Analysis of $B \to K^{(*)}\nu\bar{\nu}$ decays
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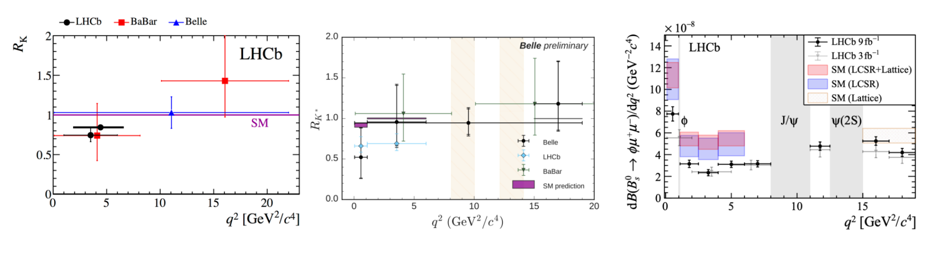
Outline

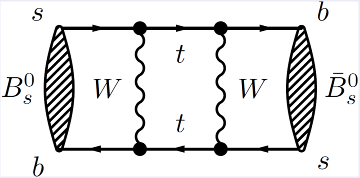
FCNC transitions

- Tensions in FCNC decay rate ratios $R_{K^{(*)}} \equiv \frac{BR(B\to K^{(*)}\mu\mu)}{BR(B\to K^{(*)}ee)}$



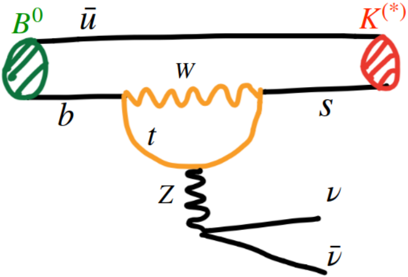
$\sim 3.1\sigma$ in R_K [Aaij:2021vac] and $\sim 2.5\sigma$ in R_{K^*} [JHEP(2017)055]

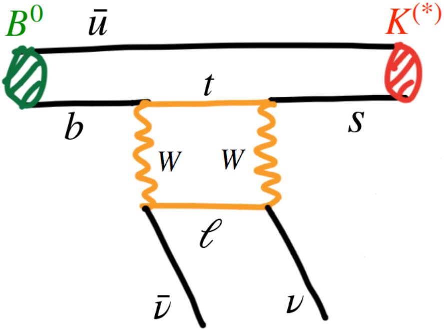
- The mass difference of the neutral $B_s - \bar{B}_s$ meson system [Amhis:2019ckw]



$$\Delta M_s^{exp} = (17.757 \pm 0.021)\ \text{ps}^{-1},$$
$$\Delta M_s^{SM} = (18.4^{+0.7}_{-1.2})\ \text{ps}^{-1}$$

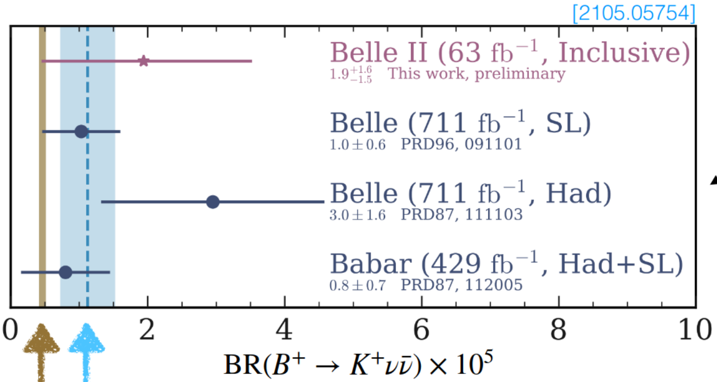
$b \to s\nu\bar{\nu}$ decays

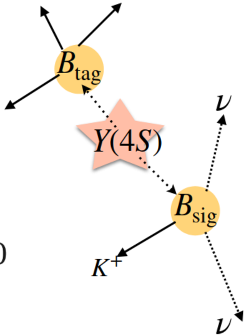




- $B \to K^{(*)}\nu\bar{\nu}$ theoretically much cleaner than $B \to K^* l^+ l^-$;
- Experimentally quite challenging due to two missing neutrinos — No signal has been observed so far.

