Minimal Flavor Constraints for Technicolor

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Outline

1. Introduction (technicolor and extended technicolor)
2. Minimal Flavor corrections from Technicolor
3. Constraining the Dynamical electroweak symmetry breaking (DEWSB) models
4. Summary

From TC to walking TC

♣ (QCD-like) Technicolor (TC) (Weinberg,1976; Susskind,1979)

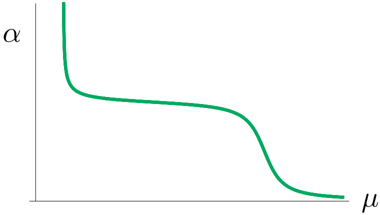
- breaks EW symmetry dynamically (w/o elementary scalar)
- do not generate the gauge hierarchy problem
- is based on a gauge theory with running gauge coupling
- conflicts with the Electroweak precision test (EWPT) (Peskin et.al.,1990,1992)

♣ Walking TC (Holdom,1981; Yamawaki et.al.,1986, Appelquist et.al.,1986)

- may solve EWPT, etc. problems
- might be the most favorable DEWSB model

"Walking" ?

♣ Walking means *slowly running/near conformal gauge coupling.*



A modern walking TC :

- $SU(2)$ with 2 □□
- $SU(3)$ with 2 □□
- controlled by IRFP

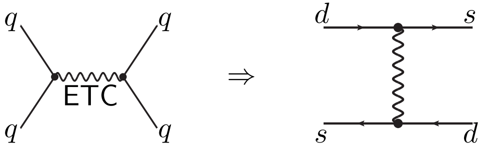
♣ S-parameter (Peskin et.al.,1990,1992) in walking TC

- # of flavors (N_f) = small in the modern walking TC.
- $S_{\rm TC}$ is expected to be smaller than $S_{\rm TC}^{\rm naive} = \dfrac{1}{6\pi}\dfrac{N_f}{2}d(R)$.

(Appelquist et.al.,1999; Harada et.al.2004,2006; Kurachi et.al.,2006)

FCNC in the extended TC (ETC) (Dimopoulos et.al.,1979; Eichten,1980)

- TC provides a flavor structure via an ETC model.
- ETC involves TC gauge group : $G_{\rm TC} \subset G_{\rm ETC}$
  - TC- & SM-quarks live in the same multilet under $G_{\rm ETC}$
  - $G_{\rm ETC}$ breaks to $G_{\rm TC}$ at scale $\Lambda_{\rm ETC}$
  - ETC generates an undesired interactions @ tree level



  - Constraints from ΔM_K : $\Lambda^2_{\rm ETC} \gtrsim (10^3\,\text{TeV})^2$

Constraints for TC-hadrons

- Focus on the constraints for the vector mesons (VMs).
- EFT : generalized hidden local symmetry (Bando et.al,1988)
  - Constraints from the EWPT have already studied.
    (Foadi et.al.,2007,2008)
  - Results imply that the light VMs are allowed to exist.
  - "light" means $M_{\rm VMs} \lesssim 1$ TeV

We would like to consider a question :

" Is a light spin-1 state allowed from flavor experiments ? "

From TC to flavor physics

Our Interest

Spin-1 state contribution to flavor observables.

$\Downarrow$

We need a full flavor model. But, unfortunately, we do not know whatever is the correct ETC model...

$\Downarrow$

We constrain models of TC with ETC interactions entering in the general scheme of minimal flavor violation (D'Ambrosio et.al., 2002)

The SM fermions couple to

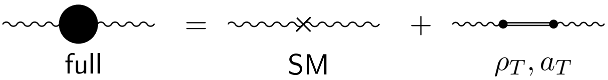
- new spin-1 states ONLY through the EW interactions
- the would-be NG bosons in the same manner as the SM

Comparison with the SM

♠ Vacuum polarization of EW gauge bosons:

(Foadi et.al.,2007,2008)

- TC contribution = contribution ONLY from spin-1 states
- vacuum polarizations are saturated by the spin-1 states



♠ The SM fermions - would-be NGB coupling:

- Flavor observables are independent of gauge parameter
- Yukawa interactions in the SM

