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

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PHENO 2015

U. of Pittsburgh

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IPPP – Durham University

Outline

1. Present status of neutrinos

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

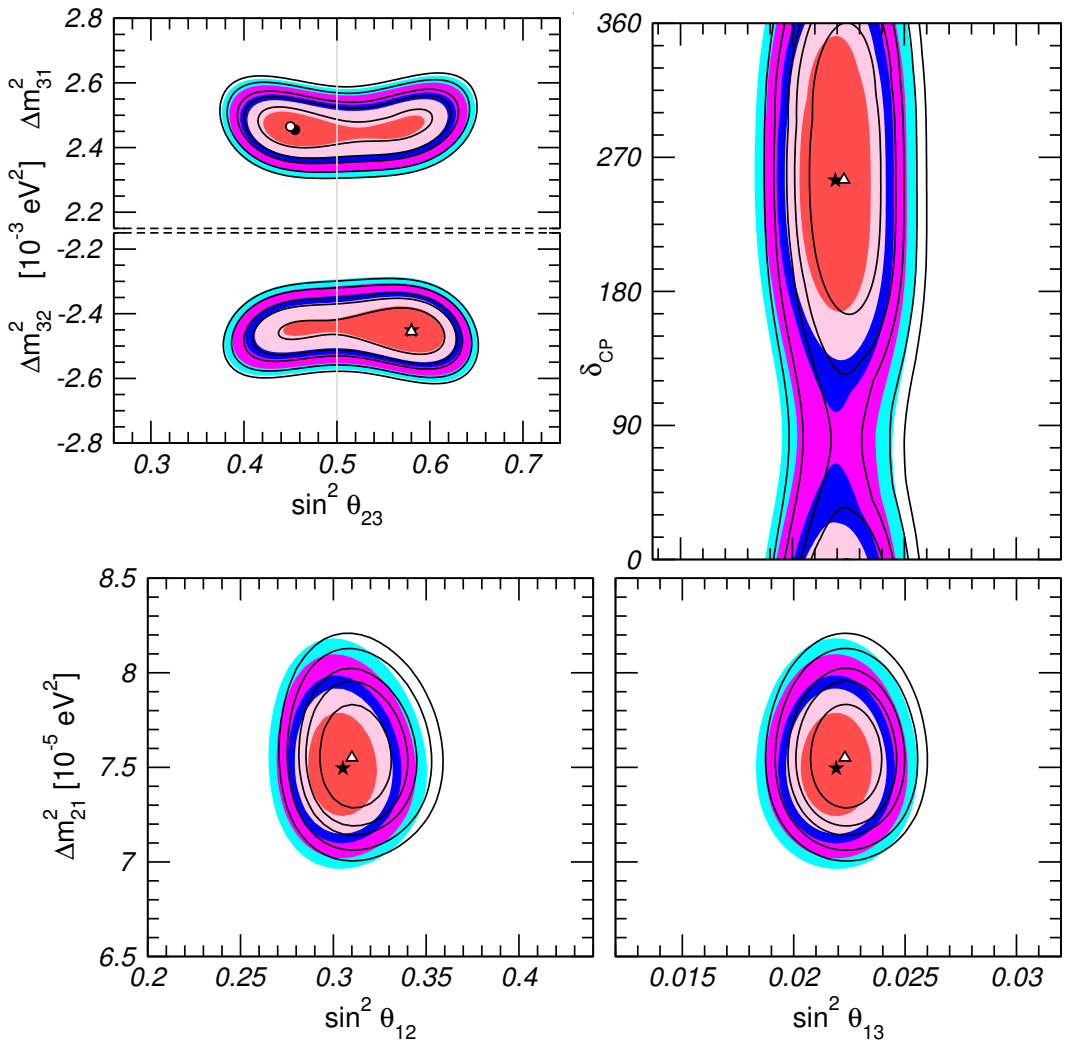
3. How to discriminate between different models of neutrino masses:
   - CLFV
   - Leptogenesis
   - Direct searches at colliders

4. An example of complementarity/ synergy between different signatures

5. Conclusions

Neutrino properties after Neutrino 2014

NuFIT 2.0 (2014)



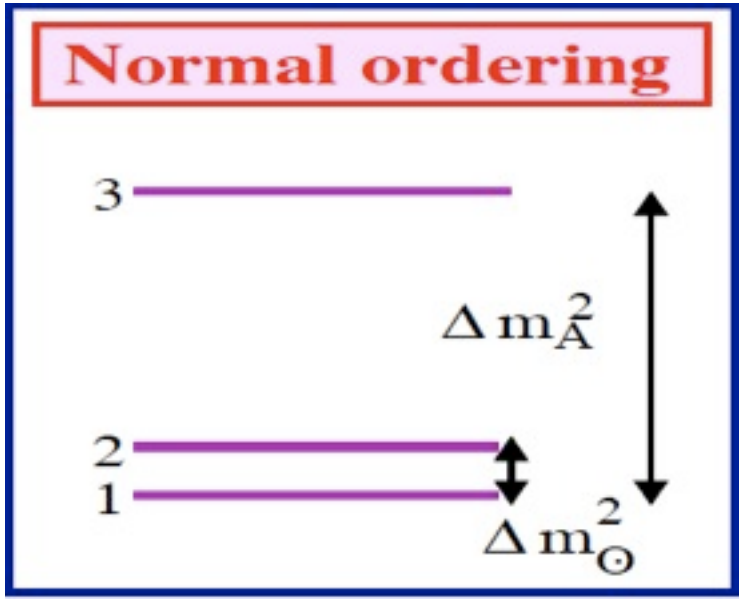
	Normal Ordering ($\Delta\chi^2 = 0.97$)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$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

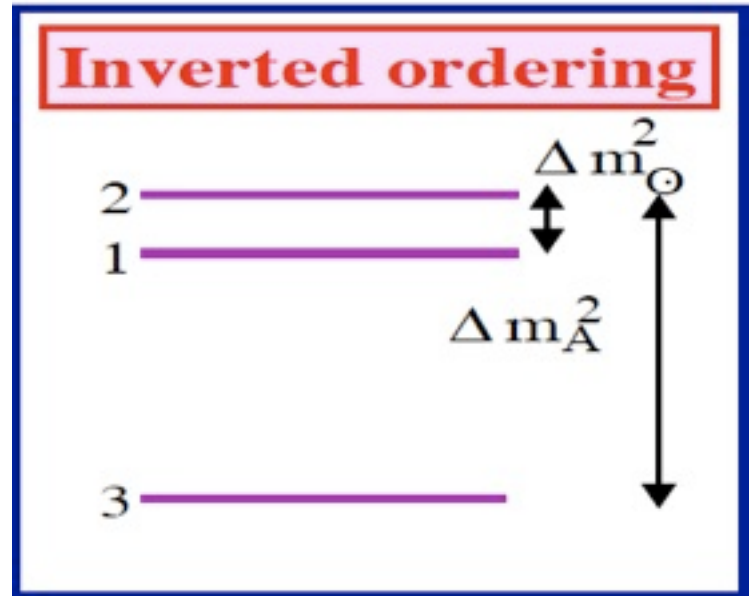
2 mass squared differences and 3 sizable mixing angles, some weak hints of CPV

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

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

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





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

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

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.
- **3. Is there CP-violation?**
- **4. What are the precise values of mixing angles?**

LBL: T2K, NOvA, DUNE, T2HK, ESSnuSB, Daedalus, nuFACT..., PINGU

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 talk by Sanchez (and also Forero, Yang)

Neutrino oscillations imply that neutrinos have mass and mix.

