Constraints on Extended Technicolor Models From Neutral Flavor-Changing Processes

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Two Important Questions

Source of Electroweak Symmetry Breaking?

- Technicolor
  Dynamical

Why?

	m_1	m_2	m_3
u_i	~ 4	~ 1300	~ 178000
d_i	~ 8	~ 100	~ 4300
e_i	~ 0.5	~ 106	~ 1800

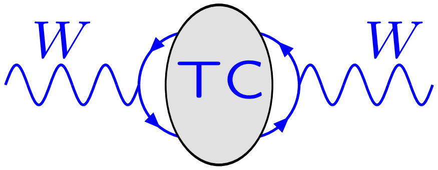
(MeV)

- SM: $g\frac{m_\psi}{M_W}\bar{\psi}\psi h$
- Most models put flavor in by hand.
- ETC attempts a dynamical explanation of flavor.

Technicolor

$$\langle \bar{U}_a U^a \rangle \, , \langle \bar{D}_a D^a \rangle \, , \langle \bar{N}_a N^a \rangle \, , \langle \bar{E}_a E^a \rangle \sim \Lambda_{tc}^3$$

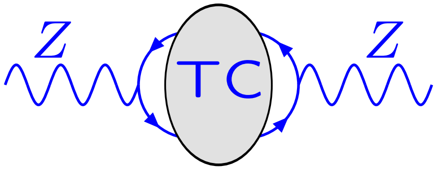
$$m_W^2 = g^2 F_{tc}^2$$



$$\mathcal{L}_{eff} \sim F_{tc}^2 Tr \left(D_\mu U D^\mu U^\dagger \right)$$

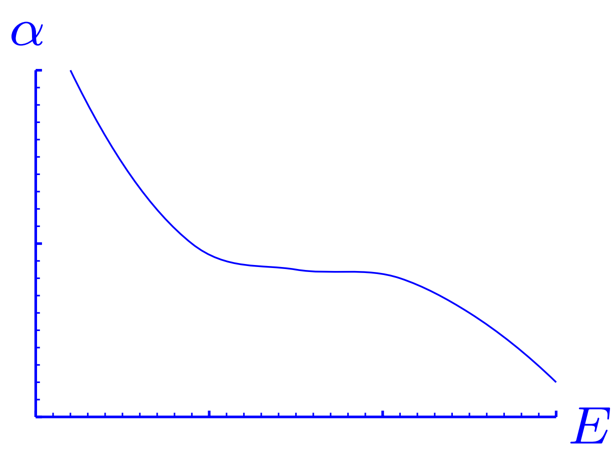
$$U = e^{i\tau \cdot \pi_{tc}/F_{tc}}$$

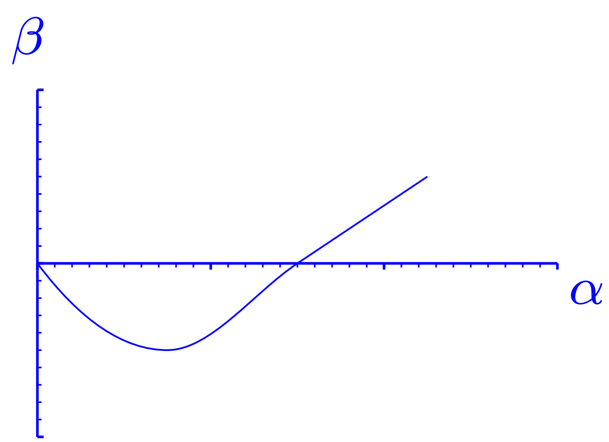
$$m_Z^2 = (g^2 + g'^2) F_{tc}^2$$



$F_{tc} \sim 130$ GeV
$\Lambda_{tc} \sim 300$ GeV

Walking TC





Important for:

