Explaining B-physics anomalies by a non-universal Z'-boson

Bednyakov Alexander & Mukhaeva Alfiia
JINR, BLTP
bednya@jinr.ru, mukhaeva@theor.jinr.ru

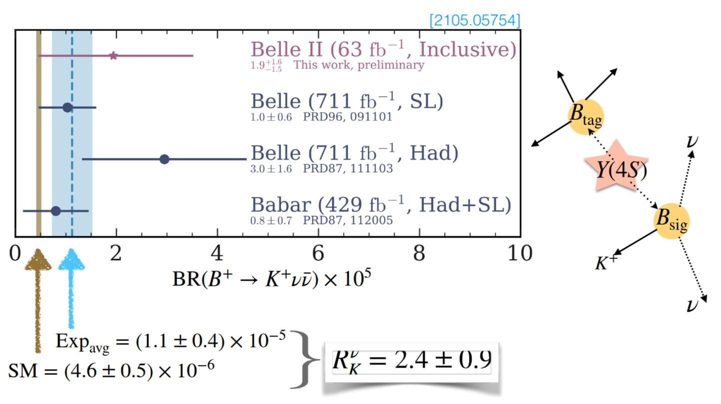
JOINT INSTITUTE FOR NUCLEAR RESEARCH

Abstract

We perform a study [Phys.Rev.D 107 (2023) 11, 115033] of the new physics effects in semileptonic FCNC processes within a low-energy approximation of the anomaly-free supersymmetric extension of the SM with additional Z' vector field [Symmetry 13 (2021) 2, 191]. The key feature of the model is the non-diagonal structure of Z' couplings to fermions, which is parameterized by few new-physics parameters in addition to well-known mixing matrices for quarks and leptons in the SM. We not only consider CP-conserving scenarios with real parameters, but also account for possible CP violation due to new physical weak phases. We analyse the dependence of the $b \to s$ observables on the parameters together with correlations between the observables predicted in the model. Special attention is paid to possible enhancement of $B \to K^{(*)}\nu\bar{\nu}$ rates and to CP-odd angular observables in $B \to K^* ll$ decays.

Motivation

- $B \to K^{(*)}\nu\bar{\nu}$ theoretically much cleaner than $B \to K^* l^+ l^-$;
- Experimentally quite challenging due to two missing neutrinos
  — No signal has been observed so far;
- Inclusive tagging technique from Belle II has higher efficiency $\sim 4\%$;



- $\sim 0.2\sigma$ in R_K and R_K^* [LHCb:2022zom]

$$R_K^{[1.1-6.0]} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 0.949^{+0.042}_{-0.041} \pm 0.022, \qquad R_K^{*[1.1-6.0]} = \frac{\mathcal{B}(B_0 \to K^*\mu^+\mu^-)}{\mathcal{B}(B_0 \to K^*e^+e^-)} = 1.027^{+0.072}_{-0.068} \pm 0.027$$

- $\sim 2.5\sigma$ in $P_5^{'[4-6]} = -0.439 \pm 0.111 \pm 0.036$ [Phys.Rev.Lett. 125 (2020) 1, 011802]
- The mass difference of the neutral $B_s - \bar{B}_s$ meson system

$$\Delta M_s^{exp} = (17.765 \pm 0.004)\ \text{ps}^{-1}, \quad \text{[HFLAV, 2023]}$$
$$\Delta M_s^{SM} = (18.77 \pm 0.76)\ \text{ps}^{-1} \quad \text{[Amhis:2019ckw]}$$

- $\sim 2.4\sigma$ in $\mathcal{B}(B_s \to \mu^+\mu^-)$

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{Exp} = 3.45 \pm 0.29, \quad \text{[HFLAV, 2023]}$$
$$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = 3.68 \pm 0.14 \quad \text{[JHEP 11 (2022) 099]}$$

