$B \to K\nu\bar{\nu}$ *measurement and new physics interpretation*

Rusa Mandal
Universität Siegen

on arXiv: 2107.01080

with Thomas Browder, N.G. Deshpande & Rahul Sinha

UNIVERSITÄT SIEGEN
Alexander von Humboldt Stiftung/Foundation

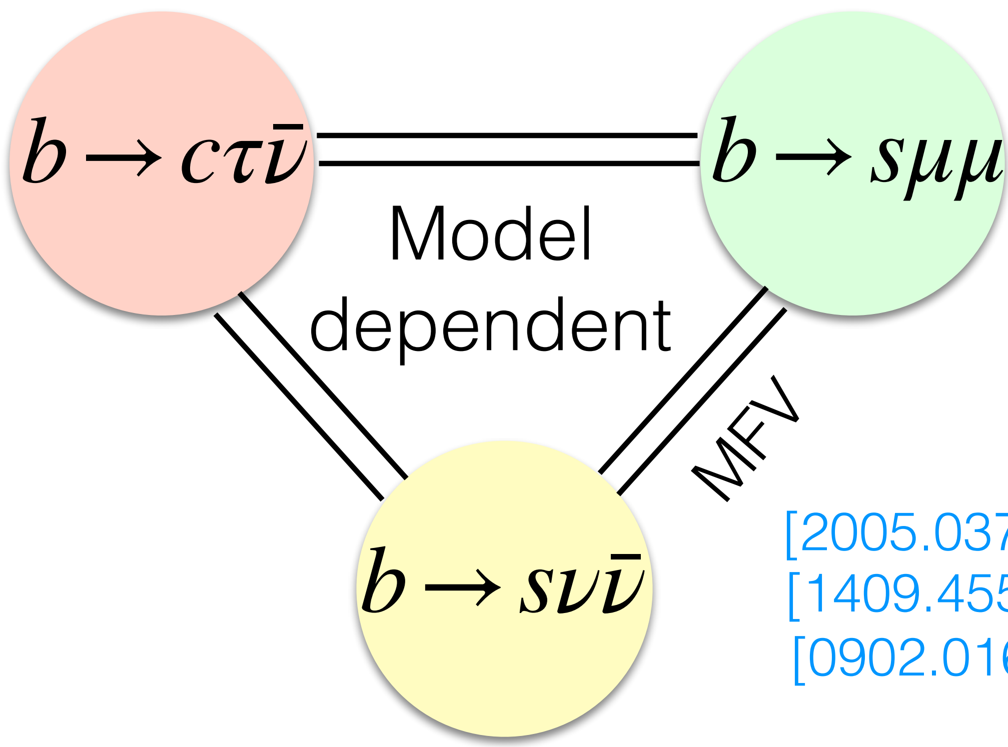
January 25, 2022

