Multi-charged TeV Scale Higgs Bosons in the Framework of a Radiative Seesaw Model

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MOTIVATION

- Non-zero tiny neutrino mass is stablished by Neutrino Oscilllation experimental findings.
- It can't be explained in the Standard Model framework of high energy physics.
- It motivates us to look into beyond the Standard Model Physics.
- Neutrino mass can be expalined by Radiative Neutrino Mass Generation mechanism in the BSM physics: Ernest Ma, Phys.Rev. D73: 077301, 2006
- In addition to neutrino mass, we have to search for collider signatures of BSM particles as well.
- We have done collider phenomenology of a BSM framework where we have extended the particle spectrum to generate neutrino mass. Kingman Cheung, Hirosi Okada, Phys.Lett.B 774 (2017) 446-450
- Main feature of this BSM framework is that we don't need any ad-hoc symmetery to forbid tree-level seesaws.

Model

♦ BSM Particle Spectrum:

	E++	k^{++}	$\Phi_{\frac{3}{2}}$	$\Phi_{\frac{5}{2}}$
<i>SU</i> (3) _C	1	1	1	1
$SU(2)_L$	1	1	2	2
$U(1)_Y$	2	2	3/2	5/2

Yukawa Lagrangian:

$$L_{Y} = m_{E}^{\alpha\beta}\overline{E_{\alpha}^{++}}E_{\beta}^{++} + f_{\frac{5}{2}}^{\alpha\beta}\overline{L_{\alpha L}} \Phi_{\frac{5}{2}}^{*}E_{\beta R}^{++} + f_{\frac{3}{2}}^{\alpha\beta}\overline{L_{\alpha L}}\Phi_{\frac{3}{2}}(E_{\beta L}^{++})^{c} + f_{k}^{\alpha\beta}\overline{e_{\alpha R}}k^{--}(e_{\beta R})^{c} + h.c.$$

 $\alpha,\beta\in {\rm 1,2,3} \mbox{ are generation indices}.$ We have considered only one generation here.

- $f_{\frac{5}{2}}^{\alpha\beta}$ and $f_{\frac{3}{2}}^{\alpha\beta}$ participate in neutrino mass generation.
- $f_k^{\alpha\beta}$ only provides decay of the BSM Higgs into the SM di-leptons.
- Scalar Potential:

$$V = \mu(H^{T} \cdot \Phi_{\frac{3}{2}})k^{--} + \mu'(H^{\dagger}\Phi_{\frac{5}{2}})k^{--} + \lambda(H^{T} \cdot \Phi_{\frac{3}{2}})(H^{T}\Phi_{\frac{5}{2}}^{*}) + c.c.$$

- Breaking of the Electro-Weak symmetry results into the mixing of the doubly charged scalars.
- The mixing of the doubly charged scalars is determined by the parameters μ , μ' and λ .
- After mixing, the physical states of the doubly charged scalars are:

$$H_{a}^{++} = O_{a1}\Phi_{\frac{5}{2}}^{++} + O_{a2}\Phi_{\frac{3}{2}}^{++} + O_{a3}k^{++}$$

- where, $a \in 1, 2, 3$ and O_{ab} is the mixing matrix.
- For the values of parameters around the SM values, mixing is very small.

$$H_1^{++} \simeq \Phi_{\frac{5}{2}}^{++}, \ H_2^{++} \simeq \Phi_{\frac{3}{2}}^{++} \text{ and } H_3^{++} \simeq k^{++}$$

- The decays of H_a^{++} and their collider signatures crucially depend on the mixing and hence, on μ , μ' and λ .
- ♦ Additionally, neutrino mass generation also have the involvement of these parameters.

NEUTRINO MASS GENERATION

• The ν -mass generates through 1-loop realizations of Weinberg's operator (LLHH).





- ♦ The regions of parameter-space (λ − μ plane) which is consistent with upper bound (0.17 eV) on the absolute neutrino mass scale are depicted for three different values of the Yukawa couplings.
- For simplicity, we have assumed $\mu = \mu'$ and $f_{\frac{5}{2}} = f_{\frac{3}{2}} = f_k = f$.



