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Working Technicolor at the LHC

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Summary. — In this talk, we will review the possibility to brake the electroweak symmetry in a dynamical way. We present a class of phenomenologically viable Walking Technicolor models, finally we analyze the potential of the Large Hadron Collider to observe signatures from this kind of models.

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1. – Introduction

The energy scale at which the Large Hadron Collider (LHC) experiment operates is determined by the need to complete the Standard Model (SM) of particle interactions and, in particular, to understand the origin of the ElectroWeak Symmetry Breaking (EWSB). Together with classical general relativity the SM constitutes one of the most successful models of nature. We shall, however, argue that experimental results and theoretical arguments call for a more fundamental description of nature.

The SM can be viewed as a low-energy effective theory valid up to an energy scale Λ. Above this scale new interactions, symmetries, extra dimensional worlds or any other extension could emerge. At sufficiently low energies with respect to this scale one expresses the existence of new physics via effective operators. The success of the SM is due to the fact that most of the corrections to its physical observables depend only logarithmically on this scale Λ. In fact, in the SM there exists only one operator which acquires corrections quadratic in Λ. This is the squared mass operator of the Higgs boson. Since Λ is expected to be the highest possible scale, in four dimensions the Planck scale (assuming that we have only the SM and gravity), it is hard to explain *naturally* why the mass of the Higgs is of the order of the Electroweak (EW) scale. This is the hierarchy problem. Due to the occurrence of quadratic corrections in the cutoff this SM sector is most sensitive to the existence of new physics.

In the models we will consider here the electroweak symmetry breaks via a fermion bilinear condensate, and the Higgs being a composite object is now free from the naturalness problem. The Higgs sector of the SM becomes an effective description of a more fundamental fermionic theory. This is similar to the Ginzburg-Landau theory of superconductivity. If the force underlying the fermion condensate driving electroweak symmetry breaking is due to a strongly interacting gauge theory these models are termed Technicolor (TC).

2. – From color to technicolor

One of the main difficulties in constructing such extensions of the SM is the very limited knowledge about generic strongly interacting theories. This has led theorists to consider specific models of TC which resemble ordinary QCD and for which the large body of experimental data at low energies can be directly exported to make predictions at high energies. To reduce the tension with experimental constraints new strongly coupled theories with dynamics different from the one featured by a scaled-up version of QCD are needed.

Let us first review the mechanism of EWSB in QCD. In fact even in complete absence of the Higgs sector in the SM the electroweak symmetry breaks [1] due to the condensation of the following quark bilinear in QCD:

$$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \neq 0. \tag{1}$$

This mechanism, however, cannot account for the whole contribution to the weak gauge bosons masses. If QCD was the only source contributing to the spontaneous breaking of the electroweak symmetry one would have

$$M_W = \frac{gF_\pi}{2} \sim 29\,\mathrm{MeV}, \tag{2}$$

with $F_\pi \simeq 93\,\mathrm{MeV}$ the pion decay constant. This contribution is very small with respect to the actual value of the W mass that one typically neglects it.

According to the original idea of TC [2, 3] one augments the SM with another gauge interaction similar to QCD but with a new dynamical scale of the order of the electroweak one. It is sufficient that the new gauge theory is asymptotically free and has global symmetry able to contain the SM $SU(2)_\mathrm{L} \times U(1)_Y$ symmetries. It is also required that the new global symmetries break dynamically in such a way that the embedded $SU(2)_\mathrm{L} \times U(1)_Y$ breaks to the electromagnetic Abelian charge $U(1)_Q$. The dynamically generated scale will then be fit to the electroweak one.

The simplest example of TC theory is the scaled-up version of QCD, *i.e.* an $SU(N_\mathrm{TC})$ non-Abelian gauge theory with two Dirac Fermions transforming according to the fundamental representation or the gauge group. We need at least two Dirac flavors to realize the $SU(2)_\mathrm{L} \times SU(2)_\mathrm{R}$ symmetry of the SM discussed in the SM Higgs section. One simply chooses the scale of the theory to be such that the new pion decaying constant is

$$F_\pi^\mathrm{TC} = v \simeq 246\,\mathrm{GeV}. \tag{3}$$

The flavor symmetries, for any N_TC larger than 2 are $SU(2)_\mathrm{L} \times SU(2)_\mathrm{R} \times U(1)_\mathrm{V}$ which spontaneously break to $SU(2)_\mathrm{V} \times U(1)_\mathrm{V}$ reproducing the correct mass for the $W^\pm$ and Z^0 bosons.

