余剰次元を用いたTwo-Higgs-Doublet Model の構築

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Introduction

Standard Model (SM) is established as an effective theory below the electroweak scale

Beyond the SM phenomena

- Baryon asymmetry in the universe
- Existence of the dark matter
- Inflation
- Neutrino oscillation

The Higgs sector still has many mysteries

⋯ Guiding principle, Number of the Higgs bosons, Hierarchy problem, etc.

Higgs physics = Stepping stone to the new physics

Top-down approach: SUSY, gauge-Higgs, composite, ...

Bottom-up approach: Two-Higgs-Doublet Model, Effective Field Theory, ...

Two-Higgs-doublet model (2HDM)

- **2HDM : SM + additional Higgs doublet**

$$\phi_1 = \begin{pmatrix} w_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + iz_1) \end{pmatrix} \quad , \quad \phi_2 = \begin{pmatrix} w_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + iz_2) \end{pmatrix}$$

The EW VEV is shared by ϕ_1, ϕ_2 : $v_1^2 + v_2^2 = v^2 \simeq 246$ GeV , $\tan\beta = \frac{v_2}{v_1}$

- **Conventional assumptions**
  - softly broken Z_2 symmetry → Flavor changing processes are avoided
  - CP invariant Higgs potential → EDM can be avoided, …
  - Custodial symmetry → ρ parameter is consistent with experimental data

Earlier work： Realized by extending the electroweak symmetry

[T. Abe, Y Omura, *JHEP* 08 (2016) 021 arXiv:1606.06537]

Our work：Realized by extra dimensions without Z_2 symmetry

Z_2 symmetry

[Glashow, Sheldon L. and Weinberg, Steven, PRD15 (1977)]

Fermions couple to ϕ_1, ϕ_2 cause the flavor changing processes

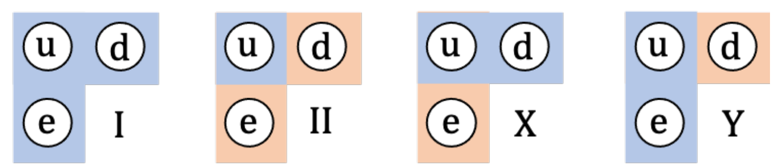
$$
\mathrm{y}^{ij}_{d\phi_1} \bar{q}^i_L \, \phi_1 \, d^j_R + \mathrm{y}^{ij}_{d\phi_2} \bar{q}^i_L \, \phi_2 \, d^j_R + \mathrm{h.c.}
$$

$$
\rightarrow \bar{d}^i_L \underline{m^{ij}} d^j_R + \bar{d}^i_L \left(\underline{h g^{ij}_h + H g^{ij}_H + A g^{ij}_A} \right) d^i_R
$$

Solutions : $y^{ij}_{d\phi_1} \propto y^{ij}_{d\phi_2}$ → aligned 2HDM

$y^{ij}_{d\phi_1}$ or $y^{ij}_{d\phi_2} = 0$ → Z_2 symmetry

4 types of the 2HDM



Our idea : $y^{ij}_{d\phi_k} \ll y^{ij}_{d\phi_l}$ **is realized by the small overlaps of the wavefunctions in extra dimensions**

Higgs potential

Higgs potential in the 2HDM ϕ_1, ϕ_2 have opposite Z_2 parity

$$V(\phi_1,\phi_2) = m_1^2\phi_1^\dagger\phi_1 + m_2^2\phi_2^\dagger\phi_2 - \underline{\left(m_3^2\phi_1^\dagger\phi_2 + \text{h.c.}\right)}$$
$$+\frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)$$
$$+\left(\frac{1}{2}\lambda_5(\phi_1^\dagger\phi_2)^2 + \cancel{\lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2)} + \cancel{\lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2)} + \text{h.c.}\right)$$

Masses of the additional Higgs bosons $H, H^\pm, A$

$$m_{H^\pm}^2 = M^2 - \frac{v^2}{2}(\lambda_4+\lambda_5)\ ,\quad m_A^2 = M^2 - v^2\lambda_5\ ,\quad m_{H,h}^2 : \text{complex}$$

$$M^2 = \frac{m_3^2}{\sin\beta\cos\beta}$$ ⋯ Softly breaking scale of the Z_2 symmetry

