BSM 3/3

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Supersymmetry (new space-time symmetry)

Composite Higgs
Strong EWSB
(Composite Higgs)

QCD  Higgs as a pGB
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

\[ \cdots \cdot \cdot \cdot = 0 \]

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

$$\Lambda_{QCD} \ll M_{\text{Planck}}$$

$$\sim 1 \text{ GeV} \quad 10^{19} \text{ GeV}$$
Theory of strong interactions.

- Exponentially separated scales from the choice of an order one number $\Lambda_{QCD}$. $\Lambda_{QCD} < 100 \text{ MeV}$.

- A strong coupling results in bound (composite) states.

More composite resonances: quark and gluon: $qg$, $K$, $\eta$, $\rho$, ...

Asymptotic freedom

Fix QCD coupling at some high scale $\rightarrow$ exponential hierarchy generated dynamically

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

$b = 7$

Asymptotic freedom
QCD: composite bound states

At strong coupling, new resonances are generated
QCD: composite bound states

- Exponentially separated scales from the choice of an order one number $g_{\text{strong}}$.
- A strong coupling results in bound (composite) states.

$g_{\text{strong}}(\mu) \Lambda_{QCD}$

$100 \text{ MeV}$

At strong coupling, new resonances are generated:

- Composite resonances: $\rho, K, a_1, \ldots$
- Quarks, gluons: $\pi^\pm, \ldots$

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

QCD dynamically breaks SM gauge symmetry

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

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

QCD dynamically breaks SM gauge symmetry

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

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

The QCD masses of W/Z are small

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

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 …

* the Higgs as the dilaton as the last bastion …
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 \rightarrow \text{corrections must be proportional to susy breaking}
Shift symmetry

Higgs mass term can be forbidden

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

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

Higgs mass term can be forbidden

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

$$\phi \rightarrow e^{i\alpha} \phi$$ does not work
Shift symmetry

Higgs mass term can be forbidden

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

- \( \phi \to e^{i\alpha} \phi \) does not work
- \( \phi \to \phi + \alpha \) works!
Shift symmetry

Higgs mass term can be forbidden

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

\[ \phi \rightarrow e^{i\alpha} \phi \] does not work

\[ \phi \rightarrow \phi + \alpha \] works!

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

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

Instead describing this with

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

redefine field to

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

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

use \[ \phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x)) \]
\[ \mathcal{L} = \left| \partial_\mu \phi \right|^2 + \mu^2 \left| \phi \right|^2 - \lambda \left| \phi \right|^4 + \ldots \]

use

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

\[ \partial^\mu \phi^\dagger \partial_\mu \phi = \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2} (1 + \sigma/f)^2 \frac{1}{2} \partial^\mu \pi \partial_\mu \pi \]
\[ \mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots \]

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

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

no dependence on \( \pi(x) \)
\[ \mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots \]

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

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\[ V(|\phi(x)|^2) = V(\sigma(x)) \quad \text{no mass term} \]

\[ V(|\phi(x)|^2) \quad \text{no dependence on } \pi(x) \]
\[
\frac{1}{2} \left(1 + \sigma(x)/f\right)^2 \frac{1}{2} \partial^\mu \pi \partial_\mu \pi + \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma - V(\sigma(x))
\]

Using this parameterization there’s a new symmetry:

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

because

\[
\partial_\mu (\pi(x) + \alpha) = \partial_\mu \pi(x)
\]
\[
\frac{1}{2} (1 + \sigma(x)/f)^2 \frac{1}{2} \partial^\mu \pi \partial_\mu \pi + \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma - V(\sigma(x))
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But what happened to the U(1) symmetry? Fields 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
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

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

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 \textbf{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 mis-alignment’

\[ SU(2)_L \text{ vs. } SU(2) \]

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

EW symmetry broken
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

$$\lambda_t \bar{Q}_i H_i^c t_R$$

i: sum over SU(2)

Fundamental field is a triplet

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

\[ \sum_{i}^{2} \lambda_{t} \bar{\phi}_{i} H_{i}^{c} t_{R} \] works, gives mass to the top

