

# A Tale of Invisibility: Constraints on New Physics in $b \rightarrow s\nu\bar{\nu}$

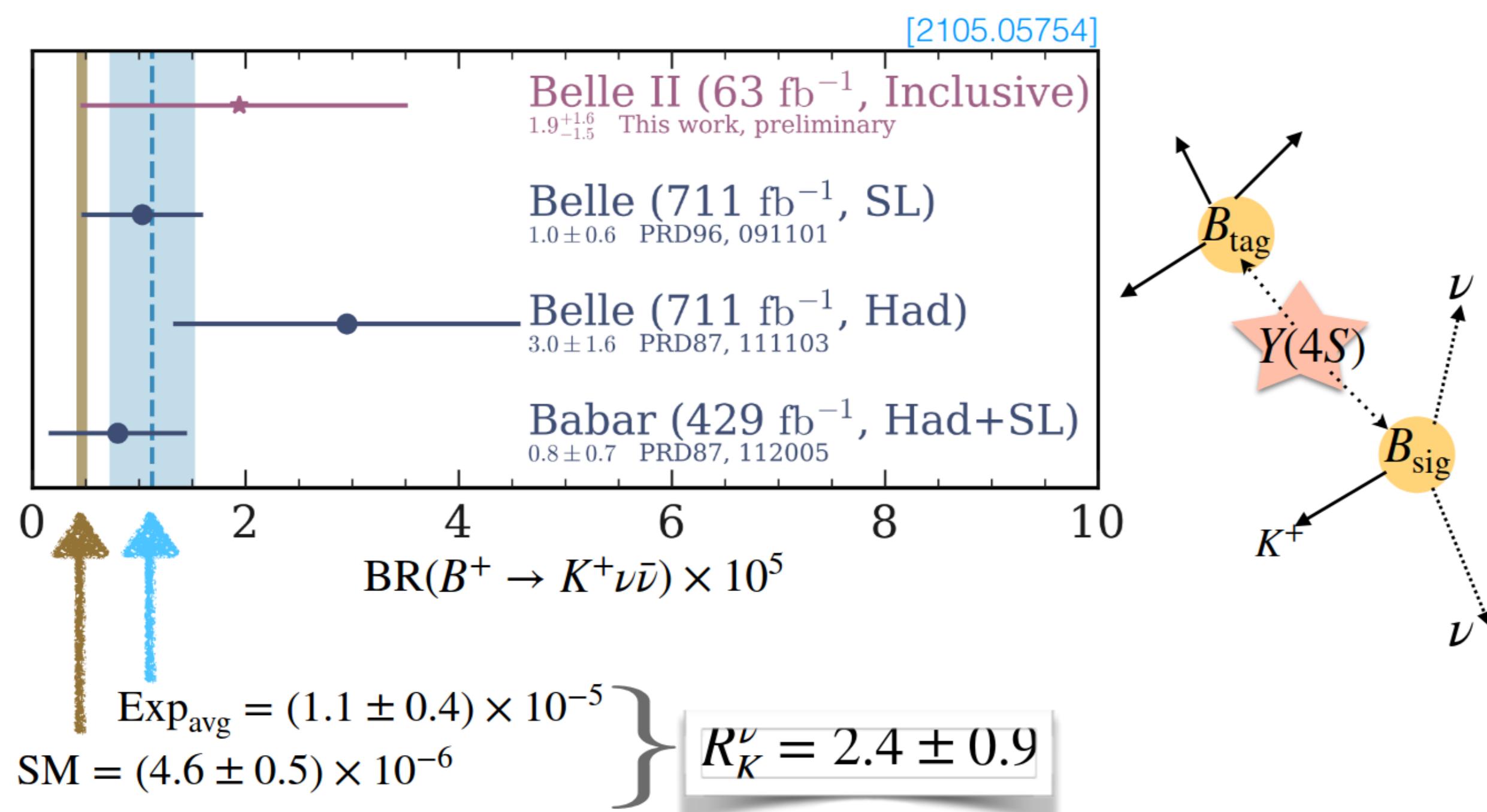
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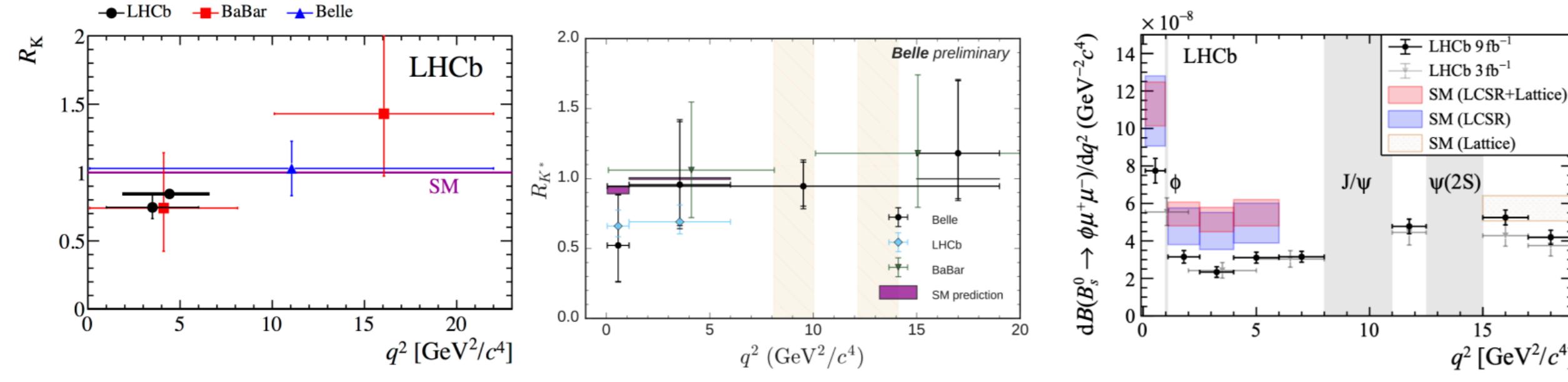