Softly broken Z_2 symmetry → Extra dimensional physics

Field Localization by a kink

[N. Arkani-Hamed, M. Schmaltz, Phys.Rev.D, 61:033005, 2000]

Background kink

5D spacetime : (x_μ, y)

$$\mathcal{L}_S = \frac{1}{M_{x_5}}\left(\frac{1}{2}(\partial_M S)^2 - \frac{\lambda^2}{2}\left(S^2 - v^2\right)^2\right) \quad \therefore S(y) = v\tanh[\lambda v(y-l)] \simeq 2\mu^2(y-l)$$

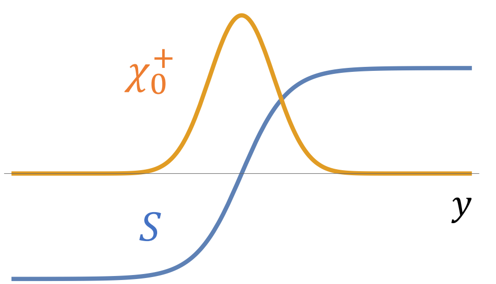
Fermions coupled to the kink are localized on the extra dimension

$$\mathcal{L}_\Psi = \bar\Psi\left[i\partial\!\!\!/_\mu + i\gamma^5\partial_y - S(y)\right]\Psi \quad , \quad \Psi = \sum_{n=0}^{\infty}\psi_R^n(x_\mu)\,\chi_n^+(x_5) + \sum_{n=0}^{\infty}\psi_L^n(x_\mu)\,\chi_n^-(x_5)$$

$$\begin{cases} (-\partial_y - S(y))\,\chi_n^+(y) = m_n\chi_n^-(y) \\ (+\partial_y - S(y))\,\chi_n^-(y) = m_n\chi_n^+(y) \end{cases} \qquad \begin{cases} i\gamma^\mu\partial_\mu\psi_R^n = m_n\psi_L^n \\ i\gamma^\mu\partial_\mu\psi_L^n = m_n\psi_R^n \end{cases}$$

$$\Rightarrow \left(-\partial_y^2 + 4\mu^4(y-l)^2 \mp 2\mu^2\right)\chi_n^\pm(y) = m_n^{\pm 2}\chi_n^\pm(y)$$

Massless chiral mode : $\chi_0^+(y) = \left(\frac{2\mu^2}{\pi}\right)^{1/4} \mathrm{e}^{-\mu^2(y-l)^2}$



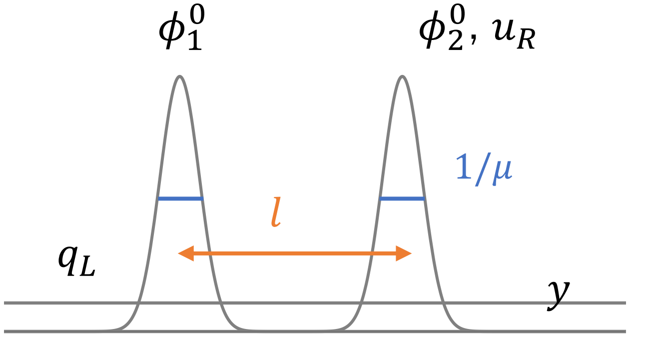
Higgs couplings in the 5D case

Zero-mode wavefunctions

$\phi_1^0, \phi_2^0, u_R^0$: localized on the y coordinate

↳ ϕ_1^0 and ϕ_2^0 are separated

q_L^0 : Flat wavefunction in the extra dimension



Configuration on the extra dimension

Effect on the Yukawa couplings

- $$y_{u\phi_1^0} = y'_{u\phi_1^0}\left(\frac{2\mu^2}{\pi}\right)^{\frac{1}{2}}\int dx_5\ \mathrm{e}^{-\mu^2(x_5-l)^2}\mathrm{e}^{-\mu^2x_5^2} = y'_{u\phi_1^0}\exp\left(-\frac{1}{2}\mu^2l^2\right)$$
- $$y_{u\phi_2^0} = y'_{u\phi_2^0}\left(\frac{2\mu^2}{\pi}\right)^{\frac{1}{2}}\int dx_5\ \mathrm{e}^{-\mu^2x_5^2}\mathrm{e}^{-\mu^2x_5^2} = y'_{u\phi_2^0}$$