… but breaks \textbf{SU}(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:
Top yukawa: 1st try

$$\sum_i 2 \lambda_t \bar{\phi}_i H_i^c t_R$$

works, gives mass to the top

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

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

we've accomplished nothing...
Collective breaking

Example: $SU(3) \rightarrow SU(2)$  (ignore $U(1)_Y$ 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

$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \quad t_{1R}, t_{2R}, b_R$$
Collective breaking

Example: $SU(3) \rightarrow SU(2)$ (ignore $U(1)_Y$ again)

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$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix}$$

$$t_{1R}, \ t_{2R}, \ b_R$$

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

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$y_1 \rightarrow 0 \Rightarrow$ exact $SU(3)_2 \rightarrow SU(2)_2$ and vice versa

Both $y_1, y_2 \neq 0$ required for non-derivative couplings of PNGB Higgs
\[ \Phi_1^\dagger \quad \Psi_L \quad t_{1R} \quad \Phi_1 \]

\[ \Phi_2^\dagger \quad \Psi_L \quad t_{2R} \quad \Phi_2 \]

\[ \sim \frac{y_1^2}{16\pi^2} \Lambda^2 \]

preserves $SU(3)_2 \rightarrow SU(2)_2$

$\Rightarrow$ no PNGB Higgs mass

\[ \sim \frac{y_2^2}{16\pi^2} \Lambda^2 \]

preserves $SU(3)_1 \rightarrow SU(2)_1$

$\Rightarrow$ no PNGB Higgs mass

Not allowed
Minimal composite Higgs

Agashe et al

Minimal bottom up construction

SO(5) → SO(4) ~ SU(2)_L x SU(2)_R
Tree level: gauge SO(4) aligned

\[
\phi = e^{i\pi T^a / f} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin(\pi / f) \\ \hat{\pi}^1 \\ \hat{\pi}^2 \\ \hat{\pi}^3 \\ \hat{\pi}^4 \end{pmatrix} = \begin{pmatrix} \sin(\theta + h(x) / f) \\ \cos(\theta + h(x) / f) \end{pmatrix}
\]

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

Higgs

\[
e^{i\lambda^i(x) A^i / v} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}
\]

eaten by \( W_L, Z_L \)
Linear couplings

\[ \mathcal{L} = \lambda_L \bar{q}_L O_R + \lambda_R \bar{u}_R O_L + h.c. \]

\[ m_q \sim \frac{\lambda_L(\mu)\lambda_R(\mu)}{g^*} v \]

Interesting consequences for flavor...
Deviations from SM Higgs

Goldstone boson nature

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

\[ \psi \rightarrow h^* \rightarrow h \rightarrow h \]

Agashe, RC, Pomarol  NPB 719 (2005) 165
Giudice et al.  JHEP 0706 (2007) 045
**EW precision tests**

![Graph showing EW precision tests](image)

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

Have been measured to 20-30% precision

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

$$\xi \equiv \frac{v^2}{f^2}$$

$$a = \sqrt{1 - \xi}$$

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

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

\[ SM + \mathcal{L} = \frac{\alpha_s c_g}{12\pi} |H|^2 G_{\mu\nu}^{a^2} + \frac{\alpha c_\gamma}{2\pi} |H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2 \]

\[ \frac{\sigma(gg \rightarrow h)}{SM} = (1 + (c_g - c_t) v^2)^2 \]

Degeneracy ‘short-distance’ vs ‘long-distance’
Higgs couplings

\[ \mathcal{L} = \frac{\alpha_s c_g}{12\pi} |H|^2 G_{\mu\nu}^a + \frac{\alpha c_\gamma}{2\pi} |H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L H t_R |H|^2 \]

\[ \frac{\sigma(gg \to h)}{\text{SM}} = (1 + (c_g - c_t) v^2)^2 \]

Degeneracy ‘short-distance’ vs ‘long-distance’

E.g. fermionic top partners MCHM: \( \Delta c_t = \Delta c_g \)
\[ \sigma(pp \rightarrow H + X)_{\text{inclusive}} \]