PRODUCTION OF THE DOUBLY CHARGED HIGGS BOSONS

- Pair production cross-section with varying mass at the LHC with center of mass energy 13 TeV shown.
- Photo-production have also taken into account with Drell-Yan processes.
- Photo-production has significant contribution and at higher mass values dominant one.
- Photo-production is significant due to enhancement of contribution by factor 2⁴ and no s-channel suppression.
- ♦ The grey solid lines correspond to the ATLAS observed 95% CL crosssection upper limit (σ⁹⁵_{Obs}) on long-lived doubly-charged particles [Phys. Rev. D99 (2019) 052003]



DECAY OF THE DOUBLY CHARGED HIGGS BOSONS

- Decay branching ratio of H_1^{++}, H_2^{++} and H_3^{++} shown as function of their mass
- SSD is the dominant deacy mode until other channels are not available kinematically.
- Total decay width Γ_{TOT} has shown in the inlet of decay plot.
- In decay BR of H_2^{++} , $H_2^{++} \rightarrow e^+ \phi^+ \nu_e$ is another important decay channel at low mixings and low Yukawa coupling f_k .



left(right) pannel: $m_{3/2}$ = 0.9 TeV, $m_{k(5/2)}$ = 1.4 TeV, m_E = 1.5 TeV, $f_{5/2} = f_{3/2} = 2 \times 10^{-4}$, $f_k = 0.1(2 \times 10^{-3})$, $\lambda = 5 \times 10^{-4}$, $\mu = 0.1(10)$ GeV



 $f_k = 5 \times 10^{-2}$, $\lambda = 5 \times 10^{-3}$, $\mu = \mu' = 0.1$ GeV. Right pannel: BR as function of f_k for $m_{3/2} = 0.8$ TeV and $m_{3/2} < m_{5/2}, m_k$ and m_E for $\mu = 0.1$ and 1 GeV

RADIATIVE NEUTRINO MASS MODEL

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Collider Search

- There are mainly two type of signatures: (1)Abnormaly large ionization charge tracks and (2) Multi-leptonic signatures.
- ♦ Only H₁⁺⁺ and H₃⁺⁺ can remain long lived inside the LHC detector for same set of μ, λ with f_k < 10⁻³(10⁻⁹).
- ♦ m_{H1(3)} below about 800 GeV is excluded from the ATLAS search for long-lived MCPs. [Phys. Rev. D99 (2019) 052003]
- In multi-lepton searches, we here focused on 4-lepton search two scenarios:

 (1) m³/₂ << m⁵/₂(k), m_E (H⁺⁺₂, φ[±] lightest)
 (II) m⁵/₂ << m³/₂(k), m_E (H⁺⁺₁, φ^{3±} lightest)

- ♦ We show the cross-section for 4-lepton signal for scenario I and II (after ATLAS selection cuts) as function of the m_{3/2}(⁵/₂) at the LHC with √s = 13 TeV.
- ♦ ATLAS search Phys. Rev. D 98 (2018) 032009 [1804.03602] is utilized to impose bound on $m_{\frac{3}{2}(\frac{5}{2})}$.
- ♦ It sets lower bound of about 650(760) GeV on $m_{\frac{3}{2}(\frac{5}{2})}$ from the ATLAS search for the 4I final state.



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- The required integrated luminosities for the 3σ and 5σ discovery of Scenario I(II) are presented as a function of $m_{\frac{3}{2}(\frac{5}{2})}$ at the LHC with $\sqrt{s} = 13$ TeV.
- ♦ The LHC with 3000 fb^{-1} integrated luminosity and $\sqrt{s} = 13$ TeV will be able to probe $m_{\frac{3}{5}(\frac{5}{2})}$ upto about 1250 (1530) GeV at 5σ significance.



- We have explored the phenomenology of an extension of the Standard Model.
- ♦ We have also accounted the photo-production of BSM Higgs Bosons and it is significant and greater than Drell-Yan contribution for higher masses.
- We have calculated production cross-section and decay branching ratios of the doubly charged Higgs Bosons and their respective phenomenology at the LHC.
- We have set the lower mass bounds on the doubly charged Higgs Bosons with ATLAS searches.
- ♦ We have calculated detection significance of the doubly charged Higgs Bosons at the LHC with luminosity 3000 fb⁻¹ and the center of mass of energy 13 TeV.
- For BSM fermion part: 2007.01766v1 [hep-ph].