Coloured Scalars in Composite Higgs Model

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Based on arXiv: 1507.02283,
Cacciapaglia, Cai, Deandrea, Flacke, Lee, and Parolini

Introduction

Composite Higgs model (CHM) is an appealing BSM scenario. Composite Higgs realized as a pseudo Goldstone Boson is first proposed by: Georgi, Kaplan, 1984.

One modern variation of CHM is built in the warped AdS5 extra dimension, realizing a holographic Higgs as the fifth component of broken gauge bosons, where the top mass is generated via partial compositeness.
Agashe, Contino, Pomarol, 2005.

We are going to discuss the UV completion to the CHM based on underlying fundamental interactions in a confining gauge group with two species of fermions.
Barnard, Gherghetta, Ray, 2014; Ferretti, 2014.

Minimal case and colored pNGBs

The minimal one contains four weyl techni-fermions Q_i in $\square$ of $Sp(2N_c)$: global symmetry breaking $SU(4) \to SP(4)$, gives 5 pNGBs: $(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$ under the $SU(2)_L \times SU(2)_R$ custodial symmetry.

For colored sector, adding six techni-fermions χ_j in $\begin{array}{|c|}\hline \ \\ \hline \ \\ \hline\end{array}$ of $Sp(2N_c)$ in order to generate top partners. With additonal global symmetry, it leads to more pNGBs, and requires the minimal Hyper-Color group to be $Sp(4)$.
Barnard, Gherghetta, Ray, 2014.

Field content

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$U(1)_Y$	SU(4)	SU(6)	U(1)
Q	$\square$	$\mathbf{1}$	$\mathbf{2}$	1	4	1	$q_Q = -3(N_c - 1)q_\chi$
$Q^\dagger$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$ $-1/2$			
χ	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
$\chi^\dagger$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

Table : Field content of the microscopic fundamental theory and transformation under the gauged symmetry group $\mathrm{Sp}(2N_c)\times\mathrm{SU}(3)_c\times$ $\mathrm{SU}(2)_L\times$ $\mathrm{U}(1)_Y$, and under the global symmetries $\mathrm{SU}(4)\times\mathrm{SU}(6)\times\mathrm{U}(1)$.

EW: $\mathrm{SU}(2)_L \subset \mathrm{SU}(4)$, $\mathrm{U}(1)_Y \subset \mathrm{SU}(4)\times\mathrm{SU}(6)$; QCD: $\mathrm{SU}(3)_c \subset \mathrm{SU}(6)$

Anomaly free $A(U(1)Sp(2N_c)^2) = 0$, i.e. $4 \times T(\square)q_Q + 6 \times T(\begin{smallmatrix}\square\\\square\end{smallmatrix})q_\chi = 0$

Bound states

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
QQ	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
χQQ	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\bar{Q}\bar{Q}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{1},\bar{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{15},\bar{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\bar{Q}\sigma^\mu Q$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\bar{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

Mesons

Baryons

Vectors

Mesons

A first class of particles are the mesons, decompose as:

$$\begin{aligned} \pi &= (1,2,2)_0 \oplus (1,1,1)_0 \,, \\ \pi_c &= (8,1,1)_0 \oplus (6,1,1)_{2x} \oplus (\bar{6},1,1)_{-2x} \,, \\ \sigma(\sigma_c) &= (1,1,1)_0 \,; \end{aligned}$$

corresponding to the representations under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$, and the subscript to the charge under $\mathrm{U}(1)_X$. The hypercharge $Y = T_R^3 + X$.

Since the mass spliting between π_6 and π_8 is small, and for simplicity, they assumed to be degenerate in the collider simulation.

π_6 and π_8 couplings

The couplings to top and bottom of the coloured mesons are obtained via pre-Yukawa interaction:

$$
\begin{aligned}
ig_{\pi_8 t_L t_R^c} &= \frac{m_{\rm top}}{f_6}\frac{2+\cos(2\phi_L)+\cos(2\phi_R)}{2\sqrt{2}} + \ldots\,, \\
ig_{\pi_6 t_R^c t_R^c} &= \frac{M_1}{f_6}\frac{\sin^2\phi_R}{\sqrt{2}} + \ldots\,, \\
ig_{\bar{\pi}_6 t_L t_L} &= 0 + \ldots\,, \\
ig_{\pi_8 b_L b_R^c} &= 0\,;
\end{aligned}
$$

$$
\tan\phi_L = \frac{y_{5L} f}{M_5}\,, \qquad \tan\phi_R = \frac{y_{1R} f}{M_1}\,.
$$

The octet coupling to tops is suppressed by a factor of $m_t/M_1 \sim \mathcal{O}(10^{-1})$ compared with the π_6-t_R-t_R coupling.

