ALCPG MEETING
SLAC 01/04

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LEPTON NUMBER VIOLATION IN $\gamma\gamma$-COLLIDERS - INITIAL THOUGHTS

- WHAT DO WE KNOW ABOUT LEPTON-NUMBER VIOLATION?
- NAIVE EXPECTATIONS FROM CURRENT NEUTRINO DATA.
  - NEUTRINO MASSES
  - NEUTRINOLESS DOUBLE-BETA DECAY
- "WORK-AROUNDS:" WHY THIS MAY TURN OUT TO BE INTERESTING.
- CONCLUDING REMARKS

WHAT DO WE KNOW ABOUT LEPTON-NUMBER VIOLATION?

- LEPTON NUMBER (L) IS AN ACCIDENTAL GLOBAL SYMMETRY OF THE "OLD S.M." [BEFORE ν-MASSES]. IT IS BROKEN BY NON-PERTURBATIVE ELECTROWEAK EFFECTS (VERY TINY!)

- THERE IS THE BELIEF THAT CONTINUOUS GLOBAL SYMMETRIES (LIKE B-L) ARE EVENTUALLY EXPLICITLY BROKEN IN A FUNDAMENTAL QUANTUM THEORY THAT INCLUDES GRAVITY.

- NEUTRINOS HAVE MASS !

  - INDIVIDUAL L_α NOT CONSERVED (EG, $\nu_\mu \to \nu_e$ TRANSITIONS)

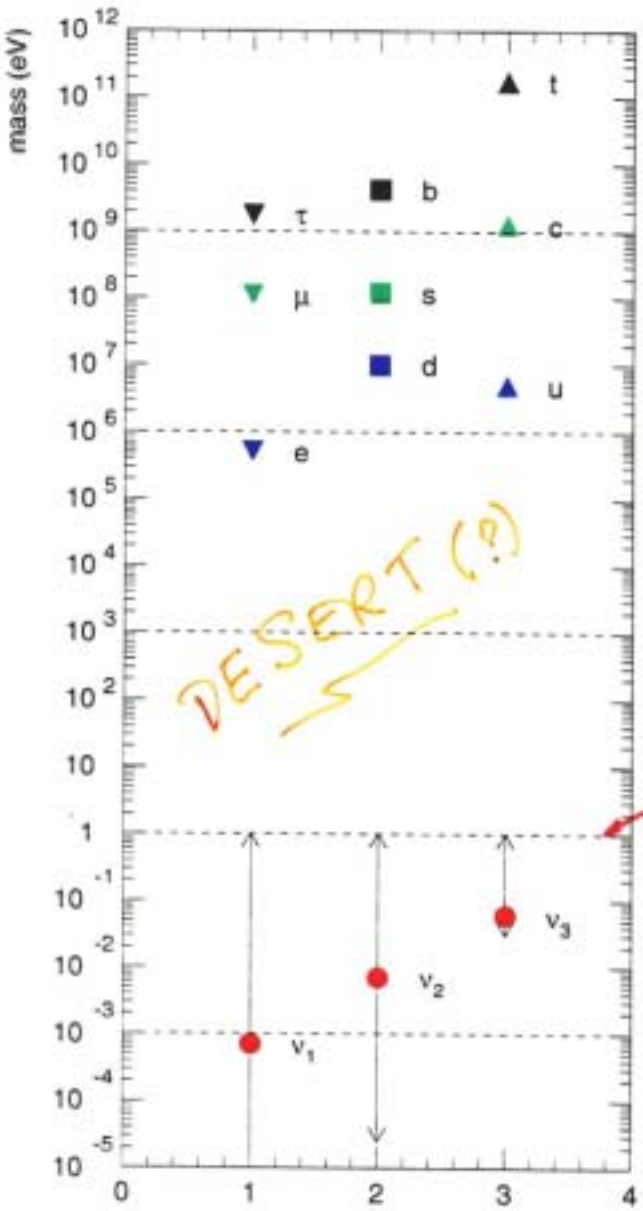
  - DO NEUTRINO MASSES VIOLATE L ? WE DO NOT KNOW,

HOWEVER

$$\mathcal{L}_{EFF} \supset -h_{\alpha\beta} \frac{L^\alpha H L^\beta H}{\Lambda} \Rightarrow$$

SIMPLEST, "NICEST" WAY TO SOLVE ν-MASS "PUZZLE"

NEUTRINO MASSES ARE REALLY TINY !