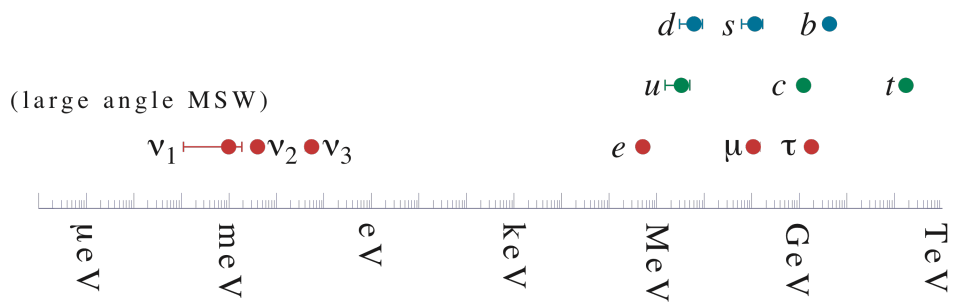
First evidence of physics beyond the SM.

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?

sub-eV eV keV MeV GeV TeV GUT scale

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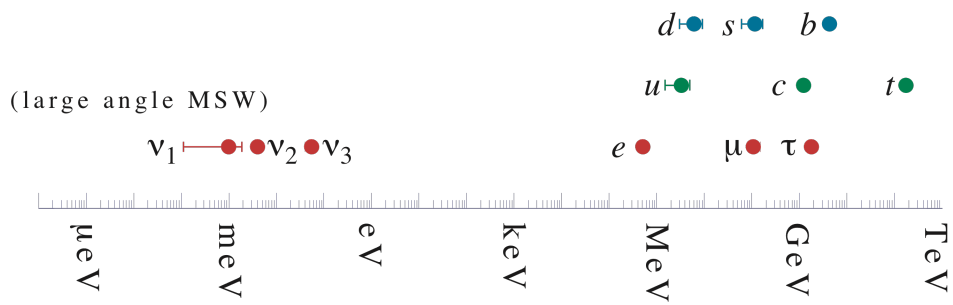

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Neutrino Masses in the SM and beyond

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

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

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

- 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

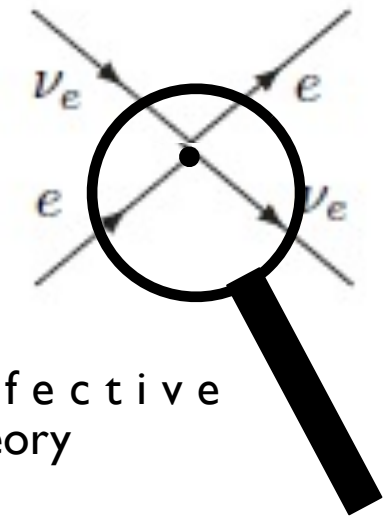
Lepton number violation!

Masses and mixing come from diagonalising the mass matrix

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

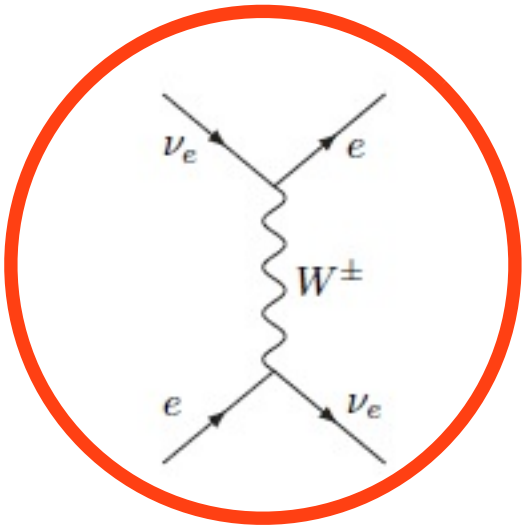
$$n_L = U^\dagger \nu_L$$

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



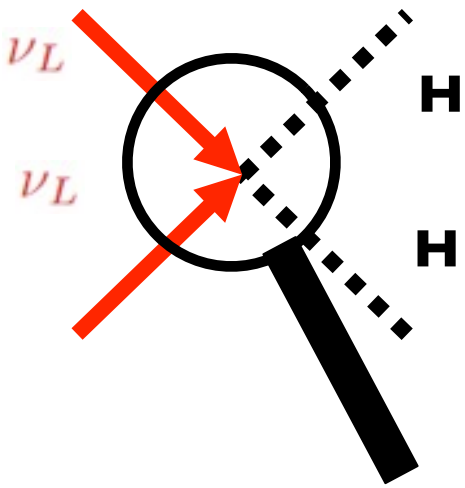
effective theory

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



Standard Model: W exchange

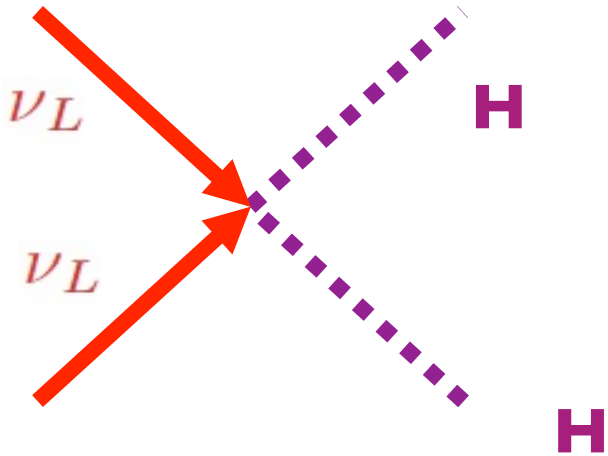
$$\mathcal{L}_{SM} \propto g\bar{\nu}_L\gamma^\mu e_L W_\mu \Rightarrow G_F \propto \frac{g^2}{m_W^2}$$



Neutrino mass

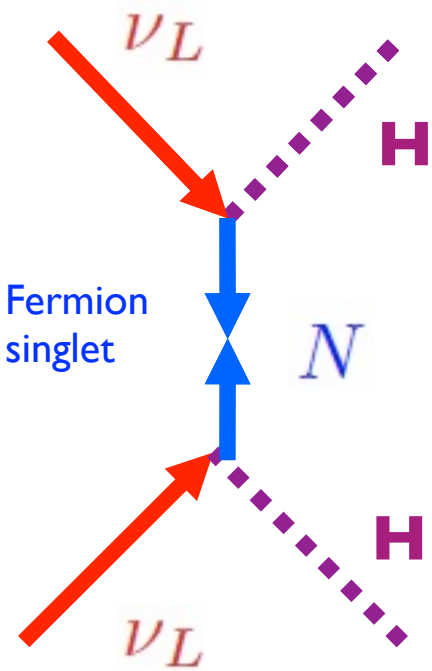
$$-\mathcal{L} = \lambda\frac{L \cdot H L \cdot H}{M}$$

