The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

Solving Flavor Anomalies in the 2HDM with Flavor Symmetries

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arXiv: 2104.03699

Outline

- Introduction: flavor anomalies
- FG2HDM
- Model solutions to flavor anomalies
- Summary and Outlook

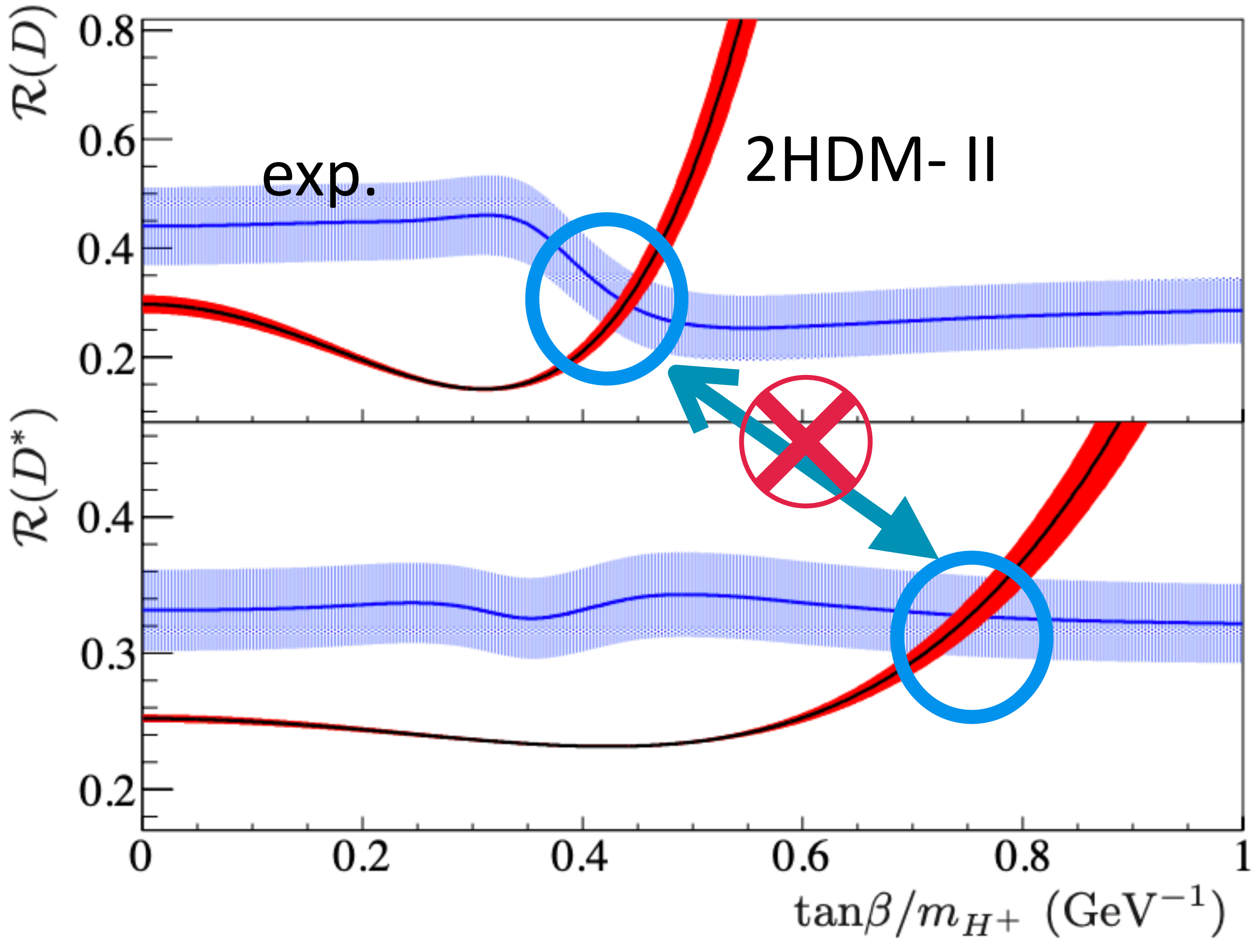
$R_{D^{(*)}}$ anomalies

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

3.4σ

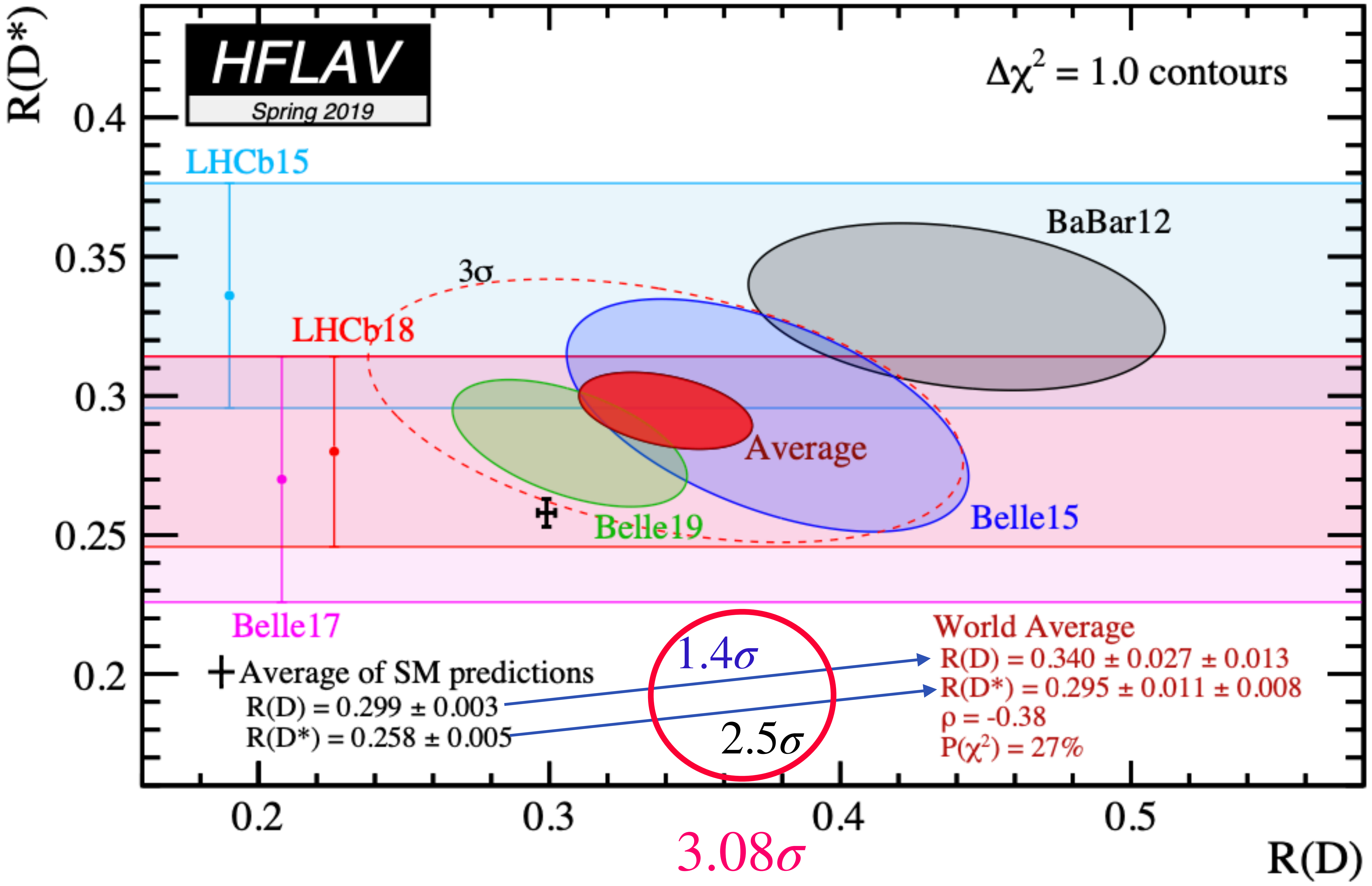
$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042 \quad \boxed{2.0\sigma}$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018 \quad \boxed{2.7\sigma}$$