3. – Extended tecnicolor

Since in a purely TC model the Higgs is a composite particle the Yukawa terms, when written in terms of the underlying TC fields, amount to four-fermion operators. The latter can be naturally interpreted as a low-energy operator induced by a new strongly coupled gauge interaction emerging at energies higher than the electroweak theory. These type of theories have been termed Extended Technicolor (ETC) interactions [4, 5].

Without specifying an ETC one can write down the most general type of four-fermion operators involving TC particles Q and ordinary fermionic fields ψ. Following the notation of Hill and Simmons [6] we write

$$\alpha_{ab}\frac{\bar{Q}\gamma_\mu T^a Q\bar{\psi}\gamma^\mu T^b\psi}{\Lambda^2_{\rm ETC}} + \beta_{ab}\frac{\bar{Q}\gamma_\mu T^a Q\bar{Q}\gamma^\mu T^b Q}{\Lambda^2_{\rm ETC}} + \gamma_{ab}\frac{\bar{\psi}\gamma_\mu T^a \psi\bar{\psi}\gamma^\mu T^b\psi}{\Lambda^2_{\rm ETC}}, \tag{4}$$

where the Ts are unspecified ETC generators.

The coefficients parametrize the ignorance on the specific ETC physics. To be more specific, the α-terms, after the TC particles have condensed, lead to mass terms for the SM fermions

$$m_q \approx \frac{g^2_{\rm ETC}}{M^2_{\rm ETC}}\langle\bar{Q}Q\rangle_{\rm ETC}, \tag{5}$$

where m_q is the mass of, *e.g.*, a SM quark, $g_{\rm ETC}$ is the ETC gauge coupling constant evaluated at the ETC scale, $M_{\rm ETC}$ is the mass of an ETC gauge boson and $\langle\bar{Q}Q\rangle_{\rm ETC}$ is the TC condensate where the operator is evaluated at the ETC scale. Note that we have not explicitly considered the different scales for the different generations of ordinary fermions but this should be taken into account for any realistic model.

The β-terms provide masses for pseudo Goldstone bosons and also provide masses for techniaxions [6]. The last class of terms, namely the γ-terms induce FCNCs. For example it may generate the following terms:

$$\frac{1}{\Lambda^2_{\rm ETC}}(\bar{s}\gamma^5 d)(\bar{s}\gamma^5 d) + \frac{1}{\Lambda^2_{\rm ETC}}(\bar{\mu}\gamma^5 e)(\bar{e}\gamma^5 e) + \ldots, \tag{6}$$

The experimental bounds on these type of operators together with the very *naive* assumption that ETC will generate these operators with γ of order one leads to a constraint on the ETC scale to be of the order of or larger than 10^3 TeV [4]. This should be the lightest ETC scale which in turn puts an upper limit on how large the ordinary fermionic masses can be. The naive estimate is that one can account up to around 100 MeV mass for a QCD-like TC theory, implying that the top quark mass value cannot be achieved.

To better understand in which direction one should go to modify the QCD dynamics, we analyze the TC condensate. The value of the TC condensate used when giving mass to the ordinary fermions should be evaluated not at the TC scale but at the ETC one. Via the renormalization group one can relate the condensate at the two scales via

$$\langle\bar{Q}Q\rangle_{\rm ETC} = \exp\left(\int_{\Lambda_{\rm TC}}^{\Lambda_{\rm ETC}} {\rm d}(\ln\mu)\gamma_m(\alpha(\mu))\right)\langle\bar{Q}Q\rangle_{\rm TC}, \tag{7}$$

where γ_m is the anomalous dimension of the techniquark mass operator. The boundaries of the integral are at the ETC scale and the TC one.

The tension between having to reduce the FCNCs and at the same time provide a sufficiently large mass for the heavy fermions in the SM as well as the pseudo-Goldstones can be reduced if the theory has a near conformal fixed point. This kind of dynamics has been denoted as of *walking* type.

