Neutrino masses in theory

European Strategy for Neutrino Oscillation Physics - II

CERN
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Outline

1. Neutrino properties: questions for the future

2. Neutrinos as an open window on the physics BSM

3. Neutrino masses

4. Neutrino mixing

5. Conclusions and outlook

The Precision Era of Neutrino Physics

Hunting for neutrino masses, mixing and their origin

With the discovery of neutrino oscillations, a **new perspective** has opened on neutrino physics with compelling questions which await their answer:

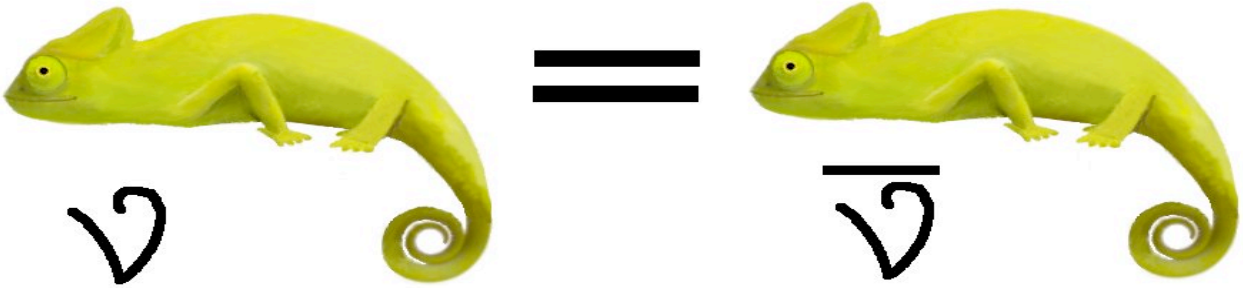
1. **What is the nature of neutrinos?**
2. **What are the values of masses and mixing?**
3. **Is the charge/parity (CP) symmetry broken?**
4. **Are there sterile neutrinos (LSND, MiniBooNE)? Non-unitarity? NSI?**

This is the information which is needed to unveil the physics BSM at the origin of neutrino masses and mixing.

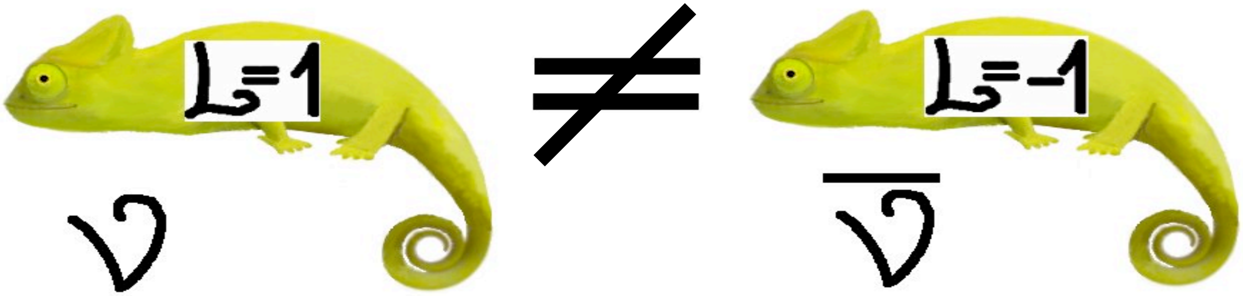
Nature of neutrinos: Dirac vs Majorana

Neutrinos can be **Majorana** or **Dirac** particles. In the SM only neutrinos can be Majorana because they are neutral.

Majorana particles are indistinguishable from antiparticles.



Dirac neutrinos are labelled by the lepton number.



The nature of neutrinos is linked to the conservation of the **Lepton number (L)**. This is testable in neutrinoless double beta decay.

Neutrino Masses in the Standard Model

In the SM, neutrinos do not acquire a mass and mixing:

- like the other fermions as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \cancel{\nu_R}$$