$\rightarrow$ SM



BaBar 2012

EPJC (2021) 81: 226

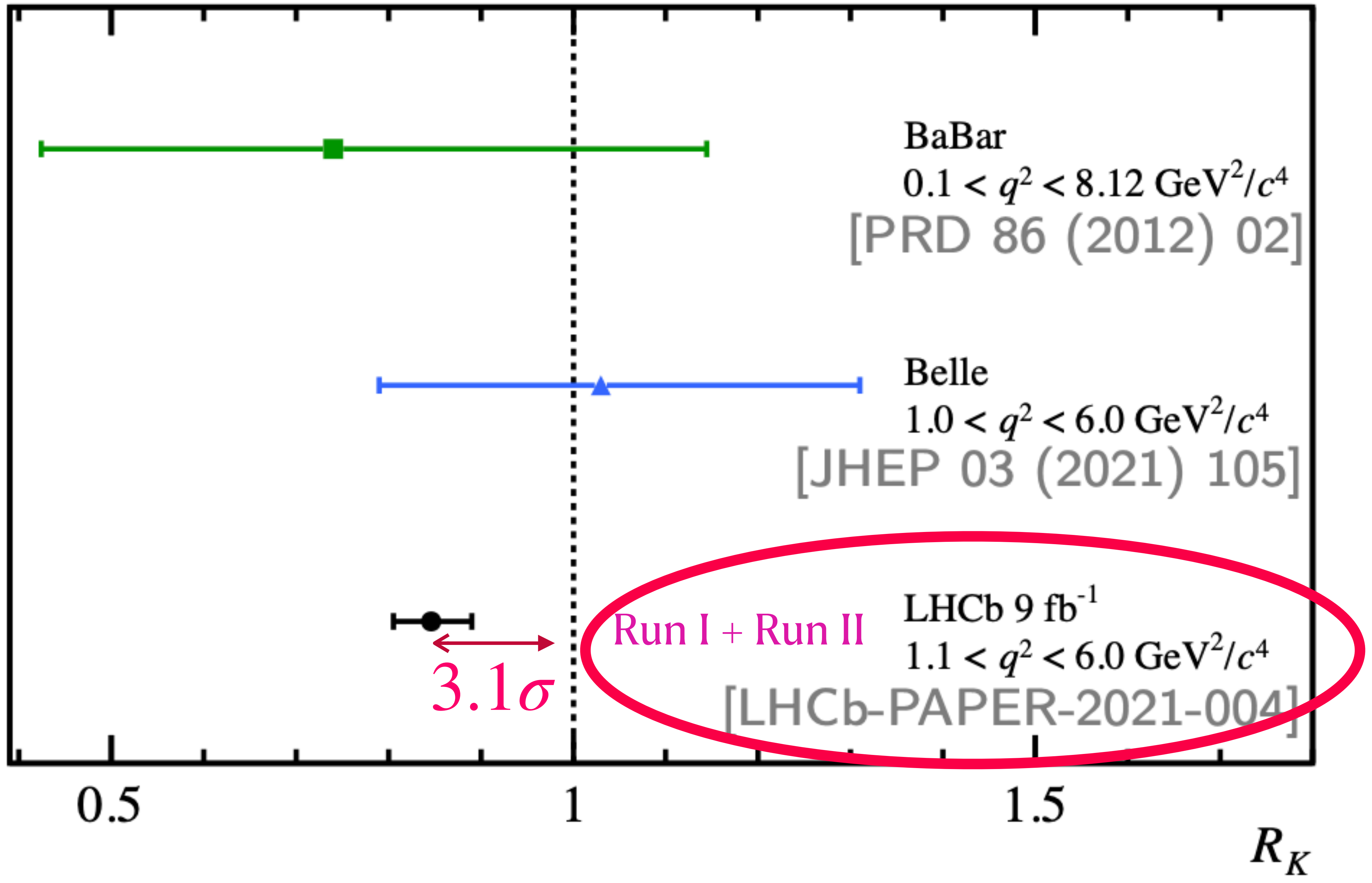


HFLAV, 2019

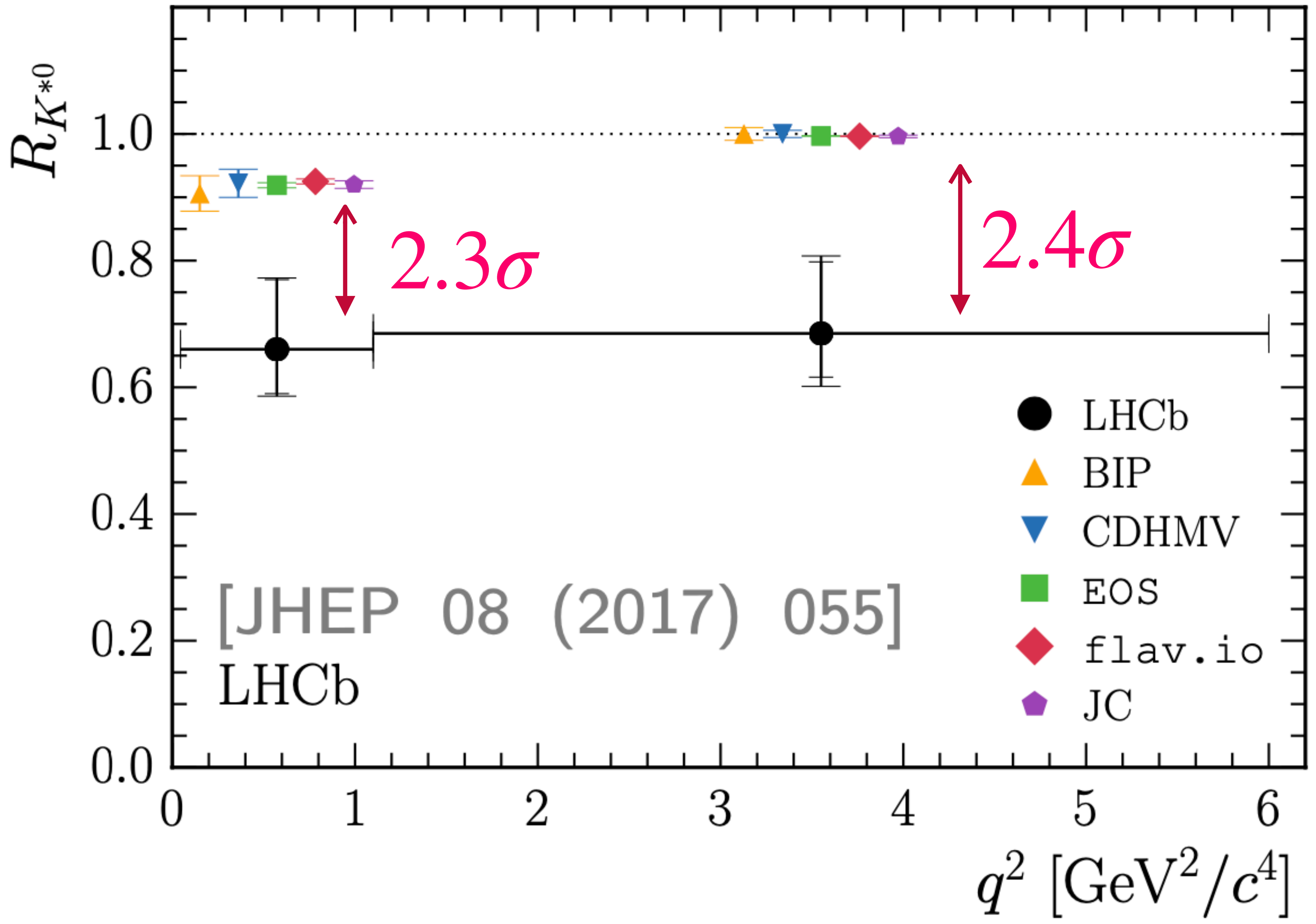
$R_{K^{(*)}}$ anomalies

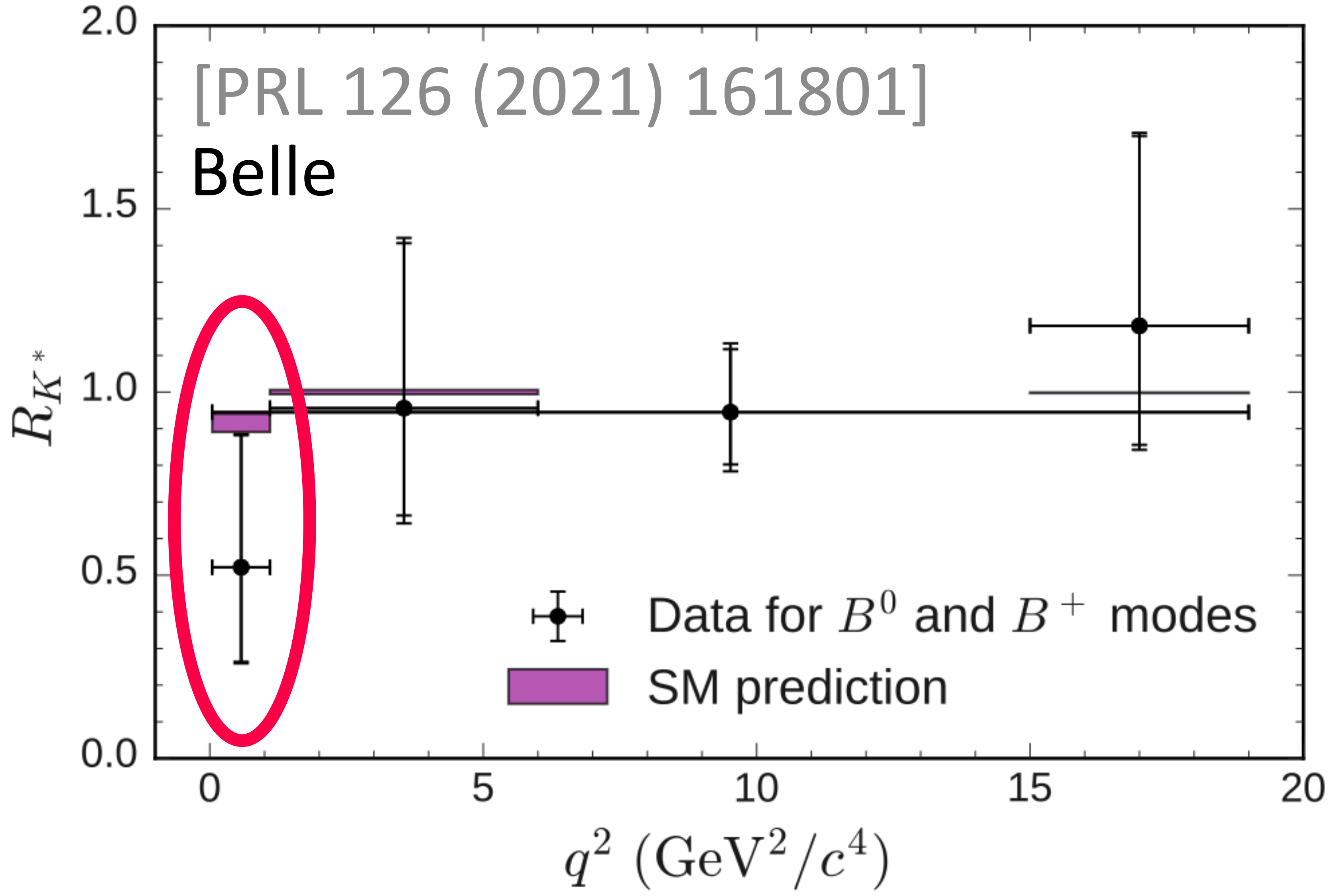
$$\boxed{R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}}$$

