2018 Sptember 4

Majorana neutrino masses in gauge-Higgs unification

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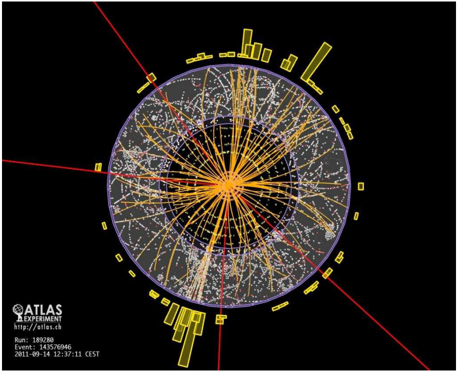
Prog.Theor.Exp.Phys.(2018)073B01 arXiv: 1804.04270 [hep-ph]

1. Introduction



$$M_H^{experiment} = 124.97 \pm 0.24 \text{ GeV} \quad \textit{(ATLAS+CMS, 2018)}$$

Standard Model (SM) : No principle to determine Higgs mass

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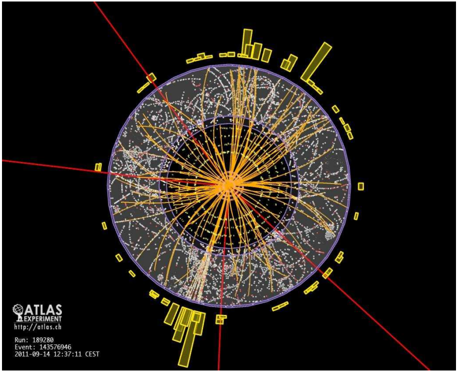

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Standard Model (SM) : No principle to determine Higgs mass

Gauge-Higgs unification (GHU) : can predict by gauge symmetry !

Gauge-Higgs unification (GHU)

Higher dimensional gauge theory $A_M = (A_\mu, A_y)$

$$A_y = H \qquad \textit{(Manton 1979, Hosotani 1983)}$$

Higgs mass can be predicted !

5D $M_H \simeq g\frac{1}{R} < \infty$ *(Hatanaka, Inami, Lim 1998)*

6D $M_H \simeq M_W, M_Z$ *(Antoniadis, Benakli, Quiros 2001)*

(Csaki, Grojean, Murayama 2003)

(Hasegawa, Lim, Maru 2016)

GHU is a nice candidate for BSM

Neutrino masses

Beta decay experiments, ... $\rightarrow \quad m_\nu < \mathcal{O}(eV)$ Very small
Neutrino oscillation experiments $\rightarrow (\Delta m^2_\odot, \Delta m^2_{atm}) \simeq (10^{-4}, 10^{-3})\mathrm{eV}^2$
Non-zero

Why so small and non-zero ?

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SM extension to explain the smallness

Seesaw Type I *(Yanagida 1979)*
(Gell-Mann, Ramond, Slansky 1979)
(Mohapatra, Senjanovic 1980)

Seesaw Type II, III, and Zee type,$\cdots$

Majorana type mass: Lepton number violation $\not{L}$

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Mechanism of small Majorana neutrino mass generation at GHU

2. Operator analysis

$$\text{GHU at higher dimension} \xrightarrow[\textit{Reduce}]{\textit{KK expansion}} \text{SM} + m_\nu \text{ at 4D}$$

4D space-time

$$\frac{1}{M}(\overline{L^c}\,\epsilon\,\Phi)(\Phi^t\,\epsilon\,L) \simeq \frac{1}{M}(L\Phi)^2 \quad \xrightarrow[\langle\Phi\rangle=\left(\begin{smallmatrix}0\\ v/\sqrt{2}\end{smallmatrix}\right)]{} \quad \frac{v^2}{M^2}\,\overline{(\nu_{\rm L})^c}\,(\nu_{\rm L})$$

Dimension 5 operator

Seesaw Type	New field ($SU(2)_L$-rep)	$\not{L}$- source
I	ν_R(1 rep)	$M_R\overline{(\nu_{\rm R})^c}\,(\nu_{\rm R})$
II	Δ(3 rep)	$\overline{(L)^c}\Delta L, \Phi^T\Delta\Phi$
III	N_R(3 rep)	$M_R\,Tr[\overline{(N_{\rm R})^c}\,(N_{\rm R})]$

