# SOME CONSEQUENCES OF NON-STANDARD NEUTRINO INTERACTIONS

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The existence of new physics beyond the standard model (SM) is suggested by the issues as that of dark matter, neutrino masses and mixing and the observed matter-antimatter asymmetry in the universe, and some possible flavor anomalies.

most of the solutions of the issues above imply new degrees of freedom having non-standard interactions (NSI) with neutrinos and the other particles of the SM

Here we pointed out that these interactions have consequences which, probably will have to be taken into account in the future neutrino experiments. They range from obscuring the neutrino mass ordering [1], to misidentification of the flavor neutrinos, or the experimental ability to distinguish neutrinos from antineutrinos.

[1] See Capozzi et al. Phys. Rev. Lett. (2021); arXiv:1908.06992

some possibilities for new physics:

Multi-Higgs extension of the SM (extended Zee model)

Left-right (symmetric or not) models

3-3-1 models

A combination of the previous ones

Grand unification

Supersymmetric version of one of the previous ones

None of the above

$$\begin{pmatrix} \nu'_a \\ l'_a \end{pmatrix}_L \sim (\mathbf{2}, -1), \quad l'_{aR} = (l'^c_a)_L \sim (\mathbf{1}, -2)$$

Similarly for quarks.

SM multi-Higgs doublet models Y=+1, n=1,2,3,...

$$-\mathcal{L}^l_Y = \overline{\psi_{aL}} G^n_{ab} l'_{bR} H^n + \overline{\psi_{aL}} K^n_{ab} \nu'_{bR} \tilde{H}^n + H.c.$$

$$a = e, \mu, \tau$$

$$V_L^{l\dagger} M^l V_R^l = \hat{M}^l, \quad V_L^{\nu\dagger} M^\nu V_R^\nu = \hat{M}^\nu,$$

$$\hat{M}^l = V_L^{l\dagger} \left( \sum_n G^n \frac{v_n}{\sqrt{2}} \right) V_R^l, \quad \hat{M}^\nu = V_L^{\nu\dagger} \left( \sum_n K^n \frac{v_n}{\sqrt{2}} \right) V_R^\nu,$$

# lepton-scalar interactions

$$-\mathcal{L}_Y^l = \sum_n [\overline{\nu_{iL}} (\mathrm{A}_\mathrm{l}^\mathrm{n})_{\mathrm{ij}}^\dagger l_{jR} \phi_n^+ + \overline{l_{iL}} (\mathrm{B}_\mathrm{l}^\mathrm{n})_{\mathrm{ij}} l_{jR} \phi_n^0 - \overline{l_{iL}} (\mathrm{D}_\mathrm{l}^\mathrm{n})_{\mathrm{ij}} \nu_{jR} \phi_n^- + \overline{\nu_{iL}} (\mathrm{E}_\mathrm{l}^\mathrm{n})_{\mathrm{ij}} \nu_{jR} \phi_n^{*0}$$

$$\mathbf{A}_\mathrm{l}^\mathrm{n} = V_L^{\nu\dagger} G^n V_R^l, \quad \mathbf{B}_\mathrm{l}^\mathrm{n} = V_L^{l\dagger} G^n V_R^l, \quad \mathbf{D}_\mathrm{l}^\mathrm{n} = V_L^{l\dagger} K^n V_R^\nu, \quad \mathbf{E}_\mathrm{l}^\mathrm{n} = V_L^{\nu\dagger} K^n V_R^\nu,$$

# In the quark-scalar sector

$$-\mathcal{L}^q_{Y\,cc} = \sum_n [\bar{D}_L \mathbf{A}^{\mathbf{n}}_{\mathbf{u}} U_R \phi^-_n + \bar{U}_L \mathbf{A}^{\mathbf{n}}_{\mathbf{d}} D_R \phi^+_n + H.c.]$$

$$\mathbf{A}^{\mathbf{n}}_{\mathbf{u}} = V_L^{D\dagger} G^n_u V^U_R\,, \qquad \mathbf{A}^{\mathbf{n}}_{\mathbf{d}} = V_L^{U\dagger} G^n_d V^D_R\,,$$

The matrices $V_L^{U,D}, \quad V_R^{U,D}$ Survive separately in neutral interactions with the Z'

