The ubiquitous pseudo-scalar in composite Higgs models

A S Cornell[a,1], **A Deandrea**[b,2], **B Fuks**[c,3,4] **and L Mason**[d,1,2]

[1] Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa,
[2] Université de Lyon, F-69622 Lyon, France: Université Lyon 1, Villeurbanne CNRS/IN2P3, UMR5822, Institut de Physique Nucléaire de Lyon,
[3] Laboratoire de Physique Theorique et Hautes Energies (LPTHE), UMR 7589, Sorbonne Université et CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France,
[4]Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France.

E-mail: [a]acornell@uj.ac.za, [b]deandrea@ipnl.in2p3.fr, [c]fuks@lpthe.jussieu.fr, [d]220031336@student.uj.ac.za

Abstract. We focus on composite models with a fermion-gauge underlying description, in which the Higgs boson is identified as a Goldstone mode of a larger broken symmetry group. Such an extension of the scalar sector offers solutions to several conceptual issues with the Standard Model, and phenomenological model building of non-minimal theories will provide an important input for further studies. A generic prediction of these models is the presence of additional resonances, which arise as pseudo-Nambu-Goldstone bosons of a broken global symmetry. In the following, the light singlet pseudo-scalar ubiquitous to all such composite Higgs theories is modelled, paving the way for non-minimal composite Higgs studies.

1. Introduction

In 2012 the ATLAS and CMS experiments at CERN announced the discovery of the Higgs boson [1, 2], measured to have a mass of 125 GeV. However, while this discovery has completed the spectrum predicted by the Standard Model (SM), it has brought into focus several issues with the theory, whose Higgs sector is now faced with a variety of problems. Spontaneous symmetry breaking (SSB), widely accepted as the method of mass generation for the electroweak gauge bosons, is modelled rather than explained as a consequence of the theory. A second question is presented by the hierarchy problem, which describes the way in which the Higgs boson, which sits at the electroweak scale unshielded from higher energies [3], receives quadratically large loop corrections to its mass.

A composite Higgs (CH) model replaces the SM Higgs sector with fundamental gauge dynamics by postulating the existence of a new strong sector. In the following, we will describe a class of CH models which are based on a gauge theory featuring fermionic matter. The models are defined in terms of a confining gauge interaction called hypercolour, where the fundamental fermions are irreducible representations of this hypercolour group [4]. CH models will undergo chiral symmetry breaking of a global group of the fundamental fermions G to a subgroup H, whose pattern will depend on the underlying gauge dynamics [3], as the breaking is achieved through the bilinear condensate of the underlying fermions [5]. The symmetry breaking produces pseudo-Nambu-Goldstone Bosons (pNGBs), including the Higgs doublet. These models, which notably do not include fundamental scalars, are considered for the reason that they may provide a UV-complete theory [6].

The confining dynamics governing the Higgs sector in a CH model solve the hierarchy problem [4], as the tension due to naturalness is removed by allowing these quadratically diverging contributions to the Higgs boson mass only up to some compositeness scale. The Higgs is modelled as a bound state of a new strongly interacting force with a TeV confinement scale, and continues to receive contributions to its mass by low energy virtual quanta as would an elementary scalar. However, the shorter wavelengths of higher energy quanta are able to resolve the finite size of the CH boson. As the energy of the mass contributions surpasses the compositeness scale, the CH boson is transparent to the quanta [7], screening the quadratic growth and resulting in a steep fall in the contributions with energy. The ability of the theory to naturally generate the Higgs boson mass allows us in turn to explain the scale of electroweak symmetry breaking (EWSB).

In CH models of this nature there always exists an anomaly-free $U(1)$ global symmetry, acting on all species of fermions [4]. Condensates of the underlying fermions result in SSB of $U(1)$ symmetries, which are also explicitly broken by the fermion masses and the gauging of the SM symmetries [10]. The CH models that we will consider postulate the existence of additional resonances, which are bound states of the underlying fermions [8]. While the details of these additional resonances depend on the model structure, the Higgs boson and a pNGB a are always present [10, 11]. The pNGB a, a pseudo-scalar and a singlet under the gauge symmetries of the SM, is the subject of this work. We will consider the case where a is light. The postulated existence of such additional resonances may be used in direct physics searches at the Large Hadron Collider (LHC) and at future colliders, and may be considered as a first indication for the mechanism of partial compositeness. In the following, a new model has been produced in order to simulate the production and dynamics of the light a, which paves the way for further non-minimal CH studies.

