Revisiting Type-II Seesaw:
Present Limits and Future Prospects at LHC

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WEINBERG OPERATOR & NEUTRINO MASS

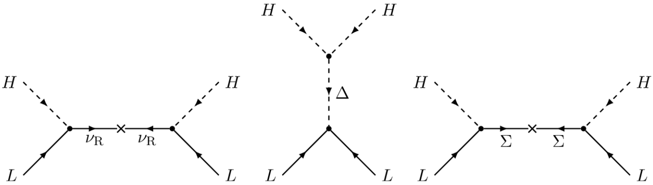
- The lowest dimensional *non-renormalizable* operator

$$\mathcal{L}_{d=5} \propto \frac{1}{\Lambda} LLHH$$

- Majorana neutrino mass

$$m_\nu \propto \frac{v^2}{\Lambda} \qquad \text{"Majorana seesaw formula"}$$

- Three tree level realisations of Weinberg operator: type-I, type-II and type-III seesaw



S. Weinberg, Phys.Rev.Lett. 43, 1566 (1979) , R.Foot, H.Lew, X.G.He and G.C.Joshi, Z.Phys. C44, 441 (1989) , Ernest Ma, Phys.Rev.Lett. 81, 1171 (1998) , Ernest Ma and Utpal Sarkar, Phys.Rev.Lett. 80, 5716 (1998)

Type-II Seesaw

- SM + $SU(2)_L$ triplet scalar field

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- Scalar potential Phys.Rev.D 84 (2011) 095005

$$V(\Phi,\Delta) = -m_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \boxed{\left[\mu(\Phi^T i\sigma^2 \Delta^\dagger \Phi) + \mathrm{h.c.}\right]} + \lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\left[\mathrm{Tr}(\Delta^\dagger\Delta)^2\right] + \boxed{\lambda_4 \Phi^\dagger\Delta\Delta^\dagger\Phi} .$$

- VEVs after the EWSB

$$\langle\Delta\rangle = \begin{pmatrix} 0 & 0 \\ v_t/\sqrt{2} & 0 \end{pmatrix} \quad \text{and} \quad \langle\Phi\rangle = \begin{pmatrix} 0 \\ v_d/\sqrt{2} \end{pmatrix} .$$

- For $v_d^2 \gg v_t^2$, minimisation of $V(\Phi,\Delta) \Rightarrow$ $v_t \approx \mu v_d^2/\sqrt{2} m_\Delta^2$ **"Seesaw spirit"**
- Yukawa interaction & neutrino mass

$$\boxed{-\mathcal{L}_\nu = Y_{ij}^\nu L_i^T C i\sigma^2 \Delta L_j + \mathrm{h.c.}} \xrightarrow{EWSB} \boxed{m_\nu = \sqrt{2} Y^\nu v_t} .$$

Type-II Seesaw Mass Spectra

- For $v_t \ll v_d$, their mass-squared differences **Remember:** $\lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi$

$$m^2_{H^{\pm\pm}} - m^2_{H^{\pm}} \approx m^2_{H^{\pm}} - m^2_{H^0/A^0} \approx \frac{\lambda_4}{4} v_d^2 \ .$$

- For usefulness, we define $\Delta m = m_{H^{\pm\pm}} - m_{H^{\pm}}$.

- Three characteristic mass spectra
  1. $\Delta m = 0$: $m_{H^{\pm\pm}} \simeq m_{H^{\pm}} \simeq m_{H^0/A^0} \Rightarrow$ **Degenerate scenario**
  2. $\Delta m > 0$: $m_{H^{\pm\pm}} > m_{H^{\pm}} > m_{H^0/A^0} \Rightarrow$ **Positive scenario**
  3. $\Delta m < 0$: $m_{H^{\pm\pm}} < m_{H^{\pm}} < m_{H^0/A^0} \Rightarrow$ **Negative scenario**

- The Lagrangian parameters can be traded in terms of the physical masses, α and v_t.
- All the physical masses can be traded in terms of $m_{H^{\pm\pm}}$ and Δm.

Therefore, phenomenology of this model, by and large, is governed by three parameters only — $m_{H^{\pm\pm}}$, Δm and v_t.

