Top compositeness, Flavor and Naturalness

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We discuss the connection between the top quark, naturalness and flavor in composite Higgs models. The phenomenological features of the top quark and the associated fermionic partners are presented. The main realizations of the flavor structure, in particular the anarchic partial compositeness scenario and its possible modifications, are also briefly reviewed.

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1 Introduction: Top Partners and Naturalness

Together with the Higgs boson, the top quark is one of the main actors in beyond the Standard Model (SM) theories. Its sizable Yukawa coupling, $y_{\text{top}}$, generates the largest radiative corrections to the Higgs potential. If these corrections are too large, which is the case if the SM has a large cut-off $\Lambda_{\text{SM}}$, a sizable amount of cancellation is required to obtain the correct Higgs mass. This is the origin of the well-known naturalness problem. To be more quantitative we can evaluate the amount of fine-tuning by comparing the physical Higgs mass $m_H \simeq 125$ GeV with the leading one-loop corrections. In such a way we can estimate the (minimal) amount of fine-tuning to be

$$\Delta \geq \frac{\delta_{\text{1-loop}} m_H^2}{m_H^2} = \frac{3y_{\text{top}}^2}{8\pi^2} \left( \frac{\Lambda_{\text{SM}}}{m_H} \right)^2 \simeq \left( \frac{\Lambda_{\text{SM}}}{450 \text{ GeV}} \right)^2.$$  \hspace{1cm} (1)

It is clear that, in order to obtain a completely natural (i.e. not fine tuned) theory, the SM cut-off must be close to the electroweak (EW) scale. The UV dynamics, moreover, must be “connected” to the top quark, in such a way to “screen” its radiative contributions to the Higgs potential. In such models the $\Lambda_{\text{SM}}$ scale can be typically identified with the mass of some “partners” of the top, which must be below or around the TeV scale to avoid too much tuning.

This conclusion proves correct in basically all classical beyond the SM (BSM) theories that aim to solve the naturalness problem. A well known example is low-energy supersymmetry, in which bosonic partners of the top, the ‘stops’, are present, which regulate the quadratic divergence in the radiative top contributions to the Higgs mass.

In the following we will focus on another class of theories, in which the Higgs boson is not an elementary state as in the SM, but instead a composite object arising from a new strongly-coupled dynamics. This idea reached nowadays a compelling embodiment, the “composite Higgs” (CH) scenario (see [1,2] for reviews). Its main assumption is the identification of the Higgs with a pseudo-Goldstone boson [3], corresponding to an SO(5)/SO(4) coset in minimal models [4].

An additional ingredient is the generation of the top mass through the partial-compositeness mechanism [5] (we will discuss this point in detail in sec. 4). Under this assumption the SM states, which are external with respect to the composite sector (with the possible exception of the $t_R$ component), are mixed with suitable composite operators. In the low-energy description these couplings can be effectively parametrized through mass mixings of the elementary states with composite fermionic resonances. As can be easily understood, the resonances corresponding to the top quark, the ‘top partners’, play a central role in the EW dynamics. First of all they give rise to the top Yukawa coupling and, second, they control the generation of the Higgs potential and therefore the amount of fine-tuning. Top partners constitute one of the most compelling predictions of CH models and are one of the privileged ways to test directly these scenarios.

Higgs and top compositeness have other important implications for phenomenology. One of them is a quite specific pattern of deviations in the Higgs and top couplings, which can be tested in collider experiments. Another interesting aspect is the flavor structure, which is deeply influenced by partial compositeness. We will discuss all these aspects in the following sections.

