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A Systematic Approach to Neutrino Mass: Effective Operator Analysis

Nick Rodd in collaboration with
Theory: Ray Volkas
Experiment: Elisabetta Barberio, Kenji Hamano and Lucas Ong

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Overview

- Seesaw models - archetypes of neutrino mass models
- Effective operators as a systematic approach to the problem of neutrino mass
- From operators back to models
  - Example: Zee-Babu Model
- How to test operators using the LHC

The problem of Neutrino Mass

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- The experimental discovery that neutrinos have mass presents a theoretical problem that is simple enough to state:
    - Neutrino mass exists and it's small.
- The Standard Model (SM) predicts massless neutrinos, so the task for any neutrino mass model is to provide a mechanism for its existence and a 'natural' explanation for why it's so small (~6 orders of magnitude lighter than the electron).
- More accurate precision measurements, such as the first values of θ_{13}, put strong constraints on such models. This has already ruled some out (e.g. Zee Model), but many still remain.
- But before going onto look at how to approach all the possible models, I first want to go through the simplest example.

Classic Example: Type I Seesaw Model

- It is natural to add ν_R~(1,1,0) to the SM.
- Once added, gauge invariance allows two new terms (a Dirac and Majorana mass term):

$$\lambda_\nu \bar{L}\bar{H}\nu_R + M\bar{\nu}_R\nu_R^c + h.c., \quad \lambda_\nu = m/ < H >$$

- Adding these terms is what is known as the Type I seesaw model and I'll briefly describe where the name comes from.
- The combination of these two terms leads to a mass matrix (for one generation):

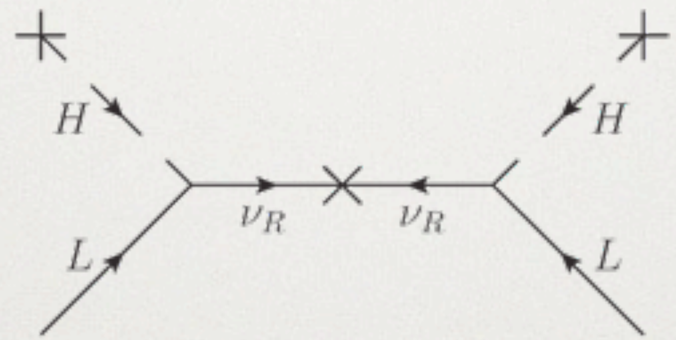
$$\frac{1}{2}(\bar{\nu}_L \;\; (\bar{\nu}_R)^c) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix}$$

Classic Example: Type I Seesaw Model

- Diagonalising yields two mass eigenstates:

$$m_{light} = -\frac{m^2}{M} \qquad m_{heavy} = M$$

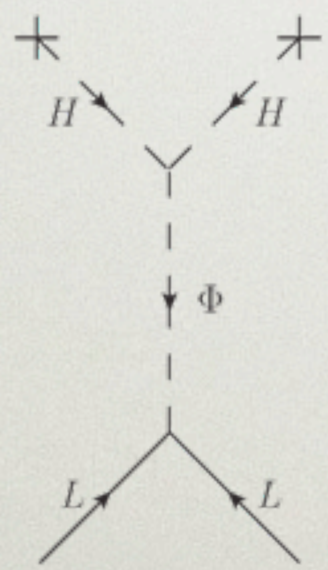
- This can also be seen through a Feynman diagram:



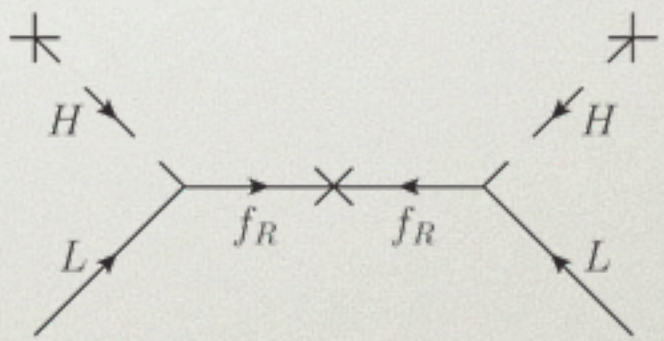
- M is not protected by a gauge symmetry, meaning it can be very large. Increasing M decreases the lighter mass and so it is called the 'seesaw' mechanism.
- M~10^{11} TeV is require to generate neutrino masses consistent with experiment. Accordingly, although its simplicity makes it theoretically favourable, this model is very hard to test experimentally.

Type II and III

- If instead of adding ν_R, we add Φ~(1,3,2) or f_R~(1,3,0), then we can also introduce neutrino mass via a seesaw type mechanism. The two new models are the Type II and III Seesaw models respectively.
- Both models produce new physics at a lower energy scale and are in fact both being looked for at the LHC.



Type II

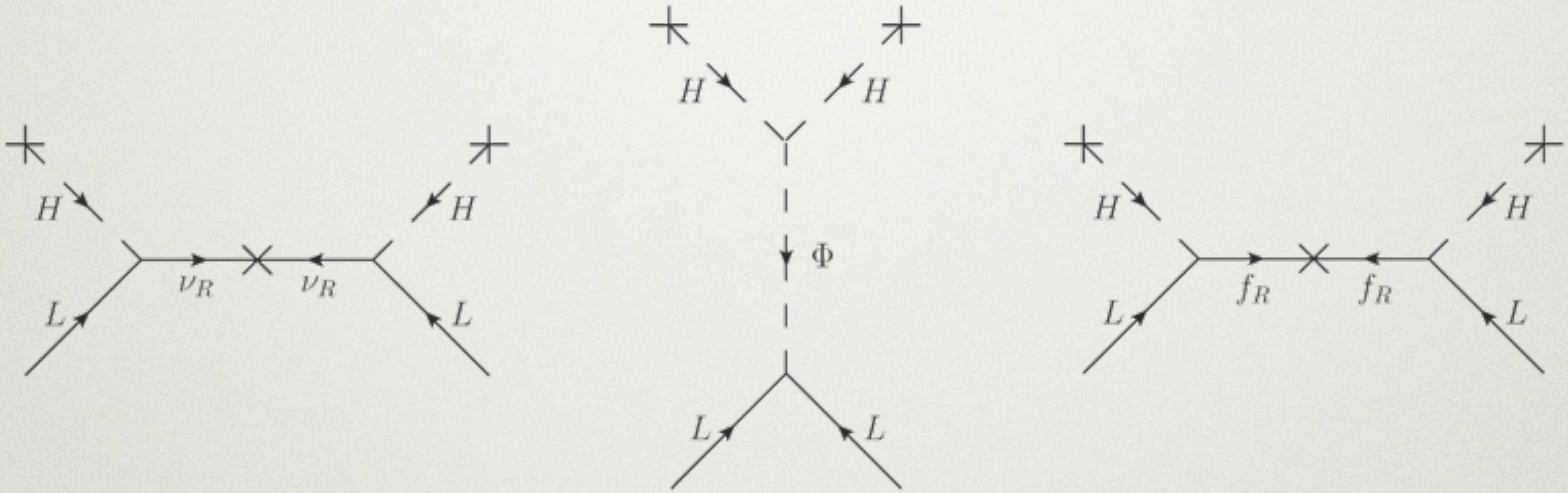


Type III

Seesaw Models - a common thread?