Solution: Introduce ν_R for Dirac masses

- they do not have a Majorana mass term

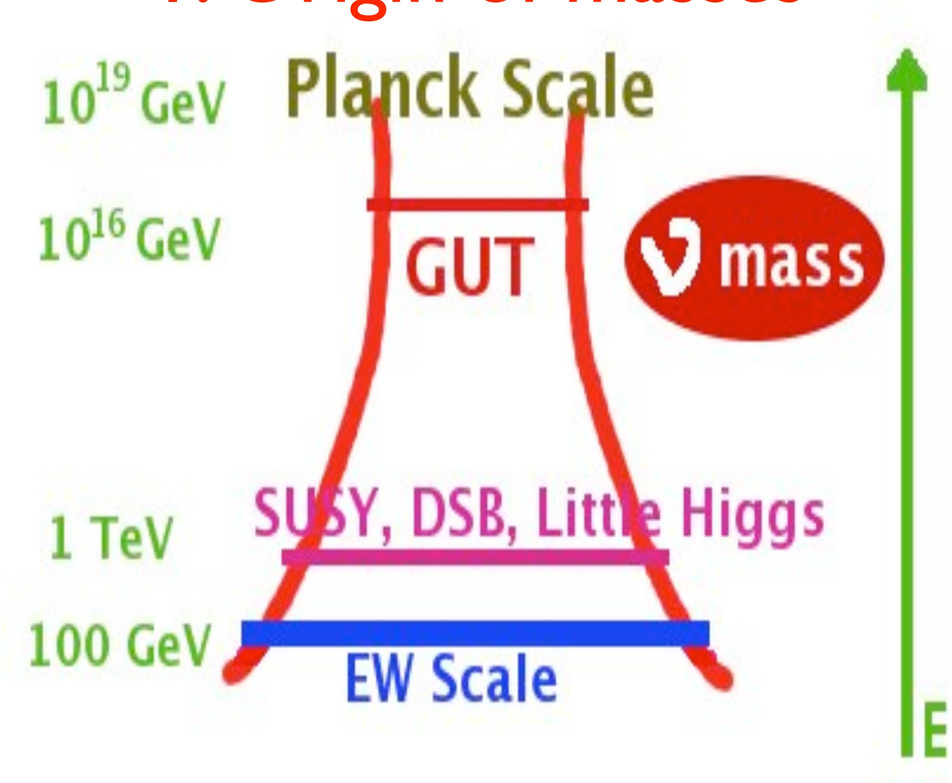
$$M \nu_L^T C \nu_L$$

as this term breaks the SU(2) gauge symmetry.
Solution: Introduce an SU(2) scalar triplet or gauge invariant non-renormalisable terms (D>4).

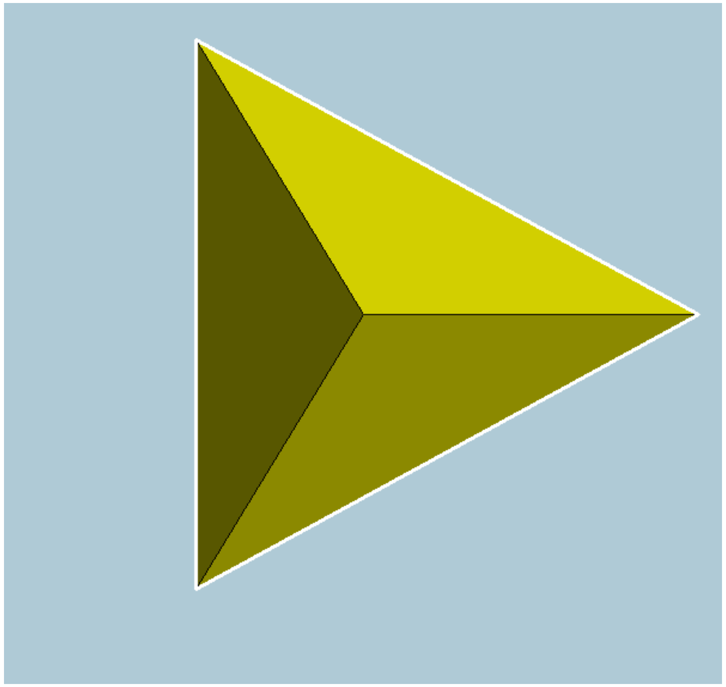
Open window on Physics beyond the SM

Neutrino physics gives a new perspective on physics BSM.