Model description

- $U(1)'$ extension of MSSM with gauge structure:

$$SU(3) \times SU(2) \times U(1) \times U(1)'$$

- MSSM chiral multiplets + singlet superfield S (allows one to break $U(1)'$ spontaneously and generate mass for the corresponding Z' boson);
- Three right-handed chiral superfields $\nu^c_{1,2,3}$;
- Non-universal charges for ACCs:

field	Q'	field	Q'	field	Q'
$Q_{1,2}$	0	$U^c_{1,2}$	0	$D^c_{1,2}$	0
Q_3	+1	U^c_3	−1	D^c_3	−1
$L_{1,2}$	−1	$E^c_{1,2}$	+1	$\nu^c_{1,2}$	+1
L_3	0	E^c_3	+1	ν^c_3	0
H_d	−1	H_u	0	S	+1

- Superpotential:

$$W = \sum_{i,j=1,2} Y_u^{ij} Q_i H_u U_j^c + Y_u^{33} Q_3 H_u U_3^c - (Q_3 H_d)(Y_d^{31} D_1^c + Y_d^{32} D_2^c)$$
$$+ \sum_{i,j=1,2} Y_\nu^{ij} L_i H_u \nu_j^c + M_3^\nu \nu_3^c \nu_3^c + Y_\nu^{33} L_3 H_u \nu_3^c$$
$$- (L_3 H_d)\left(Y_e^{31} E_1^c + Y_e^{32} E_2^c + Y_e^{33} E_c^3\right) + \lambda_S S H_u H_d \quad (1)$$

- The gauge field Z' couples to quarks and leptons as

$$\mathcal{L} \ni g_E Z'_\alpha \left[\bar{b}\gamma_\alpha b + \bar{t}\gamma_\alpha t\right]$$
$$- g_E Z'_\alpha \left[\sum_{i=1,2} \left([\bar{l}_{iL}\gamma_\alpha l_{iL} + \bar{\nu}_{iL}\gamma_\alpha \nu_{iL}] + \bar{\nu}_{iR}\gamma_\alpha \nu_{iR}\right) - \sum_{i=1,3} \bar{l}_{iR}\gamma_\alpha l_{iR}\right]. \quad (2)$$

- Non-holomorphic soft SUSY-breaking terms:

$$-\mathcal{L}^{nh}_{soft} = \sum_{i=1}^{2}\sum_{j=1}^{3} C_E^{ij}(H_u^* \tilde{l}_i)\tilde{E}_j^c + C_D^{33} H_u^* \tilde{q}_3 \tilde{d}_3^c + H_u^* \sum_{i,j=1,2} C_D^{ij} \tilde{q}_i \tilde{d}_j^c$$
$$+ H_d^* \left(\tilde{q}_1 C_U^{13} + \tilde{q}_2 C_U^{23}\right)\tilde{u}_3^c + H_d^* \left(\tilde{l}_1 C_\nu^{13} + \tilde{l}_2 C_\nu^{23}\right)\tilde{\nu}_3^c + \text{h.c.} \quad (3)$$

