Attempt on Solving Flavor Anomalies within A Flavor Specified 2HDM

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Outline

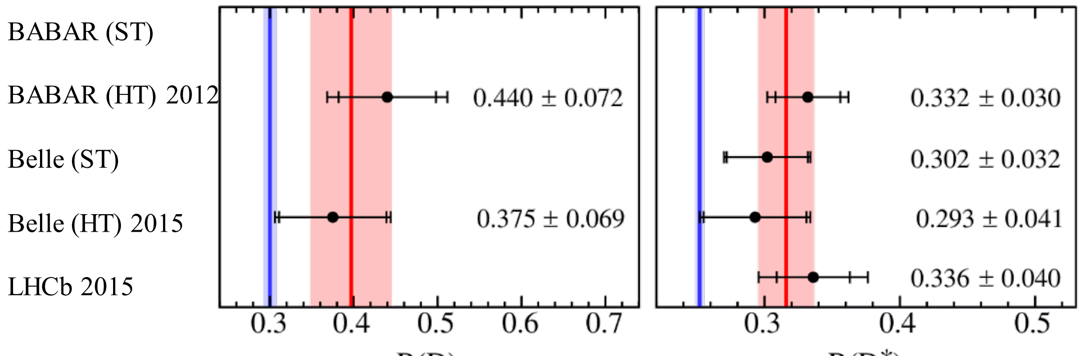
- Introduction: flavor anomalies
- F$_{\text{lavor}}$ G$_{\text{auged}}$ 2HDM
- Flavor anomalies in FG2HDM
- Summary

$R_{D^{(*)}}$ anomalies

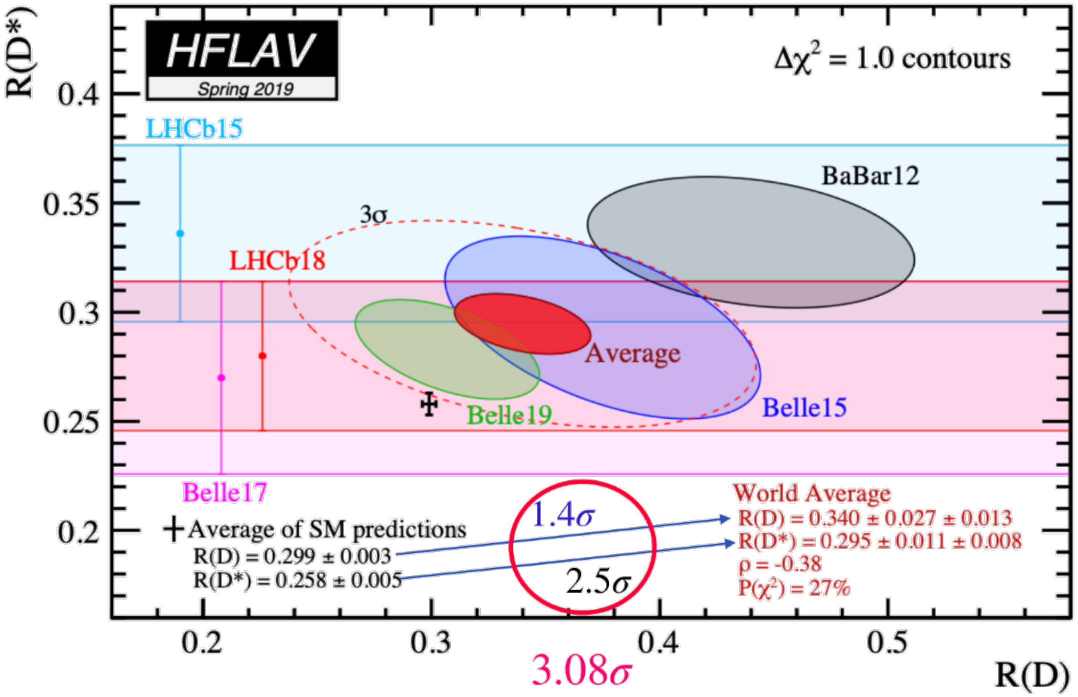
$$R_{D^{(*)}} = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\bar{\nu}\right)}\Bigg|_{\ell=e,\mu}$$

$$R_{D^*} = 0.440 \pm 0.058 \pm 0.042\ (2.0\sigma)$$
$$R_D = 0.332 \pm 0.024 \pm 0.018\ (2.7\sigma)$$

Exceed → SM



ST and HT refer to the measurements with semileptonic and hadronic tags, respectively.

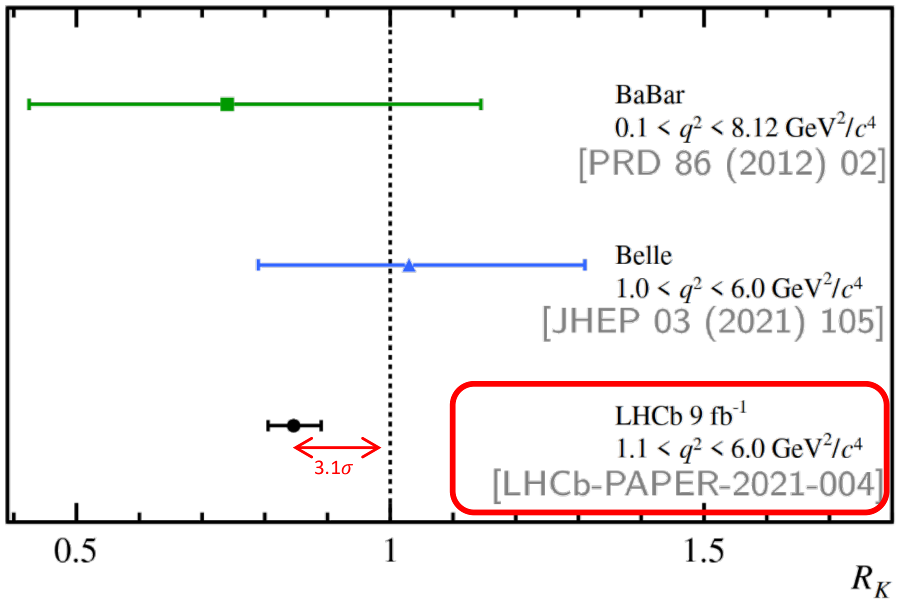


HFLAV 2019

$R_{K^{(*)}}$ anomalies

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}$$

$$R_K = 0.846\ ^{+0.042}_{-0.039}\,(\text{stat.})\ ^{+0.013}_{-0.012}\,(\text{syst.})$$



