Implications for New Physics in $b \to s\mu\mu$ transitions after recent measurements by Belle and LHCb

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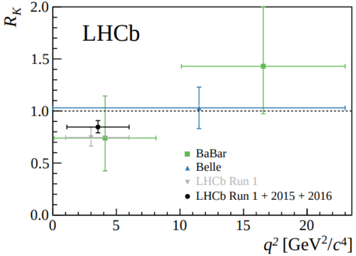
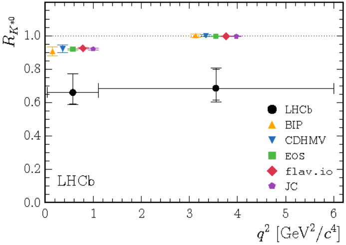
May 7, 2019

Deviations from SM in $b \to s$ sector

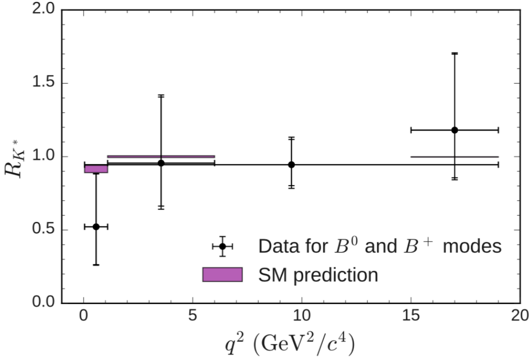
- Rare B-decays: $R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$





$\sim 2.5\sigma$ $\sim 2.5\sigma$

New measurement of R_{K^*} by Belle



Consistent with SM with large uncertainties.

Effective field theory analysis

- The effective Hamiltonian for $b \to sll$ transitions

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i^l O_i^l + C_i'^l O_i'^l) + h.c.$$

- We assume the presence of NP in semileptonic operators:

$$O_9^l = (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu l), \qquad O_9'^l = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu l)$$

$$O_{10}^l = (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu \gamma_5 l), \qquad O_{10}'^l = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu \gamma_5 l)$$

- NP in scalar and pseudoscalar operators $O_S^{(\prime)}$ and $O_P^{(\prime)}$ are severely contrained by the $B_s \to \mu^+\mu^-$ measurements. R. Alonso et al. PRL 113(2014) 241802, W. Altmannshofer et al. JHEP 05 (2017) 076.
- NP in electromagnetic dipole operator $O_7^{(\prime)}$ is tightly constrained by radiative decays. A. Paul et al. JHEP 04 (2017) 027

Model independent approach

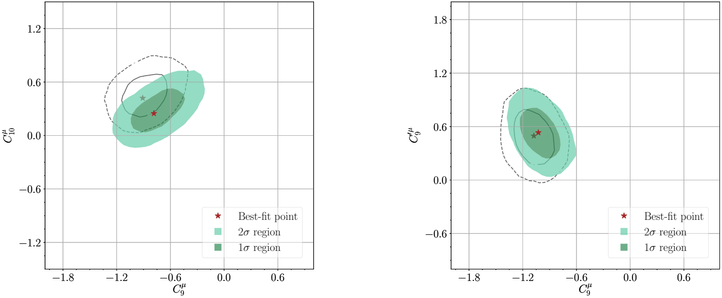
- Several fits after the measurement of R_K and R_{K^*} J. Aebischer et al. arXiv 1903.10434, M. Alguero et al., arXiv:1903.09578, A. K. Alok et al., arXiv:1903.09617, M. Ciuchini et al., arXiv:1903.09632, Alakabha et al. arXiv 1903.10086
- We consider the NP in muon or muon and electron.
- Global fit with all the relevant data in $b \to s\mu\mu$ and $b \to see$.
- We performed global fits with $1, 2, 4$ and 8 independent input parameters, plus a nuisnace parameter, V_{cb}.

