RADIATIVE NEUTRINO MASS MODELS AT THE LHC

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Collaboration between theorists and ATLAS experimentalists at CoEPP

Theory: Paul Angel, Nick Rodd, RV

Experiment: Elisabetta Barberio, Kenji Hamano, Lucas Ong, Nick Rodd

Part of the "exotics" group within ATLAS

Goals:

- To search for the physics of neutrino mass generation at the LHC
- To construct new LHC-testable models that complement existing models, e.g. Zee-Babu
- To see if a systematic analysis of all such models is possible, under reasonable assumptions

Approach on the theory side:

- Use $\Delta L=2$ effective operators as starting point for models
- Rule out as many as possible using simple criteria, e.g. ν mass too small
- "Open up" the operators, i.e. construct all possible UV completions
- Filter using flavour and other constraints
- Examine LHC signatures

Project only partially done, so progress report.

Approach on experimental side:

- **Piggyback on generic exotica searches**
- **Initial focus on like-sign dilepton production (e.g. the doubly-charged Zee-Babu scalar) and testing type-III see-saw model**
- **Some ATLAS results presented at ICHEP 2012 (mass limits soon). CMS has approx. 400 GeV lower bound on doubly-charged scalars**

Contents:

1. $\Delta L=2$ effective operators
2. Topological analysis of opening-up of operators (P. Angel MSc thesis 2011)
3. Building specific models (P. Angel 2011 and N. Rodd MSc thesis 2012)
4. Conclusions

1. $\Delta L=2$ Effective Operators

Assumption: SM gauge group and multiplets

Babu & Leung, NPB619, 667 (2001)
de Gouvêa & Jenkins, PRD77, 013008 (2008)
W. Winter et al, recent papers

Classification criteria:

- mass dimension = d
- number of fermion fields = f

d=5, f=2:

LLHH, the famous Weinberg operator

Can be opened up at tree-level: type I, II and III see-saw mechanisms

$m_\nu \sim v^2/M$ → $M \sim 10^{12}$ TeV

unless some couplings are very small

The new physics is not forced to be at TeV scale

B=Babu J=Julio L=Leung Z=Zee

d=detailed, b=brief

d	f	operator(s)	scale from m_ν (TeV)	model(s)?	comments
7	4	$O_2 = LLLe^cH$	10^7	Z (1980,d)	pure-leptonic,1-loop, ruled out
		$O_3 = LLQd^cH(2)$	$10^{5,8}$	BJ (2012,d) BL (2001,b)	2012 = 2-loop 2001 = 1-loop
		$O_4 = LL\bar{Q}\bar{u}^cH(2)$	$10^{7,9}$	BL (2001,b)	1-loop vector leptoquarks
		$O_8 = L\bar{e}^c\bar{u}^cd^cH$	10^4	BJ (2010,d)	2-loop
9	4	$O_5 = LLQd^cHH\bar{H}$	10^6	BL (2001,b)	1-loop
		$O_6 = LL\bar{Q}\bar{u}^cHH\bar{H}$	10^7		
		$O_7 = LQ\bar{e}^c\bar{Q}HHH$	10^2		
		$O_{61} = (LLHH)(Le^c\bar{H})$	10^5		purely leptonic
		$O_{66} = (LLHH)(Qd^c\bar{H})$	10^6		
		$O_{71} = (LLHH)(Qu^cH)$	10^7	BL (2001,b)	1-loop

A=Angel dGJ=deGouvêa+Jenkins

d	f	operator(s)	scale from mν (TeV)	model(s)?	comments
9	6	$O_9 = LLLe^cLe^c$	10^3	BZ (1988,d)	2-loop, purely leptonic
		$O_{10} = LLLe^cQd^c$	10^4	BL (2001,b)	two 2-loop models
		$O_{11} = LLQd^cQd^c(2)$	30, 10^4	BL (2001,b) A (2011,d)	three 2-loop models one 2-loop model
		$O_{12} = LL\bar{Q}\bar{u}^c\bar{Q}\bar{u}^c(2)$	$10^{4,7}$	BL (2001,b)	2-loop
		$O_{13} = LL\bar{Q}\bar{u}^cLe^c$	10^4		
		$O_{14} = LL\bar{Q}\bar{u}^cQd^c(2)$	$10^{3,6}$		
		$O_{15} = LLLd^c\bar{L}\bar{u}^c$	10^3		
		$O_{16} = LL\bar{e}^cd^c\bar{e}^c\bar{u}^c$	2		
		$O_{17} = LLd^cd^c\bar{d}^c\bar{u}^c$	2		
		$O_{18} = LLd^cu^c\bar{u}^c\bar{u}^c$	2		
		$O_{19} = LQd^cd^c\bar{e}^c\bar{u}^c$	1	dGJ (2008,b)	
		$O_{20} = Ld^c\bar{Q}\bar{u}^c\bar{e}^c\bar{u}^c$	40		

d=11, f=6:

40 operators + 12 which are (d=7,f=4)x(d=4,f=2)

A large number have $M < 10^3$ TeV.

