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José W. F. Valle · Sandhya Choubey · Debasish Borah · Rahul Srivastava · Debajyoti Dutta *Editors*

Proceedings of the International Conference on Future Prospects in Neutrino and Astroparticle Physics

ICFPNAP 2024; 23–24 January; Assam; India

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Foreword

I am very happy to write the foreword for the proceedings of *The International Conference on Future Prospects in Neutrino and Astroparticle Physics*, which took place during 23–24 January 2024. First and foremost, I must express my appreciation to the Physics Association of North East (PANE), which took the lead in organizing the conference, and to Assam Don Bosco University (ADBU), which played host to the conference. In particular, special thanks are due to Prof. Ngangkham Nimai Singh, the President of PANE, and Fr. (Dr.) Jose Palely, the Vice-Chancellor of ADBU for the support they gave to make the conference possible.

Ever since the discovery of neutrino oscillations, aspects of neutrino physics have taken the center stage of particle physics. It is one of the most active areas of research in the particle physics community in India. A number of physicists from India have made significant contributions to neutrino physics studies. Quite a few of them are based in the North East region and they have sown the seeds of this research among the young minds of this region.

Dr. Debajyoti Datta of the physics department of ADBU and his team put together a wonderful set of overview talks by a number of national and international experts. They also succeeded in attracting a large number of research contributions from a large number of enthusiastic young researchers. Because of the enhanced research activity in neutrino physics in the Northeast region, the largest fraction of the submissions are from that region. The research contributions were presented in a poster session and two parallel sessions. It was very heartening to see the high quality of the work that was discussed in these sessions. The present volume contains the written versions of the works presented at ICFPNAP. The editors have done a wonderful job in putting together this volume. I congratulate all the authors and the editorial team for making this volume possible. I hope this is the first in a series of many more to come.

Prof. S. Uma Sankar
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Preface

The International Conference on Future Prospects in Neutrino and Astroparticle Physics 2024 (ICFPNAP2024) was sponsored by the Science and Engineering Research Board (SERB) and was held from January 23–24, 2024, at Assam Don Bosco University. The Department of Physics at Assam Don Bosco University, Assam, organized the conference in conjunction with the Physics Academy of North East (PANE). Several participants from various Indian universities, colleges, and institutes presented their research work at the conference. A portion of the submitted papers has been included in this book after undergoing the appropriate peer review procedures.

It should be mentioned that the Physics Department at Assam Don Bosco University, which was established in 2018, has been striving to popularize both basic and advanced physics through a variety of additional means, such as workshops, refresher courses, symposiums, and so on. The department believed that an international conference on Future Prospects on Neutrino and Astroparticle Physics could provide a platform for young scientists to exchange ideas and receive advice and support from esteemed academicians in the nation and abroad.

An international advisory committee was formed to carry out this vision. We would like to take this opportunity to thank all of the esteemed members of the advisory committee who have helped us and provided sage advice. We would like to thank each and every reviewer who has improved the proceeding by reviewing each and every document. We also acknowledge the contributions made by each author to the proceedings. Lastly, we would like to thank the Science and Engineering Research Board (SERB), India, for their financial support, without which the event could not have been successfully organized.

Dr. Debajyoti Dutta
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Chapter 1
Probing Scalar Leptoquarks Using Neutrino-Nucleus Coherent Scattering

Samiran Roy

Abstract The recent measurements of the coherent elastic neutrino-nucleus scattering (CEνNS) by the COHERENT collaboration give us a capability to examine the various new physics scenarios at low energy neutrino experiments. One such new physics is the scalar leptoquarks (LQs) that arise in many extensions of the Standard Model (SM). We consider the low-scale LQ models that forbid the rapid proton decay by construction. The hypercharges of the scalar LQs are Y = 1/6 and Y = 7/6, which are part of the two electroweak doublet fields, respectively. We constrain the LQs using the COHERENT data that is consistent with the SM prediction. We find that the COHERENT measurements can put a strong bound on the LQs couplings to SM particles over a wide range of LQ masses, and the bounds are competitive with various other experiments.

1.1 Introduction

More than forty years after Freedman's prediction [1], the COHERENT collaboration [2] eventually succeeded in detecting the coherent elastic neutrino-nucleus scattering (CEνNS). The cross-section of the process scales roughly as the square of the total number of protons (Z) and neutrons (N) of the target nucleus for the low momentum transfer (q^2) to the nucleus. In the Standard Model (SM), CEνNS process is mediated by the Z-boson, and the cross-section approximately scales as the square of N since the Z-boson coupling to the neutron is an order of magnitude larger compared to the proton. The observed data by the COHERENT collaboration shows no significant departure from the SM prediction, for CsI [2, 3] and Ar [4] nuclei. Thus, we can use this experimental observation to constrain various beyond the standard model physics, *e.g.* Leptoquarks (LQs), that modifies the CEνNS cross-section. LQs arise in many extensions of the standard model. It carries both the lepton and baryon numbers and can be a scalar or a vector in nature. To prevent the proton decay, the mass of such LQs is typically assumed to be near to the GUT scale. However, there

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are LQ models which prohibit rapid proton decay by construction. We study the LQs, where proton decay does not occur at the tree level since they do not give rise to tree level interactions of the kind $(qlqq)$. Here, we concentrate on the scalar LQs, which are less restricted than the vector case where there is less freedom as the couplings are fixed by the gauge structure of the model. We employ the latest CsI and Ar data to determine the exclusion limits on scalar LQs by altering the SM event rate in the presence of LQs across a broad mass range, spanning from MeV to TeV scales, and compare the results with other experimental bounds on LQs.

