Neutrino mass models

at the TeV scale and their tests at LHC

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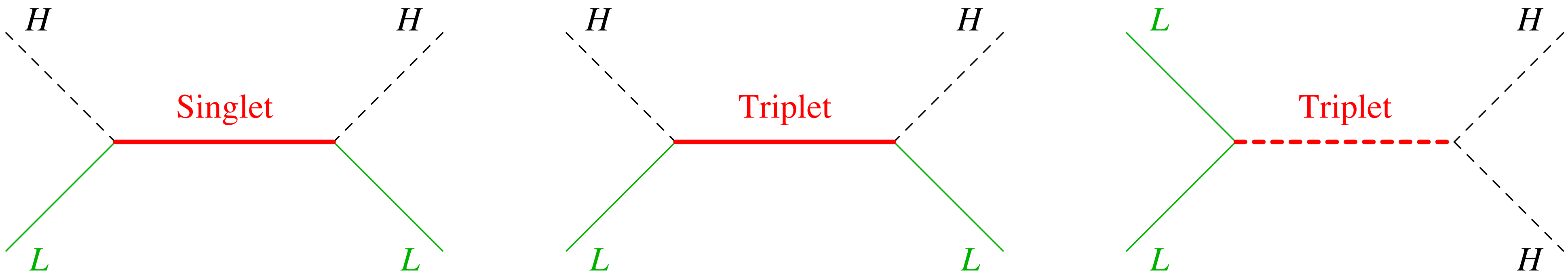
See-saw: type I, II and III

ν presumably get Majorana masses from the unique dimension-5 operator:

$$\frac{(LH)^2}{\Lambda_L} = \underbrace{\frac{v^2}{\Lambda_L}}_{m_\nu} \frac{\nu_L^2}{2} + \cdots \qquad \Lambda_L \sim 10^{14}\,\text{GeV}.$$

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



Type I	Type III	Type II
neutral fermion ν_R	fermions N^0 and $N^\pm$	scalars $T^0, T^\pm$ and $T^{\pm\pm}$

At dimension 6 they generate different negligible operators, $(H^\dagger \bar{L}_i) i\partial\!\!\!/ (HL_j)/\Lambda_L M$.

Signals at LHC if $M \lesssim$ TeV

Type I see-saw at LHC

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

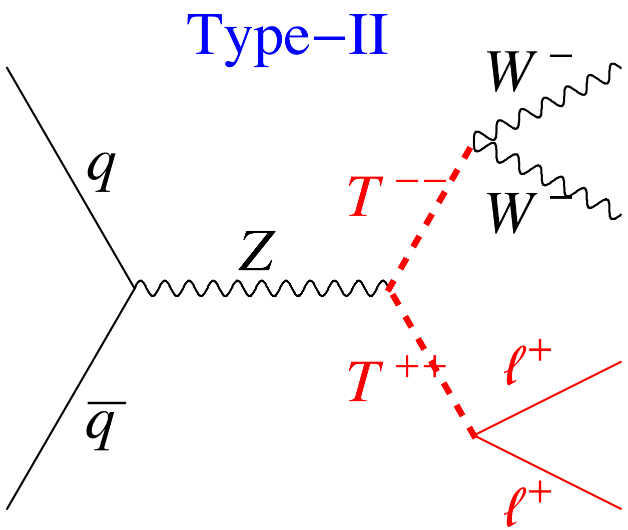
E.g. **large Yukawa couplings** $\lambda \sim 1 \ggg \lambda'$ (like winning the lottery twice):

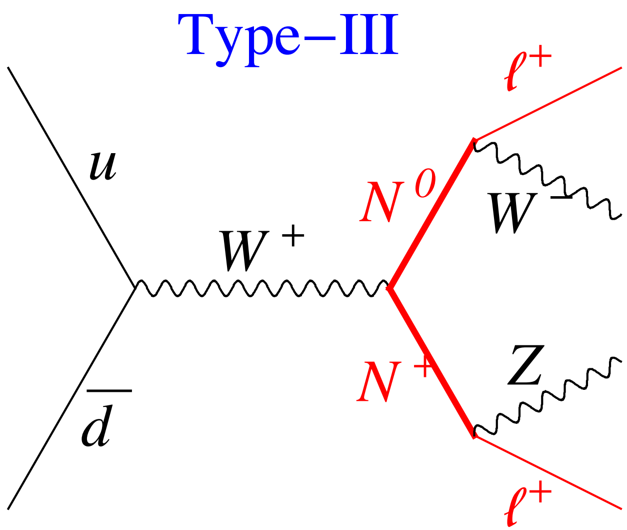
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \lambda \nu_R L H + \lambda' \nu'_R L H + M \nu_R \nu'_R \qquad m_\nu = \lambda\lambda' \frac{v^2}{M}$$

