(III) COLLIDER PHENOMENOLOGY

· Top partners

In the discussion about the Higgs potential we saw that the top partners are directly related to the amount of tuning of the CH scenario. In particular, in Natural models light top partners, with a mass $m_* \sim$ TeV, are predicted. Pushing the top partners mass scale to the $\gtrsim 2$ TeV level would already push the CH scenarios into dangerously fine-tuned territory.
This clearly shows that the top partners are a privilegded target to probe the CH idea at collider experiments. In the following I will discuss the main phenomenological properties of these resonances.

As we already anticipated, the quantum numbers of the top partners correspond to the ones of the $\mathcal{O}_F$ operators that are mixed with the SM elementary fields, q_L and t_R. A first consequence of this is the fact that the top partners are charged under QCD and transform as triplets, just like the SM quarks.
The $\mathcal{G}$ (and $\mathcal{H}$) quantum numbers of $\mathcal{O}_F$ are instead not fully fixed. The only requirement is that the $\mathcal{G}$ representation must contain some components with the $G_{EW} = SU(2)_L \times U(1)_Y$ quantum numbers of the quarks, namely

$$q_L \subset 2_{1/6} \quad , \quad t_R \subset 1_{2/3} \quad .$$

The top partners must thus contain at least two multiplets with the same quantum numbers:

$$(T, B) \subset 2_{1/6} \quad , \quad \widetilde{T} \subset 1_{2/3} \, .$$

Moreover, being the $\mathcal{H}$ subgroup unbroken in the composite sector, the top partners must fill complete $\mathcal{H}$ representations. In the $SO(5) \to SO(4)$ minimal scenario, on which we will focus, this implies that the top partners appear in complete $SO(4)$ multiplets. Exotic states accompanying the (T, B) and/or $\widetilde{T}$ states are thus often present.

Actually an additional exotic doublet

$$(X_{2/3}, X_{5/3}) \subset 2_{7/6}$$

is often present, giving rise to partners with electric charge 2/3 and 5/3.
This multiplet, together with (T, B), forms the 4 rep. of $SO(4)$ $(\times U(1)_X)$

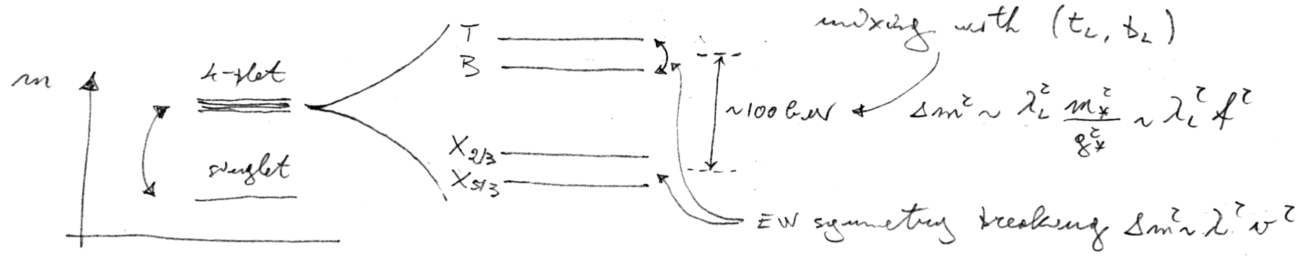
$$4_{2/3} = 2_{1/6} + 2_{7/6} \quad \text{under } SU(2)_L \times U(1)_Y \, .$$

Embedding the $2_{1/6}$ in the 4 of $SO(4)$ is preferred since this allows to avoid large deviations in the $Zb_L\bar{b}_L$ coupling, which is experimentally measured with $\sim 0.1\%$ accuracy.

The $\tilde{T}$ resonance, instead could just be a singlet of $SO(4)$, with $U(1)_X$ charge $2/3$.

Notice that the $4_{2/3}$ and $1_{2/3}$ of $SO(4)\times U(1)_X$ can be embedded in the $5_{2/3}$ of $SO(5)\times U(1)_X$; that is the $O_F^{L,R}$ operators coupling to the top compasits could transform in the fundamental of $SO(5)$.

