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S4対称性と3HDMを用いたフレーバー模型の構築

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もくじ

1. Introduction

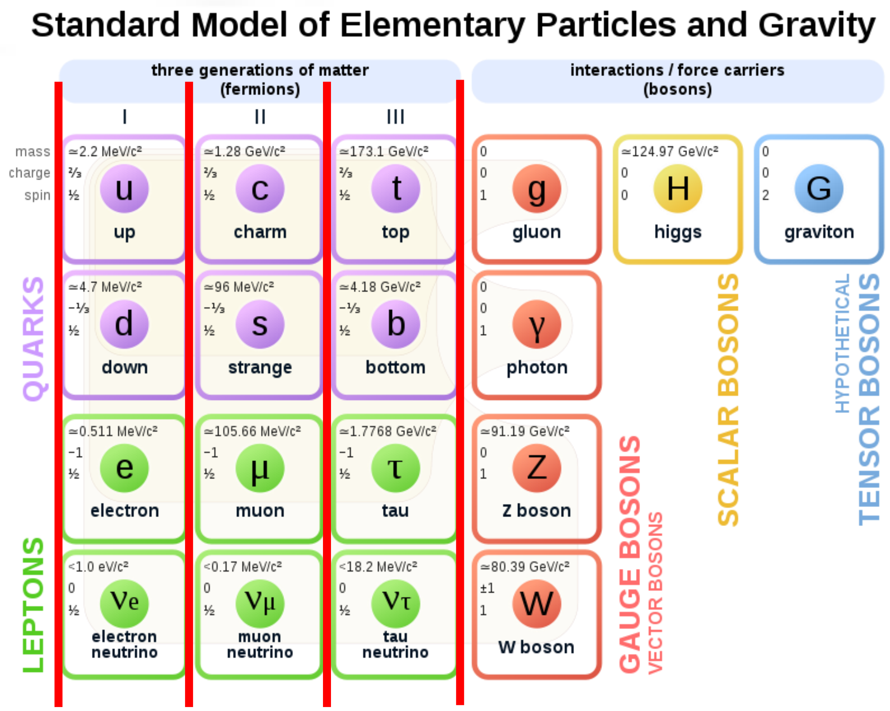
4つの力

(強い力, 弱い力, 電磁気力, 重力)

標準模型(SM)
$SU(3)\times SU(2)_L \times U(1)_Y$ gauge対称性

クォークとレプトン (SM粒子)

→ 世代構造
(質量の階層性と世代混合)
特に レプトン→大きな世代混合



https://www.wikiwand.com/

SMで理論的な説明が成されていない。
(SMはparameterを充てているのみ)

1. Introduction

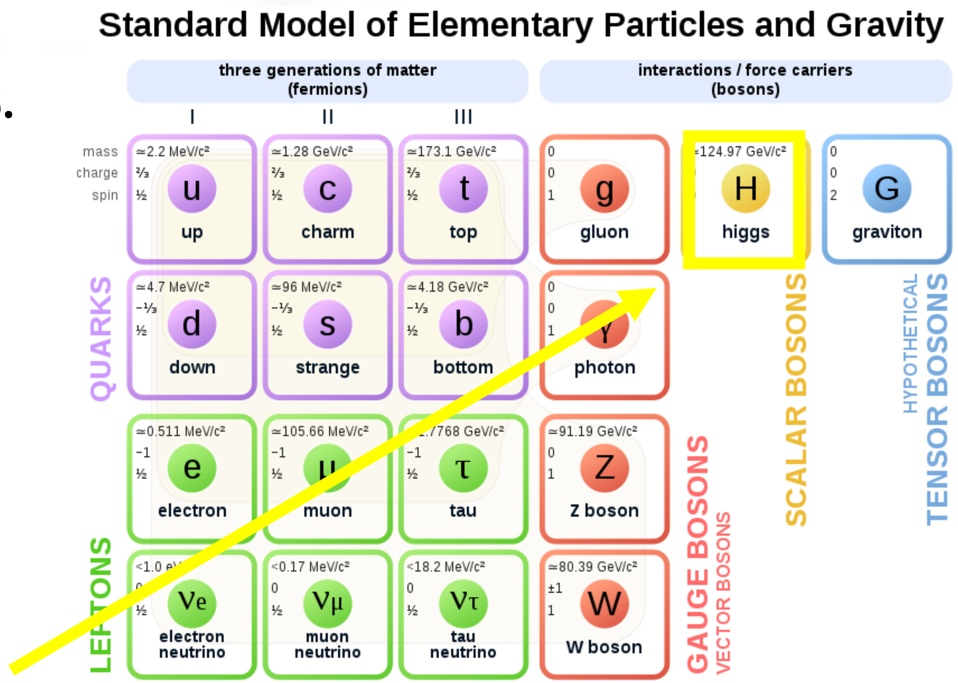
AltareliとFeruglioは非可換離散対称性を世代間に課した(flavor対称性)

G. Altarelli and F. Feruglio, Nucl. Phys. B741 (2006), 215-235.

本研究では世代対称性としてS_4対称性を用いる

加えて、three Higgs doublets model(3HDM)を用いる

新しいflavor模型を構築し、数値解析を行う



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2. S_4対称性

S_4対称性：4次の対称群

$(x_1, x_2, x_3, x_4) \to (x_i, x_j, x_k, x_l)$ 　 $4! = 24$ 要素

表現 $1_1, 1_2, \underline{2}, 3_1, 3_2$

⟷

A_4対称性：4次の交代群

表現 $1, 1', 1'', 3_S, 3_A$ 　 12 要素

掛け算測

$$3_1 \times 3_1 = 1_1 + 2 + 3_1 + 3_2$$
$$3_2 \times 3_2 = 1_1 + 2 + 3_1 + 3_2$$
$$3_1 \times 3_2 = 1_2 + 2 + 3_1 + 3_2$$
$$2 \times 2 = 1_1 + 1_2 + 2$$
$$2 \times 3_1 = 3_1 + 3_2$$
$$2 \times 3_2 = 3_1 + 3_2$$
$$3_1 \times 1_2 = 3_2$$
$$3_2 \times 1_2 = 3_1$$
$$2 \times 1_2 = 2$$

$$\begin{pmatrix}\alpha_1\\ \alpha_2\end{pmatrix}_2 \otimes \begin{pmatrix}\beta_1\\ \beta_2\end{pmatrix}_2 = (\alpha_1\beta_1 + \alpha_2\beta_2)_{1_1} \oplus (-\alpha_1\beta_2 + \alpha_2\beta_1)_{1_2} \oplus \begin{pmatrix}\alpha_1\beta_2 + \alpha_2\beta_1\\ \alpha_1\beta_1 - \alpha_2\beta_2\end{pmatrix}_2$$

$$\begin{pmatrix}\alpha_1\\ \alpha_2\\ \alpha_3\end{pmatrix}_{3_1} \otimes \begin{pmatrix}\beta_1\\ \beta_2\\ \beta_3\end{pmatrix}_{3_1} = (\alpha_1\beta_1 + \alpha_2\beta_2 + \alpha_3\beta_3)_{1_1} \oplus \begin{pmatrix}\frac{1}{\sqrt{2}}(\alpha_2\beta_2 - \alpha_3\beta_3)\\ \frac{1}{\sqrt{6}}(-2\alpha_1\beta_1 + \alpha_2\beta_2 + \alpha_3\beta_3)\end{pmatrix}_2$$

$$\oplus \begin{pmatrix}\alpha_3\beta_2 + \alpha_2\beta_3\\ \alpha_1\beta_3 + \alpha_3\beta_1\\ \alpha_2\beta_1 + \alpha_1\beta_2\end{pmatrix}_{3_1} \oplus \begin{pmatrix}\alpha_3\beta_2 - \alpha_2\beta_3\\ \alpha_1\beta_3 - \alpha_3\beta_1\\ \alpha_2\beta_1 - \alpha_1\beta_2\end{pmatrix}_{3_2}$$

