from Fig. 5. From Ref. [19], the masses of $A_2$ become small when $\tan \beta$ and $M_{H_1^\pm}$ are small, and $M_{W'}$ influence the heavy boson $Z'$. In Fig. 5 due to the large $M_{W'}$, the contribution from $Z'$ propagator is small and the contribution from $A_2$ is mainly in small $\tan \beta$ region. Fig. 5(b) shows the discrepancies from $A_2$ propagator become larger with smaller $M_{H_1^\pm}$. At the other two collision energies, the same tendency can be obtained which we didn’t show.

\[ \begin{array}{c}
\text{(a)} \\
\text{(b)} \\
\end{array} \]

Fig. 5. The cross section as a function of $\tan \beta$ for the parameters $M_{W'}$ and $M_{H_1^\pm}$ respectively at $\sqrt{s} = 240$ GeV.

The total cross sections and corresponding relative ALRM discrepancies are given in Table 2 with $\tan \beta = 50$, $M_{H_1^\pm} = 200$ GeV and $M_{W'} = 4$ TeV at $\sqrt{s} = 240$ GeV, 500 GeV, and 1 TeV respectively. The relative ALRM discrepancy is defined as $\delta = (\sigma_{\text{ALRM}} - \sigma_{\text{SM}}) / \sigma_{\text{SM}}$. In this table, we can see the relative ALRM discrepancies are increasing with $\sqrt{s}$. It is worth mentioning that the Higgs sector in ALRM is very similar to that in 2HDM, where one Higgs doublet couples to up-quarks and the second couples to down-quarks. Therefore, it does not lead to any flavor changing neutral current problem and light charged Higgs is phenomenologically acceptable.
Table 2. The total cross sections and corresponding relative ALRM discrepancies for the process $e^+e^- \rightarrow HZ$ at $\sqrt{s} = 240$ GeV, 500 GeV and 1 TeV respectively.

| $\sqrt{s}$ (GeV) | $\sigma_{\text{ALRM}}$ (fb) | $\sigma_{\text{SM}}$ (fb) | $\delta$(%) |
|------------------|-----------------------------|---------------------------|-------------|
| 240              | 220.06                      | 223.1                     | -1.36       |
| 500              | 51.66                       | 53.22                     | -2.93       |
| 1000             | 11.13                       | 11.94                     | -6.78       |

In order to analyze the discovery significance which is calculated by the formula $\frac{n_S - n_{\text{tot}}}{\sqrt{n_{\text{tot}}}}$, where $n_S = \int L dt \times (\sigma_{\text{ALRM}} - \sigma_{\text{SM}})$ is the number of discrepancy events and $n_{\text{tot}} = \int L dt \times \sigma_{\text{SM}}$ is the number of total events. The discovery significance is plotted in Fig. 6 as a function of integrated luminosity for CEPC, ILC and CLIC respectively. From Fig. 6 one can see that the integrated luminosity of all three colliders can reach several hundred specifically at 619.72 $fb^{-1}$(CEPC), 553.80 $fb^{-1}$(ILC) and 443.93 $fb^{-1}$(CLIC) when the discovery significance is 5$\sigma$. By contrast CLIC seems have an advantage in detecting it. It’s worth mentioning that the discovery significance shown in Fig. 6 is calculated with no kinetic cuts. It can not be treated as a seriously result.

3.3 ALRM effects in $e^+e^- \rightarrow HZ \rightarrow l^+l^-b\bar{b}$

In this subsection we will analyze and compute the cross section for production and subsequent decay at $\sqrt{s} = 240$ GeV, 500 GeV and 1 TeV respectively. Feynman diagrams for subsequent decay of the SM-like Higgs boson into a pair of bottom quarks and Z boson into opposite-sign di-lepton, where $l = e, \mu$ and $\tau$, are showed in Fig. 7 associated with ALRM. When doing the numerical calculation, the mass of fermions is chosen as follows:

$$M_e = 5.11 \times 10^{-4} \text{ GeV}, \quad M_\mu = 1.0566 \times 10^{-1} \text{ GeV},$$
$$M_\tau = 1.777 \text{ GeV}, \quad M_b = 4.7 \text{ GeV}.$$  (11)

In dealing with the sequential Z-boson leptonic decay and Higgs decay, the naive narrow-width approximation (NWA) method is used to produce the total cross section. Hence cross section for this process can be approximately written as:

$$\sigma(e^+e^- \rightarrow l^+l^-b\bar{b}) \simeq \sigma(e^+e^- \rightarrow HZ) \times \text{BR}(H \rightarrow b\bar{b}) \times \text{BR}(Z \rightarrow l^+l^-).$$  (12)

In order to get the precise branch ratio of $H \rightarrow b\bar{b}$ in ALRM, we set the K-factor of each channel is the same as which in SM. By adopting HDECAY program 40, dominant Higgs partial decay widths are computed and listed in Table 3. Here the scale $\mu$ of the Yukawa coupling $y_Q(\mu) = m_Q(\mu)/v$ is used to be the mass of Higgs in the calculation, $m_Q(\mu)$ is the running mass of heavy quark. The total cross section $\Gamma_{\text{tot}} = \Gamma_{bb} + \Gamma_{cc} + \Gamma_{\tau+} + \Gamma_{zz} + \Gamma_{ww} + \Gamma_{gg} = 3.93 \times 10^{-3} \text{ GeV}$. Obviously the branch ratio of $H \rightarrow b\bar{b}$ is 58.27% in SM and experiment shows that SM prediction for the decay branching fraction of Higgs boson with mass around 125.09 GeV to $b\bar{b}$ is 57.5% 22. The leading order (LO) results in SM computed by MadWidth and the corresponding K-factors ($\frac{\Gamma_{\text{HDECAY}}}{\Gamma_{\text{MadWidth}}}$) are also added in Table 3.