# Lepton-charged vector interactions (m331)

$$\mathcal{L}_{\bar{\nu}l} = i\frac{g}{2\sqrt{2}}\left[\overline{\nu_{aL}}\,(\mathbf{V_{LR}})_{\mathbf{ab}}\gamma^{\mu}(l^{c})_{aL} + \overline{l_{aR}}\,(\mathbf{V_{LR}^{T}})_{\mathbf{ab}}\gamma^{\mu}(\nu^{c})_{bR}\right] V_{\mu}^{-} + H.c.$$

$$V_{LR} = V_{L}^{\nu\dagger} V_{R}^{l*}.$$

$$V_{PMNS} = V_{L}^{l\dagger} V_{L}^{\nu},$$

We can eliminate one of the matrices using the PMNS

This sort of interactions occur in the m331 model and in the SU(15) GUT [Frampton&Kephart PR42, 3892R (1990)]

Only If $V_L^l = V_R^l = \mathbf{1}$:

Charged leptons are mass eigenstates basis from the very beginning, then

$$V_L^\nu = V_{PMNS},$$

and $\mathbf{V_{LR}} = V_{PMNS}^\dagger$ $\rightarrow$ $\nu_{aL}^W = \nu_{aL}^V$

# Vector-like quarks

$$\mathcal{L}_{G_{DU}} = \frac{g}{\sqrt{2}} \bar{D}_{Li} \gamma^{\mu} \left(\mathbf{V_{CKM}}\right)_{ij} U_{Lj} W_{\mu}^{-} + H.c., \quad \mathcal{L}_{G_{jU}} = \frac{g}{\sqrt{2}} \bar{j}_{Lk} \gamma^{\mu} (\mathbf{V_L^U})_{\mathbf{kj}} U_{Lj} U_{\mu}^{--} +$$

$$\mathcal{L}_{G_{JU}} = \frac{g}{\sqrt{2}} \bar{J}_{L} \gamma^{\mu} (\mathbf{V_L^U})_{\mathbf{3j}} U_{Lj} V_{\mu}^{+} + H.c., \quad \mathcal{L}_{G_{jD}} = -\frac{g}{\sqrt{2}} \bar{j}_{Lk} \gamma^{\mu} (\mathbf{V_L^D})_{\mathbf{kj}} D_{Lj} V_{\mu}^{-} + H.C.$$

$$\mathcal{L}_{G_{JD}} = \frac{g}{\sqrt{2}} \bar{J}_{L} \gamma^{\mu} (\mathbf{V_L^D})_{\mathbf{3j}} D_{Lj} U_{\mu}^{++} + H.c.$$

It is possible to use the definition of the CKM matrix $V_{CKM} = V_L^{D\dagger} V_L^U$ to eliminate one of the matrix $V_L^{U,D}$, for instance $V_L^U = V_L^D V_{CKM}$

Buras et al ,arXiv:2107.10866 [hep-ph]

# Effective interactions

$$-\mathcal{L}_H = \sum_i \left[ \frac{1}{m^2_{\phi_i^+}} (\bar{U}_R A_u^i D_L)(\bar{\nu}_L A_l^i l_R) + H.c. \right]$$

$$\mathcal{L}_V = \frac{g^2}{2 m_V m_W} (\bar{U}_R \gamma_\mu \mathbf{V}_{\mathbf{CKM}} D_L)(\bar{\nu}_L \gamma^\mu \mathbf{V}_{\mathbf{LR}} l_L^+) + H.c.$$

Some consequences:

# 1. Neutrino oscillations

$$\nu_{aL}^{W} = \sum_i (\mathbf{V_{PMNS}})_{\mathbf{ai}} \nu_{iL}, \quad \nu_{aL}^{H_{nk}} = \sum_i (O)_{nk} (\mathbf{A_l^n})_{\mathbf{ai}} \nu_{iL}, \quad \nu_{aL}^{V} = \sum_i (\mathbf{V_{LR}^\dagger})_{\mathbf{ai}} \nu_{iL}$$

In general

$$\nu_{aL}^{W} \neq \nu_{aL}^{H_{nk}} \neq \nu_{aL}^{V}.$$

The identification of the neutrinos of a given flavor cannot be done in a model independente way

Y. Grosmam, Phys. LettB 359, 141 (1995)

# In models with gauge symmetry

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}, \quad g_L(\mu) \neq g_L(\mu), \ \forall \mu$$

$$\nu_{aR} = \sum_i (V^R_{PMNS})_{ai} \nu_{iR}, \quad V^R_{PMNS} \neq V^L_{PMNS}$$

In this case there is a new $CP$ violating phase between the interactions (in quark and lepton sectors) with $W^\pm_L$ and $W^\pm_R$. The same occurs in 3-3-1 model and the extra singly charged vector boson, $V^\pm$.

