# Collider Signatures of Multi-charged Fermions at the LHC in the Framework of a Radiative Seesaw Model

arXiv: 2007.01766v1 [hep-ph], Avnish, Kirtiman Ghosh.

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Phenomenology Symposium, 2021.

## Outlines:

# 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 generate neutrino mass.

# Model

- BSM Particle Spectrum:

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

- Yukawa Lagrangian:

$$L_Y = m_E^{\alpha\beta}\overline{E_\alpha^{++}}E_\beta^{++} + y_{\frac{5}{2}}^{\alpha\beta}\overline{L_{\alpha L}}.\Phi_{\frac{5}{2}}^{*}E_{\beta R}^{++} + y_{\frac{3}{2}}^{\alpha\beta}\overline{L_{\alpha L}}\Phi_{\frac{3}{2}}(E_{\beta L}^{++})^c + y_k^{\alpha\beta}\overline{e_{\alpha R}}k^{--}(e_{\beta R})^c + h.c.$$

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

- Scalar Potential:

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

- Breaking of the Electro-Weak symmetry results into the mixing between the doubly charged scalars.

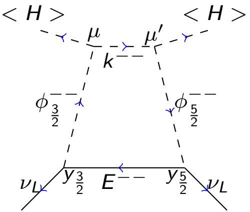
- The mixing of the doubly charged scalars is mainly determined by the parameters $\mu$, $\mu'$ and $\lambda$.
- After mixing, the physical states of the doubly charged scalars can be written as:

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

- 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. Notably, $H_1{}^{++} \sim \Phi_{\frac{5}{2}}^{++}$, $H_2{}^{++} \sim \Phi_{\frac{3}{2}}^{++}$ and $H_3{}^{++} \sim k^{++}$ .
- The decays of physical fields and their collider signatures crucially depend on the mixing and hence, on the parameters $\mu$, $\mu'$ and $\lambda$.
- Additionally, one loop neutrino mass generation have also the involvement of these parameters.

# Neutrino Mass Generation

- The neutrino mass gets contribution from two, one-loop diagrams allowed by Weinberg's operator (LLHH).




- The respective contributions from the box type diagram ($m_\nu^\square$) and the triangle type diagram ($m_\nu^\triangle$).

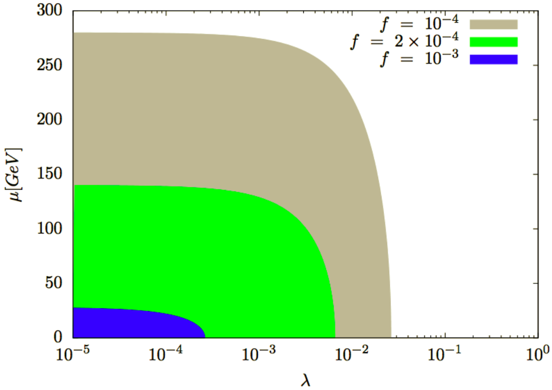
$$\frac{m_\nu^\square}{<H>^2} = \frac{\mu\mu'}{v^2}\left(y_{\frac{5}{2}}^T M_\square^{-1} y_{\frac{3}{2}} + y_{\frac{3}{2}}^T M_\square^{-1} y_{\frac{5}{2}}\right) \text{ and } \frac{m_\nu^\triangle}{<H>^2} = \lambda\left(y_{\frac{5}{2}}^T M_\triangle^{-1} y_{\frac{3}{2}} + y_{\frac{3}{2}}^T M_\triangle^{-1} y_{\frac{5}{2}}\right).$$

$$\text{with } (M_\square^{-1})^{\alpha\beta} = \sum_{a,b,c} (O_{a1} O_{b2} O_{c3})^2 m_E^{\alpha\beta} I_4(m_E^{\alpha\beta}, m_{H_a}, m_{H_b}, m_{H_c});$$

$$\text{and } (M_\triangle^{-1})^{\alpha\beta} = \sum_{a,b} (O_{a1} O_{b2})^2 m_E^{\alpha\beta} I_3(m_E^{\alpha\beta}, m_{H_a}, m_{H_b}).$$

- $I_3$ and $I_4$ are $\mathcal{O}(1)$ loop integral factors.

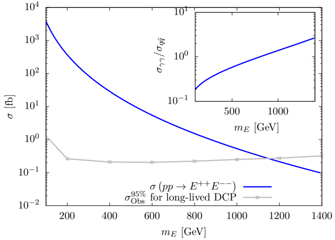
- The regions of parameter-space ($\mu$-$\lambda$ plane) which is consistent with upper bound( 0.2 eV) on the absolute neutrino mass scale are depicted for three different values of the Yukawa couplings.



