DIRECT AND INDIRECT SEARCHES OF HEAVY RESONANCES IN STRONGLY COUPLED PHYSICS BEYOND THE STANDARD MODEL

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CONTENTS

• COMPOSITE HIGGS THEORIES: A MOTIVATION FOR HEAVY RESONANCES

• AN EXAMPLE: THE MINIMAL COMPOSITE HIGGS MODEL (MCHM)

• INDIRECT SEARCHES: ELECTROWEAK PRECISION TESTS

• DIRECT SEARCHES: OBSERVATION AT LHC
COMPOSITE HIGGS THEORIES: A MOTIVATION FOR HEAVY RESONANCES
COMPOSITE HIGGS THEORIES

- The hierarchy problem:

\[ \delta M_H^2 = \left( 6y_t^2 - \frac{3}{4} \left( 3g^2 + g'^2 \right) - 6\lambda \right) \frac{\Lambda^2}{8\pi^2} \]

- If the Standard Model accounts for all physical phenomena except gravity:

\[ \Lambda = M_P \simeq 10^{19} \text{ GeV} \]

\[ M_H \sim 10^2 \text{ GeV} \]

- Experimental observation:

- Extreme fine tuning of parameters required, 1 over \(10^{34}\): naturalness problem
COMPOSITE HIGGS THEORIES

- Possible solution to the hierarchy problem: the Higgs boson is **composite**
- Virtual high-energy effects resolve its compositeness, replacing the bad SM behaviour

\[ F(q^2) \]

- Role of resonances: analogy with electromagnetic corrections to the pion mass

\[ \Delta M_\pi \propto \frac{\alpha}{16\pi^2} M_\rho^2 \]

So we expect new resonances also in the EW sector
COMPOSITE HIGGS THEORIES

- **Problem**: big mass gap between the Higgs and lightest resonances!

\[
\begin{align*}
M_H &= 125 \text{ GeV} \\
M_\rho &\sim \text{TeV} \\
M_\rho &> 800 \text{ GeV}
\end{align*}
\]

- Still learning from pions: the Higgs as a **pseudo Nambu-Goldstone boson** (PNGB) accounts naturally for such picture (Georgi, Kaplan, 1984)
COMPOSITE HIGGS THEORIES

• Spontaneous symmetry breaking $G \rightarrow H$ at a scale $f > v$ ($v = 246$ GeV, electroweak scale): effective lagrangian for massless NGBs

• Define the scale separation

  $$\xi = \left(\frac{v}{f}\right)^2$$

• A small term in the lagrangian also explicitly breaks $G$: massive PNGB

• Reproduce the SM EWSB pattern $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$
COMPOSITE HIGGS THEORIES

• **Add lightest resonances**: no rigid recipe. They will appear roughly with mass:

\[ M_\ast \approx g_\ast f \approx TeV \]

• Simplifying assumption: additional sizeable mass gap between the lightest resonances and the others

\[
\begin{align*}
\Lambda & \quad \text{\textbullet\ Effective lagrangian for resonances is expected to be weakly coupled} \\
M_\rho & \quad \text{\textbullet\ Effect of heavier states is expected to be suppressed. Their mass is taken to be the cutoff of the effective theory.}
\end{align*}
\]
AN EXAMPLE: THE MINIMAL COMPOSITE HIGGS MODEL (MCHM)
MINIMAL COMPOSITE HIGGS MODEL

- Effective theory with $G = SO(5)$, $H = SO(4) = SU(2)_L \times SU(2)_R$

$\text{SO}(5) \rightarrow \text{SO}(4)$\hspace{1cm} 4 NGBs
MINIMAL COMPOSITE HIGGS MODEL

- Effective theory with $G = SO(5)$, $H = SO(4) = SU(2)_L \times SU(2)_R$

$SO(5) \rightarrow SO(4)$

Gauge group $SU(2)_L \times U(1)_Y$

The gauge group seems to be unbroken

4 NGBs
**MINIMAL COMPOSITE HIGGS MODEL**

- Effective theory with $G = \text{SO}(5)$, $H = \text{SO}(4) = \text{SU}(2)_L \times \text{SU}(2)_R$

\[ \text{SO}(5) \rightarrow \text{SO}(4) \]

