Neutrino Masses and Some Implications to Cosmology

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Introduction

Why do we need to extend the standard model?

- Dark matter
- Matter- antimatter asymmetry of the universe
- Neutrino masses and mixings
- Hierarchy problem
- Strong CP problem
  Gauge coupling unification,
- ect...

Introduction

The standard model is not the final theory

- Dark matter

$$\left[\Omega_{DM}h^2\right]^{(obs)} = 0.1199 \pm 0.0027$$ [Planck Collaboration (2013)]

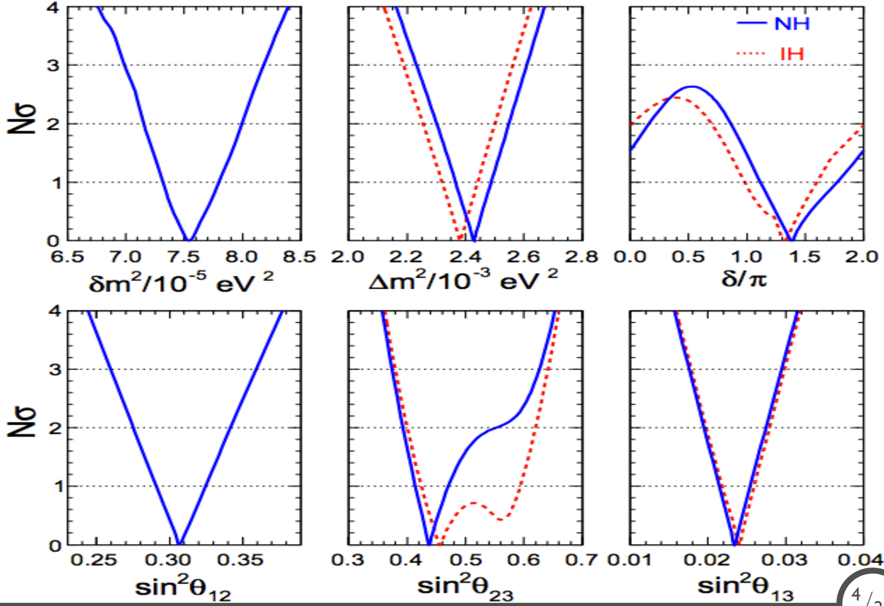
- Matter- antimatter asymmetry of the universe

$$\eta_B : \frac{n_B}{n_\gamma} = (6.047 \pm 0.074) \times 10^{-10}$$ [Planck Collaboration (2013)]

- Neutrino Oscillations (masses and mixings)
- Hierarchy problem
- Strong CP problem
- Gauge coupling unification
- ect..

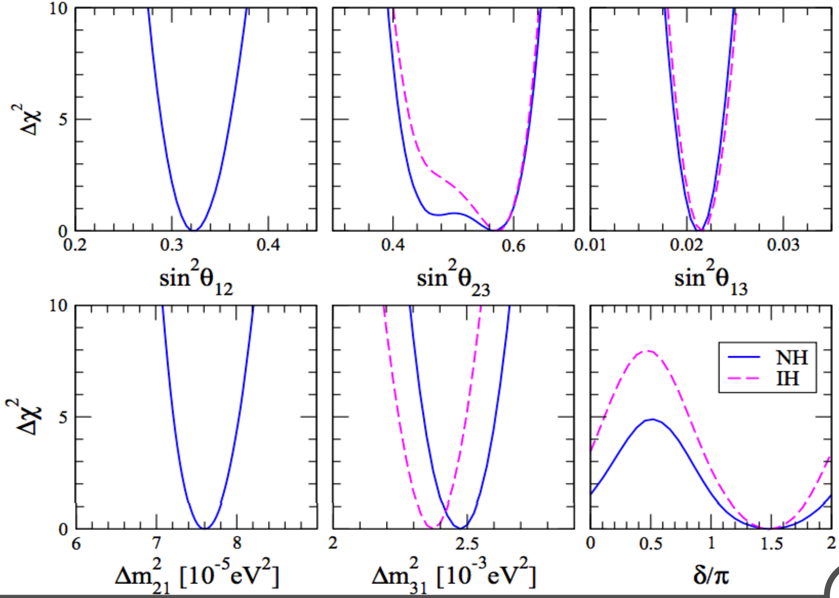
Neutrino Oscillations

[Capozzi et al. PRD 89, 093018 (2014)] .