$$\frac{y_{u\phi_1^0}}{y_{u\phi_2^0}} = \frac{y'_{u\phi_1^0}}{y'_{u\phi_2^0}}\exp\left(-\frac{1}{2}\mu^2l^2\right) \simeq 10^{-6} : (\mu l = 5)$$

$1/\mu$: width of the wavefunction

l : distance of the wavefunctions

Higgs couplings in the 5D case

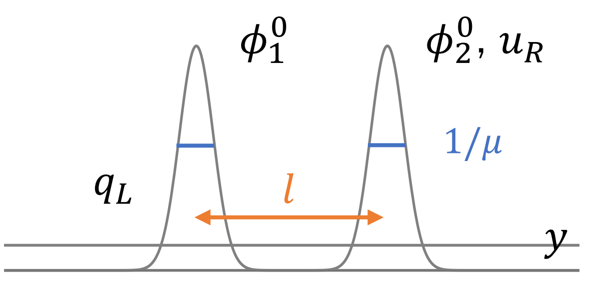
Effect on the Higgs potential

$$
\begin{aligned}
V(\phi_1^0,\phi_2^0) = {} & m_1^2 \phi_1^{0\dagger}\phi_1^0 + m_2^2 \phi_2^{0\dagger}\phi_2^0 - \left(m_3^2 \phi_1^{0\dagger}\phi_2^0 + \text{h.c.}\right) \\
& + \frac{1}{2}\lambda_1(\phi_1^{0\dagger}\phi_1^0)^2 + \frac{1}{2}\lambda_2(\phi_2^{0\dagger}\phi_2^0)^2 + \lambda_3(\phi_1^{0\dagger}\phi_1^0)(\phi_2^{0\dagger}\phi_2^0) + \lambda_4(\phi_1^{0\dagger}\phi_2^0)(\phi_2^{0\dagger}\phi_1^0) \\
& + \left(\frac{1}{2}\lambda_5(\phi_1^{0\dagger}\phi_2^0)^2 + \lambda_6(\phi_1^{0\dagger}\phi_1^0)(\phi_1^{0\dagger}\phi_2^0) + \lambda_7(\phi_2^{0\dagger}\phi_2^0)(\phi_1^{0\dagger}\phi_2^0) + \text{h.c.}\right)
\end{aligned}
$$

Couplings in the Higgs potential are exponentially suppressed

$$
m_3^2 = M_3^2 \sqrt{\frac{2\mu^2}{\pi}} \int dx_5 \; e^{-\mu^2(y-l)^2} e^{-\mu^2 y^2} = M_3^2 \, e^{-\frac{1}{2}\mu^2 l^2}
$$

$$
\lambda_3 = \lambda_3' \frac{2\mu^2}{\pi} \int dx_5 \; e^{-2\mu^2(y-l)^2} e^{-2\mu^2 y^2} = \lambda_3' \, e^{-\mu^2 l^2}
$$



Configuration on the extra space

Additional Higgs bosons are too light ⇨ Go to 6 dimensions !!

Field Localization (6D)

6D Fermions are also localized by same method

$$\mathcal{L}_\Psi = \bar{\Psi}\left(i\Gamma^M \partial_M - y_1 S_1(y) - M\right)\Psi$$ ← 8-component spinor