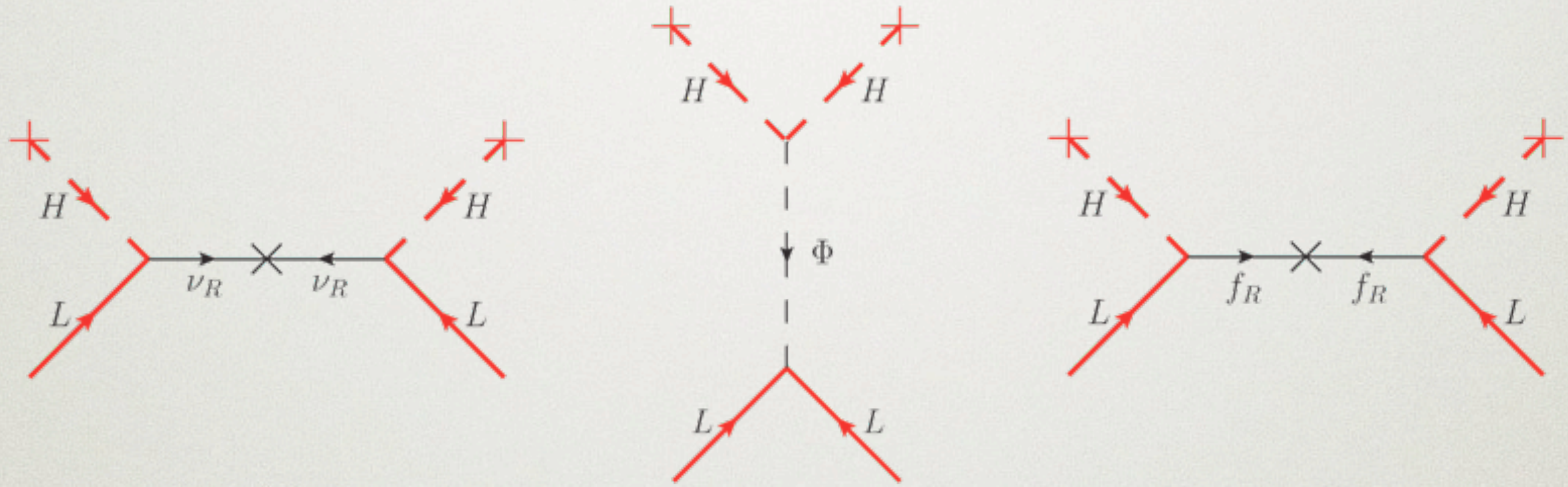
- It turns out the Seesaw Models have more in common than just their names and the fact they all explain the smallness of the observed neutrino masses using a seesaw mechanism.
- The easiest way to see this link is to look at all the diagrams.

Seesaw Models - a common thread?



Notice that all diagrams have the same external field content: LLHH

Seesaw Models - a common thread?



What remains if we integrate out the heavy fields?

Seesaw Models - a common thread?

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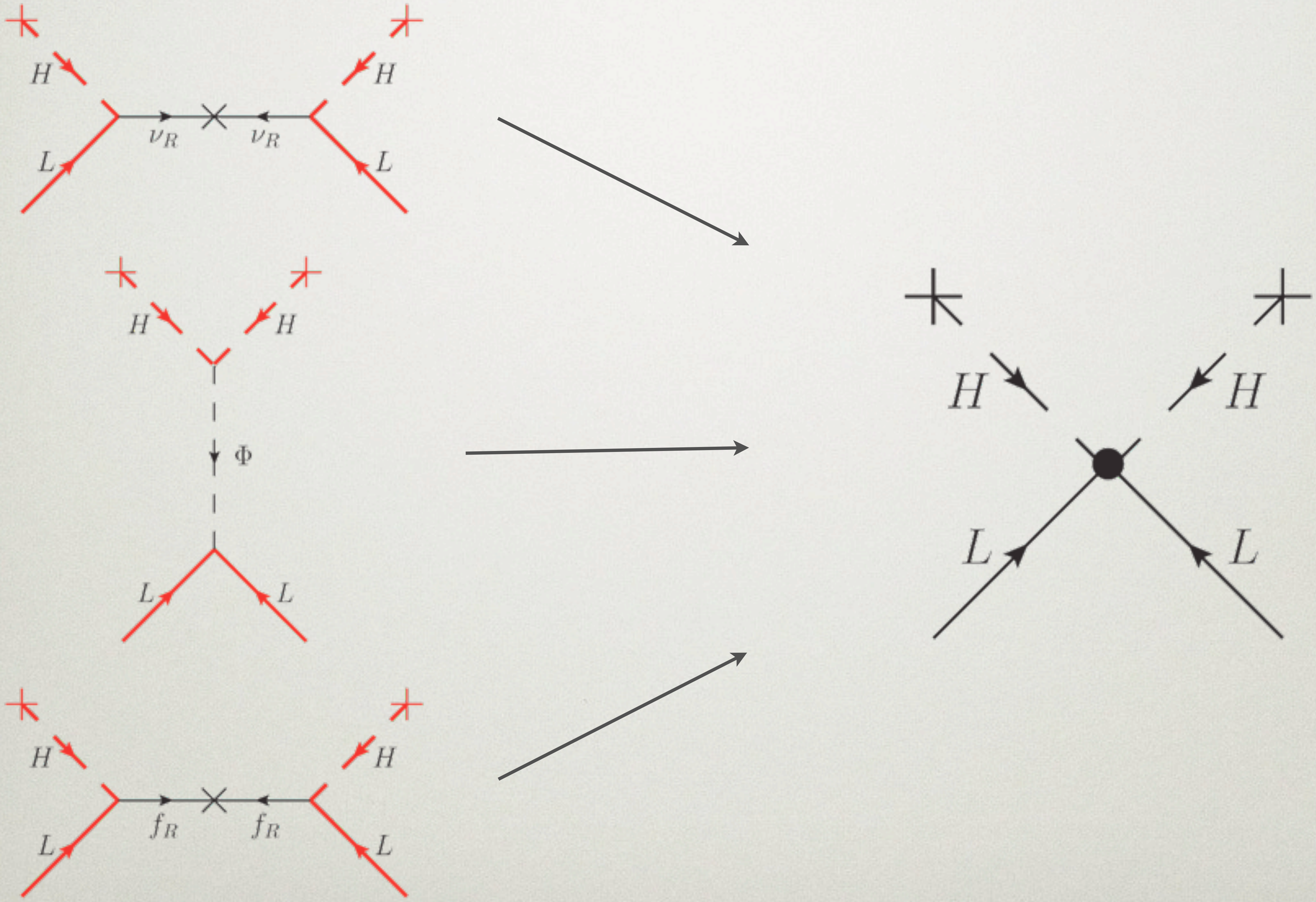

