Beyond the Standard Model

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The SM

Leptons:
- $e$, $\mu$, $\tau$
- $\nu_e$, $\nu_\mu$, $\nu_\tau$

Quarks:
- $u$, $c$, $t$
- $d$, $s$, $b$

Particles:
- Photon
- $W^+$, $W^-$
- $Z^0$
- Higgs Boson
- Gluons
The energy frontier

What can we expect to discover?
Before LHC$^{7/8}$

theorists’ statements

Susy is right around the corner

Dark matter is a WIMP and we’ll produce it at LHC

We’ll see non-SM CP and flavor violation

Extra-dimensions will manifest itself through KK-states

We’ll have a portal to hidden sectors
"It has to do with the EWSB"

Already first data gave evidence of:

True in the SM:

Scaling follows naturally if the new boson is part of the sector that breaks the EW symmetry

It does not necessarily imply that the new boson is part of an SU(2)\text{L} doublet coupling $\propto$ mass

Ex:

For a non-doublet one naively expects:

mass (GeV)

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<thead>
<tr>
<th>1</th>
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1/2 or $(g/2v)$

$\lambda_\psi \propto \frac{m_\psi}{v}$, $\lambda^2_V \equiv \frac{g_{VVh}}{2v^2} \propto \frac{m^2_V}{v}$
Good time for BSM?

• Fundamental scalars abound (Higgs, inflation)
• Are we done?

DM is an axion?  Susy at 100 TeV?
Why still expect new physics at the LHC?
Fermi theory

\[ G_F \]

\[ \frac{g^2}{M_W^2} (\bar{\nu}_\mu \gamma^\alpha_L \mu)(\bar{e} \gamma^\alpha_L \nu_e) \]

something interesting will happen around \( E \sim M_W \)

\[ \sigma \propto \frac{g^4}{M_W^4} E^2 \]

dimensional analysis
Weak interactions are gauge interactions and symmetry.

Weak interactions are short range and symmetry broken.

\[ M_Z \]

**LEP**

![Graph showing data from ALEPH, DELPHI, L3, and OPAL. The graph plots \( \sigma_{	ext{had}} \) (nb) against \( E_{cm} \) (GeV). The error bars are increased by a factor of 10.](chart.png)
SM without the Higgs

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(h^0, A_\mu, W^\pm_\mu, Z_\mu, G_\mu, q, \ell)$$  (unitary gauge)

Expansion in powers of $E^4 v_{\text{TeV}}$

Example: WW scattering

$$\sim E^4 + E^2 + \cdots \quad \sim E^4 + E^2 + \cdots$$
SM without the Higgs

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(h^0, A_\mu, W^\pm_\mu, Z_\mu, G_\mu, q, \ell) \] (unitary gauge)

Expansion in powers of \( E^4 \nu \)

Example: WW scattering

\[ \sim E^4 + E^2 + \cdots \]

\[ \sim E^4 + E^2 + \cdots \]

\[ \Lambda \approx 4\pi \nu \approx 3 \text{ TeV} \]

New physics to show up below this scale
Pre-LHC: unitarity problem =>

safe path towards new discoveries

Producing Top Quarks

- The Energy Frontier -

LHC

CERN

• 1.96 TeV pp collider
• Run II started in 2001
• Record Inst. Lum. 3.6 \(10^{32} \text{ cm}^{-2}\text{sec}^{-1}\)

Most of the results

- 14 TeV pp collider
• Restart in Nov 2009 at 7 TeV
• Inst. Lum. \(10^{32} \text{ cm}^{-2}\text{sec}^{-1}\)

Brief outlook

new physics

Energy
Post-LHC Higgs discovery => no clear experimentally-driven scale of new physics

Producing Top Quarks

Tevatron
Fermilab
1 km
CDF
D0
Main Injector

PIC 2009 – Kobe, Japan

- The Energy Frontier -

LHC
CERN
•
•
•

1.96 TeV pp collider
Run II started in 2001
Record Inst. Lum. $3.6 \times 10^{32} [\text{cm}^{-2}\text{sec}^{-1}]$

Most of the results

14 TeV pp collider
Restart in Nov 2009 at 7 TeV
Inst. Lum. $10^{32} - 10^{34} [\text{cm}^{-2}\text{sec}^{-1}]$

Brief outlook

new physics

new physics
SM-like Higgs

What if it couples only approximately like the SM?

\[ \Lambda \approx 4\pi v \rightarrow \frac{4\pi v}{\sqrt{1 - a^2}} \]

\[ W_L W_L \rightarrow W_L W_L \]

fully unitarized?
Even if we measure $a < 1$, current limits do not guarantee new physics in reach of LHC.

