Flavor in the Three-Site Model

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in collaboration with

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SUSY10

Outline

1. Introduction

2. 3site Model

3. Flavor structure in 3site Model

4. Summary

Introduction

Higgs boson has not been discovered yet

Models without Higgs boson

- Technicolor
- Higgsless model
- .... and maybe many others

Some of them may have similar low energy phenomenology.
Any efficient way to treat them at a time?

Low energy effective theory

- Bottom up approach
- Phenomenology of many models can be treated at a time

Non-linear sigma field and NG boson

How to construct an effective theory?

- Specify symmetry breaking pattern
- Use non-linear sigma field to treat (would-be) NG bosons

$$U_i = \exp\left(i \frac{\tau^a \pi_i^a}{f_i} \right)$$

If symmmetry is “gauge” symmetry, they are eaten by gauge bosons

We can construct models without physical scalar particles

An example

How about $SU(2)\times U(1)\to U(1)$ case?

- 3 would-be NG bosons as non-linear fields

$$\frac{v^2}{4} tr\left(D_\mu U\right)^\dagger \left(D^\mu U\right) \qquad U=\exp\left(i\frac{\tau^a\pi^a}{v}\right)$$

- fermion sector is the same as SM with heavy Higgs boson (One of the UV completions is SM)

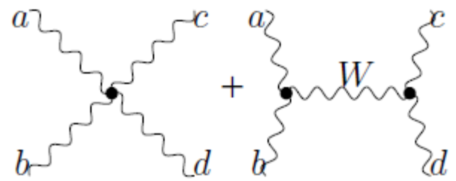
$$(\overline{q}_L)^i U \begin{pmatrix} (m_u)^{ij} & 0 \\ 0 & (m_d)^{ij} \end{pmatrix} \begin{pmatrix} (u_R)^j \\ (d_R)^j \end{pmatrix} + \cdots$$

i, j : generation indices

Perturbative unitarity

Longitudinal gauge bosons scattering

$$i\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) =$$



$$+ \text{ crossed } \propto \mathcal{O}(E^2)$$

- Perturbative unitarity is broken at around 1TeV

- New patricles should be below 1TeV
(otherwise model becomes non-perturtbative...)

- (In SM case, Higgs boson cancels the bad energy behavior)

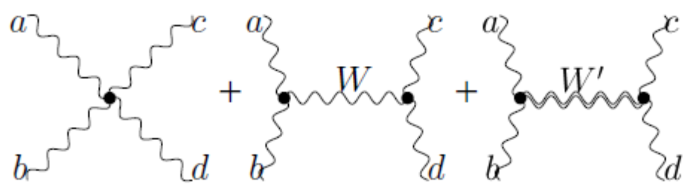
Extra gauge bosons

How to keep perturbative unitarity without Higgs boson?

→ Extra gauge bosons

C.Csaki et.al PRL92 (2004) 101802
Nomura JHEP11 (2003) 050
Barbieri et.al PLB591(2004) 141

$i\mathcal{M}(W_L^a W_L^b \to W_L^c W_L^d) =$



$+ \quad \cdots \quad$ +crossed. $\propto \mathcal{O}(E^0)$

- Infinite numer of particles $\rightarrow$ Extra dimension
- ... but we do not need to start from extra dimension
- It is enough to a few extra gauge bosons to study low energy phenomenology

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3site Model

R.S.Chivukula et.al Phys.Rev.D74:075011 (2006)
M.Bando et.al Nucl.Phys. B259 (1985) 493
R.Casalbuoni et.al Phys.Lett.B155(1985) 95

The simplest Higgsless model

- Symmetry breaking pattern is

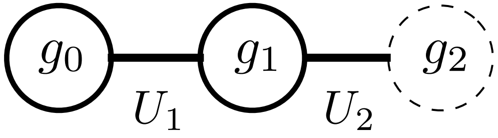
$$SU(2)_0 \times SU(2)_1 \times U(1)_2 \to U(1)_{em}$$

(3 extra gauge bosons are added)

- We need 6 would be NG bosons

$$U_1 = \exp\left(i\frac{\tau^a \pi_1^a}{f_1}\right), \; U_2 = \exp\left(i\frac{\tau^a \pi_2^a}{f_2}\right) \qquad \frac{1}{f_1^2} + \frac{1}{f_2^2} = \sqrt{2} G_F = \frac{1}{v^2}$$