R. D. Moise, Moriond 2021

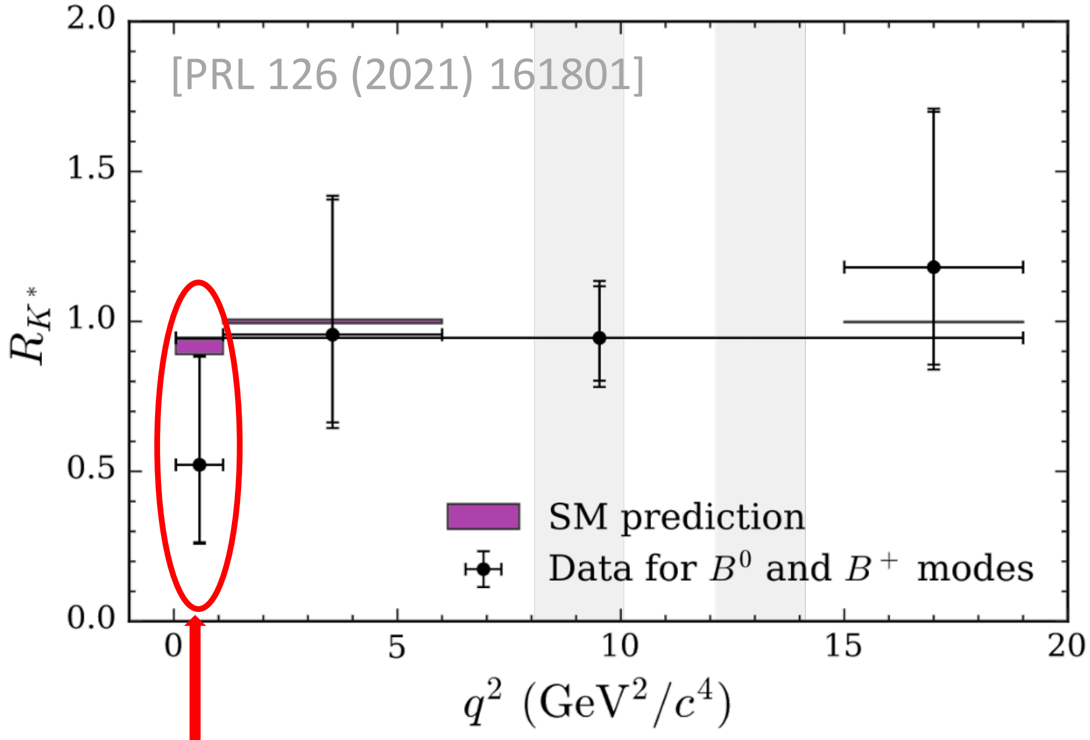


TABLE II. Results for R_{K^*}, $R_{K^{*0}}$, and $R_{K^{*+}}$. The first uncertainty is statistical and the second is systematic.

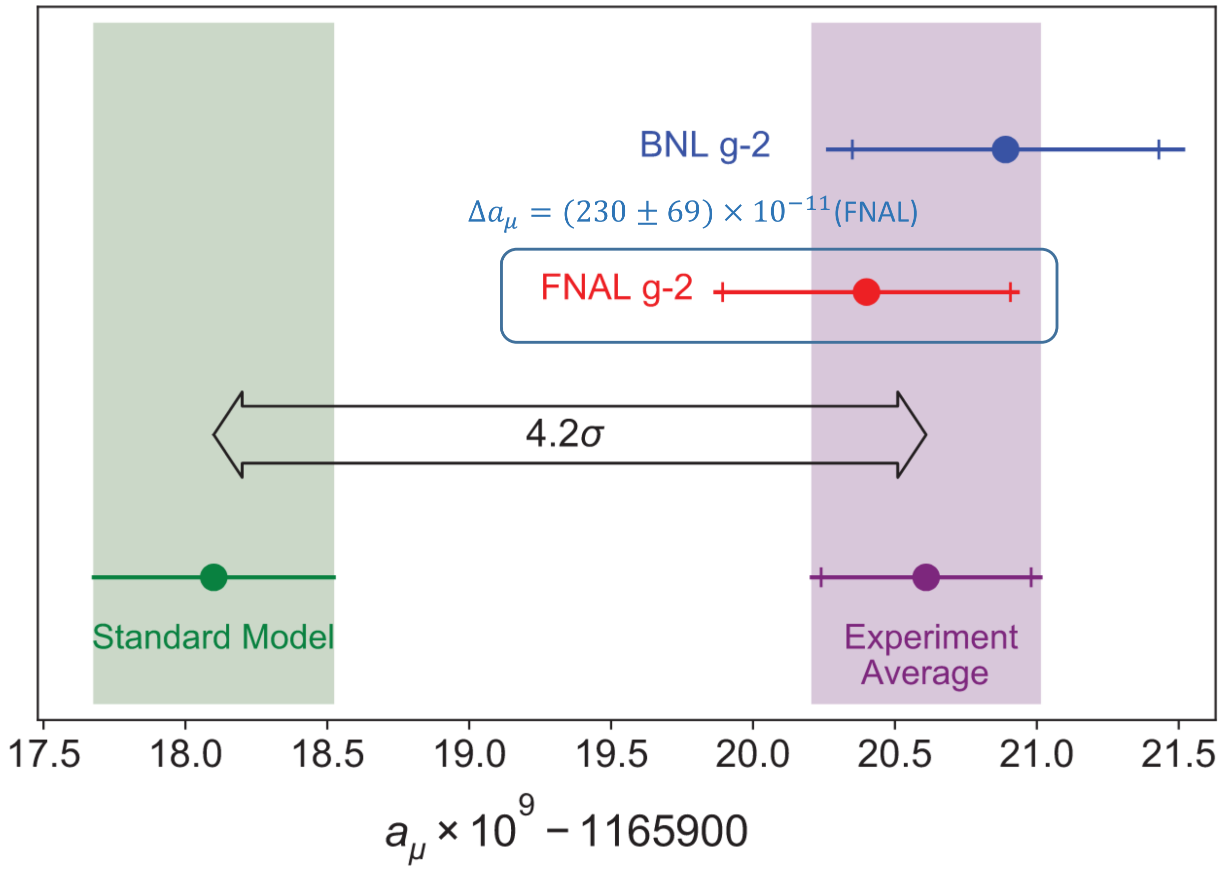
q^2 (GeV$^2/c^4$)	All modes	B^0 modes	B^+ modes
[0.045, 1.1]	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.13$	$0.62^{+0.60}_{-0.36} \pm 0.07$
[1.1, 6]	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.14$
[0.1, 8]	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.09$	$0.96^{+0.56}_{-0.35} \pm 0.13$
[15, 19]	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
[0.045, 19]	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.06$

Muon $g - 2$

Contribution	$a_\mu \times 10^{11}$
QED (order $\mathcal{O}(\alpha^5)$)	$116\ 584\ 718.93 \pm 0.10$
Electroweak	153.6 ± 1.0
QCD	
HVP (LO)	$6\ 931 \pm 40$
HVP (NLO)	-98.3 ± 0.7
HVP (NNLO)	12.4 ± 0.1
HLbL	94 ± 19
Total (theory)	$116\ 591\ 810 \pm 43$

