Multi-charged TeV scale fermions & scalars in the framework of a radiative seesaw model

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Abstract

We are exploring the phenomenology of multi-charged fermions and scalars in the framework of a radiative neutrino mass generation model. In particular, we are interested in the collider signatures of this model at the LHC with $\sqrt{s} = 13$ TeV. We have studied the production, decays and possible signatures of these multi-charged fermions and scalars at the LHC experiment and suggested required luminosities to discover them. Apart from the Drell-Yan pair production, we have also studied photo-production of these particles.

Model

Symmetry Group: $SU(3)_c \times SU(2) \times U(1)_Y$

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Yukawa lagrangian:

$$\mathcal{L}_Y = m^2 \frac{q}{2} \bar{E}_{\beta} E_{\beta} + \frac{y^2}{2} L_{at.} \Phi_{\alpha}^2 E_{\beta}^+ \Phi_{\beta} + 1 \frac{y}{2} \bar{L} \Phi \left( \frac{(E_{\beta} + c)}{\beta} \right) - \left( \frac{e_{\rho \beta} \left( e_{\rho \beta} \right)^c}{h.c.} \right) \alpha, \beta \in 1, 2, 3$$

Scalar Potential:

$$V = \mu(H^T \Phi_2 k^{-2} + \mu'(H^T \Phi_2 k^{-2} + \lambda(H^T \Phi)^2(H^T \Phi_2)^2) + c.c.$$ Physical states after mixing of doubly charged Higgs bosons (after EWSB):

$$H_{a++} = O_{a1} \Phi_{\alpha}^2 + O_{a2} \Phi_{\alpha}^2 + O_{a3} \Phi_{\alpha}^2$$

$O_{a\alpha}$ is the mixing matrix.

Decay of doubly charged fermions

- The decay branching ratios of $E^{++}$ to possible decay modes shown for a particular choice of parameters.
- Parameters $\mu, \mu'$ and $\lambda$ play vital role in decays of $E^{++}$'s through mixing of the doubly charged scalars.
- Decay to same sign di-leptons is among important decay channels of $E^{++}$.
- For $E^{++}$ being lighter than multi-charged scalars, only 3-body decay is kinematically possible.
- Total decay width of $E^{++}$, $\Gamma_{TOT}$ has also shown in the inlet.

Parameter Scan for Signatures

- $\Gamma_{TOT}$ is suppressed but not enough to ensure displaced vertex or highly ionizing tracks.
- 3-body decay lengths depend on Yukawa couplings and mixing among doubly charged scalars which are controlled by $\mu, \mu'$ and $\lambda$.
- $f_1 - \mu$ parameter space scanned to ascertain the regions for different kind of signatures.

Neutrino Mass

1-loop Feynman Diagrams $\nu$-mass bound

Branching Ratio

$$\frac{\Gamma_{TOT}}{\Gamma} = f = y_2^2$$

$$m_e \text{ [GeV]}$$

10^0 10^1 10^2 10^3 10^4 10^5

10^2 10^3 10^4 10^5 10^6 10^7 10^8

Luminosity [fb$^{-1}$] $\mu$ [GeV] $c\tau$ [cm]

Parameter Scan for Signatures

- We searched in: $PP \rightarrow E^{++} E^{--} \rightarrow 4$-lepton + missing transverse energy signal channel.

Multi-lepton signal search

- For prompt decay of $E^{++}$, the ATLAS search [Phys. Rev. D 98 (2018) 032009], 36.1 fb$^{-1}$ data of the 13 TeV LHC excludes $m_2$ below 870 GeV.
- The discovery reach of the LHC with 3000 fb$^{-1}$ integrated luminosity and 13 TeV center of mass energy, is estimated to be $m_2 = 1800$ (1600) GeV at 3$\sigma$ and 5$\sigma$ significance.
Decay of doubly charged scalars

- The decay Branching Ratios are shown (total decay width $\Gamma_{TOT}$ in inlets (Top plots)).
- Parameters $\mu, \mu'$ and $\lambda$ play vital role in decays of $H^\pm \pm$'s through mixing.
- Decay to same sign dileptons is among the important decay channels of $H^\pm \pm$'s.
- Decay to same sign dileptons is depends on $f_c$.

Total pair production of scalars

- Photo-production contributes significantly in total production cross-section.

Luminosity $[fb^{-1}]$

- Ordering in values of $\sigma_{pp} \times 10^6$ for $H^\pm \pm$ depends upon hyper-charges.
- For low mixing, $H^\pm \pm = H^{\phi^+ \phi^-} \pm \phi_1^\pm$ and $H^{\phi^+ \phi^-} = \phi_1^*$.

Decay of triply charged scalars

- Decay to same sign dileptons with a same charged W boson is among important decay channels of $\phi^{\pm \pm}$.
- Yukawa coupling $f_c$ also plays a vital role.

Multi-lepton signal search

- We searched for collider signatures in 4lepton + $B_T$ signal channel.
- This channel is selected due to its suppressed SM background after implementation of ATLAS search [Phys. Rev. D 98 (2018)032009].
- $pp \rightarrow \phi_1^+ \phi_1^- \rightarrow 4\text{lepton} + B_T$.
- $\phi_1^+ \phi_1^- \rightarrow \phi_2^{\pm \pm}$, $\phi_3^{\pm \pm}$.
- where $\phi_1$ is the lightest among all scalars and fermion.

Results:

- The mass exclusion bounds are shown in left panel plot.
- The discovery reach of the LHC with 3000 fb$^{-1}$ integrated luminosity and 13 TeV center of mass energy is shown in right panel.

References


ATLAS 95% CLs Upper Limit

- Larger $\mu$ and $f_c$ correspond to larger BR for $H^\pm \pm \rightarrow l^+ l^-$ and hence, stronger bound on $m_{3/2}$ from the ATLAS search for the SSD invariant mass peak.
- Lower bounds on $m_{3/2}$ (left panel) and $m_{5/2}$ (right panel) as a function of $\mu$ and $f_c$. 

• To constrain the parameter space, we used the existing LHC searches for a $H^\pm \pm$ decaying into a pair of same-sign dileptons (SSD) [Eur. Phys.J.C 78 (2018) 199 (1710.09748)].
• The branching ratios of the SSD decays of $H^\pm \pm$ depend on the choice of $f_c$ and $\mu$.
• Being the lightest, $H^\pm \pm$, dominantly decays into $l^+ l^-$ for larger $f_c$ and $\mu$.
• The model predictions for $H^\pm \pm$ pair-production cross-sections for Scenario I ($a = 2$), II ($a = 1$) and III ($a = 3$) as a function of $m_{3/2}$ for different values of $\mu$ and $f_c$.
• Scenario I: $(m_1 < m_{2/3} < m_{1/2} < 2.5$ TeV), II: $(m_1 < m_{2/3} < m_{1/2} < 2.5$ TeV) and III: $(m_1 < m_{2/3} < m_{1/2} < 2.5$ TeV).