Phenomenology of Minimal Composite Double Higgs Model

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Abstract. Higgs mechanism was a method to give mass into all particle in Standard Model. In 2012 research center CERN had detect Higgs particle with mass around 125 GeV. This data was not suitable with calculation, where based on Standard Model in high energy there are radiative correction to Higgs mass, so that Higgs have extremely heavy mass, we called these phenomena as hierarchy problem. Because of that reason there must be new theory based from Standard Model that can describe these phenomena, one of the theory is composite Higgs model where Higgs was a composite from Goldstone boson from symmetry breaking. Using Composite Higgs Model for minimal case and some modification to double Higgs. With this model we calculate Higgs mass correction and had same for m of Higgs mass correction in Standard Model with extra term of $1 - \xi$, where $\xi$ was one properties in composite Higgs and for $\xi \rightarrow 0$ the model become back to Standard Model. Then we calculate the cut-off energy of the model with Renormalization Group Equation by Callan-Symanzik and give us cut-off energy at $10^6$ GeV scale which far from GUT energy scale, so this model still acceptable. Otherwise This energy much higher than LHC energy, so we can not do direct observation then use Peskin-Takeuchi parameter which describe sign for new physics at high scale with calculation of vacuum polarization and the calculation results still fit with experiment data.

1. Introduction
The idea of Higgs proposed though Higgs mechanism by three independent research group in 1964 [1, 2, 3, 4, 5]. This particle was needed to generate mass in Standard Model without breaking gauge theory though Higgs field. This particle become more interesting with announcement of Higgs boson discovery by ATLAS and CMS project, CERN [6, 7]. Even the discovery was a big achievement in particle physics there are still many problems remaining. One of problem was the Higgs mass which detected in around 125 GeV. From renormalization theory, we know that there are radiative corrections to mass of scalar field [8]. This correction was proportional with cut-off energy of model, in this case we use cut-off energy of Standard Model [9]. So that the mass of Higgs seems to be unnatural, extremely small compare to cut-off energy, this problem often called naturalness problem or hierarchy problem.

In order to solve hierarchy problem, many model was built by modify Standard Model. One of the model was composite Higgs model which proposed by Georgi and Kaplan in 1985 [10]. In this model Higgs is not elementary particle but a bound state of Goldstone boson that came from symmetry breaking with strong interaction at high energy. The Goldstone bosons interact each other with similar interaction strong interaction. In this work, we will use minimal case symmetry breaking to describe Standard Model symmetry $SU(2)_L \times U(1)_Y$ which isomorphic with $SO(4)$, this model called minimal composite Higgs model [11]. Then we modified the model with double Higgs model to make model more realistic where there is asymmetry for fermion mass [12, 13]. With this model we shall show the Higgs mass correction, then we will calculate cut-off energy to see if this model still available [14]. Then we would like to calculate Peskin-Takeuchi parameter, parameter which can describe sign of new physics from vacuum polarization [15, 16].

We organize the remaining parts of the paper as follows. In section 2, we review the hierarchy problem start from renormalization theory of scalar field then we calculate mass of Higgs with radiative correction so we can show the hierarchy problem. In section 3, we build the composite Higgs model.
with minimal symmetry, start from Goldston e theorem then minimal composite Higgs model and we add some properties of double Higgs model. In chapter 4 we calculate mass off Higgs with composite Higgs model and addition of double Higgs model. In chapter 5 we calculate some low energy parameter that have connection with high energy physics. Finally we conclude this paper in last section.

2. Hierarchy Problem
In this chapter we will review the origins of hierarchy problem. We start from renormalization theory of scalar field. Then we calculate the correction to Higgs mass so hierarchy problem can be shown.