In the walking regime

$$\langle \bar{Q}Q\rangle_{\rm ETC} \sim \left(\frac{\Lambda_{\rm ETC}}{\Lambda_{\rm TC}}\right)^{\gamma_m(\alpha^*)} \langle \bar{Q}Q\rangle_{\rm TC}, \tag{8}$$

which is a much larger contribution than in QCD dynamics [7-10]. Here γ_m is evaluated at the would be fixed point value α^*. Walking can help resolving the problem of FCNCs in TC models since with a large enhancement of the $\langle \bar{Q}Q\rangle$ condensate the four-Fermi operators involving SM fermions and technifermions and the ones involving technifermions are enhanced by a factor of $\Lambda_{\rm ETC}/\Lambda_{\rm TC}$ to the γ_m power while the one involving only SM fermions is not enhanced.

Another relevant point is that a near conformal theory would still be useful to reduce the contributions to the precision data and, possibly, provide a light composite Higgs of much interest to LHC physics [11].

4. – Minmal models with walking dynamics

The existence of a new weak doublet of technifermions amounting to, at least, a global $SU(2)_{\rm L}\times SU(2)_{\rm R}$ symmetry later opportunely gauged under the electroweak interactions is the bedrock on which models of TC are built on.

It is therefore natural to construct first minimal models of TC passing precision tests while also reducing the FCNC problem by featuring near conformal dynamics. By minimal we mean with the smallest fermionic matter content. These models were put forward recently in [12, 11]. To be concrete we describe here the Minimal Walking Technicolor extension of the SM.

The extended SM gauge group is now $SU(2)_{\rm TC}\times SU(3)_{\rm C}\times SU(2)_{\rm L}\times U(1)_Y$ and the field content of the TC sector is constituted by four techni-fermions and one techni-gluon all in the adjoint representation of $SU(2)_{\rm TC}$. The model features also a pair of Dirac leptons, whose left-handed components are assembled in a weak doublet, necessary to cancel the Witten anomaly [13] arising when gauging the new technifermions with respect to the weak interactions. Summarizing, the fermionic particle content of the MWT is given explicitly by

$$Q_L^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L, \qquad U_R^a, \qquad D_R^a, \qquad a = 1,2,3, \tag{9}$$

with a being the adjoint color index of $SU(2)$. The left handed fields are arranged in three doublets of the $SU(2)_{\rm L}$ weak interactions in the standard fashion. The condensate is $\langle \bar{U}U + \bar{D}D\rangle$ which correctly breaks the electroweak symmetry as already argued for ordinary QCD in eq. (1).

To discuss the symmetry properties of the theory it is convenient to use the Weyl basis for the fermions and arrange them in the following vector transforming according to the fundamental representation of $SU(4)$

$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 U_R^* \\ -i\sigma^2 D_R^* \end{pmatrix}, \tag{10}$$

where U_L and D_L are the left-handed techniup and technidown, respectively and U_R and D_R are the corresponding right-handed particles. Assuming the standard breaking to the maximal diagonal subgroup, the $SU(4)$ symmetry spontaneously breaks to $SO(4)$. Such a breaking is driven by the following condensate:

$$\langle Q_i^\alpha Q_j^\beta \epsilon_{\alpha\beta} E^{ij} \rangle = -2\langle \overline{U}_R U_L + \overline{D}_R D_L \rangle, \tag{11}$$

where the indices $i, j = 1, \ldots, 4$ denote the components of the tetraplet of Q, and the Greek indices indicate the ordinary spin. The matrix E is a 4×4 matrix defined in terms of the 2-dimensional unit matrix as

$$E = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}. \tag{12}$$

Here $\epsilon_{\alpha\beta} = -i\sigma^2_{\alpha\beta}$ and $\langle U_L^\alpha {U_R}^{*\beta} \epsilon_{\alpha\beta} \rangle = -\langle \overline{U}_R U_L \rangle$. A similar expression holds for the D techniquark. The above condensate is invariant under an $SO(4)$ symmetry. This leaves us with nine broken generators with associated Goldstone bosons, of which three become the longitudinal degrees of freedom of the weak gauge bosons.

