Lepton number and flavour violation

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1 – Outline

- Lepton number violation
  - Nature of neutrinos
  - Neutrinoless double beta decay
  - Neutrino masses
  - CPV
- Lepton flavour violation
  - SM predictions
  - The see saw mechanism
  - Other processes

Questions for the future

- **What is the nature of neutrinos**?

Whether they Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$). Majorana neutrinos violate the lepton number.

- **Absolute value of neutrino masses**?

Needed the type of hierarchy and the mass scale of the lightest neutrino.

- **Leptonic CP-violation**?

$\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$.

- **Standard scenario**?

NSI, sterile neutrinos, violations of unitarity.

Nature of neutrinos

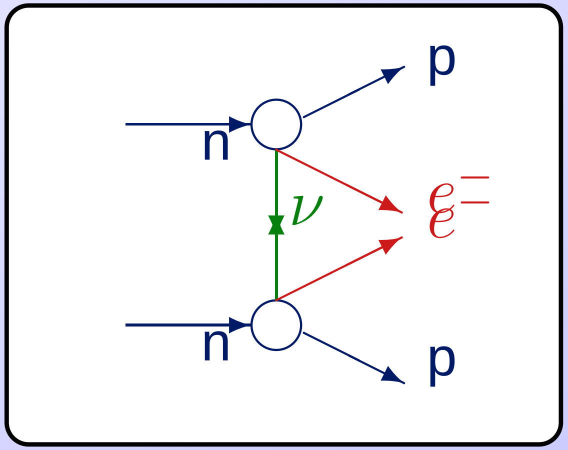
Neutrino can be either

Dirac	or	**Majorana**
lepton number conserved		lepton number broken

- The **nature of neutrinos** is directly related to the **fundamental symmetries** of elementary particles interactions.
- It provides important information on the **origin of neutrino masses**: in the see-saw mechanism neutrinos are predicted to be Majorana particles.
- Lepton number violation is one of the key ingredients of **leptogenesis** as the mechanism for generating the baryon asymmetry of the Universe.

2 – $(\beta\beta)_{0\nu}$-decay

neutrinoless double beta decay: $(A, Z) \rightarrow (A, Z+2) + 2e^-$, is the most sensitive of processes ($\Delta L = 2$) which can probe the **nature of neutrinos** (Dirac vs Majorana).



$(\beta\beta)_{0\nu}$-decay has a special role in the study of neutrino properties,

- as it probes the violation of **global lepton number**,
- it might provide information on the **neutrino mass spectrum**
- and test CP-V.

The half-life time, $T^{1/2}_{0\nu}$ can be factorized, for light Majorana neutrinos, as:

$$\left[T^{1/2}_{0\nu}(0^+ \to 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |{<m>}|^{\,2}$$

- $|{<m>}|$ **is the effective Majorana mass parameter**:

$$|{<m>}| \equiv |\, m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \,| \,,$$

The present best limit on $|{<m>}|$ reads:

$|{<m>}| < (350 - 1050)$ meV	**Heidelberg-Moscow**
$|{<m>}| < (680 - 2800)$ meV	**NEMO3**
$|{<m>}| < (190 - 680)$ meV	**CUORICINO**

A claim of $(\beta\beta)_{0\nu}$decay discovery has been published [Klapdor-Kleingrothaus et al., PLB 2004]. It implies $|{<m>}| \simeq 200 - 600$ meV .

There are prospects to improve the present limit and test the discovery claim down to $|<m>| \sim 200 - 300\ \mathrm{meV}$ in the present experiments NEMO3 and Cuoricino

and by one order of magnitude, $|<m>| \sim 10 - 30\ \mathrm{meV}$, in the new generation of experiments which is now under R&D and construction (CUORE, Majorana, SuperNEMO, EXO, GERDA, COBRA, SNO+, NEXT).

The predictions for $|<m>|$ depend strongly on the type of spectrum.

- NH: $$|<m>| \simeq \left| \sqrt{\Delta m^2_\odot} \cos^2\theta_{13} \sin^2\theta_\odot + \sqrt{\Delta m^2_{\rm atm}} \sin^2\theta_{13} e^{i\alpha_{32}} \right|$$

$$2.5 \ \text{meV} \lesssim |<m>| \lesssim 3.9 \ \text{meV}$$

- IH:

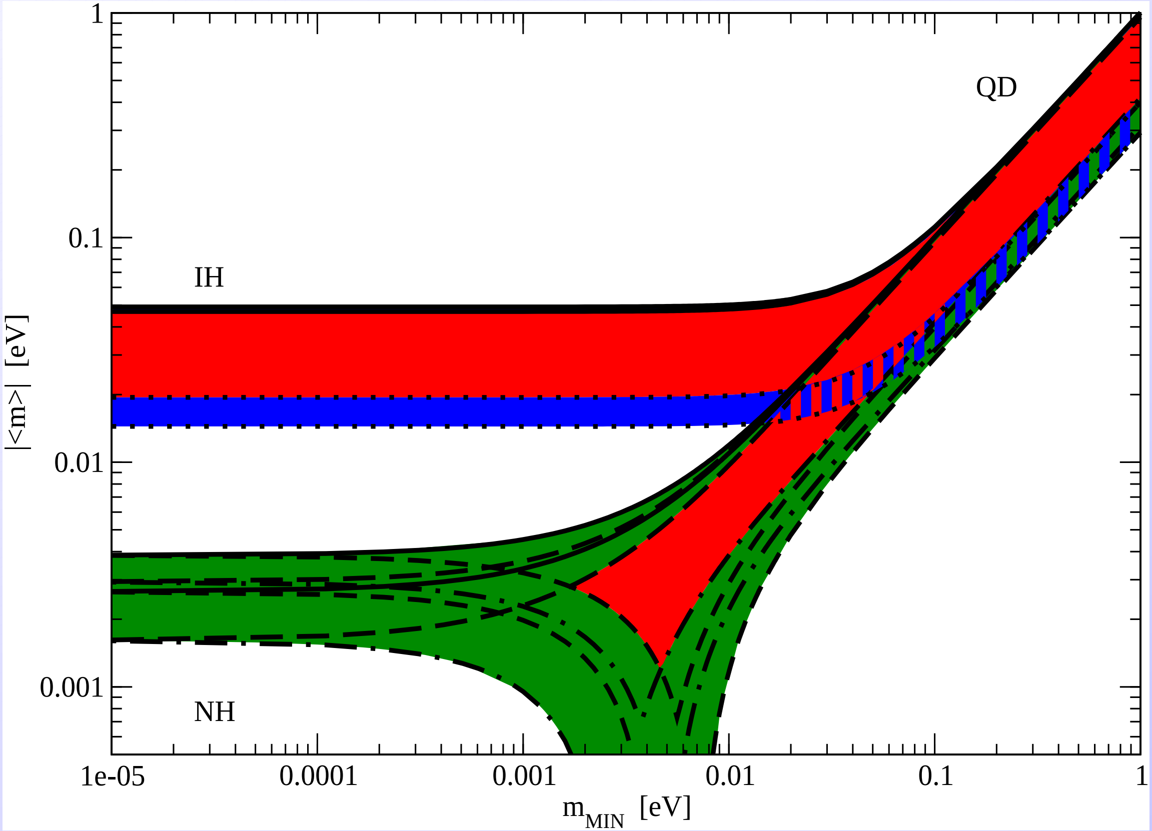
$$\sqrt{\Delta m^2_{\rm atm}} \cos 2\theta_\odot \leq |<m>| \simeq \sqrt{\left(1 - \sin^2 2\theta_\odot \sin^2 \frac{\alpha_{21}}{2}\right) \Delta m^2_{\rm atm}} \leq \sqrt{\Delta m^2_{\rm atm}}$$

$|<m>|$ has a significant lower and upper bound

$$0.01 \ \text{eV} \lesssim |<m>| \lesssim 0.05 \ \text{eV}$$

- QD: $$|<m>| \simeq m_{\bar\nu_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}\right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

