Neutrino masses at LHC?

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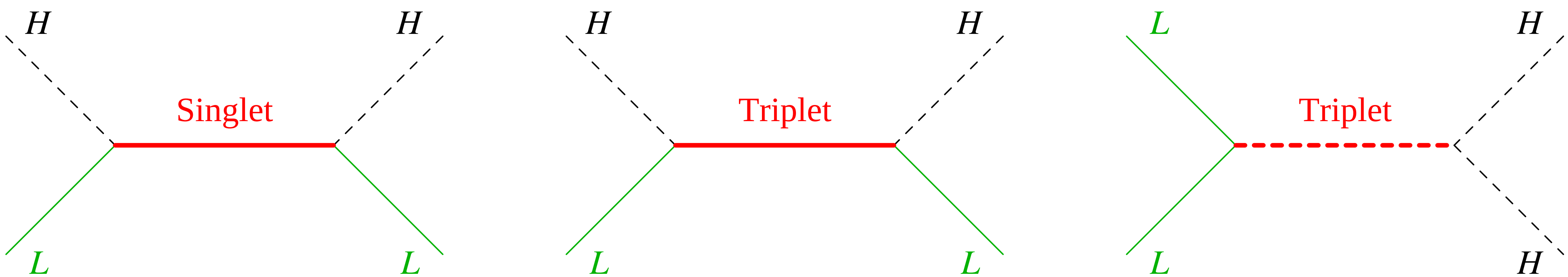
ν presumably get Majorana masses from the unique $(LH)^2/\Lambda_L$ dim-5 operator:

$$m_\nu = \frac{v^2}{\Lambda_L} \sim m_{\text{atm,sun}} \qquad \text{for} \qquad \Lambda_L \sim 10^{14}\,\text{GeV}.$$

Other components of $(LH)^2$ are negligible, e.g. $\sigma(ee \to W^-W^-) \sim 1/\Lambda_L^2$.
It can be mediated at tree level by 3 kinds of particles with mass M:



At dimension 6 they generate different negligible operators, $(H^\dagger \bar{L}_i) i\partial\!\!\!/ (HL_j)/\Lambda_L M$.
LHC needs $M \lesssim$ TeV. No motivation for that (anthropic leptogenesis?).

See-saw: type I, II and III

Type I: neutral Majorana fermion ν_R

Type III: neutral Majorana fermion N^0 and Dirac fermion $N^{\pm}$

Type II: scalars: $T^0, T^{\pm}$ and $T^{\pm\pm}$

Type I see-saw at LHC

$\sigma(pp \to \nu_R \ldots) \approx 0$ unless N has extra couplings.

E.g. if ν_R are light *and* charged under extra Z' or SU(2)$_R$ or SU(3)$_L$ or...

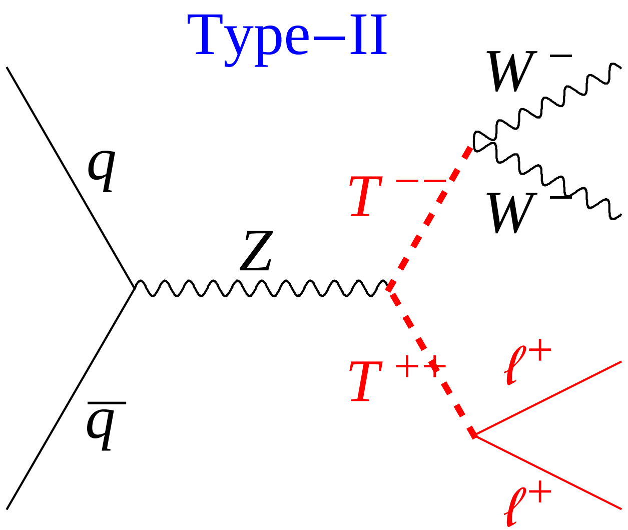
Or if ν_R have large pseudo-Dirac couplings $\lambda \ggg \lambda'$:

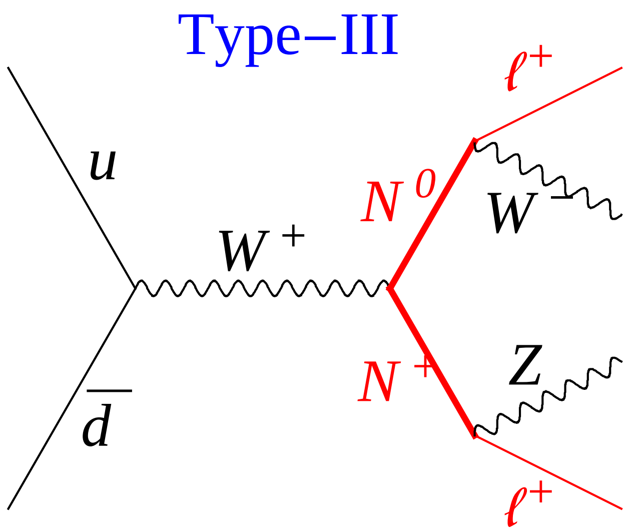
$$\lambda \nu_R L H + \lambda' \nu'_R L H + M \nu_R \nu'_R \qquad m_\nu = \lambda\lambda' \frac{v^2}{M}$$

Or...