New theory: new particle exchange with mass M



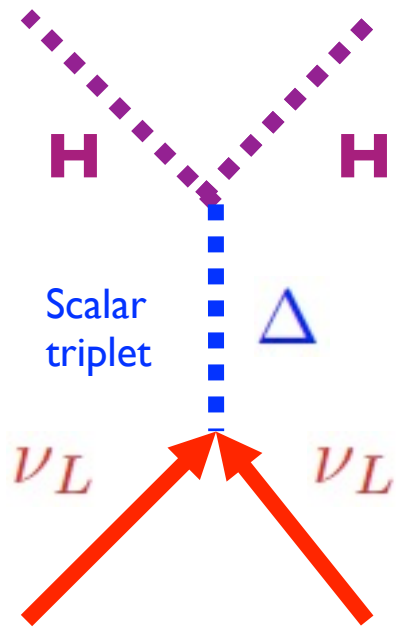
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M}$$

See-saw Type I



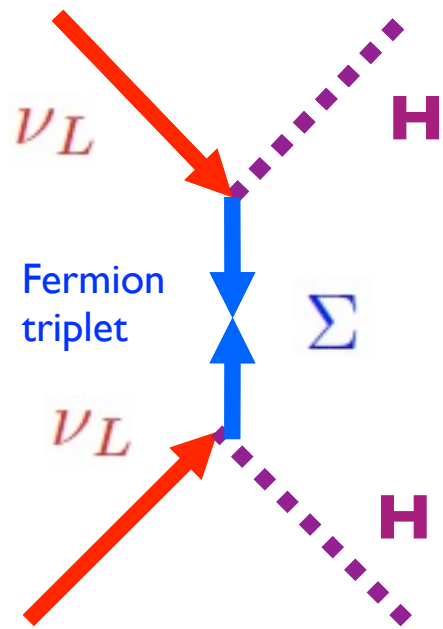
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



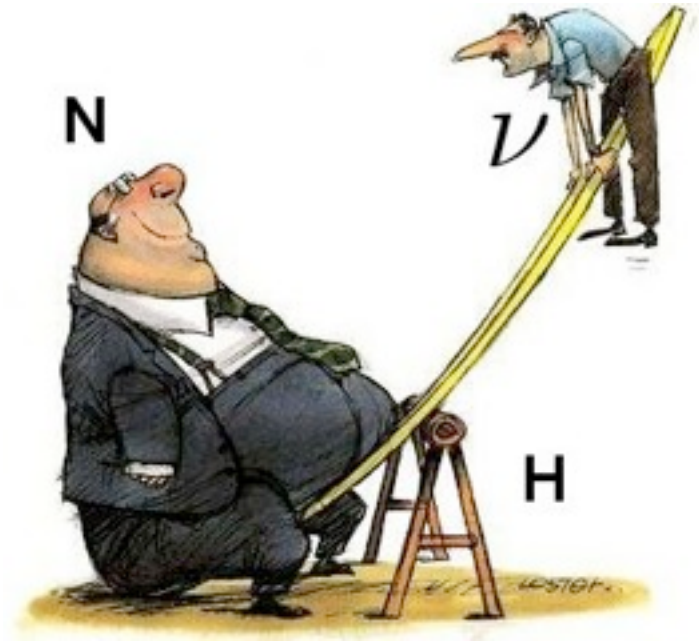
Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

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

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

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

$$m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

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.

The resulting massive states are Majorana particles and

$$\nu_{\text{active}} = U_i\, n_{i,\text{light}} + U_k\, N_{k,\text{heavy}}$$

Non unitarity

Active and heavy neutrino mixing: $m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$

Pros:

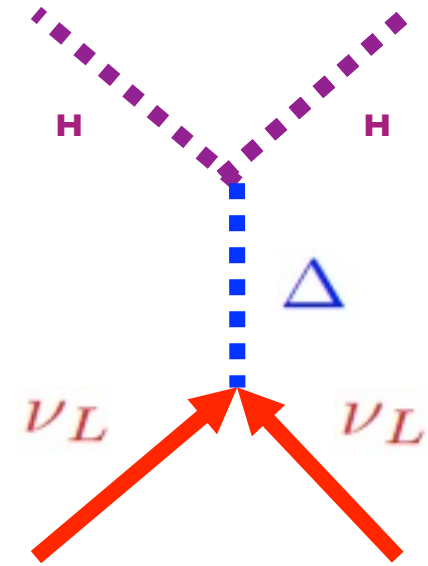
- they explain "naturally" the smallness of masses.
- can be embedded in GUT theories!
- have several phenomenological consequences (depending on the mass scale), e.g. leptogenesis, LFV

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

Neutrino masses BSM: see saw mechanism type II, III

We introduce a Higgs triplet which couples to the Higgs and left handed neutrinos. It has hypercharge 2.



$$\mathcal{L}_\Delta \propto y_\Delta L^T C^{-1} \sigma_i \Delta_i L + \text{h.c.}$$

with $$\Delta_i = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix}$$

Once the Higgs triplet gets a vev, Majorana neutrino masses arise:

$$\boxed{m_\nu \sim y_\Delta v_\Delta}$$

Cons: why the vev is very small?
Pros: the component of the Higgs triplet could tested directly at the LHC.

Similar considerations apply to see-saw type III.

Extensions of the see saw mechanism

Models in which it is possible to lower the mass scale (e.g. TeV or below), keeping large Yukawa couplings have been studied. Examples: inverse and extended see-saw.

Let's introduce two right-handed singlet neutrinos.

$$\mathcal{L} = Y\bar{L}\cdot HN_1 + Y_2\bar{L}\cdot HN_2^c + \Lambda\bar{N}_1N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

$$\begin{pmatrix} 0 & Yv & Y_2v \\ Yv & \mu' & \Lambda \\ Y_2v & \Lambda & \mu \end{pmatrix}$$

See e.g. Gavela et al., 0906.1461; Ibarra, Molinaro, Petcov, 1103.6217; Kang, Kim, 2007; Majee et al., 2008; Mitra, Senjanovic, Vissani, 1108.0004; Malinsky, Romao, Valle, 2005

$$m_{tree} \simeq -m_D^T M^{-1} m_D \simeq \frac{v^2}{2(\Lambda^2 - \mu'\mu)}\left(\mu Y_1^T Y_1 + \epsilon^2 \mu' Y_2^T Y_2 - \Lambda\epsilon(Y_2^T Y_1 + Y_1^T Y_2)\right)$$

Small neutrino masses emerge due to cancellations between the contributions of the two sterile neutrinos (typically associated to small breaking of some L).

See talk by Smirnov

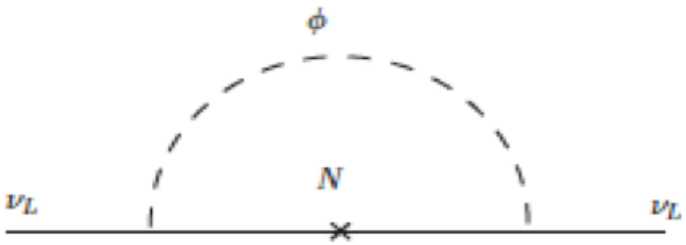
Other models of neutrino masses

See talks by Huang, Le, Bahrami, Roland

Radiative masses

If neutrino masses emerge via loops, in models in which Dirac masses are forbidden, there is an additional suppression.

