Neutrino Theory: towards an understanding of the origin of neutrino masses and mixing beyond the SM

01 July 2015

CHIPP 2015 Annual Theory Meeting
Chateau de Bossey

Silvia Pascoli

IPPP – Durham University

Outline

1. Present status of neutrinos

2. Open phenomenological questions

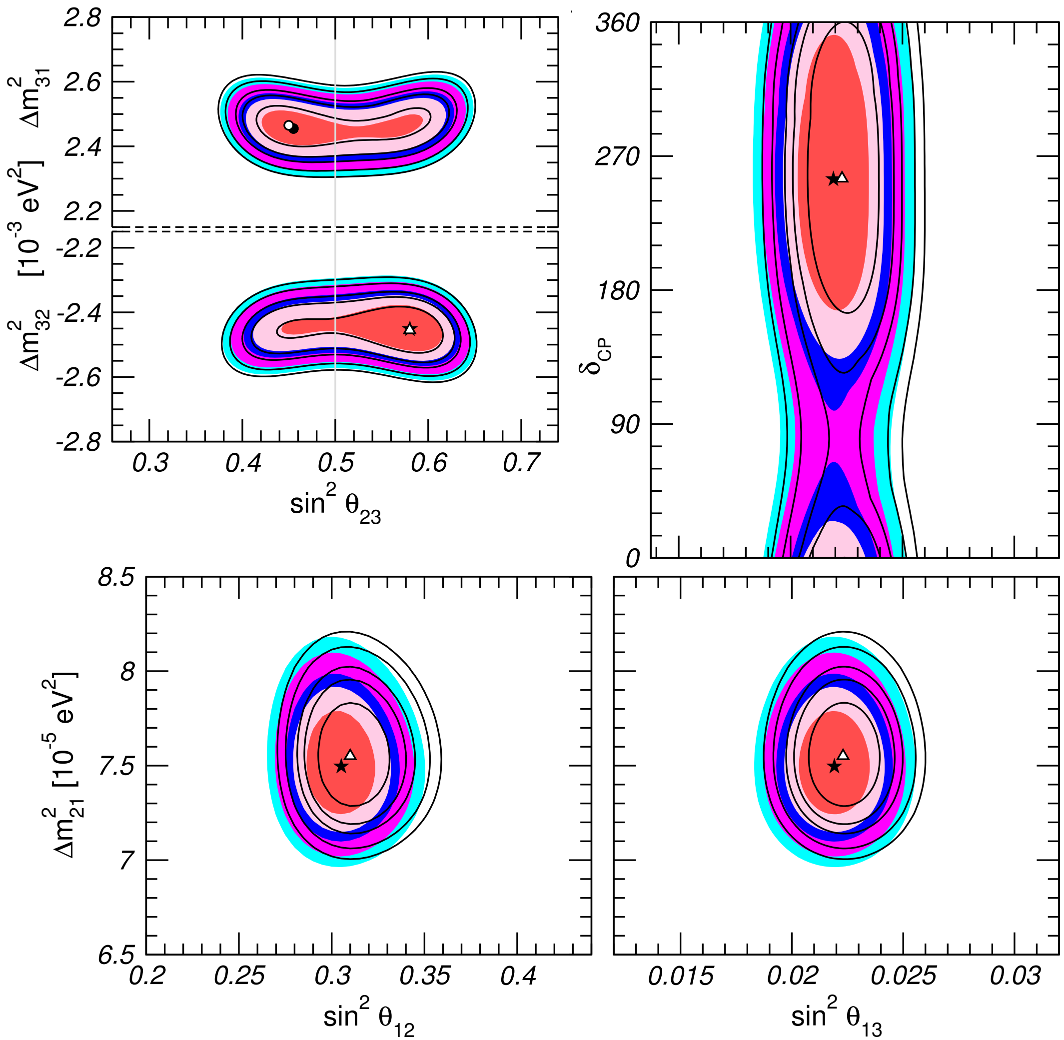
3. Neutrinos and physics BSM
   - The origin of neutrino masses
   - Leptonic flavor (very briefly)