## Motivation

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



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



$\sim 3.1\sigma$  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:2019ekw]
 
$$\Delta M_s^{exp} = (17.757 \pm 0.021) \text{ ps}^{-1},$$

$$\Delta M_s^{SM} = (18.4^{+0.7}_{-1.2}) \text{ ps}^{-1}.$$

## 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  $\nu_{1,2,3}^c$ :
 

field	$Q'$	field	$Q'$	field	$Q'$
$Q_{1,2}$	0	$U_{1,2}^c$	0	$D_{1,2}^c$	0
$Q_3$	+1	$U_3^c$	-1	$D_3^c$	-1
$L_{1,2}$	-1	$E_{1,2}^c$	+1	$\nu_{1,2}^c$	+1
$L_3$	0	$E_3^c$	+1	$\nu_3^c$	0
$H_d$	-1	$H_u$	0	$S$	+1
- Non-universal charges for ACCs:

field	$Q'$	field	$Q'$	field	$Q'$
$Q_{1,2}$	0	$U_{1,2}^c$	0	$D_{1,2}^c$	0
$Q_3$	+1	$U_3^c$	-1	$D_3^c$	-1
$L_{1,2}$	-1	$E_{1,2}^c$	+1	$\nu_{1,2}^c$	+1
$L_3$	0	$E_3^c$	+1	$\nu_3^c$	0
$H_d$	-1	$H_u$	0	$S$	+1

- Superpotential:

$$W = \sum_{i,j=1,2} Y_u^{ij} Q_i H_u U_j^c + Y_u^{33} Q_3 H_u U_3^c - (Q_3 H_d)(Y_d^{31} D_1^c + Y_d^{32} D_2^c) \\ + \sum_{i,j=1,2} Y_\nu^{ij} L_i H_u \nu_j^c + M_3^\nu \nu_3^c \nu_3^c + Y_\nu^{33} L_3 H_u \nu_3^c \\ - (L_3 H_d) (Y_e^{31} E_1^c + Y_e^{32} E_2^c + Y_e^{33} E_3^c) + \lambda_s S H_u H_d \quad (1)$$