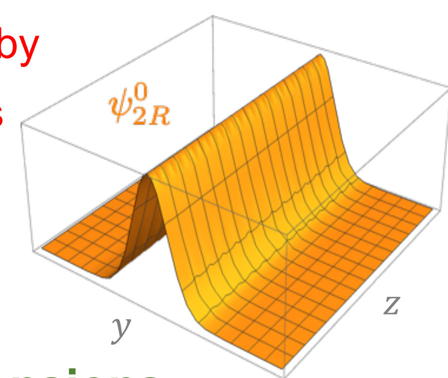
Boundary conditions : $\left(i\Psi^\dagger \Gamma^0 \Gamma^5 \delta\Psi + \text{h.c.}\right)_{y=\pm L_y} = 0$, $\left(i\Psi^\dagger \Gamma^0 \Gamma^6 \delta\Psi + \text{h.c.}\right)_{z=\pm L_z} = 0$

Only one massless chiral spinor appears

Ψ is decomposed into 4×2-component chiral spinors : $\Psi_{1R},\ \Psi_{1L},\ \Psi_{2R},\ \Psi_{2L}$

- x_μ : Free-field equation
- y : Equation with a kink
- z : Free-field equation

Ψ_R^0 only has a chiral zero-mode by the suitable boundary conditions



$$\psi_{2R}^0 : \frac{1}{\sqrt{2L_z}}\left(\frac{2\mu^2}{\pi}\right)^{1/4} \mathrm{e}^{-\mu^2 (y-l_\Psi)^2} \quad \text{where} \quad l_\Psi = \frac{M}{2\mu^2}$$

6D scalars are also localized as a band on extra dimensions

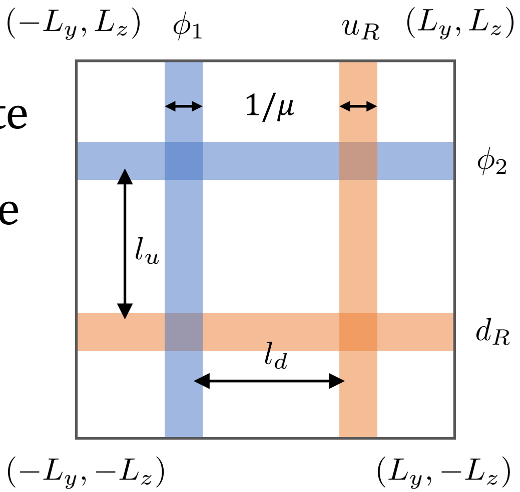
Higgs couplings in the 6D case

Zero-mode wavefunctions

- ϕ_1^0, u_R^0 : couple to $S_1(y) \rightarrow$ Localized on y coordinate
- ϕ_2^0, d_R^0 : couple to $S_2(z) \rightarrow$ Localized on z coordinate
- q_L^0: Flat wavefunction in the extra dimensions

$1/\mu$: width of the wavefunction

L_y, L_z : sizes of the extra dimensions



Yukawa couplings

Small overlaps of the wavefunctions → exponential suppression

$$y_{u\phi_1^0} = y'_{u\phi_1^0}\,(\epsilon\mu)^2\left(\frac{2\mu^2}{\pi}\right)^{\frac{1}{2}}\int dy\ \mathrm{e}^{-\mu^2(y-l_u)^2}\mathrm{e}^{-\mu^2 y^2}\int_{-1/2\epsilon\mu}^{+1/2\epsilon\mu} dz = y'_{u\phi_1^0}(\epsilon\mu)\,\exp\left(-\frac{\mu^2 l_y^2}{2}\right)$$

$$y_{u\phi_2^0} = y'_{u\phi_2^0}\,(\epsilon\mu)^2\left(\frac{2\mu^2}{\pi}\right)^{\frac{1}{2}}\int dy\ \mathrm{e}^{-\mu^2(y-l_u)^2}\int dz\ \mathrm{e}^{-\mu^2 z^2} = y'_{u\phi_2^0}\sqrt{2\pi\mu^2}\,\epsilon^2$$

Higgs couplings in the 6D case

Z_2 parity assignment

	ϕ_1	ϕ_2	q_L	l_L	u_R	d_R	e_R
Type-I	+	−	+	+	−	−	−
Type-II	+	−	+	+	−	+	+
Type-X	+	−	+	+	−	−	+
Type-Y	+	−	+	+	−	+	−