Fit methodology

- Bayes's theorem: $p(m|d) = \frac{p(d|\xi(m))\pi(m)}{p(d)}$
- Model comparison by computing the Bayes factor, defined as the ratio of evidences for two arbitrary models $\mathcal{M}_1$ and $\mathcal{M}_2$ i.e. $p(d)_{\mathcal{M}_1}/p(d)_{\mathcal{M}_2}$.
- We estimate the significance of Bayes factors according to Jeffery's scale.
- The Likelihood function is defined as

$$\mathcal{L}(m) = \exp\left\{-\frac{1}{2}\left[\mathcal{O}_{\rm th}(m) - \mathcal{O}_{\rm exp}\right]^T (\mathcal{C}^{exp} + \mathcal{C}^{th})^{-1}\left[\mathcal{O}_{\rm th}(m) - \mathcal{O}_{\rm exp}\right]\right\}$$

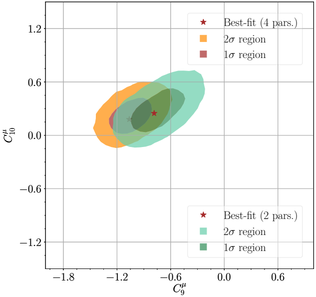
NP in (C_9^μ, C_{10}^μ) and $(C_9^\mu, C_9^{'\mu})$

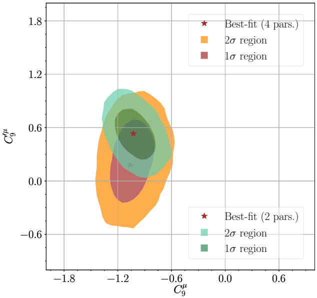


- The new measurement of R_K, higher than the previous determination, has the effect of bringing the (C_9^μ, C_{10}^μ) 2σ region closer to the axes origin.
- A tension between the measuremnts of R_K and R_{K^*} arises in this case so the posterior pdf becomes narrower.

4 parameter vs. 2 parameter scan

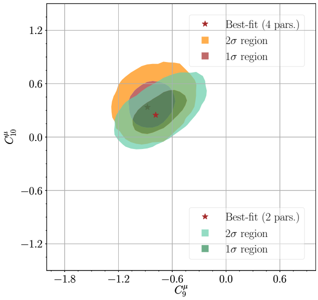
- Comparison of posterior pdf of C_9^μ, C_{10}^μ and $C_9^\mu, C_9^{\prime\mu}$ in (C_9^μ, C_{10}^μ) and $(C_9^\mu, C_9^{\prime\mu}, C_{10}^\mu, C_{10}^{\prime\mu})$



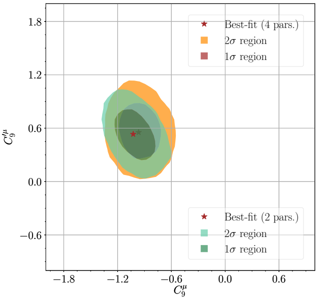


- Large negative values of C_9^μ are favored by data with 4 NP parameters.
- Ample region of parameter space with $C_9^{\prime\mu}$, due to introduction of C_{10}^μ.

4 parameter vs. 2 parameter scan

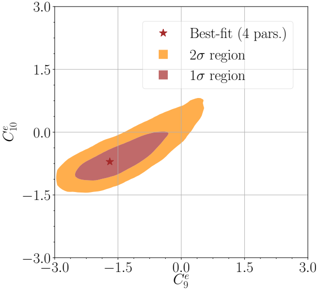


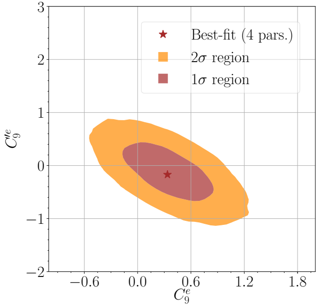
$(C_9^{\mu}, C_{10}^{\mu})$ & $(C_9^{\mu}, C_{10}^{\mu}, C_9^{e}, C_{10}^{e})$



$(C_9^{\mu}, C_9^{'\mu})$ & $(C_9^{\mu}, C_9^{\prime\mu}, C_9^{e}, C_9^{\prime e})$

NP in electron sector





- pdf of the Wilson coefficients of the electron sector remain consistent with zero at 2σ.
- The global data set can be easily explained by the presence of NP in the muon sector only.