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

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

- Non-holomorphic soft SUSY-breaking terms:

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

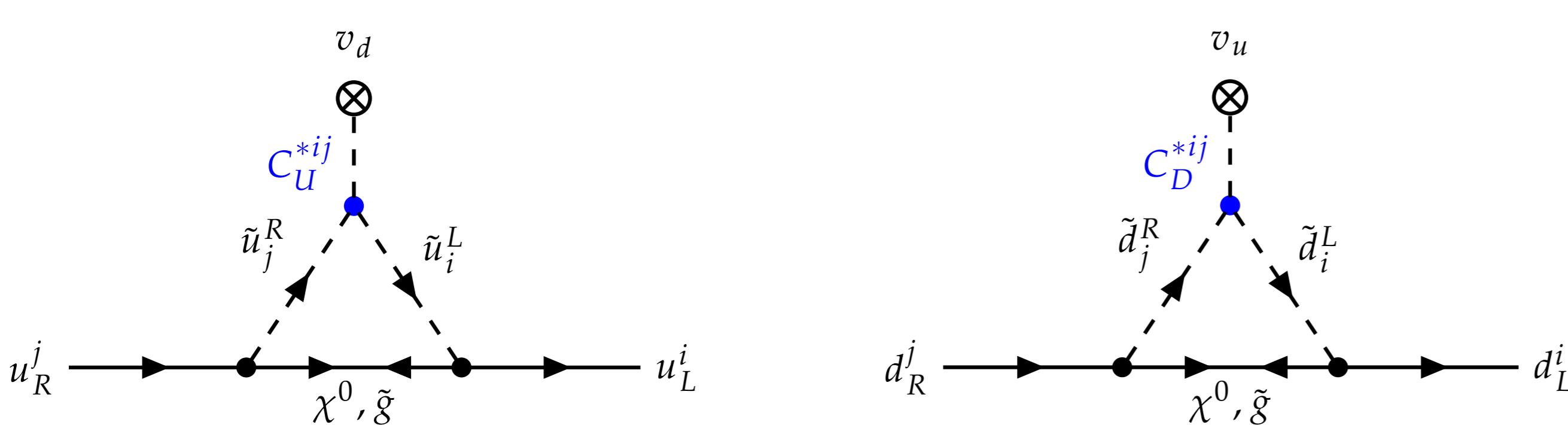


Figure 1: Some of the Feynman diagrams that give contributions  $\kappa_u^{ij} \propto C_U^{ij}$  (left) and  $\kappa_d^{ij} \propto C_D^{ij}$  (right) to the mass matrices  $m_u$  and  $m_d$ , respectively. Here  $\chi_0, g$  denote Majorana neutralinos and gluinos.

## WEFT

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

$$\mathcal{H}_{eff} = -\frac{4G_F \alpha_{EM}}{\sqrt{2} 4\pi} V_{tb} V_{ts}^* \left( C_L^{SM} \delta_{\alpha\beta} O_L^{\alpha\beta} + \sum_{\alpha\beta} \left( \sum_{A=L^{(\prime)}, R^{(\prime)}} C_A^{\alpha\beta} O_A^{\alpha\beta} + \sum_{B=9^{(\prime)}, 10^{(\prime)}} O_B^{\alpha\beta} C_B^{\alpha\beta} \right) \right) + \text{h.c.}, \quad (4)$$

with four-fermion operators:

$$\begin{aligned} O_L^{\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}^\alpha \gamma_\mu (1 - \gamma_5) \nu^\beta), & O_R^{\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{\nu}^\alpha \gamma_\mu (1 - \gamma_5) \nu^\beta), \\ O_L^{\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}^\alpha \gamma_\mu (1 + \gamma_5) \nu^\beta), & O_R^{\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{\nu}^\alpha \gamma_\mu (1 + \gamma_5) \nu^\beta), \\ O_9^{\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{l}^\alpha \gamma_\mu l^\beta), & O_{10}^{\alpha\beta} &= (\bar{s}_L \gamma^\mu b_L)(\bar{l}^\alpha \gamma_\mu \gamma_5 l^\beta), \\ O_9^{\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{l}^\alpha \gamma_\mu l^\beta), & O_{10}^{\alpha\beta} &= (\bar{s}_R \gamma^\mu b_R)(\bar{l}^\alpha \gamma_\mu \gamma_5 l^\beta). \end{aligned} \quad (5)$$

The SM FCNC contribution to  $O_A^{\alpha\beta}$  has been explicitly added to Eq. (4), where the Wilson coefficient:

$$C_L^{SM} = -2X_t/s_w^2 \quad (6)$$

with  $X_t = 1.469 \pm 0.017$  (includes NLO QCD corrections and two-loop electroweak contributions).

## Numerical equations

$$\frac{\text{Br}(B \rightarrow K\nu\bar{\nu})}{\text{Br}(B \rightarrow K\nu\bar{\nu})_{SM}} = \left[ 1 - 0.104 \sum_{\alpha} \text{Re} (C_L^{\alpha\alpha} + C_R^{\alpha\alpha}) + 0.008 \sum_{\alpha\beta} \left\{ \underbrace{|C_L^{\alpha\beta} + C_R^{\alpha\beta}|^2}_{\text{LH neutrino}} + \underbrace{|C_L'^{\alpha\beta} + C_R'^{\alpha\beta}|^2}_{\text{RH neutrino}} \right\} \pm 0.14 \right], \quad (7)$$

$$\frac{\text{Br}(B \rightarrow K^*\nu\bar{\nu})}{\text{Br}(B \rightarrow K^*\nu\bar{\nu})_{SM}} = \left[ 1 - 0.104 \sum_{\alpha} \text{Re} (C_L^{\alpha\alpha}) + 0.069 \sum_{\alpha} \text{Re} (C_R^{\alpha\alpha}) + 0.008 \sum_{\alpha\beta} \left\{ \underbrace{|C_L^{\alpha\beta}|^2 + |C_R^{\alpha\beta}|^2}_{\text{LH neutrino}} + \underbrace{|C_L'^{\alpha\beta}|^2 + |C_R'^{\alpha\beta}|^2}_{\text{RH neutrino}} \right\} - 0.011 \text{Re} (C_L^{\alpha\beta} C_R^{*\alpha\beta} + C_L'^{\alpha\beta} C_R'^{*,\alpha\beta}) \right] \pm 0.10. \quad (8)$$

## Model predictions

Obs	SM	Exp	NP
$R_K(B_0)$	$1 \pm 0.01$	$0.846 \pm 0.021$	$0.88 \pm 0.016$
$R_K^*(B_0)$	$0.996 \pm 0.01$	$0.69 \pm 0.05$	$0.79 \pm 0.07$
$P_5'$	$-0.757 \pm 0.077$	$-0.439 \pm 0.111 \pm 0.036$	$-0.51 \pm 0.097$
$\Delta M_{B_s}, \text{ps}^{-1}$	$18.98^{+0.7}_{-1.2}$	$17.757 \pm 0.021$	$18.2 \pm 0.0365$
$BR(B_s \rightarrow \mu\mu)$	$(3.67 \pm 0.14) \cdot 10^{-9}$	$3.09^{+0.46+0.15}_{-0.43-0.11} \cdot 10^{-9}$	$(3.3 \pm 0.16) \cdot 10^{-9}$
$BR(B_d \rightarrow \mu\mu)$	$1.1426 \cdot 10^{-10}$	$1.5^{+1.2+0.2}_{-1.0-0.1} \cdot 10^{-10}$	$(1.4 \pm 0.13) \cdot 10^{-10}$
$R_K^{\nu\bar{\nu}}$	1	$2.4 \pm 0.9$	$2.35 \pm 1.22$
$R_K^{\nu\bar{\nu}}_{K^*}$	1	$< 1.9$	1.6

