Probing Neutral and Doubly-Charged Scalars at Future Lepton Colliders

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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 ($H^{\pm\pm}$) scalar fields, which might couple to the SM charged leptons through Yukawa interaction:

$$\mathcal{L}_{H_3} \supset Y_{\alpha\beta}\bar{l_\alpha}H_3 l_\beta + \text{h.c.} \tag{1}$$

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

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

$$\Delta_{\text{L,R}} = \begin{pmatrix} \Delta^+_{\text{L,R}}/\sqrt{2} & \Delta^{++}_{\text{L,R}} \\ \Delta^0_{\text{L,R}} & -\Delta^+_{\text{L,R}}/\sqrt{2} \end{pmatrix} \tag{3}$$

$$\mathcal{L}_\text{Y} \supset Y_{\text{L},\alpha\beta} L^\mathsf{T}_{\text{L},\alpha} C \Delta_\text{L} L_{\text{L},\beta} + Y_{\text{R},\alpha\beta} L^\mathsf{T}_{\text{R},\alpha} C \Delta_\text{R} L_{\text{R},\beta} + \text{h.c.} \tag{4}$$

Motivation of the project

- With the characters of H_3 and $H^{\pm\pm}$, 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 $H^{\pm\pm}$ 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 $pp \to H^{++}H^{--}$ to search for the signal of doubly-charged scalars, the magnitude of Yukawa couplings cannot be probed.

Table1: The planned center-of-mass energy and expected integrated luminosity for the International Linear Collider (ILC) and two stages of Compact Linear Collider (CLIC)

Collider	$\sqrt{s}$ (TeV)	$\mathscr{L}_{\rm int}$ (ab^{-1})
ILC	1.0	1.0
CLIC	1.5	2.5
	3.0	5.0

Background & Signals at future lepton colliders

- At future lepton colliders, there are two kinds of interesting processes which can be used to probe the neutral and doubly-charged Higgs: $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^+\mu^-\mu^-/e^+e^- \to e^-e^-\mu^+\mu^+$.
- 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 $e^+e^- \to e^+e^-\mu^+\mu^-$ can be used to probe Yukawa couplings below 0.1 at future lepton colliders.

Background & Signals at future lepton colliders

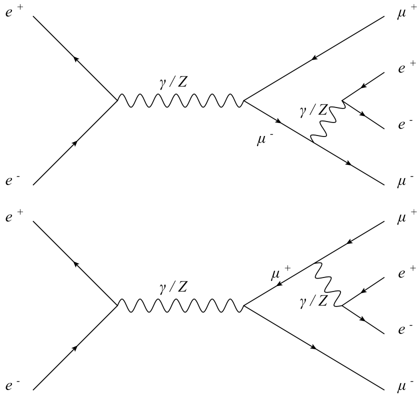

Fig.1: Feynman diagrams for the SM background

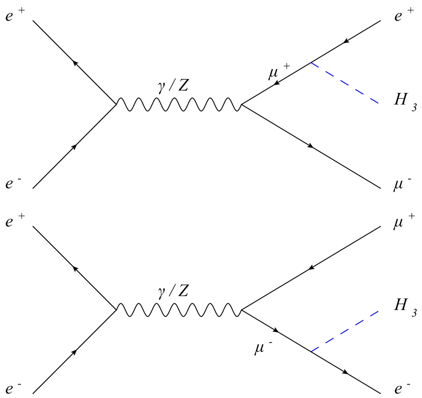

Fig.2: Feynman diagrams for the production of H_3

Background & Signals at future lepton colliders

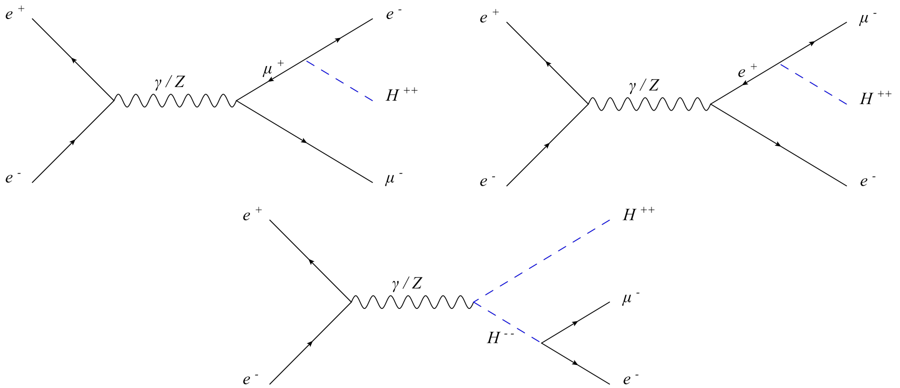

Fig.3: Feynman diagrams for the single production of H^{++}

When $\sqrt{s} \gtrsim 2M_{H^{\pm\pm}}$, cross section ($\propto \mid Y_{e\mu} \mid^2$) are dominated by the pair production modes ($\mid Y_{e\mu} \mid$ independent) for small Yukawa couplings.

