Simultaneous Explanation of the R_K and $R(D^{(*)})$ Puzzles

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$R(D^{(*)})$ puzzle

Experimental Results: BaBar: 1205.5442

$$R(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)} = 0.440 \pm 0.058 \pm 0.042\,,$$

$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)} = 0.332 \pm 0.024$$

SM predictions

$$R(D) = 0.297 \pm 0.017\,,$$

$$R(D^*) = 0.252 \pm 0.003$$

- Measurements exceed the SM calculations by $2.0\ \sigma$ and $2.7\ \sigma$ for $R(D)$ and $R(D^*)$, respectively.

R_K puzzle

Experimental Results: LHCb: 1406.6482

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$$

SM prediction

$$R_K = 1 \pm O(10^{-4})$$

- There exists a 2.6 σ difference.

NP beyond the SM

Glashow, Guadagnoli, Lane (GGL): 1411.0565

- NP couples preferentially to the third generation.

$$\text{(NP operator)} \quad G(\bar{b}'_L \gamma_\mu b'_L)(\bar{\tau}'_L \gamma^\mu \tau'_L), \quad G = O(1)/\Lambda_{NP}^2 \ll G_F \,,$$

$$d'_{L3} \equiv b'_L = \sum_i^3 U^d_{L3i} d_i, \quad \ell'_{L3} \equiv \tau'_L = \sum_i^3 U^\ell_{L3i} \ell_i$$

- Converting from the gauge basis to the mass basis, the NP operator becomes

$$G[U^{d}_{L33}U^{d*}_{L32}|U^{\ell}_{L32}|^2(\bar{b}_L\gamma_\mu s_L)(\bar{\mu}_L\gamma^\mu\mu_L) + h.c.].$$

  Also, *lepton flavor violation* occurs, e.g.
  $B \to K\mu e$,B $\to K\mu\tau$, etc.

- Under lepton flavor non-universality, GGL have R_K explained at the cost of lepton flavor violation and the breaking of the GIM mechanism.

$\Lambda_{NP} \gg \Lambda_{Weak}$: 1412.7164

- Make (NP operator) $G(\bar{b}'_L \gamma_\mu b'_L)(\bar{\tau}'_L \gamma^\mu \tau'_L)$ invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$.

$$b'_L \to Q'_L \equiv (t'_L, b'_L)^T$$

$$\tau'_L \to L'_L \equiv (\nu'_{\tau L}, \tau'_L)^T$$

2 NP operators invariant under $SU(2)_L$

$$\mathcal{O}^{(1)}_{NP} = G_1(\bar{Q}'_L \gamma_\mu Q'_L)(\bar{L}'_L \gamma^\mu L'_L),$$

$$\mathcal{O}^{(2)}_{NP} = G_2(\bar{Q}'_L \gamma_\mu \sigma^I Q'_L)(\bar{L}'_L \gamma^\mu \sigma^I L'_L)$$

- $\mathcal{O}^{(2)}{}_{NP} = \mathrm{O}_{tt\nu_\tau\nu_\tau} + O_{tt\tau\tau} + O_{bb\tau\tau} + O_{bb\nu_\tau\nu_\tau} + O_{tb\tau\nu_\tau}$,
  where last term is the charged current (CC) operator and the others are neutral current (NC) operators.

  $O_{tb\tau\nu_\tau} = 2G_2(\bar{t}'_L\gamma_\mu b'_L)(\bar{\tau}'_L\gamma^\mu\nu'_{\tau L})$.

  $O_{bb\tau\tau}$ gives the (GGL) NC operator $G_2(\bar{b}'_L\gamma_\mu b'_L)(\bar{\tau}'_L\gamma^\mu\tau'_L)$.

- Conclusion: NP NC's (CC) come from $\mathcal{O}^{(1,2)}_{NP}(\mathcal{O}^{(2)}_{NP})$

Find R_K

- Amplitude is $A_{\ell i} = A^{SM}(1 + V^{bs\ell_i})$, where

$$V^{bs\ell_i} = \frac{\kappa}{C_9} \frac{U^d_{L33} U^{d*}_{L32}}{V_{tb} V^*_{ts}} |U^\ell_{L3i}|^2 \text{ and}$$

$$\kappa = \frac{4\pi}{\alpha_{EM}} \frac{g_2^2}{g^2} \frac{M_W^2}{\Lambda_{NP}^2}.$$

- Let $U^d_{L33} \approx 1, V_{tb} \approx 1, V^*_{ts} \approx \lambda^2$.

- $R_K = \frac{1 + 2Re[V_L^{bs\mu}] + |V_L^{bs\mu}|^2}{1 + 2Re[V_L^{bse}] + |V_L^{bse}|^2}$

$$\approx 1 + \frac{8\pi}{C_9 \alpha_{EM}} \frac{g_2^2}{g^2} \frac{M_W^2}{\Lambda_{NP}^2} \frac{U_{L32}^d |U_{L32}^\ell|^2}{\lambda^2}$$

5σ limit on R_K from LHCb

$$-2 \times 10^{-4} \lesssim \frac{1}{C_9} \frac{g_2^2}{g^2} \frac{M_W^2}{\Lambda_{NP}^2} \frac{U_{L32}^d |U_{L32}^\ell|^2}{\lambda^2} \lesssim 7 \times 10^{-5}$$

Find $R(D^{(*)})$

- $\mathcal{H} = \frac{4G_F V_{cb}}{\sqrt{2}} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_{\tau_L)} + h.c.$

$$A_i = \frac{4G_F V_{cb}}{\sqrt{2}} [\delta_{i\tau} + V_L^{cb\tau\nu_i}]$$

$$V^{cb\tau\nu_i} = 4\frac{g_2^2}{g^2}\frac{M_W^2}{\Lambda_{NP}^2}\frac{U_{L33}^d U_{L32}^u U_{L33}^\ell U_{L3i}^\nu}{V_{cb}}$$

$$|A|^2 = \sum_{i=\tau,\mu,e} |A_i|^2 = |A|_{SM}^2 [1 + 2Re(V_L^{cb\tau\nu}) + |V_L^{cb\tau\nu})|^2]$$

The decay rate under lepton flavor non-universality and SM are the same apart from an overall factor.

- $\left[\frac{R(D)}{R(D^*)}\right]_{exp} = 1.33 \pm .24\,, \quad \left[\frac{R(D)}{R(D^*)}\right]_{SM} = 1.18 \pm .07$

Careful measurement of double ratio can rule out NP model.

$$\left[\frac{R(D)}{R(D^*)}\right]_{exp} = \left[\frac{R(D)}{R(D^*)}\right]_{SM}$$

- Also, $\left[\frac{R(D^*)_{exp}}{R(D^*)_{SM}}\right] = \left[\frac{R(D)_{exp}}{R(D)_{SM}}\right] \approx \left[1 + 8\frac{g_2^2}{g^2}\frac{M_W^2}{\Lambda_{NP}^2}\frac{U^u_{L32}}{V_{cb}}\right].$

  Averaging the left hand side, $8\frac{g_2^2}{g^2}\frac{M_W^2}{\Lambda_{NP}^2}\frac{U^u_{L32}}{V_{cb}} \approx 0.4.$

Conclusion

- R_K and $R(D^{(*)})$ puzzles can be explained by lepton flavor non-universality.

- A consequence of lepton flavor non-universality is lepton flavor violation as can be readily seen when converting from the gauge basis to the mass basis.

- A careful measurement of the double ratio $\left[\frac{R(D)}{R(D^*)}\right]$ can help rule out this non-universality.

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