2.1. Renormalization Theory of Scalar Field
To describe renormalization theory we consider the general form Lagrangian for scalar field
\[ \mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{g}{4!} \phi^4, \]  
where \( \phi \) was scalar field and \( g \) was a coefficient. With dimension analysis of equation (1) we know that \( g \) was dimensionless, so we need new parameter to give last term to make same dimension with the other term. We use new mass parameter as \( \mu \):
\[ \mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{g}{4!} \mu^{4-d} \phi^4. \]

General correction mass to scalar field can be known with calculate the correction to free propagator, two point loop. In momentum space correction shown as,
\[ L_2 = g \mu^{4-d} \int \frac{d^4p}{(2\pi)^d} \frac{1}{p^2 - m^2}. \]

We will use two general form of integration,
\[ \int \frac{d^dp}{(p^2 + 2pq - m^2)^2} = 2\pi \int_0^\infty dp_0 \int_0^{\pi} \frac{\Pi \sin^k \theta_k \, d\theta_k}{(p_0^2 + 2pq - m^2)^2}, \]
\[ \int_0^\pi (\sin \theta)^{2n-1} (\cos \theta)^{2m-1} d\theta = \frac{\Gamma(n)\Gamma(m)}{\Gamma(n+m)}. \]

So that we can reformulate equation (3) as,
\[ L_2 = \frac{igm^2}{32\pi^2} \left( \frac{4\pi\mu^2}{m^2} \right) \Gamma \left( 1 - \frac{d}{2} \right). \]

Then we use definition of gamma function and expansion for \( d = 4 - 2\epsilon \) where \( \epsilon \) is infinitesimal,
\[ L_2 = \frac{igm^2}{32\pi^2} \left( \frac{1}{\epsilon} + 1 - \epsilon \right) (1 - \epsilon) \ln \left( \frac{m^2}{4\pi\mu^2} \right). \]

In general case two points loop become correction to mass of scalar particle shown as,
\[ m^2 = m_c^2 + iL_2, \]
This equation we will use to calculate Higgs mass with correction in next subsection.
2.2. Naturalness of Higgs Mass

After we show the general form of mass correction, we will calculate Higgs mass correction. First we must determine Feynman diagram which contribute to correction. In this work we only calculate contribution which dominate calculation such as Higgs, W, Z boson and top quark, see Figure 1.

![Figure 1. The Contribution to Higgs mass correction [14].](image)

The contribution can be shown as,

\[ \Sigma = \int \frac{d^4p}{(2\pi)^4} \left( \frac{2\lambda}{p^2 - m_H^2} + \frac{3g_2^2}{p^2 - m_W^2} + \frac{3(g_1^2 + g_3^2)}{2(p^2 - m_Z^2)} - 4 \sum_f \frac{n_f g_f^2}{p^2 - m_f^2} \right), \]  

(9)

where \( \lambda \) is Higgs coupling, \( g_1 \) is W boson coupling, \( g_2 \) is Z boson coupling, \( g_f \) is quark coupling and \( n_f \) is degree of freedom for fermion color. If we use general form in equation (7) and we exclude the logarithmic term, because the contribution very small comparing with quadratic term, the equation (9) become

\[ \Sigma = -\frac{i\Lambda^2}{16\pi^2} \left( 2\lambda^2 + 3g_2^2 + \frac{3(g_1^2 + g_3^2)}{2} - 12g_f^2 \right), \]  

(10)

Then we use definition of boson and fermion mass so the correction in equation (10) become,

\[ \Sigma = -\frac{i\Lambda^2}{16\pi^2} \left( m_H^2 + 6m_W^2 + 3m_Z^2 - 12m_f^2 \right). \]  

(11)

If we calculate the Higgs mass with radiative correction Higgs mass become,

\[ m_H^2 = m_{Hr}^2 + i\Sigma \]

\[ = m_{Hr}^2 + \frac{\Lambda^2}{16\pi^2} \left( m_H^2 + 6m_W^2 + 3m_Z^2 - 12m_f^2 \right). \]  

(12)

We can see at equation (12) that Higgs mass should be same order with cut-off energy of Standard Model (\( \Lambda_{5M} = 10^{16} \text{ GeV} \) [17]). In otherwise, Higgs mass found at 125 GeV that made Higgs mass not natural, this called hierarchy problem. In next chapter we try to solve this problem with Composite Higgs Model.