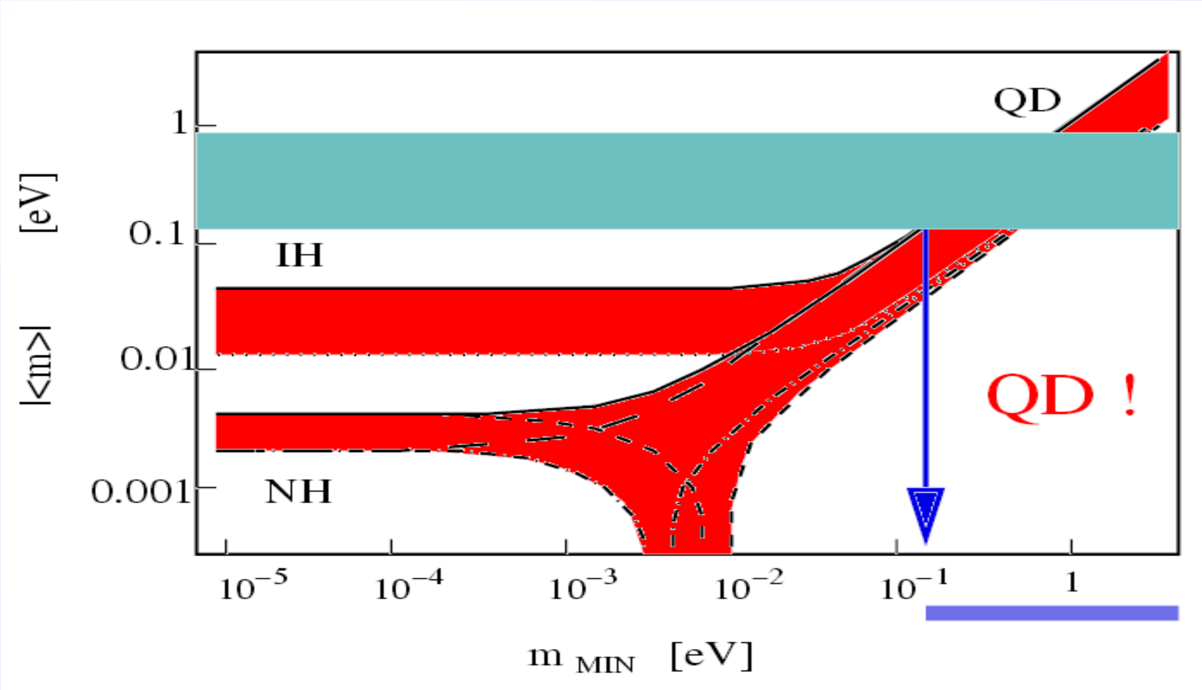
$$|<m>| \gtrsim 0.044 \ \text{eV}$$



All the allowed range for $|<m>|$ for QD and IH is in the range of sensitivity of present and upcoming $(\beta\beta)_{0\nu}$-decay experiments.

[S.P., Petcov, PLB2003; S.P., Petcov, Rodejohann, 2003;S.P., Petcov and Schwetz, 2005, S. P., Petcov, 2008]

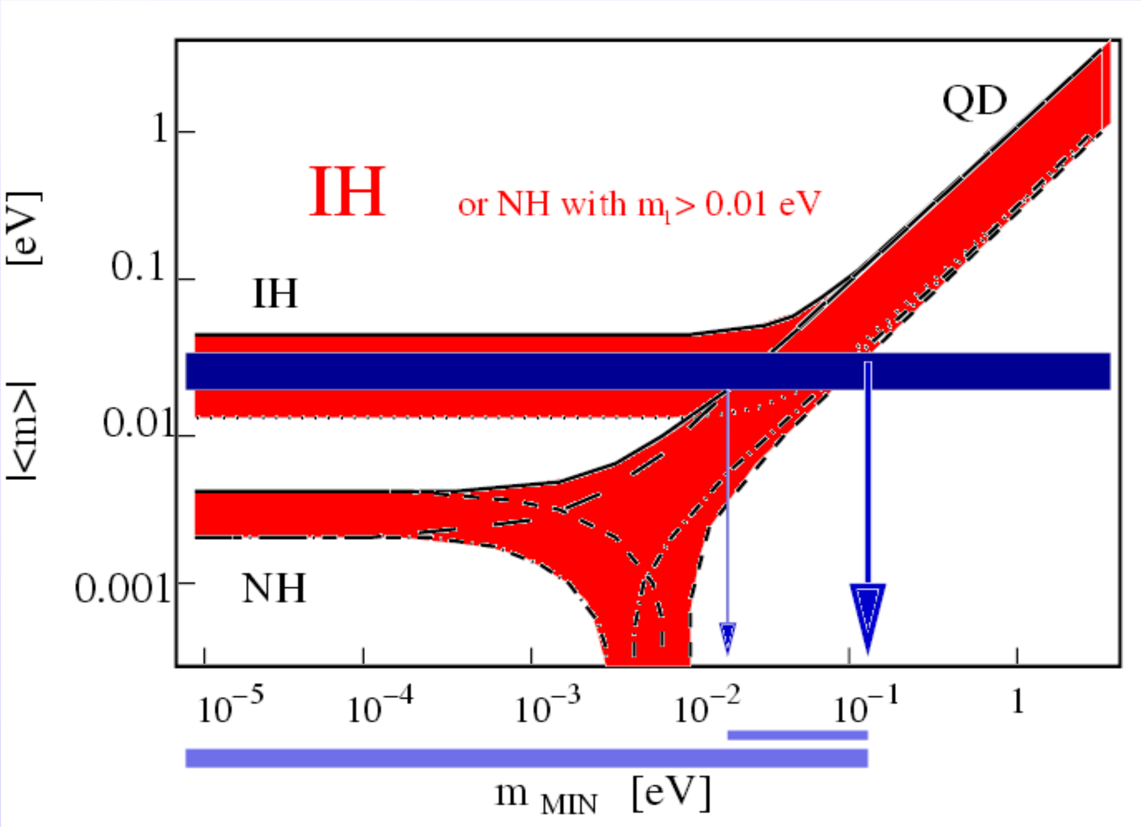
3 – $(\beta\beta)_{0\nu}$decay and determining ν masses



If $|{<}m{>}| \ > 0.2$ eV, this would imply QD spectrum ($m_0 > 0.2$ eV).