Some of these models have also dark matter candidates.



$$m_\nu \propto \frac{g^2}{16\pi^2} f(M, \mu_\phi^2)$$

See Ma, PRL81; also e.g. Boehm et al., PRD77; ...

R-parity violating SUSY

In the MSSM, there are no neutrino masses. But it is possible to introduce terms which violate R (and L).

$$V = \ldots - \mu H_1 H_2 + \epsilon_i \tilde{L}_i H_2 + \lambda'_{ijk} \tilde{L}_i \tilde{L}_j \tilde{E}_k + \ldots$$

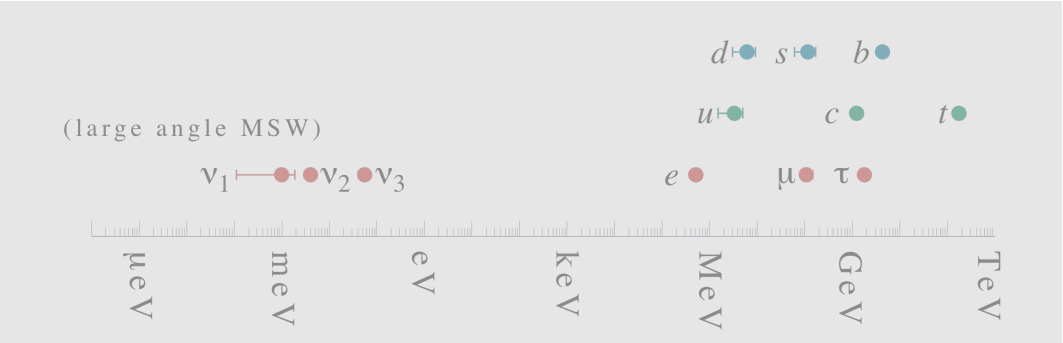
See e.g. Aulakh, Mohapatra, PLB119; Hall, Suzuki, NPB231; Ross, Valle, PLB151; Ellis et al., NPB261; Dawson, PRD57, ...

The bilinear term induces mixing between neutrinos and higgsino, the trilinear term masses at loop-level.

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?

This points towards a different origin of neutrino masses and mixing from the ones for quarks: a different window on the physics BSM.

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 $\theta_{23} \sim 45^o, \theta_{13} \sim 0^o$.

See talk by Stuart

Two necessary ingredients for testing flavour models:

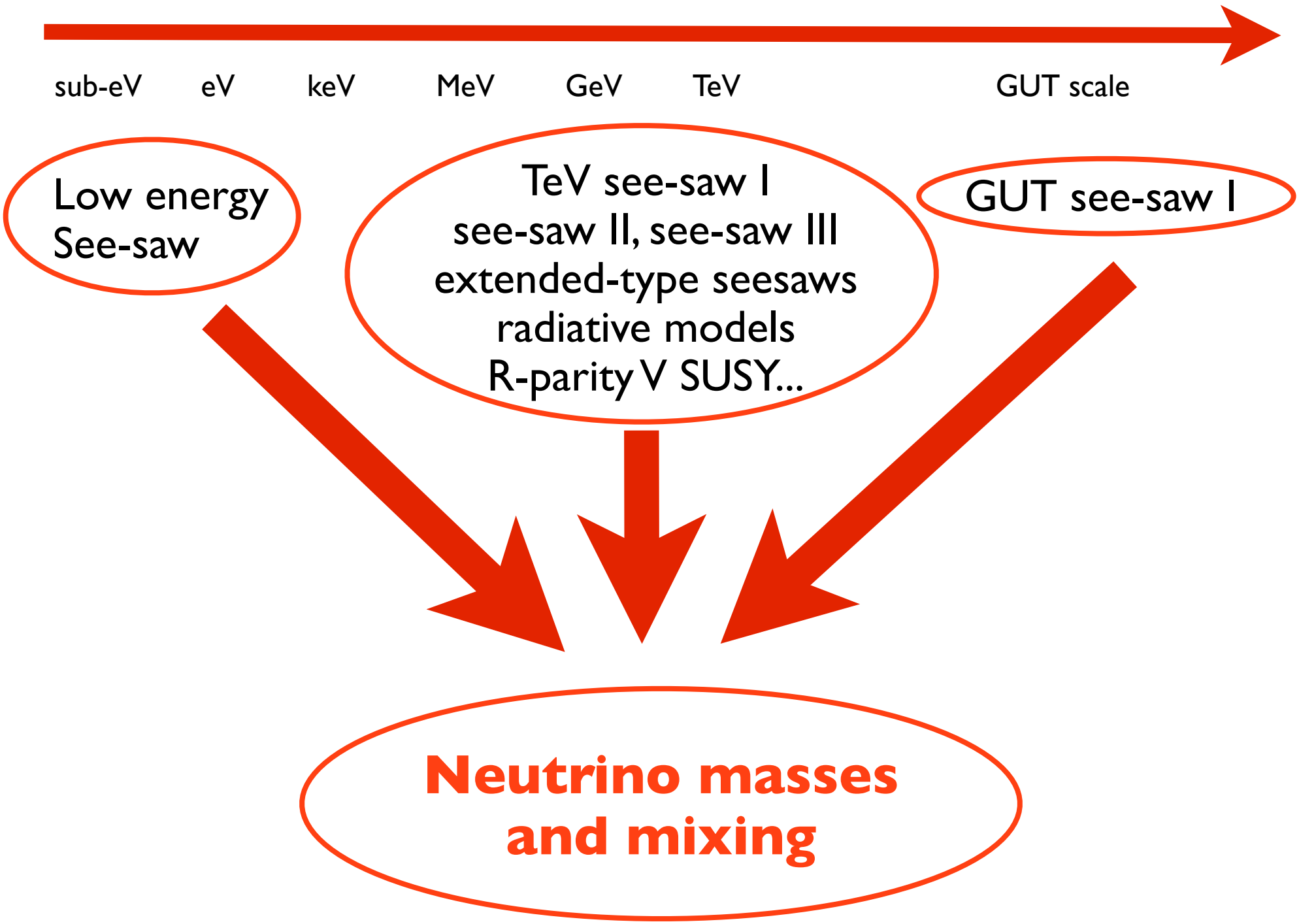
- Precision measurements of the oscillation parameters at future experiments (including the delta phase).

- 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
$L_e - L_\mu - L_\tau$ 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
S_3 and 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
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?