Seesaw Models - a common thread?

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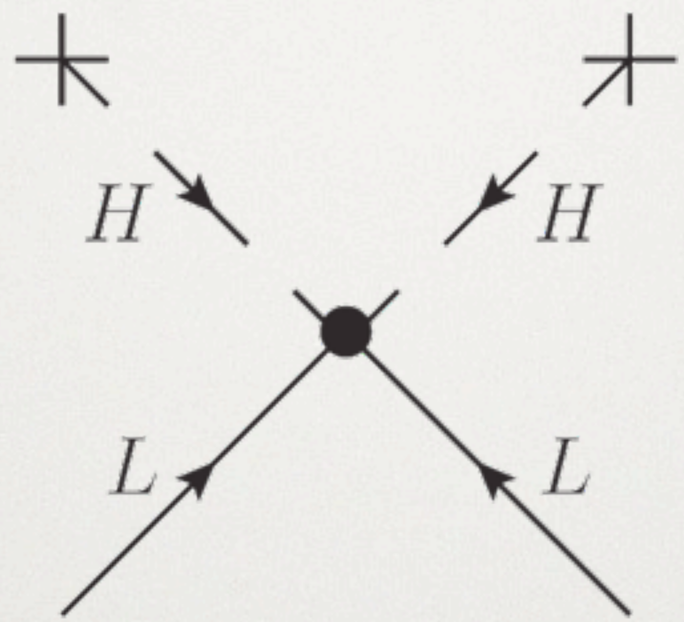
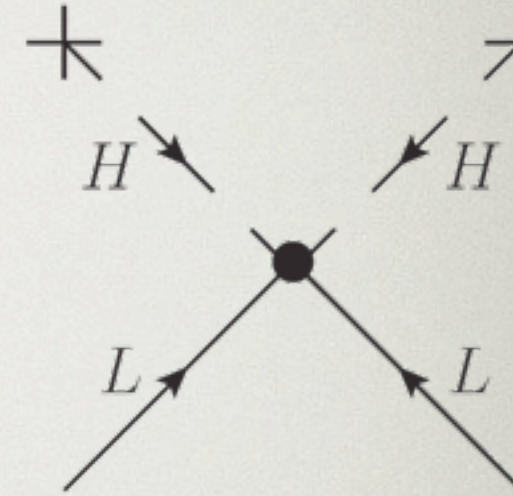


This is the simplest example of a neutrino mass effective operator - it captures the important details of all three seesaw models. It is usually represented as (Roman letters are *SU*(2) indices):

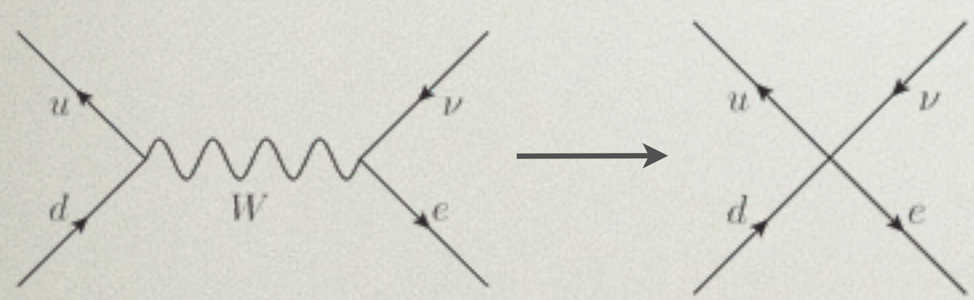
$$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik} \epsilon_{jl}$$

Towards Effective Operators

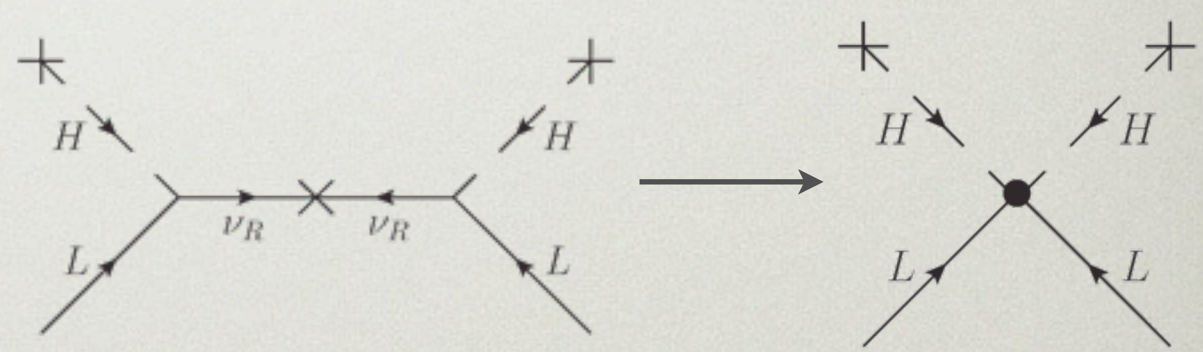


$$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$$

- An effective operator is a non-renormalizable term that captures the essential ingredients of the model.
  - In the case of Majorana neutrino mass models the essential ingredient is the ΔL=2 requirement (satisfied by L^iL^j for seesaw models).
  - It integrates out the new high energy physics, just like Fermi's four fermion theory of beta decay integrates out the W boson.



c.f.



