PROBING THE ELECTROWEAK SYMMETRY BREAKING MECHANISM AT HIGH ENERGY COLLIDERS

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Abstract

We briefly review the recent developments of probing the electroweak symmetry breaking mechanism at high energy colliders such as the CERN LEP2, the Fermilab Tevatron, the CERN LHC and the $e^+e^-$ linear colliders. Both weakly interacting and strongly interacting electroweak symmetry mechanisms are concerned.

1 Introduction

It is remarkable that the electroweak standard model (EWSM) has successfully passed all the precision tests. However, despite of the present success, the electroweak symmetry breaking mechanism (EWSBM) is not clear yet. All results of the experimental searches for the Higgs boson are negative. So far, we only know the existence of a vacuum expectation value (VEV) $v = 240$ GeV which breaks the electroweak gauge symmetry, but we don't know if it is just the VEV of the elementary Higgs boson in the EWSM or not, and we even don't know if there is really a Higgs boson below 1 TeV. The unclear EWSBM is a big puzzle in particle physics, and the probe of the EWSBM is one of the most important problems in current high energy physics. Since all particle masses come from the VEV $v$, probing the EWSBM concerns the understanding of the origin of all particle masses, which is a very fundamental problem in physics. The latest experimental bound of the Higgs boson mass given by the LEP Working Group for Higgs Boson Searches is already $m_H > 107.7$ GeV \cite{1}. New TeV energy colliders are definitely needed to further study this important problem experimentally.

From the theoretical point of view, there are several unsatisfactory features in the Higgs sector in the EWSM, e.g. there are so many free parameters related to the Higgs sector, and there are the well-known problems of triviality and unnaturalness \cite{2}. Usually, people take the point of view that the present theory of the EWSM is only valid up to a certain energy scale $\Lambda$, and new physics beyond the EWSM will become important above $\Lambda$. Possible new physics are supersymmetry (SUSY) and dynamical EWSBM concerning new strong interactions, etc. So that probing the mechanism of EWSB also concerns the discovery of new physics.

In the following, we shall give a brief review of the present developments of probing the EWSBM at various high energy colliders.
The Higgs Boson

2.1 Where is the Higgs Boson?

In the EWSM, the Higgs boson mass $m_H$ is a free parameter related to the Higgs self-coupling constant $\lambda$. We now look at some possible hints of $m_H$ from theoretical and experimental studies.

Let us first look at the theoretical hint. We know that if the EWSM is valid in the whole energy range, the renormalized coupling constant $\lambda \to 0$—triviality. Since the Higgs boson develops a nonvanishing VEV only if it has a nontrivial self-interaction $\lambda \neq 0$, triviality is a serious problem of the EWSM. To avoid triviality, people usually take the point of view that the EWSM may not be fundamental but is a low energy effective theory of a more fundamental theory below a certain physical scale $\Lambda \neq \infty$. The scale $\Lambda$ serves as a natural momentum cut-off which is the highest energy scale in the effective theory. The problem of triviality can then be avoided if the fundamental theory does not suffer from a triviality problem. The larger the scale $\Lambda$ the smaller the nonvanishing coupling $\lambda$. Note that $m_H$ is proportional to $\lambda$, so that there is an upper bound on $m_H$ for a given $\Lambda[3]$. A careful calculation of such a triviality bound on $m_H$ has been given in Ref. 3 and is shown as the upper curve in Fig. 1[3]. By definition, $m_H$ cannot exceed the highest scale $\Lambda$ in the effective theory. This determines the maximal value of $m_H$ which is of the order of 1 TeV[2, 3].

![Fig. 1. The triviality bound (upper curve) and the vacuum stability bound (lower curve) on $m_H$ in the EWSM. The solid areas as well as the crosshatched area indicate theoretical uncertainties. Quoted from Ref. 3.](image-url)

On the other hand, when loop contributions are concerned, the stable physical vacuum state should be determined by the minimum of the effective potential $V_{\text{eff}}$. In $V_{\text{eff}}$, the Higgs boson loop (with the Higgs self-interaction) tends to stabilize the physical vacuum with a nonvanishing $v$, while the fermion loop tends to destabilize the physical vacuum[2]. The heavier the fermion the stronger the violation of vacuum stability. The $t$ quark gives a strong violation of the vacuum stability. To obtain a stable physical vacuum, a large enough Higgs self-interaction is needed to overcome the destabilization from the $t$ quark loop contributions. This requirement gives a lower bound on the Higgs mass $m_H$. The vacuum stability bound on $m_H$ is shown as the lower curve in Fig. 1[3].

The region between the two curves in Fig. 1 is the allowed region. We see that there is a possibility of extrapolating the EWSM up to the Planck mass, if and only if the Higgs mass $m_H$ is around 160 GeV. Of course, Fig. 1 tells nothing about where the actual scale of new physics really is. Even if a Higgs boson of $m_H \approx 160$ GeV is found, Fig. 1 still allows $\Lambda$ to take any value below the Planck mass. Of special interest is that if a very light Higgs boson with $m_H \sim 100$...
GeV or a heavy Higgs boson with \( m_H \leq 500 \) GeV is found. Then Fig. 1 shows that \( \Lambda \) will be at most of the order of TeV, and this energy can be reached at the LHC and LCs. Furthermore, *If a Higgs boson is not found below 1 TeV, we should find new physics in this region.*

There is an important conclusion for the Higgs boson mass in the minimal SUSY extension of the standard model (MSSM). Careful theoretical studies on the MSSM Higgs mass up to two-loop calculations show that the mass of the lightest CP even Higgs boson \( h \) in the MSSM cannot exceed a bound \( m_h|_{\text{max}} \approx 130 \) GeV \(^4\) with a theoretical uncertainty about 5 GeV, which can be reached by all the designed LCs. If \( h \) is not found below 135 GeV, MSSM will be in a bad shape and SUSY models beyond the MSSM should be seriously considered.