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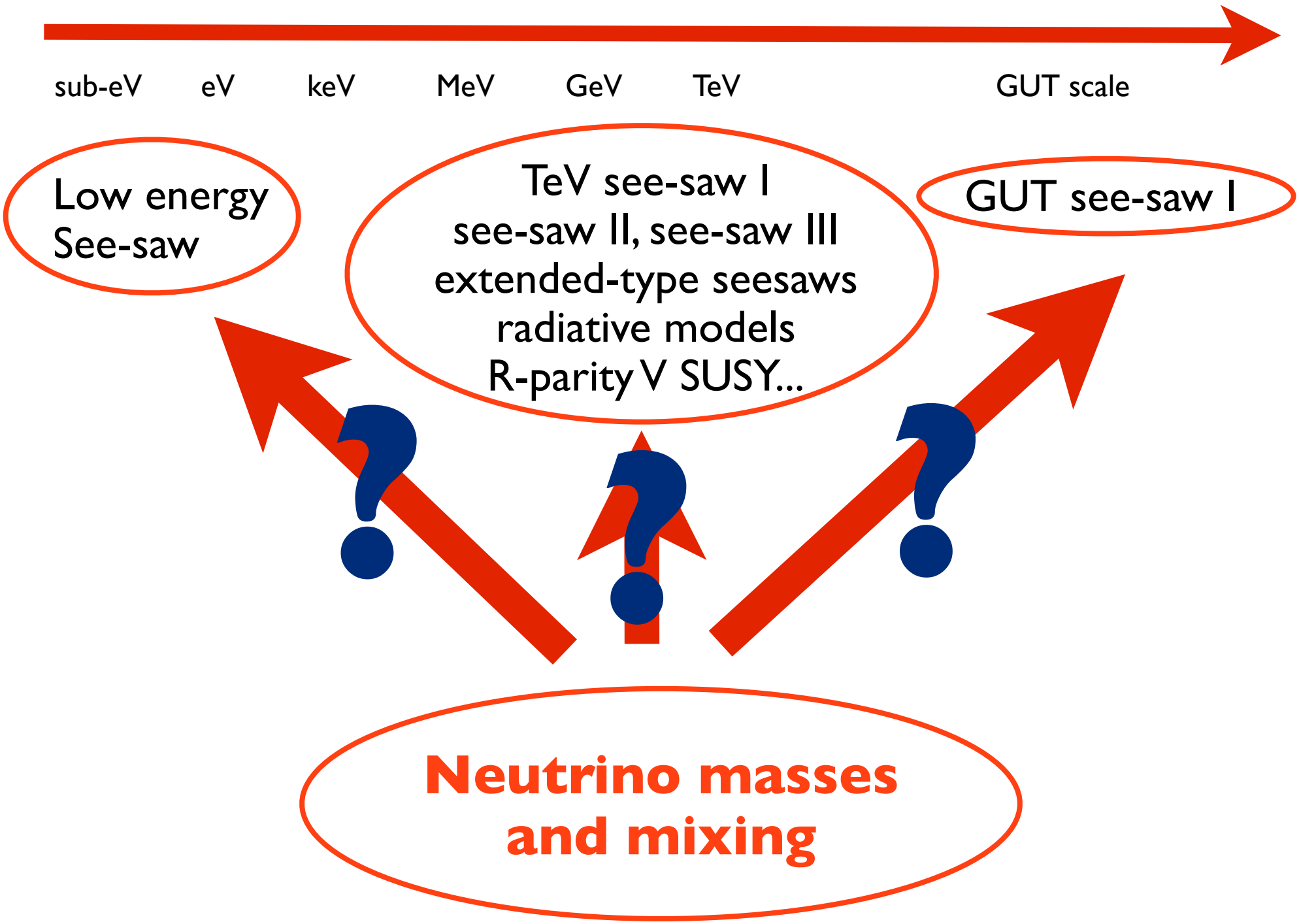
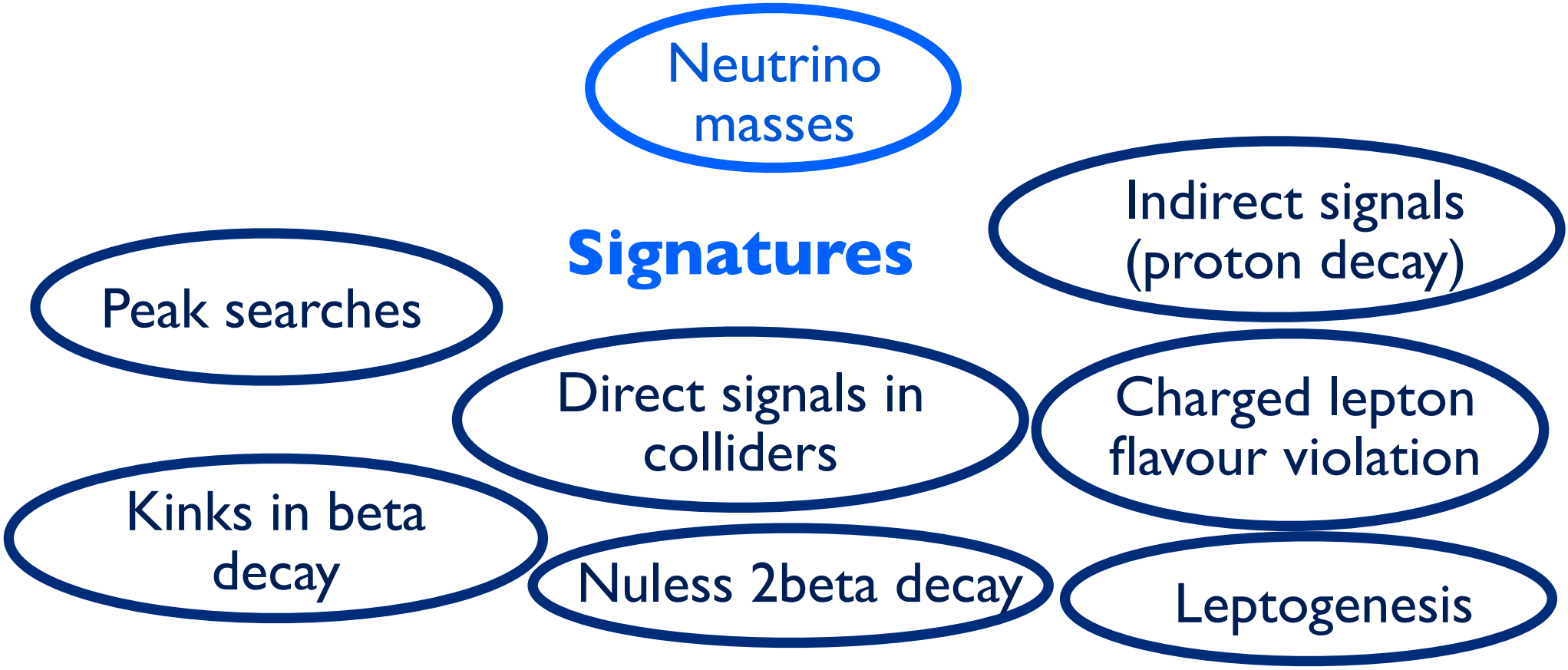


Complementarity with other searches

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

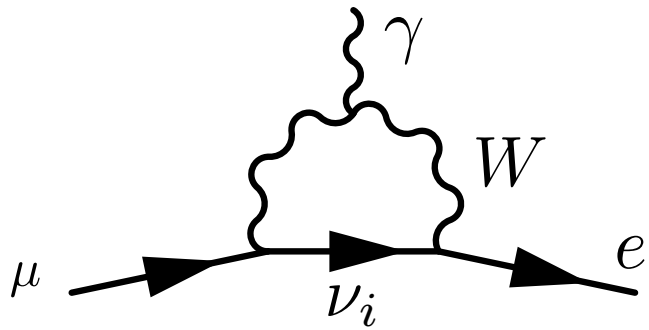


Establishing the origin of neutrino masses requires to have as much information as possible about the masses and to combine it with other signatures of the models.

