Constraining right-handed neutrinos

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Outline

- Introduction
- Data compilation:
  - Indirect constraints: Universality tests
    Neutrino oscillation
  - Direct constraints: Collider searches
- Parametrization of lepton mixing matrix
- Formalism
- 3 +1 scenario
- 3 + 3, 3 + 6 cases
- Conclusions

Work underway in collaboration with D.V. Forero, O.Miranda, M. Tórtola and J.W.F Valle

Introduction

- In the SM neutrinos are massless particles contradicting the experimental observation of neutrino oscillations.
- Models beyond the SM invoke right handed neutrinos as messengers in order to induce neutrino mass

They have both Dirac & Majorana mass terms

- Such "see-saw" mechanism accounts for the smallness of neutrino masses, type-I, type-II

- Minkowski 77
- Gellman Ramond Slansky 80
- Glashow, Yanagida 79
- Mohapatra Senjanovic 80
- Lazarides Shafi Weterrich 81
- Schechter-Valle, 80 & 82

- The neutral heavy states induce lepton flavor violation (LFV) and lepton number violating (LNV) processes, e.g. neutrinoless double beta decay

Simplest case: 3 + 1 formalism

- In this extension of the SM we introduce just one extra singlet

$$\psi_L = \begin{pmatrix} \nu_{\alpha L} \\ l_{\alpha L} \end{pmatrix} \ ; \quad N_{\alpha R}$$

so the mixing matrix has to be written as

$$U_{4x4} = \begin{pmatrix} W_{e1} & W_{e2} & W_{e3} & V_{e4} \\ W_{\mu 1} & W_{\mu 2} & W_{\mu 3} & V_{\mu 4} \\ W_{\tau 1} & W_{\tau 2} & W_{\tau 3} & V_{\tau 3} \\ T_{41} & T_{42} & T_{43} & B \end{pmatrix}$$

and mass eigensates

$$\nu_{kL} = \sum_{1}^{3} W_{k\alpha} \nu_{\alpha L} + V_{k4} \hat{N}_{4L}$$

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Current constraints on heavy neutrinos