Another example is the Next to Minimal Walking Technicolor (NMWT). The theory with three technicolors contains an even number of electroweak doublets, and hence it is not subject to a Witten anomaly. The doublet of technifermions, is then represented again as

$$Q_L^{\{C_1,C_2\}} = \begin{pmatrix} lU^{\{C_1,C_2\}} \\ D^{\{C_1,C_2\}} \end{pmatrix}_L, \qquad Q_R^{\{C_1,C_2\}} = \left(U_R^{\{C_1,C_2\}}, D_R^{\{C_1,C_2\}} \right). \tag{13}$$

Here $C_i = 1, 2, 3$ is the technicolor index and $Q_{L(R)}$ is a doublet (singlet) with respect to the weak interactions. Since the two-index symmetric representation of $SU(3)$ is complex the flavor symmetry is $SU(2)_{\rm L} \times SU(2)_{\rm R} \times U(1)$. Only three Goldstones emerge and are absorbed in the longitudinal components of the weak vector bosons.

Despite the different envisioned underlying gauge dynamics it is a fact that the SM structure alone requires the extensions to contain, at least, the following chiral symmetry breaking pattern (insisting on keeping the custodial symmetry of the SM):

$$SU(2)_{\rm L} \times SU(2)_{\rm R} \to SU(2)_{\rm V}. \tag{14}$$

Based on the previous symmetry breaking pattern we describe the low-energy spectrum in terms of the lightest spin one vector and axial-vector iso-triplets $V^{\pm,0}$, $A^{\pm,0}$ as well as the lightest iso-singlet scalar resonance H. In QCD the equivalent states are the $\rho^{\pm,0}$, $a_1^{\pm,0}$ and the $f_0(600)$. It has been argued in [14], using large-N arguments, and in [11], using the saturation of the trace of the energy momentum tensor, that models of dynamical electroweak symmetry breaking featuring (near) conformal dynamics contain a composite Higgs state which is light with respect to the new strongly coupled scale ($4\pi v$ with $v \simeq 246\,\mathrm{GeV}$). These indications have led to the construction of models of TC with a naturally *light composite* Higgs. Recent investigations using Schwinger-Dyson [15] and gauge-gravity dualities [16] also arrived to the conclusion that the composite Higgs can be light. The 3 technipions $\Pi^{\pm,0}$ produced in the symmetry breaking become the longitudinal components of the W and Z bosons.

The composite spin one and spin zero states and their interaction with the SM fields are described via the following effective Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{\rm boson} = & -\frac{1}{2}\mathrm{Tr}\left[\widetilde{W}_{\mu\nu}\widetilde{W}^{\mu\nu}\right] - \frac{1}{4}\widetilde{B}_{\mu\nu}\widetilde{B}^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\left[F_{\mathrm{L}\mu\nu}F_{\mathrm{L}}^{\mu\nu} + F_{\mathrm{R}\mu\nu}F_{\mathrm{R}}^{\mu\nu}\right] \\
& + m^2\,\mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right] + \frac{1}{2}\mathrm{Tr}\left[D_\mu M D^\mu M^\dagger\right] - \tilde{g}^2\, r_2\, \mathrm{Tr}\left[C_{\mathrm{L}\mu} M C_{\mathrm{R}}^{\mu} M^\dagger\right] \\
& - \frac{i\,\tilde{g}\,r_3}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}\left(M D^\mu M^\dagger - D^\mu M M^\dagger\right) + C_{\mathrm{R}\mu}\left(M^\dagger D^\mu M - D^\mu M^\dagger M\right)\right] \\
& + \frac{\tilde{g}^2 s}{4}\mathrm{Tr}\left[C_{\mathrm{L}\mu}^2 + C_{\mathrm{R}\mu}^2\right]\mathrm{Tr}\left[M M^\dagger\right] + \frac{\mu^2}{2}\mathrm{Tr}\left[M M^\dagger\right] - \frac{\lambda}{4}\mathrm{Tr}\left[M M^\dagger\right]^2 ,
\end{aligned} \tag{15}
$$

where $\widetilde{W}_{\mu\nu}$ and $\widetilde{B}_{\mu\nu}$ are the ordinary electroweak field strength tensors, $F_{\mathrm{L/R}\mu\nu}$ are the field strength tensors associated to the vector meson fields $A_{\mathrm{L/R}\mu}$ and the $C_{\mathrm{L}\mu}$ and $C_{\mathrm{R}\mu}$ fields are

$$
C_{\mathrm{L}\mu} \equiv A_{\mathrm{L}\mu} - \frac{g}{\tilde{g}}\widetilde{W}_\mu\,, \qquad C_{\mathrm{R}\mu} \equiv A_{\mathrm{R}\mu} - \frac{g'}{\tilde{g}}\widetilde{B}_\mu\,. \tag{16}
$$

