Phenomenology in Minimal Cascade Seesaw for Neutrino Mass

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R. Ding, Z.-L. Han, Y. Liao, H.-J. Liu, J.-Y. Liu, arXiv: 1403.2040

Outline

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What we experimentally know about ν

- **Precision data**

  3 active, almost massless neutrinos

  interact as assigned in standard model (SM)

- **Oscillation data**

  neutrinos have nondegenerate masses $m_{1,2,3}$

  leptons mix in CC weak interactions θ_{ij}

$$V = U \cdot \mathrm{Diag}\{e^{i\rho}, e^{i\sigma}, 1\},$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -c_{12}s_{23}s_{13} - s_{12}c_{23}e^{-i\delta} & -s_{12}s_{23}s_{13} + c_{12}c_{23}e^{-i\delta} & s_{23}c_{13} \\ -c_{12}c_{23}s_{13} + s_{12}s_{23}e^{-i\delta} & -s_{12}c_{23}s_{13} - c_{12}s_{23}e^{-i\delta} & c_{23}c_{13} \end{pmatrix},$$

$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij},\ ij = 12,\ 23,\ 13$

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What we experimentally know about ν

- Global 3ν oscillation analysis for NH Fogli *et al.*, 2012

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2	7.54	[7.32, 7.80]	[7.15, 8.00]	[6.99, 8.18]
$\Delta m^2/10^{-3}$ eV^2	2.43	[2.33, 2.49]	[2.27, 2.55]	[2.19, 2.62]
θ_{12}	33.6°	[32.6°, 34.8°]	[31.6°, 35.8°]	[30.6°, 36.8°]
θ_{23}	38.4°	[37.2°, 40.0°]	[36.2°, 42.0°]	[35.1°, 53.0°]
θ_{13}	8.9°	[8.5°, 9.4°]	[8.0°, 9.8°]	[7.5°, 10.2°]

$\delta m^2 \equiv m_2^2 - m_1^2$ and $\Delta m^2 \equiv m_3^2 - (m_1^2 + m_2^2)/2$.

- Almost no knowledge on CP phases; neither on mass hierarchy:
  either $m_1 < m_2 < m_3$ – normal hierarchy (NH)
  or $m_3 < m_1 < m_2$ – inverted hierarchy (IH)

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What we experimentally know about ν

Constraints on absolute neutrino mass

- nuclear β decays: $m_\beta \equiv \sqrt{\sum |V_{ei}|^2 m_i^2}$

  $m_\beta < 2.1$ eV @ 95% C.L. Troitsk Collaboration 2011

  $\Rightarrow m_\beta \sim 0.2$ eV (90% C.L) KATRIN

- lepton-number violating $0\nu\beta\beta$ decays: $m_{\beta\beta} \equiv \left|\sum V_{ei}^2 m_i\right|$

  $m_{\beta\beta} \lesssim 0.4$ eV W. Rodejohann 2012

  $\Rightarrow m_{\beta\beta} \sim 0.02$ eV

- cosmological and astrophysical considerations: $\Sigma \equiv \sum m_i$

  $\Sigma < 0.44$ eV @ 95% C.L. 9-year WMAP 2012

  $\Sigma < 0.23$ eV @ 95% C.L. Planck 2013

  $\Rightarrow \Sigma \sim 0.05$ eV

What we experimentally know about ν's relatives

ν and ℓ share CC weak interactions

$\Rightarrow$ gain info from lepton-flavor violating (LFV) transitions

- μ decays

  $\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ @ 90% C.L. MEG 2013

  $\mathrm{BR}(\mu \to 3e) < 1.0 \times 10^{-12}$ @ 90% C.L. SINDRUM 1988

- $\mu - e$ conversion in nuclei

  $\mathrm{BR}(\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}) < 4.3 \times 10^{-12}$ @ 90% C.L. SINDRUM II 1993

  $\mathrm{BR}(\mu^- \mathrm{Au} \to e^- \mathrm{Au}) < 7 \times 10^{-13}$ @ 90% C.L. SINDRUM II 2006

  $\Rightarrow 10^{-16} \sim 10^{-18}$ COMET, PRISM/PRIME, Mu2e, Project-X

- LFV decays of τ and of B mesons

  less restrictive: BRs $\sim 10^{-8}$ BaBar, Belle, CDF

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What we suppose ν to be

SM

assumes only left-handed (LH) neutrinos ν_L

– Only Majorana ν mass could be possible

– But gauge symmetries do *not* allow it!

$\Rightarrow m_\nu \neq 0$ calls for phys beyond SM

Trivial extension

add right-handed (RH) ν_R to form massive Dirac ν as we do for ℓ

must tolerate tiny Yukawa coupling of order or less than 10^{-11}

Why isn't it exactly zero at all?!

We need an understanding of tiny m_ν!