Next we look at some possible experimental hints. There are various analyses of the best fit of the electroweak theory to the LEP/SLD data at the \( Z \)-pole which give certain requirements on the Higgs mass.

**i, Best Fit of SM to the \( Z \)-pole Experiments**

The high precision of the LEP/SLD data can give certain expected value of \( m_H \) from the requirement of the best fit. For instance, the analysis in Ref. 5 shows that the best fit value of \( m_H \) is \(^5\)

\[
m_H = 107^{+67}_{-45} \text{ GeV.} \quad (1)
\]

The upper bounds of \( m_H \) at the 90% C.L. is \( m_H < 220 \) GeV \(^3\). These numbers imply that the Higgs boson may be found in the near future if it exists. It should be noticed that this is the conclusion from an analysis using *only the pure EWSM formulae without including any effects of new physics.*

**ii, Combining the \( Z \)-pole data and the Direct Search Bound**

Apart from the above hint from the \( Z \)-pole data, there have been direct searches for the Higgs boson at LEP in recent years with negative results. If one combine the two sources of data, the probability distribution of the Higgs mass will change, and the resulting expected value of the Higgs mass will be different from eq.(1). This kind of study has been carried out in Ref. 6 taking account of the direct search bound \( m_H > 89.8 \) GeV from the \( \sqrt{s} = 183 \) GeV run of LEP in 1998. The result is \(^6\)

\[
m_H = 170 \pm 80 \text{ GeV,} \quad m_H < 300 \text{ GeV,} \quad 95\% \text{ C.L.} \quad (2)
\]

An upgraded analysis by the same authors has also been given with similar conclusions \(^6\). We see that this expected \( m_H \) is higher than that obtained merely from the \( Z \)-pole data. Now the direct search bound has increased to \( m_H > 107.7 \) GeV \( \text{[1]} \) which will make the expected \( m_H \) further higher.

**iii, Considering New Physics Contribution to \( S \)**

The above results are all based on analyses using only the pure EWSM formulae. Since the EWSM may only be valid below a certain physical scale \( \Lambda \), new physics may affect the \( Z \)-pole observables, or the parameters \( S, T, U \) and \( \epsilon_b \). Ref. 7 has given an interesting with \( S \) treated as a new parameter (including unknown new physics effect), and the best fit values of \( S, m_H, m_t \) and \( \alpha_s \) are \(^7\)

\[
S = -0.20^{+0.24}_{-0.17}, \quad m_H = 300^{+690}_{-310}, m_t = 172.9 \pm 4.8 \text{ GeV}, \quad \alpha_s = 0.1221 \pm 0.0035. \quad (3)
\]
The best fit values of $m_t$ and $\alpha_s$ are all close to the world averaged values, and the expected value of $m_H$ is much uncertain (the upper value is of the order of 1 TeV) when the formula for $S$ is relaxed.

iv, Best Fit of the Electroweak Chiral Lagrangian to the Z-pole Data

Another interesting analysis was recently given in Ref. 8. Since the Higgs boson is not found, the authors consider the possibility that there is no undiscovered particles (like the Higgs boson) below $\Lambda \sim $ few TeV. Then, at the LEP energy, the only particles (unphysical) related to the EWSBM are the would-be Goldstone bosons (GBs). The system of the GBs and the electroweak gauge bosons can be generally described by the electroweak chiral Lagrangian (EWCL) \[9\] which can be regarded as the low energy effective Lagrangian of the fundamental theory of EWSBM, and can be expanded according to the powers of $p^2/\Lambda^2$,

$$L = L^{(2)} + L^{(4)} + \cdots,$$

(4)

where $L^{(2)}$ and $L^{(4)}$ are terms of $O(p^2/\Lambda^2)$ and $O(p^4/\Lambda^4)$, respectively. Actually, the Z-pole observables are not sensitive to $L^{(4)}$, so that the authors mainly considered $L^{(2)}$ in which there are two terms related to $S$ and $T$. The authors made a model-independent analysis with $S$ and $T$ taken as two unknowns which, together with the QCD coupling constant $\alpha_s$, are adjusted to make the best fit of the EWCL \[9\] to the Z-pole data. Their result shows that with the best fit values

$$S = -0.13 \pm 0.10, \quad T = 0.13 \pm 0.11, \quad \alpha_s(M_Z) = 0.119 \pm 0.003,$$

(5)

the Z-pole data can be well fitted. The best fit value of $\alpha_s(M_Z)$ is almost the same as the world averaged value, so that the result is very reasonable. This result means that the Z-pole data can be well fitted even without a Higgs boson below the scale $\Lambda$.

We see from the above analyses that the hints of the Higgs mass from the best fit to the LEP data are quite different in different approaches with or without new physics contributions. We can conclude that the LEP/SLD precision Z-pole data do not necessarily imply the existence of a light Higgs boson, so that the probe of the EWSB mechanism should be proceeded in a wide scope considering both the case of existing a light Higgs boson and the case without a Higgs boson below the scale of TeV. Note that the width of the Higgs boson is proportional to $m_H^3$, so that a light Higgs boson will look as a narrow resonance which is easy to detect. If a Higgs boson is so heavy that its width is comparable to its mass, it will not show up as a clear resonance, and the detection is hard. In this case or there is no Higgs resonance below 1 TeV, other method of probing the EWSB mechanism should be developed. We shall deal with this problem in Sec. 4.