2. A Composite Higgs Model

The SM Higgs potential can be written as [9]

$$V(h) = -\mu^2|H|^2 + \lambda|H|^4, \tag{1}$$

where $\langle H\rangle = v/\sqrt{2}$ is the vacuum expectation value (vev), with $v = 246$ GeV [9], and where the vev is obtained by minimising the scalar potential. As SSB may only arise if the vacuum of the field in question is non-vanishing under the symmetry, the vev of the Higgs field is crucial for the pattern of EWSB.

When the global symmetry group is broken by the underlying gauge dynamics, a number of pNGB are produced. For a model to be considered a CH model, we must have a Higgs doublet generated in the coset. We must therefore have that $SU(2) \times U(1)$ is embeddable within H. In a CH scenario we observe two separate phase transitions; first, at the higher compositeness scale, the free fundamental fermions condense into composite states. This is the scale at which the global symmetry group G, which governs the fundamental fermions, is broken to some subgroup H. The usual transition then occurs at the electroweak scale, where the Higgs boson develops a vev [12]. The pattern of chiral symmetry breaking in a given CH model is governed by the dimension of the underlying gauge group (the number of fermionic matter fields), and the subgroup to which the symmetry breaks [3].

In completing a CH model, it is necessary to provide mass to the fermions, as well as to break the electroweak symmetry [3]. One method of providing mass to SM particles is that of partial compositeness, which is constructed by the inclusion of a second species of fermion χ in a separate irreducible representation of the hypercolour group. In a CH model with a fermion-gauge completion which includes the mechanism of partial compositeness, we must then include at least two species of underlying fermions, ψ and χ, belonging to different irreducible representations of the confining group G [13].

2.1. Symmetry breaking

The CH model requires a global symmetry breaking to occur, through which the vector bosons are given mass and a Higgs boson is generated. Goldstone's theorem states that there shall arise at least one massless scalar boson whenever there is a spontaneously broken global symmetry, written $G \to H$. These (massless) bosons, called Goldstone bosons (GBs) or Nambu-Goldstone bosons (NGBs), span the coset G/H [14]. However, when the initial symmetry was originally explicitly broken by some small amount, the spontaneous breaking of this symmetry will give rise to a pNGB, which will have a non-zero mass.

In a given CH model, when G is dynamically broken to some subgroup H, there will be $n = \dim(G) - \dim(H)$ NGB produced in the G/H coset [7]. Several of the NGB are "eaten" in order to provide longitudinal degrees of freedom to the electroweak gauge bosons, as in conventional EWSB.

For a theory with a given species of N_f Dirac fermions, we may only have two possible unbroken global flavour symmetries; $SU(2N_f)$ for a (pseudo-)real fermion representation, or $SU(2N_f) \times SU(2N_f)$ for a complex fermion representation [3]. For a given representation, the chiral symmetry breaking may then follow

$$SU(2N_f) \to SO(2N_f) \tag{2}$$

in the case of a real representation, and

$$SU(2N_f) \to Sp(2N_f) \tag{3}$$

for pseudo-real [3]. We are therefore able to discard the generally recognised minimal CH model [16] which follows the coset structure $SO(5)/SO(4)$, as the global symmetry cannot be constructed using an underlying fundamental fermionic matter theory [3].

The most minimal cosets which may give rise to a CH scenario are then [3]

$$SO(6) \sim SU(4) \to Sp(4) \sim SO(5), \tag{4}$$

obtained with an underlying $SU(2)$ gauge theory, where the coset contains 5 pNGBs; the Higgs doublet and an additional CP-odd singlet, which is the pNGB a.

$$SU(5) \to SO(5), \tag{5}$$

which produces 14 GBs, and

$$SU(6) \to SO(6), \tag{6}$$

which features two Higgs doublets. The pNGB a arises in each case.