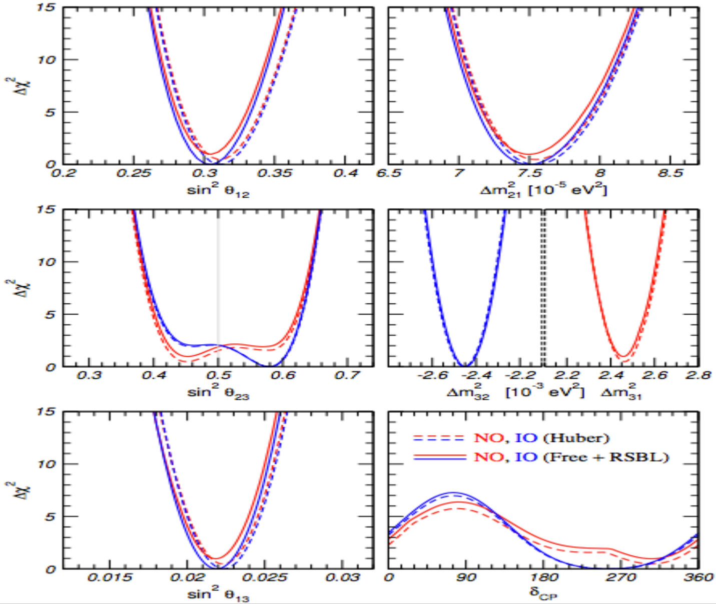
Neutrino Oscillations

[Forero, Tortola and Valle. (2014)].



Neutrino Oscillations

[Gonzalez-Garcia, Maltoni and Schwetz (2014)].



Neutrino Mixing

$$\Rightarrow ||U^{Data}_{PMNS}|| = \begin{pmatrix} 0.789-0.853 & 0.501-0.594 & 0.133-0.172 \\ 0.195-0.552 & 0.410-0.733 & 0.602-0.784 \\ 0.196-0.557 & 0.411-0.733 & 0.602-0.784 \end{pmatrix}$$

Compare it to

$$||U^{Data}_{CKM}|| = \begin{pmatrix} 0.974 & 0.225 & 0.00352 \\ 0.225 & 0.973 & 0.041 \\ 0.008 & 0.00 & 0.999 \end{pmatrix}$$

Neutrino Mixing

$$\Rightarrow ||U^{Data}_{PMNS}|| = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} + \text{small corrections}$$

$$= U_{TBM} + \text{small corrections}$$

$[Harison, Perkins, Scott(02); Xing(02); Zee, He(03)]$

Compare it to

$$||U^{Data}_{CKM}|| = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \text{small corrections}$$

Why $U_{PMNS} \simeq U_{TBM}$?

$\mu - \tau$ symmetry

$$U_{PMNS} = \mathscr{R}_{23}(\theta_{23} = \pi/4) \times \mathscr{R}_{13}(\theta_{13} = 0) \times \mathscr{R}_{12}(\theta_{12}); \ \forall\ \theta_{12}$$

$\mathbb{Z}_3^{(l)} \times [\mathbb{Z}_2 \times \mathbb{Z}_2]^{(\nu)}$ symmetry

$\mathbb{Z}_3 :< S/S^3 = e >$, $\quad \mathbb{Z}_2 \times \mathbb{Z}_2 :< T, U/T^2 = U^2 = e;\ (TU)^2 = e >$:

$$\mathbb{Z}_3 : T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix};\ \mathbb{Z}_2^S \times \mathbb{Z}_2^U : S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix},\ U = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\Rightarrow V_L^l = V_R^l = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix},\ V_L^\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \end{pmatrix},\ \omega = e^{2\pi i/3}$$

$$\Rightarrow U_{PMNS} \equiv (V_L^l)^\dagger V_L^\nu \ \equiv \ U_{TBM}$$

No-go theorem [Low and Volkas (2003)]

Can't generate $U_{PMNS} = U_{TBM}$ by an unbroken (non-trivial) flavor symmetry (abelian or non-abelian).

- Assume that at $E > v_{EW}$, the SM is invariant under some flavor symmetry group G_F that has **3**-dimensional representation(s).

  Ex: $A_4,\ S_4,\ \mathbb{Z}_7 \rtimes \mathbb{Z}_3,\ \Delta(27) \supset\ \Delta(3n^2),\ \Delta(54) \supset\ \Delta(6n^2),\ A_5,\ PSL(2,7),..$

- Extend the scalar sector with "flavons" , ϕ, that transform under G_F.