2.2 Searching for the Higgs Boson at High Energy Colliders

Searching for the Higgs boson is the first important task at the future high energy colliders. Here we briefly review various ways of searching for a light SM Higgs boson at high energy colliders.
i, LEP2

At the LEP2 energy, the dominant production mechanism for the EWSM Higgs boson is the Higgs-strahlung process

\[ e^+e^- \rightarrow Z^* \rightarrow Z H, \]  

in which the Higgs boson is emitted from a virtual Z boson. The latest experiments were the 1999 run of LEP2 at \( \sqrt{s} = 192 \text{ GeV} \) and \( \sqrt{s} = 202 \text{ GeV} \) in which no evidence of the Higgs boson was found. This leads to the 95\% C.L. lower bound on \( m_H \)

\[ m_H > 107.7 \text{ GeV}. \]  

ii, Upgraded Tevatron

It has been shown that at the upgraded Tevatron Run 2, the most promising process for the search for the Higgs boson is

\[ pp \rightarrow WH, \quad pp \rightarrow ZH, \]  

with the tagging channel \( H \rightarrow b\bar{b} \). Together with the tagging mode \( H \rightarrow \tau^+\tau^- \), the searching ability can be up to \( m - H < 130 \text{ GeV} \). This is just not enough to cover the interesting theoretical upper limit of the lightest MSSM Higgs boson \( h, m_h < 130 \pm 5 \text{ GeV} \). Recently an interesting investigation was made in Ref. 13 showing that the EWSM Higgs boson in the mass region \( 135 \text{ GeV} \leq m_H \leq 180 \text{ GeV} \) is able to be detected at the upgraded Tevatron with the \( \sqrt{s} = 2 \text{ TeV} \) and an integrated luminosity of 30 \( \text{fb}^{-1}/\text{yr} \) (Run 3 of the Tevatron) via the process

\[ pp \rightarrow gg \rightarrow H \rightarrow W^*W^* \rightarrow l\nu j j, \quad l\bar{\nu}l\bar{\nu}. \]  

Therefore the upgraded Tevatron will be the next collider of Higgs searching after LEP2. Of course, due to the low luminosity, it will take years to accumulate enough events to draw a firm conclusion.

iii, LHC

At the LHC, because of the hadronic backgrounds, searching for the Higgs boson of mass \( m_H > 140 \text{ GeV} \) and \( m_H < 140 \text{ GeV} \) are quite different. In the following, we review these two kinds of searches separately.

- \( m_H > 140 \text{ GeV} \)

In this case the following gold plated channel is available

\[ pp \rightarrow HX \rightarrow ZZ(Z^*)X \rightarrow l^+l^-l^+l^-X \quad \text{(or} \quad l^+l^-\nu\bar{\nu}X), \quad pp \rightarrow HX \rightarrow WW(W^*)X \rightarrow l^+l^-\nu\bar{\nu}X, \]  

in which the four-lepton final state is very clear with rather small backgrounds. Theoretical study shows that the resonance behavior can be clearly seen when \( m_H < 800 \text{ GeV} \). When \( m_H \geq 800 \text{ GeV} \), the width of the Higgs boson will be comparable to the mass, and the Higgs boson can hardly be seen as a resonance. Searching for such a heavy Higgs boson, as well as probing the EWSBM when there is no Higgs resonance below 1 TeV, will be reviewed in Sec. 4.
• $M_Z < m_H < 140$ GeV

If the Higgs mass is in the intermediate range $M_Z < m_H < 140$ GeV, the above detection is not possible since the branching ratio of the four-lepton channel drops very rapidly as $m_H < 140$ GeV. Detection of such an intermediate-mass SM Higgs boson is much more difficult. Fortunately, the $H \rightarrow \gamma\gamma$ branching ratio has its maximal value in this $m_H$ range. Thus the best way is to detect the $\gamma\gamma$ final state for the Higgs boson. Recently, it is shown that the EWSM Higgs boson in the mass range of 100 GeV–150 GeV can be detected at the LHC via

$$pp \rightarrow H(\gamma\gamma) + jet$$

if a transverse-momentum cut of 2 GeV on the tracks is made for reducing the background [14].

To find channels with better signal to background ratio, people suggested the following associate productions of $H$ [15].

$$pp \rightarrow WHX \rightarrow l\bar{l}\gamma\gamma X, \quad pp \rightarrow t\bar{t}HX \rightarrow l\bar{l}\gamma\gamma X.$$  \hspace{1cm} (12)

The signal and backgrounds of the $WH$ associate production channel have been calculated in Ref. 15 which shows that the backgrounds are smaller than the signal even for a mild photon detector with a 3% $\gamma\gamma$ resolution. The inclusive search for the $t\bar{t}H$ associate production suffers from a further large background from $pp \rightarrow W(\rightarrow l\bar{l})\gamma\gamma(n-jet)$, $(n = 1, \cdots, 4)$ [16], and the search is possible only when the $\gamma\gamma$ resolution of the photon detector is of the level of 1% [16]. The photon detectors of ATLAS and CMS at the LHC are just of this level. Actually, if the jets are also detected, the background can be effectively reduced with suitable choice of the jets, and such detection is possible even for the mild photon detector with 3% $\gamma\gamma$ resolution [16].