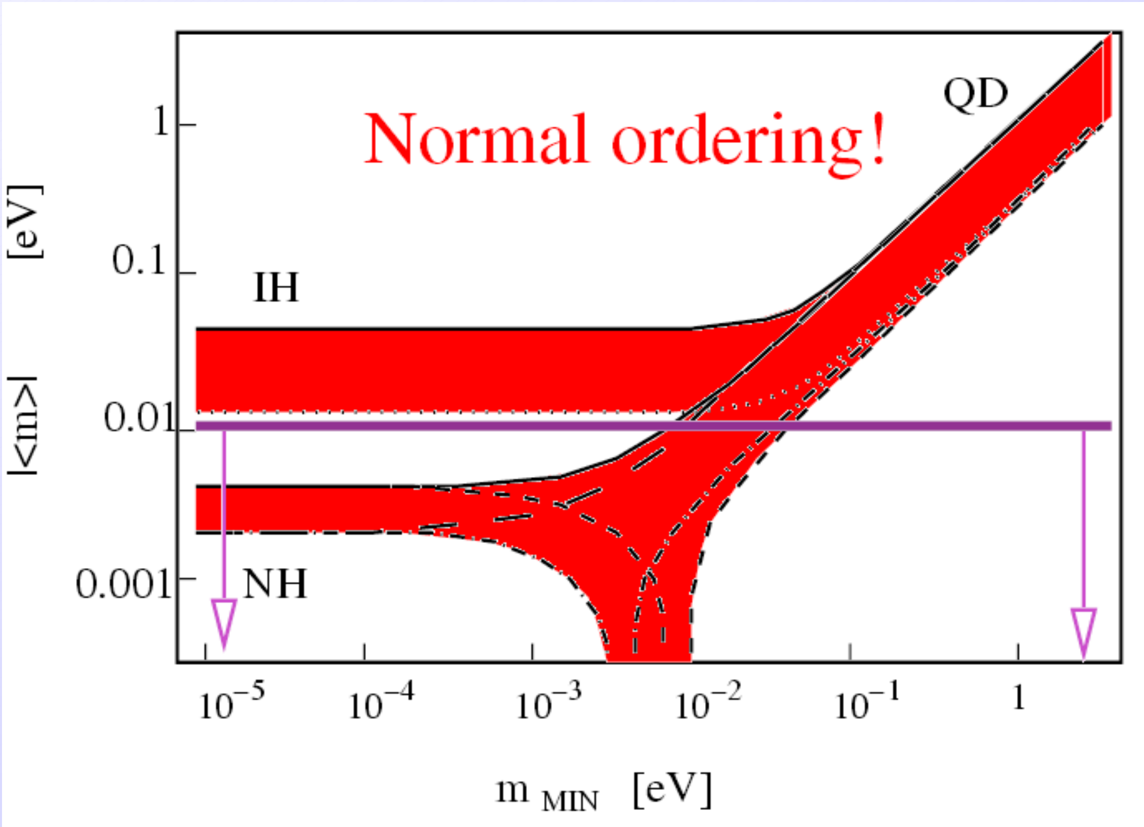
$(\beta\beta)_{0\nu}$exp can also constrain a range of m_0: $|{<}m{>}| \ \leq m_0 \leq \dfrac{|{<}m{>}|}{\cos 2\theta_\odot}$

The measurement of m_0 is entangled with the value of the Majorana CP-violating phases.



If $0.01\,\mathrm{eV} \lesssim |<m>| \lesssim 0.05\,\mathrm{eV}$, the spectrum is of the IH type: inverted hierarchy and m_{MIN} negligible.

There is a narrow range of values of m_{MIN} for which the hierarchy can be normal. To disentangle the two cases additional information is required.



If $|<m>| < 0.01 \text{ eV}$, the only possibility is normal hierarchy, for Majorana neutrinos.

