Probing Neutral and Doubly-Charged Scalars at Future Lepton Colliders

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May 4, 2020

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Motivation

- Many new physics scenarios beyond the Standard Model (BSM) often necessitate the existence of new neutral (H_3) and doubly-charged ($H^{\pm\pm}_{\rm L,R}$) scalar fields, which might couple to the SM charged leptons through Yukawa interaction:

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

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

- For example, in Left-Right Symmetric Model (LRSM), the physical fields H_3 and $H^{\pm\pm}$ comes from the triplet Higgs fields $\Delta_{\rm L,R}$: $H_3 \equiv {\rm Re}(\Delta^0)$ and $H^{\pm\pm}_{\rm L,R} \equiv \Delta^{\pm\pm}_{\rm L,R}$, where

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

$$\mathcal{L}_{\rm Y} \supset Y_{{\rm L},\alpha\beta}L^{\sf T}_{{\rm L},\alpha}C^{-1}\sigma_2\Delta_{\rm L}L_{{\rm L},\beta} + Y_{{\rm R},\alpha\beta}L^{\sf T}_{{\rm R},\alpha}C^{-1}\sigma_2\Delta_{\rm R}L_{{\rm R},\beta} + \text{h.c.} \tag{4}$$

Motivation

- 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.
- Assuming that only the elements in electron-muon sector of Yukawa matrices are not zero.

Future lepton colliders

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

- Future lepton colliders provide a clean environment for the searches of the neutral and doubly-charged scalars.
- At LHC, pair production $pp \to H^{++}H^{--}$ is a good way to search for the signal of doubly-charged scalars. But we can look at single production at lepton colliders to probe the magnitude of Yukawa couplings.

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 scalars: $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^+\mu^-\mu^-/e^-e^-\mu^+\mu^+$. And in SM, there is no process which have a final state of the second type.
- We first assume that the diagonal terms Y_{ee}, $Y_{\mu\mu}$ and off-diagonal term $Y_{e\mu}$ are not zero separately.

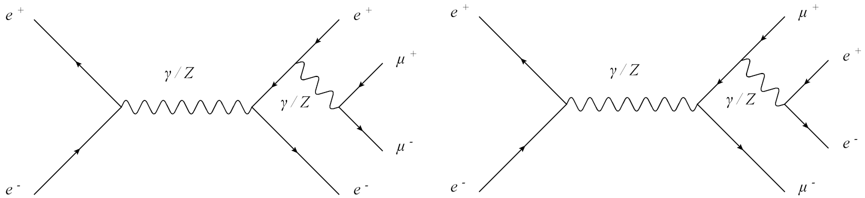

Figure 1: Feynman diagrams for the SM background

Background & Signals at future lepton colliders

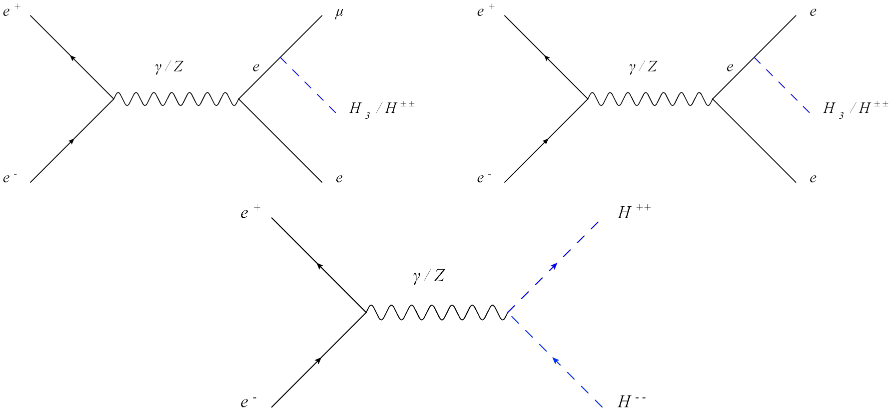

Figure 2: Feynman diagrams for the production of H_3 or $H^{\pm\pm}$

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

Invariant mass for the signal and background

- For the case of $Y_{e\mu} \neq 0$, there should be a peak around the mass of the scalar in the distribution of invariant mass of $e^{\pm}\mu^{\mp}$ (neutral H_3 case) or $e^{\pm}\mu^{\pm}$ (doubly-charged $H^{\pm\pm}$ case).

