Review of flavor in warped models

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16/3/2011
1) Can we have a sensible flavor sector without an (elementary) Higgs?

2) Does it survive the constraints from Kaon physics and the B factories?

3) Predictions for the LHC?
Weak scale is unstable

elementary scalar Higgs

\[ \mathcal{L}_{Higgs} = \Lambda^2 H^2 + \ldots \times \]
Solution: no elementary scalar composite Higgs (bound-state, like pion in QCD)

\[ \mathcal{H} \rightarrow \langle \psi_{TC} \psi_{TC}^c \rangle \quad [\mathcal{H}] \approx 3 \]
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\[ \mathcal{H} \rightarrow \langle \psi_{TC} \psi_{TC}^c \rangle \quad [\mathcal{H}] \approx 3 \]

\[ \mathcal{L}_{Higgs} = \frac{1}{\Lambda^2} \mathcal{H}^2 + \ldots \]
Flavor without an elementary Higgs Yukawas (CKM, masses)

\[ y_{ij} \bar{\psi}_i H \psi_j \]

SM
Flavor without an elementary Higgs

Yukawas (CKM, masses)

\[ y_{ij} \bar{\psi}_i H \psi_j \rightarrow \frac{1}{\Lambda^2} y_{ij} \bar{\psi}_i H \psi_j \]

SM composite

[\mathcal{H}] \approx 3
Flavor problem

\[ \frac{1}{\Lambda^2} y_{ij} \bar{\psi}_i H \psi_j + \frac{1}{\Lambda^2} c_{ijkl} \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l \]

can’t be too small, because top mass large

\[ \Lambda = \mathcal{O}(\text{TeV}) \]
Flavor problem

\[
\frac{1}{\Lambda^2} y_{ij} \bar{\psi}_i H \psi_j + \frac{1}{\Lambda^2} c_{ijkl} \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l
\]

can’t be too small, because top mass large

\[
\Lambda = \mathcal{O}(\text{TeV})
\]

must be very small because this leads to FCNCs

\[
\Lambda > 10^5 \text{ TeV}
\]
Two ways of giving mass to fermions…

Bi-linear (like SM):

\[ \mathcal{L} = y_f L \mathcal{O}_H f_R, \quad \mathcal{O}_H \sim (1, 2)^{1/2} \]

Linear:

\[ \mathcal{L} = y_f L \mathcal{O}_R + y_R f_R \mathcal{O}_L + m \mathcal{O}_L \mathcal{O}_R, \quad \mathcal{O}_R \sim (3, 2)^{1/6} \]

D.B. Kaplan '91
Partial compositeness

$$|SM\rangle = \cos \phi |elem.\rangle + \sin \phi |comp.\rangle$$

$$|heavy\rangle = -\sin \phi |elem.\rangle + \cos \phi |comp.\rangle$$

Composites are heavy ($m_\rho \approx \text{TeV}$).

Light quarks have very little composite admixture.
strong sector

Higgs, top, resonances

$\rho_\mu$

$g^*, m_\rho$

$1 \lesssim g^* \lesssim 4\pi$

elementary fields

$u, d, c, s, b, A_\mu$
AdS/CFT $\Rightarrow$ Randall Sundrum

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

Gherghetta, Pomarol; Huber, Shafi; Agashe et. al; Csaki, Falkowski, AW

UV

$u,d,c,s,b_R$

IR

$t_R, Q_L$

0 5 10 15 20 25 30 35

UV IR
KK modes

Higgs

$F(t_R)$

$F(Q_L)$
Degree of compositeness:

\[ \sin \phi = F(c) \sim \left( \frac{\text{TeV}}{M_{\text{pl}}} \right)^{c-\frac{1}{2}} \]
LHC implications

Resonance production (option 1)

\[ u \rightarrow S_{up} \rho \]

\[ \sim g_*^2 \sin^2 \theta_{u_R} \]

strongly suppressed for light quarks!
LHC implications

Resonance production (option 2)

\[ u \rightarrow \text{gluon} \quad \rho \sim \frac{g_s}{g^*} \]

similar to \( \gamma - \rho \) mixing

NB, gluon-rho-rho = 0
Resonance decay

decays dominantly into 3rd generation
(tt, bt, bb)
tops mostly collimated, need sub-jet top tagger
FCNCs
FCNC protection

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

masses from mixing in composites

\[ m_d \sim v \sin \theta_{d_L} Y^* \sin \theta_{d_R} \]

\[ K^0 - \bar{K}^0 \]
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\[ m_d \sim v \sin \theta_{d_L} Y^* \sin \theta_{d_R} \]

FCNCs suppressed by the same mixings

\[
\begin{align*}
\sim & \frac{g_*^2}{M^2 \rho} s_{d_L} s_{d_R} s_{s_L} s_{s_R} \\
\sim & \frac{g_*^2}{M^2 \rho} m_d m_s \\
\sim & \frac{g_*^2}{M^2 \rho} vY_*^2
\end{align*}
\]
masses from mixing in composites

\[ m_d \sim v \sin \theta_{d_L} Y^* \sin \theta_{d_R} \]

