Prospects of experimentally reachable beyond Standard Model physics in inverse seesaw motivated non-SUSY SO(10) GUT

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[1] Parida, arXiv:1112.1826, arXiv:1302.0672(S. Patra), arXiv:1401.1412(P. K. Sahu)

Outline

- Introduction
- Grand unification, SO(10) etc
- Non-SUSY SO(10) with TeV scale inverse seesaw
- Extended non-SUSY SO(10) with extended inverse seesaw
- Summary

Spin=1				
Gluons	$G^a_\mu, \ a = 1, 2 \ldots 8$	(1,0,8)	$SU(3)_C$	g_S
Weak Bosons	$W^i_\mu, \ i = 1, 2, 3$	(3,0,1)	$SU(2)_L$	g
Hyperon	B_μ	(1,0,1)	$U(1)_Y$	g'
Spin=1/2				
Quarks	$(2, 1/6, 3)$	$\begin{pmatrix} u^\kappa \\ d^\kappa \end{pmatrix}_L$	$\begin{pmatrix} c^\kappa \\ s^\kappa \end{pmatrix}_L$	$\begin{pmatrix} t^\kappa \\ b^\kappa \end{pmatrix}_L$
	$(1, 2/3, 3)$	u^κ_R	c^κ_R	t^κ_R
	$(1, -1/3, 3)$	d^κ_R	s^κ_R	b^κ_R
Leptons	$(2, -1/2, 1)$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$
	$(1, -1, 1)$	e_R	μ_R	τ_R
Spin=0				
Higgs	$(2, -1/2, 1)$		$\begin{pmatrix} H^0 \\ H^- \end{pmatrix}$	

Table : The Standard Model particles.

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

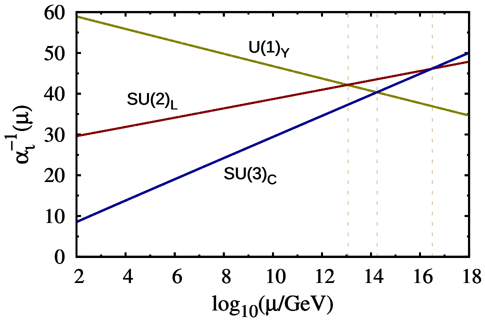
- Tested at

  LEP (e^+e^-), SLC (e^+e^-), Tevatron ($p\bar{p}$), HERA (e^-p), PEP-II (e^+e^-), KEKB (e^+e^-) and recently at LHC (pp).
- 20 GeV to 8 TeV Explored.
- All the particles predicted by the Standard Model, namely

  τ (1975), ν_τ (2000), c (1974), b (1977), t (1995), gluons (1979), W, Z (1983) and Higgs (2012),

  have been discovered.
- Fits precisely.

- Neutrino masses and mixings
  (S. Goswami, A. Raychaudhuri, Y. Y. Keum, R. Srivastava)
- Dark Matter (G. Rajasekaran, S. Vempati)
- Baryonic asymmetry of universe
- Flavor problem
- Hierarchy or naturalness problem (R. K. Kaul)
- Gauge symmetry problem
- Charge quantization (B. Bajc, Z. Tavartkiladze)



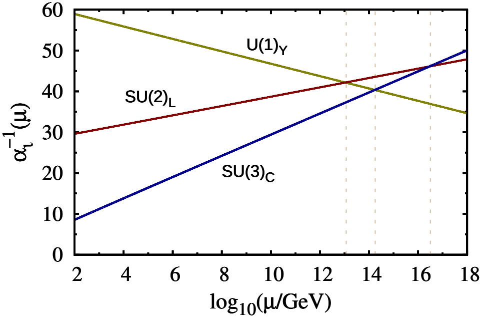
Gauge coupling evolution

$$\mu \frac{\partial \alpha_i}{\partial \mu} = \frac{b_i}{2\pi} \alpha_i^2 + \mathcal{O}(2) + Yuk. \quad (1)$$

For

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

$$b = (-19/6, 41/10, -7) \quad (2)$$



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For

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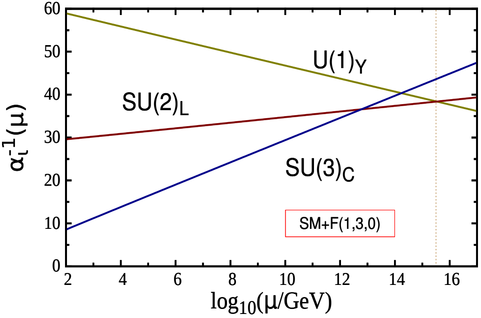


F(3, 0, 1) at M_Z.

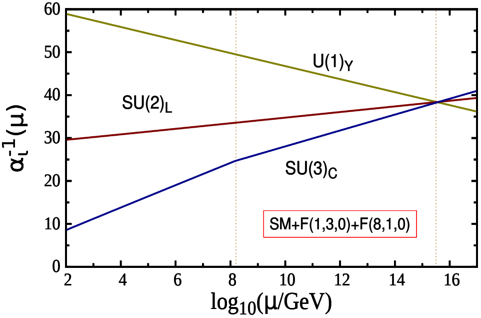
Gauge coupling evolution

$$\mu \frac{\partial \alpha_i}{\partial \mu} = \frac{b_i}{2\pi} \alpha_i^2 + \mathcal{O}(2) + Yuk. \quad (3)$$

For

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

$$b = (-11/6, 41/10, -7) \quad (4)$$



Borut Bajc, G. Senjanovic, 2007

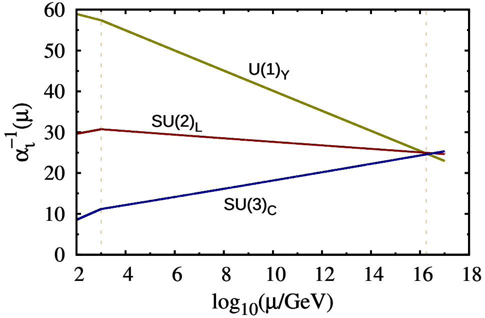
Gauge coupling evolution

$$\mu \frac{\partial \alpha_i}{\partial \mu} = \frac{b_i}{2\pi} \alpha_i^2 + \mathcal{O}(2) + Yuk. \quad (5)$$

