Gauge Model for Minimal Flavor Violation

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Based on: K.S. Babu, P. Ko, S. Saad (to appear)

Outline

- Motivations for gauging flavor symmetries
- $O(3)_L \times O(3)_R$ flavor gauge model
- Explaining B decay anomalies via $O(2)_L \times O(2)_R$ gauge bosons
- Conclusions

Gauging Flavor Symmetries

The Standard Model gauge sector has a $[U(3)]^5$ global symmetry:

$$U(3)_Q \times U(3)_{u^c} \times U(3)_{d^c} \times U(3)_L \times U(3)_{e^c}$$

Gauge Principle: "All anomaly free symmetries should be gauged"

Maximal Flavor Symmetry that is anomaly free:

(A) $O(3)_{\{Q,L\}} \times O(3)_{\{u^c,d^c,e^c\}}$ $[O(3)_L \times O(3)_R]$

(B) $O(3)_{\{Q,u^c,e^c\}} \times O(3)_{\{L,d^c\}}$ $[O(3)_{10} \times O(3)_{\overline{5}}]$

(C) $SU(3)_{\{Q,u^c,d^c\}} \times O(3)_{\{L,e^c\}}$ $[O(3)_{\rm quark} \times O(3)_{\rm lepton}]$

Among these, $O(3)_L \times O(3)_R$ is very promising – from fermion mass generation viewpoint – for gauge model of minimal flavor violation

KB, M. Frank, S. Rai (2011)

Gauging Flavor Symmetries (cont.)

The 5 $U(1)$ factors of $[U(3)]^5$ are:

$$Y,\ (B-L),\ (B+L),\ PQ,\ PQ'$$

Once ν^c field is introduced for neutrino mass generation, anomaly-free maximal subgroups of $[U(3)]^6$ become:

(A) $SO(3)_{\{Q,L\}} \times SU(3)_{\{u^c,d^c,e^c,\nu^c\}} \times U(1)_{B-L}$

(B) $SU(3)_{\{Q,u^c,d^c\}} \times SU(3)_{\{L,e^c,\nu^c\}} \times U(1)_{B-L}$

(C) $SO(3)_{\{Q,u^c,e^c\}} \times SU(3)_{\{L,d^c,\nu^c\}} \times U(1)_{B-L}$

(D) $SU(3)_{\{Q,u^c,d^c,L,e^c,\nu^c\}} \times U(1)_{B-L}$

(E) $SO(3)_{\{Q,u^c,e^c\}} \times SO(3)_{\{L,d^c\}} \times SO(3)_{\{\nu^c\}}$

(F) $SU(3)_{\{Q,u^c,d^c\}} \times SO(3)_{\{L,e^c\}} \times SO(3)_{\{\nu^c\}}$

(G) $SO(3)_{\{Q,L\}} \times SO(3)_{\{u^c,d^c,e^c\}} \times SO(3)_{\{\nu^c\}}$

Once ν^c acquires large Majorana mass, case (A) will reduce to $O(3)_L \times O(3)_R$

$O(3)_L \times O(3)_R$ Flavor Gauge Model

- Left-handed quarks and leptons transform as triplets of $O(3)_L$. Right-handed quarks and leptons are triplets of $O(3)_R$

$$Q : (3,1), \quad L : (3,1), \quad u^c : (1,3), \quad d^c : (1,3), \quad e^c : (1,3)$$

- SM Higgs doublet H is (1,1) under $O(3)_L \times O(3)_R$
- Fermion mass generation requires vector-like isosinglet fermions:

$$U_L(1,3) + U_R(3,1); \quad D_L(1,3) + D_R(3,1); \quad E_L(1,3) + E_R(1,3)$$

- To generate masses for the vector-like fermions, and for $O(3)_L \times O(3)_R$ symmetry breaking, SM singlet Higgs field $\Phi(3,3)$ is necessary
- Fermion masses are generated via a universal seesaw mechanism