UPPER BOUND FROM OSCILLATIONS + TRITIUM BETA DECAY + COSMOLOGY (CONSERVATIVE)

NEW: WMAP : $\sum m_\nu < 0.7\,eV$

ARE THEY QUALITATIVELY DIFFERENT ?

- ARE ν MAJORANA FERMIONS?
- IS THE ORIGIN OF THEIR MASS DIFFERENT FROM Q, E MASSES ?

THE "HOLY GRAIL" OF LEPTONIC PHYSICS AND, ARGUABLY, ONE OF THE MOST FUNDAMENTAL ISSUES IN HEP. TODAY IS THE EXPERIMENTAL DETERMINATION OF LEPTON-NUMBER VIOLATION (OR NOT)

LINEAR COLLIDERS OFFER THE POSSIBILITY OF STUDYING, E.G.

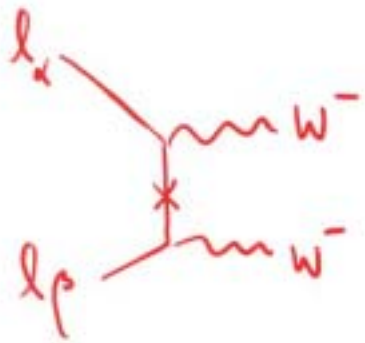
$$\boxed{\begin{array}{ll} e^-e^- \to W^-W^- & \\ e^-\gamma \to e^+W^-W^- & |\Delta L| = 2 \\ \gamma\gamma \to \ell^+\ell^+W^-W^- & \text{PROCESSES} \end{array}}$$

BUT IS THERE HOPE OF OBSERVING ANYTHING?

NAIVELY, <u>NO</u>

$$\mathcal{L} \supset \frac{(L_\alpha H)(L_\beta H)}{\Lambda} \frac{h^{\alpha\beta}}{2}$$

$$\boxed{m_\nu^{\alpha\beta} = h^{\alpha\beta} \frac{v^2}{\Lambda}}$$



$$A \propto \frac{m^{\alpha\beta}}{E}$$

"HELICITY SUPPRESSION"

$$\left.\frac{d\sigma}{d\cos\theta}\right|_{s \gg M_W^2,\, m^{\alpha\beta 2}} = \frac{g^4}{256\pi M_W^4} (m^{\alpha\beta})^2$$

PRD53, 6292 (1996)

$$\simeq 10^{-57}\ \mathrm{cm}^2 \simeq \boxed{10^{-21}\ \mathrm{fb} \left(\frac{m^{\alpha\beta}}{1\,\mathrm{eV}}\right)^2}$$

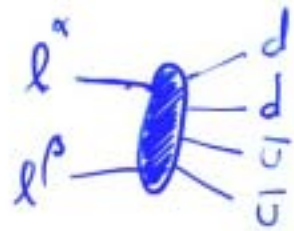
IN ORDER TO HAVE <u>ANY</u> <u>HOPE</u> OF OBSERVING ANYTHING WE NEED TO "DECOUPLE", AS MUCH AS POSSIBLE, THIS $\not{L}$ FROM THE NEUTRINO MASS.

NOTE THAT ONCE LEPTON NUMBER IS BROKEN NEUTRINOS WILL GET A MAJORANA MASS. IT NEED NOT HAPPEN AT LEADING ORDER...