Kink coupling assignment

	ϕ_1^0	ϕ_2^0	q_L^0	l_L^0	u_R^0	d_R^0	e_R^0
Type-I	S_1	S_2			S_1	S_1	S_1
Type-II	S_1	S_2			S_1	S_2	S_2
Type-X	S_1	S_2			S_1	S_1	S_2
Type-Y	S_1	S_2			S_1	S_2	S_1

Wavefunctions of ϕ_1^0 and ϕ_2^0 are overlapped

→ Couplings in the Higgs potential are not exponentially suppressed

$$m_3^2 = M_3^2(\epsilon\mu)\sqrt{\frac{2\mu^2}{\pi}}\int dy\ \mathrm{e}^{-\mu^2 y^2}\int dz\ \mathrm{e}^{-\mu^2 z^2} = \sqrt{2\pi}\epsilon M_3^2$$

$$\lambda_j = \lambda'_j\frac{2\epsilon^2\mu^4}{\pi}\int dy\ \mathrm{e}^{-2\mu^2 y^2}\int dz\ \mathrm{e}^{-2\mu^2 z^2} = \lambda'_j(\epsilon\mu)^2 \quad (j = 3, 4, 5)$$

No Z_2 symmetry
→ general Higgs potential
with λ_6 and λ_7 terms

$$\lambda_6 = \lambda'_6\frac{2\epsilon^2\mu^4}{\pi}\int dy\ \mathrm{e}^{-3\mu^2 y^2}\int dz\ \mathrm{e}^{-\mu^2 z^2} = \frac{2}{\sqrt{3}}\lambda'_6(\epsilon\mu)^2 \quad , \quad \lambda_7 = \frac{2}{\sqrt{3}}\lambda'_7(\epsilon\mu)^2$$

Summary

- We discuss how to reproduce the viable Higgs couplings in the 2HDM without imposing the Z_2 symmetry.

- By localizing the right-handed fermions and Higgs doublets on the extra dimensions using the kink, we can avoid the dangerous flavor changing processes.

- In the 6D case, 4 types of the 2HDM is classified by the kink coupling assignment. In contrast to the 2HDM with Z_2 symmetry, the λ_6 , λ_7 terms are also allowed in the Higgs potential.

Back up

6D gamma matrix, spinor decomposition

6D gamma matrix

$$\Gamma^0 = \gamma^0 \otimes \sigma^1 \ , \ \Gamma^i = \gamma^i \otimes \sigma^1 \ (i = 1, 2, 3) \ , \ \Gamma^5 = i\gamma^5 \otimes \sigma^1 \ , \ \Gamma^6 = iI_4 \otimes \sigma^2$$

6D chiral operators $P_\pm = \frac{1 \pm \Gamma^7}{2} \ ; \ \Gamma^7 = \Gamma^0\Gamma^1\Gamma^2\Gamma^3\Gamma^4\Gamma^5\Gamma^6$

4D chiral operators $P_{L/R} = \frac{1 \pm \Gamma_{L/R}}{2} \ ; \ \Gamma_{L/R} = \gamma^5 \otimes I_2$

Chiral decomposition of the 8-component spinor

The above operators are commutable since $[\Gamma^7, \Gamma_{R/L}] = 0$

$$P_{R/L} P_\pm \Psi = P_\pm P_{R/L} \Psi = \begin{pmatrix} \Psi_{L-} \\ 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ \Psi_{R-} \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ \Psi_{L+} \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ 0 \\ \Psi_{R+} \end{pmatrix}$$

6D Dirac equation with kink

6D Dirac equation with a kink is decomposed as follow

$$\mathcal{L}_\Psi = \bar{\Psi}\left(i\Gamma^M\partial_M - y_1 S_1(y) - M\right)\Psi$$

$$\Rightarrow \begin{cases} -\left[\gamma^\mu\partial_\mu\gamma^\mu\partial_\mu - \partial_y\partial_y - \partial_z\partial_z + (M + y_1 S_1(y))^2\right]\Psi_+ - y_1\gamma^5(\partial_y S_1(y))\Psi_- = 0 \\ -\left[\gamma^\mu\partial_\mu\gamma^\mu\partial_\mu - \partial_y\partial_y - \partial_z\partial_z + (M + y_1 S_1(y))^2\right]\Psi_- - y_1\gamma^5(\partial_y S_1(y))\Psi_+ = 0 \end{cases}$$