3. 3HDM

SM Higgs doubletを3つに拡張 (12個の 実scalar fields)

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}, \phi_3 = \begin{pmatrix} \phi_3^+ \\ \phi_3^0 \end{pmatrix}$$

一般的な3HDMのHiggs Potential

$$V = -\sum_{i,j=1}^{3} m_{ij}^2 (\phi_i^\dagger \phi_j) + \frac{1}{2} \sum_{i,j,k,l=1}^{3} \lambda_{ijkl} (\phi_i^\dagger \phi_j)(\phi_k^\dagger \phi_l)$$

Potentialの最小条件

$$\left(\frac{\partial V}{\partial \phi_1}\right)_{\phi_1=\langle\phi_1\rangle,\phi_2=\langle\phi_2\rangle,\phi_3=\langle\phi_3\rangle} = 0$$

$$\left(\frac{\partial V}{\partial \phi_2}\right)_{\phi_1=\langle\phi_1\rangle,\phi_2=\langle\phi_2\rangle,\phi_3=\langle\phi_3\rangle} = 0$$

$$\left(\frac{\partial V}{\partial \phi_3}\right)_{\phi_1=\langle\phi_1\rangle,\phi_2=\langle\phi_2\rangle,\phi_3=\langle\phi_3\rangle} = 0$$

⇩ 自発的対称性の破れ

3つの自由度がWとZ bosonsに食われる

➡ ϕは9 (=12−3)つの 実scalar fieldsで表わされる

$$\phi_i = \begin{pmatrix} \rho_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\chi_i) \end{pmatrix}, i = 1,2,3$$

mass eigenstates ➡

(i) Three CP-even scalar fields
(ii) Two CP-odd scalar fields
(iii) Four charged scalar fields

4. Flavor模型

	$\bar{l}=(\bar{l_e},\bar{l_\mu},\bar{l_\tau})$	$l_R=(e_R,\mu_R)$	τ_R	ν_{eR}	$\nu_R=(\nu_{\mu R},\nu_{\tau R})$	$\phi=(\phi_1,\phi_2,\phi_3)$	X	Θ
$SU(2)_L$	2	1	1	1	1	2	1	1
S_4	3	2	1	1	2	3	2	1
$U(1)_{FN}$	0	+1	0	0	0	0	−1	−1

Lagrangian： $-L_Y = L_l + L_D + L_M + h.c.$

(1) 荷電レプトンの質量項： $L_l = \frac{y_{e\mu}}{\Lambda}\bar{l}\phi l_R\Theta + y_\tau\bar{l}\phi\tau_R + \frac{y_l}{\Lambda}\bar{l}\phi l_R X$

(2) Dirac neutrinoの質量項： $L_D = y_{De}\bar{l}\tilde{\phi}\nu_{eR} + y_{D\mu\tau}\bar{l}\tilde{\phi}\nu_R$

(3) 右巻きMajorana neutrinoの質量項： $L_M = \frac{1}{2}M_{eR}\bar{\nu}_{eR}^c\nu_{eR} + \frac{1}{2}M_{\mu\tau R}\bar{\nu}_R^c\nu_R$

➡ 荷電レプトンと左巻きMajorana Neutrinoの質量行列を求める

質量行列の計算

(1) 荷電レプトンの質量項

$$L_l = \frac{y_{e\mu}}{\Lambda}\bar{l}\phi l_R\Theta + y_\tau \bar{l}\phi\tau_R + \frac{y_l}{\Lambda}\bar{l}\phi l_R X$$

$$\frac{y_l}{\Lambda}\begin{pmatrix}\bar{l}_e\\ \bar{l}_\mu\\ \bar{l}_\tau\end{pmatrix}_3 \otimes \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}_3 \otimes \begin{pmatrix}e_R\\ \mu_R\end{pmatrix}_2 \Theta = \frac{y_{e\mu}}{\Lambda}\begin{pmatrix}\frac{1}{\sqrt{2}}(\bar{l}_\mu\phi_2 - \bar{l}_\tau\phi_3)\\ \frac{1}{\sqrt{6}}(-2\bar{l}_e\phi_1 + \bar{l}_\mu\phi_2 + \bar{l}_\tau\phi_3)\end{pmatrix}_2 \otimes \begin{pmatrix}e_R\\ \mu_R\end{pmatrix}_2 \Theta$$

2

$$= \frac{y_{e\mu}}{\Lambda}\frac{1}{\sqrt{2}}(\bar{l}_\mu\phi_2 - \bar{l}_\tau\phi_3)e_R\Theta + \frac{y_{e\mu}}{\Lambda}\frac{1}{\sqrt{6}}(-2\bar{l}_e\phi_1 + \bar{l}_\mu\phi_2 + \bar{l}_\tau\phi_3)\mu_R\Theta$$

$$<\Theta> = \Theta_0, <\phi> = (v_1, v_2, v_3)$$

$$= \frac{y_{e\mu}\Theta_0}{\Lambda}\frac{1}{\sqrt{2}}(\bar{\mu}_L v_2 - \bar{\tau}_L v_3)e_R + \frac{y_{e\mu}\Theta_0}{\Lambda}\frac{1}{\sqrt{6}}(-2\bar{e}_L v_1 + \bar{\mu}_L v_2 + \bar{\tau}_L v_3)\mu_R$$

$$\begin{pmatrix}\alpha_1\\ \alpha_2\end{pmatrix}_2 \otimes \begin{pmatrix}\beta_1\\ \beta_2\end{pmatrix}_2 = (\alpha_1\beta_1 + \alpha_2\beta_2)_1$$

質量行列の計算

（1）荷電レプトンの質量項

$$L_l = \frac{y_{e\mu}}{\Lambda}\bar{l}\phi l_R \Theta + y_\tau \bar{l}\phi\tau_R + \frac{y_l}{\Lambda}\bar{l}\phi l_R X$$

$$y_\tau \begin{pmatrix} \bar{l}_e \\ \bar{l}_\mu \\ \bar{l}_\tau \end{pmatrix}_3 \otimes \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}_3 \otimes \tau_R = y_\tau(\bar{l}_e\phi_1 + \bar{l}_\mu\phi_2 + \bar{l}_\tau\phi_3)\tau_R$$

