

# What is the Energy Scale of the Physics Responsible for Neutrino Masses?

*André de Gouvêa*

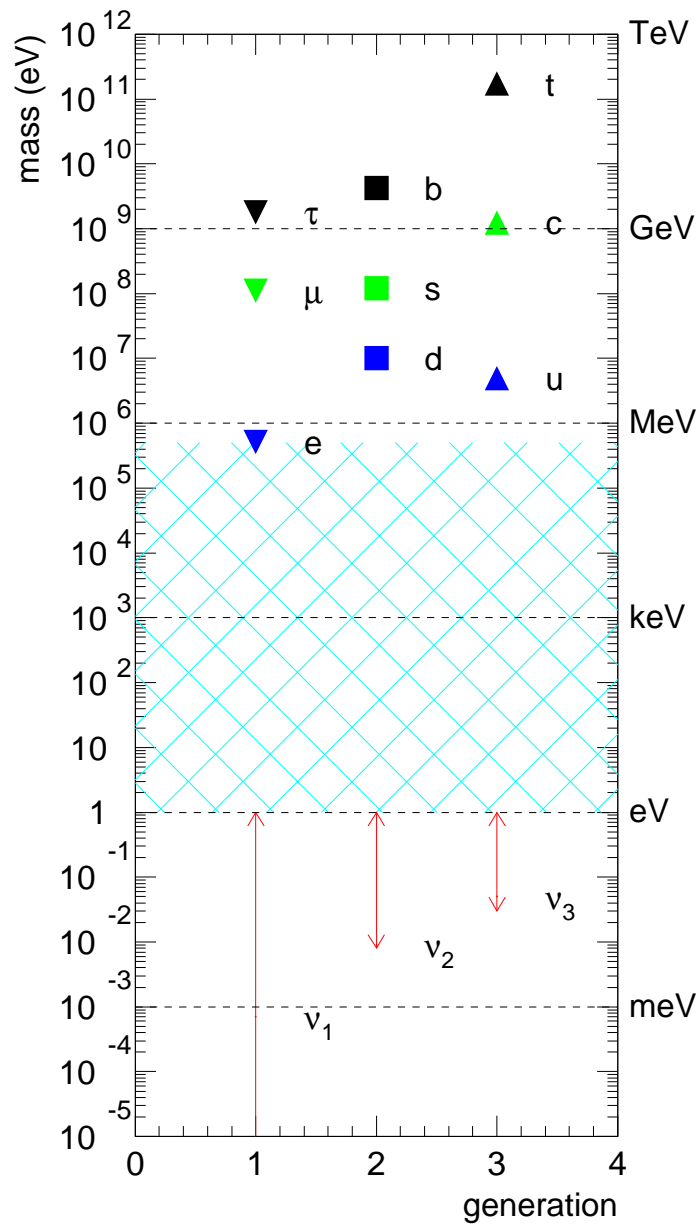
*Northwestern University*

*Neutrino Frontiers*

*University of Minnesota, October 23–26, 2008*

## Outline

1. What We Are Trying to Understand;
2. Why Are Neutrino Masses Small?;
3. Concrete Example – the Seesaw Mechanism: Three Avenues Toward Tiny Neutrino Masses, with Consequences;
4. A Fourth Avenue: Neutrino Masses from Involved  $\Delta L = 2$  New Physics (Loops);



## What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **LEPTON MIXING IS “WEIRD”** ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

**What Does It Mean?**

## What is the New Standard Model? [ $\nu$ SM]

The short answer is – WE DON'T KNOW. Not enough available info!



Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the  $\nu$ SM candidates can do. [are they falsifiable?, are they “simple”?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

## Candidate $\nu$ SM: The One I'll Concentrate On

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\text{SM}} \supset -y_{ij} \frac{L^i H L^j H}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If mass of new physics  $\gg 1$  TeV, it leads to only one observable consequence...

$$\text{after EWSB: } \mathcal{L}_{\nu\text{SM}} \supset \frac{m_{ij}}{2} \nu^i \nu^j; \quad m_{ij} = y_{ij} \frac{v^2}{\Lambda}.$$

- Neutrino masses are small:  $\Lambda \gg v \rightarrow m_\nu \ll m_f$  ( $f = e, \mu, u, d$ , etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- $\nu$ SM effective theory – not valid for energies above *at most*  $\Lambda/y$ .
- Define  $y_{\text{max}} \equiv 1 \Rightarrow$  data require  $\Lambda \sim 10^{14}$  GeV.

What else is this “good for”? Depends on the ultraviolet completion!

## The Seesaw Lagrangian

A simple<sup>a</sup>, renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\text{old}} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^3 \frac{M_i}{2} N^i N^i + H.c.,$$

where  $N_i$  ( $i = 1, 2, 3$ , for concreteness) are SM gauge singlet fermions.  $\mathcal{L}_\nu$  is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the  $N_i$  fields.

After electroweak symmetry breaking,  $\mathcal{L}_\nu$  describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos**.

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<sup>a</sup>Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

## To be determined from data: $\lambda$ and $M$ .

The data can be summarized as follows: there is evidence for three neutrinos, mostly “active” (linear combinations of  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ ). At least two of them are massive and, if there are other neutrinos, they have to be “sterile.”

This provides very little information concerning the magnitude of  $M_i$  (assume  $M_1 \sim M_2 \sim M_3$ ).

Theoretically, there is prejudice in favor of very large  $M$ :  $M \gg v$ . Popular examples include  $M \sim M_{\text{GUT}}$  (GUT scale), or  $M \sim 1 \text{ TeV}$  (EWSB scale).

Furthermore,  $\lambda \sim 1$  translates into  $M \sim 10^{14} \text{ GeV}$ , while thermal leptogenesis requires the lightest  $M_i$  to be around  $10^{10} \text{ GeV}$ .

we can impose very, very few experimental constraints on  $M$

## What We Know About $M$ :

- $M = 0$ : the six neutrinos “fuse” into three Dirac states. Neutrino mass matrix given by  $\mu_{\alpha i} \equiv \lambda_{\alpha i} \nu$ .

The symmetry of  $\mathcal{L}_\nu$  is enhanced:  $U(1)_{B-L}$  is an exact global symmetry of the Lagrangian if all  $M_i$  vanish. Small  $M_i$  values are 'tHooft natural.

- $M \gg \mu$ : the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by  $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$   $[m \propto 1/\Lambda \Rightarrow \Lambda = M/\mu^2]$ .

This the **seesaw mechanism**. Neutrinos are Majorana fermions.

Lepton number is not a good symmetry of  $\mathcal{L}_\nu$ , even though  $L$ -violating effects are hard to come by.

- $M \sim \mu$ : six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).



## Why are Neutrino Masses Small in the $M \neq 0$ Case?

If  $\mu \ll M$ , below the mass scale  $M$ ,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

Neutrino masses are small if  $\Lambda \gg \langle H \rangle$ . Data require  $\Lambda \sim 10^{14}$  GeV.

In the case of the seesaw,

$$\Lambda \sim \frac{M}{\lambda^2},$$

so neutrino masses are small if either

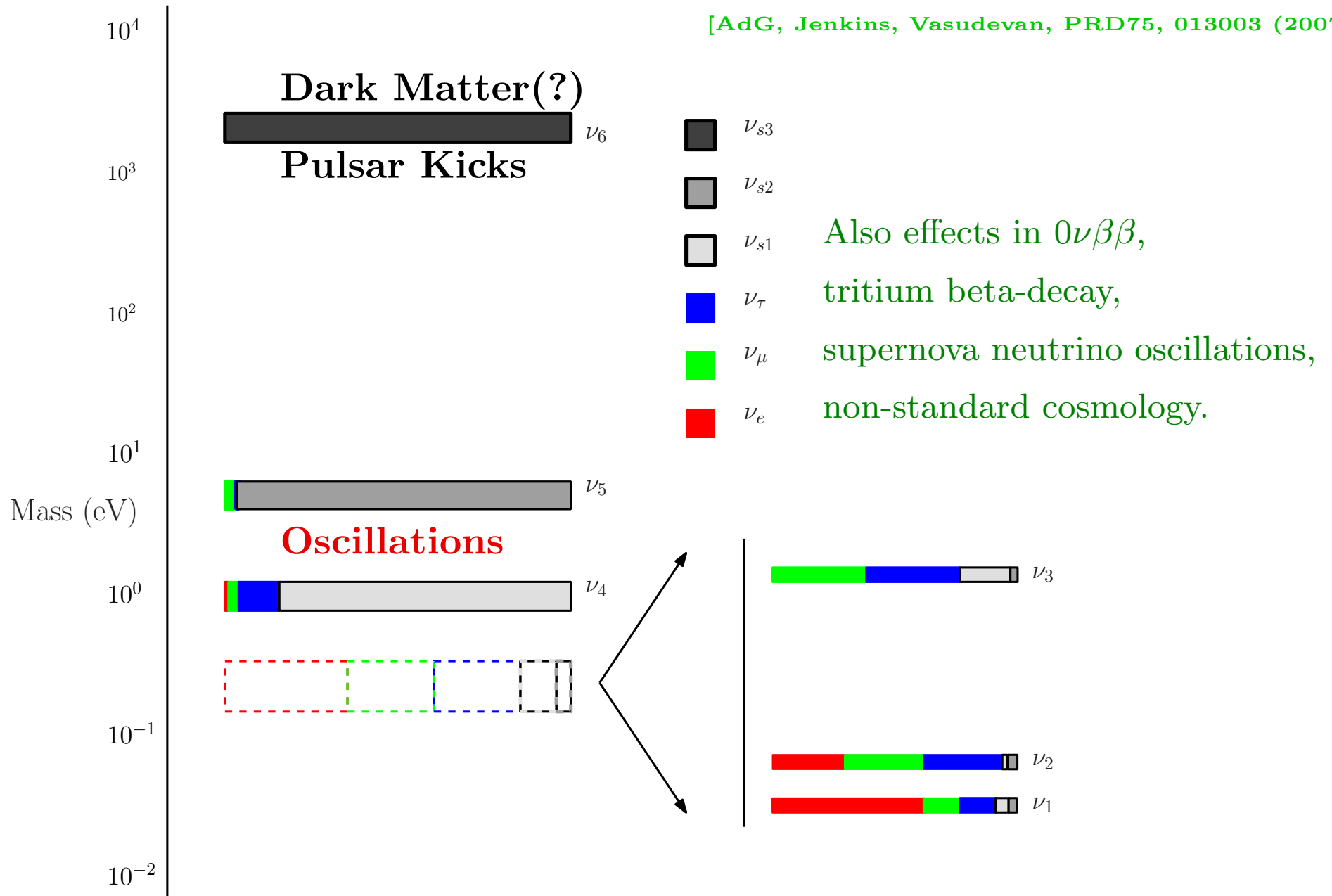
- they are generated by physics at a very high energy scale  $M \gg v$  (high-energy seesaw); **or**
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); **or**
- cancellations among different contributions render neutrino masses accidentally small (“fine-tuning”).

