PROCEEDINGS OF SCIENCE

LFU and CP violation in $b \to s\mu\mu$

Aleks Smolkovič[a,*]

[a]*Albert Einstein Center for Fundamental Physics, Institut für Theoretische Physik, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland.*

E-mail: smolkovic@itp.unibe.ch

The persistent hints of LFU violation in $b \to s\ell\ell$ may imply an existence of leptoquarks close to the TeV scale that couple to $b\mu$ and $s\mu$. These leptoquark Yukawa couplings can in full generality be complex and thus provide a new source of CP violation. We show that a large CP phase with a definite sign is perfectly viable for an S_3 leptoquark of mass below a few TeV, consistent with CP even and CP odd $b \to s\ell\ell$ and B_s mixing observables. Furthermore, we show how the direct CP asymmetries in $B \to K\mu\mu$ are significantly enhanced in the vicinity of narrow charmonia, and that their measurement in the future could provide important additional information in constraining the potentially CP violating NP in $b \to s\ell\ell$.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)715

1. Introduction

Even though the Standard Model (SM) of particle physics describes the basic constituents of matter and their interactions in unprecedented detail, it has many shortcomings, from the lack of an explanation of neutrino masses and dark matter, to the flavor puzzle, hierarchy, strong CP and the cosmological constant problem. As direct searches for physics beyond the Standard Model (BSM, or new physics – NP) to this day failed to provide clear evidence of new degrees of freedom, the language of effective field theories (EFT) is often used to extend the SM to the SMEFT - Standard Model Effective Field Theory. In the SMEFT, a tower of higher-dimensional operators is added to the renormalizable SM Lagrangian, e. g. introducing 59 new baryon number conserving operators at dimension 6 [1]. Similar to the SM, the flavor sector introduces the majority of free parameters in the theory, and assuming no flavor symmetry there are 1350 CP conserving and 1149 CP violating new, independent Wilson coefficients introduced. Hence, studying the possible new sources of CP violation might provide crucial new information on NP [2].

In the SM, the couplings of leptons to the gauge bosons are predicted to be lepton flavor universal (LFU), as was also experimentally confirmed to great precision in various processes, ranging from meson decays to weak gauge boson decays. Nevertheless in recent years hints of LFU violation (LFUV) have emerged in various B meson decays, with arguably the most striking results presented by LHCb in the LFU-sensitive ratios $R_{K^{(*)}} = \Gamma(B \to K^{(*)}\mu\mu)/\Gamma(B \to K^{(*)}ee)$, who found in the region $q^2 \in [1.1, 6]\,\mathrm{GeV}^2$: $R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$ [3–5], $R_{K^*} = 0.69^{+0.11+0.05}_{-0.07-0.05}$ [6]. The discrepancies with respect to the SM predictions of $R_{K^{(*)}} = 1.00(1)$ [7] can be studied in a model independent way with the effective Hamiltonian description $\mathcal{H}_{\mathrm{eff}} = \mathcal{H}_{\mathrm{eff}}^{\mathrm{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \delta C_i O_i$, where δC_i encapsulate the short distance NP contributions to the $b \to s\ell\ell$ process. In this work we assume NP only affects the $b \to s\mu\mu$ channel. A modification of the purely left-handed effective operator $O_9 - O_{10} \propto (\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$ can explain both the LFUV anomalies, as well as other discrepancies related to $b \to s\ell\ell$ [8, 9]. Moreover, the $\delta C_9 = -\delta C_{10}$ Wilson coefficient can in full generality be complex and thus provide a new source of CP violation [9, 10]. Measurements of CP violating observables, such as the T_{N}-odd angular observables $A_{7,8,9}$ in $B \to K^*\mu\mu$ [11], might furthermore provide a discriminating power among various possible NP scenarios behind the $R_{K^{(*)}}$ anomalies [9, 12].