Or **gauge couplings**, like a $Z' \sim B-L$ (or $\mathrm{SU}(2)_R$ or $\mathrm{SU}(3)_L$ or...) at the weak scale. It would imply a light ν_R, $M \lesssim M_{Z'}$, and open a new hierarchy problem.

LHC would see $pp \to Z' \to \ell^+\ell^-$ and possibly $pp \to Z' \to \nu_R \nu_R \to \begin{cases} \ell^\pm \ell^\pm W^\mp W^\mp \\ \ell^\pm W^\mp \nu (Z/h) \\ \nu\nu (Z/h)(Z/h) \end{cases}$

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) $\ell\ell VV$ final state can violate lepton flavor or lepton number.

Heavy triplets have two decay modes

1) Via small neutrino Yukawa couplings

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

e.g. type III has λNLH so

$$N^0 \to \begin{cases} \nu h \\ \nu \ \text{Goldstone}^0 \simeq \nu Z \\ \ell^\pm \text{Goldstone}^\mp \simeq \ell^\pm W^\mp \end{cases} \qquad N^+ \to \begin{cases} \ell^+ h & 1/4 \\ \ell^+ \ \text{Goldstone}^0 \simeq \nu Z & 1/4 \\ \nu \ \text{Goldstone}^+ \simeq \nu W^+ & 1/2 \end{cases}$$

2) Weak decays of charged components into less charged ones:

$$\Gamma(X^{Q+1} \to X^Q \pi^+) \sim G_F^2 \Delta M^3 f_\pi^2 \sim \frac{1}{\text{cm}} \qquad \Delta M \sim \alpha M_W \gtrsim m_\pi$$

Two limiting cases:

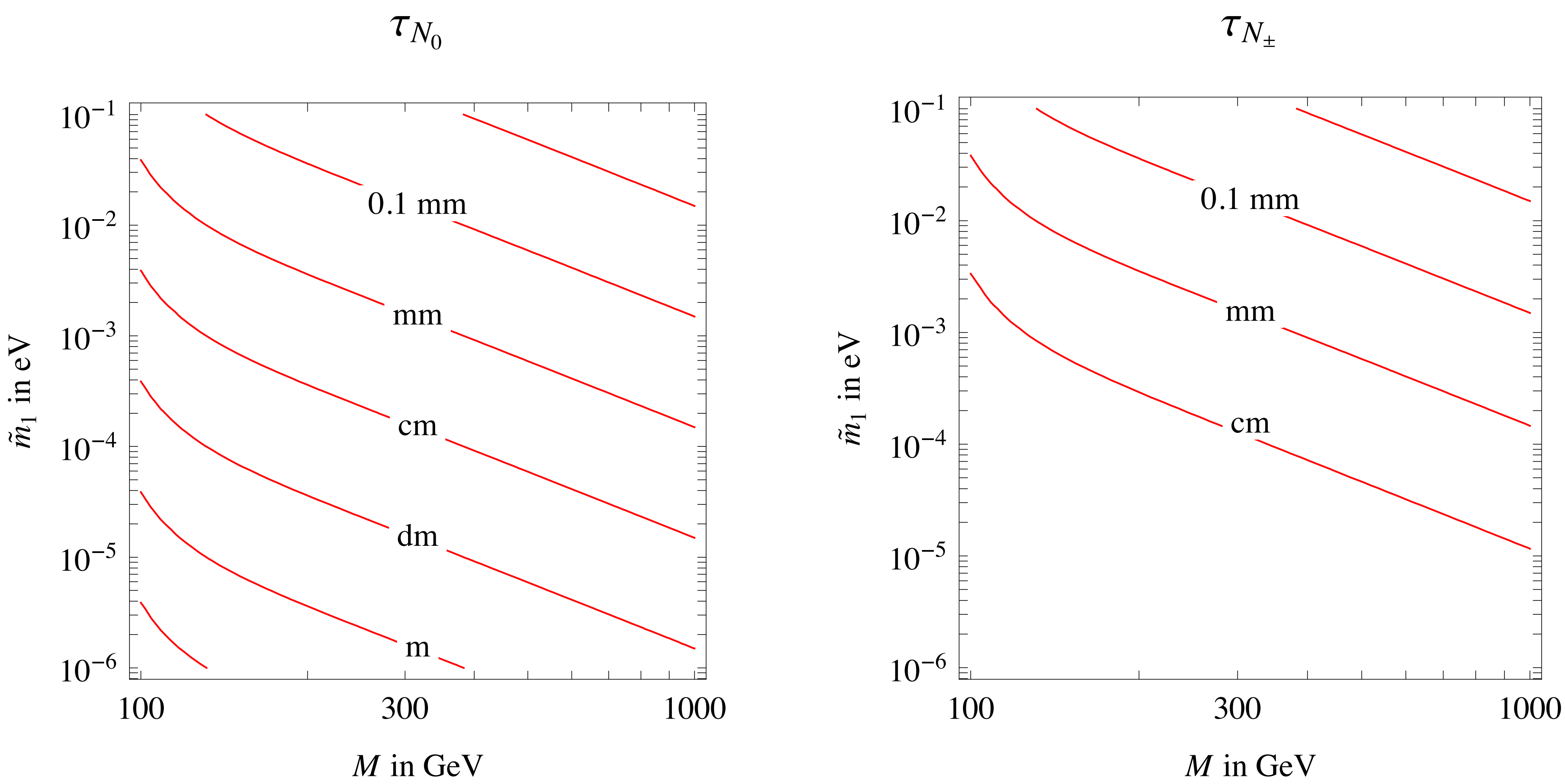
if $\lambda \gtrsim 10^{-8}$ then 1) dominates: all components decay promptly into SM + SM.

