CoEPP Workshop, Cairns, July 2013

Recent Models of Massive Neutrinos

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Based on: JHEP 1307 (2013) 020 [arXiv: 1303.4573]

and work in progress

THE UNIVERSITY OF SYDNEY

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

Outline

- Some reminders
- Some new stuff
- Some consequences

Neutrino Mass and Mixing

- Data consistent with non-zero neutrino mass

Mass splittings

$$\Delta m^2_{21} \simeq 7.6 \times 10^{-5}\ \mathrm{eV}^2$$
$$\Delta m^2_{31} \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

Mixing angles

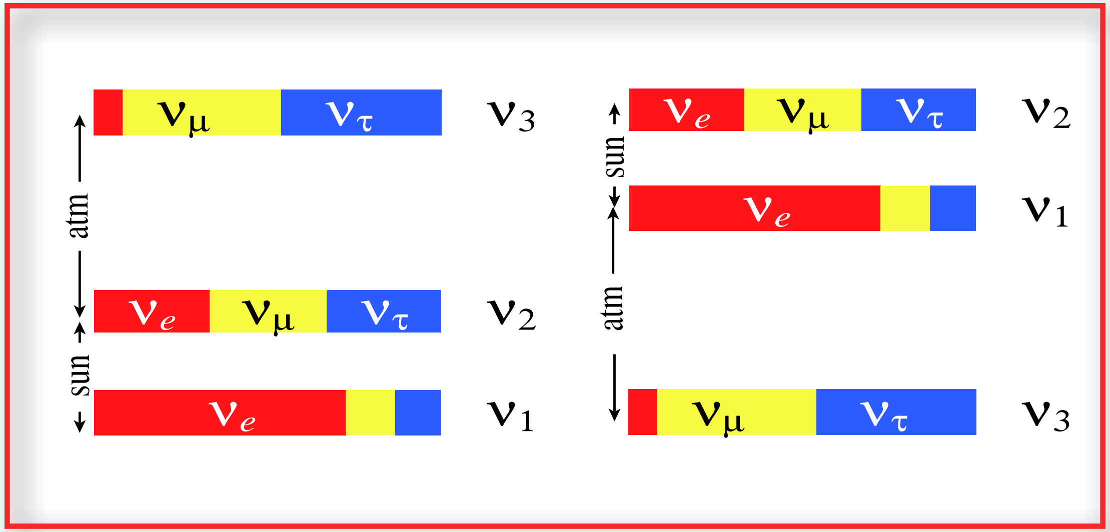
$$\sin^2\theta_{12} \simeq 0.31$$
$$\sin^2\theta_{23} \simeq 0.52$$
$$\sin^2\theta_{13} \simeq 0.013$$

(Schwetz et al, 2012)

- Evidence for BSM physics

- Number of "known unknowns" remain

Neutrino Mass and Mixing



- Still unknown: mass hierarchy (normal or inverted)
  overall mass scale

Still Unknown: Dirac or Majorana

- Dirac: add N_R

Boost (LT)

$$\nu_L \;=\; (\nu_L, \bar{\nu}_R) \qquad\qquad (\bar{\nu}_L, \nu_R) \;=\; N_R$$

CP CP

- Distinct anti-particle
- Lepton number symmetry conserved

Still Unknown: Dirac or Majorana

- Majorana: use “what we got”

Boost (LT)

$$\nu_L \;=\; (\nu_L, \bar{\nu}_R)$$

CP

- No distinct anti-particle: $\nu^c \propto \nu$
- Lepton number symmetry is broken

→ $0\nu\beta\beta$ decay

Still Unknown: Origin of Mass

- Masses are very small → $m_\nu \lesssim 0.1 \text{ eV} \sim 10^{-6} \times m_e$

Question: Why are they so tiny?

- Two main approaches → seesaw models / radiative models

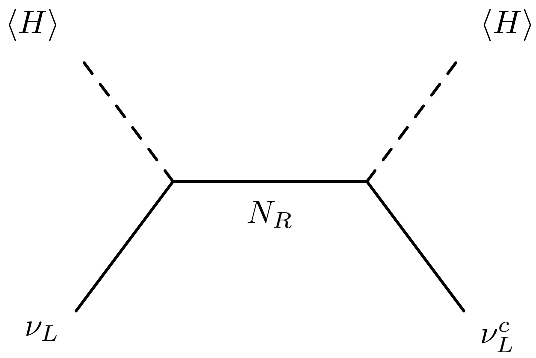
- Point of this talk:

A new class → seesaw/radiative models

The Seesaw Mechanism

- Add heavy sterile neutrino

$$\mathcal{L} \supset \lambda_\nu L H N_R \; + \; M_R N_R^c N_R$$



- Small mass due to heavy partner

$$m_\nu \simeq \lambda_\nu^2 \frac{\langle H \rangle^2}{M_R} \longrightarrow M_R \lesssim 10^{14} \text{ GeV}$$

The Seesaw Mechanism

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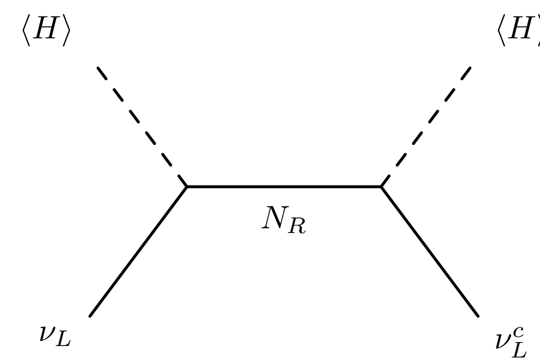