- The mixing of heavy neutrinos would produce peaks in the spectra of leptonic decays of pions and kaons.
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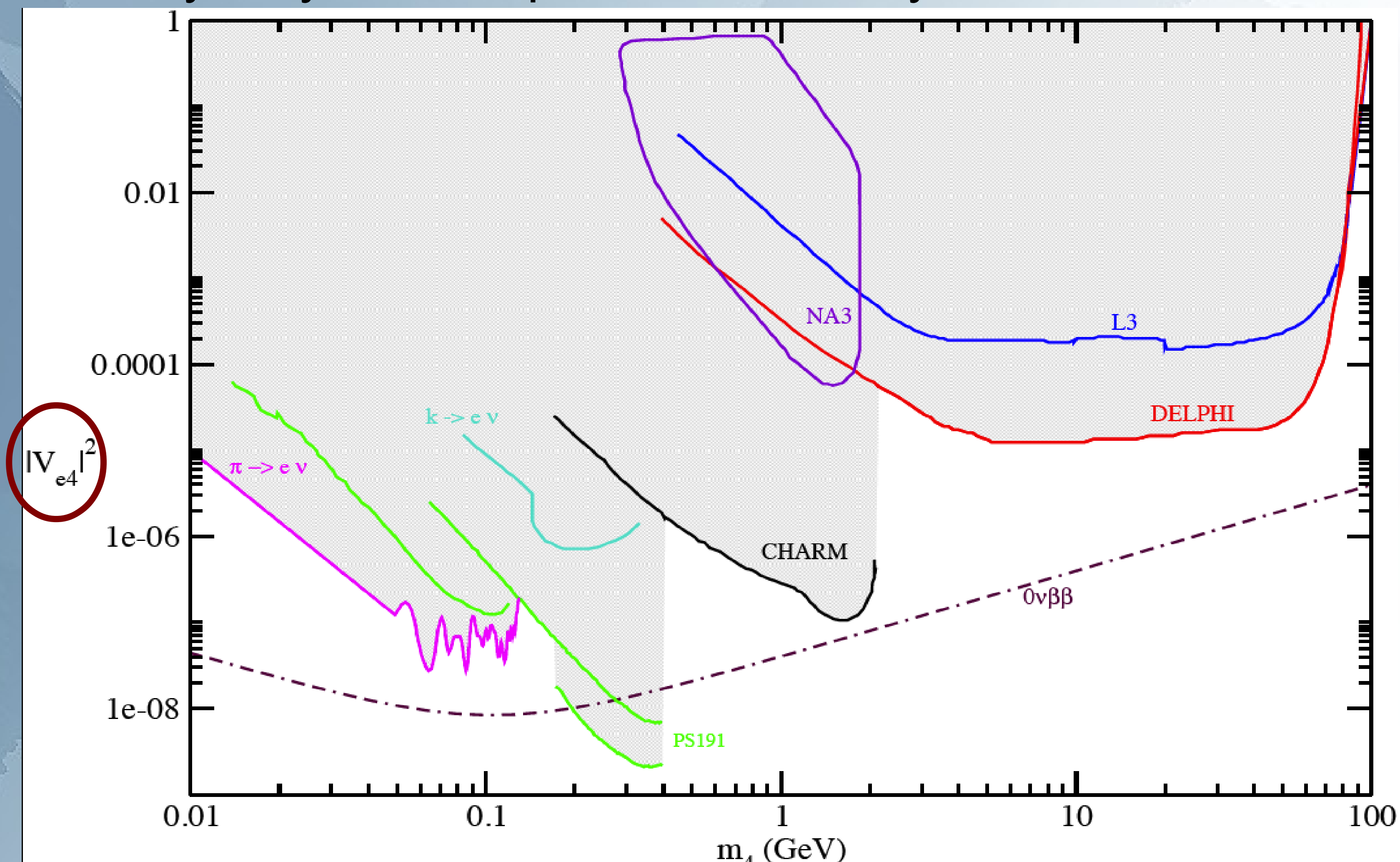

Atre, Han, Pascoli and Zhang (2009)