Does not resolve short-distance physics

<table>
<thead>
<tr>
<th>( m_H (\text{GeV}) )</th>
<th>( \frac{\sigma_{\text{NLO}}(m_t)}{\sigma_{\text{NLO}}(m_t \rightarrow \infty)} )</th>
<th>( \frac{\sigma_{\text{NLO}}(m_t,m_b)}{\sigma_{\text{NLO}}(m_t \rightarrow \infty)} )</th>
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</thead>
<tbody>
<tr>
<td>125</td>
<td>1.061</td>
<td>0.988</td>
</tr>
<tr>
<td>150</td>
<td>1.093</td>
<td>1.028</td>
</tr>
<tr>
<td>200</td>
<td>1.185</td>
<td>1.134</td>
</tr>
</tbody>
</table>

e.g. [1306.4581](http://arxiv.org/abs/1306.4581)
Beyond current observables

Cut the loop open, recoil against hard jet

$p_T \gg m_t$

$m_t \to \infty$

high $p_T$ tail resolves loop dynamics

Grazzini, Sargsyan '13

Baur, Glover '90, Langenegger et. al '06, 1308.4771
Complementary to $h\bar{t}t$

Theory frontier: $NLO_{m_t}$ not yet calculated, $1/m_t$ known to $O(\alpha_S^4)$: few % up to $p_T \sim 150$ GeV

Grojean, Salvioni, Schlaffer, AW, in progress

Harlander et al ’12
Top partner example

Inclusive

Grojean, Salvioni, Schlaffer, AW
Top partner example

Inclusive

Grojean, Salvioni, Schlaffer, AW

\[ \frac{\sigma}{\sigma_{\text{SM}}} \text{ (inclusive)} \]

\[ m_{\text{lightest}} \text{ [GeV]} \]

\[ \frac{\sigma}{\sigma_{\text{SM}}} (p_T > 650 \text{ GeV}) \]

\[ m_{\text{lightest}} \text{ [GeV]} \]

high $p_T$
New physics & naturalness

Light Higgs

- light stops, sbottom\(_L\), higgsinos, gluinos, …
- light top partners (\(Q=5/3,2/3,1/3\)), anything else?

supersymmetry

composite Higgs
Simpler derivation of the connection:

Light Higgs - Light Resonance

Deconstruction:
Matsedonskyi, Panico, Wulzer; Redi, Tesi 12

Weinberg Sum Rules:
Marzocca, Serone, Shu; AP, Riva 12

\[ m_{\pi^+}^2 + m_{\pi^0}'^2 = m_{\pi^+}^2 \log 2 \] (37 MeV)

\[ \text{Exp.} \ (35 \text{ MeV})^2 \]

quite successful!

Correlator dominated by the minimal number of resonances giving the right convergence at high momentum

Das et al '67
Implications of $m_H = 125$ GeV

Potential is fully radiatively generated 

$$V_{gauge}(h) = \frac{9}{2} \int \frac{d^4 p}{(2\pi)^4} \log \left( \Pi_0(p) + \frac{s_h^2}{4} \Pi_1(p) \right)$$

$$s_h \equiv \sin \frac{h}{f}$$

$$\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p), \quad \Pi_1(p) = 2[\Pi_{\hat{a}}(p) - \Pi_a(p)]$$

Agashe et. al
Implications of $m_H = 125$ GeV

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$$\int d^4 p \frac{\Pi_1(p)}{\Pi_0(p)} < \infty$$

Agashe et. al

$s_h \equiv \sin h/f$

Higgs dependent term

UV finite
Implications of $m_H = 125$ GeV

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$$\int d^4p \frac{\Pi_1(p)}{\Pi_0(p)} < \infty$$

$\to$ ‘Weinberg sum rules’

$$\lim_{p^2 \to \infty} \Pi_1(p) = 0, \quad \lim_{p^2 \to \infty} p^2 \Pi_1(p) = 0$$

Higgs dependent term

UV finite

Agashe et. al

$s_h \equiv \sin h/f$
UV finiteness requires at least two resonances

\[ \Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)} \quad \text{spin 1} \]
UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_P^2 m_{a_1}^2}{(p^2 + m_P^2)(p^2 + m_{a_1}^2)} \quad \text{spin l}$$