FCNCs suppressed by the same mixings

\[ \sim \frac{g^2_*}{M^2} s_{dL} s_{dR} s_{sL} s_{sR} \]

\[ \sim \frac{g^2_*}{M^2} \frac{m_d m_s}{vY^*_2} \]

RS-GIM
FCNCs from 3 TeV resonances

\[ \Lambda \ [\text{GeV}] \]

\[ 10^4 \leq \Lambda \leq 10^8 \]

- (s → d) \quad \Delta M_K, \epsilon_K
- (b → d) \quad \Delta M_d, \sin 2\beta
- (b → s) \quad \Delta M_s, A_{sl}
- (c → u) \quad D – \bar{D}

Csaki, Falkowski, A.W. '08
FCNCs from 3 TeV resonances

Csaki, Falkowski, A.W. '08

\[ \epsilon_K \propto \text{Im} \left( C_{LL} + 115 C_{LR} \right) \]

\[ \Delta M_K , \epsilon_K \quad \Delta M_d , \sin 2\beta \quad \Delta M_s , A_{sl} \quad D - \bar{D} \]
CP constraints on composite mass

Csaki, Falkowski, AW; Buras et al; Casagrande et al

$\Delta F = 2$ (strongest constraint from $\epsilon_K$)

$M_* \gtrsim 10 \left( \frac{g_*}{Y_*} \right) \text{TeV}$

$\Delta F = 1$ (strongest constraint from $\epsilon'/\epsilon$)

Gedalia et. al

$M_* \gtrsim 1.3 Y_* \text{TeV}$

$\Delta F' = 0$ neutron EDM

Agashe et. al, Delaunay et. al, Redi, AW

$M_* \gtrsim 2.5 Y_* \text{TeV}$
Flavor triviality: dynamical MFV

Cacciapaglia, Csaki, Galloway, Marandella, Terning, A.W.

strong sector $SU(3)_Q \times SU(3)_u \times SU(3)_d$

flavor trivial

mixing $\sim$ Yukawas

$s_u, s_d \sim Y_u, Y_d$

sweet spot if MFV “shines” into the bulk, $m_\rho \approx 2$ TeV

$\Rightarrow$ flavor gauge bosons predicted
Flavor gauge bosons at LHC

\[ g_{\text{eff}} G^{(1)KK}_{\mu} \bar{\psi} \psi \]

flavor gauge bosons do not have massless modes (flavor is broken)

no $\gamma - \rho$ mixing!

But quark composite mixing can be flavor universal & large

\[ \sim g_*^2 \sin^2 \theta_{u_R} \]

Drell-Yan

Figure 4: Schematic of Drell-Yan production.

Drell-Yan means the production of a pair of hard muons or electrons through quark-antiquark annihilation into a virtual photon or $Z$ boson (see Figure 4). This process has a clean final state that is relatively easy to detect experimentally. Letting $k_\mu$, $k'_\mu$ denote the 4-momenta of the leptons, the invariant mass squared of the dilepton pair is given by

\[ M^2 = (k_\mu + k'_\mu)(k_\mu + k'_\mu) \]

In the data, a plot of the lepton invariant mass versus number of events should show a strong peak around $M^2 = M^2_{Z} = (91.19 \text{ GeV})^2$. Such a peak is indeed seen in the Tevatron data (see Figure 5).
Flavor gauge bosons at LHC

$g_{\text{eff}} G^{(1)KK}_{\mu} \bar{\psi} \psi$

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But quark composite mixing can be flavor universal & large

$\sim g^2_* \sin^2 \theta_{u_R}$
Flavor scalars & gauge bosons


\[ g_x = \frac{g_s}{\sqrt{6}} \text{diag}(1, 1, -2) \]

possible explanation of FB asymmetry at Tevatron

see also Grinstein et. al.
Outlook

more on warped Models:

Suzanne Westhoff - Top FB Asymmetry (next)
Florian Goertz - Higgs physics (YSF2)
Torsten Pfoh - CPV in $B_s$ (YSF3)
Figure 7: In Fig. 7 we show the semileptonic CP-asymmetry $A_{\text{SL}}^s / (A_{\text{SL}}^s)_{\text{SM}}$ as a function of $\Delta S_{\psi \phi}$.

In addition to the plots in the left panel, we observe that due to the correlation between these two observables, a future more accurate measurement of the naturalness of the theory, the plots in the right panels of these figures fulfil the additional constraint imposed.

For instance, in Fig. 2, we find that the full range of new physics phases is possible, so that $\Delta \approx 20$ does not qualitatively modify the results obtained, although the new physics phases are most likely, being a consequence of the generic relation $\Delta \approx 20$, but the result is not available.

In addition we observe that the model-independent correlation pointed out in [63] can be enhanced by more than two orders of magnitude relative to its SM value.
Indirect tests: new physics C.S.I.