ONE POSSIBILITY IS TO ASSUME THAT OTHER EFFECTIVE OPERATORS THAT MEDIATE $\Delta L = 2$ ARE, SOMEHOW DOMINANT:

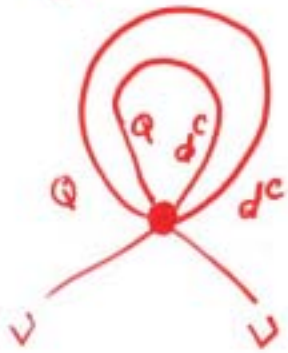
E.G.

$$\boxed{\mathcal{L}_q = h^{\alpha\beta} \frac{(L^\alpha L^\beta)(QQ)(d^c d^c)}{\Lambda^5}}$$



AT TREE LEVEL

$$m_{\alpha\beta} \sim h_{\alpha\beta} \frac{m_D^2}{\Lambda^5} \left(\frac{\Lambda^2}{16\pi^2}\right)^2$$



AT TWO-LOOPS

BABU, LEUNG NPB 619, 667 (2001)

Here i and j are $SU(2)_L$ indices, and $\bar{e^c}$ stands for either the hermitian conjugate or the Dirac adjoint of e^c. Any $\Delta L = 2$ effective operator will have one of these basic fermion bilinears accompanied by a product of other fields which is neutral under color and carries a net baryon number of zero. We classify the effective neutrino mass operators according to the number of fermion fields they contain. Three separate groups can be identified: (i) operators containing L^iL^j and no other fermion fields; (ii) operators containing four fermion fields; and (iii) operators containing six fermion fields. Operators containing four or more fermion bilinears have dimension 12 or higher and will not be considered here because, as mentioned above, the neutrino masses generated by such operators will be constrained by limits on lepton flavor violation to be typically much smaller than 0.03 eV and will not be that interesting for the current neutrino oscillation phenomenology. In case (i), neutrino masses will arise at tree level. In case (ii), one pair of fermion fields must be annihilated to generate neutrino masses, which will therefore arise at the one–loop level. And in case (iii), which requires the annihilation of two fermion pairs, neutrino masses will arise as two–loop radiative corrections.

(i) With L^iL^j not accompanied by any more fermion fields, one obtains the well–known dimension five operator for neutrino mass [6]:

$$\mathcal{O}_1 = L^iL^jH^kH^l\epsilon_{ik}\epsilon_{jl} \qquad \leftarrow \text{DIM } 5 \tag{3}$$

(ii) Operators with four fermion fields are:

$$\left.\begin{aligned}
\mathcal{O}_2 &= L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_3 &= \{L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl},\quad L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_4 &= \{L^iL^j\bar{Q}_i\bar{u^c}H^k\epsilon_{jk},\quad L^iL^j\bar{Q}_k\bar{u^c}H^k\epsilon_{ij}\}
\end{aligned}\right\} \text{DIM } 7$$

$$\left.\begin{aligned}
\mathcal{O}_5 &= L^iL^jQ^kd^cH^lH^m\bar{H}_i\epsilon_{jl}\epsilon_{km} \\
\mathcal{O}_6 &= L^iL^j\bar{Q}_k\bar{u^c}H^lH^k\bar{H}_i\epsilon_{jl} \\
\mathcal{O}_7 &= L^iQ^j\bar{e^c}\bar{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}
\end{aligned}\right\} \text{DIM } 9$$

$$\mathcal{O}_8 = L^i\bar{e^c}\bar{u^c}d^cH^j\epsilon_{ij} \qquad \text{-DIM } 7 \tag{4}$$

for the generation of neutrino masses. Nevertheless, we wish to list such $\Delta L = 2$ operators of the lowest dimension, which turns out to be 7. They are $(L^T\sigma_{\mu\nu}L)HHB^{\mu\nu}$, $(L^T\sigma_{\mu\nu}L)HHW^{\mu\nu}$, $(L^TCD_\mu D^\mu L)HH$, and $(\bar{e^c}\gamma_\mu D^\mu L)HHH$. Here $B^{\mu\nu}$ and $W^{\mu\nu}$ are the $U(1)_Y$ and $SU(2)_L$ field strength tensors and we have suppressed the $SU(2)_L$ indices for simplicity. Although we have only shown operators with the covariant derivative acting on a specific field, it is understood that one should include similar operators with the covariant derivative acting on the other fields. For example, the third operator listed above includes $(L^TCL)(D_\mu H)(D^\mu H)$, and the fourth operator includes $(\bar{e^c}\gamma_\mu L)(D^\mu H)HH$, and so on.