Like winning the lottery twice. Not well defined.

Neutrino mass signals at LHC





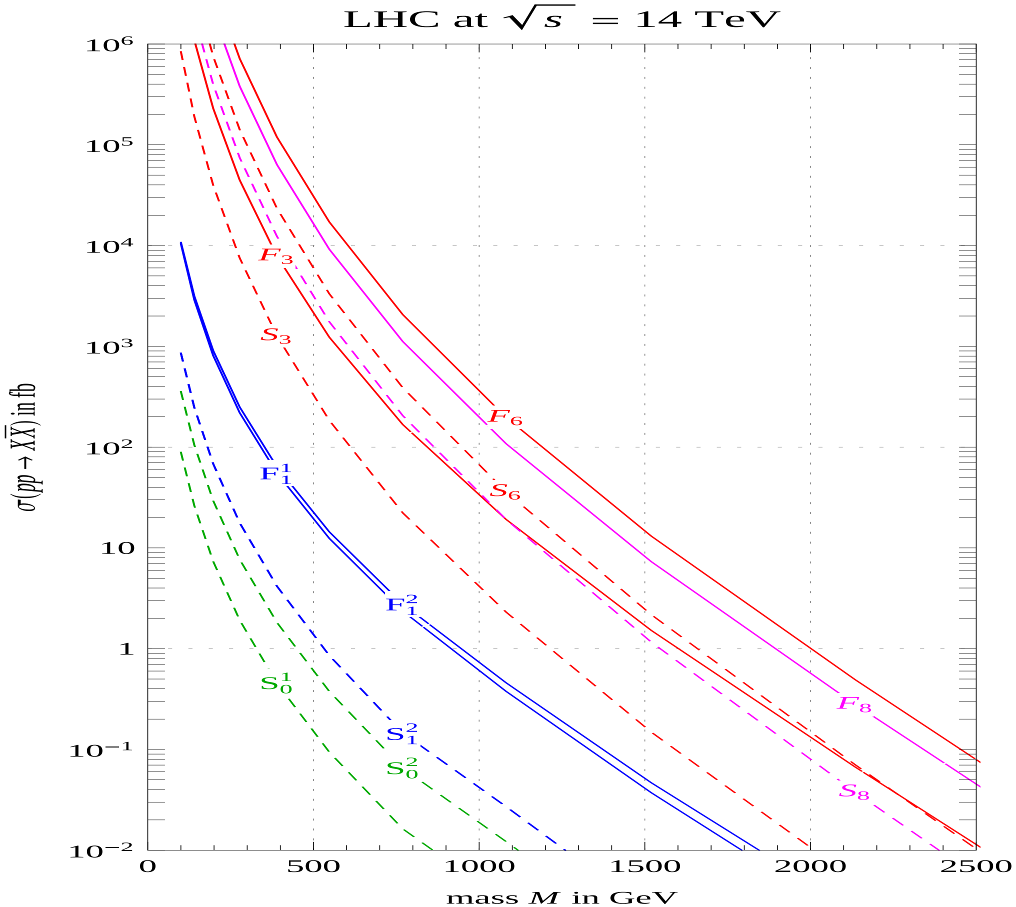
1) pair production of scalar or fermion weak triplets via gauge couplings