1

$$<\phi>= (v_1, v_2, v_3)$$

$$= y_\tau(\bar{e}_L v_1 \tau_R + \bar{\mu}_L v_2 \tau_R + \bar{\tau}_L v_3 \tau_R)$$

1項目と2項目からの
荷電レプトンの質量行列

$$M_{l1} = \begin{pmatrix} 0 & -\frac{2y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_1 & y_\tau v_1 \\ \frac{y_{e\mu}\Theta_0}{\sqrt{2}\Lambda}v_2 & \frac{y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_2 & y_\tau v_2 \\ -\frac{y_{e\mu}\Theta_0}{\sqrt{2}\Lambda}v_3 & \frac{y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_3 & y_\tau v_3 \end{pmatrix}_{LR}$$

質量行列の計算

(1) 荷電レプトンの質量項

$$L_l = \frac{y_{e\mu}}{\Lambda}\bar{l}\phi l_R \Theta + y_\tau \bar{l}\phi\tau_R + \frac{y_l}{\Lambda}\bar{l}\phi l_R X$$

$$\frac{y_l}{\Lambda}\begin{pmatrix}\bar{l}_e\\ \bar{l}_\mu\\ \bar{l}_\tau\end{pmatrix}_3 \otimes \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}_3 \otimes \begin{pmatrix}e_R\\ \mu_R\end{pmatrix}_2 \otimes \begin{pmatrix}X_1\\ X_2\end{pmatrix}_2$$

1,2　1,2

$$= \frac{y_{l1}}{\Lambda}(\bar{l}_e\phi_1 + \bar{l}_\mu\phi_2 + \bar{l}_\tau\phi_3)_1 \otimes (e_R X_1 + \mu_R X_2)_1 + \frac{y_{l2}}{\Lambda}\begin{pmatrix}\frac{1}{\sqrt{2}}(\bar{l}_\mu\phi_2 - \bar{l}_\tau\phi_3)\\ \frac{1}{\sqrt{6}}(-2\bar{l}_e\phi_1 + \bar{l}_\mu\phi_2 + \bar{l}_\tau\phi_3)\end{pmatrix}_2 \otimes \begin{pmatrix}e_R X_2 + \mu_R X_1\\ e_R X_1 - \mu_R X_2\end{pmatrix}_2$$

$$= \frac{y_{l1}}{\Lambda}(\bar{l}_e\phi_1 e_R X_1 + \bar{l}_e\phi_1\mu_R X_2 + \bar{l}_\mu\phi_2 e_R X_1 + \bar{l}_\mu\phi_2\mu_R X_2 + \bar{l}_\tau\phi_3 e_R X_1 + \bar{l}_\tau\phi_3\mu_R X_2)$$
$$+ \frac{y_{l2}}{\Lambda}\left[\frac{1}{\sqrt{2}}(\bar{l}_\mu\phi_2 e_R X_2 + \bar{l}_\mu\phi_2\mu_R X_1 - \bar{l}_\tau\phi_3 e_R X_2 - \bar{l}_\tau\phi_3\mu_R X_1)\right.$$
$$\left. + \frac{1}{\sqrt{6}}(-2\bar{l}_e\phi_1 e_R X_1 + 2\bar{l}_e\phi_1\mu_R X_2 + \bar{l}_\mu\phi_2 e_R X_1 - \bar{l}_\mu\phi_2\mu_R X_2 + \bar{l}_\tau\phi_3 e_R X_1 - \bar{l}_\tau\phi_3\mu_R X_2)\right]$$

$$\begin{pmatrix}\alpha_1\\ \alpha_2\\ \alpha_3\end{pmatrix}_3 \otimes \begin{pmatrix}\beta_1\\ \beta_2\\ \beta_3\end{pmatrix}_3 = \begin{pmatrix}\frac{1}{\sqrt{2}}(\alpha_2\beta_2 - \alpha_3\beta_3)\\ \frac{1}{\sqrt{6}}(-2\alpha_1\beta_1 + \alpha_2\beta_2 + \alpha_3\beta_3)\end{pmatrix}_2$$

$$\begin{pmatrix}\alpha_1\\ \alpha_2\end{pmatrix}_2 \otimes \begin{pmatrix}\beta_1\\ \beta_2\end{pmatrix}_2 = (\alpha_1\beta_1 + \alpha_2\beta_2)_1 \oplus \begin{pmatrix}\alpha_1\beta_2 + \alpha_2\beta_1\\ \alpha_1\beta_1 - \alpha_2\beta_2\end{pmatrix}_2$$

質量行列の計算

(1) 荷電レプトンの質量項

$$L_l = \frac{y_{e\mu}}{\Lambda}\bar{l}\phi l_R\Theta + y_\tau \bar{l}\phi\tau_R + \frac{y_l}{\Lambda}\bar{l}\phi l_R X$$

$$<\phi>= (v_1, v_2, v_3), <X> = (\mathrm{X}_1, 0)$$

3つ目の項からの荷電レプトンの質量行列

$$M_{l2} = \begin{pmatrix} \left(\frac{y_{l1}}{\Lambda} - \frac{2y_{l2}}{\sqrt{6}\Lambda}\right)v_1\mathrm{X}_1 & 0 & 0 \\ \left(\frac{y_{l1}}{\Lambda} + \frac{y_{l2}}{\sqrt{6}\Lambda}\right)v_2\mathrm{X}_1 & \frac{y_{l2}}{\sqrt{2}\Lambda}v_2\mathrm{X}_1 & 0 \\ \left(\frac{y_{l1}}{\Lambda} - \frac{y_{l2}}{\sqrt{6}\Lambda}\right)v_3\mathrm{X}_1 & -\frac{y_{l2}}{\sqrt{2}\Lambda}v_3\mathrm{X}_1 & 0 \end{pmatrix}_{LR}$$

荷電レプトンの質量行列

$$M_l = M_{l1} + M_{l2} = \begin{pmatrix} 0 & -\frac{2y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_1 & y_\tau v_1 \\ \frac{y_{e\mu}\Theta_0}{\sqrt{2}\Lambda}v_2 & \frac{y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_2 & y_\tau v_2 \\ -\frac{y_{e\mu}\Theta_0}{\sqrt{2}\Lambda}v_3 & \frac{y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_3 & y_\tau v_3 \end{pmatrix}_{LR} + \begin{pmatrix} \left(\frac{y_{l1}}{\Lambda} - \frac{2y_{l2}}{\sqrt{6}\Lambda}\right)v_1\mathrm{X}_1 & 0 & 0 \\ \left(\frac{y_{l1}}{\Lambda} + \frac{y_{l2}}{\sqrt{6}\Lambda}\right)v_2\mathrm{X}_1 & \frac{y_{l2}}{\sqrt{2}\Lambda}v_2\mathrm{X}_1 & 0 \\ \left(\frac{y_{l1}}{\Lambda} - \frac{y_{l2}}{\sqrt{6}\Lambda}\right)v_3\mathrm{X}_1 & -\frac{y_{l2}}{\sqrt{2}\Lambda}v_3\mathrm{X}_1 & 0 \end{pmatrix}_{LR}$$