- Schematically this can be written as follows (moose notation)



3site Model

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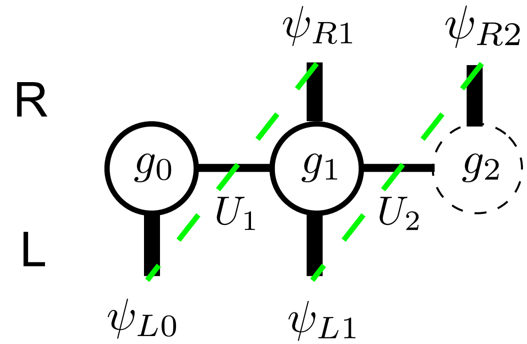
Fermion sector



$$U_i = \exp\left(i \frac{\tau^a \pi_i^a}{f_i} \right)$$

$$\frac{1}{f_1^2} + \frac{1}{f_2^2} = \sqrt{2} G_F = \frac{1}{v^2}$$

(quark case)	$SU(2)_0$	$SU(2)_1$	$U(1)_2$
ψ_{L0}	2	1	1/6
ψ_{L1}, ψ_{R1}	1	2	1/6
$\psi_{R2} \equiv \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix}$	1	1	2/3 −1/3

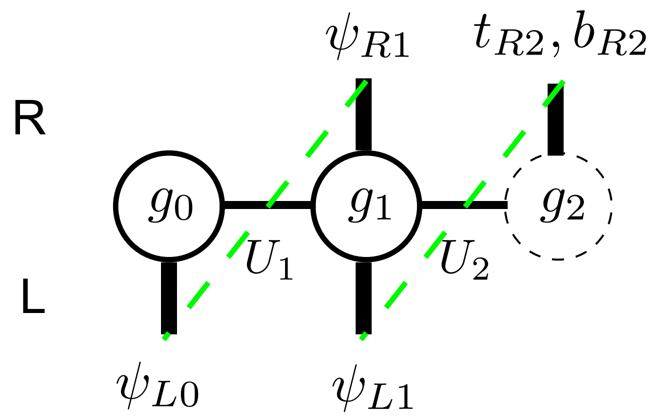
$$-(\overline{q}_{L0})^i U_1 (m_1)^{ij} (q_{R1})^j - (\overline{q}_{L1})^i M^{ij} (q_{R1})^j - (\overline{q}_{L1})^i U_2 \begin{pmatrix} (m_{2u})^{ij} & 0 \\ 0 & (m_{2d})^{ij} \end{pmatrix} \begin{pmatrix} (u_{2R})^j \\ (d_{2R})^j \end{pmatrix} + h.c.$$

i, j : generation indices

3site Model

R.S.Chivukula et.al Phys.Rev.D74:075011 (2006)
M.Bando et.al Nucl.Phys. B259 (1985) 493
R.Casalbuoni et.al Phys.Lett.B155(1985) 95

$$SU(2)_0 \times SU(2)_1 \times U(1)_2 \to U(1)_{em}$$



matter contents

SM particles

$$\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix} \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix}$$

$$\gamma \; W \;\; Z \; G$$

Extra particles

$$\begin{pmatrix} u' & c' & t' \\ d' & s' & b' \end{pmatrix} \begin{pmatrix} \nu'_e & \nu'_\mu & \nu'_\tau \\ e' & \mu' & \tau' \end{pmatrix}$$

$$W' \; Z'$$

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FCNC and 3site Model

Dimension 4 operator

$$\eta^{ij}(\overline{\psi}_{L0})^i \left[\gamma^\mu (iD_\mu U_1)U_1^\dagger\right] (\psi_{L0})^j$$

i, j : generation indices

This operator

- contributes to S parameter
- can make FCNC

Origins of this operator

- by integrating out heavy fermions (appriximately ψ_{L1} and ψ_{R1})
- loop corrections

$$\eta = (m_1 M^{-1})(m_1 M^{-1})^\dagger + (\text{loop corrections})$$

Diagonal components of η

Dimension 4 operator

$$\eta^{ij}(\overline{\psi}_{L0})^i\left[\gamma^\mu(iD_\mu U_1)U_1^\dagger\right](\psi_{L0})^j$$

i, j : generation indices

To avoid a large contribution to S parameter

$$\eta^{diag} \approx \epsilon_L^{ideal} \equiv \sqrt{2}\frac{M_W}{M_{W'}} = 0.28\left(\frac{400\text{GeV}}{M_{W'}}\right)$$

R.S.Chivukula et.al
Phys.Rev.D74:075011 (2006)

How about off-diagonal conponents of η?