Fermion Mass Generation

Yukawa couplings of fermions:

$$\mathcal{Y}_{\rm Yukawa} = y_u \overline{Q}_L \, \mathbb{I} \, U_R \tilde{H} + m_u^0 \overline{U}_L \, \mathbb{I} \, u_R + Y_U \overline{U}_L \, \Phi(3,3) \, U_R + h.c. + \ldots$$

Fermion mass matrices:

$$\mathcal{M}_{u,d,e} = \begin{pmatrix} 0_{3\times 3} & y_{u,d,e} v \, \mathbb{I}_{3\times 3} \\ m^0_{u,d,e} \, \mathbb{I}_{3\times 3} & M_{U,D,E} \end{pmatrix}, M_{U,D,E} = Y_{U,D,E} \begin{pmatrix} V_1 & & \\ & V_2 & \\ & & V_3 \end{pmatrix}$$

Light fermion masses:

$$m_u = \frac{y_u m_u^0 v}{M_1^u}, \quad m_c = \frac{y_u m_u^0 v}{M_2^u}, \quad m_t = \frac{y_u m_u^0 v}{M_3^u}$$

$$m_d = \frac{y_d m_d^0 v}{M_1^d}, \quad m_s = \frac{y_d m_d^0 v}{M_2^d}, \quad m_b = \frac{y_d m_d^0 v}{M_3^d}$$

$$m_e = \frac{y_e m_e^0 v}{M_1^e}, \quad m_\mu = \frac{y_e m^e v}{M_2^e}, \quad m_\tau = \frac{y_e m_e^0 v}{M_3^e}$$

Inverse hierarchy of heavy fermion masses: $M_1^u \gg M_2^u \gg M_3^u$

Features of Heavy Fermions/Gauge Bosons

- $m_d : m_s : m_b = M_3^d : M_2^d : M_1^d \Rightarrow$ Inverse mass hierarchy among heavy fermions
- $M_1^d = Y_D V_1,\ M_2^d = Y_D V_2,\ M_3^d = Y_D V_3 \Rightarrow V_1 \gg V_2 \gg V_3$
- The 6 $O(3)_L \times O(3)_R$ gauge bosons $(X_{L,R}, Y_{L,R}, Z_{L,R})$ have masses:

$$M_{X_L} = g_L V_2,\ M_{X_R} = g_R V_2,$$
$$M_{Y_L} = M_{Z_L} = g_L V_1,\ M_{Y_R} = M_{Z_R} = g_R V_1$$

- Since $V_1 \gg V_2$, $M_{X_L,X_R} \ll M_{Y_L,Y_R} \simeq M_{Z_L,Z_R}$
- V_1 breaks $O(3)_L \times O(3)_R$ down to $O(2)_L \times O(2)_R$ leaving $X_{L,R}$ gauge bosons massless. V_2 breaks $O(2)_L \times O(2)_R$ to nothing.
- Lighter $X_{L,R}$ couple to second and third families:

$$\mathcal{L}^X = -ig_L \left\{(\overline{b}_L\gamma_\mu s_L - \overline{s}_L\gamma_\mu b_L) + (\overline{\tau}_L\gamma_\mu \mu_L - \overline{\mu}_L\gamma_\mu \tau_L)\right\} X_L^\mu$$
$$- ig_R \left\{(\overline{b}_R\gamma_\mu s_R - \overline{s}_R\gamma_\mu b_R) + (\overline{\tau}_R\gamma_\mu \mu_R - \overline{\mu}_R\gamma_\mu \tau_R)\right\} X_R^\mu$$

- Interesting phenomenology for B anomalies possible via exchange of $X_{L,R}$ gauge bosons

Minimal Flavor Violation?