Outline

- Introduction

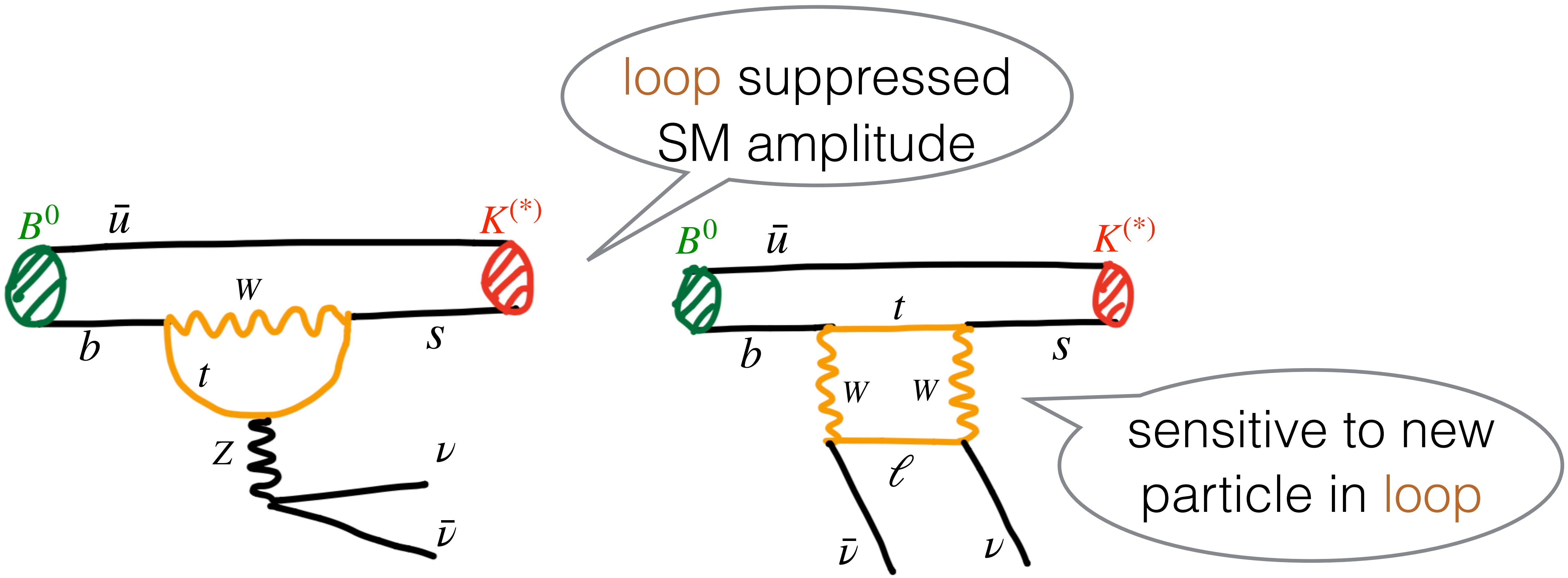
- New Physics analysis
  - Leptoquarks
  - Heavy Z'

- Summary



[2005.03734]
[1409.4557]
[0902.0160]

Introduction



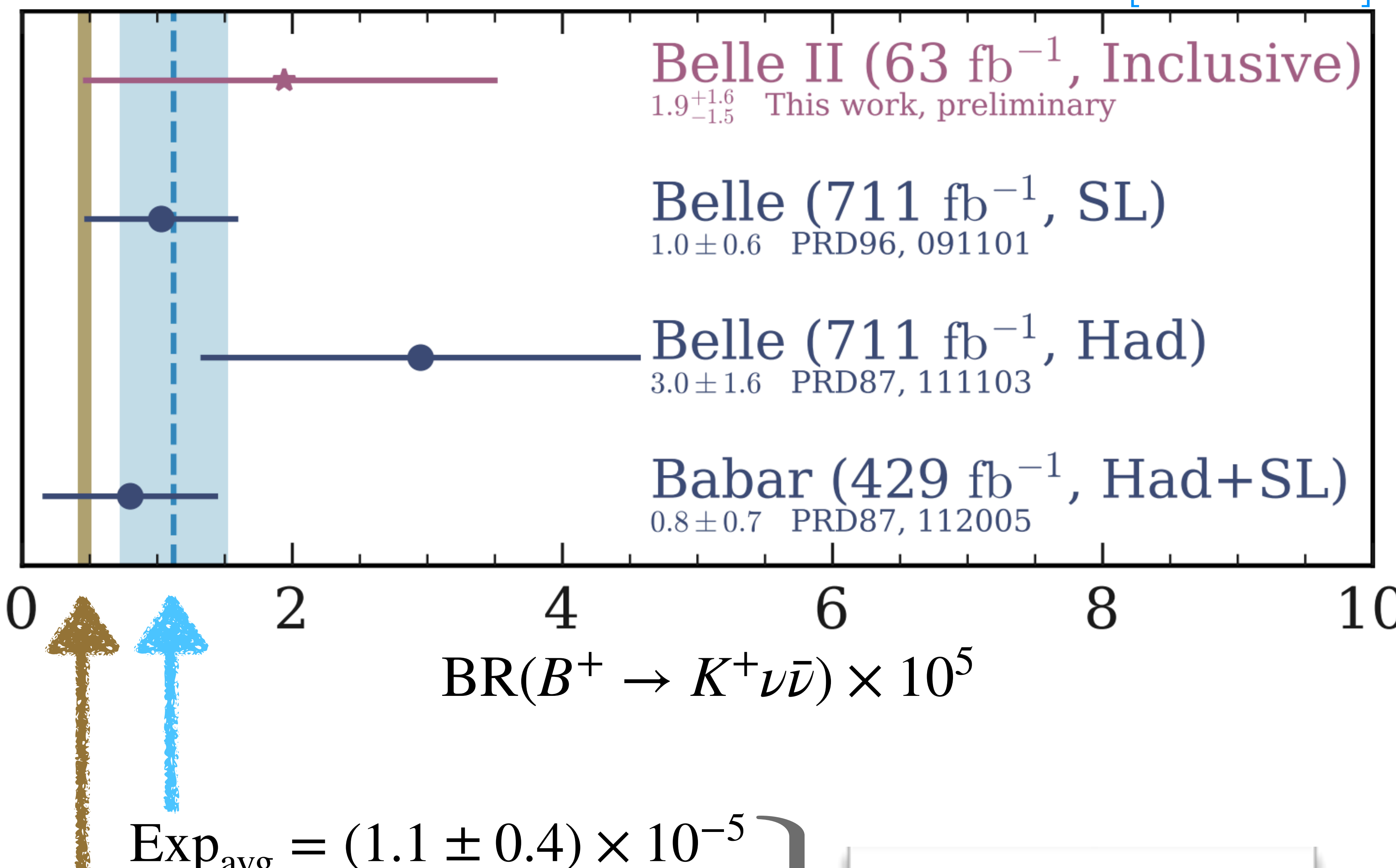
- [x] Theoretically much cleaner than $B \to K^* \ell^- \ell^+$