4 – $(\beta\beta)_{0\nu}$-decay and CP-violation

Let's consider the most favourable case: Mass quasi degeneracy (QD)

$(m_1 \simeq m_2 \simeq m_3 \equiv m_{\bar{\nu}_e})$

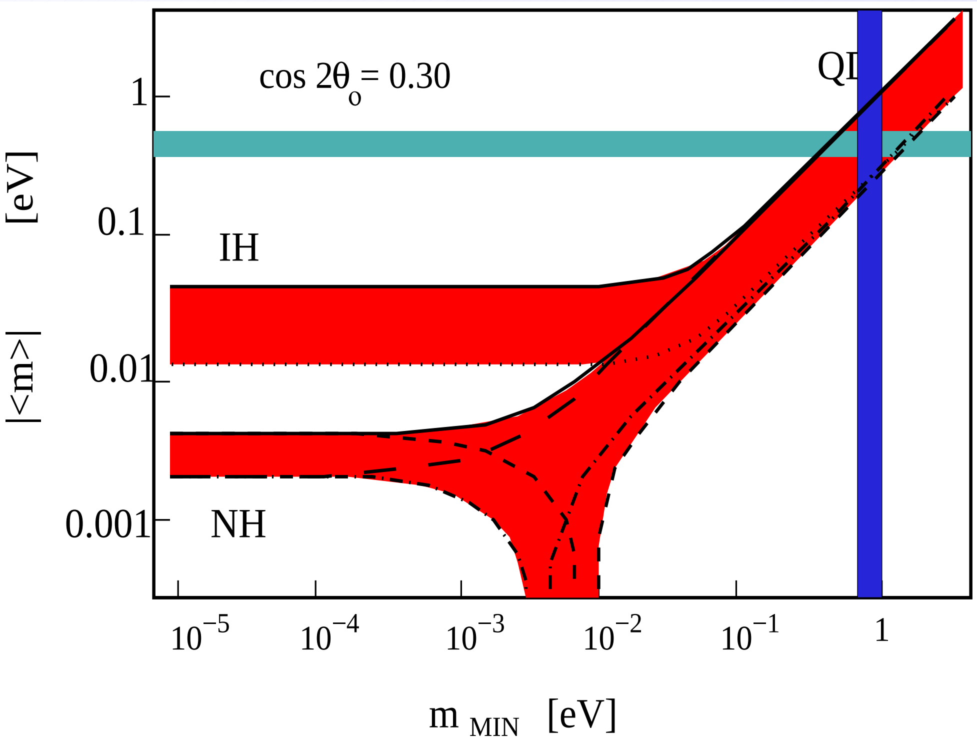
$$|{<}m{>}| \simeq m_{\bar{\nu}_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}} \right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

$|{<}m{>}|$ can provide information on m_1, α_{21} and α_{31}.

It is necessary to know with very good precision:

- the oscillation parameters ($\theta_\odot$)
- the neutrino mass values $m_{\bar{\nu}_e}$
- $|{<}m{>}|$

Challenging task!



In principle, measuring $|<m>|$

combined with a measurement of m_1

(in β-decay exp. and/or cosmology)

would allow to establish if

CP is violated

and to constrain the CPV phases,

with known neutrino mass spectrum.

Due to the experimental errors on the parameters and nuclear matrix elements uncertainties, determining that CP is violated in the lepton sector due to Majorana CPV phases is challenging. (Barger et al.; S.P., Petcov, Rodejohann)

5 – $(\beta\beta)_{0\nu}$-decay and Leptogenesis

- Leptogenesis takes place in the context of see-saw models, which explain the origin of neutrino masses. It can successfully explain the observed baryon asymmetry.

It requires:

- L violation;
- C and CP violation;
- out of equilibrium (expansion of the Universe).

The observation of L-violation and of CPV in the lepton sector would be an indication, even if not a proof, of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

$(\beta\beta)_{0\nu}$-decay plays a crucial role in testing the conditions necessary for leptogenesis.

6 – The use of different nuclei

It is important to have experiments which use different nuclei.

1. independent evidences

2. reduce the impact of nuclear matrix elements

$$(\mathrm{T}_{0\nu}^{1/2})^{-1} \propto M_{\mathrm{nuclear}}{}^{2} |{<}m{>}|^{\,2}$$

M_{nuclear} are the limiting factor in extracting information on CP-violation from $(\beta\beta)_{0\nu}$-decay and affect the sensitivity to neutrino masses!

3. distinguishing the mechanism of neutrinoless double beta decay

7 – Sinergy between $(\beta\beta)_{0\nu}$-decay and neutrino exp

- $(\beta\beta)_{0\nu}$-decay and LBL exp are **complementary** in the quest for ν-masses.

They exploit completely different physics effects.

1) If $\sin^2 2\theta_{13} \ll 0.001 - 0.0001$, future generation LBL experiments will not be able to resolve the type of hierarchy. $(\beta\beta)_{0\nu}$-decay is a viable alternative.

