Probing Neutral and Doubly-Charged Scalars at Future Lepton Colliders

Fang Xu

Collaborators: B. Dev, Y. Zhang

Washington University in St. Louis

xufang@wustl.edu

October 13, 2019
Overview

1 Introduction
   - Motivation of the project
   - Future lepton colliders

2 Probing Yukawa couplings of $H_3$ and $H^{\pm\pm}$ in $e\mu$ sector
   - Background & Signals at future lepton colliders
   - Signals of neutral $H_3$ and doubly-charged $H^{\pm\pm}$ Higgs
   - Invariant mass for the signal and background
   - Yukawa couplings in parameter space

3 Conclusions
Motivation of the project

- Many new physics scenarios beyond the Standard Model (SM) often necessitate the existence of new neutral ($H_3$) and/or doubly-charged ($H^{±±}$) scalar fields, which might couple to the SM charged leptons through Yukawa interaction:

$$\mathcal{L}_{H_3} \supset Y_{\alpha\beta} \bar{l}_\alpha H_3 l_\beta + h.c.$$ (1)

$$\mathcal{L}_{H^{++}} \supset Y_{\alpha\beta} l_\alpha H^{++} l_\beta + h.c.$$ (2)

- For example, in left-right symmetric model (LRSM), the physical fields $H_3$ and $H^{±±}$ comes from the triplet Higgs fields $\Delta_R$:
  
  $H_3 \equiv \text{Re}(\Delta^0)$ and $H^{±±}_R \equiv \Delta^{±±}_R$, where

$$\Delta_{L,R} = \begin{pmatrix}
\Delta^+_L,R / \sqrt{2} & \Delta^{++}_L,R \\
\Delta^0_L,R & -\Delta^+_L,R / \sqrt{2}
\end{pmatrix}$$ (3)

$$\mathcal{L}_Y \supset Y_{L,\alpha\beta} L_{L,\alpha}^T C \Delta_L L_{L,\beta} + Y_{R,\alpha\beta} L_{R,\alpha}^T C \Delta_R L_{R,\beta} + h.c.$$ (4)
Motivation of the project

- With the characters of $H_3$ and $H^{±±}$, we can explore the discovery prospect of them as well as the magnitude of the corresponding Yukawa couplings.
- We treat the center-of-mass energy $\sqrt{s}$, Yukawa couplings $Y_{\alpha\beta}$ and the mass of $H_3$ and $H^{±±}$ as parameters to simulate the $e^+e^-$ collisions at future lepton colliders and to see to what extent the couplings can be probed.
- For now, we are only working in the electron-muon sector of Yukawa matrices.
Future lepton colliders

- Future lepton colliders provide a clean environment for the searches of the neutral and doubly-charged scalars.
- At LHC, although we can use pair production $pp \rightarrow H^{++} H^{--}$ to search for the signal of doubly-charged scalars, the magnitude of Yukawa couplings cannot be probed.

Table 1: The planned center-of-mass energy and expected integrated luminosity for the International Linear Collider (ILC) and two stages of Compact Linear Collider (CLIC)

<table>
<thead>
<tr>
<th>Collider</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\mathcal{L}_{\text{int}}$ (ab$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>CLIC</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>
At future lepton colliders, there are two kinds of interesting processes which can be used to probe the neutral and doubly-charged Higgs: 
\[ e^+e^- \rightarrow e^+e^-\mu^+\mu^- \text{ and } e^+e^- \rightarrow e^+e^-\mu^-/e^+e^- \rightarrow e^-e^-\mu^+\mu^+. \]

And we notice that in SM, there is no process which can give a final state of the second type.

For the simplest case, we assume only the off-diagonal terms of Yukawa matrices \( Y_{e\mu} \) are non-zero, which will cause lepton flavor violating (LFV) signals.

In this case, the process \( e^+e^- \rightarrow e^+e^-\mu^+\mu^- \) can be used to probe Yukawa couplings below 0.1 at future lepton colliders.
Fig.1: Feynman diagrams for the SM background
Fig. 2: Feynman diagrams for the production of $H_3$
Fig. 3: Feynman diagrams for the single production of $H^{++}$

When $\sqrt{s} \gtrsim 2M_{H^{\pm\pm}}$, cross section ($\propto |Y_{e\mu}|^2$) are dominated by the pair production modes ($|Y_{e\mu}|$ independent) for small Yukawa couplings.
Here we are considering the on-shell single production.

The decay branching ratios (BR) of $H_3 \rightarrow e^{\pm} \mu^{\mp}$ are considered to be 50% respectively.

The decay branching ratios of $H^{\pm\pm} \rightarrow e^{\pm} \mu^{\pm}$ are considered to be 100%.