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



R. D. Moise, Moriond 2021





What we learnt about

If existed, the lepton non-universality (LFU)

☑ exists in B meson decays

- $b \to c\ell\bar{\nu}$: τ vs (μ, e)

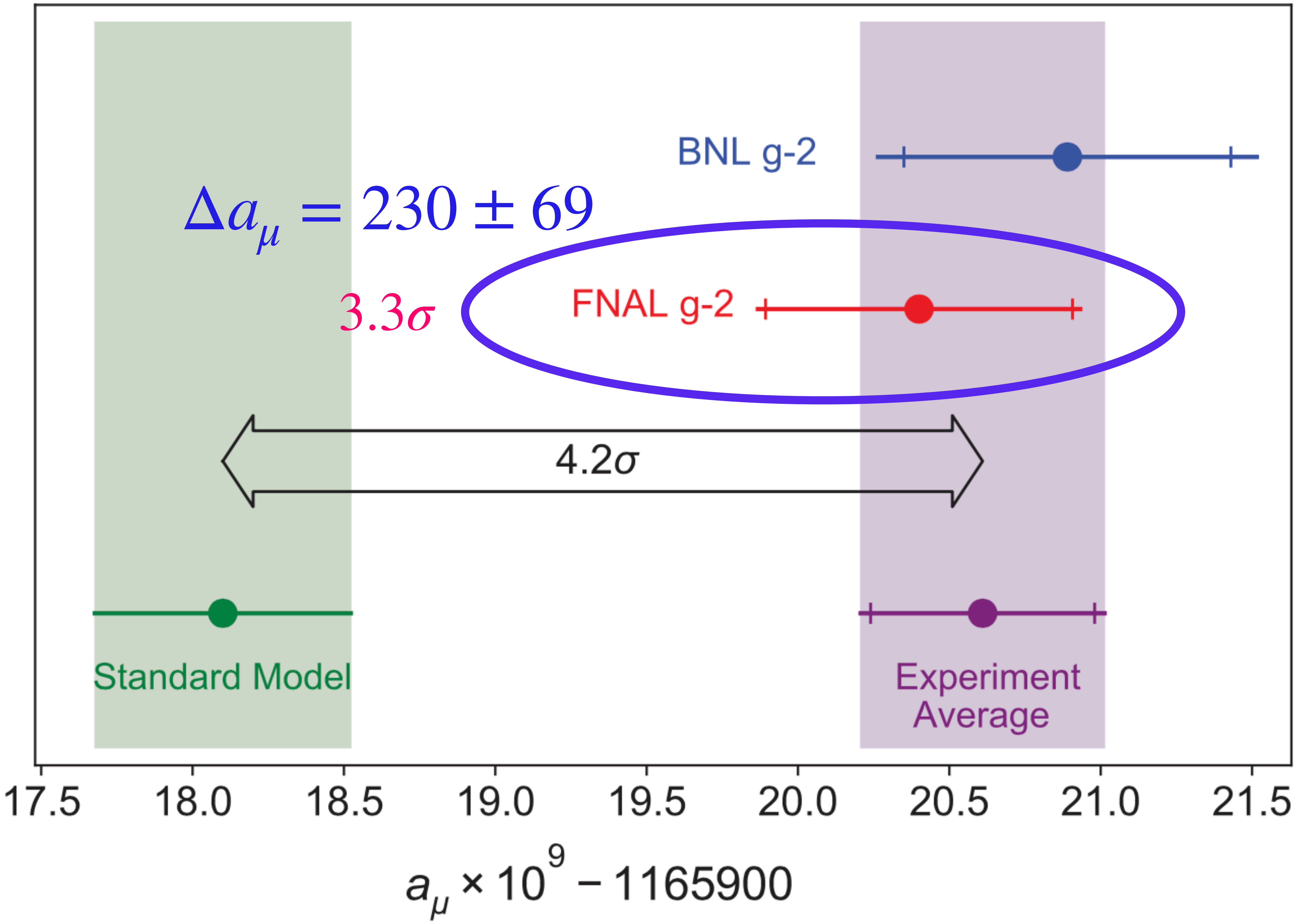
- $b \to s\ell\bar{\ell}$: μ vs e

▷ how about in pure lepton sector ?

Muon g-2

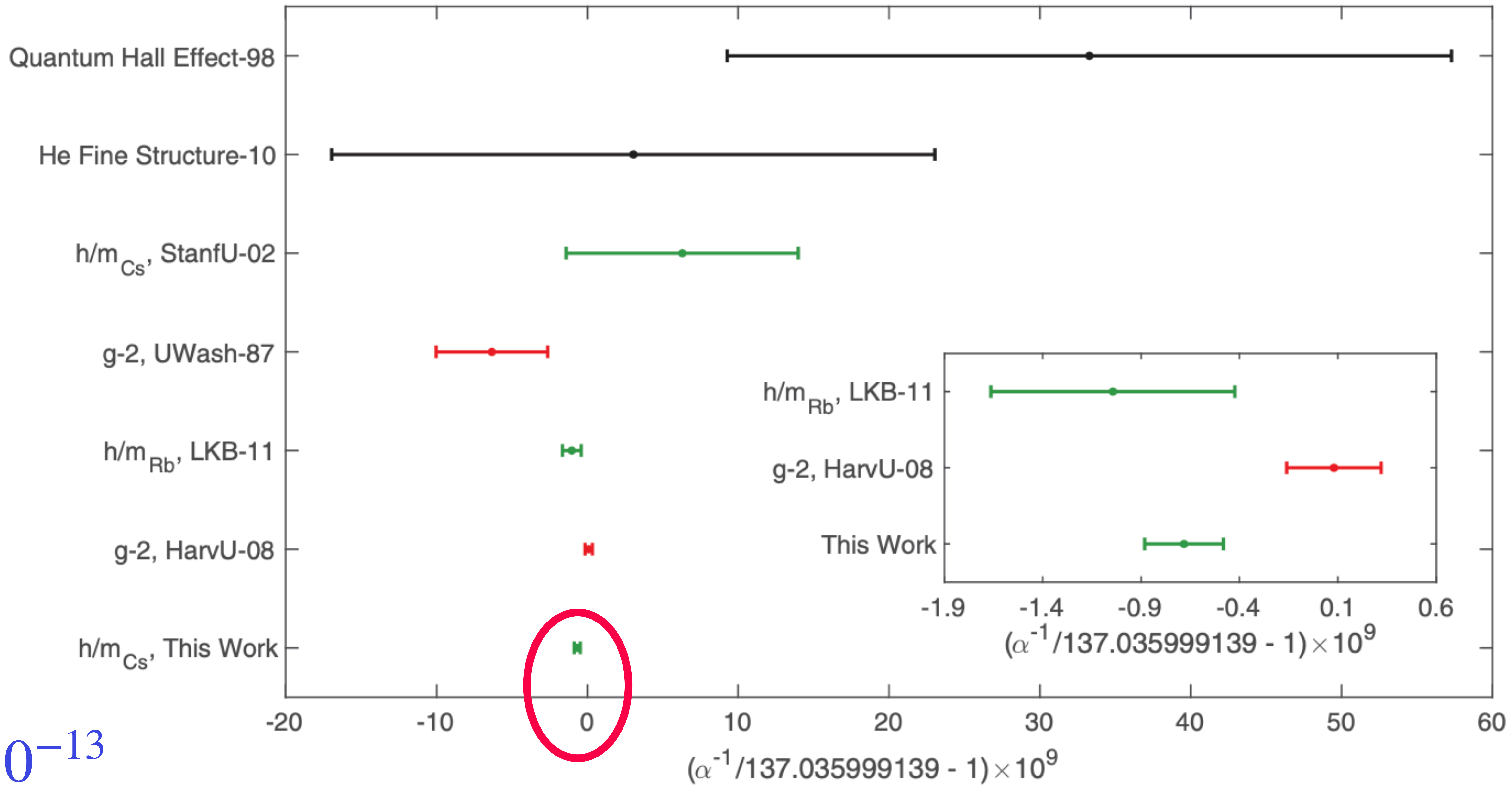
Contribution	$a_\mu \times 10^{11}$
QED (order $\mathcal{O}(\alpha^5)$)	$116\ 584\ 718.93 \pm 0.10$
Electroweak	153.6 ± 1.0
QCD	
HVP (LO)	$6\ 931 \pm 40$
HVP (NLO)	-98.3 ± 0.7
HVP (NNLO)	12.4 ± 0.1
HLbL	94 ± 19
Total (theory)	$116\ 591\ 810 \pm 43$