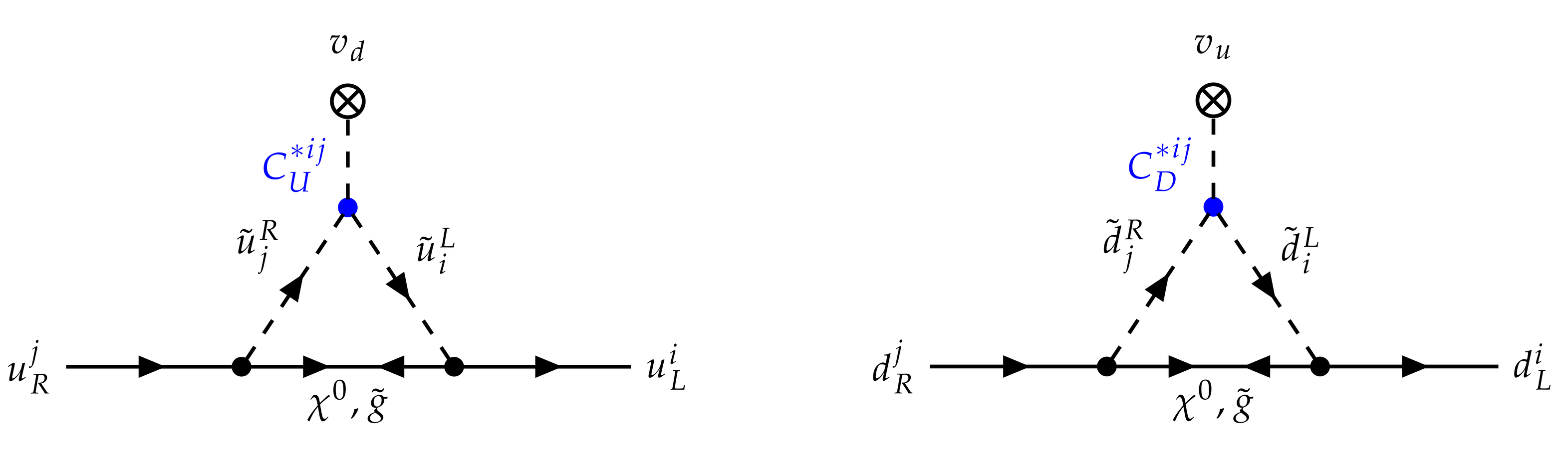


Figure 1: Some of the Feynman diagrams that give contributions $\kappa_u^{ij} \propto C_U^{*ij}$ (left) and $\kappa_d^{ij} \propto C_D^{*ij}$ (right) to the mass matrices m_u and m_d, respectively. Here $\chi_0, \tilde{g}$ denote Majorana neutralinos and gluinos.

WEFT

Including light RHN fields, the most general dimension-6 effective Hamiltonian relevant for $b \to s$ transitions can be written, at the bottom quark-mass scale, as

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi} V_{tb}V_{ts}^* \left[C_L^{SM}\delta_{\alpha\beta}O_L^{\alpha\beta} + \sum_{\alpha\beta}\left(\sum_{i=L^{(\prime)},R^{(\prime)}} C_i^{\alpha\beta}O_i^{\alpha\beta} + \sum_{j=9^{(\prime)},10^{(\prime)}} O_j^{\alpha\beta}C_j^{\alpha\beta}\right)\right.$$
$$\left. - \frac{(V_{tb}V_{ts}^*)}{\alpha_e}\sum_{i=LL,LR,RR} C_i^{bs}O_i^{bs}\right] + \text{h.c.}, \quad (4)$$

with four-fermion operators:

$$O_L^{\alpha\beta} = (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}^\alpha\gamma_\mu(1-\gamma_5)\nu^\beta), \qquad O_R^{\alpha\beta} = (\bar{s}_R\gamma^\mu b_R)(\bar{\nu}^\alpha\gamma_\mu(1-\gamma_5)\nu^\beta),$$
$$O_L^{\prime\alpha\beta} = (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}^\alpha\gamma_\mu(1+\gamma_5)\nu^\beta), \qquad O_R^{\prime\alpha\beta} = (\bar{s}_R\gamma^\mu b_R)(\bar{\nu}^\alpha\gamma_\mu(1+\gamma_5)\nu^\beta),$$
$$O_9^{\alpha\beta} = (\bar{s}_L\gamma^\mu b_L)(\bar{l}^\alpha\gamma_\mu l^\beta), \qquad O_{10}^{\alpha\beta} = (\bar{s}_L\gamma^\mu b_L)(\bar{l}^\alpha\gamma_\mu\gamma_5 l^\beta),$$
$$O_9^{\prime\alpha\beta} = (\bar{s}_R\gamma^\mu b_R)(\bar{l}^\alpha\gamma_\mu l^\beta), \qquad O_{10}^{\prime\alpha\beta} = (\bar{s}_R\gamma^\mu b_R)(\bar{l}^\alpha\gamma_\mu\gamma_5 l^\beta),$$
$$O_{LL(RR)}^{bs} = (\bar{s}_{L(R)}\gamma^\mu b_{L(R)})(\bar{s}_{L(R)}\gamma^\mu b_{L(R)}), \qquad O_{LR}^{bs} = (\bar{s}_L\gamma^\mu b_L)(\bar{s}_R\gamma^\mu b_R), \quad (5)$$

