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

14 January 2016

2016 Aspen Winter Conference on Particle Physics
ACP, Aspen, CO

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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)**

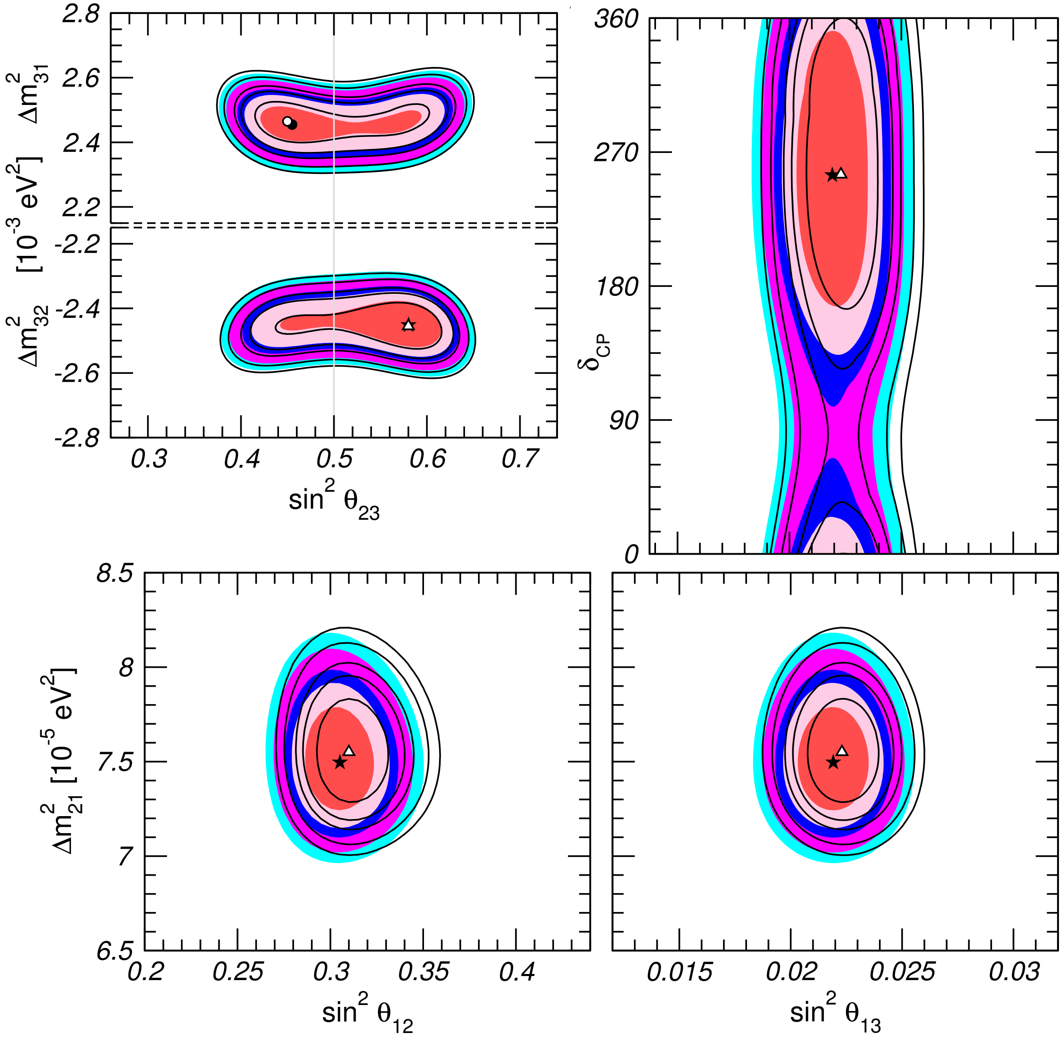
3. **Searching for the new physics scale:**
    - **CLFV**
    - **Leptogenesis**
    - **Direct searches at colliders**

4. **An example of complementarity/ synergy between different signatures**

5. **Conclusions**

Neutrino properties after NOW 2014

NuFIT 2.0 (2014)



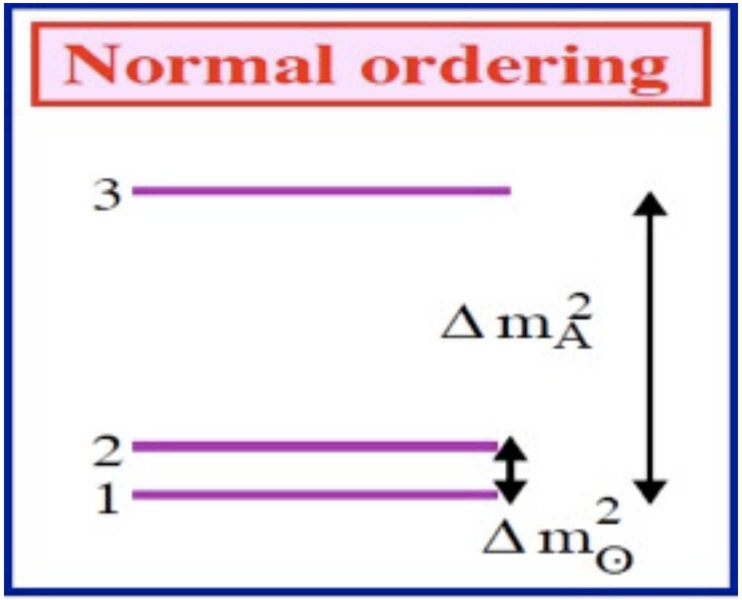
	Normal Ordering ($\Delta\chi^2 = 0.97$)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$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

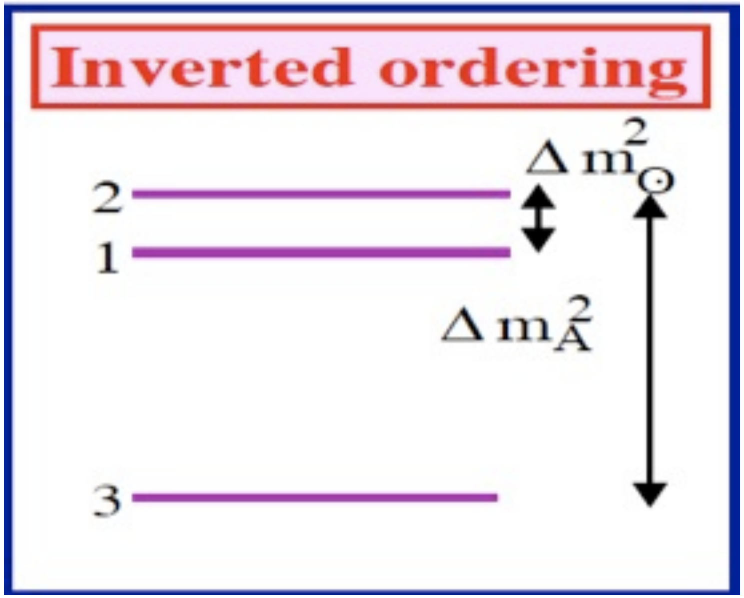
2 mass squared differences and 3 sizable mixing angles, some weak hints of CPV

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

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

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





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

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Measuring the masses requires:

- the mass scale: m_{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? MINOS+, MicroBooNE, SoLid, ...

Very exciting experimental programme now and for the future.

See talks by Messier, Heeger, Gratta, Marisic, Link, Barbeau, Wongjirad

Neutrino oscillations imply that neutrinos have mass and mix.

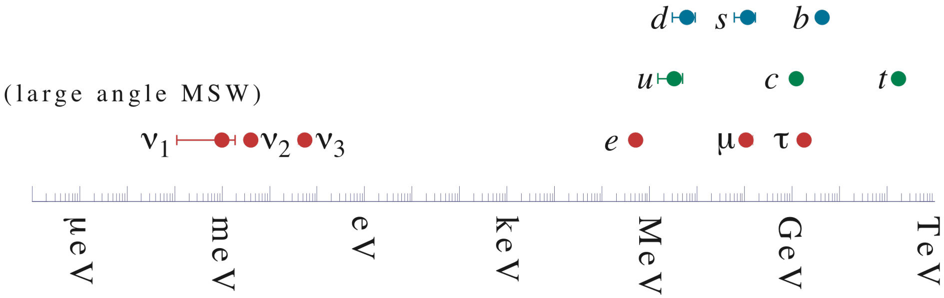
First particle physics evidence of physics
beyond the SM.