- Small mass due to heavy partner

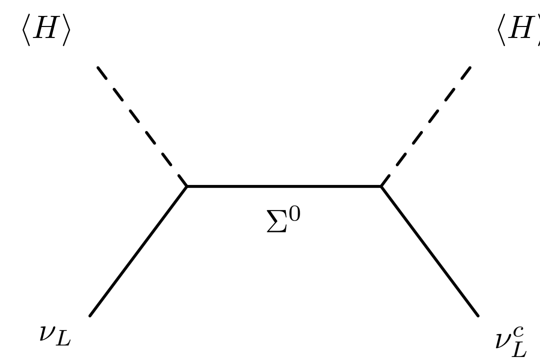
$$m_\nu \simeq \lambda_\nu^2 \frac{\langle H \rangle^2}{M_R} \;\longrightarrow\; M_R \lesssim 10^{14}\ \text{GeV}$$

- Type-III: use fermion triplet

Foot, Lew, He, Joshi (1989)

$$\Sigma \sim (1,3,0) = \begin{pmatrix} \Sigma^0 & \Sigma^+/\sqrt{2} \\ \Sigma^-/\sqrt{2} & -\Sigma^0 \end{pmatrix}$$

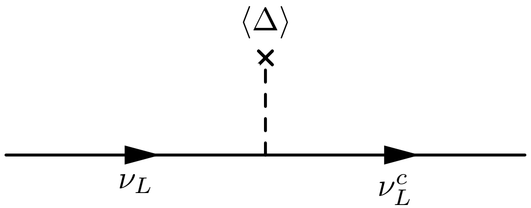
$$\mathcal{L} \supset \lambda_\nu L \Sigma H \; + \; M_\Sigma \Sigma^c \Sigma$$



The Type-II Seesaw Mechanism

- Use scalar triplet $\Delta \sim (1,3,2) = \begin{pmatrix} \Delta^+ & \Delta^{++} \\ \Delta^0 & -\Delta^+ \end{pmatrix}$

$$\mathcal{L} \supset \lambda_\nu L^c \Delta L \; - \; M_\Delta^2 \Delta^2 \; + \; \mu H \Delta H \;\longrightarrow$$

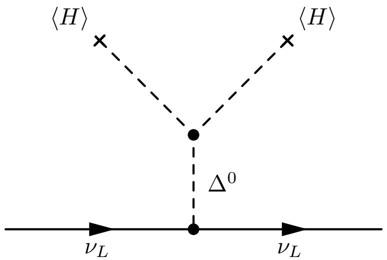


$$m_\nu = \lambda_\nu \langle\Delta\rangle \simeq \lambda_\nu \times \frac{\mu \langle H\rangle^2}{M_\Delta^2} \longrightarrow$$ **VEV seesaw** $$\langle H\rangle = \sqrt{\frac{-\mu_H^2}{\lambda}}$$

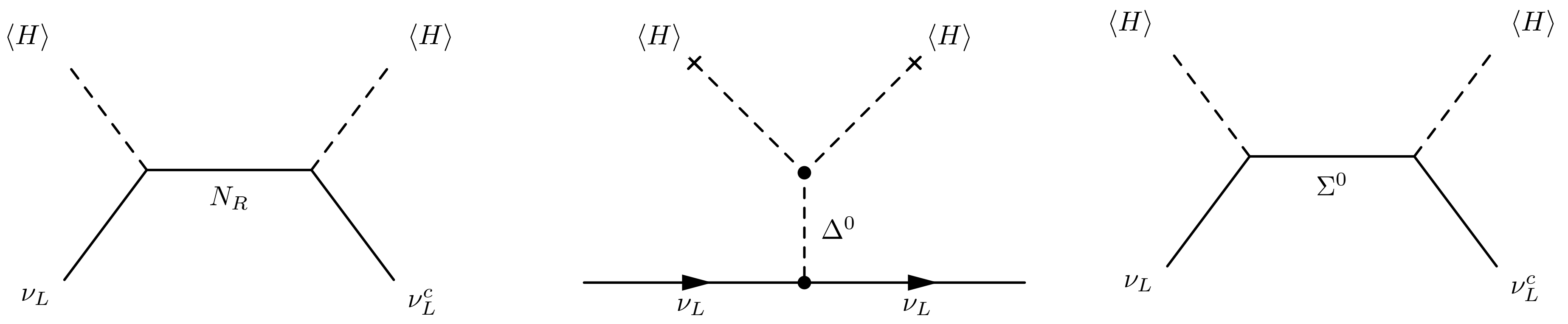
- Satisfies constraint $\rho = \dfrac{M_W^2}{\cos^2\theta_W M_Z^2} \neq 1 \longrightarrow \langle\Delta\rangle \lesssim \mathcal{O}(\mathrm{GeV})$

Heavy scalar can also explain small mass

$\longrightarrow$



Only Three d=5 Seesaws



- Non-renormalizable operator: $\mathcal{O}_\nu = \frac{1}{\Lambda}(LH)^2$

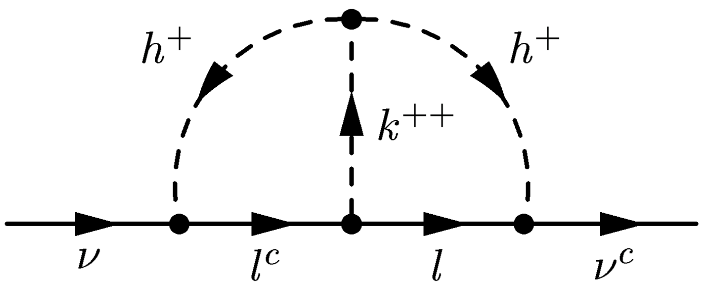
$$\longrightarrow \quad d = [\mathcal{O}_\nu] = 5$$

$$\frac{1}{\Lambda} \sim \frac{1}{M_R} \qquad \frac{1}{\Lambda} \sim \frac{\mu}{M_\Delta^2} \qquad \frac{1}{\Lambda} \sim \frac{1}{M_\Sigma}$$

Other main mechanism ....

