Flavor physics hints for a natural Higgs

Higgs Hunting 2012 - 18/07/2012

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A Higgs boson has been discovered, and it is weirdly SM like. Too early to be excited.
Spontaneous symmetry breaking at weak coupling?
Two (non anthropic) solution:

- Compositness
- Supersymmetry

In both cases the point $m_h = 0$ is made special by symmetries and the weak scale is generated dynamically.

Both examples predict new states around the weak scale and they have to face the extraordinary agreement of the SM with low energy experiments.
Any hint?

Direct CP asymmetry measurement in D decays:

LHCb: $\Delta A_{CP}^{dir} = -(0.82 \pm 0.21 \pm 0.11)\%$

CDF: $\Delta A_{CP}^{dir} = -(0.62 \pm 0.21 \pm 0.10)\%$

Avg.: $\Delta A_{CP}^{dir} = -(0.64 \pm 0.218)\%$

Naive expectation (SU(3) symmetry):

$\Delta A_{CP}^{dir} \approx 4 \frac{V_{cb} V_{ub}}{V_{cs} V_{us}} \frac{P}{T} \approx 4 \lambda^4 \frac{\alpha_s(m_c)}{\pi} \approx 0.1\%$

A SM explanation cannot be excluded (non-nominal SU(3) breaking, large penguins...)

If new physics, it can be explained by

$$O(1) \times \frac{\lambda m_c}{(10\text{TeV})^2} \bar{u}_L \sigma^{\mu \nu} \cdot g_s G_{\mu \nu} c_R$$

consistently with $\Delta S = 1$ e $\Delta C = 2$ in the low energy theory. (Isidori et al. (‘11))

Watch out, as usual non trivial flavor structure is required for $\Delta S = 2$
Partial compositness

Partial compositness is introduced in composite Higgs models to generate fermion masses and decouple the technicolor flavor problem without reintroducing a hierarchy. Elementary fermions couple to the strong sector via bilinears.

\[ \mathcal{L}_{PC} = \lambda_q q_L L \bar{q}_R + \lambda_u u_R u_L + \lambda_d d_R d_L + \text{h.c.} \]

3x3 matrices

Yukawas: \( y = \frac{\lambda L \lambda_R}{g_\rho} \equiv g_\rho \epsilon_L \epsilon_R \)

Quark sector: CKM + quark masses leave 2 free parameters (+O(1))

\[
\begin{align*}
\frac{\epsilon_1^q}{\epsilon_2^q} & \sim \lambda \\
\frac{\epsilon_2^q}{\epsilon_3^q} & \sim \lambda^2 \\
\frac{\epsilon_3^q}{\epsilon_3^q} & \sim \lambda^3 \\
\frac{\epsilon_{u,d}^i}{\epsilon_{u,d}^j} & = \frac{y_{u,d}^i}{y_{u,d}^j} \frac{\epsilon_{u,d}^q}{\epsilon_{u,d}^q}.
\end{align*}
\]
**Lepton sector**: more freedom due to anarchic PMNS + small neutrino masses

In general one would expect

\[ V_{PMNS}^{ij} \sim \min \left( \frac{e_i^\ell}{e_j^\ell}, \frac{e_i^\ell}{e_j^\ell} \right) \Rightarrow \frac{e_i^\ell}{e_j^\ell} \approx 1, \quad \frac{e_i^e}{e_j^e} \sim \frac{m_i^e}{m_j^e} \]

It may be that the \( \epsilon \)'s which are necessary for neutrino masses are too small (e.g., large operator dimension) so that the dominant operators are

\[ O(1)_{ij} \ell_i \ell_j O_{HH} \quad O(1)_{ij} \ell_i \nu_j O_H \quad \Lambda_{UV} \]

Majorana

Dirac

These generate anarchic neutrino masses and an anarchic rotation to the neutrino mass basis which is enough to obtain an anarchic PMNS matrix. Charged leptons still described by partial compositness

Taking:

\[ \frac{e_i^\ell}{e_j^\ell} \sim \frac{e_i^e}{e_j^e} \sim \sqrt{\frac{m_i^e}{m_j^e}} \]

minimizes the constraint from LFV
Effective lagrangian at $m_\rho$

$$\mathcal{L}_{\text{NDA}} = \frac{m_\rho^4}{g_\rho^2} \left[ \mathcal{L}^{(0)} \left( \frac{g_\rho e f}{m_\rho^{3/2}}, \frac{D_\mu}{m_\rho}, \frac{g_\rho H}{m_\rho} \right) + \frac{g_\rho^2}{16\pi^2} \mathcal{L}^{(1)} \left( \ldots \right) + \ldots \right]$$

We expect the chromomagnetic operator to come from here

$$\mathcal{L}_{\Delta F=1} \sim \epsilon^a_i \epsilon^b_j g_\rho \frac{v}{m_\rho^2} \frac{g_\rho^2}{(4\pi)^2} f_i^a \sigma_{\mu\nu} g_{\text{SM}} F_{\text{SM}}^{\mu\nu} f_j^b \quad \Lambda \equiv \frac{4\pi m_\rho}{g_\rho} \approx 10\text{TeV (LHCb)}$$

Large $g_\rho$ suppresses four fermion operators

$$\mathcal{L}_{\Delta F=2} \sim \epsilon^a_i \epsilon^b_j \epsilon^c_k \epsilon^d_l \frac{g_\rho^2}{m_\rho^2} f_i^a \gamma^\mu f_j^b f_k \gamma^\mu f_l^d$$

Chromomagnetic ops. can be controlled by a chiral symmetry (‘Higgs’ coupling to fermion) while four fermion ops. are typically generated by tree level vector exchange.