1.2 Models

We consider two scalar LQ doublets under $SU(2)_L$, $\tilde{R}_2 = (\Delta_1^{2/3}, \Delta_1^{-1/3})^T$ and $R_2 = (\Delta_2^{5/3}, \Delta_2^{2/3})^T$ with hypercharges Y = 1/6 and Y = 7/6, respectively. The pertinent portion of the Lagrangian involved in the coherent process of neutrino-nucleon scattering is given by

$$\begin{aligned}\mathcal{L}^{\Delta_1} &\supset -y_{ij}^{(1)}\bar{d}_R^i \tilde{R}_2 L_L^j + h.c. \\ &= -y_{ij}^{(1)}\bar{d}^i P_L \ell^j \Delta_1^{2/3} - y_{ij}^{(1)}\bar{d}^i P_L \nu^j \Delta_1^{-1/3} + h.c.\end{aligned} \tag{1.1}$$

$$\begin{aligned}\mathcal{L}^{\Delta_2} &\supset -y_{ij}^{(2)}\bar{u}_R^i R_2 L_L^j + h.c. \\ &= -y_{ij}^{(2)}\bar{u}^i P_L \ell^j \Delta_2^{5/3} - y_{ij}^{(2)}\bar{u}^i P_L \nu^j \Delta_2^{2/3} + h.c.,\end{aligned} \tag{1.2}$$

where $P_{L,R}$, are the usual left and right chiral projection operators, $L_L^j = \left(\nu^j \;\; \ell^j\right)^T$ are the lepton doublets, d^i and u^i are the down-type and up-type quark fields, respectively, and y's are the Yukawa coupling matrices. We only take into account couplings with the first generation of quarks in order to prevent Flavour Changing Neutral Current (FCNC) problem at the tree level. Our forecast for the CEνNS is unaffected by this choice because the process solely depends on the first generation of valence quarks.

1.3 Signal Prediction in COHERENT

In this section, we show the signal prediction for both the SM and LQs cases at COHERENT experiments. The differential neutrino fluxes from the Spallation Neutron Source (SNS) are as follows:

$$\frac{dN_{\nu_\mu}}{dE} = \eta\,\delta\left(E - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right) \tag{1.3}$$

$$\frac{dN_{\bar{\nu}_\mu}}{dE} = \eta\,\frac{64E^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E}{m_\mu}\right) \tag{1.4}$$

$$\frac{dN_{\nu_e}}{dE} = \eta\,\frac{192E^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E}{m_\mu}\right), \tag{1.5}$$

where m_π and m_μ are the masses of pion and muon, respectively, $\eta = r\,\mathrm{N_{POT}}/4\text{ßL}^2$ is a normalization factor, $\mathrm{N_{POT}}$ corresponds to the total number of protons on target (POT), L is the distance from source to detector, and r represents per flavour neutrino produced for each POT. For the CsI detector $r = 0.08$, L = 19.3 m and $\mathrm{N_{POT}} = 3.198 \times 10^{23}$ [3] while for Ar $r = (9 \pm 0.9) \times 10^{-2}$, L = 27.5 m and $\mathrm{N_{POT}} = 13.7 \times 10^{22}$. As a function of the nuclear-recoil kinetic energy (T_{nr}), the SM contribution to the cross-section for a given neutrino flavour (ν_l) is given by

$$\frac{d\sigma_{\nu_l - N}}{dT_{nr}}(E, T_{nr}) = \frac{G_F^2 M}{\pi}\left(1 - \frac{M T_{nr}}{2E^2}\right) Q_{l,SM}^2. \tag{1.6}$$

Here E represents the energy of incoming neutrino, M is the detector material mass, G_F is the Fermi constant, and

$$Q_{l,SM}^2 = [g_V^p(\nu_l) Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)]^2. \tag{1.7}$$

$$g_V^p(\nu_e) = 0.0401,\;\; g_V^p(\nu_\mu) = 0.0318,\;\; g_V^n = -0.5094. \tag{1.8}$$

The distributions of proton and neutron in the nucleus are represented by the Helm form factor [5]

$$F(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0} e^{-|\vec{q}|^2 s^2/2}, \tag{1.9}$$

where $j_1(x) = \sin(x)/x^2 - \cos(x)/x$ is the spherical Bessel function, the rms radius R is connected to R_0 by $R_{p,n}^2 = 3R_0^2/5 + 3s^2$, and $s = 0.9$ fm.