What we suppose ν to be

We are *apt to believe* a tiny number like m_ν is a remnant of some high-scale phys

We are not certain about what it is

but we can parameterize our ignorance systematically –

regard SM as a low-energy EFT

$\Rightarrow m_\nu$ may arise from an effective higher-dim interaction Weinberg 1980

$$\mathscr{L}_{\rm int} = \frac{\lambda}{\Lambda}\mathcal{O}_5 + {\rm h.c.}, \quad \mathcal{O}_5 = \left(\overline{F_L{}^C}\epsilon H\right)\left(H^T\epsilon F_L\right),\ H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix},\ F_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$$

$$\Rightarrow \frac{\lambda}{\Lambda}\frac{v^2}{2}\overline{\nu_L{}^C}\nu_L + {\rm h.c., via}\ \langle H^0\rangle = \frac{v}{\sqrt{2}} \qquad \text{Majorana mass}$$

Very roughly, for $v \sim 250\ {\rm GeV},\ \lambda \sim 1,\ m_\nu \sim 0.1\ {\rm eV}$ requires

$$\Lambda \sim 10^{15}\ {\rm GeV}$$

Main questions to address

What's the origin of such a tiny mass? Seesaw models?

Of Majorana nature as most seesaws assume?

Possible to test? At colliders?

Dilemma:

m_ν tends to demand extremely large Λ, while

accessibility to new phys responsible for m_ν relies on a not-too-high Λ

What to do with this tension?

Even higher-dim interactions?

Outline

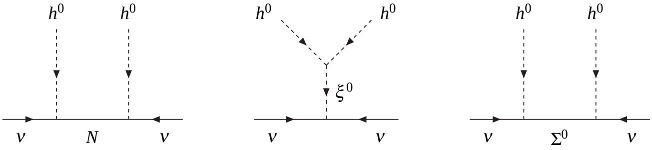
Weinberg operator and its tree level realizations

Weinberg operator $\mathcal{O}_5$ for m_ν is unique   Weinberg 1980

Group theor. analysis shows that it has 3 and only 3 apparently different realizations of $\mathcal{O}_5$ at tree level   Ma 1998

They hint at 3 different origins from an underlying theory

– 3 types of conventional seesaws



(a) Type I   (b) Type II   (c) Type III

Type I seesaw

New particles: n_s sterile neutrinos N_R; lepton # violated by 2 units

$$\cdots + \overline{N_R} i \partial\!\!\!/ N_R - \left[\overline{F_L} Y_N \tilde{H} N_R + \frac{1}{2} \overline{N_R{}^C} M_R N_R + \text{h.c.} \right]$$

Mass matrix for $n_s + 3$ neutral particles:

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}, \quad M_D = Y_N v/\sqrt{2}$$

Seesaw limit: $|M_D| \ll |M_R|$; generally 3 light and n_s heavy:

$$M_{\text{light}} \simeq -M_D M_R^{-1} M_D^T, \; M_{\text{heavy}} \simeq M_R$$

$n_s \geq 2$ to gain at least 2 massive light ν's

Heavy neutrinos interact with SM particles only through

Yukawa coupling Y_N and mixing with light neutrinos

$\Rightarrow$ very hard to test a *genuine type I* seesaw!

Collider test of *effective type I* seesaw

- Most works study *effective type I* seesaw; assuming
  - essentially one sterile neutrino at work
  - masses, mixing and couplings as free parameters, not restricted by theoretical relations as in genuine type I seesaw, but by various data: precision electroweak data, LFV processes, $0\nu\beta\beta$ decay, etc.
- Main signal: $pp \to W^\pm \to \ell^\pm N \to \ell^\pm \ell^\pm jj$ like-sign dilepton events
- Works differ mainly in background analysis.

Type II seesaw

New particles: scalar triplet Δ of $Y = +2$

doubly-charged, singly-charged, and neutral

$$\mathscr{L} \supset \frac{1}{2}\mathrm{Tr}(D^\mu\Delta)^\dagger(D_\mu\Delta) - \left[f_{ij}\overline{F^C_{Li}}(i\sigma_2)\Delta F_{Lj} + \text{h.c.}\right]$$

$$V \supset -m_H^2 H^\dagger H + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu(H^\dagger\Delta\tilde{H}) + \text{h.c.}\right]$$
$$+\frac{1}{2}\lambda_1(H^\dagger H)^2 + \lambda_4(H^\dagger H)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_6(H^\dagger\Delta\Delta^\dagger H)$$

vev's and Majorana ν mass:

$$\langle H\rangle = v \simeq \sqrt{\frac{m_H^2}{\lambda_1}},\ \langle\Delta\rangle = v_\Delta \simeq \frac{-\mu v^2}{m_\Delta^2 + (\lambda_4+\lambda_6)v^2}$$
$$m_\nu = f v_\Delta$$

enjoy electroweak interactions

$\Rightarrow$ rich phenomenology expected, details depending on v_Δ.

Type III seesaw

New particles: fermion triplet of $Y = 0$:

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

$$\mathscr{L} \supset \mathrm{Tr}\overline{\Sigma_R} i\not{D}\Sigma_R - \left[\frac{1}{2}\mathrm{Tr}\left(\overline{\Sigma_R} M_\Sigma \Sigma_R^C\right) + \overline{F_L} Y_\Sigma \tilde{H} \Sigma_R + \text{h.c.}\right]$$

Mass matrix of neutral particles:

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D & M_\Sigma \end{pmatrix}, \quad \text{where } M_D = Y_\Sigma v/\sqrt{2}$$

can be diagonalized as in type I seesaw

Differences to type I:
electroweak interactions; charged heavy-light mixing

Relatively less extensively studied

Outline

Why going beyond conventional seesaws

Tension between tiny m_ν and accessibility of new phys
(large mass of new particles or/and small couplings)

can be relaxed in two basic approaches

- m_ν induced radiatively:

one loop (Zee '80),

two loops (Zee '85, Babu '88),

three loops (Krauss et al '03), ...