For

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

$$b = (-11/6, 41/10, -5) \quad (6)$$



Below TeV

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

$$b = (-19/6, 41/10, -7) \quad (7)$$

Above TeV

$$b = (1, 33/5, -3) \quad (8)$$

- TeV scale SUSY.
- Stabilizes the fine tunings.
- Cold dark matter candidate.[2]
- MSSM+Seesaw extension$\Rightarrow$ Neutrino parameters || SUSY-GUT.[3]
- But, no SUSY has been seen yet.[4]

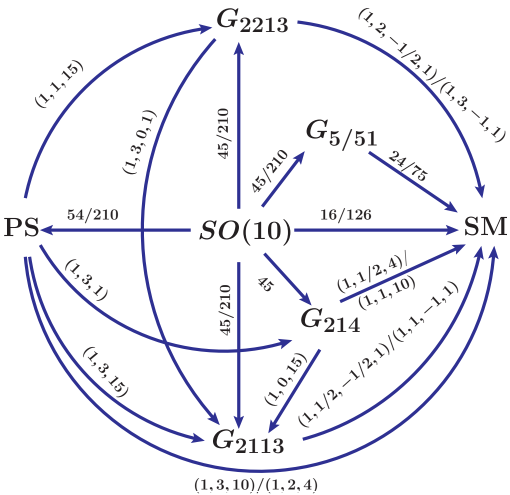
C.S. Aulakh, S. Vempati, U. A. Yajnik, K. S. Babu, R. Mohapatra...

[2] Fowlie et al, Han et al
[3] Mohapatra, Altarelli, Babu, Senjanovic, Aulakh, Ma
[4] ATLAS and CMS results

Grand unification

non-SUSY

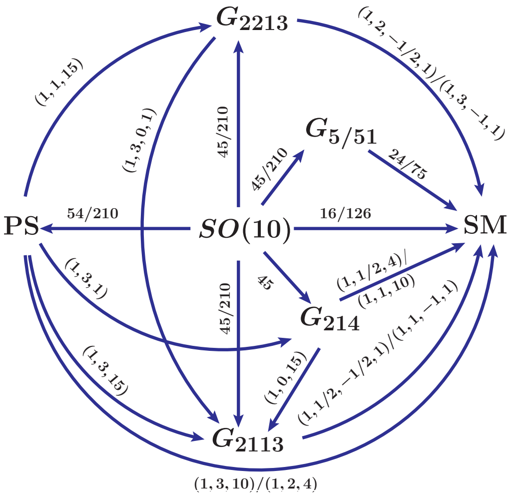
- Intermediate symmetries for unification of interactions.
- Low energy predictions?


G_{2213}
$(1,1,15)$
$(1,3,0,1)$
$45/210$
$(1,2,-1/2,1)/(1,3,-1,1)$
$G_{5/51}$
$45/210$
$24/75$
PS
$54/210$
$SO(10)$
$16/126$
SM
$(1,3,1)$
45
$(1,1/2,4)/$
$(1,1,10)$
$45/210$
G_{214}
$(1,3,15)$
$(1,0,15)$
$(1,1/2,-1/2,1)/(1,1,-1,1)$
G_{2113}
$(1,3,10)/(1,2,4)$

$$
\begin{aligned}
G_{13} &= U(1)_{\mathrm{QED}} \otimes SU(3)_C \\
G_{5/51} &= SU(5)/SU(5) \otimes U(1)_X \\
G_{213} &= SU(2)_L \otimes U(1)_Y \otimes SU(3)_C \;\; (\mathrm{SM}) \\
G_{214} &= SU(2)_L \otimes U(1)_X \otimes SU(4)_C \\
G_{224} &= SU(2)_L \otimes SU(2)_R \otimes SU(4)_C \;\; (\mathrm{PS}) \\
G_{224D} &= SU(2)_L \otimes SU(2)_R \otimes SU(4)_C \otimes D \;\; (\mathrm{PS}D) \\
G_{2113} &= SU(2)_L \otimes U(1)_{B-L} \otimes U(1)_R \otimes SU(3)_C \\
G_{2213} &= SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes SU(3)_C \;\; (\mathrm{LR}) \\
G_{2213D} &= SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes SU(3)_C \otimes D \;\; (\mathrm{LR}D)
\end{aligned} \tag{9}
$$

$$(1,1,15)_{G_{224}} \subset 45, 210$$
$$(1,3,0,1)_{G_{2213}} \subset (1,3,1)_{G_{224}} \subset 45$$
$$(1,0,15)_{G_{214}} \subset (1,3,15)_{G_{224}} \subset 210$$
$$(1,3,0,1)_{G_{2213}} \subset (1,3,15)_{G_{224}} \subset 210$$
$$(1,1,-1,1)_{G_{2113}} \subset (1,1,10)_{G_{214}} \subset (1,3,10)_{G_{224}} \subset 126^{\dagger}$$
$$(1,1,-1,1)_{G_{2113}} \subset (1,3,-1,1)_{G_{2213}} \subset (1,3,10)_{G_{224}} \subset 126^{\dagger}$$
$$(1,1/2,-1/2,1)_{G_{2113}} \subset (1,1/2,4)_{G_{214}} \subset (1,2,4)_{G_{224}} \subset 16^{\dagger}$$
$$(1,1/2,-1/2,1)_{G_{2113}} \subset (1,2,-1/2,1)_{G_{2213}} \subset (1,2,4)_{G_{224}} \subset 16^{\dagger}$$

Table : The multiplets participating in SSB by acquiring VEVs in the invariant direction of the residual symmetry.