Recently, the $b$-tagging efficiency is much improved. Tagging a light Higgs boson (with large enough $B(H \rightarrow b\bar{b})$) via the $H \rightarrow b\bar{b}$ mode with a detectable signal to background ratio is already possible at LHC. The number of events will be larger than that in the $H \rightarrow \gamma\gamma$ tagging mode.

In summary, a Higgs boson with mass $m_H < 800$ GeV can definitely be detected as a resonance at the LHC.

iv, LC

The advantage of searching for the Higgs boson at the LC is the smallness of the hadronic backgrounds. Then, the $H \rightarrow b\bar{b}$ mode can be taken as the main tagging mode to have larger number of events.

At the LC, the Higgs boson can be produced either by the Higgs-strahlung process (6) or by $WW$ and $ZZ$ fusions

$$e^+e^- \rightarrow \nu\bar{\nu}(WW) \rightarrow \nu\bar{\nu}H, \quad e^+e^- \rightarrow e^+e^-(ZZ) \rightarrow e^+e^-H.$$  \hspace{1cm} (13)

The cross sections for the Higgs-strahlung and $WW$ fusion processes are $\sigma \sim 1/s$ and $\sigma \sim (\ln \frac{s}{M_W^2})/M_W^2$, respectively. So that the Higgs-strahlung process is important at $\sqrt{s} \leq 500$ GeV, while the $WW$ fusion process is important at $\sqrt{s} > 500$ GeV. With the $H \rightarrow b\bar{b}$ tagging mode, several thousands of events can be produced for the envisaged luminosities [17].
Furthermore, by means of laser back-scattering, \( \gamma \gamma \) and \( e \gamma \) colliders can be constructed based on the LC. It has been shown recently that the \( s \)-channel Higgs production rate at the photon collider will be about an order of magnitude larger than the production rate in the Higgs-strahlung process at the LC \([18]\).

### 2.3 Testing Higgs Boson Interactions

If a light Higgs resonance is found from the above searches, it is not the end of the story. It is needed to test whether it is the EWSM Higgs or something else. This can be done by examining its interactions. We know the self-interactions of the SM Higgs boson contain the following trilinear and quartic terms

\[
\frac{1}{8} \frac{m_H^2}{v^2} \left[ 4vH^3 + H^4 \right],
\]

where \( v = 246 \text{ GeV} \) is the VEV of the Higgs field. For detecting the trilinear interaction, it is possible to look at the double Higgs-boson productions \( pp \to HHX \) at the LHC and \( e^+e^- \to HHZ, \ HH\nu\nu \) at the LC. It has been shown that the detection at the LHC is almost impossible due to the large background \([17,14]\), while the detection at the LC is possible at the C.M. energy \( E = 1.6 \text{ TeV} \) requiring a very large integrated luminosity, \( \int L dt = 1000 \text{ fb}^{-1} \). Therefore the detection is not easy. The signals of the quartic interactions are so small that it is hard to detect.

Since the top quark has the largest Yukawa coupling to the EWSM Higgs boson, it is possible to detect the Higgs Yukawa coupling via the process

\[
e^+e^- \to t\bar{t}H,
\]

which can test the \( Ht\bar{t} \) Yukawa coupling and see whether the discovered Higgs boson is really the one responsible for the top quark mass. This detection has been studied in Refs.\([19,20]\).

### 3 Strongly Interacting Electroweak Symmetry Breaking Mechanism

Introducing elementary Higgs field is the simplest but not unique EWSBM. The way of completely avoiding triviality and unnaturalness is to abandon elementary scalar fields and introducing new strong interactions causing certain fermion condensates to break the electroweak gauge symmetry. This idea is similar to those in the theory of superconductivity and chiral symmetry breaking in QCD. The simplest model realizing this idea is the original QCD-like technicolor (TC) model. However, such a simple model predicts a too large value of \( S \) and is already ruled out by the LEP data. A series of improved models have been proposed to overcome the shortcomings of the simplest model. In the following, we briefly review two of the recently proposed models.

#### i, Topcolor-Assisted Technicolor Models

This model combines the technicolor and the top-condensate ideas \([21]\). It is assumed in this model that at the energy scale \( \Lambda \sim 1 \text{ TeV} \), there is a topcolor theory with the gauge group \( SU(3)_1 \times U(1)_{Y1} \times SU(3)_2 \times U(1)_{Y2} \times SU(2)_L \) in which \( SU(3)_1 \times U(1)_{Y1} \) preferentially
couples to the third-family fermions and $SU(3)_2 \times U(1)_{Y2}$ preferentially couples to the first- and second-family fermions. It is assumed that there is also a TC sector which is the main part in the EWSBM and will break the topcolor gauge group into $SU(3)_{QCD}$ and $U(1)_Y$ at the scale $\Lambda$. The $SU(3)_1 \times U(1)_{Y1}$ couplings are assumed to be much stronger than those of $SU(3)_2 \times U(1)_{Y2}$. The strong $SU(3)_1 \times U(1)_{Y1}$ interactions will form top quark condensate $\langle t\bar{t} \rangle$ but not bottom quark condensate from the simultaneous effects of the $SU(3)_1$ and $U(1)_{Y1}$ interactions. The TC dynamics gives rise to the masses of the $u$, $d$, $s$, $c$, and $b$ quarks and a small portion of the top quark mass, while the main part of the top quark mass comes from the topcolor dynamics causing the top quark condensate just like the constituent quarks acquiring their large dynamical masses from the dynamics causing the quark condensates in QCD. In this prescription, the TC dynamics does not cause a large oblique correction parameter $T$ even the mass difference $m_t - m_b$ is so large. Improvement of this kind of model is still in progress.