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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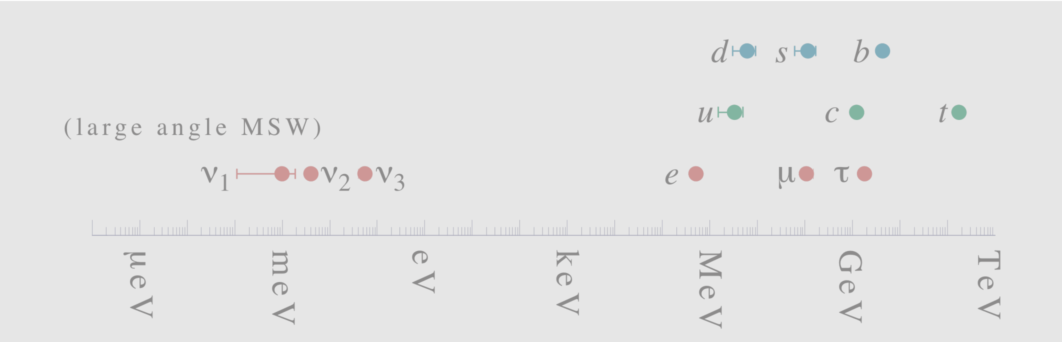

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Is there CP violation in the lepton sector?

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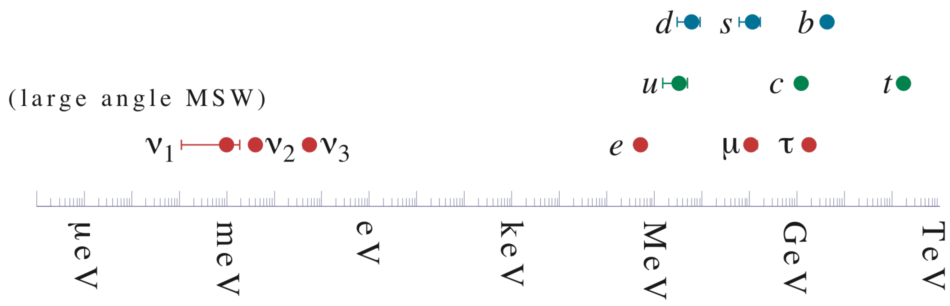

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Neutrino Masses in the SM and beyond

Dirac Masses

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

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

This conserves lepton number!

Masses and Mixing emerge from diagonalising this matrix.

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

$$n_L = \enclose{circle}{U^\dagger} \nu_L \quad n_R = V^\dagger \nu_R$$

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

Tiny couplings!

- why the coupling is so small????
- why the mixing angles 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

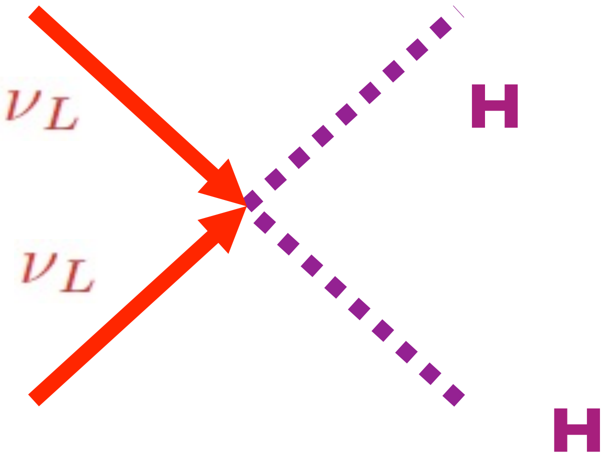
Lepton number violation!

Masses and mixing come from diagonalising the mass matrix

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

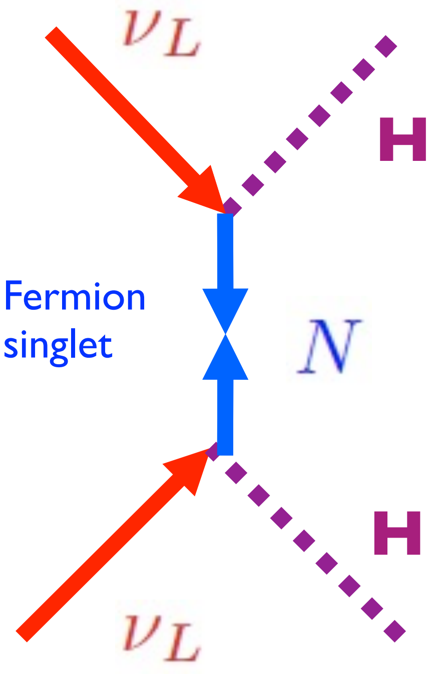
$$\boxed{n_L = U^\dagger \nu_L}$$

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



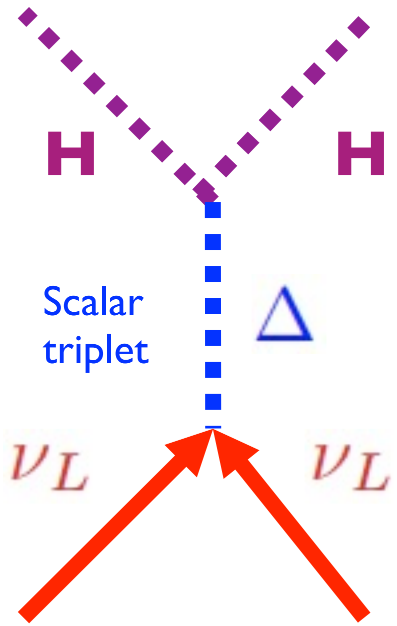
$$-\mathcal{L} = \lambda \frac{L\cdot H L\cdot H}{M}$$

See-saw Type I



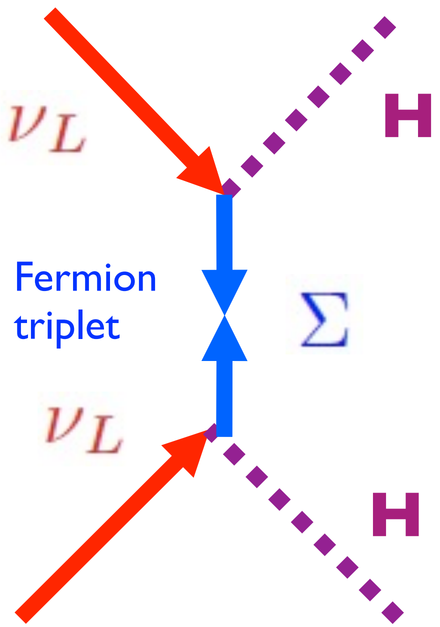
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



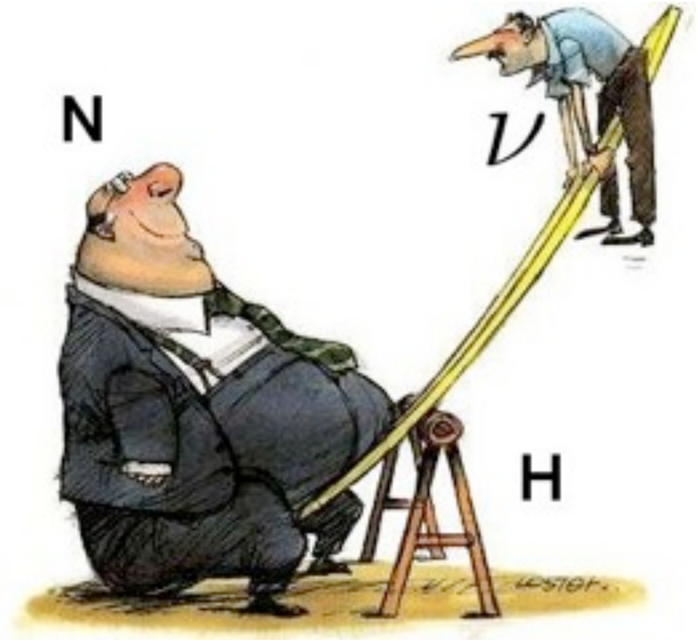
Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

See-saw Type III



Ma, Roy, Senjanovic, Hambye

Neutrino masses BSM: see saw mechanism type I



- Introduce a right handed neutrino N
- Being a gauge singlet it can have a Majorana mass
- Couple it to the Higgs

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

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

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. There is no strong theoretical motivation for the mass scale.