質量行列の計算

(2) Dirac neutrinoの質量項

$$L_D = y_{De}\bar{l}\tilde{\phi}\nu_{eR} + y_{D\mu\tau}\bar{l}\tilde{\phi}\nu_R$$

Dirac neutrinoの質量行列

$$M_D = \begin{pmatrix} y_{De}v_1 & 0 & -2/\sqrt{6}y_{D\mu\tau}v_1 \\ y_{De}v_2 & 1/\sqrt{2}y_{D\mu\tau}v_2 & 1/\sqrt{6}y_{D\mu\tau}v_2 \\ y_{De}v_3 & -1/\sqrt{2}y_{D\mu\tau}v_3 & 1/\sqrt{6}y_{D\mu\tau}v_3 \end{pmatrix}_{LR}$$

(3) 右巻きのMajorana neutrinoの質量項

$$L_M = \frac{1}{2}M_{eR}\bar{\nu}_{eR}^c\nu_{eR} + \frac{1}{2}M_{\mu\tau R}\bar{\nu}_R^c\nu_R$$

右巻きのMajorana neutrino の質量行列

$$M_R = \begin{pmatrix} M_{eR} & 0 & 0 \\ 0 & M_{\mu\tau R} & 0 \\ 0 & 0 & M_{\mu\tau R} \end{pmatrix}$$

type-I seesaw機構を用いて、左巻きのMajorana neutrinoの質量項 $m_\nu = -M_D M_R^{-1} M_D^T$

$$m_\nu = \begin{pmatrix} -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_1^2}{M_{eR}} - \frac{2e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_1^2}{3M_{\mu\tau R}} & -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_1v_2}{M_{eR}} + \frac{e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_1v_2}{3M_{\mu\tau R}} & -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_3v_1}{M_{eR}} + \frac{e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_3v_1}{3M_{\mu\tau R}} \\ -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_1v_2}{M_{eR}} + \frac{e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_1v_2}{3M_{\mu\tau R}} & -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_2^2}{M_{eR}} - \frac{2e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_2^2}{3M_{\mu\tau R}} & -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_2v_3}{M_{eR}} + \frac{e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_2v_3}{3M_{\mu\tau R}} \\ -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_3v_1}{M_{eR}} + \frac{e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_3v_1}{3M_{\mu\tau R}} & -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_2v_3}{M_{eR}} + \frac{e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_2v_3}{3M_{\mu\tau R}} & -\frac{e^{2i\phi_{y_{De}}}y_{De}^2v_3^2}{M_{eR}} - \frac{2e^{2i\phi_{y_{\mu\tau}}}y_{D\mu\tau}^2v_3^2}{3M_{\mu\tau R}} \end{pmatrix}$$

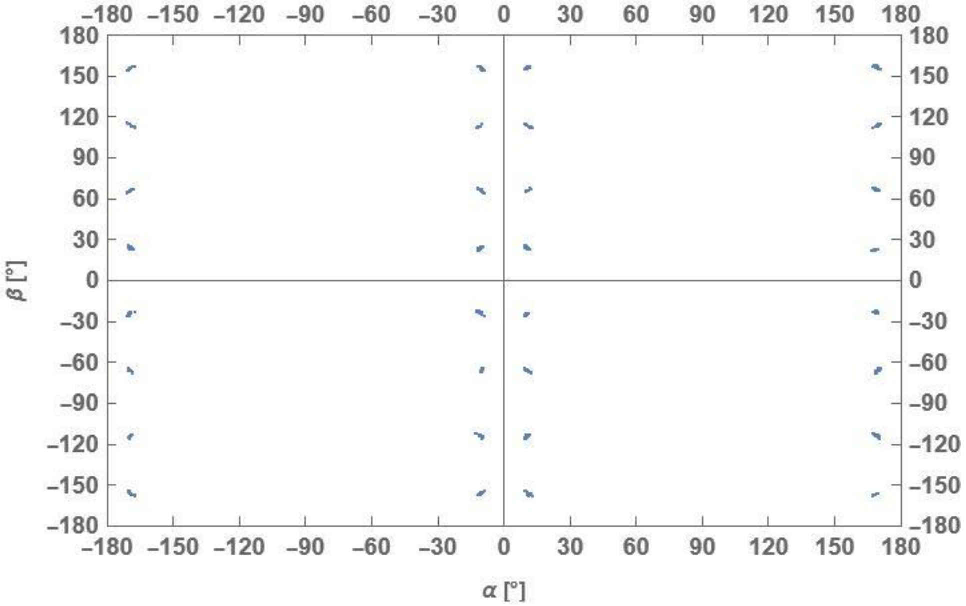
5. 数値解析

Satisfy $m_e, m_\mu, m_\tau, \Delta m_{21}^2, \Delta m_{31}^2, \sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}$

Parameter $\alpha, \beta, y_{e\mu}, y_\tau, y_{l1}, y_{l2}, X_1, m_1, y_{De}, y_{D\mu\tau}, \phi_{y_{De}}$

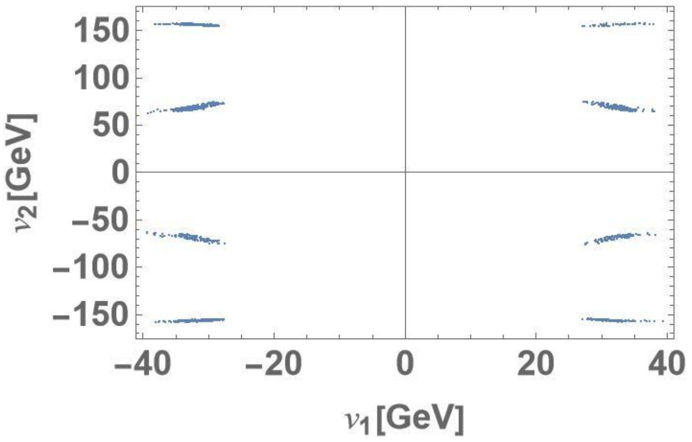
Prediction $\sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{CP}, m_{light}, m_1 + m_2 + m_3,$
m_{ee}, η_1, η_2