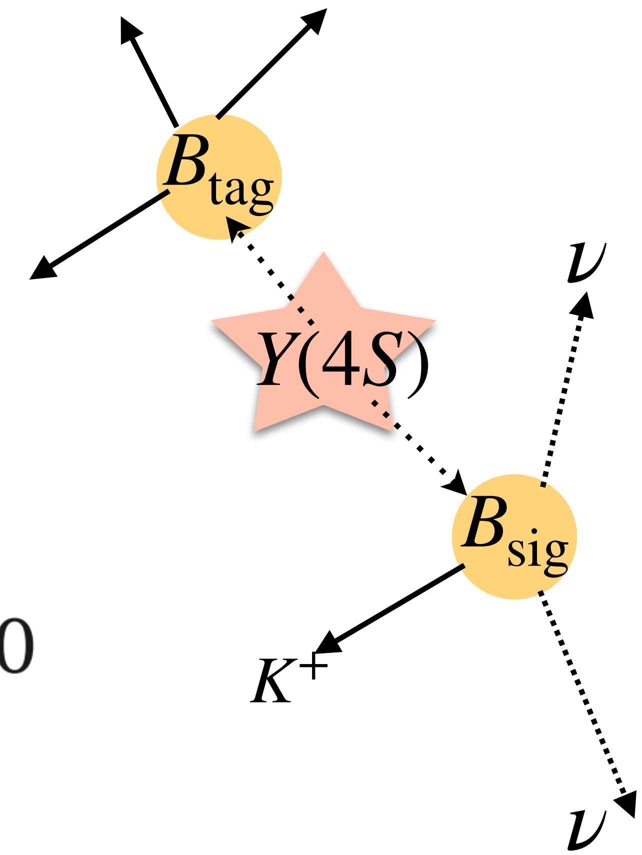
- [ ] Experimentally quite challenging due to two missing neutrinos—— No signal has been observed so far

Introduction

- Inclusive tagging technique from Belle II has higher efficiency~4%

[2104.12624]





$$\left.\begin{array}{l} \mathrm{Exp}_{\rm avg} = (1.1 \pm 0.4) \times 10^{-5} \\ \mathrm{SM} = (4.6 \pm 0.5) \times 10^{-6} \end{array}\right\} \boxed{R_K^\nu = 2.4 \pm 0.9}$$