The SM contribution to C_9, C_{10} to NNLO accuracy, $C_L^{\alpha\alpha}$ to NLO and C_{LL}^{bs} at the scale $\mu = m_b = 4.8$ GeV is given by:

$$C_9^{SM} = 4.211, \qquad C_{10}^{SM} = -4.103, \qquad C_L^{\alpha\alpha} \equiv C_L^{SM} = -2X_t/s_w^2, \qquad X_t = 1.469 \pm 0.017, \quad (6)$$
$$C_{LL}^{bs(SM)} = \eta_{B_s}x_t\left[1 + \frac{9}{1-x_t} - \frac{6}{(1-x_t)^2} - \frac{6x_t^2\ln x_t}{(1-x_t)^3}\right], \qquad x_t \equiv m_t^2/m_W^2, \qquad \eta_{B_s} = 0.551. \quad (7)$$

After integrating out the heavy Z', we get the effective four-fermion Hamiltonian. The relevant terms in the effective Hamiltonian is given by

$$\mathcal{H}_{eff}^{Z'} = \frac{g_E^2}{2M_{Z'}^2}J_\alpha J^\alpha \supset \frac{g_E^2}{M_{Z'}^2}g_L^{bs}(\bar{s}\gamma^\alpha P_L b)[\bar{l}\gamma_\alpha(g_L^{ll'}P_L + g_R^{ll'}P_R)l']$$
$$+ \frac{g_E^2}{M_{Z'}^2}g_R^{bs}(\bar{s}\gamma^\alpha P_R b)[\bar{l}\gamma_\alpha(g_L^{ll'}P_L + g_R^{ll'}P_R)l]$$
$$+ \frac{g_E^2}{2M_{Z'}^2}(g_{L(R)}^{bs})^2(\bar{s}\gamma^\alpha P_{L(R)}b)(\bar{s}\gamma^\alpha P_{L(R)}b)$$
$$+ \frac{g_E^2}{M_{Z'}^2}(g_L^{bs})(g_R^{bs})(\bar{s}\gamma^\alpha P_L b)(\bar{s}\gamma^\alpha P_R b)$$
$$+ \frac{g_E^2}{M_{Z'}^2}g_L^{bs}(\bar{s}\gamma^\alpha P_L b)[\bar{\nu}\gamma_\alpha(g_L^{\nu\nu'}P_L + g_R^{\nu\nu'}P_R)\nu']$$
$$+ \frac{g_E^2}{M_{Z'}^2}g_R^{bs}(\bar{s}\gamma^\alpha P_R b)[\bar{\nu}\gamma_\alpha(g_L^{\nu\nu'}P_L + g_R^{\nu\nu'}P_R)\nu'] + \text{h.c.} \quad (8)$$

Here $M_{Z'}$ denotes the Z'-boson mass, g_E - $U(1)'$ gauge coupling. Comparing Eq. (8) with Eq. (4), one gets the expressions for the Wilson coefficients induced by the Z' exchange