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[5] Chang *et al* (1984), Gipson *et al* (1984), Bertolini (2009), Fukuyama *et al* (2004)

Required multiplets

$$(3 \otimes 16 + 3 \otimes 1)_F + (2 \otimes 10 + 16 + 45)_H + 45_G \qquad (10)$$

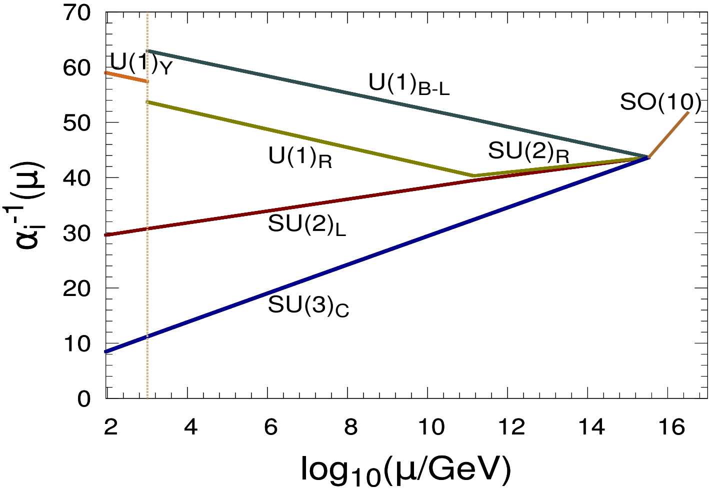
- Two step breaking scheme

$$SO(10) \xrightarrow[45]{M_U} G_{2213} \xrightarrow[45]{M_R^+} G_{2113} \xrightarrow[16]{M_R^0} \mathrm{SM} \qquad (11)$$

[6] SUSY analog: Bhupal dev, Mohapatra, 2010

Non-SUSY SO(10) with TeV scale Z' and Inverse seesaw

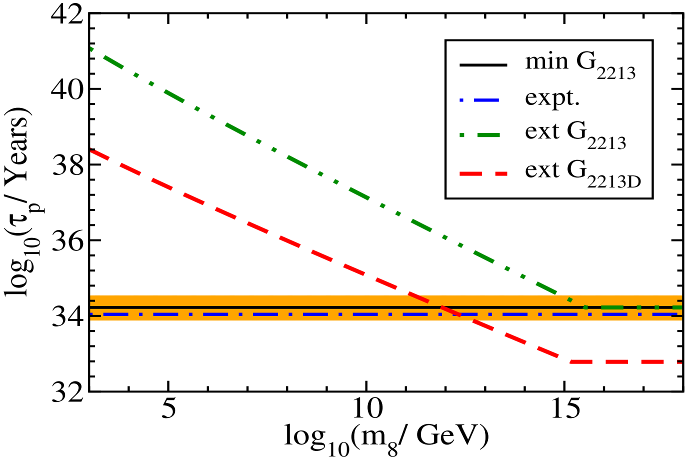
Excellent Gauge coupling unification



- $M_{Z'} = 1\text{TeV}$, $M_U = 10^{15.53}$ GeV, $M_R^+ = 10^{11.15}$ GeV

- $\Gamma(p \to e^+\pi^0) \propto \left(\frac{g_G^4}{M_U^4}\right)$
- Exp bound: $1.01(1.4) \times 10^{34}$yrs, [7]
- Model Prediction: $2 \times 10^{34 \pm 0.32}$yrs

[7] Nishino et at (2009), Babu in arXiv:1205.2671



- Enhancement in proton lifetime is due to presence of a color octet scalar (1,0,8) in the model extension.

$$\mathcal{L}_{Yuk} = Y^a 16.16.10^a_H + y_\chi 16.1.16^\dagger_H + \mu_S 1.1$$
$$\supset Y^a \overline{\psi}_L \psi_R \Phi^a + y_\chi \overline{\psi_R} S \chi_R + \mu_S S^T S + h.c. \quad (12)$$

- In $(\nu, N^C, S)^T$ basis the full neutrino mass matrix[8] is

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu_S \end{pmatrix}_{9\times 9} \quad (13)$$

- $M_D = Y_\nu v_u$, $M = Y_\chi v_\chi$ and μ_S are unknown at low energy.
- $\mu_S << M_D < M$.

S. Vempati, K. S. Babu

[8] Mohapatra (1986,2010)

$$\begin{aligned} \mathcal{L}_{Yuk} &= Y^a 16.16.10^a_H + y_\chi 16.1.16^\dagger_H + \mu_S 1.1 \\ &\supset Y^a \overline{\psi}_L \psi_R \Phi^a + y_\chi \overline{\psi_R} S \chi_R + \mu_S S^T S + h.c. \end{aligned} \tag{12}$$

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- $\mu_S << M_D < M$.

[8]Mohapatra (1986,2010)

[9]Grimus(2000)

- This complex symmetric matrix can be block diagonalized by a 9×9 unitary matrix $\mathcal{V}$ such that

$$\mathcal{V}^\dagger \mathcal{M}_\nu \mathcal{V}^* = \hat{\mathcal{M}}_\nu = \begin{pmatrix} m_\nu & 0 \\ 0 & M_H \end{pmatrix} \tag{14}$$

  where m_ν is light neutrino mass matrix and is further diagonalized by a unitary matrix, say, PMNS; and M_H is the heavy neutrino mass matrix.

- In $\mu_S << M_D << M$ limits, The full diagonalizing matrix looks like

$$\mathcal{V} \simeq \begin{pmatrix} 1-\frac{1}{2}XX^\dagger & -y & X \\ y^\dagger & 1-\frac{1}{2}y^\dagger y & \frac{1}{2}y^\dagger X \\ -X^\dagger & \frac{1}{2}X^\dagger y & 1-\frac{1}{2}X^\dagger X \end{pmatrix} \begin{pmatrix} U_\nu & 0 \\ 0 & U_H \end{pmatrix} \quad (15)$$

where $y = -\frac{M_D}{M}\frac{\mu_S}{M^T}$ and $X = \frac{M_D}{M}$.