Flavor bound

Integrating out the π_6 scalar leads to four quarks interactions. The coefficient of induced operator $(\bar{c}_R \sigma^\mu u_R)(\bar{c}_R \sigma_\mu u_R)$ is nonzero:

$$\frac{|a_R|^2}{m_\Phi^2} \left(V^*_{uR,23} \right)^2 V_{uR,13}{}^2 \sim \frac{10^{-9}}{(1\ \mathrm{TeV})^2} \left(\frac{|a_R|^2}{1} \right) \left(\frac{1\ \mathrm{TeV}}{m_\Phi} \right)^2$$

The $D^0 - \bar{D}^0$ mixing is experimentally bound to be less than 10^{-7}, thus giving a mild bound in a Baryon number conserving theory:

$$m_{\pi_6} > 0.1\, |a_R|\, \mathrm{TeV}\,.$$

Baryon number violation

Including Baryon number violation, one can write a dimension-7 operator:

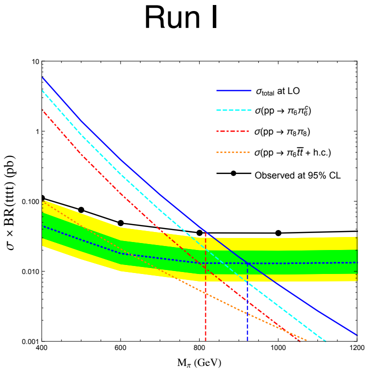
$$\Delta\mathcal{L}_{\rm eff} = c_R\ \pi_6 b_R b_R b_R b_R + h.c.\,, \quad (\Delta B = 2)$$

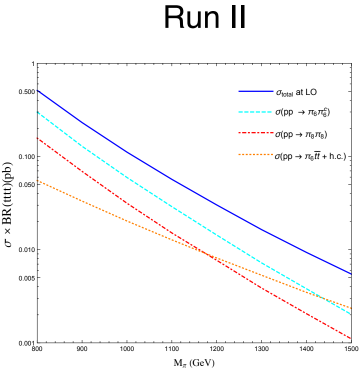
translating to the off-diagonal $n\bar{n}$ oscillation will be:

$$\delta m = O(10^{-33}\ \text{GeV})\left(\frac{a_R}{1}\right)\left(\frac{c_R}{(1\ \text{TeV})^{-3}}\right)\left(\frac{1\ \text{TeV}}{m_{\pi_6}}\right)^2,$$

Assuming $\mathcal{O}(1)$ couplings, this is compatible with experiment for $m_{\pi_6} \sim 1$ TeV.

4t @ LHC Run I and II





Comparison of Run I result with ATLAS 2SSL search, the lower bound is set to be 800 GeV.

Event selection

The 2SSL signature arises from a final state with $4\ b + \ell^{\pm}\ell^{\pm} + 4\ jets + \not{E}_T$. The following event-selection criteria are imposed:

- at least two b-tagged jets
- two same sign leptons and at least 4 additional jets.

  $\Rightarrow$ Ignore the diboson process background.
- basic kinematic cuts:

  $p_T^{\ell,j} > 24$ GeV, $|\eta_{\ell,j}| < 2.5$, $\Delta R_{jj} > 0.4$, $\Delta R_{jl} > 0.4$, $\Delta R_{ll} > 0.4$
- For neutrinos, we require missing energy cut: $\not{E}_T > 40$ GeV
- hard jet cuts: max $(p_T^j) > 100\ \mathrm{GeV}$, and next-max $(p_T^j) > 50\ \mathrm{GeV}$.

  $\Rightarrow$ no influence on the signals, while reducing backgroud by 50%.
- a large scalar sum of transverse momentum i.e. $H_T > 650\mathrm{GeV}$.

  $\Rightarrow$ H_T can distinguish the signals from the SM background.

Cut table - Run II

	$t\bar{t}w^+jj$	$t\bar{t}zjj$	$t\bar{t}w^+w^-$	$t\bar{t}t\bar{t}$	m_π 0.9 TeV
no cut	800	787	11.4	7.40	192
basic cuts ($\not{E}_T > 40\text{GeV}$)	85.1	107	1.60	2.05	64.5
$p_T^{j1} > 100\text{GeV}, p_T^{j2} > 50\text{GeV}$ ($p_T^{\ell^-} < 10\text{GeV}$, or $\|\eta_{\ell^-}\| > 2.5$)	36.4	2.03	0.72	1.83	63.4
$H_T > 650\text{GeV}$	28.1	1.36	0.51	1.68	63.2
Acceptance	3.5%	0.17%	4.5%	23%	33%

Table : Number of events for major backgrounds in the SM and for the signals from the single and pair productions after each cut-criterion, with Acceptance reported in the bottom.