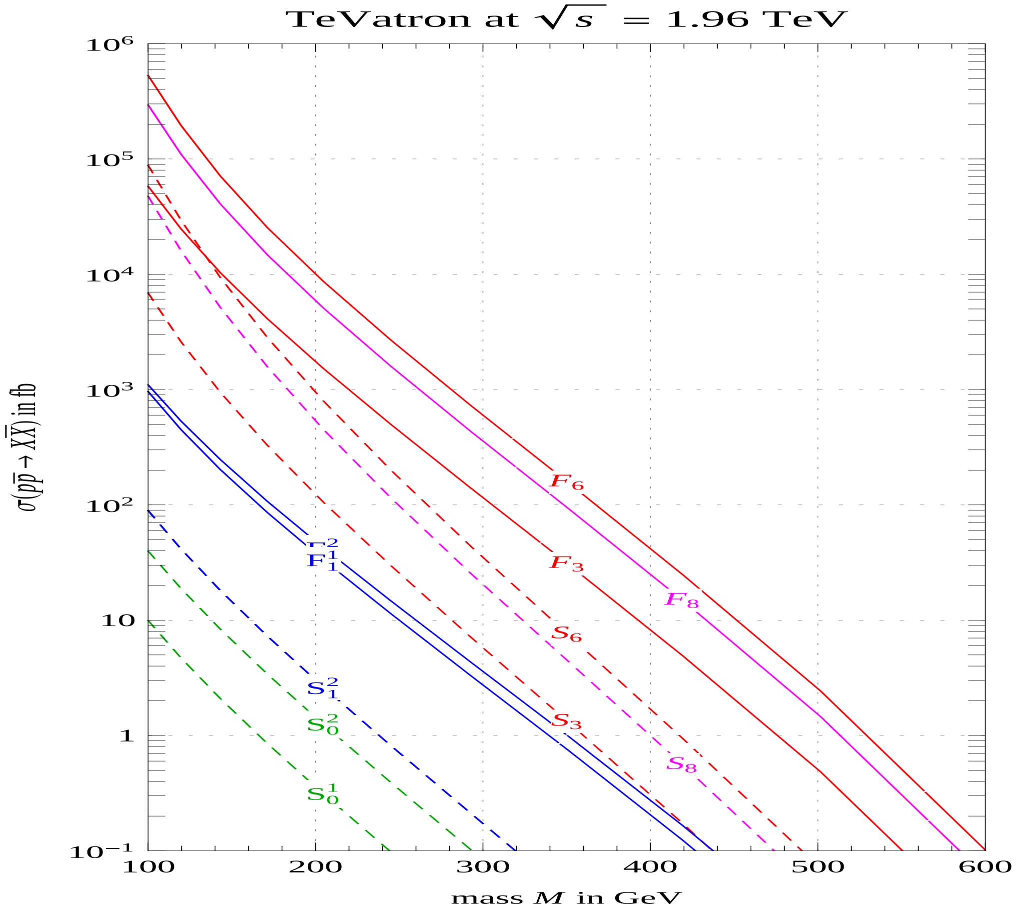
2) decay via Yukawa couplings (if very small one gets displaced vertices)

3) $2\ell\,2V$ final state: can violate lepton flavor or lepton number.

Pair production via gauge couplings

depends only on spin (S or F), color (1, 3, 6, 8), T_3, Q. In general:





Type III has $F_{T_3=Q}^{Q=0,1}$: blue continuous line. Type II has $S_{T_3=Q-1}^{Q=0,1,2}$:

If LHC only reaches $\sqrt{s} < 14\,\text{TeV}$, rescale M down by the $\sim$same amount.

Decay mode 1

The triplet couplings that violate lepton-number giving ν masses are small.

Not a problem for LHC: triplets anyhow decay, at worst with displaced vertices.

For $M \gg v$ all components have the same life-time, e.g.: $\lambda\ NLH$ gives

$$\Gamma(N_0 \to \nu h, \ell^\pm \chi^\pm) = \Gamma(N^\pm \to \ell^\pm h, \nu \chi^\pm) = \frac{\lambda^2 M}{32\pi}$$

Goldstones in H are eaten to vectors, so $\chi^\pm \to W^\pm$, $\eta \to Z$.

Decay mode 2

A mass splitting is generated at one loop

The charged components get heavier due to their electro-weak-static energy

$$\Delta M \sim \alpha M_W \gtrsim m_\pi$$

and have two competing decay modes: weak decays

$$\Gamma(X^{Q+1} \to X^Q \pi^+) \sim G_\mathrm{F}^2 \Delta M^3 f_\pi^2 \sim \frac{1}{\mathrm{cm}}$$

and

$$\Gamma(X \to \mathrm{SM\ SM}) \sim \frac{\lambda^2 M}{16\pi} \sim \frac{1}{10\,\mathrm{cm}} (\frac{\lambda}{10^{-8}})^2 \frac{M}{\mathrm{TeV}}$$

a) if $\lambda \gtrsim 10^{-8}$ all components decay promptly into SM + SM.

b) heavier components decay after a cm into the less charged component (plus undetectably soft $\pi^\pm$), which might make long tracks.

Decay in type II

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + |D_\mu T|^2 - M^2|T|^2 + \frac{1}{2}(\lambda_L LLT + M\lambda_H HHT^* + \text{h.c.})$$

One scalar triplet T can give all neutrino masses: $m_\nu = \lambda_L \lambda_H v^2/M$. So

- Flavor of $T \to LL$ predicted in terms of neutrino masses: mostly μ and τ if normal hierarchy.