αとβの関係図

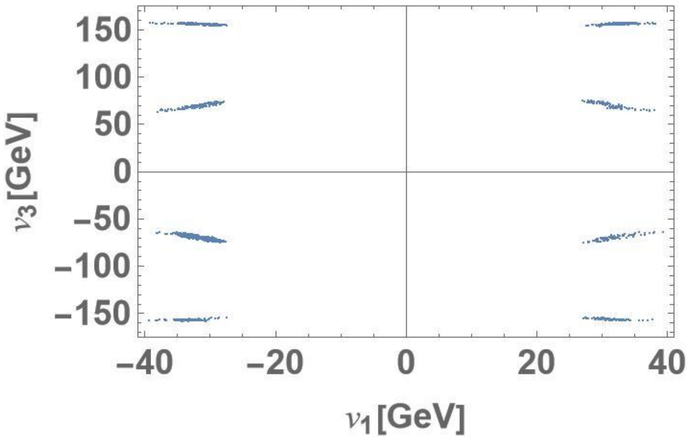


$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = \begin{pmatrix} v\sin\alpha \\ v\cos\alpha\sin\beta \\ v\cos\alpha\cos\beta \end{pmatrix}$$

v_1と v_2の関係図

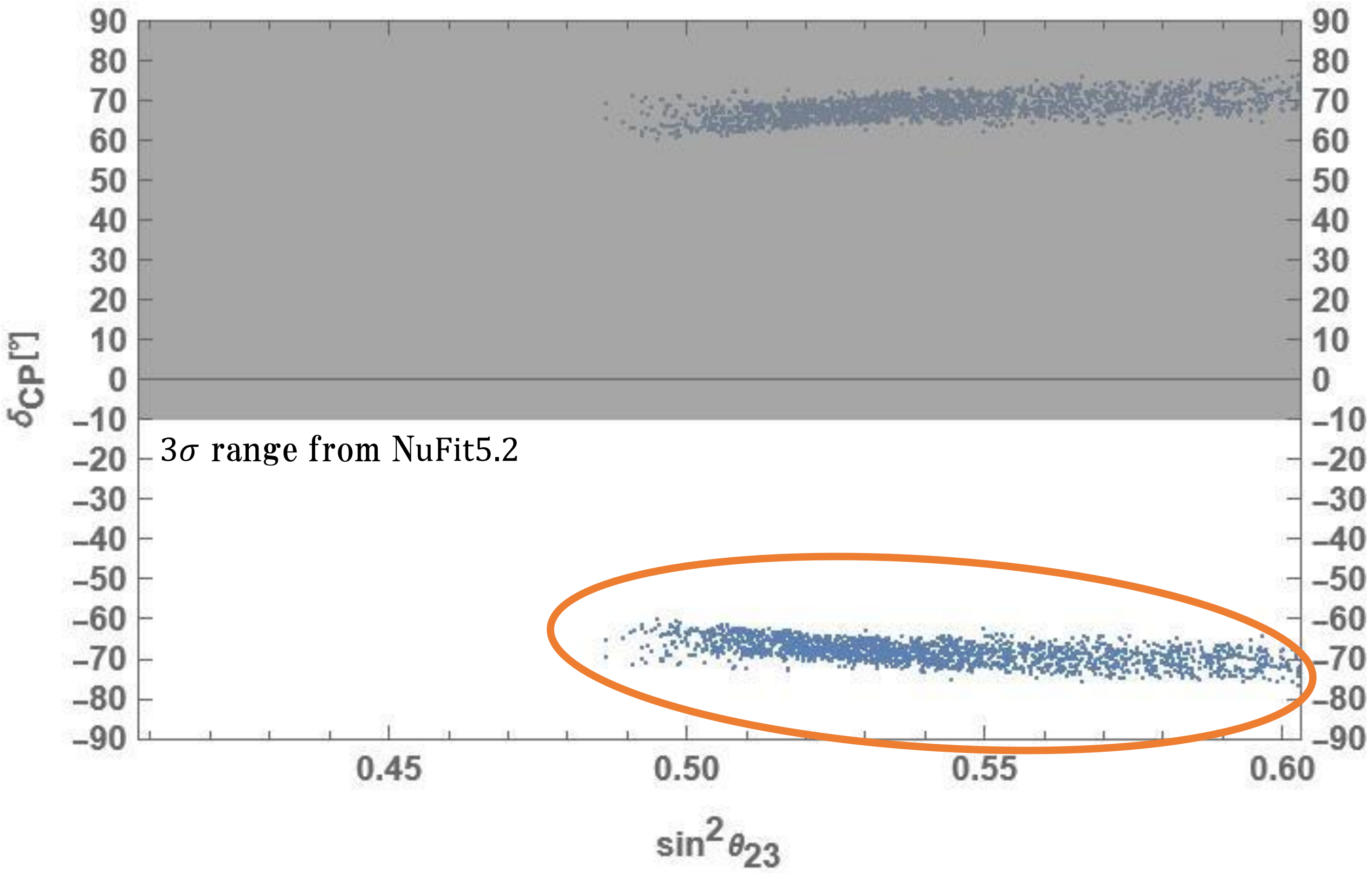


v_1と v_3の関係図



数値解析

δ_{CP} と $\sin^2\theta_{23}$ の予測



NuFIT 5.2

$0.408 \leq \sin^2\theta_{23} \leq 0.603$

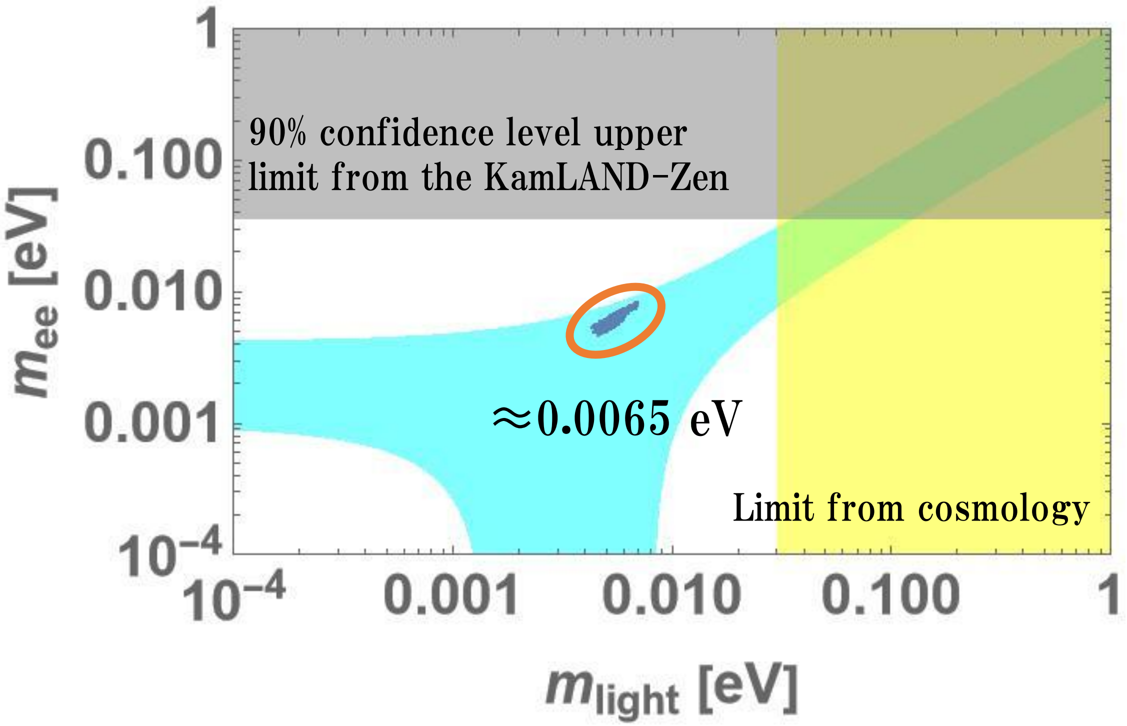
$0.488 \leq \sin^2\theta_{23} \leq 0.603$