The veto cut for additional negative lepton, in the third row of the cut table, effectively suppresses the $ttZ+$ jets background.

m_{T2} criterion

For events with 2 missing particles with mass of μ_N in two identical decay chains, the quantity m_{T2}^2 is evaluated as the minimum of transverse mass square over all partitions of the measured $\not{p}_T$, i.e.

$$\min_{\not{p}_T^1+\not{p}_T^2=\not{p}_T} \left[\max\{m_T^2(p_T^a,\ \not{p}_T^1;\ \mu_N),\ m_T^2(p_T^b,\ \not{p}_T^2;\ \mu_N)\}\right],$$

Under the correct assignment of (b-ℓ^+) cluster, the m_{T2} method will give us the lower mass bound for the top quark.
Barr, Lester, Stephens, 2003; Cheng, Han, 2008

Thus in the simulation, we mark the combination (b_1, ℓ_1^+) which gives a smaller m_{T2} for the top quark as the best choice.

The m_{T2} efficiency is around 90% for choosing the correct combination, much better than other variables, e.g. invariant mass of $(b\text{-}\ell^+)$ cluster.

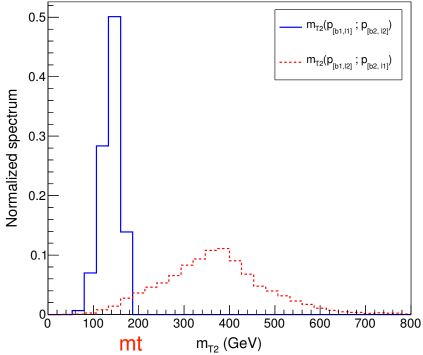


Figure : m_{T2} distributions for two combinations of $b\text{-}\ell^+$, the blue solid line corresponds to the correct combination and the red dashed line corresponds to the switched combination.

Resonance mass peak

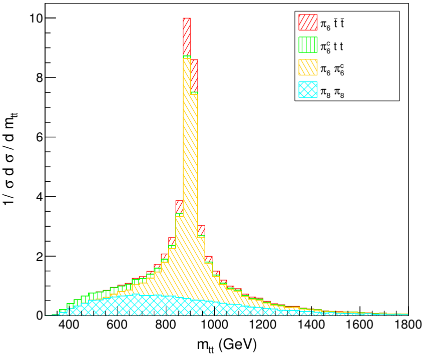


Figure : Invariant mass m_{tt} distribution from dilepton decay after applying the mass reconstruction technology for the case of $m_\pi = 900$ GeV .

Leptonic angular distribution

As the leptonically decayed tt pair will be fully reconstructed , the chiral structure of the top quark can be identified by using the leptonic angular distribution:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{t\ell^+}} = \frac{1}{2}(1 + a\cos\theta_{t\ell^+}),$$

with $a = 1$ for a pure t_R and $a = -1$ for a pure t_L.

We boost the p_{ℓ^+} of the positive lepton into the rest frame of top quark and also boost the p_t into the rest frame of the tt pair .

In this figure, we display the $\cos\theta_{t\ell^+}$ distributions for each channel:

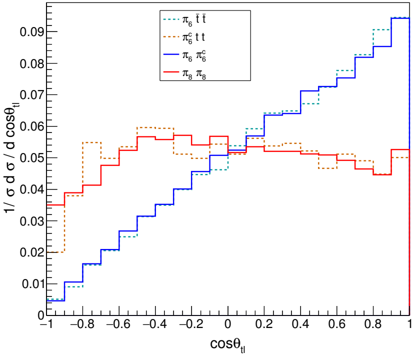


Figure : Leptonic angular distribution relative to the top quark momentum for the events with top quark reconstructed and passing the basic cut. Note that we also impose a mass window selection rule $|m_{tt} - 900 \text{ GeV}| < 100$ GeV.

Conclusion

- We consider UV completion to Dynamic CHMs, one concrete example is based on $SU(4) \times SU(6)/Sp(4) \times SO(6)$, giving arise to a Higgs-like state plus a singlet, as well as a neutral octet and a charged sextet as pNGBs.
- We investigated the possibility of distinguishing the presence of a sextet from a octet in the 2SSL channel of $4t$ final states. The best strategy will be to reconstruct Inv. mass distribution of the resonance.
- With the full reconstruction of the 2 SSL + MET signature, we can use the leptonic angular distribution to differentiate the resonance contribution from the non-resonance one.