Update on the $b \to s$ anomalies

A. Arbey,[1,5,*,†] T. Hurth,[2,‡] F. Mahmoudi,[1,5,*,§] D. Martínez Santos,[3,∥] and S. Neshatpour[4,¶]

[1]*Univ Lyon, Univ Lyon 1, CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, UMR5822, F-69622 Villeurbanne, France*

[2]*PRISMA+ Cluster of Excellence and Institute for Physics (THEP) Johannes Gutenberg University, D-55099 Mainz, Germany*

[3]*Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compotela, Spain*

[4]*School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM) P.O. Box 19395-5531, Tehran, Iran*

[5]*Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

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We present a brief update of our model-independent analyses of the $b \to s$ data presented in the articles published in Phys. Rev. D **96**, 095034 (2017) and Phys. Rev. D **98**, 095027 (2018) based on new data on R_K by LHCb, on R_{K^*} by Belle, and on $B_{s,d} \to \mu^+\mu^-$ by ATLAS.

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I. NEW DATA

Using the theoretical framework introduced in Refs. [1,2] we update our results in view of the following new experimental measurements:

(i) The most awaited one is the LHCb measurement of the lepton-universality testing observable $R_K \equiv \mathrm{BR}(B^+ \to K^+\mu^+\mu^-)/\mathrm{BR}(B^+ \to K^+e^+e^-)$. The LHCb measurement using 5 fb^{-1} of data [3] collected with the center of mass energies of 7, 8, and 13 TeV for R_K in the low-dilepton mass (q^2) bin leads to

$$R_K([1.1, 6.0]\ \mathrm{GeV}^2) = 0.846^{+0.060+0.016}_{-0.054-0.014}, \quad (1)$$

where the first and second uncertainties are the systematic and statistical errors, respectively. Compared to the previous LHCb measurement based on 3 fb^{-1} of data [4], the central value is now closer to the Standard Model (SM) prediction, but the significance of the tension is still 2.5σ due to the smaller uncertainty of the new measurement.

(ii) Moreover, there has been new experimental results on another lepton-universality testing observable $R_{K^*} \equiv \mathrm{BR}(B \to K^*\mu^+\mu^-)/\mathrm{BR}(B \to K^*e^+e^-)$ by the Belle collaboration [5], both for the neutral and charged B mesons. The results are given in three low-q^2 bins and one high-q^2 bin which for the combined charged and neutral channels are

$$\begin{aligned} R_{K^*}([0.045, 1.1]\ \mathrm{GeV}^2) &= 0.52^{+0.36}_{-0.26} \pm 0.05, \\ R_{K^*}([1.1, 6.0]\ \mathrm{GeV}^2) &= 0.96^{+0.45}_{-0.29} \pm 0.11, \\ R_{K^*}([0.1, 8]\ \mathrm{GeV}^2) &= 0.90^{+0.27}_{-0.21} \pm 0.10, \\ R_{K^*}([15, 19]\ \mathrm{GeV}^2) &= 1.18^{+0.52}_{-0.32} \pm 0.10. \end{aligned} \quad (2)$$

For our analysis we consider the $[0.1, 8]$ GeV^2 bin (together with the high-q^2 bin) and do not use the very low q^2 bin below 0.1 GeV^2 as advocated by Ref. [6] in order to avoid near-threshold uncertainties which would be present when the lower range of the bin is set to the dimuon threshold. Although the ideal bin would be the $[0.1, 6]$ GeV^2—to avoid the $q^2 > 6$ GeV^2 region in which the validity of the QCD factorization approach is questionable—no result in this bin has been presented by Belle.

We note that the Belle measurement for the low-q^2 bin, [0.045, 1.0], which we do not use, has a tension with the SM prediction which is slightly more than 1σ, while the other bins are all well in agreement with the SM at the 1σ-level. All the R_{K^*} measurements of Belle are in agreement with the LHCb measurement [7] due to the large uncertainties of the Belle results.