- If the flavons get VEVs that breaks G_F in such a way that

$$G_F \to \begin{cases} G_\nu = \mathbb{Z}_2 \times \mathbb{Z}_2 & : \text{in the } \nu\text{-sector} \\ G_e \supset \mathbb{Z}_3 & : \text{in the l - sector} \end{cases}$$

[He, Keum, Volkas(06); Lam(07, 08)]

  Then one might obtain $U_e^\dagger U_\nu = U_{TBM}$.

- Add soft breaking terms or (more) higher dimensional operators to get the corrections as required by the data.

Some remarques

- To obtain the desired vacuum alignment, usually, requires fine tuning in the flavons potential. Use of Susy (+ R parity); X-tra dim (branes); auxillary symmetries (e.g. Z_3,....).

- After 2012 the TBM is not consistent with the data. Corrections to the LO, at least in the simple implementations, result in a solar mixing angle outside the experimental range.
  [Altarelli, Feruglio, Merlo, E. Stamou (2012); Varzielas, Pidt (2013)]

- One can look for finite groups that predict sizable leptonic mixing patterns at LO. A scan of all finite groups of order $|G_F| < 1536$ (more than 13 million) with $G_\nu = \mathbb{Z}_2 \times \mathbb{Z}_2 \subset G_F$ yields that only few groups can give lepton mixing consistent with the neutrino oscillation data.
  □ [Holthausen, Lim and M. Lindner (2013)]

Why $m_e >> m_\nu \neq 0$?

SM is an effective theory

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{(5)} + \mathcal{L}_{eff}^{(6)} + ..$$ [Weinberg, (1979)]

$$\mathcal{L}_{eff}^{(5)} \sim \frac{1}{\Lambda} L\Phi L\Phi \Rightarrow m_\nu \sim \frac{\upsilon^2}{\Lambda_{NP}} \Rightarrow \Lambda \sim 10^{14}\ GeV$$

Can be written in **3 diff. forms**:

$$Type\ I = \quad ....+\frac{C_{\alpha\beta}}{2\Lambda_{NP}}\,(\bar{L^c_\alpha}\ i\sigma_2\ \Phi)(L^T_\beta\ i\sigma_2\ \Phi) + h.c$$

$$Type\ II = \quad ....-\frac{C_{\alpha\beta}}{4\ \Lambda_{NP}}\,(\bar{L^c_\alpha}\ i\sigma_2\ \vec{\sigma}\ L_\beta)(\Phi^T\ i\sigma_2\ \vec{\sigma}\ \Phi) + h.c$$

$$Type\ III = \quad ....+\frac{C_{\alpha\beta}}{2\Lambda_{NP}}\,(\bar{L^c_\alpha}\ i\sigma_2\ \vec{\sigma}\ \Phi)(L^T_\beta\ i\sigma_2\ \vec{\sigma}\ \Phi) + h.c$$

Seesaw mechanisms

Type I

$$= \ldots + \bar{L}\,\tilde{\Phi}\,Y_\nu\,N_R + \frac{1}{2}\,N_R^T\,C\,M_R\,N_R + h.c \quad \Rightarrow \quad \frac{C_{\alpha\beta}}{\Lambda_{NP}} = Y_\nu^T\,M^{-1}\,Y_\nu$$

[Minkowski; Yanagida; Ramond and Gell-Mann; Mohapatra and Senjanovic]

Type II

$$= \ldots + M_\Delta^2 Tr(\Delta^\dagger \Delta) + \mu_\Delta \Phi^T i\tau_2 \Delta^\dagger \Phi + \frac{h_{\alpha\beta}}{2}\,L^T C i\tau_2 \Delta\,L_\beta + h.c \quad \frac{C_{\alpha\beta}}{\Lambda_{NP}} = \frac{h_{\alpha\beta}\mu_\Delta}{M_\Delta^2}$$

[Maag, Watterich, Shafi, Lazaridis; Mohapatra, Senjanovic; Schechter, Valle]