Example: composite pseudo-Goldstone Higgs:

$$a = \sqrt{1 - (v/f)^2} \approx 0.8 \ldots 0.9$$

$$\Lambda > 6 \ldots 8 \text{ TeV}$$
Where is the next scale?

- 13/14 TeV enough to reveal fundamental physics?
- First time in history without nearby new scale: all couplings dimensionless (marginal) or of positive mass dimension (relevant)
- Remaining hopes?
  - Landau pole of hyper charge $U(1)_Y$
  - Gravity scale ($M_{\text{Planck}}$)
SM Hyper-charge

Hyper-charge is not asymptotically free, will blow up at (very) high energies — Landau Pole

\[
\frac{1}{\alpha_Y(M_Z)} = \frac{1}{\alpha_Y(\Lambda)} + \frac{b_Y}{2\pi} \ln \frac{\Lambda}{M_Z}
\]

\[b_Y = \frac{41}{10}\]

\[\Lambda \sim M_Z e^{2\pi/\alpha_Y b_Y} \sim 10^{41} \text{ GeV}\]
Gravity

• Strong coupling problem, e.g. graviton-graviton scattering

\[ \sigma \sim \frac{E^n}{M_{pl}^{n+2}} \]

\[ M_{pl} \sim 10^{19} \text{ GeV} \]
Open questions of the SM
The SM is incomplete

 Origin of SM flavor and mass hierarchies?

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 Fine-tuning?

 Unity of forces?

 The SM is incomplete

 Origin of SM flavor and mass hierarchies?

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The SM

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

\[ + i \bar{\psi} D \psi + h.c. \]

\[ + \chi_i Y_{ij} \chi_j \phi + h.c. \]

\[ + i \bar{\psi} D \psi + V(\phi) \]
Quark and Lepton mass hierarchy
Masses on a Log-scale
SM quark masses: mostly small & hierarchical.

Origin of this structure?

Compare to: \( g_s \sim 1, \ g \sim 0.6, \ g' \sim 0.3, \ \lambda_{\text{Higgs}} \sim 1 \)
Analog to mysterious spectral lines before QM

Explained by Bohr

\[ \nu = \left( \frac{1}{n^2} - \frac{1}{m^2} \right) R \]

\[ E_n = -\frac{2\pi^2 e^4 m_e}{\hbar^2 n^2} \]

Is there an analogue to the Bohr atom, we might discover at the LHC?
Flavor dynamics @ LHC?

Possible, but …

1) Lack of scale

$${\mathcal L}_{\text{flavor}} = [Y^U]_{ij} \bar{Q}_i H_c u_j + \ldots$$

$$\text{dim} \quad 0 + 3/2 + 1 + 3/2 = 4$$

2) Very strong constraints from flavor physics:
Generic flavor dynamics $\gg 100$ TeV
The SM

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \overline{\psi} D\psi + h.c. + \chi_i y_{ij} x_j \phi + h.c. \]

\[ + |D_\mu \phi|^2 - V(\phi) \]
Top as a destabilizing agent
Stability and meta-stability

Tree-level

\[ V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \]

What happens at \( |\phi| \gg v \)? Focus on \( \lambda, \mu^2 \ll |\phi|^2 \)
Quantum fluctuations change potential

\[ V \sim \lambda(|\phi|) |\phi|^4 \]

decreasing at large Energies

\[ \sim e^{-\frac{8\pi}{3/\lambda}} \]

tunneling
Stability and meta-stability

SM vacuum is unstable but sufficiently long-lived, (depends on $m_{top}$, $m_{Higgs}$)

Unlikely the full story, assumes nothing but SM up to the Planck scale …

decisive uncertainty

$m_{top}$

Message n.2: For $m_{h} \approx 125-126$ GeV and the present central value of $m_{top}$, the SM vacuum is unstable but sufficiently long-lived, compared to the age of the Universe.

N.B.: we cannot trust the estimate of the tunneling rate too close to $M_{Pl}$.

cf Elias-Miro et al. '12
Degrassi et al. '12
Buttazzo et al. '12
If metastable: How did we end up in the energetically disfavoured vacuum?