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



muon g-2 Collaboration, PRL 2021

Electron g-2



$\Delta a_e = (-8.8 \pm 3.6) \times 10^{-13}$

2.4σ

Parker *et al.*,
Science 360, 191-195 (2018)

What we learnt about

If existed, the lepton non-universality (LFU)

- ☑ exists in B meson decays
- ☑ how about in pure lepton sector ?
  - ☑ anomaly exists both in muon and electron
  - ☑ non-universality appears
- ▷ What kind of New Physics we expect ?

2HDMs: Yukawa

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

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

$$M_f = U_{fL}^\dagger \tilde{M}_f U_{fR},$$

$$\tilde{M}_f = \frac{1}{\sqrt{2}}(v_1 Y_1^f + v_2 Y_2^f)$$

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

2HDM-III

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

- general 2HDM-III: too many Yukawa parameters
- the price: dangerous FCNHs brought in
- one attempt: Cheng-Sher ansatz
- designed symmetry:

  extended but limited parameters & protected FCNHs

FG2HDM

Flavor Gauged Two-Higgs Doublet Model (BGL-like model)

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 condition

2 model parameters

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

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

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

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

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

FG2HDM: scalar

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

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

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

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

$$\mathscr{L}_\eta = 0$$

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

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

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

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

- 3 Goldstone bosons: eaten by $W^\pm, Z, Z'$;
- 2 extra physical scalar left: H^0 and H^+

FG2HDM: Yukawa

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

$$
\begin{aligned}
N_u &= -\frac{v_2}{v_1} \mathrm{diag}(m_u, m_c, 0) + \frac{v_1}{v_2} \mathrm{diag}(0, 0, m_t), \\
(N_d)_{ij} &= -\frac{v_2}{v_1} (M_d)_{ij} + \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) V_{i3}^\dagger V_{3j} (M_d)_{jj},
\end{aligned}
$$

$$
\begin{aligned}
N_\nu &= -\frac{v_2}{v_1} M_\nu, \\
N_\ell &= -\frac{v_2}{v_1} \mathrm{diag}(0, m_\mu, m_\tau) + \frac{v_1}{v_2} \mathrm{diag}(m_e, 0, 0)
\end{aligned}
$$

FCNH occurs only in down-type quark with CKM suppression.

FG2HDM: gauge bosons

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

$$\tilde{M} = \frac{1}{2} m_Z^2 \begin{pmatrix} \sin^2\theta_W & -\sin\theta_W \cos\theta_W & a\sin\theta_W \\ -\sin\theta_W \cos\theta_W & \cos^2\theta_W & -a\cos\theta_W \\ a\sin\theta_W & -a\cos\theta_W & b \end{pmatrix}$$

$$M_d = \frac{1}{2} m_Z^2 \begin{pmatrix} 0 & & \\ & \mu_Z & \\ & & \mu_{Z'} \end{pmatrix},$$

$$\begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} = U \begin{pmatrix} B \\ W^3 \\ \hat{Z}' \end{pmatrix}, \qquad U = \begin{pmatrix} \cos\theta_W & \sin\theta_W & 0 \\ -\sin\theta_W \sin\theta_1 & \cos\theta_W \sin\theta_1 & \cos\theta_1 \\ -\sin\theta_W \sin\theta_2 & \cos\theta_W \sin\theta_2 & \cos\theta_2 \end{pmatrix}.$$

$$\begin{aligned} \mathcal{L}_{\rm FG} = e Q_f A_\mu \bar{f} \gamma^\mu f \; &+ \frac{g_2 \sin\theta_1}{\cos\theta_W} Z_\mu \bar{f} \left[I_f^3 \gamma^\mu \mathbb{P}_L - Q_f \sin^2\theta_W \gamma^\mu \right] f + g' \cos\theta_1 Z_\mu \bar{f} \left[\mathcal{Q}_{fL} \gamma^\mu \mathbb{P}_L + \mathcal{Q}_{fR} \gamma^\mu \mathbb{P}_R \right] f \\ &+ \frac{g_2 \sin\theta_2}{\cos\theta_W} Z'_\mu \bar{f} \left[I_f^3 \gamma^\mu \mathbb{P}_L - Q_f \sin^2\theta_W \gamma^\mu \right] f + g' \cos\theta_2 Z'_\mu \bar{f} \left[\mathcal{Q}_{fL} \gamma^\mu \mathbb{P}_L + \mathcal{Q}_{fR} \gamma^\mu \mathbb{P}_R \right] f \end{aligned}$$

FG2HDM: gauge bosons

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

$$\mu_Z \to 1, \quad \mu_{Z'} \to b$$

$$\sin\theta_1 \to 1,\ \cos\theta_1 \to 0,\ \sin\theta_2 \to 0,\ \cos\theta_2 \to 1$$

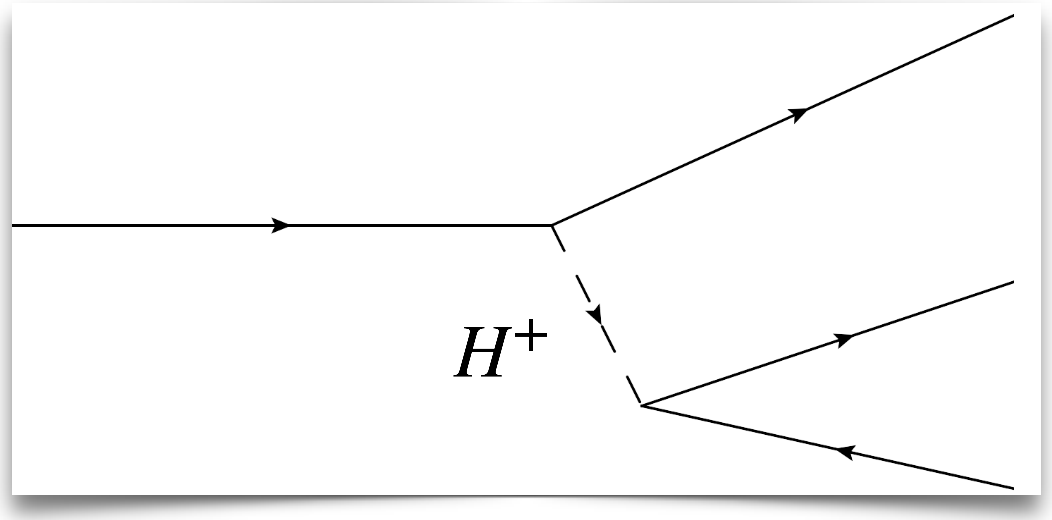
$$U \to \begin{pmatrix} \cos\theta_W & \sin\theta_W & 0 \\ -\sin\theta_W & \cos\theta_W & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$\boxed{\mathcal{Q}_{dL} = \frac{1}{2}(Q_{u_R} + Q_{d_R}) \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} + \frac{1}{2}(Q_{t_R} - Q_{u_R}) \begin{pmatrix} |c_1|^2 & c_1^* c_2 & c_1^* c_3 \\ c_2^* c_1 & |c_2|^2 & c_2^* c_3 \\ c_3^* c_1 & c_3^* c_2 & |c_3|^2 \end{pmatrix}}$$