(iii) We now proceed to write down the operators with six fermion fields through dimension 11. The procedure we follow is analogous to the case of the operators containing four fermion fields. There are 12 such operators at the dimension 9 level:

$$
\begin{aligned}
\mathcal{O}_9 &= L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_{10} &= L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_{11} &= \{L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl},\ \ L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_{12} &= \{L^iL^j\bar{Q}_i\bar{u^c}\bar{Q}_j\bar{u^c},\ \ L^iL^j\bar{Q}_k\bar{u^c}\bar{Q}_l\bar{u^c}\epsilon_{ij}\epsilon^{kl}\} \\
\mathcal{O}_{13} &= L^iL^j\bar{Q}_i\bar{u^c}L^le^c\epsilon_{jl} \\
\mathcal{O}_{14} &= \{L^iL^j\bar{Q}_k\bar{u^c}Q^kd^c\epsilon_{ij},\ \ L^iL^j\bar{Q}_i\bar{u^c}Q^ld^c\epsilon_{jl}\} \\
\mathcal{O}_{15} &= L^iL^jL^kd^c\bar{L}_i\bar{u^c}\epsilon_{jk} \\
\mathcal{O}_{16} &= L^iL^je^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{17} &= L^iL^jd^cd^c\bar{d^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{18} &= L^iL^jd^cu^c\bar{u^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{19} &= L^iQ^jd^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{20} &= L^id^c\bar{Q}_i\bar{u^c}\bar{e^c}\bar{u^c}
\end{aligned}
\tag{7}
$$

And there are 40 operators with $d = 11$:

$$\mathcal{O}_{21} = \{L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln}, \quad L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{il}\epsilon_{jm}\epsilon_{kn}\}$$

$$\mathcal{O}_{22} = L^i L^j L^k e^c \bar{L}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm}$$

$$\mathcal{O}_{23} = L^i L^j L^k e^c \bar{Q}_k \bar{d}^c H^l H^m \epsilon_{il}\epsilon_{jm}$$

$$\mathcal{O}_{24} = \{L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{jk}\epsilon_{lm}, \quad L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{jm}\epsilon_{kl}\}$$

$$\mathcal{O}_{25} = L^i L^j Q^k d^c Q^l u^c H^m H^n \epsilon_{im}\epsilon_{jn}\epsilon_{kl}$$

$$\mathcal{O}_{26} = \{L^i L^j Q^k d^c \bar{L}_i \bar{e}^c H^l H^m \epsilon_{jl}\epsilon_{km}, \quad L^i L^j Q^k d^c \bar{L}_k \bar{e}^c H^l H^m \epsilon_{il}\epsilon_{jm}\}$$

$$\mathcal{O}_{27} = \{L^i L^j Q^k d^c \bar{Q}_i \bar{d}^c H^l H^m \epsilon_{jl}\epsilon_{km}, \quad L^i L^j Q^k d^c \bar{Q}_k \bar{d}^c H^l H^m \epsilon_{il}\epsilon_{jm}\}$$

$$\mathcal{O}_{28} = \{L^i L^j Q^k d^c \bar{Q}_j \bar{u}^c H^l \bar{H}_i \epsilon_{kl}, \quad L^i L^j Q^k d^c \bar{Q}_k \bar{u}^c H^l \bar{H}_i \epsilon_{jl},$$
$$L^i L^j Q^k d^c \bar{Q}_l \bar{u}^c H^l \bar{H}_i \epsilon_{jk}\}$$