Hamiltonian

- Effective Hamiltonian with all possible dim-6 operators for $b \to s\nu\bar{\nu}$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_{\rm EM}}{4\pi}V_{tb}V_{ts}^*\left(C_{LL}^{\rm SM}\delta_{\alpha\beta}[\mathcal{O}_{LL}^V]^{\alpha\beta} + \sum_{\substack{X=S,V,T\\ A,B=L,R}}[C_{AB}^X]^{\alpha\beta}[\mathcal{O}_{AB}^X]^{\alpha\beta}\right)$$

SM FCNC contribution

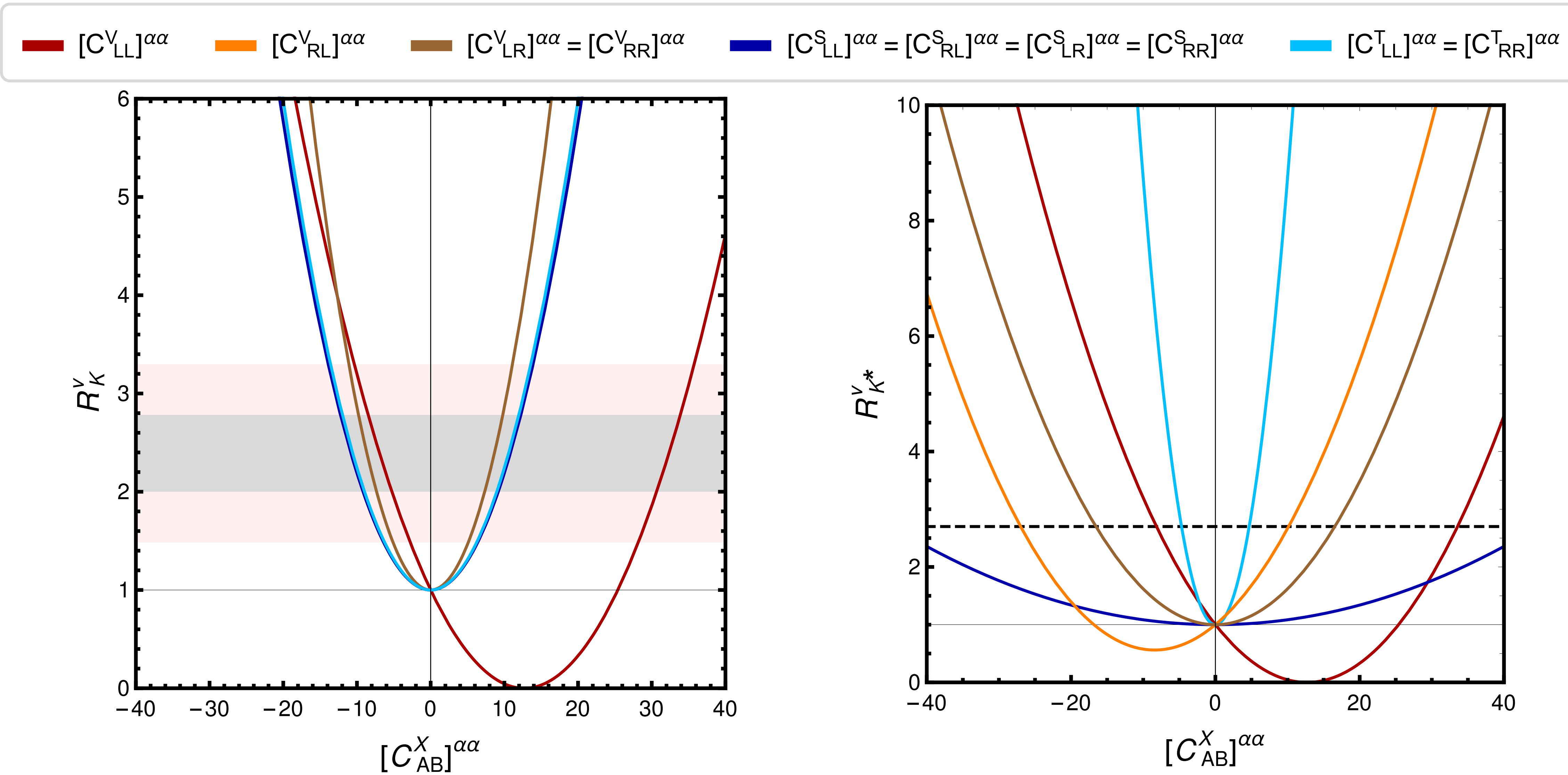
$C_{LL}^{\rm SM} = -2X_t/s_w^2$ = -12.7

Includes light right-handed neutrinos

$$[\mathcal{O}_{AB}^V]^{\alpha\beta} \equiv (\bar{s}\,\gamma^\mu P_A b)\,(\bar{\nu}^\alpha\gamma_\mu P_B\nu^\beta)\ ,$$