$\delta_{CP} \approx -67.7°$

δ_{CP} に対して強い予言

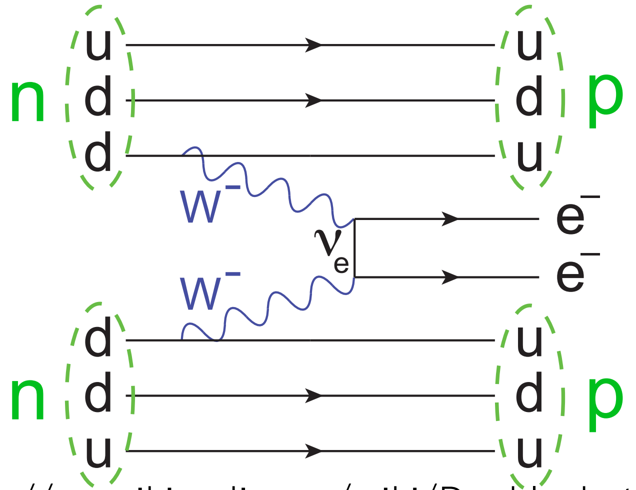
数値解析

Neutrinoの有効質量 m_{ee} と最も軽いneutrinoの質量 m_{light}の予測



比較的制限に近い場所に値が得られた

$0\nu\beta\beta$ decay



https://en.wikipedia.org/wiki/Double_beta_decay

Decay rate

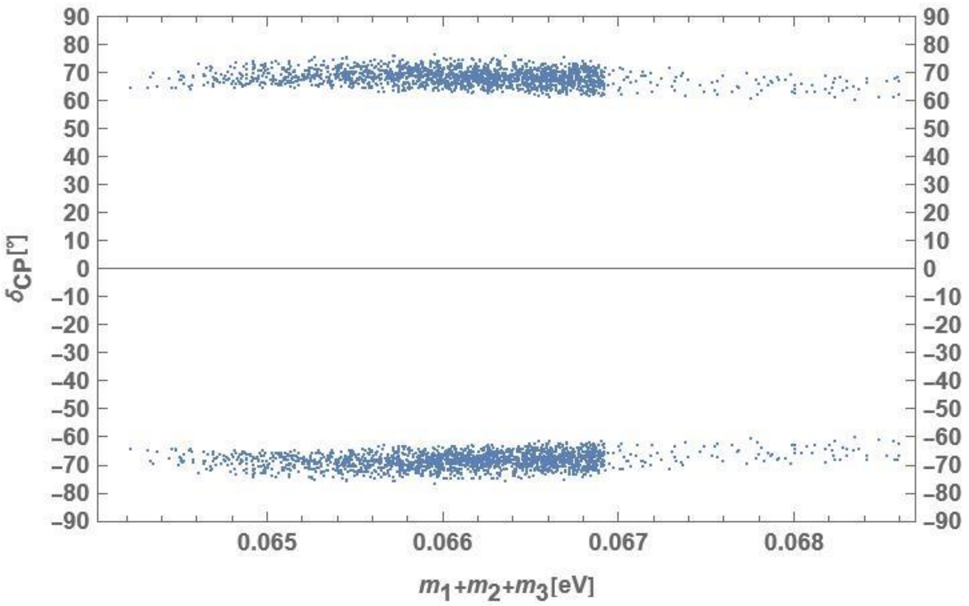
$$\Gamma \propto m_{ee}^2$$

Neutrinoの有効質量

$$m_{ee} = \left|m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2\right|$$