4. How to discriminate between different models of neutrino masses

5. Conclusions

Neutrino properties after Neutrino 2014

NuFIT 2.0 (2014)



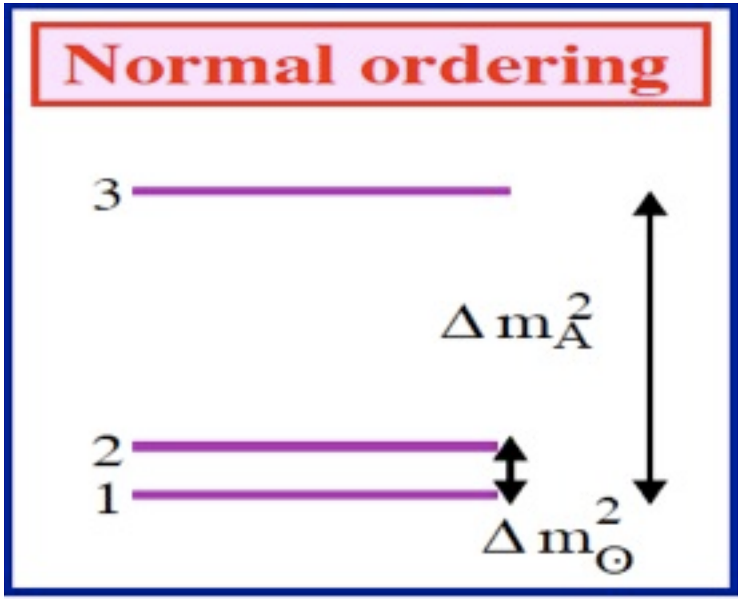
	Normal Ordering ($\Delta\chi^2 = 0.97$)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$

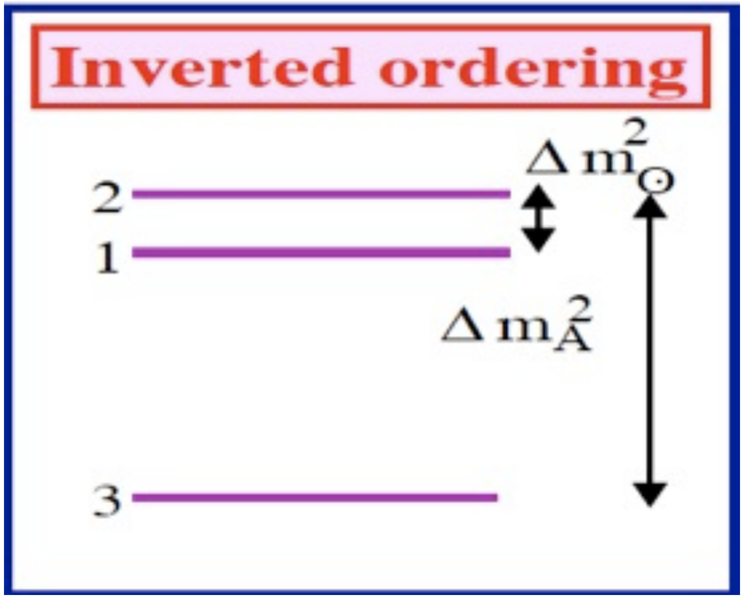
2 mass squared differences and 3 sizable mixing angles, some weak hints of CPV

http://www.nu-fit.org/

M. C. Gonzalez-Garcia et al., 1409.5439

$\Delta m_{\rm s}^2 \ll \Delta m_{\rm A}^2$ implies at least 3 massive neutrinos.





$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 - \Delta m_{\rm sol}^2}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering.

Phenomenology questions for the future

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **3. Is there CP-violation?**
- **4. What are the precise values of mixing angles?**
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

Very exciting experimental programme now and for the future.

Phenomenology questions for the future

- **1. What is the nature of neutrinos?** Neutrinoless dbeta decay
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering. LBL: T2K, NOvA, DUNE, T2HK, ESSnuSB, Daedalus, nuFACT..., PINGU
- **3. Is there CP-violation?**
- **4. What are the precise values of mixing angles?** reactor SBL and MBL, atm, LBL, ...
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects? MINOS+, MicroBooNE, ...