1. Origin of masses



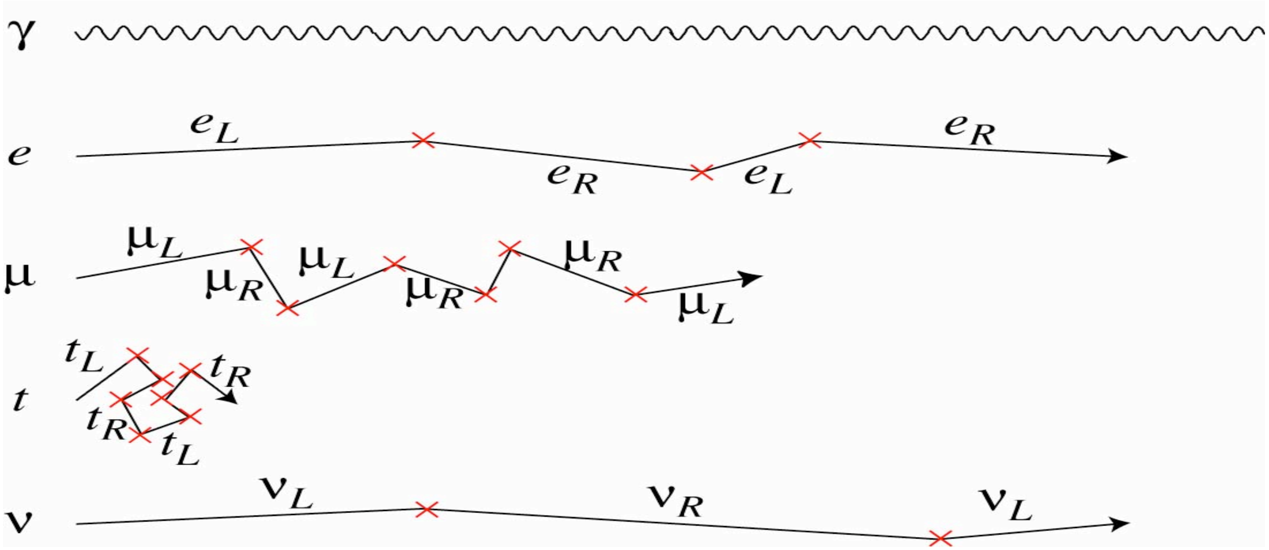
2. Problem of flavour



This information is **complementary** with the one which comes from flavour physics experiments and from colliders.

Dirac Masses

Neutrino masses in the sub-eV range cannot be explained naturally within the SM. If neutrinos had the same interactions with the Higgs as the top quark, they would be **1000000000000** times heavier!