The resulting massive states are Majorana particles and

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

Non unitarity

Active and heavy neutrino mixing: $\sin^2\theta \simeq \frac{m_\nu}{M} \sim \frac{0.1\,\text{eV}}{1\,\text{TeV}} = 10^{-13}$

Pros:

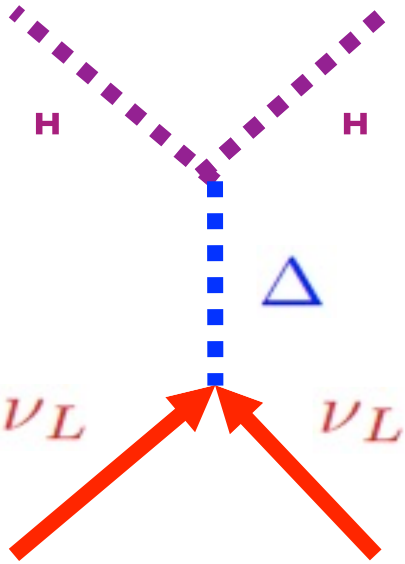
- they explain "naturally" the smallness of masses.
- can be embedded in GUT theories!
- have several phenomenological consequences (depending on the mass scale), e.g. leptogenesis, CLFV

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.

$$\mathcal{L} = Y\bar{L}\cdot H N_1 + Y_2\bar{L}\cdot H N_2^c + \Lambda \bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

$$\begin{pmatrix} 0 & Yv & Y_2 v \\ Yv & \mu' & \Lambda \\ Y_2 v & \Lambda & \mu \end{pmatrix}$$

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

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

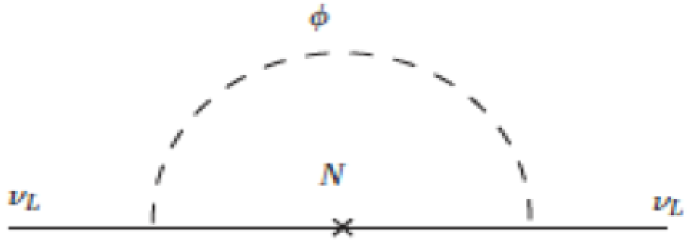
Small neutrino masses emerge due to cancellations between the contributions of the two sterile neutrinos (typically associated to small breaking of some L).

Other models of neutrino masses

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

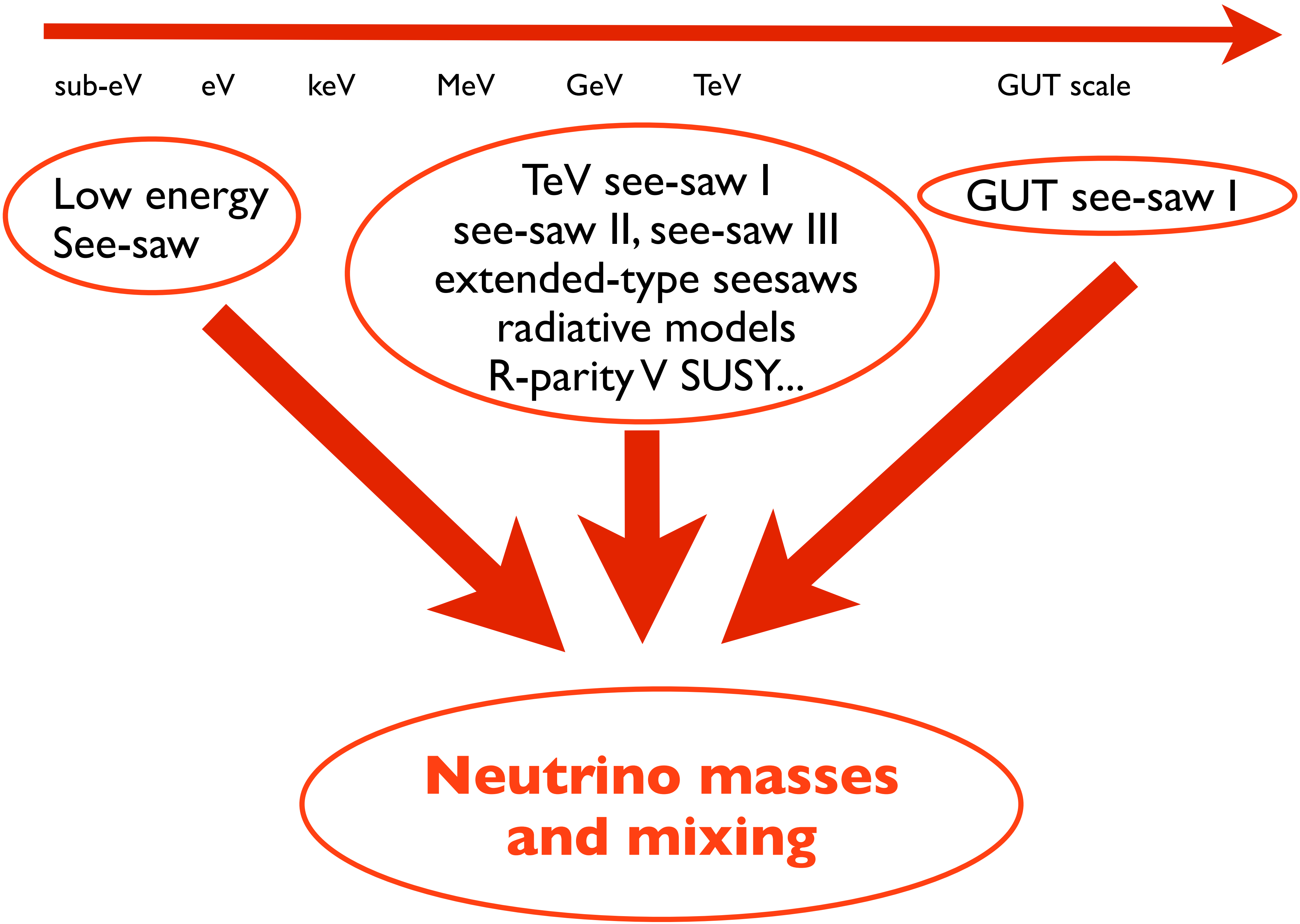
In the MSSM, there are no neutrino masses. But it is possible to introduce terms which violate R (and L).