Diaz et al J. Phys. G48, 085010 (2021)

$$\text{production}: \quad S \to X_\alpha + \nu,$$

$$\text{Detection}: \nu T \to Y_\beta$$

The source S is separated from the target T by a macroscopic distance L: use the formalism in

A. Falkowski et al, JHEP11, 048 (2020)[arXiv:1910.02971

# 2. Glashow resonance (SM)

S. Glashow, Phys. Ver. 118, 316 (1960)

$$(\nu_e^c)_R + e_L^- \;\to\; W^- \;\to\; (\nu_e^c)_R + e_R^-((\nu_\mu^c)_R + \mu_L^-)$$

$$(\nu_e^c)_R + e_L^- \to W^- \to \mathrm{hadrons},$$

$$E_\nu \approx 6\ \mathrm{PeV}$$

IceCube: Nature 591 (7849) 220-224 (2021),
[erratum: Nature 592 (7855) E11 (2021)]

$$\nu_{eL} + e^+_L \to H^+ \to \nu_{lL} + l^+_R,$$

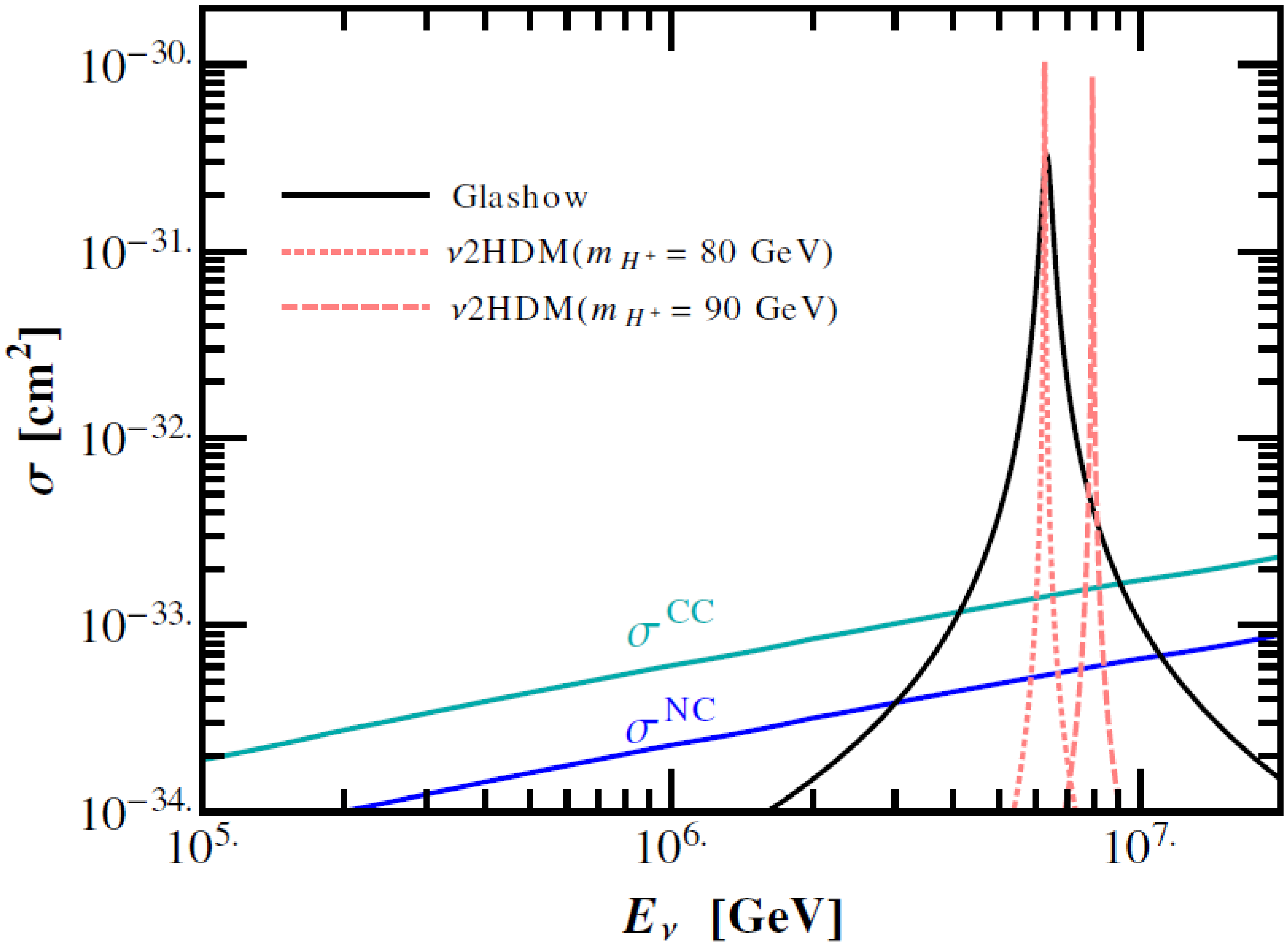
$$\nu_{eL} + e^+_L \to H^+ \to \text{known hadrons},$$