FCNC only occurs in down-type quark sector

Solution I



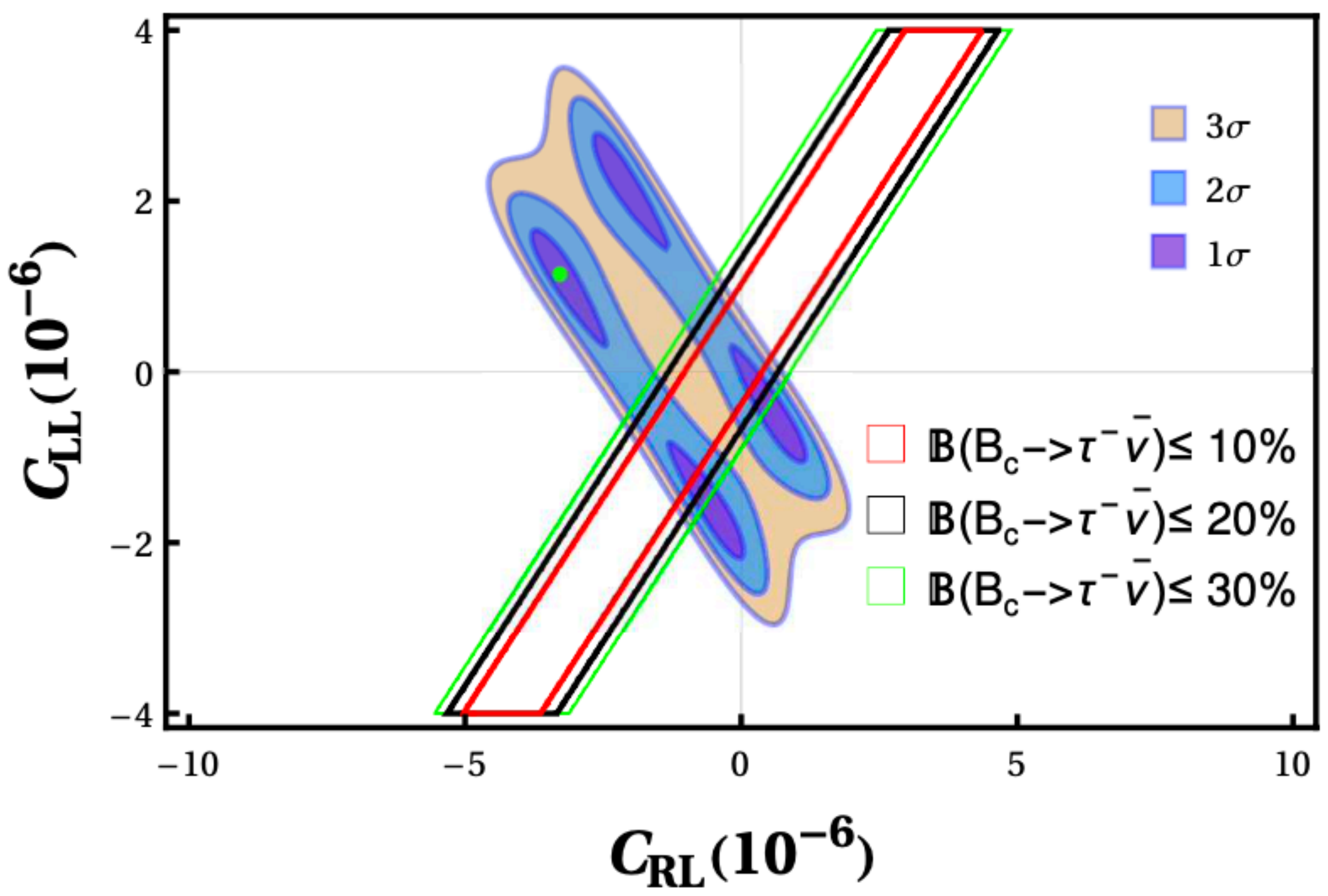
$R_{D^{(*)}}$

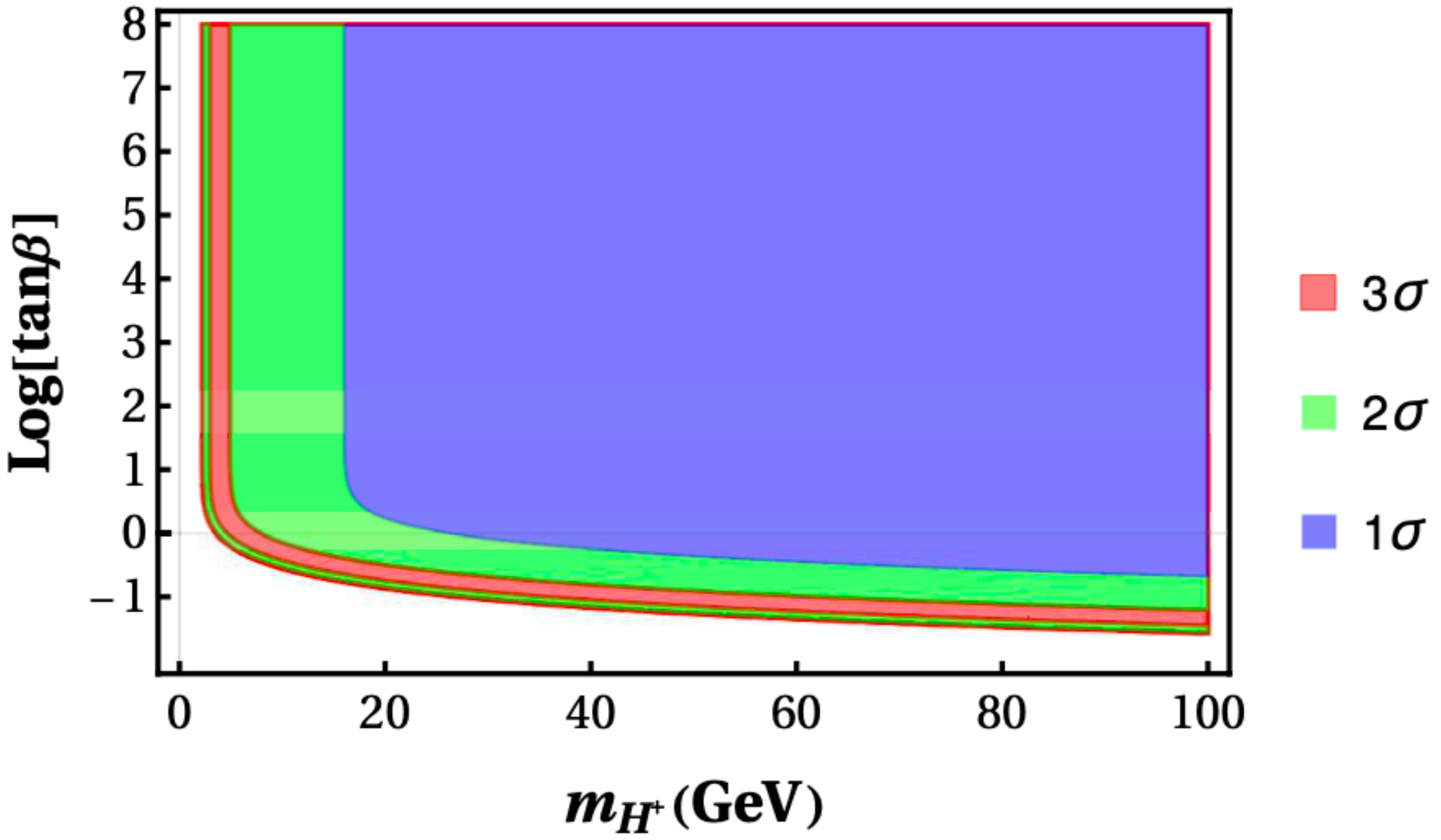
$$R_D = R_D^{\rm SM}\left[1 + 1.5{\rm Re}\left(\frac{C_{RL}^{\tau 3}+C_{LL}^{\tau 3}}{C_{\rm SM}^{cb}}\right) + 1.0\left|\frac{C_{RL}^{\tau 3}+C_{LL}^{\tau 3}}{C_{\rm SM}^{cb}}\right|^2\right],$$

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

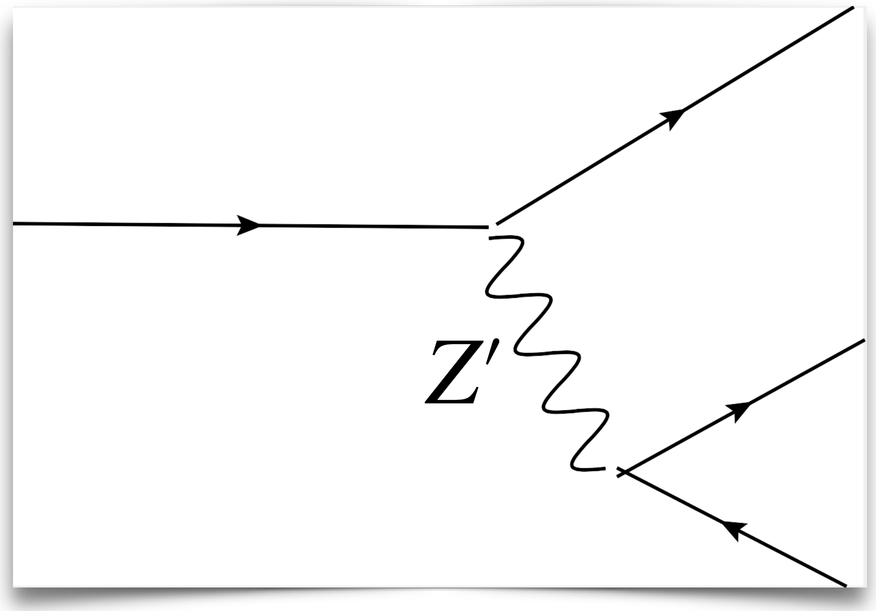
$$C_{RL}^{\tau 3} \approx -2\sqrt{2}G_F V_{cb}\frac{m_b m_\tau}{m_H^2}\left(\frac{2}{\tan^2\beta}+1\right)$$

$$C_{LL}^{\tau 3} = -2\sqrt{2}G_F V_{cb}\frac{m_c m_\tau}{m_H^2}.$$





Global fit of ΔC_i^{ℓ}



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[89] K. Kowalska, D. Kumar and E. M. Sessolo, *Implications for new physics in $b \to s\mu\mu$ transitions after recent measurements by Belle and LHCb*, *Eur. Phys. J. C* **79** (2019) 840 [1903.10932].