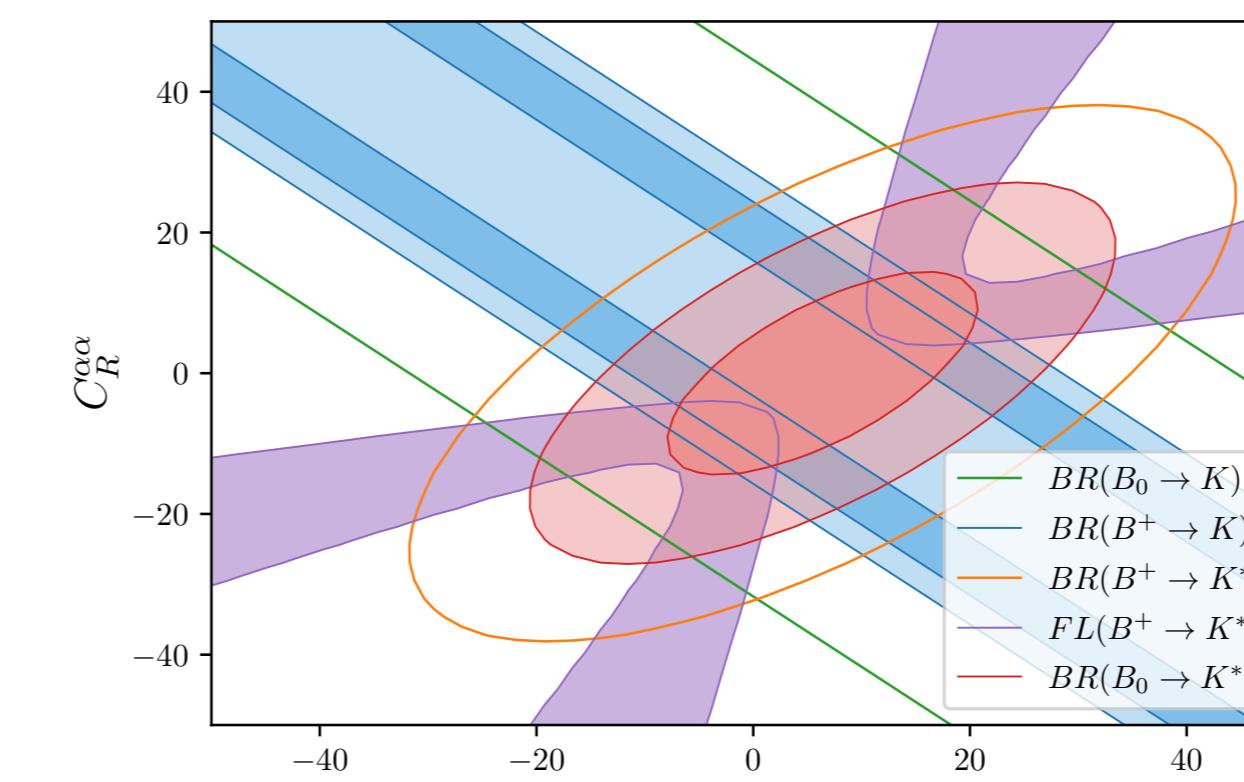


Figure 2: The allowed parameter space for the Wilson coefficients for several  $b \rightarrow s\nu\bar{\nu}$  observables will confirm the SM predictions. In the shown cases, interference with the SM occurs for the left figure, for the right figure no interference with the SM contribution. For the neutrino flavor indices,  $\alpha, \beta \subset (1, 2, 3)$ .

