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 particularly, 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: $SU(3)_C \times SU(2)_L \times U(1)_Y$

Particle⇒	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:

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

$\alpha, \beta \in$ 1,2,3 are generation indices.

Scalar Potential:

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

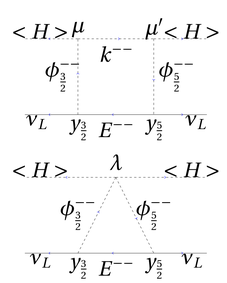
Physical states after mixing of doubly charged Higgs bosons (after EWSB):

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

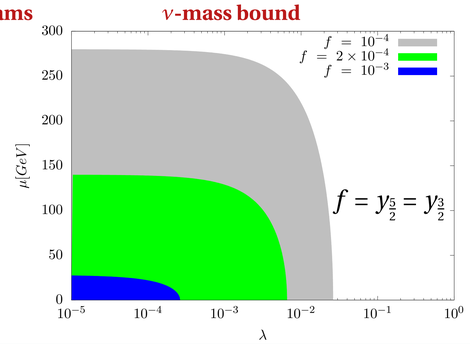
O_{ab} is the mixing matrix.

Neutrino Mass

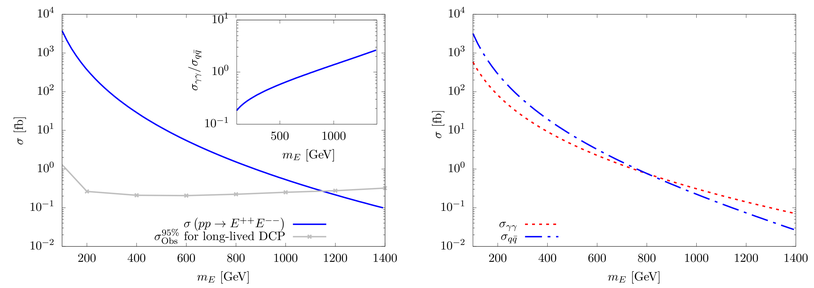
1-loop Feynman Diagrams



ν-mass bound



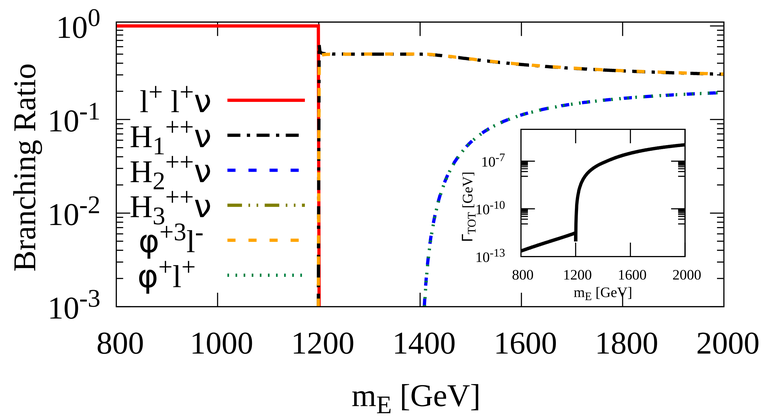
Total pair production of fermions



- The total cross-section is shown along with the ratio of contributions from photo-proction and Drell-Yan production channels (inlet left panel).
- Being the doubly charged of E^{++} make **Photo-production** significant.
- **Photo-production** is significant contributor and at higher mass values the dominant one (right panel).
- The grey solid line (left panel) correspond to the ATLAS observed 95% CL cross-section upper limit (σ^{95} Obs) on long-lived doubly-charged particles.

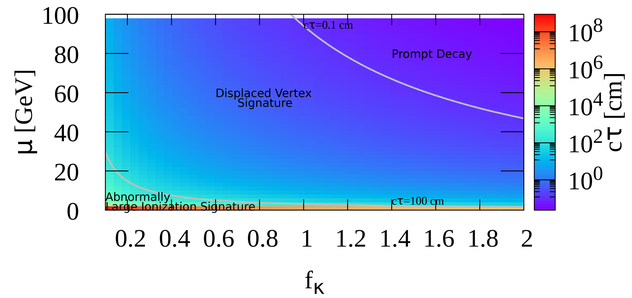
Decay of doubly charged fermions

- The decay branching ratios of E^{++} to possible decay modes shown for a particular choice of parameters.
- Parameters μ, μ' **and** λ 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^{++}'s.
- For E_a^{++} being lighter than multi-charged scalars,only 3-body decay is kinematically possible.
- Total decay width of E^{++}, Γ_{TOT} has also shown in the inlet



Parameter Scan for Signatures

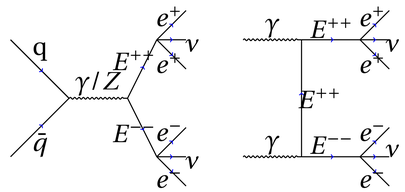
- Γ_{TOT} is suppressed but not enough to ensure displaced vertex or highly ionizing tracks.
- 3-body decay lengths depend on Yukawa couplings and mixing among doubly charged scalars which are controlled by μ, μ' and λ.
- $f_k - \mu$ parameter space scanned to acertain the regions for differnt kind of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



