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:

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

Dictum: "All anomaly free symmetries should be gauged"

Maximal Flavor Symmetry that is anomaly free:

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

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

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

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)

$O(3)_L \times O(3)_R$ 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 introduced
- Fermion masses are generated via a universal seesaw mechanism

Fermion Mass Generation

Yukawa couplings of fermions:

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

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:

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

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

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

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

Features of Heavy Fermions/Gauge Bosons

- $m_d : m_s : m_b = M_3^d : M_2^d : M_1^d \Rightarrow$ Follows same mass (inverse) hierarchy
- $M_1^d = Y_D V_1,\ M_2^d = Y_D V_2,\ M_3^d = Y_D V_3 \Rightarrow V_1 \gg V_2 \gg V_3$
- 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:

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

- 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
- Two possibilities are explored:

  (i) $\Phi(3,3) + \Phi(3,3)$

  (ii) $\Phi(3,3) + \chi_5(1,5) + \chi_3(1,3)$

- In case (i) there are only 2 Yukawa matrices for u, d, e – most minimal flavor violation (MMFV)
- Case (ii) is minimal FV (MFV) with 3 Yukawa matrices for u, d, e

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

Masses (in GeV) and Mixing parameters	Inputs (at $\mu = 10^8$ GeV)	Fitted values (at $\mu = 10^8$ GeV)	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±0,01	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):

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

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

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

$$Y_2^{u,d,e} = \{0.84 - i\,0.29, 0.15 - i\,0.03, -0.05 - i\,3 \times 10^{-6}\}$$

$$\langle\Phi_1\rangle = \begin{pmatrix} 1.2 \times 10^7 & 0 & 0 \\ 0 & 1.1 \times 10^5 & 0 \\ 0 & 0 & 2.9 \times 10^3 \end{pmatrix} GeV, \quad \langle\Phi_2\rangle = \begin{pmatrix} 1.1 \times 10^8 & 7.3 \times 10^6 & 1.1 \times 10^5 \\ 7.3 \times 10^6 & 7.9 \times 10^5 & 2.3 \times 10^4 \\ 1.1 \times 10^5 & 2.3 \times 10^4 & 2.2 \times 10^3 \end{pmatrix} GeV$$

Flavor Gauge Model and B Decay Anomalies

- The MMFV gauge model is not easily accessible to experiments, owing to large masses $(> 10^6 \text{ GeV})$ 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
- $\Phi(3,3) + \chi_5(1,5) + \chi_3(1,3)$ scalar fields are used for fermion masses and symmetry breaking
- M_X/g can be at the $\sim O(10-22)$ TeV scale

Flavor Gauge Model and B Decay Anomalies

- the effective Lagrangian for $b \to s\ell\ell$ transiiton at low energies in the SM

$$\mathcal{H}_{eff}^{SM} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_{ps}(C_1 O_1^p + C_2 O_2^p + \sum_{i=3}^{10} C_i O_i)$$

- Among all the possible operators present in $\mathcal{H}_{eff}$, only semileptonic ones that can explain the R_K, R_{K^*}:

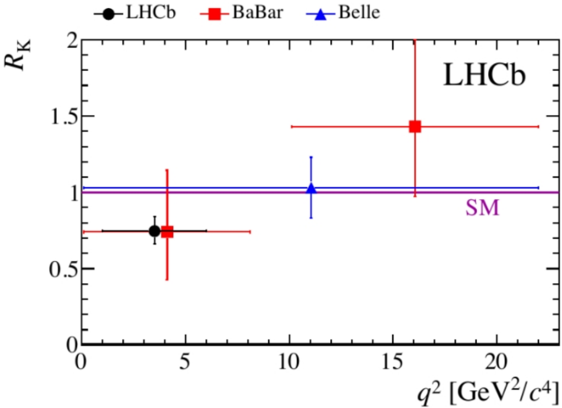
$$O_9^{(\prime)\ell} = \frac{\alpha_{em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)} b)(\ell\gamma_\mu\ell), O_{10}^{(\prime)\ell} = \frac{\alpha_{em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)} b)(\ell\gamma_\mu\gamma_5\ell)$$