- With a single bi-fundamental $\Phi(3,3)$ coupling to all fermions, there is no CKM mixing. Additional Higgs fields are needed
- The structure of the theory allows Yukawa couplings of these multiplets under $O(3)_L \times O(3)_R$:

$$\chi_3(1,3); \quad \chi_5(1,5), \quad \Phi(3,3)$$

- At least two of these fields are needed to generate CKM mixing
- Few possibilities are explored:
  - (i) Two $\Phi(3,3)$ fields
  - (ii) One $\Phi(3,3)$, one $\chi_5(1,5)$ field and one $\chi_3(1,3)$ field
  - (iii) Two $\Phi(3,3)$ fields, one $\chi_5(1,5)$ field and one $\chi_3(1,3)$ field
- Results for cases (i) and (iii) will be presented
- In case (i) there are only 2 Yukawa matrices for u, d, e – most minimal flavor violation (MMFV)
- Case (iii) is next to minimal FV (NMFV) with 4 Yukawa matrices for u, d, e

Gauge Model for MMFV

- Two copies of $\Phi(3,3)$ Higgs fields are utilized for symmetry breaking and fermion mass generation
- Two Yukawa matrices $\langle\Phi_1\rangle$ and $\langle\Phi_2\rangle$ must fit up, down and charged lepton masses as well as CKM mixings $\Rightarrow$ MMFV
- Fermion mass matrices:

$$\mathcal{M}_{u,d,e} = \begin{pmatrix} 0_{3\times3} & y_{u,d,e} v\, \mathbb{I}_{3\times3} \\ m^0_{u,d,e} \mathbb{I}_{3\times3} & M_{u,d,e} \end{pmatrix}, M_{u,d,e} = Y_1^{u,d,e}\langle\Phi_1\rangle + Y_2^{u,d,e}\langle\Phi_2\rangle$$

- Yukawa coupling are complex, while all VEVs are real
- Only 3 relative phases in Yukawa couplings
- Excellent fit to fermion masses and CKM mixing angles is found

MMFV Scalar Potential

- Higgs potential with two bifundamental scalar fields $\Phi_{1,2}(3,3)$:

$$
\begin{aligned}
V = & -\mu_1^2 Tr[\Phi_1\Phi_1^T] + \lambda_1 Tr[\Phi_1\Phi_1^T]^2 + \lambda_2 Tr[\Phi_1\Phi_1^T\Phi_1\Phi_1^T] + \xi_1 Det[\Phi_1] \\
& + -\mu_2^2 Tr[\Phi_2\Phi_2^T] + \lambda_3 Tr[\Phi_2\Phi_2^T]^2 + \lambda_4 Tr[\Phi_2\Phi_2^T\Phi_2\Phi_2^T] + \xi_2 Det[\Phi_2] \\
& + \lambda_5 Tr[\Phi_1\Phi_1^T] Tr[\Phi_2\Phi_2^T] + \lambda_6 Tr[\Phi_1\Phi_2^T]^2 + \lambda_7 Tr[\Phi_1\Phi_1^T\Phi_2\Phi_2^T] \\
& + \lambda_8 Tr[\Phi_1\Phi_2^T\Phi_1\Phi_2^T] + \xi_3\Phi_1\Phi_1\Phi_2 + \xi_4\Phi_1\Phi_2\Phi_2 \\
& + \lambda_9 Tr[\Phi_1\Phi_1^T] Tr[\Phi_1\Phi_2^T] + \lambda_{10} Tr[\Phi_1\Phi_1^T\Phi_1\Phi_2^T] \\
& + \lambda_{11} Tr[\Phi_2\Phi_2^T] Tr[\Phi_2\Phi_1^T] + \lambda_{12} Tr[\Phi_2\Phi_2^T\Phi_2\Phi_1^T]
\end{aligned}
$$

- Any fit for fermion masses should be generated from this Higgs potential
- This is found to be satisfied for the fermion fit that follows

