Neutrino Physics at Colliders

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Special thanks to Dr. Ji-Yuan Liu for collaboration and help

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}

$$\begin{aligned} V &= U\cdot\mathrm{Diag}\{e^{i\rho},\ e^{i\sigma},\ 1\},\\ U &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\\ -c_{12}s_{23}s_{13}-s_{12}c_{23}e^{-i\delta} & -s_{12}s_{23}s_{13}+c_{12}c_{23}e^{-i\delta} & s_{23}c_{13}\\ -c_{12}c_{23}s_{13}+s_{12}s_{23}e^{-i\delta} & -s_{12}c_{23}s_{13}-c_{12}s_{23}e^{-i\delta} & c_{23}c_{13} \end{pmatrix},\end{aligned}$$

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

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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°	$[32.6^\circ, 34.8^\circ]$	$[31.6^\circ, 35.8^\circ]$	$[30.6^\circ, 36.8^\circ]$
θ_{23}	38.4°	$[37.2^\circ, 40.0^\circ]$	$[36.2^\circ, 42.0^\circ]$	$[35.1^\circ, 53.0^\circ]$
θ_{13}	8.9°	$[8.5^\circ, 9.4^\circ]$	$[8.0^\circ, 9.8^\circ]$	$[7.5^\circ, 10.2^\circ]$

$\delta m^2 \equiv m_2^2 - m_1^2$ 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: $m_\beta \equiv \sqrt{\sum |V_{ei}|^2 m_i^2}$

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

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

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

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

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

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

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

  $\Sigma < 0.23~\mathrm{eV}$ @ 95% C.L. Planck 2013

  $\Rightarrow \Sigma \sim 0.05~\mathrm{eV}$

What we experimentally know about ν's relatives

ν and ℓ share CC weak interactions

⇒ 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: $\mathrm{BRs} \sim 10^{-8}$ 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_ν may arise from an effective higher-dim interaction Weinberg 1980

$$\begin{aligned}\mathscr{L}_{\rm int} &= \frac{\lambda}{\Lambda}\mathscr{O}_5+{\rm h.c.},\quad \mathscr{O}_5=\left(\overline{F_L{}^C}\epsilon H\right)\left(H^T\epsilon F_L\right),\ H=\begin{pmatrix}H^+\\ H^0\end{pmatrix},\ F_L=\begin{pmatrix}\nu_L\\ \ell_L\end{pmatrix}\\ &\Rightarrow \frac{\lambda}{\Lambda}\frac{v^2}{2}\overline{\nu_L{}^C}\nu_L+{\rm h.c., via}\ \langle H^0\rangle=\frac{v}{\sqrt{2}}\qquad \text{Majorana mass}\end{aligned}$$

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

1. Basics about neutrinos
2. Conventional seesaws and tests
3. Going beyond conventional seesaws
4. Summary and outlook

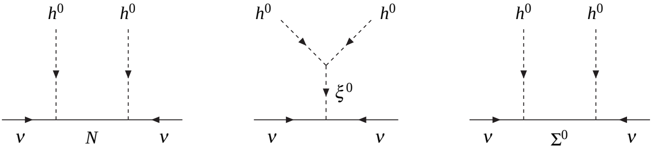
Weinberg operator and its tree level realizations

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

⇒ 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.
- I show a few typical results.

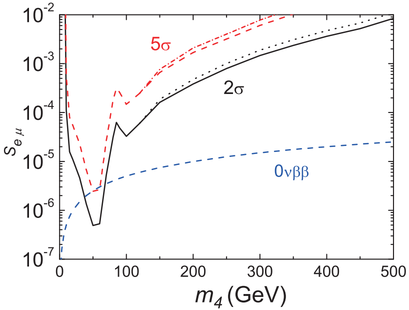
Collider test of *effective type I seesaw*

$$\sigma(pp\to \ell_1^\pm\ell_2^\pm W^\mp)\approx(2-\delta_{\ell_1\ell_2})S_{\ell_1\ell_2}\sigma_0$$ Han and Zhang 2006

$$S_{\ell_1\ell_2}=\frac{|V_{\ell_1 N}V_{\ell_2 N}|^2}{\sum_\ell |V_{\ell N}|^2},\ \sigma_0:$$ largely indept of mixing parameters

Sensitivity at 14 TeV LHC with 100 fb^{-1} Atre et al 2009

$m_N\sim 375\ (250)$ GeV or $S_{e\mu}\sim 7\times10^{-7}\ (3\times10^{-6})$ for 2σ (5σ)