In SM, there is no decay of the kind $X \rightarrow e\mu$ (LFV) which can be distinguished from the SM background.

The distribution of invariant mass of $e^{\pm} \mu^{\mp}$ should have a peak around the mass of $H_3$ for the signal.

The distribution of invariant mass of $e^{\pm} \mu^{\pm}$ should have a peak around the mass of $H^{\pm\pm}$ for the signal.
Invariant mass for the signal and background

**Fig. 4:** Distributions of invariant mass $M_{e^{+}\mu^{-}}$ (left) and $M_{e^{-}\mu^{+}}$ (right) at $\sqrt{s} = 1\text{TeV}$, $|Y_{e\mu}| = 0.2$, mass of neutral Higgs $M_{H_3} = 800\text{GeV}$. 
Fig. 5: Distributions of invariant mass $M_{e^+\mu^+}$ (left) and $M_{e^-\mu^-}$ (right) at $\sqrt{s} = 1\text{TeV}$, $|Y_{e\mu}| = 0.2$, mass of doubly-charged Higgs $M_{H^{\pm\pm}} = 800\text{GeV}$.
Yukawa couplings in parameter space

- Signal significance: $N \geq 3$ for a good confidence level

\[ N = \frac{S}{\sqrt{S + B}} \]  

where $S$ and $B$ are the number of events for the signal and SM background.

- Signal significance can be improved through choosing cut properly. This will allow us to probe Yukawa couplings in a larger region of parameter space.

- For $H_3$, we choose the cut to be $M_{e^\pm \mu^\mp} \geq 500\text{GeV}$ (ILC 1TeV), $600\text{GeV}$ (CLIC 1.5TeV) and $700\text{GeV}$ (CLIC 3TeV).

- For $H^{\pm\pm}$, we choose the cut to be $M_{e^\pm \mu^\pm} \geq 500\text{GeV}$ (ILC 1TeV), $750\text{GeV}$ (CLIC 1.5TeV) and $1500\text{GeV}$ (CLIC 3TeV).
Fig. 6: Yukawa couplings as a function of neutral Higgs mass $M_{H_3}$ at ILC (1TeV, $1ab^{-1}$), CLIC (1.5TeV, $2.5ab^{-1}$ & 3TeV, $5ab^{-1}$) when $N = 3$. 

$\text{BR}(H_3 \rightarrow e^\pm \mu^\mp) = 50\%$

$I\!L\!C$ 1TeV
$\text{CLIC}$ 1.5TeV
$\text{CLIC}$ 3TeV
$\text{BR}(H_3 \rightarrow e^\pm \mu^\mp) = 50\%$

before cut
after cut

0.05
0.10
0.50
1

$|Y_{e\mu}|$

$g-2_e$

$\mu$onium oscillation

$\text{ee} \rightarrow \mu\mu$ (LEP)
Fig. 7: Yukawa couplings as a function of doubly-charged Higgs mass $M_{H_L^{±±}}$ at ILC (1TeV, 1ab$^{-1}$), CLIC (1.5TeV, 2.5ab$^{-1}$ & 3TeV, 5ab$^{-1}$) when $N = 3$. 
Fig. 8: Yukawa couplings as a function of doubly-charged Higgs mass $M_{H_R^{±±}}$ at ILC (1TeV, 1ab$^{-1}$), CLIC (1.5TeV, 2.5ab$^{-1}$ & 3TeV, 5ab$^{-1}$) when $N = 3$. 

$\text{BR}(H_R^{±±}\rightarrow e^±\mu^±) = 100\%$

$|Y_{e\mu}|$

$M_{H_R^{±±}}$ [TeV]

0.1 0.5 1 1.0 1.5 2.0 2.5 3.0

$H_R^{±±}$ at future lepton colliders

Washington University in St. Louis
Conclusions

- At ILC 1TeV stage, it is hard to probe the doubly-charged Higgs while we still have some sensitive region for the search of neutral Higgs around $|Y_{e\mu}| \sim 0.1$.

- At CLIC 1.5TeV and 3TeV stages, both neutral and doubly-charged Higgs have some sensitive region in the parameter space. But the pair production modes of doubly-charged Higgs will prevent us from probing the Yukawa couplings at the region $M_{H^{\pm\pm}} \lesssim \sqrt{s}/2$.

- For now, we have just considered the off-diagonal terms in the Yukawa coupling matrices of neutral and doubly-charged Higgs fields. The next step is to include all the elements in the $e\mu$ sector of Yukawa coupling matrices, in which another process $e^+e^- \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp$ will also give a signal that SM does not have. And this process would be a good platform for the search of neutral and doubly-charged Higgs.
Thank You!