数値解析

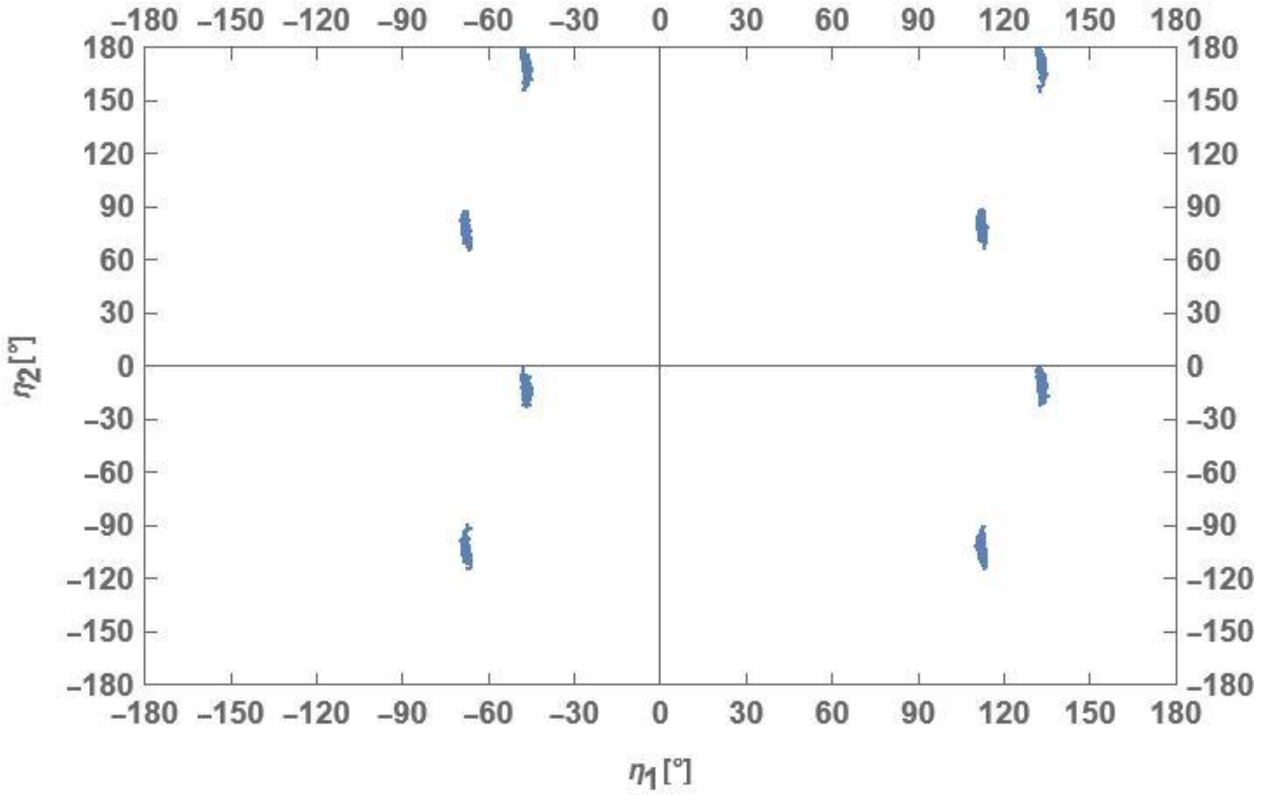
neutrinoの質量和 $m_1+m_2+m_3$ と δ_{CP}の予言



実験の制限(宇宙論)
(arXiv:1807.06209)
$m_1+m_2+m_3 \leq 0.12\mathrm{eV}$

数値解析

Majorana phases η_1, η_2 の予測



$$\eta_1 = \arg\left[\frac{U_{e1}U_{e3}^*}{\cos\theta_{12}\cos\theta_{13}\sin\theta_{13}e^{i\delta_{CP}}}\right], \quad \eta_2 = \arg\left[\frac{U_{e2}U_{e3}^*}{\sin\theta_{12}\cos\theta_{13}\sin\theta_{13}e^{i\delta_{CP}}}\right]$$

6. Potential解析

Higgs VEV $\quad <\phi> = (v_1, v_2, v_3)$

3HDM + S_4対称性

ϕ を S_4 triplet と考える $\quad \phi = (\phi_1, \phi_2, \phi_3)$

Higgs potential の計算 $\quad V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + c\phi^\dagger\phi X^\dagger X + k\phi^\dagger\phi\Theta^\dagger\Theta + (g\phi^\dagger\phi X^\dagger\Theta + h.c.)$

$$\phi^\dagger\phi = \begin{pmatrix}\phi_1^\dagger \\ \phi_2^\dagger \\ \phi_3^\dagger\end{pmatrix}_3 \otimes \begin{pmatrix}\phi_1 \\ \phi_2 \\ \phi_3\end{pmatrix}_3 = (\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3)_1 = |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2$$

Potential解析

Higgs potentialの計算　$V=-\mu^2\phi^\dagger\phi+\lambda(\phi^\dagger\phi)^2+c\phi^\dagger\phi X^\dagger X+k\phi^\dagger\phi\Theta^\dagger\Theta+(g\phi^\dagger\phi\Theta^\dagger X+h.c.)$

$$(\phi^\dagger\phi)^2=\begin{pmatrix}\phi_1^\dagger\\ \phi_2^\dagger\\ \phi_3^\dagger\end{pmatrix}_3\otimes\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}_3\otimes\begin{pmatrix}\phi_1^\dagger\\ \phi_2^\dagger\\ \phi_3^\dagger\end{pmatrix}_3\otimes\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}_3=(|\phi_1|^2+|\phi_2|^2+|\phi_3|^2)^2\oplus\begin{pmatrix}\frac{1}{\sqrt{2}}(\phi_2^\dagger\phi_2-\phi_3^\dagger\phi_3)\\ \frac{1}{\sqrt{6}}(-2\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3)\end{pmatrix}_2\otimes\begin{pmatrix}\frac{1}{\sqrt{2}}(\phi_2^\dagger\phi_2-\phi_3^\dagger\phi_3)\\ \frac{1}{\sqrt{6}}(-2\phi_1^\dagger\phi_1+\phi_2^\dagger\phi_2+\phi_3^\dagger\phi_3)\end{pmatrix}_2$$

$1,2,3,3'$　　$1,2,3,3'$

$$\oplus\begin{pmatrix}\phi_3^\dagger\phi_2+\phi_2^\dagger\phi_3\\ \phi_1^\dagger\phi_3+\phi_3^\dagger\phi_1\\ \phi_2^\dagger\phi_1+\phi_1^\dagger\phi_2\end{pmatrix}_3\otimes\begin{pmatrix}\phi_3^\dagger\phi_2+\phi_2^\dagger\phi_3\\ \phi_1^\dagger\phi_3+\phi_3^\dagger\phi_1\\ \phi_2^\dagger\phi_1+\phi_1^\dagger\phi_2\end{pmatrix}_3\oplus\begin{pmatrix}\phi_3^\dagger\phi_2-\phi_2^\dagger\phi_3\\ \phi_1^\dagger\phi_3-\phi_3^\dagger\phi_1\\ \phi_2^\dagger\phi_1-\phi_1^\dagger\phi_2\end{pmatrix}_{3'}\otimes\begin{pmatrix}\phi_3^\dagger\phi_2-\phi_2^\dagger\phi_3\\ \phi_1^\dagger\phi_3-\phi_3^\dagger\phi_1\\ \phi_2^\dagger\phi_1-\phi_1^\dagger\phi_2\end{pmatrix}_{3'}$$

$$\begin{aligned}=\;&(|\phi_1|^2+|\phi_2|^2+|\phi_3|^2)^2\\ &\oplus\frac{2}{3}(|\phi_1|^4+|\phi_2|^4+|\phi_3|^4-|\phi_1|^2|\phi_2|^2-|\phi_2|^2|\phi_3|^2-|\phi_3|^2|\phi_1|^2)\\ &\oplus\left[(\phi_1^\dagger\phi_2)^2+(\phi_2^\dagger\phi_3)^2+(\phi_3^\dagger\phi_1)^2+|\phi_1|^2|\phi_2|^2+|\phi_2|^2|\phi_3|^2+|\phi_3|^2|\phi_1|^2+h.c.\right]\\ &\oplus\left[(\phi_1^\dagger\phi_2)^2+(\phi_2^\dagger\phi_3)^2+(\phi_3^\dagger\phi_1)^2-|\phi_1|^2|\phi_2|^2-|\phi_2|^2|\phi_3|^2-|\phi_3|^2|\phi_1|^2+h.c.\right]\end{aligned}$$

Potential解析

Higgs potentialの計算 $V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + c\phi^\dagger\phi X^\dagger X + k\phi^\dagger\phi\Theta^\dagger\Theta + (g\phi^\dagger\phi\Theta^\dagger X + h.c.)$

$$\phi^\dagger\phi X^\dagger X = \begin{pmatrix}\phi_1^\dagger\\ \phi_2^\dagger\\ \phi_3^\dagger\end{pmatrix}_3 \otimes \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}_3 \otimes \begin{pmatrix}X_1^\dagger\\ X_2^\dagger\end{pmatrix}_2 \otimes \begin{pmatrix}X_1\\ X_2\end{pmatrix}_2 = (\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3)_1 \otimes (X_1^\dagger X_1 + X_2^\dagger X_2)_1 + \begin{pmatrix}\frac{1}{\sqrt{2}}(\phi_2^\dagger\phi_2 - \phi_3^\dagger\phi_3)\\ \frac{1}{\sqrt{6}}(-2\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3)\end{pmatrix}_2 \otimes \begin{pmatrix}X_1^\dagger X_2 + X_2^\dagger X_1\\ X_1^\dagger X_1 - X_2^\dagger X_2\end{pmatrix}_2$$