T. Aoyama. et al.,
Phys. Rept. 887(2020) 1-166

$$\Delta a_\mu = (251 \pm 59) \times 10^{-11}$$



PRL 126 (2021) 141801

2HDMs

$$-\mathcal{L}_Y = \overline{Q_L^0}(Y_1^d\Phi_1 + Y_2^d\Phi_2)d_R^0 + \overline{Q_L^0}(Y_1^u\tilde{\Phi}_1 + Y_2^u\tilde{\Phi}_2)u_R^0$$
$$+\overline{L_L^0}(Y_1^\ell\Phi_1 + Y_2^\ell\Phi_2)e_R^0 + \overline{L_L^0}(Y_1^\nu\tilde{\Phi}_1 + Y_2^\nu\tilde{\Phi}_2)\nu_R^0 + h.c.$$

$$-\mathcal{L}_m = \bar{u}_L M_u u_R + \bar{d}_L M_d d_R + \bar{\ell}_L M_\ell \ell_R + \bar{\nu}_L M_\nu \nu_R + h.c.$$

$$M_f = U_{fL}^\dagger \tilde{M}_f U_{fR}, \qquad \tilde{M}_f = \frac{1}{\sqrt{2}}(v_1 Y_1^f + v_2 Y_2^f)$$

	Model	u_R^0	d_R^0	e_R^0	$Y_1^u = 0$
	Type I	Φ_2	Φ_2	Φ_2	(Y_2^u, Y_2^d, Y_2^ℓ)
	Type II	Φ_2	Φ_1	Φ_1	(Y_2^u, Y_1^d, Y_1^ℓ)
(Lepton-specific)	Type X	Φ_2	Φ_2	Φ_1	(Y_2^u, Y_2^d, Y_1^ℓ)
(Flipped)	Type Y	Φ_2	Φ_1	Φ_2	(Y_2^u, Y_1^d, Y_2^ℓ)

Type III 2HDM

$$-\mathcal{L}_Y = \overline{Q_L^0}(Y_1^d\Phi_1 + Y_2^d\Phi_2)d_R^0 + \overline{Q_L^0}(Y_1^u\tilde{\Phi}_1 + Y_2^u\tilde{\Phi}_2)u_R^0 + \overline{L_L^0}(Y_1^\ell\Phi_1 + Y_2^\ell\Phi_2)e_R^0 + \overline{L_L^0}(Y_1^\nu\tilde{\Phi}_1 + Y_2^\nu\tilde{\Phi}_2)\nu_R^0 + h.c.$$

- Yukawa: too many parameters
- Cost: Dangerous FCNHs introduced

Designed symmetry can be extended but limited parameters added

Flavor Gauged 2HDM: U(1)' symmetry

Flavor Gauged 2HDM:

Flavor-dependent U(1)' gauge symmetry

$$\phi \to \phi' = e^{i\theta X_\phi}\phi$$

$$X_{Q_L} = \frac{1}{2}\begin{pmatrix} Q_{u_R}+Q_{d_R} & & \\ & Q_{u_R}+Q_{d_R} & \\ & & Q_{t_R}+Q_{d_R} \end{pmatrix},$$

$$X_{u_R} = \begin{pmatrix} Q_{u_R} & & \\ & Q_{u_R} & \\ & & Q_{t_R} \end{pmatrix}, \quad X_{d_R} = \begin{pmatrix} Q_{d_R} & & \\ & Q_{d_R} & \\ & & Q_{d_R} \end{pmatrix},$$

$$X_\Phi = \frac{1}{2}\begin{pmatrix} Q_{u_R}-Q_{d_R} & \\ & Q_{t_R}-Q_{d_R} \end{pmatrix},$$

$$X_{L_L} = \begin{pmatrix} Q_{e_L} & & \\ & Q_{\mu_L} & \\ & & Q_{\tau_L} \end{pmatrix},$$

$$X_{\ell_R} = \begin{pmatrix} Q_{e_R} & & \\ & Q_{\mu_R} & \\ & & Q_{\tau_R} \end{pmatrix}, \quad X_{\nu_R} = 0.$$

Anomaly cancellation conditions

Only two model parameters left

$$Q_{u_R} = -Q_{d_R} - \frac{1}{3}Q_{\mu_R}, \quad Q_{t_R} = -4Q_{d_R} + \frac{2}{3}Q_{\mu_R},$$

$$Q_{\tau_L} = Q_{d_R} + \frac{1}{6}Q_{\mu_R}, \quad Q_{\mu_L} = -Q_{d_R} + \frac{5}{6}Q_{\mu_R}, \quad Q_{e_L} = \frac{9}{2}Q_{d_R} - Q_{\mu_R},$$

$$Q_{\tau_R} = 2Q_{d_R} + \frac{1}{3}Q_{\mu_R}, \quad Q_{e_R} = 7Q_{d_R} - \frac{4}{3}Q_{\mu_R}$$

Quark sector: $Y_1^u = \begin{pmatrix} * & * & 0 \\ * & * & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_2^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & * \end{pmatrix}, \quad Y_1^d = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_2^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$

Lepton sector: $Y_1^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix}, \quad Y_2^\ell = \begin{pmatrix} * & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_1^\nu = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}, \quad Y_2^\nu = 0$

$F_{\text{lavor}}\ G_{\text{auged}}$ 2HDM: Scalar potential

Flavor Gauged 2HDM :

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2+\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2+\left(\Phi_2^\dagger\Phi_1\right)^2\right]$$

$$\Phi_i = \left(\phi_i^+, \frac{1}{\sqrt{2}}(\rho_i + i\eta_i + v_i)\right)^T$$

$$X_\Phi = \frac{1}{2}\begin{pmatrix} Q_{u_R}-Q_{d_R} & \\ & Q_{t_R}-Q_{d_R}\end{pmatrix}$$

Generic potential without m_{12} and λ_5 terms

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right),$$

$$\mathcal{L}_{\eta\ \text{mass}} = \frac{m_A^2}{v_1^2+v_2^2}\begin{pmatrix}\eta_1 & \eta_2\end{pmatrix}\begin{pmatrix} v_2^2 & -v_1v_2 \\ -v_1v_2 & v_1^2\end{pmatrix}\begin{pmatrix}\eta_1\\ \eta_2\end{pmatrix} = 0, \quad m_A = \left[\frac{m_{12}^2}{v_1v_2} - 2\lambda_5\right](v_1^2+v_2^2).$$

$$\mathcal{L}_{\phi^\pm} = -\frac{1}{2}\lambda_4 v_1 v_2\left(\phi_1^-, \phi_2^-\right)\begin{pmatrix}\frac{v_2}{v_1} & -1\\ -1 & \frac{v_1}{v_2}\end{pmatrix}\begin{pmatrix}\phi_1^+\\ \phi_2^+\end{pmatrix}$$

$$\mathcal{L}_\rho = -\frac{1}{2}\left(\rho_1,\rho_2\right)\begin{pmatrix}\lambda_1 v_1^2 & \lambda_{34}v_1v_2\\ \lambda_{34}v_1v_2 & \lambda_2 v_2^2\end{pmatrix}\begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix}$$

- 2 Exotic introduced: $H^\pm$ and H^0
- 3 Goldstone boson eaten by $W^\pm$ 、Z、new gauge boson Z'

$$\begin{pmatrix}h\\ H^0\end{pmatrix} = \begin{pmatrix}\cos\alpha & \sin\alpha\\ -\sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix},$$

$$\begin{pmatrix}G^\pm\\ H^\pm\end{pmatrix} = \begin{pmatrix}\cos\beta & \sin\beta\\ -\sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}\phi_1^\pm\\ \phi_2^\pm\end{pmatrix}.$$