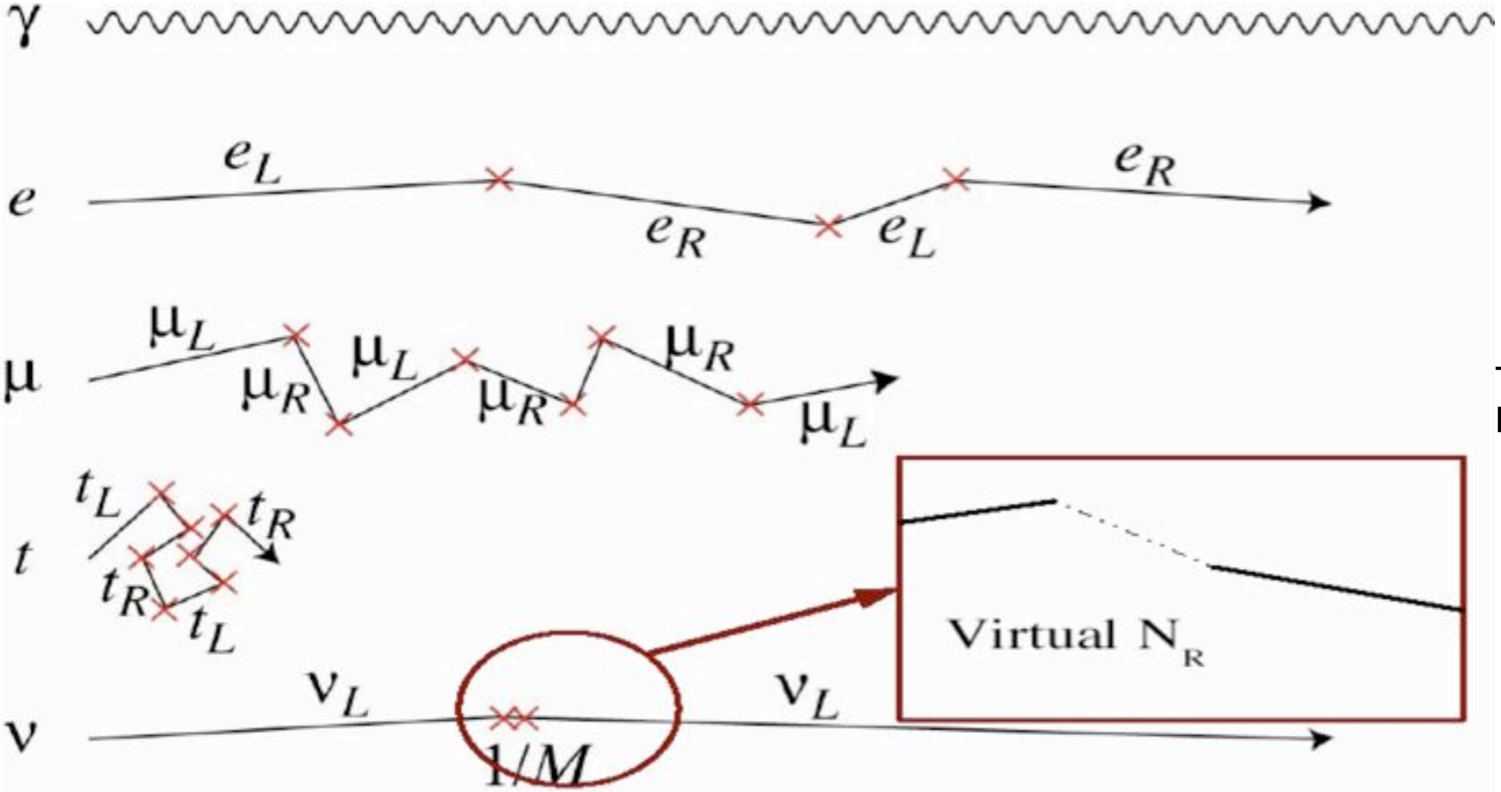
Thanks to
H. Murayama

$$y_\nu = \frac{m_\nu}{v} = \frac{0.1\,\mathrm{eV}}{250\,\mathrm{GeV}} = 4 \times 10^{-13}$$

Many theorists consider this explanation of neutrino masses unnatural, unless an explanation can be given for the extreme smallness of the coupling (e.g. large or warped extra-D models).

Majorana Masses

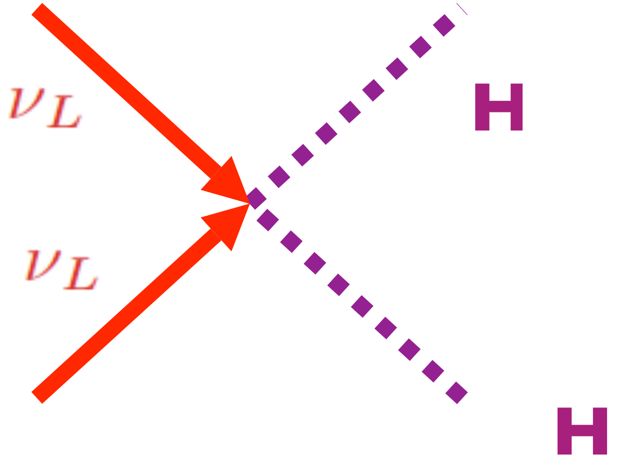
If neutrino are Majorana particles, a **Majorana mass** can be generated and can arise as the **low energy realisation of a higher energy theory**.



Thanks to
H. Murayama

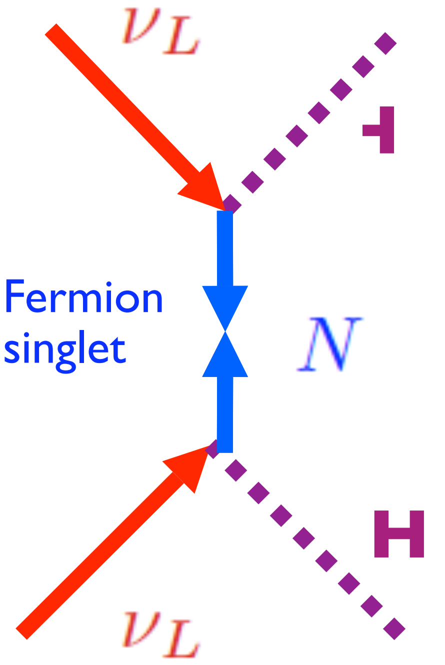
$$-\mathcal{L} = \lambda \frac{\nu_L H \, \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$

D=5 term



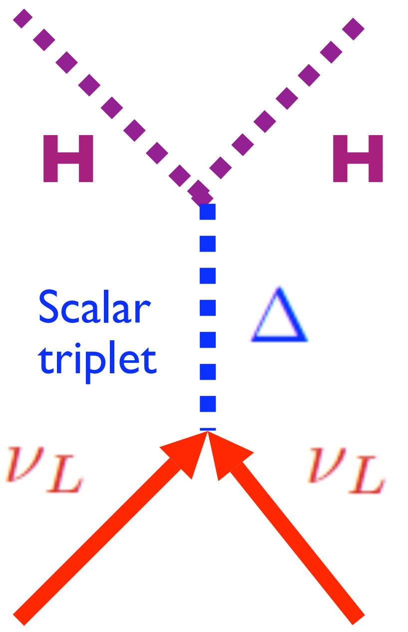
$$\frac{\nu_L H \ \nu_L H}{\Lambda}$$

See-saw Type I



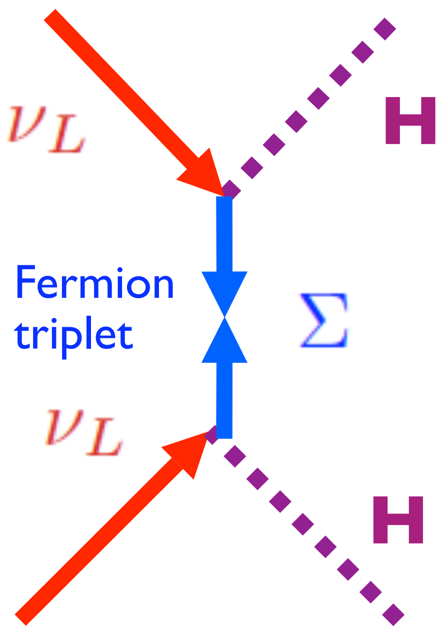
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