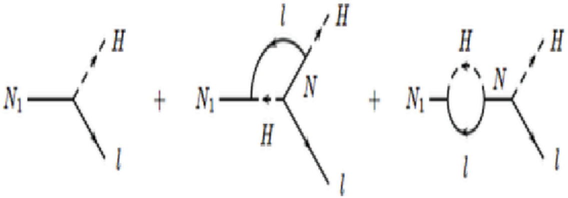
Type III

$$= \ldots + \frac{1}{2}\left[\overline{\Sigma_{R_i}} M_{\Sigma_i} \Sigma_{R_i}^c + \overline{\Sigma_R^c} M_\Sigma^* \Sigma_R\right] + h_{\alpha i}\bar{L}_\alpha\,\Sigma_{R_i}\,\tilde{\Phi} + h.c \quad \Rightarrow \quad m_\nu = \frac{C_{\alpha\beta}\,\upsilon^2}{\Lambda_{NP}}$$

[Foot, He, Lew, Joshi; Ma]

Leptogenesis. Ex: Type I

- Generate a B-L asymmetry through the out-of-equilibrium decays of N_{iR} into leptons and anti-leptons. ☐ [Fukugita and Yanagida (86)]



- The CP-asymmetry from the decay of N_i into lepton and anti-leptons:

$$\varepsilon_i = \frac{\Gamma(N_i \to L\,\Phi) - \Gamma(N_i \to \bar{L}\,\bar{\Phi})}{\Gamma(N_i \to L\,\Phi) + \Gamma(N_i \to \bar{L}\,\bar{\Phi})}$$ [Flanz et al, 94; Covi, Roulet, Vissani, 94]

- Part of it get converted to a baryon asymmetry via sphaleron transitions.

Leptogenesis. Ex: Type I

- Wash out effects (in addition to the inverse decay)

  1. off-shell $\Delta L = 1$ scatterings involving top quark:

$$N_1\, L \quad \leftrightarrow \quad t\, \bar{q}, \quad N_1\, \bar{L} \leftrightarrow t\, \bar{q} \quad \text{(s-channel)}$$
$$N_1\, t \quad \leftrightarrow \quad \bar{L}\, q, \quad N_1\, \bar{t} \leftrightarrow L\, \bar{q} \quad \text{(t-channel)}$$

  2. $\Delta L = 2$ scatterings

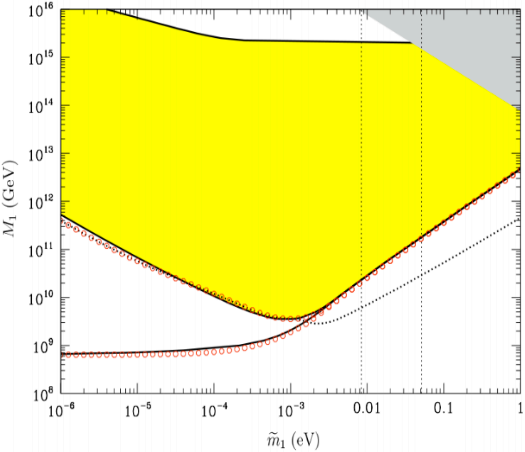
$$L\, \Phi \quad \leftrightarrow \quad \bar{L}\, \bar{\Phi}, \quad L\, L \leftrightarrow \bar{\Phi}\, \bar{\Phi}, \quad \bar{L}\, \bar{L} \leftrightarrow \Phi\, \Phi$$

- The final baryon asymmetry : $Y_B := \frac{n_B}{s} \simeq -4 \times 10^{-3} \times \varepsilon_1 \times \kappa_f \times C_s$

$C_s = \frac{28}{79}$: [Conversion factor]; $\kappa_f(\tilde{m}_1)$ [Efficiency factor]; $\tilde{m}_1 = \frac{(YY^\dagger)_{11} v^2}{M_1}$

Leptogenesis. Ex: Type I

After solving the Boltzmann equations:



$$\varepsilon_1 \leq \frac{3}{16\pi}\frac{M_1}{\upsilon^2}(m_3 - m_1)$$

[Davidson and Ibarra(2002)]

$\Rightarrow$ $M_1 > 10^9\ GeV$

[Buchmuller, Di Bari, Plumacher(2004)]

Wash-out from $\Delta L = 2$ processes $\rightarrow$ $\bar{m} := \sqrt{m_1^2 + m_2^2 + m_3^2} < 0.2\ eV$

$\Rightarrow$ □ $m_i < 0.11\ eV$

Some remarques

- $M_1 > 10^9\ GeV \Rightarrow T_{RH} > 10^9\ GeV \Rightarrow$ Gravitino problem (if SUSY).