Basis transformation enables the separation of variables

$$\Psi_{1,2} = (\Psi_+ \pm \Psi_-)/\sqrt{2}$$

x_μ , z direction : $\left(\partial^\mu\partial_\mu + m_y^2 + m_z^2\right)\psi = 0$, $\left(\partial_z^2 + m_z^2\right) g = 0$

y dir. $\begin{cases} (\partial_y^2 - (2\mu_\Psi^2(y - l_\Psi))^2 + 2\mu_\Psi^2 + m_y^2) f_{1R,2L}(y) = 0 & \therefore m_y^2 = 4\mu_\Psi^2(n_y + 1) \\ (\partial_y^2 - (2\mu_\Psi^2(y - l_\Psi))^2 - 2\mu_\Psi^2 + m_y^2) f_{1L,2R}(y) = 0 & \therefore m_y^2 = 4\mu_\Psi^2 n_y \end{cases}$

Higgs couplings in the 6D case

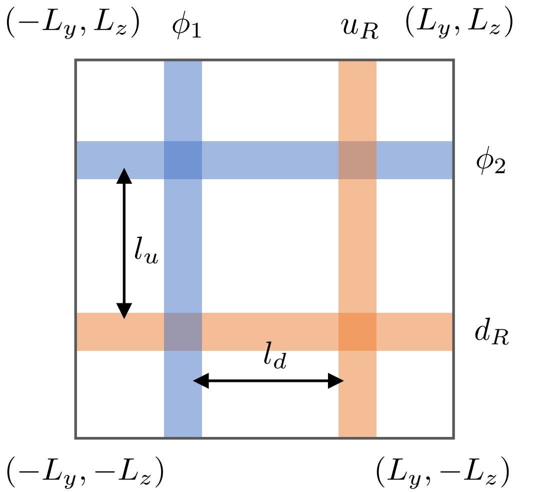
Zero-mode wavefunctions

$$\phi_1^0 : \ \sqrt{\epsilon\mu}\left(\frac{2\mu^2}{\pi}\right)^{1/4} \exp\left[-\mu^2 y^2\right] \ \text{ with } \ m_1^2 = M_1^2 + 2\mu^2$$

$$\phi_2^0 : \ \sqrt{\epsilon\mu}\left(\frac{2\mu^2}{\pi}\right)^{1/4} \exp\left[-\mu^2 z^2\right] \ \text{ with } \ m_2^2 = M_2^2 + 2\mu^2$$

$$u_R^0 : \ \sqrt{\epsilon\mu}\left(\frac{2\mu^2}{\pi}\right)^{1/4} \exp\left[-\mu^2 (y-l_u)^2\right] \ \text{ with } \ m_{u_R}^2 = 0$$

$$q_L^0 : \ \epsilon\mu \ \text{ with } \ m_{q_L}^2 = 0$$



Yukawa couplings with ϕ_1^0 and ϕ_2^0

About 10^{-6} for $\mu l = 5$

$$y_{u\phi_1^0} = y'_{u\phi_1^0}\,(\epsilon\mu)^2\left(\frac{2\mu^2}{\pi}\right)^{\frac{1}{2}}\int dy\ \mathrm{e}^{-\mu^2(y-l_u)^2}\mathrm{e}^{-\mu^2 y^2}\int_{-1/2\epsilon\mu}^{+1/2\epsilon\mu} dz = y'_{u\phi_1^0}(\epsilon\mu)\exp\left(-\frac{\mu^2 l_y^2}{2}\right)$$

$$y_{u\phi_1^0} = y'_{u\phi_1^0}\,(\epsilon\mu)^2\left(\frac{2\mu^2}{\pi}\right)^{\frac{1}{2}}\int dy\ \mathrm{e}^{-\mu^2(y-l_u)^2}\int dz\ \mathrm{e}^{-\mu^2 z^2} = y'_{u\phi_1^0}\sqrt{2\pi\mu^2}\epsilon^2$$