Similarly for SO(5) fermionic contribution

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

Pomarol et al; Marzocca

similar result in deconstruction: Matsedonskyi et al; Redi et al

$$5 = 4 + 1 \quad \text{with EM charges } 5/3, 2/3, -1/3$$

$$Q_4 \quad Q_1$$

\[ \rightarrow \text{solve for } m_h = 125 \text{ GeV} \]
Light Higgs implies light fermionic top partners

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

Pomarol et al; Marzocca
Light Higgs implies light fermionic top partners

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

125 GeV Higgs

\[ 5 = 4 + 1 \]
\[ Q_4 \quad Q_1 \]

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

Contino et al; Pomarol, Riva; Matsedonskyi, Panico, Wulzer; Redi, Tesi; Marzocca, Serone, Shu;
Scan over composite Higgs parameter space

$$\xi = 0.2$$

from 1204.6333

$Q = \frac{2}{3}$

$Q = \frac{5}{3}$

$m_H = 115 \ldots 130$ GeV

$m_H > 130$

see e.g. ATLAS-CONF-2013-051
Top partners

Typical spectrum of top partners
and the coupling is large.

can be present and contribute to the same–sign dilepton signal, or other channels could open for the decay

not. The results could change quantitatively in other specific models because for instance other partners

of the proto–Yukawa, implies that the

which requires that the

the

T), or in the model of [11]. To account for these situations we will also consider the possibility that only

T

with the

longitudinal EW bosons. From the Lagrangian above it is easy to see that only the

contributions by imposing, as in the model of [8] (see also [22]), a "Custodial Symmetry for

imply (for moderate tuning

b

bigger in realistic models where the amount of compositeness of

therefore consider

for the partners (which is however strongly disfavored by combined bounds from

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= (B

B

T

partners will be visible in the final state we want to study, which contains two hard and separated

same–sign leptons; the pair and single production diagrams are shown in fig. 1.

Figure 1: Typical single and pair production diagrams for

Our analysis, though performed in the specific model we have described, has a wide range of applica-

In this case, our analysis perfectly applies to the model proposed in [11], where the

partner is present.

, the

partners (which is however strongly disfavored by combined bounds from

e.g. Perelstein, Pierce, Peskin

Contino, Servant; Mrazek, Wulzer;

De Simone, Matsedonkyi, Rattazzi, Wulzer

Double
Decay modes

\[ T, X_{2/3}, \tilde{T} \quad W^+ / Z, h \quad \rightarrow \quad b / t \]

\[ B \quad W^- / Z, h \quad \rightarrow \quad t / b \]

\[ X_{5/3} \quad W^+ \quad \rightarrow \quad t \]

Current limits

\[ > 700 - 800 \text{ GeV} \]
Decay modes

$T, X_{2/3}, \bar{T}$

$T_X / Z, \phi$

$b / t$

$B$

$t / b$

$X_{5/3}$

$t$

Current limits

$> 700 - 800$ GeV

$BR(T \rightarrow Wb)$

$\sqrt{s} = 8$ TeV

$\int L \, dt = 14.3$ fb$^{-1}$

$95\%$ CL exp. excl.

$95\%$ CL obs. excl.

ATLAS Preliminary

Status: Lepton-Photon 2013

CMS preliminary $\sqrt{s} = 8$ TeV

$\int L \, dt = 14.3$ fb$^{-1}$

$95\%$ CL exp. excl.

$95\%$ CL obs. excl.

ATLAS-CONF-2013-018

ATLAS-CONF-2013-051

ATLAS-CONF-2013-056

ATLAS-CONF-2013-060

SU(2) (T,B) doub.

SU(2) singlet

Forbidden

$m_T = 600$ GeV
Flavor used to be a showstopper

CPV in Kaon mixing

\[ |\epsilon| = 2.3 \times 10^{-3} \implies \frac{M_{ETC}}{g_{ETC} \sqrt{\text{Im}(V_{sd}^2)}} \gtrsim 16,000 \text{ TeV} \]

\[ m_{q,\ell,T}(M_{ETC}) \approx \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T \rangle_{ETC} \lesssim \frac{0.1 \text{ MeV}}{|V_{sd}|^2 N^{3/2}} \]
“Into the Extra-dimension and back”
Exciting journey...
Depends on the perspective...
Extra-dimensions
General Properties of ED theories
General Properties of ED theories