3. Composite Higgs Model

In previous chapter we shown where the hierarchy problem come from. In this we will build the model with minimal symmetry breaking that include Standard Model. Then we add some properties of Double Higgs Model into Minimal Composite Higgs Model.

3.1. Minimal Composite Higgs Model

In Composite Higgs Model, Higgs become a bound state of goldstone boson that rise from spontaneous symmetry breaking (\( G \rightarrow H \)), we use notation where \( G \) is a group, \( H \) is sub group of \( G \) and \( G/H \) is coset of symmetry breaking.
In this spontaneous symmetry breaking, generator of group $G (T^A)$ decompose to generator of subgroup $H (T^a)$ and generator of coset $G/H (\bar{T}^i)$,

$$
\langle T^A \rangle = \langle T^a, \bar{T}^i \rangle,
$$

where we choose configuration to vacuum $\vec{F}$ as $T^a\vec{F} = 0$ and $\bar{T}^i\vec{F} \neq 0$.

In this case Goldstone boson field become a local transformation of Vacuum in generator of coset direction,

$$
\vec{\phi}(x) = e^{i\bar{\theta}\vec{T}^i}\vec{F}(14)
$$

where $\bar{\theta}$ is four real component of Higgs doublet. The Vacuum Expectation Value of the field denoted as $\langle \theta \rangle$ which describe vacuum misalignment angle, see Figure 2. (a). Then we define new parameter $\xi$

$$
\xi = \sin^2\langle \theta \rangle = \frac{\nu^2}{f^2}(15)
$$

where $f$ is magnitude of vector $\vec{F}$.

Now we know general scheme of symmetry breaking, so we want to do minimal scheme of symmetry breaking which include symmetry of Standard Model in sub group $H$. Group of Standard Model contains chiral group $SU(2)_L \times SU(2)_R$ which isomorphic with $SO(4)$ group, so we choose $SO(4)$ for subgroup $H$. Because we want to have one doublet Higgs, we need at least four goldstone boson in coset space, then we choose group $SO(5)$ as group $G$. The illustration of symmetry breaking $SO(5) \rightarrow SO(4)$ shown in Figure 2. (b). Then we decompose generator of $SO(5)$ as $(T^A) = (T^a, \bar{T}^i)$.

Let us construct Minimal Composite Higgs Model, start from Lagrangian of scalar real field fiveplet $\vec{\phi}$ as,

$$
\mathcal{L}_C = \frac{1}{2} \partial_\mu \vec{\phi}^\dagger \partial^\mu \vec{\phi} - \frac{g^2}{8} (\vec{\phi}^\dagger \vec{\phi} - f^2).
$$

Then we choose minimum condition $\langle \vec{\phi}^\dagger \vec{\phi} \rangle = f^2$ to give non vanish Vacuum Expectation Value in symmetry breaking. Base on equation (14) vacuum state defines as,

$$
\vec{F} = \begin{bmatrix} \vec{0}_4 \\ f \end{bmatrix}
$$

Figure 2. (a) Geometric illustration of symmetry breaking. Breaking of group $G$ from vacuum misalignment proportional to the $\vec{F}$ projection on subgroup $H$ plane, (b) General illustration of spontaneous symmetry breaking process $(G \rightarrow H)$ [10].
In order to study the fluctuation around the vacuum it is convenient to perform a field redefinition and trade the five $\phi$ component with one radial component $\sigma(x)$ and four angle variables $\Pi_{(1,2,3,4)}$ which is Goldstone field. So fiveplet of scalar field become,

$$\bar{\phi}(x) = e^{i\sqrt{2}\Pi_t(x)} r^t \left[ \begin{array}{c} 0 \\ f + \sigma(x) \end{array} \right]$$