2) If ν's are Dirac particles, $(\beta\beta)_{0\nu}$-decay will not find any signal. Neutrino oscillations in LBL exp. do not depend on neutrino nature and can determine the type of hierarchy.

- $(\beta\beta)_{0\nu}$-decay and LBL have a strong sinergy: important information can be obtained from **combining** their results.

Probing Dirac particles and lepton number conservation:

If LBL establishes that is IH and $(\beta\beta)_{0\nu}$-decay reach a sensitivity of $|{<}m{>}| \sim 10$ meV without finding a signal, this implies that neutrinos are **Dirac particles**.

- $(\beta\beta)_{0\nu}$-decay and β-decay have a strong sinergy:

Determine CP-V using the measurement of m_1 in β-decay exp together with $|{<}m{>}|$ from $(\beta\beta)_{0\nu}$-decay.

8 – $(\beta\beta)_{0\nu}$-decay: Conclusions

- Establishing the nature of neutrinos, their masses and CPV is of fundamental importance for understanding the origin of neutrino masses and flavour.
- $(\beta\beta)_{0\nu}$-decay plays a special role as it can test lepton number violation, provide information on the neutrino mass spectrum and, possibly, on CPV.
- The next generation of experiments will be able to probe all the allowed range of values for $|<m>|$ in the case of QD and most of it for IH.
- $(\beta\beta)_{0\nu}$-decay is crucial in testing the conditions for leptogenesis.
- $(\beta\beta)_{0\nu}$-decay has important synergies and complementarities with other experiments.

9 – Lepton flavour violation

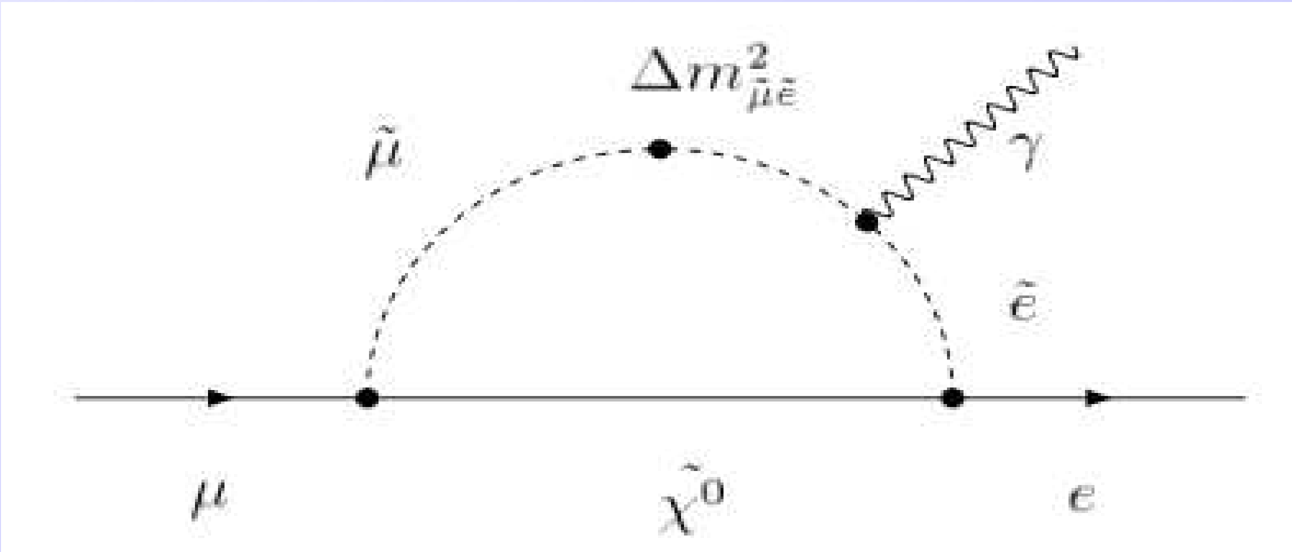
Neutrino oscillations imply **lepton flavour violation**. So we expect LFV processes:

$$\mu \to e\gamma, \mu N \to eN, \mu \to eee$$

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_j U^*_{\mu j} U_{ej} \frac{\Delta m^2_{1j}}{M^2_W} \right|^2 < 10^{-54}$$

We expect much larger rates if there is new physics at the electroweak scale and if mixing in the lepton sector is large.

$$\mathcal{L} = \frac{m_\mu}{(k+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{k}{(1+k)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$



[Kuno, Okada, 99]

10 – The see-saw mechanism

The see-saw mechanism provides a natural explanation for the smallness of neutrino masses. [Minkovski; Yanagida; Gell-Mann, Ramond, Slansky]

At high energy ($10^9 - 10^{15}$ GeV), RH neutrinos are introduced. They are singlets with respect to the gauge group of the SM and possess very heavy Majorana masses:

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

- **Lepton number is violated.**
- The see-saw mechanism can be embedded in GUT theories.