2.2. Particle content

In a CH model we expect a low energy spectrum which includes, as the name indicates, a Higgs boson which is expected to be composite. This is accompanied by exotic composite scalars, some of which are ubiquitous to all CH models. All models contain at least two species of underlying fermions, χ and ψ, belonging to different irreducible representations of the confining hypercolour group [13]. During the breaking of the global symmetry we may have the electroweak coset ($\psi\psi$ condensate), the QCD coset ($\chi\chi$ condensate) and two $U(1)$ singlets, a and η' [4]. These singlets, associated with the Abelian symmetries $U(1)_{\chi,\psi}$, occur if both species of fermion condense [10].

The two mass eigenstates, a and η', are then subject to some mixing, and their masses receive contributions from the masses of the underlying fermions, ψ and χ, and the anomalous $U(1)$ combination [4].

The light pNGB on which we focus, a, is associated to the global $U(1)$ symmetry, and occurs when at least one fermion species condenses. It results from the breaking of a non-anomalous $U(1)$ charge by the chiral condensate in the Higgs sector, and will therefore carry electroweak quantum numbers [4]. The pNGB η' expected in addition to the a is a coloured octet, associated to the anomalous $U(1)$ charge, which may arise as a result of the underlying fermions χ which are responsible for the mechanism of partial compositeness [13]. The mechanism of partial compositeness may therefore be indicated by the presence of pNGBs.

The light a can be produced at the LHC via gluon-gluon fusion. By specifying the underlying theory we can predict the couplings to other states [4]. We are interested in the case where only the non-anomalous pseudo-scalar is light, but the anomalous $U(1)$ scalar may also be light in other theories.

3. Model construction

In this first implementation, the composite pseudo-scalar a is added to the SM. This new resonance is self-conjugate, and expected to have a mass of less than 100 GeV. In order to describe it, the SM Lagrangian is augmented with the following effective Lagrangian [10]

$$\begin{aligned}\mathcal{L} =& \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2}m_a^2 a^2 - \Sigma_f \frac{iC_f m_f}{f_a} a\bar{\Psi}_f\gamma^5\Psi_f \\ &+ \frac{g_s^2 K_g}{16\pi^2 f_a} aG^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W}{16\pi^2 f_a} aW^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2 K_B}{16\pi^2 f_a} aB_{\mu\nu}\tilde{B}^{\mu\nu},\end{aligned} \tag{7}$$

where C_f, K_g, K_W and K_B are model-specific parameters determining the coupling to gauge bosons, and f_a and f_ψ are the decay constants of the pseudo-scalar and Higgs boson respectively. The models are numbered M1 - M12, and are based upon the underlying fermionic representation, featuring a variety of hypercolour and flavour cosets. The parameters of the models are described in Ref. [10]. They are based upon a class of theories with two distinct cosets associated respectively to the electroweak quantum numbers and colour [10].

The fermion coupling term can be examined via an expansion in its component spinors

$$\begin{aligned}\bar{\Psi}_f\gamma^5\Psi_f &= (\bar{\Psi}_L + \bar{\Psi}_R)\gamma^5(\Psi_L + \Psi_R) \\ &= \bar{\Psi}_L\Psi_R - \bar{\Psi}_L\Psi_L + \bar{\Psi}_R\Psi_R - \bar{\Psi}_R\Psi_L \\ &= \bar{\Psi}_L\Psi_R - \bar{\Psi}_R\Psi_L\end{aligned} \tag{8}$$

where the terms composed of two $SU(2)$ singlets disappear. The two remaining terms, composed of a doublet and a singlet under $SU(2)$, are not gauge invariant. In order to construct the model it is then necessary to couple to them the Φ field as in a SM Yukawa Lagrangian, after which we obtain additional interactions of the type $Ha\bar{\Psi}_f\Psi_f$.

Additionally, couplings to the Higgs boson and Z bosons are included at loop level, and are written as [10]

$$\mathcal{L}_{haa} = \frac{3C_t^2 m_t^2 \kappa_t}{8\pi^2 f_a^2 v}\log\frac{\Lambda^2}{m_t^2} h\left(\partial_\mu a\right)\left(\partial^\mu a\right), \tag{9}$$

$$\mathcal{L}_{hZa} = \frac{3C_t m_t^2 g_A}{2\pi^2 f_a v}\left(\kappa_t - \kappa_V\right)\log\frac{\Lambda^2}{m_t^2} h\left(\partial_\mu a\right) Z^\mu. \tag{10}$$

The pseudo-scalar Lagrangian therefore depends on the free parameters m_a, f_a and f_ψ.