(iii) Our update also takes into account new experimental data on $B_{s,d} \to \mu^+\mu^-$ by ATLAS [8]. We have

[*]Also at Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France.
[†]alexandre.arbey@ens-lyon.fr
[‡]tobias.hurth@cern.ch
[§]nazila@cern.ch
[∥]Diego.Martinez.Santos@cern.ch
[¶]neshatpour@ipm.ir

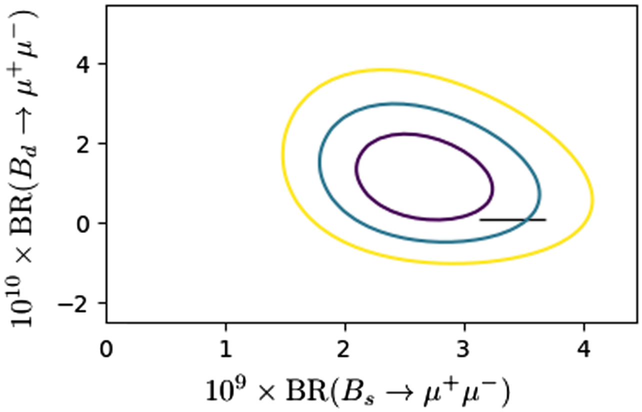

FIG. 1. 2D likelihood plot where the contours are 1, 2, and 3σ (in terms of $\Delta\chi^2$).

combined this new result with the previous results of CMS [9] and LHCb [10] building a joint 2D likelihood (see Fig. 1) with common f_d/f_s and $\mathrm{BR}(B^+ \to J/\psi K^+) \times \mathrm{BR}(J/\psi \to \mu^+\mu^-)$ which finally leads us to

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 2.65^{+0.43}_{-0.39} \times 10^{-9},$$
$$\mathrm{BR}(B_d \to \mu^+\mu^-) = 1.09^{+0.74}_{-0.68} \times 10^{-10}. \quad (3)$$

The calculation of the observables is performed with SuperIso v4.1 [11]. The statistical methods used for our study are described in [12,13]. In particular, we compute the theoretical covariance matrix for all the observables and consider the experimental correlations provided by the experiments. For the hadronic corrections, we do not consider hadronic parameters as in Refs. [2,14] but use 10% error assumption as explained in [13].

II. COMPARISON OF R_K AND R_{K^*} DATA WITH OTHER $b \to s$ DATA

The hadronic contributions which are usually the main source of theoretical uncertainty cancel out in the case of the potentially lepton flavor violating ratios R_K and R_{K^*} and thus, very precise predictions are possible in the SM [15]. In contrast, the power corrections to the angular observables and other observables in the exclusive $b \to s$ sector are still not really under control and are usually guesstimated to 10%, 20% or even higher percentages of the leading nonfactorizable contributions to those observables.[1] However, there is a promising approach based on analyticity, which may lead to a clear estimate of such effects and which may allow for a clear separation of hadronic and new physics (NP) effects in these observables [16].

As argued in Ref. [1], the present situation suggests separate analyses of the theoretically very clean ratios and the other $b \to s$ observables. In Table I, the one-operator fits to new physics have been compared when considering all the relevant data on $b \to s$ transitions except for R_K and R_{K^*} and when only considering the data on R_K and R_{K^*}.[2] We note that the NP significance of the ratios is reduced compared to our previous analysis [1], mainly because of the new measurements of R_{K^*} by Belle which are compatible with the SM predictions at the 1σ-level as stated above. But within the one-operator fits we find again that the NP analyses of the two sets of observables are less coherent than often stated, especially regarding the coefficients $C_{10}^{\mu,e}$.

One may expect that the observables $B_{s,d} \to \mu^+\mu^-$ are responsible for the finding that NP in $C_{10}^{\mu,e}$ is favored in the fit to the ratios $R_{K^{(*)}}$ but not in the fit to the rest of the $b \to s$ transitions. However, when besides R_K, R_{K^*} also the

TABLE I. Comparison of one-operator NP fits where the δC_{LL}^{ℓ} basis corresponds to $\delta C_9^{\ell} = -\delta C_{10}^{\ell}$. On the upper table all relevant data on $b \to s$ transitions except R_K and R_{K^*} (with 10% error assumption for the power corrections) is used and on the lower table only the data on R_K, R_{K^*} is considered.