Usually amounts to higher-dim operators with additional small factors

Global symmetries or new quantum numbers usually required to forbid lower-loop contri.

Why going beyond conventional seesaws

- m_ν induced at tree level from higher-dim operators

Fields live in higher-dim reps so that seesaw operates in several steps to avoid lower-dim operators

Global symmetries not necessary

Unique operator at each dim $\mathcal{O}_{5+2n} = \mathcal{O}_5 (H^\dagger H)^n$ Liao 2010

I focus below on the second approach.

New fields in higher-dim reps: higher seesaws at tree

Too many, arbitrary possibilities. Use as our criteria: Liao 2010

- For a given set of fields, lowest-dim operator $\mathcal{O}_{5+2n}$ dominates m_ν
- For a given $\mathcal{O}_{5+2n}$, use as few new fields as possible.
- No symmetry other than SM gauge symmetry imposed.

Consequences:

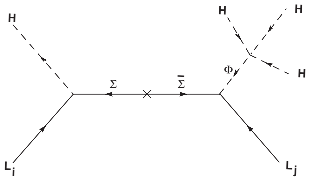
- New scalars Φ and fermions Σ are both required to go beyond conventional seesaws.
- Can be classified according to *whether SM H can Yukawa couple to Σ*

New fields in higher-dim reps: (H, Σ) *coupled* $\Rightarrow \mathcal{O}_7$

Unique option: one fermion $\Sigma = (1, 2)$ plus one scalar $\Phi = (3/2, 3)$

This is the model proposed in Babu et al 2009

$\mathcal{O}_7$ from



LHC pheno briefly analysed:

pair-production of multiply charged $\Phi^{\pm\pm\pm}$, $\Phi^{\pm\pm} \to$ multiple $\ell^{\pm}$, $W^{\pm}$

testability yet to be studied

New fields in higher-dim reps: (H, Σ) *not coupled* $\Rightarrow \mathscr{O}_{5+4n}$

Cascade seesaw Liao 2010

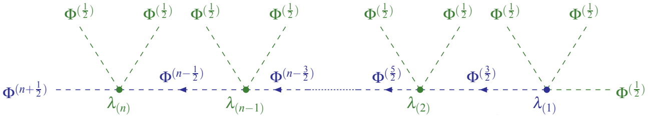
one fermion $\Sigma = (n+1, 0)$ with integral $n \geq 1$

A sequence of scalars $\Phi^{(m+\frac{1}{2})} = (m+1/2, 1)$ with $m = 1,\ 2, \ldots,\ n$

Consequences:

- Only $\Phi^{(n+\frac{1}{2})}$ can Yukawa couple to (Σ, F_L)
- Only $\Phi^{(\frac{3}{2})}$ can directly develop a naturally small vev,

while others develop smaller and smaller vev's by a *cascading process*:



- m_ν from $\mathscr{O}_{5+4n}$ without imposing a global sym

Outline

Summary of minimal cascade seesaw

one scalar Φ with $(I,Y)=(3/2,1)$, $\Phi=(\Phi_{+2},\Phi_{+1},\Phi_0,\Phi_{-1})$
one fermion Σ with $(I,Y)=(2,0)$, $\Sigma=(\Sigma_{+2},\Sigma_{+1},\Sigma_0,\Sigma_{-1},\Sigma_{-2})$
relevant SM fields, $\phi=(\phi_+,\phi_0)$, $F_L=(n_L,f_L)$, f_R

$$\begin{aligned} V =& -\mu_\phi^2\phi^\dagger\phi+\lambda_\phi(\phi^\dagger\phi)^2+\mu_\Phi^2\Phi^\dagger\Phi \\ & -\lambda_1(\Phi\tilde{\Phi})_0(\phi\tilde{\phi})_0-\lambda_2\big((\Phi\tilde{\Phi})_1(\phi\tilde{\phi})_1\big)_0 \\ & +\lambda_3\big((\Phi\Phi)_1(\tilde{\Phi}\tilde{\Phi})_1\big)_0+\lambda_4\big((\Phi\Phi)_3(\tilde{\Phi}\tilde{\Phi})_3\big)_0 \\ & -\left[\kappa_1(\Phi\tilde{\phi}\phi\tilde{\phi})_0+\text{h.c.}\right]-\left[\kappa_2\big((\Phi\Phi)_1(\tilde{\phi}\tilde{\phi})_1\big)_0+\text{h.c.}\right] \\ & -\left[\kappa_3\big((\Phi\Phi)_1(\tilde{\Phi}\tilde{\phi})_1\big)_0+\text{h.c.}\right] \end{aligned}$$