Less optimistic due to large background from $b\bar{b}$ decays

of $\ell^\pm\ell^\pm jj$ events at LHC for 30 fb^{-1}: Aguila et al 2007

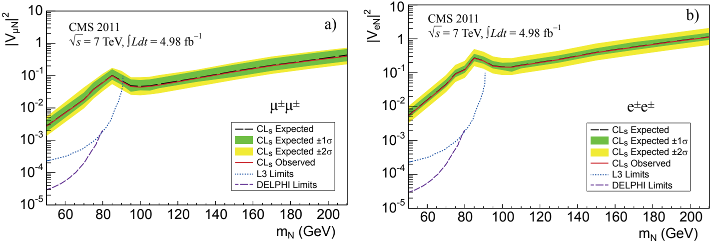
$m_N = 150~\mathrm{GeV}$.(a) $V_{\mu N} = 0.098$;(b) $V_{eN} = 0.073$; (c) both

	Pre-selection			Selection		
	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$\mu^\pm e^\pm$
N (a)	113.6	0	0	59.1	0	0
N (b)	0	72.0	0	0	17.6	0
N (c)	78.4	25.5	82.6	41.6	4.7	22.4
$b\bar{b}nj$	14800	52000	82000	0	0	0
$c\bar{c}nj$	(11)	300	200	(0)	0	0
$t\bar{t}nj$	1162.1	8133.0	15625.3	2.4	8.3	7.7
tj	60.8	176.5	461.5	0.0	0.0	0.1
$Wb\bar{b}nj$	124.9	346.7	927.3	0.4	0.6	0.3
$Wt\bar{t}nj$	75.7	87.2	166.9	0.3	0.0	0.0
$Zb\bar{b}nj$	12.2	68.9	117.0	0.0	0.2	0.0
$WWnj$	82.8	89.0	174.8	0.5	0.1	0.7
$WZnj$	162.4	252.0	409.2	4.8	1.8	2.3
$ZZnj$	3.8	13.3	12.9	0.0	0.6	0.1
$WWWnj$	31.9	30.1	64.8	0.9	0.1	0.0

5σ sensitivity for m_N up to $200~\mathrm{GeV}$ with $V_{\mu N} = 0.098$

5σ sensitivity for m_N up to $145~\mathrm{GeV}$ with $V_{eN} = 0.073$

Collider test of *effective type I* seesaw: LHC data



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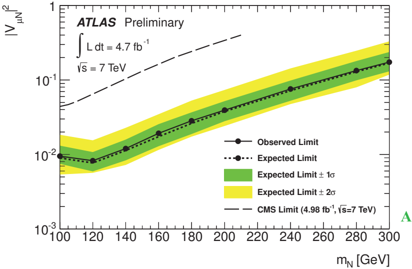


ATLAS-CONF-2012-139

Type II seesaw

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

doubly-charged, singly-charged, and neutral

$$\begin{aligned}\mathscr{L} &\supset \frac{1}{2}\mathrm{Tr}(D^\mu\Delta)^\dagger(D_\mu\Delta) - \left[f_{ij}\overline{F^C_{Li}}(i\sigma_2)\Delta F_{Lj} + \text{h.c.}\right] \\ V &\supset -m_H^2 H^\dagger H + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu(H^\dagger\Delta\tilde{H}) + \text{h.c.}\right] \\ &\quad + \frac{1}{2}\lambda_1(H^\dagger H)^2 + \lambda_4(H^\dagger H)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_6(H^\dagger\Delta\Delta^\dagger H)\end{aligned}$$

vev's and Majorana ν mass:

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

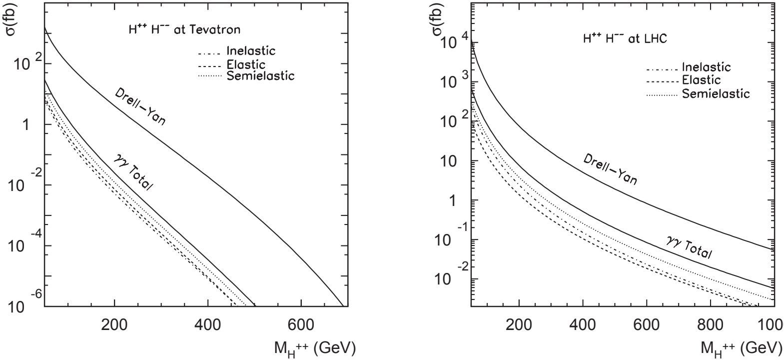
$$m_\nu = f v_\Delta$$

enjoy electroweak interactions

⇒ rich phenomenology expected, details depending on v_Δ.