All observables except R_K, R_{K^*} ($\chi^2_{\rm SM} = 100.2$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-1.00 ± 0.20	82.5	4.2σ
δC_9^{μ}	-1.03 ± 0.20	80.3	4.5σ
δC_9^{e}	0.72 ± 0.58	98.9	1.1σ
δC_{10}	0.25 ± 0.23	98.9	1.1σ
δC_{10}^{μ}	0.32 ± 0.22	98.0	1.5σ
δC_{10}^{e}	-0.56 ± 0.50	99.1	1.0σ
δC_{LL}^{μ}	-0.48 ± 0.15	89.1	3.3σ
δC_{LL}^{e}	0.33 ± 0.29	99.0	1.1σ

Only R_K, R_{K^*} ($\chi^2_{\rm SM} = 16.9$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-2.04 ± 5.93	16.8	0.3σ
δC_9^{μ}	-0.74 ± 0.28	8.4	2.9σ
δC_9^{e}	0.79 ± 0.29	7.7	3.0σ
δC_{10}	4.10 ± 11.87	16.7	0.5σ
δC_{10}^{μ}	0.77 ± 0.26	6.1	3.3σ
δC_{10}^{e}	-0.78 ± 0.27	6.0	3.3σ
δC_{LL}^{μ}	-0.37 ± 0.12	7.0	3.1σ
δC_{LL}^{e}	0.41 ± 0.15	6.8	3.2σ

[1]The various methods used to treat the power corrections, are mostly in agreement, however, the significance of the NP fits somewhat varies depending on the employed method (e.g., see Ref. [2])

[2]The lower (upper) results of Table I in this paper give the updated results of Table 1 (2) in Ref. [1] where here we have not normalized to the SM values.

TABLE II. Comparison of one operator NP fits where the $\delta C_{\mathrm{LL}}^{\ell}$ basis corresponds to $\delta C_9^{\ell} = -\delta C_{10}^{\ell}$. On the upper table all relevant data on $b \to s$ transitions except R_K, R_{K^*}, $B_{s,d} \to \mu^+\mu^-$ (with 10% error assumption for the power corrections) is used and on the lower table only the data on R_K, R_{K^*}, $B_{s,d} \to \mu^+\mu^-$ is considered.

All observables except R_K, R_{K^*}, $B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\mathrm{SM}} = 99.7$)			
	b.f. value	χ^2_{min}	$\mathrm{Pull}_{\mathrm{SM}}$
δC_9	-1.03 ± 0.20	81.0	4.3σ
δC_9^{μ}	-1.05 ± 0.19	78.8	4.6σ
δC_9^{e}	0.72 ± 0.58	98.5	1.1σ
δC_{10}	0.27 ± 0.28	98.7	1.0σ
δC_{10}^{μ}	0.38 ± 0.28	97.7	1.4σ
δC_{10}^{e}	-0.56 ± 0.50	98.7	1.0σ
$\delta C_{\mathrm{LL}}^{\mu}$	-0.50 ± 0.16	88.8	3.3σ
$\delta C_{\mathrm{LL}}^{e}$	0.33 ± 0.29	98.6	1.1σ

Only R_K, R_{K^*}, $B_{s,d} \to \mu^+\mu^-$ ($\chi^2_{\mathrm{SM}} = 19.0$)			
	b.f. value	χ^2_{min}	$\mathrm{Pull}_{\mathrm{SM}}$
δC_9	-2.04 ± 5.93	18.9	0.3σ
δC_9^{μ}	-0.74 ± 0.28	10.6	2.9σ
δC_9^{e}	0.79 ± 0.29	9.9	3.0σ
δC_{10}	0.43 ± 0.32	17.0	1.4σ
δC_{10}^{μ}	0.65 ± 0.20	6.9	3.5σ
δC_{10}^{e}	-0.78 ± 0.27	8.2	3.3σ
$\delta C_{\mathrm{LL}}^{\mu}$	-0.37 ± 0.11	7.2	3.4σ
$\delta C_{\mathrm{LL}}^{e}$	0.41 ± 0.15	9.0	3.2σ