- The two independent scalar operators are severely constrained by the $B_q \to \ell\ell$ decay rates and can not explain R_K, R_{K^*}
- 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

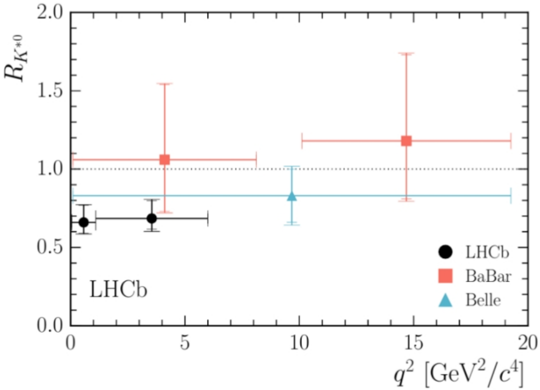
R_K Anomaly



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

Deviates from SM $R_K \simeq 1$ by $\sim 2.6\ \sigma$

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 $\sim 2.3\,\sigma$ and $2.4\,\sigma$ respectively

LHCb, arXiv:1705.05802 [hep-ex]

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]

- 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

Main Features of MFV Model

- $\Phi(3,3)$: its VEV is taken to be diagonal
- $\chi_3(1,3)$: has flavor antisymmetric VEV structure
- $\chi_5(1,5)$: has flavor-symmetric VEV structure
- Mass matrices are given by:

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

- $y^d_{3,5}$ couplings are taken to be small, to suppress $X_{L,R}$ mediated FCNC in K, B_d systems
- To suppress $X_{L,R}$ contributions to $B_s - \overline{B_s}$ mixing, the relevant phase playing role in X_L and X_R contribution to B anomalies is somewhat fine tuned

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

Fermion mass matrices:

$$\mathcal{M}_{u,d,e} = \begin{pmatrix} 0 & y_{u,d,e} v\, \mathbb{I} \\ m_0^{u,d,e}\, \mathbb{I} + y_3^{u,d,e}\, \langle \chi_3 \rangle + y_5^{u,d,e}\, \langle \chi_5 \rangle & Y^{u,d,e}\, \langle \Phi \rangle \end{pmatrix} = \begin{pmatrix} 0_{3\times3} & y_{u,d,e} v\, \mathbb{I}_{3\times3} \\ X_{u,d,e} & M_{u,d,e} \end{pmatrix}$$

$$m_{u,d,e} \sim -y_{u,d,e}\; v\; M^{-1}_{u,d,e}\; X_{u,d,e}$$

$$\boxed{\begin{array}{l} \dfrac{-y_u v\ m_0^u}{Y^u V_3} = 465.63 GeV,\ \dfrac{V_3}{V_1} = 0.001023,\ \dfrac{V_3}{V_2} = 0.019423, \\ \dfrac{y_3^u\ \langle \chi_3 \rangle_{12}}{m_0^u} = -0.096 e^{-1.19i},\ \dfrac{y_3^u\ \langle \chi_3 \rangle_{13}}{m_0^u} = -0.33 e^{-1.19i},\ \dfrac{y_3^u\ \langle \chi_3 \rangle_{23}}{m_0^u} = 0.07 e^{-1.19i}, \\ \dfrac{y_5^u\ \langle \chi_5 \rangle_{12}}{m_0^u} = -0.7 e^{-0.018i},\ \dfrac{y_5^u\ \langle \chi_5 \rangle_{13}}{m_0^u} = -0.08 e^{-0.018i},\ \dfrac{y_5^u\ \langle \chi_5 \rangle_{22}}{m_0^u} = -0.8 e^{-0.018i}, \\ \dfrac{y_5^u\ \langle \chi_5 \rangle_{23}}{m_0^u} = 0.01 e^{-0.018i},\ \dfrac{y_5^u\ \langle \chi_5 \rangle_{33}}{m_0^u} = -0.9 e^{-0.018i} \end{array}}$$

$$\boxed{\dfrac{-y_d v\ m_0^d}{Y^d V_3} = 2.4 GeV,\ \ y_3^d \sim 0,\ \ y_5^d \sim 0}$$