- Inclusive tagging technique from Belle II has higher efficiency $\sim 4\%$





$\mathrm{Exp}_{\rm avg} = (1.1 \pm 0.4) \times 10^{-5}$

$\mathrm{SM} = (4.6 \pm 0.5) \times 10^{-6}$

$$R_K^\nu = 2.4 \pm 0.9$$

Effective Electroweak Hamiltonian for $b \to s$ FCNCs

- Theoretically, calculations are convenient to do within the Effective Electroweak Hamiltonian approach

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_{EM}}{4\pi}V_{tb}V_{ts}^* \left(C_L^{SM}\delta_{\alpha\beta}O_L^{\alpha\beta} + \sum_{\alpha\beta}\left(\sum_{i=L^{(\prime)},R^{(\prime)}} C_i^{\alpha\beta}O_i^{\alpha\beta} + \sum_{j=9^{(\prime)},10^{(\prime)}} O_j^{\alpha\beta}C_j^{\alpha\beta} \right)\right) \tag{1}$$

- G_F – Fermi constant
  $V_{tb}V_{ts}^*$ – CKM matrix element
  $C_i(\mu)$ – Wilson coefficients
  $O_i(\mu)$ – Four-fermion operators for $b \to s$ transition

Operator Basis

- For most phenomenological applications, only operators $O_i(\mu)$ of the dimension d = 6 are relevant

$$
\begin{aligned}
O_L^{\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}^\alpha \gamma_\mu (1-\gamma_5)\nu^\beta), & O_R^{\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{\nu}^\alpha \gamma_\mu (1-\gamma_5)\nu^\beta), \\
O_L^{\prime\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}^\alpha \gamma_\mu (1+\gamma_5)\nu^\beta), & O_R^{\prime\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{\nu}^\alpha \gamma_\mu (1+\gamma_5)\nu^\beta), \\
O_9^{\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{l}^\alpha \gamma_\mu l^\beta), & O_{10}^{\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{l}^\alpha \gamma_\mu \gamma_5 l^\beta), \\
O_9^{\prime\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{l}^\alpha \gamma_\mu l^\beta), & O_{10}^{\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{l}^\alpha \gamma_\mu \gamma_5 l^\beta).
\end{aligned}
\tag{2}
$$

- SM FCNC contribution

$$
C_L^{SM} = -2X_t/s_w^2 = -12.7, \qquad C_9^{SM} = 4.211 \qquad C_{10}^{SM} = -4.103
$$

- Correlation between $C_{9,10} \leftrightarrow C_L$ and $C'_{9,10} \leftrightarrow C_R$

Observables for $b \to s\nu\bar{\nu}$

Observable	SM prediction LQCD+LCSR	Exp. constraint (90% CL)	Belle II 5ab^{-1}	Belle II 50ab^{-1}
$\mathcal{B}(B^0 \to K^0\nu\bar{\nu}) \cdot 10^{-6}$	4.1 ± 0.5	< 26		
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \cdot 10^{-6}$	4.6 ± 0.5	$11 \pm 4, < 19$	30%	11%
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) \cdot 10^{-6}$	9.6 ± 0.9	< 18	26%	9.6%
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu}) \cdot 10^{-6}$	9.6 ± 0.9	< 61	25%	9.3%
$F_L(B \to K^*\nu\bar{\nu})$	0.47 ± 0.03			0.079
$R_K^{\nu\bar{\nu}}(B^+)$	1	2.4 ± 0.9		
$R_{K^*}^{\nu\bar{\nu}}(B^0)$	1	< 1.9		

Таблица: The last two columns list the Belle II sensitivities to exclusive B-meson decays to a $K^{(*)}$ meson [Belle-II:2018jsg] if the respective SM predictions are assumed. We estimate $R_{K^{(*)}}$ from the values in the second and third columns for the corresponding modes. The current constraint for $B^+ \to K^+\nu\bar{\nu}$ is the world average for the branching fraction presented in [Dattola:2021cmw].