## Low-Energy Seesaw [AdG PRD72,033005]

The other end of the  $M$  spectrum ( $M < 100$  GeV). What do we get?

- Neutrino masses are small because the Yukawa couplings are very small  $\lambda \in [10^{-6}, 10^{-11}]$ ;
- No standard thermal leptogenesis – right-handed neutrinos way too light;
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos  $\Rightarrow$  sterile neutrinos associated with the fact that the active neutrinos have mass;
- sterile–active mixing can be predicted – hypothesis is falsifiable!
- Small values of  $M$  are natural (in the ‘tHooft sense). In fact, theoretically, no value of  $M$  should be discriminated against!

[AdG, Jenkins, Vasudevan, PRD75, 013003 (2007)]



## Predictions: Neutrinoless Double-Beta Decay

The exchange of Majorana neutrinos mediates lepton-number violating neutrinoless double-beta decay,  $0\nu\beta\beta$ :  $Z \rightarrow (Z + 2)e^-e^-$ .

For light enough neutrinos, the amplitude for  $0\nu\beta\beta$  is proportional to the effective neutrino mass

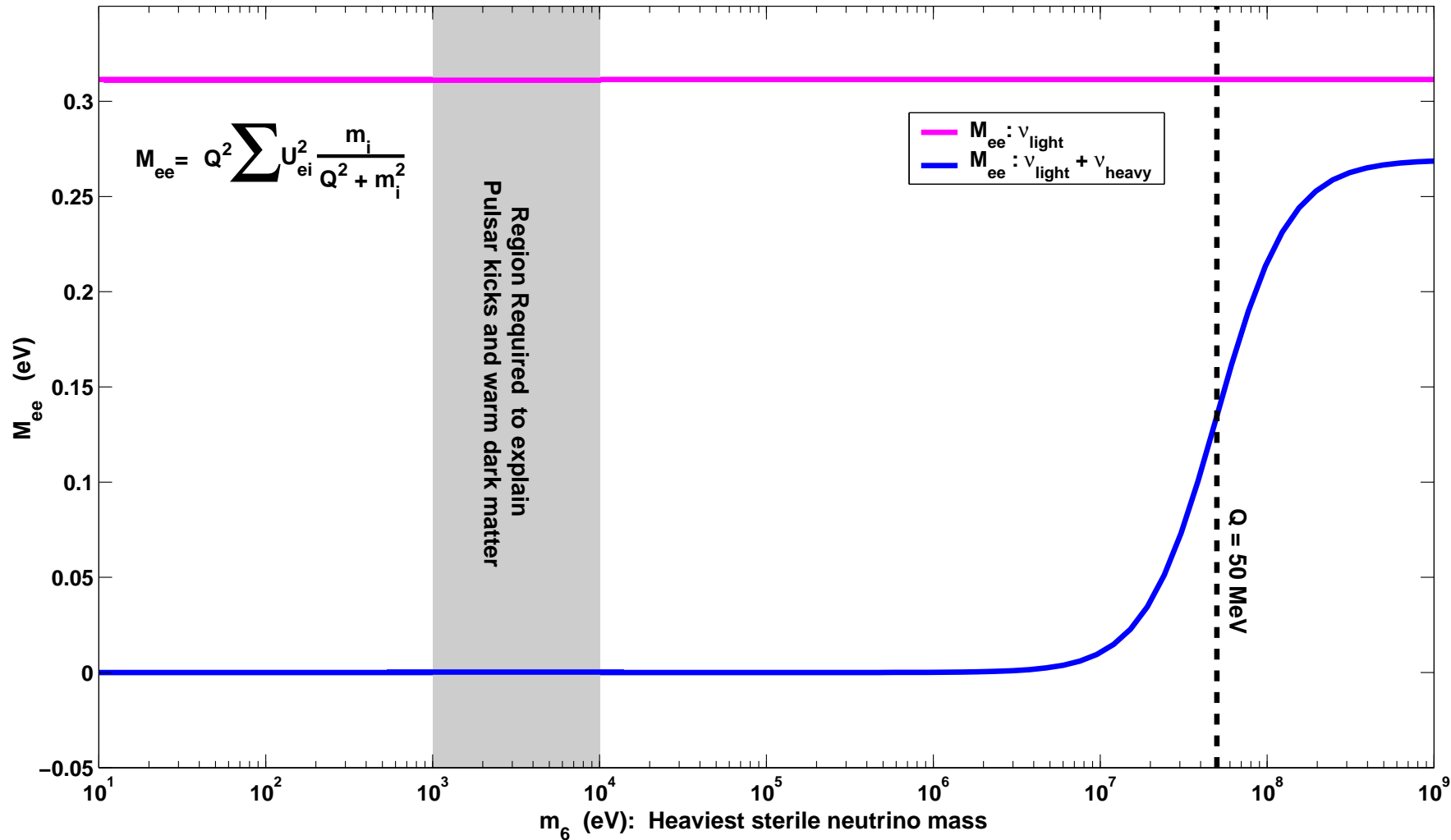
$$m_{ee} = \left| \sum_{i=1}^6 U_{ei}^2 m_i \right| \sim \left| \sum_{i=1}^3 U_{ei}^2 m_i + \sum_{i=1}^3 \vartheta_{ei}^2 M_i \right|.$$

However, upon further examination,  $m_{ee} = 0$  in the eV-seesaw. **The contribution of light and heavy neutrinos exactly cancels!** This seems to remain true to a good approximation as long as  $M_i \ll 1$  MeV.

$$\left[ \mathcal{M} = \begin{pmatrix} 0 & \mu^T \\ \mu & M \end{pmatrix} \rightarrow m_{ee} \text{ is identically zero!} \right]$$

# (lack of) sensitivity in $0\nu\beta\beta$ due to seesaw sterile neutrinos

[AdG, Jenkins, Vasudevan, hep-ph/0608147]



## Fourth Avenue: Higher Order Neutrino Masses from $\Delta L = 2$ Physics.

Imagine that there is **new physics that breaks lepton number by 2 units** at some energy scale  $\Lambda$ , but that it does not, in general, lead to neutrino masses **at the tree level**.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

For example:

- SUSY with trilinear R-parity violation – neutrino masses at one-loop;
- Zee model – neutrino masses at one-loop;
- Babu and Ma – neutrino masses at two loops;
- Chen, *et al.* 0706.1964 – neutrino masses at two loops;
- etc

André de Gouvêa  
AdG, Jenkins,  
0708.1344 [hep-ph]

## Effective Operator Approach

(there are 129  
of them if you  
discount different  
Lorentz structures!)

classified by Babu  
and Leung in  
NPB619,667(2001)

