RADIATIVE NEUTRINO MASS MODELS AT THE LHC

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ARC Centre of Excellence for Particle Physics at the Terascale

BeNe 2012
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. $\nu$ 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. Overlap with talk by Babu.
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)
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)

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**

\[ m_\nu \sim \frac{v^2}{M} \rightarrow M \sim 10^{12} \text{ TeV} \]

unless some couplings are very small

The new physics is not **forced** to be at TeV scale
<table>
<thead>
<tr>
<th>d</th>
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<td>$O_3 = LLQ d^c H (2)$</td>
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<td>$O_{19} = LQd^c d^c \bar{e}^c \bar{u}^c$</td>
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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:

\[ O_{21} = LLL e^c Qu^c HH (2) \quad \text{BL (2001), three models} \quad M < 10^3 \text{ TeV} \]

\[ O_{56} = LQ d^c d^c \bar{e}^c \bar{d}^c HH \quad \text{dGJ (2008), } M < 500 \text{ GeV} \]
2. Diagram topologies

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

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:

\[ O_{15-20}, O_{34-38}, O_{43}, O_{50}, O_{52-60}, O_{65}, O_{70}, O_{75}. \]
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2-loop external line dressing to give \( m_\nu \)

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.

Models with exotic fermions as well as exotic scalars have not been looked at much.
\( f = 4 \) operators leading to 2-loop models

\[
O_7 = LQ\bar{e}^c \bar{Q} H H H \quad \quad O_8 = L\bar{e}^c \bar{u}^c d^c H
\]

plus 1 or 3 Higgs lines heading in to effective vertex
d = 9, f = 6 operators (all models are 2-loop)

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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:

O₁₀ examples
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:
3. Models

Some general issues:

- Chirality – some diagrams vanish via LR = 0
- Divergent subdiagrams
- Generating lower-d operators
Angelic $O_{11}$ model

\[ O_{11} = LLQd^c Qd^c \]  

\[ \phi \sim (3^*, 1, 2/3) \quad f \sim (8, 1, 0) \]

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

$\Delta L=2$ term
Neutrino mass and mixing angles can be fitted with $m_f, m_{\phi} \sim \text{TeV}$ 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 $\nu$ 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?