Collider test of type II seesaw

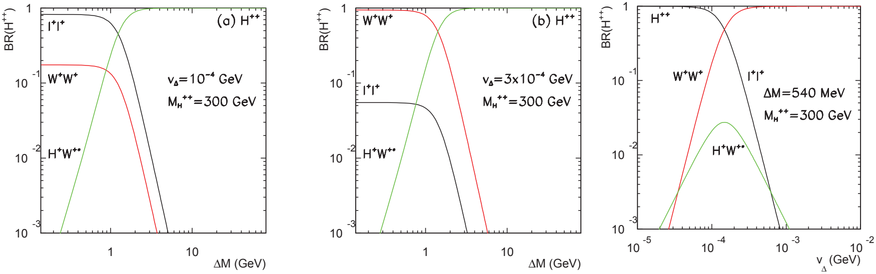
$\sigma(pp(\bar{p}) \to H^{\pm\pm}H^{\pm\pm})$ by Drell-Yan and $\gamma\gamma$ fusion



Han, Mukhopadhyaya, Si and Wang, PRD76, 2007

Collider test of type II seesaw

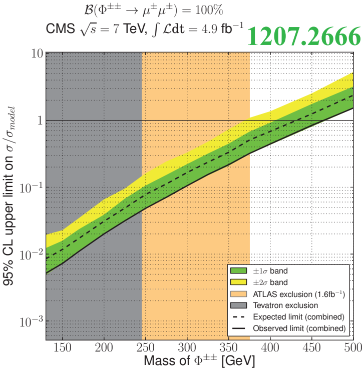
Br$(H^{\pm\pm})$ vs mass splitting $\Delta M \equiv M_{H^{++}} - M_{H^{+}}$ and v_Δ



Fileviez Perez, Han, Huang, Li and Wang 2008

For $v_\Delta < 10^{-4}$ GeV, $\ell^\pm\ell^\pm$ signals at LHC with 300 fb^{-1} should be observable up to $M_{H^{++}} \sim 1$ TeV.

Collider test of type II seesaw: LHC data



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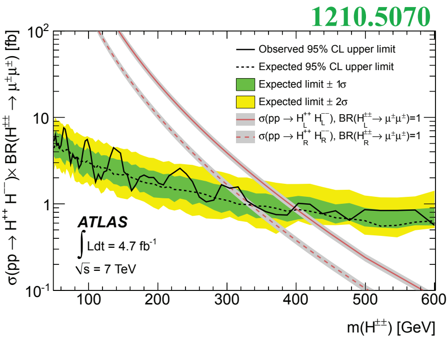


1210.5070

CMS: $m_{\Phi^{++}} \geq (204 - 459)$ GeV assuming $\mathrm{BR}(\Phi^{++} \to \ell^+\ell'^+) \sim 100\%$

$(383 - 408)$ GeV at 4 benchmark points

ATLAS: $m_{\Phi^{++}} \lesssim 409$ $(e^\pm e^\pm)$, 398 $(\mu^\pm\mu^\pm)$, 375 GeV $(e^\pm\mu^\pm)$ excl. at 95% CL

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:

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

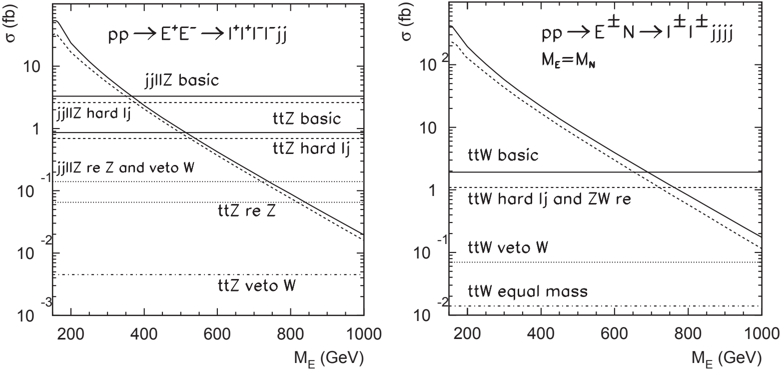
can be diagonalized as in type I seesaw

Differences to type I:

electroweak interactions; charged heavy-light mixing

Relatively less extensively studied

Collider test of type III seesaw

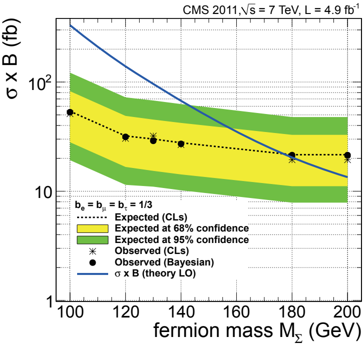


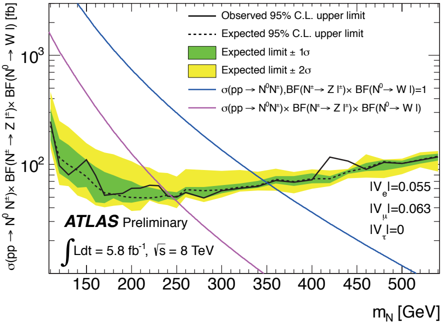
Li and He 2009

A displaced vertex of heavy triplet leptons could be visible at LHC.

Possible to detect them up to 1 TeV.

Collider test of type III seesaw: LHC data





CMS 1210.1797

$M_\Sigma > 180 - 210$ GeV at 95% CL

ATLAS-CONF-2013-019

$M_\Sigma > 245$ GeV at 95% CL

A partial list of other papers on conventional seesaws

Type I seesaw at various colliders (ILC, CLIC, etc) Aguila et al 2005, 2006 (see backup pages)

Comparative study on 3 seesaws and importance of tri-lepton channel $\ell^\pm\ell^\pm\ell^\mp$ for discovery Aguila et al 2009 (see backup pages)

Variants of 3 seesaws:

Type I+II: Chao, Si, Xing and Zhou 2008

Type I+III from $SU(5)$: Bajc et al 2007; Arhrib et al 2010

Type I + $\ell N H^+$ interaction Bar-Shalom, Eilam, Han and Soni 2008

Type I + $U(1)_{B-L}$ symmetry Fileviez Perez, Han and Li 2009

Type I + W' Han, Lewis, Ruiz and Si 2013

Type II + scalar multiplets Aguila and Chala 2013

……

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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 show one example for each approach

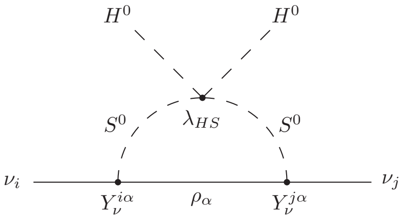
Radiatively induced m_ν: color-octet model

New particles: Fileviez Perez and Wise 2009

one scalar $S \sim (8,2,1)$ and two fermions $\rho_\alpha \sim (8,1,0)$

$$\begin{aligned}\mathscr{L} &\supset -Y_\nu^{i\alpha}\overline{F_{Li}}\tilde{S}\rho_\alpha + \text{h.c.},\\ V &\supset \frac{1}{2}\lambda_{HS}(S^\dagger H)^2 + \text{h.c.}\end{aligned}$$