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

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

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

What is the new physics?



sub-eV eV keV MeV GeV TeV GUT scale

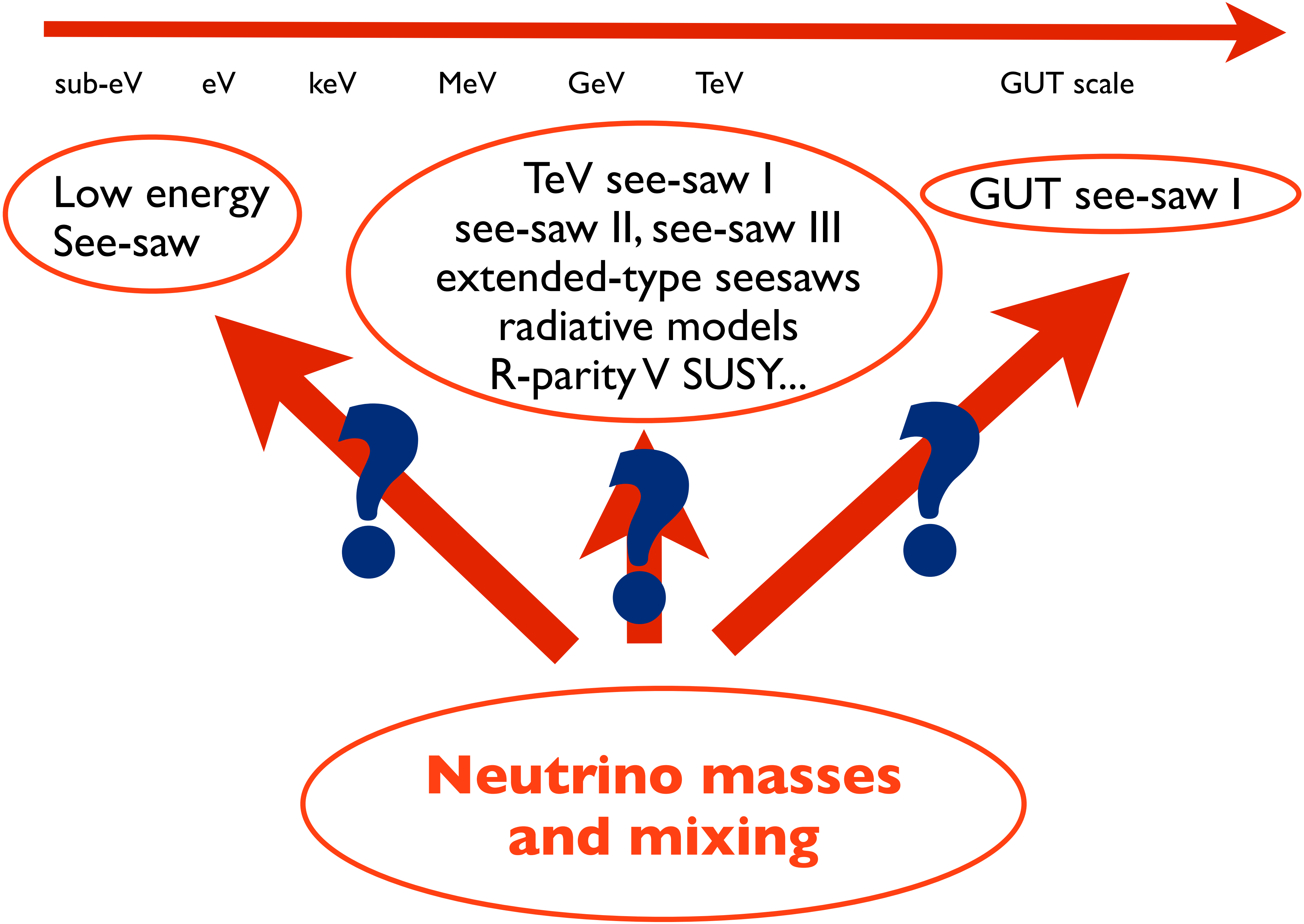
Low energy
See-saw

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?



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Neutrino masses and mixing

Complementarity with other searches

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

Neutrino masses

Signatures

Peak searches

Indirect signals (proton decay)

Direct signals in colliders

Charged lepton flavour violation

Kinks in beta decay

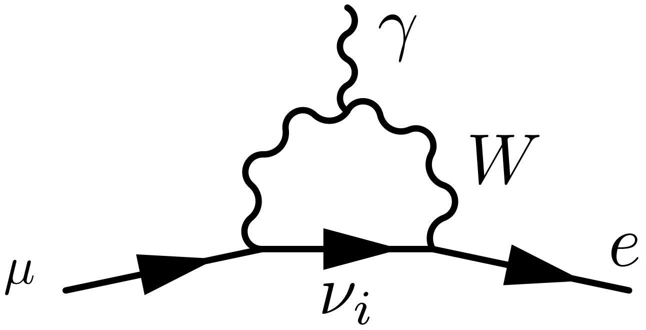
Nuless 2beta decay

Leptogenesis

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

Neutrino masses induce very suppressed LFV processes.



$$Br(\mu \to e\gamma)$$

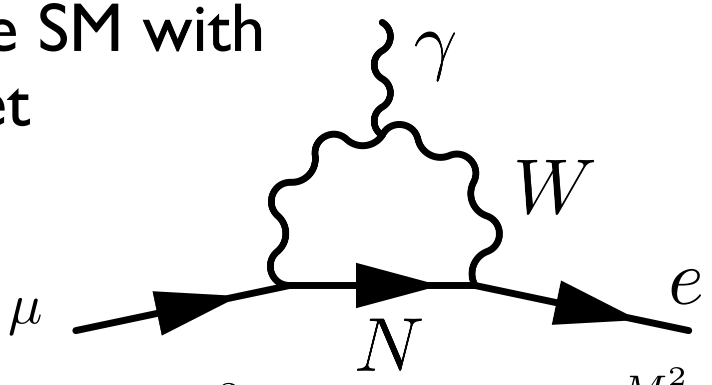
$$\sim \frac{3\alpha}{32\pi}\Big(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta^2 m_{i1}}{m_W^2}\Big)^2 \sim 10^{-53}$$

S. Petcov, SJNP 25 (1977)

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

See talk by Casey

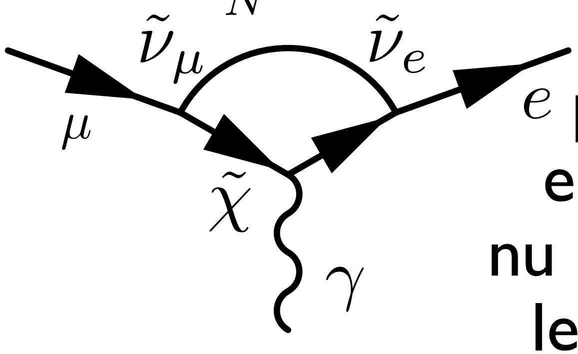
Example: extension of the SM with singlet N



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

Example: SUSY see-saw

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



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

Borzumati, Masiero, PRL 57

Leptogenesis and the Baryon asymmetry

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

- B (or L) violation

typically present in BSM models.

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$
$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$
$$X \to \bar{q}q \qquad X \to \ell q$$

- C, CP violation;

$$\frac{dB}{dt} \propto \Gamma(X^c \to Y^c + B^c) - \Gamma(X \to Y + B)$$

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$
$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$
$$X \to \bar{q}q \qquad X \to \ell q$$

- departure from thermal equilibrium.

$$X^c \leftrightarrow \bar{q}q \qquad X \leftrightarrow \bar{q}q$$
$$X \leftrightarrow \ell q \qquad X^c \leftrightarrow \bar{\ell}\bar{q}$$
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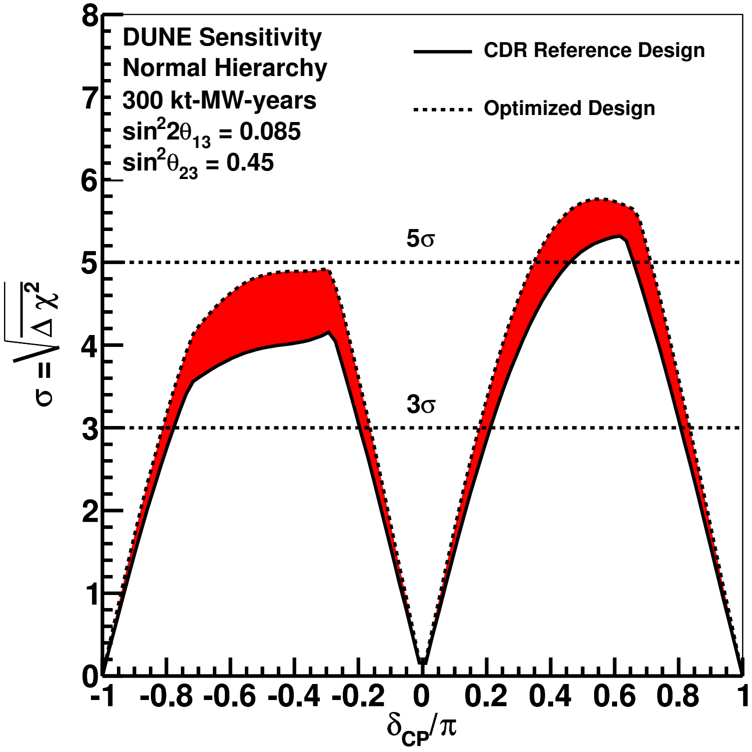
$$\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$$

