CP phase from Higgs's boundary condition

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Outline

We propose a new mechanism for generating CP phase via Higgs's twisted boundary condition in the context of higher dimensional gauge theories. With this mechanism, we construct a phenomenological model on S^1 with point interactions which can explain the origin of fermion generation, quark mass hierarchy and the structure of Cabibbo-Kobayashi-Maskawa matrix with CP phase.

• Mysteries of the Standard Model

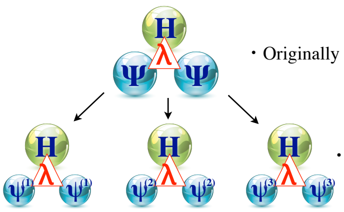
1. **The origin of CP phase** : Where does the CP phase come from !?
2. **Generations** : Who ordered the three same things in this world !?
3. **Mass Hierarchy**: Why so different the masses of the fermions are !?
4. **Flavor Mixing** : What is the origin of CKM structure !?

We want to clarify these mysteries of the Standard Model in the context of **5d gauge theories on a circle.**

• Difficulty

◆ **CP phase VS Generations**

Generations from one fermion does not allow us to introduce non-trivial phases in Yukawa couplings.



・Originally we have only one Yukawa coupling.

・All copies possess the same Yukawa couplings, which phase can be removed by re-phasing.

CP phase ?

• Setting

◆ 5d gauge theories on a circle. $W_M^a(x,y), B_M(x,y)$

with ・5d doublet Higgs field $H(x,y)$

・5d fermions (one generation) $\begin{pmatrix} u(x,y) \\ d(x,y) \end{pmatrix}, u'(x,y), d'(x,y)$

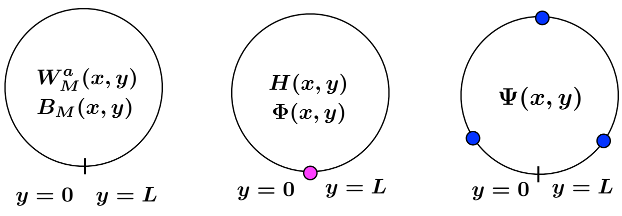
・5d singlet scalar $\Phi(x,y)$

◆ Put point interactions on a circle

・Gauge fields do not feel them.

・Higgs and singlet scalar feel one point interaction.

・Fermions feel several point interactions.



◆ Impose Boundary Conditions

・Gauge fields

$$\begin{cases} W_M^a(0) = W_M^a(L) \\ \partial_y W_M^a(0) = \partial_y W_M^a(L) \end{cases}$$

$$\begin{cases} B_M(0) = B_M(L) \\ \partial_y B_M(0) = \partial_y B_M(L) \end{cases}$$

・Higgs & singlet scalar

$$H(y+L) = e^{i\theta} H(y)$$

$$\begin{cases} \Phi(0) + L_+ \partial_y \Phi(0) = 0 \\ \Phi(L) - L_- \partial_y \Phi(L) = 0 \end{cases}$$

・Fermions

$$\begin{pmatrix} u(y) \\ d(y) \end{pmatrix}_R = 0$$

$$u'(y)_L = 0$$
$$d'(y)_L = 0$$

@ Point Interactions

• Results

5d gauge theories on a circle
with specified boundary conditions

↓ The low energy effective theory

4d gauge theories

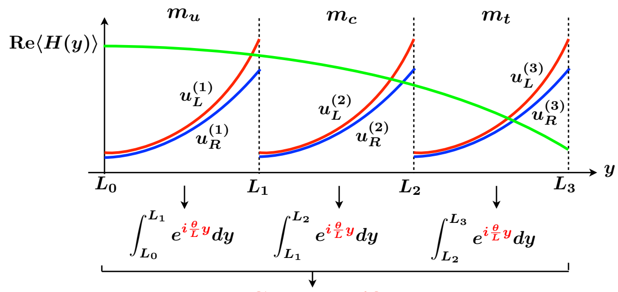
・CP phase ・Generations
・Mass hierarchy ・Flavor mixing

• CP phase

◆ The key element for CP phase is a non-trivial y-dependent phase which appears in Higgs VEV through the Boundary condition.
(y-independent phase does not help us.)

$$\langle H(y) \rangle = \frac{v}{\sqrt{2}} e^{i\frac{\theta}{L}y} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

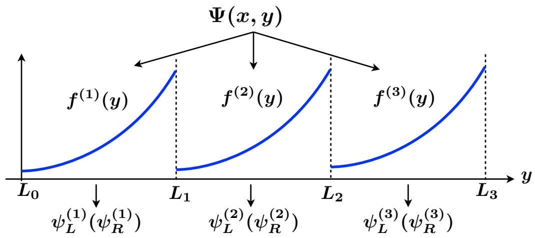
◆ Localized fermions pick up different phases in their masses from overlap integrals.



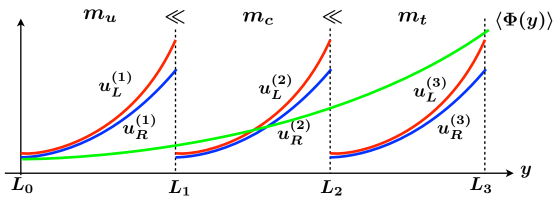
CP phase !?

• Our Model

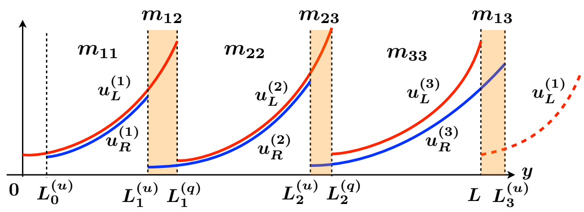
◆ Generation comes from the boundary conditions for fermions.



◆ Mass hierarchy appears due to the y-dependent singlet scalar VEV.



◆ Flavor mixing appears from off-diagonal overlap integrals. The form of mass matrices are restricted via the geometry.



$$M_u = \begin{pmatrix} m_{11}^{(u)} & m_{12}^{(u)} & m_{13}^{(u)} \\ 0 & m_{22}^{(u)} & m_{23}^{(u)} \\ 0 & 0 & m_{33}^{(u)} \end{pmatrix}, \quad M_u = \begin{pmatrix} m_{11}^{(d)} & m_{12}^{(d)} & m_{13}^{(d)} \\ 0 & m_{22}^{(d)} & m_{23}^{(d)} \\ 0 & 0 & m_{33}^{(d)} \end{pmatrix}$$

• Numerical Results

◆ We found a parameter set which reproduces experimental values within 20%.

$m_{\mathrm{up}} = 2.06\,\mathrm{MeV}$ $m_{\mathrm{charm}} = 1.25\,\mathrm{GeV}$ $m_{\mathrm{top}} = 174\,\mathrm{GeV}$

$m_{\mathrm{down}} = 4.91\,\mathrm{MeV}$ $m_{\mathrm{strange}} = 102\,\mathrm{MeV}$ $m_{\mathrm{bottom}} = 4.18\,\mathrm{GeV}$

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.971 & 0.238 & 0.00318 \\ 0.238 & 0.970 & 0.0372 \\ 0.00829 & 0.0364 & 0.999 \end{pmatrix}$$

$$J = \mathrm{Im}[(V_{\mathrm{CKM}})_{11}(V_{\mathrm{CKM}})_{22}(V_{\mathrm{CKM}}^*)_{12}(V_{\mathrm{CKM}}^*)_{21}] = 2.56 \times 10^{-5}$$