Fit to Fermion Spectrum with Two $\Phi(3,3)$

Masses (in GeV) and Mixing parameters	Inputs (at $\mu = 10^8$ GeV)	Fitted values (at $\mu = M_{GUT}$)	pulls	Heavy Fermions	Heavy Fermion Masses (in GeV)
$m_u/10^{-4}$	6.5 ± 2.2	8.3	0.8	M_U	1×10^8
m_c	0.35 ± 0.01	0.35	-0.07	M_C	2.4×10^5
m_t	104.9 ± 0.9	104.3	-0.7	M_T	8.2×10^2
$m_d/10^{-3}$	1.6 ± 0.1	1.5	-0.7	M_D	5.6×10^6
$m_s/10^{-2}$	3.1 ± 0.1	3.1	0.19	M_S	2.7×10^5
m_b	$1.5\pm0,01$	1.5	0.03	M_B	5.7×10^3
$m_e/10^{-4}$	5.03 ± 0.05	5.03	-0.02	M_E	8×10^6
$m_\mu/10^{-2}$	10.6 ± 0.1	10.6	0.05	M_μ	3.8×10^4
m_τ	1.8 ± 0.01	1.79	-0.5	M_τ	2.2×10^3
$\lvert V_{us}\rvert/10^{-2}$	22.7 ± 0.07	22.7	0.04	Heavy Gauge Bosons	Heavy Gauge Boson Masses (in GeV)
$\lvert V_{cb}\rvert/10^{-2}$	4.5 ± 0.06	4.5	0.02	$M_{Z_{L,R}}/g_{L,R}$	1.71×10^8
$\lvert V_{ub}\rvert/10^{-3}$	3.9 ± 0.1	3.9	-0.08	$M_{Y_{L,R}}/g_{L,R}$	1.70×10^8
δ_{CKM}	1.2 ± 0.05	1.19	-0.26	$M_{X_{L,R}}/g_{L,R}$	1.16×10^6
χ^2	-	-	2	-	-

Parameter set ($Y_2^{u,d,e}$ are complex parameters):

$$y_{u,d,e} = \{-0.79, -0.016, -0.01\},$$

$$m^0_{u,d,e} = \{620, 3110, 2203\}\,GeV$$

$$Y_1^{u,d,e} = \{-0.45, -1.73, -0.13\},$$

$$Y_2^{u,d,e} = \{0.84 - i\,0.29, 0.15 - i\,0.03, -0.05 - i\,3\times10^{-6}\}$$

$$\langle\Phi_1\rangle = \begin{pmatrix} 1.2\times10^7 & 0 & 0 \\ 0 & 1.1\times10^5 & 0 \\ 0 & 0 & 2.9\times10^3 \end{pmatrix} GeV, \ \langle\Phi_2\rangle = \begin{pmatrix} 1.1\times10^8 & 7.3\times10^6 & 1.1\times10^5 \\ 7.3\times10^6 & 7.9\times10^5 & 2.3\times10^4 \\ 1.1\times10^5 & 2.3\times10^4 & 2.2\times10^3 \end{pmatrix} GeV$$

Flavor Gauge Model and B Decay Anomalies

- The MMFV gauge model is not easily accessible to experiments, owing to large masses ($> 10^6$ GeV) of flavor gauge bosons
- However, the framework appears to be suitable to explain recently reported B decay anomalies, especially in the lepton flavor universality violating ratios R_K and R_{K^*}. This is because the lightest flavor gauge bosons, $X_{L,R}$, couple to second and third family fermions off-diagonally
- We have explored the case of a modified scalar spectrum within the $O(3)_L \times O(3)_R$ gauge model to explain these anomalies
- Two copies of $\Phi(3,3)$ scalars, and one copy of $\chi_3(1,3) + \chi_5(1,3)$ scalar fields are used for fermion masses and symmetry breaking
- This model generates operators $C_9 = -C_{10}$ that works very well in explaining the B anomalies

B Decay Anomalies

- There has been indications for new physics in b to $s\mu^+\mu^-$ transition matrix elements for some time
- Hints for new physics come from $B_s \to \phi\mu^+\mu^-$ decay (LHCb measurement is 3σ lower than SM), $B^\pm \to K^\pm\mu^+\mu^-$ (LHCb 2σ low in several q^2 bins), $B \to K^*\mu^+\mu^-$ angular distribution, ...
- These discrepancies suggest new contrbutions to C_9 and/or C_{10} operators:

$$C_9 = (\overline{b}_L\gamma_\mu s_L)(\overline{\mu}\gamma^\mu\mu), \qquad C_{10} = (\overline{b}_L\gamma_\mu s_L)(\overline{\mu}\gamma^\mu\gamma_5\mu)$$