Radiative Neutrino Mass

- Add extra scalars (Zee, Babu)
- Mass at one- (Zee) or two-loop level (Zee, Babu)



$h \sim (1,1,2) \qquad k \sim (1,1,4)$

$$m_\nu \sim \frac{f^2 \lambda}{(16\pi^2)^2} \frac{\mu}{m_k} \frac{m_\ell^2}{m_k} \log(m_k^2/m_h^2)$$

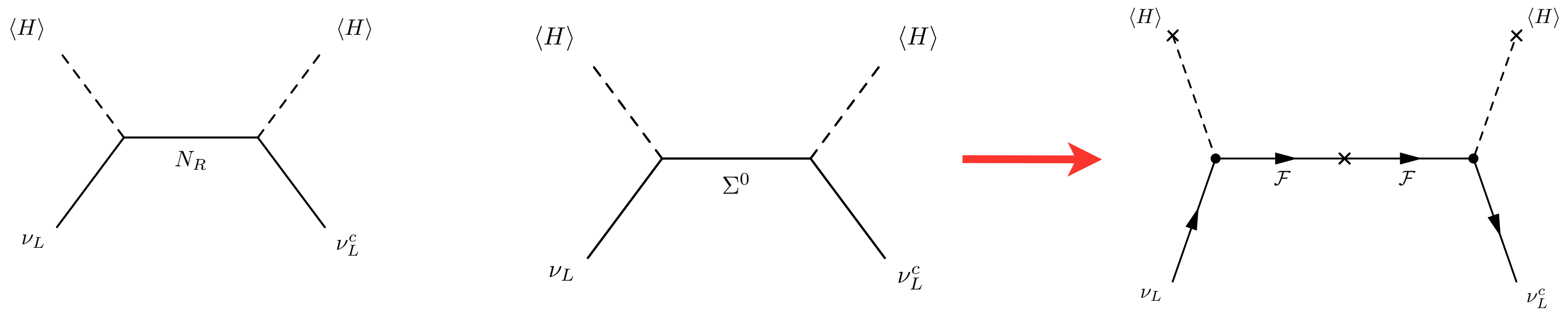
- New physics *can* be light (ie observable)
- No more complex than Type-I (or III) seesaw

Two new scalars ⟷ Two new fermions

Radiative mass or seesaw? Only experiment can tell.

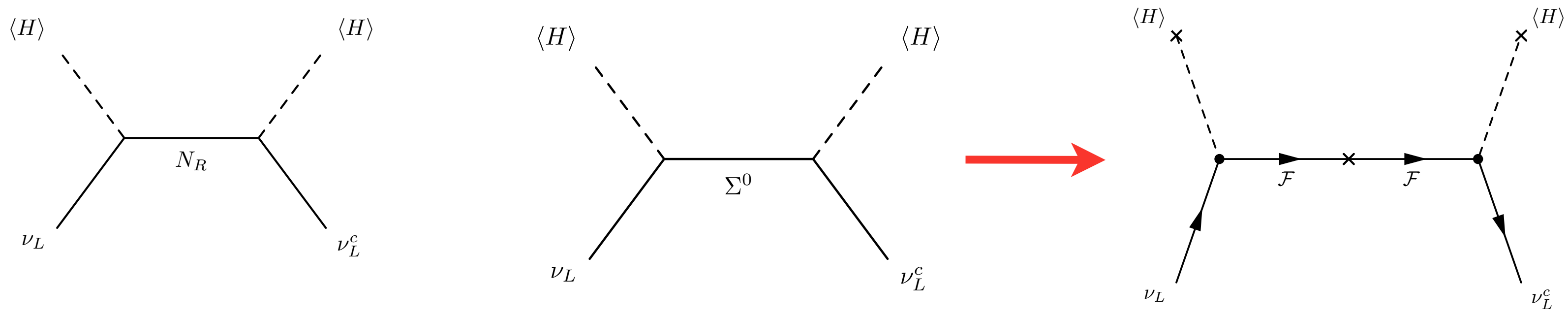
Generalized Seesaws

- Type-I and -III are similar:

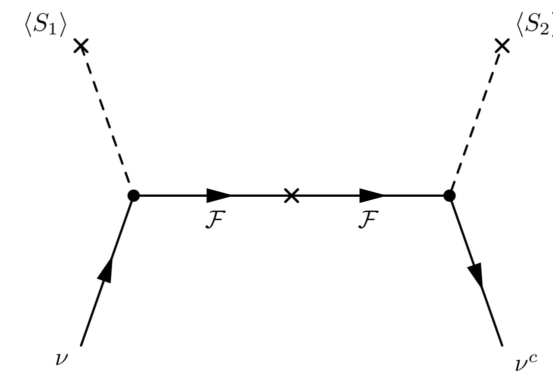


Generalized Seesaws

- Type-I and -III are similar:



- Generalize to generic diagram

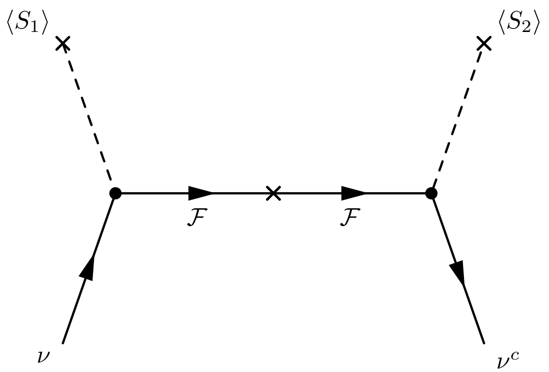


- Simple minded question: Are there more seesaws?