$B_{s,d} \to \mu^+\mu^-$ observables are removed from the rest of the $b \to s$ observables and compared to the fit when considering the data on R_K, R_{K^*}, $B_{s,d} \to \mu^+\mu^-$ we find that at least within the one-operator fits the observables $B_{s,d} \to \mu^+\mu^-$ do not play a major role: The results in Table II are very similar to the ones in Table I. This feature is consistent with our finding in Ref. [1] that the observables $B_{s,d} \to \mu^+\mu^-$ will not play a primary role in the future differentiation between the NP hypotheses for the ratios $R_{K^{(*)}}$. However, with the new average for $\mathrm{BR}(B_s \to \mu^+\mu^-)$ which includes the ATLAS measurement, there is a tension of 1.5σ with the SM prediction which suggests the same direction for C_{10}^{μ} as it is preferred by the $R_{K^{(*)}}$ fit. This can also be seen by comparing the lower parts of Tables I and II where there is a slight increase in the SM-Pull when the data on $B_s \to \mu^+\mu^-$ is added to the $R_{K^{(*)}}$ fit.

In the next step we compare the two sets of observables in two-operator fits. In Fig. 2 the two operator fits for $\{C_9^e, C_9^{\mu}\}$, $\{C_{10}^{\mu}, C_9^{\mu}\}$, and for $\{C_{10}^{\mu}, C_{10}^{e}\}$ are shown, using only the data on R_K, R_{K^*}, or all observables except R_K, R_{K^*} where the effect of moving the data on $B_{s,d} \to \mu^+\mu^-$ observables from one set to the other has been shown with the black and gray contours. The latter ones nicely show the influence of these observables when more than one operator is considered. Independent of these effects one finds that the two sets of observables are compatible at least at the 2σ-level.

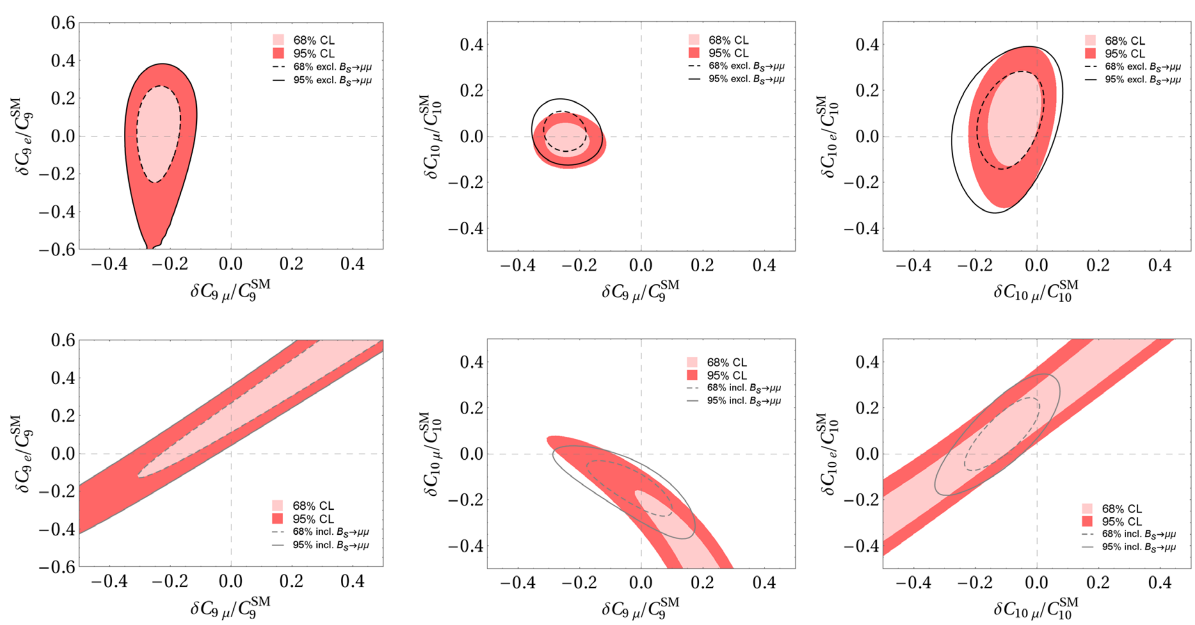

FIG. 2. Two operator fits to NP. The contours correspond to the 68% and 95% confidence level regions. On the upper row we have considered all observables except R_K and R_{K^*} with the assumption of 10% power corrections. On the lower row we have only used the data on R_K, R_{K^*}. $\mathrm{Pull}_{\mathrm{SM}}$ for the 1st, 2nd, 3rd column are respectively, $4.1, 4.1, 1.1\sigma$ ($3.1, 3.2, 3.1\sigma$), for the upper (lower) plots. The black (gray) dashed and solid contours correspond to excluding (including) the data on $B_{s,d} \to \mu^+\mu^-$ from (to) the fits of the upper (lower) plots.