Universe is overwhelmingly likely to evolve to wrong minimum

Fine-tuning of initial conditions?

\[ \sim \frac{\Lambda_{\text{instability}}}{M_{\text{Planck}}} \]

For \( \Lambda_{\text{instability}} \sim 10^{10} \text{ GeV} \rightarrow 10^{-8} \text{ tuning} \)
Higgs potential

\[ V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \]

quantum fluctuations destabilise Higgs mass^2
Effective Field Theory

An approximate field theory which works up to a certain energy scale ($\Lambda$), using only degrees of freedom with $m \ll \Lambda$.

Example: QED ($e, \gamma$), for $E \ll M_W$

Is the SM an EFT?

Yes! Breaks down latest at the gravity scale (details unknown).
Principle: UV insensitivity

**Naturalness**: absence of special conspiracies between phenomena occurring at very different length scales.

Planets do not care about QED.

QED at $E \sim m_e$ does not care about the Higgs.
Hierarchy problem

- Higgs mass sensitive to thresholds (GUT, gravity)
- Enormous quantum corrections $\mathcal{O}(\text{highest scale})$ exceed Higgs mass physical value, need to fine-tune parameters

$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i \Lambda^2$$
$\Lambda = 1 \text{ TeV}$
• The ‘cancelation of divergencies’ is not the question

• Rather: parameters in the effective theory are strongly sensitive to fundamental ones

\[
H \rightarrow X \rightarrow \Delta m_H^2 \sim \frac{g_{\text{GUT}}^2}{16\pi^2} M_X^2 \sim (10^{15} \text{ GeV})^2
\]

• The hierarchy problem needs a ‘hierarchy of scales’. The SM alone (no gravity, nothing else) if fine \(\rightarrow\) no hierarchy, no problem!
Only the SM?

We seem to be living close to a critical condition, similar to Planck-Weak hierarchy …

Giudice, Rattazzi, ‘Self-organized criticality’
Fine-tuning not an inconsistency of physics since we can always cancel bare vs. quantum. However, it might help us understand where new physics could set in.
Example: Electron Mass

Ex 1: divergent self energy of electric field

\[
\int_{r=\Lambda^{-1}} d^3r \vec{E}^2 \sim \alpha \Lambda \quad \text{vs.} \quad m_e
\]

\[
\vec{E} \sim \vec{n}/r^2 \quad \text{Coulomb}
\]

New physics expected at

\[
\Lambda \sim m_e/\alpha
\]
New physics: the positron

- Extension of spacetime symmetry: Lorentz symmetry + quantum mechanics

- Log divergence (very mild).

- Proportional to $m_e$.

- $\delta m_e \sim \frac{\alpha}{\pi} m_e \log \left( \frac{\Lambda}{m_e} \right)$

$\Rightarrow$ natural electron mass.

Classically:

$$\int_{r=\Lambda^{-1}} d^3r \, \vec{E}^2 \approx \alpha \Lambda$$
Another example: Pion mass

Ex2 Neutral-charged pion mass difference

\[ \delta m_{\pi^+}^2 \sim \frac{3\alpha}{4\pi} \Lambda^2 < (m_{\pi^+}^2 - m_{\pi^0}^2)_{\text{exp}} \approx (4 \text{ MeV})^2 \]

Expect \( \Lambda < 850 \text{ MeV} \)

‘New physics’: comes in at \( m_\rho = 770 \text{ MeV} \)

\[ m_{\pi^\pm}^2 - m_{\pi^0}^2 \simeq \frac{3\alpha_{em}}{4\pi} \frac{m_\rho^2 m_{a_1}^2}{m_{a_1}^2 - m_\rho^2} \log \left( \frac{m_{a_1}^2}{m_\rho^2} \right) \]

\( (m_{\pi^\pm} - m_{\pi^0})|_{\text{TH}} \approx 5.8 \text{ MeV} ! \)
Famous naturalness disaster

• We don’t understand the cosmological constant

\[ CC = \Lambda_0 \approx (10^{-3} \text{ eV})^4 \]

\[ S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left( R - \Lambda_0 \right) \]

\[ \delta \Lambda_0 \approx \Lambda^4 \quad \rightarrow \text{new physics at } 10^{-3} \text{ eV or } \sim \text{few mm} \]
Supersymmetry (new space-time symmetry)

Composite Higgs

Multiverse

anthropic principle?
Supersymmetry (new space-time symmetry) - Yael’s lectures

Composite Higgs
Strong EWSB
(Composite Higgs)
Why is the Higgs light?

Kaplan; Agashe et. al

Inspired by QCD: (pseudo) scalar pion is the lightest state

Shift symmetry...\[
\pi \rightarrow \pi + C
\]

... protects its mass.