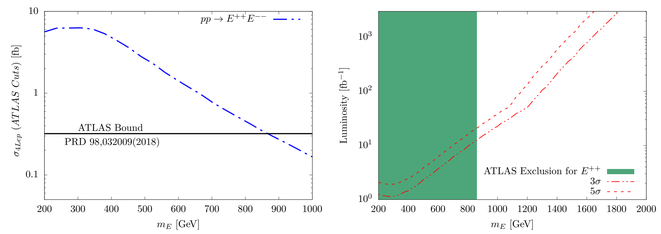
For m_E= 800 GeV, $m_{5/2(3/2)}$= 1.2(1.4) TeV, m_k =1.5 TeV, $y_{5/2(3/2)} = 2\times10^{-4}$ and λ= 0.005.

Multi-lepton signal search

- We searched in: **P P** → E^{++} E^{--} → **4-lepton + missing transverse energy** signal channel.



- 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_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 3σ and 5σ significance.



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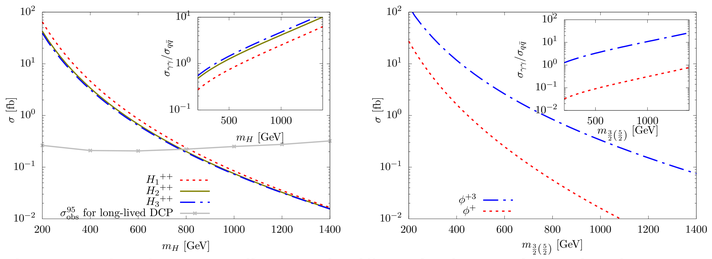
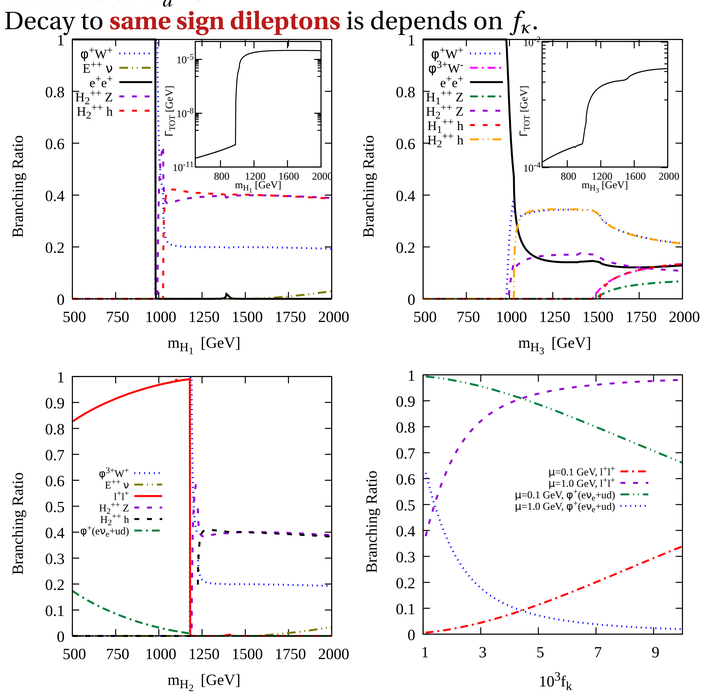
Total pair production of scalars



- **Photo-production contributes significantly in total production cross-section.**
- **Ordering in values of σ_{prod} for H_a^{++} depends upon hyper-charges.**
- **For low mixing, $H_1^{++} \simeq \phi_{\frac{5}{2}}^{++}$, $H_2^{++} \simeq \phi_{\frac{3}{2}}^{++}$ and $H_3^{++} \simeq k^{++}$.**

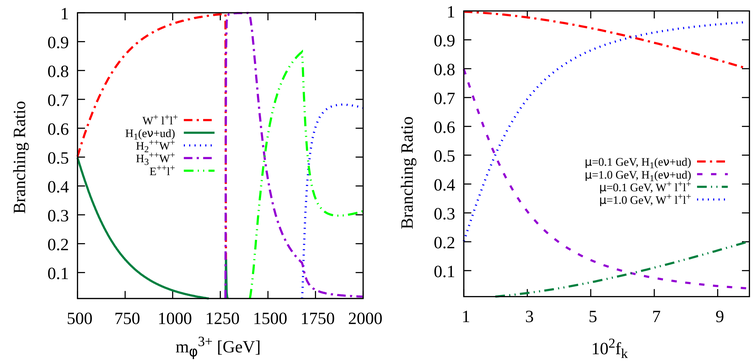
Decay of doubly charged scalars

- The decay Branching Ratios are showm(total decay width Γ_{TOT} in inlets (Top plots)).
- Parameters μ, μ' **and** λ play vital role in decays of H_a^{++}'s **through mixing**.
- Decay to **same sign dileptons** is among the important decay channels of H_a^{++}'s.
- Decay to **same sign dileptons** is depends on f_κ.