Flavor Gauged 2HDM: Yukawa interacion

$$-\mathcal{L}_Y = \overline{Q_L^0}(Y_1^d\Phi_1 + Y_2^d\Phi_2)d_R^0 + \overline{Q_L^0}(Y_1^u\tilde{\Phi}_1 + Y_2^u\tilde{\Phi}_2)u_R^0 + \overline{L_L^0}(Y_1^\ell\Phi_1 + Y_2^\ell\Phi_2)e_R^0 + \overline{L_L^0}(Y_1^\nu\tilde{\Phi}_1 + Y_2^\nu\tilde{\Phi}_2)\nu_R^0 + h.c.$$

$$\begin{aligned}-\mathcal{L} = &\frac{\sqrt{2}}{v}H^+\left[\bar{u}\left(V_{\rm CKM}N_d\mathbb{P}_R - N_u^\dagger V_{\rm CKM}\mathbb{P}_L\right)d + \bar{\nu}\left(V_{\rm PMNS}N_\ell\mathbb{P}_R - N_\nu^\dagger V_{\rm PMNS}\mathbb{P}_L\right)\ell\right] + h.c.\\ &+\frac{1}{v}\left[\cos(\beta-\alpha)H^0 - \sin(\beta-\alpha)h\right]\left[\bar{u}N_u u + \bar{d}N_d d + \bar{\ell}N_\ell\ell + \bar{\nu}N_\nu\nu\right]\\ &+\frac{1}{v}\left[\sin(\beta-\alpha)H^0 + \cos(\beta-\alpha)h\right]\left[\bar{u}M_u u + \bar{d}M_d d + \bar{\ell}M_\ell\ell + \bar{\nu}M_\nu\nu\right]\end{aligned}$$

$$N_u = -\frac{v_2}{v_1}\text{diag}(m_u, m_c, 0) + \frac{v_1}{v_2}\text{diag}(0,0,m_t),$$

$$(N_d)_{ij} = -\frac{v_2}{v_1}(M_d)_{ij} + \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)V_{i3}^\dagger V_{3j}(M_d)_{jj},$$

$$N_\nu = -\frac{v_2}{v_1}M_\nu,$$

$$N_\ell = -\frac{v_2}{v_1}\text{diag}(0, m_\mu, m_\tau) + \frac{v_1}{v_2}\text{diag}(m_e, 0, 0)$$

Flavor mixing scalar coupling only happens in down-type quark sector.

Flavor Gauged 2HDM: Gauge boson

$$\mathcal{L}_m^G = \begin{pmatrix} B & W^3 & \hat{Z}' \end{pmatrix} \tilde{M} \begin{pmatrix} B \\ W^3 \\ \hat{Z}' \end{pmatrix} = \begin{pmatrix} A & Z & Z' \end{pmatrix} M_d \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_W & (-\sin\theta_W)\sin\theta_1 & (-\sin\theta_W)\sin\theta_2 \\ \sin\theta_W & (\cos\theta_W)\sin\theta_1 & (\cos\theta_W)\sin\theta_2 \\ 0 & \cos\theta_1 & \cos\theta_2 \end{pmatrix}$$

$$\tilde{M} = \frac{1}{2} m_Z^2 \begin{pmatrix} \sin^2\theta_W & -\sin\theta_W\cos\theta_W & a\sin\theta_W \\ -\sin\theta_W\cos\theta_W & \cos^2\theta_W & -a\cos\theta_W \\ a\sin\theta_W & -a\cos\theta_W & b \end{pmatrix} \rightarrow M_d = \frac{1}{2} m_Z^2 \begin{pmatrix} 0 & & \\ & \mu_Z & \\ & & \mu_{Z'} \end{pmatrix}$$

$$\mathcal{L}_{\rm FG} = eQ_f A_\mu \bar{f}\gamma^\mu f$$

$$+ \frac{g_2 \sin\theta_1}{\cos\theta_W} Z_\mu \bar{f}\left[I_f^3\gamma^\mu \mathbb{P}_L - Q_f \sin^2\theta_W \gamma^\mu\right] f + g' \cos\theta_1 Z_\mu \bar{f}\left[\mathcal{Q}_{fL}\gamma^\mu\mathbb{P}_L + \mathcal{Q}_{fR}\gamma^\mu\mathbb{P}_R\right] f$$

$$+ \frac{g_2 \sin\theta_2}{\cos\theta_W} Z'_\mu \bar{f}\left[I_f^3\gamma^\mu \mathbb{P}_L - Q_f \sin^2\theta_W \gamma^\mu\right] f + g' \cos\theta_2 Z'_\mu \bar{f}\left[\mathcal{Q}_{fL}\gamma^\mu\mathbb{P}_L + \mathcal{Q}_{fR}\gamma^\mu\mathbb{P}_R\right] f$$

Flavor Gauged 2HDM: Gauge boson

In an extreme case: $Q_1 = -Q_2 \tan^2\beta$

$$\mu_Z \to 1,\ \mu_{Z'} \to b$$
$$\sin\theta_1 \to 1,\ \cos\theta_1 \to 0,\ \sin\theta_2 \to 0,\ \cos\theta_2 \to 1$$

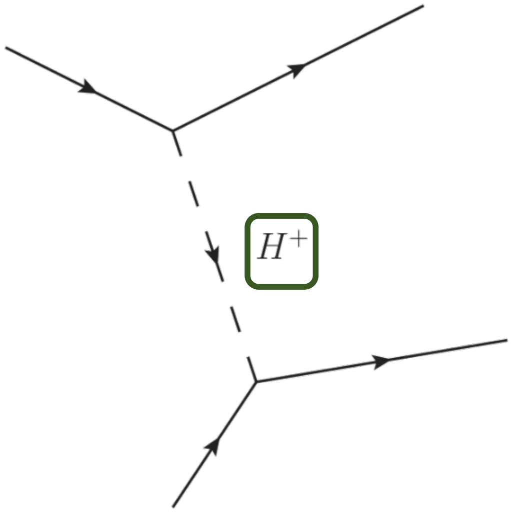
$$U \longrightarrow \begin{pmatrix} \cos\theta_W & -\sin\theta_W & 0 \\ \sin\theta_W & \cos\theta_W & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathcal{L}_{Z'} = Z'_\mu J^\mu,$$
$$J^\mu = g'\bar{f}(\mathcal{Q}_{fL}\gamma^\mu \mathbb{P}_L + \mathcal{Q}_{fR}\gamma^\mu \mathbb{P}_R)f$$

$$\mathcal{Q}_{dL} = \frac{1}{2}(Q_{u_R} + Q_{d_R})\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} + \frac{1}{2}(Q_{t_R} - Q_{u_R})\begin{pmatrix} |c_1|^2 & c_1^* c_2 & c_1^* c_3 \\ c_2^* c_1 & |c_2|^2 & c_2^* c_3 \\ c_3^* c_1 & c_3^* c_2 & |c_3|^2 \end{pmatrix},\ c_i \equiv V_{ti}^{\rm CKM}, i = d, s, b.$$

Flavor mixing gauge coupling only happens in down-type quark sector too.