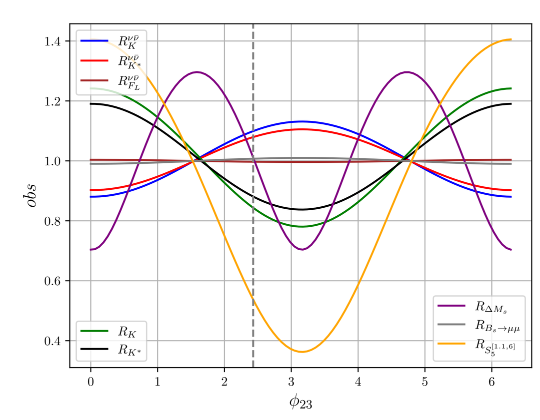
$$C_9^{ll'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_L^{bs}[g_R + g_L]^{ll'} \qquad C_9^{\prime ll'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_R^{bs}[g_R + g_L]^{ll'}, \quad (9)$$
$$C_{10}^{ll'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_L^{bs}[g_R - g_L]^{ll'} \qquad C_{10}^{\prime ll'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_R^{bs}[g_R - g_L]^{ll'}, \quad (10)$$
$$C_L^{\nu\nu'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_L^{bs}[g_L]^{\nu\nu'} \qquad C_L^{\prime\nu\nu'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_L^{bs}[g_R]^{\nu\nu'}, \quad (11)$$
$$C_R^{\nu\nu'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_R^{bs}[g_L]^{\nu\nu'} \qquad C_R^{\prime\nu\nu'} = \mathcal{N}\frac{g_E^2}{M_{Z'}^2}g_R^{bs}[g_R]^{\nu\nu'}, \quad (12)$$
$$C_{LL(RR)}^{bs} = -\frac{1}{4\sqrt{2}G_F(V_{tb}V_{ts}^*)^2}\frac{g_E^2}{M_{Z'}^2}(g_{L(R)}^{bs})^2$$
$$C_{LR}^{bs} = -\frac{1}{2\sqrt{2}G_F(V_{tb}V_{ts}^*)^2}\frac{g_E^2}{M_{Z'}^2}(g_L^{bs})(g_R^{bs}), \quad (13)$$

where the overall factor is given by $\mathcal{N} = -\frac{\pi}{\sqrt{2}G_F\alpha_e V_{tb}V_{ts}^*}$.

Model predictions

CP conserving $\quad \alpha_{13} = (2.0 \pm 4)\cdot 10^{-3}, \quad \alpha_{23} = -0.207 \pm 0.022, \quad \beta_{13} = 0.61 \pm 0.10, \quad \beta_{23} = 0 \pm 0.5, \quad M_{Z'}/g_E = 16.1 \pm 0.6\text{TeV}, \quad \phi_{13} = \phi_{23} = \chi_{13} = \chi_{23} = 0,$

CP violating $\quad \alpha_{13} = (8 \pm 2)\cdot 10^{-3}, \quad \alpha_{23} = 0.34 \pm 0.08, \quad \beta_{13} = 0.76 \pm 0.17, \quad \beta_{23} = 0.0 \pm 0.3, \quad M_{Z'}/g_E = 18.4 \pm 1.7\text{TeV}, \quad \phi_{23} = -0.65 \pm 0.24, \quad \chi_{13} = \chi_{23} = 0.$



Obs	SM	Exp	FIT$_1$	FIT$_2$
$R_K(B^+)^{[1.1,6.0]}$	1 ± 0.01	$0.949^{+0.042}_{-0.041} \pm 0.022$	0.894 ± 0.011	0.897 ± 0.012
$R_K^*(B^0)^{[1.1,6.0]}$	1 ± 0.01	$1.027^{+0.072}_{-0.068} \pm 0.027$	0.955 ± 0.025	0.923 ± 0.032
$P_5^{\prime[4,6]}$	-0.757 ± 0.077	$-0.439 \pm 0.111 \pm 0.036$	-0.53 ± 0.13	-0.56 ± 0.13
ΔM_{B_s}, ps^{-1}	18.77 ± 0.76	17.765 ± 0.004	17.74 ± 2.45	17.27 ± 1.19
$\mathcal{B}(B_s \to \mu\mu)\cdot 10^{-9}$	3.68 ± 0.14	3.45 ± 0.29	3.69 ± 0.23	3.68 ± 0.22
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \times 10^{-6}$	4.6 ± 0.5	$11 \pm 4, < 19$	5.38 ± 0.38	5.22 ± 0.34
$\mathcal{B}(B^0 \to K^0\nu\bar{\nu}) \times 10^{-6}$	4.1 ± 0.5	< 26	4.99 ± 0.31	4.83 ± 0.32
$\mathcal{B}(B^0 \to K^{0*}\nu\bar{\nu}) \times 10^{-6}$	9.6 ± 0.9	< 18	10.10 ± 1.46	10.30 ± 1.36
$\mathcal{B}(B^+ \to K^{+*}\nu\bar{\nu}) \times 10^{-6}$	9.6 ± 0.9	< 61	10.90 ± 1.33	11.10 ± 0.96
$F_L^{B^0 \to K^*\nu\bar{\nu}}$	0.47 ± 0.03	-	0.479 ± 0.05	0.484 ± 0.06
$R_K^{\nu\bar{\nu}}$	1	2.4 ± 0.9	1.14 ± 0.028	1.10 ± 0.024
$R_{K^*}^{\nu\bar{\nu}}$	1	< 1.9	1.07 ± 0.024	1.08 ± 0.022