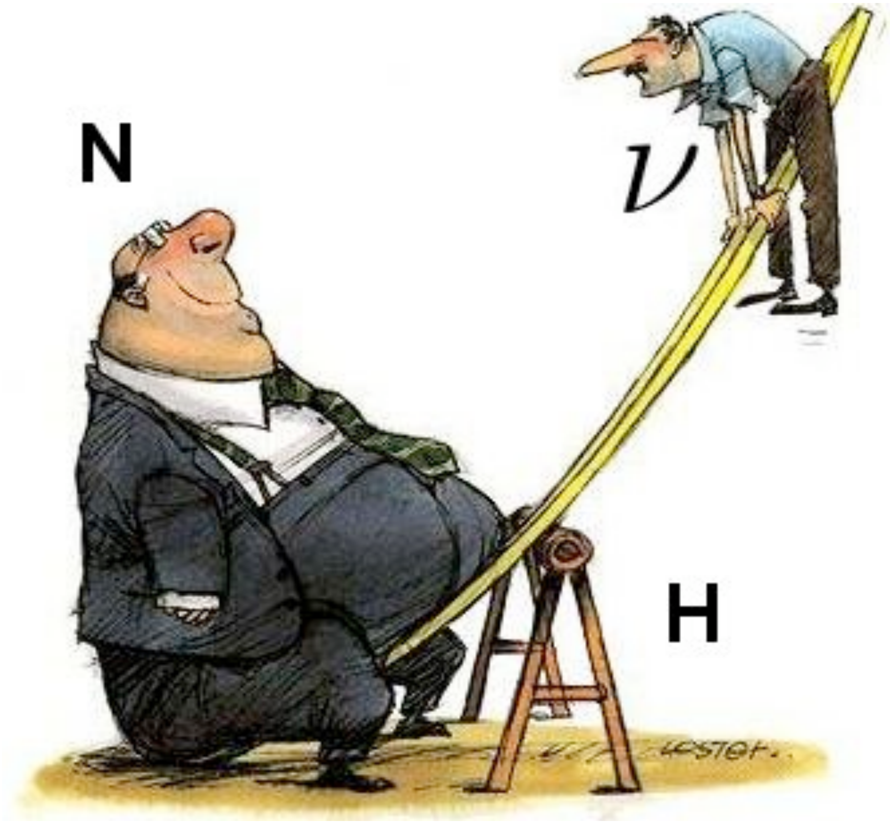
Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

See-saw Type III



Ma, Roy, Senjanovic, Hambye

See-saw mechanism: type I at the GUT scale



- Introduce a right handed neutrino **N**
- Couple it to the Higgs and left handed neutrinos