$R_{D^{(*)}}$ anomalies in FG2HDM



$$\mathcal{H} = C^{\alpha}_{RL}O^{\alpha}_{RL} + C^{\alpha}_{LL}O^{\alpha}_{LL} + C^{\alpha}_{LR}O^{\alpha}_{LR} + C^{\alpha}_{RR}O^{\alpha}_{RR}$$

$$O^{\alpha k}_{RL} = (\bar{c}\mathbb{P}_R b)(\bar{\ell}_k \mathbb{P}_L \nu_\alpha), \quad O^{\alpha k}_{LL} = (\bar{c}\mathbb{P}_L b)(\bar{\ell}_k \mathbb{P}_L \nu_\alpha),$$
$$O^{\alpha k}_{LR} = (\bar{c}\mathbb{P}_L b)(\bar{\ell}_k \mathbb{P}_R \nu_\alpha), \quad O^{\alpha k}_{RR} = (\bar{c}\mathbb{P}_R b)(\bar{\ell}_k \mathbb{P}_R \nu_\alpha),$$

$$R_D = R_D^{\rm SM}\left[1 + 1.5{\rm Re}\left(\frac{C^{\tau 3}_{RL} + C^{\tau 3}_{LL}}{C^{cb}_{\rm SM}}\right) + 1.0\left|\frac{C^{\tau 3}_{RL} + C^{\tau 3}_{LL}}{C^{cb}_{\rm SM}}\right|^2\right],$$

$$R_{D^*} = R_{D^*}^{\rm SM}\left[1 + 0.12{\rm Re}\left(\frac{C^{\tau 3}_{RL} - C^{\tau 3}_{LL}}{C^{cb}_{\rm SM}}\right) + 0.05\left|\frac{C^{\tau 3}_{RL} - C^{\tau 3}_{LL}}{C^{cb}_{\rm SM}}\right|^2\right]$$

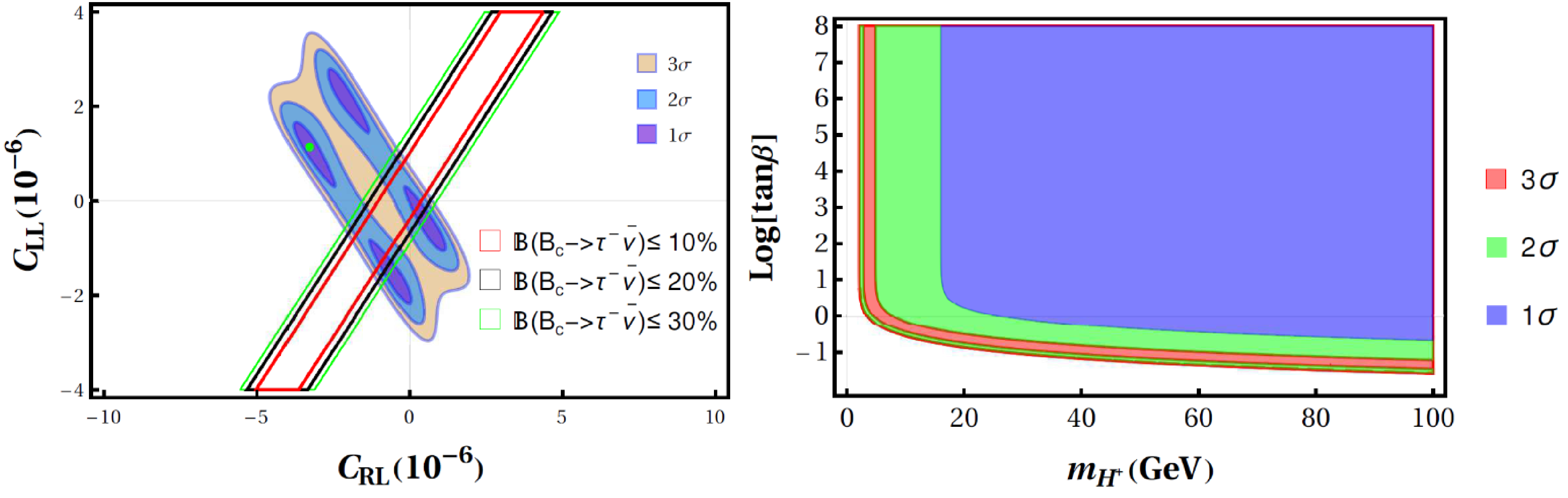
$$C^{\tau 3}_{RL} \approx -2\sqrt{2}G_F V_{cb}\frac{m_b m_\tau}{m_H^2}\left(\frac{2}{\tan^2\beta} + 1\right)$$
$$C^{\tau 3}_{LL} = -2\sqrt{2}G_F V_{cb}\frac{m_c m_\tau}{m_H^2}.$$
$$C^{cb}_{\rm SM} = 2\sqrt{2}G_F V_{cb}.$$

S. Fajfer. , Phys. Rev. D 85 (2012) 094025

Correlated process:

$$\mathcal{B}(B_c \to \tau^- \bar{\nu}) = \frac{1}{8\pi}\tau_{B_c} G_F^2 |V_{cb}|^2 m_{B_c} m_\tau^2 f_{B_c}^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left|1 + \frac{m_{B_c}^2}{(m_b + m_c)m_\tau} C_P\right|^2 \qquad C_P = \left(C^{\tau 3}_{RL} - C^{\tau 3}_{LL}\right)/C^{cb}_{\rm SM}.$$

The result of $R_{D^{(*)}}$ anomalies in FG2HDM



(a) (b)

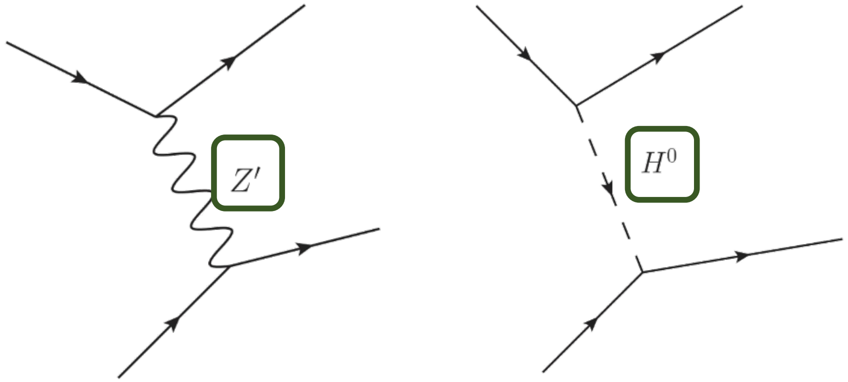
R_K anomaly in FG2HDM

$$\mathscr{H} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + h.c.$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu \mathbb{P}_L b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_9' = (\bar{s}\gamma_\mu \mathbb{P}_R b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu \mathbb{P}_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu \mathbb{P}_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$\mathcal{O}_S = m_b(\bar{s}\mathbb{P}_R b)(\bar{\ell}\ell), \qquad \mathcal{O}_S' = m_b(\bar{s}\mathbb{P}_L b)(\bar{\ell}\ell),$$



$$R_K \equiv \frac{\Gamma_\mu}{\Gamma_e} = \int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma_\mu}{dq^2} \Bigg/ \int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma_e}{dq^2}$$

$$\frac{\mathrm{d}\Gamma_\ell}{\mathrm{d}q^2} \propto q^2 \left(\beta_l^2 |F_S|^2 + |F_P|^2 \right) + \frac{\lambda^2 M_B^4}{4} \left(|F_A|^2 + |F_V|^2 \right) + 2m_l \left(M_B^2 - M_K^2 + q^2 \right) \Re \left(F_P F_A^* \right) + 4m_l^2 M_B^2 |F_A|^2 - \frac{1}{3} \frac{\lambda^2 M_B^4}{4} \beta_l^2 \left(|F_A|^2 + |F_V|^2 \right)$$