October 23, 2008

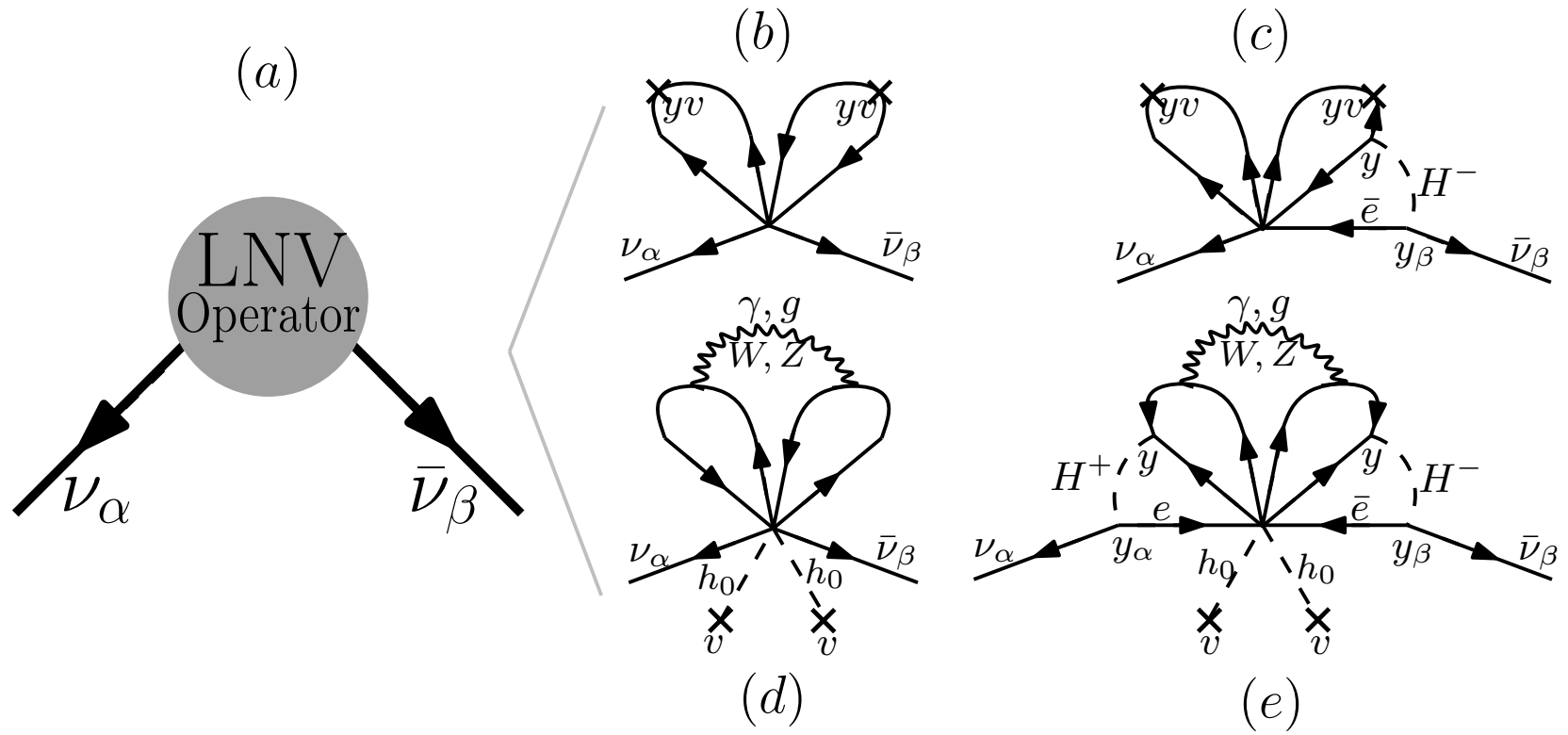
13	$L^i L^j \bar{Q}_i \bar{u}^c L^l e^c \epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$2 \times 10^5$	$\beta\beta\nu$
14 <sub>a</sub>	$L^i L^j \bar{Q}_k \bar{u}^c Q^k d^c \epsilon_{ij}$	$\frac{y_d y_u g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^3$	Northwest $\beta\beta\nu$
14 <sub>b</sub>	$L^i L^j \bar{Q}_i \bar{u}^c Q^l d^c \epsilon_{jl}$	$\frac{y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$6 \times 10^5$	$\beta\beta\nu$
15	$L^i L^j L^k d^c \bar{L}_i \bar{u}^c \epsilon_{jkl}$	$\frac{y_d y_u g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^3$	$\beta\beta\nu$
16	$L^i L^j e^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij}$	$\frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda}$	2	$\beta\beta\nu$ , LHC
17	$L^i L^j d^c d^c \bar{d}^c \bar{u}^c \epsilon_{ij}$	$\frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda}$	2	$\beta\beta\nu$ , LHC
18	$L^i L^j d^c u^c \bar{u}^c \bar{u}^c \epsilon_{ij}$	$\frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda}$	2	$\beta\beta\nu$ , LHC
19	$L^i Q^j d^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij}$	$y_\ell y_\beta \frac{y_d^2 y_u}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	1	$\beta\beta\nu$ , HEInν, LHC, m
20	$L^i d^c \bar{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c$	$y_\ell y_\beta \frac{y_d y_u^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	40	$\beta\beta\nu$ , mix
21 <sub>a</sub>	$L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{ij} \epsilon_{km} \epsilon_{ln}$	$\frac{y_\ell y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$2 \times 10^3$	$\beta\beta\nu$
21 <sub>b</sub>	$L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{il} \epsilon_{jm} \epsilon_{kn}$	$\frac{y_\ell y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$2 \times 10^3$	$\beta\beta\nu$
22	$L^i L^j L^k e^c \bar{L}_k \bar{e}^c H^l H^m \epsilon_{il} \epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^4$	$\beta\beta\nu$
23	$L^i L^j L^k e^c \bar{Q}_k \bar{d}^c H^l H^m \epsilon_{il} \epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	40	$\beta\beta\nu$
24 <sub>a</sub>	$L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{jkl} \epsilon_{lm}$	$\frac{y_d^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^2$	$\beta\beta\nu$
24 <sub>b</sub>	$L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{jm} \epsilon_{kl}$	$\frac{y_d^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^2$	$\beta\beta\nu$
25	$L^i L^j Q^k d^c Q^l u^c H^m H^n \epsilon_{im} \epsilon_{jn} \epsilon_{kl}$	$\frac{y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$4 \times 10^3$	$\beta\beta\nu$
26 <sub>a</sub>	$L^i L^j Q^k d^c \bar{L}_i \bar{e}^c H^l H^m \epsilon_{jl} \epsilon_{km}$	$\frac{y_\ell y_d}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	40	$\beta\beta\nu$
26 <sub>b</sub>	$L^i L^j Q^k d^c \bar{L}_k \bar{e}^c H^l H^m \epsilon_{il} \epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	40	$\beta\beta\nu$
27 <sub>a</sub>	$L^i L^j Q^k d^c \bar{Q}_i \bar{d}^c H^l H^m \epsilon_{jl} \epsilon_{km}$	$\frac{g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^4$	$\beta\beta\nu$
27 <sub>b</sub>	$L^i L^j Q^k d^c \bar{Q}_k \bar{d}^c H^l H^m \epsilon_{il} \epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^4$	$\beta\beta\nu$
28 <sub>a</sub>	$L^i L^j Q^k d^c \bar{Q}_j \bar{u}^c H^l \bar{H}_i \epsilon_{kl}$	$\frac{y_d y_u}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^3$	$\beta\beta\nu$
28 <sub>b</sub>	$L^i L^j Q^k d^c \bar{Q}_k \bar{u}^c H^l \bar{H}_i \epsilon_{jl}$	$\frac{y_d y_u}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^3$	$\beta\beta\nu$
28 <sub>c</sub>	$L^i L^j Q^k d^c \bar{Q}_l \bar{u}^c H^l \bar{H}_i \epsilon_{jk}$	$\frac{y_d y_u}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^3$	$\beta\beta\nu$
29 <sub>a</sub>	$L^i L^j Q^k u^c \bar{Q}_k \bar{u}^c H^l H^m \epsilon_{il} \epsilon_{jm}$	$\frac{y_u^2}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$2 \times 10^5$	$\beta\beta\nu$
29 <sub>b</sub>	$L^i L^j Q^k u^c \bar{Q}_l \bar{u}^c H^l H^m \epsilon_{ik} \epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^4$	$\beta\beta\nu$
30 <sub>a</sub>	$L^i L^j \bar{L}_i \bar{e}^c \bar{Q}_k \bar{u}^c H^k H^l \epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$2 \times 10^3$	$\beta\beta\nu$
30 <sub>b</sub>	$L^i L^j \bar{L}_m e^c \bar{Q}_n u^c H^k H^l \epsilon_{ik} \epsilon_{jl} \epsilon^{mn}$	$\frac{y_\ell y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$2 \times 10^3$	$\nu$ Mass Scale $\beta\beta\nu$
31 <sub>a</sub>	$L^i L^j \bar{Q}_i \bar{d}^c \bar{Q}_l \bar{u}^c H^k H^l \epsilon_{ij}$	$\frac{y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$4 \times 10^3$	$\beta\beta\nu$

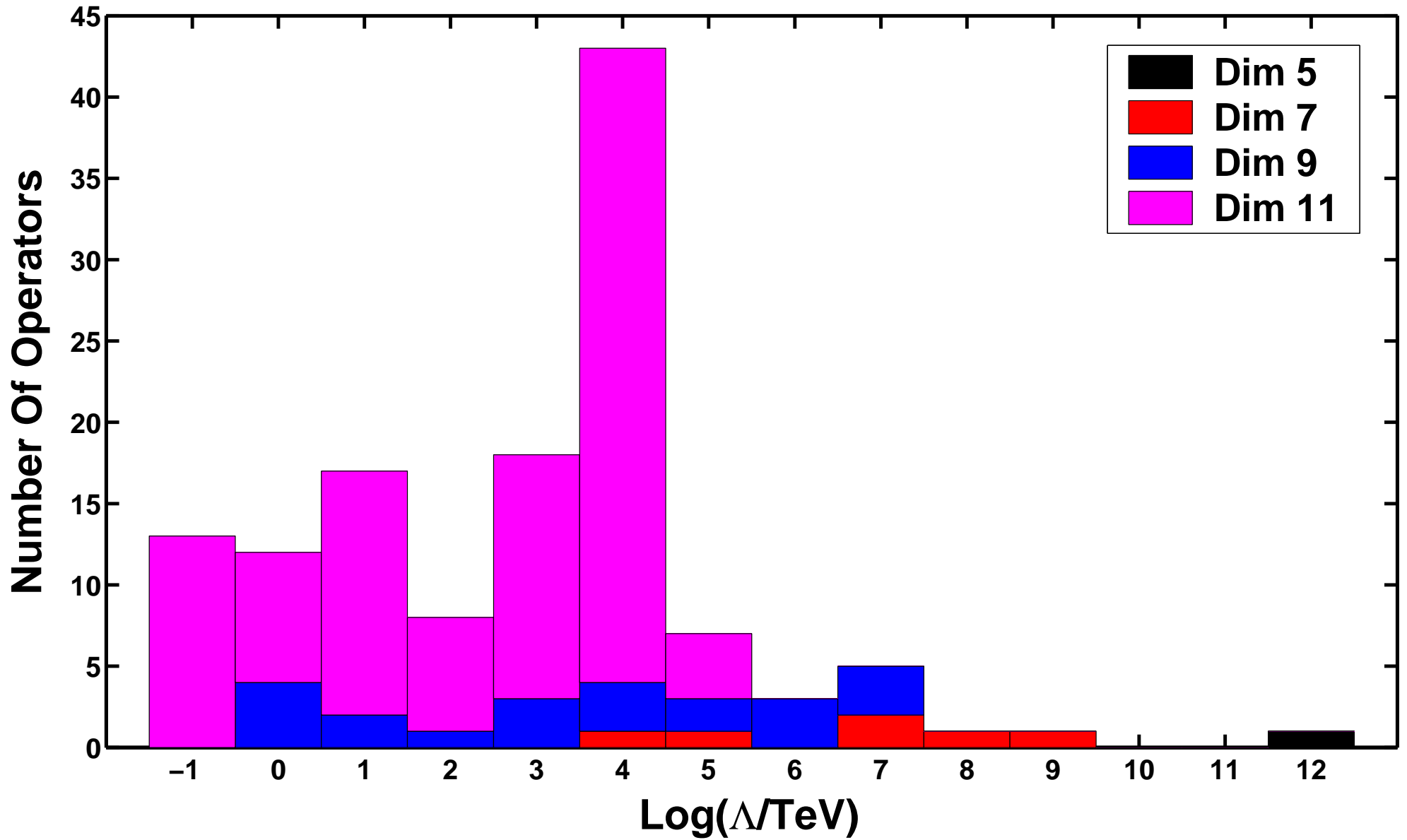
## Assumptions:

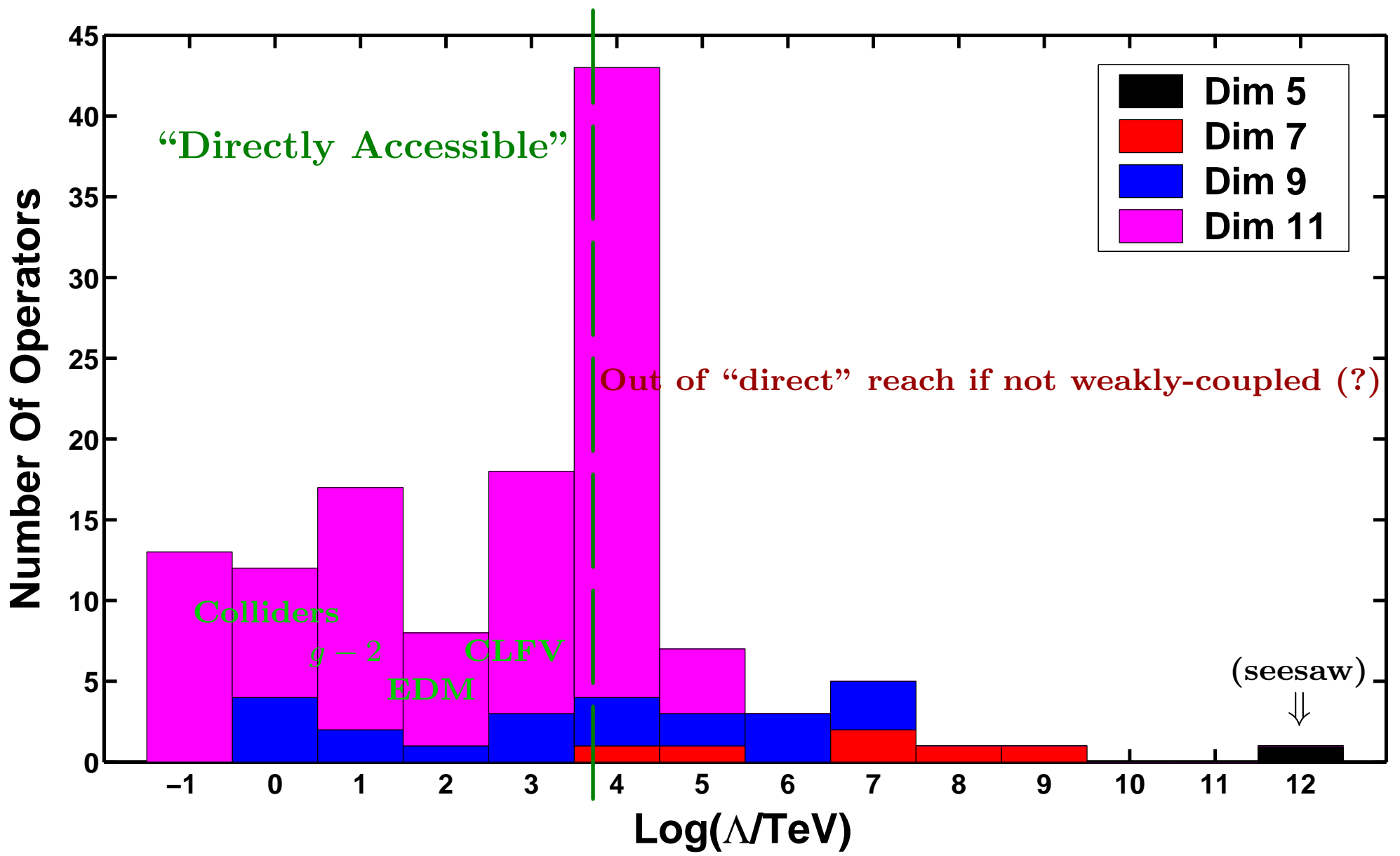
- Only consider  $\Delta L = 2$  operators;
- Operators made up of only standard model fermions and the Higgs doublet (no gauge bosons);
- Electroweak symmetry breaking characterized by SM Higgs doublet field;
- Effective operator couplings assumed to be “flavor indifferent”;
- Operators “turned on” one at a time, assumed to be leading order (tree-level) contribution of new lepton number violating physics.
- We can use the effective operator to estimate the coefficient of all other lepton-number violating lower-dimensional effective operators (loop effects, computed with a hard cutoff).

All results presented are order of magnitude *estimates*, not precise quantitative results.