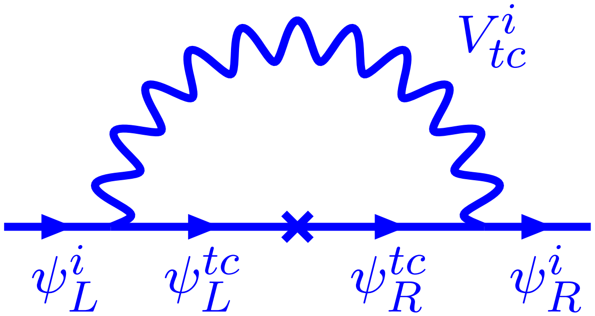
- Sufficiently large Top quark mass
- Enabling use of larger ETC scales,
  suppressing FCNC's

$SU(2)_{tc}$:

- Plausibly yields IR fixed point $\rightarrow$ walking.
- Reduces tc contribution to S parameter.
- Enables generation of light neutrino masses.
- Enables t-b splitting.

Extended Technicolor

$$SU(3)_{Gen} \times SU(2)_{tc} \subset SU(5)_{etc}$$



$$m_i \sim \kappa\eta\frac{\Lambda_{tc}^3}{\Lambda_i^2}$$

- $\kappa \sim 10$:
  Integration factor.
- $\eta \sim 10$:
  Scaling factor from walking.

$SU(5)_{etc}$

$\downarrow$ $\Lambda_1 \sim 1000 TeV$

$SU(4)_{etc}$

$\downarrow$ $\Lambda_2 \sim 100 TeV$

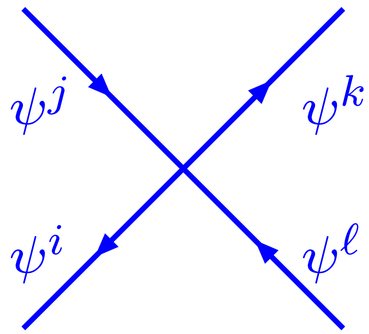
$SU(3)_{etc}$

$\downarrow$ $\Lambda_3 \sim 4 TeV$

$SU(2)_{tc}$

$\Lambda_{tc} \sim 300 GeV$

Motivation



$$\sim \frac{1}{\Lambda_{etc}^2}$$

- Early investigations:
  No UV complete model.
  All coefficients were naively $1/\Lambda_{etc}^2$.

- Modern ETC:
  UV complete model ✓.
  New analysis of these coefficients.

Fermion Representations

Vectorial:

- ψ^i_L, ψ^i_R
  Fundamental
- ψ_{Li}, ψ_{Ri}
  Conjugate Fundamental

Relatively Conjugate:

- ψ^i_L, ψ_{Ri}
- ψ_{Li}, ψ^i_R

VSM

$$\begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix} \quad u^i_R \quad d^i_R$$

- t-b splitting?
- FCNC's not a problem ✓

CSM

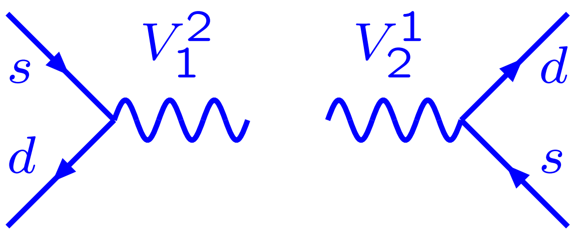
$$\begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix} \quad u^i_R \quad d_{Ri}$$

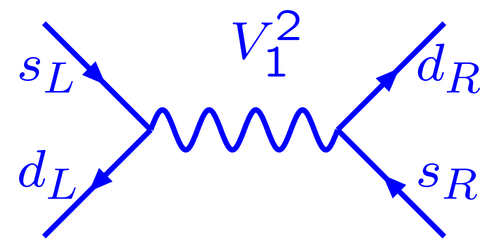
- t-b splitting ✓
  keeping $\rho \sim 1$
  Phys.Rev.D69, 015002 (2004)
- FCNC's a problem.