2. Operator analysis

Embedded to GHU space − time $M^4 \times C^n$, gauge group G = SU(n)

$$L \subset \Psi \qquad\qquad \Phi \subset A_y$$

Trial

$$(L\Phi)^2 \subset (\Psi A_y)^2 = (\Psi \times \text{adjoint-rep})^2$$

If Ψ = G–fund rep $\rightarrow$ Gauge non-invariant

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Model 1 $(L\Phi)^2 \subset (\Psi A_y)^2 \subset Tr[(D_M\Psi_A)(D^M\Psi_A)]$

Ψ_A = G–adj rep

Model 2 $(L\Phi)^2 \subset (\langle s^\dagger \rangle L\Phi)^2 \subset (\Sigma^\dagger \Psi A_y)^2 \subset (\Sigma_F^\dagger D_M \Psi_F)^2$

Ψ_F = G–fund rep

s = SM-singlet $\subset \Sigma_F$ = G–fund rep

3. Model 1

SU(3) on 5D space-time $M^4 \times S^1/Z_2$
Lepton $\Psi = \Psi^a t^a$: SU(3)$-$8 rep

Action

$$S = \int d^4x \int_{-\pi R}^{\pi R} dy \ Tr \left[2\bar{\Psi} i\gamma^B D_B \Psi - M(\bar{\Psi}\gamma^5\Psi^c - \overline{\Psi^c}\gamma^5\Psi) \right]$$

with 4D charge conjugation $\psi^c = (\psi^a)^c \, t^a = \gamma^2 (\psi^a)^* \, t^a$

$$\not{L} - \text{source} \quad M \, Tr \left[\bar{\Psi}\gamma^5\Psi^c - \overline{\Psi^c}\gamma^5\Psi \right]$$

- At 5D, No Majorana spinor/mass
- Gauge invariance (similar to Type III at 4D)
- 5D Lorentz invariance $\rightarrow$ $\bar{\Psi}\gamma^5\Psi^c$

Better understanding: Symplectic Majorana spinor at 6D

3. Model 1

Gauge symmetry breaking

$$\mathrm{SU}(3) \xrightarrow[S^1/Z_2]{P=diag(1,1,-1)} \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \xrightarrow[\langle A_y \rangle = v \cdot t^6]{} \mathrm{U}(1)_{em}$$

Gauge zero modes

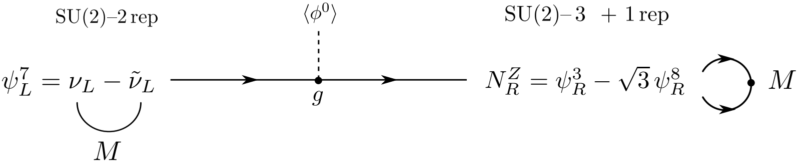
$$A_\mu^{(0)} = \left(\begin{array}{c|c|c} \gamma & W^+ & 0 \\ \hline W^- & -Z-\gamma & 0 \\ \hline 0 & 0 & Z-\gamma \end{array}\right) \quad A_y^{(0)} = \frac{1}{\sqrt{2}} \left(\begin{array}{c|c|c} 0 & 0 & \phi^+ \\ \hline 0 & 0 & \phi^0 \\ \hline \phi^- & \phi^{0*} & 0 \end{array}\right)$$

3. Model 1

Lepton zero modes

$$\psi_L^{(0)} = \frac{1}{\sqrt{2}} \left(\begin{array}{c|c|c} 0 & 0 & \tilde{e}^+ \\ \hline 0 & 0 & \tilde{\nu} \\ \hline e^- & \nu & 0 \end{array} \right)_L \qquad \psi_R^{(0)} = \left(\begin{array}{c|c|c} 2N^\gamma & \tilde{E}^+/\sqrt{2} & 0 \\ \hline E^-/\sqrt{2} & -N^z - N^\gamma & 0 \\ \hline 0 & 0 & N^z - N^\gamma \end{array} \right)_R$$

Yukawa int $Tr\left[\bar{\Psi}\gamma^y D_y \Psi\right] \supset g Tr\left[\overline{\psi_L^7} t^7 \left[\langle\phi^0\rangle t^6, N_R^Z(t^3 - \sqrt{3}t^8)\right]\right]$



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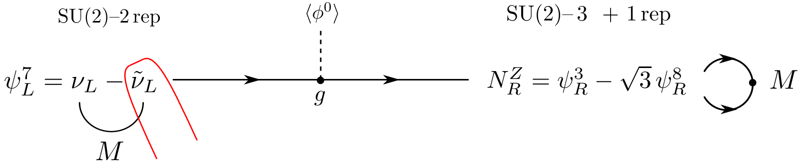