Very exciting experimental programme now and for the future. See Weber's, Rubbia's, Blondel's and Baudis's talks

Neutrino oscillations imply that neutrinos have mass and mix.

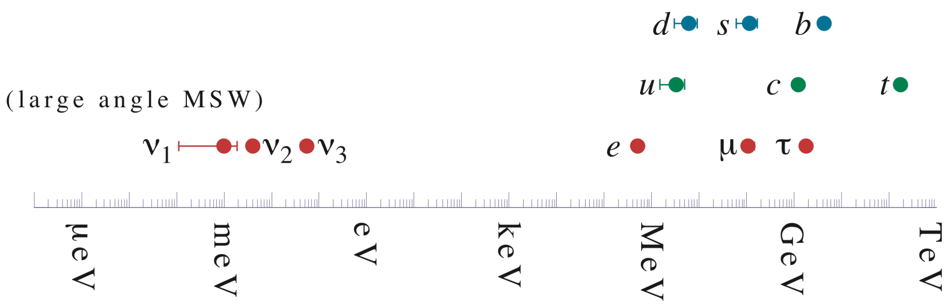
First evidence of physics beyond the SM.

The ultimate goal is to understand
- where do neutrino masses come from?
- what is the origin of leptonic mixing?

Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



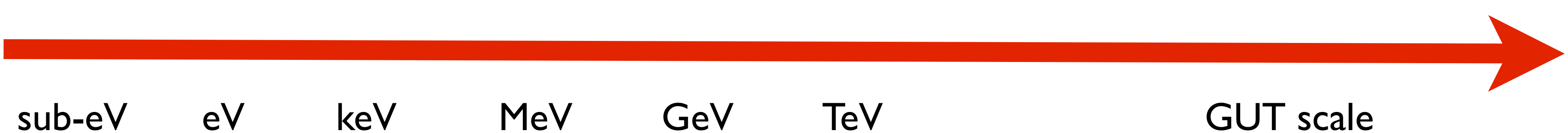
Why neutrinos have mass?
and why are they so light?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

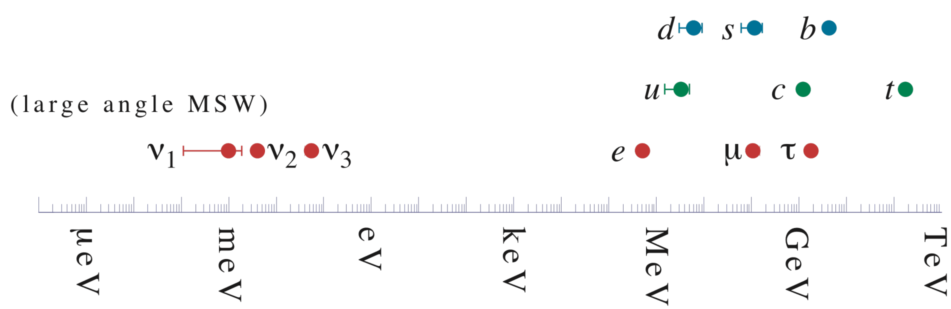
Why leptonic mixing is so different from quark mixing?
What is the CPV's origin?



Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so light?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?
What is the CPV's origin?

sub-eV eV keV MeV GeV TeV GUT scale

Neutrino Masses in the SM and beyond

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

- Dirac masses do not arise as there are no right-handed neutrinos.

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

- They do not have a Majorana mass term

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

as this term breaks the SU(2) gauge symmetry.
This term breaks Lepton Number.

Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson is allowed.

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}$$

This conserves lepton number!

Masses and Mixing emerge from diagonalising this matrix.

$$m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

$$n_L = U^\dagger \nu_L \quad n_R = V^\dagger \nu_R$$

$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$$

Tiny couplings!

- why the coupling is so small????
- why the mixings are large?
- why neutrino masses have at most a mild hierarchy?