FCNC's I

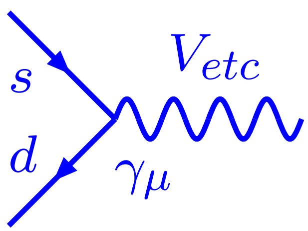
VSM	CSM

$K\bar{K}$ Mixing

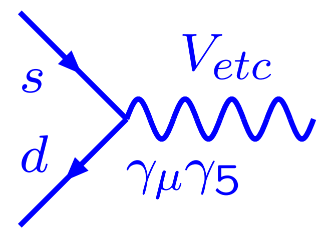




$K_L \to \mu^\pm e^\mp$



$$\left\langle 0|\bar{d}\gamma_\mu s|K_L\right\rangle = 0$$

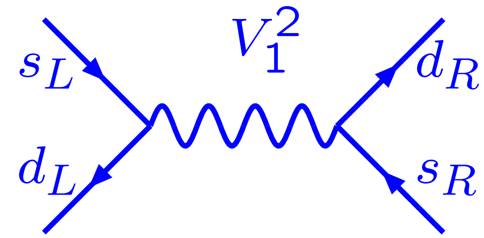


$$\left\langle 0|\bar{d}\gamma_\mu\gamma_5 s|K_L\right\rangle \neq 0$$

CSM FCNC's

$K\bar{K}$ Mixing

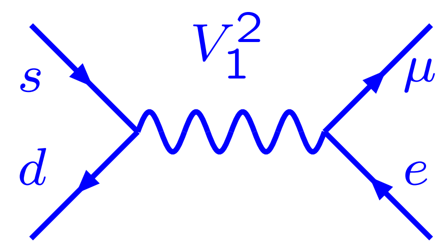
$$\frac{(\Delta m_K)_{etc}}{(\Delta m_K)_{SM}} \sim \frac{64\pi^2}{G_F^2 m_c^2 \Lambda_1^2 \Re(V_{cs}^* V_{cd})^2} \sim 10^2$$



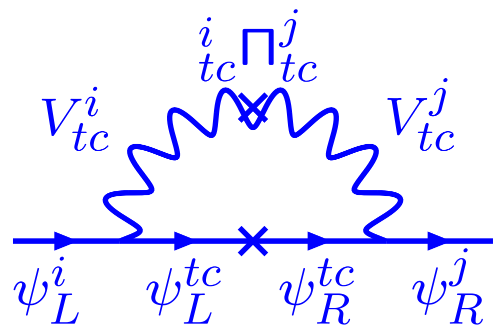
$K_L \to \mu^- e^+$

$$\frac{\Gamma(K_L \to \mu^- e^+)_{etc}}{\Gamma(K^- \to \mu^- \bar{\nu}_\mu)_{SM}} \sim \frac{256}{G_F^2 \Lambda_1^4 |V_{us}|^2} \sim 5 \times 10^{-11}$$

$$> \frac{\frac{BR(K_L \to \mu^- e^+)_{etc}}{\tau(K_L \to \mu^- e^+)}}{\frac{BR(K^- \to \mu^- \bar{\nu}_\mu)_{SM}}{\tau(K^- \to \mu^- \bar{\nu}_\mu)}} \lesssim 2 \times 10^{-12}$$



Mass Basis



$$m_{ij} \sim 10^2 \frac{\Lambda_{tc}^3\, {}_{tc}^{i}\Pi_{tc}^{j}(0)}{\Lambda_i^2 \Lambda_j^2}$$

Transform to Mass Basis:

$$m_{diag} = U_L m U_R^{-1}$$
$$U_L = e^{i\phi} U_R$$

$$\psi_{Lm} = U_L \psi_L$$
$$\psi_{Rm} = U_R \psi_R$$

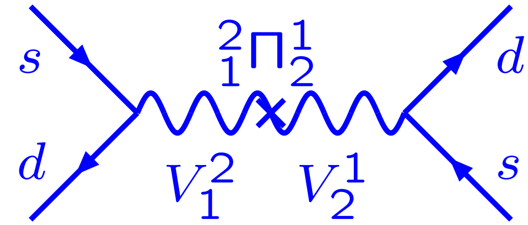
$$\begin{aligned} \mathcal{L}_{int} &= g_{etc} \bar{\psi}_\chi \not{V} \psi_\chi \\ &= g_{etc} \bar{\psi}_{\chi m} U_\chi \not{V} U_\chi^{-1} \psi_{\chi m} \end{aligned}$$