This kind of model contains various pseudo-Goldstone bosons (PGBs) including technipions in the technicolor sector and an isospin triplet top-pions with masses in a few hundred GeV range. It has been shown that the LEP/SLD data of $R_b$ put constraint on the top-pion mass [23]. These light particles characterizing the phenomenology of the model.

**ii, Top Quark Seesaw Theory**

Recently, a new promising theory of strongly interacting EWSB related to the top quark condensate called *top quark seesaw theory* was proposed in Ref. 22. The gauge group in this theory is

$$G \times G_{tc} \times SU(2)_W \times U(1)_Y,$$

(16)

where $G_{tc}$ is the topcolor gauge group (for instance, $SU(3)_1 \times SU(3)_2$ or even larger), $G$ is a gauge group for new strong interactions which breaks $G_{tc}$ into $SU(3)_{QCD} \times U(1)_{Y}$ at a scale $\Lambda$. Instead of introducing techniquarks, certain $SU(2)_W$-singlet quarks, $\chi, \ldots$, with topcolor interactions and specially assigned $U(1)_{Y}$ quantum numbers are introduced in this theory. For instance, the simplest model can be constructed by assigning the left-handed third family quark-field $\psi_L$, the right-handed top quark $t_R$, and an $SU(2)_W$-singlet quark $\chi$ in the following representations of $SU(3)_1 \times SU(3)_2 \times SU(2)_W \times U(1)_{Y}$

$$\psi_L : (3, \ 1, \ 2, \ +1/3), \quad \chi_R : (3, \ 1, \ 1, \ +4/3), \quad t_R, \quad \chi_L : (1, \ 3, \ 1, \ +4/3).$$

(17)

Topcolor will cause the following $t$ ($b$) and $\chi$ bound state scalar field

$$\varphi = \left(\frac{\chi_R t_L}{\chi_R b_L}\right)$$

(18)

which behaves like a Higgs doublet whose VEV breaks the electroweak symmetry. Furthermore, the VEV of $\varphi$ will cause a dynamical mass $m_{t\chi} \sim 600$ GeV, and the dynamics in this theory causes a seesaw mechanism for the mass terms in the $\chi - t$ sector which leads to the following top quark mass

$$m_t \approx m_{t\chi} \frac{\mu_{t\chi}}{\mu_{\chi\chi}},$$

(19)

where $\frac{\mu_{t\chi}}{\mu_{\chi\chi}}$ is determined by the dynamics and can yield the desired top quark mass.

This theory has several advantages. (a) In this model, one of the particles responsible for the EWSBM is just the known top quark, and the $SU(2)_W$-doublet nature of the Higgs field just
comes from the same nature of the third family quarks. (b) The new quark $\chi$ introduced in this theory is $SU(2)_W$-singlet so that there is no large custodial symmetry violation causing a too large $T$. (c) The problem of predicting a too large $S$ in technicolor theories due to introducing many technifermion-doublets does not exist in the present theory since there is only one top quark condensate. (d) Unlike the original top quark condensate model which leads to a too large top quark mass, the present theory can give rise to the desired top quark mass via the seesaw mechanism.

There can be various ways of building realistic models in this theory. Very recently, two realistic models which can fit all the precision electroweak data have been built in Ref. 22. We briefly review these two models.

The first model is a one-Higgs-doublet model with the composite Higgs field $\varphi$ defined in (18). The precision data can be fitted with $m_H \sim 0.5 - 1$ TeV

$$m_H \sim 0.5 - 1 \text{ TeV}$$

(20)
corresponding to $m_\chi \sim 5 - 8$ TeV. The lower limit of $m_H$ is $m_H|_{\min} = 159$ GeV corresponding to $m_\chi \to \infty$.

The second model is a two-Higgs doublet model. In addition to the $SU(2)_W$-singlet quark $\chi$ introduced in (17), another $SU(2)_W$-singlet quark in the representation

$$\omega_R : (3, 1, 1, -2/3), \quad b_R, \omega_L : (1, 3, 1, ! -2/3)$$

(21)
is introduced. Then, $\chi_R$ and $\omega - R$ can form a doublet

$$\lambda_R = \begin{pmatrix} \chi_R \\ \omega_R \end{pmatrix}$$

(22)
and two composite Higgs doublets can be formed by the composite object

$$\overline{\lambda_R} \psi_L.$$  

(23)
It contains the three would-be Goldstone bosons and five Higgs bosons: two CP even neutral scalar Higgs fields $h^0$ and $H^0$, one CP odd pseudoscalar Higgs field $A^0$, and a pair of charged Higgs $H^\pm$. The precision data can be fitted with

$$m_A \sim 100 \text{ GeV}, \quad m_{h^0} \sim m_{H^0} \sim m_{H^\pm} \sim 800 \text{ GeV}$$

(24)
corresponding to $m_\chi \sim 3 - 5$ TeV and $m_\omega \sim 12$ TeV.

These results are obtained from quite complicated arrangements of the gauge group $G$ [22], and there may exist some extra scalar (pseudoscalar) bound states in the theory[22].

Due to the nonperturbative nature of the strong interaction dynamics, it is hard to make precision predictions from the strongly interacting EWSM. However, some models contain extra heavy gauge bosons below 1 TeV, and most of the models contain certain model-dependent PGBs with masses in the region of few hundred GeV. Their effects can be experimentally tested.

Direct productions of PGBs have been extensively studied in the literature [24, 25]. It is shown that the detection are possible but not all easy.