$\tilde{\Phi}=(\Phi^*_{-1},-\Phi^*_0,\Phi^*_{+1},-\Phi^*_{+2})$

$\tilde{\phi}=(\phi^*_0,-\phi^*_+)$

Approximation: $\kappa_1\approx\kappa_3\approx\kappa$, $\kappa_2\approx\kappa^2$ with κ being real and small:

$$v_\phi\approx\sqrt{\frac{\mu_\phi^2}{2\lambda_\phi}},\ v_\Phi\approx\frac{\kappa v_\phi}{2\sqrt{3}r_\Phi};\ r_\Phi=\frac{\mu_\Phi^2}{v_\phi^2}+\frac{\lambda_1}{2\sqrt{2}}+\frac{\lambda_2}{2\sqrt{30}}$$

Essential parameters: v_Φ, M_Φ

Summary of minimal cascade seesaw

Yukawa couplings:

$$-\mathscr{L}_\Phi^{\text{Yuk}} = 2\sqrt{5}\left[x_i(\overline{F_{Li}^C}\Phi\Sigma)_0 + z_i(\overline{\tilde{\Sigma}}\Phi F_{Li})_0 + \text{h.c.}\right]$$

$$-\mathscr{L}_\phi^{\text{Yuk}} = (y_\phi)_{ij}\overline{F_{Li}}\phi f_{Rj} + \text{h.c.} \qquad \tilde{\Sigma} = (\overline{\Sigma_{-2}},\ -\overline{\Sigma_{-1}},\ \overline{\Sigma_0},\ -\overline{\Sigma_{+1}},\ \overline{\Sigma_{+2}})$$

including a bare mass for Σ:

$$-\mathscr{L}_{\text{m}} = \frac{1}{2}\overline{N_L}M_N N_R + \overline{E_L}M_E E_R + \overline{D_L}M_D D_R + \text{h.c.},$$

$$M_N = \begin{pmatrix} 0_3 & (x+z)^* v_\Phi & i(x-z)^* v_\Phi \\ (x+z)^\dagger v_\Phi & M_\Sigma & 0 \\ i(x-z)^\dagger v_\Phi & 0 & M_\Sigma \end{pmatrix},$$

$$M_E = \begin{pmatrix} y_\phi v_\phi & \sqrt{3/2}(x+z)^* v_\Phi & i\sqrt{3/2}(x-z)^* v_\Phi \\ 0 & M_\Sigma & 0 \\ 0 & 0 & M_\Sigma \end{pmatrix}, \quad M_D = M_\Sigma \mathbf{1}_2$$

Summary of minimal cascade seesaw

in the basis of

$$N_L = \begin{pmatrix} n_L \\ \Sigma^0_{1L} \\ \Sigma^0_{2L} \end{pmatrix},\ N_R = N_L^C,\ E = \begin{pmatrix} f \\ \Sigma^-_1 \\ \Sigma^-_2 \end{pmatrix},\ D = \begin{pmatrix} \Sigma^{--}_1 \\ \Sigma^{--}_2 \end{pmatrix},$$

where the subscripts 1, 2 denote two new fermions of equal charge.

The fermion masses are diagonalized in an elegant way.

Essential parameters:

M_Σ, $U_{\text{PMNS}} = (\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)$, $m_{\nu_{1,2,3}}$, and 3×2 matrix $Z = (\mathbf{z}_1, \mathbf{z}_2)$ with

NH: $m_{\nu_1} = 0,\ m_{\nu_2} = \lambda_-,\ m_{\nu_3} = \lambda_+,\ \mathbf{z}_1 = c_-\mathbf{x}_2 + c_+\mathbf{x}_3,\ \mathbf{z}_2 = d_-\mathbf{x}_2 + d_+\mathbf{x}_3$

IH: $m_{\nu_3} = 0,\ m_{\nu_1} = \lambda_-,\ m_{\nu_2} = \lambda_+,\ \mathbf{z}_1 = c_-\mathbf{x}_1 + c_+\mathbf{x}_2,\ \mathbf{z}_2 = d_-\mathbf{x}_1 + d_+\mathbf{x}_2$

both $c_- = i\lambda_-^{\frac{1}{2}}\dfrac{2t}{1+t^2},\ d_- = i\lambda_-^{\frac{1}{2}}\dfrac{1-t^2}{1+t^2};\ c_+ = i\lambda_+^{\frac{1}{2}}\dfrac{1-t^2}{1+t^2},\ d_+ = -i\lambda_+^{\frac{1}{2}}\dfrac{2t}{1+t^2}$

Constraints on minimal cascade seesaw

lepton flavor violating (LFV) transitions, including

$\ell_i \to \ell_j \gamma$

$\ell_i \to \ell_j \ell_k \overline{\ell}_l$

$\mu - e$ conversion in nuclei

dominant contributions from Yukawa couplings

most significant: $\mu \to e\gamma$

Fo instance,

at $M_\Phi = 200~\mathrm{GeV},~M_\Sigma = 300~\mathrm{GeV}$, best-fit oscillation parameters

$\Rightarrow v_\Phi \geq 10^{-4}~\mathrm{GeV}$

– to be respected in LHC analysis

Minimal cascade seesaw at LHC

Working strategy:

- implement model in `FeynRules1.7` with output `UFO` model file fed into
- `Madgraph5` to generate parton level events, which then pass through
- `Pythia6` to include initial- and final-state radiation, fragmentation, and hadronization

`PGS` for detector simulation and `MadAnalysis5` for analysis

PDF: `CTEQ6L1`

Simplifying assumption:

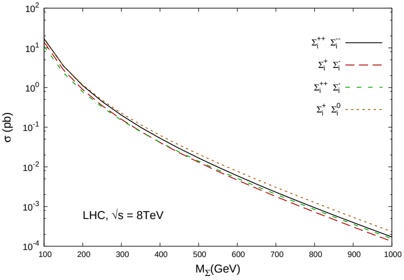
degenerate Φs, degenerate Σs, which decay directly into SM particles

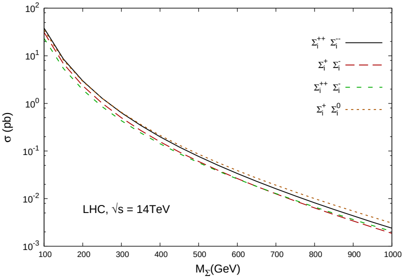
Benchmark point for parameters:

$M_\Phi = M_\Sigma = 300\ \mathrm{GeV}$, $t = 1 + i$, $v_\Phi = 10^{-4}$ or $10^{-2}\ \mathrm{GeV}$

Production of new particles at LHC

$$
\begin{aligned}
pp &\to \gamma^*/Z^* \to \Phi^*_{+2}\Phi_{+2}/\Phi^*_{+1}\Phi_{+1}/\Phi^*_{-1}\Phi_{-1}/A_0H_0, \\
&\to \gamma^*/Z^* \to \Sigma^{++}\Sigma^{--}/\Sigma^{+}\Sigma^{-}, \text{ pair production} \\
&\to W^* \to \Phi^*_{+1}\Phi_{+2}/A_0\Phi_{+1}/A_0\Phi^*_{-1}/H_0\Phi_{+1}/H_0\Phi^*_{-1} + \text{c.c.}, \\
&\to W^* \to \Sigma^{++}\Sigma^{-}/\Sigma^{+}\Sigma^{0} + \text{c.c. associated production}
\end{aligned}
$$





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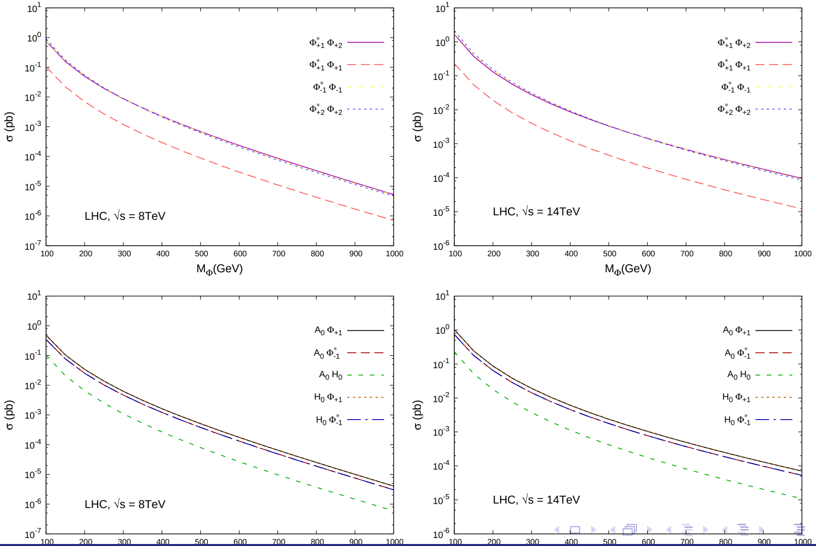


Decay branching ratios of Φ_{+2}

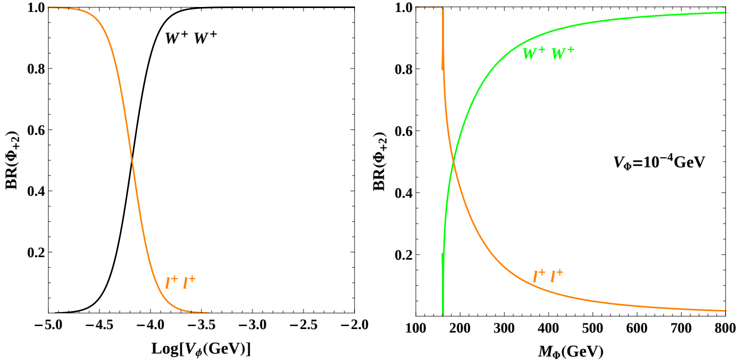
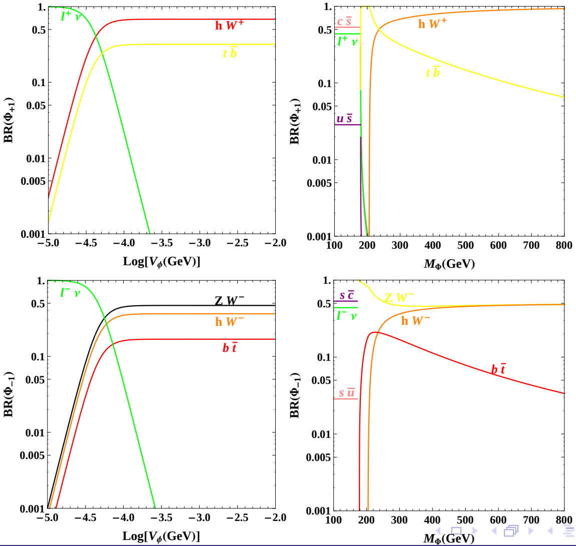