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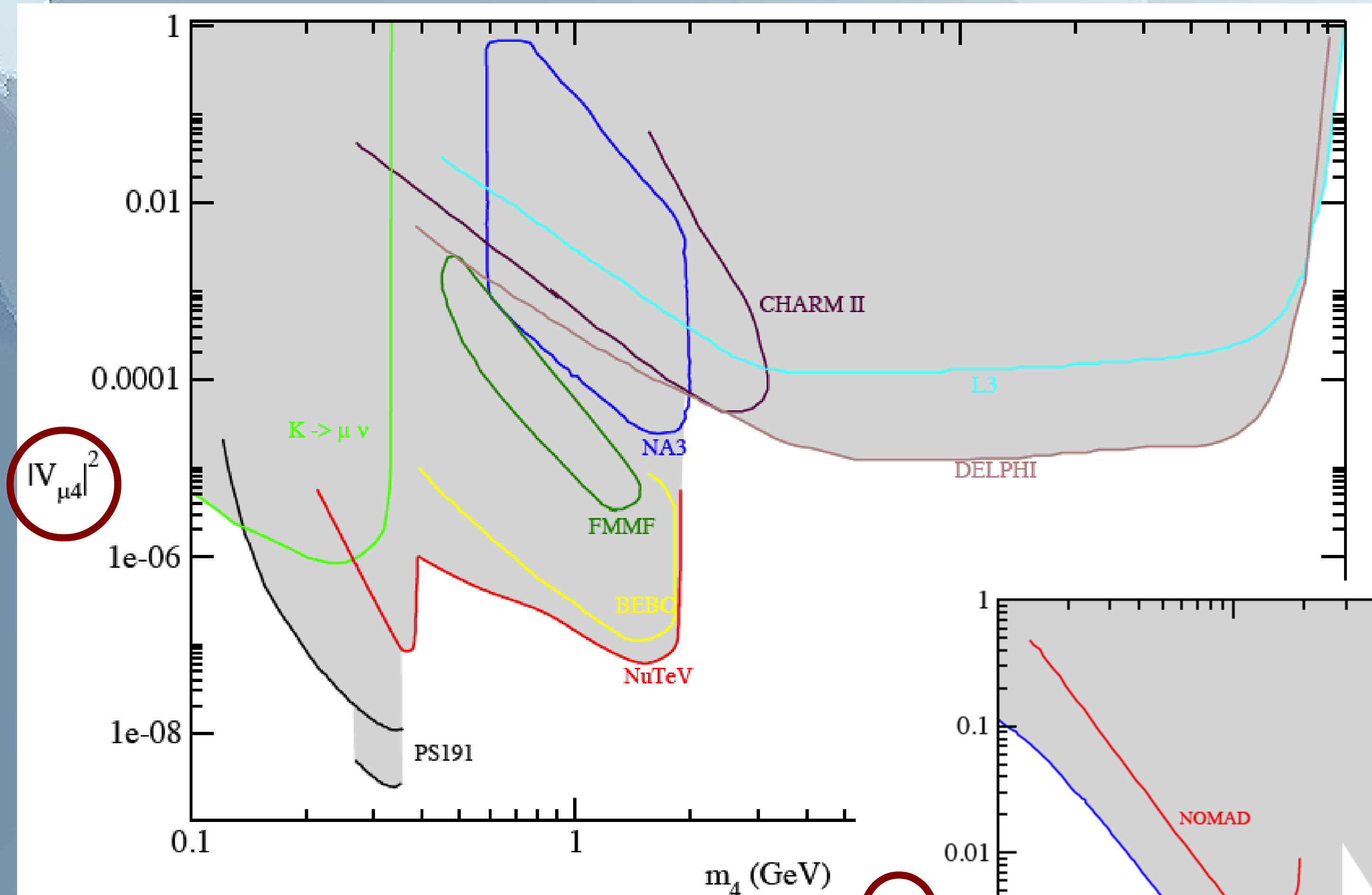

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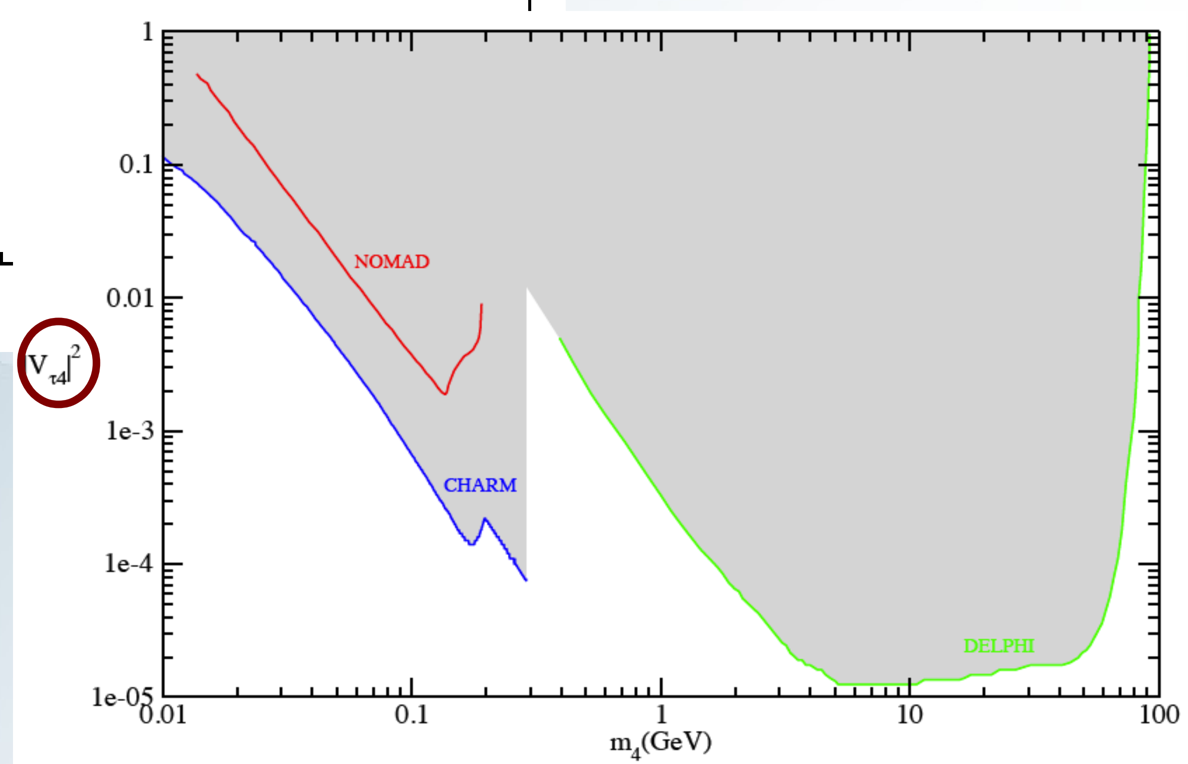