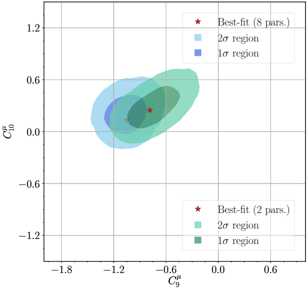
Favoured model

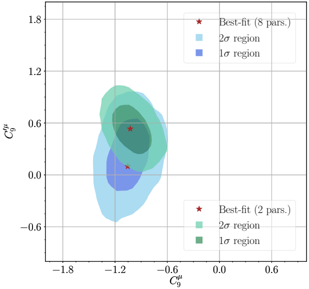
- Bayes factor $\frac{p(d)_{M_1}}{p(d)_{M_2}}$

$$
\begin{aligned}
\frac{\mathcal{Z}_{C_9^\mu, C_9^{\prime\mu}}}{\mathcal{Z}_{C_9^\mu, C_{10}^\mu}} &= 6.0 \quad \text{(Positive)} \\
\frac{\mathcal{Z}_{C_9^\mu, C_{10}^\mu, C_9^{\prime\mu}, C_{10}^{\prime\mu}}}{\mathcal{Z}_{C_9^\mu, C_{10}^\mu}} &= 5.0 \quad \text{(Positive)} \\
\frac{\mathcal{Z}_{C_9^\mu, C_9^{\prime\mu}}}{\mathcal{Z}_{C_9^\mu, C_{10}^\mu, C_9^{\prime\mu}, C_{10}^{\prime\mu}}} &= 1.2 \quad \text{(Barely worth mentioning)} \\
\frac{\mathcal{Z}_{C_9^\mu, C_{10}^\mu, C_9^{\prime\mu}, C_{10}^{\prime\mu}}}{\mathcal{Z}_{C_9^\mu, C_{10}^\mu, C_9^e, C_{10}^e}} &= 7.4 \quad \text{(Positive)} \\
\frac{\mathcal{Z}_{C_9^\mu, C_{10}^\mu, C_9^{\prime\mu}, C_{10}^{\prime\mu}}}{\mathcal{Z}_{C_9^\mu, C_9^{\prime\mu}, C_9^e, C_9^{\prime e}}} &= 5.6\,, \quad \text{(Positive)}
\end{aligned}
$$

$(C_9^\mu, C_9^{'\mu})$ and $(C_9^\mu, C_{10}^\mu, C_9^{'\mu}, C_{10}^{'\mu})$ are slightly favored by the data.

8 parameter vs. 2 parameter scan





limited impact the Wilson coefficients of the electron sector bring to the fit.

Heavy Z'

- The most generic Lagrangian, parametrizing LFUV couplings of Z' to the b-s current and the muons

$$\mathcal{L} \supset Z'_\alpha \left(\Delta_L^{sb}\, \bar{s}_L\gamma^\alpha\, b_L + \Delta_R^{sb}\, \bar{s}_R\gamma^\alpha\, b_R + \mathrm{H.c.}\right) + Z'_\alpha \left(\Delta_L^{\mu\mu}\, \bar{\mu}_L\gamma^\alpha\mu_L + \Delta_R^{\mu\mu}\, \bar{\mu}_R\gamma^\alpha\mu_R\right.$$

- The relevant Wilson coefficients are then given by

$$\begin{aligned} C^\mu_{9,\mathrm{NP}} &= -2\frac{\Delta_L^{sb}\Delta_9^{\mu\mu}}{V_{tb}V_{ts}^*}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2, \qquad C'^\mu_{9,\mathrm{NP}} = -2\frac{\Delta_R^{sb}\Delta_9^{\mu\mu}}{V_{tb}V_{ts}^*}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2, \\ C^\mu_{10,\mathrm{NP}} &= -2\frac{\Delta_L^{sb}\Delta_{10}^{\mu\mu}}{V_{tb}V_{ts}^*}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2, \qquad C'^\mu_{10,\mathrm{NP}} = -2\frac{\Delta_R^{sb}\Delta_{10}^{\mu\mu}}{V_{tb}V_{ts}^*}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2, \end{aligned}$$

- If the heavy Z' is the gauge boson of a new $\mathrm{U}(1)_X$ gauge group, its couplings to the gauge eigenstates must be flavor-conserving, and an additional structure is required to generate Δ_L^{sb} and Δ_R^{sb}.
- we also consider the impact of the new LHCb and Belle data on the masses and couplings of a few simplified but UV complete models.