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

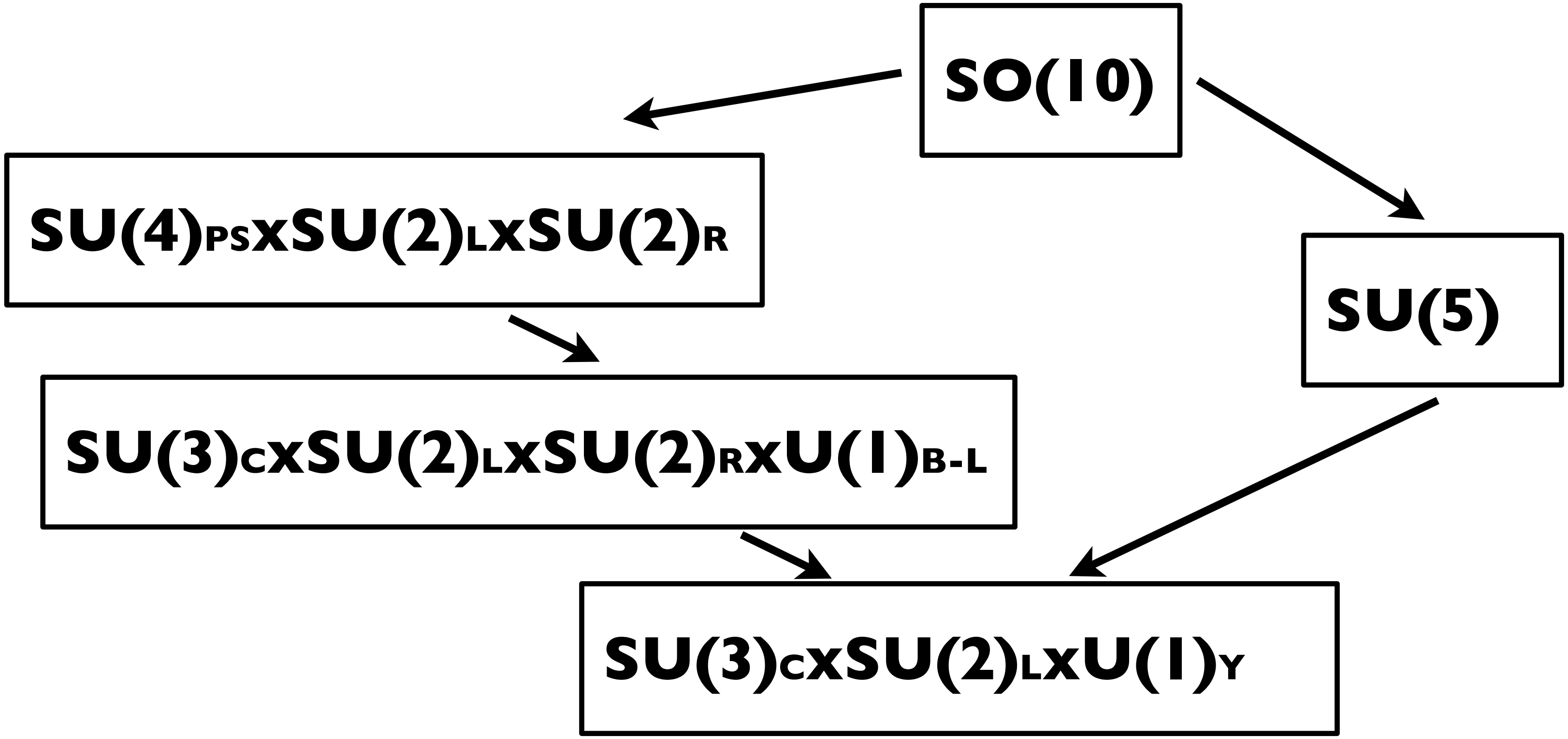
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{y_\nu^2 v_H^2}{M_N}$$

$$\downarrow$$

$$M_N \sim 10^{14} \text{ GeV}$$

The see-saw can emerge naturally in **GUTheories**: e.g. SO(10). They provide the necessary elements: N, large M and L violation.



SO(10)

$SU(4)_{PS}\times SU(2)_L\times SU(2)_R$

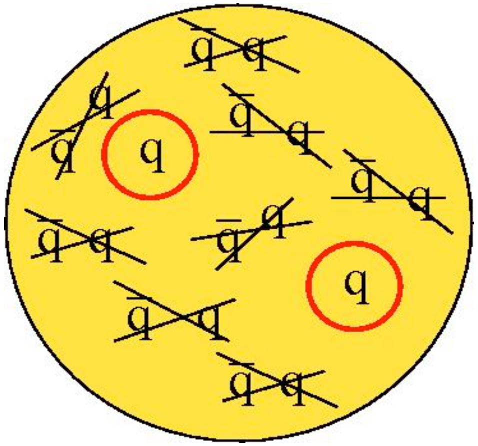
SU(5)

$SU(3)_c\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$

$SU(3)_c\times SU(2)_L\times U(1)_Y$

They typically lead to relations between quark and lepton masses. Understanding the origin of neutrino masses might shed light on the physics at energy scales which could not be tested directly in any experiments.

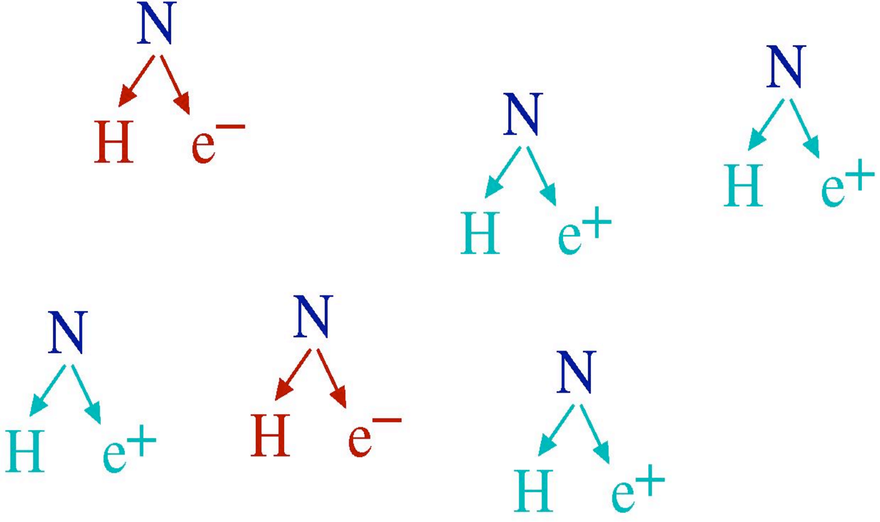
In the Early Universe



As the temperature drops, only quarks are left:

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.2) \times 10^{-10}$$

The excess of quarks can be explained by **Leptogenesis** (Fukugita, Yanagida): the heavy N responsible for neutrino masses generate a lepton asymmetry.