- How many other ΔL=2 operators can be written down? Babu and Leung found there are 75

Effective Operators

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1 5D Operator

$$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$$

7 four fermion Operators

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl},$$
$$\mathcal{O}_3 = \left\{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl},\ L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\right\},$$
$$\mathcal{O}_4 = \left\{L^i L^j \overline{Q}_i \bar{u}^c H^k \epsilon_{jk},\ L^i L^j \overline{Q}_k \bar{u}^c H^k \epsilon_{ij}\right\},$$
$$\mathcal{O}_5 = L^i L^j Q^k d^c H^l H^m \overline{H}_i \epsilon_{jl}\epsilon_{km},$$
$$\mathcal{O}_6 = L^i L^j \overline{Q}_k \bar{u}^c H^l H^k \overline{H}_i \epsilon_{jl},$$
$$\mathcal{O}_7 = L^i Q^j \bar{e}^c \overline{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm},$$
$$\mathcal{O}_8 = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}.$$

12 9D Operators

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl},$$
$$\mathcal{O}_{10} = L^i L^j L^k e^c Q^l d^c \epsilon_{ij}\epsilon_{kl},$$
$$\mathcal{O}_{11} = \left\{L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl},\ L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}\right\},$$
$$\mathcal{O}_{12} = \left\{L^i L^j \overline{Q}_i \bar{u}^c \overline{Q}_j \bar{u}^c,\ L^i L^j \overline{Q}_k \bar{u}^c \overline{Q}_l \bar{u}^c \epsilon_{ij}\epsilon^{kl}\right\},$$
$$\mathcal{O}_{13} = L^i L^j \overline{Q}_i \bar{u}^c L^l e^c \epsilon_{jl},$$
$$\mathcal{O}_{14} = \left\{L^i L^j \overline{Q}_k \bar{u}^c Q^k d^c \epsilon_{ij},\ L^i L^j \overline{Q}_i \bar{u}^c Q^l d^c \epsilon_{jl}\right\},$$
$$\mathcal{O}_{15} = L^i L^j L^k d^c \overline{L}_i \bar{u}^c \epsilon_{jk},$$
$$\mathcal{O}_{16} = L^i L^j e^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij},$$
$$\mathcal{O}_{17} = L^i L^j d^c d^c \bar{d}^c \bar{u}^c \epsilon_{ij},$$
$$\mathcal{O}_{18} = L^i L^j d^c u^c \bar{u}^c \bar{u}^c \epsilon_{ij},$$
$$\mathcal{O}_{19} = L^i Q^j d^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij},$$
$$\mathcal{O}_{20} = L^i d^c \overline{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c.$$