2. An S_3 leptoquark model

The scalar leptoquark (LQ) $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ couples to the SM fermions with the Yukawa interactions $\mathcal{L} \supset y_{ij}\overline{Q_i^C}(i\tau^2\tau^I)L_j\, S_3^I + h.c.$ [13], where Q (L) is a SM left-handed quark (lepton) doublet, and $I = 1, 2, 3$ is the weak isospin index. We work in the down-diagonal mass basis and assume that only the $y_{b\mu}$ and $y_{s\mu}$ Yukawa couplings are non-zero, as well as that the diquark couplings that could cause a rapid proton decay are forbidden by a suitable symmetry. At the level of the SMEFT, the LQ generates the semileptonic operators $Q_{lq}^{(1,3)}$ at tree level and the four-quark operators $Q_{qq}^{(1,3)}$ at one-loop level, with the following Wilson coefficients with flavor indices $(prst) = (\mu\mu sb)$ [14]

$$C_{lq}^{(1)} = \frac{3y_{b\mu}y_{s\mu}^*}{4m_{S_3}^2}, \quad C_{lq}^{(3)} = \frac{y_{b\mu}y_{s\mu}^*}{4m_{S_3}^2}, \quad C_{qq}^{(1)} = -\frac{9(y_{b\mu}y_{s\mu}^*)^2}{256\pi^2 m_{S_3}^2}, \quad C_{qq}^{(3)} = -\frac{(y_{b\mu}y_{s\mu}^*)^2}{256\pi^2 m_{S_3}^2}. \tag{1}$$

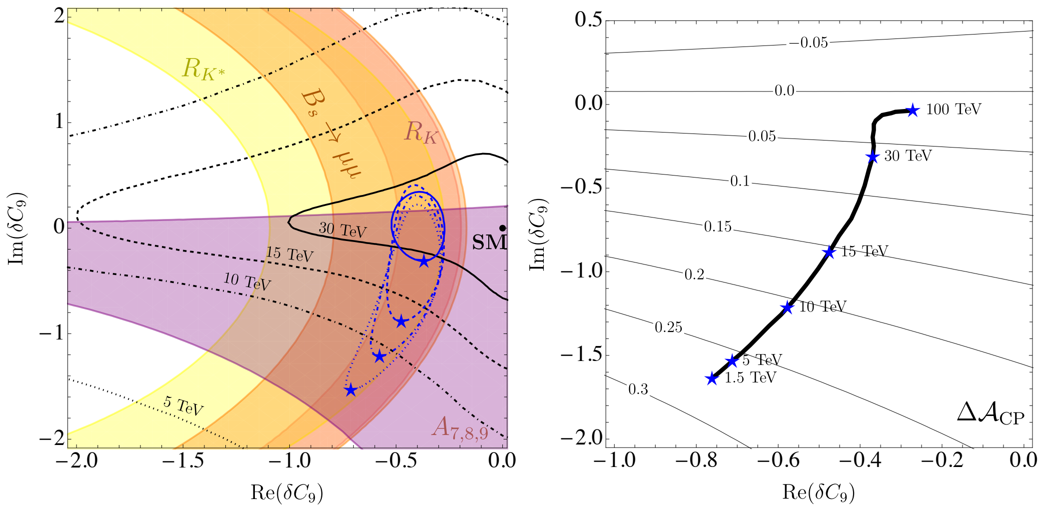

Figure 1: Left: Constraints on the S_3 LQ model in the $\delta C_9 = -\delta C_{10}$ complex plane at 1σ level. The black contour lines show combined B_s-mixing constraints from ΔM_s and $S_{\psi\phi}$ at various LQ masses, whereas the blue contours show the combined fit regions. The blue stars denote the maximal allowed ImδC_9 for each benchmark. Right: Benchmark predictions of $\Delta\mathcal{A}_{\rm CP}$, see Eq. (4).

At the scale $\mu = m_b$ the S_3 LQ generates the appropriate purely left-handed current scenario, able to explain the $R_{K^{(*)}}$ anomalies at tree level

$$\delta C_9 = -\delta C_{10} = \frac{\pi y_{b\mu} y^*_{s\mu}}{\sqrt{2} G_F V_{tb} V^*_{ts} \alpha_{\rm em} m^2_{S_3}}. \tag{2}$$

At one-loop level however we generate important contributions to B_s-mixing observables. Matching onto the $\Delta B = \Delta S = 2$ effective Lagrangian with exclusively left-handed quarks $\mathcal{L}_{bs} = -\frac{4G_F}{\sqrt{2}}(V_{tb}V^*_{ts})^2 C^{LL}_{bs}(\mu)\,(\bar{s}_L\gamma^\mu b_L)^2$ [15], with $C^{LL}_{bs} = C^{LL({\rm SM})}_{bs} + \delta C^{LL}_{bs}$ and the SM part given in Refs. [15, 16], we can express the NP contribution as

$$\delta C^{LL}_{bs} = \eta^{6/23} \frac{5 G_F \alpha^2_{\rm em}}{128\sqrt{2}\pi^4} (\delta C_9)^2 m^2_{S_3}, \tag{3}$$

where $\eta = \alpha_s(m_{S_3})/\alpha_s(m_b)$ at leading order [17, 18].