The decay width of $H \rightarrow gg$ is directly used the SM result by HDECAY. To this way we can estimate the branch ratio of $H \rightarrow b\bar{b}$ in ALRM as a function of $M_{H^\pm}$. As for the branch ratio of $Z \rightarrow l^+l^-$, the result is 10.31% in both SM and ALRM which is independent of $M_{H^\pm}$.
Table 3. Higgs boson partial decay widths in the framework of SM computed by HDECAy and MadWidth, and the corresponding K factors.

| Decay mode | HDECAy [MeV] | MadWidth [MeV] | K factor |
|------------|--------------|----------------|----------|
| $H \rightarrow bb$ | 2.29 | 1.8320 | 1.2514 |
| $H \rightarrow c\bar{c}$ | 0.1043 | 0.0824 | 1.2658 |
| $H \rightarrow Z^+Z^-$ | 0.2474 | 0.2499 | 0.9903 |
| $H \rightarrow W^+W^-$ | 0.1047 | 0.0607 | 1.7249 |
| $H \rightarrow Zf\bar{f}$ | 0.3261 |

The total cross sections and corresponding relative discrepancies are shown in Table 4 at $\sqrt{s}=240$ GeV, 500 GeV and 1 TeV respectively, where the relative deviation is defined as $\delta = (\sigma_{ALRM} - \sigma_{SM}) / \sigma_{SM}$. From Table 4 one finds that with the increasing of $\sqrt{s}$, the cross sections both in ALRM and SM are decreasing. While the corresponding relative discrepancies are increasing significantly, which will be phenomenologically accessible.

Table 4. The total cross sections and corresponding relative discrepancies for the process $e^+e^\rightarrow Hz \rightarrow l^+l^- b\bar{b}$ by NWA with $M_{H^\pm}=600$ GeV at $\sqrt{s}=240$ GeV, 500 GeV and 1 TeV respectively.

| $\sqrt{s}$(GeV) | $\sigma_{ALRM}(fb)$ | $\sigma_{SM}(fb)$ | $\delta(\%)$ |
|-----------------|---------------------|------------------|--------------|
| 240             | 13.522              | 13.397           | 0.93         |
| 500             | 3.174               | 3.197            | -0.72        |
| 1000            | 0.684               | 0.717            | -4.60        |

To analyze the feasibility of experiment, the discovery significance is chosen the same as last subsection: $\sqrt{n_\text{tot}}$, where $n_\text{tot} = \int Ldt \times BR(Z \rightarrow l^+l^-) \times (\sigma_{ALRM} \times BR_{ALRM}(H \rightarrow b\bar{b}) - \sigma_{SM} \times BR_{SM}(H \rightarrow b\bar{b}))$ is the number of discrepancy events and $n_\text{tot} = \int Ldt \times BR(Z \rightarrow l^+l^-) \times \sigma_{SM} \times BR_{SM}(H \rightarrow b\bar{b})$ is the total events. In Fig. 8 we depict the integrated luminosity needed for $5\sigma$ discovery significance as a function of $M_{H^\pm}$ for CEPC, ILC and CLIC determined by $\sqrt{n_\text{tot}}$. For $e^+e^- \rightarrow HZ \rightarrow l^+l^- b\bar{b}$ process, The discrepancies between SM and ALRM are mainly influenced by the cross section of $e^+e^- \rightarrow HZ$ and the branching ratio of Higgs to $b\bar{b}$. The cross sections of $e^+e^- \rightarrow HZ$ in ALRM is a little smaller than that in SM but the branching ratio of $H \rightarrow b\bar{b}$ is opposite. In the middle of $M_{H^\pm}$ region, the two part of the contribution counteracts each other, the cross section of $e^+e^- \rightarrow HZ \rightarrow l^+l^- b\bar{b}$ in ALRM and SM are approaching. So in order to detect the discrepancies, the required integrated luminosity is very large, which means that the region is difficult to search new physics. This corresponds to the peak in Fig. 8.

4 Summary

In the present paper, we have analyzed Higgs decay in each channel, Higgs and Z boson associated production and decay at CEPC and future $e^+e^-$ colliders in Alternative Left-Right model(ALRM), motivated by superstring inspired $E_6$ model. We found that the contribution of charged Higgs boson $M_{H^\pm}$ to Higgs decay is quite negligible due to the large $\tan\beta$, while $M_{H^\pm}$ plays an essential role in the decay channel of $H \rightarrow b\bar{b}$ due to the mixing of scalars. And the model predictions for the signal strengths of Higgs decay, in particularly of $H \rightarrow ZZ$ that are consistent with SM expectations. We also analyzed the discrepancies of cross sections about Higgs and Z boson production between ALRM and SM and found that it can enhance to 6.78% when $\sqrt{s}$ increase to 1 TeV. Finally we study the sequential decay of Higgs and Z boson respectively to $b\bar{b}$ and $l^+l^-$, where

![Graph](image-url)
l = e, \mu and \tau, with NWA method. We found that the cross sections of sequential decay are much more dependent on the branch ratio of $H \rightarrow b\bar{b}$. We also shown that the typical value of cross sections are of $O(1)$ fb which can be measured by future colliders.

This work was partially supported by the National Natural Science Foundation of China(No.11375008, No.11647307).

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