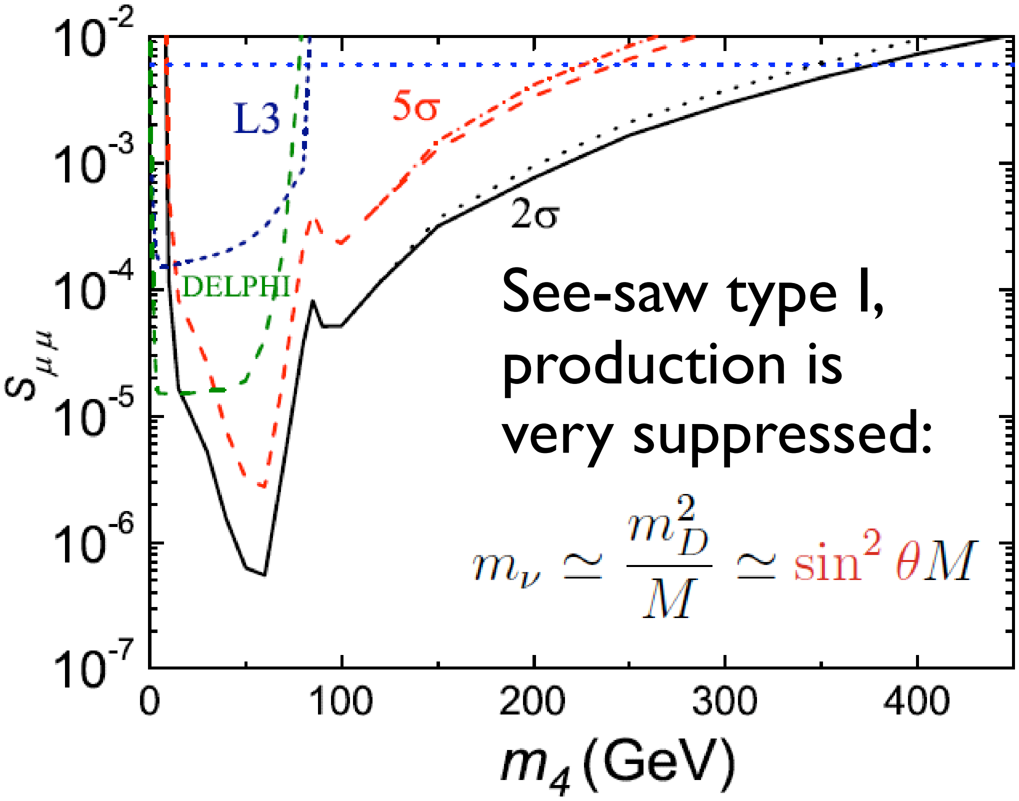


Excess of $e^+ \longrightarrow$ excess of q over $\bar{q}$

Observing L violation and CPV would constitute a **strong hint in favour of leptogenesis as the origin of the baryon asymmetry**.

Neutrino masses at the TeV scale

For smaller Yukawa couplings, small masses can arise from new physics at the TeV scale: in principle testable at the LHC by looking at same-sign dileptons.



See-saw type I, production is very suppressed:

$$m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$$

Atre et al., 0901.3589

- Gauge B-L: pp → Z' → N N
- See-saw type II: Scalar Triplets
- Triplet see-saw. Triplet N produced in gauge interactions

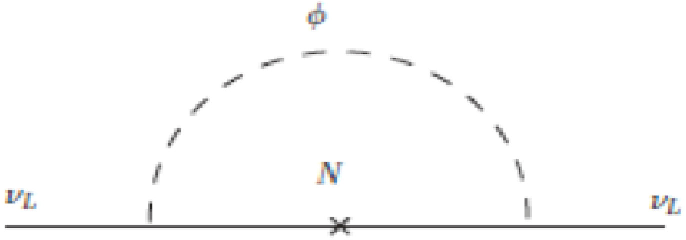
$$pp \to N^+N^0 \to \ell_1^+\ell_2^+ZW^-$$