The number of events in the i-th bin of nuclear-recoil energy is calculated using the following equation:

$$N_i^{\mathrm{CE}\nu\mathrm{NS}} = N(\mathcal{N}) \int_{T_{\mathrm{nr}}^i}^{T_{\mathrm{nr}}^{i+1}} dT_{\mathrm{nr}}\, A(T_{\mathrm{nr}}) \int_{E_{\min}}^{E_{\max}} dE \sum_{\nu=\nu_e,\nu_\mu,\overline{\nu}_\mu} \frac{dN_\nu}{dE} \frac{d\sigma_{\nu\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}(E, T_{\mathrm{nr}})\,, \tag{1.10}$$

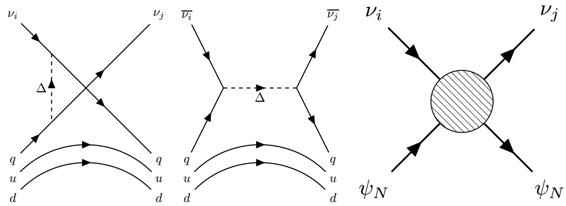

Fig. 1.1 Tree level CEνNS processes mediated by the Leptoquark. The final state neutrinos are experimentally indistinguishable

where $E_{\min} = \sqrt{MT_{\rm nr}/2}$, $E_{\max} = m_\mu/2 \sim 52.8$ MeV, and $A(T_{\rm nr})$ corresponds to the energy-dependent reconstruction efficiency.

The standard cross-section will be altered due to the extra contribution coming from LQs as shown in Fig. 1.1. As the momentum transfer to the nucleus is low, these diagrams can be represented by the effective four fermion interaction like

$$\mathcal{L}^{\Delta}_{\rm eff} = \frac{y^2}{m^2_{\Delta}} \, (\bar{\psi}_N P_L \nu) \, (\bar{\nu} P_R \psi_N) \,, \tag{1.11}$$

where ψ_N represents either a u or d quark. Utilizing the Fierz transformations, we can factorize this diagram into a hadronic current and a neutrino current as

$$\mathcal{L}^{\Delta}_{\rm eff} \sim -\frac{y^2}{2\, m^2_{\Delta}} \, (\bar{\psi}_N \gamma^\mu P_R \psi_N) \, (\bar{\nu} \gamma_\mu P_L \nu). \tag{1.12}$$

The new cross-section combining the effect of both SM and LQs is given by

$$\frac{d\sigma_{\nu_i - N}}{dT_{nr}}(E, T_{nr}) = \frac{G_F^2 M}{\pi} \left(1 - \frac{M T_{nr}}{2E^2}\right) Q^2_{i,\,k} \tag{1.13}$$

$$Q^2_{i,\,k} = \left(\left(Q_{i,\,SM} + Q_{ii,\,\Delta_k}\right)^2 + \sum_{j \neq i} Q^2_{ij,\,\Delta_k} \right) \tag{1.14}$$

where

$$\begin{aligned} Q_{ij,\,\Delta_1} &= \frac{\tilde{y}^{(1)}_{1i}\, \tilde{y}^{(1)}_{1j}}{4\sqrt{2}\, G_F} \, \frac{Z F_Z(|\vec{q}\,|^2) + 2\, N F_N(|\vec{q}\,|^2)}{|\vec{q}\,|^2 + m^2_{\Delta_1^{-1/3}}}, \\ Q_{ij,\,\Delta_2} &= \frac{\tilde{y}^{(2)}_{1i}\, \tilde{y}^{(2)}_{1j}}{4\sqrt{2}\, G_F} \, \frac{2\, Z F_Z(|\vec{q}\,|^2) + N F_N(|\vec{q}\,|^2)}{|\vec{q}\,|^2 + m^2_{\Delta_2^{2/3}}}. \end{aligned} \tag{1.15}$$

Here, we examine three possible cases for simplicity. In case A, Δ_k has the coupling to both ν_e and ν_μ. In cases B and C, Δ_k couples only to one of ν_μ and ν_e type neutrinos, respectively, as mentioned in Table 1.1. For more details, see the reference [6].

Table 1.1 The benchmark cases for LQs

LQCase	A	B	C
$\Delta_1^{-1/3}$	$\tilde{y}^{(1)} = \begin{pmatrix} g_{\Delta_1} & g_{\Delta_1} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\tilde{y}^{(1)} = \begin{pmatrix} 0 & g_{\Delta_1} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\tilde{y}^{(1)} = \begin{pmatrix} g_{\Delta_1} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
$\Delta_2^{2/3}$	$\tilde{y}^{(2)} = \begin{pmatrix} g_{\Delta_2} & g_{\Delta_2} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\tilde{y}^{(2)} = \begin{pmatrix} 0 & g_{\Delta_2} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\tilde{y}^{(2)} = \begin{pmatrix} g_{\Delta_2} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

1.4 Results

For each scenario listed in Table 1.1, we present the bounds on the Yukawa coupling strength as a function of the LQ masses in Fig. 1.2. The constraints on case A only and cases B and C are shown in the left and right panels, whereas the top and bottom panels correspond to CsI and Ar detectors, respectively. We represent the limits on $\Delta_{1,2}$ as a single solid line since they differ only at the percent level. As anticipated, the strongest bounds come from scenario A, as all of the ν_μ , $\bar{\nu}_\mu$, and ν_e fluxes contribute to the CEνNS process, while for the B and C cases only the $\nu_{\mu,\bar{\mu}}$ and only the ν_e participate in the process, respectively. The constraints become insensitive to very low LQs masses (around 10 MeV), since the cross-section depends mostly on the momentum