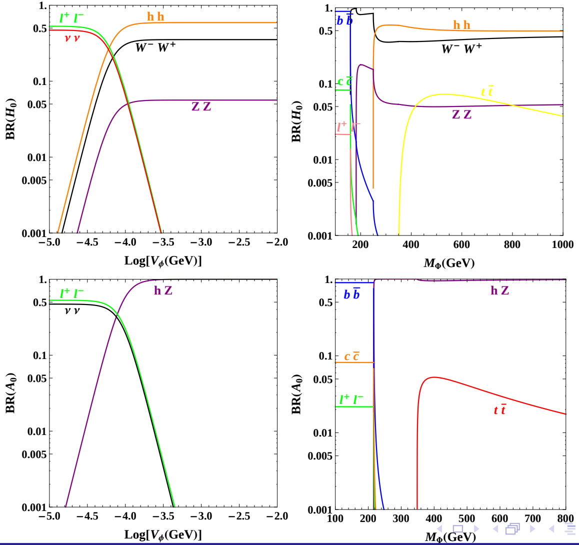
Figure: Left: $M_\Phi = 300$ GeV; right: $v_\Phi = 10^{-4}$ GeV.

$$\frac{\Gamma(\Phi_{+2} \to \ell_i^+ \ell_j^+)}{\Gamma(\Phi_{+2} \to W^+ W^+)} \sim \left(\frac{m_\nu}{M_\Phi}\right)^2 \left(\frac{v_\phi}{v_\Phi}\right)^4$$

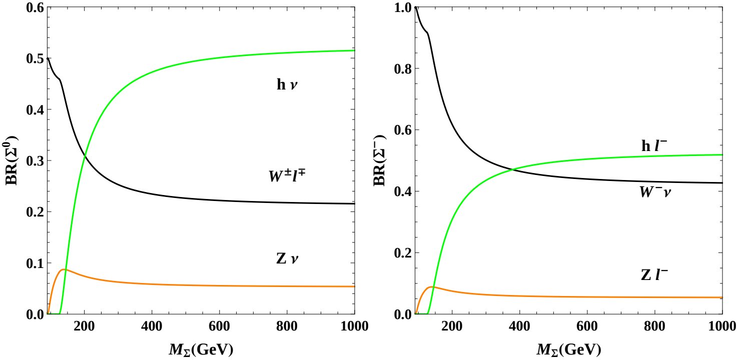
Decay branching ratios of $\Phi_{\pm 1}$ [right: $v_\Phi = 10^{-2}$ GeV]



Decay branching ratios of H_0, A_0 [right: $v_\Phi = 10^{-2}$ GeV]



Decay branching ratios of $\Sigma^{0,-}$



LHC signatures of new particles

Limits from CMS and ATLAS on type II and III seesaws *not directly applicable* due to different production and decay properties and special assumptions.

Final states classified according to multiplicity of charged leptons; 7 channels considered.

Scalar signal channels sensitive to v_Φ; choose $v_\Phi = 10^{-4},\ 10^{-2}$ GeV.

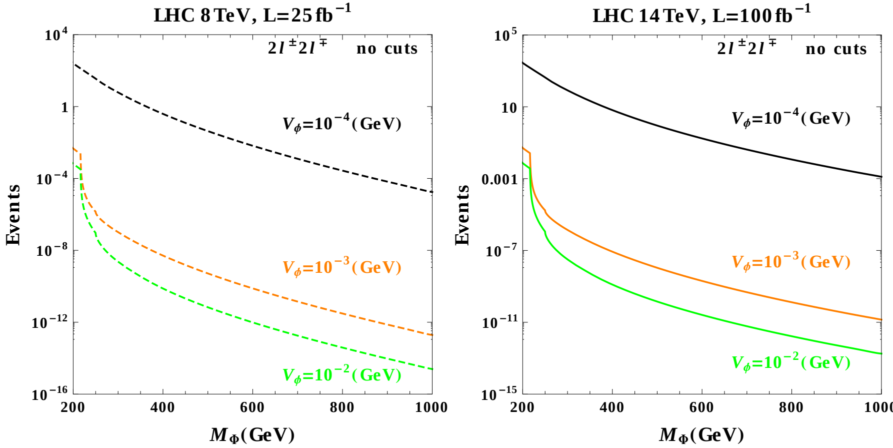
SM backgrounds estimated by `Madgraph5`; only irreducible ones included.