$$\mathcal{O}_{29} = \{L^i L^j Q^k u^c \bar{Q}_k \bar{u}^c H^l H^m \epsilon_{il}\epsilon_{jm}, \quad L^i L^j Q^k u^c \bar{Q}_l \bar{u}^c H^l H^m \epsilon_{ik}\epsilon_{jm}\}$$

$$\mathcal{O}_{30} = \{L^i L^j \bar{L}_i \bar{e}^c \bar{Q}_k \bar{u}^c H^k H^l \epsilon_{jl}, \quad L^i L^j \bar{L}_m \bar{e}^c \bar{Q}_n \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}\}$$

$$\mathcal{O}_{31} = \{L^i L^j \bar{Q}_i \bar{d}^c \bar{Q}_k \bar{u}^c H^k H^l \epsilon_{jl}, \quad L^i L^j \bar{Q}_m \bar{d}^c \bar{Q}_n \bar{u}^c H^k H^l \epsilon_{ik}\epsilon_{jl}\epsilon^{mn}\}$$

$$\mathcal{O}_{32} = \{L^i L^j \bar{Q}_j \bar{u}^c \bar{Q}_k \bar{u}^c H^k \bar{H}_i, \quad L^i L^j \bar{Q}_m \bar{u}^c \bar{Q}_n \bar{u}^c H^k \bar{H}_i \epsilon_{jk}\epsilon^{mn}\}$$

$$\mathcal{O}_{33} = \bar{e}^c \bar{e}^c L^i L^j e^c e^c H^k H^l \epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{34} = \bar{e}^c \bar{e}^c L^i Q^j e^c d^c H^k H^l \epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{35} = \bar{e}^c \bar{e}^c L^i e^c \bar{Q}_j \bar{u}^c H^j H^k \epsilon_{ik}$$

$$\mathcal{O}_{36} = \bar{e}^c \bar{e}^c Q^i d^c Q^j d^c H^k H^l \epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{37} = \bar{e}^c \bar{e}^c Q^i d^c \bar{Q}_j \bar{u}^c H^j H^k \epsilon_{ik}$$

$$\mathcal{O}_{38} = \bar{e}^c \bar{e}^c \bar{Q}_i \bar{u}^c \bar{Q}_j \bar{u}^c H^i H^j$$

$$\mathcal{O}_{39} = \{L^i L^j L^k L^l \bar{L}_i \bar{L}_j H^m H^n \epsilon_{jm}\epsilon_{kl}, \quad L^i L^j L^k L^l \bar{L}_m \bar{L}_n H^m H^n \epsilon_{ij}\epsilon_{kl},$$
$$L^i L^j L^k L^l \bar{L}_i \bar{L}_m H^m H^n \epsilon_{jk}\epsilon_{ln}, \quad L^i L^j L^k L^l \bar{L}_p \bar{L}_q H^m H^n \epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}\}$$

$$\mathcal{O}_{40} = \{L^i L^j L^k Q^l \bar{L}_i \bar{Q}_j H^m H^n \epsilon_{km}\epsilon_{ln}, \quad L^i L^j L^k Q^l \bar{L}_i \bar{Q}_l H^m H^n \epsilon_{jm}\epsilon_{kn},$$
$$L^i L^j L^k Q^l \bar{L}_l \bar{Q}_i H^m H^n \epsilon_{jm}\epsilon_{kn}, \quad L^i L^j L^k Q^l \bar{L}_i \bar{Q}_m H^m H^n \epsilon_{jk}\epsilon_{ln},$$
$$L^i L^j L^k Q^l \bar{L}_i \bar{Q}_m H^m H^n \epsilon_{jl}\epsilon_{kn}, \quad L^i L^j L^k Q^l \bar{L}_m \bar{Q}_i H^m H^n \epsilon_{jk}\epsilon_{ln},$$

$$L^iL^jL^kQ^l\bar{L}_m\bar{Q}_iH^mH^n\epsilon_{jl}\epsilon_{kn}, \quad L^iL^jL^kQ^l\bar{L}_m\bar{Q}_nH^mH^n\epsilon_{ij}\epsilon_{kl},$$