$e^+e^- \to e^\pm\mu^\mp H_3 \to e^\pm\mu^\mp(e^\mp\mu^\pm)$
$e^+e^- \to e^\mp\mu^\mp H^{\pm\pm} \to e^\mp\mu^\mp(e^\pm\mu^\pm)$

- Here we are considering the on-shell single production.
- The decay branching ratios (BR) of $H_3 \to e^\pm\mu^\mp$ are considered to be 50% respectively.
- The decay branching ratios of $H^{\pm\pm} \to e^\pm\mu^\pm$ are considered to be 100%.
- In SM, there is no decay of the kind $X \to e\mu$ (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

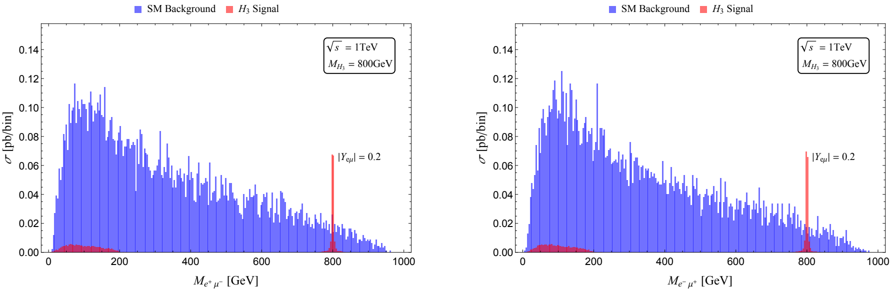

Fig.4: Distributions of invariant mass $M_{e^+\mu^-}$ (left) and $M_{e^-\mu^+}$ (right) at $\sqrt{s} = 1$TeV, $| Y_{e\mu} |= 0.2$, mass of neutral Higgs $M_{H_3} = 800$GeV.

Invariant mass for the signal and background

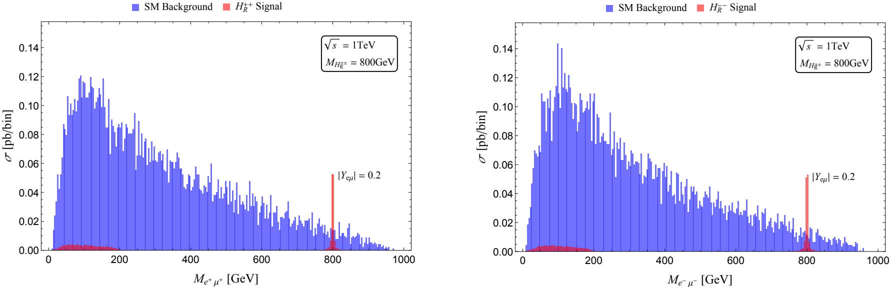

Fig.5: Distributions of invariant mass $M_{e^+\mu^+}$ (left) and $M_{e^-\mu^-}$ (right) at $\sqrt{s} = 1$TeV, $\mid Y_{e\mu} \mid = 0.2$, mass of doubly-charged Higgs $M_{H_R^{\pm\pm}} = 800$GeV.

Yukawa couplings in parameter space

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

$$N = \frac{S}{\sqrt{S+B}} \tag{5}$$

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 $M_{e^\pm \mu^\mp} \geq$ 500GeV (ILC 1TeV), 600GeV (CLIC 1.5TeV) and 700GeV (CLIC 3TeV)
- For $H^{\pm\pm}$, we choose the cut to be $M_{e^\pm \mu^\pm} \geq$ 500GeV (ILC 1TeV), 750GeV (CLIC 1.5TeV) and 1500GeV (CLIC 3TeV).