Many already require O(1) couplings or worse to get $m_\nu \sim 0.05$eV with the new physics at O(TeV).

There are no models worked out in detail yet.

This largely unexplored class is of interest for LHC searches. Do any of them work?

Sketched models exist for:

$O_{21} = LLLe^cQu^cHH(2)$ **BL (2001), three models**
M < 10^3 TeV

$O_{56} = LQd^cd^c\bar{e}^c\bar{d}^cHH$ **dGJ (2008), M < 500 GeV**

2. Diagram topologies

P. Angel, MSc thesis (2011)
A. de Gouvêa & Jenkins (2008)
K. Babu & C.N. Leung (2001)

The Weinberg operator O_1=LLHH is the only one that, when opened, produces tree-level neutrino mass models.

Our study is thus necessarily of radiative neutrino mass generation.

How many loops?

Three looks difficult.

You have to fight $\left(\frac{1}{16\pi^2}\right)^3 \simeq 10^{-7}$ to get $m_\nu \sim 0.05$eV.

This may not be completely ruled out – deG&J considered such cases – but we shall stop at two loops.

There are two places loops can arise:

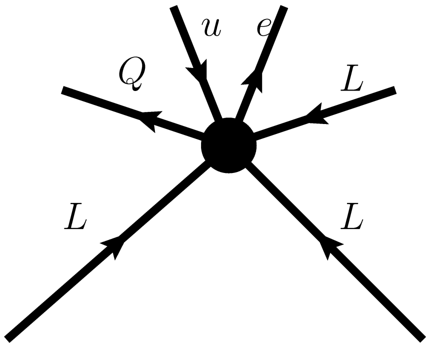
- on external lines of the effective operator
- in the opening-up of the operator itself

It is easy to examine the external lines to see how many can close into loops. Doing that, you find that the following operators require >2 loops:

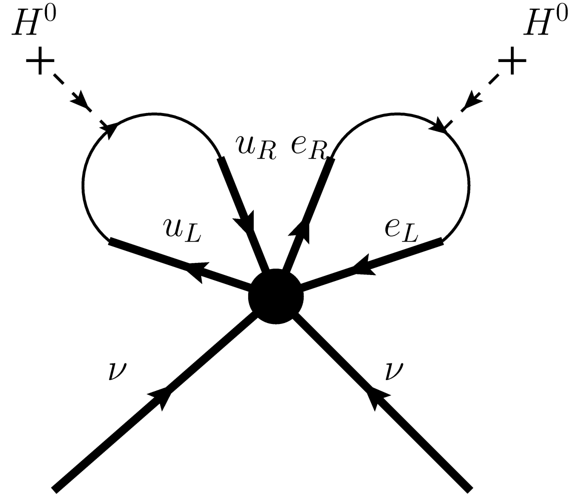
$$O_{15-20},\ O_{34-38},\ O_{43},\ O_{50},\ O_{52-60},\ O_{65},\ O_{70},\ O_{75}.$$

A=Angel   dGJ=deGouvêa+Jenkins

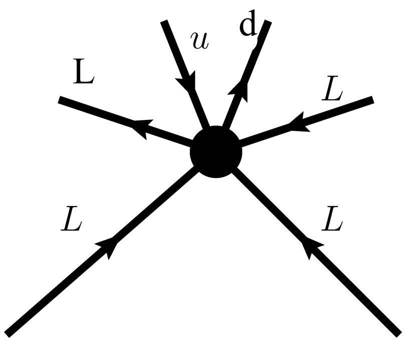
d	f	operator(s)	scale from mν (TeV)	model(s)?	comments
9	6	$O_9 = LLLe^cLe^c$	10^3	BZ (1988,d)	2-loop, purely leptonic
		$O_{10} = LLLe^cQd^c$	10^4	BL (2001,b)	two 2-loop models
		$O_{11} = LLQd^cQd^c(2)$	30, 10^4	BL (2001,b) A (2011,d)	three 2-loop models one 2-loop model
		$O_{12} = LL\bar{Q}\bar{u}^c\bar{Q}\bar{u}^c(2)$	$10^{4,7}$	BL (2001,b)	2-loop
		$O_{13} = LL\bar{Q}\bar{u}^cLe^c$	10^4		
		$O_{14} = LL\bar{Q}\bar{u}^cQd^c(2)$	$10^{3,6}$		
		$O_{15} = LLL$ … $\bar{u}^c$	10^3		
		$O_{16} = LL$ …			
		$O_{17} = LLd^cd^c$ …			
		$O_{18} = LLd^cu^c\bar{u}^c\bar{u}^c$			
		$O_{19} = LQ$ …		dGJ (…	
		$O_{20} = Ld^cQ$ …	40		



$$O_{13} = LL\bar{Q}\bar{u}^c Le^c$$



2-loop external line dressing to give m_ν



No such dressing possible

$$O_{15} = LLLd^c\bar{L}\bar{u}^c$$

That leaves 75 - 1 - 25 = 49 operators:

All four d=7, f=4 ops.