Constraint on v_t, Δm and α

- ρ parameter:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_w} = \frac{v_d^2 + 2v_t^2}{v_d^2 + 4v_t^2} \,.$$

EWPD: $\rho = 1.00038(20)$ leads to an upper bound of $\mathcal{O}(1)$ GeV on v_t ($\ll v_d$).

- For $v_t \ll v_d$, CP-even Higgs rotation angle

$$\tan 2\alpha \approx \frac{4v_t}{v_d}\left(1 - \frac{m_{h^0}^2}{m_{H^0}^2}\right)^{-1} \,.$$

- $h \to \gamma\gamma$ at LHC: $|\sin\alpha| \lesssim 0.3$ at 95% CL.

- Δm, dictated by $\lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi$, affects EWPD observables.

Oblique parameters: $|\Delta m| \lesssim 40$ GeV.

- LFV decays: $\ell_\alpha \to \ell_\beta \gamma$ at 1-loop and $\ell_\alpha \to \ell_\beta \ell_\gamma \ell_\delta$ at tree level.

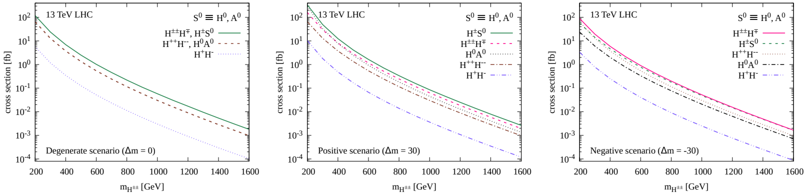
- MEG and SINDRUM collaboration:

$$v_t \gtrsim 0.6\text{–}2.3 \times 10^{-9}\ \text{GeV} \times \frac{1\ \text{TeV}}{m_{H^{\pm\pm}}} \,.$$

Production of Triplet-like Scalars

- **Drell-Yan processes:**

$$q\bar{q}' \to W^* \to H^{\pm\pm}H^{\mp}, H^{\pm}S^0 \text{ with } S^0 \ni \{H^0, A^0\},$$
$$q\bar{q} \to \gamma^*/Z^* \to H^{\pm\pm}H^{\mp\mp}, H^{\pm}H^{\mp}, H^0A^0.$$



All the Drell-Yan production mechanisms are of handsome cross-sections, and, hence, all the channels entail to be incorporated in the analyses.

Decays of Triple-like Scalars

	leptonic	hadronic	di-boson	cascade	
				$\Delta m > 0$	$\Delta m < 0$
$H^{\pm\pm}$	$\ell^{\pm}\ell^{\pm}$	-	$W^{\pm}W^{\pm}$	$H^{\pm}W^{\pm *}$	-
$H^{\pm}$	$\ell^{\pm}\nu$	$t\bar{b}$	$W^{\pm}Z/h^0$	$H^0/A^0W^{\pm *}$	$H^{\pm\pm}W^{\mp *}$
H^0	$\nu\nu$	$b\bar{b},t\bar{t}$	WW,ZZ,h^0h^0	-	$H^{\pm}W^{\mp *}$
A^0	$\nu\nu$	$b\bar{b},t\bar{t}$	h^0Z	-	$H^{\pm}W^{\mp *}$

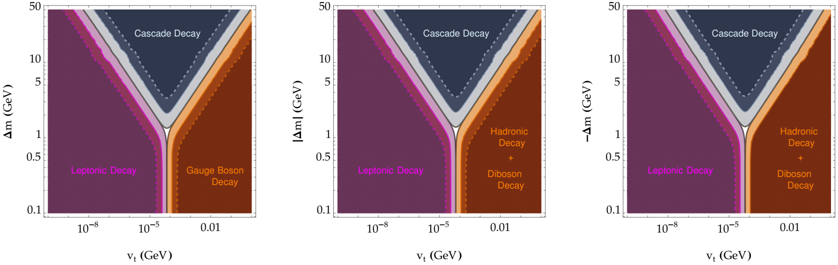


FIGURE: Left to right: decay phase diagrams for $H^{\pm\pm}$, $H^{\pm}$ & H^0/A^0 with $m_{H^{\pm\pm}} = 500$ GeV. Magenta/Orange/Light-Blue dashed and solid contours, respectively, correspond to 99 and 90%, and Black solid contours to 50% branching ratios in different decay regions.