Compact Extra-dimension $\Rightarrow$ momentum in ED direction is quantized: $p_{ED} = n/(\text{size of ED})$
General Properties of ED theories

Compact Extra-dimension => momentum in ED direction is quantized: $p_{ED} = n/(\text{size of ED})$

$$p^2 = m^2 \quad \rightarrow \quad p_{5D}^2 = p^2 - \left(\frac{n}{R}\right)^2 = m^2$$

4D \quad \quad \quad \quad \quad 5D
General Properties of ED theories

Compact Extra-dimension => momentum in ED direction is quantized: \( p_{\text{ED}} = n/\text{(size of ED)} \)

\[
p^2 = m^2 \quad \rightarrow \quad p_{5D}^2 = p^2 - \left( \frac{n}{R} \right)^2 = m^2
\]

4D \hspace{1cm} 5D

Two pictures (\( n/R \) on LHS or RHS):

1) 5D field with quantized momentum and mass \( m^2 \)
General Properties of ED theories

Compact Extra-dimension $\Rightarrow$ momentum in ED direction is quantized: $p_{\text{ED}} = n/(\text{size of ED})$

\[ p^2 = m^2 \quad \Rightarrow \quad p_{5D}^2 = p^2 - \left(\frac{n}{R}\right)^2 = m^2 \]

Two pictures ($n/R$ on LHS or RHS):

1) 5D field with quantized momentum and mass $m^2$

2) infinite tower of 4D fields labeled by 5 momentum $n/R$ with masses $M^2_n = m^2 + \left(\frac{n}{R}\right)^2$

new particles: Kaluza Klein (KK) modes
The SM flavor puzzle

\[
Y_D \approx \text{diag}(2 \cdot 10^{-5}, 0.0005, 0.02)
\]

\[
Y_U \approx \begin{pmatrix}
6 \cdot 10^{-6} & -0.001 & 0.008 + 0.004i \\
1 \cdot 10^{-6} & 0.004 & -0.04 + 0.001 \\
8 \cdot 10^{-9} + 2 \cdot 10^{-8}i & 0.0002 & 0.98
\end{pmatrix}
\]

Why this structure?

Other dimensionless parameters of the SM:
\[
g_s \sim 1, \ g \sim 0.6, \ g' \sim 0.3, \ \lambda_{\text{Higgs}} \sim 1, \ |\theta| < 10^{-9}
\]
Log(SM flavor puzzle)

$- \log |Y_D| \approx \text{diag} (11 \ 8 \ 4)$

$- \log |Y_U| \approx \begin{pmatrix} 12 & 7 & 5 \\ 14 & 6 & 3 \\ 18 & 9 & 0 \end{pmatrix}$

If $Y = e^{-\Delta}$, then the $\Delta$ don’t look crazy.
Hierarchies w/o Symmetries
Arkani-Hamed, Schmaltz
SM on thick brane & domain wall ⇒ chiral localization

\[ S = \int d^5x \sum_{i,j} \bar{\Psi}_i [i \Phi_5 + \lambda \Phi(x_5) - m_{ij}] \Psi_j \]

\[ \Psi = \left( \begin{array}{c} \Psi_L \\ \Psi_R \end{array} \right) = \left( \begin{array}{c} \psi^0_L \\ 0 \end{array} \right) + \text{KK modes} \]
Hierarchies w/o Symmetries

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Arkani-Hamed, Schmaltz

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Hierarchies w/o Symmetries

SM on thick brane & domain wall \( \Rightarrow \) chiral localization

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S = \int d^5x \sum_{i,j} \bar{\Psi}_i [i \phi_5 + \lambda \Phi(x_5) - m]_{ij} \Psi_j
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\]

\[
\int dx_5 \phi_l(x_5) \phi_{e^c}(x_5) = \frac{\sqrt{2} \mu}{\sqrt{\pi}} \int dx_5 e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5-r)^2} = e^{-\mu^2 r^2 / 2}
\]
Hierarchies w/o Symmetries
Arkani-Hamed, Schmaltz