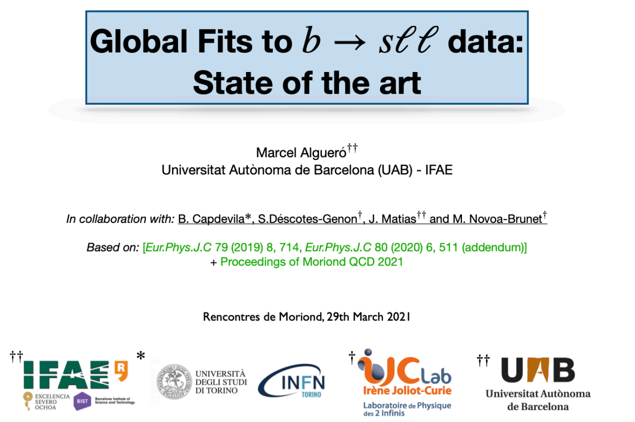
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu \mathbb{P}_L b)(\bar{\ell}\gamma^\mu \ell),$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu \mathbb{P}_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

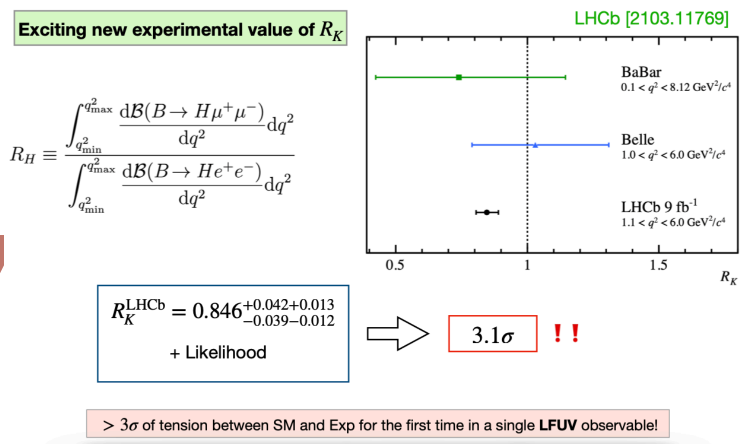
i) large and negative δC_9^{μ}(best fit ~ -1)

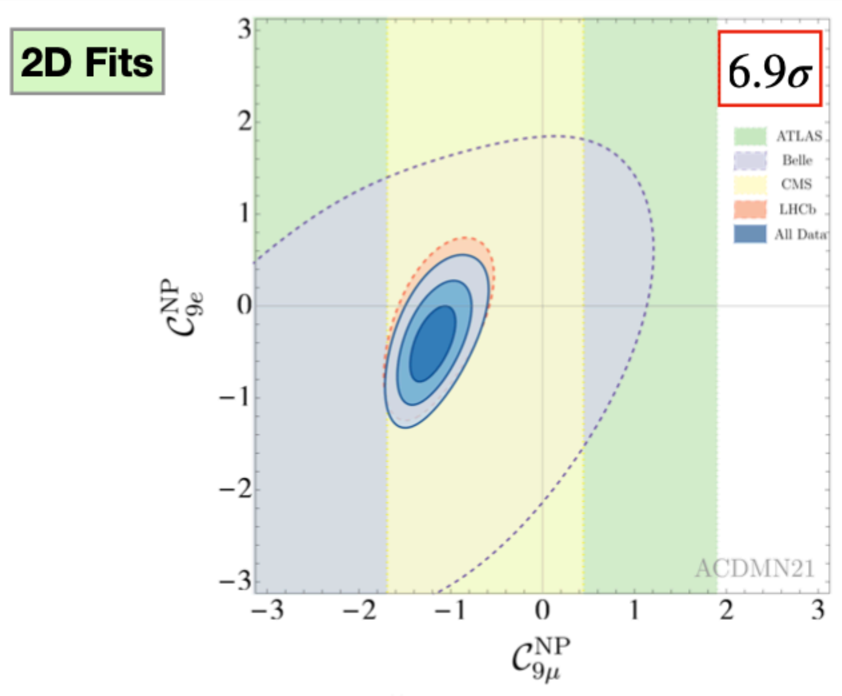
ii) relative small and positive ΔC_{10}^{μ}(best fit ~ 0.5)

i) positive and relative large ΔC_9^{e}(best fit ~ 0.8)

ii) negative and relative large ΔC_{10}^{e}(best fit ~ -0.78)







change of the sign of central value

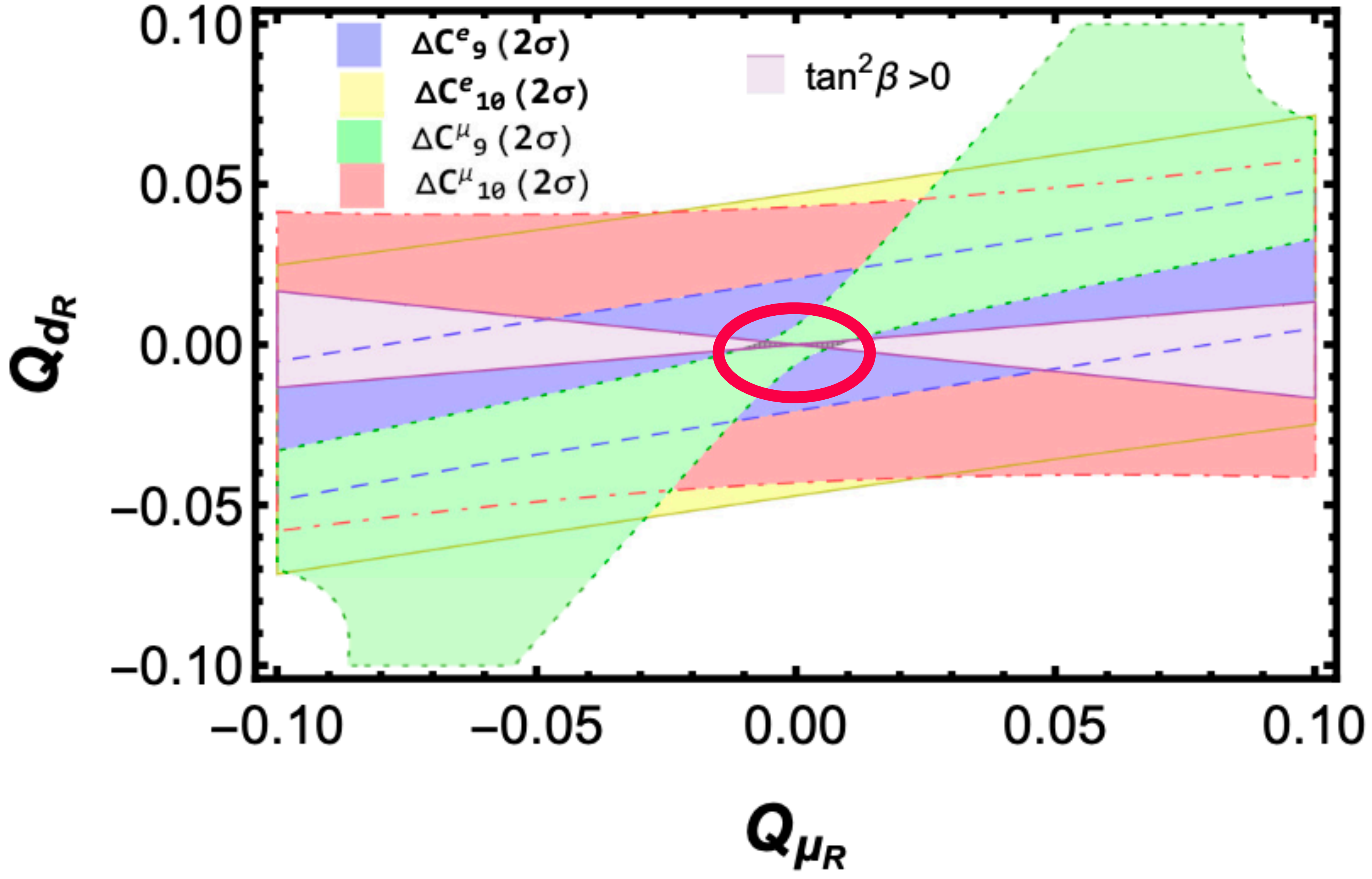
$$\Delta C_9^{\mu} = -1.21 \pm 0.20, \qquad \Delta C_9^{e} = -0.40 \pm 0.40,$$
$$\Delta C_{10}^{\mu} = 0.15 \pm 0.20, \qquad \Delta C_{10}^{e} = -0.78 \pm 0.40.$$