Current constraints on heavy neutrinos

- **Neutrino oscillations:**
  - The existence of a fourth neutrino would change the electron neutrino survival probability

$$P_{ee} = \cos^4\theta_{(14)}[1-\cos^4\theta_{(13)}\sin^2 2\theta_{(12)}\sin^2 \Delta_{(12)}-\sin^2 2\theta_{(13)}\sin^2 \Delta_{(13)}]$$

introducing a factor which violates unitarity

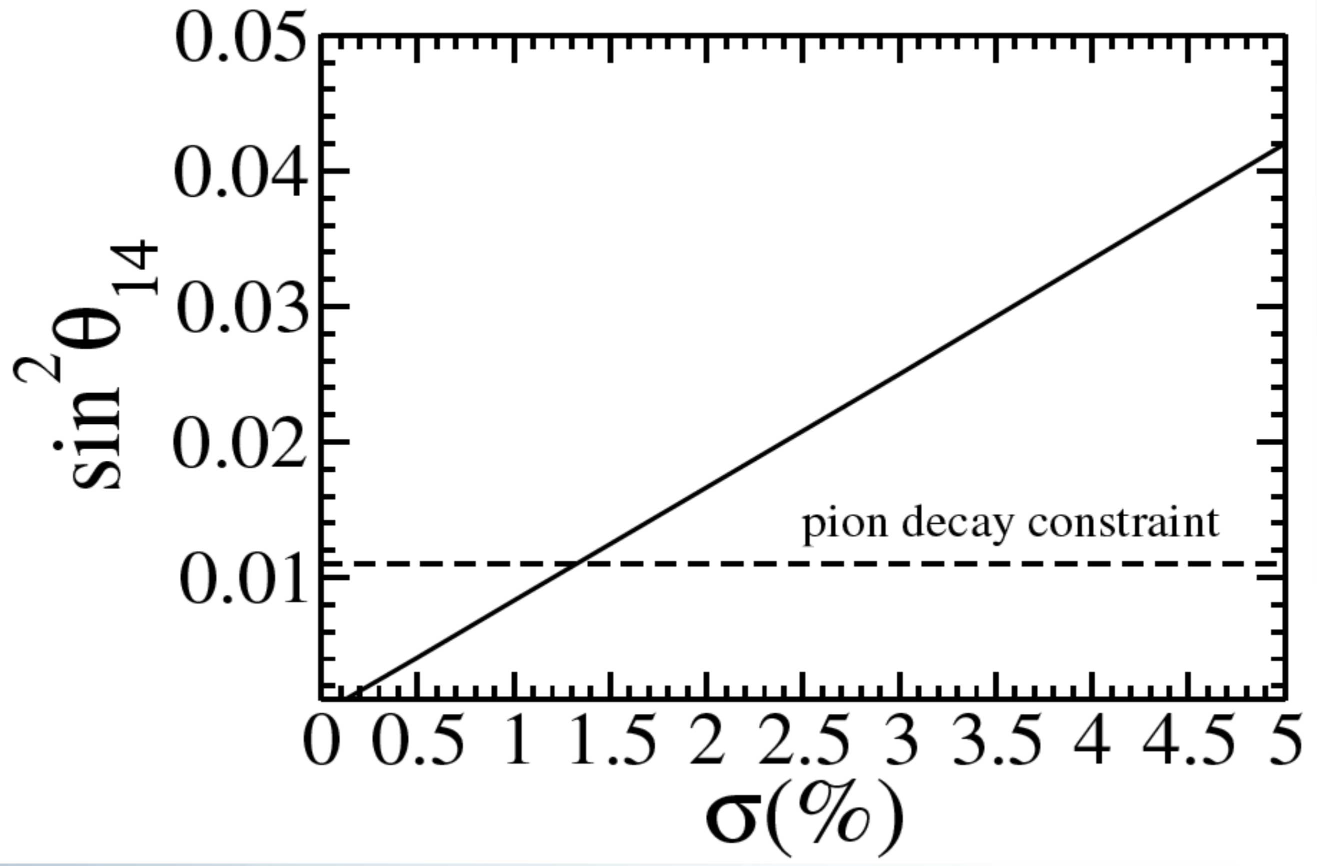
$$\cos^4(\theta_{14}) = (1 - |V_{14}|^2) \Longrightarrow |V_{14}|^2 \approx 0.04$$