SM on thick brane & domain wall ⇒ chiral localization

\[ S = \int d^5 x \sum_{i,j} \bar{\Psi}_i [i \, \phi_5 + \lambda \Phi(x_5) - m]_{ij} \Psi_j \]

\[ \Psi = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} = \begin{pmatrix} \psi_0^0 \\ 0 \end{pmatrix} + \text{KK modes} \]

\[ \int dx_5 \, \phi_l(x_5) \, \phi_e(x_5) = \frac{\sqrt{2} \mu}{\sqrt{\pi}} \int dx_5 \, e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5-r)^2} = e^{-\mu^2 r^2 / 2} \]
Hierarchies w/o Symmetries

SM on thick brane & domain wall $\Rightarrow$ chiral localization

$S = \int d^5x \sum_{i,j} \bar{\Psi}_i [i \phi_5 + \lambda \Phi(x_5) - m_{ij}] \Psi_j$

$\Psi = \left( \begin{array}{c} \Psi_L \\ \Psi_R \end{array} \right) = \left( \begin{array}{c} \psi_L^0 \\ 0 \end{array} \right) + \text{KK modes}$

Log(flavor hierarchy)!

$\int dx_5 \phi_l(x_5) \phi_{ec}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int dx_5 e^{-\mu^2 x_5^2} e^{-\mu^2(x_5-r)^2} = e^{-\mu^2 r^2 / 2}$
Warped Extra Dimensions

- $y = 0$
- $y = r_c$
- warped bulk $AdS$
- inter-brane distance
- reduced Planck scale
- brane 1: positive tension
- brane 2: negative tension
**AdS/CFT dictionary**

$$ds^2 = \left( \frac{R}{z} \right)^2 \left( dx_\mu dx_\nu - dz^2 \right)$$

Randall, Sundrum

- Anti-de-Sitter (AdS)
- Compactification
- Red-shifting of scales

---

$$m_W = \sqrt{\frac{g(IR)}{g(UV)}} \ M_P \ll M_P$$

$$m_W \sim e^{-4\pi/\alpha} M_P$$
Flavor in RS

Grossman, Neubert; Gherghetta, Pomarol; Huber;

zero modes like in flat ED

UV

IR

light

heavy

Higgs

0 5 10 15 20 25 30 35
Flavor in RS

Grossman, Neubert; Gherghetta, Pomarol; Huber;

zero modes like in flat ED

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Fermion-KK coupling of light fields almost universal!

UV

light

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KK modes

Higgs
Flavor in RS

Grossman, Neubert; Gherghetta, Pomarol; Huber;

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Fermion-KK coupling of light fields almost universal!
Fermion zero mode on the IR brane

\[ F(c) \sim \begin{cases} 
(\text{TeV/Planck})^{c-\frac{1}{2}} & c > \frac{1}{2} \\
\sqrt{1 - 2c} & c < \frac{1}{2}
\end{cases} \]

UV

IR

light

heavy

Higgs
Fermion zero mode on the IR brane

\[ F(c) \sim \begin{cases} 
\left(\frac{\text{TeV}}{\text{Planck}}\right)^{c-\frac{1}{2}} & c > 1/2 \\
\sqrt{1 - 2c} & c < 1/2
\end{cases} \]
RS GIM - partial compositeness

Gherghetta, Pomarol; Huber; Agashe, Perez, Soni;

Flavor hierarchy from hierarchy in $F_i$

$$m_d \sim v F_{d_L} Y^* F_{d_R}$$
RS GIM - partial compositeness

Flavor hierarchy from hierarchy in $F_i$

$$m_d \sim v F_{dL} Y^* F_{dR}$$

KK gluon FCNCs proportional to the same small $F_i$:

$$\sim \frac{(g^*)^2}{M_{KK}^2} F_{dL} F_{dR} F_{sL} F_{sR}$$

$$\sim \frac{(g^*)^2}{M_{KK}^2} \frac{m_d m_s}{(vY^*)^2}$$
Back to 4D …
A Minimal Flavor Violating Composite Higgs

\[ H \]

\[ Q_L \rightarrow g_\rho \sin \theta_R \]

Universal

SM Yukawa

\[ Y_u \frac{g_\rho}{\sin \theta_R g_\rho} \]

*for RS realization: Csaki, AW et al; Delaunay et al; da Rold; see also Barbieri et al
A Minimal Flavor Violating Composite Higgs