$U\nu_R MSSM$ 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

$U\nu_R MSSM$ description

- Superpotential:

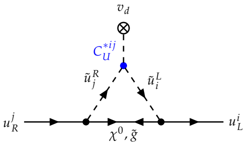
$$W = \sum_{i,j=1,2} Y_u^{ij} Q_i H_u U_j^c + Y_u^{33} Q_3 H_u U_3^c - (Q_3 H_d)(Y_d^{31} D_1^c + Y_d^{32} D_2^c)$$
$$+ \sum_{i,j=1,2} Y_\nu^{ij} L_i H_u \nu_j^c + M_3^\nu \nu_3^c \nu_3^c + Y_\nu^{33} L_3 H_u \nu_3^c$$
$$- (L_3 H_d)\left(Y_e^{31} E_1^c + Y_e^{32} E_2^c + Y_e^{33} E_c^3\right) + \lambda_s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

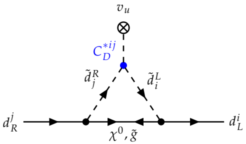
- The gauge field Z' couples to quarks and leptons as

$$\mathcal{L} \ni g_E Z'_\alpha \left[\bar{b}\gamma_\alpha b + \bar{t}\gamma_\alpha t\right]$$
$$- g_E Z'_\alpha \left[\sum_{i=1,2} ([\bar{l}_{iL}\gamma_\alpha l_{iL} + \bar{\nu}_{iL}\gamma_\alpha \nu_{iL}] + \bar{\nu}_{iR}\gamma_\alpha \nu_{iR}) - \sum_{i=1,3} \bar{l}_{iR}\gamma_\alpha l_{iR}\right]. \qquad (4)$$

- Non-holomorphic soft SUSY-breaking terms:

$$-\mathcal{L}_{soft}^{nh} = \sum_{i=1}^{2}\sum_{j=1}^{3} C_E^{ij} (H_u^* \tilde{l}_i) \tilde{E}_j^c + C_D^{33} H_u^* \tilde{q}_3 \tilde{d}_3^c + H_u^* \sum_{i,j=1,2} C_D^{ij} \tilde{q}_i \tilde{d}_j^c$$
$$+ H_d^* \left(\tilde{q}_1 C_U^{13} + \tilde{q}_2 C_U^{23}\right) \tilde{u}_3^c + H_d^* \left(\tilde{l}_1 C_\nu^{13} + \tilde{l}_2 C_\nu^{23}\right) \tilde{\nu}_3^c + \text{h.c.}. \qquad (5)$$





Numerical equations for $b \to s\nu\bar{\nu}$ transition

$$R_K^{\nu\bar{\nu}} = \Bigg[1 - 0.1041 \sum_\alpha \mathrm{Re}\,(C_L^{\alpha\alpha} + C_R^{\alpha\alpha}) + 0.0081 \sum_{\alpha\beta} \Big\{ \underbrace{\left|C_L^{\alpha\beta} + C_R^{\alpha\beta}\right|^2}_{\text{LH neutrino}} + \underbrace{\left|C_L^{\prime\alpha\beta} + C_R^{\prime\alpha\beta}\right|^2}_{\text{RH neutrino}} \Big\} \Bigg], \quad (6)$$