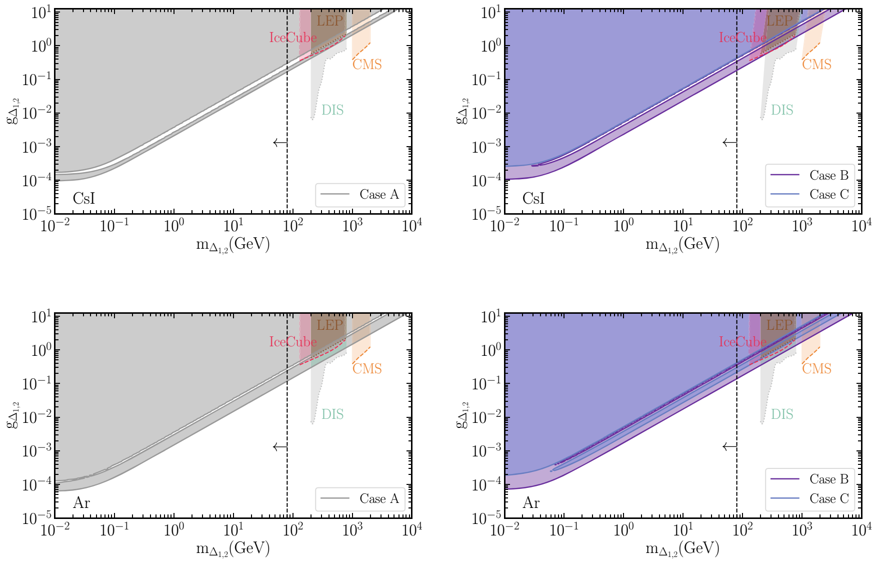

Fig. 1.2 Bounds obtained in the plane $g_\Delta - m_\Delta$ for various cases. In the upper (lower) panel we represent the constraints obtained using CsI (Ar)

transfer (q^2) in this domain. In each figure, we display some of the current limits on LQs for comparison. The LEP searches via the unsuppressed channel ($e^+e^- \to \gamma^* \to \Delta^+\Delta^-$) severely limit the low mass (< 80 GeV) LQs. The constraints coming from COHERENT data are comparable to other experiment bounds such as IceCube, LEP, and CMS and in some region the bounds improved slightly. There are some regions where we cannot put constraint due to the degeneracy with SM prediction. By looking at Eqs. 1.7 and 1.8 and considering the values of the form factors to be unity, we get the value of $Q_{i\,SM} \simeq -N/2$. On the other hand, $Q_{ij,\Delta_K} > 0$. Hence, there is a degenerate point where the total new charge becomes $N/2$. From Eq. 1.14, we get

$$\begin{aligned} &\text{for case A}: \left(-\frac{N}{2} + Q_{ii,\Delta_K}\right)^2 + \sum_{i\neq j} Q^2_{ij,\Delta_K} \simeq \left(\frac{N}{2}\right)^2, \\ &\text{for case B and C}: \left(-\frac{N}{2} + Q_{ii,\Delta_K}\right)^2 \simeq \left(\frac{N}{2}\right)^2, \end{aligned} \tag{1.16}$$

which almost replicates the SM values. As the ratio g_Δ/m_Δ increases from zero, the predicted events with LQs are initially decreasing from the SM prediction. At a certain g_Δ/m_Δ the predicted events become equal to the SM one (see Eq. 1.16), and the $\Delta\chi^2 = 0$. This is the degeneracy which gives the discontinuity in our constraints plots.

1.5 Conclusions

We constrain the scalar LQs parameter space using the most recent data of the COHERENT collaboration for CSI and Ar detectors. Neutrino-nucleus coherent scattering involves just the valence quarks (u and d) of the nuclei. As a result, the specific form of the Yukawa matrix that links to the first generation of quarks and neutrinos can be constrained as listed in Table 1.1. We are able to strongly constrain the scalar LQs Yukawa coupling over a wide mass range using the low energy COHERENT experiment. The bounds are comparable to the constraints coming from other existing high energy experiments.

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Chapter 2
Relevance of Golden Ratio in Neutrino Physics

Ngangkham Nimai Singh and Y. Monitar Singh

Abstract We study the implication of golden ratio in neutrino physics where the solar mixing angle (θ_{12}) which is one of the three neutrino mixing angles is closely related to this ratio. An exact leptonic mixing pattern which predicts golden ratio can be generated by certain discrete symmetry groups such as A_5. We use these three mixing angles given by the exact golden ratio neutrino mixing pattern as input values at a high energy scale, to obtain the low energy neutrino oscillation parameters through the numerical analysis of the relevant renormalization group equations (RGEs) of neutrino masses and mixing angles. Such radiative correction establishes the validity of golden ratio neutrino mixings defined at high energy scale from certain discrete symmetry, consistent with latest Planck cosmological data $\sum |m_i| < 0.12$ eV, for normal hierarchical mass model at a larger value of $\tan\beta > 60$ and SUSY breaking scale m_s=1TeV. The sensitivity on the values of $\sum |m_i|$ on m_s is also discussed.