m_ν induced by

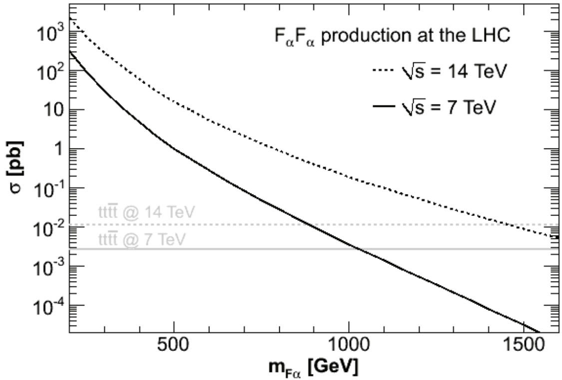


Radiatively induced m_ν: color-octet model at LHC

Fileviez Perez, Han, Spinner and Trenkel 2010

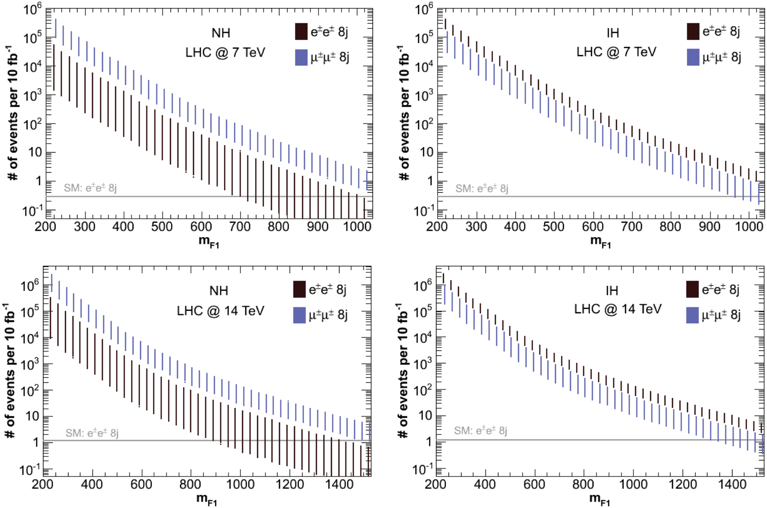
Signal: like-sign dileptons via $F_\alpha F_\alpha$ production with $F_\alpha \to \ell t b \to \ell 4j$

Pair production cross section of octet fermions: $F_\alpha \equiv (\rho^C_{R\alpha}, \rho_{R\alpha})$



# of like-sign dileptons per $10/\mathrm{fb}$ exceeds bkg up to $m_{F_1} \approx m_{F_2} \sim 1\ \mathrm{TeV}$

$m_S = 2\ \mathrm{TeV}$, vertical line: scanning over parameters



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:

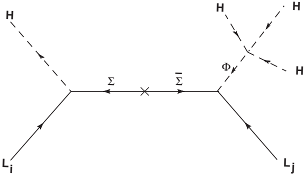
- New scalars Φ and fermions Σ are both required to go beyond conventional seesaws.
- Can be classified according to *whether SM H can Yukawa couple to Σ*

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

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

This is the model proposed in Babu et al 2009

$\mathscr{O}_7$ from



LHC pheno briefly analysed:

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

testability yet to be studied

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

General case: *cascade seesaw* Liao 2010

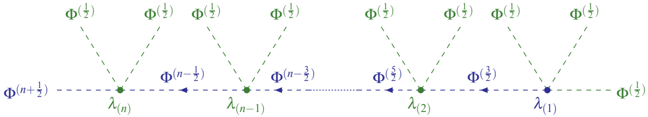
one fermion $\Sigma = (n+1,0)$ with integral $n \geq 1$

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,

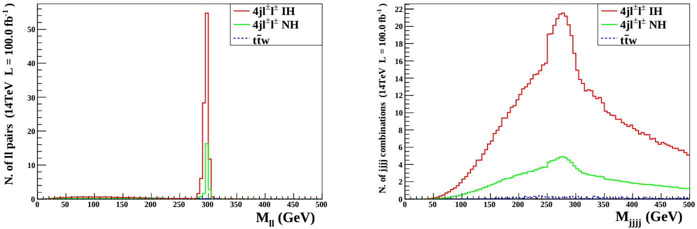
while others develop smaller and smaller vev's by a *cascading process*:



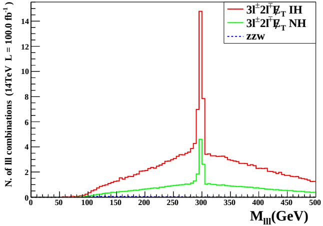
- m_ν from $\mathcal{O}_{5+4n}$ without imposing a global sym

New fields in higher-dim reps: LHC pheno with $\mathscr{O}_9$

of events of $pp \to \Phi^{++}\Phi^{+} \to 4j2\ell$ for $M_{\Phi^{++},\Phi^{+}} = 300\ \mathrm{GeV}$ at 14 TeV



# of events of $pp \to \Sigma^{\pm}\Sigma^{0} \to 3\ell^{\pm}2\ell^{\mp} + \not{E}_T$ for $M_{\Sigma} = 300\ \mathrm{GeV}$ at 14 TeV



Ding et al 1403.xxxx

see also Chen and Zheng 1312.7207

Outline

1. Basics about neutrinos
2. Conventional seesaws and tests
3. Going beyond conventional seesaws
4. **Summary and outlook**

Summary and outlook

- 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. An open but challenging task is how to distinguish them at colliders.
- Neutrino phys at lepton colliders has been less intensively studied because of limited achievable energy for heavy particles, while study at very high energy colliders has just started.