$$R_{K^*}^{\nu\bar{\nu}} = \Bigg[1 - 0.1041 \sum_\alpha \mathrm{Re}\,(C_L^{\alpha\alpha}) + 0.0692 \sum_\alpha \mathrm{Re}\,(C_R^{\alpha\alpha}) + 0.00135 \sum_{\alpha\beta} \Big\{ \underbrace{\left|C_R^{\alpha\beta} + C_L^{\alpha\beta}\right|^2}_{\text{LH neutrino}} + \underbrace{\left|C_R^{\prime\alpha\beta} + C_L^{\prime\alpha\beta}\right|^2}_{\text{RH neutrino}} \Big\} + 0.00675 \sum_{\alpha\beta} \Big\{ \underbrace{\left|C_R^{\alpha\beta} - C_L^{\alpha\beta}\right|^2}_{\text{LH neutrino}} + \underbrace{\left|C_R^{\prime\alpha\beta} - C_L^{\prime\alpha\beta}\right|^2}_{\text{RH neutrino}} \Big\} \Bigg], \quad (7)$$

$$R_{F_L}^{\nu\bar{\nu}} \cdot R_{K^*}^{\nu\bar{\nu}} = \Bigg[1 + 0.1041 \sum_\alpha \mathrm{Re}\,(C_R^{\alpha\alpha} - C_L^{\alpha\alpha}) + 0.0081 \sum_{\alpha\beta} \Big[|C_L^{\alpha\beta} - C_R^{\alpha\beta}|^2 + |C_L^{\prime\alpha\beta} - C_R^{\prime\alpha\beta}|^2 \Big] \Bigg]. \quad (8)$$

Model independent analysis: Single operator contribution

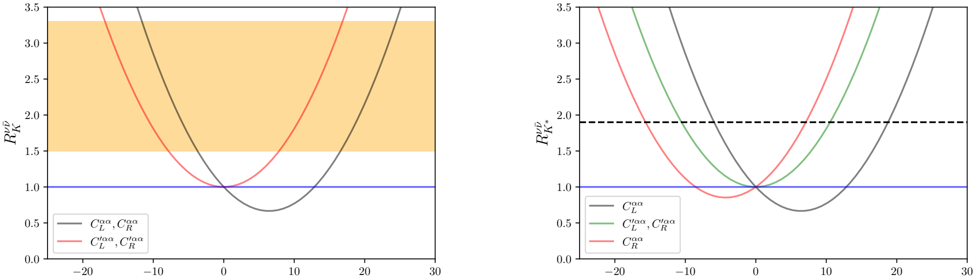
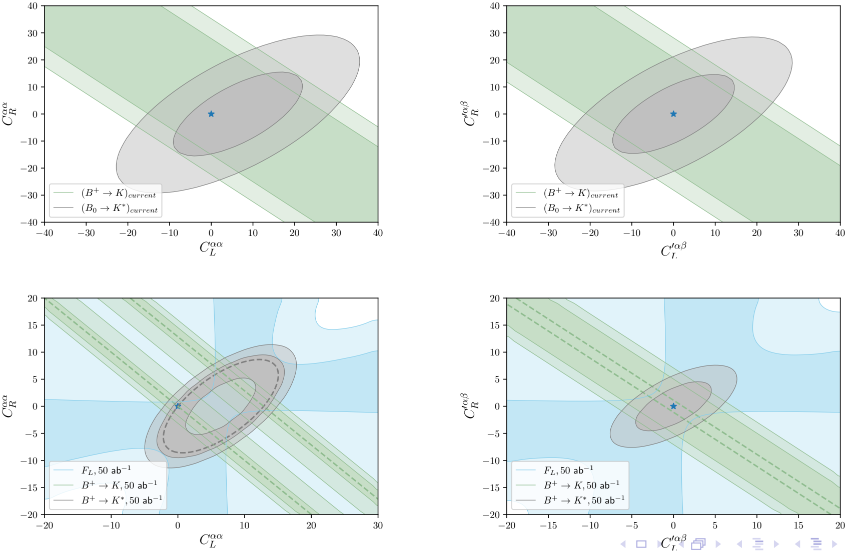


Рис.: Variations of flavor diagonal individual NP Wilson coefficients (assuming contributions from all three generations are equal) are shown for the observables $R_K^{\nu\bar{\nu}}$ and $R_{K^*}^{\nu\bar{\nu}}$ in the left and right panels, respectively. The orange band in the left panel show the $\pm 1\sigma$ signal strength quoted in Tab.1, whereas the black dashed line in the right panel is the upper bound given in Tab.1.