40 11D Operators

$$\mathcal{O}_{21} = \left\{L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln},\ L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{il}\epsilon_{jm}\epsilon_{kn}\right\},$$
$$\mathcal{O}_{22} = L^i L^j L^k e^c \overline{L}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm},$$
$$\mathcal{O}_{23} = L^i L^j L^k e^c \overline{Q}_k \bar{d}^c H^l H^m \epsilon_{il}\epsilon_{jm},$$
$$\mathcal{O}_{24} = \left\{L^i L^j Q^k d^c Q^l d^c H^m \overline{H}_i \epsilon_{jk}\epsilon_{lm},\ L^i L^j Q^k d^c Q^l d^c H^m \overline{H}_i \epsilon_{jm}\epsilon_{kl}\right\},$$
$$\mathcal{O}_{25} = L^i L^j Q^k d^c Q^l u^c H^m H^n \epsilon_{im}\epsilon_{jn}\epsilon_{kl},$$
$$\mathcal{O}_{26} = \left\{L^i L^j Q^k d^c \overline{L}_i \bar{e}^c H^l H^m \epsilon_{jl}\epsilon_{km},\ L^i L^j Q^k d^c \overline{L}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm}\right\},$$
$$\mathcal{O}_{27} = \left\{L^i L^j Q^k d^c \overline{Q}_i \bar{d}^c H^l H^m \epsilon_{jl}\epsilon_{km},\ L^i L^j Q^k d^c \overline{Q}_k \bar{d}^c H^l H^m \epsilon_{il}\epsilon_{jm}\right\},$$
$$\mathcal{O}_{28} = \left\{L^i L^j Q^k d^c \overline{Q}_j \bar{u}^c H^l \overline{H}_i \epsilon_{kl},\ L^i L^j Q^k d^c \overline{Q}_k \bar{u}^c H^l \overline{H}_i \epsilon_{jl},\right.$$
$$\left. L^i L^j Q^k d^c \overline{Q}_l \bar{u}^c H^l \overline{H}_i \epsilon_{jk}\right\},$$
$$\mathcal{O}_{29} = \left\{L^i L^j Q^k u^c \overline{Q}_k \bar{u}^c H^l H^m \epsilon_{il}\epsilon_{jm},\ L^i L^j Q^k u^c \overline{Q}_l \bar{u}^c H^l H^m \epsilon_{ik}\epsilon_{jm}\right\},$$
$$\mathcal{O}_{30} = \left\{L^i L^j \overline{L}_i \bar{e}^c \overline{Q}_k \bar{u}^c H^k H^l \epsilon_{jl},\ L^i L^j \overline{L}_m \bar{e}^c \overline{Q}_n \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}\right\},$$
$$\mathcal{O}_{31} = \left\{L^i L^j \overline{Q}_i \bar{d}^c \overline{Q}_k \bar{u}^c H^k H^l \epsilon_{jl},\ L^i L^j \overline{Q}_m \bar{d}^c \overline{Q}_n \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}\right\},$$
$$\mathcal{O}_{32} = \left\{L^i L^j \overline{Q}_j \bar{u}^c \overline{Q}_k \bar{u}^c H^k \overline{H}_i,\ L^i L^j \overline{Q}_m \bar{u}^c \overline{Q}_n \bar{u}^c H^k \overline{H}_i \epsilon_{jk}\epsilon^{mn}\right\},$$
$$\mathcal{O}_{33} = \bar{e}^c \bar{e}^c L^i L^j e^c e^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{34} = \bar{e}^c \bar{e}^c L^i Q^j e^c d^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{35} = \bar{e}^c \bar{e}^c L^i e^c \overline{Q}_j \bar{u}^c H^j H^k \epsilon_{ik},$$
$$\mathcal{O}_{36} = \bar{e}^c \bar{e}^c Q^i d^c Q^j d^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{37} = \bar{e}^c \bar{e}^c Q^i d^c \overline{Q}_j \bar{u}^c H^j H^k \epsilon_{ik},$$
$$\mathcal{O}_{38} = \bar{e}^c \bar{e}^c \overline{Q}_i \bar{u}^c \overline{Q}_j \bar{u}^c H^i H^j,$$
$$\mathcal{O}_{39} = \left\{L^i L^j L^k L^l \overline{L}_i \overline{L}_j H^m H^n \epsilon_{jm}\epsilon_{kl},\ L^i L^j L^k L^l \overline{L}_m \overline{L}_n H^m H^n \epsilon_{ij}\epsilon_{kl},\right.$$
$$\left. L^i L^j L^k L^l \overline{L}_i \overline{L}_m H^m H^n \epsilon_{jk}\epsilon_{ln},\ L^i L^j L^k L^l \overline{L}_p \overline{L}_q H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}\right\},$$
$$\mathcal{O}_{40} = \left\{L^i L^j L^k Q^l \overline{L}_i \overline{Q}_j H^m H^n \epsilon_{km}\epsilon_{ln},\ L^i L^j L^k Q^l \overline{L}_i \overline{Q}_l H^m H^n \epsilon_{jm}\epsilon_{kn},\right.$$
$$L^i L^j L^k Q^l \overline{L}_l \overline{Q}_i H^m H^n \epsilon_{jm}\epsilon_{kn},\ L^i L^j L^k Q^l \overline{L}_i \overline{Q}_m H^m H^n \epsilon_{jk}\epsilon_{ln},$$
$$L^i L^j L^k Q^l \overline{L}_i \overline{Q}_m H^m H^n \epsilon_{jl}\epsilon_{kn},\ L^i L^j L^k Q^l \overline{L}_m \overline{Q}_i H^m H^n \epsilon_{jk}\epsilon_{ln},$$
$$L^i L^j L^k Q^l \overline{L}_m \overline{Q}_i H^m H^n \epsilon_{jl}\epsilon_{kn},\ L^i L^j L^k Q^l \overline{L}_m \overline{Q}_n H^m H^n \epsilon_{ij}\epsilon_{kl},$$
$$L^i L^j L^k Q^l \overline{L}_m \overline{Q}_n H^p H^q \epsilon_{ip}\epsilon_{jq}\epsilon_{kl}\epsilon^{mn},$$
$$\left. L^i L^j L^k Q^l \overline{L}_m \overline{Q}_n H^p H^q \epsilon_{ip}\epsilon_{lq}\epsilon_{jk}\epsilon^{mn}\right\},$$
$$\mathcal{O}_{41} = \left\{L^i L^j L^k d^c \overline{L}_i \bar{d}^c H^l H^m \epsilon_{jl}\epsilon_{km},\ L^i L^j L^k d^c \overline{L}_l \bar{d}^c H^l H^m \epsilon_{ij}\epsilon_{km}\right\},$$
$$\mathcal{O}_{42} = \left\{L^i L^j L^k u^c \overline{L}_i \bar{u}^c H^l H^m \epsilon_{jl}\epsilon_{km},\ L^i L^j L^k u^c \overline{L}_l \bar{u}^c H^l H^m \epsilon_{ij}\epsilon_{km}\right\},$$
$$\mathcal{O}_{43} = \left\{L^i L^j L^k d^c \overline{L}_l \bar{u}^c H^l \overline{H}_i \epsilon_{jk},\ L^i L^j L^k d^c \overline{L}_j \bar{u}^c H^l \overline{H}_i \epsilon_{kl},\right.$$
$$\left. L^i L^j L^k d^c \overline{L}_l \bar{u}^c H^m \overline{H}_n \epsilon_{ij}\epsilon_{km}\epsilon^{ln}\right\},$$
$$\mathcal{O}_{44} = \left\{L^i L^j Q^k e^c \overline{Q}_i \bar{e}^c H^l H^m \epsilon_{jl}\epsilon_{km},\ L^i L^j Q^k e^c \overline{Q}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm},\right.$$
$$\left. L^i L^j Q^k e^c \overline{Q}_l \bar{e}^c H^l H^m \epsilon_{ij}\epsilon_{km},\ L^i L^j Q^k e^c \overline{Q}_l \bar{e}^c H^l H^m \epsilon_{ik}\epsilon_{jm}\right\},$$
$$\mathcal{O}_{45} = L^i L^j e^c d^c \bar{e}^c \bar{d}^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{46} = L^i L^j e^c u^c \bar{e}^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{47} = \left\{L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_j H^m H^n \epsilon_{km}\epsilon_{ln},\ L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_k H^m H^n \epsilon_{jm}\epsilon_{ln},\right.$$
$$L^i L^j Q^k Q^l \overline{Q}_k \overline{Q}_l H^m H^n \epsilon_{im}\epsilon_{jn},\ L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_m H^m H^n \epsilon_{jk}\epsilon_{ln},$$
$$L^i L^j Q^k Q^l \overline{Q}_i \overline{Q}_m H^m H^n \epsilon_{jn}\epsilon_{kl},\ L^i L^j Q^k Q^l \overline{Q}_k \overline{Q}_m H^m H^n \epsilon_{ij}\epsilon_{ln},$$
$$L^i L^j Q^k Q^l \overline{Q}_k \overline{Q}_m H^m H^n \epsilon_{il}\epsilon_{jn},\ L^i L^j Q^k Q^l \overline{Q}_p \overline{Q}_q H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq},$$
$$L^i L^j Q^k Q^l \overline{Q}_p \overline{Q}_q H^m H^n \epsilon_{ik}\epsilon_{jm}\epsilon_{ln}\epsilon^{pq},$$
$$\left. L^i L^j Q^k Q^l \overline{Q}_p \overline{Q}_q H^m H^n \epsilon_{im}\epsilon_{jn}\epsilon_{kl}\epsilon^{pq}\right\},$$
$$\mathcal{O}_{48} = L^i L^j d^c d^c \bar{d}^c \bar{d}^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{49} = L^i L^j d^c u^c \bar{d}^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{50} = L^i L^j d^c d^c \bar{d}^c \bar{u}^c H^k \overline{H}_i \epsilon_{jk},$$
$$\mathcal{O}_{51} = L^i L^j u^c u^c \bar{u}^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{52} = L^i L^j d^c u^c \bar{u}^c \bar{u}^c H^k \overline{H}_i \epsilon_{jk},$$
$$\mathcal{O}_{53} = L^i L^j d^c d^c \bar{u}^c \bar{u}^c \overline{H}_i \overline{H}_j,$$
$$\mathcal{O}_{54} = \left\{L^i Q^j Q^k d^c \overline{Q}_i \bar{e}^c H^l H^m \epsilon_{jl}\epsilon_{km},\ L^i Q^j Q^k d^c \overline{Q}_j \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{km},\right.$$
$$\left. L^i Q^j Q^k d^c \overline{Q}_l \bar{e}^c H^l H^m \epsilon_{im}\epsilon_{jk},\ L^i Q^j Q^k d^c \overline{Q}_l \bar{e}^c H^l H^m \epsilon_{ij}\epsilon_{km}\right\},$$
$$\mathcal{O}_{55} = \left\{L^i Q^j \overline{Q}_i \overline{Q}_k \bar{e}^c \bar{u}^c H^k H^l \epsilon_{jl},\ L^i Q^j \overline{Q}_j \overline{Q}_k \bar{e}^c \bar{u}^c H^k H^l \epsilon_{il},\right.$$
$$\left. L^i Q^j \overline{Q}_m \overline{Q}_n \bar{e}^c \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}\right\},$$
$$\mathcal{O}_{56} = L^i Q^j d^c d^c \bar{e}^c \bar{d}^c H^k H^l \epsilon_{ik}\epsilon_{jl},$$
$$\mathcal{O}_{57} = L^i d^c \overline{Q}_j \bar{u}^c \bar{e}^c \bar{d}^c H^j H^k \epsilon_{ik},$$
$$\mathcal{O}_{58} = L^i u^c \overline{Q}_j \bar{u}^c \bar{e}^c \bar{u}^c H^j H^k \epsilon_{ik},$$
$$\mathcal{O}_{59} = L^i Q^j d^c d^c \bar{e}^c \bar{u}^c H^k \overline{H}_i \epsilon_{jk},$$
$$\mathcal{O}_{60} = L^i d^c \overline{Q}_j \bar{u}^c \bar{e}^c \bar{u}^c H^j \overline{H}_i.$$