Taking $g_\psi < g_\rho$ flavor worsen, **Higgs mass gets better (smaller)**.

Tuning Higgs VEV: $\frac{v^2}{f^2} \approx 10\%$ + quartic coupling tuning!
Analysis of flavor bounds

<table>
<thead>
<tr>
<th>Operators $\Delta F = 2$</th>
<th>Re $c$</th>
<th>Im $c$</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(s_R d_L)^2$</td>
<td>500</td>
<td>2</td>
<td>$\Delta m_K, \epsilon_K$</td>
</tr>
<tr>
<td>$(s_R d_L)(s_L d_R)$</td>
<td>200</td>
<td>0.6</td>
<td>$\Delta m_D,</td>
</tr>
<tr>
<td>$(\bar{c}_L u_R)^2$</td>
<td>30</td>
<td>6</td>
<td>$\Delta m_{B_d}, S_{\psi K_S}$</td>
</tr>
<tr>
<td>$(\bar{b}_L \gamma^\mu d_L)^2$</td>
<td>5 $(\epsilon_3^u/\epsilon_3^q)^2$</td>
<td>2 $(\epsilon_3^u/\epsilon_3^q)^2$</td>
<td>$\Delta m_{B_d}$</td>
</tr>
<tr>
<td>$(\bar{b}_L \gamma^\mu s_L)^2$</td>
<td>6 $(\epsilon_3^u/\epsilon_3^q)^2$</td>
<td></td>
<td>$\Delta m_{B_s}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operators $\Delta F = 1$</th>
<th>Re $c$</th>
<th>Im $c$</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_R \sigma^{\mu\nu} e F_{\mu\nu} b_L$</td>
<td>2</td>
<td>9</td>
<td>$B \rightarrow X_s$</td>
</tr>
<tr>
<td>$s_L \sigma^{\mu\nu} e F_{\mu\nu} b_R$</td>
<td>-</td>
<td>0.4</td>
<td>$K \rightarrow 2\pi; \epsilon'/\epsilon$</td>
</tr>
<tr>
<td>$s_R \sigma^{\mu\nu} g_s G_{\mu\nu} d_L$</td>
<td>-</td>
<td>0.4</td>
<td>$B \rightarrow X_s$</td>
</tr>
<tr>
<td>$s_L \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$</td>
<td>-</td>
<td>0.4</td>
<td>$K \rightarrow 2\pi; \epsilon'/\epsilon$</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Operators $\Delta F = 0$</th>
<th>Re $c$</th>
<th>Im $c$</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d \sigma^{\mu\nu} e F_{\mu\nu} d_{L,R}$</td>
<td>-</td>
<td>0.03</td>
<td>neutron EDM</td>
</tr>
<tr>
<td>$\bar{u} \sigma^{\mu\nu} e F_{\mu\nu} u_{L,R}$</td>
<td>-</td>
<td>0.3</td>
<td>$B \rightarrow X_s$</td>
</tr>
<tr>
<td>$d \sigma^{\mu\nu} g_s G_{\mu\nu} d_{L,R}$</td>
<td>-</td>
<td>0.04</td>
<td>$K \rightarrow 2\pi; \epsilon'/\epsilon$</td>
</tr>
<tr>
<td>$\bar{u} \sigma^{\mu\nu} g_s G_{\mu\nu} u_{L,R}$</td>
<td>-</td>
<td>0.2</td>
<td>$B \rightarrow X_s$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leptonic Operators</th>
<th>Re $c$</th>
<th>Im $c$</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{e} \sigma^{\mu\nu} e F_{\mu\nu} e_{L,R}$</td>
<td>-</td>
<td>0.05</td>
<td>electron EDM</td>
</tr>
<tr>
<td>$\bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu} e_{L,R}$</td>
<td>$4 \times 10^{-3}$</td>
<td></td>
<td>$\mu \rightarrow e\gamma$</td>
</tr>
<tr>
<td>$\bar{e} \gamma^\mu \mu_{L,R} H^i i \overleftrightarrow{D}_\mu H$</td>
<td>1.5$(\epsilon_3^e/\epsilon_3^q)$</td>
<td></td>
<td>$\mu(Au) \rightarrow e(Au)$</td>
</tr>
</tbody>
</table>

$g_\rho \approx 4\pi \ m_\rho = 10 \text{ TeV}$

**Observable effects** $K^+ \rightarrow \pi^+ \nu\bar{\nu}$  
Also $B_s \rightarrow \mu^+ \mu^-$, $B \rightarrow X_s \ell^+ \ell^-$

**Up chromoelectric dipole** is expected to be quite solid. Mild tension, O(1) uncertainty on matrix elements.

**Very bad**

$\mu \rightarrow e\gamma \Rightarrow m_\rho \sim 150 \text{ TeV}$

Separation between $m_\rho$ and the flavor scale? Vecchi ('12)
Partial compositness + Supersymmetry

At $\Lambda_S$ soft terms for the SM fields (universal) and for the heavy sector.