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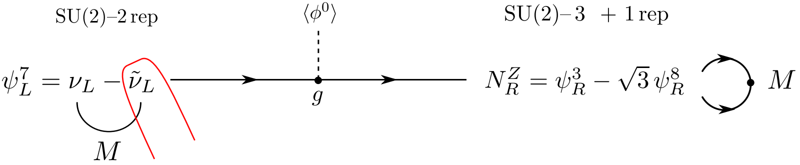
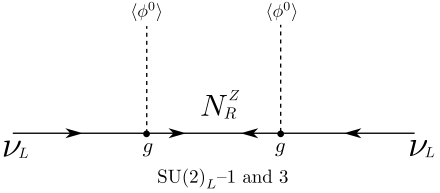


Brane mass term : $\delta(y)\, M_{brane}\, \overline{(e_b^+,\ \nu_b)_R} \begin{pmatrix} \tilde{e}^+ \\ \tilde{\nu} \end{pmatrix}_L$

$$M_{brane} \gg M \gg M_W$$

3. Model 1

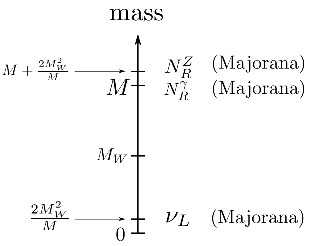
Diagram for left-handed Majorana neutrino mass



$\subset\ (L\,\Phi)^2\ \subset\ (\Psi\,A_y)^2$

Mixture of seesaw Type-I and III at 4D

Mass spectra



4. Model 2

$$(L\Phi)^2 \subset (\langle s^\dagger \rangle L\Phi)^2 \subset (\Sigma_F^\dagger A_y \Psi_F)^2$$

G=SU(3)-3 rep Electric charge (+2/3,-1/3,-1/3)

G=SU(4) on $M^4 \times S^1/Z_2$

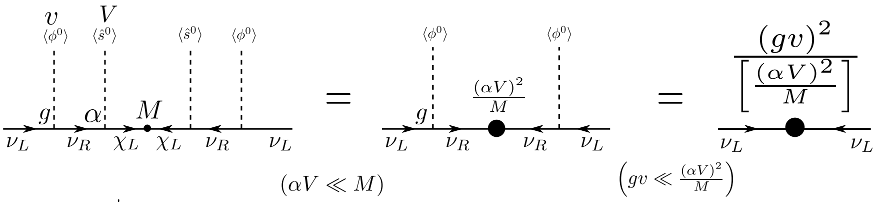
$$\text{4-rep} \quad \Psi = \begin{pmatrix} \nu_L \\ e_L^- \\ e_L^+ \\ \hline \nu_R \end{pmatrix} \quad \Sigma = \begin{pmatrix} \hat{\phi}^0 \\ \hat{\phi}^- \\ \hat{\phi}^+ \\ \hline \hat{s}^0 \end{pmatrix}, \qquad \text{Zero mode}$$

$$A_y = \left(\begin{array}{ccc|c} -\frac{2}{\sqrt{6}}a_Z & w^+ & w^{++} & \phi^0 \\ w^- & -\frac{1}{\sqrt{2}}a_\gamma + \frac{1}{\sqrt{6}}a_Z & \tilde{w}^+ & \phi^- \\ w^{--} & \tilde{w}^- & \frac{1}{\sqrt{2}}a_\gamma + \frac{1}{\sqrt{6}}a_Z & s^+ \\ \hline \phi^{0*} & \phi^+ & s^- & a_{Z'} \end{array}\right)$$

1 rep χ with $M\bar{\chi}\gamma^5\chi^c$ $\not{L}$- source, and Yukawa interaction $\alpha\bar{\Psi}\Sigma\chi$

4. Model 2

Left-handed Majorana neutrino mass



$(\Sigma_F^\dagger A_y \Psi_F)^2$

Dimension 7

Double seesaw mechanism

(Hosotani, Yamatsu 2017)

4. Summary

- Mechanism of small Majorana neutrino mass generation at GHU
- Operator analysis

  Model 1 $(L\Phi)^2 \subset (\Psi A_y)^2 \subset Tr[(D_M\Psi_A)(D^M\Psi_A)]$

  Model 2 $(L\Phi)^2 \subset (\langle s^\dagger \rangle L\Phi)^2 \subset (\Sigma_F^\dagger D_M \Psi_F)^2$