Let us now analyze the spectrum of the top partners. If we ignore the breaking induced by the mixing with the SM fields, the composite sector is invariant under $SO(4)\times U(1)_X$, thus all the components of a single $SO(4)$ multiplet are degenerate. Notice that this is in general not true for the components of an $SO(5)$ multiplet, since the spontaneous breaking to $SO(4)$ allows to generate different mass terms for the different $SO(4)$ submultiplets.



When the mixing with the SM is taken into account, the $SO(4)$ invariance is mildly broken, so that only the $G_{EW} = SU(2)_L\,(\times U(1)_Y)$ subgroup is unbroken. The $SO(4)$ multiplets thus split into $SU(2)_L$ multiplets. The mass splitting is however small, being controlled by the small mixing with the SM states. In the case of the 4 indeed we get a ~ 100 GeV splitting between the (T, B) and the $(X_{2/3}, X_{5/3})$ doublets, which is typically much smaller than the m_* mass of the 4 plet.

After EW symmetry breaking also $SU(2)_L$ is broken, thus the states inside the multiplets (T,B) and $(X_{2/3}, X_{5/3})$ are split. This effect, however, is even smaller than the $SO(4)$ breaking, since it is suppressed both by the elementary/composite mixings and by v/f factors.

The branching ratios of the top partners are (almost) universal and are fixed by the quantum numbers of the resonances. Non-universal effects are suppressed by v/f factors, thus are usually small.

The branching ratios for the 4-plet and the singlet are summarized by the following table

	Wt	Wb	Zt	ht
$X_{5/3}$	1			
$X_{2/3}$			1/2	1/2
T			1/2	1/2
B	1			
$\tilde{T}$		1/2	1/4	1/4

Being charged under QCD, the top partners can be copiously produced in pairs through QCD interactions. Notice that this production mode is "universal", i.e. the production cross section depends only on the top partner mass.

The present bounds from pair production push the partners to masses

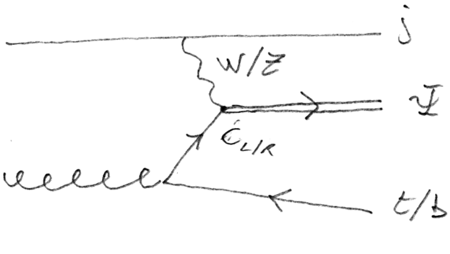
$$m_\Psi \gtrsim 800 - 900 \text{ GeV}$$

almost independently of the considered state and of the decay BR's. Plots of the current bounds are shown in the slides.

Since QCD interactions only allow pair production, this production mode fastly looses efficiency at larger m_Ψ. In this case single production through EW gauge interactions can lead to larger cross sections. The relevant couplings have the form

$$\mathcal{L}_{single} \sim c_{L/R}\, A_\mu\, \bar{\Psi}\, \gamma^\mu\, q_{L/R}$$

where A_μ denotes the W or Z bosons and $q_{L/R}$ are the SM quarks, in particular the top and bottom, whose mixing with the composite dynamics is larger. These interactions lead to single production through diagrams of the form



Single production dominates over pair production for $m_T \gtrsim 1$ TeV for typical k_{LR} couplings, thus can give the possibility to test higher masses not accessible through pair production.

LHC run 2 could test $m_T \sim 1.2 - 1.5$ TeV, but masses above ~ 1.7 TeV are likely unaccessible at LHC, even at the high-luminosity upgrade.

Single production, on the other hand is nowadays not competitive with pair production bounds. However, for typical values of the single production couplings, could allow to test top partners up to ~ 2 TeV at HL-LHC. Of course the limitation of single production is the fact that it is much more model dependent, since it depends on the single production couplings that are not universal.

The current single production bounds are shown in the slides.

