Flavor and PGB Higgs more generally

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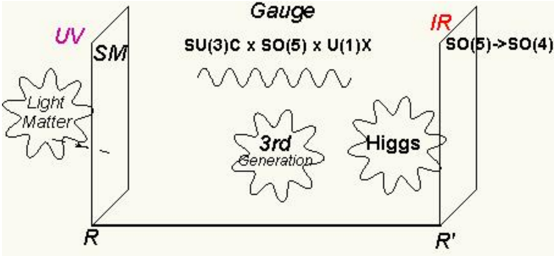
5D PGB and flavor

Agashe, Contino, Pomarol [2005]



- $SO(5) \times U(1)_X$ gauge symmetry and fermions in bulk
- UV breaking to $SU(2)_L \times U(1)_Y$ and IR brane breaking to $SO(4) \times U(1)_X$
- Fifth component of gauge bosons from $SO(5)/SO(4)$ coset becoming PGB Higgs
- Masses of bulk fermions depend on localization Arkani-Hamed, Schmaltz [ph/9903417] , Grossman, Neubert [ph/9912408]
- Light fermions localized near UV, heavy fermions near IR where Higgs lives
- Flavor mixing from IR brane localized mass terms
- FCNC suppressed by RS-GIM mechanism Gherghetta, Pomarol [ph/0003129] , Agashe, Perez, Soni [ph/0408134]

Flavor Bounds

Csaki,AA,Weiler [0804.1854]

Flavor Bounds from ϵ_K on 5D PGB flavor scenario

$$M_{KK} \gtrsim 30\,\mathrm{TeV}$$

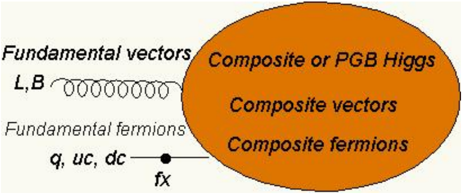
which kills naturalness and prospects for LHC signals.

- This is a generic, statistical limit. Some models with random IR boundary mass terms and a lighter KK gluon may pass the bound due to accidental cancellations
- The bound depends on the composite strong and weak coupling and can be changed in the presence of boundary kinetic terms
- Presumably, changing the background, or Higgs localization also affects the bounds

What are the general bounds on this type of scenario?

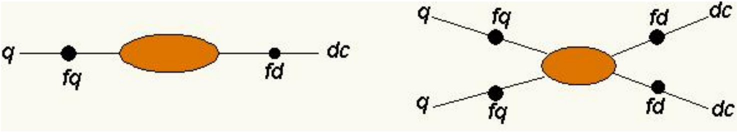
Partial compositeness

Contino,Kramer,Son,Sundrum [ph/0612180] Idea behind flavor 5D theory: Partial Compositeness



- Fundamental sector with chiral fermions; no masses and no flavor violation from the fundamental sector alone
- Composite sector as a black box hosting Higgs and vector-like fermions exhibiting full monty flavor anarchy
- Fundamental fermions mix with composite ones and acquire mass proportional to the mixing angles
- Light fermions mix lightly, heavy fermions mix more strongly, top mixes nearly maximally

Partial compositeness and FCNC



$(m_d)_{ij} \sim f_{q_i} f_{d_j}$ $\qquad$ $C_{d_i d_j d_k^c d_l^c} \sim f_{q_i} f_{q_j} f_{d_k} f_{d_l}$

- Hierarchies: masses proportional to hierarchical mixing angles of the fundamental fermions with the composite sector
- RS-GIM: for the light quarks, FCNCs suppressed by the same small mixing angles that suppress the light quark masses

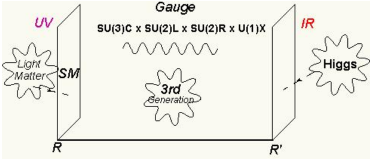
Two-site approach

- RS or 5D PGB are examples of a calculable model of the composite black box
- Another, more general approach is to represent the 5D as a two-site deconstruction model a-la Contino,Kramer,Son,Sundrum [ph/0612180] which can be thought of as an effective description of the first KK level
- Sufficient from the LHC point of view (the tower experimentally inaccessible; lucky if we can see the first KK mode)
- Describes almost any 5D scenario with given low-energy symmetries (regardless of the shape of warp factor, bulk vs brane localization of Higgs, size of brane kinetic terms, etc)
- Or forget about 5D - two-site as another calculable model of the black box