- $\Gamma(T \to LL)$ vs $\Gamma(T \to VV)$ unknown:

$$\Gamma(T^{++} \to W^+W^+) \approx \lambda_H^2 M/4\pi \qquad \Gamma(T^{++} \to \ell_1^+\ell_2^+) \approx \lambda_L^2 M/4\pi$$

  Similar for other components: $T^+ \to W^+Z$, $\ell^+\nu$ and $T^0 \to ZZ$, $\nu\nu$.

  Lepton-number is violated by λ_H **and** λ_L: observable LFV only if $\lambda_H \sim \lambda_L$:

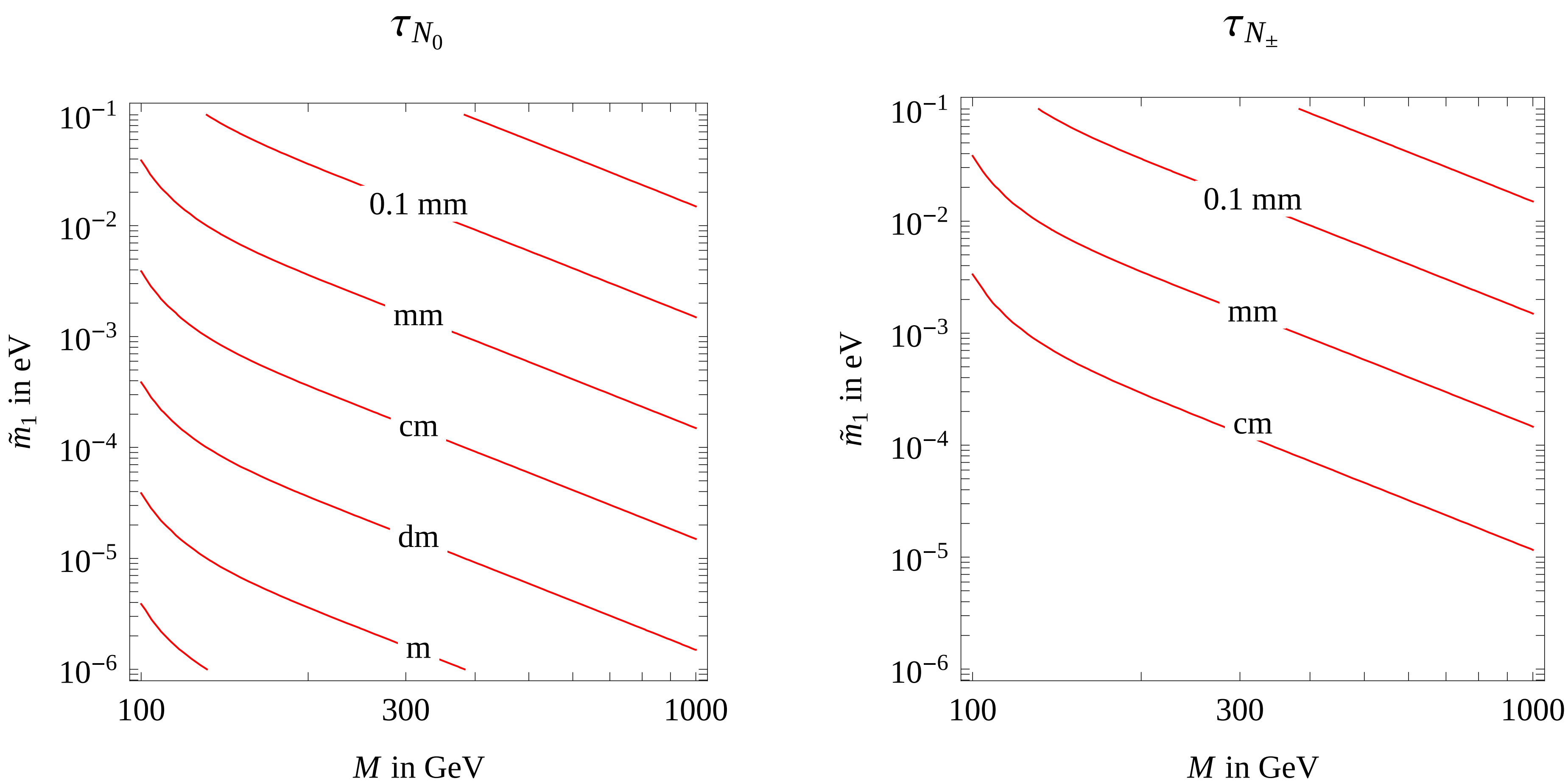
$$pp \to T^{++}T^{--} \to \begin{cases} \ell_1\ell_2\bar{\ell}_1\bar{\ell}_2 & \propto \lambda_L^4 \\ W^+W^+W^-W^- & \propto \lambda_H^4 \\ \ell_1\ell_2W^+W^+ & \propto \lambda_L^2\lambda_H^2 \end{cases}$$

- Only a lower bound on the lifetime, minimal if $\lambda_L \approx \lambda_H$. Weak decays subdominant.