  - Unfortunately the presence of an extra heavy lepton would not be enough to explain current neutrino anomalies. Hence we concentrate on constraints
  - For this, we go into more detail on the parametrization of right-handed neutrinos in the charged current weak interaction using the symmetric parametrization

Why relevant ? Future perspectives

- Future oscillation experiments could improve the constraints on heavy neutrino mixings. An example could be LENA, which number of events would be in presence of an extra heavy neutrino:

$$N_i = \cos^4\theta_{14} n_e \phi_{Cr} \Delta t \int_{T_i}^{T_i+1} \int \frac{d\sigma}{dT} R(T, T') dT' dT$$



Technical comments on the method

- Schechter-Valle PRD22(1980) 2227

- If we extend the SM neutrino sector introducing n heavy neutrinos, we can write the U mixing matrix as

$$U = \omega_{n-1\,n}\,\omega_{n-2\,n}\ldots\omega_{1\,n}\,\omega_{n-2\,n-1}\,\omega_{n-3\,n-1}\ldots\omega_{1\,n-1}\ldots\omega_{23}\,\omega_{13}\,\omega_{12}$$

where ω_{ij} are the rotation matrix in the ij plane

$$(\omega_{ij})_{\alpha\beta} = \delta_{\alpha\beta}\sqrt{1-\delta_{\alpha i}\delta_{\beta j}s^2_{ij}-\delta_{\alpha j}\delta_{\beta i}s^2_{ij}}+\tilde{s}_{ij}\,\delta_{\alpha i}\,\delta_{\beta j}\,\bar{s}_{ij}\,\delta_{\alpha j}\,\delta_{\beta i}$$

$$\tilde{s}_{ij} = \sin\theta_{ij}\; e^{-i\phi_{ij}}$$

$$\bar{s}_{ij} = -\sin\theta_{ij}\; e^{i\phi_{ij}}$$

- The U matrix has this structure

$$U_{nxn} = \begin{pmatrix} N_{3x3} & S_{3x(n-3)} \\ T_{(n-3)x3} & V_{(n-3)x(n-3)} \end{pmatrix} = R^{NP}\; R^{SM}$$