- The light and heavy neutrino mass matrices get the form

$$m_\nu \simeq \frac{M_D}{M}\mu_S\left(\frac{M_D}{M}\right)^T \equiv X\mu_S X^T \quad (16)$$

$$M_h \simeq \begin{pmatrix} -M & 0 \\ 0 & M \end{pmatrix} + \mathcal{O}(\mp M_D^2/M) \quad (17)$$

- $|\eta|_{33} \equiv |XX^\dagger|_{33} < [2.7 \times 10^{-3}]$[10]

[10] Kanaya, Antusch, Smirnov, Altarelli, Malinsky, Aguila, Schaff etc.

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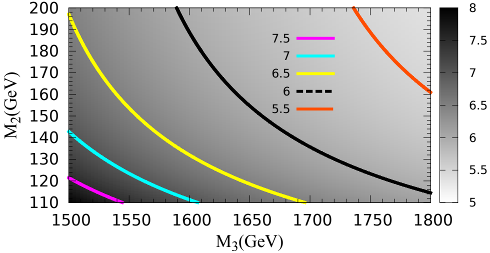
[10]Kanaya, Antusch, Smirnov, Altarelli, Malinsky, Aguila, Schaff etc.

$$M_D = \begin{pmatrix} 0.0151 & 0.0674 - 0.0113i & 0.1030 - 0.2718i \\ 0.0674 + 0.0113i & 0.4758 & 3.4410 + 0.0002i \\ 0.1030 + 0.2718i & 3.4410 - 0.0002i & 83.45 \end{pmatrix} \text{ GeV.} \tag{18}$$

Non-unitarity constraint

$$\frac{1}{2}\left[\frac{0.0845}{M_1^2} + \frac{11.8405}{M_2^2} + \frac{6963.9}{M_3^2}\right] \text{GeV}^2 < 2.7 \times 10^{-3}, \tag{19}$$



- Heavy neutrino contribute to Lepton flavour violating (LFV) decays[11]

$$\mathcal{L}_{CC} = -\frac{g_{2L}}{\sqrt{2}}\bar{l}_L\gamma^\mu(\mathcal{N}\hat{\nu}^T + \mathcal{K}P^T)W_\mu^- + h.c. \tag{20}$$

$$BR(l_\alpha \to l_\beta\gamma) \quad \propto \quad \left|\sum_{i=1}^{6}\mathcal{K}_{\alpha i}\mathcal{K}^*_{\beta i} I\left(\frac{M_i^2}{M_W^2}\right)\right|^2 \tag{21}$$

where $\mathcal{K} \equiv \mathcal{V}_{3\times 6} \simeq (0, M_D M^{-1})U_{6\times 6}$.

- LFV decay are severally suppressed in Type-I seesaw scenario.

- The matrix $(\mathcal{K}\mathcal{K}^\dagger)$ may lead to large LFV decay in inverse seesaw.

[11] Ilakovac and Pilaftsis (1995)

$$\begin{aligned} BR(\mu \to e\gamma) &= 2.0 \times 10^{-16} \, (< 5.7 \times 10^{-13}), \\ BR(\tau \to e\gamma) &= 2.2 \times 10^{-14} \, (< 3.3 \times 10^{-8}), \\ BR(\tau \to \mu\gamma) &= 3.0 \times 10^{-12} \, (< 4.4 \times 10^{-8}). \end{aligned} \tag{22}$$

Current experimental constraints[12] are given in the brackets.

[12] MEG (arxiv:1303.0754), Bell (2010, 2011, 2012), BaBar (2009, 2010), PDG (2012)

- TeV scale $W_R, \; Z_R$
- $n - \bar{n}$
- Rare Kaon decay
- Lepton flavor violation
- New contribution to $0\nu\beta\beta$.

Non-SUSY SO(10) with extended inverse seesaw

Breaking scheme[13]

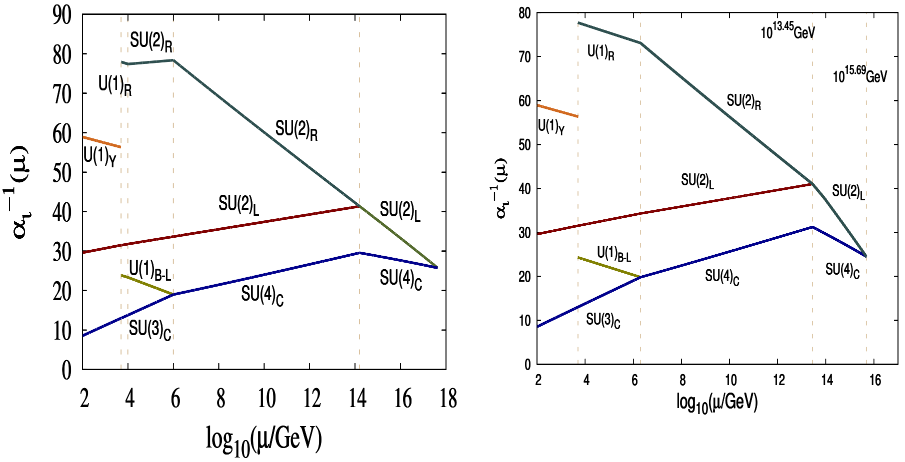
$$
\begin{aligned}
SO(10) \quad & \xrightarrow[54]{M_U} \quad G_{224D} \parallel g_{2L} = g_{2R} \\
& \xrightarrow[210]{M_P} \quad G_{224} \parallel g_{2L} \neq g_{2R} \\
& \xrightarrow[45]{M_C} \quad G_{2213} \\
& \xrightarrow[210]{M_R^+} \quad G_{2113} \\
& \xrightarrow[126+16]{M_R^0} \quad SM \\
& \xrightarrow[10]{M_Z} \quad G_{13}.
\end{aligned} \tag{23}
$$

$$
\begin{aligned}
SO(10) \quad & \xrightarrow[54]{M_U} \quad G_{224D} \parallel g_{2L} = g_{2R} \\
& \xrightarrow[210]{M_P} \quad G_{224} \parallel g_{2L} \neq g_{2R} \\
& \xrightarrow[210]{M^C} \quad G_{2113} \\
& \xrightarrow[126+16]{M_R^0} \quad SM \\
& \xrightarrow[10]{M_Z} \quad G_{13}.
\end{aligned} \tag{24}
$$