$$U_\chi = e^{i\phi_\chi} P_\alpha R_{23}(\theta_{23}) P_\delta^* R_{13}(\theta_{13}) P_\delta R_{12}(\theta_{12}) P_\beta$$
$$P_\alpha = diag(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i(\alpha_1+\alpha_2)})$$
$$P_\beta = diag(e^{i\beta_1}, e^{i\beta_2}, e^{-i(\beta_1+\beta_2)})$$
$$P_\delta = diag(e^{i\delta}, 1, 1)$$

$$\theta_{ij} \sim \frac{\Lambda_l^n}{\Lambda_h^n} \ll 1$$

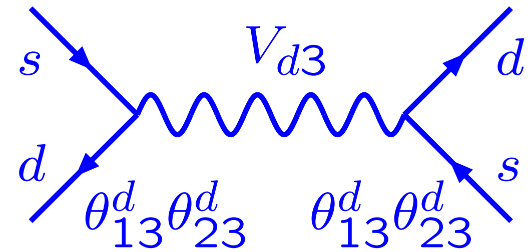
$K\bar{K}$ Mixing (VSM)

$$\frac{(\Delta m_K)_{etc}}{(\Delta m_K)_{SM}} \sim \frac{128\pi^2\Lambda_3^2}{G_F^2 m_c^2 \Lambda_1^4 \Re(V_{cs}^* V_{cd})^2} \sim 10^{-3}$$



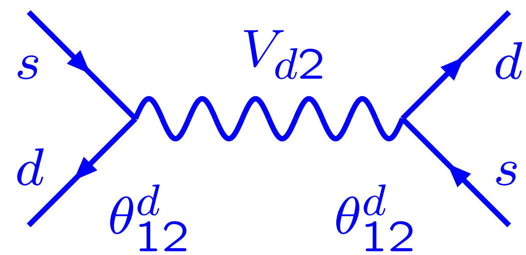
$$\frac{(\Delta m_K)_{etc}}{(\Delta m_K)_{SM}} \sim \frac{256\pi^2(\theta_{13}^d\theta_{23}^d)^2}{3G_F^2 m_c^2 \Lambda_3^2 \Re(V_{cs}^* V_{cd})^2} \lesssim 1$$

$$\Rightarrow |\theta_{13}^d\theta_{23}^d| \lesssim 4 \times 10^{-4}$$



$$\frac{(\Delta m_K)_{etc}}{(\Delta m_K)_{SM}} \sim \frac{96\pi^2(\theta_{12}^d)^2}{G_F^2 m_c^2 \Lambda_2^2 \Re(V_{cs}^* V_{cd})^2} \lesssim 1$$

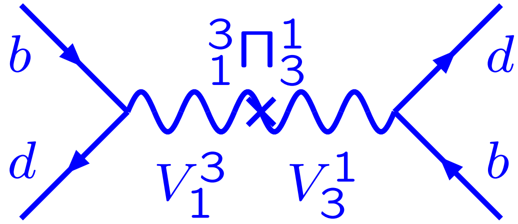
$$\Rightarrow |\theta_{12}^d| \lesssim 10^{-2}$$



$B_d\bar{B}_d$ Mixing (VSM)

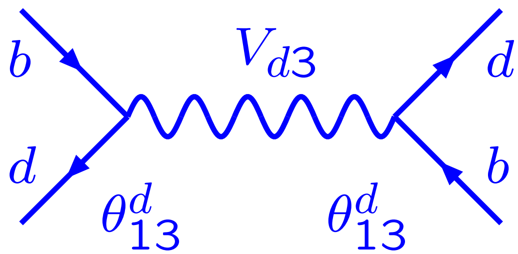
$$(\Delta m_{B_d})_{exp} \sim (\Delta m_{B_d})_{SM}$$

$$\frac{(\Delta m_{B_d})_{etc}}{(\Delta m_{B_d})_{SM}} \sim \frac{128\pi^2\Lambda_3^2}{G_F^2 m_t^2 \Lambda_1^4 \Re(V_{tb}^* V_{td})^2} \sim 10^{-4}$$