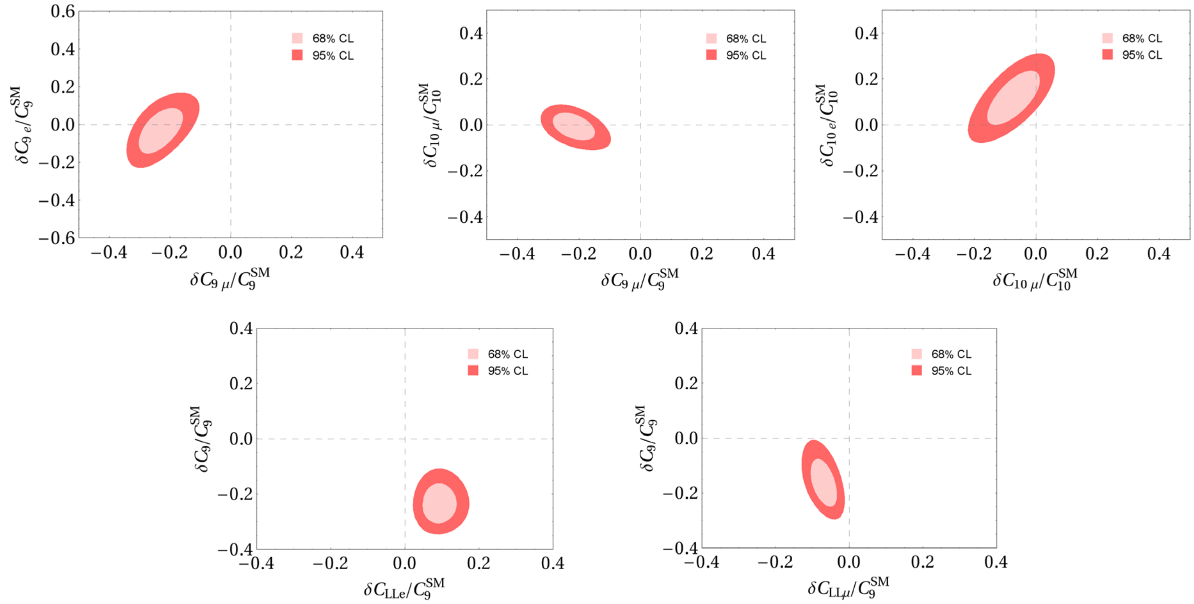

FIG. 3. Two operator fits to NP, considering all observables (with the assumption of 10% power corrections). $\mathrm{Pull}_{\rm SM}$ in the $\{C_9^e, C_9^\mu\}$, $\{C_{10}^\mu, C_9^\mu\}$, $\{C_{10}^e, C_{10}^\mu\}$ fits are 4.9, 4.9, 3.2σ, respectively. $\mathrm{Pull}_{\rm SM}$ for the $\{C_{LL}^e, C_9\}$ and $\{C_{LL}^\mu, C_9\}$ fits of the lower row are 5.0 and 4.8σ, respectively.

III. GLOBAL FIT

In Table III, the global one-operator fits to NP are given where *all* the relevant data on $b \to s$ transitions are considered.[3] In Fig. 3, the two operator fits for $\{C_9^e, C_9^\mu\}$, $\{C_{10}^\mu, C_9^\mu\}$, and $\{C_{10}^\mu, C_{10}^e\}$ (the same set as in Fig. 2) can be seen. Moreover, the fits for $\{C_{LL}^\mu, C_9\}$ and $\{C_{LL}^e, C_9\}$ are given which are also motivated for model building (e.g., see Ref. [17]). These fits are always done under the assumption of 10% power corrections in the angular observables. Compared with our previous analysis in Ref. [2] the NP significance in the one- and also in the two-operator fits is reduced by at least 0.5σ. Only in cases of flavor-symmetric C_9 and C_{10} which are independent from the changes in the ratios one finds the same NP significance as expected.