Interactions are perturbative for \( E \ll 4\pi f \)

No pure composite effects due to Goldstone symmetry

Shift symmetry broken by elementary-composite couplings:

\[
m_h^2 \sim \frac{\lambda^2}{16\pi^2} \Lambda_{\text{comp}}^2
\]

\( \lambda \ll 4\pi \)
Supersymmetry is a weakly coupled solution to the hierarchy problem. We can extrapolate physics to the Planck scale, complete the MSSM in a GUT.

There is another way and it’s already in use. Nature already employs a strongly coupled mechanism to explain why

\[ \Lambda_{\text{QCD}} \ll M_{\text{Planck}} \]

\[ \sim 1 \text{ GeV} \quad 10^{19} \text{ GeV} \]
QCD

Fix QCD coupling at some high scale
→ exponential hierarchy generated dynamically

$$\frac{\Lambda_{\text{QCD}}}{\Lambda_{\text{UV}}} = e^{-\frac{8\pi^2}{g_0^2 b}}$$, \(\Lambda_{\text{QCD}} \lesssim \text{GeV}\)

\(b = 7\)

Asymptotic freedom
QCD: composite bound states

At strong coupling, new resonances are generated.
QCD vs. EWSB

QCD dynamically breaks SM gauge symmetry

\[ SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \]

\[
\langle \bar{q}_L q_R \rangle \simeq \Lambda_{QCD}^3 \sim (\text{GeV})^3
\]

The QCD masses of W/Z are small

\[ m_{W,Z} \sim \frac{g}{4\pi} \Lambda_{QCD} \sim 100 \text{ MeV} \]

Longitudinal components of W & Z have tiny admixture of pions…
Technicolor

Scaled up version of QCD mechanism

$$\langle \bar{q}'_L q'_R \rangle \sim \Lambda_{TC}^3, \quad \Lambda_{TC} \sim \text{TeV}$$

Technicolor, doesn’t have a Higgs ...
Composite Higgs

- Want to copy QCD, but extend pion sector (QCD: $\pi^0, \pi^\pm$)
- Higgs as a (pseudo) Goldstone boson
Need to learn about goldstone bosons…
Quantum Protection

Symmetries can soften quantum behaviour

\[ \mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots \]

breaks susy → corrections must be proportional to susy breaking
Shift symmetry

Higgs mass term can be forbidden

\[ \mathcal{L} = \left| \partial_\mu \phi \right|^2 + \mu^2 \left| \phi \right|^2 - \lambda \left| \phi \right|^4 + \ldots \]

\( \phi \rightarrow e^{i\alpha} \phi \)

does not forbid the mass^2

\( \phi \rightarrow \phi + \alpha \)

works!

Can we make the Higgs transform this way?
Spontaneous breaking of U(1)

\[ \langle \Phi \rangle = \frac{f}{\sqrt{2}} \]

\[ \mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots \]

Instead using complex field

\[ \phi = \phi_1 + i\phi_2 \]

use real parametrisation

\[ \phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x)) \]

‘phase’ ‘modulos’
\[
\mathcal{L} = \left| \partial_\mu \phi \right|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots
\]

use
\[
\phi(x) = \frac{1}{2} e^{i \pi(x)/f} (f + \sigma(x))
\]

\[
\partial^\mu \phi^\dagger \partial_\mu \phi = \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2} (1 + \sigma/f)^2 \frac{1}{2} \partial^\mu \pi \partial_\mu \pi
\]

\[
V(|\phi(x)|^2) = V(\sigma(x))
\]

no mass term

no dependence on \( \pi(x) \)
Using this parameterization a new symmetry is visible:

\[ \pi(x) \rightarrow \pi(x) + \alpha \]

because \( \pi(x) \) has only ‘derivative interactions’

\[ \partial_\mu (\pi(x) + \alpha) = \partial_\mu \pi(x) \]

But what happened to the U(1) symmetry? \( \pi(x), \sigma(x) \) are real...
But what happened to the U(1) symmetry?

\[ \phi \rightarrow e^{i\alpha} \phi \]

\[ e^{i\pi(x)/f} (f + \sigma(x)) \rightarrow e^{i\alpha} e^{i\pi(x)/f} (f + \sigma(x)) \]

\[ \sigma(x) \rightarrow \sigma(x) \]
\[ \pi(x) \rightarrow \pi(x) + \alpha \]

Phase rotation becomes shift symmetry

\[ \pi(x) \text{ is massless but also no} \]