$$L^iL^jL^kQ^l\bar{L}_m\bar{Q}_nH^pH^q\epsilon_{ip}\epsilon_{jq}\epsilon_{kl}\epsilon^{mn}, \quad L^iL^jL^kQ^l\bar{L}_m\bar{Q}_nH^pH^q\epsilon_{ip}\epsilon_{lq}\epsilon_{jk}\epsilon^{mn}\}$$

$$\mathcal{O}_{41} = \{L^iL^jL^kd^c\bar{L}_i\bar{d}^cH^lH^m\epsilon_{jl}\epsilon_{km}, \quad L^iL^jL^kd^c\bar{L}_l\bar{d}^cH^lH^m\epsilon_{ij}\epsilon_{km}\}$$

$$\mathcal{O}_{42} = \{L^iL^jL^ku^c\bar{L}_i\bar{u}^cH^lH^m\epsilon_{jl}\epsilon_{km}, \quad L^iL^jL^ku^c\bar{L}_l\bar{u}^cH^lH^m\epsilon_{ij}\epsilon_{km}\}$$

$$\mathcal{O}_{43} = \{L^iL^jL^kd^c\bar{L}_l\bar{u}^cH^l\bar{H}_i\epsilon_{jk}, \quad L^iL^jL^kd^c\bar{L}_j\bar{u}^cH^l\bar{H}_i\epsilon_{kl},$$

$$L^iL^jL^kd^c\bar{L}_l\bar{u}^cH^m\bar{H}_n\epsilon_{ij}\epsilon_{km}\epsilon^{ln}\}$$

$$\mathcal{O}_{44} = \{L^iL^jQ^ke^c\bar{Q}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}, \quad L^iL^jQ^ke^c\bar{Q}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm},$$

$$L^iL^jQ^ke^c\bar{Q}_l\bar{e}^cH^lH^m\epsilon_{ij}\epsilon_{km}, \quad L^iL^jQ^ke^c\bar{Q}_l\bar{e}^cH^lH^m\epsilon_{ik}\epsilon_{jm}\}$$

$$\mathcal{O}_{45} = L^iL^je^cd^c\bar{e}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{46} = L^iL^je^cu^c\bar{e}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{47} = \{L^iL^jQ^kQ^l\bar{Q}_i\bar{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}, \quad L^iL^jQ^kQ^l\bar{Q}_i\bar{Q}_kH^mH^n\epsilon_{jm}\epsilon_{ln},$$

$$L^iL^jQ^kQ^l\bar{Q}_k\bar{Q}_lH^mH^n\epsilon_{im}\epsilon_{jn}, \quad L^iL^jQ^kQ^l\bar{Q}_i\bar{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln},$$

$$L^iL^jQ^kQ^l\bar{Q}_i\bar{Q}_mH^mH^n\epsilon_{jn}\epsilon_{kl}, \quad L^iL^jQ^kQ^l\bar{Q}_k\bar{Q}_mH^mH^n\epsilon_{ij}\epsilon_{ln},$$

$$L^iL^jQ^kQ^l\bar{Q}_k\bar{Q}_mH^mH^n\epsilon_{il}\epsilon_{jn}, \quad L^iL^jQ^kQ^l\bar{Q}_p\bar{Q}_qH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$$

$$L^iL^jQ^kQ^l\bar{Q}_p\bar{Q}_qH^mH^n\epsilon_{ik}\epsilon_{jm}\epsilon_{ln}\epsilon^{pq}, \quad L^iL^jQ^kQ^l\bar{Q}_p\bar{Q}_qH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}\epsilon^{pq}\}$$

$$\mathcal{O}_{48} = L^iL^jd^cd^c\bar{d}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{49} = L^iL^jd^cu^c\bar{d}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{50} = L^iL^jd^cd^c\bar{d}^c\bar{u}^cH^k\bar{H}_i\epsilon_{jk}$$