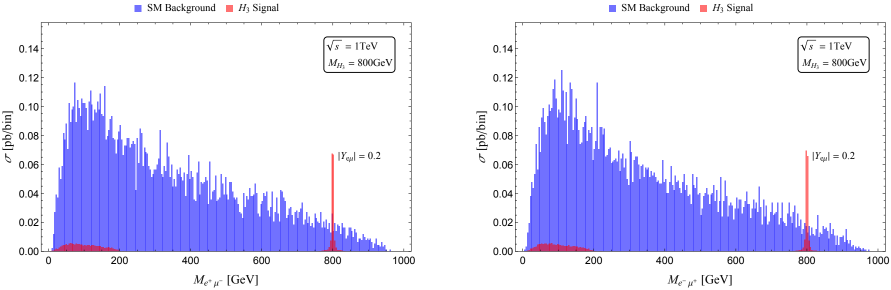

Figure 3: Distributions of invariant mass $M_{e^+\mu^-}$ (left) and $M_{e^-\mu^+}$ (right) at $\sqrt{s} = 1\text{TeV}$, $\mid Y_{e\mu} \mid = 0.2$, mass of neutral scalar $M_{H_3} = 800\text{GeV}$.

Invariant mass for the signal and background

- These could be clear signals of lepton flavor violation (LFV). And we can also use this to choose some cuts to exclude most of the background events which will allow us to probe Yukawa couplings in a larger region of parameter space.

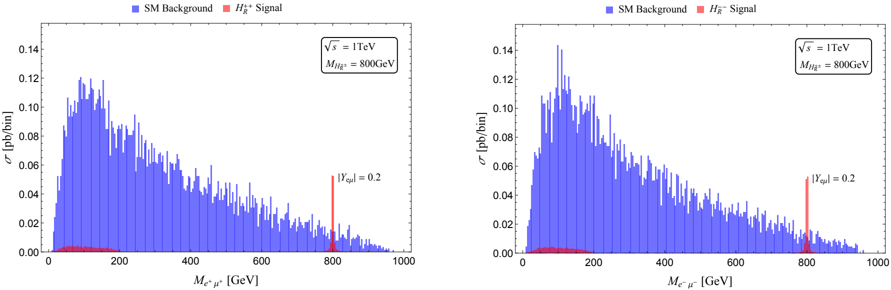

Figure 4: Distributions of invariant mass $M_{e^+\mu^+}$ (left) and $M_{e^-\mu^-}$ (right) at $\sqrt{s} = 1\text{TeV}$, $\mid Y_{e\mu} \mid = 0.2$, mass of doubly-charged Higgs $M_{H_{\text{R}}^{\pm\pm}} = 800\text{GeV}$.

Yukawa couplings in parameter space

- Signal significance: $N = \frac{S}{\sqrt{S+B}}$ and we take $N = 3$ for the plots. S and B are the number of events for the signal and SM background.
- For the off-diagonal coupling $Y_{e\mu} \neq 0$ case:
  - For H_3, choose the cut to be $M_{e^\pm\mu^\mp} \geq$ 500GeV (ILC 1TeV), 600GeV (CLIC 1.5TeV) and 700GeV (CLIC 3TeV)
  - For $H^{\pm\pm}$, choose the cut to be $M_{e^\pm\mu^\pm} \geq$ 500GeV (ILC 1TeV), 750GeV (CLIC 1.5TeV) and 1500GeV (CLIC 3TeV)
- For the diagonal couplings $Y_{ee}, Y_{\mu\mu} \neq 0$ case, only neutral scalar H_3 can give a final state of $e^+e^-\mu^+\mu^-$, choose the cut to be $M_{\mu^+\mu^-} \geq$ 500GeV (ILC 1TeV), 600GeV (CLIC 1.5TeV) and 700GeV (CLIC 3TeV)