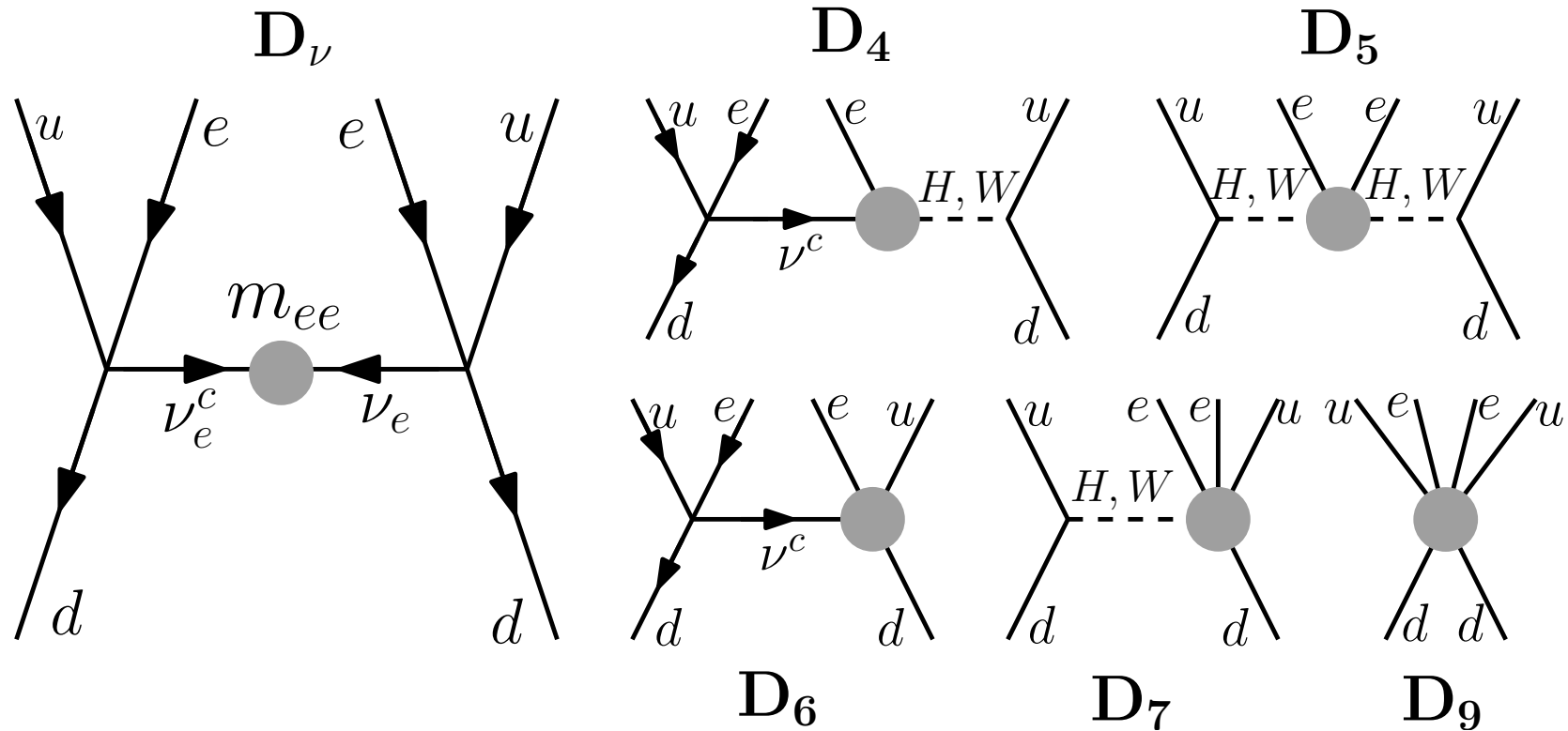




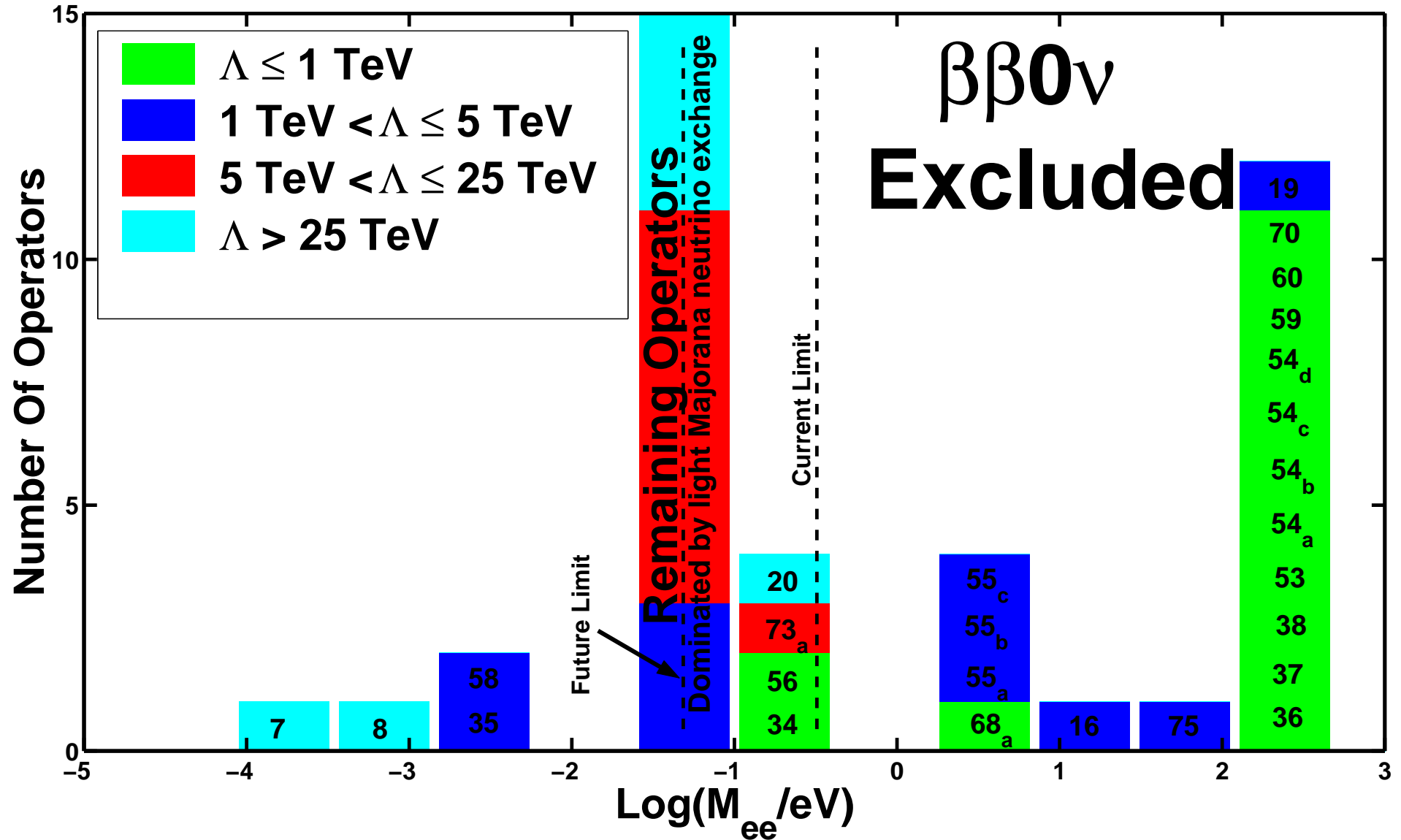




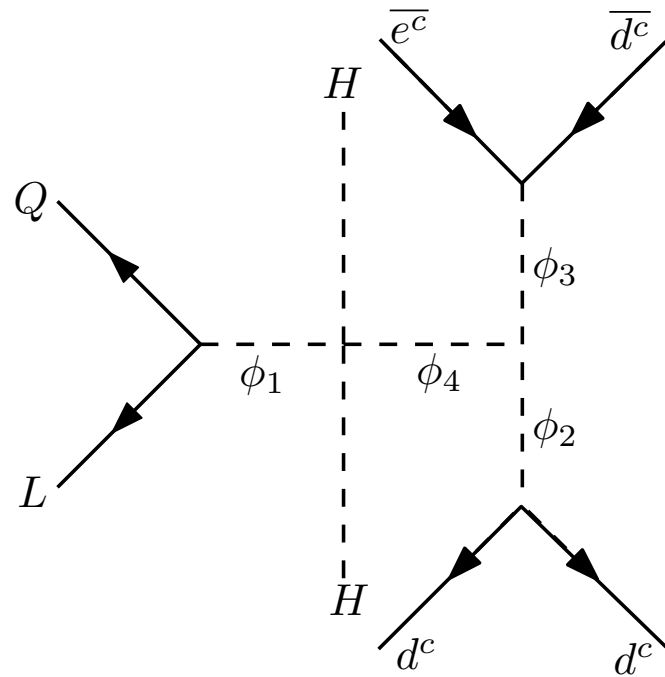
## Other Experimental Consequences: LNV Observables



## Neutrinoless Double-beta Decay ( $0\nu\beta\beta$ )



[arXiv:0708.1344 [hep-ph]]



Order-One Coupled, Weak Scale Physics

Can Also Explain Naturally Small

Majorana Neutrino Masses:

Multi-loop neutrino masses from lepton number violating new physics.

$$-\mathcal{L}_{\nu\text{SM}} \supset \sum_{i=1}^4 M_i \phi_i \bar{\phi}_i + iy_1 QL\phi_1 + y_2 d^c d^c \phi_2 + y_3 e^c d^c \phi_3 + \lambda_{14} \bar{\phi}_1 \phi_4 HH + \lambda_{234} M \phi_2 \bar{\phi}_3 \phi_4 + h.c.$$

$$m_\nu \propto (y_1 y_2 y_3 \lambda_{234}) \lambda_{14} / (16\pi)^4 \rightarrow \text{neutrino masses at 4 loops, requires } M_i \sim 100 \text{ GeV!}$$

WARNING: For illustrative purposes only. Details still to be worked out. Scenario most likely ruled out by charged-lepton flavor-violation, LEP, Tevatron, and HERA.

## How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;  
( $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow e$ -conversion in nuclei, etc)
- searches for lepton number violation;  
(neutrinoless double beta decay, etc)
- neutrino oscillation experiments;  
(Daya Bay, NO $\nu$ A, etc)
- searches for fermion electric/magnetic dipole moments  
(electron edm, muon  $g - 2$ , etc);

- precision studies of neutrino – matter interactions;  
(Miner $\nu$ a, NuSOng, etc)
- collider experiments:  
(LHC, etc)
  - *Can* we “see” the physics responsible for neutrino masses at the LHC?  
– YES!  
*Must* we see it? – NO, but we won’t find out until we try!
  - we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).



## CONCLUSIONS

1. we have a very successful parametrization of the neutrino sector, but we still don't understand where neutrino masses (and lepton mixing) come from;
2. neutrino masses are very small – we don't know why, but we think it means something important;
3. we need a minimal  $\nu$ SM Lagrangian. In order to decide which one is “correct” we must uncover the fate of baryon number minus lepton number ( $0\nu\beta\beta$  is the best bet? Likely, but not guaranteed).

4. We know very little about the new physics uncovered by neutrino oscillations.
  - It could be renormalizable  $\rightarrow$  “boring” Dirac neutrinos
  - It could be due to Physics at absurdly high energy scales  $M \gg 1$  TeV  $\rightarrow$  high energy seesaw. How can we ever convince ourselves that this is correct?
  - It could be due to very light new physics  $\rightarrow$  low energy seesaw. Prediction: new light propagating degrees of freedom – sterile neutrinos
  - It could be due to new physics at the TeV scale  $\rightarrow$  either weakly coupled, or via a more subtle lepton number breaking sector. Predictions: charged lepton flavor violation, collider signatures!
5. We need more experimental data in order to decide what is really going on!

# Backup Slides . . .



## Low-Energy Seesaw Predictions: **Tritium beta-decay**

Heavy neutrinos participate in tritium  $\beta$ -decay. Their contribution can be parameterized by

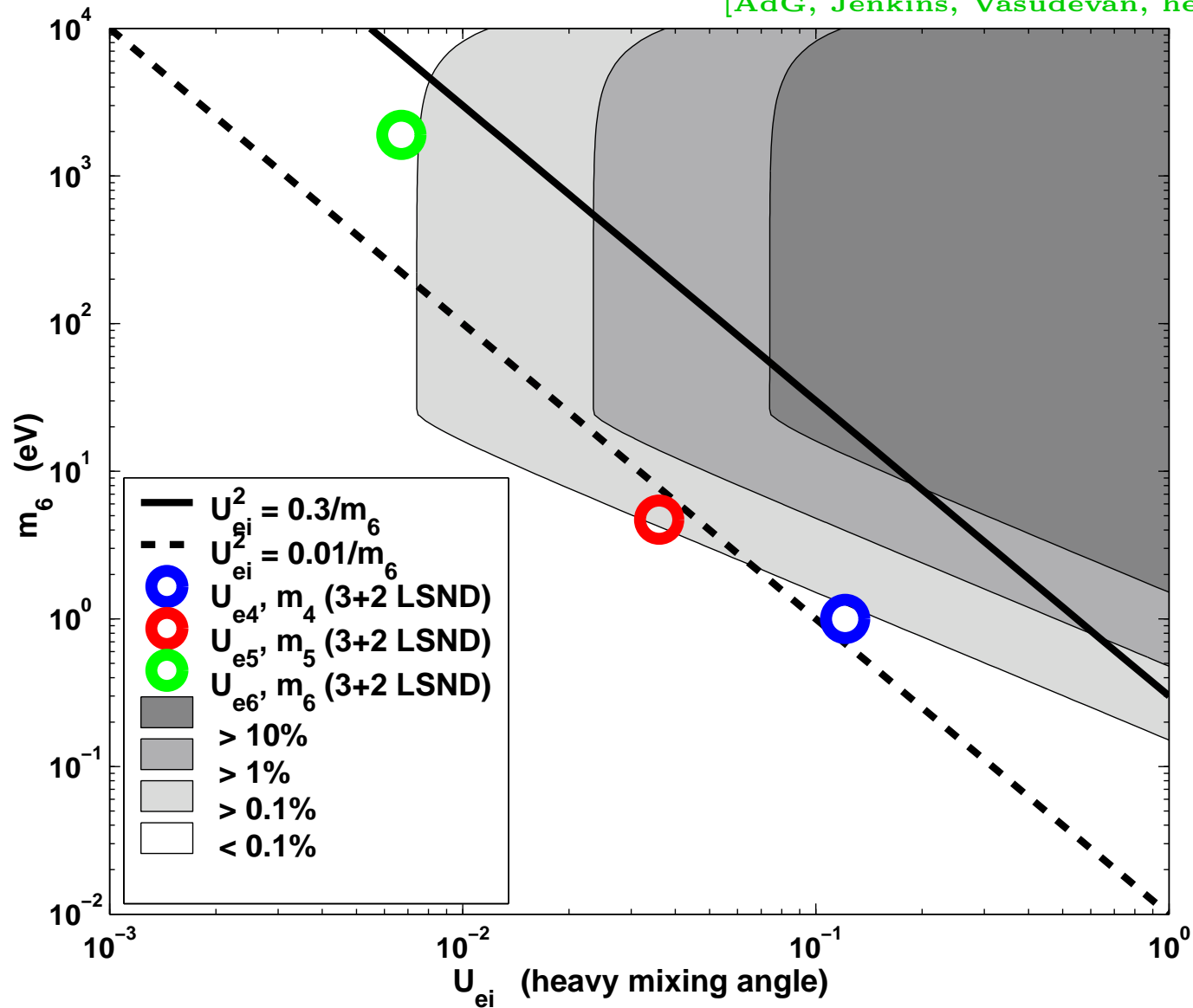
$$m_{\beta}^2 = \sum_{i=1}^6 |U_{ei}|^2 m_i^2 \simeq \sum_{i=1}^3 |U_{ei}|^2 m_i^2 + \sum_{i=1}^3 |U_{ei}|^2 m_i M_i,$$

as long as  $M_i$  is not too heavy (above tens of eV). For example, in the case of a 3+2 solution to the LSND anomaly, the heaviest sterile state (with mass  $M_1$ ) contributes the most:  $m_{\beta}^2 \simeq 0.7 \text{ eV}^2 \left( \frac{|U_{e1}|^2}{0.7} \right) \left( \frac{m_1}{0.1 \text{ eV}} \right) \left( \frac{M_1}{10 \text{ eV}} \right)$ .

