Partial compositeness: a partial view

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I'm not a believer . . .

(@LHCb: why so coy?)

I’m not a believer . . .
. . . but if I were, I’d be an evangelist.

- SM as a theory of flavour
- SM vs. PC
- B anomalies
- GUT?

Flavour physics addresses the deepest and simplest questions of the Universe

The Groucho Marx criterion

'A 4-year old child could understand this ...
... Run out and find me a 4-year old child.' G. Marx, Duck Soup

e.g. Why 3 generations?

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1 or 100 seem like much better choices . . .

e.g. Why 5 multiplets per generation?

e.g. Why hierarchy vs. anarchy in quark/lepton masses/mixings?

The SM fails to answer even these most basic of questions

DRAWINGS BY RUDYARD KIPLING
AND
COLOR PLATES BY
JOSEPH M. GLEESON

But the SM (plus $d = 5$ operators with $\Lambda \sim 10^{13-16}$ GeV) is a pretty good model of flavour nevertheless.

1. $O(1000)$ datapoints explained by $O(10)$ parameters

2. It answers some basic questions:

Q. Why no $p \to e\pi$, $n \to 3\nu$, $\mu \to e\gamma$, $\tau \to \mu\gamma \ldots$?

A. Accidental $U(1)_B \times \Pi_i U(1)_{L_i}$ below Λ

3. Doubtless other basic questions could be answered above Λ

4. The devil vs. the deep blue sea . . .

SM: tune 2 parameters: ρ, μ^2
TeV BSM: tune 2500 parameters (=2499+1)

SM flavour: beauty and the beast

beast: 3 x 3 x 3 x 2 parameters: Y_u, Y_d, Y_e (plus dim 5) beauty:

- most of these parameters have no effect
- remnants fit data perfectly (mod B anomalies)

beast:

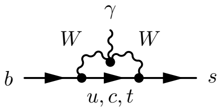
- empirically these are hierarchical: $m_t \gg m_c \gg m_u$, $m_b \gg m_s \gg m_d$
- and aligned: $V_{CKM} \simeq 1$
- qualitative and quantitative

beauty: no tree-level FCNC from

- gluons, photons (unbroken in vacuo: coupling matrix is 1)
- Z-bosons (same rep of $SU(3) \times U(1)_Q \implies$ same rep of $SU(3) \times SU(2) \times U(1)_Y$: coupling matrix is 1)
- Higgs (in 1HDM, v aligns masses with couplings)

a bag of 3 tricks

beauty/beast: suppression of loop-level FCNC



- $\sum_{uct} V_{ib} V_{is}^{*} f(m_i^2 / m_W^2)$
- $\simeq 1$ at $m_i^2 \ll m_W^2$

SM (elementary Higgs) vs. composite Higgs, cf. $\pi,^0 H$.

H is a scalar operator with quantum no.s of the Higgs

...a bilinear coupling to SM fermions, Hqu, is at best marginal:

$$\mathscr{L} \sim \frac{Hqu}{\Lambda^{d-1}} + \frac{qqqq}{\Lambda^2}$$

m_t + FCNC $\implies d \lesssim 1.2 - 1.3$

$d \to 1 \implies d[H^\dagger H] \to 2$ (cf. WTC: $d \sim 2-3$, RS $d = \infty$)

Strassler, 0309122

Luty & Okui, 0409274

Rattazzi, Rychkov & Vichi, 0807.0004

Rychkov & Vichi, 0905.2211

Can't solve flavour & hierarchy problems in this way.

SM (elementary Higgs) vs. partial compositeness

…a linear coupling to SM fermions, $\overline{Q}q$, can be relevant and flavour problems can be decoupled!

$$\mathscr{L} \sim g_\rho HQU + m_\rho(\overline{Q}Q + \overline{U}U) + \varepsilon^q g_\rho \overline{Q}q + \varepsilon^u g_\rho \overline{U}u$$

Kaplan, 91

beauty of PC $$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u\,, \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d.$$

$$g_\rho v \epsilon_i^q \epsilon_i^u \sim m_i^u, \qquad g_\rho v \epsilon_i^q \epsilon_i^d \sim m_i^d$$

$$\frac{\epsilon_1^q}{\epsilon_2^q} \sim \lambda, \qquad \frac{\epsilon_2^q}{\epsilon_3^q} \sim \lambda^2, \qquad \frac{\epsilon_1^q}{\epsilon_3^q} \sim \lambda^3,$$

- flavour could be decoupled
- large mixings from $O(1)$ anomalous dimensions
- predicts mass/mixing hierarchies
- BSM flavour aligned with SM

beast of PC

- but is flavour decoupled?! UV completion
- strong coupling: $O(1)$ predictions
- neutrinos?

In fact there are more serious problems:
p decay, $\mu \to e\gamma$, n/e EDM, ε_K

Fiat: make $U(1)_B$ a global symmetry of strong sector and of the mixing.
($\mathbb{Z}/2$ won't do: $n \leftrightarrow \overline{n}$)

If you tolerate this, then why not $\Pi_i U(1)_{L_i}$ as well?
(Or just in the strong sector)
Maintain hierarchy generation

Frigerio, 1807.04279

CP symmetry is not an option

CP in strong sector only is viable; with $\Pi_i U(1)_{L_i/B_i}$ suppresses e/n EDM.

Frigerio, 1807.04279

(Alternative: multiple flavour scales)

Vecchi, 1206.4701

Panico & Pomarol, 1603.06609

Partial compositeness and B anomalies

strongly-coupled sectors feature lots of resonances, e.g. Z', LQ
cf. γ, Z, L, Q,
n.b. $(3, 2, \frac{1}{6}) \otimes (1, 2, -\frac{1}{2}) \supset (3, 3, -\frac{1}{3})$
n.b. $(3, 2, \frac{1}{6}) \otimes (3, 2, \frac{1}{6}) \supset (\overline{3}, 3, \frac{1}{3})$

strongly-coupled sectors feature lots of resonances, e.g. Z', LQ but they need to be light

- scalars: pseudo-Goldstone bosons
- vectors: gauged Goldstone bosons

(And with LQs, must reanalyse $U(1)_B \times \Pi_i U(1)_{L_i}$)

$B \to K\mu\mu$ comes out roughly the right size

BMG, 0910.1789

BMG, Nardecchia & Renner, 1412.1791

Unification

Recall that in PC, the composite sector is charged under electroweak and colour . . .

Recall that in PC, the composite sector is charged under electroweak and colour . . . so there is hope for unification, of a sort

- SM: unifies just about
- SUSY $= SM + \tilde{h}_{u,d}$ unifies perfectly
- Composite H $= SM - t_R, t_R^c$ unifies perfectly

Agashe, Contino, & Sundrum, 0502222

- PNGB H comes in GUT rep $\implies$ PNGBLQ
- e.g. $SO(11)/SO(10)$ has 10 PNGBs: a Higgs plus a $(3, 1, \frac{1}{3})$.
- e.g. $(SO(6) \times SO(6))/(SU(3) \times U(1) \times SO(5))$ has Higgs plus singlet scalar plus vector LQ plus massless vector

BMG & al., 0902.1483

I can't make this work; can you?

Summary: a partial view

I don't believe in B-anomalies, but if I did:

- I'd bet on partial compositeness
- it predicts $B \to K$ (forget $B \to D$)
- it's got a lot else going for it: EW/flavour hierarchy, unification?
- other models kiplinesque IMHO