→

- ΔF = 2 processes
- LFV processes

K^0-$\overline{K}^0$, B_d^0-$\overline{B}_d^0$, B_s^0-$\overline{B}_s^0$

$\mu^- \to e^- e^+ e^-$

$\tau^- \to \mu^- e^+ e^-$

$\tau^- \to e^- \tau^+ \tau^-$

Bound on off-diagonal component of η

Experimental bound on off-diagonal component of η (preliminary result...)

$$\eta^{\text{quark}} \approx (\epsilon_L^{ideal})^2 \left(\frac{400\text{GeV}}{M_{W'}}\right)^2 \begin{pmatrix} 1 & < 0.006 & < 0.0285 \\ < 0.006 & 1 & < 0.202 \\ < 0.0285 & < 0.202 & 1 \end{pmatrix}$$

$$\eta^{\text{lepton}} \approx (\epsilon_L^{ideal})^2 \left(\frac{400\text{GeV}}{M_{W'}}\right)^2 \begin{pmatrix} 1 & < 0.00013 & < 0.034 \\ < 0.00013 & 1 & < 0.036 \\ < 0.034 & < 0.036 & 1 \end{pmatrix}$$

Almost proportional to identity

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Summary

- We focused on low energy effective theory without Higgs bosons
- 3site model is the simplest Higgsless model
- There are three parameter making flavor structure, m_1, M and $m_{2u,d}$
- η can make FCNC
- We found current experimental bound of off-diagonal component of η

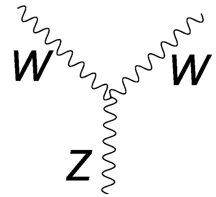
Thank you for your attention!

BACK-UP SLIDES

Electroweak Precision Test

W' mass from WWZ coupling

- constraint from WWZ coupling (LEP)



K.Hagiwara, R.D.Peccei, D.Zeppenfeld, and K.Hikasa, Nucl.Phys. B282,253(1987)

$$\mathcal{L} = -ig^{SM}_{WZZ}\left(1+\Delta\kappa_Z\right) W^+_\mu W^-_\nu Z^{\mu\nu} -ig^{SM}_{WZZ}\left(1+\Delta g_1^Z\right)\left(W^+_{\mu\nu}W^-_\nu - W^-_{\mu\nu}W^+_\nu\right)Z_\nu$$

$$g^{3site}_{WWZ} = g^{SM}_{WWZ}\left(1+\frac{1}{2c^2}\frac{M_W^2}{M_{W'}^2}+\cdots\right)$$

$$= \Delta\kappa_Z = \Delta g_1^Z < 0.028$$

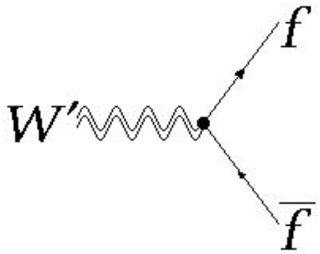
$$\rightarrow \quad M_{W'} \geq 380\text{GeV}$$

S, T parameter

- 3site Higgsless model

$$
\begin{aligned}
\alpha S &= -4s^2 \frac{M_W}{M_{W'}} \frac{g_{W'ff}}{g_{Wff}} - \frac{\alpha}{24\pi} \frac{M_{W'}}{M_W} \frac{g_{W'ff}}{g_{Wff}} \ln \frac{M_{W'}^2}{M_F^2} - \frac{\alpha}{24\pi} \ln \frac{M_{W'}^2}{M_F^2} + \frac{\alpha}{12\pi} \ln \frac{\Lambda^2}{M_{Href}^2} \\
\alpha T &= -\frac{\sqrt{2} G_F}{64\pi^2} \left(\frac{M_t}{M_F} \right)^2 \frac{M_t^2}{\left(\frac{M_W}{M_{W'}} \right)^4 \left[1 - \frac{M_{W'}}{M_W} \frac{g_{W'ff}}{g_{Wff}} \right]^2} - \frac{3\alpha}{32\pi c^2} \ln \frac{M_{W'}^2}{M_{Href}^2} - \frac{3\alpha}{32\pi c^2} \ln \frac{\Lambda^2}{M_{Href}^2}
\end{aligned}
$$