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- In this case, the matrix N_{3x3} involving the light neutrinos, which is not unitary, can be decomposed as

$$N = N^{NP}\, N^{SM} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} N^{SM}$$

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- The α_{ij} terms agglutinate extra heavy neutrino contributions:

$$\alpha_{11} = (\omega_{n-1\ n})_{11}(\omega_{n-2\ n})_{11}\dots(\omega_{n-1\ n})_{14} = c_{1\mathrm{n}}c_{1\,n-1}\dots c_{14}$$
$$\alpha_{22} = c_{2\mathrm{n}}c_{2\,n-1}\dots c_{24}$$
$$\alpha_{33} = c_{3\mathrm{n}}c_{3\,n-1}\dots c_{34}$$
$$\alpha_{21} = c_{2\mathrm{n}}c_{2\,n-1}\dots c_{25}\tilde{s}_{24}\bar{s}_{14} + c_{2\mathrm{n}}c_{2\,n-1}\dots\tilde{s}_{25}\bar{s}_{15}c_{14} + \dots + \tilde{s}_{2\,n}\bar{s}_{1\,n}c_{1\,n-1}\dots c_{14}$$
$$\alpha_{31} = c_{3\mathrm{n}}c_{3\,n-1}\dots c_{35}\tilde{s}_{34}\bar{s}_{14} + c_{3\mathrm{n}}c_{3\,n-1}\dots\tilde{s}_{35}\bar{s}_{15}c_{14} + \dots + \tilde{s}_{3\,n}\bar{s}_{1\,n}c_{1\,n-1}\dots c_{14}$$
$$\alpha_{32} = c_{3\mathrm{n}}c_{3\,n-1}\dots c_{35}\tilde{s}_{34}\bar{s}_{34} + c_{3\mathrm{n}}c_{3\,n-1}\dots\tilde{s}_{35}\bar{s}_{25}c_{24} + \dots + \tilde{s}_{3\,n}\bar{s}_{2\,n}c_{2\,n-1}\dots c_{24}$$

Simplest example: 3 + 1

- Introducing one heavy extra neutrino our formalism has the next expression

$$U_{4x4} = \begin{pmatrix} N_{3x3} & S_{3x1} \\ T_{1x3} & V \end{pmatrix}$$

$$N = N^{NP} \; N^{SM} =$$

$$= \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} c_{12}c_{13} & \tilde{s}_{12}c_{13} & \tilde{s}_{13} \\ \tilde{s}_{23}\bar{s}_{13}+c_{23}\bar{s}_{12} & \tilde{s}_{23}\tilde{s}_{12}\bar{s}_{13}+c_{23}c_{12} & c_{13}\tilde{s}_{23} \\ c_{12}c_{23}\bar{s}_{13}+\bar{s}_{23}\bar{s}_{12} & c_{23}\tilde{s}_{12}\bar{s}_{13}+\bar{s}_{23}c_{12} & c_{13}c_{23} \end{pmatrix}$$

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$$\alpha_{11} = c_{14}$$

$$\alpha_{22} = c_{24}$$

$$\alpha_{33} = c_{34}$$

$$\alpha_{21} = \tilde{s}_{24}\bar{s}_{14}$$

$$\alpha_{31} = \tilde{s}_{34}c_{24}\bar{s}_{14}$$

$$\alpha_{32} = \tilde{s}_{34}\bar{s}_{24}$$

3 + 3 model

- See-saw mechanisms introduce 3 or 6 extra singlets:

$$U_{6x6} = \begin{pmatrix} N_{3x3} & S_{3x3} \\ T_{3x3} & V_{3x3} \end{pmatrix}$$

$$N = N^{NP} \; N^{SM} =$$

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$$\alpha_{11} = c_{16}c_{15}c_{14}$$