On Fig. 1 we present the constraints on the S_3 model in the complex $\delta C_9 = -\delta C_{10}$ plane, showing contours from the CP-even $R_{K^{(*)}}$ and $B_s \to \mu\mu$, CP-odd $A_{7,8,9}$, and CP-mixed constraints from B_s-mixing. For details on expressions and measurements used see Ref. [19]. In line with Eq. (3), the constraining power of B_s-mixing observables grows with increasing LQ mass. The constraints from $A_{7,8,9}$ show a preferred direction towards negative values of ImδC_9. For a LQ of mass of $\mathcal{O}(1\text{TeV})$ a large CP-violating ImδC_9 is allowed, whereas the interplay with B_s mixing observables can significantly limit the allowed ImδC_9 for higher masses of the LQ.

3. Resonantly enhanced CP asymmetries

Direct CP asymmetries, defined as $\mathcal{A}_{\rm CP} = (\Gamma - \bar{\Gamma})/(\Gamma + \bar{\Gamma})$, where $\bar{\Gamma}(\Gamma)$ is a decay width of a (CP-conjugated) decay mode, potentially integrated in a q^2 bin, are sensitive to CP violating phases

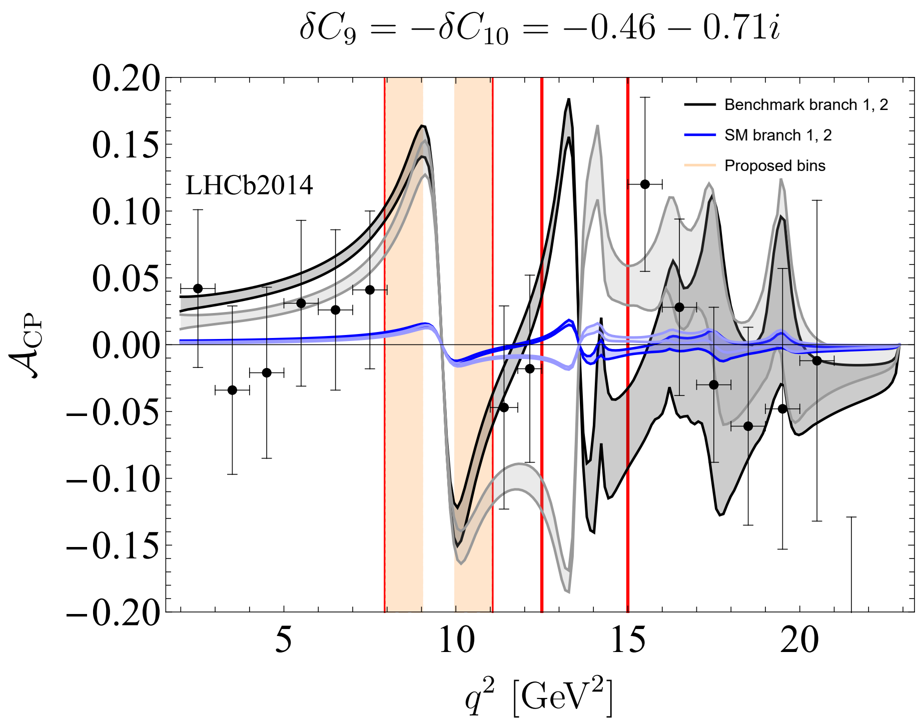

Figure 2: The measurements [20] and our SM and NP predictions of $\mathcal{A}_{\rm CP}(B \to K\mu\mu)$ as a function of q^2 [21]. The vertical red lines show regions of narrow charmonia which are vetoed in the measurement, and where a significant enhancement of $\mathcal{A}_{\rm CP}$ could be observed. In orange we show our proposed bins of $q^2 \in [8, 9]$ GeV^2 and $q^2 \in [10, 11]$ GeV^2 for future measurements of $\mathcal{A}_{\rm CP}$.

