Université Mohammed V
Faculté des Sciences
Rabat

Bypassing domain walls in NMSSM augmented by $\mathbb{A}_4 \times Z_3$ flavor symmetry

Presented by :

Mohamed-Amine OUAHID, *LPHE Modelisation and Simulation*

1st Mediterranean Conference on Higgs Physics (23-27 September) Tangier, Morocco

[illegible] septembre 2019

Plan

1 Introduction

Plan

1. Introduction
2. Neutrino masses and Trimaximal mixing in FNMSSM

Plan

1. Introduction
2. Neutrino masses and Trimaximal mixing in FNMSSM
3. Phenomenological implications

Plan

1. Introduction
2. Neutrino masses and Trimaximal mixing in FNMSSM
3. Phenomenological implications
4. Bypassing domain walls

Plan

1. Introduction
2. Neutrino masses and Trimaximal mixing in FNMSSM
3. Phenomenological implications
4. Bypassing domain walls
5. Conclusion

Neutrinos in the Standard Model are :
Left-handed (anti-neutrinos are right-handed), electrically neutral, have three flavors (Electron, Muon, Tau), Only interact via the Weak force and **Massless**.
Neutrino oscillations $\Longrightarrow$ Neutrinos are massive particles (Nobel Prize 2015).
Also, we have observational evidences for dark matter and baryon asymmetry.
So, We need to go beyond the SM $\Longrightarrow$ **Physics Beyond the SM**

Familiar SM extensions

$\Longrightarrow$ Particular extensions :

∘ The SM + Right handed neutrinos (Type I seesaw). **[Minkowski 1977]**

∘ The SM + Higgs triplet (Type II seesaw). **[Konetschnov, Kummer 1977]**

∘ The SM + fermions triplet (Type III seesaw). **[R. Foot, et al 1989]**

∘ ...

$\Longrightarrow$ Fondamental extensions (GUT models) :

∘ SO(10) **[Fritsch et Minkowski]**

∘ SU(5) **[Georgi-Glashow]**

∘ E6 **[Gürsey, Ramond and Sikivie]**

∘ ...

Flavor Symmetry

Generally, the total structure of a symmetry in a model based on flavor symmetry is given as :

$$G_{gauge} \times G_{flavor}$$

The flavor symmetry group could be
Continuous group : SU(2), SU(3), SO(3)...
or **Discrete group** -Non-Abelian- : S_3, S_4, A_4, A_5, D_4...
On the other hand, recent experimental data of neutrino flavor mixing suggest **Non-Abelian Discrete Symmetry for flavors**.
○ S_3 has two singlets and one doublet (no triplet representation).
○ Non-Abelian discrete groups with **triplet representation**, which are often used in Flavor symmetry $S_4, A_4, A_5 \ldots$

Flavor symmetry $G_{\rm f} = \mathbb{A}_4 \times \boldsymbol{Z}_3$

○ The alternating $\mathbb{A}_4$ subsymmetry of $G_{\rm f}$ is a non-Abelian discrete group living inside of the well known permutation group $\mathbb{S}_4$.
It is generated by two noncommuting operators $\mathcal{S}$ and $\mathcal{T}$ ($\mathcal{S}\mathcal{T} \neq \mathcal{T}\mathcal{S}$) with the property $\mathcal{S}^2 = \mathcal{T}^3 = I$

$$\mathcal{S} = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix} \quad , \quad \mathcal{T} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \bar{\omega} & 0 \\ 0 & 0 & \omega \end{pmatrix}$$

The order of the $\mathbb{A}_4$ group is 12 ; it is related to the dimensions of its four irreducible representations through the character relation

$$\mathbb{A}_4 : 12 = (1)^2 + (1')^2 + (1'')^2 + (3)^2$$

○ The $\boldsymbol{Z}_3$ subsymmetry of $G_{\rm f}$ is an Abelian discrete group, it has three different one- dimensional representations $\mathbf{1}_1$, $\mathbf{1}_Q$ and $\mathbf{1}_{Q^2}$ with $Q = e^{i\frac{2\pi}{3}}$.