All six d=9, f=4 ops.

Six out of twelve d=9, f=6 ops.

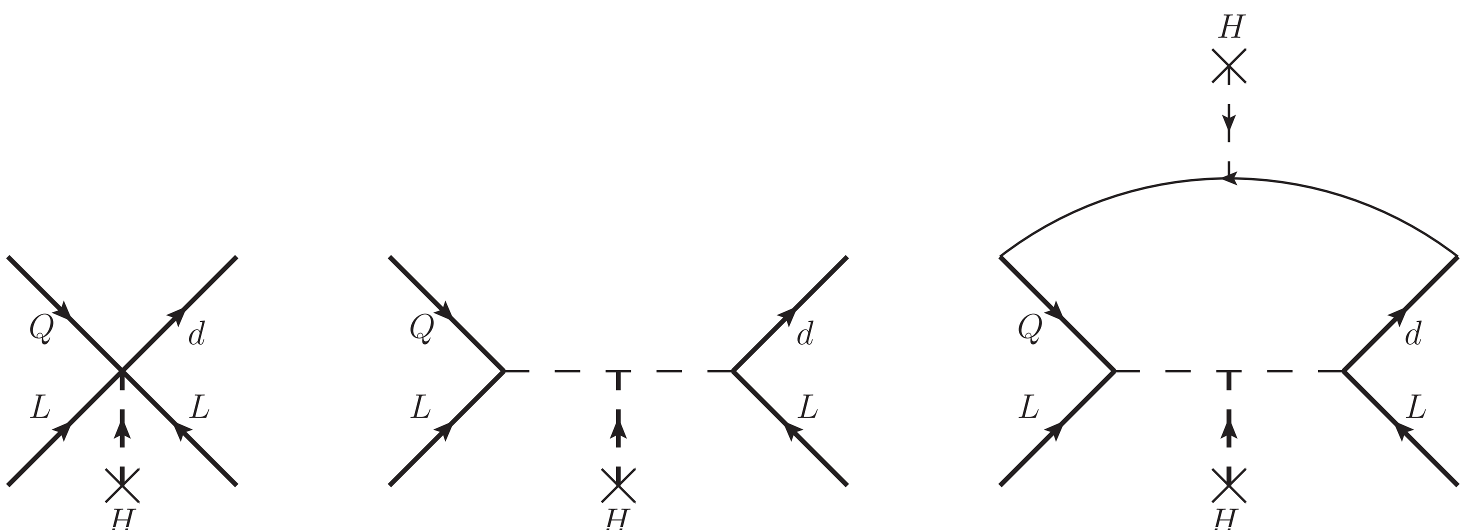
Thirty-three d=11, f=6 ops.

f = 4 operators leading to 1-loop models:

$$O_{2-6},\ O_{61},\ O_{66},\ O_{71}$$

Examples:

Exotic scalar completion of $O_3 = LLQd^cH$

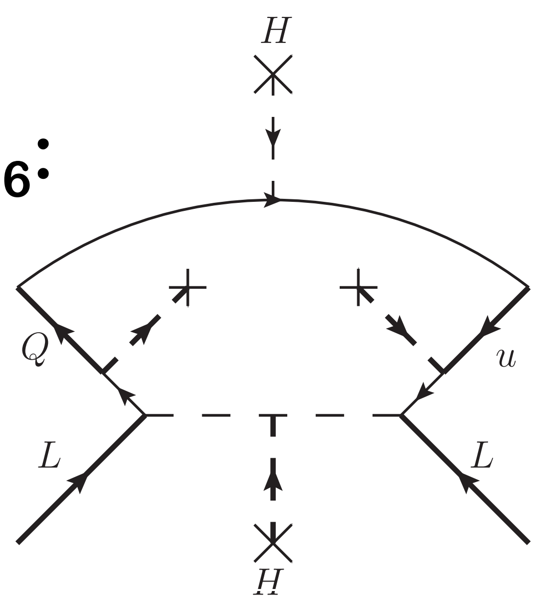


$$O_4 = LL\bar{Q}\bar{u}^c H(2) \quad O_6 = LL\bar{Q}\bar{u}^c HH\bar{H}$$

require exotic vector-like fermions
in addition to exotic scalars.

Scalars-only not allowed because you get structures like $\bar{L}_L Q_L S$ which are identically zero.