[13] Chang et al (1985), Chang and Kumar (1986)

Non-SUSY SO(10) with extended inverse seesaw

Gauge coupling unification



Non-SUSY SO(10) with extended inverse seesaw

Proton decay prediction in the model at left

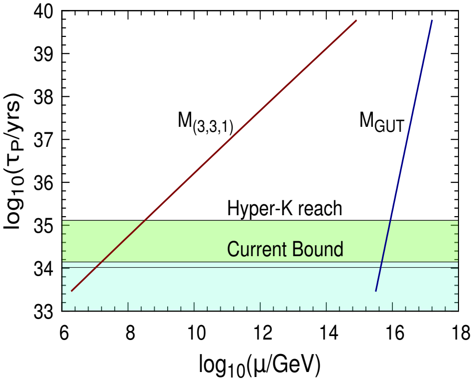


Figure : Dependence of unification scale on the mass of bi-triplet (3,3,1) in the model at left.

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &= Y^{\ell}\overline{\psi}_L\,\psi_R\,\Phi + f\,\psi_R^c\,\psi_R\Delta_R + F\,\overline{\psi}_R\,S\,\chi_R \\ &+ S^T\mu_S S + \text{h.c.} \end{aligned} \tag{25}$$

- In the $(\nu, S, N^C)^T$ basis the mass matrix is

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & 0 & M_D \\ 0 & \mu_S & M \\ M_D^T & M^T & M_N \end{pmatrix} \tag{26}$$

- Here $M_D = Y^l\langle\Phi\rangle$, $M_N = f\langle\Delta_R^0\rangle$, $M = F\langle\chi_R^0\rangle$.

$$\mathcal{L}_{\text{Yuk}} = Y^{\ell}\overline{\psi}_L \psi_R \Phi + f\, \psi_R^c \psi_R \Delta_R + F\, \overline{\psi}_R S \chi_R + S^T \mu_S S + \text{h.c.} \quad (25)$$

- In the $(\nu, S, N^C)^T$ basis the mass matrix is

$$\mathcal{M}_\nu = \left(\begin{array}{cc|c} 0 & 0 & M_D \\ 0 & \mu_S & M \\ \hline M_D^T & M^T & M_N \end{array}\right) \quad (26)$$

- Here $M_D = Y^l \langle \Phi \rangle$, $M_N = f \langle \Delta_R^0 \rangle$, $M = F \langle \chi_R^0 \rangle$.

$$m_\nu \simeq M_D M^{-1} \mu_S (M_D M^{-1})^T \quad (27)$$

$$m_{\mathcal{S}} \simeq \mu_S - M M_N^{-1} M^T \quad (28)$$

$$\& \quad m_{\mathcal{N}} \simeq M_N \,. \quad (29)$$

The collective mixing matrix is

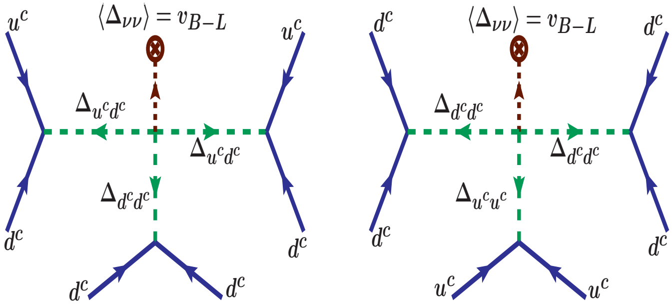
$$\mathcal{V} \equiv \begin{pmatrix} \mathcal{V}^{\nu\hat{\nu}}_{\alpha i} & \mathcal{V}^{\nu\hat{S}}_{\alpha j} & \mathcal{V}^{\nu\hat{N}}_{\alpha k} \\ \mathcal{V}^{S\hat{\nu}}_{\beta i} & \mathcal{V}^{S\hat{S}}_{\beta j} & \mathcal{V}^{S\hat{N}}_{\beta k} \\ \mathcal{V}^{N\hat{\nu}}_{\gamma i} & \mathcal{V}^{N\hat{S}}_{\gamma j} & \mathcal{V}^{N\hat{N}}_{\gamma k} \end{pmatrix}$$

$$\simeq \begin{pmatrix} \left(1 - \frac{1}{2}XX^\dagger\right) U_\nu & \left(X - \frac{1}{2}ZY^\dagger\right) U_S & Z\, U_N \\ -X^\dagger\, U_\nu & \left(1 - \frac{1}{2}\{X^\dagger X + YY^\dagger\}\right) U_S & \left(Y - \frac{1}{2}X^\dagger Z\right) U_N \\ y^*\, X^\dagger\, U_\nu & -Y^\dagger\, U_S & \left(1 - \frac{1}{2}Y^\dagger Y\right)\, U_N \end{pmatrix}, \quad (30)$$

where $X = M_D\, M^{-1}$, $Y = M\, M_N^{-1}$, $Z = M_D\, M_N^{-1}$, and $y = M^{-1}\, \mu_S$

★ Lepton flavor violation predictions are same as discussed in previous model.