Building blocks in flavon extended NMSSM

Lepton and right-handed neutrino superfields and their quantum numbers under $\mathbb{A}_4 \times \boldsymbol{Z}_3$:

Superfields	L_i	e^c	μ^c	τ^c	N_i^c
$\mathbb{A}_4$	$\mathbf{3}_{(-1,0)}$	$\mathbf{1}_{(1,1)}$	$\mathbf{1}_{(1,\omega^2)}$	$\mathbf{1}_{(1,\omega)}$	$\mathbf{3}_{(-1,0)}$
$\boldsymbol{Z}_3$	$\mathbf{1}_Q$	$\mathbf{1}_Q$	$\mathbf{1}_Q$	$\mathbf{1}_Q$	$\mathbf{1}_{Q^2}$

Higgs and flavon superfields and their quantum numbers under $\mathbb{A}_4 \times \boldsymbol{Z}_3$:

Superfields	H_u	H_d	Φ	Ω	S	χ
$\mathbb{A}_4$	$\mathbf{1}_{(1,1)}$	$\mathbf{1}_{(1,1)}$	$\mathbf{3}_{(-1,0)}$	$\mathbf{3}_{(-1,0)}$	$\mathbf{1}_{(1,1)}$	$\mathbf{1}_{(1,\omega)}$
$\boldsymbol{Z}_3$	$\mathbf{1}_1$	$\mathbf{1}_Q$	$\mathbf{1}_1$	$\mathbf{1}_{Q^2}$	$\mathbf{1}_{Q^2}$	$\mathbf{1}_{Q^2}$

Dirac neutrino mass

The relevant chiral superpotential W_D respecting gauge and flavor symmetries of the model is as follows

$$W_D = Tr_{\mathbb{A}_4}\left(Y^{ij} L_i N_j^c H_u\right)$$

where $L_i = (L_e, L_\mu, L_\tau)$ and $N_i^c = (\nu_e^c, \nu_\mu^c, \nu_\tau^c)$.
reading explicitly as

$$W_D = Y_0 H_u \left(L_1 N_1^c + L_2 N_3^c + L_3 N_2^c\right)$$

The Dirac mass matrix of neutrinos

$$m_D = Y_0 \upsilon_u \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

Majorana neutrino mass

The superpotential is expressed at the renormalizable level as

$$W_R = \lambda Tr_{\mathbb{A}_4}\left(SN^cN^c\right) + \lambda' Tr_{\mathbb{A}_4}\left(\Omega N^cN^c\right) + \lambda'' Tr_{\mathbb{A}_4}\left(\chi N^cN^c\right)$$

After flavor and electroweak symmetry breaking, the Majorana neutrino mass matrix is given by the following symmetric matrix

$$M_R = \begin{pmatrix} a+\frac{2b}{3} & -\frac{b}{3} & -\frac{b}{3}+\varepsilon \\ -\frac{b}{3} & \frac{2b}{3}+\varepsilon & a-\frac{b}{3} \\ -\frac{b}{3}+\varepsilon & a-\frac{b}{3} & \frac{2b}{3} \end{pmatrix}$$

with $a = 2\lambda\upsilon_S$, $b = 2\lambda'\upsilon_\Omega$ and $\varepsilon = 2\lambda''\upsilon_\chi$

Light neutrino masses

Now we calculate the light neutrino masses by applying the type-I seesaw formula : $m_\nu = m_D^T M_R^{-1} m_D$.
Thus, the light neutrino masses are given by

$$U^*_{TM_2} m_\nu \left(U^*_{TM_2}\right)^T = \mathrm{diag}(m_1, m_2, m_3)$$

Using the best fit values of the neutrino oscillation parameters, We find for NH

$$m_1 \simeq 0.0055 \text{ eV} \quad , \quad m_2 \simeq 0.0102 \text{ eV} \quad , \quad m_3 \simeq 0.0503 \text{ eV}$$

while for IH we find

$$m_1 \simeq 0.0606 \text{ eV} \quad , \quad m_2 \simeq 0.0612 \text{ eV} \quad , \quad m_3 \simeq 0.035 \text{ eV}$$

where

$$U_{TM_2} = \begin{pmatrix} \sqrt{\frac{2}{3}}\cos\theta & \frac{1}{\sqrt{3}} & \sqrt{\frac{2}{3}}\sin\theta e^{-i\sigma} \\ -\frac{\cos\theta}{\sqrt{6}} + \frac{\sin\theta}{\sqrt{2}} e^{i\sigma} & \frac{1}{\sqrt{3}} & -\frac{\cos\theta}{\sqrt{2}} - \frac{\sin\theta}{\sqrt{6}} e^{-i\sigma} \\ -\frac{\cos\theta}{\sqrt{6}} - \frac{\sin\theta}{\sqrt{2}} e^{i\sigma} & \frac{1}{\sqrt{3}} & \frac{\cos\theta}{\sqrt{2}} - \frac{\sin\theta}{\sqrt{6}} e^{-i\sigma} \end{pmatrix}$$

Mixing angles

We obtain the expressions of the three θ_{13}, θ_{23} and θ_{12} mixing angles

$$\sin^2\theta_{12} = \frac{1}{3(1-\sin^2\theta_{13})}$$

$$\sin^2\theta_{13} = \frac{2}{3}\sin^2\theta$$

$$\sin^2\theta_{23} = \frac{1}{2} + \frac{\sin\theta_{13}\left(1-\frac{3}{2}\sin^2\theta_{13}\right)^{1/2}}{\sqrt{2}\left(1-\sin^2\theta_{13}\right)}\cos\delta_{CP}$$