- Left-Right models via W_R
- Inverse or extended see-saw models

Other models of Neutrino Masses

There are also other possibilities for generating neutrino masses. For example

- via loops in models in which Dirac masses are forbidden

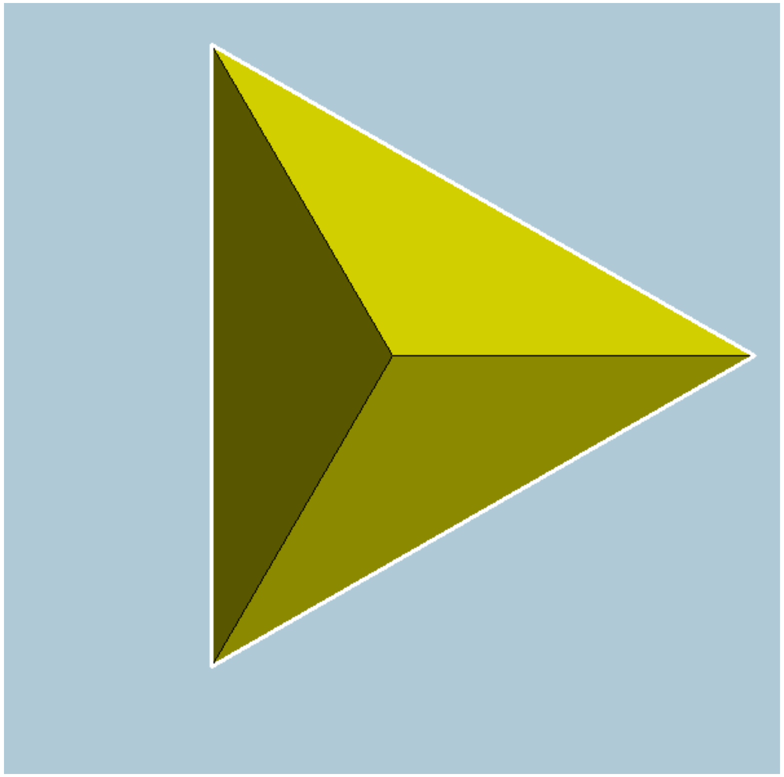


- Low energy see-saw: sterile neutrinos m<< GeV
- R-parity violating SUSY: neutrinos can mix with neutralinos

Establishing the origin of neutrino masses requires to have as much information as possible about the masses and to combine it with other signatures of the models (proton decay, LHC searches, LFV, sterile neutrinos, ...).

The problem of flavour

Mixing in the leptonic sector is very different from the quark one: angles are large (even θ_{13}!) and there can be new sources of CP-violation. Neutrinos provide a different perspective on the flavour problem.



Why three generations?

Why massive and flavour states are not the same?

Why the angles have the values measured?

What is the origin of CPV?

Trying to understand the leptonic flavour structure and its relation to the one present in the quark sector.

Tri-bimaximal mixing:
implies the existence of flavour symmetries, e.g. A4.

Quark-Lepton complementarity:
quark + lepton mixing ~maximal

Quark-Lepton universality:
the difference between mixing might be due to smallness of masses and mild hierarchy

Anarchy:
all entries in mass matrix of O(1)

The precise values of the mixing angles have a strong theoretical impact for understanding the flavour problem. Symmetry motivated patterns:

$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \Rightarrow \theta_{23} = 45^o, \theta_{12} = 45^o, \theta_{13} = 0$$

$$U_{TBM} = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \Rightarrow \theta_{23} = 45^o, \theta_{12} \sim 35^o, \theta_{13} = 0$$

$$U_{GR} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -\frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \Rightarrow \theta_{23} = 45^o, \theta_{12} = 32^o, \theta_{13} = 0$$

Deviation from these patterns is expected theoretically, e.g. GUTs, and is required by experimental data. Theoretical models typically lead to correlations between parameters (sum rules) or specific predictions for their values.

Connecting masses and mixing

In some models, the masses (and the type of neutrino mass hierarchy) can be connected to the mixing. For example

$$m_\nu = m_0 \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 1+\epsilon & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

Normal mass hierarchy

maximal θ_{23} , large θ_{12}

$\epsilon \sim \lambda$

$$m_\nu = m_0 \begin{pmatrix} \epsilon & c_{23} & s_{23} \\ c_{23} & \epsilon & \epsilon \\ s_{23} & \epsilon & \epsilon \end{pmatrix}$$

Inverted mass hierarchy

maximal θ_{23} , large θ_{12}

$L_e - L_\mu - L$

Determining the mass hierarchy and the values of the angles is of critical importance to understand the physics BSM.

Conclusions

- Neutrino masses cannot be accommodated in the SM (at least in its minimal form) and this is the **first evidence of physics BSM**.
- Masses are much smaller than those of other fermions. Mixing is large, differently from quark sector.
- Understanding the origin of neutrino masses will shed light on the physics beyond the standard model possibly at scales which might not be tested in direct experiments or in models reachable at the LHC.
- Mixing in the leptonic sector provides a complementary window on the problem of flavour.