C. Bobeth. et al. ,
JHEP 12 (2007) 040

General case:

$$F_A = C_{10}, \qquad F_T = \frac{2\lambda M_B^2 \beta_l}{M_B + M_K} \frac{f_T(q^2)}{f_+(q^2)} C_T^l, \qquad F_{T5} = \frac{2\lambda M_B^2 \beta_l}{M_B + M_K} \frac{f_T(q^2)}{f_+(q^2)} C_{T5}^l,$$

$$F_P = \frac{1}{2} \frac{M_B^2 - M_K^2}{m_b - m_s} \frac{f_0(q^2)}{f_+(q^2)} \left(C_P^l + C_P'^l \right) + m_l C_{10} \left[\frac{M_B^2 - M_K^2}{q^2} \left(\frac{f_0(q^2)}{f_+(q^2)} - 1 \right) - 1 \right],$$

$$F_S = \frac{1}{2} \frac{M_B^2 - M_K^2}{m_b - m_s} \frac{f_0(q^2)}{f_+(q^2)} \left(C_S^l + C_S'^l \right), \qquad F_V = C_9 + \frac{2m_b}{M_B} \frac{\mathcal{T}_P(q^2)}{\xi_P(q^2)} + \frac{8m_l}{M_B + M_K} \frac{f_T(q^2)}{f_+(q^2)} C_T^l,$$

FG2HDM case:

$$F_A = C_{10}, \quad Z'$$

$$F_P \approx m_l C_{10} \left[\frac{M_B^2 - M_K^2}{q^2} \left(\frac{2E}{M_B} - 1 \right) - 1 \right],$$

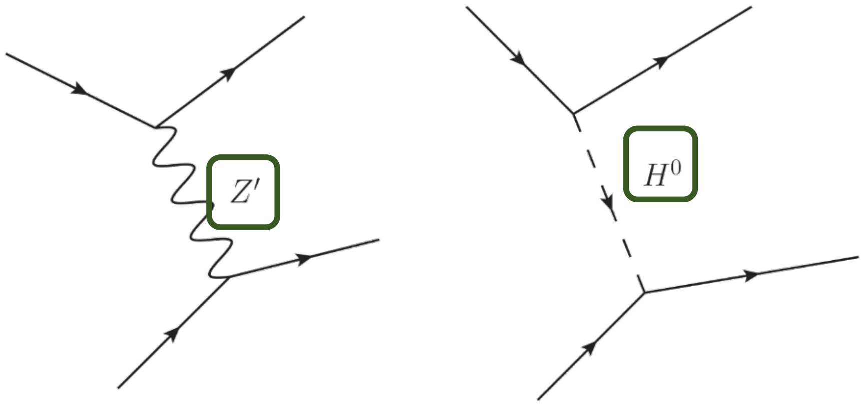
$$F_S = \frac{M_B^2 - M_K^2}{m_b - m_s} \frac{f_0(q^2)}{f_+(q^2)} C_S^l \approx \frac{M_B^2 - M_K^2}{m_b - m_s} \frac{2E}{M_B} C_S^l$$

$$F_V = C_9 + \frac{2m_b}{M_B} \frac{\mathcal{T}_P(q^2)}{\xi_P(q^2)} \quad H^0$$

Z'

R_{K^*} anomaly in FG2HDM

$$R_{K^*} \equiv \frac{\Gamma_\mu}{\Gamma_e} = \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\Gamma_\mu}{dq^2} \Bigg/ \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\Gamma_e}{dq^2}$$



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_{K^*}, \phi)\,,$$

where

$$\begin{aligned} I(q^2, \theta_l, \theta_{K^*}, \phi) = {} & I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l \\ & + I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi \\ & + I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi \\ & + (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}) \cos\theta_l + I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi \\ & + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi\,. \end{aligned}$$

Z'

$$I_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right] + \frac{4m_\mu^2}{q^2} \mathrm{Re}\left(A_\perp^L A_\perp^{R^*} + A_\parallel^L A_\parallel^{R^*}\right)$$

$$I_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R^*})\right] + \beta_\mu^2 |A_S|^2,$$

H^0

$$I_2^s = \frac{\beta_\mu^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)\right],$$

$$I_2^c = -\beta_\mu^2\left[|A_0^L|^2 + (L \to R)\right],$$

A.J.Buras. et al. , JHEP 01 (2009) 019

Form factor:

$$V(q^2) = \left(1 + \frac{m_{K^*}}{M}\right)\xi_\perp(M,E),$$

$$A_1(q^2) = \frac{2E}{M + m_{K^*}}\xi_\perp(M,E),$$

$$A_2(q^2) = \left(1 + \frac{m_{K^*}}{M}\right)\left[\xi_\perp(M,E) - \frac{m_{K^*}}{E}\xi_\parallel(M,E)\right],$$

$$A_0(q^2) = \left(1 - \frac{m_{K^*}}{ME}\right)\xi_\parallel(M,E) + \frac{m_{K^*}}{M}\xi_\perp(M,E),$$

$$T_1(q^2) = \xi_\perp(M,E),$$

$$T_2(q^2) = \left(1 - \frac{q^2}{M^2 - m_{K^*}^2}\right)\xi_\perp(M,E),$$

$$T_2(q^2) = \xi_\perp(M,E) - \frac{m_{K^*}}{E}\left(1 - \frac{m_{K^*}}{M^2}\right)\xi_\parallel(M,E).$$

$$\xi_\perp(q^2) = \xi_\perp(0)\left(\frac{1}{1 - q^2/M_B^2}\right)^2,$$

$$\xi_\parallel(q^2) = \xi_\parallel(0)\left(\frac{1}{1 - q^2/M_B^2}\right)^3.$$

G.Burdman. , Phys.Rev D 63 (2001) 113008

M.Beneke. , Nuclear Physics B 612 (2001) 25–58

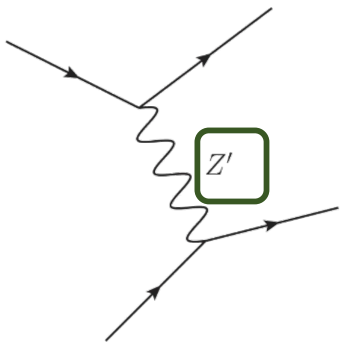
$B_s \to \mu^+\mu^-$ in FG2HDM

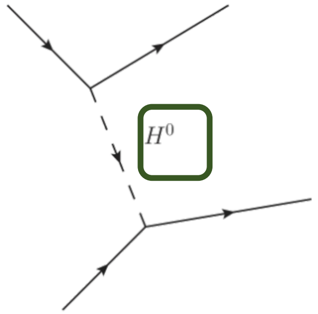
$$\mathscr{H} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + h.c.$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu \mathbb{P}_L b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_9' = (\bar{s}\gamma_\mu \mathbb{P}_R b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu \mathbb{P}_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu \mathbb{P}_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$\mathcal{O}_S = m_b (\bar{s}\mathbb{P}_R b)(\bar{\ell}\ell), \qquad \mathcal{O}_S' = m_b (\bar{s}\mathbb{P}_L b)(\bar{\ell}\ell),$$