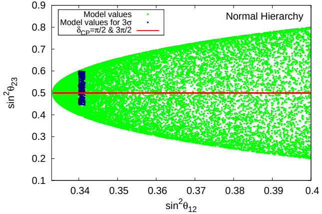
provided the following condition holds

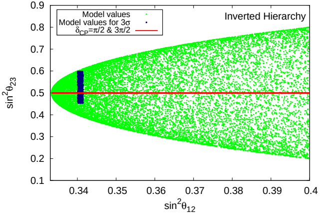
$$\tan 2\theta = \frac{2\sqrt{3}\varepsilon}{(2a-2b-\varepsilon)\,e^{-i\sigma}+(2a+2b-\varepsilon)\,e^{i\sigma}}$$

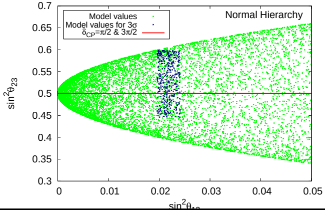
It is clear that $\theta_{13} \neq 0$ (2012 : T2K, Daya Bay, MINOS, RENO) and $\theta_{23} \neq \frac{\pi}{4}$ (2018 : NOvA).

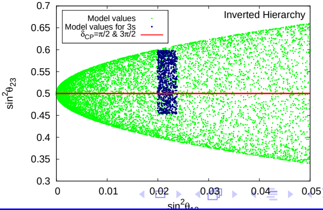
Mixing angles

Using the 3σ ranges of neutrino oscillation parameters for both hierarchies, the correlation plots between the different mixing angles :







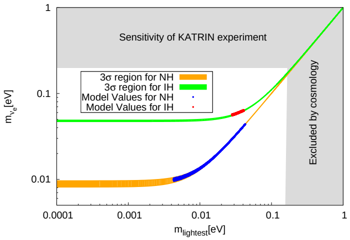


Tritium beta decay

The KATRIN experiment is the current generation of direct neutrino mass measurement which is designed to measure the effective electron neutrino mass $m_{\nu_e}^2 = \sum_i |U_{ei}|^2 m_i^2$ with a sensitivity of $m_{\nu_e} < 0.2\,\mathrm{eV}$ (at 90 % C.L.). In this model is given by

$$m_{\nu_e}^2 = \frac{1}{3}\left(2m_1^2\cos^2\theta + m_2^2 + 2m_3^2\sin^2\theta\right)$$

The effective neutrino mass m_{ν_e} as function of the lightest neutrino mass



Tritium beta decay

The model predict :
for NH :

$$m_{\nu_e}(\mathrm{eV}) \in [0.00959 - 0.0439]$$

for IH

$$m_{\nu_e}(\mathrm{eV}) \in [0.0554 - 0.0638]$$

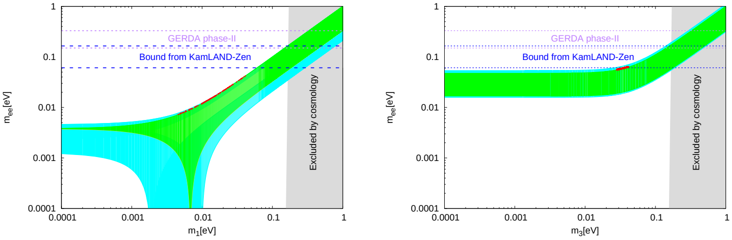
Although the obtained intervals of m_{ν_e} are compatible with current data, the anticipated **future** sensitivity from **Project 8 experiment** is as low as **0.04** eV, which means that if no signal is observed around this value in the future there is a good chance **to exclude the inverted mass hierarchy** (the smallest value of m_{ν_e} in our model is 0.0554 for IH).

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The most sensitive probe of the **Majorana nature** of neutrinos is provided by the neutrinoless double beta decay experiments.