Since the top quark couples to the EWSB sector strongly due to its large mass, a feasible way of testing the strongly interacting EWSBM is to test the extra gauge boson and PGB effects in top quark productions at high energy colliders. This kind of study has been carried out in various papers [26]. The conclusions of these studies are that not only the PGB effects can be detected, but also different models can be experimentally distinguished (also can be distinguished from the MSSM) by measuring the production cross sections and the invariant mass distributions [27].
4 Model-Independent Probe of Electroweak Symmetry Breaking Mechanism

We have seen that there are various kinds of EWSBMs proposed. We do not know whether the actual EWSBM in the nature looks like one of them or not. Therefore, only testing the proposed models seems to be not enough, and certain model-independent probe of the EWSBM is needed. Since the scale of new physics is likely to be several TeV, electroweak physics at energy $E \leq 1$ TeV can be effectively described by the electroweak effective Lagrangian in which composite fields are approximately described by effective local fields. The electroweak effective Lagrangian is a general description (including all kinds of models) which contains certain yet unknown coefficients whose values are, in principle, determined by the underlying dynamics. Different EWSBMs give rise to different sets of coefficients. The model-independent probe is to investigate through what processes and to what precision we can measure these coefficients in the experiments. From the experimental point of view, the most challenging case of probing the EWSBM is that there is no light scalar resonance found below 1 TeV. We shall take this case as the example in this review. Effective Lagrangian including a light Higgs boson has also been studied in the literature [2]. In the case we are considering, the effective Lagrangian is the so-called electroweak chiral Lagrangian (EWCL) which is a Lagrangian for the would-be Goldstone bosons $\pi^a$ in the nonlinear realization $U = e^{i\tau^a \pi^a/f_\pi}$ with electroweak interactions. The bosonic sector of which, up to the $p^4$-order, reads [1, 28]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_G + \mathcal{L}_S,$$

where $\mathcal{L}_G$ is the weak gauge boson kinetic energy term, and

$$\mathcal{L}_S = \mathcal{L}^{(2)} + \mathcal{L}^{(2)'} + \sum_{n=1}^{14} \mathcal{L}_n,$$

with

$$\mathcal{L}^{(2)} = \frac{f_\pi^2}{4} \text{Tr}[(D_\mu U)\dagger(D^\mu U)] \quad \text{and} \quad \mathcal{L}^{(2)'} = \ell_0 \frac{f_\pi^2}{4} \left[ \text{Tr}(T\nu) \right]^2,$$

$$\mathcal{L}_1 = \ell_1 \frac{f_\pi^2}{2} \frac{g}{2} B_{\mu\nu} \text{Tr}(T\mathcal{W}^{\mu\nu}) \quad \text{and} \quad \mathcal{L}_2 = \ell_2 \frac{f_\pi^2}{2} \frac{ig}{2} B_{\mu\nu} \text{Tr}(T[\nu^\mu, \nu^\nu]),$$

$$\mathcal{L}_3 = \ell_3 \frac{f_\pi^2}{2} i g \text{Tr}(\mathcal{W}_{\mu\nu}[\nu^\mu, \nu^\nu]) \quad \text{and} \quad \mathcal{L}_4 = \ell_4 \frac{f_\pi^2}{4} \left[ \text{Tr}(\nu^\mu \nu^\nu) \right]^2,$$

$$\mathcal{L}_5 = \ell_5 \frac{f_\pi^2}{4} \left[ \text{Tr}(\nu^\mu \nu^\nu) \right]^2 \quad \text{and} \quad \mathcal{L}_6 = \ell_6 \frac{f_\pi^2}{4} \left[ \text{Tr}(\nu^\mu \nu^\nu) \right] \text{Tr}(T\nu^\mu) \text{Tr}(T\nu^\nu),$$

$$\mathcal{L}_7 = \ell_7 \frac{f_\pi^2}{4} \left[ \text{Tr}(\nu^\mu \nu^\nu) \right] \text{Tr}(T\nu^\mu) \text{Tr}(T\nu^\nu) \quad \text{and} \quad \mathcal{L}_8 = \ell_8 \frac{f_\pi^2}{4} \frac{g}{2} \left[ \text{Tr}(T\mathcal{W}^{\mu\nu}) \right]^2,$$

$$\mathcal{L}_9 = \ell_9 \frac{f_\pi^2}{2} \frac{g}{2} \text{Tr}(T\mathcal{W}^{\mu\nu}) \text{Tr}(T[\nu^\mu, \nu^\nu]) \quad \text{and} \quad \mathcal{L}_{10} = \ell_{10} \frac{f_\pi^2}{2} \frac{1}{2} \left[ \text{Tr}(T\nu^\mu) \text{Tr}(T\nu^\nu) \right]^2,$$

$$\mathcal{L}_{11} = \ell_{11} \frac{f_\pi^2}{4} g e^{\mu\nu\rho\lambda} \text{Tr}(T\nu^\mu) \text{Tr}(\nu^\rho \mathcal{W}^{\nu^\lambda}) \quad \text{and} \quad \mathcal{L}_{12} = \ell_{12} \frac{f_\pi^2}{2} g \text{Tr}(T\nu^\mu) \text{Tr}(\nu^\rho \mathcal{W}^{\nu^\lambda}),$$

$$\mathcal{L}_{13} = \ell_{13} \frac{f_\pi^2}{4} \frac{gg'}{4} e^{\mu\nu\rho\lambda} \text{Tr}(T\mathcal{W}^{\mu\nu}) \text{Tr}(T\mathcal{W}^{\rho\lambda}),$$

$$\mathcal{L}_{14} = \ell_{14} \frac{f_\pi^2}{4} \frac{g^2}{8} \epsilon_{\mu\nu\rho\lambda} \text{Tr}(T\mathcal{W}^{\mu\nu}) \text{Tr}(T\mathcal{W}^{\rho\lambda}).$$

(27)
in which \( D_\mu U = \partial_\mu U + igW_\mu U - igUB_\mu \), \( \nu_\mu \equiv (D_\mu U)U^\dagger \), and \( T \equiv U\tau_3U^\dagger \).