Signal channels considered at LHC

final states	Φ production process in pp collision
$2\ell^\pm 2\ell^\mp$	$\Phi_{+2}\Phi^*_{+2}/A_0H_0 \to 2\ell^\pm 2\ell^\mp$
$4j2\ell^\pm + \not{E}_T$	$\Phi_{+2}\Phi^*_{+2} \to W^\pm W^\pm W^\mp W^\mp \to jjjj\ell^\pm\ell^\pm\nu\nu$, $\Phi_{+2}\Phi^*_{+1}(\Phi^*_{+2}\Phi_{+1}) \to W^\pm W^\pm + hW^\mp/\bar{t}b(t\bar{b}) \to jjb\bar{b}\ell^\pm\ell^\pm\nu\nu$
$4j2\ell^\pm$	$\Phi_{+2}\Phi^*_{+2} \to \ell^\pm\ell^\pm W^\mp W^\mp \to jjjj\ell^\pm\ell^\pm$, $\Phi_{+2}\Phi^*_{+1}(\Phi^*_{+2}\Phi_{+1}) \to \ell^\pm\ell^\pm + hW^\mp/\bar{t}b(t\bar{b}) \to jjb\bar{b}\ell^\pm\ell^\pm$

final states	Σ production process in pp collision
$2\ell^\pm 2\ell^\mp 2j$	$\Sigma^\pm\Sigma^\mp/\Sigma^0\Sigma^\pm/\Sigma^\pm\Sigma^{\mp\mp} \to hZ(ZZ)\ell^\pm\ell^\mp/W^\pm\ell^\mp Z\ell^\pm/Z\ell^\pm W^\mp\ell^\mp$ $\to jj2\ell^\pm 2\ell^\mp$
$3\ell^\pm\ell^\mp 2j$	$\Sigma^\pm\Sigma^0 \to W^\mp\ell^\pm Z\ell^\pm \to jj3\ell^\pm\ell^\mp$
$3\ell^\pm 2\ell^\mp + \not{E}_T$	$\Sigma^\pm\Sigma^0/\Sigma^{\pm\pm}\Sigma^\mp \to Z\ell^\pm W^\pm\ell^\mp(Z\ell^\pm Z\nu)/W^\pm\ell^\pm Z\ell^\mp \to 3\ell^\pm 2\ell^\mp\nu$
$3\ell^\pm 3\ell^\mp$	$\Sigma^\pm\Sigma^\mp \to \ell^\pm Z\ell^\mp Z \to 3\ell^\pm 3\ell^\mp$

Predicted number of signals in Φ production: no cuts



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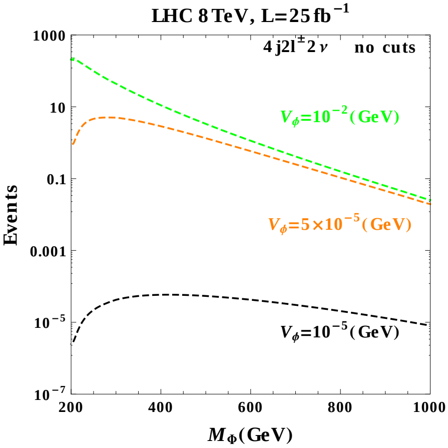
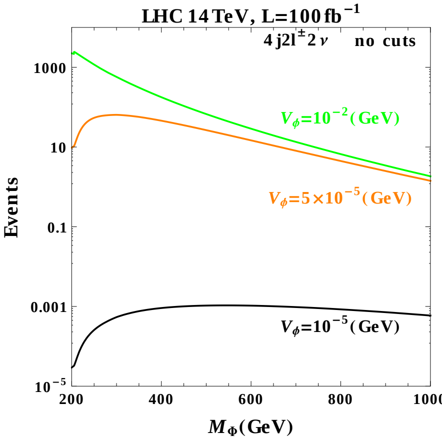
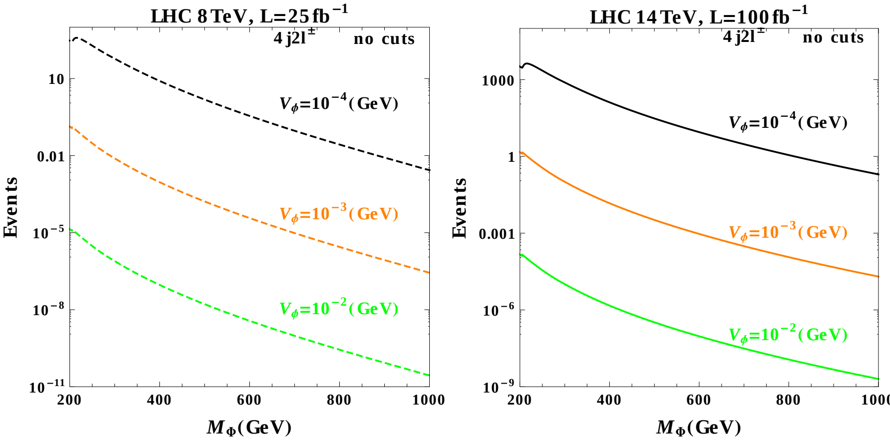
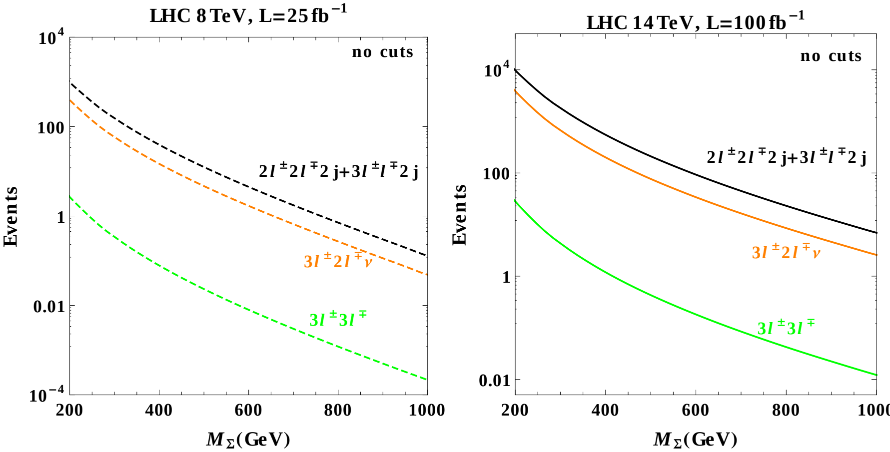