- From these we make constraint for
  - KK fermion mass
  - W'ff coupling

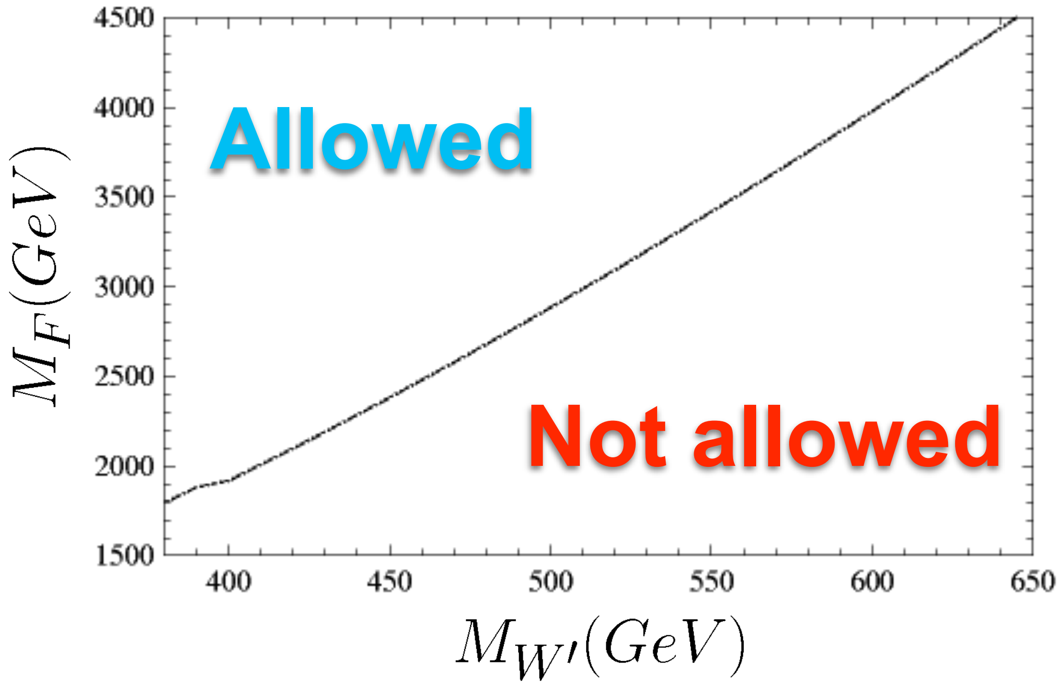


Lower bound for KK fermion mass

T.A, S.Matsuzaki, M.Tanabashi Phys.Rev.D78:055020,2008

- KK fermion mass vs KK gauge boson mass

$$\alpha T = -\frac{\sqrt{2}G_F}{64\pi^2}\left(\frac{M_t^2}{M_W^2}\right)^2\left(\frac{M_{W'}^2}{M_F}\right)^2 + \cdots$$

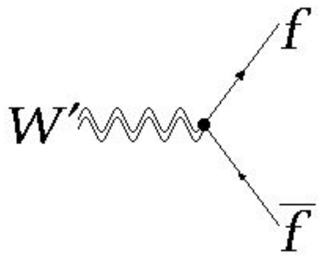


$$380\,\text{GeV} \leq M_{W'}$$
$$1.8\,\text{TeV} \leq M_F$$

W'ff coupling

Important for

- W' decay to fermions
- DY process



Strongly restricted by EWPM

$$\alpha S = -4s^2 \frac{M_W}{M_{W'}} \frac{g_{W'ff}}{g_{Wff}} + (1 \text{ loop})$$