The coefficients \( \ell \)'s reflect the strengths of the \( \pi^a \) interactions, i.e. the EWSBM. \( \ell_1, \ell_0 \) and \( \ell_8 \) are related to the oblique correction parameters \( S, T \) and \( U \), respectively; \( \ell_2, \ell_3, \ell_9 \) are related to the triple-gauge-couplings; \( \mathcal{L}_{12}, \mathcal{L}_{13} \) and \( \mathcal{L}_{14} \) are CP-violating. The task now is to find out experimental processes to measure the yet undetermined \( \ell \)'s.

Note that \( \pi^a \) are not physical particles, so that they are not experimentally observable. However, due to the Higgs mechanism, the degrees of freedom of \( \pi^a \) are related to the longitudinal components of the weak bosons \( V_L^a (W_L^\pm, Z_L^-) \) which are experimentally observable. Thus the \( \ell \)'s are able to be measured via \( V_L^a \)-processes. So that we need to know the quantitative relation between the \( V_L^a \)-amplitude (related to the experimental data) and the GB-amplitude (reflecting the EWSB mechanism), which is the so-called *equivalence theorem* (ET). ET has been studied by many papers, and the final precise formulation of the ET and its rigorous proof are given in Refs. \[29\]. The precise formulation of the ET is

\[
T[V_L^{a_1}, V_L^{a_2}, \cdots] = C \cdot T[-i\pi^{a_1}, 1\pi^{a_2}, \cdots] + B , \tag{28}
\]

with

\[
E_j \sim k_j \gg M_W, \quad ( j = 1, 2, \cdots, n ) ,
\]

\[
C \cdot T[-i\pi^{a_1}, -i\pi^{a_2}, \cdots] \gg B , \tag{29}
\]

where \( T[V_L^{a_1}, V_L^{a_2}, \cdots] \) and \( T[-i\pi^{a_1}, -i\pi^{a_2}, \cdots] \) are, respectively, the \( V_L^a \)-amplitude and the \( \pi^a \)-amplitude, \( E_j \) is the energy of the \( j \)-th external line, \( C \) is a gauge and renormalization scheme dependent constant factor, and \( B \) is a process-dependent function of the energy \( E \). By taking special convenient renormalization scheme, the constant \( C \) can be simplified to \( C = 1 \) \[29\]. In the EWCL theory, the \( B \)-term may not be small even when the center-of-mass energy \( E \gg M_W \), and it is not sensitive to the EWSB mechanism. Therefore the \( B \)-term serves as an intrinsic background when probing \( \pi^a \)-amplitude via the \( V_L^a \)-amplitude in (28). Only when \( |B| \ll |C \cdot T[-i\pi^{a_1}, -i\pi^{a_2}, \cdots]| \) the probe can be sensitive. In Ref. \[29\], a new power counting rule for semi-quantitatively estimating the amplitudes in the EWCL theory was proposed, and with which a systematic analysis on the sensitivities of probing the EWSB mechanism via the \( V_L^a \) processes were given. The results are summarized in Table 1.

We see that the coefficients \( \ell \)'s can be experimentally determined via various \( V_L^a \) processes at various phases of the LHC and the LC (including the \( e\gamma \) collider) complementarily. Without the LC, the LHC itself is not enough for determining all the coefficients. Quantitative calculations on the determination of the quartic-\( V_L^a \)-couplings

**TABLE I.** Probing the EWSB Sector at High Energy Colliders: A Global Classification for the NLO Bosonic Operators. Quoted from Ref. 28.

(Notations: \( \sqrt{\ } = \) Leading contributions, \( \triangle = \) Sub-leading contributions, and \( \perp = \) Low-energy contributions. Notes: \[1\] Here, \( \mathcal{L}_{13} \) or \( \mathcal{L}_{14} \) does not contribute at \( O(1/\Lambda^2) \). \[1\] At LHC(14), \( W^+W^+ \rightarrow W^+W^+ \) should also be included.)
Determining the coefficients $\ell_4$ and $\ell_5$ at the 1.6 TeV LC has been carried out in Ref. 30. The results are shown in Fig. 2 which shows that with polarized electron beams, $\ell_4$ and $\ell_5$ can be determined at a higher accuracy. Determination of custodial-symmetry-violating-term coefficients $\ell_6$ and $\ell_7$ via the interplay between the $V_LV_L$ fusion and $VVV$ production has been studied in Ref. 31.