	$A_7^{[1.1,6]}(\%)$	$A_8^{[1.1,6]}(\%)$	$A_9^{[1.1,6]}(\%)$	$A_{CP}^{[1.1,6]}(K^*)(\%)$	$A_{CP}^{[1.1,6]}(K)(\%)$	$A_{FB}^{[1.1,6]}(\%)$	$F_L^{[1.1,6]}$
EXP	$-4.5^{+5.0}_{-5.0} \pm 0.6$	$-4.7^{+5.8}_{-5.7} \pm 0.8$	$-3.3^{+4.0}_{-4.2} \pm 0.4$	-9.4 ± 4.7	0.4 ± 2.8	$-7.3 \pm 2.1 \pm 0.2$	$0.700 \pm 0.025 \pm 0.013$
FIT$_1$	0.24 ± 0.11	0.03 ± 0.04	0.02 ± 0.01	0.05 ± 0.09	0.09 ± 0.09	-5.31 ± 4.86	0.721 ± 0.061
FIT$_2$	0.32 ± 0.13	$\mathbf{-2.40 \pm 1.26}$	-0.24 ± 0.14	0.10 ± 0.68	-0.26 ± 0.78	-5.06 ± 5.02	0.715 ± 0.060

	$A_7^{[15,19]}(\%)$	$A_8^{[15,19]}(\%)$	$A_9^{[15,19]}(\%)$	$A_{CP}^{[15,19]}(K^*)(\%)$	$A_{CP}^{[15,19]}(K)(\%)$	$A_{FB}^{[15,19]}(\%)$	$F_L^{[15,19]}$
EXP	$-4.0^{+4.5}_{-4.4} \pm 0.6$	$2.5^{+4.8}_{-4.7} \pm 0.3$	$6.1^{+4.3}_{-4.4} \pm 0.2$	-7.4 ± 4.4	-0.5 ± 3.0	$35.3 \pm 2.0 \pm 1.0$	$0.345 \pm 0.020 \pm 0.007$
FIT$_1$	0.011 ± 0.08	-0.01 ± 0.02	-0.03 ± 0.02	-0.10 ± 0.05	-0.21 ± 0.11	31.72 ± 4.99	0.346 ± 0.043
FIT$_2$	0.014 ± 0.08	-0.44 ± 0.24	-0.69 ± 0.20	-1.18 ± 0.44	$\mathbf{-2.99 \pm 1.24}$	33.08 ± 4.86	0.341 ± 0.044

