Rare decays vs. BSM

Ben Gripaios

Cambridge

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Focus on just 1 particular scenario . . .

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. . . which illustrates the general picture:

1. flavourful BSM unlikely to be around the corner (LHC, FC, . . .)
2. but if it is, we are likely to learn a lot!
3. potential signals/constraints everywhere (inc. rare K-decays)

Experiment: B to K anomalies
Theory: leptoquarks in composite higgs models

BMG & Coradeschi, in progress

BMG, Marco Nardecchia & Sophie Renner, 1412.1791

BMG, 0910.1789

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Composite leptoquarks at the LHC

Ben Gripaios

CERN PH-TH,
Geneva 23, 1211 Switzerland

There are also interesting possibilities for the observation of leptoquark-mediated rare processes, including $B \to K\mu\overline{\mu}$, $\mu \to e\gamma$, $\tau \to \mu\gamma$, and $\mu - e$ conversion in nuclei, where my estimates for the leptoquark couplings, which may be considered as rough theoretical lower bounds, lie close to experimental upper bounds, either actual or envisaged.

2 remarks:

- a theory of everything
- a theory of nothing

6 motivations . . .

1. $\exists$ a light scale/scalar, H ...

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...suggesting compositeness c.f. $*$,He,$\alpha, \pi^{\pm,0}$

...but on what scale?

Earth-Sun, eV, MeV, GeV

For H EWPT, LHC, and FCNC all suggest some tuning;
we'll take $m_\rho \sim 10\,TeV$)

2. the composite sector yields fermion masses . . .

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... 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. TC: $d \sim 2 - 3$)

Strassler, 0309122

Luty & Okui, 0409274

Rattazzi, Rychkov & Vichi, 0807.0004

Rychkov & Vichi, 0905.2211

2. the composite sector yields fermion masses ...

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

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

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

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

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

a.k.a partial compositeness

Kaplan the Elder, 91

3. partial compositeness $\Longrightarrow$ composite coloured fermions

cf. $\mathscr{L} \subset \varepsilon^q g_\rho \overline{Q} q$

strong dynamics charged under $SU(2) \times U(1)$ and $SU(3)$: GUT?

4. composite coloured fermions $\Longrightarrow$ composite coloured scalars

$$SU(3)xSU(2)xU(1) : (3, 2, 1/6) \otimes (3, 2, 1/6) \subset (\bar{3}, 3, 1/3)$$

a. k. a. leptoquarks/diquarks

BMG, 0910.1789

Giudice, BMG, & Sundrum, 1105.3161

5. LQs can be light (e.g. PNGBs); if so give peculiarly large effects in e.g. $B \to K\mu\mu$, $K \to \pi\mu\mu$, $K \to \pi\nu_\tau\nu_\tau$

6. Unification

- SM: unifies just about
- SUSY $= SM + \tilde{h}_{u,d}$ unifies perfectly
- Composite H $= SM - t_R, t_R^c$ unifies perfectly
- PNGB H comes in GUT rep: +LQ!

LQs can be light (e.g. PNGBs); if so give peculiarly large effects in e.g. $B \to K\mu\mu$, $K \to \pi\mu\mu$, $K \to \pi\nu_\tau\nu_\tau$

Predictions . . .

Can we fit the $B \to K\mu\mu$ (and all other FCNC) data?

BMG, Marco Nardecchia & Sophie Renner, 1412.1791

Need the right light LQ state
Need the right LQ couplings

Quark sector:

10 parameters: $g_\rho, \varepsilon_i^{q,u,d}$
9 quark masses and mixings fix all but g_ρ and ε_3^q:

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

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

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

Lepton sector:

6 parameters: $\varepsilon_i^{l,e}$
Assume $\varepsilon_i^l \sim \varepsilon_i^e$ to minimise $\mu \to e\gamma$
3 charged lepton masses fix all 6

Leptoquark couplings:

Let $c_{ij} \sim O(1)$ parameterise our ignorance of strong dynamics

$$\lambda_{ij} = g_\rho c_{ij} \epsilon_i^\ell \epsilon_j^q,$$

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j = 1$	$j = 2$	$j = 3$
$i = 1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i = 2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i = 3$	1.16×10^{-3}	5.16×10^{-3}	0.101

LQ effects fixed by $g_\rho \lesssim 4\pi, \varepsilon_3^q < 1$, and $M \sim$ TeV.

R_K:

$$\mathrm{Re}(c_{22}^{*}c_{23}) \in [1.42, 2.98] \left(\frac{4\pi}{g_\rho}\right) \left(\frac{1}{\epsilon_3^q}\right)^2 \left(\frac{M}{\mathrm{TeV}}\right)^2 \quad \text{(at } 1\sigma\text{)}.$$

Decay	(ij)(kl)*	$\lvert\lambda_{ij}\lambda^*_{kl}\rvert / \left(\frac{M}{\mathrm{TeV}}\right)^2$	$\lvert c_{ij}c^*_{kl}\rvert \left(\frac{g_\rho}{4\pi}\right)(\epsilon^q_3)^2 / \left(\frac{M}{\mathrm{TeV}}\right)^2$
$K_S \to e^+e^-$	$(12)(11)^*$	< 1.0	$< 4.9 \times 10^7$
$K_L \to e^+e^-$	$(12)(11)^*$	$< 2.7 \times 10^{-3}$	$< 1.3 \times 10^5$
$\dagger\ K_S \to \mu^+\mu^-$	$(22)(21)^*$	$< 5.1 \times 10^{-3}$	$< 1.2 \times 10^3$
$K_L \to \mu^+\mu^-$	$(22)(21)^*$	$< 3.6 \times 10^{-5}$	< 8.3
$K^+ \to \pi^+e^+e^-$	$(11)(12)^*$	$< 6.7 \times 10^{-4}$	$< 3.3 \times 10^4$
$K_L \to \pi^0e^+e^-$	$(11)(12)^*$	$< 1.6 \times 10^{-4}$	$< 7.8 \times 10^3$
$K^+ \to \pi^+\mu^+\mu^-$	$(21)(22)^*$	$< 5.3 \times 10^{-3}$	$< 1.2 \times 10^3$
$K_L \to \pi^0\nu\bar{\nu}$	$(31)(32)^*$	$< 3.2 \times 10^{-3}$	< 42.5
$\dagger\ B_d \to \mu^+\mu^-$	$(21)(23)^*$	$< 3.9 \times 10^{-3}$	< 46.0
$B_d \to \tau^+\tau^-$	$(31)(33)^*$	< 0.67	$< 4.6 \times 10^2$
$\dagger\ B^+ \to \pi^+e^+e^-$	$(11)(13)^*$	$< 2.8 \times 10^{-4}$	$< 6.9 \times 10^2$
$\dagger\ B^+ \to \pi^+\mu^+\mu^-$	$(21)(23)^*$	$< 2.3 \times 10^{-4}$	< 2.7

Opportunities in $B \to K\nu\nu$ (Belle II), $K_L \to \mu\mu$, $K \to \pi\nu\nu$ (NA62), $\mu \to e\gamma$ (MEG), $B \to \pi\mu\mu$, Δm_{B_s}, ...

General summary:

1. flavourful BSM unlikely to be around the corner (LHC, FC, . . .)
2. but if it is, we are likely to learn a lot!
3. look everywhere!