Apparently not answered ....

Generalized Seesaws

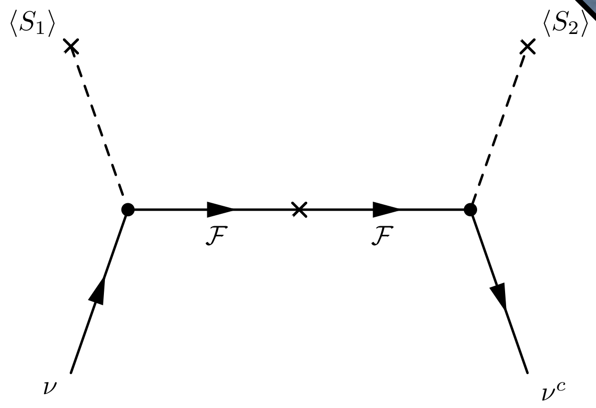
- Generic diagram →



- Features:
  - Two external scalars
  - Heavy intermediate fermion
  - Mass insertion on internal line → Majorana / Dirac

- Neutrino mass → $m_\nu \simeq \lambda_1 \lambda_2 \frac{\langle S_1 \rangle \langle S_2 \rangle}{M_{\mathcal{F}}}$

Rules of The Game



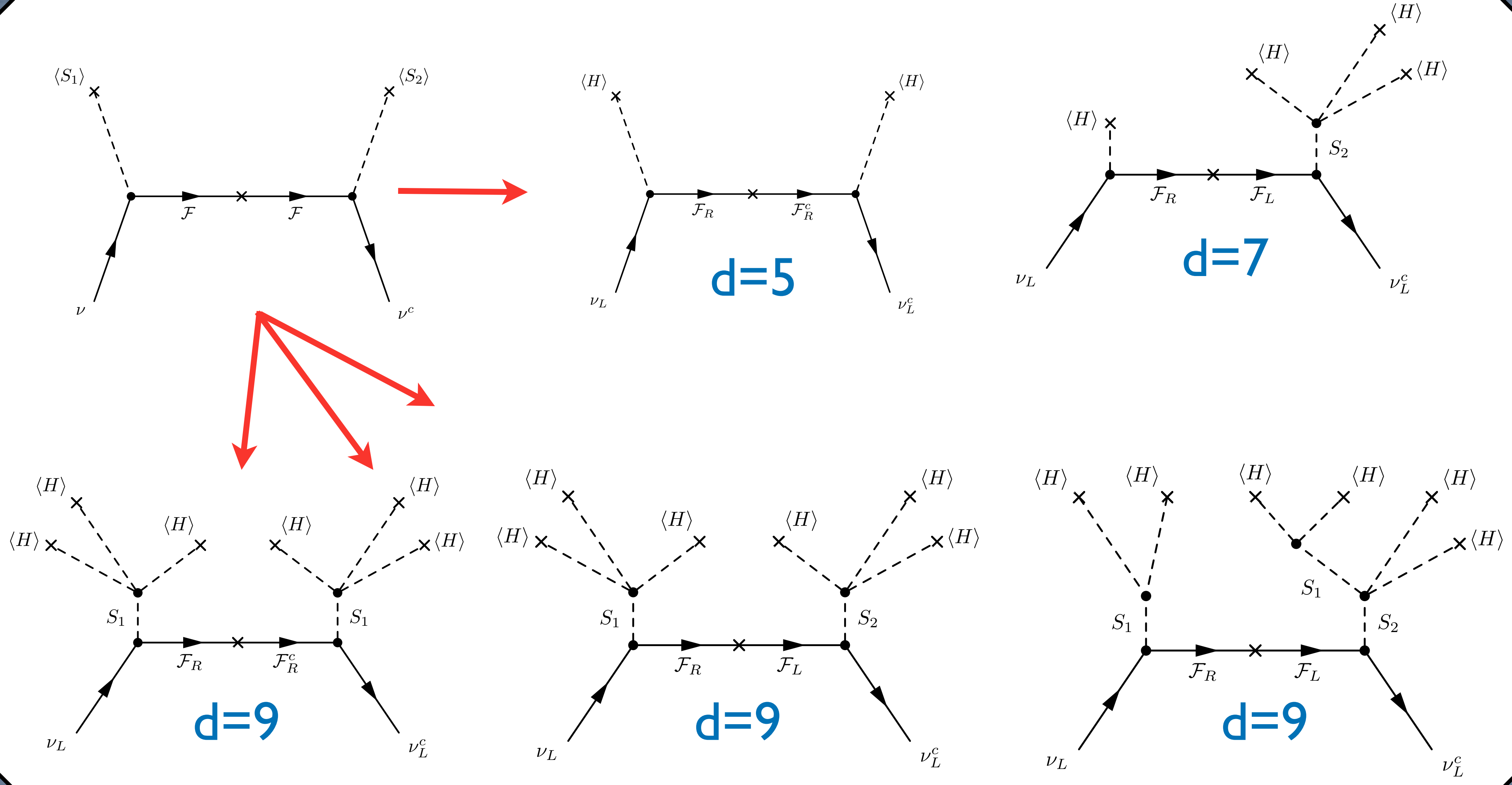
- Minimal particle extension
- Don't rely on new symmetries
- Small VEV's are naturally suppressed → VEV seesaw (cf Type-II)
- Determine all possibilities