- List due to Babu and Leung
- There are 15 others they didn't originally list
- So in total 75 operators

Effective Operators

- The list realises basically all existing models for neutrino mass, e.g. $\mathcal{O}_3$ can give rise to an *R*-parity violating SUSY model.
- While the list is long, there is a straightforward recipe for its construction: can't violate baryon number (constraints too strong); must have a $\Delta L=2$ term; and then can add Higgs or $\Delta L=\Delta B=0$ number conserving terms.
- A key feature is that the list is finite because 13D operators generate a mass too small to be consistent with atmospheric data.
  - De Gouvea and Jenkins have shown 25 are already strongly disfavoured and that many are testable at LHC and upcoming measurements (e.g. oscillation and neutrinoless double beta decay).
  - After talking to Babu at ICHEP, Ray and I are planning to investigate the possibility that in fact 11D operators may also be inconsistent - this would reduce the list from 75 to 20 operators!
- So the approach is to pick an operator that can be tested with existing experiments, generate all possible models from it and set constraints.

Operators back to Models

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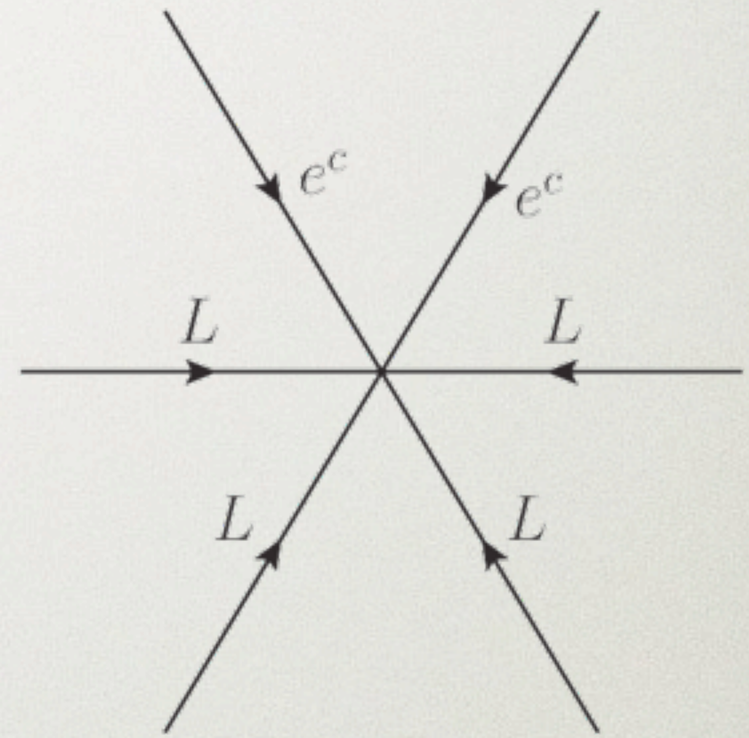
- I've shown how you can go from models to operators, but not how to go from an operator back to all the models it can generate.
- The question of how to go from operators back to models in general was answered by Paul Angel's thesis last year (a Masters student of Ray), where he provided a step by step procedure for generating one and two loop models.
    - Note that only $\mathcal{O}_1$ generates tree level models. Loop models don't have the seesaw mechanism, but rather they explain the smallness of neutrino masses through loop suppression.
    - It is assumed, but has yet to be proved, that three loop models are inconsistent with the data.
- Rather than go through Paul's procedure I will give an example:

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl}$$

Operators back to Models

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij} \epsilon_{kl} \longrightarrow$$