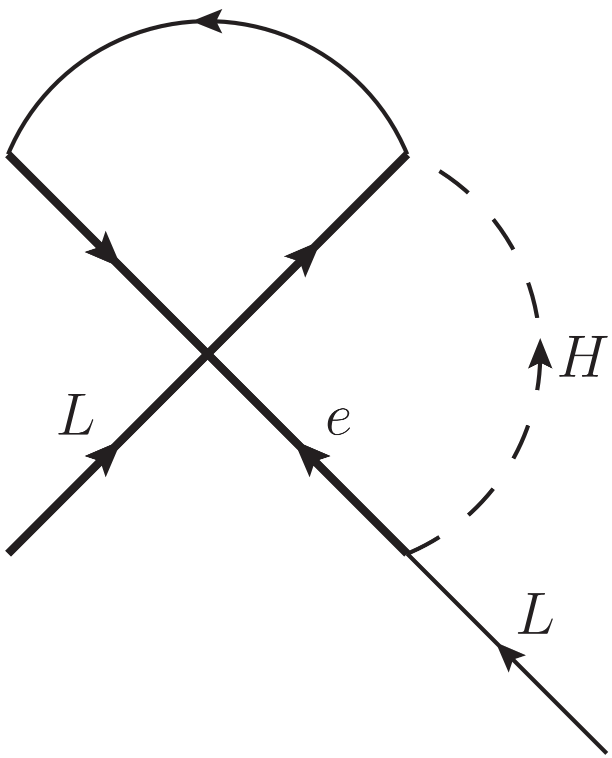
O$_6$:



Models with exotic fermions as well as exotic scalars have not been looked at much.

f = 4 operators leading to 2-loop models

$$O_7 = LQ\bar{e}^c\bar{Q}HHH \qquad O_8 = L\bar{e}^c\bar{u}^c d^c H$$



plus 1 or 3 Higgs lines heading in to effective vertex

d = 9, f = 6 operators (all models are 2-loop)

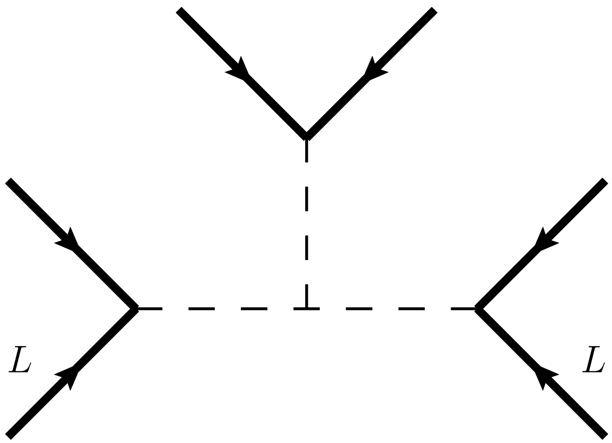
d	f	operator(s)	scale from mν (TeV)	model(s)?	comments
9	6	$O_9 = LLLe^cLe^c$	10^3	BZ (1988,d)	2-loop, purely leptonic
		$O_{10} = LLLe^cQd^c$	10^4	BL (2001,b)	two 2-loop models
		$O_{11} = LLQd^cQd^c(2)$	30, 10^4	BL (2001,b) A (2011,d)	three 2-loop models one 2-loop model
		$O_{12} = LL\bar{Q}\bar{u}^c\bar{Q}\bar{u}^c(2)$	$10^{4,7}$	BL (2001,b)	2-loop
		$O_{13} = LL\bar{Q}\bar{u}^cLe^c$	10^4		
		$O_{14} = LL\bar{Q}\bar{u}^cQd^c(2)$	$10^{3,6}$		

BZ (1988) very well studied and used by ATLAS as exemplar 2-loop model. This whole class can be thoroughly analysed, but not done yet.

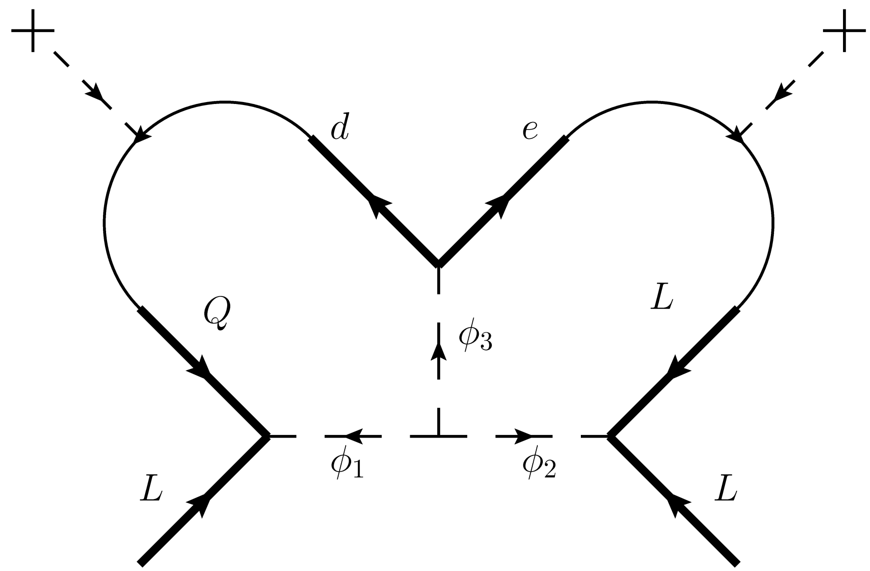
Each of the operators contains LL.

The other 4 fermions join to give 2 loops.

The effective operator completion must be tree-level.