2.1 Introduction

The relevance of golden ratio is naturally found in classic architecture(The Great Pyramid of Giza, Parthenon, Taj Mahal, etc.), artwork (Famous Artworks by Leonardo da Vinci: Mona Lisa, Vitruvian Man, etc.), nature(Plants, Animals), and even music. It is mathematically defined as the ratio of a line segment cut into two pieces of different lengths such that the ratio of the whole segment (**a+b**) to that of the longer segment (**a**) is equal to the longer segment (**a**) to shorter segment (**b**), i.e. $\frac{\mathbf{a+b}}{\mathbf{a}} = \frac{\mathbf{a}}{\mathbf{b}}$. This ratio numerically comes out as $\phi = \frac{1+\sqrt{5}}{2} \approx 1.618$. This ratio is also related to the neutrino physics in the sense that it can give the value of solar neutrino mixing angle as $\theta_{12} = \tan^{-1}(\frac{1}{\phi}) \approx 31.7^0$ [1, 2]. The value of solar neutrino mixing angle (θ_{12}) is one of the very special parameters for characterizing various

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leptonic mixing patterns. In neutrino physics, some discrete symmetries like A_5 can lead to the generation of exact golden ratio mixing pattern as follows [3, 4]:

$$U_{GR} = U_{PMNS} = \begin{pmatrix} \frac{\phi}{\sqrt{2+\phi}} & \frac{1}{\sqrt{2+\phi}} & 0 \\ -\frac{1}{\sqrt{4+2\phi}} & \frac{\phi}{\sqrt{4+2\phi}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{4+2\phi}} & -\frac{\phi}{\sqrt{4+2\phi}} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{2.1}$$

where ϕ has following properties:

$$\phi = \phi^2 - 1 = 1 + \frac{1}{\phi} = \frac{1+\sqrt{5}}{2} \approx 1.62$$

The three neutrino mixing angles predicted by the above exact golden ratio mixing matrix in Eq. (2.1) are $\theta_{12} = 31.7^0$, $\theta_{23} = 45^0$, and $\theta_{13} = 0$. Although the two mixing angles θ_{12} and θ_{23} are consistent within 3σ bound of experimental data, the third mixing angle, θ_{13}, is not consistent with the experimental non-zero value defined at low energy scale. This inconsistency in the mixing angle θ_{13} can be removed by giving a suitable perturbation to the exact golden ratio mixing pattern in some discrete symmetry models, which can be originated from any one of the followings: (i) contribution from charged lepton sector; (ii) corrections to vacuum alignment of A_5 triplets and quintuplets; and (iii)contribution from corrections in neutrino sector [5]. We can have another approach for studying the effect of perturbation to neutrino masses and mixings given by the exact mixing pattern in Eq. (2.1) through the radiative corrections using renormalization group equations (RGEs). This method of taking the radiative correction is model independent in the sense that all the neutrino masses at high energy scale are taken as free input parameters so that all generated neutrino oscillation parameters at low energy scale are consistent with experimental data within 3σ bound. We also take the three golden ratio mixing angles as input parameters at a high energy scale in running the RGEs to study the validity of the golden ratio in neutrino physics. We impose the latest updated Planck upper bound on the sum of neutrino masses $\sum |m_i| < 0.12$ eV as the most stringent constraint in the generation of neutrino oscillation parameters consistent with experimental data [6].

2.2 Numerical Analysis Through Renormalization Group Equations

The perturbation of the exact golden ratio neutrino mixing pattern Eq. (2.1) is studied through RGEs in running from high to low energy scale within SUSY framework. In such radiative analysis, the exact golden ratio mixing pattern with discrete symmetry group A_5 is assumed to be defined at the high energy scale M_R near the unification scale. The radiative generation of the non-zero value of the reactor neutrino mixing angle (θ_{13}) at low energy scale is consistent with the other two mixing angles, within the 3σ bound of the latest experimental data [6]. One of the most stringent constraints is the sum of three absolute neutrino mass eigenvalues given by the latest Planck data, $\sum|m_i| < 0.12$ eV [7, 8]. The neutrino oscillation parameters include three mixing angles, i.e. the solar mixing angle (θ_{12}), the atmospheric mixing angle θ_{23}, and the reactor mixing angle(θ_{13}) and two mass squared differences, i.e. solar mass squared difference (Δm^2_{21}) and atmospheric mass squared difference ($\Delta m^2_{32} \approx \Delta m^2_{31}$). The radiative correction is numerically evaluated by running renormalization group equations (RGEs). We follow a two-step procedure: (i) bottom-up approach for evaluating the values of three gauge and third generation Yukawa coupling constants from low energy scale to high energy scale, and (ii) top-down approach for generating neutrino oscillation parameters at a low energy scale evolved from high energy scale. The RGEs of neutrino mass eigenvalues are given by the following equations [9, 10]

$$\frac{d}{dt}m_i = -2F_\tau(P_i + Q_i)m_i - F_u m_i, (i = 1, 2, 3). \tag{2.2}$$

The RGEs of neutrino mixing angles are given by the following equations [9, 10]

$$\frac{ds_{12}}{dt} = \frac{F_\tau c_{12} \sin 2\theta_{12} s^2_{23}}{2(m^2_2 - m^2_1)}[m^2_1 + m^2_2 + 2m_1 m_2 \cos(2\alpha_2 - 2\alpha_1)] \tag{2.3}$$