Variations of the $L_\mu - L_\tau$ model

- quite popular model $U(1)_X$ with $X = L_\mu - L_\tau$ W. Altmannshofer et al. PRD 89 (2014) 095033.
- SM leptons carry an additional charge in $L_\mu - L_\tau$ model ($SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$)

$$
\begin{aligned}
l_1 &: (\mathbf{1}, \mathbf{2}, -1/2, 0) & e_R &: (\mathbf{1}, \mathbf{1}, 1, 0)\\
l_2 &: (\mathbf{1}, \mathbf{2}, -1/2, 1) & \mu_R &: (\mathbf{1}, \mathbf{1}, 1, -1)\\
l_3 &: (\mathbf{1}, \mathbf{2}, -1/2, -1) & \tau_R &: (\mathbf{1}, \mathbf{1}, 1, 1)\,.
\end{aligned}
$$

- Model 1: $Z' +$ a scalar singlet S + VL quark pairs Buras et al. JHEP 04 (2017) 079.

$$
\begin{aligned}
&S : (\mathbf{1}, \mathbf{1}, 0, -1)\,,\\
&Q : (\mathbf{3}, \mathbf{2}, 1/6, -1) \quad Q' : (\bar{\mathbf{3}}, \mathbf{2}, -1/6, 1)\,,\\
&D : (\bar{\mathbf{3}}, \mathbf{1}, 1/3, -1) \quad D' : (\mathbf{3}, \mathbf{1}, -1/3, 1)\,.
\end{aligned}
$$

$$
\mathcal{L} \supset \left(-\lambda_{Q,i} S Q' q_i - \lambda_{D,i} S D' d_{R,i} + \mathrm{H.c.}\right) - M_Q Q' Q - M_D D' D\,,
$$

$$
C^{\mu}_{9,\mathrm{NP}} = \frac{2\Lambda_v^2}{V_{tb}V_{ts}^*} \frac{\lambda_{Q,2}\lambda_{Q,3}}{2M_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right) v_S^2}\,, \qquad C'^{\mu}_{9,\mathrm{NP}} = -\frac{2\Lambda_v^2}{V_{tb}V_{ts}^*} \frac{\lambda_{D,2}\lambda_{D,3}}{2M_D^2 + \left(\lambda_{D,2}^2 + \lambda_{D,3}^2\right) v_S^2}\,,
$$

Variations of the $L_\mu - L_\tau$ model

- Model 2: Z' + a scalar singlet S + one pair of VL quarks + one pair of VL leptons W. Altmannshofer et al. PRD 94 (2016) 9 095026, L. Darme et al. JHEP 10 (2018) 052.

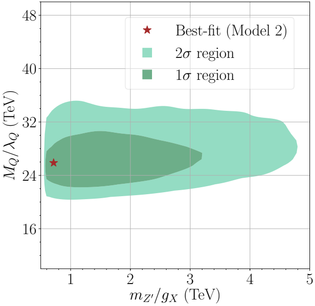
$$S : (\mathbf{1}, \mathbf{1}, 0, -1)\,,\; Q : (\mathbf{3}, \mathbf{2}, 1/6, -1) \quad Q' : (\bar{\mathbf{3}}, \mathbf{2}, -1/6, 1)\,,\; E : (\mathbf{1}, \mathbf{1}, 1, 0) \quad E' : (\mathbf{1}, \mathbf{1}, -1, 0)\,.$$