- No relation or correlation between ε_1 and the low energy CP violation in the ν-sector. $\Rightarrow$ Need to reduce the number of parameters: Flavor Symmetries/Textures/Ansatz. [E.g: Frampton, Glashow, Yanagida; Branco, Felipe, Joaquim, Masina, Rebelo and Savoy; Mohapatra, S. N, Yu, ...]

- A super-heavy RHN is not accessible to collider experiments.

- If one take naturalness seriously, then a super-heavy RH neutrinos distablises the EW scale (hierarchy problem):

$$|\delta m_h^2| \simeq \frac{1}{4\pi^2}|Y_{\alpha i}|^2 M_i; \qquad \frac{1}{4\pi^2}\frac{m_\nu M^3}{\upsilon^2} < \upsilon^2 \Rightarrow M < 10^7\ GeV$$

[De Gouvea, Hernandez and Tait (2014)]

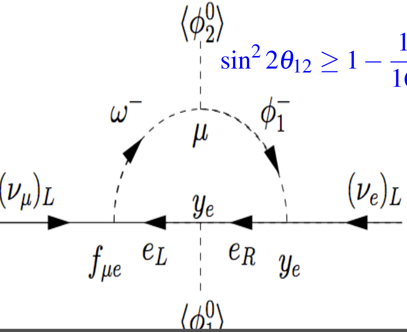
- Super-heavy RHN could render the SM Higgs vacuum stability issue worse.

M_ν at One loop

(a) Zee Model

$$S^{(+)} \sim (1,1,+1), \;\; \Phi_2 \sim (1,2,+1/2),$$

$$\mathcal{M}_\nu = A\left[f\, m_l^2 + m_l^2\, f^T\right]\,;\; A \propto \frac{\mu \cot\beta}{16\pi^2 M_2^2}$$



$$\sin^2 2\theta_{12} \geq 1 - \frac{1}{16}\left(\frac{\Delta m_{12}^2}{\Delta^2 m_{23}}\right)^2$$ [Koide; Frampton, Oh, Yoshikawa; He]

$$\Rightarrow \sin^2 2\theta_{12} > 0.999$$

Ruled out by solar neutrino oscillation data.

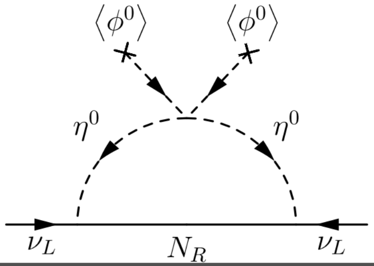
M_ν at One loop

(b) Scotogenic Model [Ma (2006)]

$$N_i \sim (1,1,0),\ \eta \sim (1,2,+1/2), \quad \mathbb{Z}_2:\ N_i, \eta_i \to -N_i, -\eta$$

$$(M_\nu)_{\alpha\beta} \simeq \frac{\lambda_5\, v^2}{8\pi^2} \sum_n \frac{h_{\alpha n}\, M_n\, h_{\beta n}}{m_0^2 - M_n^2} \left[1 - \frac{M_n^2}{m_0^2 - M_n^2} \ln \frac{m_0^2}{M_n^2}\right]$$

For $\left[1 - \frac{M_n^2}{m_0^2 - M_n^2} \ln \frac{m_0^2}{M_n^2}\right] \sim 1 \Rightarrow \lambda_5 h_i^2 \sim 10^{-10} \left(\frac{M_i}{TeV}\right)$



The possible DM candidates:

- The lightest N_i if min (M_i) < m$_{R,I}$, or
- η_R if $m_R < m_I$, min (M_i), or
- η_I if $m_I < m_R$, min (M_i).

Radiative Neutrino Masses

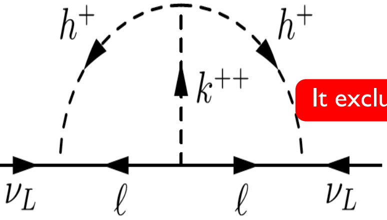
M_ν at two loops

Zee-Babu Model

$$S^+ \sim (1,1,+1),\; k^{++} \sim (1,1,+2)$$

$$(M_\nu)_{\alpha\beta} \simeq \frac{3}{2}\frac{J(\frac{m_k^2}{m_h^2})}{(4\pi^2)^2}\,\mu\,\frac{m_\tau^2}{M^2}\; f_{\alpha\tau}\; h^*_{\tau\tau}\; f_{\beta\tau}$$

$$J(x) = \begin{cases} 1 + \frac{3}{\pi^2}\left[(\ln x)^2 - 1\right] & x >> 1 \\ 1 & x \to 0 \end{cases}$$