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow new scalar fields, e.g. a triplet):

$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

D=5 term

Weinberg operator, PRL 43

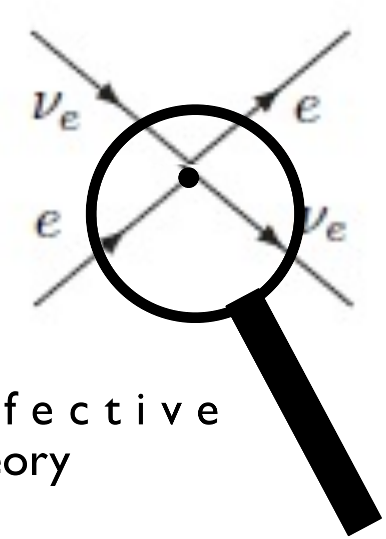
Lepton number violation!

Masses and mixing come from diagonalising the mass matrix

$$M_M = (U^\dagger)^T m_{\mathrm{diag}} U^\dagger$$

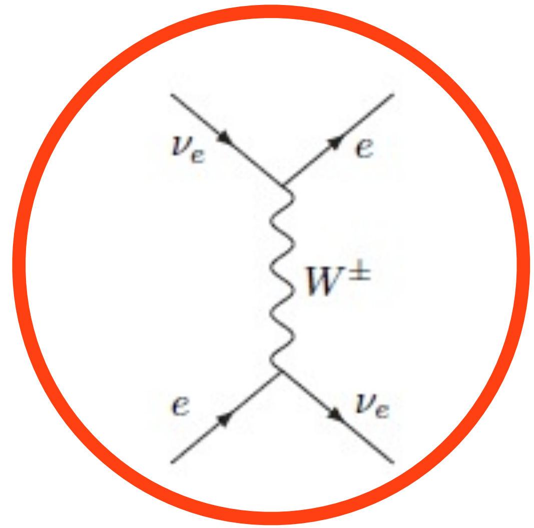
$$n_L = U^\dagger \nu_L$$

If neutrino are Majorana particles, a **Majorana mass** can arise as the low energy realisation of a higher energy theory (new mass scale!).



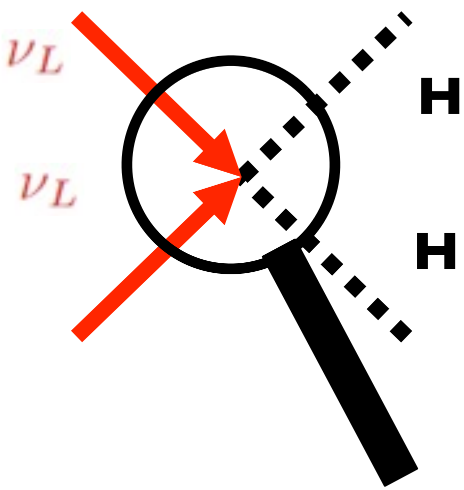
effective theory

$$\mathcal{L} \propto G_F(\bar{e}_L\gamma_\mu\nu_L)(\bar{\nu}_L\gamma^\mu e_L)$$



Standard Model:
W exchange

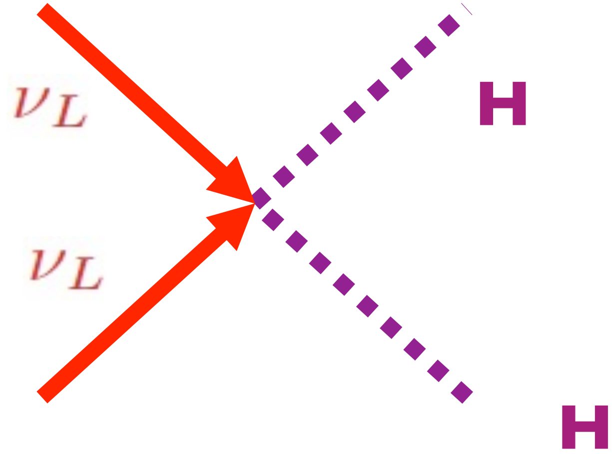
$$\mathcal{L}_{SM} \propto g\bar{\nu}_L\gamma^\mu e_L W_\mu \Rightarrow G_F \propto \frac{g^2}{m_W^2}$$