Results

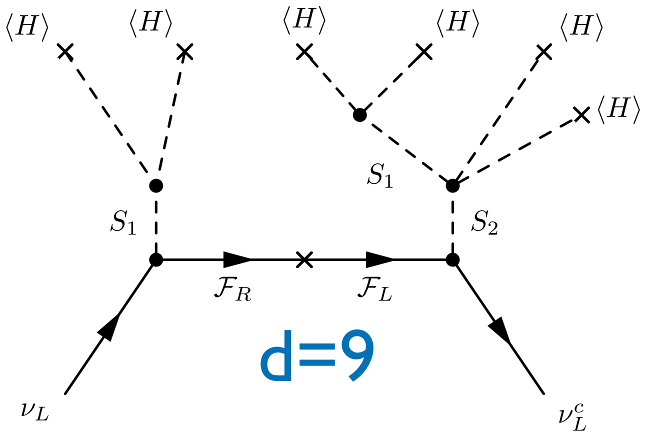
Model	S_1	$\mathcal{F}$	S_2	Mass Insertion	$[\mathcal{O}_\nu]$	Ref.
(a)	$(1,2,1)$	$(1,1,0)$	–	Majorana	$d=5$	Type I
(b)	$(1,2,1)$	$(1,3,0)$	–	Majorana	$d=5$	Type III
(c)	$(1,4,-3)$	$(1,3,2)$	$(1,2,1)$	Dirac	$d=7$	Babu et al (2009)
(d)	$(1,4,1)$	$(1,5,0)$	–	Majorana	$d=9$	Kumericki et al (2012)
(e)	$(1,3,0)$	$(1,4,-1)$	$(1,5,-2)$	Dirac	$d=9$	KM (2013)
(f)	$(1,4,-3)$	$(1,5,2)$	$(1,4,1)$	Dirac	$d=9$	Picek et al (2011)

- Six with d<=9
- Two more with d=11 → But that's all!

Tree-Level Seesaws with d>5



Tree-Level Seesaws with d>5



$$[\mathcal{O}_\nu] = d \quad \longrightarrow \quad \mathcal{O}_\nu = \frac{1}{M^{d-4}} L^2 H^{d-3}$$

$$\longrightarrow \quad m_\nu \sim \frac{\langle H \rangle^{d-3}}{M^{d-4}}$$

For example: $d = 5 \quad \longrightarrow \quad m_\nu \sim \frac{\langle H \rangle^2}{M} \quad \longrightarrow \quad M \lesssim 10^{14}\ \mathrm{GeV}$

or: $M \sim \mathrm{TeV} \quad \longrightarrow \quad \lambda \sim 10^{-6}$

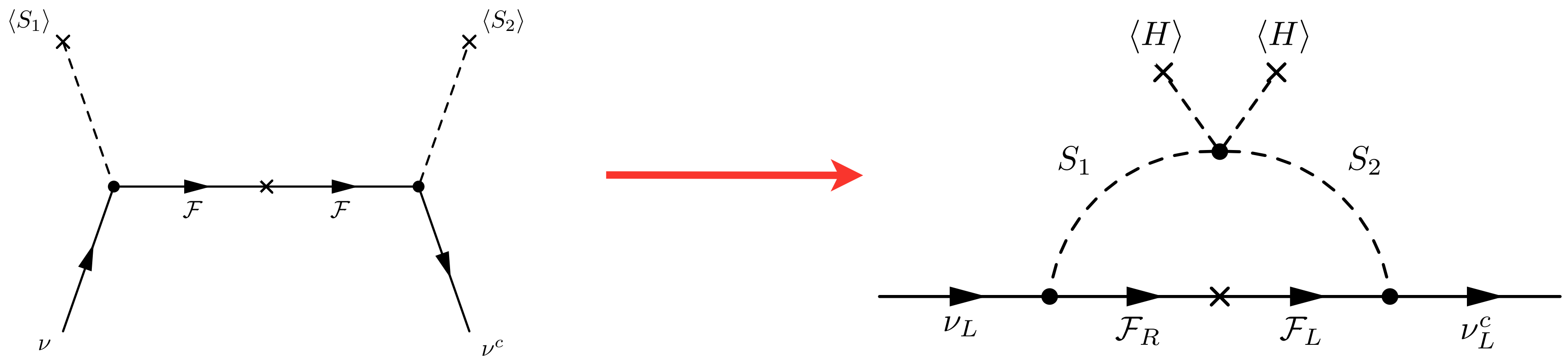
$d = 9 \quad \longrightarrow \quad m_\nu \sim \frac{\langle H \rangle^6}{M^5} \quad \longrightarrow \quad M \lesssim 10^7\ \mathrm{GeV}$