One of the neutrinos must be massless

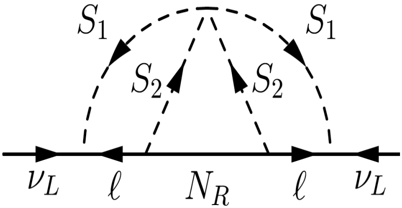
It excludes the possibility for a quasi-degenerate ν spectrum

Radiative Neutrino Masses

M_ν at three loops

$$\mathscr{L} \supset \mathscr{L}_{SM} + f_{\alpha\beta}\, L_\alpha^T C\, i\sigma^2 L_\beta\, S_1^+ + g_{\alpha n}\, N_n^T C\, l_{R_\alpha} - \frac{1}{2} M_n\, \overline{N_i^c}\, N_n + h.c - V(\Phi, S_1, S_2)$$

$$N_i \sim (1,1,0),\; S_{1,2}^+ \sim (1,1,+1); \quad \mathbb{Z}_2 :\; (N_i, S_1^+, S_2^+) \;\rightarrow\; (-N_i, S_1^+, -S_2^+)$$



$$(M_\nu)_{\alpha\beta} = \frac{\lambda_s}{(4\pi^2)^3} (f\, m_l\, g)_{\alpha n}\, \mathcal{F}\left(\frac{M_n^2}{m_{S_2}^2}, \frac{m_{S_1}^2}{m_{S_2}^2}\right) \left(g^T\, m_l\, f^T\right)_{n\beta}$$

$$\mathcal{F}(a,b) = \frac{\sqrt{a}}{8b^2} \int_0^\infty \frac{r\, dr}{r+a} \left[\int_0^1 dx\, \ln \frac{x(1-x)r + (1-x)\beta + x}{x(1-x)r + x}\right]^2$$

[Krauss, S. N, Trodden (2003)]

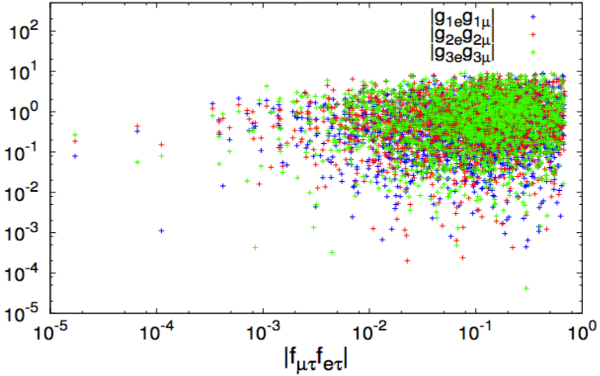
[Other examples: Aoki, Kanemura, Seto (2004), Ng and Puente (2013)]

Lightest of $N_i's$ is a candidate for DM

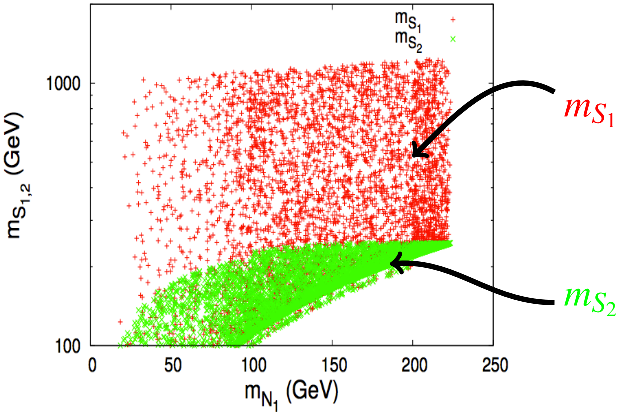
M_ν at three loops: Constraints

- Fit the observed neutrino mass squared differences and mixings;
- Satisfy the bound on LFV processes; [$\rightarrow$ $Br(\mu \rightarrow e+\gamma) < 5\times 10^{-13}$];

[Ahriche, S. N; JCAP (2013)]



Only 15% of the scanned points survive the $\mu \rightarrow e+\gamma$ constraints