★ The predicted values are only $3 - 6$ order less than present experimental bound.



$$\text{Amp}^{(a)}_{n-\bar{n}} = \frac{f^3_{11}\lambda v_{B-L}}{M^4_{\Delta_{u^c d^c}} M^2_{\Delta_{d^c d^c}}}, \quad \text{Amp}^{(b)}_{n-\bar{n}} = \frac{f^3_{11}\lambda v_{B-L}}{M^4_{\Delta_{d^c d^c}} M^2_{\Delta_{u^c u^c}}},^{14} \tag{31}$$

where $f_{11} = \left(f_{\Delta_{u^c d^c}}\right)_{11} = \left(f_{\Delta_{d^c d^c}}\right)_{11} = \left(f_{\Delta_{u^c u^c}}\right)_{11} \subset 126_H$

$$\sim \mathcal{O}(0.1) - \mathcal{O}(1).$$

[14] Babu et al (2013)

The $n - \bar{n}$ mixing mass element

$$\delta m_{\mathrm{n\bar{n}}} = \left(10^{-4}\,\mathrm{GeV}^6\right) \cdot W_{B=2}. \tag{32}$$

where $W_{B=2} = Amp^{(a)} + Amp^{(b)}$.

The experimentally measurable mixing time

$$\tau_{\mathrm{n-\bar{n}}} = \frac{1}{\delta m_{\mathrm{n\bar{n}}}} = 10^8 - 10^{10}\ \mathrm{secs}. \tag{33}$$

★ Accessible at ongoing experiments.

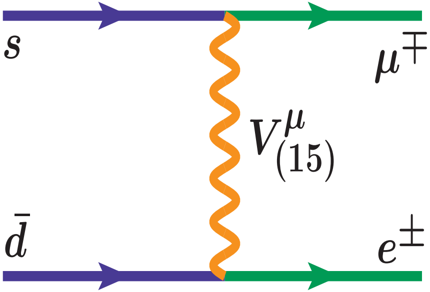


Figure : $K_L^0 \to \mu^{\mp} e^{\pm}$

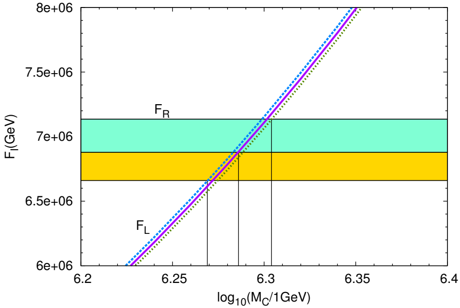
$$\mathrm{Br}\left(K_L \to \mu \bar{e}\right)_{\mathrm{expt.}} \equiv \frac{\Gamma\left(K_L \to \mu^{\pm} e^{\mp}\right)}{\Gamma\left(K_L \to \mathrm{all}\right)} < 4.7 \times 10^{-12}, \tag{34}$$

$$\mathrm{Br}\left(K_L \to \mu \bar{e}\right) = \frac{4\pi^2 \alpha_s^2(M_C)\, m_K^4\, R}{G_F^2\, \sin^2\theta_C m_\mu^2 (m_s + m_d)^2\, M_C^4}\,.^{15} \tag{35}$$

$$R = \left[R_{2113} R_{213}^{(6)} R_{213}^{(5)} R_{QCD}^{(5)} R_{QCD}^{(4)} R_{QCD}^{(3)}\right]^{-2} \tag{36}$$

$$\left[F_L(M_C, M_R^0)\right]_{\mathrm{Model\ dependent}} = \left[F_R\right]_{\mathrm{Model\ independent}} \tag{37}$$

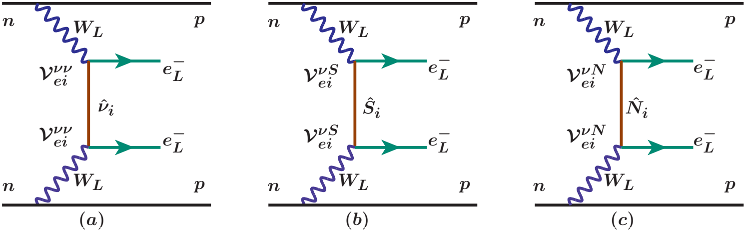
[15] Parida and Pusrkayastha (1996), Deshpande and Johnson (1984)



$$M_C > 1.86 \times 10^6 \mathrm{GeV}. \tag{38}$$

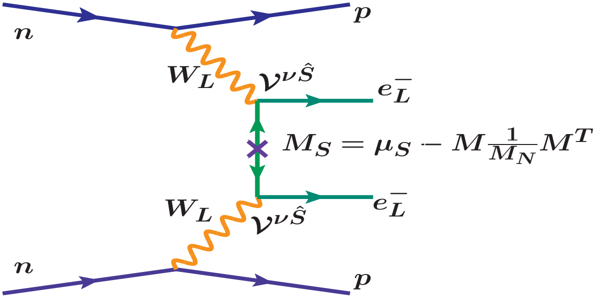
Non-SUSY SO(10) with extended inverse seesaw

$0\nu\beta\beta$[16]



[16] Bilenki, Mohapatra, Mitra, Rodejohan, Senjanovic, Vergados, Vissani etc

$$\mathcal{A}_S^{LL} \propto \frac{1}{M_{W_L}^4} \sum_{j=1,2,3} \frac{\left(\mathcal{V}_{ej}^{\nu\hat{S}}\right)^2}{m_{S_j}} \tag{39}$$



$$\mathcal{A}_{\nu}^{LL} \propto \frac{1}{M_{W_L}^4} \sum_{i=1,2,3} \frac{\left(\mathcal{V}_{e\,i}^{\nu\hat{\nu}}\right)^2 m_{\nu_i}}{p^2},$$

$$\mathcal{A}_{S}^{LL} \propto \frac{1}{M_{W_L}^4} \sum_{j=1,2,3} \frac{\left(\mathcal{V}_{e\,j}^{\nu\hat{S}}\right)^2}{m_{S_j}},$$

$$\mathcal{A}_{N}^{LL} \propto \frac{1}{M_{W_L}^4} \sum_{k=1,2,3} \frac{\left(\mathcal{V}_{e\,k}^{\nu\hat{N}}\right)^2}{m_{N_k}}, \qquad (40)$$

which lead to effective mass parameters

$$\mathrm{m}_{LL}^{\nu} \sim \sum_i \mathcal{N}_{ei}^2 m_{\nu_i}, \quad \mathcal{N} = \mathcal{V}^{\nu\hat{\nu}}$$

$$\mathrm{m}_{LL}^{S} \sim -\sum_i \frac{M_{D\,ei}^2 M_{N_i}}{M_i^4} |p^2|$$

$$\mathrm{m}_{LL}^{N} \sim \sum_i \frac{M_{D\,ei}^2}{M_{N_i}^3} |p^2| \qquad (41)$$