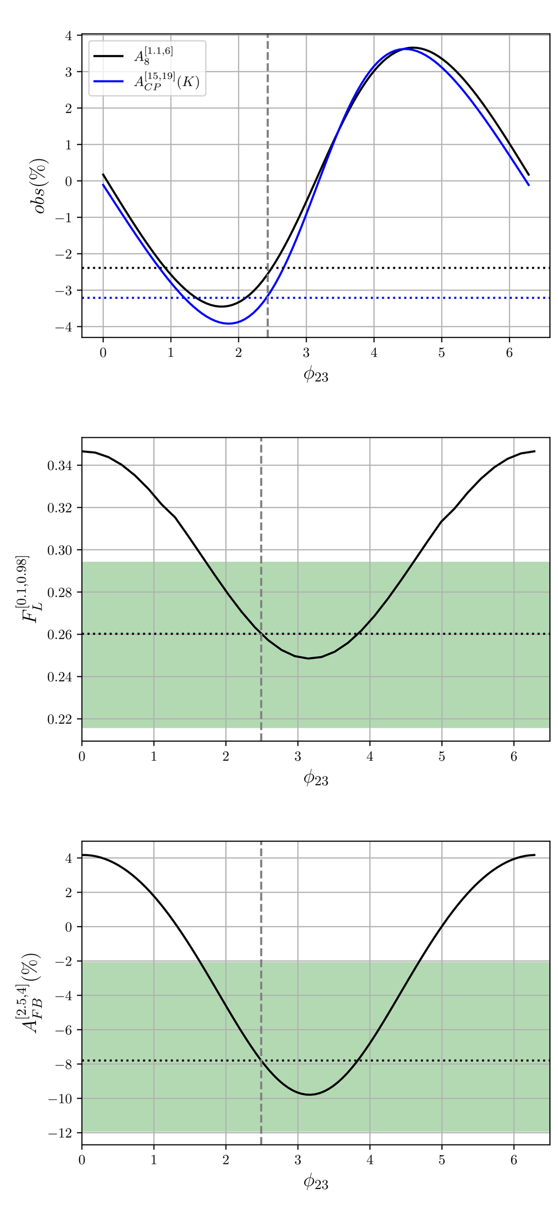


Figure 2: The new weak phase dependence of the $A_8^{[1.1,6]}$, $A_{CP}^{[15,19]}(K)$, $F_L^{[0.1,0.98]}$, $A_{FB}^{[2.5,4]}$ observables. Here green band is 1σ experimental limit. Dotted line is central value of model prediction for FIT$_2$.

Future prospects & Results

- A_i, S_i and A_{CP} measurements for $B^0 \to K^*\mu^+\mu^-$ decay:
  - $3 fb^{-1}$ [JHEP 02 (2016) 104]: $\sim 4 - 6\%$
  - $4.7 fb^{-1}$ [Phys.Rev.Lett. 125 (2020) 1, 011802]: $\sim 2 - 4\%$
  - $50 fb^{-1}$ [LHCb:2022ine]: $\sim 1 - 1.5\%$
  - $300 fb^{-1}$ [LHCb:2022ine]: $\sim 0.4 - 0.6\%$

  Thus, the enhancements in A_8 and $A_{CP}(K)$ predicted by FIT$_2$ can be tested experimentally.
- Dineutrino modes [Belle-II:2022cgf] $50ab^{-1}$: $R_K^{\nu\bar{\nu}}$ 0.08 and $R_{K^*}^{\nu\bar{\nu}}$ 0.23. Obviously, this is not enough to favour or exclude our benchmark points. Nevertheless, some scenarios lying in the vicinity of the FIT$_2$, predict $R_K^{\nu\bar{\nu}} \sim 1.3 - 1.35$, and, thus, can be probed by future Belle II measurements.

1. Sizeable CP violation in $B^0 \to K^*\mu^+\mu^-$ observables, for example, in $A_8^{[1.1,6]}$, $A_{CP}^{[15,19]}(K)$ and $A_{CP}^{[15,19]}(K^*)$, is predicted;
2. Have found that $A_{CP}(K^{(*)})$ can be enhanced only in high-q^2 region up to $\sim -8\%$ for K-mode and up to $\sim -4\%$ for K^*-mode;
3. Have observed that the triple product A_7, A_8, A_9 asymmetries are more prominent to the new CP violating phase, and can attain a few percent in the central- and high-q^2;
4. Estimated future prospects of A_i, S_i and A_{CP} measurements for $B^0 \to K^*\mu^+\mu^-$ decay and for dineutrino modes.