Composite $u,d$ quarks, very large cross-sections

$Y_u \frac{g_{\rho}}{\sin \theta_R g_{\rho}}$

$m_{top}: \sin \theta_R \gtrsim \frac{1}{g_{\rho}} \sim \frac{1}{8}$

*for RS realization: Csaki,AW et al; Delaunay et al; da Rold; see also Barbieri et al
LHC8 limits

\[ \sigma(pp \to \rho \to qq)[pb] \quad \text{CMS 8 TeV} \]

Vector mass

...similar plot using ATLAS results

de Vries, Redi, Sanz, AW, 13
**LHC8 limits**

$$\sigma(pp\rightarrow \rho \rightarrow qq)[pb] \quad \text{CMS 8 TeV}$$

- $L = \frac{2\pi}{\Lambda^2} (\bar{q}_{L,R} \gamma^\mu q_{L,R})^2$

**Vector mass**

CMS dijet angular searches

...similar plot using ATLAS results

de Vries, Redi, Sanz, AW, 13
Strong Signatures

Heavy Colour Octet
Heavy partner of the gluon
Couples strongly to coloured fermions

Dijet resonance search ($pp \rightarrow \rho \rightarrow qq$)

First analyze decay modes and width

CMS dijet angular searches

$\mathcal{L} = \frac{2\pi}{\Lambda^2} (\bar{q}_{L,R} \gamma^\mu q_{L,R})^2$

Dijet bump search

CMS

Vector mass

...similar plot using ATLAS results

de Vries, Redi, Sanz, AW, 13
Figure 9: Fermion production modes: detail.

Dedicated searches that could improve the bounds will be discussed in the section 6. CMS and ATLAS searches will be recast to obtain exclusion limits for the heavy fermion partners.

The phenomenology and experimental strategies are strongly dependent on whether the two body or three body decay occurs. Contrary to the right-handed partners, the left-handed ones can couple strongly to the first generation. This leads to large cross sections for the single channel, while for double production this is a conservative estimate.

The mass of the top partner should be typically below 1 TeV in a natural theory. In MFV scenarios the mass of the top is the same as the one of the light generations, up to mixing. The lightest top partner should be light if the theory shall remain natural. Recent analyses have shown that the lightest top quark mass is often excluded up to 2 TeV and always below 1.5 TeV. This can be avoided in theory based on necessary to reproduce the mass of the top.

We emphasize that this is an extremely strong bound that pushes the model into fine tuning territory.

In view of the recent discovery of a 125 GeV resonance, it is shown in what regions of parameter space the two body or three body decay is possible. Consequently, we can translate effective reductions to this while for double production this is a conservative estimate.

In the MFV scenario the electroweak two-body decay is entirely negligible for the first generation as it is suppressed by the light quark mass over the vacuum expectation value. It can also be subleading if the quark mass is large. This decay structure quantitatively reduces to this while for double production this is a conservative estimate.

The two-body decay through QED and QCD interactions dominates producing single production. As we will explain the dominant decay is into 2 or 3 jets leading to multi jet final states. The majority of multi-jets searches at LHC assume a large missing energy (with all light quark masses set to zero) and a low bound with central values.

The phenomenology and experimental strategies are strongly dependent on whether the two body decay through QCD or electroweak occurs. The structure quantitatively reduces to this while for double production this is a conservative estimate.

QCD vs. Composite Partners

The interesting fact is that for or three-body decay dominates. Since this will result in either two or three jet final states. One effectively reduces to this while for double production this is a conservative estimate.

Hence, we can translate effectively reduces to this while for double production this is a conservative estimate.
bump in sub-leading jets

QCD vs. Composite Partners
signal are weaker at low \( m_{Q} \), and a harder cut on both variables should be done to keep QCD under control. Although the two variables are clearly correlated, and modified ABCD method could be used here to estimate the amount of QCD background leaking into the signal region.

Obtaining \( S/B = 1 \):

We would like to quantify the effect of the cuts on signal and QCD background using the variables described above. In table 1 we describe the cut-flow of those variables for the 2+1 case. The 3+1 case behaves very similarly in terms of signal efficiencies. Note that the QCD background of 3 \( \times 10^{4} \) pb and 3 \( \times 10^{3} \) pb, respectively. The signal cross section can be read in figure 9 for specific values of \( g_{\phi}, s_{\sin R_{u,d}} \), and it typically varies between 1 to 10 pb for \( m_{\phi} \).