or: $M \sim \mathrm{TeV} \quad \longrightarrow \quad \lambda \sim 10^{-2}$

Larger d means: Will be probed/ruled-out first

Loop Masses

- All the new models have: $V(H, S_1, S_2) \supset \lambda S_1\, S_2\, H\, H$



- Neutrino mass: $M_\nu \; = \; M^{tree} \; + \; M^{loop}$

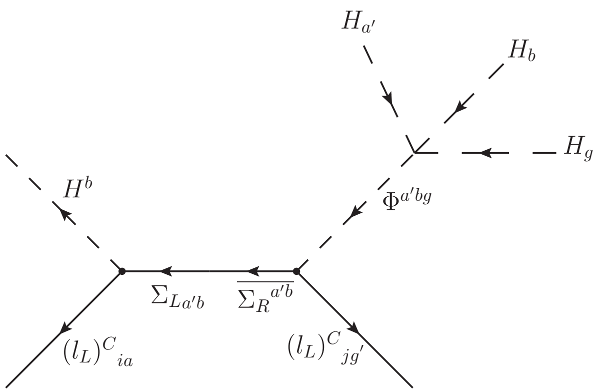
They are seesaw/radiative models

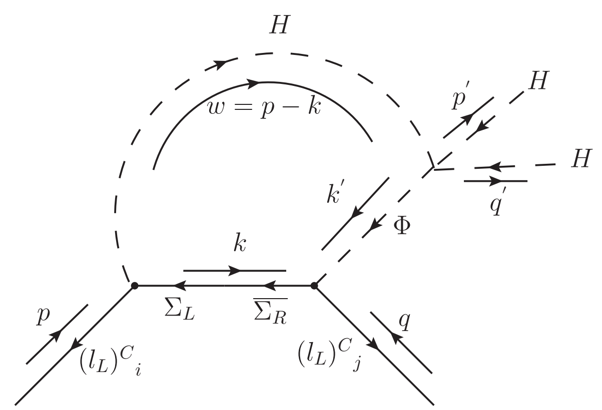
Seesaw/Radiative Models

- All have doubly charged fields
- Some have triply charged fields (!)
- Consider the d=7 model (Babu et al, 2009)

Beyond SM fields: $\Sigma \sim (1,3,2) \;=\; (\Sigma^{++},\, \Sigma^{+},\, \Sigma^{0})$

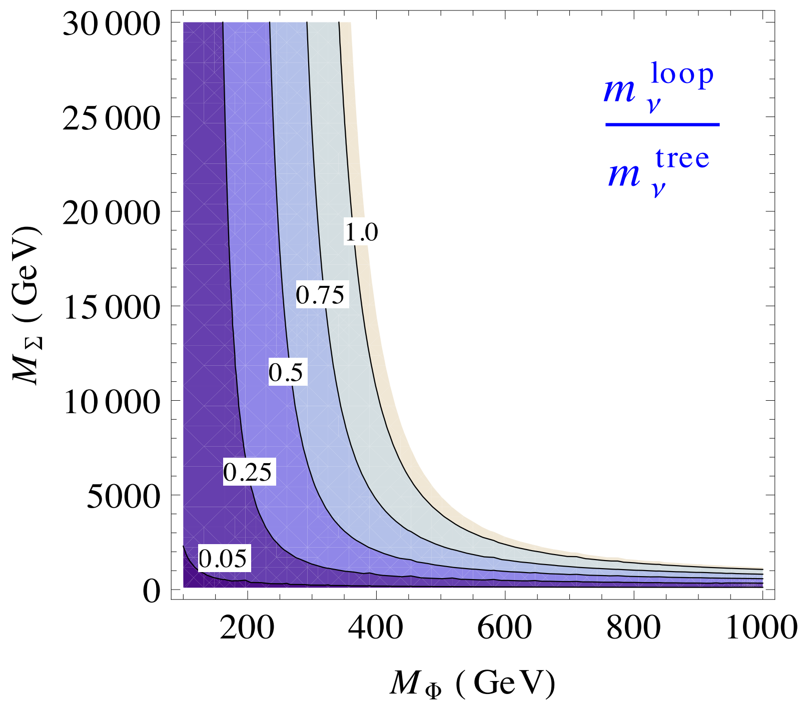
$$\Phi \sim (1,4,3) \;=\; (\Phi^{+++},\, \Phi^{++},\, \Phi^{+},\, \Phi^{0})$$





Seesaw/Radiative Models

$$M_\nu = M^{tree} + M^{loop}$$

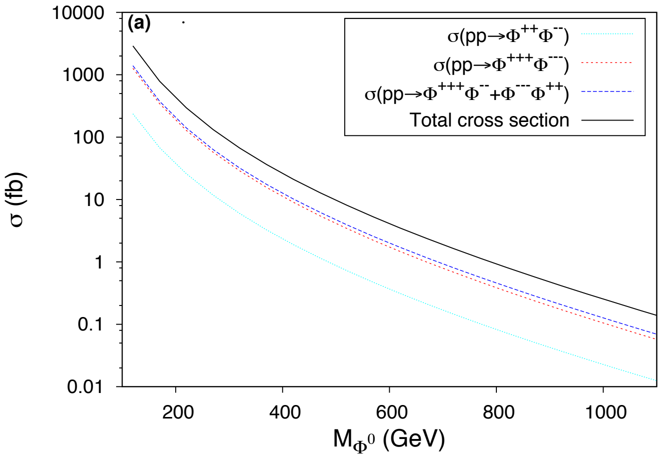


(Bambhaniya et al, 2013)

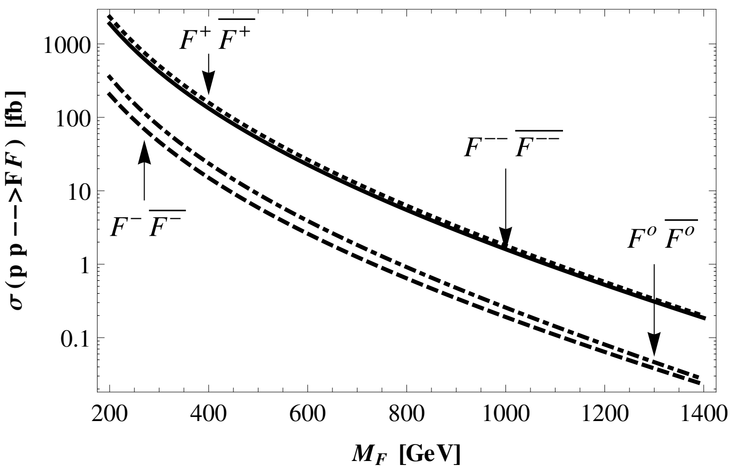
- Seesaw region “more accessible” at the LHC
- Similar results for all the new models