$$\nu_{eL} + e^-_R \to V^- \to \nu_l + l^-_R,$$

$$\nu_{eL} + e^-_R \to V^- \to \text{exotic hadrons}$$

For exotic resonances see:
De Conto and Pleitez, Phys. Ver. D 96, 075028 (2017); arXiv:1708.06285

# In 2DSM model and right-handed neutrinos




Dey, et al, arXiv:2010.05797

# 3. Neutrino---antineutrino confusion

SM:

$$\nu_{eL} \to l_L^- + W^+, \quad \text{neutrino}$$

$$\nu_{eR}^c \to l_R^+ + W^-, \quad \text{anti-neutrino}$$

m331

$$\nu_{eL} \to l_L^+ + V^-, \quad \text{neutrino!}$$

$$\nu_{eR}^c \to l_R^- + V^-, \quad \text{anti-neutrino!}$$

It is necessary to measure the helicity of the charged lepton helicity to distinguish among the four cases

# 4. Other processes

$$\nu_{\mu L} + N \to \mu_L^+ + X_j^-(jud) \quad (a), \quad \bar{\nu}_{\mu R} + N \to \mu_R^- + Y_J^-(Jdd) \quad (b)$$

$$\overset{(-)}{\nu}_{aL} + N \to l_{1L}^- l_{2L}^+ l_{3R}^- + X^- \quad (c), \quad \nu_{\mu L} + e_L^- \to l_{1L}^- l_{2L}^+ l_{3R}^- \nu_{aL} \quad (d)$$

$$\overset{(-)}{\nu}_a + N \to \overset{(-)}{\nu}_\ell \, l^+ l^- + X \quad (e), \quad \mu_L^- + N \to \mu_L^+ l^- l^- + N \quad (f)$$

$$\overset{(-)}{\nu}_a + N \to \overset{(-)}{\nu}_\ell + X, \quad (g) \quad \overset{(-)}{\nu} + N \to \mu^\pm + X, \quad (h)$$

In the SM:

$$\nu_{\mu L}(\bar{\nu}_{\mu R}) + N \to \mu_L^-(\mu_R^+) + \text{hadrons}$$

In the m331:

$$\nu_{\mu L} + N \to \mu_L^+ + X_j^-(jud) \quad (a),$$

Elementary process:

$$\nu_{\mu L} + d_L \to \mu_L^+ + j_L,$$

# Conclusions

1. Depending of the model, neutrino may have interactions with new scalars, vectors and/or férmions.

2. These interactions can make even the definition of the flavor of a neutrino to be model dependent.

3. Also the experimental distinction of what is a neutrino or antineutrino can be complicated because there are models in which neutrinos have interactions that fake an antineutrino.

# THANK YOU VERY MUCH!