At low energy, integrating out the heavy neutrinos, the light neutrino masses are naturally small.

$$\mathcal{L} = (\nu_L^T N^T) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

$$\boxed{\begin{array}{l} M_1 \simeq M_R \\ m_2 \simeq \frac{m_D^2}{M_R} \sim \frac{1\ \mathrm{GeV}^2}{10^9\ \mathrm{GeV}} \sim 1\,\mathrm{eV} \end{array}}$$

In a 3 neutrino mixing, light masses are given by:

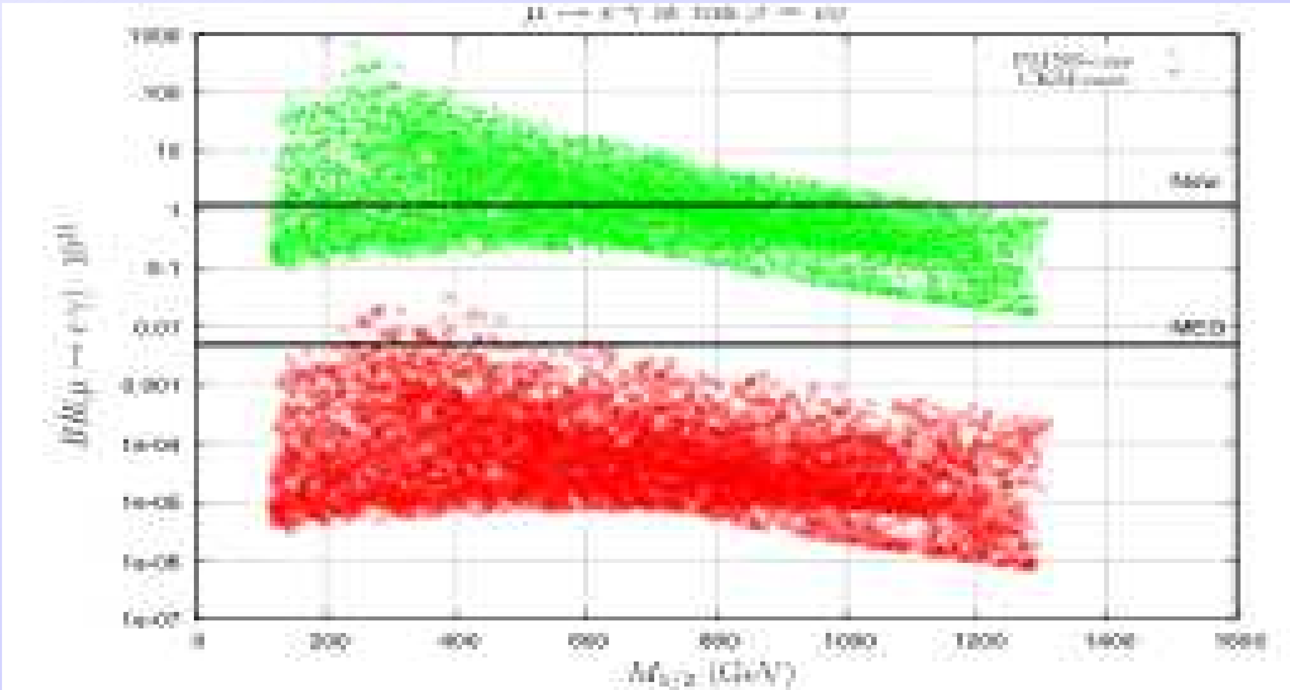
$$\boxed{m_\nu = U^* d_m U^\dagger \simeq -Y_\nu^T M_R^{-1} Y_\nu v^2}$$

- Light neutrinos are predicted to be Majorana particles.

Even if the soft breaking terms are diagonal at the SUSY breaking scale M_X, the radiative corrections due to Y_ν induce off-diagonal soft terms.