1,2 1,2

$$< X > = (X_1, 0)$$

$$= |X_1|^2(|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2) + \frac{|X_1|^2}{\sqrt{6}}(-2|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2)$$

$$\phi^\dagger\phi\Theta^\dagger\Theta = \begin{pmatrix}\phi_1^\dagger\\ \phi_2^\dagger\\ \phi_3^\dagger\end{pmatrix}_3 \otimes \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}_3 \Theta^\dagger\Theta = |\Theta_0|^2(|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2)$$

$$< \Theta > = \Theta_0$$

$$\phi^\dagger\phi\Theta^\dagger X = \begin{pmatrix}\phi_1^\dagger\\ \phi_2^\dagger\\ \phi_3^\dagger\end{pmatrix}_3 \otimes \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}_3 \otimes \begin{pmatrix}X_1\\ X_2\end{pmatrix}_2 \Theta^\dagger = \begin{pmatrix}\frac{1}{\sqrt{2}}(\phi_2^\dagger\phi_2 - \phi_3^\dagger\phi_3)\\ \frac{1}{\sqrt{6}}(-2\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2 + \phi_3^\dagger\phi_3)\end{pmatrix}_2 \otimes \begin{pmatrix}X_1\\ X_2\end{pmatrix}_2 \Theta^\dagger = \frac{\Theta_0^* X_1}{\sqrt{2}}(|\phi_2|^2 - |\phi_3|^2)$$

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$$< X > = (X_1, 0), < \Theta > = \Theta_0$$

真空構造

Potential

$$V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + c\phi^\dagger\phi X^\dagger X + k\phi^\dagger\phi\Theta^\dagger\Theta + (g\phi^\dagger\phi\Theta^\dagger X + h.c.)$$

$$= \frac{\Lambda_1}{2}(|\phi_1|^4 + |\phi_2|^4 + |\phi_3|^4) + \Lambda_2(|\phi_1|^2|\phi_2|^2 + |\phi_2|^2|\phi_3|^2 + |\phi_3|^2|\phi_1|^2)$$

$$+ \frac{\Lambda_3}{2}\left[(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_3)^2 + (\phi_3^\dagger\phi_1)^2 + h.c.\right]$$

$$+ \left(-\mu^2 + c_1 X_1^2 + \frac{2c_2 X_1^2}{\sqrt{6}}\right)|\phi_1|^2 + \left(-\mu^2 + c_1 X_1^2 + \frac{c_2 X_1^2}{\sqrt{6}} + \frac{g X_1 \Theta_0}{\sqrt{2}}\right)|\phi_2|^2 + \left(-\mu^2 + c_1 X_1^2 + \frac{c_2 X_1^2}{\sqrt{6}} - \frac{g X_1 \Theta_0}{\sqrt{2}}\right)|\phi_3|^2$$

Potentialの最小条件

$$\left(\frac{\partial V}{\partial \phi_i}\right)_{\phi_1=v_1,\phi_2=v_2,\phi_3=v_3} = 0, \quad i = 1,2,3$$

vacuum expectation values

$$v_1 = \pm\sqrt{\frac{\mu'^2}{\Lambda_1 + 2\Lambda'} - \frac{2\Lambda_1 c_2{}'}{(\Lambda_1 + 2\Lambda')(\Lambda_1 - \Lambda')}}$$

$$v_2 = \pm\sqrt{\frac{\mu'^2}{\Lambda_1 + 2\Lambda'} - \frac{\Lambda_1 - 2\Lambda'}{(\Lambda_1 + 2\Lambda')(\Lambda_1 - \Lambda')}c'_2 - \frac{g'}{\Lambda_1 - \Lambda'}}$$

$$v_3 = \pm\sqrt{\frac{\mu'^2}{\Lambda_1 + 2\Lambda'} - \frac{\Lambda_1 - 2\Lambda'}{(\Lambda_1 + 2\Lambda')(\Lambda_1 - \Lambda')}c'_2 + \frac{g'}{\Lambda_1 - \Lambda'}}$$

VEVを
v, α, β で書く

$$\langle\phi\rangle = \begin{pmatrix} v\sin\alpha \\ v\cos\alpha\sin\beta \\ v\cos\alpha\cos\beta \end{pmatrix}$$

v：Higgs VEV
α, β：free parameter

7. Summary

flavor symmetryとしてS_4対称性を用いた
Scalar field ϕ を S_4 tripletとした

3HDM と S_4対称性を用いたflavor模型を構築した
荷電レプトンとneutrinosの質量行列を計算した

荷電レプトンの質量行列

$$M_l = M_{l1} + M_{l2}$$

$$= \begin{pmatrix} 0 & -\frac{2y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_1 & y_\tau v_1 \\ \frac{y_{e\mu}\Theta_0}{\sqrt{2}\Lambda}v_2 & \frac{y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_2 & y_\tau v_2 \\ -\frac{y_{e\mu}\Theta_0}{\sqrt{2}\Lambda}v_3 & \frac{y_{e\mu}\Theta_0}{\sqrt{6}\Lambda}v_3 & y_\tau v_3 \end{pmatrix}_{LR} + \begin{pmatrix} \left(\frac{y_{l1}}{\Lambda} - \frac{2y_{l2}}{\sqrt{6}\Lambda}\right)v_1 X_1 & 0 & 0 \\ \left(\frac{y_{l1}}{\Lambda} + \frac{y_{l2}}{\sqrt{6}\Lambda}\right)v_2 X_1 & \frac{y_{l2}}{\sqrt{2}\Lambda}v_2 X_1 & 0 \\ \left(\frac{y_{l1}}{\Lambda} - \frac{y_{l2}}{\sqrt{6}\Lambda}\right)v_3 X_1 & -\frac{y_{l2}}{\sqrt{2}\Lambda}v_3 X_1 & 0 \end{pmatrix}_{LR}$$

neutrinoの質量行列

$$m_\nu = -M_D M_R^{-1} M_D^\dagger$$

$$M_D = \begin{pmatrix} y_{De}v_1 & 0 & -2/\sqrt{6}y_{D\mu\tau}v_1 \\ y_{De}v_2 & 1/\sqrt{2}y_{D\mu\tau}v_2 & 1/\sqrt{6}y_{D\mu\tau}v_2 \\ y_{De}v_3 & -1/\sqrt{2}y_{D\mu\tau}v_3 & 1/\sqrt{6}y_{D\mu\tau}v_3 \end{pmatrix}_{LR} \quad M_R = \begin{pmatrix} M_{eR} & 0 & 0 \\ 0 & M_{\mu\tau R} & 0 \\ 0 & 0 & M_{\mu\tau R} \end{pmatrix}$$

数値解析を行い、δ_{CP} , neutrinoの有効質量 m_{ee} , Majorana phases η_1, η_2.
δ_{CP} と m_{ee} ($m_{ee} \approx 0.0065$[eV])に対して強い予言が得られた
→比較的実験で確かめやすい場所に結果が得られた
最後にHiggs potentialの解析を行い、 VEVを $<\phi> = (v_1, v_2, v_3)$の形で得た