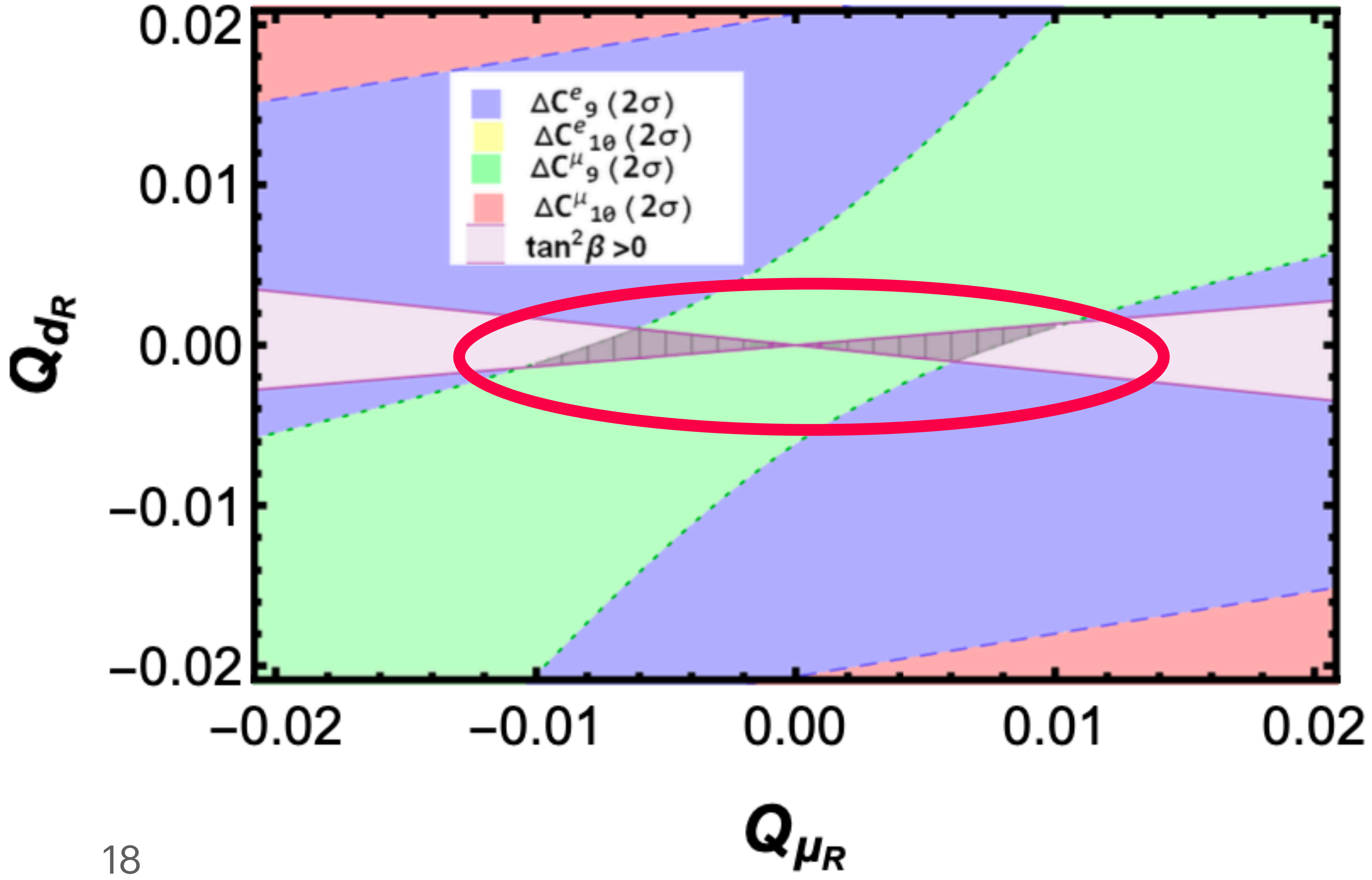
Solution II

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

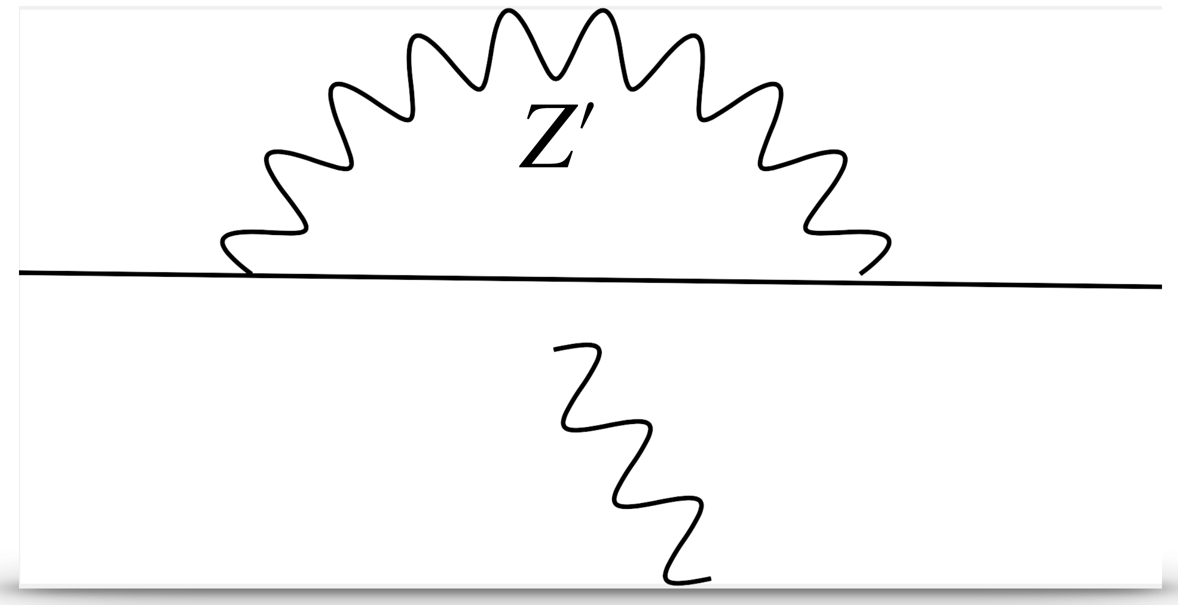
$$\Delta C_9^{\mu} = -1.21 \pm 0.20, \qquad \Delta C_9^{e} = -0.40 \pm 0.40,$$
$$\Delta C_{10}^{\mu} = 0.15 \pm 0.20, \qquad \Delta C_{10}^{e} = -0.78 \pm 0.40.$$

$$\Delta C_9^{\ell} = \frac{1}{N}\frac{g'^2}{m_{Z'}^2}\frac{1}{4}V_{ts}^* V_{tb}(Q_{t_R} - Q_{u_R})(Q_{\ell_R} + Q_{\ell_L}),$$
$$\Delta C_{10}^{\ell} = \frac{1}{N}\frac{g'^2}{m_{Z'}^2}\frac{1}{4}V_{ts}^* V_{tb}(Q_{t_R} - Q_{u_R})(Q_{\ell_R} - Q_{\ell_L}),$$