Decay in type III

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{N} i \not{D} N + [\frac{M}{2} NN + \lambda\ N^a (L \tau^a H) + \text{h.c.}]$$

One N can only give mass to one neutrino: $\tilde{m}_1 = \lambda^2 v^2 / M$ is unknown in size and in flavor and fixes N decay. Weak decays dominate if $\tilde{m}_1 \ll m_{\rm atm,sun}$:



Signal of scalar triplets at LHC

- $pp \to \ell^+\ell^+\ell^-\ell^-$.
  Negligible bck after imposing $M_{\text{eff}}(\ell^+,\ell^+) = M_{\text{eff}}(\ell^-,\ell^-)$.

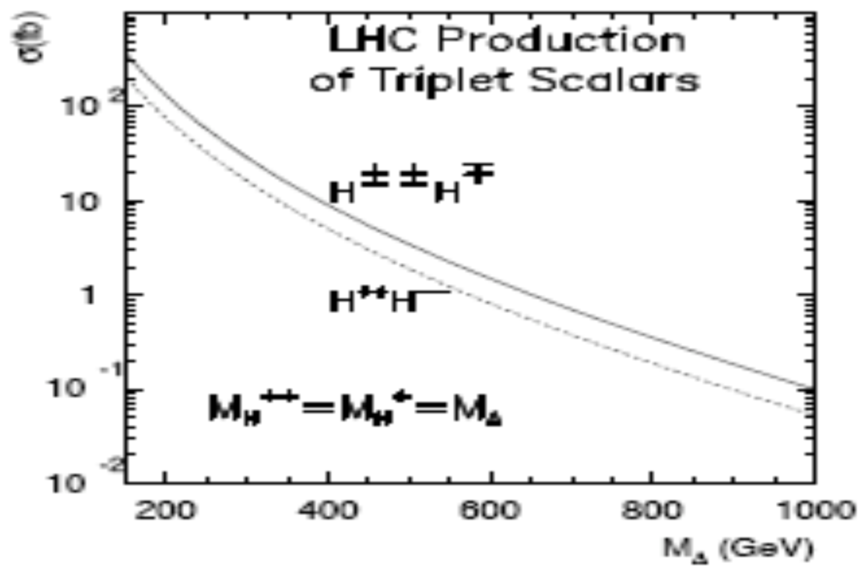
- $pp \to W^+W^+W^-W^- \stackrel{4.4\%}{\longrightarrow} 2\ell\ 4j\ \not{E}_T$.
  Main bck: $t\bar{t}W$, $S/B \sim 1$ after all cuts. For heavier M boosted W give a fat Jet: $W \to jj \simeq J$.

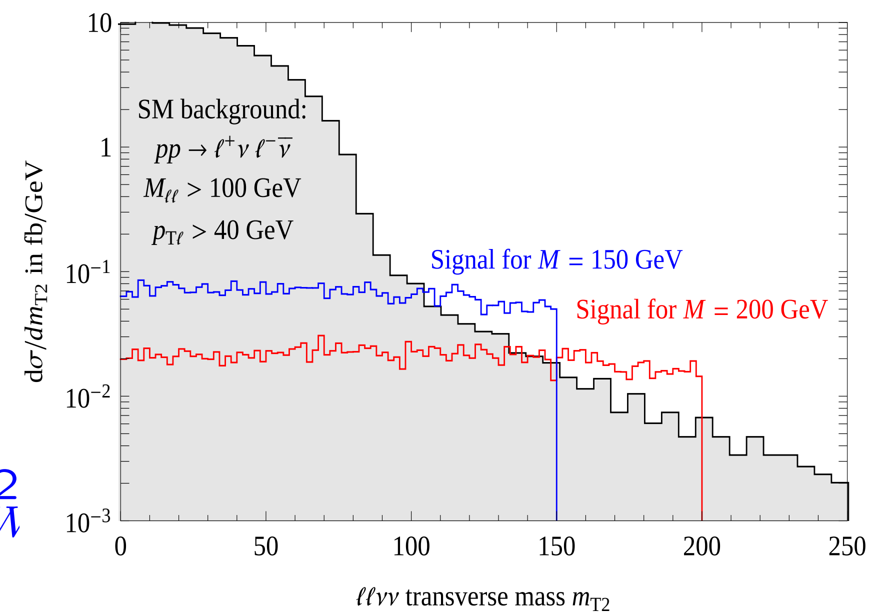
- $pp \to \ell^+\ell^+W^-W^-$.
  Discussed in fermion triplet.