The observables $B_{s,d} \to \mu^+\mu^-$ are usually used to strongly constrain NP effects in scalar and pseudoscalar operators. As a consequence, a general usage is to consider the contributions from the scalar and pseudoscalar Wilson coefficients as vanishingly small. However, as mentioned in Ref. [2], this is only valid when the relation between the scalar and pseudoscalar operators ($C_{Q_1} = -C_{Q_2}$) is assumed, which breaks the possible degeneracy between C_{Q_2} and C_{10} and allows for strong constraints on $C_{Q_{1,2}}$. In general scenarios, C_{Q_2} and C_{10} can have simultaneously large values which compensates, while indeed C_{Q_1} is rather constrained (for more details see Ref. [2]). Since beyond simplified NP models, there can be scenarios which contain various new particles and several new couplings we also perform a multidimensional fit in Table IV where all the relevant Wilson coefficients which amounts to 20 coefficients are modified.[4] We note that large contributions to the electron Wilson coefficients are mostly driven by the ratios as there are few measurements on purely electron observables.

Finally, we note that there have been other model-independent analyses presented recently which update previous analyses [1,2,18–22] based on the new experimental data. We find small differences with these updated analyses [22–27] only in the NP significances. This can be explained by the different choices of bins in the new Belle measurement and by slightly different treatments of power corrections and of form factors.

In summary, the overall picture of the $b \to s$ anomalies remains the same as before taking into account the new results from LHCb, Belle, and ATLAS on R_K, R_{K^*}, and $B_s \to \mu^+\mu^-$. Although, the significance of the new physics description of the $R_K{}^{(*)}$ data is now reduced by more than half a σ. Nevertheless, the future measurements of these theoretically very clean ratios and similar observables which are sensitive to lepton flavor nonuniversality have a great potential to unambiguously establish lepton non-universal new physics.

[3]This table includes updated results of Table 5 in Ref. [2].

[4]This table updates the results given in Table 8 of Ref. [2].

TABLE III. Best fit values and errors in the one operator fits to all the relevant data on $b \to s$ transitions, assuming 10% error for the power corrections.

All observables ($\chi^2_{\rm SM} = 117.03$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-1.01 ± 0.20	99.2	4.2σ
δC_9^μ	-0.93 ± 0.17	89.4	5.3σ
δC_9^e	0.78 ± 0.26	106.6	3.2σ
δC_{10}	0.25 ± 0.23	115.7	1.1σ
δC_{10}^μ	0.53 ± 0.17	105.8	3.3σ
δC_{10}^e	-0.73 ± 0.23	105.2	3.4σ
$\delta C_{\rm LL}^\mu$	-0.41 ± 0.10	96.6	4.5σ
$\delta C_{\rm LL}^e$	0.40 ± 0.13	105.8	3.3σ

TABLE IV. Best fit values for the 20 operator global fit to the $b \to s$ data, assuming 10% error for the power corrections. $\mathrm{Pull}_{\rm SM} = 3.3\sigma(3.8\sigma)$ when considering 20 (16) degrees of freedom. The number in the parenthesis corresponds to the effective number of degrees of freedom in which the insensitive coefficients are not counted (see Ref. [2] for more details).

All observables with $\chi^2_{\rm SM} = 117.03$, $\chi^2_{\rm min} = 71.96$; $\mathrm{Pull}_{\rm SM} = 3.3\sigma(3.8\sigma)$			
δC_7	$\delta C_7'$	δC_8	$\delta C_8'$
-0.01 ± 0.04	0.01 ± 0.03	0.82 ± 0.72	-1.65 ± 0.47
δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
-1.37 ± 0.25	-6.55 ± 2.37	-0.11 ± 0.27	2.34 ± 3.11
$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
0.23 ± 0.62	0.75 ± 2.82	-0.16 ± 0.36	1.67 ± 3.05
$C_{Q_1}^\mu$	$C_{Q_1}^e$	$C_{Q_2}^\mu$	$C_{Q_2}^e$
-0.01 ± 0.09	undetermined	-0.05 ± 0.19	undetermined
$C_{Q_1}'^\mu$	$C_{Q_1}'^e$	$C_{Q_2}'^\mu$	$C_{Q_2}'^e$
0.13 ± 0.09	undetermined	-0.18 ± 0.20	undetermined

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