Collider Searches at LHC

- Variety of final state signatures including two pairs of same-sign lepton or two pairs of same-sign W-boson.
- No significant excess over SM background in any LHC seraches $\Rightarrow$ limits on $m_{H^{\pm\pm}}$.

1. CMS: 716–761 GeV for $H^{\pm\pm}$ decaying 100% into SSDL.
2. ATLAS: 770–870(450) GeV for $H^{\pm\pm}$ decaying 100%(10%) into $ee, e\mu, \mu\mu$.
3. ATLAS: 350(230) GeV considering pair(associated) production modes for $H^{\pm\pm}$ decaying 100% into WW assuming α to be 10^{-4} .

1. These limits are not befitting to the entire parameter space, rather valid only for a constrained parameter space.
2. These limits are often a bit conservative as these searches do not incorporate all production channels for the triplet scalars.
3. The triplet components are conceivably non-degenerate ($\Delta m \neq 0$). Pheneomenology for $\Delta m \neq 0$ is substantially contrasting than that for $\Delta m = 0$.
4. These limits are derived in the context of simplified scenarios without reckoning the footprints of the low-energy neutrino parameters.

Our aim: To derive the most stringent 95% CL lower limit on $m_{H^{\pm\pm}}$ for a wide range of v_t and Δm incorporating all production modes for the triplet scalars and taking into account all-encompassing complexity of their decays by recasting already existing LHC searches.

Final State Signatures at LHC

	Degenerate scenario	Negative scenario	Positive scenario
small v_t	multilepton (1)	enhanced (1)	diminished (1)
large v_t	multiboson $\rightarrow$ multilepton (2)	enhanced (2)	diminished (2)
moderate v_t	(1)+(2)	enhanced (1)+(2)	Nightmare scenario 4ν plus up to 4 W^*

Table: Possible final state signatures for different parts of the parameter space.

The most optimistic final states in **Nightmare scenario** would be an energetic jet plus missing transverse momentum or two or three soft leptons plus missing transverse momentum.

We proceed to implement the following LHC searches:

1. Multilepton final states search by CMS with 137.1 fb^{-1} of data at $\sqrt{s} = 13$ TeV. JHEP 03 (2020) 051
2. Multiboson leading to multilepton final states search by ATLAS with 139 fb^{-1} of data at $\sqrt{s} = 13$ TeV. arXiv: 2101.11961 [hep-ex]
3. ~~An energetic jet and missing transverse momentum search by ATLAS~~ Phys. Rev. D 103, 112006 (2021)
4. ~~Two or three soft leptons and missing transverse momentum search by CMS~~ CMS-PAS-SUS-18-004

Potentially Sensitive LHC Searches

- CMS multilepton search
  - originally intended to probe few hundred GeV triplet fermions in **Type-III seesaw**
  - Exploits high momenta of the decay products ⇒ nifty in discriminating the signal from background.
  - Also expected to be sensitive in probing **Type-II seesaw**.

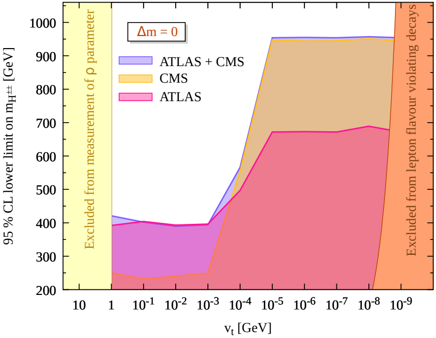
- ATLAS multiboson leading to multilepton search
  - intended to probe doubly and singly charged Higgs bosons in **Type-II seesaw**
  - Exploits high momenta of the decay products ⇒ nifty in discriminating the signal from background.

Search implementation steps:

- **MadGraph5** (MC event generation) → **Pythia8** (decays, ISR, FSR, showering, fragmentation and hadronization) → **Delphes** (object reconstruction and selection, defining SRs and event selection)

For the 'Delphes' step, we rigorously follow the said CMS/ATLAS seach strategy.