$$[\mathcal{O}_{AB}^S]^{\alpha\beta} \equiv (\bar{s}\,P_A b)\,(\bar{\nu}^\alpha P_B\nu^\beta)\ ,$$
$$[\mathcal{O}_{AB}^T]^{\alpha\beta} \equiv \delta_{AB}\ (\bar{s}\,\sigma^{\mu\nu}P_A b)\,(\bar{\nu}^\alpha\sigma_{\mu\nu}P_B\nu^\beta)$$

- Observables: Branching ratio, differential distribution in q^2
  Longitudinal polarization fraction in $B \to K^*\nu\bar{\nu}$

Hamiltonian

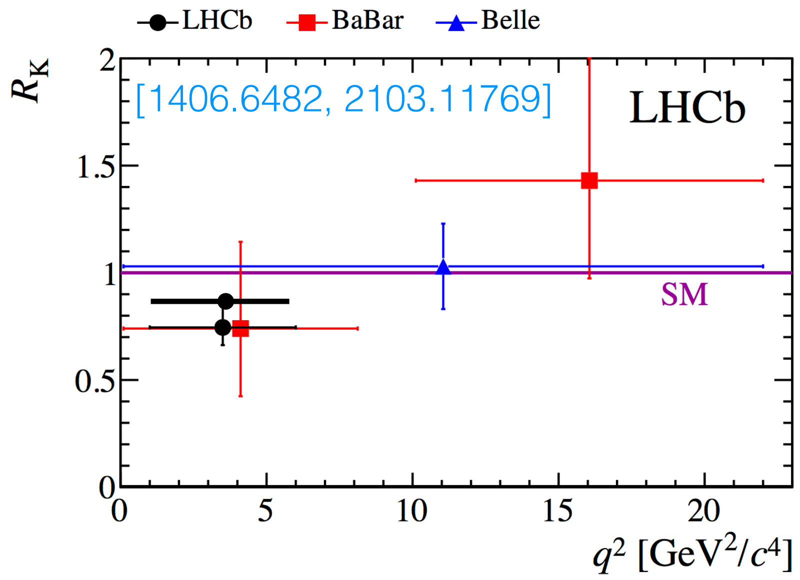


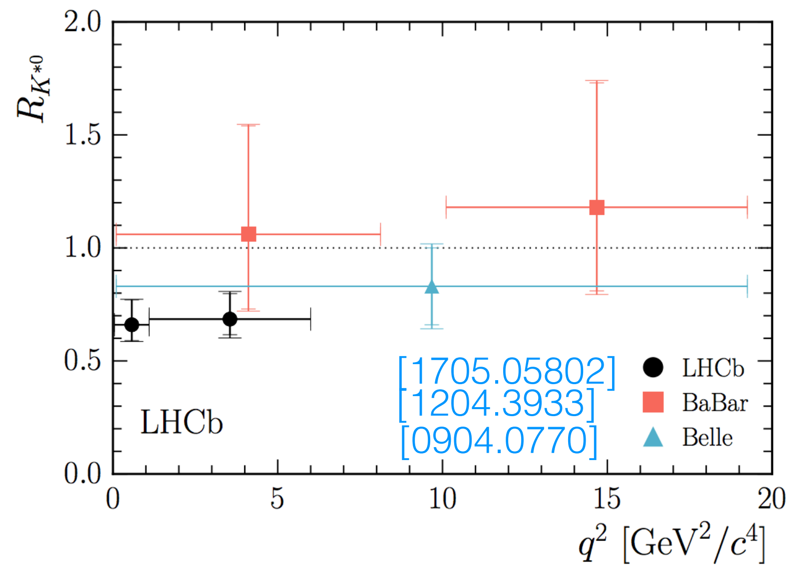
Variation with individual Wilson coefficients