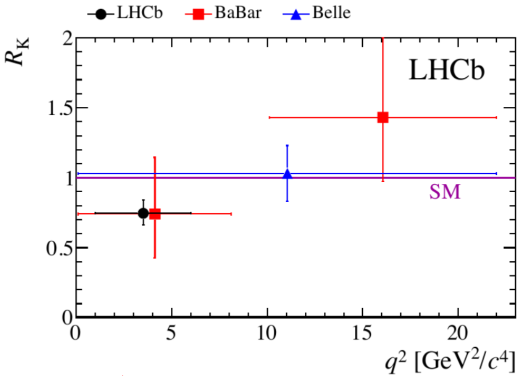
- For $C_9 = -C_{10}$ (only left-handed fields involved in new physics), best fit is $C_9 = -0.67$, which is about 4.8 σ improvement compared to SM in a global fit
- R_K and R_{K^*} measurements add to the significance

Global Fit to B Observables Without R_K and R_{K^*}

Coeff.	best fit	1σ	2σ	pull
$C_9^{\rm NP}$	-1.21	$[-1.41, -1.00]$	$[-1.61, -0.77]$	5.2σ
C_9'	$+0.19$	$[-0.01, +0.40]$	$[-0.22, +0.60]$	0.9σ
$C_{10}^{\rm NP}$	$+0.79$	$[+0.55, +1.05]$	$[+0.32, +1.31]$	3.4σ
C_{10}'	-0.10	$[-0.26, +0.07]$	$[-0.42, +0.24]$	0.6σ
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.30	$[-0.50, -0.08]$	$[-0.69, +0.18]$	1.3σ
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.67	$[-0.83, -0.52]$	$[-0.99, -0.38]$	4.8σ
$C_9' = C_{10}'$	$+0.06$	$[-0.18, +0.30]$	$[-0.42, +0.55]$	0.3σ
$C_9' = -C_{10}'$	$+0.08$	$[-0.02, +0.18]$	$[-0.12, +0.28]$	0.8σ

Altmannshofer, Niehoff, Stangl, Straub [arXiv: 1703.09189]

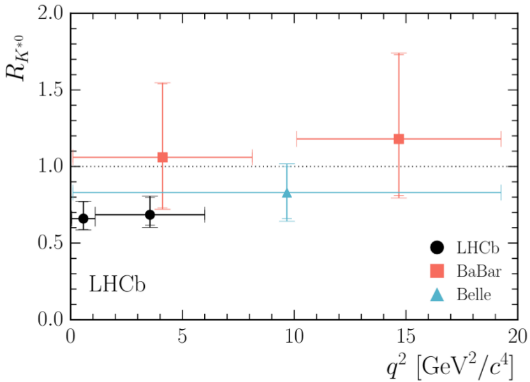
R_K Anomaly



$$R_K[1,6] = \frac{Br(B\to K\mu^+\mu^-)}{Br(B\to K e^+ e^-)} = 0.745^{+090}_{-074} \pm 0.036 \text{ [LHCb 1406.6482]}$$

Deviates from SM $R_K \simeq 1$ by $\sim 2\ \sigma$

R_{K^*} Anomaly



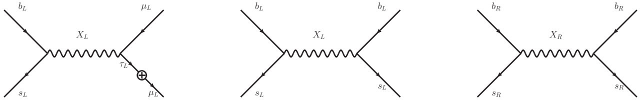
$R_{K^*}[0.045, 1.1] = 0.660^{+0.110}_{-0.070} \pm 0.024,\ R_{K^*}[1.1, 6] = 0.685^{+0.113}_{-0.069} \pm 0.04$

Deviates from SM $R_{K^*} \simeq 1$ by $\sim 2.5\ \sigma$ in each bin

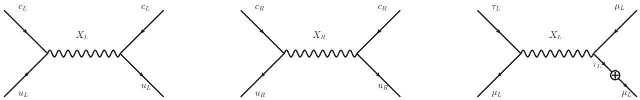
LHCb, arXiv:1705.05802 [hep-ex]