$$\begin{aligned}\frac{ds_{23}}{dt} = \frac{F_\tau c_{23} \sin 2\theta_{23}}{2(m^2_3 - m^2_2)}[c^2_{12}(m^2_3 + m^2_2 + 2m_3 m_2 \cos 2\alpha_2)\\ + \frac{s^2_{12}(m^2_3 + m^2_1 + 2m_3 m_1 \cos 2\alpha_1)}{R + 1}\end{aligned} \tag{2.4}$$

$$\begin{aligned}\frac{ds_{13}}{dt} = -\frac{F_\tau c_{13} \sin 2\theta_{12} \sin 2\theta_{23} m_3}{2(m^2_3 - m^2_1)}\\ [m_1 \cos(2\alpha_1 - \delta) - (1 + R)m_2 \cos(2\alpha_2 - \delta) - Rm_3 \cos\delta]\end{aligned} \tag{2.5}$$

where $P_1 = (s_{12}s_{23})^2$; $P_2 = (c_{12}s_{23})^2$; $P_3 = (c_{13}c_{23})^2$; $Q_1 = -\frac{1}{2}s_{12} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta + (c_{12}c_{23}c_{13})^2$; $Q_2 = \frac{1}{2}s_{12} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta + (s_{12}c_{23}s_{13})^2$; $Q_3 = 0$ and

$$R = \frac{m^2_2 - m^2_1}{m^2_3 - m^2_2}.$$

For scale-dependent VEV in the case of MSSM with $\mu \geq m_s$ [10, 11], we have taken as

$$F_\tau = -\frac{h^2_\tau}{16\pi^2 \cos^2 2\beta}$$

$$F_u = \frac{1}{16\pi^2}\left(\frac{9}{10}g_1^2 + \frac{9}{2}g_2^2\right)$$

and for SM case with $\mu \leq m_s$, we have

$$F_\tau = \frac{3h_\tau^2}{32\pi^2}$$

$$F_u = \frac{1}{16\pi^2}\left(-\frac{9}{10}g_1^2 - \frac{3}{2}g_2^2 + 6h_b^2 - 2\lambda\right)$$

where g_1, g_2, g_3 are gauge couplings, and h_t, h_b, h_τ, and λ are top-quark, bottom-quark, tau-lepton Yukawa couplings, and SM quartic Higgs coupling, respectively. The RGEs for phases and other coupling constants given above are also given in Refs. [10–14]. The RGEs of non-SUSY (SM) are used for energy scale,$m_t \leq \mu \leq m_s$ and the RGEs of SUSY (MSSM) are used for energy scale, $m_s \leq \mu \leq M_R$. The values of coupling constants at a very high energy scale are significant in giving the low energy neutrino oscillation parameters consistent with the latest Planck mass bound, $\sum |m_i| < 0.12$ eV. These coupling constants are affected by the variation of some free parameters such as $\tan\beta$, the SUSY breaking scale (m_s), the threshold parameter ($\bar{\eta_b}$), and the value of the high energy seesaw scale (M_R). The unification of three gauge couplings (g_1, g_2, g_3) at high energy scale is maintained with the input values of the above parameters.

2.3 Results and Discussion

The observed numerical values of oscillation parameters at low energy scale with suitable input parameters at high energy scale are given in Table 2.2. The values of coupling constants evaluated at high energy scale with various input values of free parameters of $\tan\beta$, $\bar{\eta_b}$, m_s, and M_R are very significant in the generation of neutrino oscillation parameters at low energy scale consistent with the latest Planck

Table 2.1 Observational data of neutrino oscillation parameters for normal hierarchy (NH) and inverted hierarchy (IH)in 3σ range

Parameter	Normal Hierarchy (best-fit$\pm 1\sigma$)	Inverted Hierarchy (best-fit$\pm 1\sigma$)
$\lvert\Delta m_{21}^2\rvert[10^{-5}eV^2]$	6.82–8.03 ($7.41^{+0.21}_{-0.20}$)	6.82–8.03 ($7.41^{+0.21}_{-0.20}$)
$\lvert\Delta m_{31}^2\rvert[10^{-3}eV^2]$	2.428–2.597 ($2.511^{+0.028}_{-0.027}$)	2.408–2.581 ($2.498^{+0.032}_{-0.025}$)
$\sin\theta_{12}$	0.519–0.585 ($0.303^{+0.012}_{-0.011}$)	0.519–0.585 ($0.303^{+0.012}_{-0.011}$)
$\sin\theta_{23}$	0.636–0.788 ($0.572^{+0.018}_{-0.023}$)	0.640–789 ($0.578^{+0.016}_{-0.021}$)
$\sin\theta_{13}/10^{-2}$	0.142–0.155 ($2.203^{+0.056}_{-0.059}$)	0.143–0.156 ($2.219^{+0.060}_{-0.057}$)
$\delta_{CP}/^o$	105–405 ($197^{+0.42}_{-0.25}$)	192–361 ($286^{+0.27}_{-0.32}$)