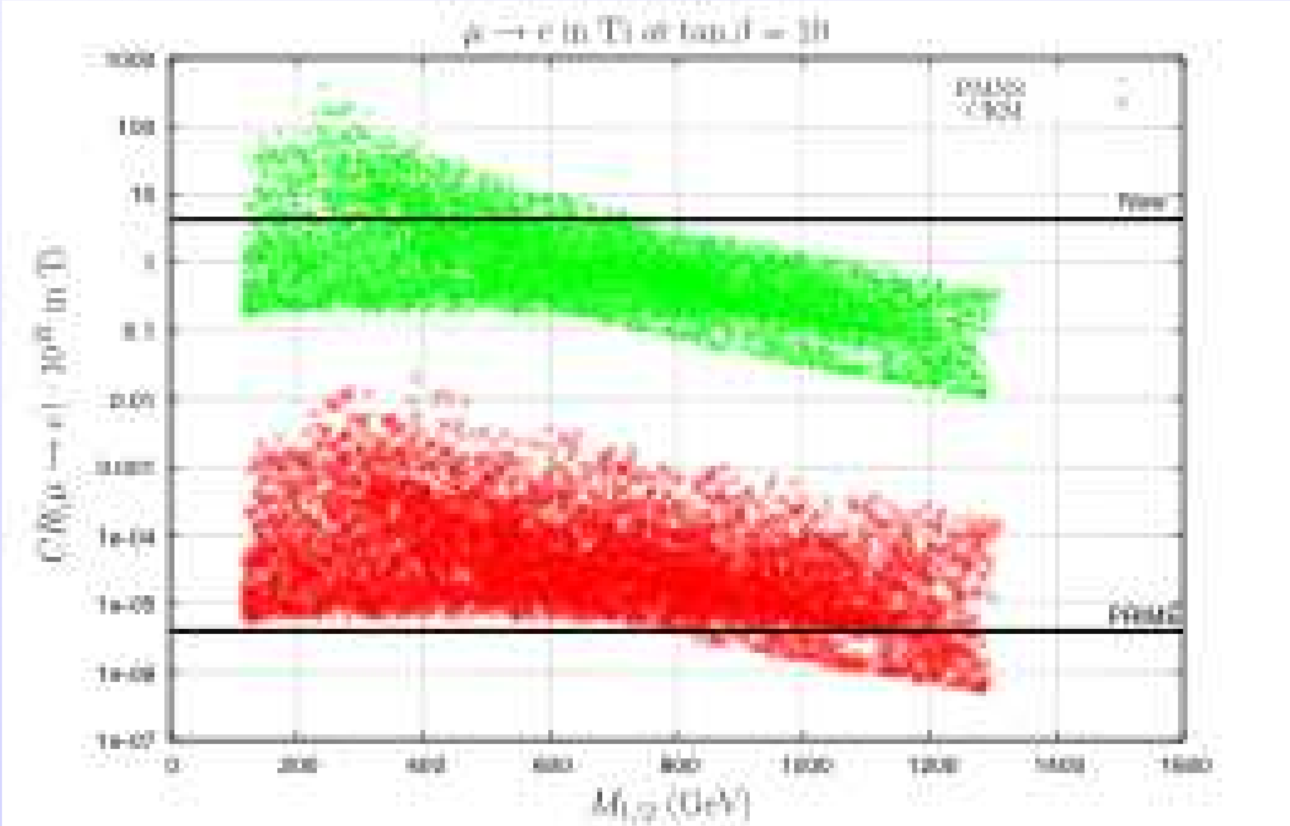
$$BR(l_i \to l_j \gamma) \propto |P_{ij}|^2$$

$$P = Y_\nu^\dagger \log \frac{M_X}{M} Y_\nu .$$



[Calibbi et al, 2006]

Predictions for $\mu - e$ conversion. They can be enhanced with respect to the other LFV processes.



[Calibbi et al, 2006]

Leptogenesis and LFV

The baryon asymmetry depends on

$$Y_B \simeq -\frac{12}{37 g_*} \left(\epsilon_\tau \eta \left(\frac{390}{589} \widetilde{m_\tau} \right) - \epsilon_2 \eta \left(\frac{417}{589} \widetilde{m_2} \right) \right)$$

where the CP-asymmetry depends on Y_ν as

$$\epsilon_l \propto \sum_j \mathrm{Im} \left((Y_\nu)_{1l} (Y_\nu Y_\nu^\dagger)_{1j} (Y_\nu)^*_{jl} \right) \frac{M_1}{M_j}$$

Observing LFV processes would allow to get independent information on Y_ν and further constrain leptogenesis.

Other mechanisms can also enhance LFV processes:

- SUSY with R-parity violation
- heavy sterile neutrinos which mix with light ones
- extra-dimension models

The dominance of one channel ($\mu \longrightarrow e\gamma$, $\mu - e$ conversion, $\mu \longrightarrow eee$) depends on the specific model.

11 – LFV: Conclusions

- LFV processes are expected at an enhanced rate if new physics at the 100 GeV–1 TeV scale and large mixing in the leptonic sector.

- Indirect information can be obtain on the new physics.

- Combine this information with the one coming from low energy neutrino physics and leptogenesis as well as direct searches of new physics at colliders.