- B (or L) violation;

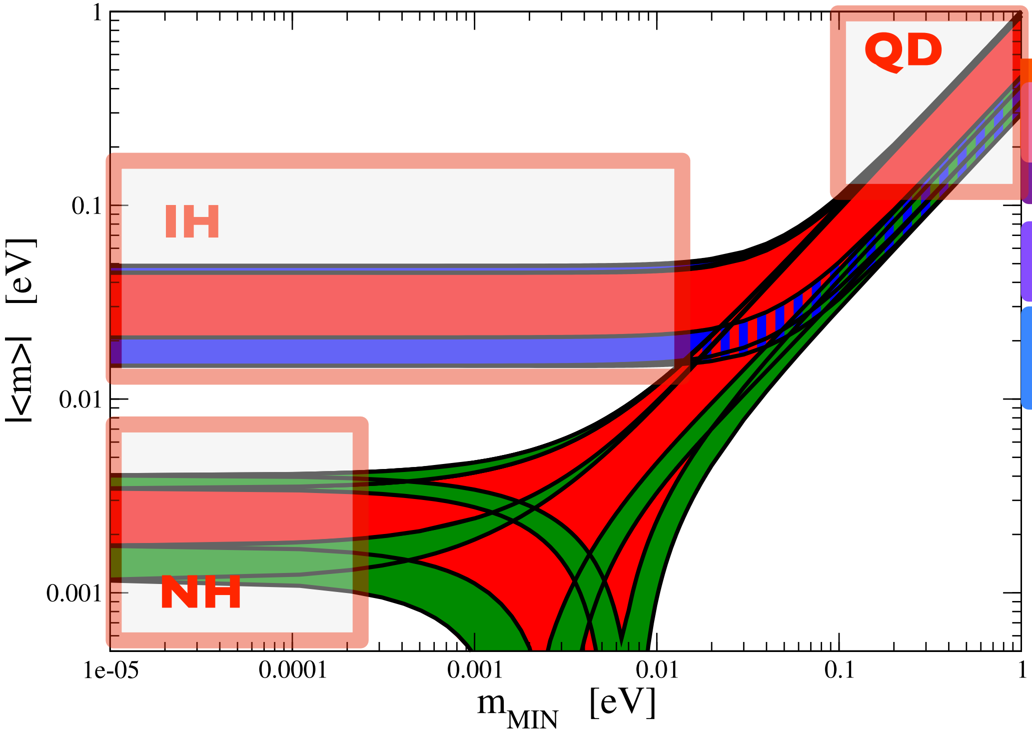
Neutrinoless double beta decay

- C, CP violation;

Long baseline oscillation exp: DUNE, T2HK



DUNE coll., 1512.06148

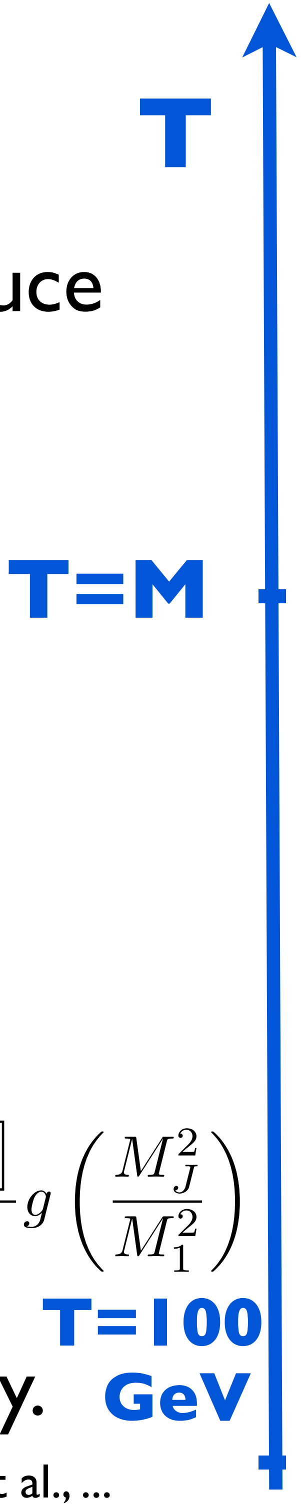


SP from Nakamura, Petcov review in PDG

- departure from thermal equilibrium.

An observation of LNV and leptonic CPV would be a hint in favor 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:

$$\epsilon_1 \equiv \frac{\sum_l \left[\Gamma(N_1 \to H\ell_l) - \Gamma(N_1 \to H^c \ell_l^c)\right]}{\sum_l \left[\Gamma(N_1 \to H\ell_l) + \Gamma(N_1 \to H^c \ell_l^c)\right]} = \frac{1}{8\pi} \sum_{j\neq 1} \frac{\mathrm{Im}\left[(YY^\dagger)^2_{j1}\right]}{(YY^\dagger)_{11}}\, g\left(\frac{M_J^2}{M_1^2}\right)$$

- Sphalerons convert it into a baryon asymmetry.

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

What is the new physics scale?

sub-eV eV keV MeV GeV TeV GUT scale

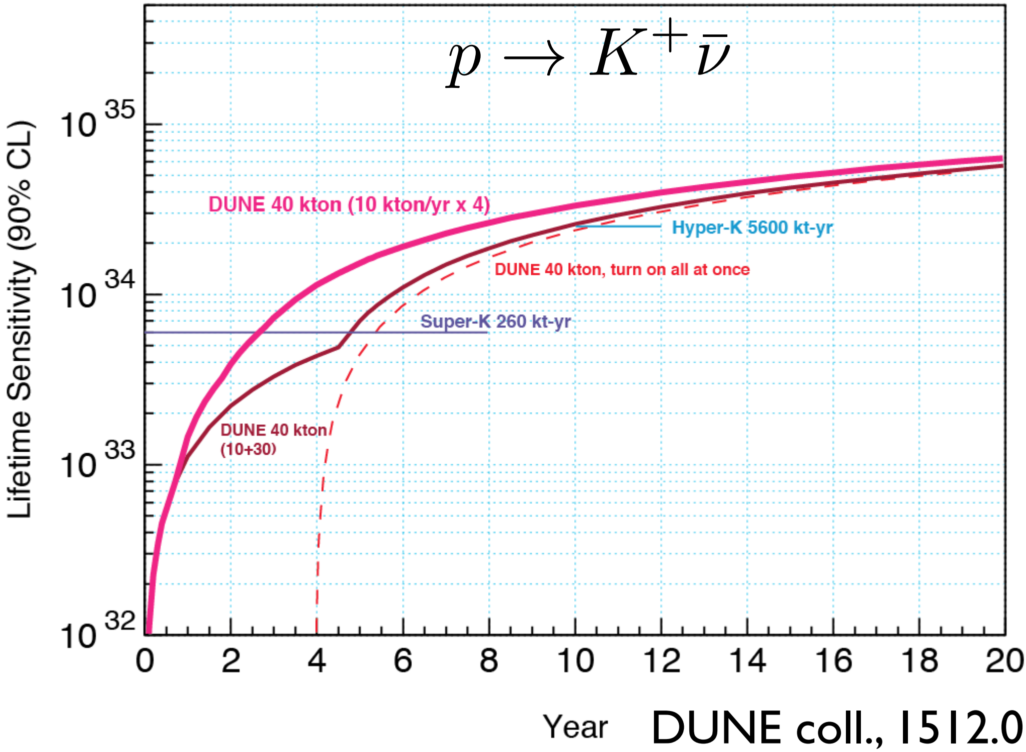
Signatures

Neutrino masses

Leptogenesis

Charged lepton flavour violation, for SUSY models

Proton decay



DUNE coll., 1512.06148

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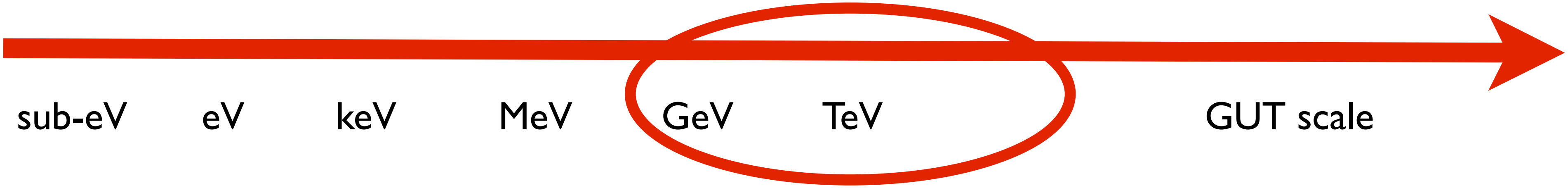