WC	Current bound Value	NP scale (TeV)	Observable	Future Sensitivity (50ab^{-1}) Value	NP scale (TeV)
$C_L^{\alpha\alpha} > 0$	26 (16) 19	6.7 (8.6) 8	$B \to K$ $B \to K^*$	15	8.9
$C_L^{\alpha\alpha} < 0$	13 (4) 6	8.5 (17) 14	$B \to K$ $B \to K^*$	3	20
$C_R^{\alpha\alpha} > 0$	26 (16) 7	6.7 (8.6) 13	$B \to K$ $B \to K^*$	3.2	19
$C_R^{\alpha\alpha} < 0$	13 (4) 16	8.5 (17) 8.6	$B \to K$ $B \to K^*$	11.7	10
$C_{L(R)}^{\alpha\neq\beta}, C_{L(R)}^{\prime\alpha\beta}$	18 (8) 10	8 (12) 11	$B \to K$ $B \to K^*$	6.1	13.9

Таблица: Bounds imposed on the absolute value of the respective Wilson coefficients if only one of them gets (sizeable) contributions from new physics at a time, both for the current situation and for the projections for the 50ab^{-1} Belle II data set. In the latter case we assume that future measurement would confirm the SM predictions and $R_{K^{(*)}} > 1.3$ is excluded at $\approx 3\sigma$. We also provide rough estimates for the corresponding new physics scale and the observables from which the respective bound arises. Note that, we give upper (lower) current bounds on WCs for $B \to K$, originating from $B^+ \to K^+\nu\bar{\nu}$ world average.

Two operator contribution: Parameter space which is compatible with the $1(3)\sigma$ current (future) bounds on $B^+ \to K^+ \nu\bar{\nu}$ and $B^0 \to K^* \nu\bar{\nu}$