if 2) dominates, the charged components decay after a cm into the neutral component (plus undetectably soft $\pi^\pm$), which decays after a longer track.

Decay in type III

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

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 $\tilde{m}_1 \ll m_{\text{atm,sun}}$:



Decay in type II

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

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 $\not{L}$ 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.

Signal of type II at LHC

- - $pp \to \ell^+\ell^+\ell^-\ell^-$, $M_{\ell^+,\ell^+} = M_{\ell^-,\ell^-}$.
  First result from CMS at .98/fb:

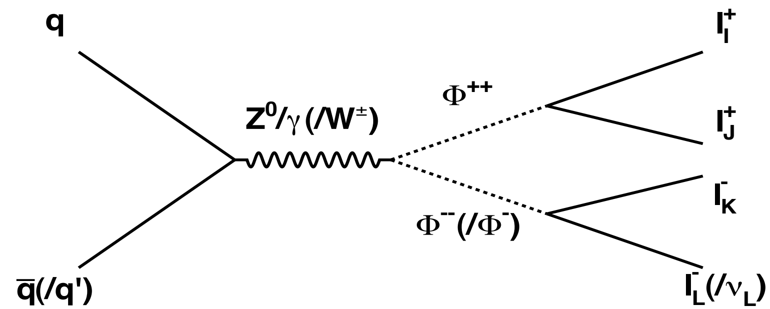
  $M > 300$ GeV if $\text{BR}_{\ell\ell} = 1$ and e, μ

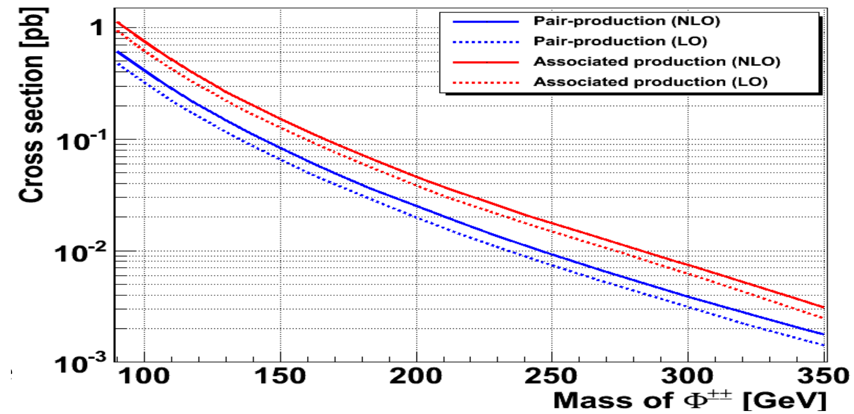
  - $pp \to \ell^+\ell^+\ell^+\nu$.
  - $pp \to \ell^+\ell^-\nu\bar{\nu}$, end-point of m_{T2}^2:

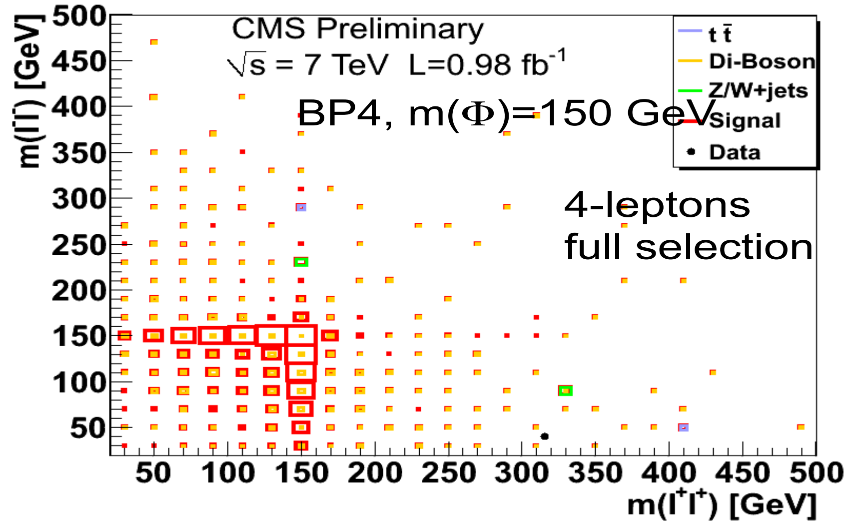
  $\min\max(m_T^2(\ell_1\nu_1), m_T^2(\ell_2\nu_2)) > M_W^2$

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

- $pp \to \ell^+\ell^+W^-W^-$, see in type-III.







Signals of type III 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 $1 \div 10\,\text{fb}$ imposing $M_{\text{eff}}(jj) \approx M_W + p_T^\ell > 0.25M$.

LFV: $pp \to \ell_1\bar{\ell}_2ZW^+ \to \ell_1\bar{\ell}_2 4j$.
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: $pp \to (N^+ \to \ell_1^+Z)(N^0 \to \ell_2^+W^-) = \ell_1^+\ell_2^+ZW^-$.
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

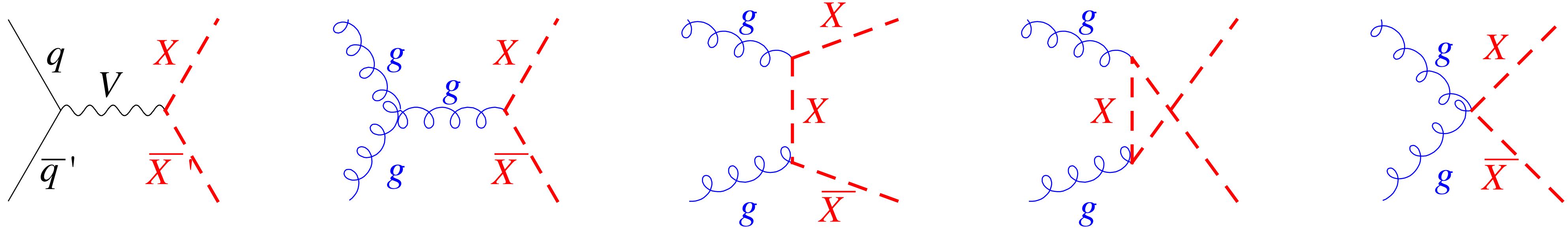
More general class of models

One new unstable electroweak multiplet coupled to a pair of 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 pair produced via their gauge couplings: **known rate**.



- They decay via the λ couplings: **known signals**.