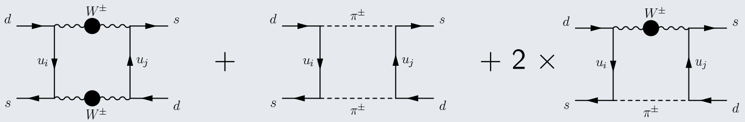
$$\mathcal{L}^{\rm SM}_{\rm yukawa} = \frac{\sqrt{2}\, m_{u_i}}{v} V_{ij} \cdot \bar{u}_{Ri} \pi^+ d_{Lj} - \frac{\sqrt{2}\, m_{d_i}}{v} V^*_{ji} \cdot \bar{d}_{Ri} \pi^- u_{Lj} + h.c.$$

where V_{ij} : (i, j)-element in the CKM matrix

$\Delta F = 2$ FCNC effective Lagrangian (for example $F = S$)

◇ First step : Computation of box diagrams

Box diagram ($\Delta S = 2$)



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◇ Second step : from box to effective Lagrangian (Inami et.al.,1981)

Effective Lagrangian for $\Delta S = 2$

$$\mathcal{L}_{\rm eff}^{\Delta S=2} = -\frac{G_F^2 M_W^2}{4\pi^2} \cdot A \cdot (\bar{s}_L \gamma^\mu d_L)(\bar{s}_L \gamma_\mu d_L)$$

where A is so-called Inami-Lim function.

The difference from the SM case

♠ Inami-Lim function in the SM + TC case:

$$A(a_V, a_A) = A_0 + \frac{g_{\rm EW}^2}{\tilde{g}^2} \cdot \Delta A(a_V, a_A) \ , \ a_i \equiv \frac{m_i^2}{M_W^2}$$

where A_0 : IL fn. in the SM and $\tilde{g}$: self-coupling of spin-1 states.

$\Delta F = 2$ FCNC observables : Mass difference

◇ Mass difference (SM case):

- $(\Delta M_Q)_{\rm SM} = \dfrac{G_F^2 M_W^2}{6\pi^2} \cdot f_Q^2 \cdot M_Q \times B_Q \times |A_0|$
- given : $\{G_F, M_W, M_Q, f_K\}$ (PDG,2008) and $\{B_K, f_{Bq}\sqrt{B_{Bq}}\}$ (Nierste,2009)

◇ Mass difference (SM + TC case):

$$(\Delta M_Q)_{\rm full} = (\Delta M_Q)_{\rm SM} \times \left|1 + \delta_{M_Q}\right| \;,\; \delta_{M_Q} \equiv \frac{g_{\rm EW}^2}{\tilde{g}^2} \cdot \frac{\Delta A(a_V, a_A)}{A_0}$$

	SM(short distance)	exp.(PDG 2008)
$\Delta M_K ({\rm ns}^{-1})$	$3.55^{+1.09}_{-1.00}$	5.292 ± 0.0009
$\Delta M_{Bd} ({\rm ps}^{-1})$	$0.56^{+0.19}_{-0.16}$	0.567 ± 0.005
$\Delta M_{Bs} ({\rm ps}^{-1})$	$17.67^{+6.38}_{-5.40}$	17.77 ± 0.10

$\Delta F = 2$ FCNC observables : CP-violation parameter in K^0

◇ CP-violation parameter in K^0 (SM case)

$$(|\epsilon_K|)_{\rm SM} = \frac{G_F^2 M_W^2}{12\sqrt{2}\pi^2} \times \left[\frac{M_K}{\Delta M_K}\right]_{\rm exp.} \times B_K f_K^2 \times [-{\rm Im} A_0]$$

◇ CP-violation parameter in K^0 (SM + TC case)

$$(|\epsilon_K|)_{\rm full} = (|\epsilon_K|)_{\rm SM} \times (1 + \delta_\epsilon)\ ,\ \delta_\epsilon \equiv \frac{g_{\rm EW}^2}{\tilde{g}^2} \cdot \frac{{\rm Im}\Delta A(a_V, a_A)}{{\rm Im} A_0}$$

	SM(short distance)	exp.(PDG,2008)
$\epsilon_K(10^{-3})$	$2.08^{+0.14}_{-0.13}$	2.229 ± 0.012

Constraints

As a result we have constraints for TC sector @ 68% C.L. :

$$|1+\delta_{M_K}| \leq 2.08 \ , \ |1+\delta_{M_{Bd}}| = 0.91^{+0.38}_{-0.24} \ , \ |1+\delta_{M_{Bs}}| = 1.01^{+0.44}_{-0.27}$$

$$\delta_\epsilon = \left(7.05^{+7.93}_{-7.07}\right) \times 10^{-2}$$

Note : We can not neglect the long distance contribution to ΔM_K. But, it is difficult to pinpoint its contribution. So, the constraint from ΔM_K is very weak constraint.