SM has accidental symmetries (B, L), e.g.

\[ \mathcal{L}_{SM} + \frac{C_B}{\Lambda^2} (\bar{u}^c u)(\bar{e}^+ d) \]

\[ \Rightarrow \text{absence} \text{ of violation probes very high scales} \]

Flavor symmetries are only weakly broken (except top) & FCNCs require 1-loop

\[ \mathcal{L}_{SM} + \frac{C_{\text{flavor}}}{\Lambda^2} (\bar{b} d)(\bar{b} d) \]

\[ \Rightarrow \text{smallness} \text{ of violation probes high scales} \]
### 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? Small & hierarchical.

Other dimensionless parameters of the SM:

\[g_s \sim 1, \ g \sim 0.6, \ g' \sim 0.3, \ \lambda_{\text{Higgs}} \sim 1, \ |\theta| < 10^{-9}\]
<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on ( \Lambda ) in TeV ((c_{ij} = 1))</th>
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<th>Observables</th>
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### Observables

- $\Delta m_K$; $\epsilon_K$
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- $\Delta m_D$; $|q/p|$, $\phi_D$
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- $\Delta m_{B_d}$; $S_{\psi K_S}$
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**Very strong suppression! New flavor violation must either approximately follow SM pattern...**
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Very strong suppression! New flavor violation must either approximately follow SM pattern...

... or exist only at very high scales ($10^2 - 10^5$ TeV)
Why are FCNCs so suppressed in the SM?

No tree FCNCs: \( g^4/(4\pi)^2 \sim (1/30)^2 \)

Mixing & Gluino:
\[
\frac{m_c^2 - m_u^2}{m_W^2} \sin^2 \theta_C \sim (1/400)^2
\]

\[\Rightarrow\]
\[
\frac{1}{(30 \cdot 400)^2} \frac{1}{m_W^2} \sim \frac{1}{(10^3 \text{ TeV})^2}
\]
Flavor and CP in the SM

Experimental picture
+ spectrum, $BR$, $A_{CP}$, particle-antiparticle oscillations
+ determine masses, mixing angles and phases

Theorist’s view
+ In the absence of Yukawas, SM globally

$$SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$$

symmetric

$$v Y_u = U_u \begin{pmatrix} m_u & m_c & m_t \end{pmatrix} V_u \quad v Y_d = U_d \begin{pmatrix} m_d & m_s & m_b \end{pmatrix} V_d$$
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\[ V_{ckm} \]

unphysical due to $SU(3)^3$!
Yukawa matrices $Y_U$ & $Y_D$ encode flavor violation

$(\bar{Q}_L^i Q_L^j)$

$Y_U Y_U^\dagger$

$Y_D Y_D^\dagger$

$V_{\text{CKM}}$

$(\bar{d}_R^i d_R^j)$

$Y_U^\dagger Y_U$

$Y_D^\dagger Y_D$

$\bar{u}_R^i u_R^j$

$+ \text{LR, RL}$
MFV Technicolor?

Chivukula, Georgi '87; Chivukula, Georgi, Randall '87; Randall '93; Georgi '94, Skiba '96
MFV Technicolor?

Chivukula, Georgi '87; Chivukula, Georgi, Randall '87; Randall '93; Georgi '94, Skiba '96

![Diagram of MFV Technicolor model](image)
MFV Technicolor?
Chivukula, Georgi ‘87; Chivukula, Georgi, Randall ‘87; Randall ‘93; Georgi ‘94, Skiba ‘96

Simpler proposal:
AdS/CFT construction: 5D GIM mechanism
Cacciapaglia, Csaki, Galloway, Marandella, Terning, A.W., ‘08
Bounds on generic flavor violation

\[ \mathcal{L}_{SM} + \frac{1}{\Lambda^2} (\bar{Q}_i Q_j)(\bar{Q}_i Q_j) \]

UTfit (0707.0636), Gedalia et al '09

- \( \Lambda \) [GeV]
- \( \Delta M_K, \epsilon_K \)
- \( \Delta M_d, \sin 2\beta \)
- \( \Delta M_s, A_{sl} \)
- \( D - \bar{D} \)
Bound for pGB Higgs

Csaki, Falkowski, A.W;

\[ C_K^4 \sim \frac{1}{M_G^2} \frac{g_{s*}^2}{g_*^2} \frac{8m_dm_s}{v^2} \frac{1 + m^2}{\tilde{m}_d^2} \]

\( (s \rightarrow d) \text{Im} \Lambda_{LR} \)

\( M_{KK} > 30 \text{ TeV} \)

FCNC constraint more severe in composite pGB!

Why? \( Y^* \rightarrow g^*/2 \) & fermionic kinetic mixings
Bound for pGB Higgs

(Csaki, Falkowski, A.W.;)

\[
C^4_K \sim \frac{1}{M_G^2} \frac{g^2_{s*}}{g_*^2} \frac{8m_dm_s}{v^2} \frac{1 + m^2}{\tilde{m}_d^2}
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