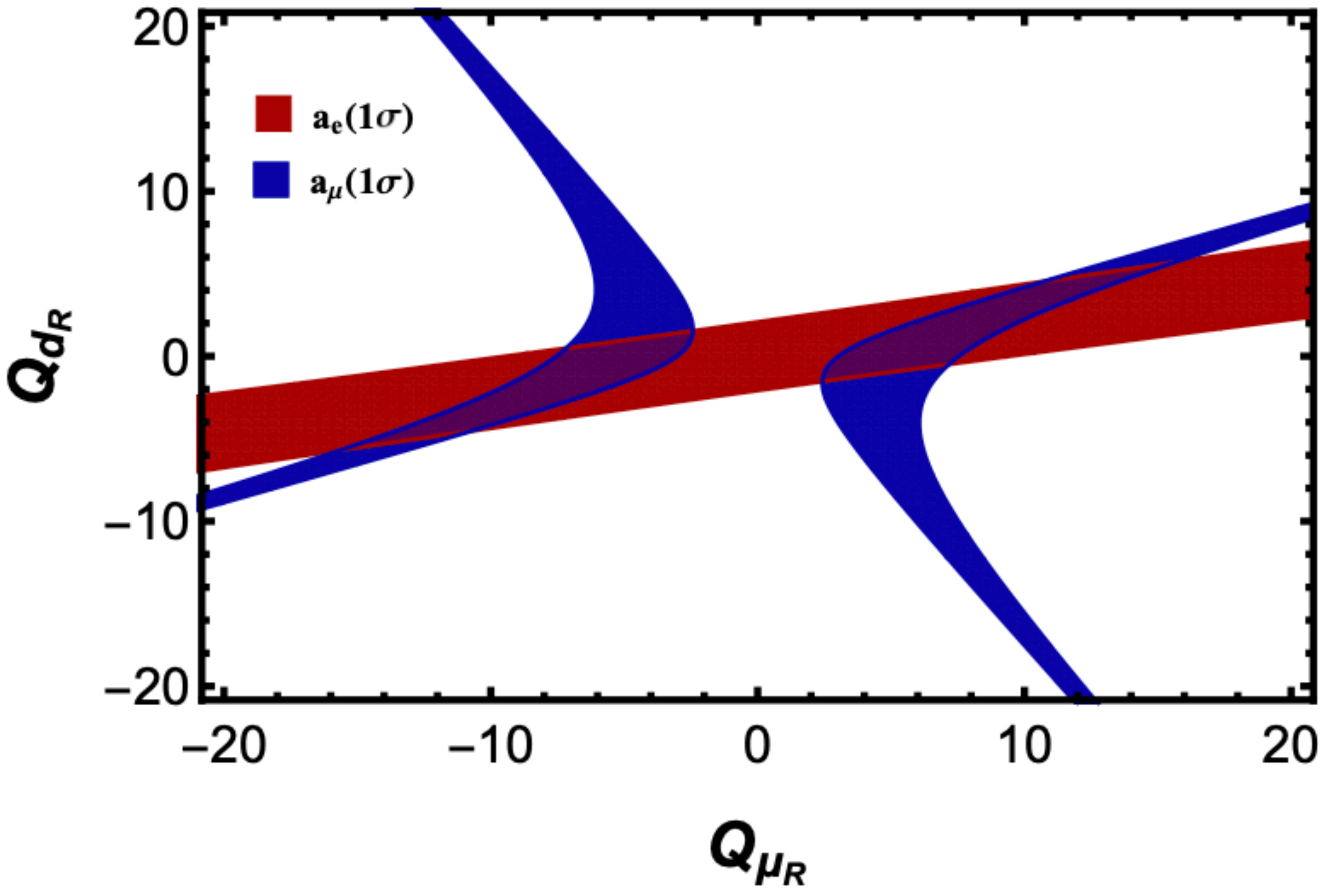


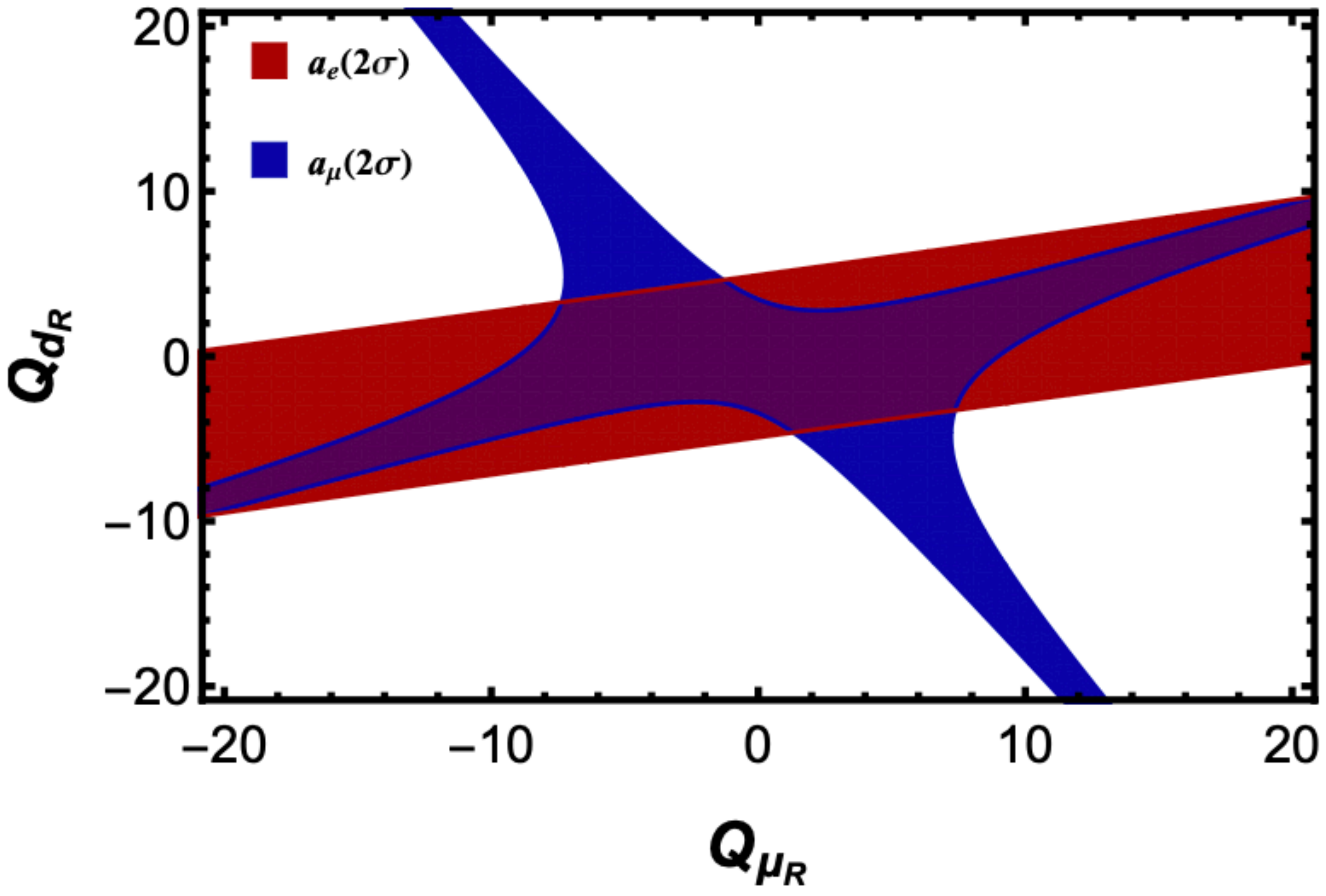
Solution II



$R_{K^{(*)}}$ & $g-2$

$$\Delta a_\ell = -\frac{m_\ell^2}{8\pi^2}\frac{g'^2}{m_{Z'}^2}\frac{2}{3}\left[(Q_{\ell_L}^2 + Q_{\ell_R}^2) - 3Q_{\ell_L}Q_{\ell_R}\right]$$

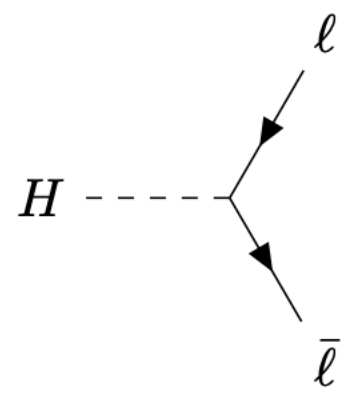




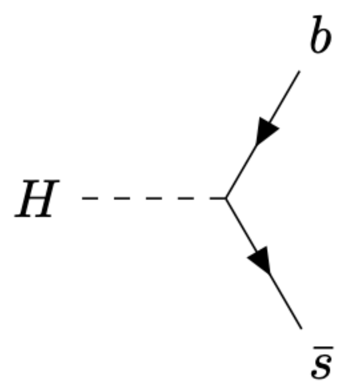
Summary and Outlook

- FG2HDM, a type of flavor gauged 2HDM-III, is proposed.
- Only two exotic Higgs bosons and one gauge boson are added into particle spectrum.
- In an extreme case of FG2HDM,
  - FCNC processes only occur in down-type quark sector;
  - Plenty of room for $R_{D^{(*)}}$;
  - $R_{K^{(*)}}$ & Δa_μ, Δa_e can be explained at 2σ level;
- More general cases to be explored...

Backup



$$= \frac{-i\left[\cos(\beta-\alpha)N_\ell + \sin(\beta-\alpha)M_\ell\right]}{v}$$



$$= \frac{-i\left[\cos(\beta-\alpha)(N_d)_{23} + \sin(\beta-\alpha)(M_d)_{23}\right]}{v}$$

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

$$\begin{aligned} C_S^\ell &= C_S^{\prime\ell} \\ &= -\frac{1}{N}\frac{\boxed{G_\mathrm{F}} V_{tb}V_{ts}^*}{m_H^2\sin(2\beta)}\left[\cos^2(\beta-\alpha)N_\ell + \cos(\beta-\alpha)\sin(\beta-\alpha)M_\ell\right] \end{aligned}$$

$$C_9^\ell = \frac{1}{N}\frac{g'^2}{m_{Z'}^2}\frac{1}{4}V_{tb}V_{ts}^*(Q_{t_R} - Q_{u_R})(Q_{l_R} + Q_{l_L}),$$

$$C_{10}^\ell = \frac{1}{N}\frac{g'^2}{m_{Z'}^2}\frac{1}{4}V_{tb}V_{ts}^*(Q_{t_R} - Q_{u_R})(Q_{l_R} - Q_{l_L}),$$

negligible scalar operator contributions due to a Fermi constant suppression!