The decay rate of $0\nu\beta\beta$ is proportional to the squared of the effective Majorana mass $|m_{ee}|$ defined as $|m_{ee}| = \left|\sum_i U_{ei}^2 m_i\right|$. In this model we find

$$|m_{ee}| = \frac{1}{3}\left|2m_1\cos^2\theta + m_2 e^{i\alpha_1} + 2m_3\sin^2\theta e^{i\alpha_2}\right|$$



Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The most recent bounds of $|m_{ee}|$ come from the **KamLAND-Zen** and **GERDA** experiments which are given respectively by

$$|m_{ee}| < 0.061 - 0.165 \text{ eV} \quad , \quad |m_{ee}| < 0.15 - 0.33 \text{ eV}$$

We find in our calculation that :
NH :

$$|m_{ee}(\text{eV})| \in [0.007271 - 0.04202]$$

IH

$$|m_{ee}(\text{eV})| \in [0.05519 - 0.0641]$$

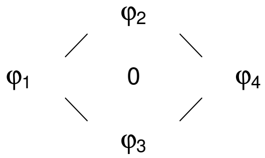
The obtained region of the effective Majorana mass in the **IH case** can be **reached** in **future** experiments like **KamLAND-Zen** which plans to reach a sensitivity below **0.04** eV on $|m_{ee}|$.

Breaking pattern of $\mathbb{A}_4$ to $\mathbb{Z}_3$

In the charged lepton sector we deal with the spontaneous breaking of the non-Abelian $\mathbb{A}_4$ group down to $\mathbb{Z}_3$ The breaking of the flavor symmetry driven by the flavon triplet Φ may be expressed as

$$\mathbb{A}_4 \times \boldsymbol{Z}_3 \quad \xrightarrow{\langle\Phi\rangle} \quad \mathbb{Z}_3 \times \boldsymbol{Z}_3$$

So, the domain walls separating the $\varphi_1, \varphi_2, \varphi_3, \varphi_4$ flavon vacua can be completely characterised by the elements of the broken **Klein symmetry** $\mathbb{V}_4 \simeq \mathbb{Z}_2 \times \mathbb{Z}_2$ living inside $\mathbb{A}_4$.



The flavon triplet Φ acquired its VEV before the end of inflation, ($\upsilon_\Phi > 1.4 \times 10^{14}$ GeV). Consequently, the **domain walls** produced in this case are **inflated away**.

Breaking pattern of $\mathbb{A}_4$ to $\mathbb{Z}_2$

The breaking pattern in neutrino sector can be expressed like

$$\mathbb{A}_4 \quad \xrightarrow{\langle\Omega\rangle} \quad \mathbb{Z}_2$$

The discrete $\mathbb{A}_4$ symmetry group gets broken down to a $\mathbb{Z}_2$ subsymmetry with broken part behaving like $\mathbb{Z}_3 \times \mathbb{Z}_2'$.
We obtain **six degenerate vacua**

$$\vartheta_1^{\pm} = \pm\upsilon_\Omega \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \quad \vartheta_2^{\pm} = \pm\upsilon_\Omega \begin{pmatrix} 1 \\ \bar{\omega} \\ \omega \end{pmatrix}, \quad \vartheta_3^{\pm} = \pm\upsilon_\Omega \begin{pmatrix} 1 \\ \omega \\ \bar{\omega} \end{pmatrix}$$

The domain walls in the neutrino sector ($10^2 \precsim \upsilon_\Omega \precsim 10^8$ GeV)are created **below the inflationary scale** ; they are **inevitable** and then inconsistent with the standard cosmology ; they **must be avoided**.

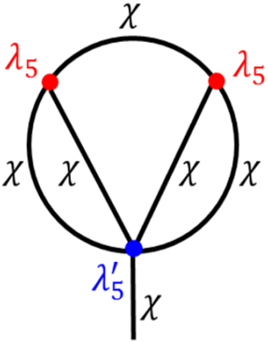
Solving the DW problem

To solve the domain wall problem, the **discrete symmetry** must be **broken explicitly** before the spontaneous breaking takes place.
By introducing **higher dimensional operators** $\frac{1}{M_{Pl}^n}\mathcal{O}_{n+3}$ suppressed by powers of the **Planck scale** M_{Pl} leading to favor one of the vacua over the others, and consequently no walls will be formed and the domain wall problem is **resolved**.
The most suitable one that can break explicitly the full $\mathbb{A}_4 \times \boldsymbol{Z}_3$ flavor symmetry down to $\mathbb{Z}_2$ is given by the following operator

$$\mathcal{W}_{NR} = \frac{\lambda_5'}{M_{Pl}^2}\chi^5$$

Solving the DW problem

The contribution arises from this operator can be generated through the following Feynman diagram



This operator induces a linear term in the soft SUSY breaking scalar potential.

$$\mathcal{V}_{soft} \supset \eta M_W^3 \chi_s + h.c$$

Conclusion

We have first studied the extension of the usual **NMSSM** with $G_{\rm f} = \mathbb{A}_4 \times \boldsymbol{Z}_3$ and three right-handed neutrino in order to engineer appropriate neutrino masses, mixing and the phenomenological implications.

Secondly, we have investigated the problem of **domain walls** and provided a solution to this issue by using the **explicite breaking** of the flavour symmetry and the effective scalar potential approach.

Thank you for your attention.