Signatures

Neutrino masses

Charged lepton flavour violation

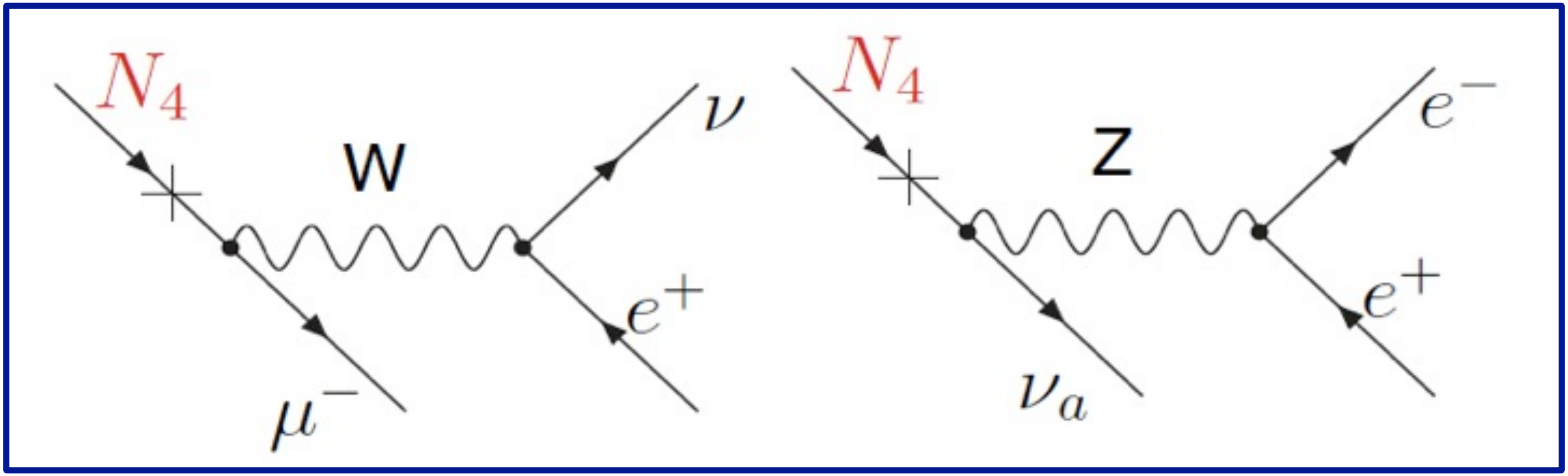
Direct signals in colliders

Leptogenesis with enhancements of effects

Signatures of TeV scale see-saw

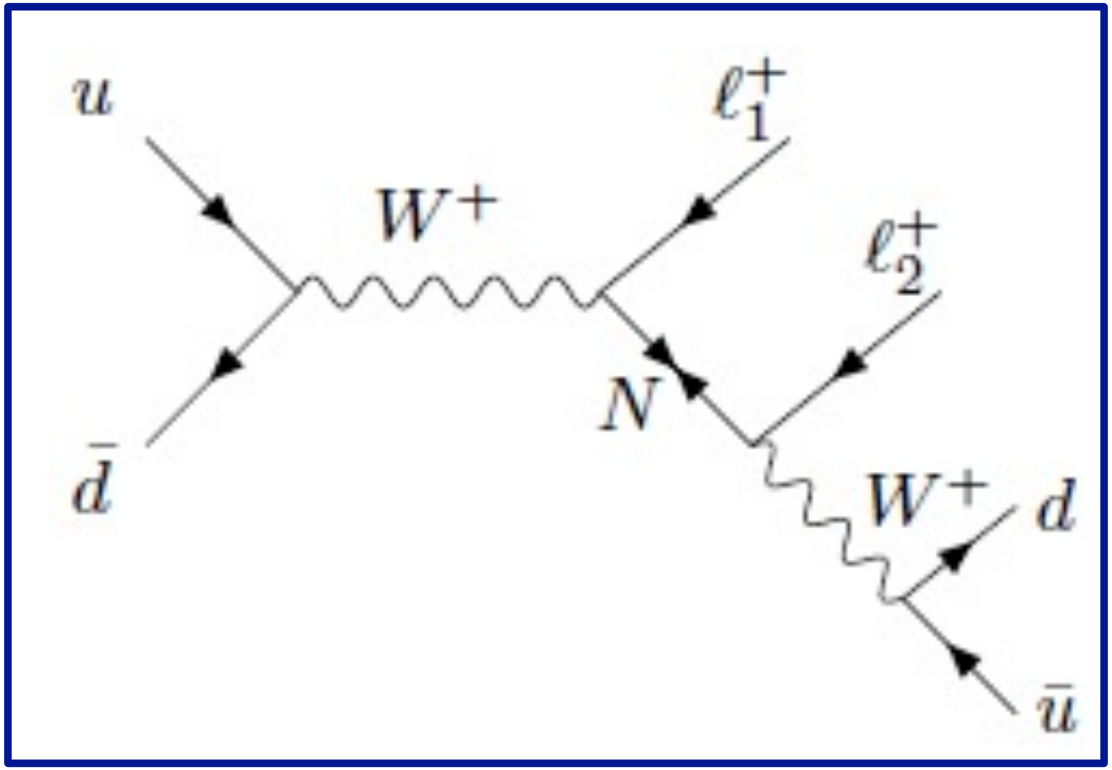
One would need to probe:
1) the existence of (multiple) N;
2) the LNV parameter (Majorana mass for N);
3) the interaction LHN

1) Once produced, N can decay via mixing and the decay products detected.



2) The characteristic signature is LNV which shows up as a same-sign dilepton signal with no missing energy.

- LNV effects due to active neutrinos will depend on m1, m2, m3. Completely negligible in colliders.
- But can be relevant if heavy sterile neutrinos are present.



@Silvia Pascoli

2) The characteristic signature is LNV which shows up as a same-sign dilepton signal with no missing energy.