Decay of tripply charged scalars

- Decay to **same sign dileptons with a same charged W boson** is among important decay channels of ϕ^{3+}.
- **Yukawa coupling f_κ** also plays a vital role.

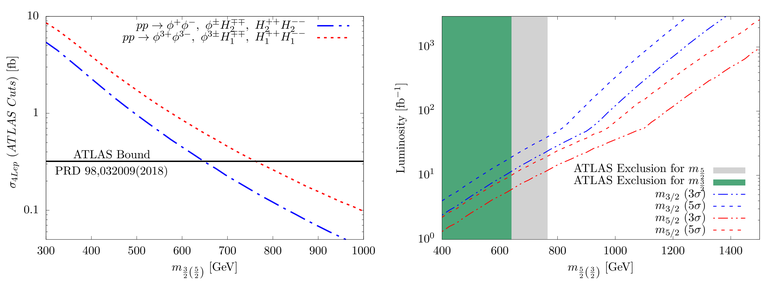


Multi-lepton signal search

- We searched for collider signatures in 4lepton + $\not{E}_T$ signal channel.
- This channel is selected due to its suppressed SM background after implementation of ATLAS search [Phys. Rev. D 98 (2018)032009].
- **pp $\to \phi_s\, \phi_{s'}^{\dagger} \to$ 4lepton + $\not{E}_T$.**
- **ϕ_s and $\phi_{s'} \in \phi^{3\pm}, \phi^{\pm}, H_1^{\pm\pm}, H_2^{\pm\pm}$.**
- where ϕ_s is **the lighest** among all scalars and fermion.

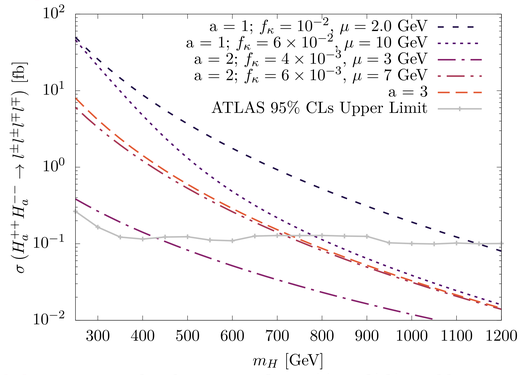
Results:

- 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.

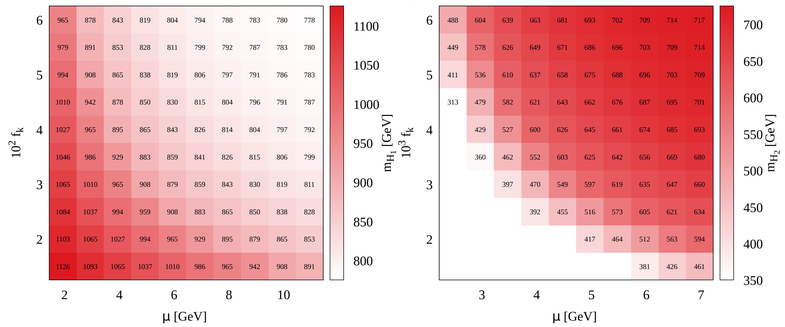


Search for the doubly-charged scalars

- To constrain the parameter space, we used the existing LHC searches for a H_a^{++} 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_a^{++} depend on the choice of f_κ and μ.
- Being the **lightest**, H_a^{++}, dominantly decays into l^+l^+ for larger f_κ and μ.
- The model predictions for H_a^{++} pair-production cross-sections for Scenario I(a = 2), II(a = 1) and III(a = 3) as a function of m_{H_a} for different values of μ and f_κ.
- Scenario I$\to(m_{\frac{3}{2}} << m_{\frac{3}{2}(k)}$, $m_E \sim 2.5$ TeV), II$\to(m_{\frac{5}{2}} << m_{\frac{3}{2}(k)}$, $m_E \sim 2.5$ TeV) and III$\to(m_k << m_{\frac{3(5)}{2}}$, $m_E \sim 2.5$ TeV).



- Larger μ and f_κ correspond to larger BR for $H_a^{++} \to l^+l^+$ and hence, stronger bound on m_{H_a} from the ATLAS search for the SSD invariant mass peak.
- Lower bounds on m_{H_1}(left panel) and m_{H_2}(right panel) as a function of μ and f_κ.



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- (4) ATLAS collaboration, Search for supersymmetry in events with four or more leptons in $\sqrt{s}$ = 13 TeV pp collisions with ATLAS, Phys. Rev. D 98 (2018) 032009 [1804.03602].
- (5)**Avnish, Kirtiman Ghosh, arXive: 2007.01766 [ph].**