- The same with $\ell \to \nu$ and $W \to Z, h$:

$$m_{T2}^2 \equiv \min\max(m_T^2(\ell_1\nu_1), m_T^2(\ell_2\nu_2)) > M_W^2$$

and its end-point





Signal of fermion triplets at LHC

Majorana N^0 with Dirac $N^\pm$

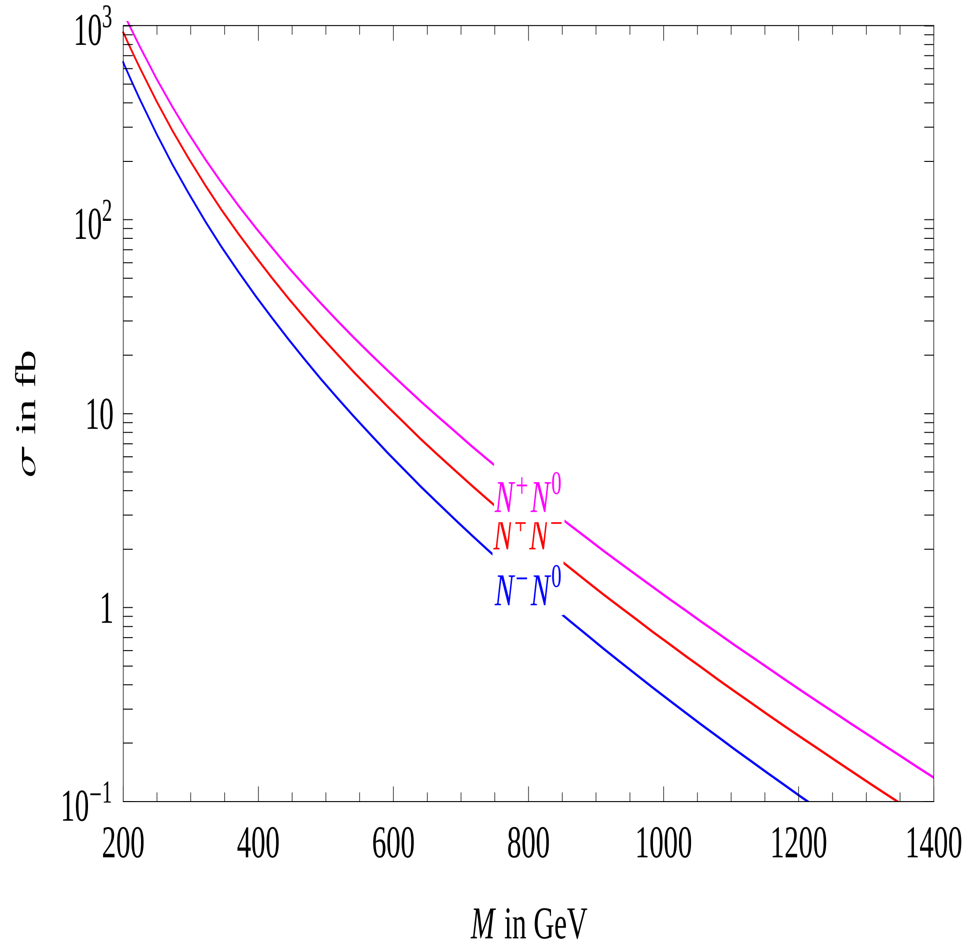
$$\tilde{m}_1 = \lambda^2 v^2 / M$$

Production via gauge interactions: $\sigma \sim \beta g^4/4\pi s$, peaked at $\beta \sim 0.7$, is $10\times$ bigger than for scalars.

Decay via neutrino Yukawas:

$$\tau_{N_0} \simeq \tau_{N_\pm} \overset{M \gg v}{\simeq} \frac{8\pi v^2}{\tilde{m}_1 M^2}$$

detectably displaced if $\tau \gtrsim 0.1\,\text{mm}$.



Decays violate lepton flavor. $N_0 \to \ell^\pm W^\mp$ decays violate lepton number.

Signal of fermion triplets at LHC: $2\ell\ 2V$

- Highest rate: $pp \to N^+ N^0 \to \bar{\nu} W^+ W^\pm \ell^\mp \to \ell\ 4j\ \ \not{E}_T$.
  Bck 1) $\sigma(pp \to (t \to b(W^- \to \ell\bar{\nu}))(\bar{t} \to \bar{b}jj)) \approx 160\,\text{pb}$.
  Bck 2) $\sigma(pp \to 4j(W^- \to \ell\bar{\nu})) \approx 4.5\,\text{pb}$.
  Bck 3) $\sigma(pp \to (V \to 2j)(V \to 2j)(W^- \to \ell\bar{\nu})) \approx 37\,\text{fb}$.
  Kill them cutting $m_T^2(\ell,\nu) \equiv 2E_T^\ell \not{E}_T(1 - \cos\phi_{e\nu}^T) > M_W^2$.
  Bck 4) $\sigma(pp \to 4j(Z \to \nu\bar{\nu})(W^- \to \ell\bar{\nu})) \approx 200\,\text{fb}$.
  Down to $\sim 1 \div 10\,\text{fb}$ imposing $M_{\text{eff}}(jj) \approx M_W$ and hard ℓ: $p_T^\ell > 0.25M$.