$$\mathcal{O}_{51} = L^iL^ju^cu^c\bar{u}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{52} = L^iL^jd^cu^c\bar{u}^c\bar{u}^cH^k\bar{H}_i\epsilon_{jk}$$

$$\mathcal{O}_{53} = L^iL^jd^cd^c\bar{u}^c\bar{u}^c\bar{H}_i\bar{H}_j$$

$$\mathcal{O}_{54} = \{L^iQ^jQ^kd^c\bar{Q}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}, \quad L^iQ^jQ^kd^c\bar{Q}_j\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{km},$$

$$L^iQ^jQ^kd^c\bar{Q}_l\bar{e}^cH^lH^m\epsilon_{im}\epsilon_{jk}, \quad L^iQ^jQ^kd^c\bar{Q}_l\bar{e}^cH^lH^m\epsilon_{ij}\epsilon_{km}\}$$

$$\mathcal{O}_{55} = \{L^iQ^j\bar{Q}_i\bar{Q}_k\bar{e}^c\bar{u}^cH^kH^l\epsilon_{jl}, \quad L^iQ^j\bar{Q}_j\bar{Q}_k\bar{e}^c\bar{u}^cH^kH^l\epsilon_{il},$$

$$L^i Q^j \bar{Q}_m \bar{Q}_n \bar{e}^c \bar{u}^c H^k H^l \epsilon_{ik} \epsilon_{jl} \epsilon^{mn}\}$$

$$\mathcal{O}_{56} = L^i Q^j d^c d^c \bar{e}^c \bar{d}^c H^k H^l \epsilon_{ik} \epsilon_{jl}$$

$$\mathcal{O}_{57} = L^i d^c \bar{Q}_j \bar{u}^c \bar{e}^c \bar{d}^c H^j H^k \epsilon_{ik}$$

$$\mathcal{O}_{58} = L^i u^c \bar{Q}_j \bar{u}^c \bar{e}^c \bar{u}^c H^j H^k \epsilon_{ik}$$

$$\mathcal{O}_{59} = L^i Q^j d^c d^c \bar{e}^c \bar{u}^c H^k \bar{H}_i \epsilon_{jk}$$

$$\mathcal{O}_{60} = L^i d^c \bar{Q}_j \bar{u}^c \bar{e}^c \bar{u}^c H^j \bar{H}_i \tag{8}$$

III. RENORMALIZABLE MODELS OF NEUTRINO MASS

The classification of the effective $\Delta L = 2$ operators given in the previous section can be quite useful in building renormalizable models of neutrino mass. We shall describe in this section how to systematically identify from these operators interesting neutrino mass models. We will see that this method reproduces several well–known models. More interestingly, many new models of neutrino mass will be uncovered. While we will not present an exhaustive discussion of all these new models, we will outline the most interesting features for neutrino mass and phenomenology in several of these models.

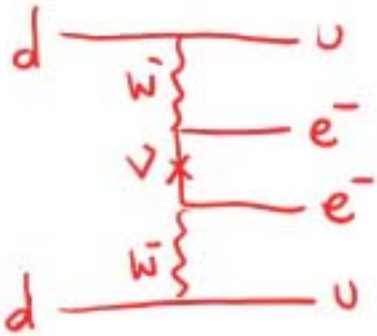
A. Tree–level neutrino mass models

The operator $\mathcal{O}_1$ of Eq. (3) can generate small neutrino masses at tree level. The simplest way to induce $\mathcal{O}_1$ is by the seesaw mechanism. As shown in Fig. 1, $\mathcal{O}_1$ will result after the heavy fields $N_{1,3}$ are integrated out. Here N_1 denotes the familiar $SU(2)_L$ singlet right–handed neutrinos. It is also possible to induce $\mathcal{O}_1$ using N_3, which are $SU(2)_L$ triplets and have zero hypercharge [9].