$O(3)_L \times O(3)_R$ Model for B Anomalies

- $C_9 = -C_{10} \sim -0.63$ can be induced in next to minimal FV model



- Requires $M_{X_L}/g_L \sim (10 - 22)$ TeV
- $B_s - \overline{B}_s$ mixing provides a strong constraint. However, X_R exchange almost exactly cancels the X_L contribution. Note: $M_{X_L}/g_L \simeq M_{X_R}/g_R$



- New contrbutions to $D^0 - \overline{D^0}$ mixing near experimental limit
- Predicts $\tau \to 3\mu$ with a branching ratio of $\sim 10^{-10}$

Main Features of NMFV Model

- Uses two copies of $\Phi(3,3)$ scalar fields. Their VEVs are taken to be nearly diagonal
- One $\chi_3(1,3)$ and one $\chi_5(1,3)$ scalars are used. χ_3 has flavor antisymmetric Yukawa couplings, χ_5 has flavor-symmetric couplings
- Mass matrices are given by:

$$M^{u,d,e} = \begin{pmatrix} 0 & y_{u,d,e} v \, \mathbb{I} \\ m_0^{u,d,e} \, \mathbb{I} + y_3^{u,d,e} \langle \chi_3 \rangle + y_5^{u,d,e} \langle \chi_5 \rangle & Y_1^{u,d,e} \langle \Phi_1 \rangle + Y_2^{u,d,e} \langle \Phi_2 \rangle \end{pmatrix}$$

- $y_{3,5}^d$ couplings are taken to be small, to suppress $X_{L,R}$ mediated FCNC in K, B_d systems
- Desired sign of X_L contribution to B anomalies fixes sign of X_R coupling so as to cancel $X_{L,R}$ contributions to $B_s - \overline{B_s}$ mixing

Fit for NMFV Model: $2 \times \Phi(3,3) + \chi_3(1,3) + \chi_5(1,5)$

$$\mathcal{M}_u \sim -y_u v M_u^{-1} X_u$$

$$M_u^{-1} = \begin{pmatrix} M_1^u & 0 & 0 \\ 0 & M_2^u & 0 \\ 0 & 0 & M_3^u \end{pmatrix}^{-1} = \frac{1}{M_3^u} P_u \; r_u,$$

$$r_u = \begin{pmatrix} r_{31}^u & 0 & 0 \\ 0 & r_{32}^u & 0 \\ 0 & 0 & 1 \end{pmatrix}, \; P_u = \begin{pmatrix} e^{i\phi_1^u} & 0 & 0 \\ 0 & e^{i\phi_2^u} & 0 \\ 0 & 0 & e^{i\phi_3^u} \end{pmatrix},$$

$$X_u = m_0^u \mathbb{I}_{3\times 3} + e^{i\chi_3^u} Y_3^u \langle A \rangle + e^{i\chi_5^u} Y_5^u \langle S \rangle,$$

$$\mathcal{M}_u \sim \left(\frac{-y_u v m_0^u}{M_3^u}\right) P_u r_u \left(\mathbb{I}_{3\times 3} + e^{i\chi_3^u} \frac{Y_3^u \langle A \rangle}{m_0^u} + e^{i\chi_5^u} \frac{Y_5^u \langle S \rangle}{m_0^u}\right)$$

$$\frac{-y_u v m_0^u}{M_3^u} = 36 GeV, \; r_{31}^u = 0.06, \; r_{32}^u = 0.12,$$

$$\chi_3^u = 3.11, \; \chi_5^u = -0.02,$$

$$\frac{Y_3^u A_{12}}{m_0^u} = 0.33, \; \frac{Y_3^u A_{13}}{m_0^u} = 0.12, \; \frac{Y_3^u A_{23}}{m_0^u} = 1.59,$$

$$\frac{Y_5^u S_{12}}{m_0^u} = -0.21, \; \frac{Y_5^u S_{13}}{m_0^u} = -0.12, \; \frac{Y_5^u S_{22}}{m_0^u} = 0.28, \; \frac{Y_5^u S_{23}}{m_0^u} = 2.19, \; \frac{Y_5^u S_{33}}{m_0^u} = 0.76$$