Anarchic interactions among the heavy fields generate $O(1)$ non-universality among their soft terms at $\Lambda_F$

Non-universality transmitted to SM fields.

see also Nomura et al. ('08)

$\delta_{ij}^{u,d} \equiv \Lambda_F$

Realizes ‘disoriented A-terms’ of Giudice et al ('12)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Upper bound</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(c_{11}^u)_{LR}$</td>
<td>0.4</td>
<td>EDMs</td>
</tr>
<tr>
<td>$(c_{11}^d)_{LR}$</td>
<td>0.09</td>
<td>EDMs</td>
</tr>
<tr>
<td>$(c_{12}^e)_{LR,RL}$</td>
<td>0.6</td>
<td>$\mu \rightarrow e\gamma$</td>
</tr>
<tr>
<td>$(c_{11}^e)_{LR}$</td>
<td>0.5</td>
<td>electron EDM</td>
</tr>
</tbody>
</table>

$(c_{12}^u)_{LR} = 4$, $\frac{A_0}{\tilde{m}} = 2$,

$\tilde{m} = \tilde{m}_0 = 2\mu = 1\text{ TeV}$

Negative collider searches generate some tension with LHCb result
Partial compositness + Supersymmetry + RPV

Partial compositness provides an organizing principle to introduce RPV in the MSSM. Proton decay prohibits lepton and baryon number violation with high accuracy. Small neutrino masses disfavors RPV+lepton number violation.

\[ UDD \quad LLE \quad QLD \quad LH_u \]

All flavor bounds are easily escaped provided \( m_{\tilde{G}} > m_p - m_K \) to avoid \( p \to K^+ \tilde{G} \) \((*)\)

Collider bounds are relaxed due to reduced MET. Phenomenology varies according to the nature of the LSP. Generically one expects final states containing top quarks.

\[
\lambda_{ijk}^{RPV} \sim \left( \frac{g \beta}{4\pi} \right) \left( \frac{\tan \beta}{3} \right)^2 \left( \frac{\epsilon_3}{0.5} \right)^3 \times \begin{cases} 
2.7 \times 10^{-3} & (tbs) \\
0.6 \times 10^{-3} & (tbd) \\
1.7 \times 10^{-4} & (cbs) \\
0.5 \times 10^{-4} & (cbd) \\
1.7 \times 10^{-6} & (ubs) \\
0.4 \times 10^{-6} & (ubd) 
\end{cases}
\]

A good fit to the LHCb result with superpartners around 500-600 GeV is possible.

Need some help for the Higgs boson mass (NMSSM?)

\((*) \sim \) high scale mediation
Constraints from SS dileptons from top decays (Allanach et al. ('12)): gluino $\sim 600$ GeV

Poorly constrained spectrum (realizable in PC+SUSY for $\text{grho}\sim 1$)

Bounds gluino $\sim 460$ GeV from gluino pair production and $\tilde{g} \rightarrow 3j$ 

Stronger bound if $u$ squark light. (CMS EXO-11-060)

350-400 GeV bound on $u, c$ squark mass from squark pair production and dijet searches
Conclusions

Partial compositness

Composite Higgs
  - Quark flavor, EDM, lepton flavor

Supersymmetry
  - Quark flavor, EDM, lepton flavor

Baryonic RPV

LHCb
BACKUP
Partial Compositness vs MFV

A full comparison between the two approaches requires the specification of a **coupling** and a **mass scale** to completely define the structure of flavor-violating higher dimensional operators.

Eg: in SUSY with gauge mediation universal soft masses are generated at $M_{mess}$, non-universality generated through running respect MFV.

Four-fermions operator at superpartner scale have the form

$$\tilde{m}^2 = m^2_0 \left( 1 + c \frac{Y_U Y_U^\dagger}{(4\pi)^2} + \ldots \right)$$

$$\tilde{m} = m_0 \left( \tilde{M}_{mess} \right)$$

### d-d structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>MFV</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{d}<em>{iL}d</em>{jL}$</td>
<td>$V_{3i}^*V_{3j}$</td>
<td>$V_{3i}^*V_{3j}$</td>
</tr>
<tr>
<td>$\bar{d}<em>{iR}d</em>{jR}$</td>
<td>$y_i^d y_j^d V_{3i}^*V_{3j}$</td>
<td>$y_i^d y_j^d \frac{V_{3i}^*V_{3j}}{V_{3i}^*V_{3j}}$</td>
</tr>
<tr>
<td>$\bar{d}<em>{iL}d</em>{jR}$</td>
<td>$y_j^d V_{3i}^*V_{3j}$</td>
<td>$y_j^d \frac{V_{3i}}{V_{3j}}$</td>
</tr>
</tbody>
</table>

Shows only the structure in flavor space other coupling constants have been suppressed.