2 Phenomenology of Top Partners

Goldstone symmetry and partial compositeness determine the main properties of top partners. Being part of the composite sector, they necessarily fill extended EW multiplets corresponding to representations of the unbroken custodial group SO(4) ≃ SU(2)_L × SU(2)_R. Since they mix with the top quarks, top partners must be charged under QCD transforming in the fundamental of SO(3).
As we mentioned the top and its partners give rise to the leading contribution to the Higgs potential through radiative effects. The size of the Higgs mass term is controlled by the typical mass of the top partners (roughly coinciding with the mass of the first complete SO(5) representation of states). Light top partners are thus needed to reduce the fine tuning \[7\]. The amount of tuning can be easily estimated through eq. (1) identifying \(\Lambda_{\text{IR}}\) with the top partners mass. Notice that this is a only a lower bound on the fine-tuning, since in several models peculiarities of the structure of the Higgs potential require additional cancellations \[7\].

Top partners can be copiously produced at hadron colliders since they are colored objects. For low masses the dominant production channel is QCD pair production, whose cross section only depends on the resonance mass. This channel can thus be used to extract model-independent bounds on top partners. An additional production channel is single production in association with a top or a bottom quark. This channel crucially depends on the EW gauge couplings that mix the SM quarks with the composite partners and is thus model-dependent \[8\]. It is more relevant for high partner masses, since its cross section decreases more slowly than pair production.

To give an idea of the LHC reach on top partners we show in fig. 1 some projections for the bounds on typical top partners multiplets at the 13 TeV LHC \[9\] (updated bounds can be found in \[10\]). Current bounds from pair production are of order 1.2 TeV, basically independent of the top partner quantum numbers. Single production bounds instead are more sensitive to the details of the model. In the plots we also show the estimates of the minimal amount of fine-tuning obtained from eq. (1). One can see that configurations with relatively low tuning (\(\sim 10\%\)) are still allowed at present, whereas the end of the LHC program will test parameter space points up to \(\sim 1\%\) tuning.

In minimal CH scenarios, such as the holographic MCHM constructions \[4\], the mass of the lightest top partners can be directly related to the compositeness scale \(f\), corresponding to the Goldstone Higgs decay constant \[6\]. In this case the bounds from top partners direct searches can be translated into a lower bound on \(f\). Current exclusions correspond to \(f \gtrsim 800\) GeV (or \(\xi = v^2/f^2 \lesssim 0.1\), where \(v = 246\) GeV is the Higgs VEV), while the end of the LHC program could push the bound to \(f \gtrsim 1.1\) TeV (\(\xi \lesssim 0.05\) \[9\]).

### 3 Top Couplings

The CH set-up gives rise to peculiar deviations in the Higgs and top couplings. The main effects are the modification of Yukawa and gauge interactions and the presence of 4-top effective operators.
All these effects are controlled by the Goldstone symmetry. The couplings to the gauge fields are affected in a universal way. In models based on the $\text{SO}(5) \rightarrow \text{SO}(4)$ symmetry structure, the couplings to the $W$ and $Z$ bosons are rescaled by a factor $\kappa_V = \sqrt{1-\xi}$. The Yukawa couplings, on the other hand, are modified in a way that depends on the quantum numbers of the fermion partners. Popular scenarios are the ones in which the SM fermions are mixed with operators in the fundamental $\text{SO}(5)$ representation, in which case the top Yukawa is rescaled by a factor $\kappa_F = (1 - 2\xi)/\sqrt{1-\xi}$, or in the spinorial representation, which gives $\kappa_F = \sqrt{1-\xi}$.

The LHC measurement of the Higgs couplings can be used to derive robust bounds on the value of $\xi$. The current data give a bound $\xi \lesssim 0.1$ (they are derived in scenarios in which the bottom and top Yukawa’s are modified in the same way, however similar bounds are typically found in more generic models) \cite{11}. The present constraints are roughly a factor of two stronger than the expected ones, due to a positive shift in the central value fit of $\kappa_V$. High-luminosity LHC data are not expected to significantly improve the bounds if the central value will move closer to the SM prediction, whereas the bound could change substantially if some deviation will persist.

It is interesting to notice that values $\xi \simeq 0.1$ allow for sizable deviations in the top Yukawa. In models with composite operators in the fundamental $\text{SO}(5)$ representation corrections $\delta m_{\text{top}} \simeq 15 - 20\%$ are still compatible with the experimental data. Such deviations could be tested by the direct determination of the top Yukawa in Higgs associated production with a $t\bar{t}$ pair.