Predicted number of signals in Φ production: no cuts



Predicted number of signals in Σ production: no cuts



Example 1: Φ reconstruction in $4j2\ell^{\pm}$ channel

$v_\Phi = 10^{-4}$ GeV (two decay modes of Φ_{+2} comparable), $M_\Phi = 300$ GeV

$$\Phi_{+2}\Phi^*_{+2} \to \ell^{\pm}\ell^{\pm}W^{\mp}W^{\mp} \to \ell^{\pm}\ell^{\pm}jjjj,$$
$$\Phi_{+2}\Phi^*_{+1}(\Phi^*_{+2}\Phi_{+1}) \to \ell^{\pm}\ell^{\pm} + hW^{\mp}/\bar{t}b(t\bar{b}) \to \ell^{\pm}\ell^{\pm}jjb\bar{b}$$

Basic cuts:

$$p_T(\ell) > 15 \text{ GeV}, \ |\eta(\ell)| < 2.5,$$
$$p_T(j) > 20 \text{ GeV}, \ |\eta(j)| < 2.5,$$
$$\Delta R_{\ell\ell} > 0.4, \ \Delta R_{j\ell} > 0.4, \ \Delta R_{jj} > 0.4.$$

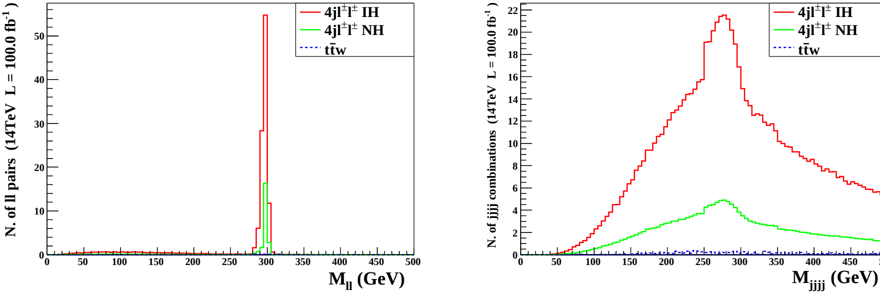
Specific cuts on bkg $t\bar{t}W$:

$$p_T(\ell) > 50 \text{ GeV}, \ p_T(j) > 100 \text{ GeV}, \not{E}_T < 30 \text{ GeV (cutting } \nu)$$

Reconstruction of resonances:

$$250 \text{ GeV} < M_{jjjj} < 350 \text{ GeV} \qquad 280 \text{ GeV} < M_{\ell\ell} < 320 \text{ GeV}$$

Example 1: Φ reconstruction in $4j2\ell^{\pm}$ channel

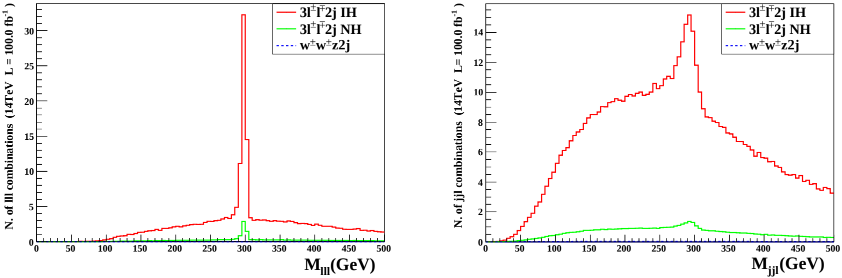


$>$ 100 events for IH case and $\sim$ 20 events for NH

Example 2: Σ reconstruction in $3\ell^{\pm}\ell^{\mp}2j$ channel

$$\Sigma^{\pm}\Sigma^{0} \to \ell^{\pm} Z \ell^{\pm} W^{\mp} \to \ell^{\pm}\ell^{+}\ell^{-}\ell^{\pm} q\bar{q}'$$

basic cuts sufficient



$\sim$ 100 events for IH case and $\sim$ 9 events for NH

Outline

Summary

- Great progress in measurements on neutrino parameters, including the oscillation data, cosmological observations, and other low-energy experiments, is very helpful for us to do realistic collider phenomenology.
- Conventional seesaw models have been fully studied in the literature except for type III. Type I has been done for *effective case*.
- There are a variety of models beyond conventional seesaws, some of which have been studied and some are being considered. A challenging task is how to distinguish them at colliders.
- We made a comprehensive analysis on minimal cascade seesaw. With low energy constraints respected, it is possible to detect new particles in a few channels, like $4j2\ell^{\pm}$ for scalars and $2\ell^{\pm}2\ell^{\mp}2j$, $3\ell^{\pm}\ell^{\mp}2j$ and $3\ell^{\pm}2\ell^{\mp}+\not{E}_T$ channels for fermions.

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