LINEAR $\sigma$ MODEL FOR THE GOLDSTONE $H$ – EXPERIMENTAL TESTS

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In order to explore a possible dynamical nature for the Higgs field (such as its being a pseudo-Goldstone boson) we develop a renormalizable Lagrangian based on the minimal $SO(5)$ linear $\sigma$-model with the symmetry softly broken to $SO(4)$, including gauge bosons and fermions. We then present the phenomenological implications and constraints from precision observables and the impact on present and future LHC data.

1 Motivation

The LHC data in 2012 showed the existence of a spin zero particle of mass around 125 GeV\textsuperscript{1,2}. This has been identified with the boson of the Brout-Englert-Higgs mechanism\textsuperscript{3,4,5} (for simplicity, from here on just called the “Higgs boson”), responsible for the mass of the Standard Model (SM) particles.

However, theoretical considerations like the so-called electroweak (EW) hierarchy problem pose questions about the naturalness of an elementary scalar. In particular, about the lightness of the Higgs boson with respect to any higher new scale that couples to it. The simpler way to sort this out is to try to protect its mass through a symmetry, like in supersymmetry, composite Higgs, little Higgs... The Higgs boson is thus an excellent window to look into the dynamics of the spontaneous electroweak symmetry breaking (EWSB).

In this work we focus on a framework in which the Higgs is a pseudo-Goldstone boson. This idea was suggested by the fact that the only other elemental scalars already existing in the SM are the Goldstone bosons of the EWSB. In particular, our model is inspired by the composite Higgs framework\textsuperscript{a}, first proposed in a seminal paper\textsuperscript{6}, where all Goldstone bosons originate from the spontaneous breaking of a global $SU(5)$ group into $SO(5)$ at some high scale $\Lambda$; such that $\Lambda \leq 4\pi f$, where $f$ corresponds to the pion scale $f_\pi$, in analogy to chiral symmetry breaking in QCD. Recent implementations seek to produce just the minimal set that provides the Higgs and the three longitudinal components of the EW gauge bosons, which is achieved by an $SO(5) \rightarrow SO(4)$ breaking scheme\textsuperscript{7}.

In the absence of an explicit breaking of the global symmetry the Higgs boson is massless, as the other three Goldstone bosons generated. Therefore, some additional explicit breaking of $SO(5)$ is needed. This is provided through the coupling of the $SO(5)$ sector\textsuperscript{b} to the SM fermions and gauge bosons and results in an effective potential whose minimum breaks spontaneously the EW symmetry at scale $v$, which is determined by the Fermi decay constant. This scale is in

\textsuperscript{a} Also in theories such as “little Higgs” or models based on extra dimensions the Higgs is considered to have a Goldstone boson origin.

\textsuperscript{b} Besides the scalar multiplet, the $SO(5)$ sector contains also some vectorial heavy fermions which will mix directly to the SM ones. For brevity, we will omit here the details of these; which can be consulted in the paper\textsuperscript{8}. 

general different from $f$, being the difference between them a known source of fine-tuning in this type of theories. The breaking also provides the Higgs particle with a mass so it becomes a pseudo-Goldstone boson.

Most of the literature on composite Higgs uses an effective non-linear approach to study the models\cite{9,10,11,12,13}. Instead, we study here a renormalizable model, a particular UV completion of those, which includes a new scalar, $\sigma$, singlet under the EW gauge group. This extra scalar gets a mass due to the spontaneous breaking of $SO(5)$. By varying it one can sweep from the linear, weakly coupled regime (light $\sigma$ particle) to the non-linear one ($m_\sigma \to \infty$), where one should fall onto the standard effective approach. Another advantage of this model is that it might be considered as a renormalizable UV completion of some deeper dynamics; such as the so-called linear $\sigma$ model for QCD at low energies\cite{14}, but it can be also regarded as a renormalizable model made out of elementary fields.

2 The $SO(5)/SO(4)$ scalar sector

We have defined\cite{8} a complete Lagrangian composed of pure gauge, scalar and fermionic parts and their interactions. However, here we will just focus on the scalar sector; which instead of being the usual SM Higgs sector is now substituted by a Higgs-$\sigma$ sector. Thus we will consider the five scalars in the fundamental of $SO(5)$:

$$\phi = (\pi_1, \pi_2, \pi_3, h, \sigma)^T \quad \overset{u.g.}{\rightarrow} \quad (0, 0, 0, h, \sigma)^T, \quad (1)$$

where $h$ corresponds to the Higgs particle and $\sigma$ is the extra scalar aforementioned. For simplicity, from now on, we will work in the unitary gauge (u.g.); where the three components, $\pi_i$, associated with the longitudinal components of the EW gauge bosons are set to zero.

The potential

$$V(h, \sigma) = \lambda \left( h^2 + \sigma^2 - f^2 \right)^2 + \alpha f^3 \sigma - \beta f^2 h^2 \quad (2)$$

contains one term ($\lambda$) parametrizing the spontaneous breaking and two terms ($\alpha$ and $\beta$) which break $SO(5)$ explicitly, while preserving the $SO(4)$ symmetry. The inclusion of these terms can be argued through the computation of the one-loop Coleman-Weinberg effective potential; since they are needed as counterterms to absorb the divergences generated (see Appendix in the full paper\cite{8}). Terms like these have also been used in a previous attempt in this direction\cite{15}, where phenomenology is discussed in a simpler fermionic setup.