$$\alpha_{22} = c_{26}c_{25}c_{24}$$

$$\alpha_{33} = c_{36}c_{35}c_{34}$$

$$\alpha_{21} = c_{14}\tilde{s}_{26}\bar{s}_{16}c_{15}+c_{26}\tilde{s}_{25}\bar{s}_{15}c_{14}+\tilde{s}_{26}c_{25}\tilde{s}_{24}\bar{s}_{14}$$

$$\alpha_{31} = c_{36}c_{35}c_{34}c_{24}\bar{s}_{14}+c_{36}\tilde{s}_{35}c_{25}\bar{s}_{15}\bar{s}_{14}+\tilde{s}_{36}c_{26}\bar{s}_{16}c_{15}c_{14}+c_{36}\tilde{s}_{35}\bar{s}_{25}\tilde{s}_{24}\bar{s}_{14}+ \\ +\tilde{s}_{36}\bar{s}_{26}c_{25}\tilde{s}_{24}\bar{s}_{14}+\tilde{s}_{36}\bar{s}_{26}\tilde{s}_{25}\bar{s}_{15}c_{14}$$

$$\alpha_{32} = c_{36}c_{35}\tilde{s}_{34}\bar{s}_{24}+c_{36}c_{35}\bar{s}_{25}c_{24}+\tilde{s}_{36}\bar{s}_{26}c_{25}c_{24}$$

Conclusions

- Extra neutral heavy leptons are motivated in order to introduce neutrino mass.
- Signatures of heavy neutrinos arising from their mixing with light ones could be looked for at laboratory experiments.
- A compilation of these is useful to give some light to models beyond SM and probe the scale of neutrino mass generation
- Such heavy neutrino (seesaw) models imply a high number of parameters.
- The symmetric parametrization of lepton mixing provides the most useful way to separate “new physics” from SM physics

Thank you!

Backup slides

Current constraints on heavy neutrinos

- The presence of extra heavy fermions would imply the non-unitarity of W_{3x3} and would modify some SM observables.
- **Universality tests:**
  - $\mu - e$ ***tests***

$$\begin{array}{l} \pi \to e\,\bar{\nu} \\ \pi \to \mu\,\bar{\nu} \end{array} \Longrightarrow \left(\frac{g_e}{g_\mu}\right)^2 = \frac{1-|V_{e4}|^2}{1-|V_{\mu 4}|^2}$$

$$CKM \Longrightarrow \sum_1^3 |U_{ui}|^2 = \left(\frac{G_F}{G_\mu}\sqrt{1-|V_{e4}|^2}\right) = \frac{1}{1-|V_{\mu 4}|^2}$$

$$|V_{e4}|^2 < 0.0084\,(0.0124) \quad ; \quad |V_{\mu 4}|^2 < 0.0005\,(0.0011)$$

  - $\mu - \tau$ ***tests***

$$\left(\frac{g_e}{g_\mu}\right)^2 = \frac{1-|V_{\tau 4}|^2}{1-|V_{\mu 4}|^2} \Longrightarrow |V_{e4}|^2 < 0.0207\,(0.0264)$$