Fit for NMFV Model: $2 \times \Phi(3,3) + \chi_3(1,3) + \chi_5(1,5)$

$$\mathcal{M}_d \sim (\frac{-y_d v m_0^d}{M_3^d}) P_d r_d (\mathbb{I}_{3\times 3} + e^{i\chi_3^d} \frac{Y_3^d \langle A \rangle}{m_0^d} + e^{i\chi_5^d} \frac{Y_5^d \langle S \rangle}{m_0^d})$$

$\frac{-y_e v m_0^e}{M_3^e} = 2.4 GeV$, $r_{31}^e = 0.002$, $r_{32}^e = 0.019$,

$Y_3^d \sim 0$, $Y_3^d \sim 0$

$$\mathcal{M}_e \sim (\frac{-y_e v m_0^e}{M_3^e}) P_e r_e (\mathbb{I}_{3\times 3} + e^{i\chi_3^e} f_e \frac{Y_3^u \langle A \rangle}{m_0^u} + e^{i\chi_5^e} g_e \frac{Y_5^u \langle S \rangle}{m_0^u})$$

$\frac{-y_e v m_0^e}{M_3^e} = 1 GeV$, $r_{31}^e = 0.001$, $r_{32}^e = 0.38$,

$\chi_3^e = 0.91$, $\chi_5^e = 1.72$,

$f_e = \frac{y_3^e}{y_3^u} \frac{m_0^u}{m_0^e} = -0.8$, $g_e = \frac{y_5^e}{y_5^u} \frac{m_0^u}{m_0^e} = 0.5$

Fit for NMFV Model: $2 \times \Phi(3,3) + \chi_3(1,3) + \chi_5(1,5)$

Masses (in GeV) and Mixing parameters	Inputs (at $\mu = 10^8$ GeV)	Fitted values (at $\mu = M_{GUT}$)	pulls
$m_u/10^{-4}$	9.8±3.3	9.8	0.002
m_c	0.54±0.01	0.54	0.001
m_t	151.2±1.5	151.2	0.002
$m_d/10^{-3}2.4$	±0.2	2.4	0.0
$m_s/10^{-3}$	46.9±2.5	46.9	0.0
m_b	2.4±0.02	2.4	0.0
$m_e/10^{-4}$	4.95±0.04	4.95	0.001
$m_\mu/10^{-3}$	104.6±0.1	104.6	0.001
m_τ	1.7±0.01	1.7	0.002
$\theta_{12}/10^{-2}22.7$	±0.07	22.7	-0.001
$\theta_{23}/10^{-2}$	4.2±0.06	4.2	-0.002
$\theta_{23}/10^{-3}$	3.7±0.1	3.7	-0.005
δ_{CKM}	1.208±0.05	1.208	0.008
χ^2	-	-	0.0001

Flavor Structure of $X_{L,R}$ Couplings

$$L(X_L, X_R) = -ig_L(\overline{f}_L \gamma_\mu K_L^f f_L) X_L^\mu - ig_R(\overline{f}_R \gamma_\mu K_R^f f_R) X_R^\mu$$

$$K_L^u = \begin{pmatrix} (1\times10^{-3}\cos(\phi^u) + 6\times10^{-4}\sin(\phi^u))i & (8\times10^{-3} - 7\times10^{-4}i)\cos(\phi^u) - (7\times10^{-3} + 8\times10^{-3}i)\sin(\phi^u) & (-0.2 + 0.09i)\cos(\phi^u) + (0.09 + 0.2i)\sin(\phi^u) \\ (8\times10^{-3} - 7\times10^{-4}i)\cos(\phi^u) - (7\times10^{-3} + 8\times10^{-3}i)\sin(\phi^u) & -3\times10^{-3}i\cos(\phi^u) - 0.08i\sin(\phi^u) & (-0.9 - 1\times10^{-4}i)\cos(\phi^u) + (1\times10^{-4} + 0.9i)\sin(\phi^u) \\ (0.2 + 0.09i)\cos(\phi^u) + (-0.09 + 0.2i)\sin(\phi^u) & (0.9 - 1\times10^{-4}i)\cos(\phi^u) + (-1\times10^{-4} + 0.9i)\sin(\phi^u) & 1\times10^{-3}i\cos(\phi^u) + 0.08i\sin(\phi^u) \end{pmatrix}$$