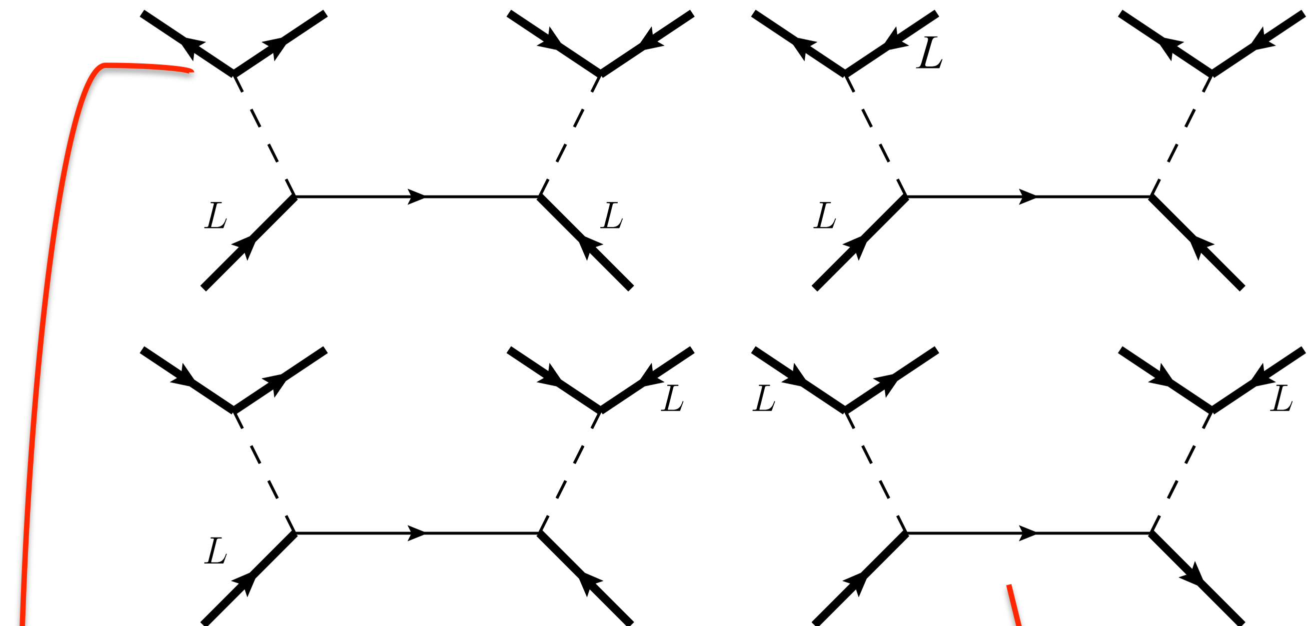
scalar-only completion

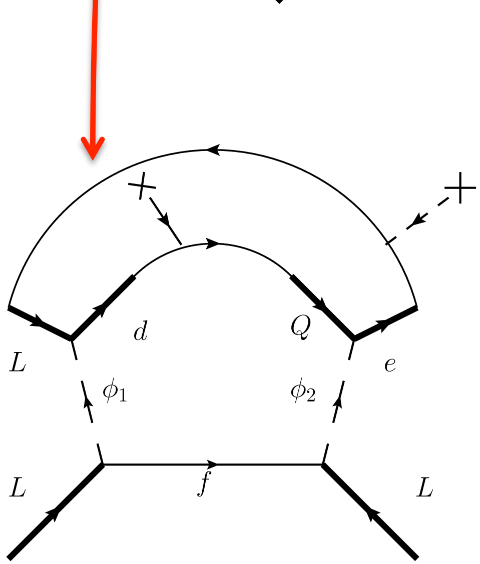


O_{10} example

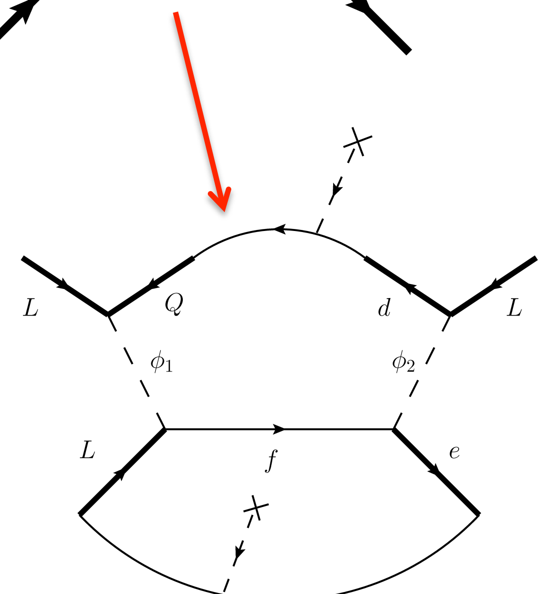
Note: the two L's are separated to avoid a type-II see-saw triplet – not an absolute requirement

Including exotic fermions:





O_{10} examples

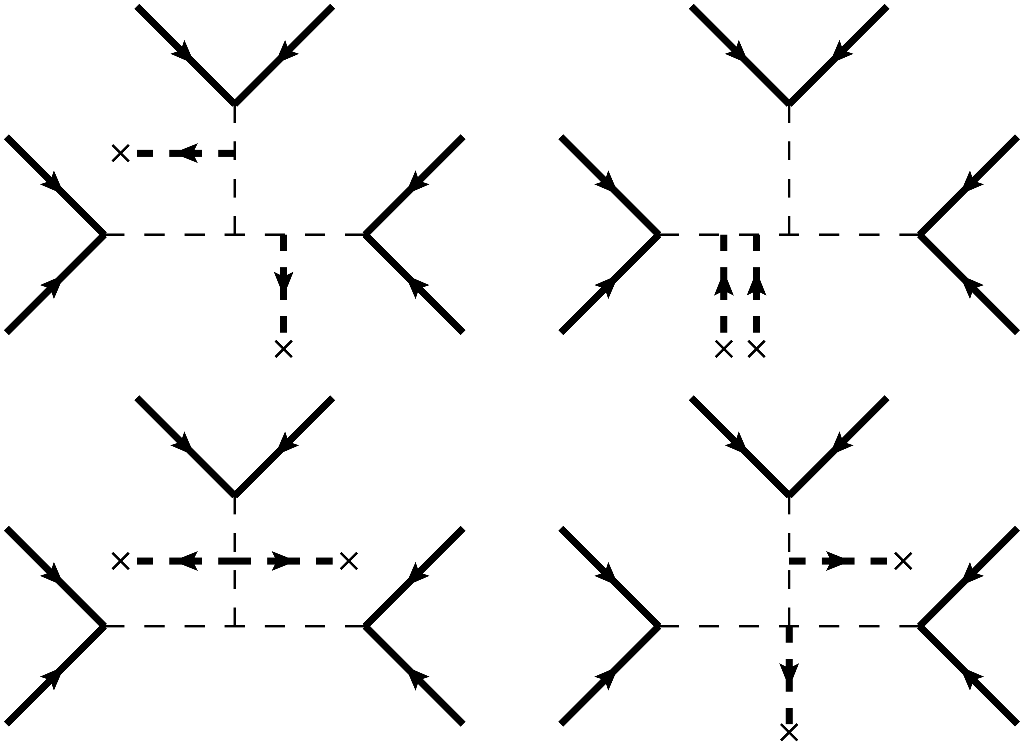


d = 11, f = 6 operators and 2-loop models

The 33 operators all contain LL and either HH or H$\bar{H}$.

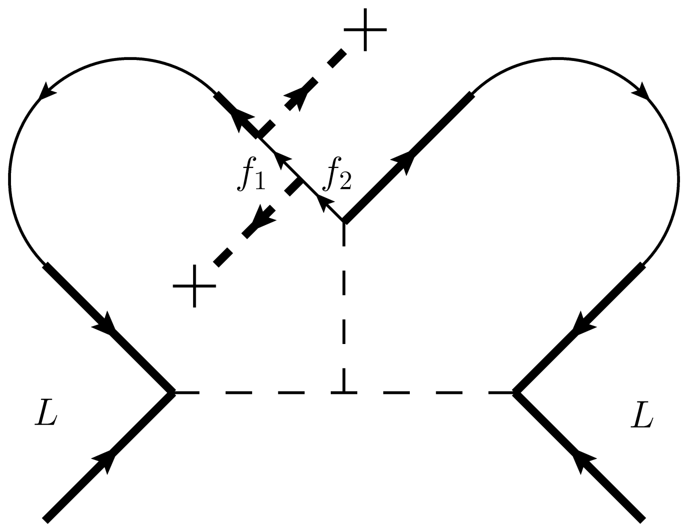
The previous f = 6 rules can be adapted to accommodate the two Higgs lines.

Exotic-scalar-only completion case:

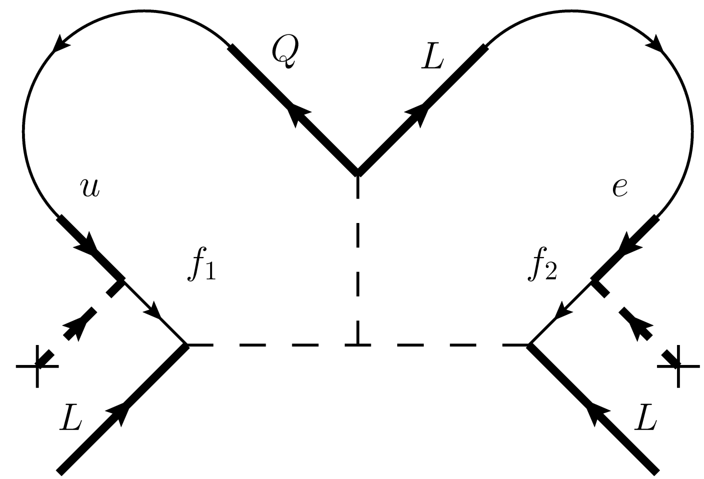


Including exotic fermions

An incomplete list:

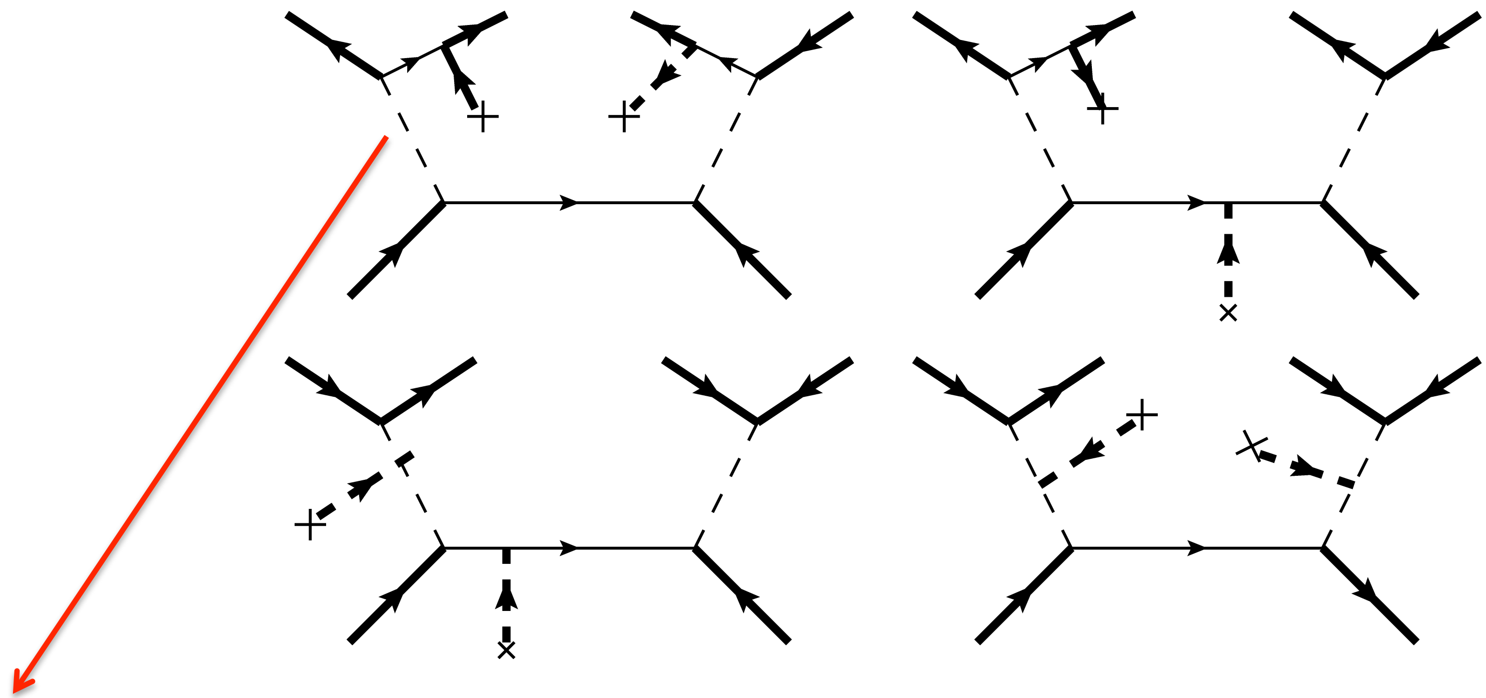


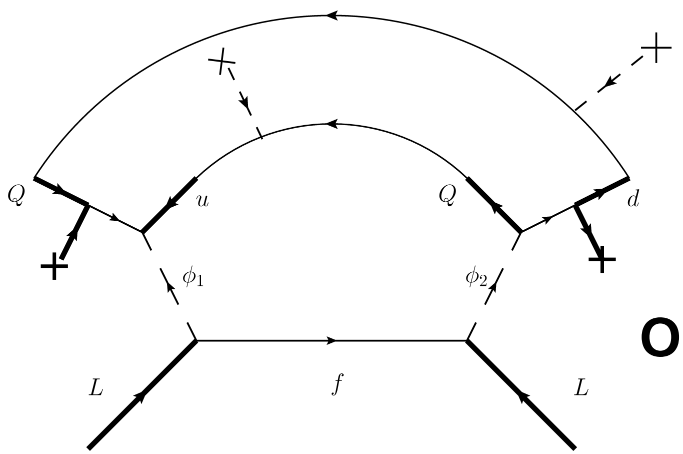
one generic topology



O_{12} example displaying another topology

More generic topologies:





O_{28} example

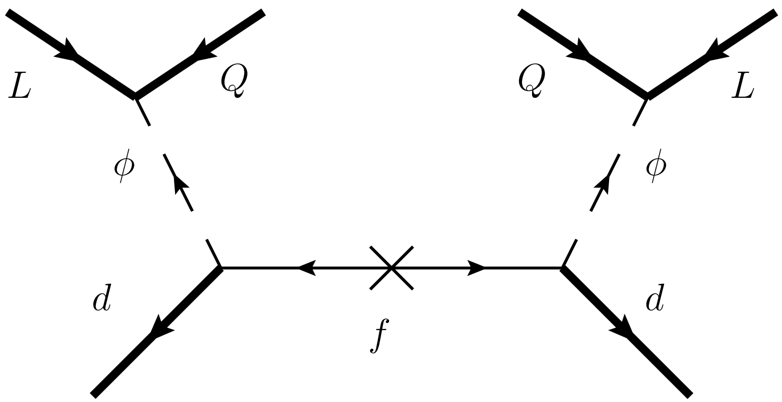
3. Models

Some general issues:

- Chirality – some diagrams vanish via LR = 0
- Divergent subdiagrams
- Generating lower-d operators

Angelic O_{11} model

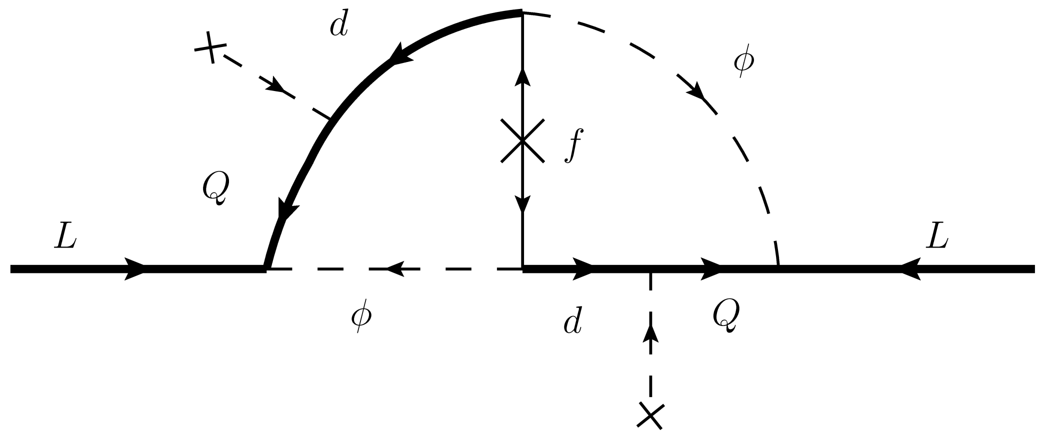
$$O_{11} = LLQd^cQd^c(2)$$



$$\phi \sim (3^*, 1, 2/3) \qquad f \sim (8, 1, 0)$$

$$\mathcal{L} = \lambda^{LQ}_{ab} \overline{L}^c_a Q_b \phi + \lambda^f_a \overline{d}_a f \phi^* + \frac{1}{2} m_f \overline{f}^c f + H.c.$$

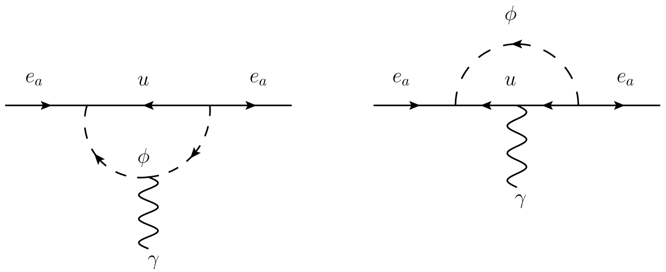
ΔL=2 term



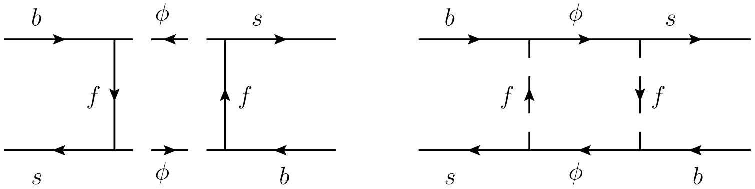
Neutrino mass and mixing angles can be fitted with m_f, m_ϕ ~ TeV and couplings 0.01–0.1

Constraints (under study):

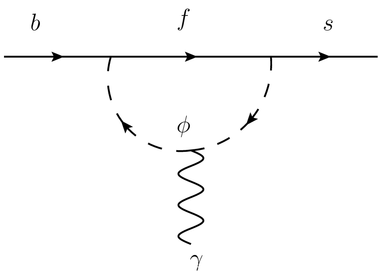
g-2 and $l_1 \rightarrow l_2 \gamma$:



meson mixing:



$b \rightarrow s \gamma$:



Rodd's investigation:

See if any viable models can arise from the d=11 operators.

Generic issue: it is not so easy to write a d=11 completion that does not also generate a lower d operator.

We have been looking at specific operators, and having noted this recurring problem are now trying to determine general rules for lower d operator generation.

4. Conclusions

1. Radiative ν mass models can be tested at the LHC.
2. Analysis of 2-loop diagram topologies exists.
3. New models can be generated.
4. All scalar+fermion models to d=9 can be constructed, but this has not yet been completed.
5. Are there any viable d=11 models?