Yukawa couplings in parameter space

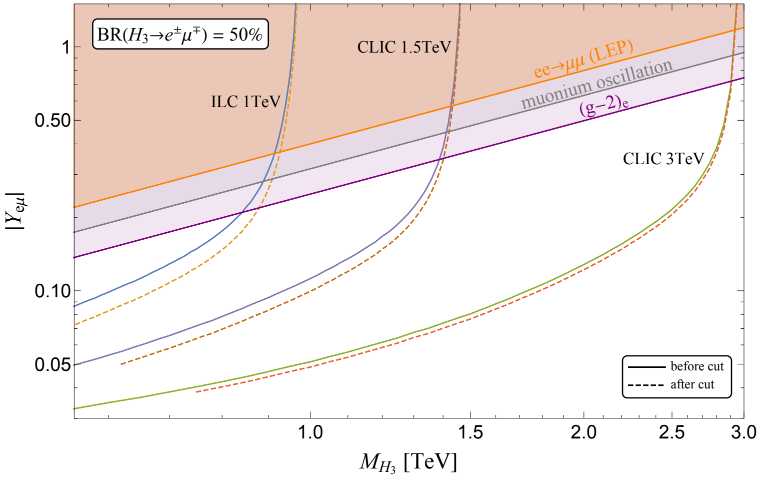

Fig.6: Yukawa couplings as a function of neutral Higgs mass M_{H_3} at ILC (1TeV, 1ab^{-1}), CLIC (1.5TeV, 2.5ab^{-1} & 3TeV, 5ab^{-1}) when $N = 3$.

Yukawa couplings in parameter space

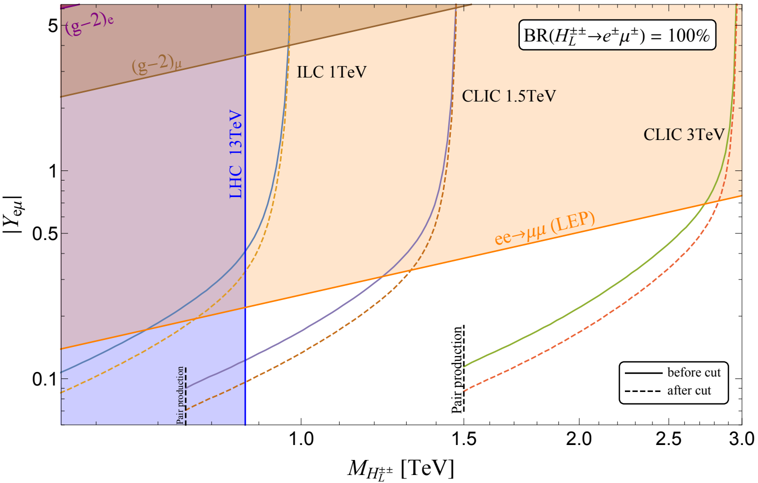

Fig.7: Yukawa couplings as a function of doubly-charged Higgs mass $M_{H_L^{\pm\pm}}$ at ILC (1TeV, 1ab^{-1}), CLIC (1.5TeV, 2.5ab^{-1} & 3TeV, 5ab^{-1}) when $N = 3$.

Yukawa couplings in parameter space

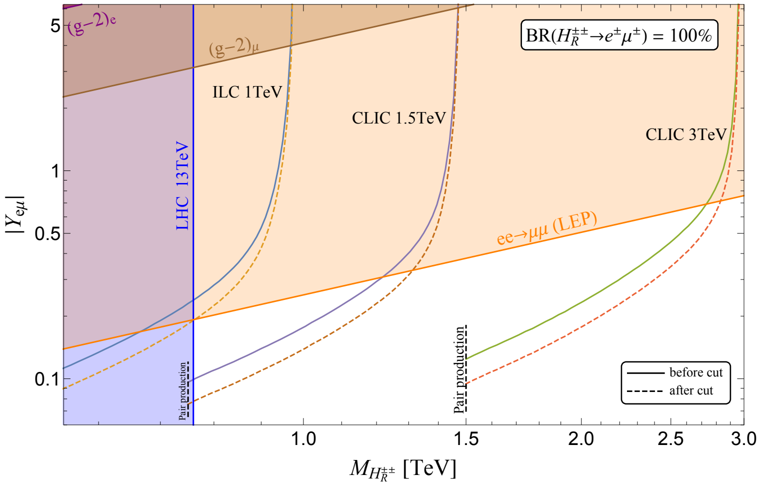

Fig.8: Yukawa couplings as a function of doubly-charged Higgs mass $M_{H_R^{\pm\pm}}$ at ILC (1TeV, 1ab^{-1}), CLIC (1.5TeV, 2.5ab^{-1} & 3TeV, 5ab^{-1}) when $N = 3$.

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 $\mid Y_{e\mu} \mid \sim 0.1$
- 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 $e^+e^- \to e^\pm e^\pm \mu^\mp \mu^\mp$ 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 !