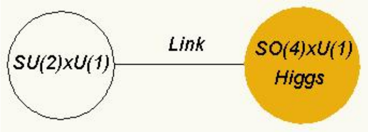
But, no geometric explanation of flavor hierarchies! Small parameters put in by hand from the point of view of the effective 2-site model

Composite Flavor in two-site approach

Agashe, Azatov, Liu [0810.1016]



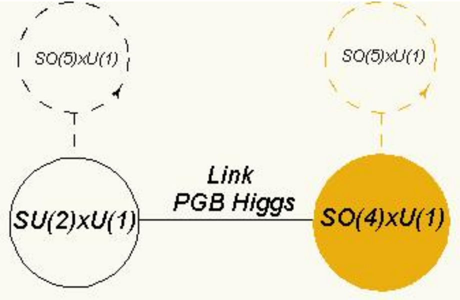
$\longrightarrow$



- Flavor bounds less severe in the whole parameter space of the 2-site model; $M_{KK} \gtrsim 5 TeV$
- But electroweak symmetry breaking not calculable in this set-up; little hierarchy problem not addressed

PGB Flavor in two-site approach

Azatov, Falkowski, Liu, Okui, Son [in progress]



- Fundamental site with SM gauge symmetry
- Composite site with $SO(4)_{LR} \times U(1)_X$ gauge symmetry ensuring custodial symmetry
- Larger $SO(5) \times SO(5)$ *global* symmetry of the link sector
- Link Higgs breaking the gauge symmetry to the diagonal SM
- Another angle: Little Higgs married to anarchic flavor

Gauge fields and PGB Higgs

- Fundamental gauge fields $\bar{L}$, $\bar{B}$ mixing with composite SO(4) gauge fields $\tilde{A}$ via the link Φ,

$$D\Phi = d\Phi - i\bar{g}\bar{L}\Phi - i\bar{g}_Y\bar{B}\Phi + i\tilde{g}\Phi\tilde{A}$$

- Also, fundamental gluons $\bar{G}$ mixing with composite gluons $\tilde{G}$ via another link Φ_s

$$D\Phi_s = d\Phi_s - i\bar{g}_s\bar{G}\Phi_s + i\tilde{g}_s\Phi_s\tilde{G}$$

- Links get vevs breaking gauge group to diagonal SM group

$$\langle\Phi\rangle = f I_{5\times5} \qquad \langle\Phi_s\rangle = f_s I_{3\times3}$$

- 10 broken global SO(5) generators gives rise to $10 - 6 = 4$ PGB degrees of freedom

$$\Phi \to f \begin{bmatrix} 1_{3\times3} & 0 & 0 \\ 0 & \cos\left(\frac{h}{\sqrt{2}f}\right) & -\sin\left(\frac{h}{\sqrt{2}f}\right) \\ 0 & \sin\left(\frac{h}{\sqrt{2}f}\right) & \cos\left(\frac{h}{\sqrt{2}f}\right) \end{bmatrix}$$

Gauge fields and PGB Higgs

- PGB Higgs with compositeness scale $f \sim 1$ TeV
- Massive weak gauge bosons with mass scale set by f and composite weak coupling $\tilde{g}$

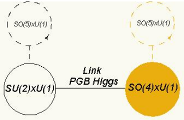
$$m_{L*} \approx m_{B*} \approx \tilde{g} f$$