NOTE: next generation experiment (KATRIN) will be sensitive to  $O(10^{-1}) \text{ eV}^2$ .

# sensitivity of tritium beta decay to seesaw sterile neutrinos

[AdG, Jenkins, Vasudevan, hep-ph/0608147]



## GeV Seesaw: Brief Summary of Constraints

### Double-Beta Decay:

$$m_{ee}^{\text{heavy}} = \sum_{i=1}^n (\lambda v)_{ei}^2 M_i^{-3} Q^2.$$

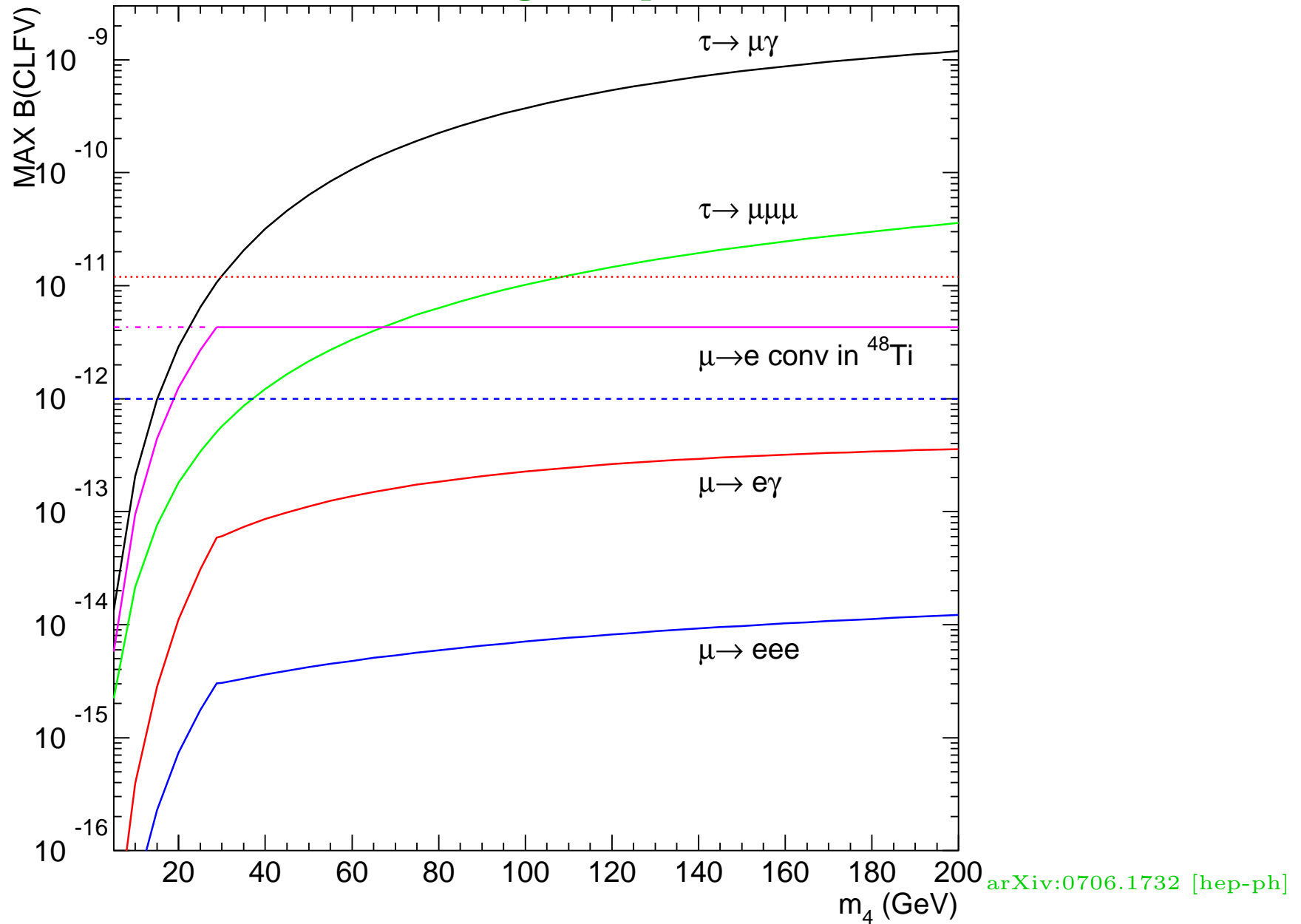
### Universality tests:

$$\left| \sum_{k=4}^{3+n} (|U_{ek}|^2 - |U_{\mu k}|^2) \right| < 0.004, \quad (\pi \text{ decay})$$

$$\left| \sum_{k=4}^{3+n} (|U_{ek}|^2 - |U_{\tau k}|^2) \right| < 0.006, \quad (\tau \text{ decay})$$

$$\left| \sum_{k=4}^{3+n} (|U_{\mu k}|^2 - |U_{\tau k}|^2) \right| < 0.006, \quad (\tau \text{ decay})$$

## Constraint From Charged Lepton Flavor Violation



### Another stringent constraint: LEP

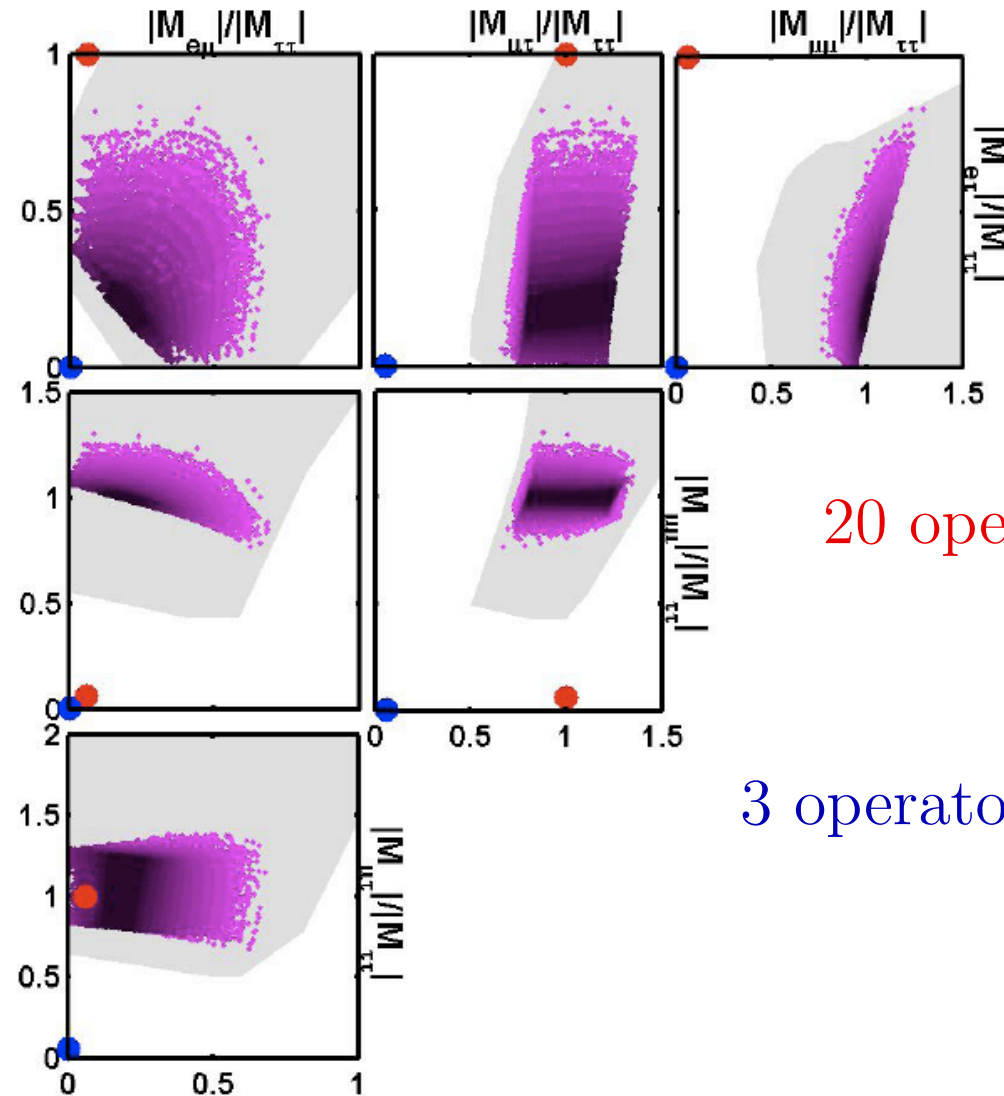
If right handed neutrino masses are below  $\sim 70$  GeV, the flavor changing neutral current decay

$$Z \rightarrow \nu\nu_4 \rightarrow \nu\ell W^*$$

Places the most severe constraints on  $|U_{\alpha 4}|^2$  ( $\alpha$  independent!)