(18)

In spontaneous symmetry breaking we define Goldstone matrix as ($\Pi = \sqrt{\Pi^T \Pi}$),

$$U[\Pi] = \exp i \frac{\sqrt{2}}{f} \Pi_t(x) P^t$$

$$= \left[ \begin{array}{cc} 1 - 1 \left( 1 - \cos \frac{\Pi}{f} \right) & \sin \frac{\Pi}{f} \\
-\sin \frac{\Pi}{f} & \cos \frac{\Pi}{f} \end{array} \right]$$

(19)

Using equation (19) we have scalar field as,

$$\hat{\phi}(x) = (f + \sigma(x)) \left[ \begin{array}{c} \Pi \Pi^t \\ f \Pi \\ \cos \frac{\Pi}{f} \end{array} \right]$$

(20)

Then Lagrangian in equation (16) become (eliminate $\sigma$ term),

$$\mathcal{L}_c = \frac{f^2}{4\Pi^2} \sin^2 \frac{\Pi}{f} \partial_\mu \Pi^T \partial^\mu \Pi - \frac{f^2}{8\Pi^4} \left( \Pi^2 - \sin^2 \frac{\Pi}{f} \right) \partial_\mu \Pi^2 \partial^\mu \Pi^2.$$  

(21)

The isomorphic of $SO(4)$ with $SU(2)_L \times SU(2)_R$ give us Higgs doublet in terms of Goldstone boson,

$$H = \begin{bmatrix} h_u \\ h_d \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \Pi^2 + i\Pi^4 \\ \Pi^4 - i\Pi^3 \end{bmatrix}.$$  

(22)

Then we replace derivate with covariant derivative for Higgs field,

$$D_\mu H = \left( \partial_\mu - ig W^a_\mu \frac{\sigma^a}{2} - ig' B^a_\mu \frac{I_2}{2} \right) H.$$  

(23)

So the equation (21) in Higgs terms become,

$$\mathcal{L}_H = \frac{f^2}{2|H|^2} \sin^2 \frac{\sqrt{2}|H|}{f} D_\mu H^\dagger D^\mu H - \frac{f^2}{8|H|^4} \left( \frac{2|H|^2}{f^2} - \sin^2 \frac{\sqrt{2}|H|}{f} \right) \left( D_\mu |H|^2 \right)^2.$$  

(24)

If we concern on fluctuation around vacuum, Higgs field can determine as,

$$H = \begin{bmatrix} 0 \\ v + h(x) \end{bmatrix},$$  

(25)

where $v$ is vacuum expectation value and $h(x)$ is Higgs fluctuation around vacuum. Using equation (25) and by Taylor expansion around $h = 0$ we have,

$$\mathcal{L}_H = \frac{g^2 v^2}{4} \left( |W|^2 + \frac{1}{2c_w^2} Z^2 \right) \left( 2\sqrt{1 - \frac{h}{v}} + (1 - 2\xi) \frac{h^2}{v^2} + \cdots \right).$$  

(26)
Lagrangian in equation (26) have exactly same form with Standard Model Lagrangian where there are single and double Higgs vertices but with modified coupling as \((V = W, Z)\),

\[
\begin{align*}
    g_{hVV}^{CH} &= g_{hVV}^{SM} \sqrt{1 - \xi}, \\
    g_{hhVV}^{CH} &= g_{hhVV}^{SM} (1 - 2\xi),
\end{align*}
\]

(27)

With equation (27) if we take limit \(\xi \to 0\), Composite Higgs Model become back to Standard Model. So that the composite Higgs becomes effectively elementary in this limit on the other side Composite Higgs Model back to Standard Model.