- Massive gluons with mass scale set by f_s and compostie strong coupling $\tilde{g}_s$

$$m_{G*} \approx \tilde{g}_s f_s$$

In two-site, the KK gluon mass is not directly related to naturalness

Partial Compositeness for fermions



- Fundamental chiral quarks q, u_c, d_c mixing with composite vector-like quarks Q, Q_c, U, U_c, D, D_c via the link

$$\lambda f_q q \Phi Q_c + \lambda f_u u_c \Phi U + \lambda f_d d_c \Phi D$$

Flavor hierarchies from hierarchical mixing parameters $f_{q,u,d}$

- Composite fermions have masses of order λf

$$\lambda f \left(Q_c Q + U_c U + D_c D \right)$$

- Composite quarks have anarchic mixing via mass terms (schematically)

$$\lambda f U_c y_u Q + \lambda f D_c y_d Q$$

Flavor mixing originating from anarchic 3x3 matrices y_u, y_d

Electroweak precision constraints

- $T = 0$ because of custodial symmetry
- $S = 1/\tilde{g}^2 f^2 \approx 1/M_{Z'}^2$. Imposing $S < 0.2$ leads to the bound $M_{Z'} \gtrsim 2.5$ TeV.
- W and Y are suppressed by $\bar{g}^2/\tilde{g}^2$ and are less constraining than S as long as fundamental coupling $\bar{g}$ smaller than composite coupling $\tilde{g}$
- Zbb less constraining when custodial parity protection imposed

Effective lagrangian for down quarks

Integrate out composite quarks, living fundamental quarks as the degrees of freedom in the effective theory. The effective lagrangian (schematically)

$$\bar{d}\left[1 + f_q(1+y^2)f_q\right]\bar{\sigma}\cdot p d + d_c\left[1 + f_d(1+y^2)f_d\right]\sigma\cdot p\bar{d}_c$$
$$+v\lambda d_c[f_d y f_q]d + \mathrm{h.c.}$$

- `First step:` diagonalize and normalize kinetic terms by Hermitian transformation

$$d \to H_q d \qquad d_c \to d_c H_d$$

- `Second step:` diagonalize mass matrix by bi-unitary rotation

$$d \to L_d d \qquad d_c \to d_c R_d^\dagger$$

- As usual, hierarchical masses and mixing angles

$$m_{d_i} \sim \lambda v y_* f_{d_i} f_{q_i} \qquad (L_d)_{ij} \sim f_{q_i}/f_{q_j} \qquad (R_d)_{ij} \sim f_{d_i}/f_{d_j} \qquad i < j$$

FCNC

After rotations to mass eigenstate basis, non-diagonal couplings to heavy gluons and

$$g^G_{L,d} = \tilde{g}_s L_d^\dagger H_q^2 L_d \qquad g^G_{R,d} = \tilde{g}_s R_d^\dagger H_d^2 R_d$$

Non-diagonal couplings because Hermitian transformation matrices are not unit matrices:

$$H_q \sim 1 - \frac{1}{2} f_q y^2 f_q \qquad H_d \sim 1 - \frac{1}{2} f_d y^2 f_d$$

Leading to

$$[g^G_{L,d}]_{ij} \sim \tilde{g}_s f_{q_i} f_{q_j} \qquad [g^G_{R,d}]_{ij} \sim \tilde{g}_s f_{d_i} f_{d_j}$$

Similarly, non-diagonal couplings to heavy weak gauge bosons

$$g^L_{L,d} = \tilde{g} L_d^\dagger H_q^2 L_d T_3 \qquad g^B_{L,d} = \tilde{g} L_d^\dagger H_q^2 L_d Y \qquad g^B_{R,d} = \tilde{g} R_d^\dagger H_d^2 R_d Y$$

Flavor bounds from ϵ_K

Tree-level KK gluon exchange contribution to ϵ_K via C_4

$$\Delta_G C_4 \sim \frac{1}{f_s^2}\frac{4 m_s m_d}{\lambda^2 v^2} \qquad \rightarrow \qquad f_s \geq \frac{15\,\mathrm{TeV}}{\lambda}$$

Color compositeness scale constrained to be a few TeV (heavy gluon 5 TeV or heavier)
Tree-level Z prime exchange contribution to ϵ_K via C_1

$$\Delta_L C_1 \sim \frac{1}{f^2}\frac{m_t^2 y^4 \lambda_c^{10}}{2\lambda^2 v^2} \qquad \rightarrow \qquad f \geq \frac{3.75\,\mathrm{TeV}}{\lambda}$$