Charged lepton flavour violation

See talk by Lynch

Neutrino masses induce very suppressed LFV processes.

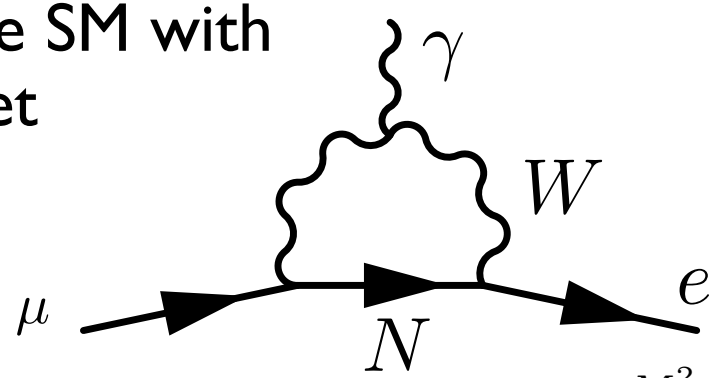


$$Br(\mu \to e\gamma)$$
$$\sim \frac{3\alpha}{32\pi}\left(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta^2 m_{i1}}{m_W^2}\right)^2 \sim 10^{-53}$$

S. Petcov, SJNP 25 (1977)

Any observation of CLFV would show new physics BSM and provide clues on the origin of neutrino masses.

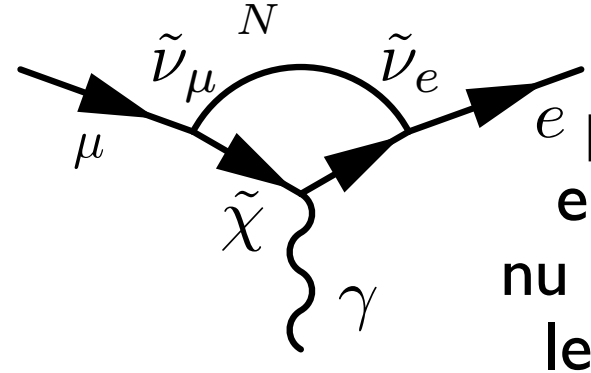
Example: extension of the SM with singlet N



$$Br(\mu \to e\gamma) \sim \frac{3\alpha}{8\pi}\left(\sum_j U^*_{\mu j} U_{ej} g\left(\frac{M_N^2}{m_W^2}\right)\right)^2$$

Example: SUSY see-saw

$$Br \propto \left|\sum_N Y^*_{N\mu} Y_{Ne} \ln(m_0/m_N)\right|^2$$



The same parameters enter in LFV, nu masses and leptogenesis.

Borzumati, Masiero, PRL 57

CLFV are mediated by D=6 effective operators and are controlled by LFV.

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$

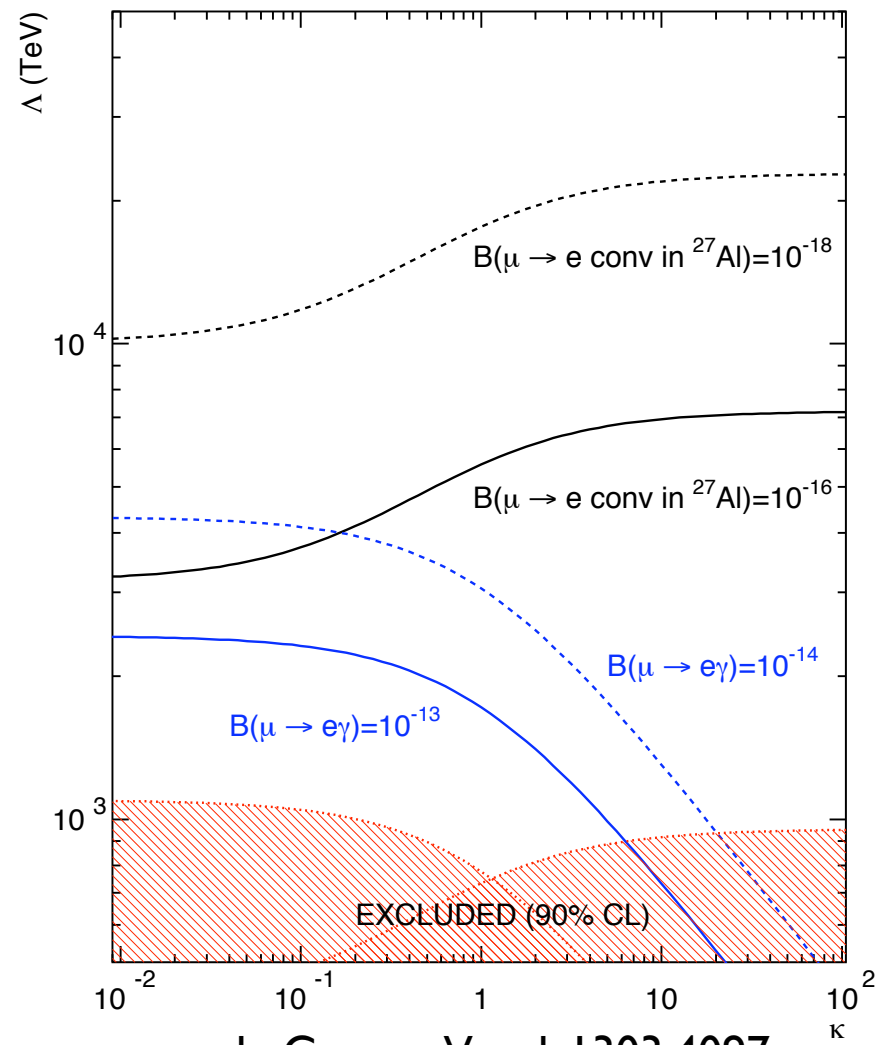
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right) + h.c..$$

Different terms dominate in the various processes

- $\mu \to e\gamma$
- $\mu - e$ conversion
- $\mu \to eee$
- LFV τ decay

Their relative Br depend on the underlying new physics BSM and flavour structure.

See talk by Lynch



de Gouvea, Vogel, 1303.4097

Leptogenesis and the Baryon asymmetry

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.14 \pm 0.08) \times 10^{-10}$$

Planck, 1303.5076

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

- C, CP violation;

- departure from thermal equilibrium.

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Neutrinoless double beta decay

See Lee's talk

LBL

Expansion of the Universe

An observation of LNV and CPV would be a hint in favour of leptogenesis.

Leptogenesis in see-saw type I

- At T>M, the right-handed neutrinos N are in equilibrium thanks to the processes which produce and destroy them:

$$N \leftrightarrow \ell H$$

- When T<M, N drops out of equilibrium

$$N \to \ell H \qquad\qquad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- Sphalerons convert it into a baryon asymmetry.