Table 2.2 Low energy neutrino oscillation parameters obtained from radiative corrections in MSSM while running from $M_R = 1.84 \times 10^{15}$GeV to low energy scale, $m_t = 172.76$GeV for $\tan\beta = 68$, $m_s = 1TeV$, and $\bar{\eta_b} = 0.02$ for NH model

Parameter	High energy scale input values (NH)	Low energy scale output values (NH)
$m_1[eV]$	0.0224	0.0303
$m_2[eV]$	−0.0255	−0.0316
$m_3[eV]$	0.0482	0.0579
$\|\Delta m^2_{21}\|[10^{-5}eV^2]$	14.84	7.54
$\|\Delta m^2_{31}\|[10^{-3}eV^2]$	1.82	2.43
$\sin\theta_{12}$	0.5257	0.5355
$\sin\theta_{23}$	0.7071	0.789
$\sin\theta_{13}$	0.0	0.1428
$\delta_{CP}/^o$	175	200.63
α_1	2	12.35
α_2	0.5	4.55
$\sum\|m_i\|[eV]$	0.0962	0.119

upper bound. The effect of the variation of free parameters $\tan\beta$, $\bar{\eta_b}$, m_s and M_R with $\sum|m_i|$ is also studied and their graphical representations are shown in Fig. 2.1. At particular specific values of these parameters, $\tan\beta = 68$, $m_s = 1$TeV, $\bar{\eta_b} = 0.02$, and $M_R = 1.84 \times 10^{15}$ GeV, the golden ratio mixing pattern is valid in giving the low energy oscillation parameters consistent with the latest Planck upper bound. There is a wide range of allowed values of the free parameters if the cosmological upper bound on the sum of three neutrino masses is relaxed upto $\sum|m_i| < 0.23$ eV [15, 16] and the graphical representation is shown in Fig. 2.2. The validity of the golden ratio mixings at high energy scale lies in the values that are chosen for the above three unknown parameters. The SUSY breaking scale (m_s) is one of the very important unknown parameters in the minimal super-symmetric model (MSSM). As there is no evidence for the existence of SUSY particles in the lower TeV range, the validity of golden ratio neutrino mixings in the higher TeV range is also discussed. The use of the latest updated Planck cosmological upper bound on the sum of neutrino masses as a constraint is an important factor for the validity of various leptonic mixing patterns in the radiative corrections of neutrino masses and mixings at low energy scale from high energy scale through their respective renormalization group equations. From the analysis of Fig. 2.2, it is seen that the golden ratio mixing pattern is found to be valid for Planck upper bound, $\sum|m_i| < 0.12$ at only around $m_s = 1$TeV, and for $\sum|m_i| < 0.23$ eV, it is valid up to $m_s = 14$ TeV. This higher Planck bound also allows lower values of $\tan\beta \sim 55$ as shown in Fig. 2.1a. This is consistent with the analysis of combined Planck plus James Webb Space Telescope (JWST)[16] and also gives the validity of golden ratio neutrino mixings in inverted hierarchy (IH) in addition to NH (Table 2.2).