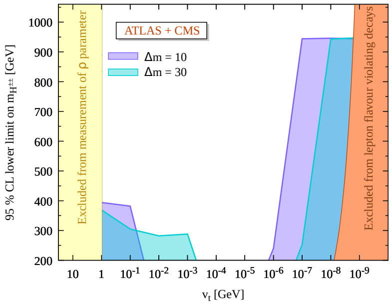
95% CL lower limit on $m_{H^{\pm\pm}}$



- Small v_t: triplet-like scalars below 950 GeV are excluded from the CMS search.
  This limit is beyond those from the previous LHC searches by approximately 200–230 GeV.

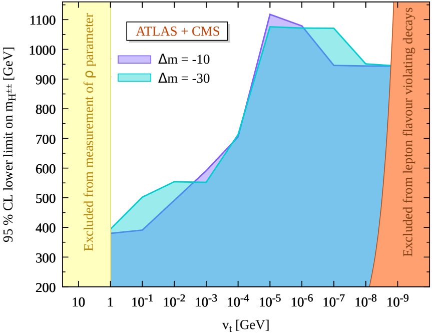
- Large v_t: the ATLAS search excludes the triplet-like scalars up to 400 GeV.
  This limit is beyond those from the previous LHC searches by approximately 50 GeV.

95% CL lower limit on $m_{H^{\pm\pm}}$



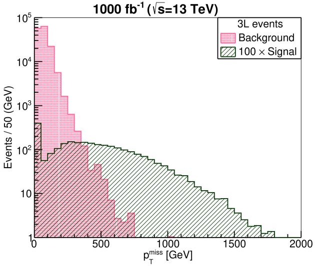
- Very large/small v_t: limits for $\Delta m = 10, 30$ GeV are similar to those for $\Delta m = 0$.
- Moderate v_t: $H^{\pm\pm}$ and $H^{\pm}$ decay into off-shell $W^{\pm *}$s and H^0/A^0.
- For H^0/A^0 decaying into $\nu\nu$, there are hardly visible objects in the final state $\Rightarrow$ monojet search and soft leptons search fail to constrain this region.
- For H^0/A^0 decaying into $h^0 h^0, ZZ/h^0 Z$, the signal cross-section is small compared to the overwhelming background from either QCD jets or Drell-Yan processes. This makes such a scenario challenging to probe.

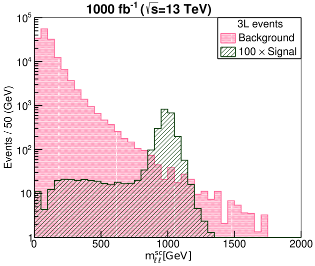
95% CL lower limit on $m_{H^{\pm\pm}}$



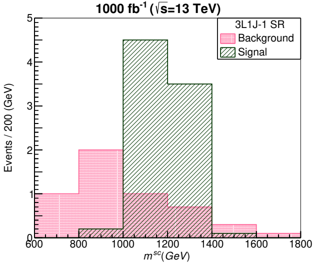
- Very large/small v_t: limits for $\Delta m = 10, 30$ GeV are similar to those for $\Delta m = 0$.
- Moderate v_t: H^0/A^0 and $H^\pm$ decay into off-shell $W^{\pm *}$s and $H^{\pm\pm}$.
  $\Rightarrow$ enhanced pair production of $H^{\pm\pm}$.
- The exclusion limit extends up to 1115(1076) GeV compared to 955 GeV for $\Delta m = 0$

Proposed multilepton search for small v_t: 3L events

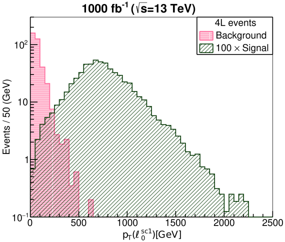


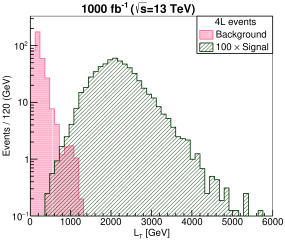


SR	Selection cuts	Background	Signal
(3L events)	Basic	151444	24.9
	$p_T(\ell_0^{sc}) > 300$	1277	23.7
	$p_T(\ell_1^{sc}) > 100$	501	22.7
	$m_{eff} > 1500$	46.0	20.8
3L0J	$n_J = 0$ & $p_T^{miss} > 150$	1.0	6.5
	$m_{\ell\ell}^{sc} > 800$	0.0	6.2
3L1J-1	$n_J \geq 1$ & $p_T^{miss} > 150$	22.0	10.3
	$p_T^{miss}/H_T > 1.0$	5.1	8.3
3L1J-2	$n_J \geq 1$ & $p_T^{miss} < 150$	23.0	3.0