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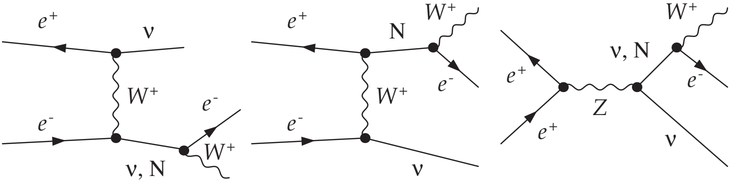
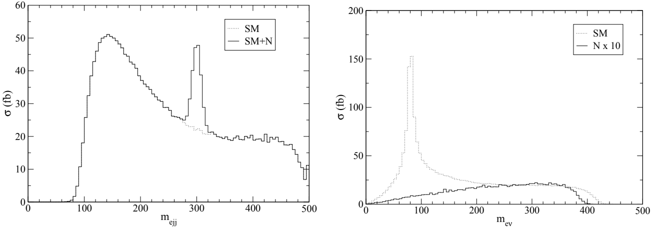
Backup: Simulation on type I seesaw at ILC

- $e^+e^- \to N\nu \to \ell W\nu$ at ILC Aguila et. al., PLB613, 2005



s-channel is suppressed compared to the first two

- Kinematial distributions of m_{ejj} (left) and $m_{e\nu}$ (right) for $V_{eN} = 0.073,\ V_{\mu N} = V_{\tau N} = 0$, and $m_N = 300\ \mathrm{GeV}$.



- Cross sections (in fb) for $e^+e^- \to e^\mp W^\pm \nu$

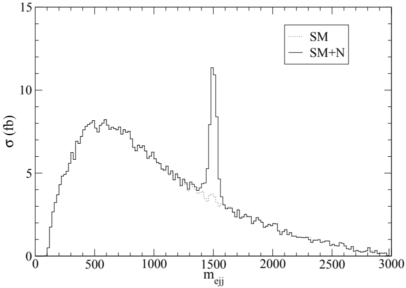
	No cuts	m_{ejj}	$m_{e\nu}$	$m_{ejj},\ m_{e\nu}$
SM	2253	89.1	1387	53.6
SM + N	2339	173.7	1489	130.8

before and after the kinematial cuts:

$$290\ \mathrm{GeV} \le m_{ejj} \le 310\ \mathrm{GeV},\ m_{e\nu} \le 40\ \mathrm{GeV}\ \text{or}\ m_{e\nu} \ge 110\ \mathrm{GeV}.$$

Backup: Simulation on type I seesaw at CLIC

- Kinematial distributions for $e^+e^- \to e^\mp W^\pm \nu$ of m_{ejj} with $V_{eN} = 0.05,\ V_{\mu N} = V_{\tau N} = 0$, and $m_N = 1500\ \text{GeV}$. Aguila et. al., JHEP0505, 2005



	No cut	With cut
SM	516	14.6
SM + N	548	39.4

Cross sections (in fb) before and after the kinematial cut: $1460\ \text{GeV} \le m_{ejj} \le 1540\ \text{GeV}$.

- Their conclusions: if no signal is found at ILC or CLIC:
  - ILC: $V_{eN} \le 0.007$ for $m_N = 200-400\ \text{GeV}$.
  - CLIC: $V_{eN} \le 0.002-0.006$ for $m_N = 1-2\ \text{TeV}$.

Backup: Distinguish 3 conventional seesaws at LHC

Luminosity for discovery in each model Aguila et. al., NPB813, 2009

	Seesaw I $m_N = 100$ GeV	Seesaw II $m_\Delta = 300$ GeV	Seesaw III $m_\Sigma = 300$ GeV
Six leptons	–	–	×
Five leptons	–	–	28 fb^{-1}
$\ell^\pm\ell^\pm\ell^\pm\ell^\mp$	–	–	15 fb^{-1} m_E rec
$\ell^+\ell^+\ell^-\ell^-$	–	19 / 2.8 fb^{-1} $m_{\Delta^{++}}$ rec	7 fb^{-1} m_E rec
$\ell^\pm\ell^\pm\ell^\pm$	–	–	30 fb^{-1}
$\ell^\pm\ell^\pm\ell^\mp$	< 180 fb^{-1}	3.6 / 0.9 fb^{-1} $m_{\Delta^{++}}$ rec	2.5 fb^{-1} m_N rec
$\ell^\pm\ell^\pm$	< 180 fb^{-1} m_N rec	17.4 / 4.4 fb^{-1} $m_{\Delta^{++}}$ rec	1.7 fb^{-1} m_Σ rec
$\ell^+\ell^-$	×	15 / 27 fb^{-1} m_Δ rec	80 fb^{-1} m_Σ rec
$\ell^\pm$	×	×	×