Neutrino mass

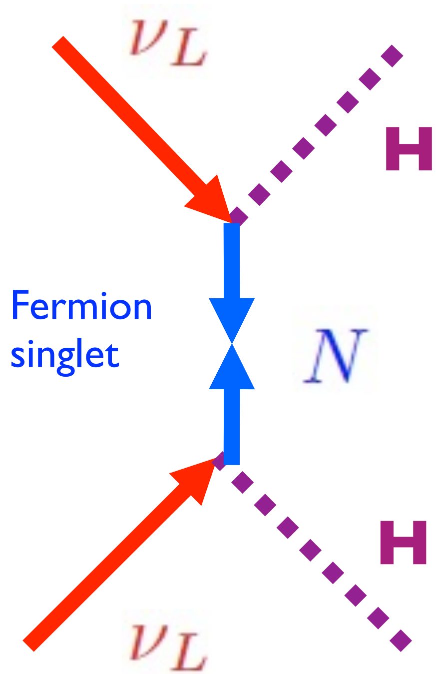
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M}$$

New theory:
new particle
exchange with
mass M



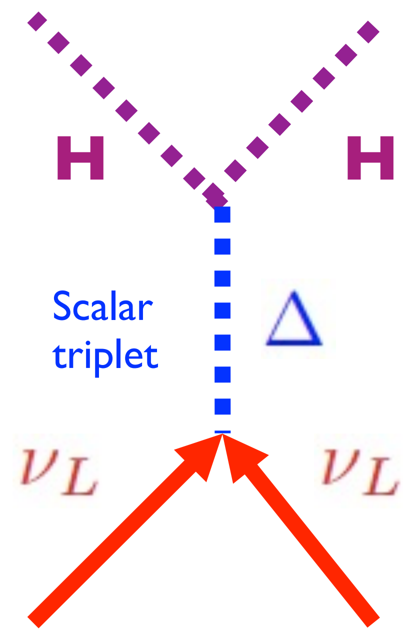
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M}$$

See-saw Type I



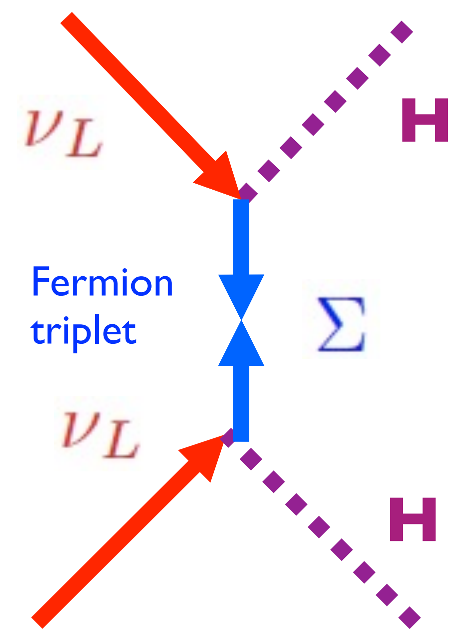
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



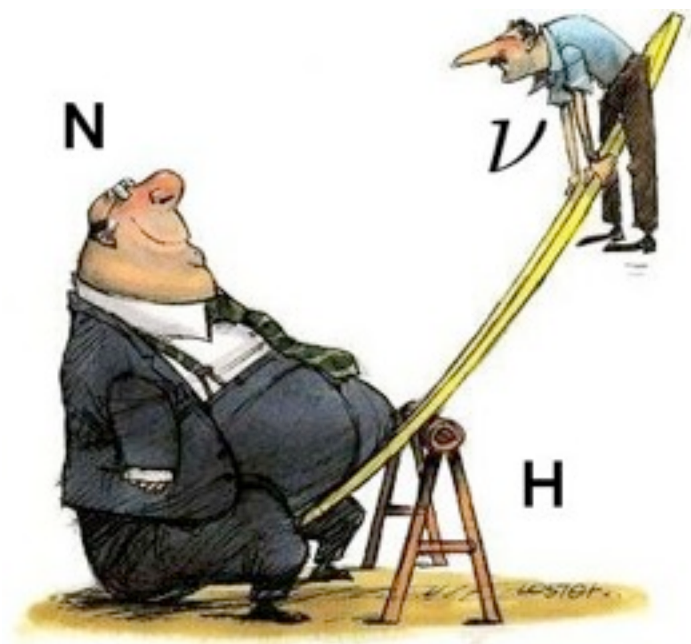
Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