Due to the explicit breaking, both $\sigma$ and $h$ acquire a non-trivial vev and, as a consequence, they mix in the light and heavy mass eigenstates, which will be parametrized by an angle $\gamma$.

From the kinetic scalar Lagrangian, which contains the interaction with the SM gauge bosons through the covariant derivative, it is easy to show that the vev of $h$ should correspond to the EW scale in order to yield the observed $W$ and $Z$ masses

$$\mathcal{L}_{s, \text{kin}} = \frac{1}{2} (D_\mu \phi)^T (D^\mu \phi) \quad \rightarrow \quad \langle h \rangle = v = 246 \text{ GeV}. \quad (3)$$

In order to understand the parameter space of the model, we show in Fig. 1 the scalar mixing versus the mass of $\sigma$ for the known Higgs mass and vev. We find that the Higgs being a pseudo-Goldstone boson philosophy only holds in the white region on the bottom right corner of the plot, where $h$ has the smaller vev and mass. There is another region, on the top left corner, where $h$ is also a pseudo-Goldstone boson; despite being heavier. This is because in this area the allowed mixing is large, thus inverting the $h$ and $\sigma$ character inside the mass eigenstates. Despite its phenomenological interest, due to naturalness reasons, we will focus in the $m_\sigma > m_h$ white area in what follows.
Figure 1 – Parameter space for the scalar mixing and $\sigma$ mass for the observed Higgs mass and vev. The brown region corresponds to $\langle \sigma \rangle \equiv v < v$; while in the white region, $v < v_s$. The pseudo-Goldstone boson in each region corresponds to that with the smaller vev. In the red region, $f_2 < 0$, and thus the spontaneous symmetry breaking is lost. The relative importance of the explicit breaking is shown through the $\beta/\lambda$ and $\alpha/\beta$ curves.

3 Phenomenology

Precision tests

We have computed the contributions of scalars and exotic fermions to precision parameters $\Delta S$ and $\Delta T$\textsuperscript{16}. In brief, as shown in the left plot in Fig. 2, the fermionic contribution is typically quite spread in $\Delta T$; while the deviations from the SM due to the $\sigma$ particle push $\Delta S$ and $\Delta T$ towards positive and negative values, respectively. Thus, in general, including a lighter $\sigma$ in the model will help alleviate the tension with precision parameters.

Figure 2 – Left: coloured points stand for the contribution from exotic fermions alone; blue, green, red and grey represent $1\sigma$, $2\sigma$, $3\sigma$ and $> 4 \sigma$ deviations from the SM, respectively; from a global fit to $S$, $T$ and the modification to $Z_b b_L$, and black dots are the contribution of the $\sigma$ scalar. Centre: bounds on scalar parameters from current LHC data (fundamentally diboson searches\textsuperscript{17,18,19,20}). Right: future prospects for the 14 TeV LHC run with an integrated luminosity of $3 \text{ab}^{-1}$\textsuperscript{21}, assuming a 5% precision on Higgs couplings. The production of the $\sigma$ particle is assumed to be dominated by gluon fusion, due to the large gluon pdfs. This is somewhat model-dependent, depending on the coupling between the $\sigma$ and the exotic fermions.

The $\sigma$ particle and LHC data

In the centre and right plots in Fig. 2 we show the bounds from different LHC searches for heavy scalars translated onto the parameter space of our model. We have determined the excluded grey area from the modification to the couplings of $h$ to fermions and gauge bosons\textsuperscript{22}. In contrast to the precision tests, where a lighter $\sigma$ is preferred, in order to consider the Higgs as a pseudo-Goldstone boson, the parameters allowed in the plots need to be to the right of the black curve. This sets a lower bound of around $m_\sigma > 550$ GeV from current data, which can be pushed above 900 GeV in the future. This is a consequence of the underlying symmetry
of the model; while in analyses for a generic scalar singlet that mixes with $h$ the allowed region would be the whole white area.

**Can the $\sigma$ be the 750 GeV diphoton excess?**

The 750 GeV diphoton excess observed by ATLAS and CMS\textsuperscript{22} could be explained by a zero-spin resonance such as the $\sigma$ scalar. However, there are reasons to consider this somewhat unnatural. First, both the production through gluon fusion and the decay into photons are loop induced and too small to account for the signal unless the mixing is made extremely suppressed in order to prevent a large decay into $WW$ and $ZZ$. A tiny mixing angle leads to a very fine-tuned $\alpha$ against $\beta$ parameter and, moreover, for 750 GeV, we would fall onto the red area in figure 1, where no spontaneous symmetry breaking takes place. Another way out would be to provide a larger amount of heavy fermions to increase the multiplicities in the loops.

### 4 Conclusions

We have analysed in depth a linear framework for the Higgs as pseudo-Goldstone boson. The model contains an extra scalar, $\sigma$, whose mass acts as the ultraviolet scale. A light $\sigma$ particle is found to help decrease part of the tension with precision tests; while LHC data together with naturalness considerations impose a lower bound on its mass.

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