•LHS is 1-loop order
•1st term in RHS comes from tree level contribution

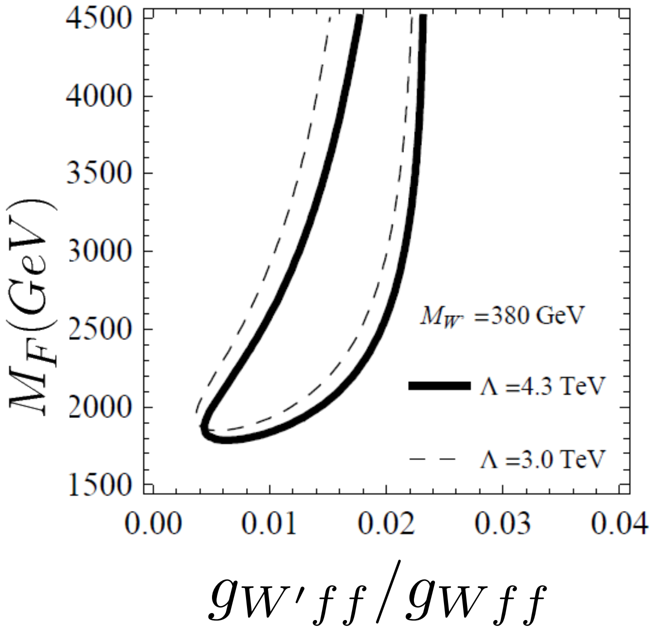
•In qualiteativly $g_{W'ff} \sim 0$
•In quantitatively 1loop calculation is needed

W'ff coupling

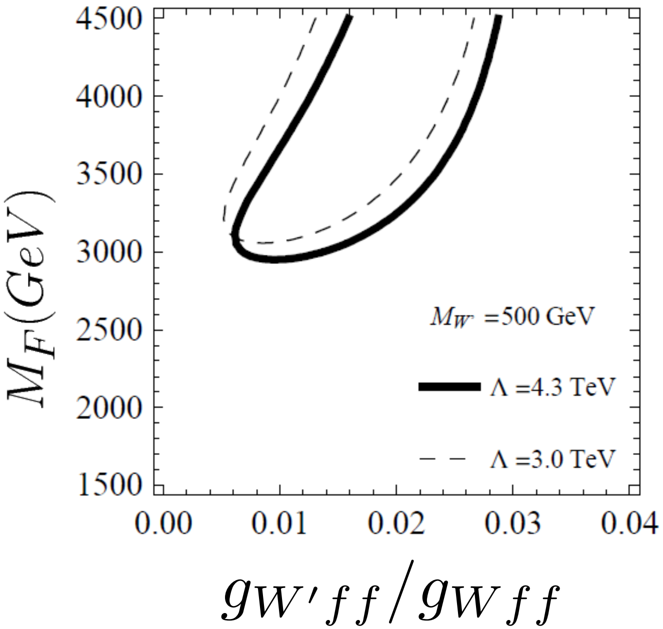
T.A, S.Matsuzaki, M.Tanabashi Phys.Rev.D78:055020,2008

- 1 loop level analysis

$M_{W'} = 380\text{GeV}$



$M_{W'} = 500\text{GeV}$



$$g_{W'ff} \neq 0$$

$$g_{W'ff}/g_{Wff} \sim \mathcal{O}(10^{-2})$$

Flavor structure

Yukawa and mass terms

T.A, S Matsuzaki, M. Tanabashi, Phys.Rev.D78:055020,2008.

$$-(\overline{q}_{L0})^i U_1 (m_1)^{ij} (q_{R1})^j - (\overline{q}_{L1})^i M^{ij} (q_{R1})^j - (\overline{q}_{L1})^i U_2 \begin{pmatrix} (m_{2u})^{ij} & 0 \\ 0 & (m_{2d})^{ij} \end{pmatrix} \begin{pmatrix} (u_{2R})^j \\ (d_{2R})^j \end{pmatrix} + h.c.$$

Assumption in original 3site paper

$$m_1^{ij} \propto \delta^{ij}, \ M^{ij} \propto \delta^{ij}$$

→
- Dangerous FCNC does not occur at tree level
- Flavor violation is carried by m_{2u} and m_{2d}

This assumption is unstable under the loop corrections

$$\begin{aligned} \mu \frac{d}{d\mu} m_1 &= \frac{m_1}{(4\pi)^2} \left[-8 g_s^2 - \frac{1}{6} g_2^2 - 3 \frac{m_1^2}{f_1^2} \right] \\ \mu \frac{d}{d\mu} M &= \frac{M}{(4\pi)^2} \left[-8 g_s^2 - \frac{9}{2} g_1^2 - \frac{1}{6} g_2^2 - \frac{3}{2} \frac{m_1^2}{f_1^2} - \frac{m_{2u}^2}{f_2^2} - \frac{m_{2d}^2}{f_2^2} \right] \end{aligned}$$