See-saw Type III



Ma, Roy, Senjanovic, Hambye

Neutrino masses BSM: see saw mechanism type I



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

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

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \text{GeV}^2}{10^{10}\text{GeV}} \sim 0.1\ \text{eV}$$

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

See-saw type I models can be embedded in GUT and explain the baryon asymmetry via leptogenesis.

Pros:

- they explain "naturally" the smallness of masses.
- can be embedded in GUT theories!
- have several phenomenological consequences (depending on the mass scale), e.g. leptogenesis, LFV

Cons:

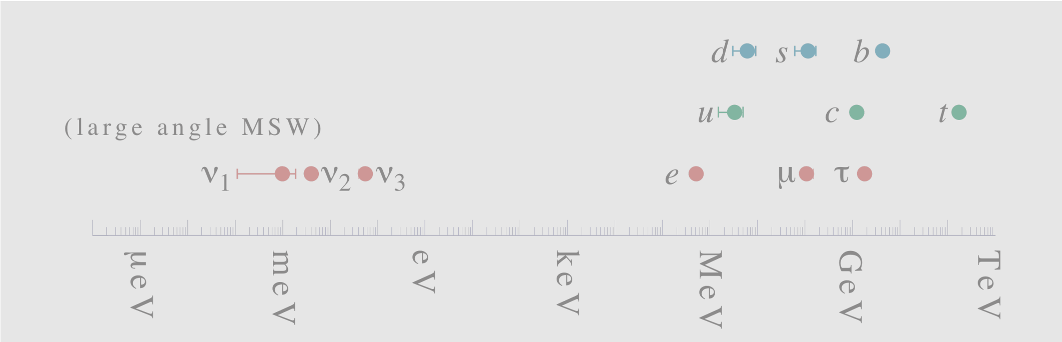
- the new particles are typically too heavy to be produced at colliders (but TeV scale see-saws)
- the mixing with the new states are tiny
- many more parameters than measurable
- in general: difficult to test

Many other models have been proposed:
- TeV scale see-saw (type I, II and III, inverse and extended)
- R-parity violating SUSY, radiative neutrino masses...

Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass? and why are they so lighter? and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

What is the CPV's origin?

Various strategies and ideas can be employed to understand the observed pattern (many many models!).

- Texture zero models with

$$\theta_{12,23,13} = \text{function}(\frac{m_e}{m_\mu}, \ldots, \frac{m_1}{m_2})$$

- Flavour symmetries: A4, A5, S4, ...

- Complementarity between quarks and leptons

$$\theta_{12} + \theta_C \simeq 45^o$$

- Anarchy (all elements of the matrix of same order).

The models predict specific values for the mixing angles and specific relations between the deviations from special values $\theta_{23} \sim 45^o, \theta_{13} \sim 0^o$.

Two necessary ingredients for testing flavour models:

- Precision measurements of the oscillation parameters at future experiments (including the delta phase).

- The determination of the mass hierarchy and of the neutrino mass spectrum.

Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2 \theta_{12}$	$\sin^2 \theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$\mathbf{L_e - L_\mu - L_\tau}$ **Models:**					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
$\mathbf{S_3}$ **and** $\mathbf{S_4}$ **Models:**					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
$\mathbf{A_4}$ **Tetrahedral Models:**					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

Albright, Chen, PRD 74

What is the new physics?

sub-eV eV keV MeV GeV TeV GUT scale

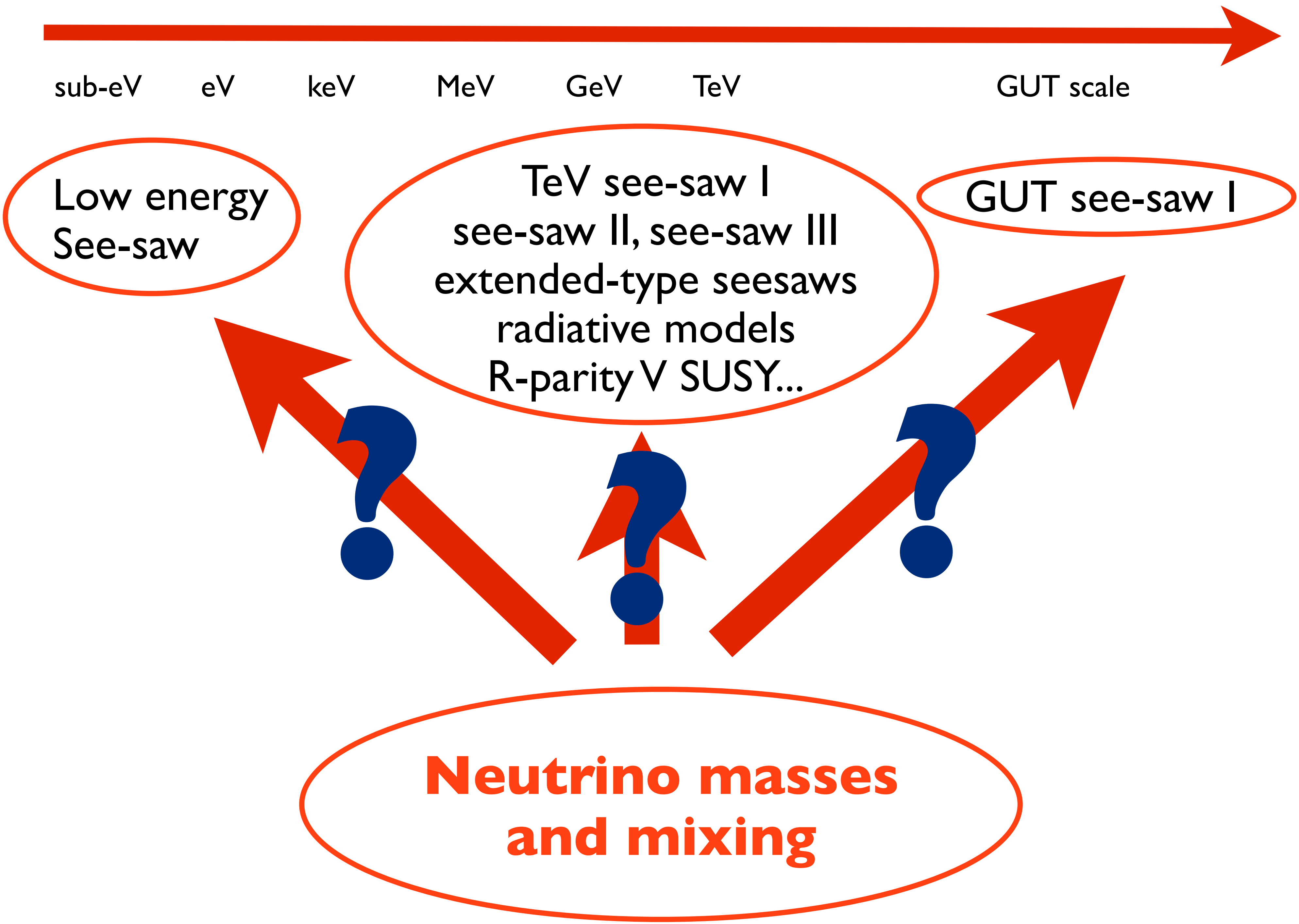
Low energy
See-saw

TeV see-saw I
see-saw II, see-saw III
extended-type seesaws
radiative models
R-parity V SUSY...