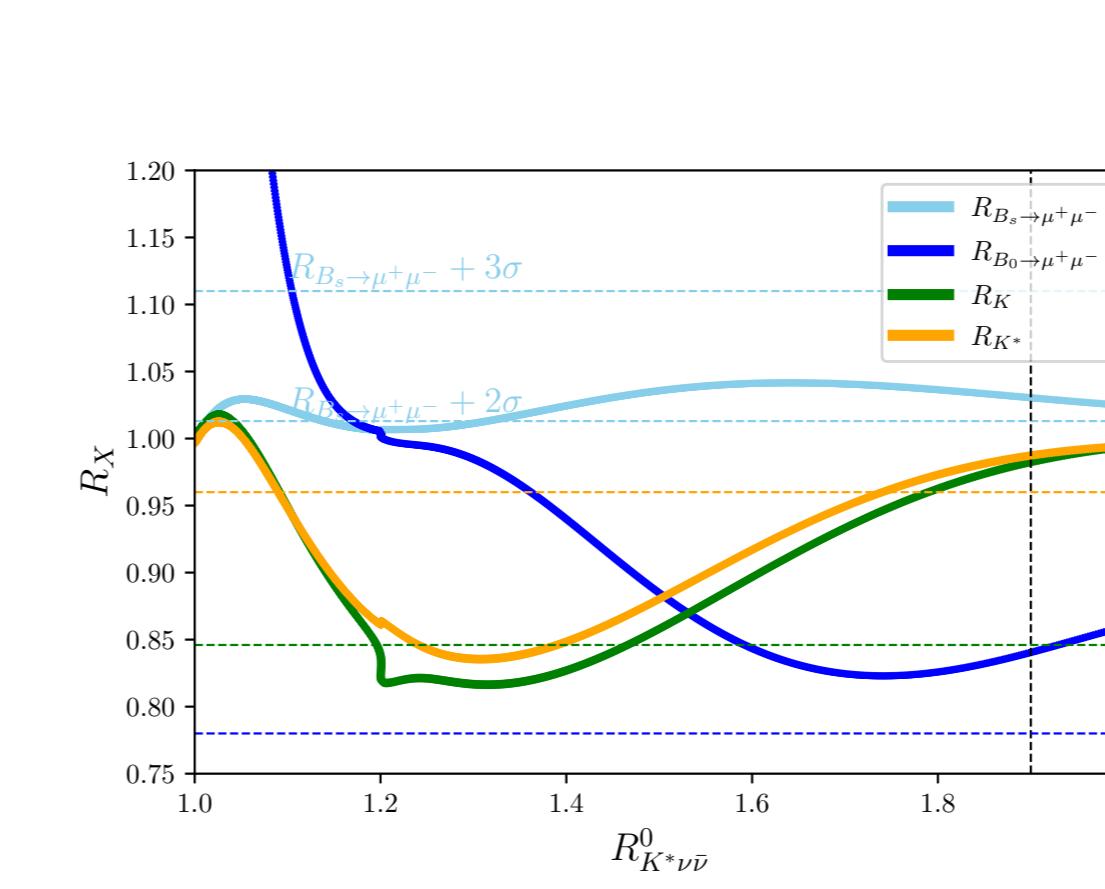


Figure 3: Correlations between  $b \rightarrow sll$  and  $b \rightarrow s\nu\bar{\nu}$  observables.

## Conclusion

- $B \rightarrow K^{(*)}\nu\bar{\nu}$  are important probe for new physics;
- Experimental challenges might be overcome with inclusive tag technique@Belle II — expecting signal soon!?
- Possibilities to connect the indicated excess with neutral current B-anomalies in ‘simplified’ models;
- Heavy  $Z'$  explaining  $b \rightarrow s\mu\mu$  with minimal setup can enhance  $B^+ \rightarrow K^+\nu\bar{\nu}$ ;
- $b \rightarrow s\nu\bar{\nu}$  processes exhibit different sensitivity to operators  $C_L^{(\prime)\alpha\beta}, C_R^{(\prime)\alpha\beta}$ .