♠ Simplified forms of δ in the limit $M_V^2, M_A^2 \gg m_t^2, m_c^2$:

$$\delta_\epsilon^{(\mathrm{iVL})} \simeq -2.14 \times W \quad , \quad \delta_{B_d}^{(\mathrm{iVL})} = \delta_{B_s}^{(\mathrm{iVL})} \simeq -2.90 \times W$$

where $W = \dfrac{g_{\mathrm{EW}}^2}{2\tilde{g}^2}\left[\dfrac{1}{a_V} + \dfrac{(1-\chi)^2}{a_A}\right]$

and χ : a parameter in the EFT

of parameters in the DEWSB model

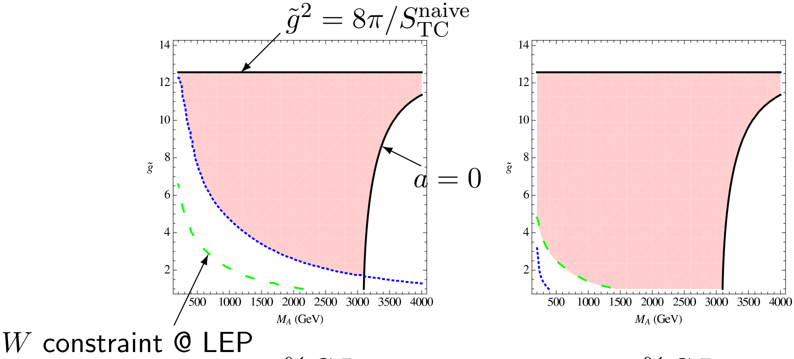
- parameters : $\{\tilde{g}, M_V, M_A, \chi\}$
- decay constants : $f_V^2 = \dfrac{M_V^2}{\tilde{g}^2}$, $f_A^2 = \dfrac{M_A^2}{\tilde{g}^2}(1-\chi)^2$
- 0th and 1st Weinberg Sum Rules (WSRs) ($f_\pi = v_{\rm EW}/\sqrt{2}$) :
  - 0th : $S = 8\pi \left[\dfrac{f_V^2}{M_V^2} - \dfrac{f_A^2}{M_A^2} \right] \Longrightarrow (1-\chi)^2 = 1 - \dfrac{\tilde{g}^2 S}{8\pi} > 0$
  - 1st : $f_V^2 - f_A^2 = f_\pi^2 \qquad \Longrightarrow a_V = (1-\chi)^2 \cdot a_A + \dfrac{2\tilde{g}^2}{g_{\rm EW}^2}$

Independent parameters

$$\{\tilde{g}, M_V, M_A, \chi\} \to \{\tilde{g}, M_A\} \text{ for given } S$$

Constraining the walking TC: MWT ($SU(2)$ w/ 2 $\square\square$)

- 0th and 1st WSRs + 2nd WSR : $f_V^2\, M_V^2 - f_A^2\, M_A^2 = a \cdot \dfrac{16\pi^2}{d(\mathrm{R})} f_\pi^4$ (Appelquist et.al., 1999)
- $d(R) = 3 \to S_{\mathrm{TC}}^{\mathrm{naive}} = \dfrac{1}{2\pi}$ and $a \sim \mathcal{O}(1)$.

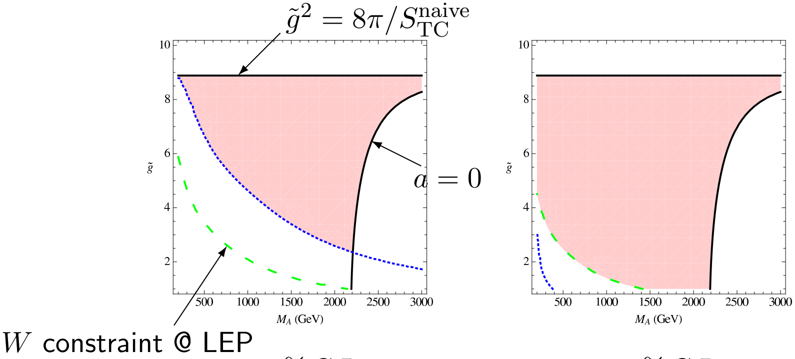


68% C.L. 95% C.L.