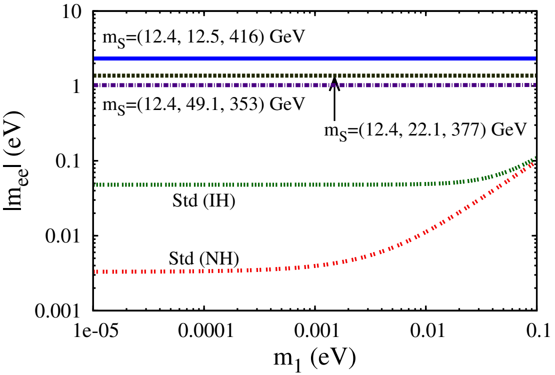


Figure : Effective mass due to sterile contribution.

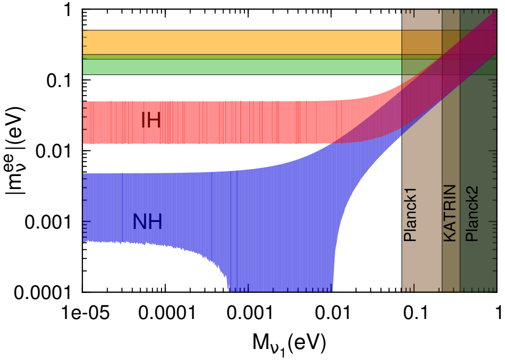


Figure : The Yellow and green horizontal bands correspond to the range of effective mass for Heidelberg Moskow result and combined ^{136}Xe bound.

S. Goswami, Y. Y. Keum

- The combined absolute effective mass

$$|m_{eff}^{ee}|^2 = |m_\nu^{ee}|^2 + |m_S^{ee}|^2 + 2|m_\nu^{ee}| \cdot |m_S^{ee}| \cos(\phi) \quad (42)$$

and may lie between $(|m_\nu^{ee}| - |m_S^{ee}|)^2$ and $(|m_\nu^{ee}| + |m_S^{ee}|)^2$.

- $$m_\nu^{ee} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3 s_{13}^2 e^{2i\alpha_3 + \delta_{CP}}. \quad (43)$$

- $$m_S^{ee} = -|p|^2 \sum_i \mathcal{V}_{ei}^{\nu \hat{S}^2} \frac{1}{M_{S_i}}. \quad (44)$$

[17] Pascoli et al. (2013)

Non-SUSY SO(10) with extended inverse seesaw

Effective mass vs lightest sterile mass (Cancellation in light and sterile contributions)

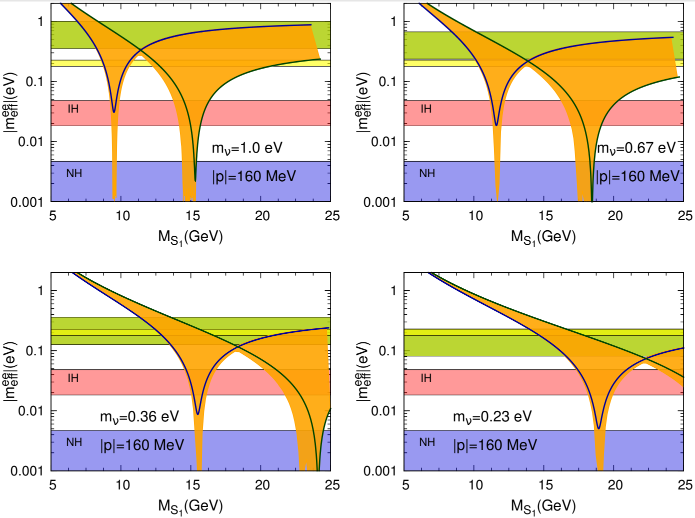


Figure : Green band → allowed light neutrino contribution. Yellow band → combined ^{76}Ge experiment exclusion limit. Orange band → light+sterile contribution for fixed $|p| = 160\,\text{MeV}$. Blue curve → ν oscillation best fit. Green curve → $\alpha_2 = \pi/2$, $\alpha_3 + \delta_{CP} = \pi/2$.

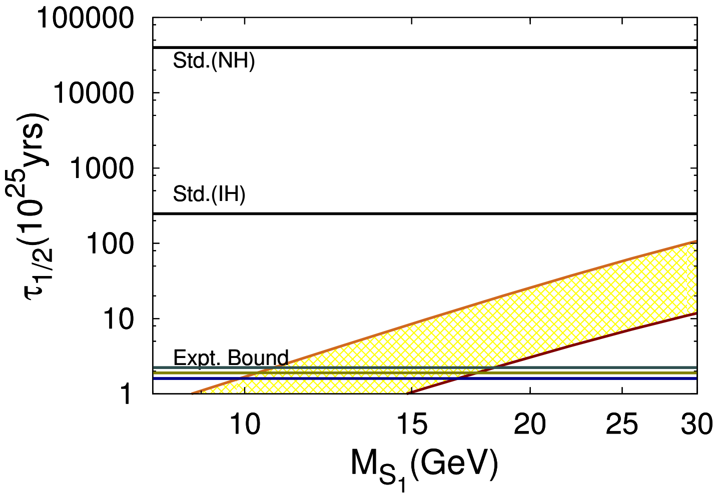


Figure : Sterile contribution in normal and inverted hierarchy scenario. Virtual momentum varies in [160 – 200] MeV range.