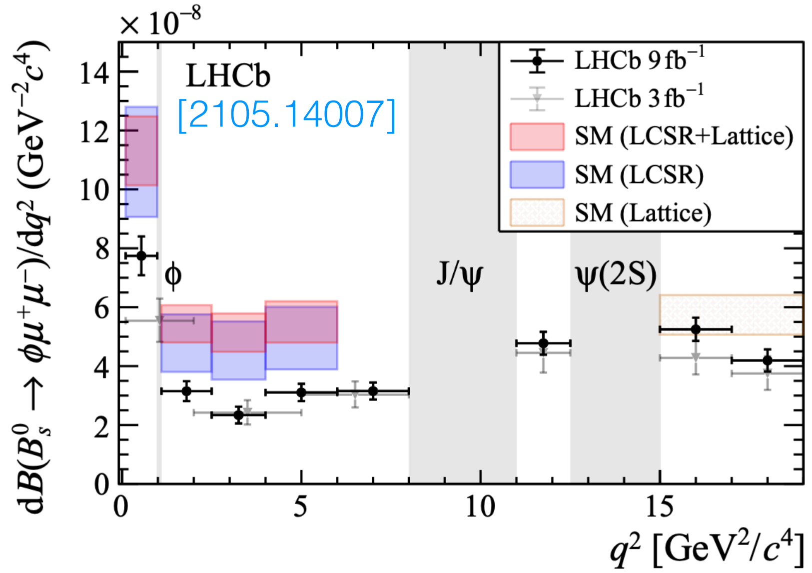
All operators can achieve the expected range