# Implied neutrino mass textures (numerical results)



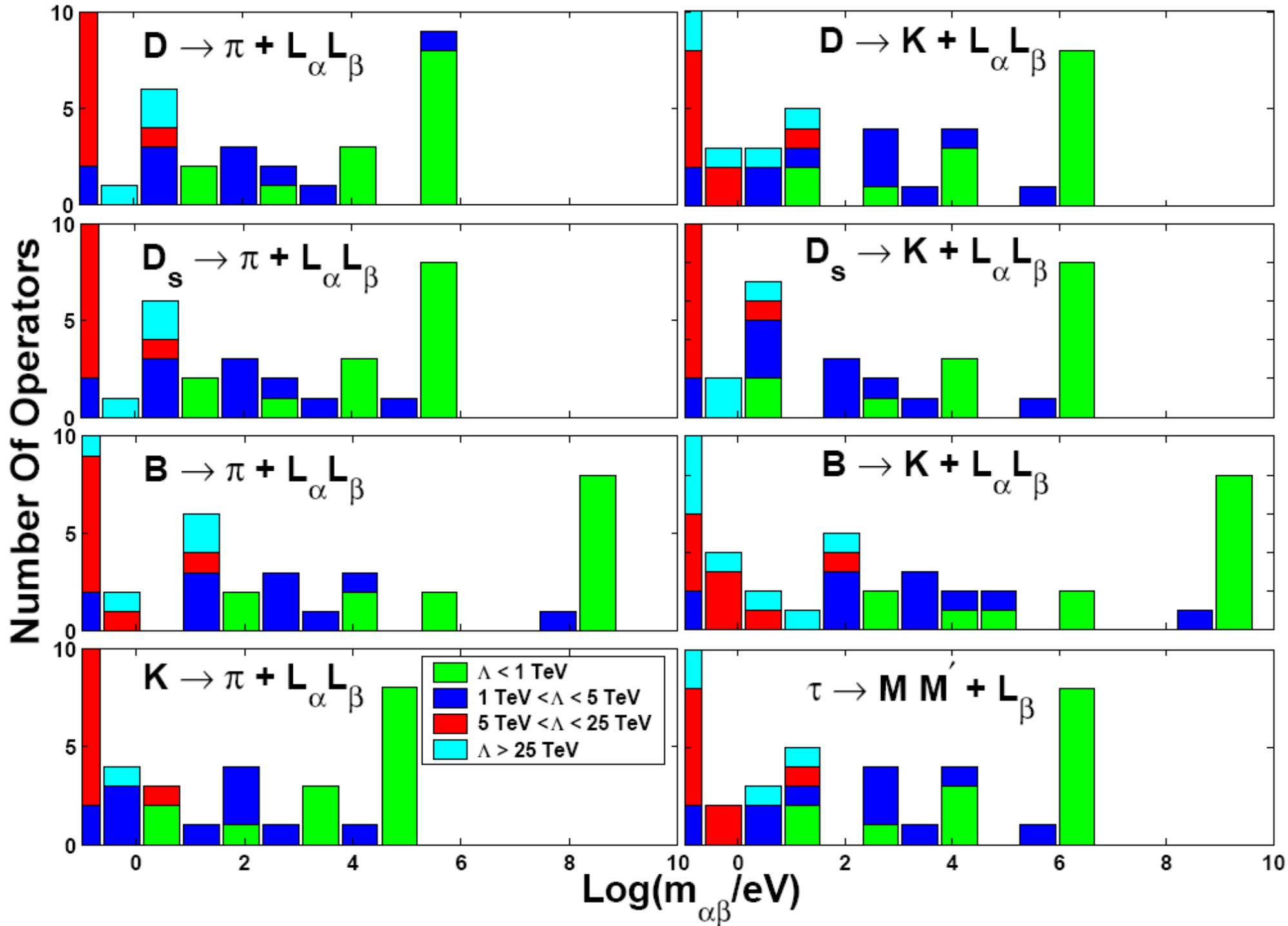
- Require  $m_{ee} < 10^{-4}$  eV
- all phases vary freely
- 95% confidence limits
- $\theta_{13}$  varies from  $0^\circ - 14^\circ$

20 operators:  $M \propto \begin{pmatrix} \lambda_e & \lambda_\mu & \lambda_\tau \\ \lambda_\mu & \lambda_\mu & \lambda_\tau \\ \lambda_\tau & \lambda_\tau & \lambda_\tau \end{pmatrix}$

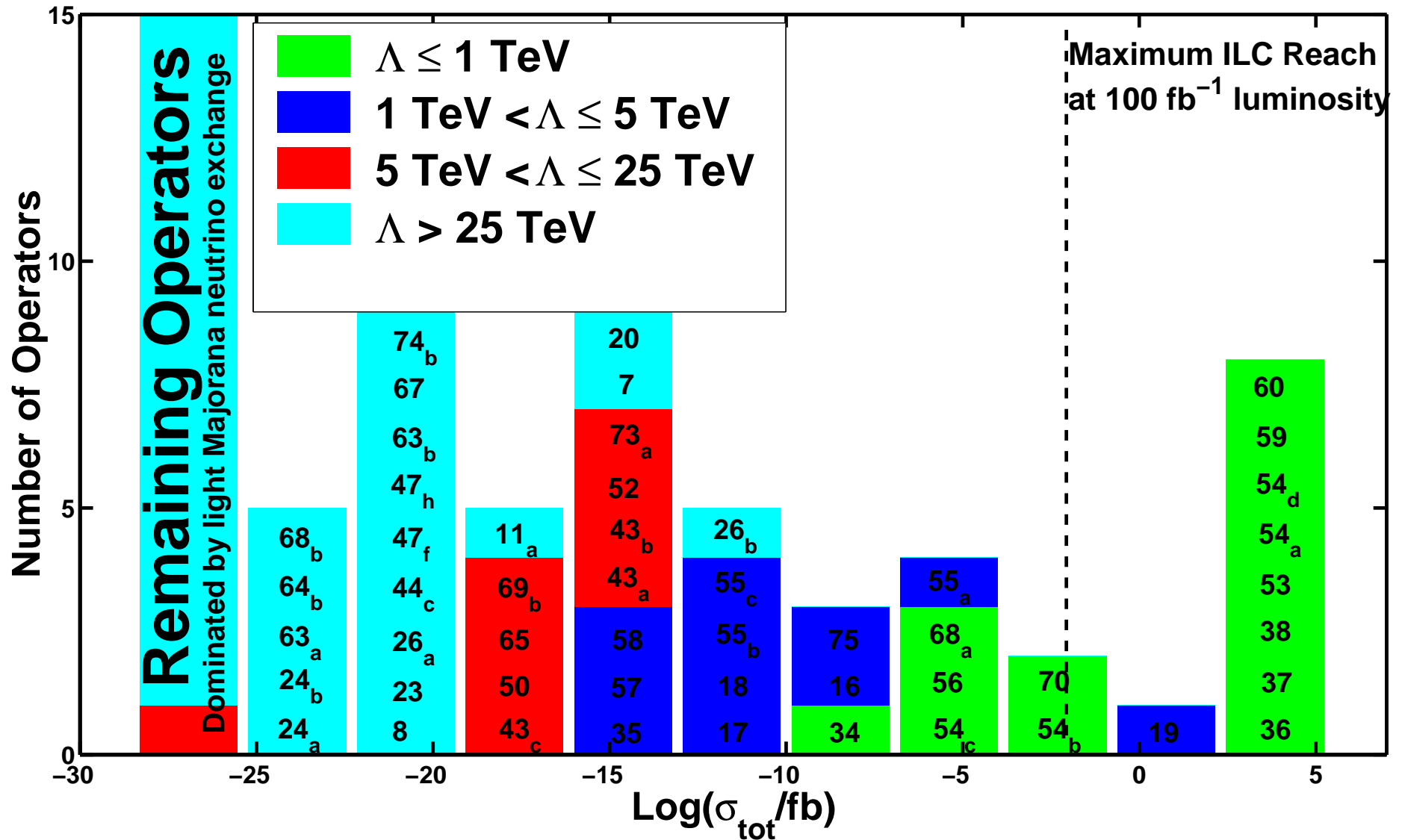
3 operators:  $M \propto \begin{pmatrix} \lambda_e \lambda_e & \lambda_e \lambda_\mu & \lambda_e \lambda_\tau \\ \lambda_e \lambda_\mu & \lambda_\mu \lambda_\mu & \lambda_\mu \lambda_\tau \\ \lambda_e \lambda_\tau & \lambda_\mu \lambda_\tau & \lambda_\tau \lambda_\tau \end{pmatrix}$

Rest are “anarchical”

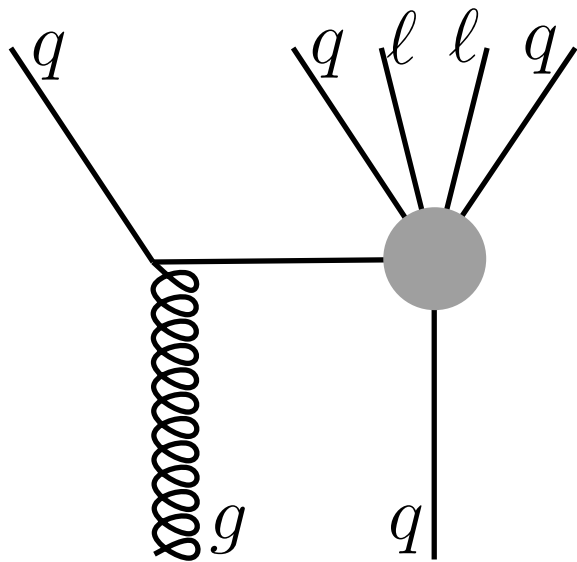




LNV at Colliders  $\Rightarrow$  1 TeV ILC:  $e^-e^- \rightarrow 4$  jets, no missing energy