T

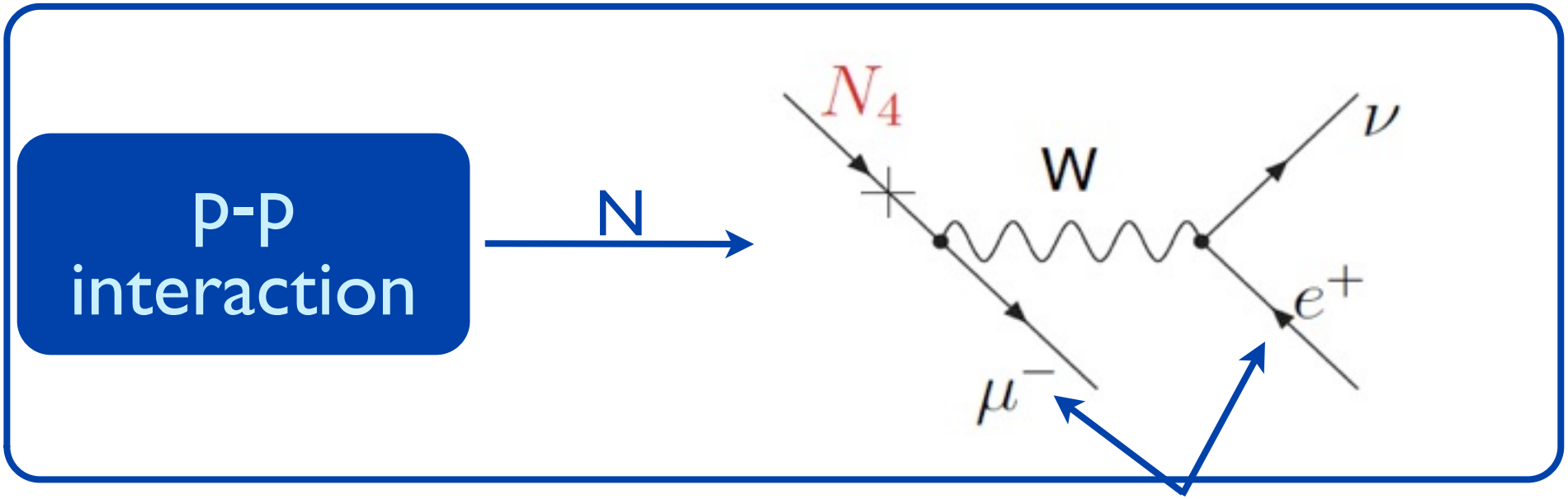
T=M

T=100 GeV

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

Direct searches at the TeV scale

- LNV: same-sign dilepton signal with no missing energy
- multilepton production.

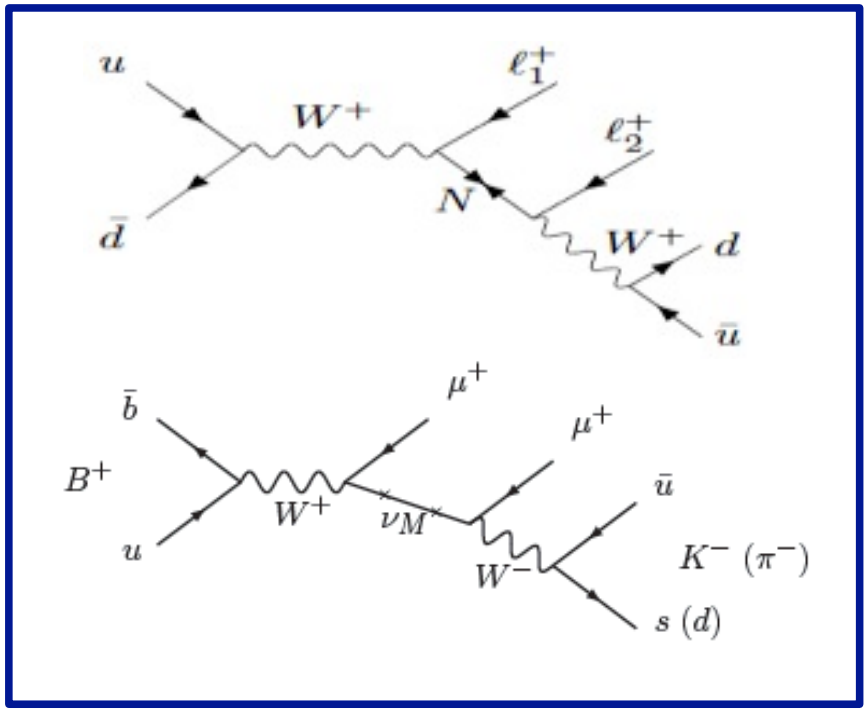


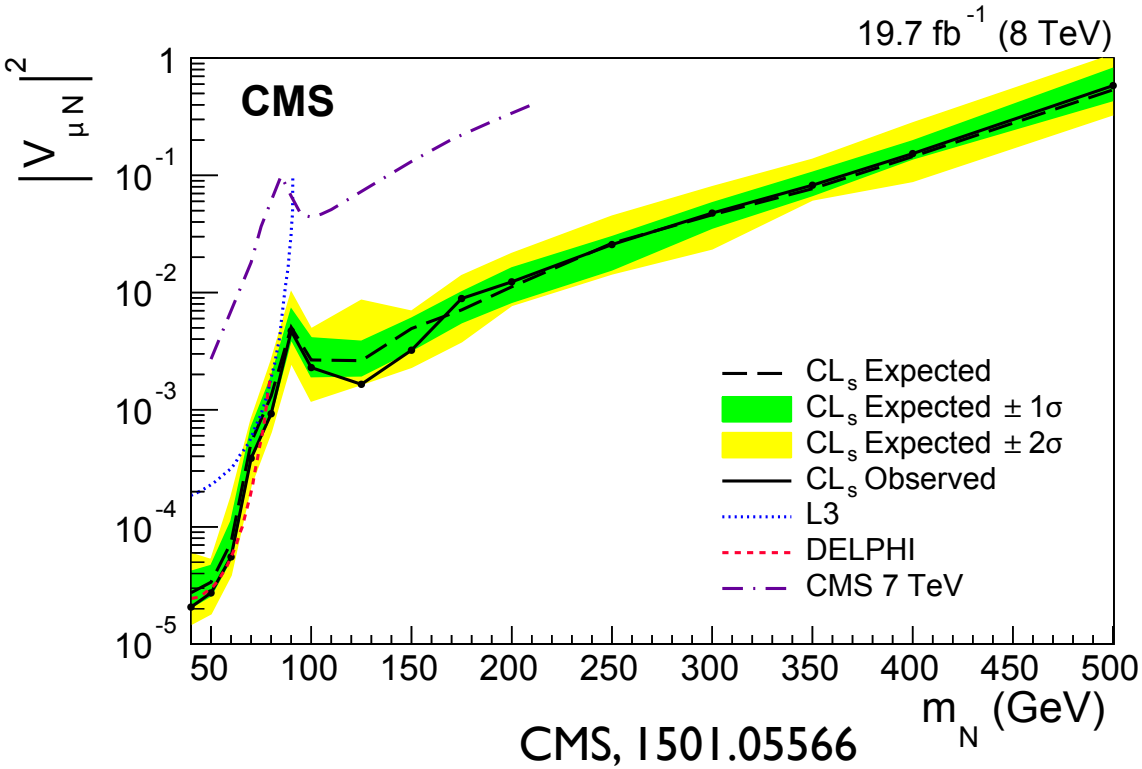
visible particles: photons, electrons, muons,....