In Fig. 2, we show an alternate way of inducing $\mathcal{O}_1$ by the exchange of an $SU(2)_L$ triplet scalar Φ_3 which carries $Y = +1$. The neutral component of Φ_3 will receive an induced vacuum expectation value (VEV) through its trilinear coupling with the Standard Model Higgs doublet. This is sometimes referred to as the Type II seesaw mechanism [10], which

FINAL WORRY: NEUTRINOLESS DOUBLE BETA DECAY

IN MINIMAL SCENARIO



$m_{ee} \lesssim 1\,eV$

BUT ALSO OCCURS AT TREE-LEVEL WITH $\mathcal{L}_q$:

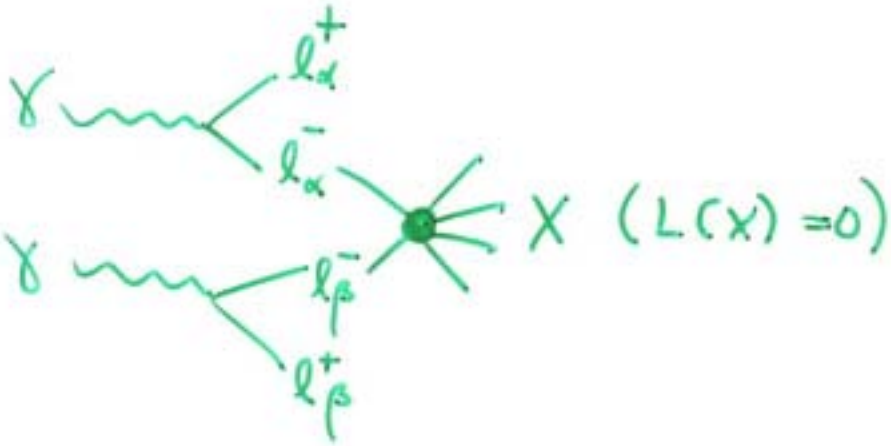
$\rightsquigarrow$ REALLY STRONG CONSTRAINT ON Λ !

ONE SHOULD ALSO "AVOID" PROCESS WITH

1ST GENERATION INITIAL STATES AND FINAL STATES

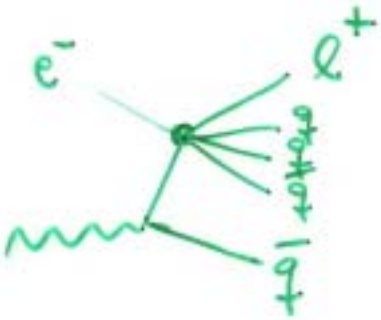
$\Rightarrow$ PROBLEM FOR e^-e^- SCATTERING !

HENCE



$$\boxed{\gamma\gamma \to \ell_\alpha^+ \ell_\beta^+ X \qquad \alpha \text{ OR } \beta \neq e}$$

OR



$$\boxed{e^-\gamma \to \ell^+ X \qquad \ell \neq e}$$

MIGHT TURN OUT TO BE

"OBSERVABLE" AND IN AGREEMENT

WITH CURRENT CONSTRAINTS! (?)

SUMMARY

- EXPERIMENTALLY ESTABLISHING $\not{L}$ IS OF THE UTMOST IMPORTANCE $\Rightarrow$ LOOK FOR IT "EVERYWHERE"

- IN A COLLIDER ENVIRONMENT $\not{L}$ DIRECTLY RELATED TO NEUTRINO MASSES IS HOPELESSLY SMALL !

- FURTHERMORE, CONSTRAINTS FROM $0\nu\beta\beta$ PROBABLY TELL US THAT WE SHOULD LOOK IN THE $\ell_\alpha^- \ell_\beta^- \to X$ CHANNEL α OR $\beta \neq e$

- THERE ARE WAYS OF "DELAYING" NEUTRINO MASSES, WHILE THE COLLIDER SIGNAL HAPPENS AT TREE-LEVEL $\Rightarrow$ HOPE?

WARNING: THESE ARE JUST ROUGH THOUGHTS THAT MAY OR MAY NOT TURN OUT TO BE INTERESTING! (ROUGH THOUGHT $\equiv$ PRE-WORK IN PROGRESS)