Seesaw/Radiative Models

- LHC production: controlled by E/W interactions



(Bambhaniya et al, 2013)



Fermions in new d=9 model

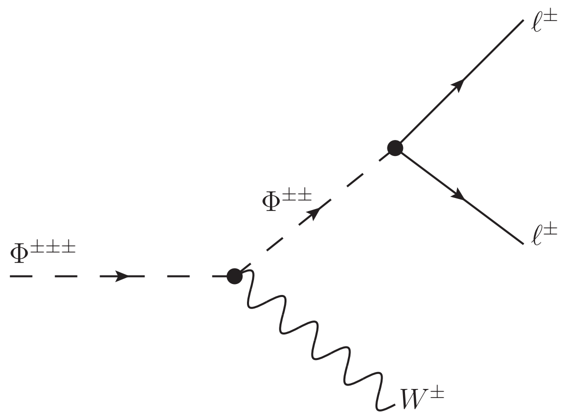
For $\sqrt{s} = 14\ \text{TeV}$

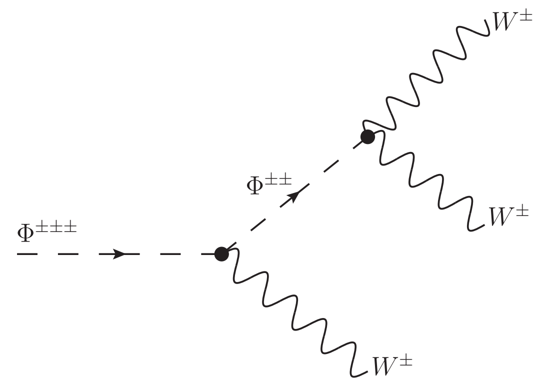
- Similar results for all the models

Triply Charged Scalar

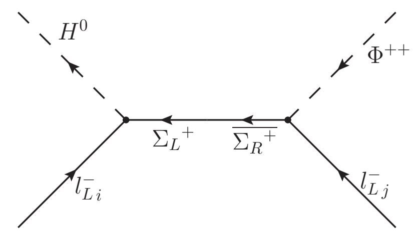
- Decays

$$\Phi^{+++} \to W^+ \ell^+ \ell^+ \qquad \Phi^{+++} \to W^+ W^+ W^+$$



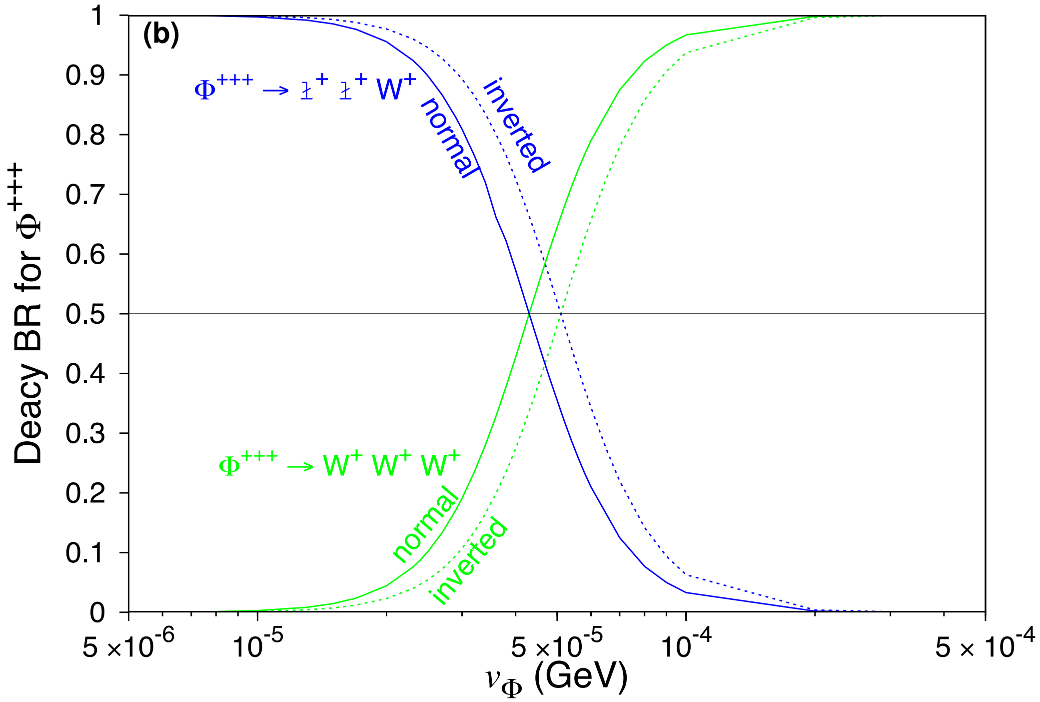


- Sensitive to neutrino mass



This is only for the d=7 model

Triply Charged Scalar



(Bambhaniya et al, 2013)

Detection

- Detection: multi-lepton final states (3,4,5,6)
- Including: same sign tri-lepton events
- Some model dependencies: e.g. Branching fractions etc
- General trend: “Some” signal has little SM background