The 2×2 matrix M is

$$
M = \frac{1}{\sqrt{2}}\left[v + H + 2\,i\,\pi^a\,T^a\right], \qquad a = 1,2,3, \tag{17}
$$

where π^a are the Goldstone bosons produced in the chiral symmetry breaking, $v = \mu/\sqrt{\lambda}$ is the corresponding VEV, H is the composite Higgs, and $T^a = \sigma^a/2$, where σ^a are the Pauli matrices. The covariant derivative is

$$
D_\mu M = \partial_\mu M - i\,g\,\widetilde{W}_\mu^a\,T^a M + i\,g'\,M\,\widetilde{B}_\mu\,T^3. \tag{18}
$$

When M acquires a VEV, the Lagrangian of eq. (15) contains mixing matrices for the spin one fields. The mass eigenstates are the ordinary SM bosons, and two triplets of heavy mesons, of which the lighter (heavier) ones are denoted by $R_1^\pm$ ($R_2^\pm$) and R_1^0 (R_2^0). These heavy mesons are the only new particles, at low energy, relative to the SM.

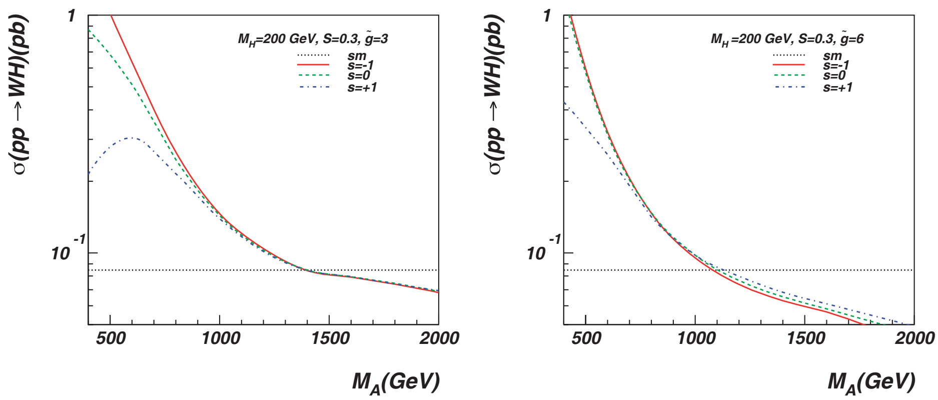

Fig. 1. – The cross section for $pp \to WH$ production at 7 TeV in the center of mass (W^+H and W^-H modes are summed up) *versus* M_A for $S = 0.3$, $s = (+1, 0, 1)$ and $\tilde{g} = 3$ (left) and $\tilde{g} = 6$ (right). The dotted line at the bottom indicates the SM cross section level.

5. – Phenomenological implications

New physics signals are expected from the vector meson and the composite Higgs sectors.

The heavy spin-one resonances, $R^0_{1,2}$ and $R^{\pm}_{1,2}$, can be produced trough DY precesses. In particular very important signature are given by the following processes with lepton signatures:

1) $\ell^+\ell^-$ signature from the process $pp \to R^0_{1,2} \to \ell^+\ell^-$,

2) $\ell + \not{E}_T$ signature from the process $pp \to R^{\pm}_{1,2} \to \ell^{\pm}\nu$,

3) $3\ell + \not{E}_T$ signature from the process $pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$,

where ℓ denotes a charged lepton (electron or muon) and $\not{E}_T$ is the missing transverse energy. A detailed analysis of this and other channel is presented in [17, 18].

The presence of the heavy vectors is prominent in the associate production of the composite Higgs with SM vector bosons, as first pointed out in [19].

The resonant production of heavy vectors can enhance HW and ZH production by a factor 10 as one can see in fig. 1 (right). This enhancement occurs for low values of the vector meson mass and large values of $\tilde{g}$.

6. – Conclusions

We introduced extensions of the SM in which the Higgs emerges as a composite state. In particular we motivated TC, constructed underlying gauge theories leading to minimal models of TC and constructed the low-energy effective theory.

LHC can be sensitive to spin one states as heavy as 2 TeV. One TeV spin one states can be observed already with 100 pb^{-1} integrated luminosity in the dilepton channel. The enhancement of the composite Higgs production is another promising signature.

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