NP:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \tau_{B_s} f_{B_s}^2 m_{B_s} \frac{\alpha_{\rm em}^2 G_F^2}{16\pi^3} |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \left[|S|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + |P|^2 \right],$$

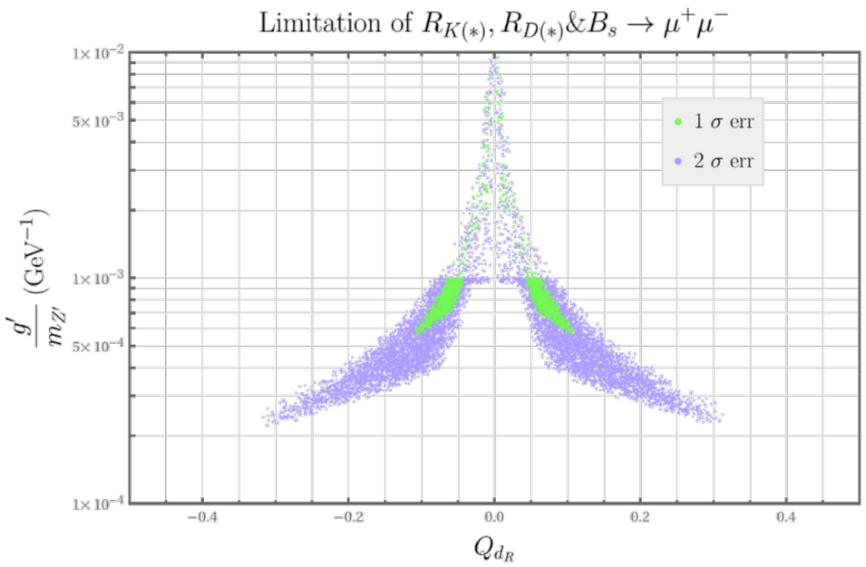
where

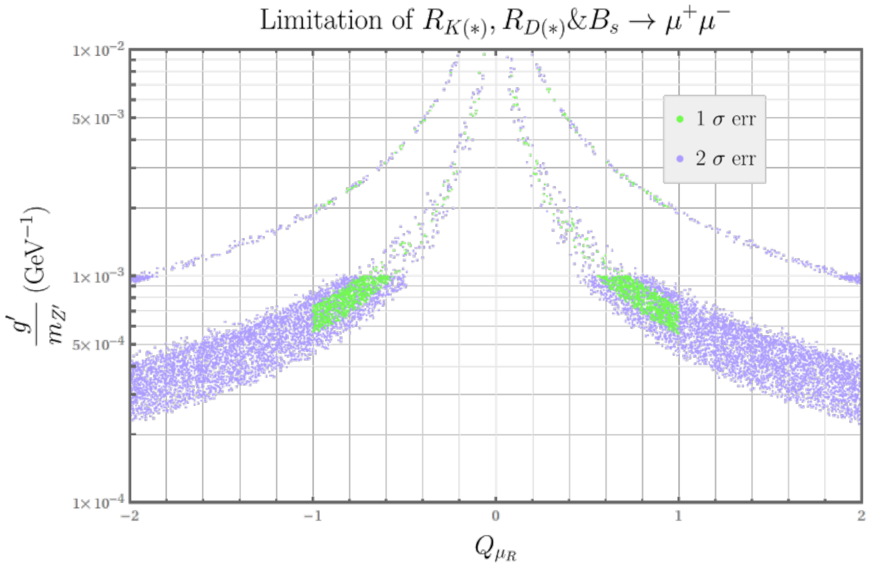
$$S = \frac{m_{B_s}^2}{2} (\underbrace{C_S}_{} - \overbrace{C_S'}^{H^0}), \qquad P = \frac{m_{B_s}^2}{2} (C_P - C_P') + m_\mu (\overbrace{C_{10}}^{Z'} - C_{10}').$$

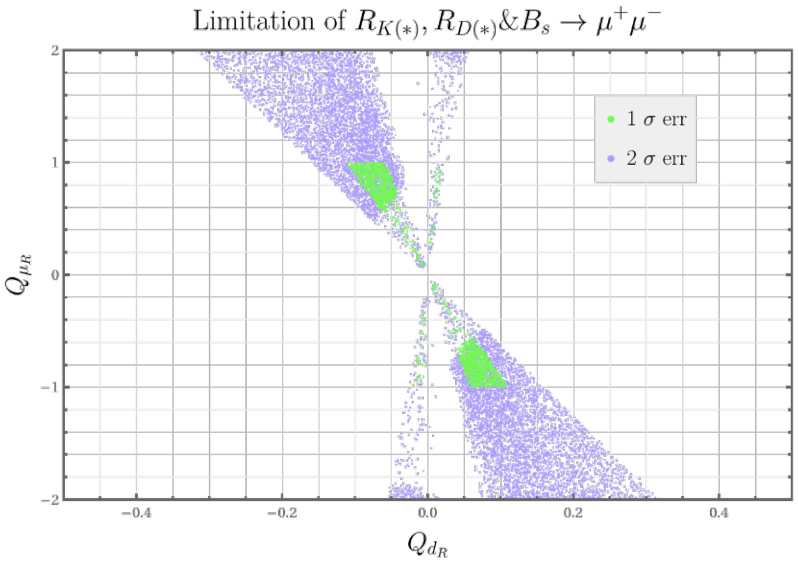
A.J.Buras. et al. , JHEP 01 (2009) 019

Parameter space scan result for $R_{K^{(*)}}, R_{D^{(*)}}$ & $B_s \to \mu^+\mu^-$

$$\frac{g'}{m_{Z'}} \in [10^{-1},\ 10^{-5}]\ \text{GeV}^{-1}$$
$$Q_{d_R},\ Q_{\mu_R} \in [-2, 2]$$
$$\tan\beta \in [1,\ 100]$$
$$\cos\alpha \in [-1,\ 1]$$
$$m_{H^0},\ m_{H^\pm} \in [350,\ 1000]\ \text{GeV}$$