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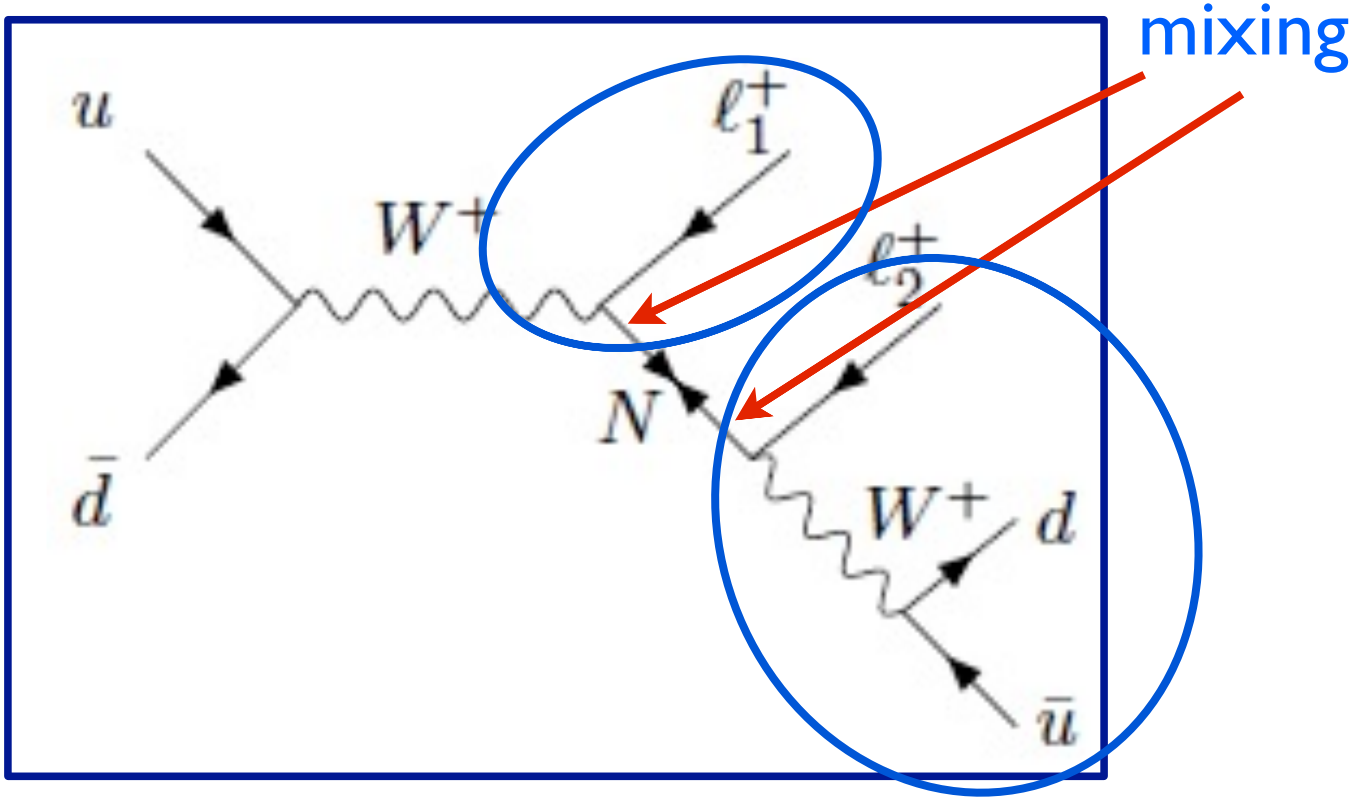
- But can be relevant if heavy sterile neutrinos are present.



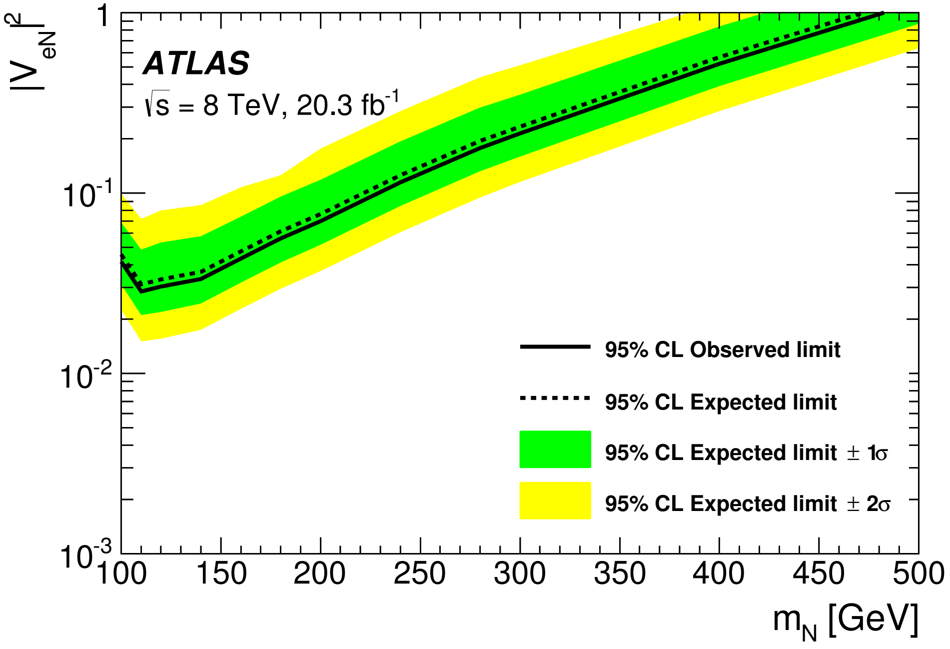
The production due to mixing is very suppressed by the constraints due to neutrino masses ($m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$). Sufficient N production can be achieved if Ns have additional interactions and the relation between LNV at collider and in neutrino masses is broken.

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

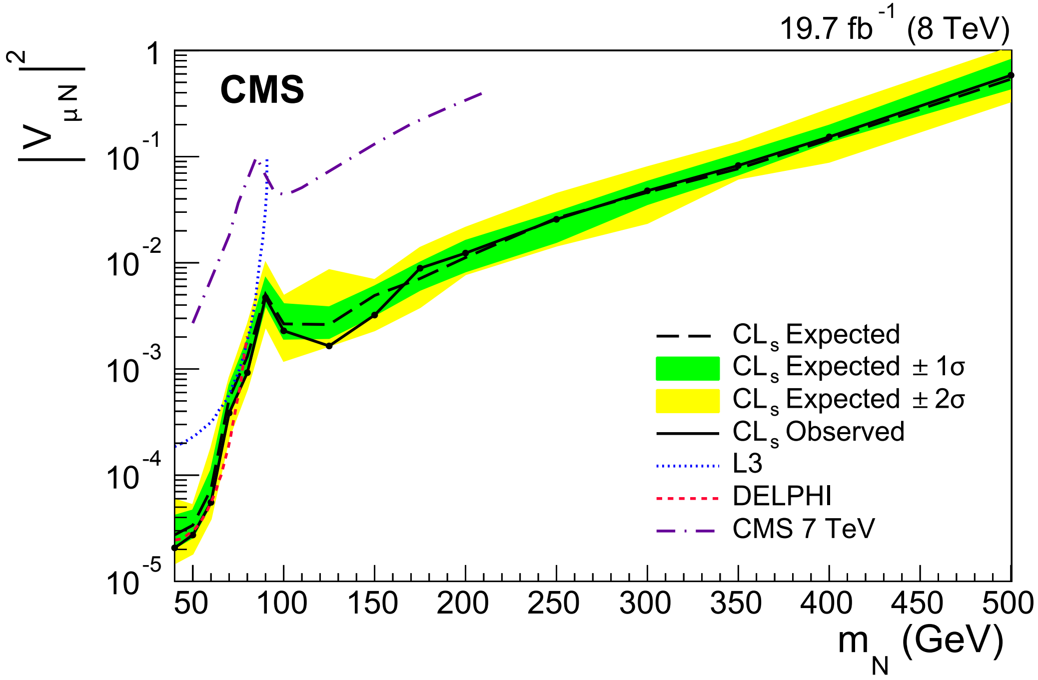
$$pp \to N^+ N^0 \to \ell_1^+ \ell_2^+ Z W^-$$

- Left-Right models via WR
- Inverse or extended see-saw models
- R-parity violating SUSY