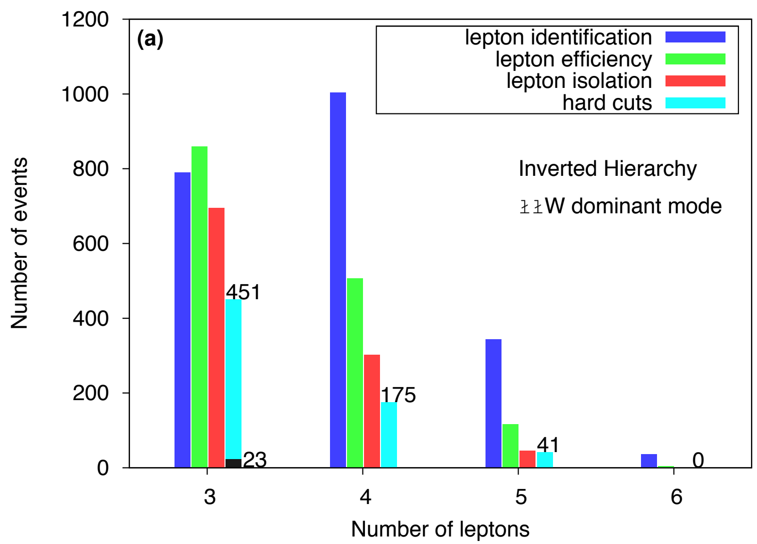
Background for the d=7 Model

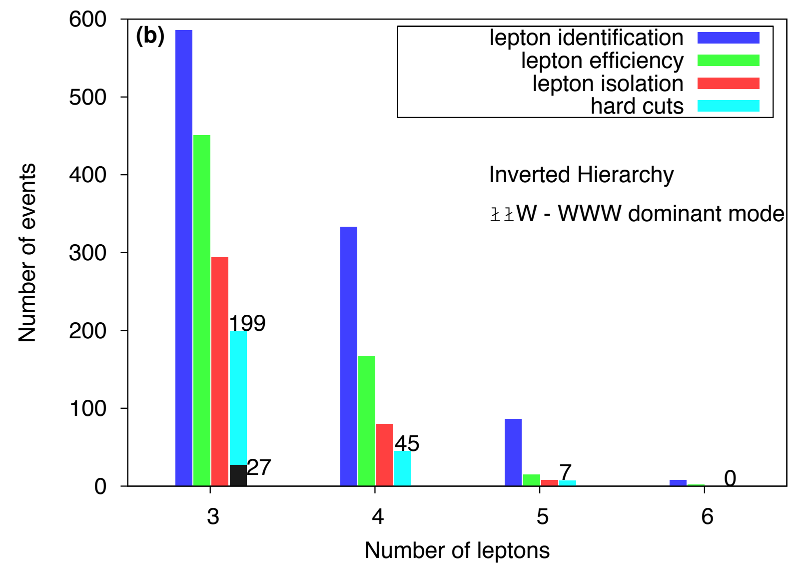
- After cuts

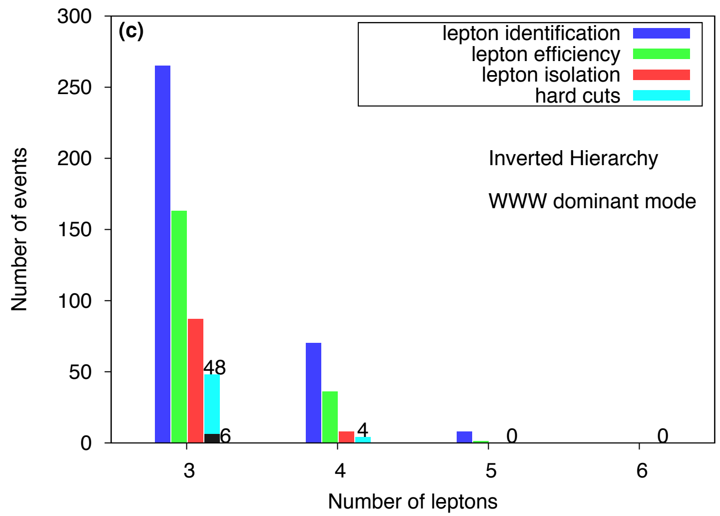
$\Downarrow$ **processes** $\backslash$ **multi-lepton channel** $\Rightarrow$	**3**ℓ (fb)	**SS3**ℓ (fb)	**4**ℓ (fb)
$t\bar{t}$	18.245	–	–
$t\bar{t}(Z/\gamma^\star)$	1.121	7.066×10^{-4}	0.069
$t\bar{t}W^\pm$	0.656	3.836×10^{-3}	–
$t\bar{t}t\bar{t}$	–	1.327×10^{-4}	–
$t\bar{t}b\bar{b}$	–	$< 10^{-4}$	–
$W^\pm(Z/\gamma^\star)$	10.590	–	–
$(Z/\gamma^\star)(Z/\gamma^\star)$	1.287	–	0.047
TOTAL	**31.899**	$\mathbf{4.675 \times 10^{-3}}$	**0.116**

(Bambhaniya et al, 2013)

Signal Events







- Integrated luminosity: 100 fb^(-1)
- Note: SS3L --- tiny background
- Significance > 10
- Similar for normal hierarchy

(Bambhaniya et al, 2013)

Mass Hierarchy Dependence

$\mathbf{4}\ell$	$eeee$	$eee\mu$	$ee\mu\mu$	$e\mu\mu\mu$	$\mu\mu\mu\mu$	Total events
IH	14	47	69	29	16	175
NH	1	1	23	40	61	126

- But not all the models have this feature

Conclusion

- Small mass: Seesaw or radiative
- New models: seesaw/radiative
- Seesaw: d>5 → lighter new physics
- Probe at LHC: Multi-lepton signals