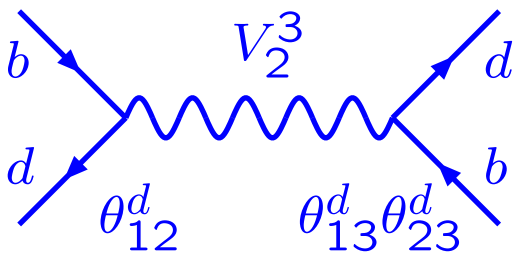
$$\frac{(\Delta m_{B_d})_{etc}}{(\Delta m_{B_d})_{SM}} \sim \frac{256\pi^2(\theta^d_{13})^2}{3G_F^2 m_t^2 \Lambda_3^2 \Re(V_{tb}^* V_{td})^2} \lesssim \frac{1}{10}$$

$$\Rightarrow |\theta^d_{13}| \lesssim 10^{-3}$$



$$\frac{(\Delta m_{B_d})_{etc}}{(\Delta m_{B_d})_{SM}} \sim \frac{128\pi^2|\theta^d_{12}\theta^d_{13}\theta^d_{23}|}{G_F^2 m_t^2 \Lambda_2^2 \Re(V_{tb}^* V_{td})^2} \lesssim \frac{1}{10}$$

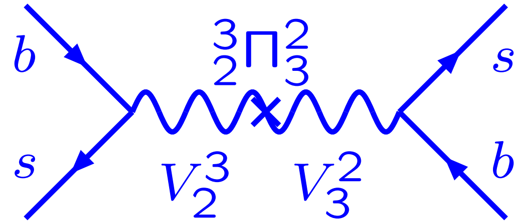
$$\Rightarrow |\theta^d_{12}\theta^d_{13}\theta^d_{23}| \lesssim 4 \times 10^{-5}$$



$B_s\bar{B}_s$ Mixing (VSM)

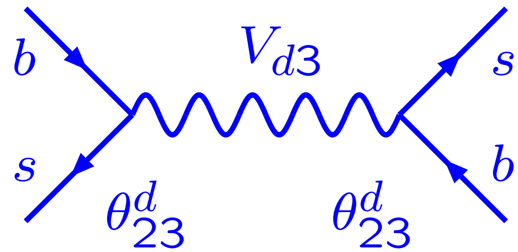
$$(\Delta m_{B_s})_{exp} \gtrsim (\Delta m_{B_s})_{SM}$$

$$\frac{(\Delta m_{B_s})_{etc}}{(\Delta m_{B_s})_{SM}} \sim \frac{128\pi^2\Lambda_3^2}{G_F^2 m_t^2 \Lambda_2^4 \Re(V_{tb}^* V_{ts})^2} \sim 10^{-2}$$



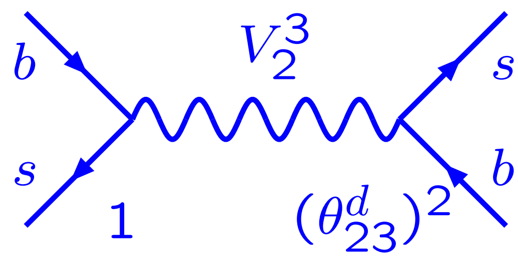
$$\frac{(\Delta m_{B_s})_{etc}}{(\Delta m_{B_s})_{SM}} \sim \frac{256\pi^2(\theta_{23}^d)^2}{3G_F^2 m_t^2 \Lambda_3^2 \Re(V_{tb}^* V_{ts})^2} \lesssim 1$$

$$\Rightarrow |\theta_{23}^d| \lesssim 10^{-2}$$



$$\frac{(\Delta m_{B_s})_{etc}}{(\Delta m_{B_s})_{SM}} \sim \frac{128\pi^2|\theta_{23}^d|^2}{G_F^2 m_t^2 \Lambda_2^2 \Re(V_{tb}^* V_{ts})^2} \lesssim 1$$