Yukawa and mass terms

$$-(\overline{q}_{L0})^i U_1 (m_1)^{ij} (q_{R1})^j - (\overline{q}_{L1})^i M^{ij} (q_{R1})^j - (\overline{q}_{L1})^i U_2 \begin{pmatrix} (m_{2u})^{ij} & 0 \\ 0 & (m_{2d})^{ij} \end{pmatrix} \begin{pmatrix} (u_{2R})^j \\ (d_{2R})^j \end{pmatrix} + h.c.$$

Mass param. can be diagonalized by biunitary transformation

$$m_1 = L_1 m_1^{diag} R_1^\dagger, \;\; M = L_M M^{diag} R_M^\dagger, \quad \begin{array}{rcl} m_{2u} & = & L_{2u} m_{2u}^{diag} R_{2u}^\dagger \\ m_{2d} & = & L_{2d} m_{2d}^{diag} R_{2d}^\dagger \end{array}$$

After redefinition of fermion field.....

$$-\overline{q}_{L0} U_1 m_1^{diag} q_{R1} - \overline{q}_{L1} (L_{2d}^\dagger L_M M^{diag} R_M^\dagger R_1) q_{R1} - \overline{q}_{L1} U_2 \begin{pmatrix} L_{2d}^\dagger L_{2u} m_{2u}^{diag} & 0 \\ 0 & m_{2d}^{diag} \end{pmatrix} \begin{pmatrix} u_{2R} \\ d_{2R} \end{pmatrix} + h.c.$$

So generally we can teke m_1 and m_{2d} (or m_{2u}) as diagonal

Left-handed FCNC

Constraint (UT fit collaboration)

M. Bona et al. [UTfit Collaboration] JHEP 0803, 049 (2008)

$$C_K^1(\bar{s}_L\gamma^\mu d_L)(\bar{s}_L\gamma_\mu d_L)$$
$$C_{B_d}^1(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$
$$C_{B_s}^1(\bar{b}_L\gamma^\mu s_L)(\bar{b}_L\gamma_\mu s_L)\,.$$

$$\begin{aligned}
-9.6\times10^{-13}\,GeV^{-2} < \Re(C_K^1) &< 9.6\times10^{-13}\,\mathrm{GeV}^{-2}\\
-4.4\times10^{-15}\,GeV^{-2} < \Im(C_K^1) &< 2.8\times10^{-15}\,\mathrm{GeV}^{-2}\\
|C_{B_d}^1| &< 2.3\times10^{-11}\,\mathrm{GeV}^{-2}\\
|C_{B_s}^1| &< 1.1\times10^{-9}\,\mathrm{GeV}^{-2}\,.
\end{aligned}$$

3site model case

Almost proportional to identity

$$\eta^{\mathrm{quark}} \approx (\epsilon_L^{ideal})^2\left(\frac{400\mathrm{GeV}}{M_{W'}}\right)^2\begin{pmatrix} 1 & <0.006 & <0.0285\\ <0.006 & 1 & <0.202\\ <0.0285 & <0.202 & 1\end{pmatrix}$$

Left-handed FCNC

Lepton sector

$$\frac{BR(\mu \to 3e)}{BR(\mu \to e\nu_\mu \bar{\nu}_e)} \approx \frac{1}{2} \cdot \left[\frac{\eta_{\ell 12}}{2} \left(-\frac{1}{2} + \sin^2\theta \right) \right]^2 < 1.0 \times 10^{-12}$$

$$\frac{BR(\tau \to e\mu\mu)}{BR(\tau \to e\nu_\tau \bar{\nu}_e)} = \left[\frac{\eta_{\ell 13}}{2} \left(-\frac{1}{2} + \sin^2\theta \right) \right]^2 < \frac{2.3 \times 10^{-8}}{BR(\tau \to e\nu_\tau \bar{\nu}_e)}$$

$$\frac{BR(\tau \to \mu ee)}{BR(\tau \to e\nu_\tau \bar{\nu}_e)} = \left[\frac{\eta_{\ell 23}}{2} \left(-\frac{1}{2} + \sin^2\theta \right) \right]^2 < \frac{2.7 \times 10^{-8}}{BR(\tau \to e\nu_\tau \bar{\nu}_e)}$$

Almost proportional to identity

$$\eta^{\mathrm{lepton}} \approx (\epsilon_L^{ideal})^2 \left(\frac{400\mathrm{GeV}}{M_{W'}} \right)^2 \begin{pmatrix} 1 & < 0.00013 & < 0.034 \\ < 0.00013 & 1 & < 0.036 \\ < 0.034 & < 0.036 & 1 \end{pmatrix}$$