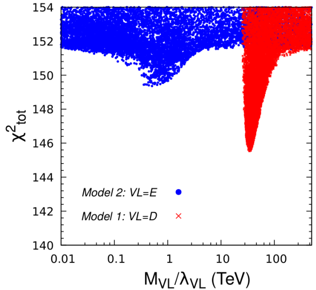
$$\mathcal{L} \supset \left(-\lambda_{E,2} S^* E' \mu_R - \lambda_{E,3} S E' \tau_R - \widetilde{Y}_E \phi^\dagger l_1 E + \mathrm{H.c.}\right) - M_E E' E\,,$$

$$C^{\mu}_{9,\mathrm{NP}} = \frac{\Lambda_v^2}{V_{tb} V_{ts}^*} \left(\frac{\lambda_{Q,2}\lambda_{Q,3}}{2M_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right) v_S^2}\right) \left(1 + \frac{2M_E^2}{2M_E^2 + \lambda_{E,2}^2 v_S^2}\right),$$

$$C^{\mu}_{10,\mathrm{NP}} = \frac{\Lambda_v^2}{V_{tb} V_{ts}^*} \left(\frac{\lambda_{Q,2}\lambda_{Q,3}}{2M_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right) v_S^2}\right) \left(-1 + \frac{2M_E^2}{2M_E^2 + \lambda_{E,2}^2 v_S^2}\right).$$

Results of Z' model





- VL mass range is determined by the 2σ range in $C_9^{\mu,NP}$.
- The second VL mass is unbounded from the above at the 2σ level. This is a consequnece of the fact that $C'^{\mu}_{9,NP}$ in Model 1 and especially $C^{\mu}_{10,NP}$ in Model 2 are consistent with the zero at the 2σ level.
- $m_{Z'}/g_X$ is limited to values below $5\,TeV$, as a result of the B_s mixing constraint.

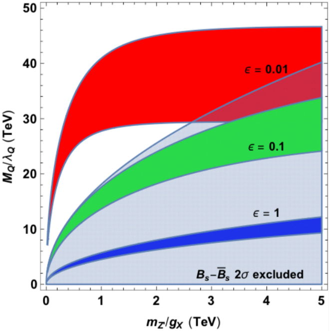
A model with $U(1)_X$ charged leptons

- We consider the VL leptons charged under the $U(1)_X$ symmetry and leaves the SM leptons uncharged D. Aristizabal Sierra et al. PRD 92 (2015) 1 015001

$$S : (\mathbf{1}, \mathbf{1}, 0, -1)\,,\; Q : (\mathbf{3}, \mathbf{2}, 1/6, -1) \quad Q' : (\bar{\mathbf{3}}, \mathbf{2}, -1/6, 1)\,,\; L : (\mathbf{1}, \mathbf{2}, -1/2, 1)\,, \quad L' : (\mathbf{1}, \mathbf{2}, 1/2, -1)\,.$$

$$C_9^\mu = -C_{10}^\mu = \frac{2\Lambda_v^2}{V_{tb}V_{ts}^*}\left(\frac{\lambda_{Q,2}\lambda_{Q,3}}{2M_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right)v_S^2}\right)\left(\frac{\lambda_{L,2}^2 v_S^2}{2M_L^2 + \lambda_{L,2}^2 v_S^2}\right)\,.$$

- 3 parameters: $m_{Z'}/g_X$, M_Q/λ_Q, where $M_L/\lambda_{L,2} = \epsilon M_Q/\lambda_Q$.
- Apply $C_9^\mu = -C_{10}^\mu \in (-0.68, -0.29)$ together with bound from B_s mixing.
- The severe bound on mixing limits this model to strong hierarchies between VL quark and lepton masses.



Conclusions

- Global Bayesian analysis of NP effects with new measurements of R_K and $R_{K^{(*)}}$ in Morionod 2019.
- R_K shifts closer to SM predicitons hence (C_9^μ, C_{10}^μ) shifts slightly towards zero.
- Confirmed previous observations that the impact of the Wilson coefficients of the electron sector on the data is negligible w.r.t. to muon sector.
- $(C_9^\mu, C_9^{\prime\mu})$ and $(C_9^\mu, C_{10}^\mu, C_9^{\prime\mu}, C_{10}^{\prime\mu})$ are favored by the data.
- The masses for second VL is unbounded from the below for variations of Z' model.