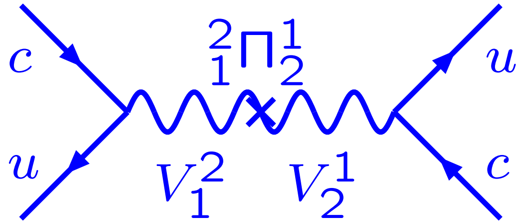
$$\Rightarrow |\theta_{23}^d| \lesssim 0.2$$



$D\bar{D}$ **Mixing** (VSM)

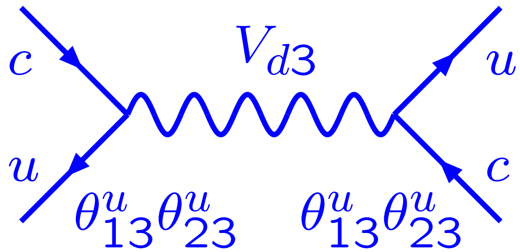
$$(\Delta m_D)_{exp} < 10^4 (\Delta m_D)_{SM}$$

$$\frac{(\Delta m_D)_{etc}}{(\Delta m_D)_{SM}} \sim \frac{128\pi^2\Lambda_3^2}{G_F^2 m_s^2 \Lambda_1^4 \Re(V_{cs}^* V_{us})^2} \sim 0.4$$



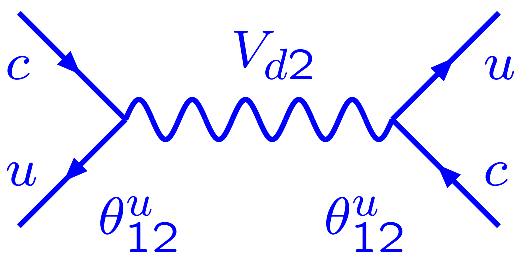
$$\frac{(\Delta m_D)_{etc}}{(\Delta m_D)_{SM}} \sim \frac{256\pi^2(\theta^u_{13}\theta^u_{23})^2}{3G_F^2 m_s^2 \Lambda_3^2 \Re(V_{cs}^* V_{us})^2} \lesssim 10^4$$

$$\Rightarrow |\theta^u_{13}\theta^u_{23}| \lesssim 3 \times 10^{-2}$$



$$\frac{(\Delta m_D)_{etc}}{(\Delta m_D)_{SM}} \sim \frac{96\pi^2(\theta^u_{12})^2}{G_F^2 m_s^2 \Lambda_2^2 \Re(V_{cs}^* V_{us})^2} \lesssim 10^4$$

$$\Rightarrow |\theta^u_{12}| \lesssim 0.7$$



Leptons

VSM

$$\begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \quad u_R^i \quad d_R^i$$

DES

$$\begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \quad \nu_R^i \quad e_R^i$$

DEC

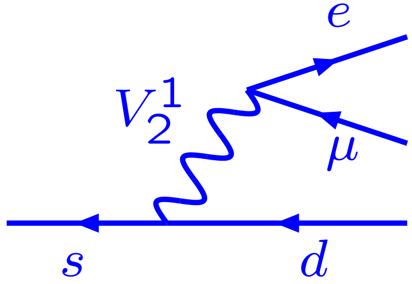
$$\begin{pmatrix} \nu_{Li} \\ e_{Li} \end{pmatrix} \quad \nu_{Ri} \quad e_{Ri}$$

$K^+ \to \pi^+ \mu^\pm e^\mp$

$BR_{(K^+ \to \pi^+ \mu^+ e^-)exp} < 2.8 \times 10^{-11}$ $BR_{(K^+ \to \pi^+ \mu^- e^+)exp} < 5.2 \times 10^{-10}$