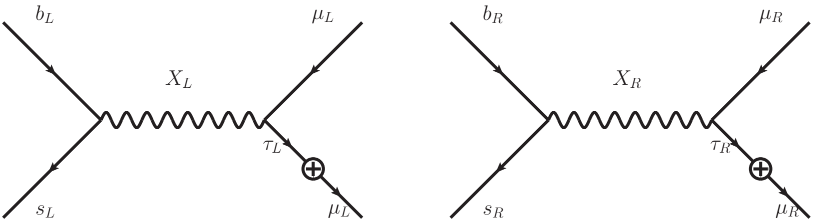
$$\boxed{\dfrac{-y_e v\ m_0^e}{Y^e V_3} = 18.60 GeV,\ f_e = \dfrac{y_3^e}{y_3^u} \dfrac{m_0^u}{m_0^e} = -0.35 e^{-2.36i},\ g_e = \dfrac{y_5^e}{y_5^u} \dfrac{m_0^u}{m_0^e} = -1.01 e^{-3.14i}}$$

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

Masses (in GeV) and Mixing parameters	Inputs (at $\mu = 10^3$ GeV)	Fitted values (at $\mu = 10^3$ GeV)	pulls
$m_u/10^{-4}$	9.8$\pm$3.3	9.8	0.01
m_c	0.54$\pm$0.01	0.54	0.01
m_t	151.2$\pm$1.5	151.2	-0.004
$m_d/10^{-3}$	2.4$\pm$0.2	2.4	0.0
$m_s/10^{-3}$	46.9$\pm$2.5	46.9	0.0
m_b	2.4$\pm$0.02	2.4	-0.0
$m_e/10^{-4}$	4.95$\pm$0.04	4.95	0.003
$m_\mu/10^{-3}$	104.6$\pm$0.1	104.6	-0.0006
m_τ	1.7$\pm$0.01	1.7	-0.003
$\theta_{12}/10^{-2}$22.7	$\pm$0.07	22.7	-0.05
$\theta_{23}/10^{-2}$	4.2$\pm$0.06	4.2	-0.2
$\theta_{23}/10^{-3}$	3.7$\pm$0.1	3.7	0.07
δ_{CKM}	1.208$\pm$0.05	1.208	0.2
χ^2	-	-	0.09

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

- $C_9 = -C_{10} \sim -0.67$ can be induced in MFV model



- Requires $M_{X_L}/g_L \sim (10-22)$ TeV
- both $(K^e_{L,R})_{22}$ are large, so $C_9 = -C_{10}$ and $C_9^{(\prime)} = -C_{10}^{(\prime)}$ will be induced for B decays requirement can be achieved naturally

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

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

$$K_L^u = \begin{pmatrix} 6\cdot 10^{-4}i & 0.008+0.007i & -0.19+1\cdot 10^{-1}i \\ -0.008+0.007i & 8\cdot 10^{-2}i & -0.9+3\cdot 10^{-5}i \\ 0.19+1\cdot 10^{-1}i & 0.9+3\cdot 10^{-5}i & -8\cdot 10^{-2}i \end{pmatrix}$$

$$K_R^u = \begin{pmatrix} -9\cdot 10^{-1}i & -4\cdot 10^{-5}+1\cdot 10^{-5}i & -2\cdot 10^{-1}+2\cdot 10^{-2}i \\ 4\cdot 10^{-5}+1\cdot 10^{-5}i & 9\cdot 10^{-1}i & -3\cdot 10^{-2}-2\cdot 10^{-2}i \\ 2\cdot 10^{-1}+2\cdot 10^{-2}i & 3\cdot 10^{-2}-2\cdot 10^{-2}i & -6\cdot 10^{-2}i \end{pmatrix}$$