- Model 1

  SU(3)-adj (8 rep) Lepton

  $\not{L}$-source: Majorana mass term of Ψ_A

  Mixture of seesaw Type-I and III

- Model 2

  SU(4)-fund (4 rep) Lepton and scalar, singlet χ

  $\not{L}$-source: Majorana mass term of χ

  Double seesaw mechanism

- Future subject

  Model which can predict the neutrino masses and mixing angles

Backup Slides

Majorana mass term at 5D

$$M\, Tr\left[\bar{\Psi}\gamma^5\Psi^c - \overline{\Psi^c}\,\gamma^5\Psi\right] \quad \rightarrow \quad M\,\overline{N_R^0}\,(N_R^0)^c + h.c. \text{ at } 4D$$

SU(3) gauge invariance

$$Tr\left[\Psi^{a\,*}t^a\Psi^{b\,*}t^b\right] = \frac{1}{2}\Psi^{a\,*}\Psi^{a\,*}$$
$$\Psi^{a\,\prime} = (U_{adj})_{ab}\Psi^b \quad \text{with} \quad U_{adj} = e^{i\theta^a t^a_{adj}} = U^*_{adj}$$

5D Lorentz invariance

$$\overline{\Psi^a}\;\gamma^5(\Psi^a)^c$$
$$\Psi(x', y')^{a\,\prime} = \Lambda_{1/2}\Psi(x, y)^a \quad \text{with} \quad \Lambda_{1/2} = e^{i\omega_{MN}\frac{i}{4}[\gamma^M,\gamma^M]}$$
$$\gamma^2, \gamma^y \subset \mathcal{I}$$

Symplectic Majorana spinor at 6D

(Kugo, Townsend 1983, Mirabelli, Peskin 1998)

$M^4 \times T^2$, U(1) gauge symmetry

$$S = \int d^4x \int dy^1 dy^2 \;\; \bar{\psi}(x,y)(i\Gamma^N D_N - M)\psi(x,y)$$

Charge conjugation

$$A_N^c = -A_N$$
$$\psi^c = C\psi^*$$

6−dimensional chiral representation $\Gamma^7 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

Charge conjugation invariance $\rightarrow \;\; C = \Gamma^2 \Gamma^{y_1} \Gamma^7$

$\rightarrow \;\; (\psi^c)^c = -\psi$

$\rightarrow$ Majorana spinor impossible at 6D

Symplectic Majorana spinor at 6D

Naive dimensional reduction of y_2 : 6D $\rightarrow$ 5D
y_2–zero mode does not feel $\bar{\psi}\Gamma^{y2}\partial_{y2}\psi$

$$\rightarrow \;\; C_{sy} = \Gamma^2\Gamma^{y_1}\Gamma^{y_2}$$

$$\rightarrow \;\; (\psi^{c_{sy}})^{c_{sy}} = +\psi$$

$$\rightarrow \;\; \text{Symplectic Majorana spinor} \;\; \psi_{sy} = \psi + \psi^{c_{sy}}$$

$$(\psi_{sy})^{c_{sy}} = \psi_{sy}$$

For $\Gamma^7\psi_\pm = \pm\psi_\pm$,

$$\psi_{sy,+} = \psi_+ + (\psi_+)^{c_{sy}} = \begin{pmatrix} \psi_{4,+} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ e^{\imath\phi} i\gamma^2\gamma^5\psi_{4,+}^* \end{pmatrix}$$

Majorana mass term

$$M\,\overline{\psi_{sy,+}}\,\psi_{sy,+} = M\,[\overline{\psi_{4,+}}\,\gamma^5(\psi_{4,+})^{c_4} - \overline{(\psi_{4,+})^{c_4}}\,\gamma^5\psi_{4,+}]$$

with $(\psi_{4,+})^{c_4} = \gamma^2(\psi_{4,+})^*$

6D chiral representation

$$\Gamma^{\mu} = \begin{pmatrix} 0 & \gamma^{\mu} \\ \gamma^{\mu} & 0 \end{pmatrix} \quad \Gamma^{y_1} = \begin{pmatrix} 0 & i\gamma^5 \\ i\gamma^5 & 0 \end{pmatrix} \quad \Gamma^{y_2} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

where $\gamma^{\mu} = \begin{pmatrix} 0 & \sigma^{\mu} \\ \bar{\sigma}^{\mu} & 0 \end{pmatrix}$ (4D chiral rep)

$$\rightarrow \; \Gamma^7 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$