as well as strong phases, both having to be non-zero for $\mathcal{A}_{\rm CP} \neq 0$. In the case of $B \to K\mu\mu$, the SM weak phases entering the process are negligible, hence one expects $\mathcal{A}_{\rm CP} \sim 0$. LHCb has measured a (binned) $\mathcal{A}_{\rm CP}$ for this decay mode in Ref. [20], reporting results consistent with the SM prediction. However, $\mathcal{A}_{\rm CP}$ can be enhanced in the vicinity of narrow charmonium resonances in the spectrum [10, 22]. These regions have been vetoed in the analysis presented in Ref. [20], however in Ref. [23] the CP-averaged spectrum of $B \to K\mu\mu$ has been measured, including a model of non-perturbative, long distance contributions due to intermediary charmonium resonances, in the form of $C_9^{\rm eff}(q^2) = C_9 + \sum_j \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i\, m_j \Gamma_j(q^2)}$, where each term j in the sum of the Breit-Wigners parameterizes the contribution of a resonance $j \in \{J/\psi, \psi(2S), \ldots\}$. The model parameters have been extracted from a fit to the measured spectrum, and crucially the phases δ_j of narrow charmonia have been determined as $\delta_{J/\psi} = -1.66(-1.50), \delta_{\psi(2S)} = -1.93(2.08)$ for branch 1(2) of the 4 degenerate fit solutions (see Ref. [23] for the rest of the branches, as well as the rest of the fit parameters and their uncertainties).

On Fig. 2 we show the measurement of $\mathcal{A}_{\rm CP}$ [20], as well as its prediction throughout the physical q^2 region, including the vetoed narrow charomina regions (denoted by vertical red lines), for a benchmark scenario $\delta C_9 = -\delta C_{10} = 0.46 - 0.71i$ in black, and for the SM in blue. We observe a significant enhancement of $\mathcal{A}_{\rm CP}$ in the regions of narrow charmonia, especially striking around the J/ψ with its asymmetric behavior. Due to this, we propose a measurement of $\mathcal{A}_{\rm CP}$ in the bins of $q^2 \in [8, 9]$ GeV^2 and $q^2 \in [10, 11]$ GeV^2, which could lead to a significant enhancement of the sensitivity of such measurements to CP violating NP effects[1], which could be further enhanced by exploiting the asymmetric behavior of $\mathcal{A}_{\rm CP}$ by measuring

$$\Delta\mathcal{A}_{\rm CP} \equiv \frac{\bar{\Gamma}_{[8,9]} - \Gamma_{[8,9]} - \bar{\Gamma}_{[10,11]} + \Gamma_{[10,11]}}{\bar{\Gamma}_{[8,9]} + \Gamma_{[8,9]} + \bar{\Gamma}_{[10,11]} + \Gamma_{[10,11]}}. \quad (4)$$

On Fig. 1 (right) we show the predictions of $\Delta\mathcal{A}_{\rm CP}$ for various benchmark scenarios of the S_3 LQ model. For $m_{S_3} = O(\text{TeV})$ an effect of $\Delta\mathcal{A}_{\rm CP} = O(25\%)$ could potentially be observed.

4. Conclusion

The LFUV ratios $R_{K^{(*)}}$ and other $b \to s\mu\mu$ observables might be hinting at NP at the scale of $O(\text{TeV})$, and the CP nature of this NP should be scrutinized. Measurements of CPV observables could help discriminate among various NP scenarios, as well as between non-perturbative and genuine NP effects. We have proposed a measurement of the resonantly enhanced direct CP asymmetry in $B \to K\mu\mu$, $\Delta\mathcal{A}_{\rm CP}$ (4), as an effective probe of such CPV effects. In the S_3 LQ model, we have shown that a large CP-violating ImδC_9 of $O(1)$ is consistent with current constraints from CP even and CP odd $b \to s\mu\mu$ and B_s mixing measurements, and that such a LQ could induce a large effect in the measurement of $\Delta\mathcal{A}_{\rm CP}$ of up to $O(25\%)$.

References

[1] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, JHEP **10** (2010), 085 doi:10.1007/JHEP10(2010)085 [arXiv:1008.4884 [hep-ph]].

[2] Q. Bonnefoy, E. Gendy, C. Grojean and J. T. Ruderman, JHEP **08** (2022), 032 doi:10.1007/JHEP08(2022)032 [arXiv:2112.03889 [hep-ph]].

[3] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **113** (2014), 151601 doi:10.1103/PhysRevLett.113.151601 [arXiv:1406.6482 [hep-ex]].

[4] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **122** (2019) no.19, 191801 doi:10.1103/PhysRevLett.122.191801 [arXiv:1903.09252 [hep-ex]].

[5] D. Lancierini, [arXiv:2105.10303 [hep-ex]].