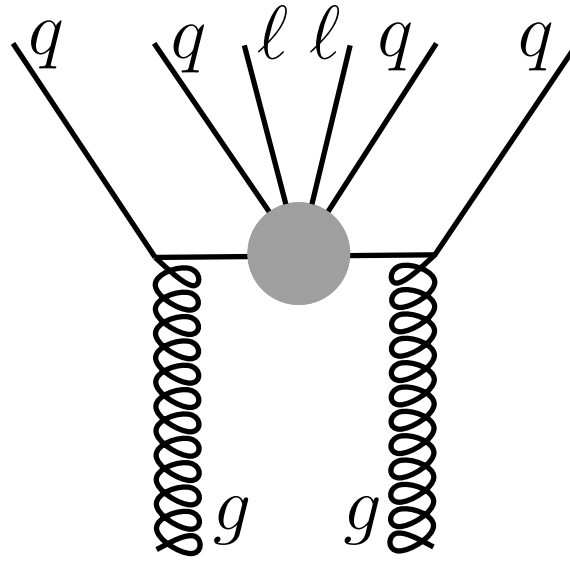


LNV at Colliders  $\Rightarrow$  LHC:  $pp \rightarrow \ell^\pm \ell^\pm + \text{multi-jets}$



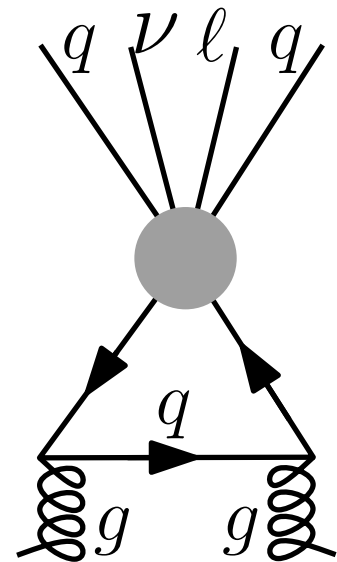
(a)

OK



(b)

OK



(c)

$\nu$  in final state

## The neutrino mass matrix in the seesaw case, after electroweak symmetry breaking.

Assuming three right-handed neutrinos  $N$ :

$$m_\nu = \begin{pmatrix} 0 & \lambda v \\ (\lambda v)^t & M \end{pmatrix},$$

$M$  is diagonal, and all its eigenvalues are real and positive. The charged lepton mass matrix also diagonal, real, and positive.

To leading order in  $(\lambda v)M^{-1}$ , the three lightest neutrino mass eigenvalues are given by the eigenvalues of

$$m_a = \lambda v M^{-1} (\lambda v)^t,$$

where  $m_a$  is the mostly active neutrino mass matrix, while the heavy sterile neutrino masses coincide with the eigenvalues of  $M$ .

$6 \times 6$  mixing matrix  $U$  [ $U^t m_\nu U = \text{diag}(m_1, m_2, m_3, m_4, m_5, m_6)$ ] is

$$U = \begin{pmatrix} V & \Theta \\ -\Theta^\dagger V & 1_{n \times n} \end{pmatrix},$$

where  $V$  is the active neutrino mixing matrix (MNS matrix)

$$V^t m_a V = \text{diag}(m_1, m_2, m_3),$$

and the matrix that governs active–sterile mixing is

$$\Theta = (\lambda\nu)^* M^{-1}.$$

One can solve for the Yukawa couplings and re-express

$$\Theta = V \sqrt{\text{diag}(m_1, m_2, m_3)} R^\dagger M^{-1/2},$$

where  $R$  is a complex orthogonal matrix  $RR^t = 1$ .

## What if $1 \text{ GeV} < M < 1 \text{ TeV}$ ?

Naively, one expects

$$\Theta \sim \sqrt{\frac{m_a}{M}} < 10^{-5} \sqrt{\frac{1 \text{ GeV}}{M}},$$

where  $\Theta$  is the matrix of active–sterile mixing angles. For  $M = 1 \text{ GeV}$  and above, sterile neutrino effects are mostly negligible.

However,

$$\Theta = V \sqrt{\text{diag}(m_1, m_2, m_3)} R^\dagger M^{-1/2},$$

where  $R$  is a complex orthogonal matrix ( $RR^t = 1$ ) and the magnitude of the entries of  $R$  can be arbitrarily large [ $\cos(ix) = \cosh x \gg 1$  if  $x > 1$ ].

This is true as long as

- $\lambda v \ll M$  (seesaw approximation holds)
- $\lambda < 4\pi$  (theory is “well-defined”)

This implies that, in principle,  $\Theta$  is a quasi-free parameter – independent from light neutrino masses and mixing – as long as  $\Theta \ll 1$  and  $M < 1 \text{ TeV}$ .

## What Does $R \gg 1$ Mean?

It is illustrative to consider the case of one active neutrino of mass  $m_3$  and two sterile ones, and further assume that  $M_1 = M_2 = M$ . In this case,

$$\Theta = \sqrt{\frac{m_3}{M}} \begin{pmatrix} \cos \zeta & \sin \zeta \end{pmatrix},$$

$$\lambda v = \sqrt{m_3 M} \begin{pmatrix} \cos \zeta^* & \sin \zeta^* \end{pmatrix} \equiv \begin{pmatrix} \lambda_1 & \lambda_2 \end{pmatrix}.$$

If  $\zeta$  has a large imaginary part  $\Rightarrow \Theta$  is (exponentially) larger than  $(m_3/M)^{1/2}$ ,  $\lambda_i$  neutrino Yukawa couplings are much larger than  $\sqrt{m_3 M}/v$

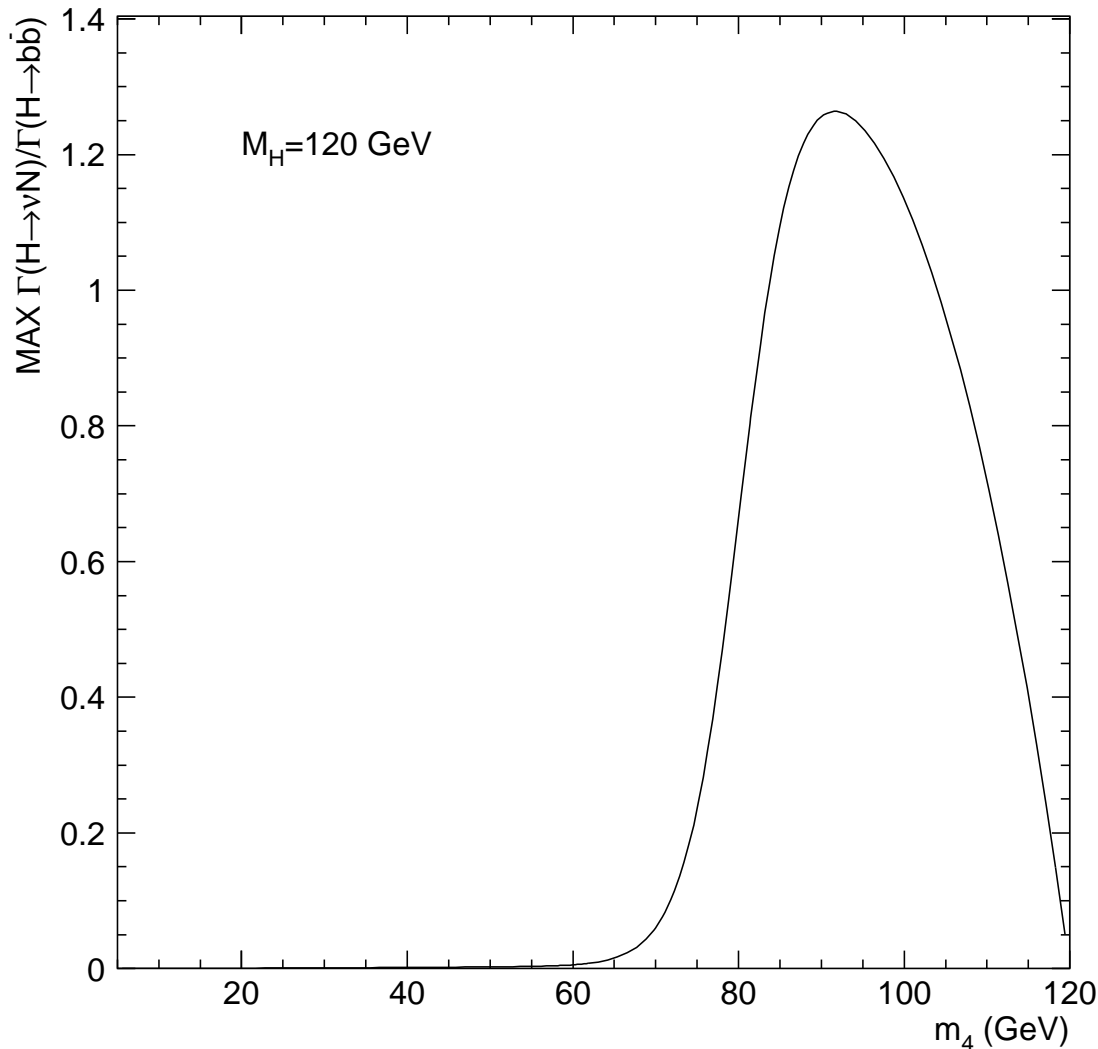
The reason for this is a strong cancellation between the contribution of the two different Yukawa couplings to the active neutrino mass  
 $\Rightarrow m_3 = \lambda_1^2 v^2 / M + \lambda_2^2 v^2 / M$ .

For example:  $m_3 = 0.1$  eV,  $M = 100$  GeV,  $\zeta = 14i \Rightarrow$   
 $\lambda_1 \sim 0.244$ ,  $\lambda_2 \sim -0.244i$ , while  $|y_1| - |y_2| \sim 3.38 \times 10^{-13}$ .



## Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732 [hep-ph]]



What does the seesaw Lagrangian predict for the LHC?

Nothing much, unless...

- $M_N \sim 1 - 100$  GeV,
- Yukawa couplings larger than naive expectations.

$\Leftarrow H \rightarrow \nu N$  as likely as  $H \rightarrow b\bar{b}$ !

(NOTE:  $N \rightarrow \ell q' \bar{q}$  or  $\ell \ell' \nu$  (prompt)  
“Weird” Higgs decay signature! )

[+ Lepton Number Violation at Colliders]