- LFV: $pp \to \ell_1 \bar{\ell}_2 Z W^+ \to \ell_1 \bar{\ell}_2 4j$.
  Bck 1) $\sigma(pp \to (\bar{t} \to \bar{b}\ell_1\bar{\nu}_{\ell_1})(t \to b\bar{\ell}_2\nu_{\ell_2})2j) \approx 7\,\text{pb}$.
  Cut on p_ℓ^T, $M_{\text{eff}}(jj) = M_W$ down to $S/B \sim 1$.
  Bck 2) $\sigma(pp \to (W^- \to \ell_1\bar{\nu}_{\ell_1})(W^+ \to \bar{\ell}_2\nu_{\ell_2})4j) \approx 50\,\text{fb}$, reducible

- LV: $pp \to (N^+ \to \ell_1^+ Z)(N^0 \to \ell_2^+ W^-) = \ell_1^+ \ell_2^+ Z W^-$.
  Bck 1): $\sigma(pp \to W^+ W^+ VV) \sim$ fb with unseen ν.
  Bck 2): $\sigma(pp \to (W^- \to \ell_1\bar{\nu}_{\ell_1})(W^- \to \ell_2\bar{\nu}_{\ell_2})4j) \approx 20\,\text{fb}$ to the $2\ell 4j$ signal.
  Cut: reconstruct V.

Leptogenesis?

In the standard scenario where the CP asymmetry is related to neutrino masses

$$M > 1000000\,\text{TeV}$$

Even in the most optimistic scenario, with a maximal CP asymmetry from an unspecified source, decays of see-saw fermion or scalar triplets can produce the observed baryogenesis only if

$$M > 1.6\,\text{TeV}.$$

Indeed triplets go out of thermal equilibrium at $T < M/\ln(M_{\text{Pl}}/M) \sim M/20$, and this must happen before that sphalerons decouple at $T \sim 100\,\text{GeV}$.

Models of neutrino masses that can provide successful thermal leptogenesis are beyond the LHC reach

Minimal New Matter

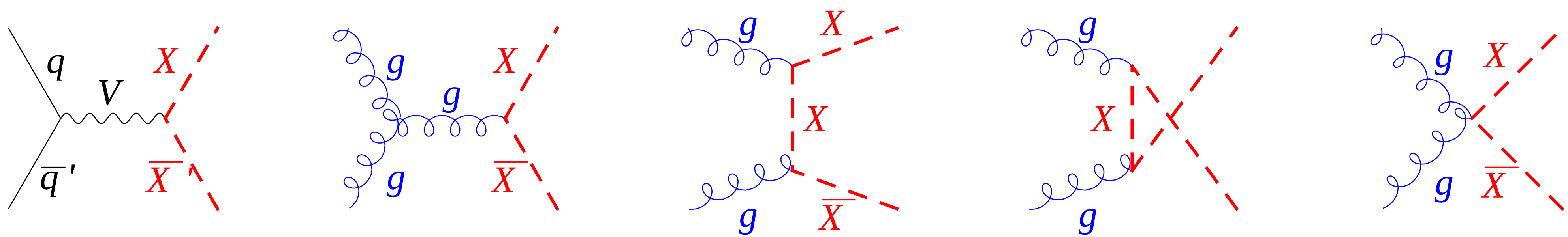
Ignoring deep motivations one can do many complicated things.

In order to suggest exotic concrete searches we consider this simple scenario: one new electroweak multiplet not separated from SM particles

$$\lambda \text{ (SM particle)} \cdot \text{(SM particle)} \cdot \text{(new particle)}.$$

The coupling λ is assumed to be small enough to avoid problems. Physics:

- New particles are produced via their gauge couplings: known production.