| Operators | $\mathcal{L}^{(2)}$ | $\mathcal{L}_{1,13}$ | $\mathcal{L}_{2,6,7}$ | $\mathcal{L}_{4,4,5}$ | $\mathcal{L}_{8,8,14}$ | $\mathcal{L}_{9,9}$ | $\mathcal{L}_{10,10}$ | $\mathcal{L}_{11,11}$ | $\mathcal{L}_{12,12}$ | $T_1$ | $B$ | Processes |
|-----------|-----------------|--------------------|-----------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|------|------|-----------|
| LEP-I (S,T,U) | ⊥ ⊥ ⊥ | ⊥ ⊥ | ⊥ ⊥ | ⊥ ⊥ | ⊥ ⊥ | $g^4\frac{E_2}{E}E_3 \parallel g^2\frac{M_W}{E}$ | $e^{-e^+} \rightarrow Z \rightarrow f\bar{f}$ |
| LEP-II | ⊥ ⊥ ⊥ | ⊥ ⊥ | ⊥ | ⊥ | ⊥ | $g^2\frac{E_2}{E}E_3 \parallel g^2\frac{M_W}{E}$ | $f\bar{f} \rightarrow W^-W^+/\ell(\ell LL)$ |
| LC(0.5)/LHC(14) | ⊥ ⊥ ⊥ | ⊥ | ⊥ ⊥ | ⊥ | ⊥ | $g^2\frac{E_2}{E}E_3 \parallel g^2\frac{M_W}{E}$ | $f\bar{f} \rightarrow W^-W^+/\ell(\ell LT)$ |
| LC(1.5)/LHC(14) | ⊥ ⊥ ⊥ | ⊥ | ⊥ ⊥ | ⊥ | ⊥ | $g^2\frac{E_2}{E}E_3 \parallel g^2\frac{M_W}{E}$ | $f\bar{f} \rightarrow ZZZ/(\ell LL)$ |
| LHC(14) | ⊥ ⊥ ⊥ | ⊥ | ⊥ ⊥ | ⊥ | ⊥ | $g^2\frac{E_2}{E}E_3 \parallel g^2\frac{M_W}{E}$ | $f\bar{f} \rightarrow W^-W^+/\ell(\ell LT)$ |
| LC($\gamma\gamma$) | ⊥ ⊥ ⊥ | ⊥ | ⊥ ⊥ | ⊥ | ⊥ | $g^2\frac{E_2}{E}E_3 \parallel g^2\frac{M_W}{E}$ | $Ze^{-} \rightarrow \nu_{e}W^{-}Z, e^{-}WW/(\ell LL)$ |

**Fig. 2.** Determining the coefficients $\ell_4$, $\ell_5$ at the 1.6 TeV $e^+e^-/e^-e^-$ LC’s. The ±1σ exclusion contours are displayed. (a) unpolarized case; (b) the case of 90%(65%) polarized $e^- (e^+)$ beam. The thick solid lines are contributions from certain simple theoretical models. Quoted from Ref. 30.
Once the coefficients $\ell_n$s are measured at the LHC and the LC, the next problem needed to solve is to study what underlying theory will give rise to this set of coefficients. Only with this theoretical study the probe of the EWSB mechanism can be complete. Such a study is difficult due to the nonperturbative nature, and there is no such kind of systematic study yet.

This kind of study is similar to the problem of deriving the Gasser-Leutwyler Lagrangian for low lying pseudoscalar mesons (the chiral Lagrangian) from the fundamental theory of QCD. Very recently, some progress in this case has been made in Ref. 33 in which the Gasser-Leutwyler Lagrangian is formally derived from the first principles of QCD without taking approximations, and all the coefficients in the Gasser-Leutwyler Lagrangian are expressed in terms of certain Green’s functions in QCD, which can be regarded as the QCD definitions of the Gasser-Leutwyler coefficients. The method in Ref. 33 can be applied to the electroweak theory to make the above desired study.

VII. Conclusions

Despite of the success of the SM, its EWSB sector is still not clear. The assumed elementary Higgs boson in the EWSM has not been found, and the present LEP2 bound on the Higgs boson mass is $m_H > 107.7$ GeV. Since the EWSB mechanism concerns the understanding of the origin of particle masses, the probe of it is a very interesting and important topic in current particle physics. The SM Higgs sector suffers from the well-known problems of triviality and unnaturalness, so that the EWSB sector may concern new physics. From various analyses in Sec. 2, we see that the Z-pole precision data do not necessarily imply the existence of a light Higgs boson. So that the search for the Higgs boson should be carried out in the whole possible energy range up to 1 TeV. If a light Higgs boson (elementary or composite) exists, it can certainly be found, as we have seen, at the future high energy colliders such as the LHC, the LC (including the $\gamma\gamma$ and $e\gamma$ colliders), etc. The LC has the advantage of low hadronic backgrounds. After finding the Higgs boson, we have to further study its properties to see if it is just the EWSM Higgs boson, or a Higgs boson in a more complicated new physics model (e.g. the MSSM), or it is composite.

If there is no light Higgs boson, the EWSB mechanism must be strongly interacting. Some strongly interacting EWSB models contain extra heavy gauge bosons below 1 TeV, and many strongly interacting EWSB models contain certain pseudo Goldstone bosons (PGBs) in the few hundred GeV range characterizing the models. Therefore, a feasible way of probing the EWSN mechanism in this case is to test the extra gauge boson and PGB effects in certain processes at the high energy colliders, especially in top quark production processes. Another way of probing the EWSB mechanism, which is most direct but not easiest, is the study of the longitudinal weak boson reactions at high energy colliders. it is specially important if there is neither light Higgs boson nor a light resonance related to the EWSM mechanism below 1 TeV. We have seen that there can be a general model-independent probe of the EWSB mechanism from measuring the coefficients in the EWCL via the study of longitudinal weak boson reactions. We have also seen that those coefficients can all be measured at the LHC and the LC, and for this purpose, the LHC alone is not enough.

In summary, particle physics will be in a crucial status of clarifying the choice of different directions of new physics when we go to the TeV energy scale. The LHC and the LC will be important equipments for studying TeV physics and will help us to know to which direction we should further go.
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