To achieve \( S/B \ll 1 \), one would need to have a relative suppression of efficiencies of \( 10^{3} \). In the table, one can see how this can be achieved by implementing cuts on the variables described above.

### Table 1:

<table>
<thead>
<tr>
<th>Cut-flow</th>
<th>( m_{Q} = 600 ) GeV</th>
<th>( m_{Q} = 1200 ) GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>signal</td>
<td>QCD</td>
</tr>
<tr>
<td>( p_{T} ) leading jet &gt; 450 GeV</td>
<td>0.51</td>
<td>0.0067</td>
</tr>
<tr>
<td>( H_T &gt; m_{Q} )</td>
<td>0.51</td>
<td>0.0067</td>
</tr>
<tr>
<td>(</td>
<td>m_{jj} - m_{Q}</td>
<td>&lt; (30, 50) ) GeV</td>
</tr>
<tr>
<td>( \Delta \phi_{jj} &gt; 1.5 )</td>
<td>0.045</td>
<td>9.9 ( \times 10^{-5} )</td>
</tr>
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We would like to quantify the effect of the cuts on signal and QCD background using the variables described above. In table 1 we describe the cut-flow of those variables for the 2+1 case. The 3+1 case behaves very similarly in terms of signal efficiencies. Note that the QCD background of 3 jets with $p_T > 70$ GeV and $|\phi_j| < 2.5$ at LHC8 is $3 \times 10^4$ pb and $3 \times 10^3$ pb, respectively. The signal cross section can be read in figure 9 for specific values of $g_{\phi}$, $\sin \theta_R$, and it typically varies between 1 to 10 pb for $m_\phi > 2.5$ TeV. To achieve $S/B \approx 1$, one would need to have a relative suppression of efficiencies of $10^{-2}$ to $10^{-4}$. In the table, one can see how this can be achieved by implementing cuts on the variables described above.

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</tr>
<tr>
<td>$p_T$ leading jet $&gt; 450$ GeV</td>
<td>0.51</td>
<td>0.0067</td>
<td>0.90</td>
<td>0.0067</td>
</tr>
<tr>
<td>$H_T &gt; m_Q$</td>
<td>0.51</td>
<td>0.0067</td>
<td>0.80</td>
<td>0.0015</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_Q</td>
<td>&lt; (30, 50)$ GeV</td>
<td>0.15</td>
<td>0.00037</td>
</tr>
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<td>$\Delta \phi_{jj} &gt; 1.5$</td>
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<td>$9.9 \times 10^{-5}$</td>
<td>0.060</td>
<td>$2.1 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
Dedicated search

deVries, Redi, Sanz, AW, '13

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</table>

QCD prefers mercedes

$$M \sim 3(p_T)_{\text{min}}$$

vs

$$M \sim 4(p_T)_{\text{min}}$$
Discovery potential of a dedicated search

deVries, Redi, Sanz, AW, ’13

10 fb⁻¹ at LHC8

Signal $m_Q = 600$ GeV

QCD before cuts

QCD after cuts

heavier signal easier, 3jet final state easier, no optimization
Composite Higgs

• ‘SM-like’ light Higgs

• Correlated deviations in Higgs couplings, e.g. $g_{hVV} = g_{hVV}^{(SM)} \cos \theta \ (V = W, Z)$

• Double Higgs production smoking gun

• Keep an eye on $W_L W_L \rightarrow W_L W_L$

• Top partners ($Q = 5/3, 2/3, -1/3$)
Conclusion
What is the mass telling us?

- MSSM
- Composite Higgs
- Technicolor

100 150 200 300 GeV

Higgs mass term (FT)

Finite in CH
Log divergent in SUSY

Higgs quartic coupling

CH: tends to be too large
SUSY: tends to be too small

Summary: CH vs SUSY

Bellazzini
Conclusions

The battle for a natural resolution of the hierarchy problem goes on

Where is everybody?

LHC\textsubscript{14} will be decisive