· Vector resonances

An additional class of resonances coming from the composite sector are massive vector resonances. The presence of these resonances is a consequence of the global invariance of the composite dynamics. As we saw, the fermionic partners correspond to the composite fermionic operators $O_F^{L,R}$ coupled to the SM fermions, analogously the vector resonances ρ correspond to the global currents J_μ coming from the composite dynamics:

$$\langle \rho | J | 0 \rangle \neq 0 .$$

The quantum numbers of the ρ resonances correspond to the ones of the J_μ currents. The vector resonances are the analog of the ρ, ω and a_1 mesons in QCD.

Notice that the current operators J_μ are coupled to the SM gauge fields in the gauging of the SM subgroup of G:

$$\mathcal{L}_{int} = g A_\mu J^\mu$$

thus the vector resonances can be interpreted as "partners" of the gauge fields.

In minimal models we expect vector resonances with quantum numbers in the adjoint of $SO(5)$

$$10 \rightarrow 3_0 \oplus 1_0 \oplus 1_1 \oplus 2_{1/2} \quad \text{of } SU(2)_L \times U(1)_Y$$

moreover the $U(1)_X$ factor gives rise to an additional singlet.

We also saw that the composite dynamics must be charged under QCD in order to allow partial compositeness, thus vector resonances with the quantum numbers of the gluons are also expected. These resonances are usually called "heavy gluons" or "KK gluons" (borrowing from extra-dimensional theories).

As an example we will consider vector resonances in the 3_0 representation. These states are unavoidable in any CH scenario, since they correspond to the $SU(2)_L$ group which must necessarily be a subgroup of H. Similar results, however, are valid for the other classes of vector resonances (in some cases with obvious modifications). The mass of the vector resonances is expected to be of the order of the energy scale of the composite dynamics, $m_\rho \sim m_*$.

Let's now discuss the couplings of these resonances. Being composite states, their largest couplings are the ones with the other composite states. The typical strength of these couplings is g_*, that is the usual coupling of the strong dynamics.

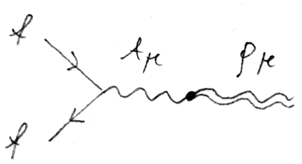
Since the Higgs is also a composite state a sizable coupling of the type

$$\sim g_* \rho^a_\mu \, i H^\dagger \tau^a \overleftrightarrow{D}^\mu H$$

is present. This operator generates couplings of the ρ with the physical Higgs plus couplings with the three longitudinal components of the SM $W^\pm$ and Z massive vector bosons. These couplings mediate the ρ decays:

$$\Gamma_{\rho_0 \to W^+W^-} \simeq \Gamma_{\rho_0 \to Zh} \simeq \Gamma_{\rho_\pm \to W^\pm Z} \simeq \Gamma_{\rho_\pm \to W^\pm h} .$$

Additional couplings with the SM fermions (leptons and quarks) are present. These couplings arise from a mixing of the ρ with the SM gauge fields induced by the weak gauging



$$\sim \frac{g^2}{g_*} .$$

We thus find an interesting result, while the ρ coupling to the gauge bosons increases at large g_*, the coupling to the (light) SM fermions decreases at large g_*.

The coupling to the fermions allows for Drell-Yan production, moreover it allows the decays into leptons, which provide an extremely sensitive final state

$$\Gamma_{\rho_\pm \to \ell^\pm \nu} \simeq 2\, \Gamma_{\rho_\pm \to \ell^+ \ell^-} .$$

Current bounds exclude vector resonances for $m_\rho \lesssim 2$ TeV for not too large g_* ($g_* \lesssim 3$). These bounds are of the same order of additional indirect bounds coming from EW precision measurements. The ρ_0 states indeed generate a tree level correction to S of order

$$\Delta S \sim \frac{m_W^2}{m_\rho^2}$$

which implies a bound $m_\rho \gtrsim 2.5$ TeV.

High luminosity LHC will raise the bound to $m_\rho \gtrsim 4$ TeV, thus becoming more stringent than the EW indirect bounds.

See plots in the slides.