Constraining the walking TC: NMWT ($SU(3)$ w/ 2 $\Box\Box$)

- 0th and 1st WSRs + 2nd WSR : $f_V^2 \, M_V^2 - f_A^2 \, M_A^2 = a \cdot \dfrac{16\pi^2}{d(\mathrm{R})} f_\pi^4$

  (Appelquist et.al., 1999)
- $d(R) = 6 \rightarrow S_{\mathrm{TC}}^{\mathrm{naive}} = \dfrac{1}{\pi}$ and $a \sim \mathcal{O}(1)$.



68% C.L. 95% C.L.

Summary

- We have studied the DEWSB model with light spin-1 states from a viewpoint of flavor physics
- We have used the scheme of MFV in order to see the contribution to flavor observables from TC sector
- Flavor constraints are stronger than the EWPT constraints @ $68\,\mathrm{C.L.}$, but the former is milder than the later @ $95\,\mathrm{C.L.}$.
- Not only EWPT but also flavor experiments can constrain the TC model.

Summary

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- We have used the scheme of MFV in order to see the contribution to flavor observables from TC sector
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Thank you very much !!

Backup : EFT for MWT based on GHLS

Lagrangian for $G/H = SU(4)/SO(4)$:

$$\mathcal{L}_{\rm GHLS}^{\rm MWT} = f_s^2 \cdot \text{tr}\left[(\hat{\alpha}_{\mu||}(\mathcal{V}))^2\right] + f_p^2 \cdot \text{tr}\left[(\hat{\alpha}_{\mu\perp}(p) + (1-\chi)\cdot\hat{\alpha}_{\mu\perp}(\pi))^2\right]$$
$$+ f_\pi^2 \cdot \text{tr}\left[\hat{\alpha}_{\mu\perp}^2(\pi)\right]$$

$\rho_\mu^{\rm TC} \subset \alpha_{\mu||}(\mathcal{V})$ and $a_\mu^{\rm TC} \subset \alpha_{\mu\perp}(p)$

Mass : $M_V^2 = \tilde{g}^2 f_s^2$ and $M_A^2 = \tilde{g}^2 f_p^2$

decay constant : $f_V^2 = f_s^2$ and $f_A^2 = f_p^2(1-\chi)^2$

Input parameters

G_F	1.1664×10^{-5}	GeV^{-2}	PDG, 2008
M_W	80.398	GeV	PDG, 2008
m_t	161.3 ± 1.8	GeV	$\overline{\text{MS}}$ mass in PDG, 2008
m_c	$1.274^{+0.036}_{-0.045}$	GeV	$\overline{\text{MS}}$ mass in PDG, 2008
M_K	497.61 ± 0.02	MeV	PDG, 2008
f_K	155.5	MeV	PDG, 2008
B_K	0.72 ± 0.040		Nierste, 2009
M_{B_d}	5279.5 ± 0.3	MeV	PDG, 2008
M_{B_s}	5366.3 ± 0.6	MeV	PDG, 2008
$f_{B_d}\sqrt{B_{B_d}}$	225 ± 35	MeV	Nierste, 2009
$f_{B_s}\sqrt{B_{B_s}}$	270 ± 45	MeV	Nierste, 2009

Wolfenstein parameterization of the CKM matrix

Wolfenstein parameterization of the CKM matrix at $\mathcal{O}(\lambda^4)$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^2 \end{pmatrix}$$

where $\lambda, A, \bar{\rho}=\rho(1-\lambda^2/2), \bar{\eta}=\eta(1-\lambda^2/2)$ are

$$\lambda = 0.2257^{+0.009}_{-0.001},\ A = 0.814^{+0.021}_{-0.022},\ \bar{\rho} = 0.135^{+0.031}_{-0.016},\ \bar{\eta} = 0.349^{+0.015}_{-0.017}$$

in PDG, 2008