Tree-level B prime exchange contribution to ϵ_K via C_5

$$\Delta_B C_5 \sim \frac{1}{f^2}\frac{4 m_s m_d}{9\lambda^2 v^2} \qquad \rightarrow \qquad f \geq \frac{4.5\,\mathrm{TeV}}{\lambda}$$

Higgs compositeness scale $f \sim 1$ TeV possible for large but perturbative λ

Summary

- Two-site approach offers an effective description of the RS-type (partial compositeness) flavor scenario
- Entire parameter space relevant for the LHC can be explored
- Bounds from electroweak precision tests and $\Delta F = 2$ processes allow for a fairly natural Higgs compositeness scale of order 1 TeV and for heavy weak gauge bosons within the LHC reach
- Bounds from $\Delta F = 1$ processes in progress

Model independent parametrization of $\Delta F = 2$ operators

$$
\mathcal{H} = C^1(\Lambda)(\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\,(\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) + \tilde{C}^1(\Lambda)(\bar{q}_R^{i\alpha}\gamma_\mu q_{R\alpha}^j)\,(\bar{q}_R^{k\beta}\gamma^\mu q_{R\beta}^l)
$$

$$
+C^2(\Lambda)(\bar{q}_R^{i\alpha} q_{L\alpha}^k)(\bar{q}_R^{l\beta} q_{L\beta}^j) + C^3(\Lambda)(\bar{q}_R^{i\alpha} q_{L\beta}^l)\,(\bar{q}_R^{k\beta} q_{L\alpha}^j) + (L \to R, C \to \tilde{C})
$$

$$
+C^4(\Lambda)(\bar{q}_R^{i\alpha} q_{L\alpha}^k)(\bar{q}_L^{l\beta} q_{R\beta}^j) + C^5(\Lambda)(\bar{q}_R^{i\alpha} q_{L\beta}^l)(\bar{q}_L^{k\beta} q_{R\alpha}^j)
$$

UT fit bounds on $\Delta F = 2$ operators

Parameter	Limit on Λ (TeV)	Suppression in RS (TeV)
$\mathrm{Re}C_K^1$	$1.0 \cdot 10^3$	$\sqrt{6}M_G/(g_{s*}\lambda^5 f_{q_3}^2) = 23 \cdot 10^3$
$\mathrm{Re}C_K^4$	$12 \cdot 10^3$	$M_G(vY_*)/(g_{s*}\sqrt{2\, m_d m_s}) = 22 \cdot 10^3$
$\mathrm{Im}C_K^1$	$15 \cdot 10^3$	$\sqrt{6}M_G/(g_{s*}\lambda^5 f_{q_3}^2) = 23 \cdot 10^3$
$\mathrm{Im}C_K^4$	$160 \cdot 10^3$	$M_G(vY_*)/(g_{s*}\sqrt{2\, m_d m_s}) = 22 \cdot 10^3$
$\lvert C_D^1 \rvert$	$1.2 \cdot 10^3$	$\sqrt{6}M_G/(g_{s*}\lambda^5 f_{q_3}^2) = 23 \cdot 10^3$
$\lvert C_D^4 \rvert$	$3.5 \cdot 10^3$	$M_G(vY_*)/(g_{s*}\sqrt{2\, m_u m_c}) = 12 \cdot 10^3$
$\lvert C_{B_d}^1 \rvert$	$0.21 \cdot 10^3$	$\sqrt{6}M_G/(g_{s*}\lambda^3 f_{q_3}^2) = 1.2 \cdot 10^3$
$\lvert C_{B_d}^4 \rvert$	$1.7 \cdot 10^3$	$M_G(vY_*)/(g_{s*}\sqrt{2 m_b m_d}) = 3.1 \cdot 10^3$
$\lvert C_{B_s}^1 \rvert$	30	$\sqrt{6}M_G/(g_{s*}\lambda^2 f_{q_3}^2) = 270$
$\lvert C_{B_s}^4 \rvert$	230	$M_G(vY_*)/(g_{s*}\sqrt{2 m_b m_s}) = 780$