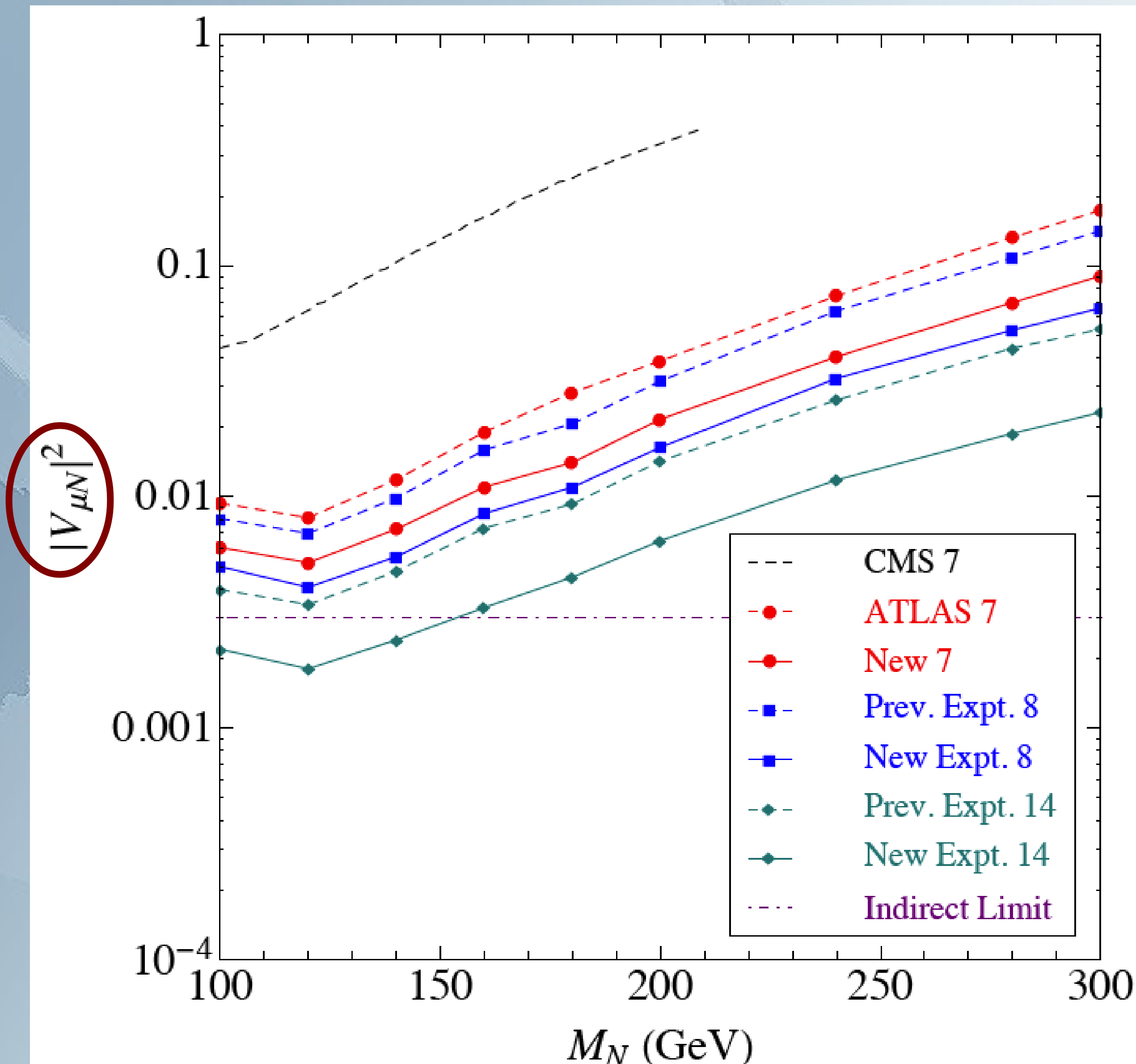
Bounds

Mixing	Range of m_4	EW measure
$\|V_{e4}\|^2$	$m_4 \geq O(m_\pi)$	< 0.003
$\|V_{\mu 4}\|^2$	$m_4 \geq O(m_\Lambda)$	< 0.003
$\|V_{\tau 4}\|^2$	$m_4 \geq O(m_\tau)$	< 0.006

del Aguila, de Blas and Pérez Victoria (2008)

LHC

- Limits coming from LHC



Buphal, Pilaftsis and Yang (2014)

Plot

- As we know, if we introduce any extra heavy neutrino the unitarity is violated

$$|N_{e1}|^2 + |N_{e2}|^2 + |N_{e3}|^2 = |\alpha_{11}|^2$$