- They decay via the λ couplings: known signals

There is a tedious but finite list of possibilities compatible with SU(2) $\otimes$ U(1)

New fermions

Name	spin	$U(1)_Y$	$SU(2)_L$	$SU(3)_c$	$\lvert Q\rvert = \lvert T_3 + Y\rvert$	couplings to	type
N	$\frac{1}{2}$	0	1	1	0	LH	type-I see-saw
L	$\frac{1}{2}$	$-\frac{1}{2}$	2	1	$0, 1$	$EH^*, \ldots$	LH
E	$\frac{1}{2}$	1	1	1	1	$LH^*, \ldots$	LH
N_3	$\frac{1}{2}$	0	3	1	$0, 1$	LH	type-III see-saw
E_3	$\frac{1}{2}$	1	3	1	$0, 1, 2$	LH^*	LH
$L^{3/2}$	$\frac{1}{2}$	$\frac{3}{2}$	2	1	$1, 2$	EH	LH
Q	$\frac{1}{2}$	$\frac{1}{6}$	2	3	$1/3, 2/3$	$HU, H^*D, \ldots$	QH
U	$\frac{1}{2}$	$-\frac{2}{3}$	1	$\bar{3}$	$2/3$	$HQ, \ldots$	QH
D	$\frac{1}{2}$	$\frac{1}{3}$	1	$\bar{3}$	$1/3$	$H^*Q, \ldots$	QH
U_3	$\frac{1}{2}$	$\frac{2}{3}$	3	3	$1/3, 2/3, 5/3$	QH	QH
D_3	$\frac{1}{2}$	$\frac{1}{3}$	3	$\bar{3}$	$1/3, 2/3, 4/3$	QH^*	QH
$Q^{5/6}$	$\frac{1}{2}$	$\frac{5}{6}$	2	$\bar{3}$	$1/3, 4/3$	DH	QH
$Q^{7/6}$	$\frac{1}{2}$	$\frac{7}{6}$	2	3	$2/3, 5/3$	UH^*	QH

New scalars

Name	spin	$\mathrm{U}(1)_Y$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(3)_c$	$\lvert Q\rvert = \lvert T_3 + Y\rvert$	couplings to	type
H'	0	$\frac{1}{2}$	2	1	$0, 1$	LE, QU, DU	second Higgs
$\tilde{E}$	0	1	1	1	1	LL	LL
$\tilde{E}^2$	0	2	1	1	2	EE	LL
$\tilde{E}_3$	0	1	3	1	$0, 1, 2$	LL, HH	type-II see-saw
$\tilde{Q}$	0	$\frac{1}{6}$	2	3	$1/3, 2/3$	LD	LQ
$\tilde{Q}^{7/6}$	0	$\frac{7}{6}$	2	3	$2/3, 5/3$	$LU, \bar{E}\bar{Q}$	LQ
$\tilde{D}$	0	$\frac{1}{3}$	1	$\bar{3}$	$1/3$	LQ, EU, QQ	LQ/QQ
$\tilde{D}_3$	0	$\frac{1}{3}$	3	$\bar{3}$	$1/3, 2/3, 4/3$	LQ, QQ	LQ/QQ
$\tilde{D}_6$	0	$\frac{1}{3}$	1	6	$1/3$	UD, QQ	QQ
$\tilde{D}_{36}$	0	$\frac{1}{3}$	3	6	$1/3, 2/3, 4/3$	QQ	QQ
$\tilde{U}$	0	$\frac{2}{3}$	1	$\bar{3}$	$2/3$	DD	QQ
$\tilde{U}_6$	0	$\frac{2}{3}$	1	$\bar{6}$	$2/3$	DD	QQ
$\tilde{q}^{4/3}$	0	$\frac{4}{3}$	1	$\bar{3}$	$4/3$	UU	QQ
$\tilde{q}_6^{4/3}$	0	$\frac{4}{3}$	1	6	$4/3$	UU	QQ
H_8	0	$\frac{1}{2}$	2	8	$0, 1$	QU, QD	QQ

Signals at LHC

Couplings to eaten components of the H doublet become couplings to W, Z.

- LQ: $pp \to \ell^+\ell^- q\bar{q}$ (already studyed as leptoquark).
- LL: $pp \to \ell^+\ell^+\ell^-\ell^-$ (type-II see-saw).
- QQ: $pp \to q\bar{q}q\bar{q}$.
- HH: $pp \to W^+W^+W^-W^-$ (type-II see-saw).
- LH: $pp \to \ell^+\ell^-W^+W^-$ (type-III see-saw)
- QH: $pp \to W^+W^-q\bar{q}$.

In each case also $W \to Z, h$.
Each case predicts a well defined peak in $M_{\text{eff}}(i, j)$.
Each case predicts a well defined combination of $\ell^\pm$ and ν.
Flavor is not predicted, possibly $q = t \to Wb$ gives better signatures.

Conclusions

LHC can discover type-II or type-III see-saw if $M \lesssim$ TeV.

LLLL or VVVV or LLVV final states with peaks in invariant mass.

Most characteristic signals violate lepton flavor or lepton number.

A set of well defined searches, low backgrounds, but σ at sub-pb level.

Let's see in 2012