Thank You

Parameter	Range	Prior
C_9^{μ}	$(-3,3)$	Flat
$C_9^{\mu}=-C_{10}^{\mu}$	$(-3,3)$	Flat
$C_9^{\mu},\ C_{10}^{\mu}$	$(-3,3)$	Flat
$C_9^{\mu},\ C_9^{\prime\mu}$	$(-3,3)$	Flat
$C_9^{\mu},\ C_{10}^{\mu},\ C_9^{\prime\mu},\ C_{10}^{\prime\mu}$	$(-3,3)$	Flat
$C_9^{\mu},\ C_{10}^{\mu},\ C_9^{e},\ C_{10}^{e}$	$(-3,3)$	Flat
$C_9^{\mu},\ C_9^{\prime\mu},\ C_9^{e},\ C_9^{\prime e}$	$(-3,3)$	Flat
$C_9^{\mu},\ C_9^{\prime\mu},\ C_{10}^{\mu},\ C_{10}^{\prime\mu}$ $C_9^{e},\ C_9^{\prime e},\ C_{10}^{e},\ C_{10}^{\prime e}$	$(-3,3)$	Flat
$m_{Z'}/g_X$ $M_Q/\lambda_Q,\ M_D/\lambda_D$	500–5000GeV 0.1–500TeV	Log Log
$m_{Z'}/g_X$ $M_Q/\lambda_Q,\ M_E/\lambda_{E,2}$	500–5000 GeV 0.1–500TeV	Log Log
Nuisance parameter	Central value, error $(\times 10^{-2})$	
CKM matrix element V_{cb}	(4.22, 0.08)	Gaussian

Table: Input parameters, their ranges, and prior distributions.

Input Parameters	$-\ln \mathcal{Z}$	Best fit	Pull
SM	88.5	-	-
	88.3	-	-
C_9^μ	75.8	-1.02	5.0σ
	77.3	-0.90	4.7σ
$C_9^\mu = -C_{10}^\mu$	74.4	-0.64	5.3σ
	77.5	-0.48	4.8σ
C_9^μ, C_{10}^μ	74.5	-0.91	5.3σ
	77.6	-0.78	4.7σ
C_9^μ, $C_9'^\mu$	75.1	(-1.08,0.49)	5.2σ
	75.8	(-1.03,0.53)	5.0σ
C_9^μ, C_{10}^μ, $C_9'^\mu$, $C_{10}'^\mu$	74.0	(-1.14,0.28,0.21,-0.31)	5.4σ
	76.0	(-1.06,0.18,0.18,-0.34)	5.2σ
C_9^μ, C_{10}^μ, C_9^e, C_{10}^e	75.6	(-0.92,0.40,-1.50,-0.90)	4.9σ
	78.0	(-0.88,0.34,-1.69,-0.71)	4.5σ
C_9^μ, $C_9'^\mu$, C_9^e, $C_9'^e$	75.8	(-1.02,0.54,0.58,-0.17)	4.9σ
	77.7	(-0.97,0.55,0.34,-0.17)	4.6σ
C_9^μ, $C_9'^\mu$, C_{10}^μ, $C_{10}'^\mu$	76.2	(-1.10,0.21,0.21,-0.30,-0.80,-0.63,-0.73,-0.57)	4.7σ
C_9^e, $C_9'^e$, C_{10}^e, $C_{10}'^e$	78.3	(-1.05,0.13.0.10.-0.38,-2.18,-0.07,-2.73,-1.34)	4.4σ

Table: Evidence, best fit and pull from the SM of the considered scenarios.

- The approximate formulae for R_K and R_{K^*} with real Wilson coefficents and the polarization fraction of the K^* meson set at $p = 0.86$

$$
\begin{aligned}
R_K &\approx 1 + 0.24\left(C_9^{\mu} - C_{10}^{\mu} + C_9^{\prime\mu} - C_{10}^{\prime\mu}\right) - (\mu \to e), \\
R_{K^*} &\approx 1 + 0.24\left(C_9^{\mu} - C_{10}^{\mu}\right) - 0.17\left(C_9^{\prime\mu} - C_{10}^{\prime\mu}\right) - (\mu \to e).
\end{aligned}
$$