### 3.2. Minimal Composite Double Higgs Model

In previous chapter we have built Composite Higgs Model for minimal symmetry breaking. Then we will add some Double Higgs Model properties. Double Higgs Model have been built to describe different mass for each fermion in one family. In this model Higgs become two doublet, which each doublet interact with different family of fermion so give unique mass to each fermion [13],

Double Higgs define Higgs fields as two doublet,

\[
H^{(i)} = \begin{bmatrix} h_u^{(i)} \\ h_d^{(i)} \end{bmatrix}, \quad (i = 1, 2),
\]

(28)

with properties for Higgs coupling and vacuum follow,

\[
\begin{align*}
    v^2 &= v_1^2 + v_2^2, \\
    g_{hVV} &= g_{h1VV}^2 + g_{h2VV}^2.
\end{align*}
\]

(29, 30)

With these properties, Lagrangian in equation (24) become,

\[
\mathcal{L}_H = \frac{f^2}{2|H|^2} \left( \sin^2 \frac{\sqrt{2}|H_1|}{f} D_\mu H_1^\dagger D^\mu H_1 + \sin^2 \frac{\sqrt{2}|H_2|}{f} D_\mu H_2^\dagger D^\mu H_2 \right) - \frac{f^2}{8|H|^4} \left( \frac{2|H|^2}{f^2} - \sin^2 \frac{\sqrt{2}|H_1|}{f} - \sin^2 \frac{\sqrt{2}|H_2|}{f} \right) (D_\mu |H|^2)^2.
\]

(31)

Concern on fluctuation around vacuum, Higgs field define as,

\[
H^{(i)} = \begin{bmatrix} 0 \\ v_i + h(x) \end{bmatrix},
\]

(32)

which give Taylor expanded Lagrangian as,

\[
\mathcal{L}_H = \left( g_1^2 + g_2^2 \right) (v_1^2 + v_2^2) \left( |W|^2 + \frac{1}{2c_w^2} Z^2 \right) \left( 2\sqrt{1 - \xi_\nu} + (1 - 2\xi) \frac{h^2}{v^2} + \ldots \right).
\]

(33)

Using properties of Double Higgs Model we have exactly same Lagrangian with equation(26). So that we can conclude that no difference coupling correlation between Minimal Composite Higgs Model while we add some Double Higgs Model properties.

### 3.3. Higgs Mass Correction

Since we built the model in previous chapter, we will calculate Higgs mass correction. Using coupling connection with the original one in equation (27) without loss any generality we have,

\[
\delta m_H \sim \frac{\Lambda^2 g_{SM}^2}{8\pi^2 v^2} \sqrt{1 - \xi}.
\]

(34)
Looking at equation (34) we still have correction proportional to cut-off energy, but we have $\sqrt{1 - \xi}$ terms which able to make correction smaller. In other side if we take $\xi \to 0$ we have hierarchy problem exactly same with Standard Model did. So that for $\xi$ small or while vacuum misalignment angle is small, Composite Higgs Model turn back to Standard Model.

3.4. Cut-Off Energy

In order to know the energy for direct observation the model, we must calculate cut-off energy for this model. If cut-off energy already passed in experiment, we cannot use this model again because there are no sign for composite Higgs until now.

To calculate cut-off energy, we start from Renormalization Group Equation by Callan-Symanzik [18, 19],

\[
\left[ \mu \frac{\partial}{\partial \mu} + \beta(g) \frac{\partial}{\partial g} - n_\gamma (g) + m_Y (g) \frac{\partial}{\partial m} \right] \Gamma^{(n)} = 0. \tag{35}
\]

Considering beta function on second term, which we define as,

\[
\beta(g) = \mu \frac{\partial}{\partial \mu} \left( g \mu^{2e} g - \frac{g^2 \mu^{2e}}{\pi^2 e} \right)
\Rightarrow \lim_{\epsilon \to 0} \beta(g) = \frac{g^2}{\pi^2}, \tag{36}
\]

so that with do integration in beta function we have running coupling as,

\[
g = \frac{g_0}{1 - \pi^{-2} g_0 \ln(\mu/\mu_0)}. \tag{37}
\]

In equation (37) we cannot describe the coupling at $\mu = \mu_0 e^{\pi^2 / g_0}$. Using vacuum expectation value as $\mu_0$, Higgs coupling constant as $g_0$, we have,

\[
\Lambda_{CH} = v \exp \left( \frac{v n^2}{m_t \sqrt{1 - \xi}} \right)
\approx 4.6237 \times 10^6 \text{ GeV}. \tag{38}
\]

The result for cut-off energy calculation still far from energy scale of LHC, $10^3$ GeV, but to small compare with GUT energy scale. Because of the reason, this model still acceptable.