H_3 in $e^+e^- \to e^+e^-\mu^+\mu^-$

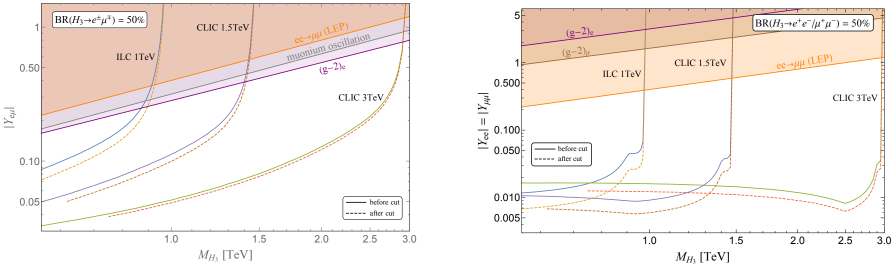

Figure 5: 3σ sensitivity reach of $Y_{e\mu}$ (left) and Y_{ee},$Y_{\mu\mu}$ (right) as a function of neutral scalar mass: M_{H_3} at ILC (1TeV, 1ab^{-1}), CLIC (1.5TeV, 2.5ab^{-1} & 3TeV, 5ab^{-1}).

$H^{\pm\pm}_{\mathrm{L,R}}$ in $e^+e^- \to e^+e^-\mu^+\mu^-$

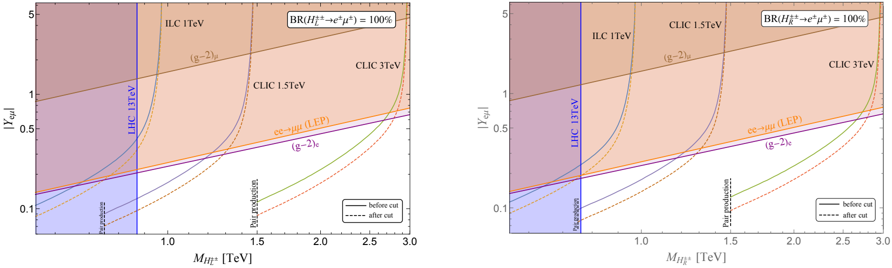

Figure 6: 3σ sensitivity reach of $Y_{e\mu}$ as a function of doubly-charged scalar mass: left-handed $M_{H^{\pm\pm}_{\mathrm{L}}}$ (left) and right-handed $M_{H^{\pm\pm}_{\mathrm{R}}}$ (right) at ILC (1TeV, 1ab^{-1}), CLIC (1.5TeV, 2.5ab^{-1} & 3TeV, 5ab^{-1}).

Doubly-charged scalar cannot have this final state with only $Y_{ee}, Y_{\mu\mu} \neq 0$

H_3 in $e^+e^- \to e^+e^+\mu^-\mu^-/e^-e^-\mu^+\mu^+$

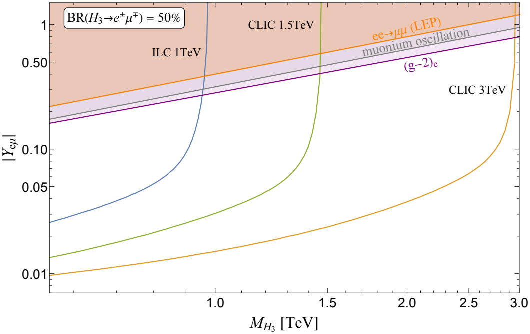

Figure 7: 3σ sensitivity reach of $Y_{e\mu}$ as a function of neutral scalar mass: M_{H_3} at ILC (1TeV, 1ab^{-1}), CLIC (1.5TeV, 2.5ab^{-1} & 3TeV, 5ab^{-1}).