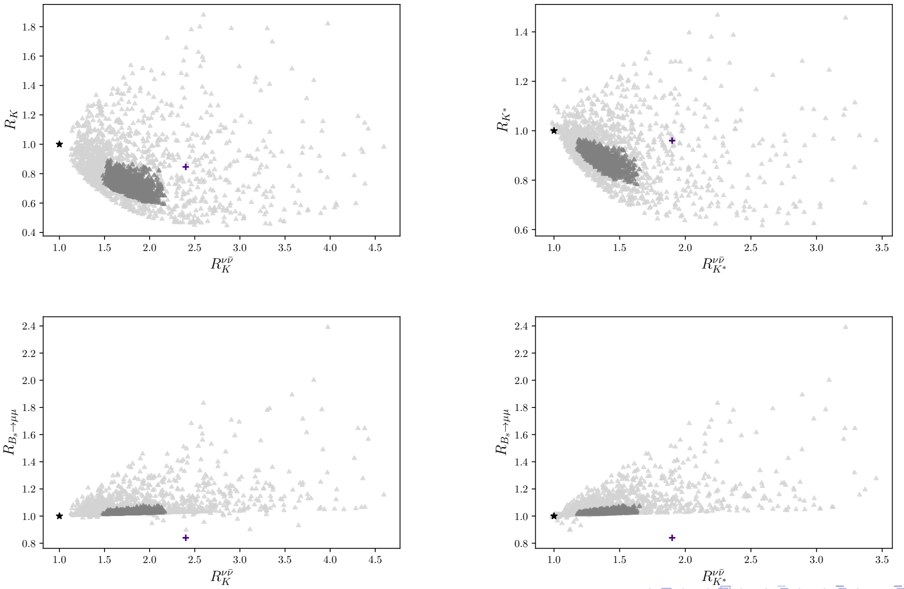


Model dependent analysis: Predictions

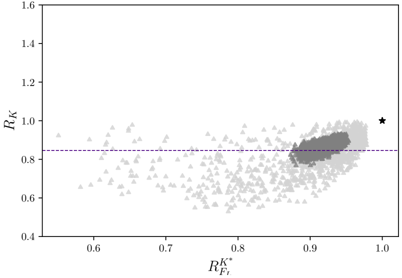
Obs	SM	Exp	FIT
$R_K(B^+)^{[1.1,6.0]}$	1 ± 0.01 [1], [2]	$0.846^{+0.044}_{-0.041}$ [3]	0.845 ± 0.05
$R_K^*(B^0)^{[1.1,6.0]}$	1 ± 0.01 [1], [2]	$0.96^{+0.45}_{-0.29} \pm 0.11$ [4] $0.69^{+0.113}_{-0.069} \pm 0.05$ [5]	0.93 ± 0.03
$P_5'^{[4,6]}$	-0.757 ± 0.077 [6]	$-0.439 \pm 0.111 \pm 0.036$[7]	-0.52 ± 0.14
ΔM_{B_s}, ps^{-1}	18.77 ± 0.76 [8]	17.765 ± 0.004 [9]	18.51 ± 2.30
$BR(B_s \to \mu\mu) \cdot 10^{-9}$	3.68 ± 0.14 [10]	$3.09^{+0.46+0.15}_{-0.43-0.11}$[11]	3.69 ± 0.16
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \times 10^{-6}$	4.6 ± 0.5 [12]	11 ± 4[13],< 19[14]	5.05 ± 0.80
$\mathcal{B}(B^0 \to K^0\nu\bar{\nu}) \times 10^{-6}$	4.1 ± 0.5 [15]	< 26 [14]	4.67 ± 0.92
$\mathcal{B}(B^0 \to K^{0*}\nu\bar{\nu}) \times 10^{-6}$	9.6 ± 0.9 [12]	< 18 [14]	10.20 ± 0.96
$\mathcal{B}(B^+ \to K^{+*}\nu\bar{\nu}) \times 10^{-6}$	9.6 ± 0.9 [12]	< 61 [14]	11.00 ± 0.90
$F_L^{B^0 \to K^* \nu\bar{\nu}}$	0.47 ± 0.03 [16]	-	0.696 ± 0.04
$R_K^{\nu\bar{\nu}}$	1	2.4 ± 0.9	1.14 ± 0.45
$R_{K^*}^{\nu\bar{\nu}}$	1	< 1.9	1.07 ± 0.66

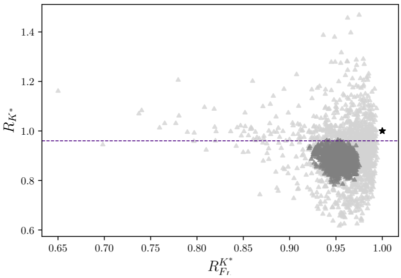
Таблица: Model predictions for $b \to sll$ and $b \to s\nu\bar{\nu}$ observables.

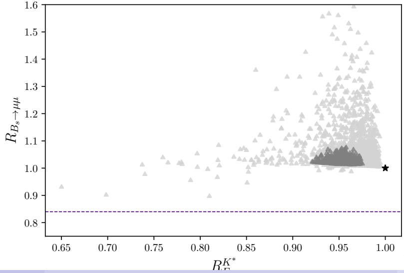
Correlations between $b \to sll$ and $b \to s\nu\bar{\nu}$



Correlations between $b \to sll$ and $b \to s\nu\bar{\nu}$







Results

- $B \to K^{(*)}\nu\bar{\nu}$ are important probe for new physics
- Experimental challenges might be overcome with inclusive tag technique@Belle II — expecting signal soon?!
- We have studied how new physics contributing to $b \to s\nu\bar{\nu}$ transition is constrained by current bounds on the branching ratios of $B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$ and what improvements can be expected from the projected measurement of these processes at Belle II
- Have found regions in the space of WC compatible with current and future experimental bounds
- Analysed dineutrino decays in SUSY model with additional U(1) group
- Considered correlations between $b \to sll$ and $b \to s\nu\bar{\nu}$ transitions

Thank you for your attention!

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