Proposed multilepton search for small v_t: 4L events

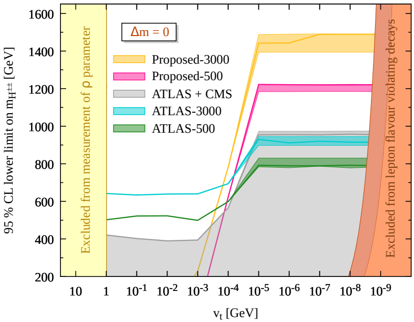




Selection cuts	Background	Signal
Basic	350	6.0
$p_T(\ell_0^{sc1}) > 300$	5.3	5.8
$p_T(\ell_1^{sc1}) > 100$	2.0	5.5
$p_T(\ell_0^{sc2}) > 300$	0.7	5.3
$p_T(\ell_1^{sc2}) > 100$	0.1	5.1
$L_T > 1500$ & $r < 0.1$	0.0	4.9

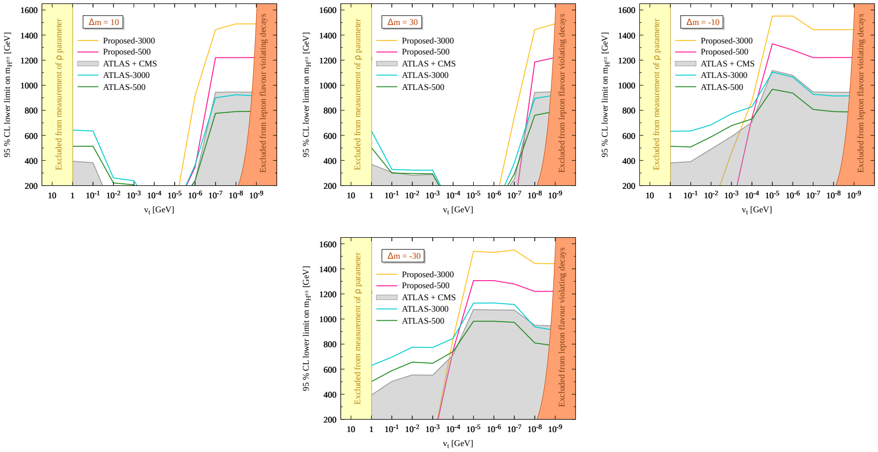
where $r = |m_{\ell\ell}^{sc1} - m_{\ell\ell}^{sc2}|/(m_{\ell\ell}^{sc1} + m_{\ell\ell}^{sc2})$

95% CL lower limit on $m_{H^{\pm\pm}}$



- For small (large) v_t, future reach extends up to 1220 and 1490 (520 and 640) GeV, respectively, for 500 and 3000 fb^{-1} of luminosity.

95% CL lower limit on $m_{H^{\pm\pm}}$



- Expected reach from our proposed search extends up to 1330(1310) and 1555(1550) GeV, respectively, at 500 and 3000 fb^{-1} of luminiosity.

Outlook

We perform a **systematic and comprehensive collider study** of this model:

1. incorporating all production modes for the triplet-like scalars, and
2. taking into account all-encompassing complexity of their decays .

- We derive the most stringent 95% CL lower limit on $m_{H^{\pm\pm}}$ for a vast range of v_t and Δm by implementing existing direct collider searches by CMS and ATLAS.

  $H^{\pm\pm}$ up to masses 420(955) GeV are already excluded from the existing ATLAS and CMS combined search.

  These exclusion limits are beyond those from the previous LHC searches by approximately 50(200–230) GeV .

  We find that for moderate v_t and large enough positive Δm, the LHC searches fail to constrain the triplet-like scalars.

- We forecast future limits by extending the same ATLAS search at high-luminosity
- We propose a search that yields improved limits for a part of the parameter space.
- To the extent of our apprehension, such a study of up-to-the-minute collider limits for a vast range of parameter space is still lacking. This work intends to fill the gap.