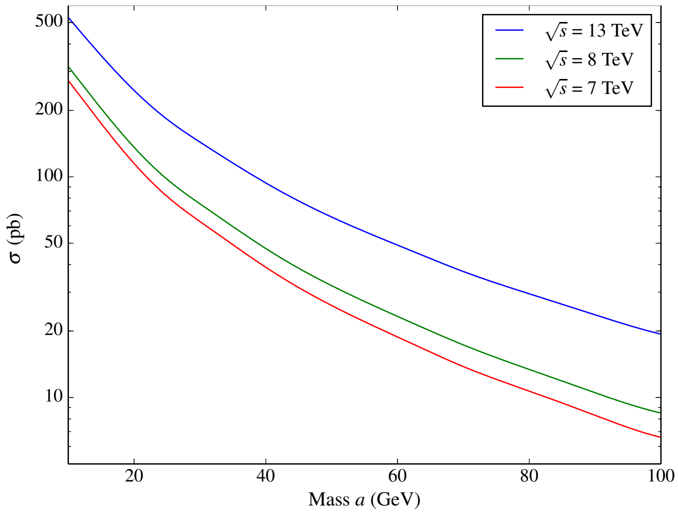

Figure 1. The gluon gluon fusion cross section for a range of LHC energies over the mass range of the light pNGB a.

3.1. FeynRules implementation

In this work we have constructed a new FeynRules [17] implementation of an additional pseudo-scalar a. The model includes small a couplings to SM leptons, quarks, and gauge bosons, where the gauge boson couplings are anomalous couplings which include contributions by top loops. The implementation of the model includes a scan over the mass of the pseudo-scalar, which is free, where the results have been verified by comparison to those of Ref. [10], with good initial agreement.

This light pNGB is expected to be produced copiously via gluon-gluon fusion, where the cross section is plotted in figure 1 for a sample of LHC energies. In this figure the coupling of the pseudo-scalar to gluons has been considered as an effective vertex, but in reality we may expect significant contributions from top and bottom quark loops, particularly for higher masses of a. Branching ratios to quarks and leptons have been calculated, a sample of which are plotted in figure 2.

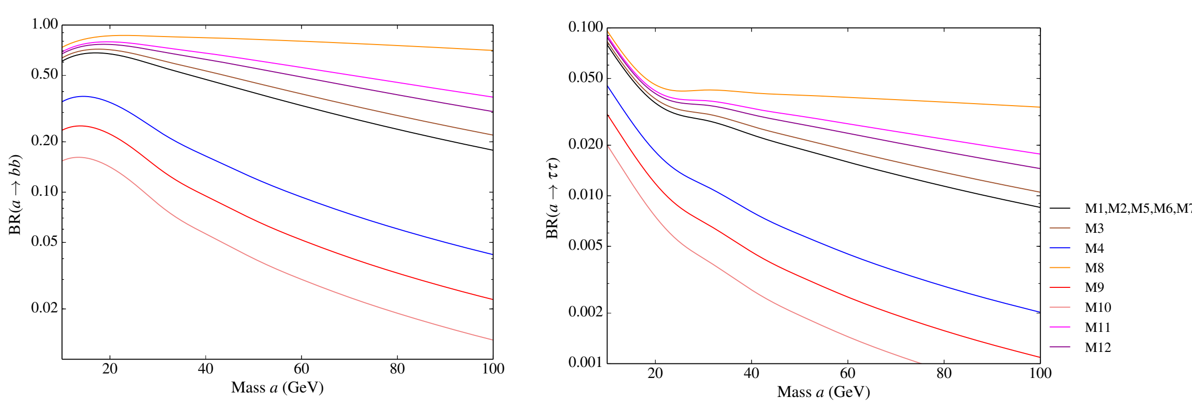

Figure 2. Branching ratios of a to b quarks (left) and τ leptons (right) for each model.

The model, which has been implemented here, offers the possibility of extensions to larger

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symmetry groups and non-minimal CH models, as well as forming the basis of phenomenology on which LHC investigations may be based. As a next step, the effective couplings may be replaced by the complete leading order vertices by the inclusion of top and bottom loops, which may afford a better understanding of the couplings of the pseudo-scalar to gauge bosons.

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