Other interesting modifications arise for the gauge interactions involving the top quark. Viable models typically require a discrete custodial $\mathcal{P}_{\text{LR}}$ symmetry to keep under control the $Z$ couplings to the bottom field \cite{12}, which are tested at the 0.1% level. This symmetry, however, can not protect at the same time the top interactions. Deviations of order $\xi$ are thus generically present, induced both by the mixing if the top with its partners and by the presence of vector resonances that mix with the SM gauge fields. Deviations in the $Zt_Lt_L$ coupling are constrained by the EW precision measurement to be $|\delta g_{Zt_L}| \lesssim 8\%$ \cite{13}. The $Zt_Rt_R$ interaction, on the other hand, is much more elusive, since its SM value is suppressed, and is basically unconstrained.

Another coupling that can receive sizable modifications is $Wt_Lb_L$, which corresponds to the $V_{tb}$ CKM element. In minimal models with custodial $P_{\text{LR}}$, deviations in this coupling are related to the corrections in the $Zt_Lt_L$ vertex, namely $\delta g_{Zt_L} = \delta V_{tb}$ \cite{14}. The bounds on $\delta V_{tb}$ can imply non-trivial constraints on the top partners parameter space, which can be competitive with direct searches for heavy resonances (see for instance the right panel of fig. 1).

Finally the sizable mixing of the top with its composite partners gives rise to effective 4-fermion contact interactions of the type $\mathcal{O} = c/f^2(\overline{t}_\mu t)^2$. The coefficient $c$ parametrizes the amount of mixing of the top with its partners and takes values $c \sim 1$ for sizable top compositeness. Contact 4-top interactions can be tested in $tt\bar{t}t$ production at the LHC. The current bounds are of order $c/f^2 \lesssim 1/(590 \text{ GeV})^2$ \cite{15}.

### 4 Flavor Structure

Let’s now discuss the implications for flavor physics. Contrary to models with an elementary Higgs, in which the Yukawa structure can originate in the far UV, in CH models the origin of flavor must be addressed at much lower energies. Since the Higgs is associated with a composite operator $\mathcal{O}_H$ whose dimension must satisfy $d_H > 2$ to avoid the hierarchy problem, the Yukawa interactions $\bar{f}_L\mathcal{O}_H f_R$ have dimension larger than 4 and are irrelevant operators. If $\bar{f}_L\mathcal{O}_H f_R$ is generated at very high energies fermion masses are necessarily too small. To be more quantitative, if $d_H \gtrsim 2$, the maximal energy scale at which a realistic top Yukawa can be generated is $\Lambda_t \lesssim 10 \text{ TeV}$.

The classical approach to flavor in composite Higgs models is based on the partial compositeness
idea, in which the SM fermions get masses by mixing linearly with strong sector operators $L_{\text{lin}} = \varepsilon_{f_i} \bar{T}_i O_f$. At the strong scale, $\Lambda_{\text{IR}} \sim \text{TeV}$, the fermion Yukawa’s are generated with a pattern $\mathcal{Y}_f \sim g_s \varepsilon_{f_i} \varepsilon_{f_j}$, where $g_s$ is the typical strong-sector coupling. The appealing feature of this scenario, usually dubbed “anarchic partial compositeness” \cite{5,16}, is the fact that the smallness of the mixings $\varepsilon_{f_i}$ can simultaneously explain the smallness of the fermion masses and mixing angles.

This set-up, however, also predicts sizable flavor-violating effects. Large contributions are expected for the neutron EDM and for $\epsilon_K$, which force the $\Lambda_{\text{IR}}$ scale to be of order 10 TeV requiring a significant amount of tuning \cite{2,17}. The situation is even worse if anarchic partial compositeness is naively extended to the lepton sector, in which case corrections to the electron EDM and large $\mu \to e\gamma$ transitions require $\Lambda_{\text{IR}} \gtrsim 100 \text{ TeV}$ \cite{2}.