Neutral scalar cannot have this final state with only $Y_{ee}, Y_{\mu\mu} \neq 0$

$H^{\pm\pm}_{\rm L,R}$ in $e^+e^- \to e^+e^+\mu^-\mu^-/e^-e^-\mu^+\mu^+$

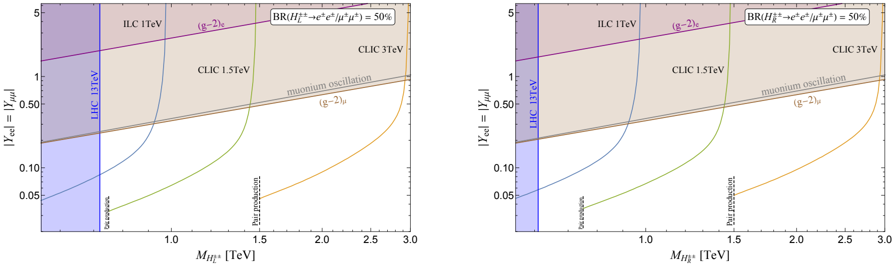

Figure 8: 3σ sensitivity reach of Y_{ee},$Y_{\mu\mu}$ as a function of doubly-charged scalar mass: left-handed $M_{H_{\rm L}^{\pm\pm}}$ (left) and right-handed $M_{H_{\rm R}^{\pm\pm}}$ (right) at ILC (1TeV, 1ab^{-1}), CLIC (1.5TeV, 2.5ab^{-1} & 3TeV, 5ab^{-1}).

Doubly-charged scalar cannot have this final state with only $Y_{e\mu} \neq 0$

$\mu \to e\gamma$

- Even if we assume that the diagonal terms $Y_{ee}, Y_{\mu\mu}$ and off-diagonal term $Y_{e\mu}$ are not zero separately, there is still a process could give a $\mu \to e\gamma$ signal with only $Y_{e\mu}$ of H_3 not 0

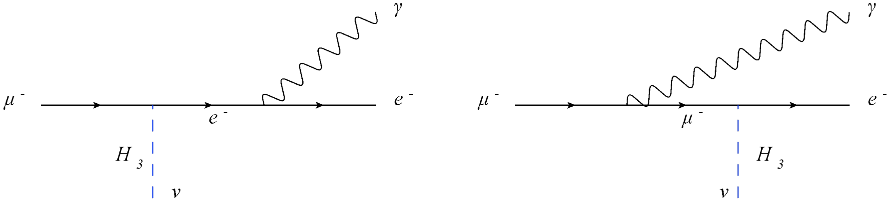

Figure 9: $\mu \to e\gamma$ diagrams with only $Y_{e\mu} \neq 0$. v stands for the vev which could be very large and looks like the contribution of these two diagrams is large.

- Indeed the amplitude square of the first and second diagram is $4e^2 Y_{e\mu}^2 v^2 \frac{p_1 \cdot p_2 - 2m_e m_\mu}{(m_\mu - m_e)^2}$. But the interference terms will cancel this identically.

Conclusions

- We have considered the $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^+\mu^-\mu^-/e^-e^-\mu^+\mu^+$ at future lepton colliders such as ILC 1TeV, CLIC 1.5TeV and CLIC 3TeV.
- There are still some sensitive regions for the search of neutral and doubly-charged Higgs. But we cannot probe the Yukawa couplings to a very low magnitude.
- The next step is to consider both diagonal and off-diagonal terms of Yukawa couplings not zero, where the $\mu \to e\gamma$ would be a strong constraint that could prevent the search of new Higgs.