Gauge group $\text{SU}(2)_L \times \text{U}(1)_Y$

The gauge group seems to be unbroken

Interaction terms between electroweak gauge bosons and NGBs break the global $\text{SO}(5)$

- A **Higgs potential** is generated at one loop, which correctly accounts for the Higgs mass and the EWSB
- Gauge bosons become massive eating 3 NGBs, one is left as a massive PNGB, the composite Higgs boson

**Phd in physics**

**XXXVIII cycle**
Formally different approach: EWSB made manifest

The gauge group is no more a subset of the unbroken SO(4), but rather of an SO(4)' rotated by an angle $\theta$

The gauge group is manifestly broken

The degree of misalignement $\theta$ correctly triggers the EWSB at tree level

Completely equivalent to the previous construction
MINIMAL COMPOSITE HIGGS MODEL

- Generators of SO(5):

\[ \{T\} = \left\{ T^\hat{a} \in SO(5)/SO(4), T_{\theta}^{(L,R)a} \in SO(4) \right\} \]

\[ \hat{a} = 1 \ldots 4, \ a = 1 \ldots 3 \]

- Usual parametrization of NGBs: massless excitations around the vacuum along broken generators

\[ \Phi = \exp \left( i \sqrt{2} \frac{\pi^a}{f} T^{\hat{a}} \right) \Phi_0 \]

\[ \Phi_0 = (0, 0, 0, \sin(\theta), \cos(\theta)) \]

\[ T^{L,R}_{\theta} \Phi_0 = 0 \]
MINIMAL COMPOSITE HIGGS MODEL

- **Misaligned gauging:**

\[ D_\mu = \partial_\mu + igW^i_\mu T^{(L)i}_0 + ig'B_\mu T^{(R)i}_0 \]

- **NGBs kinetic term:**

\[
\frac{f^2}{2}(D_\mu \Phi)^T (D_\mu \Phi) \supset \frac{1}{2} \left( \frac{1}{4} g^2 f^2 \sin^2(\theta) \right) W^i_\mu W^i_\mu \\
+ \frac{1}{2} \left( \frac{1}{4} g'^2 f^2 \sin^2(\theta) \right) B_\mu B_\mu
\]

Mass terms expected from EWSB

\[ v = f \sin(\theta) \]
INDIRECT SEARCHES: ELECTROWEAK PRECISION TESTS
INDIRECT SEARCHES

- Primary reference: electroweak precision tests on $e^+e^-$ processes at LEP (EWPT)

- Assume there are only oblique corrections:

\[ \Pi_{ij}^{(H)}(q^2), \text{Heavy physics contribution} \]

- Four measurable quantities parametrize all corrections, experimentally constrained to be small ($-10^{-3}$):

\[ \hat{S} = g^2 \Pi_{W^3B}^{(H)}(0) \]
\[ \hat{T} = \frac{g^2}{M_W^2} \left( \Pi_{W^3W^3}^{(H)}(0) - \Pi_{W^+W^-}^{(H)}(0) \right) \]
\[ W = \frac{g^2 M_W^2}{2} \Pi_{W^3W^3}^{(H)\prime\prime}(0) \]
\[ Y = \frac{g^2 M_W^2}{2} \Pi_{BB}^{(H)\prime\prime}(0) \]

- Suitable new physics models must provide small $S$, $T$, $W$, $Y$ in some region of their parameter space.
**INDIRECT SEARCHES**

Linked to new physics in the EWSB sector.
Dominant in composite Higgs models

Linked to new structures in the gauging sector.
Subleading in composite Higgs models