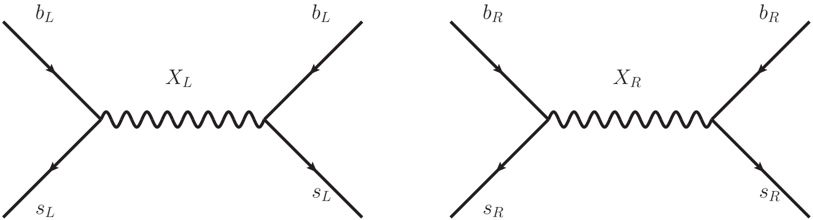
$$K_L^e = \begin{pmatrix} -6\cdot 10^{-6}i & 0.004-2\cdot 10^{-2}i & -0.2-1\cdot 10^{-2}i \\ -0.004-2\cdot 10^{-2}i & -2\cdot 10^{-1}i & -0.9-2\cdot 10^{-3}i \\ 0.2-1\cdot 10^{-2}i & 0.9-2\cdot 10^{-3}i & 2\cdot 10^{-1}i \end{pmatrix}$$

$$K_R^e = \begin{pmatrix} 0.17i & -0.8-0.013i & 0.012-0.41i \\ 0.85-0.013i & -0.3i & -0.09+0.01i \\ -0.012-0.41i & 0.09+0.01i & 0.1i \end{pmatrix}$$

- By construction, $X_{L,R}$ contributions to $K^0-\overline{K^0}$ mixing, $B_d^0-\overline{B_d^0}$ mixing are small

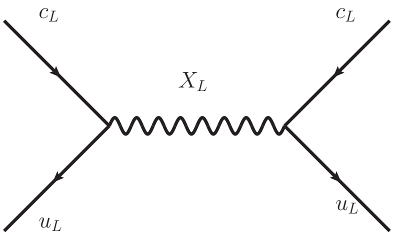
$O(3)_L \times O(3)_R$ Model for B Anomalies

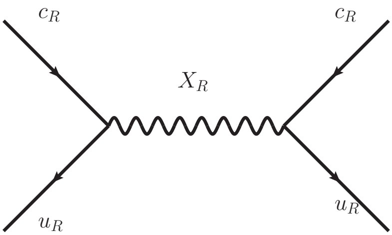
- $B_s - \overline{B}_s$ mixing provides a strong constraint



- X_R exchange almost exactly cancels the X_L contribution.
Note: $M_{X_L}/g_L = M_{X_R}/g_R$

$D^0 - \overline{D^0}$ mixing in $O(3)_L \times O(3)_R$ Model

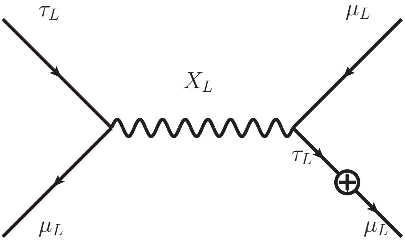




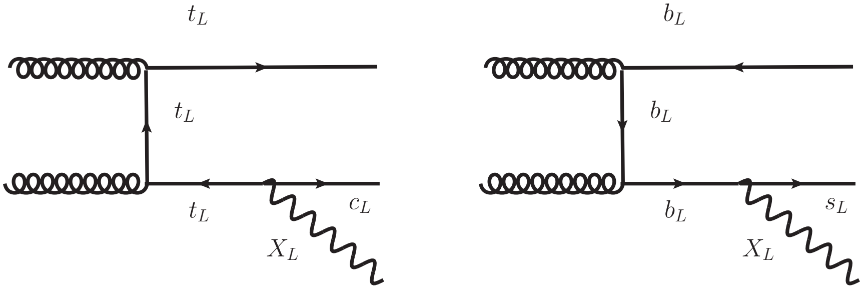
- $|(K_L^u)_{12}^2 + (K_R^u)_{12}^2| \sim 1.3 \times 10^{-4}$ leads to new contributions to $D^0 - \overline{D^0}$ mixing. Close to experimental limit for $M_X/g \sim 10$ TeV
- CP violation in mixing is also in interesting range: $Im[(K_L^u)_{12}^2 + (K_R^u)_{12}^2] \sim 1.8 \times 10^{-5}$ for $M_X/g \sim 10$ TeV

$\tau \to 3\mu$ decay in $O(3)_L \times O(3)_R$ Model

- Predicts $\tau \to 3\mu$ with a branching ratio of $\sim 10^{-10}$



Production Mechanism of X Gauge Boson



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 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