B-anomalies

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

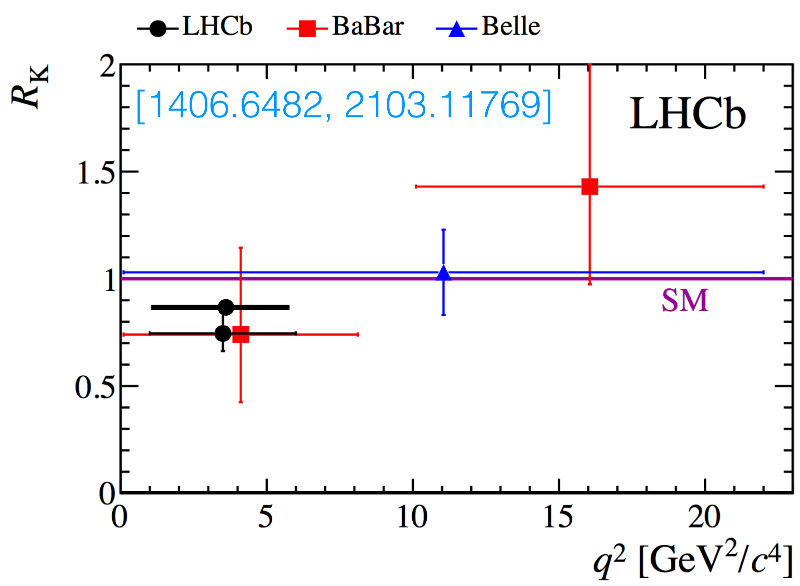


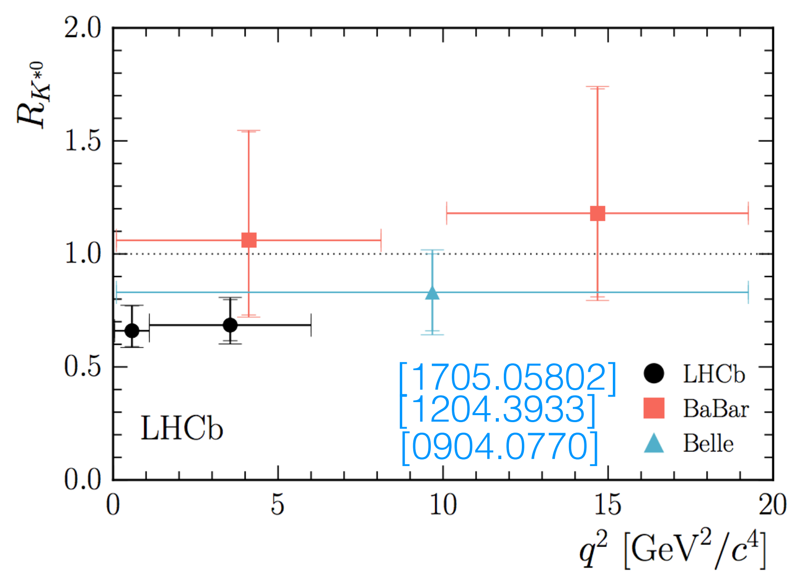


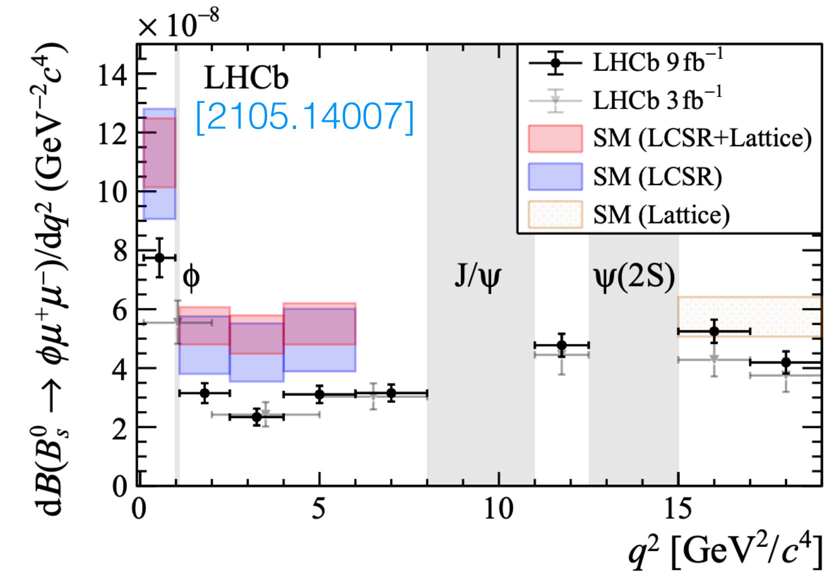


B-anomalies

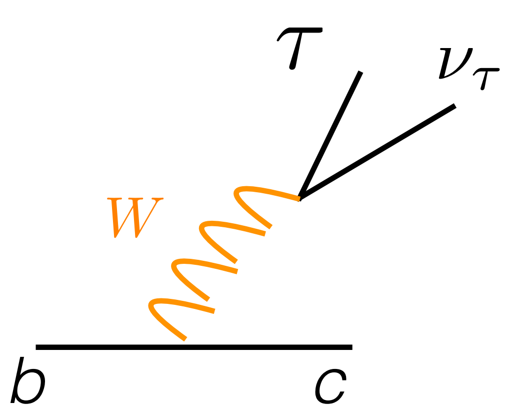
- Tensions in FCNC decay rate ratios $R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$