GUT see-saw I

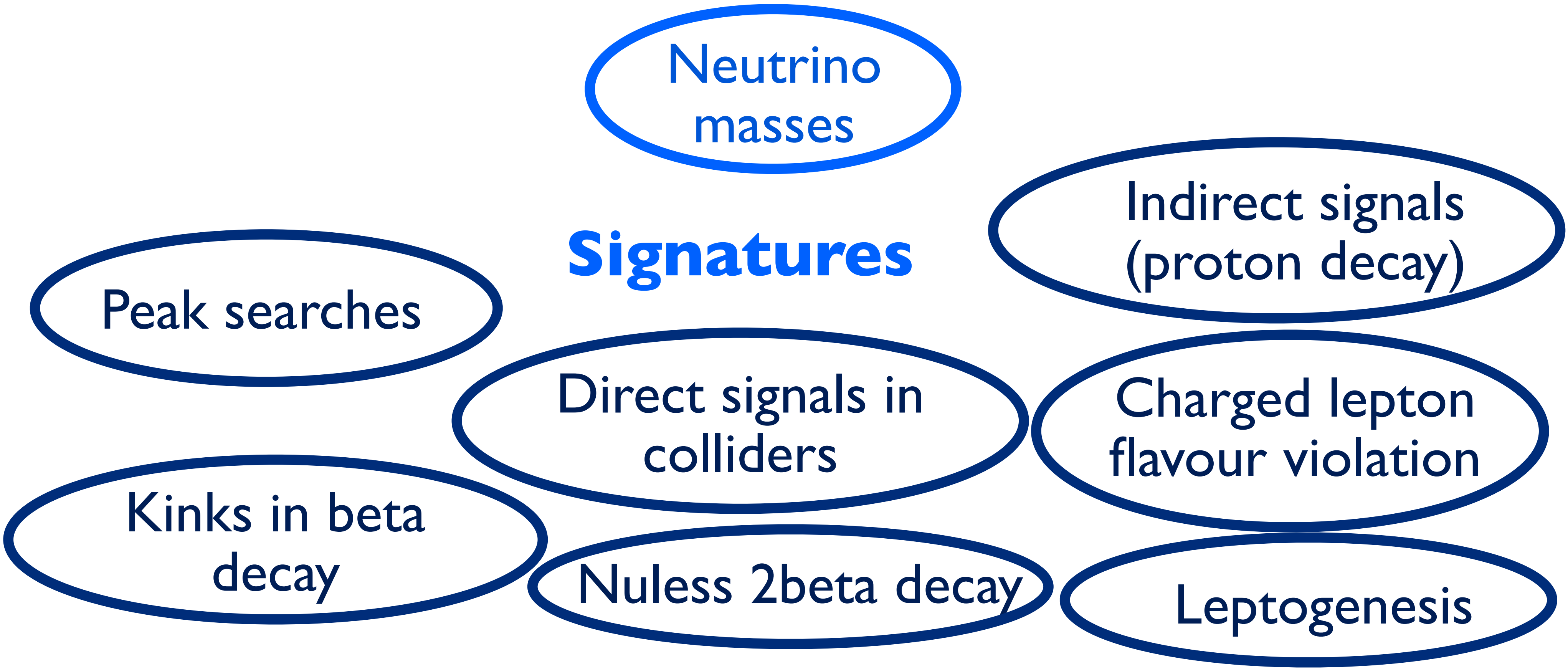
Neutrino masses and mixing

What is the new physics?



Complementarity with other searches

There are many (direct and indirect) signatures of these extensions of the SM.



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.

Conclusions

- Neutrino masses are the first evidence of Physics BSM and they provide a new complementary window w.r.t. collider and flavour physics searches.

- It is necessary to have precise information on the values of the masses and on the mixing angles and CPV phase. This is crucial to understand the origin of the leptonic flavour structure (e.g. flavour symmetries).

- Determining the New Standard Model (nuSM), responsible for neutrino masses, is the ultimate goal. It requires complementary information: CLFV, leptogenesis, direct searches at TeV scale and below, low energy probes (e.g. short baseline neutrino oscillations).