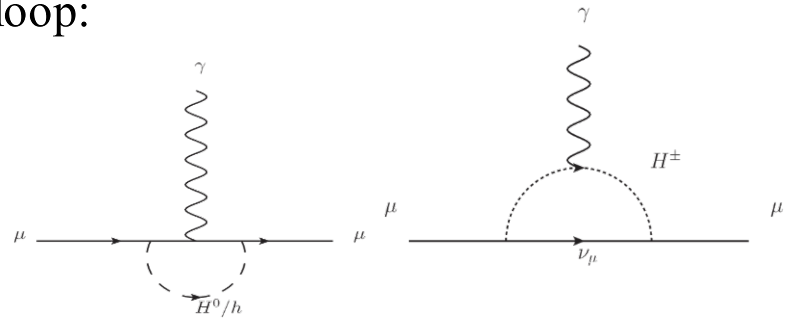




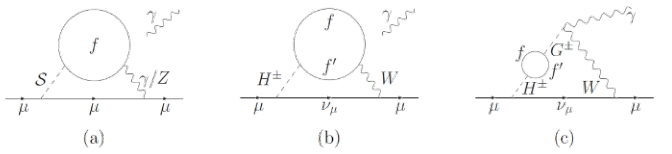


Δa_μ in FG2HDM

1-loop:



2-loop:



$$\Delta a_\mu^{1\text{Loop}} = a_\mu^{1\text{Loop},H^0} + a_\mu^{1\text{Loop},h} + a_\mu^{1\text{Loop},H^\pm} - a_\mu^{1\text{Loop},h_{\text{SM}}}$$

$$a_\mu^{1\text{Loop},H^0} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}(\mathcal{Y}_l^{H^0})^2 \frac{m_\mu^2}{m_{H^0}^2}\, F_{H^0}\left(\frac{m_\mu^2}{m_{H^0}^2}\right)$$

$$a_\mu^{1\text{Loop},h} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}(\mathcal{Y}_l^{h})^2 \frac{m_\mu^2}{m_h^2}\, F_h\left(\frac{m_\mu^2}{m_h^2}\right)$$

$$a_\mu^{1\text{Loop},H^\pm} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}(\mathcal{Y}_l^{H^\pm})^2 \frac{m_\mu^2}{m_{H^\pm}^2}\, F_{H^\pm}\left(\frac{m_\mu^2}{m_{H^\pm}^2}\right)$$

$$a_\mu^{1\text{Loop},h_{sm}} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}(\ 1\ )^2 \frac{m_\mu^2}{m_{h_{sm}}^2}\, F_{h_{sm}}\left(\frac{m_\mu^2}{m_{h_{sm}}^2}\right)$$

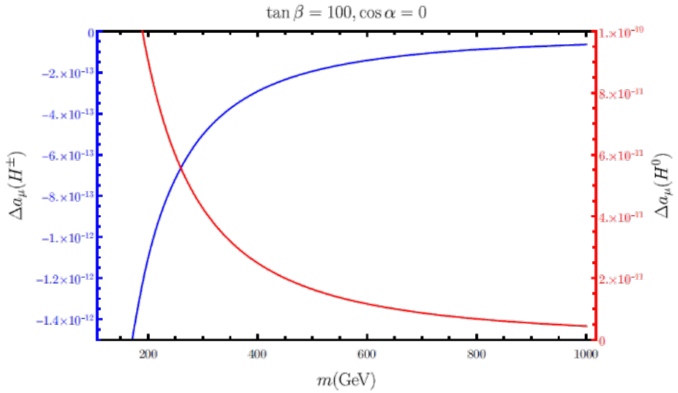
A.Cherchiglia. et al. , JHEP 01 (2017) 007

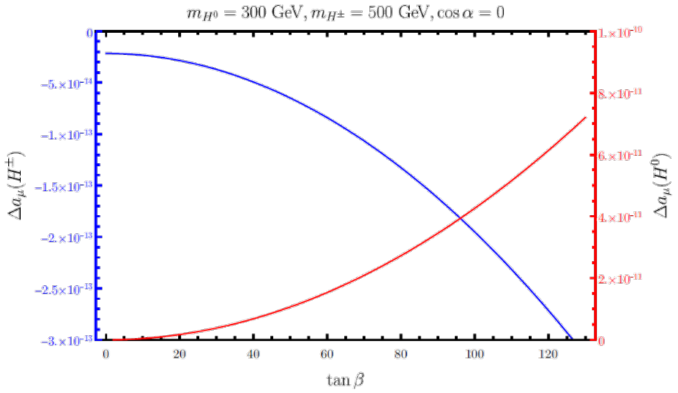
$$\mathcal{Y}_f^{H^\pm} = \frac{1}{m_f}N_f \quad (f = d, l)$$

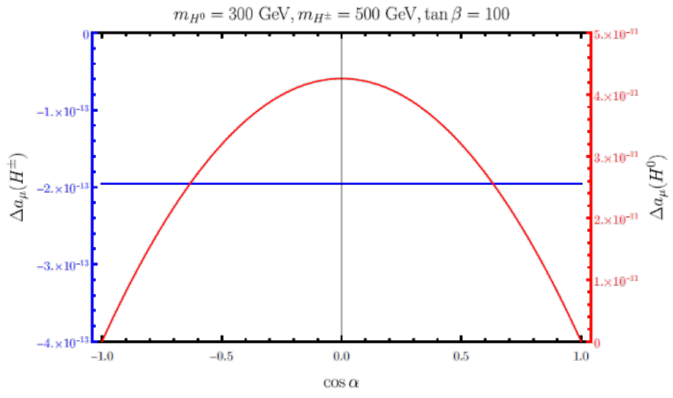
$$\mathcal{Y}_f^{H^\pm} = -\frac{1}{m_f}N_f \quad (f = u, \nu)$$

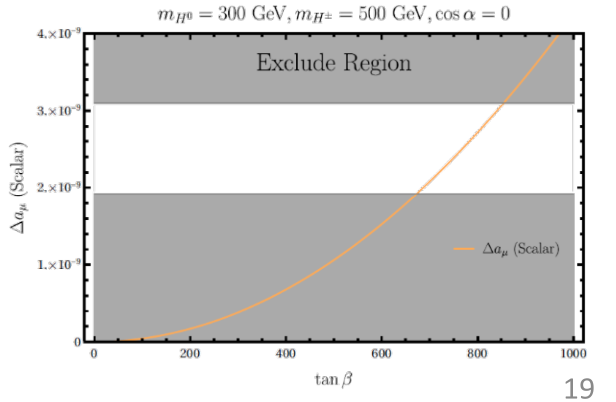
$$\mathcal{Y}_f^{H^0} = \frac{1}{m_f}\left[\cos(\beta-\alpha)N_f + \sin(\beta-\alpha)M_f\right]$$

$$\mathcal{Y}_f^{h} = \frac{1}{m_f}\left[-\sin(\beta-\alpha)N_f + \cos(\beta-\alpha)M_f\right]$$









Summary

- FG2HDM, a type of flavor gauged 2HDM, is proposed.
- Only two exotic Higgs bosons and one gauge boson are added into particle spectrum.
- In an extreme case of 2HDM,
  - ✓ FCNC, FCNH can occur in down type quark sector on tree level;
  - ✓ $R_{D^{(*)}}$ contributed form Charged Higgs H^+ still have lots of living rooms;
  - ✓ $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies can be accommodated at 1σ level;
  - ✓ 1-Loop contribution of exotic Higgs are small, up to 10^{-10} for low $\tan\beta$;
  - ✓ $R_{D^{(*)}}, R_{K^{(*)}}$and Δa_μ are likely to be explained at 1σ level for large $\tan\beta$.
- More generals cases to be explored...