- **Peskin, Takeuchi, 1992**
- **Barbieri, Rattazzi, 2004**

\[
\hat{S} = g^2 \Pi_{W^3 B}^{(H)} (0)
\]

\[
\hat{T} = \frac{g^2}{M_W^2} \left( \Pi_{W^3 W^3}^{(H)} (0) - \Pi_{W^+ W^-}^{(H)} (0) \right)
\]

\[
W = \frac{g^2 M_W^2}{2} \Pi_{W^3 W^3}^{(H)''} (0)
\]

\[
Y = \frac{g'^2 M_W^2}{2} \Pi_{BB}^{(H)''} (0)
\]

**Aim of the project:** obtain indirect constraints on parameters of various specific models by computing S and T parameters.
INDIRECT SEARCHES

- Electroweak fit

Experimentally allowed regions: 68%, 90%, 99% CL

SM prediction: $S = 0, T = 0$ (by definition)
INDIRECT SEARCHES

• Electroweak fit

Composite Higgs boson effect: SM Higgs couplings rescaled by a factor: \( \cos(\theta) = \sqrt{1 - \xi} \)

\[
\Delta S = \frac{1}{6\pi} \sin^2(\theta) \log\left(\frac{\Lambda}{M_H}\right)
\]

\[
\Delta T = -\frac{3}{8\pi \cos^2(\theta_W)} \sin^2(\theta) \log\left(\frac{\Lambda}{M_H}\right)
\]

• Resonances can improve this picture
INDIRECT SEARCHES

- Electroweak fit

Loops of fermionic resonances can provide a leading positive contribution to $T$

$$
\Delta T \sim y_L^4 \sin^2(\theta) \frac{f^2}{M^2_\Psi}
$$
INDIRECT SEARCHES

- Electroweak fit

Tree level exchange of vector resonances contribute positively to $S$

$$\Delta S \sim \sin^2(\theta) \frac{g^2}{g^2_{\rho}} \sim \frac{M_W^2}{M_{\rho}^2}$$
INDIRECT SEARCHES

• Electroweak fit

Many more effects possible, some already studied in literature, depending on specific models and assumptions made
DIRECT SEARCHES: OBSERVATION AT LHC
DIRECT SEARCHES

• S, T values are influenced by the whole particle content of a theory

• Parameter space constraints from indirect searches can thus be sensible to UV effects above the cutoff $\Lambda$ (mass of heavier resonances)

• Direct effects would be free from such problem, but up to now no states have been even found

• **LHC Run 1**: $\sim 20 \text{ fb}^{-1}$ dataset at $\sqrt{s} = 7, 8 \text{ TeV}$ between 2010-2013 is being used to place experimental lower bounds on resonance masses

• **Aim of the project**: obtain direct constraints on parameters of various specific models by comparing experimental exclusion limits with theoretical simulations of production events
DIRECT SEARCHES

FERMIONS (TOP PARTNERS)

- Exotic-charged resonances: $T_{2/3}, X_{5/3}$...
- Pair-produced through gluon fusion or singularly with associated top quark

- Sample decays: SM quarks + SM gauge boson or Higgs boson
DIRECT SEARCHES

FERMIONS
(TOP PARTNERS)

- Current experimental exclusion plots for pair produced $X_{5/3} \rightarrow tW$ and $T_{2/3} \rightarrow bW, tH, tZ$ (right)

\[ \sigma \times BF(T_{5/3} \rightarrow \bar{t}W \rightarrow \bar{t}W^* + X) \text{ (pb)} \]

\[ \text{BF}(T_{5/3} \rightarrow tW^*) = 100\% \]

\[ \text{CMS} \quad L = 19.5 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV} \]

\[ \sigma \text{ [pb]} \]

\[ M_T \text{ [GeV]} \]
DIRECT SEARCHES

VECTORS

- Dominant production expected: single drell-yan

- Sample decays: SM gauge bosons, SM gauge bosons + Higgs, ttbar, heavy fermions
DIRECT SEARCHES

VECTORS

- Current experimental exclusion plots for vector resonances in WZ channel (left) and ttbar channel (right)