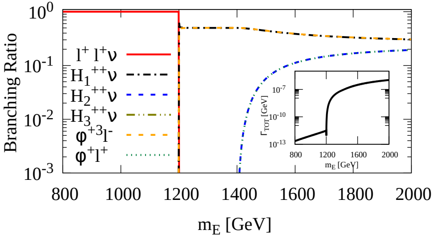

- For simplicity, we have assumed $\mu = \mu'$ and $y_{\frac{5}{2}} = y_{\frac{3}{2}} =$ f.

# Phenomenology of the Doubly Charged Fermion

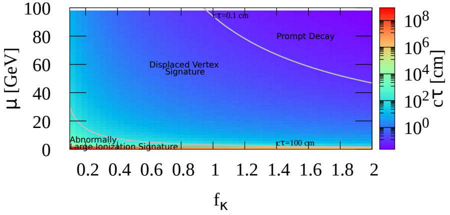
- Pair production cross-section of $E^{++}$with varying mass at the LHC with center of mass ebergy 13 TeV has shown:
- Photo-production have also taken into account with Drell-Yan processes.
- Photo-production is significant contributor and at higher mass values the dominant one.
- The grey solid lines correspond to the ATLAS observed 95% CL cross-section upper limit ($\sigma_{Obs}^{95}$) on long-lived doubly-charged particles. [Phys. Rev. D99 (2019) 052003]
- Decay branching ratios of doubly charged fermion $E^{++}$ have shown as:
- SSD is the dominant deacy mode till other decay modes are kinematically forbiden.
- Total decay width of $E^{++}$, $\Gamma_{TOT}$ has also shown in the inlet of decay plot.




$m_{5/2(3/2)}$= 1.2(1.4) TeV, $m_k$=1.5 TeV, $\mu = \mu' = 100$ GeV, $y_{5/2(3/2)} = 2 \times 10^{-4}$, $\lambda$= 0.005 and $y_k$=1.0

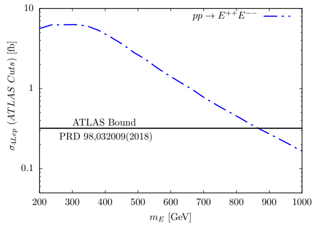


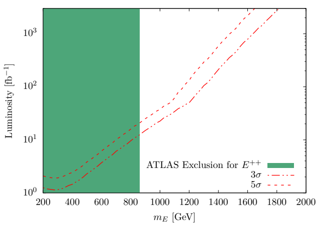
- For $E^{++}$ being lighter than multi-charged scalars, only 3-body decay is kinematically possible.
- And $\Gamma_{TOT}$ is suppressed but not enough to ensure displaced vertex or highly ionizing tracks.
- 3-body decay lengths depend on Yukawa couplings and mixing among doubly charged scalars which are controlled by $\mu$, $\mu'$ and $\lambda$.
- To identify such regions, we scanned $y_k - \mu$ parameter space for $m_E = 800$ GeV.
- By the ATLAS search for long lived charged particles [Phys. Rev. D99 (2019) 052003], we get a lower bound of 1150 GeV on $m_E$.




For $m_E$= 800 GeV, $m_{5/2(3/2)}$= 1.2(1.4) TeV, $m_k$=1.5 TeV, $y_{5/2(3/2)} = 2 \times 10^{-4}$ and $\lambda$= 0.005.

- The collider signatures of $E^{++}E^{--}$-pairs at the LHC can be broadly categorized into two classes depending on the $\Gamma_{TOT}$ of $E^{++}$.
- If $\Gamma_{TOT} > 10^{-13}$ GeV, the decay length is small enough ($< 1$ mm), $E^{++}$ decays inside the detector, the collider signatures are the SM leptons/jets and missing energy.
- If $\Gamma_{TOT} < 10^{-16}$ GeV, and $E^{++}$ remains stable inside the LHC detectors i.e., the decay length is larger than few meters, production of $E^{++}E^{--}$-pairs give rise to abnormally large ionization at the LHC detectors.
- For $E^{++}$ being lighter than multi-charged scalars, it goes to 3 -body decays.
- For prompt decay of $E^{++}$, the ATLAS search [ Phys. Rev. D 98 (2018) 032009] for 4 lepton $+\not{E}_T$ , 36.1 fb$^{-1}$ data of the 13 TeV LHC excludes $m_E$ 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 $m_E = 1800$ (1600) GeV at $3\sigma$ and $5\sigma$ significance.



# Summary

- We have explored the phenomenology of an extension of the Standard Model.
- We have also accounted the photo-production of BSM particles 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 fermions and their respective phenomenology at the LHC.
- We have calculated detection significance of the doubly charged fermion at the LHC with luminosity 3000 $\text{fb}^{-1}$ and the center of mass of energy 13 TeV.
- For BSM scalar part: 2007.01766v1 [hep-ph].