- gauge couplings
- potential
- yukawas
Semi-realistic model
\[ \Lambda = 4\pi f \quad \text{UV completion} \]
\[ m_\rho = g_\rho f \quad \text{resonances} \]
\[ \nu = 246 \text{ GeV} \quad \text{EW scale} \]
pGB Higgs

\[ SU(3) \rightarrow SU(2) \]

Break symmetry using \[ \langle \Phi \rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \]

\# Goldstone bosons = \# broken generators

\[ \Phi = \frac{1}{\sqrt{2}} e^{i \Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \]

\[ \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1^* \\ 0 & \eta/\sqrt{3} & H_2^* \\ H_1 & H_2 & -2\eta/\sqrt{3} \end{pmatrix} \]
\[ \Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \quad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2^* \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix} \]

Expand

\[ \Phi(x) = \begin{pmatrix} H_1(x) \\ H_2(x) \\ -\frac{2}{\sqrt{2}} \eta(x) \end{pmatrix} + \ldots \]

Contains a Higgs: \[ H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = SU(2) \text{ doublet} \]
pGB Higgs

Unbroken gauge symmetry in global SU(2), dynamics generates ‘vacuum misalignment’

\[ \langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin \theta \\ \cos \theta \end{pmatrix} \quad \text{SU}(2)_L \]

EW symmetry broken
vacuum misalignment
pGB Higgs

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin \theta \\ \cos \theta \end{pmatrix}^{\text{SU(2)}_L}$$

Electro-weak scale \( v = f \sin \theta \)

\( f \sim \) scale of new physics

\( \sin \theta \ll 1 \iff f \gg v \) (SM limit)

$$\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$
Collective Breaking

We now want to add a yukawa coupling to give mass to the top quark

$$\lambda_t \bar{Q}_i H^c_i t_R$$

$i$: sum over SU(2)

Fundamental field is a triplet

$$\phi = \exp \left\{ i \left( \begin{array}{cc} h_1^* & h_1 \\ h_2^* & h_2 \end{array} \right) \right\} \left( \begin{array}{c} f \end{array} \right)$$
Top yukawa: 1st try

\[ \sum_{i}^{2} \lambda_t \phi_i^c \bar{Q}_i t_R \]

works, gives mass to the top

… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:

\[ Q \sim \frac{\lambda_t^2}{16\pi^2} \Lambda^2 \]

we've accomplished nothing...
2nd try: Collective breaking

Example: $SU(3) \to SU(2)$  
(\text{ignore } U(1)_Y \text{ again})

\[
\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 2 \end{pmatrix}
\]

Gauge full $SU(3) \Rightarrow$ exact symmetry

\[
\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \quad t_{1R}, \, t_{2R}, \, b_R
\]

\[
\mathcal{L}_{\text{Yukawa}} = y_1 \bar{\Psi}_L \Phi_1 t_{1R} + y_2 \bar{\Psi}_L \Phi_2 t_{2R}
\]

$y_1 \to 0 \Rightarrow$ exact $SU(3)_2 \to SU(2)_2$ and \textit{vice versa}

Both $y_1, y_2 \neq 0$ required for non-derivative couplings of PNGB Higgs
Collective Symmetry Breaking

\[ t_1 R \quad \Leftrightarrow \quad R t_1 \]

\[ t_2 R \quad \Leftrightarrow \quad R t_2 \]

\[ y_1^2 \left( \frac{1}{16\pi^2} \right) \Lambda^2 \]

Not allowed

\[ SU(3)_2 \rightarrow SU(2)_2 \]

\[ \text{no PNGB Higgs mass} \]

\[ \text{Predicts top-partners} \]

\[ \Phi_1^\dagger \quad \Phi_2 \]

\[ \Psi_L \]

\[ t_1 \quad t_2 \]

\[ \Phi_2^\dagger \quad \Phi_2 \]

\[ \Phi_1^\dagger \quad \Phi_1 \]

\[ t_1 \quad t_2 \]

Not allowed

\[ SU(3)_1 \rightarrow SU(2)_1 \]

\[ \text{no PNGB Higgs mass} \]
Light Higgs implies light fermionic top partners

\[ m_h^2 \simeq \frac{N_c}{\pi^2} \left[ \frac{m_t^2}{f^2} \frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_4}^2 - m_{Q_1}^2} \log \left( \frac{m_{Q_1}^2}{m_{Q_4}^2} \right) \right] \]