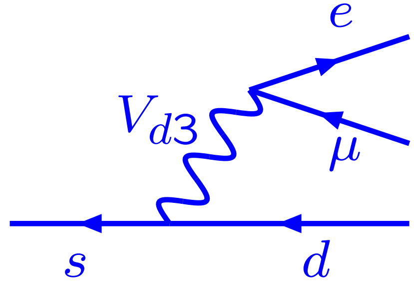
$$\frac{BR_{(K^+ \to \pi^+ \mu^+ e^-)}}{BR_{(K^+ \to \pi^0 \mu^+ \nu_\mu)}} \sim \left(\frac{16}{G_F \Lambda_1^2}\right)^2 \sim 10^{-12}$$

$$< \frac{BR_{(K^+ \to \pi^+ \mu^+ e^-)exp}}{BR_{(K^+ \to \pi^0 \mu^+ \nu_\mu)exp}} \lesssim 10^{-9}$$



$$\frac{BR_{(K^+ \to \pi^+ \mu^+ e^-)}}{BR_{(K^+ \to \pi^0 \mu^+ \nu_\mu)}} \sim \left(\frac{16\theta_{13}^d \theta_{23}^d \theta_{13}^e \theta_{23}^e}{G_F \Lambda_3^2}\right)^2 \lesssim 10^{-9}$$

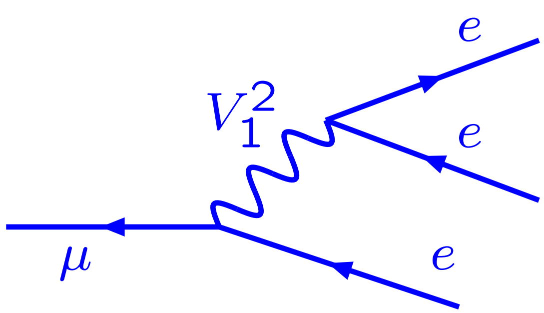
$$\Rightarrow |\theta_{13}^d \theta_{23}^d \theta_{13}^e \theta_{23}^e| \lesssim 3 \times 10^{-4}$$



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

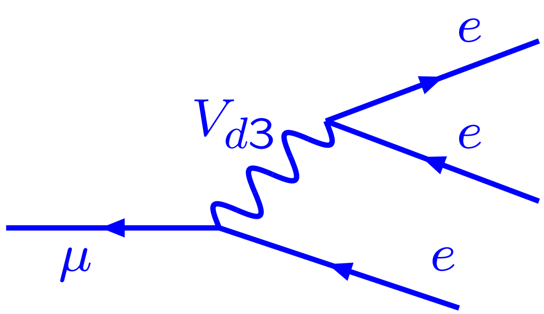
$$BR_{(\mu^+ \to e^+ e^+ e^-)} < 10^{-12}$$

$$\frac{BR_{(\mu^+ \to e^+ e^+ e^-)}}{BR_{(\mu^+ \to e^+ \nu_\mu \nu_e)}} \sim \left(\frac{16\theta^e_{12}}{G_F \Lambda_1^2}\right)^2 < 10^{-12}$$



$$\Rightarrow |\theta^e_{12}| < 0.6$$

$$\frac{BR_{(\mu^+ \to e^+ e^+ e^-)}}{BR_{(\mu^+ \to e^+ \nu_\mu \nu_e)}} \sim \left(\frac{16(\theta^e_{13})^3 \theta^e_{23}}{G_F \Lambda_1^2}\right)^2 < 10^{-12}$$



$$\Rightarrow |(\theta^e_{13})^3 \theta^e_{23}| < 0.6$$

Constraints

Constraint	Process
$\|\theta^d_{13}\theta^d_{23}\| \lesssim 4 \times 10^{-4}$	Δm_K
$\|\theta^d_{12}\| \lesssim 10^{-2}$	Δm_K
$\|\theta^d_{13}\| \lesssim 10^{-3}$	Δm_{B_d}
$\|\theta^u_{13}\theta^u_{23}\| \lesssim 3 \times 10^{-2}$	Δm_D
$\|\theta^d_{13}\theta^d_{23}\theta^e_{13}\theta^e_{23}\| \lesssim 3 \times 10^{-4}$	$K^+ \to \pi^+\mu^+e^-$

Conclusions

- Recent ultraviolet complete ETC models have been constructed.

- We have reanalyzed constraints on these from FCNC's.

- We show that there is a natural mechanism for suppressing these FCNC's in VSM type models.

- Bounds on mixing angles that we obtain can plausibly be satisfied in VSM ETC models.

- More work is necessary to build fully realistic models.

- We look forward to the future LHC results which should tell us whether new strong dynamics breaks the EWS.