Write as a vertex

Operators back to Models

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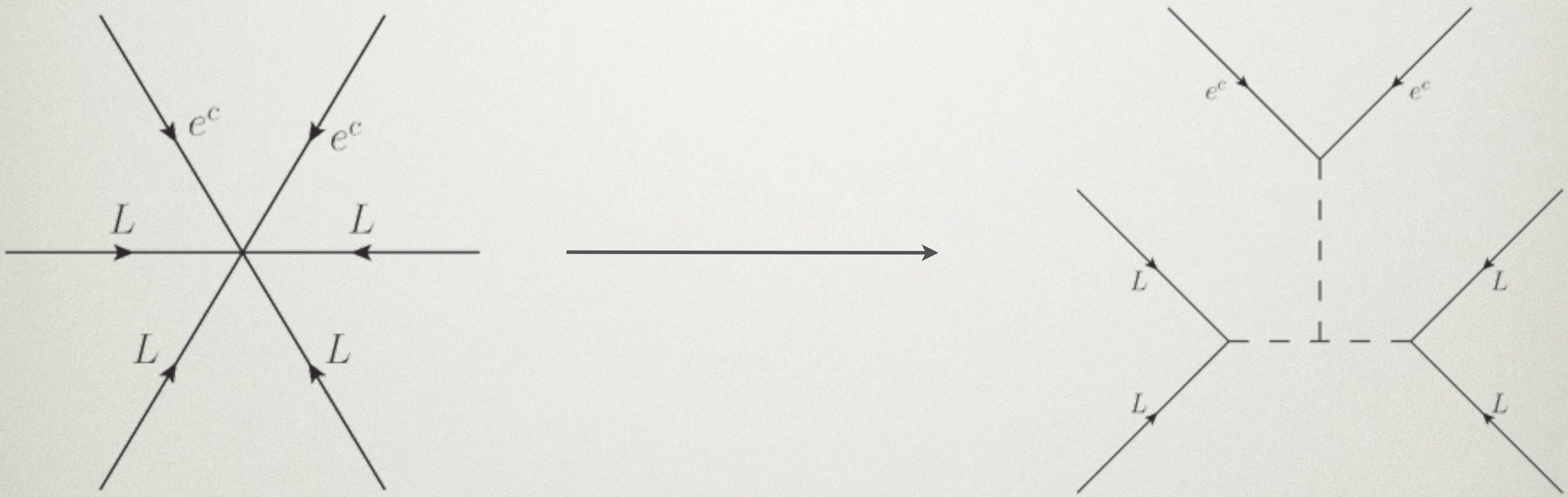

Use Paul's method to e.g.
complete with scalars
(several possible UV completions)

Operators back to Models

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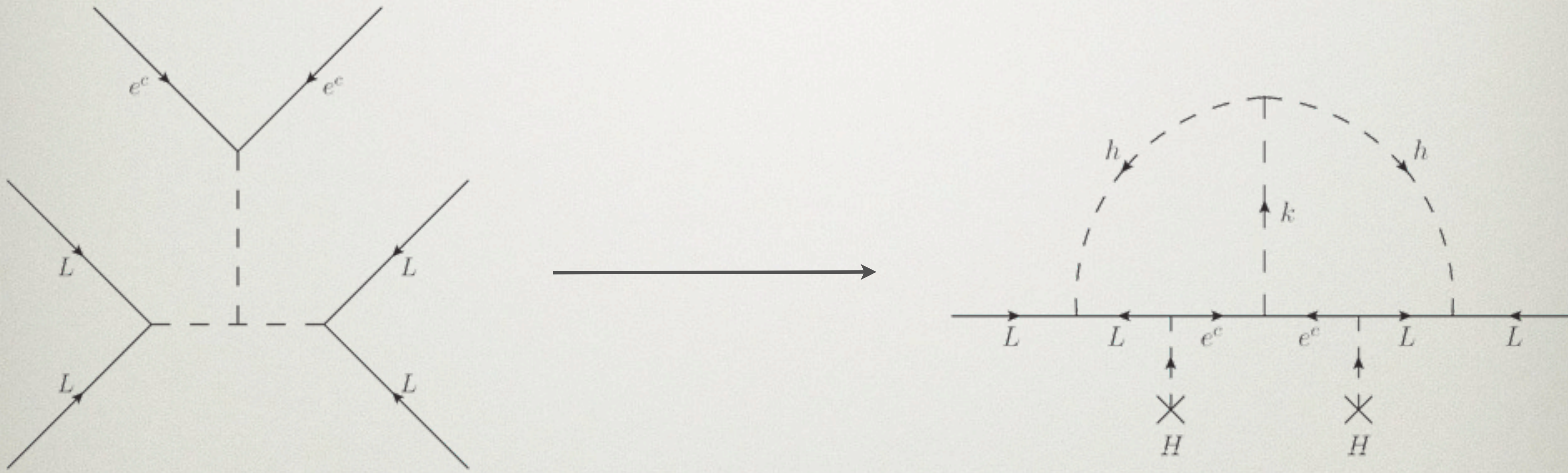
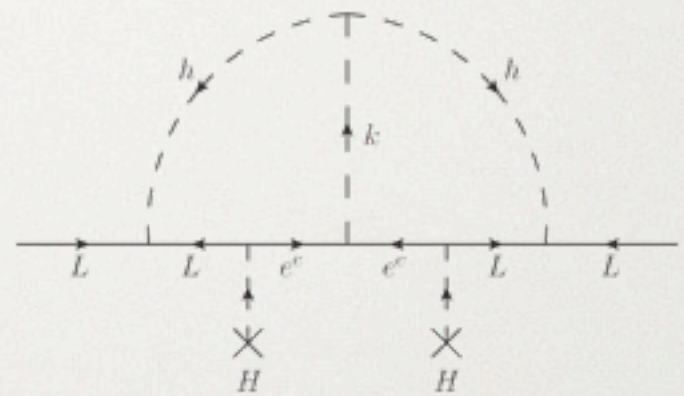