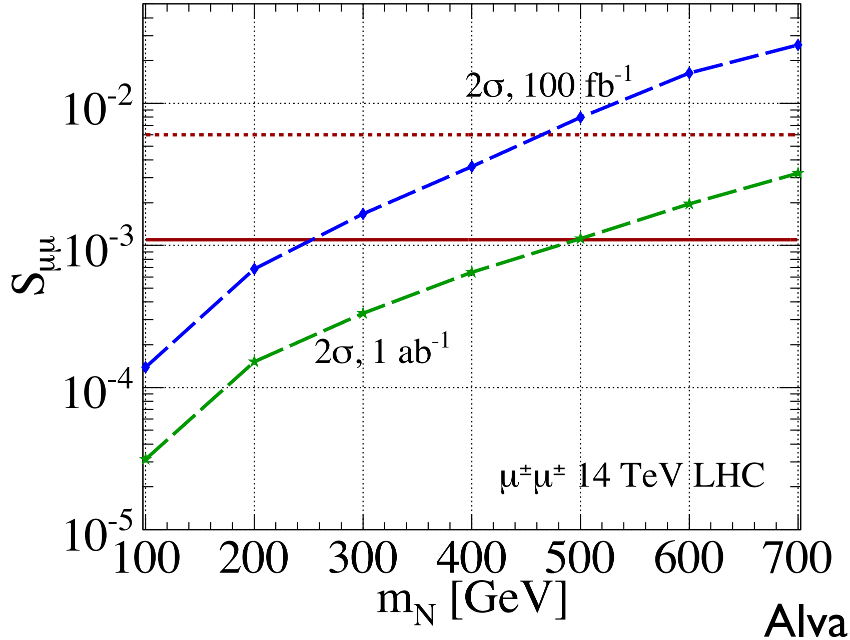
Searches for LNV decays at colliders



ATLAS, 1506.06020



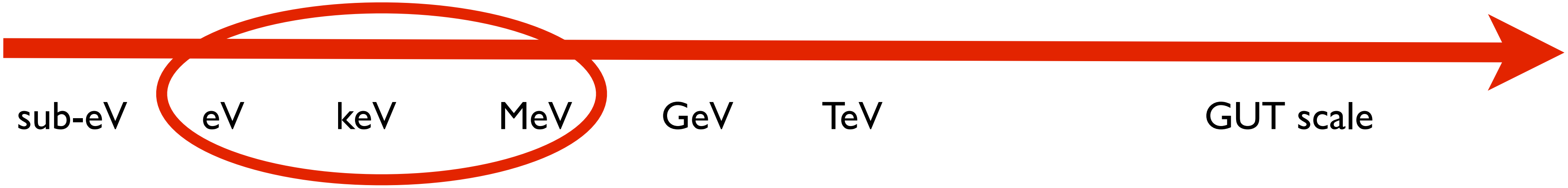
CMS, 1501.05566



Alva, Han, Ruiz, 1411.7305

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

What is the new physics scale?



sub-eV eV keV MeV GeV TeV GUT scale

Signatures

Neutrino masses

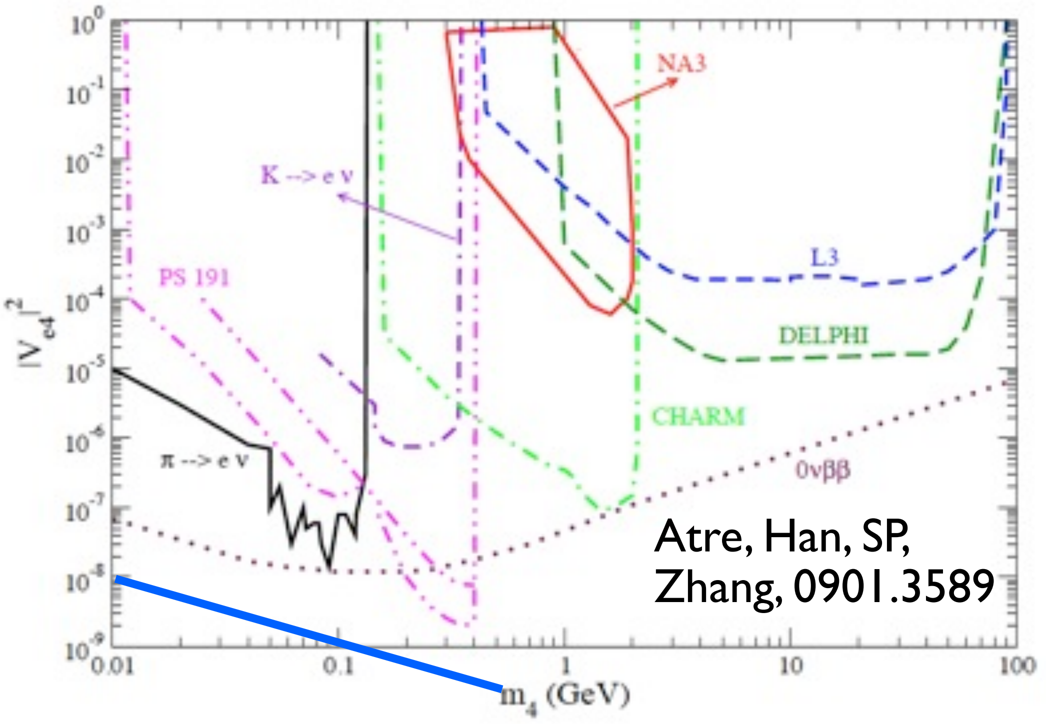
Peak searches

Kinks in beta decay

Nu oscillations

Dark Matter, WDM, HDM

Neutrinoless double beta decay



Atre, Han, SP, Zhang, 0901.3589

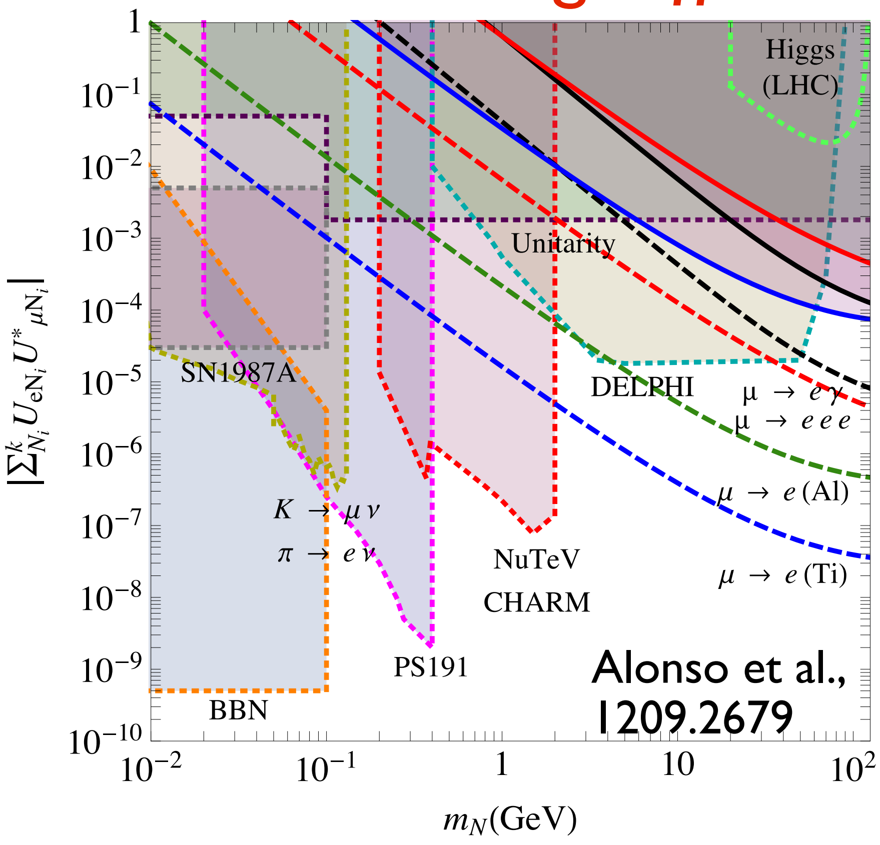
Conclusions

- 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).

Connecting different signatures: Ex. TeV see-saw



Alonso et al., 1209.2679

CLFV (depends on 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)

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 (multileptons and same sign leptons, LNV): can test the existence of the Ns if production is enhanced by additional interactions (Z', triplets...). LNV typically strongly constrained by neutrino masses and difficult to observe. Interaction with Higgs very difficult to test as the Yukawa couplings are typically small.

Various signatures provide information on different parameters: complementarity.