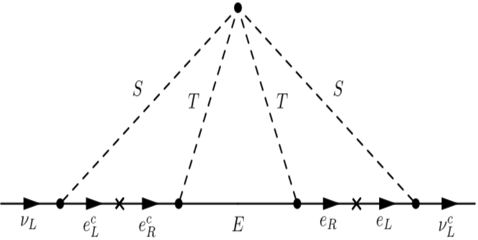


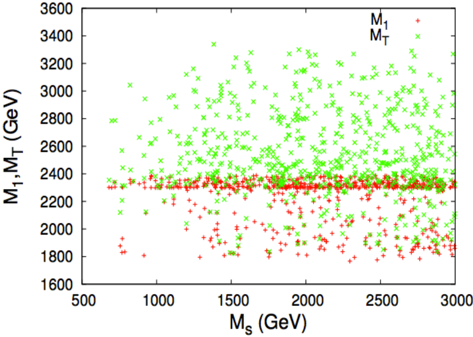
N_1 depletion : $N_1 N_1 \to l_\alpha l_\beta$ (via exchange of $S_2^\pm$)

$$\Omega_{N_1} h^2 \simeq \frac{1.3\times 10^{-2}}{\sum_{\alpha,\beta} |g_{1\alpha} g^*_{1\beta}|^2} \left(\frac{m_{N_1}}{135\ GeV}\right)^2 \frac{\left(1+m^2_{S_2}/m^2_{S_1}\right)^4}{1+m^4_{S_2}/m^4_{S_1}}$$

M_ν at three loops: Type III

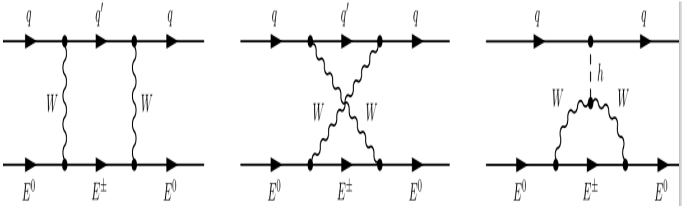
[Chen, McDonald, S. N. (PLB 2014); Ahriche, McDonald, S. N (PRD 2014)]





$E^0 =$ DM; $M_1 \sim 2.7\ TeV$

$\sigma(E^0\ N \to E^0\ N) \sim 10^{-45}\ cm^2$; below the LUX bound.

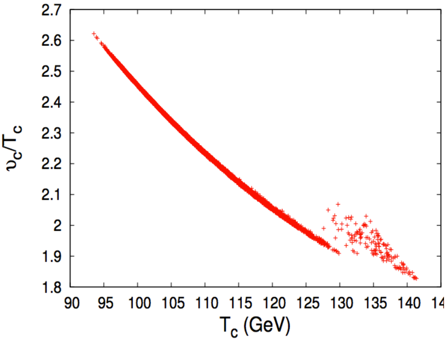


Conclusion

- Neutrino masses and mixings can be a window to NP beyond the SM.
- If M_ν is generated via the see-saw mechanism, then the origin of $\Omega_b \sim 5\%$ might be explained (leptogenesis).
- See-saw models + Flavor symmetries might connect/correlate the high energy CP asymmetry with low energy neutrino mixing and CP phases.
- If M_ν is generated at loop-level, then
  - The origin of $\Omega_{DM} \sim 27\%$ might be explained if NP contain neutral particle(s).
  - New degrees of freedom (particles) might be be accessible at low energy (e.g Collider, EWPhT ...).
  - Radiative Models with three loops are testable and can be falsifiable (LFV) .

Back-Up

M_ν at three loops: $S_{1,2}$- Strongly First order EWPhT



$$V_{eff}(h,T) = V^{T=0}(h) + \frac{T^4}{2\pi^2}\sum_i n_i J_{B,F}\left(m_i^2/T^2\right) + V_{ring}(h,T);$$

$$J_{B,F}(\alpha) = \int_0^\infty x^2 \log(1 \mp \exp(-\sqrt{x^2+\alpha})),$$

$$V_{ring}(h,T) = -\frac{T}{12\pi}\sum_i n_i \left\{\tilde{m}_i^3(h,T) - m_i^3(h)\right\},$$

$$V^{T=0}(h, S_1, S_2) \supset \frac{\lambda_1}{2}|S_1|^2\, h^2 + \frac{\lambda_2}{2}|S_2|^2\, h^2$$

Requires $\lambda_{1,2}$ to be order 1.