See, Dittmar et al., NPB332; Keung, Senjanovic PRL50; Dicus et al., PRD44; Datta et al., PRD 50; Almeida et al., PRD62; Panella et al., PRD65; Han, Zhang, PRL97, Del Aguila et al., JPCS53, JHEP 0710; Atre et al., 0901.3589

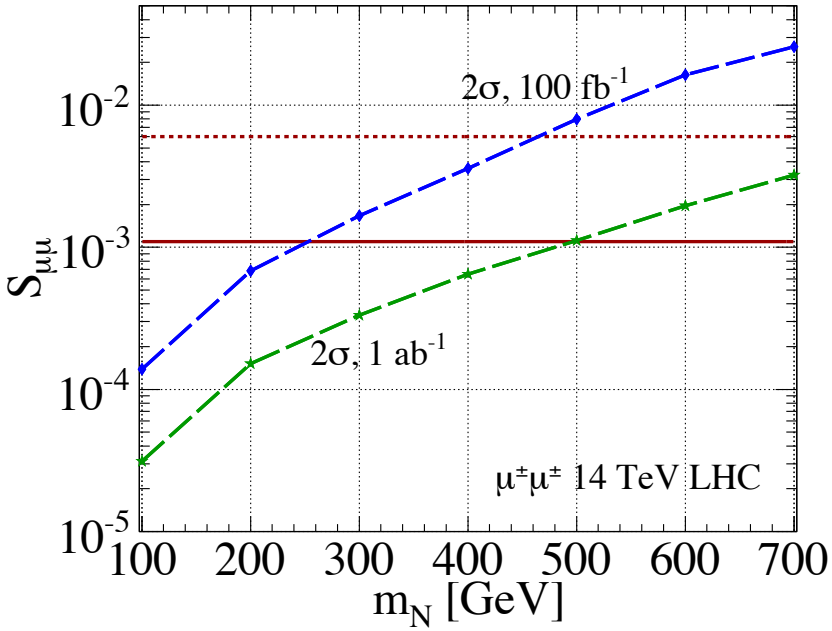
The decay length is controlled by the mixing angle and the branching ratios by SM interactions (and kinematics). Number of events is given by the production mechanism.

Searches for LNV decays at colliders





CMS, 1501.05566

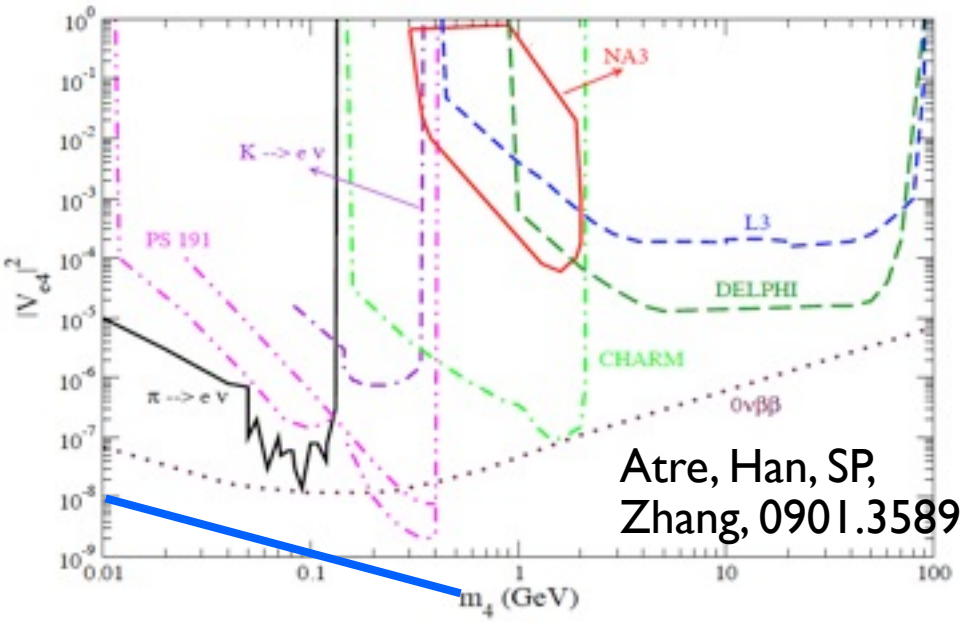


ATLAS, CMS and LHC-b have put new bounds and with higher luminosity significantly stronger bounds can be obtained.

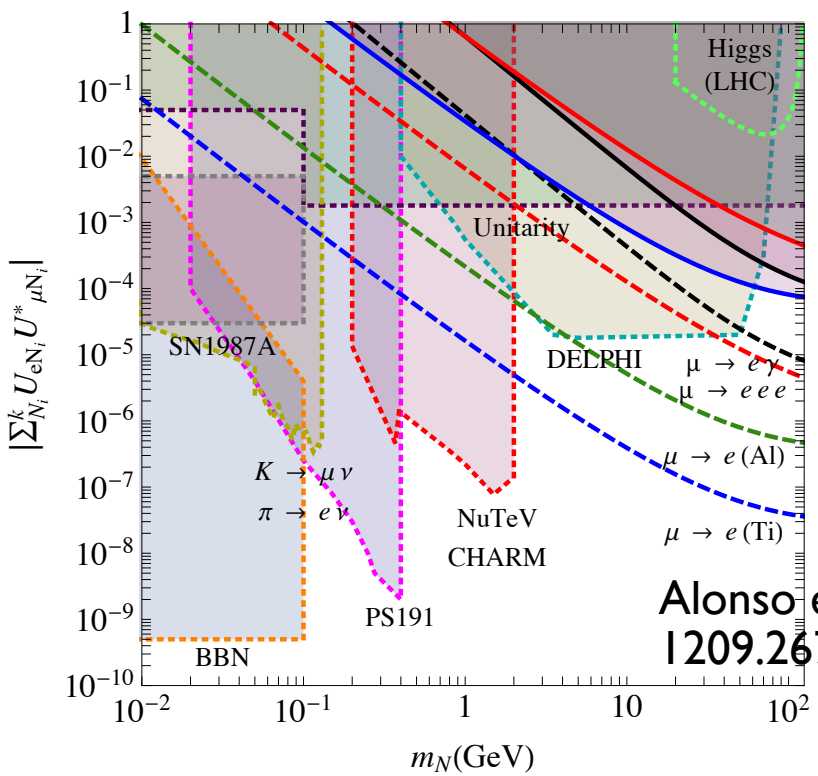
See talks by Ruiz, Das, Dev, Hoang

Alva, Han, Ruiz, 1411.7305

Connecting different signatures: Ex. TeV scale see-saw



Atre, Han, SP, Zhang, 0901.3589



Alonso et al., 1209.2679

Neutrino masses $\sim U_{\alpha 4} U^*_{\beta 4} m_4$

Neutrinoless double beta decay (LNV): usually subdominant contribution w.r.t. light masses

$$\mathcal{A} \propto U_{e4}^2 1/m_4^2$$

Decays at colliders (same sign leptons, LNV): typically strongly constrained by neutrino masses. Production can be enhanced by additional interactions (Z', triplets...)

CLFV (does not depend on LNV but requires LFV):

$$Br(\mu \to e\gamma) \sim \frac{3\alpha}{8\pi}\left(\sum_j U^*_{\mu j} U_{ej} g\left(\frac{M_N^2}{m_W^2}\right)\right)^2$$

Resonant leptogenesis (CPV, LNV)

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).