Close the excess fermion lines,
here using Higgs, and rearrange

Operators back to Models

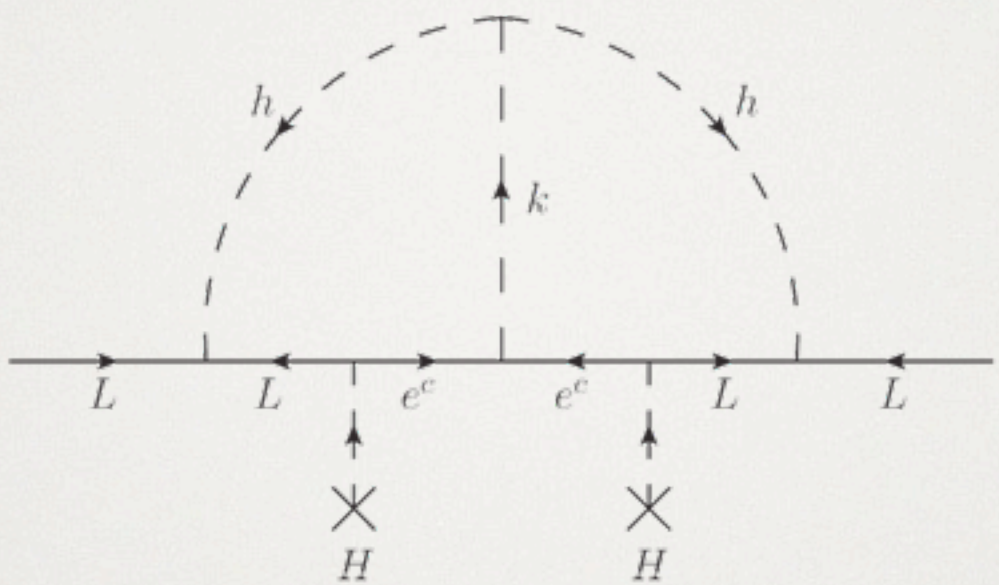
- Thus we have gone from an operator to a model:

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl} \longrightarrow$$



- A similar procedure can be used for any operator to create models involving either scalars or scalars and fermions in the UV completion.
- Incidentally the model generated here happens to be the Zee-Babu Model, which was known before the effective operators. Kenji Hamano and I are currently working on a ZBM search at ATLAS, so I'll say a few words on the status of this analysis.

The Zee-Babu Model



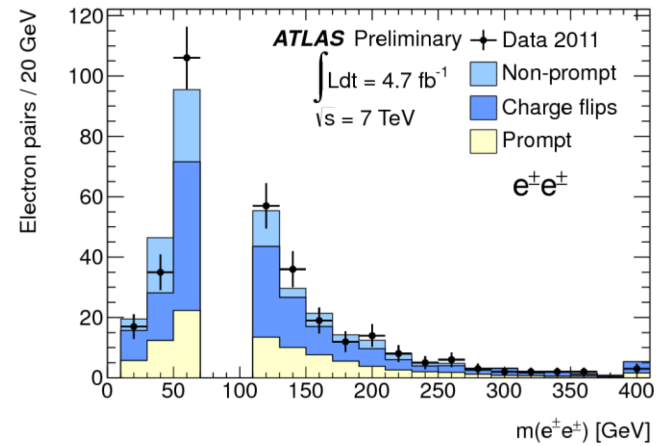
- The model introduces two new particles: singly charged h~(1,1,2) and doubly charged k~(1,1,4).
- Kenji and I have joined the same-sign dilepton analysis as it was determined this analysis can strongly constrain the k particle. The most up to date results from this analysis were presented at ICHEP and the limits (unfortunately no discovery) should be published shortly.
- We also have people working on a Type III Seesaw analysis and hope to have results out this year.
- Undoubtedly the LHC is a rich source of constraints on many of these models, especially leptonic analyses currently underway in exotics.

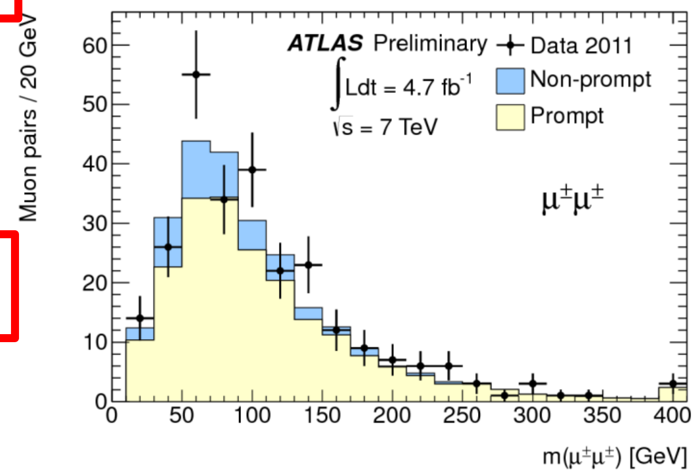
Like-sign incl: Results

Slide taken from Else Lytken's parallel talk at ICHEP

In bins of like-sign mass, using 4.7 fb^{-1}:

Sample	Number of electron pairs with $m(e^{\pm}e^{\pm})$				
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV	> 400 GeV
Prompt	93.6 ± 9.4	52.9 ± 5.7	13.6 ± 1.6	4.0 ± 0.6	1.3 ± 0.2
Non-prompt	75 ± 29	29 ± 12	6.0 ± 2.8	$0.6^{+1.0}_{-0.6}$	$0.0^{+0.2}_{-0.0}$
Charge flips and conversions	161 ± 25	86 ± 13	21.0 ± 3.5	7.9 ± 1.4	3.5 ± 0.8
Sum of backgrounds	330 ± 39	169 ± 19	40.6 ± 4.7	$12.4^{+1.8}_{-1.7}$	$4.8^{+0.9}_{-0.8}$
Data	329	171	38	10	3
	Number of muon pairs with $m(\mu^{\pm}\mu^{\pm})$				
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV	> 400 GeV
Prompt	205 ± 26	90 ± 11	21.8 ± 2.8	5.8 ± 0.9	2.2 ± 0.4
Non-prompt	42 ± 14	12.1 ± 4.6	1.0 ± 0.6	$0.0^{+0.3}_{-0.0}$	$0.0^{+0.3}_{-0.0}$
Charge flips	$0.0^{+4.9}_{-0.0}$	$0.0^{+2.5}_{-0.0}$	$0.0^{+1.8}_{-0.0}$	$0.0^{+1.7}_{-0.0}$	$0.0^{+1.7}_{-0.0}$
Sum of backgrounds	247^{+30}_{-29}	102 ± 12	$22.8^{+3.4}_{-2.9}$	$5.8^{+1.9}_{-0.9}$	$2.2^{+1.7}_{-0.4}$
Data	265	111	29	6	2





All mass bins consistent with SM only hypothesis

Conclusion

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- Effective operators provide a systematic way to approach neutrino mass, operating at the boundaries of both theory and experiment.
- Our group is contributing to that goal with the Type III Seesaw and ZBM LHC analyses and may ultimately move to look at other operators and models.
- But there are many more models left to analyse and this represents a great opportunity to use our involvement with the LHC, and also draw on many upcoming precision measurements.
- Ruling out other operators can indirectly give weight to favourable models like the Type I Seesaw or perhaps reveal nature isn't 'natural' as we thought.