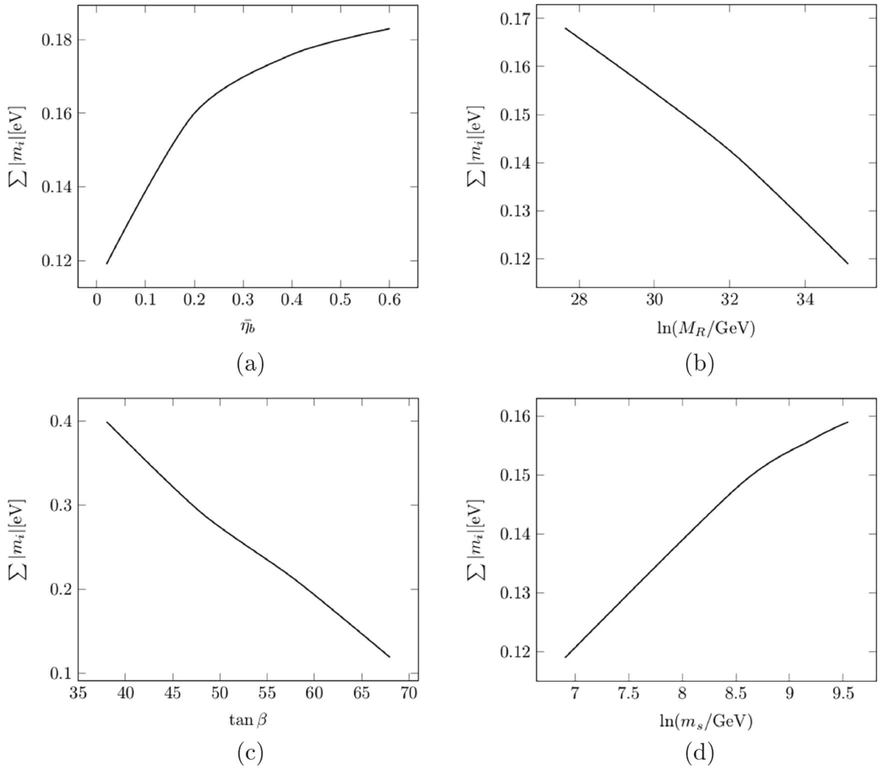

Fig. 2.1 **a** Variation of $\sum |m_i|$[eV] with $\bar{\eta_b}$ for $M_R = 1.84 \times 10^{15}$ GeV,$\tan\beta = 68$,$m_s = 1TeV$; **b** Variation of $\sum |m_i|$[eV] with M_R for $\bar{\eta_b} = 0.02$ GeV, $\tan\beta = 68$,$m_s = 1TeV$; **c** Variation of $\sum |m_i|$[eV] with $\tan\beta$ for $M_R = 1.84 \times 10^{15}$ GeV,$\bar{\eta_b} = 0.02$,$m_s = 1TeV$; **d** Variation of $\sum |m_i|$[eV] with m_s for $M_R = 1.84 \times 10^{15}$ GeV, $\tan\beta = 68$,$\bar{\eta_b} = 0.02$

2.4 Summary and Conclusion

The three neutrino mixing angles after the radiative correction at low energy scale are found to be $\theta_{12} = 32.37^0$, $\theta_{13} = 8.2^0$, and $\theta_{23} = 52.0^0$ which are consistent with the recent oscillation data 3σ range. Thus, all the neutrino oscillation parameters at low energy scale can be generated from high energy scale using the exact golden ratio mixing pattern. The latest Planck cosmological upper bound $\sum |m_i| < 0.12$eV is found to be satisfied in the normal hierarchical mass model. The larger value of $\tan\beta > 60$ is found to be consistent with the Planck bound in the numerical analysis. Our analysis does not favour the inverted hierarchical model within this latest Planck cosmological upper bound. Similar analysis shows that other symmetries based on tri-bimaximal(TBM), bimaximal (BM), and hexagonal mixing (HM) are found to be invalid within this latest Planck cosmological upper bound at low energy scale of

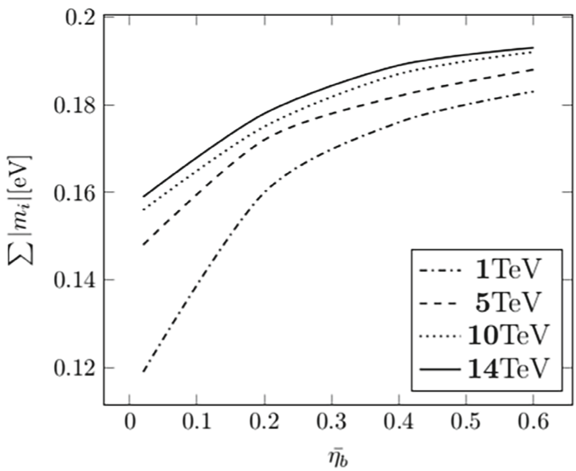

Fig. 2.2 Allowed range of graphical representations for the variation of $\sum |m_i|$[eV] with the different values of SUSY threshold parameter ($\bar{\eta_b} = 0.02, 0.2, 0.4, 0.6$) for different cases of SUSY breaking scale m_s=1TeV, 5TeV, 10TeV,14TeV. Higher values of $\sum |m_i|$ <0.23 eV can accommodate wide range of parameters, ($\bar{\eta_b} = 0.02 - 0.6$) and ($m_s$ =1TeV-14TeV) for particular values of $M_R = 1.84 \times 10^{15}$GeV and $\tan\beta = 68$

neutrino oscillation parameters. The present numerical analysis of radiative correction shows the validity of golden ratio in neutrino physics at around $m_s = 1$TeV for $\sum |m_i| < 0.12$ eV and it is valid up to $m_s = 14$ TeV for $\sum |m_i| < 0.23$ eV.

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Chapter 3
Randomly Generated Majorana Neutrino Mass Matrix for CP-Conserving Case

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Abstract The present work aims to discriminate among the theoretically predicted different forms of Majorana neutrino mass matrix including texture zeros. The neutrino oscillation parameters are numerically extracted by diagonalizing a general charge-parity (CP)-conserving Majorana neutrino mass matrix whose elements are randomly generated within a certain range of allowed values using adaptive Monte Carlo method. The latest neutrino oscillation experimental data within 3σ determines allowed values of the elements of the neutrino mass matrix. The latest Planck upper bound on the sum of three absolute masses $\sum |m_i| < 0.12$ eV is imposed in the numerical analysis. Both normal hierarchy (NH) and inverted hierarchy (IH) mass models are allowed, thus showing the possibility of both mass hierarchies within 3σ. Further, the detailed numerical analysis confirms that the normal hierarchical mass model is valid up to mass bound, $\sum |m_i| \geq 0.06$ eV while the inverted hierarchical mass model is valid up to mass bound, $\sum |m_i| \geq 0.1$eV. In both models, the value of θ_{23} is allowed in both below and above 45^0. However, $\theta_{23} > 45^0$ is found to be more favourable for NH whereas $\theta_{23} < 45^0$ is more favourable for IH.

3.1 Introduction

The present neutrino oscillation data confirms that neutrinos have very tiny but non-zero masses. These tiny masses of neutrinos are elegantly explained by the celebrated seesaw mechanism. A neutrino mass matrix can be theoretically generated from various discrete symmetries. All neutrino oscillation parameters can be extracted from the mass matrix which is possible for both normal and inverted hierarchical mass models.

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