Tedious but finite list of possibilities compatible with $SU(2) \otimes U(1)$

Signals at LHC

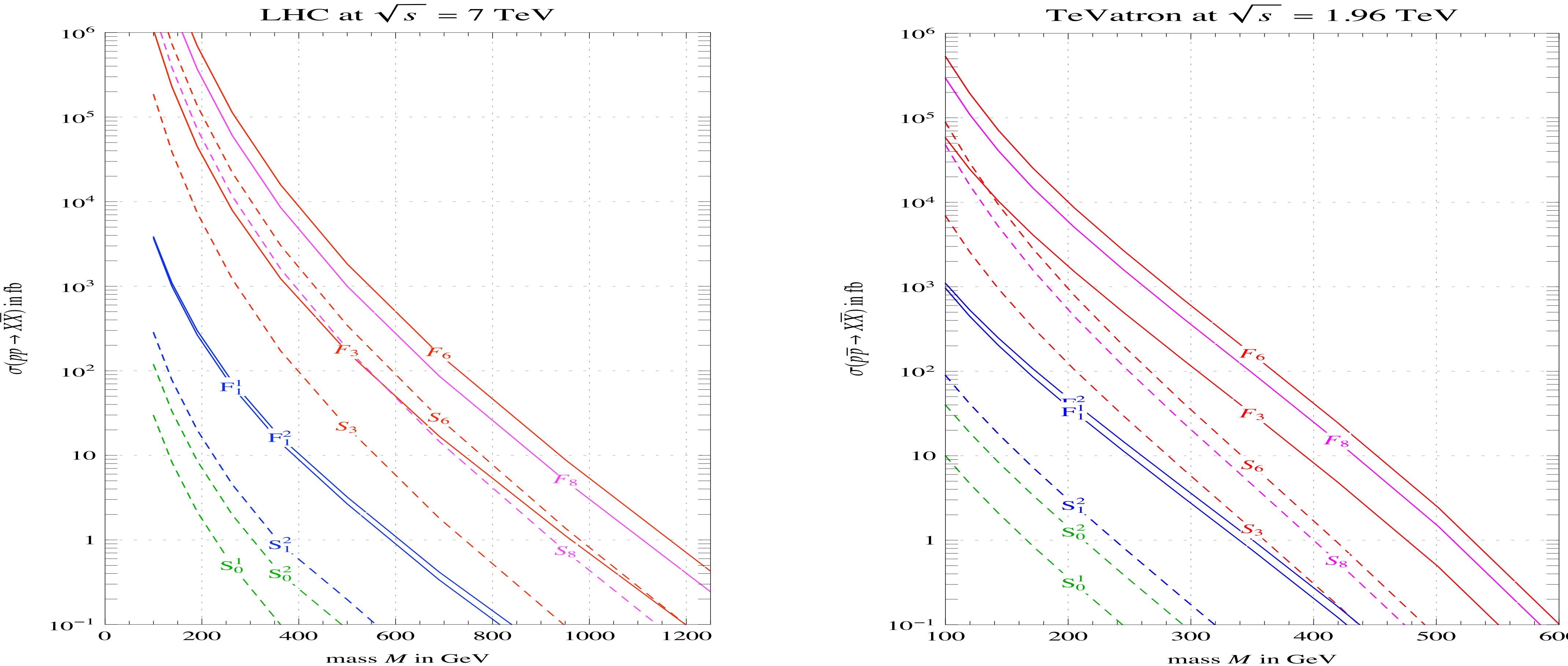
SM particles are L (lepton), Q (quark) or H (higgs$+W_L+Z_L$): the signals are

coupled to	signals	models
LH	$pp \to \ell\ell VV$	type-II and III see-saw, heavy lepton
LL	$pp \to \ell\ell\ell\ell$	type-II see-saw, di-lepton
HH	$pp \to VVVV$	type-II see-saw
QH	$pp \to jjVV$	heavy quark
LQ	$pp \to \ell\ell jj$	lepto-quark
QQ	$pp \to jjjj$	di-quark

Depending on specific multiplet, ℓ can be $\ell^\pm$ or ν; V can be $W^\pm, Z$ or h.
Each case predicts a well defined peak in $M_{\text{eff}}(i,j)$, e.g. $M_{j_1j_2} = M_{j_3j_4}$.
Flavor is not predicted, possibly b or t instead of j gives better signatures.

Pair production via gauge couplings

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



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

LHC reached now the luminosity to test production via weak couplings.

Conclusions

LHC can discover type-III and type-II see-saw if $M \lesssim$ TeV.
Type-I see-saw needs extra couplings, e.g. a $B - L$ Z'.

A set of well defined signals: $\ell\ell\ell\ell$ or $VVVV$ or $\ell\ell VV$ final states.

Low backgrounds, peaks in appropriate invariant masses.

Most characteristic signals violate lepton flavor or lepton number.

Searches possible with present luminosity