$$K_R^u = \begin{pmatrix} -1.2\times10^{-2}i & 2.9\times10^{-5} + 1.02\times10^{-4}i & 9.9\times10^{-1} - 5.9\times10^{-3}i \\ -2.9\times10^{-5} + 1.0\times10^{-4}i & 5.1\times10^{-5}i & 1.1\times10^{-2} - 6.3\times10^{-2}i \\ -9.9\times10^{-1} - 5.9\times10^{-3}i & -1.1\times10^{-2} - 6.3\times10^{-2}i & 1.2\times10^{-2}i \end{pmatrix}$$

$$K_L^e = \begin{pmatrix} (-7\times10^{-5}\cos(\phi^e) - 5\times10^{-5}\sin(\phi^e))i & (-5\times10^{-3} - 4\times10^{-3}i)\cos(\phi^e) - (4\times10^{-3} + 3\times10^{-3}i)\sin(\phi^e) & (-6\times10^{-3} + 2\times10^{-3}i)\cos(\phi^e) + (7\times10^{-3} + 2\times10^{-3}i)\sin(\phi^e) \\ (5\times10^{-3} - 4\times10^{-3}i)\cos(\phi^e) - (-4\times10^{-3} + 3\times10^{-3}i)\sin(\phi^e) & -0.7i\cos(\phi^e) + 0.5i\sin(\phi^e) & (-0.6 - 0.3i)\cos(\phi^e) + (0.3 + 0.7i)\sin(\phi^e) \\ (6\times10^{-3} + 2\times10^{-3}i)\cos(\phi^e) + (-7\times10^{-3} + 2\times10^{-3}i)\sin(\phi^e) & (0.6 - 0.3i)\cos(\phi^e) + (-0.3 + 0.7i)\sin(\phi^e) & 0.7i\cos(\phi^e) + 0.5i\sin(\phi^e) \end{pmatrix}$$

$$K_R^e = \begin{pmatrix} -1.2\times10^{-2}i & 2.9\times10^{-5} + 1.02\times10^{-4}i & 9.9\times10^{-1} - 5.9\times10^{-3}i \\ -2.9\times10^{-5} + 1.0\times10^{-4}i & 5.1\times10^{-5}i & 1.1\times10^{-2} - 6.3\times10^{-2}i \\ -9.9\times10^{-1} - 5.9\times10^{-3}i & -1.1\times10^{-2} - 6.3\times10^{-2}i & 1.2\times10^{-2}i \end{pmatrix}$$

- $(K_L^e)_{22}$ is large, while $(K_R^e)_{22}$ is small. Only $C_9 = -C_{10}$ will be induced for B decays
- $(K_L^u)_{12} \sim 8\times10^{-3}$ leads to new contributions to $D^0 - \overline{D^0}$ mixing. Close to experimental limit. CP violation in mixing is also in interesting range
- By construction, $X_{L,R}$ contributions to $K^0 - \overline{K^0}$ mixing, $B_d^0 - \overline{B_d^0}$ mixing are small

Conclusions

- Gauge model realizations of minimal flavor violation presented based on $O(3)_L \times O(3)_R$ flavor symmetry
- In the most minimal realization, two flavor matrices can explain up, down and charged lepton flavor structure. However, symmetry breaking scale is $> 10^6$ GeV
- In a next to minimal flavor violation model, B decay anomalies can be nicely explained. Lightness of flavor gauge bosons is linked to fermion mass hierarchy
- Future tests can come in $D^0 - \overline{D^0}$ mixing and CP violation, $\tau \to 3\mu$ decay, and precise measurement of $B_s \to \mu^+\mu^-$ decay