Non-SUSY SO(10) with extended inverse seesaw

Life-time vs lightest sterile mass (Scatter plot)

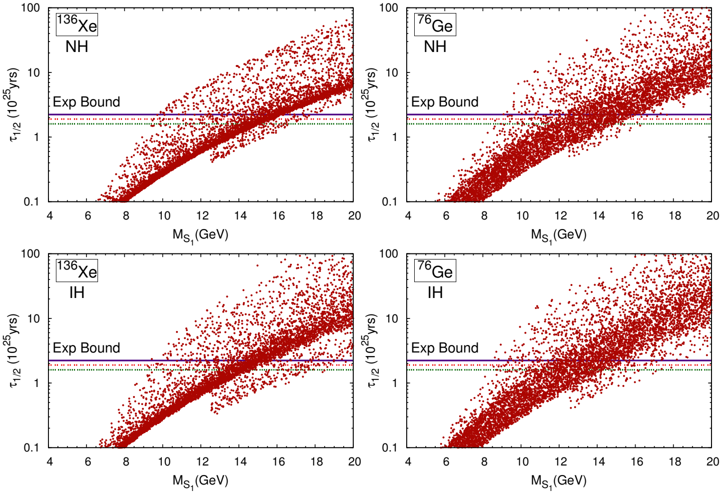


Figure : Comparative study of $0\nu\beta\beta$ contribution due to sterile neutrino, in two popular isotopes ^{76}Ge (left) and ^{136}Xe (right). Normal hierarchy and inverted hierarchy solutions are assumed in going from top to bottom.

Non-SUSY SO(10) with extended inverse seesaw

Life-time vs lightest sterile mass (Scatter plot)

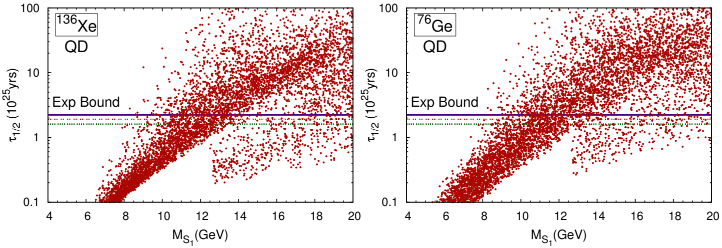


Figure : Same as previous figure but light neutrinos in quasi-degenerate ($m_{\nu_1} = 0.23$ eV) state.

Non-SUSY SO(10) with extended inverse seesaw

Life-time vs lightest sterile mass (Xe predictions in QD scenario)

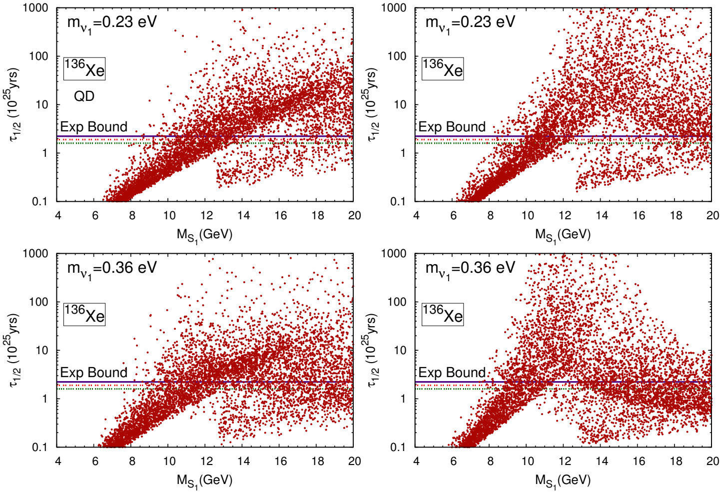


Figure : Left panel corresponds to best fit for light neutrino with zero Majorana phases. Right panel due to allowing Majorana phase $\alpha_2, \alpha_3 \in [0, 2\pi]$.

Summary and Conclusion

1. We have investigated signature of BSM physics from non-SUSY SO(10).
2. Implementation of inverse seesaw in SO(10) gives
   - $\tau_p(e^+\pi^0)$ accessible to SuperK.
   - TeV scale Z' accessible to LHC.
   - LFV decay branching ratios $3-6$ orders smaller than the current experimental limits.
   - RH N's are Pseudo-Dirac.
3. Extended seesaw in SO(10)
   - $W_R^{\pm}, Z_R \sim (1.2-3.5)$ TeV, accessible to LHC.
   - LFV decays branching ratios $3-6$ order smaller than experimental limit.
   - New dominant contribution to $0\nu\beta\beta$ due to Sterile ν-exchange in the $W_L - W_L$ channel.

3. Extended seesaw in SO(10)

- $W_R^{\pm}, Z_R \sim (1.2 - 3.5)$ TeV, accessible to LHC
- LFV decays branching ratios $3 - 6$ order smaller than experimental limit
- New dominant contribution to $0\nu\beta\beta$ due to Sterile ν-exchange in the $W_L - W_L$ channel
- Bound $M_{S_1} > 14 \pm 4$ GeV
- Observable $n - \bar{n}$ oscillation $\tau_{n-\bar{n}} \simeq 10^8 - 10^{10}$ secs
- Current bound on rare Kaon decay branching ratio predicts PS breaking scale at $\gtrsim 10^6$ GeV.
- Proton is stable and $p \to e^+\pi^0$ not observable in possible future if $M_{W_R} \simeq 3 - 5$ TeV
- But if $M_{W_R} \geq 100$ TeV, $\tau_p \simeq 5.5 \times 10^{35 \pm 0.32}$ yrs (Within experimentally accessible range of SuperK and HyperK).
- All other predictions are unchanged.

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