Pomarol et al; Marzocca

5 = 4 + 1

\[ Q_4 \; Q_1 \]

with EM charges 5/3, 2/3, -1/3

Contino et al; Pomarol, Riva; Matsedonskyi, Panico, Wulzer; Redi, Tesi; Marzocca, Serone, Shu;
Figure 3: Scatter plots of the masses of the lightest exotic state of charge 5/3 and of the lightest resonance for $\xi = 0.2$ (left panel) and $\xi = 0.1$ (right panel) in the three-site DCHM model. The black dots denote the points for which $115 \text{ GeV} \leq m_H \leq 130 \text{ GeV}$, while the gray dots have $m_H > 130 \text{ GeV}$. The scans have been obtained by varying all the composite sector masses in the range $[8 f, 8 f]$ and keeping the top mass fixed at the value $m_t = 150 \text{ GeV}$.

The numerical results clearly show that resonances with a mass of the order or below 1.5 TeV are needed in order to get a realistic Higgs mass both in the case $\xi = 0.2$ and $\xi = 0.1$. The prediction is even sharper for the cases in which only one state, namely the $e_T$, is light. In these regions of the parameter space a light Higgs requires states with masses around 400 GeV for the $\xi = 0.2$ case and around 600 GeV for $\xi = 0.1$.

The situation becomes even more interesting if we also consider the masses of the other composite resonances. As we already discussed, the first level of resonances contains, in addition to the $T$ and $e_T$, three other states: a top-like state, the $T_{2/3}$, a bottom-like state, the $B$, and an exotic state with charge 5/3, the $X_{5/3}$. These three states together with the $T$ form a fourplet of SO(4). Obviously the $X_{5/3}$ cannot mix with any other state even after EWSB, and therefore it remains always lighter than the other particles in the fourplet. In particular (see fig. 9 for a schematic picture of the spectrum), it is significantly lighter than the $T$.

In fig. 3 we show the scatter plots of the masses of the lightest exotic charge 5/3 state and of the $e_T$. In the parameter space region in which the Higgs is light the $X_{5/3}$ resonance can be much lighter than the other

See e.g. ATLAS-CONF-2013-051
Minimal composite Higgs

Agashe et. al

Minimal bottom up construction

$$\text{SO}(5) \rightarrow \text{SO}(4) \sim \text{SU}(2)_L \times \text{SU}(2)_R$$

The Higgs as a composite pseudo-NG boson

$$A_\mu \quad \psi \quad G \rightarrow G'$$

The Higgs doublet $H$ is the NG boson associated to the global symmetry $G \rightarrow G'$ of a new strong dynamics

$$\psi \quad \psi$$

[Georgi & Kaplan, `80]

Minimal example (with custodial symmetry):

Agashe, RC, Pomarol, NPB 719 (2005) 165

$SO(5)/SO(4)$

Tree level: gauge $SO(4)$ aligned

$$\phi = e^{i\pi \hat{a} T_{\hat{a}}/f} \left( \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{array} \right) = \left( \begin{array}{c} \sin(\pi/f) \\ \hat{\pi}^1 \\ \hat{\pi}^2 \\ \hat{\pi}^3 \\ \hat{\pi}^4 \end{array} \sin(\pi/f) \right) = \left( \begin{array}{c} \sin(\theta + h(x)/f) \\ \hat{\pi}^4 \right) e^{i\chi(x) A^i/v} \left( \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{array} \right)$$

1-loop $\langle \phi(x) \rangle = \theta \cdot f$

Higgs

eaten by $W_L, Z_L$
Deviations from SM Higgs

Goldstone boson nature

\[ f^2 \left| \partial_\mu e^{i\pi/f} \right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2} [\partial_\mu (H^\dagger H)]^2 + \frac{c'_H}{2f^4} (H^\dagger H) [\partial_\mu (H^\dagger H)]^2 + \ldots \]

Giudice et al. JHEP 0706 (2007) 045
EW precision tests

\[ \Lambda = \frac{4\pi v}{\sqrt{1 - v^2}} \]

\[ \begin{align*}
M_W & \quad \Gamma_Z \\
P_{\tau}^{\text{Pol}} & \quad A_l \\
A_{FB}^{0,b} & \quad c_V
\end{align*} \]

Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644
Higgs couplings

Have been measured to 20-30% precision

\[ \xi = \frac{v^2}{f^2} \]

Expect deviations \( \sim (v/f)^2 \)

\[ a = \sqrt{1 - \xi} \]

\[ c_f = \frac{1 - (1 + n)\xi}{1 - \xi} \]
Higgs couplings

Red points at $\xi \equiv (v/f)^2 = 0.2, 0.5, 0.8$