[6] R. Aaij *et al.* [LHCb], JHEP **08** (2017), 055 doi:10.1007/JHEP08(2017)055 [arXiv:1705.05802 [hep-ex]].

[7] M. Bordone, G. Isidori and A. Pattori, Eur. Phys. J. C **76** (2016) no.8, 440 doi:10.1140/epjc/s10052-016-4274-7 [arXiv:1605.07633 [hep-ph]].

[8] T. Hurth, F. Mahmoudi, D. M. Santos and S. Neshatpour, Phys. Lett. B **824** (2022), 136838 doi:10.1016/j.physletb.2021.136838 [arXiv:2104.10058 [hep-ph]].

[1] See Ref. [19] for discussion on other recently proposed CPV observables [24, 25].

PoS(ICHEP2022)715

[9] W. Altmannshofer and P. Stangl, Eur. Phys. J. C **81** (2021) no.10, 952 doi:10.1140/epjc/s10052-021-09725-1 [arXiv:2103.13370 [hep-ph]].

[10] D. Bečirević, S. Fajfer, N. Košnik and A. Smolkovič, Eur. Phys. J. C **80** (2020) no.10, 940 doi:10.1140/epjc/s10052-020-08518-2 [arXiv:2008.09064 [hep-ph]].

[11] C. Bobeth, G. Hiller and G. Piranishvili, JHEP **07** (2008), 106 doi:10.1088/1126-6708/2008/07/106 [arXiv:0805.2525 [hep-ph]].

[12] A. K. Alok, B. Bhattacharya, A. Datta, D. Kumar, J. Kumar and D. London, Phys. Rev. D **96** (2017) no.9, 095009 doi:10.1103/PhysRevD.96.095009 [arXiv:1704.07397 [hep-ph]].

[13] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Košnik, Phys. Rept. **641** (2016), 1-68 doi:10.1016/j.physrep.2016.06.001 [arXiv:1603.04993 [hep-ph]].

[14] V. Gherardi, D. Marzocca and E. Venturini, JHEP **07** (2020), 225 [erratum: JHEP **01** (2021), 006] doi:10.1007/JHEP07(2020)225 [arXiv:2003.12525 [hep-ph]].

[15] L. Di Luzio, M. Kirk, A. Lenz and T. Rauh, JHEP **12** (2019), 009 doi:10.1007/JHEP12(2019)009 [arXiv:1909.11087 [hep-ph]].

[16] M. Artuso, G. Borissov and A. Lenz, Rev. Mod. Phys. **88** (2016) no.4, 045002 doi:10.1103/RevModPhys.88.045002 [arXiv:1511.09466 [hep-ph]].

[17] A. J. Buras, M. Jamin and P. H. Weisz, Nucl. Phys. B **347** (1990), 491-536 doi:10.1016/0550-3213(90)90373-L

[18] L. Di Luzio, M. Kirk and A. Lenz, Phys. Rev. D **97** (2018) no.9, 095035 doi:10.1103/PhysRevD.97.095035 [arXiv:1712.06572 [hep-ph]].

[19] N. Košnik and A. Smolkovič, Phys. Rev. D **104** (2021) no.11, 115004 doi:10.1103/PhysRevD.104.115004 [arXiv:2108.11929 [hep-ph]].

[20] R. Aaij *et al.* [LHCb], JHEP **09** (2014), 177 doi:10.1007/JHEP09(2014)177 [arXiv:1408.0978 [hep-ex]].

[21] A. Smolkovič, Probing the flavor structure of new physics models with precision observables, Ljubljana U., 2021

[22] T. Blake, U. Egede, P. Owen, K. A. Petridis and G. Pomery, Eur. Phys. J. C **78** (2018) no.6, 453 doi:10.1140/epjc/s10052-018-5937-3 [arXiv:1709.03921 [hep-ph]].

[23] R. Aaij *et al.* [LHCb], Eur. Phys. J. C **77** (2017) no.3, 161 doi:10.1140/epjc/s10052-017-4703-2 [arXiv:1612.06764 [hep-ex]].

[24] A. Carvunis, F. Dettori, S. Gangal, D. Guadagnoli and C. Normand, JHEP **12** (2021), 078 doi:10.1007/JHEP12(2021)078 [arXiv:2102.13390 [hep-ph]].

[25] S. Descotes-Genon, M. Novoa-Brunet and K. K. Vos, JHEP **02** (2021), 129 doi:10.1007/JHEP02(2021)129 [arXiv:2008.08000 [hep-ph]].

PoS(ICHEP2022)715