4. The Phenomenology

We have built Minimal Composite Double Higgs Model in previous chapter, then we calculate Higgs mass correction and cut-off energy. Because of very high cut-off energy, we still cannot observe interaction for this model directly. So that we have to calculate some parameter in low energy physics which have correlation to model in high energy. One of the parameter is Peskin-Takeuchi (oblique) parameter which describe new physics at high energy scale.

Oblique parameters originally have 3 parameters which have different purpose, S parameter to describe contribution of new physics on neutral current on different energy, T parameter to measure difference neutral current to charge current from new physics at low energy, and U parameter to describe new physics contribution for neutral current. At first this parameter proposed by Peskin and Takeuchi define as,

\[
aS = \frac{4 s_w^2 c_w^2}{m_w^2} \left( \frac{s_w^2 - c_w^2}{s_w c_w} \left( \Pi_{\gamma Z}(m_Z^2) - \Pi_{\gamma Z}(0) \right) + \left( \Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0) \right) \right)
+ \left( \frac{s_w^2 - 1}{c_w^2} \right) \left( \Pi_{YY}(m_Z^2) - \Pi_{YY}(0) \right) \right), \tag{39}
\]
\[ \alpha T = \frac{1}{m_w^2} \left( \Pi_{WW}(0) - 2s_w c_w \Pi_{YZ}(0) - c_w^2 \Pi_{ZZ}(0) - s_w^2 \Pi_{YY}(0) \right). \]  
\[ \alpha U = \frac{4s_w^2}{m_w^2} \left( \left( \Pi_{WW}(m_Z^2) - \Pi_{WW}(0) \right) - 2s_w c_w \left( \Pi_{YZ}(m_Z^2) - \Pi_{YZ}(0) \right) \right). \]

The result of oblique parameter calculation shown on Table 1. In Table 1 we can see that each calculation still fit with experiment data. But small value for each parameter give sign to us that there are still no indication for new physics on the experiment.

**Table 1.** Comparison of oblique parameter analytic calculation with experiment data [20].

| Parameter | Calculation | Data     |
|-----------|-------------|----------|
| \( S \)  | 0.03522     | 0.04 ± 0.1 |
| \( T \)  | -0.04934    | 0.05 ± 0.11 |
| \( U \)  | -0.03519    | 0.08 ± 0.11 |

### 5. Conclusion

In this paper we already review the hierarchy problem from Higgs mass. The problem came from renormalization of scalar field where the correction for mass should be proportional to cut-off energy of the model. Then we have been built Minimal Composite Double Higgs Model, where Higgs treat as a bound state of goldstone boson from symmetry breaking. With this model we have same form of Higgs mass correction, but with extra term of \( 1 - \xi \). The parameter \( \xi \) was one properties in composite Higgs, in limit \( \xi \rightarrow 0 \) the model back to Standard Model. The cut-off energy of this model has been calculated at \( 10^6 \) GeV scale which far from GUT energy scale, so this model still acceptable. Otherwise This energy much higher than LHC energy, so we cannot do direct observation, so that we must calculate a correlated parameter which can be measured in low energy. In this work we choose Peskin-Takeuchi parameter which describe sign for new physics at high scale with calculation of vacuum polarization. The comparison of the calculation and experiment data given in Table 1. The calculation still fit in experiment data, which give another acceptance for this model. But the small value for all parameters give information that still no sign for new physics on recent experiment.

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