A possible way to avoid large flavor effects is to introduce flavor symmetries, assuming that the right-handed quarks are fully-composite objects \cite{18}. Although these models can pass the flavor bounds for $\Lambda_{\text{IR}} \sim \text{TeV}$, they predict sizable deviations in dijet distributions and large production cross sections for multi-TeV resonances that translate in stringent collider bounds \cite{19}.

A recently proposed departure from the classical anarchic paradigm can be used to avoid severe flavor and CP-violating constraints \cite{20,21}. The main idea is to assume that the operators $O_{f_i}$, that mediate the mixing between the SM fermions and the Higgs, decouple at different energy scales $\Lambda_{f_i} \gg \Lambda_{\text{IR}} \sim \text{TeV}$. This implies that Yukawa-like couplings $\bar{T}_i O_H f_j$ are generated at scales larger than $\Lambda_{\text{IR}}$, avoiding sizable flavor and CP-violating effects. The hierarchies in the fermion spectrum and the smallness of the mixing angles is now explained in a “dynamical” way by the different $\Lambda_{f_i}$ scales: the larger the decoupling scale, the smaller the Yukawa coupling. In this set-up the only Yukawa that needs to be generated at a low scale is the top one, so that the usual partial compositeness structure will still be valid for the top sector. All the other Yukawa’s can be generated at significantly higher scales, up to $\sim 10^7 \text{ TeV}$ for the first-generation fermions.

The structure of the Yukawa matrix for the down quark sector is approximately

$$Y_{\text{down}} \simeq \begin{pmatrix} Y_d & \alpha_{d}^{s} Y_d & \alpha_{d}^{b} Y_d \\ \alpha_{d}^{s} Y_d & Y_{s} & \alpha_{d}^{s} Y_{s} \\ \alpha_{d}^{b} Y_d & \alpha_{d}^{b} Y_{s} & Y_{b} \end{pmatrix},$$

where $Y_i$ denote the SM Yukawa’s and $\alpha_{L,R}$ are numerical coefficients typically of order one. An analogous formula holds for the up sector. The off-diagonal terms are much smaller than in the anarchic case (in particular for the up sector), leading to a suppression of flavor-changing effects.

In this scenario the leading flavor and CP-violating effects arise from the top partial compositeness \cite{21}. Additional contributions originating at the decoupling scale of the other SM fermions are instead well below the current bounds. The leading effects come from the two operators

$$(1/\Lambda_{\text{IR}}) (\bar{Q}_{L3} \gamma^\mu Q_{L3})^2, \quad (g_\ast / \Lambda_{\text{IR}}) \bar{Q}_{L3} \gamma^\mu Q_{L3} i H D_{\mu} H.$$  \hspace{1cm} (3)

After the rotation to the mass eigenstate basis, these two operators give rise to $\Delta F = 2$ and $\Delta F = 1$ transitions respectively. An interesting consequence is the fact that these corrections automatically follow a minimal flavor violation structure, thus significantly ameliorating the compatibility with the experimental data. The current constraints (in particular from $\epsilon_K, \Delta M_B, \epsilon'/\epsilon, K \to \mu\mu$ and $B \to (X)\ell\ell$) can be satisfied for $\Lambda_{\text{IR}} \sim \text{few TeV}$.

Remarkably, the extension of this construction to the lepton sector avoids large corrections to the electron electric dipole moment (EDM) and $\mu \to e\gamma$, relaxing the strong bounds of anarchic models to the level $\Lambda_{\text{IR}} \sim \text{few TeV}$ \cite{21}. The leading bounds arise from two-loop Barr–Zee contributions to the electron EDM involving a loop of the top and its partners. The present experimental bounds
allow to test partner masses of order few TeV, whereas near future experiments will improve the reach by more than one order of magnitude, testing the natural parameter space of these models [10].

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