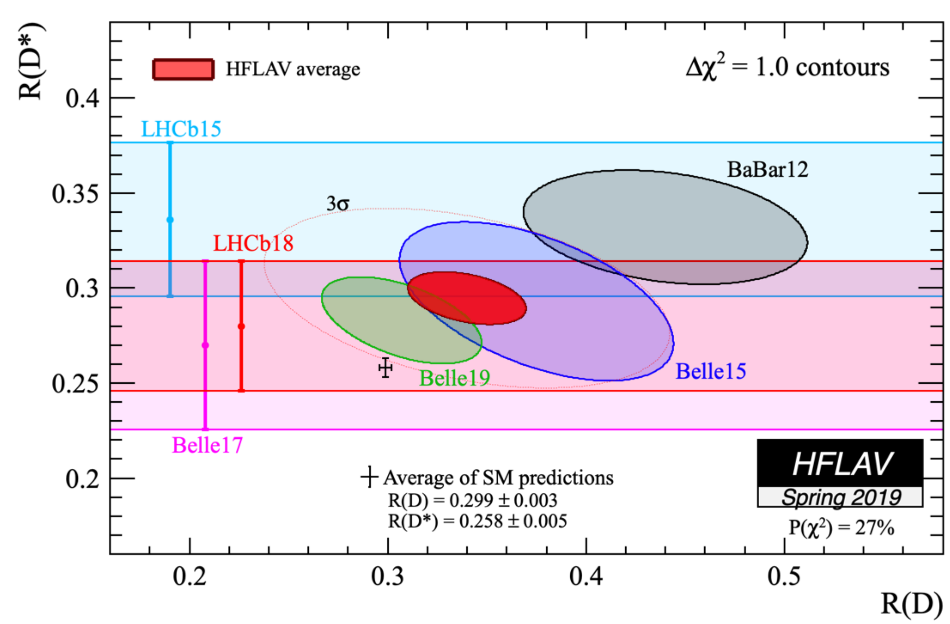






- Exciting discrepancies observed in charged current B decays also



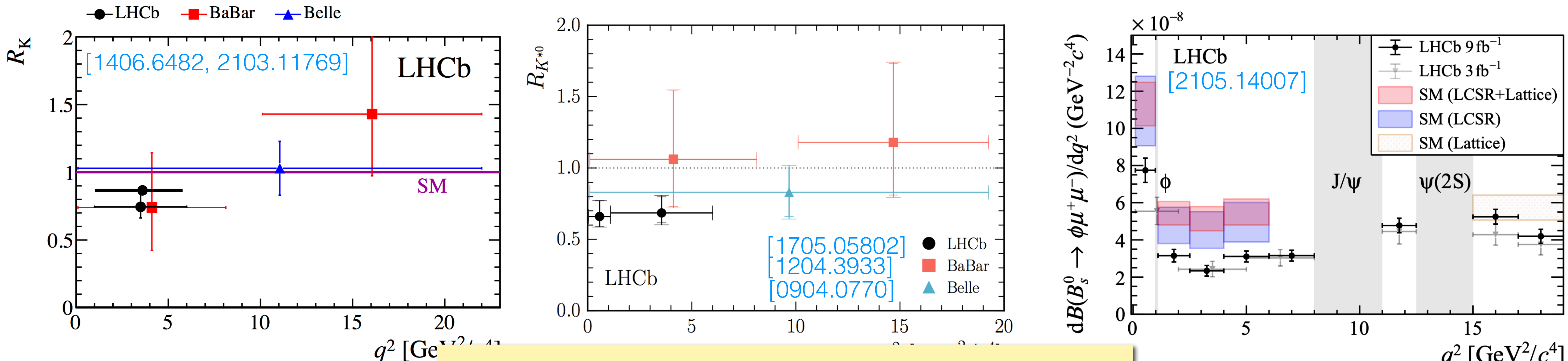


$$R(D^{(*)}) \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$

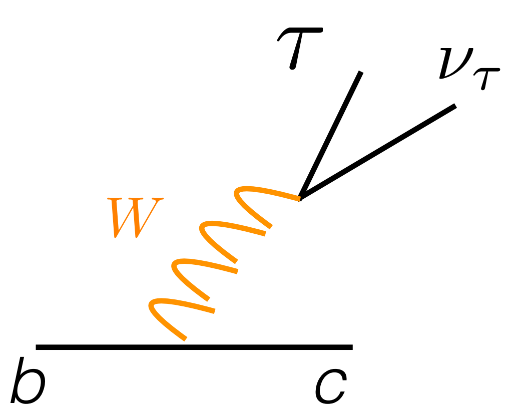
B-anomalies

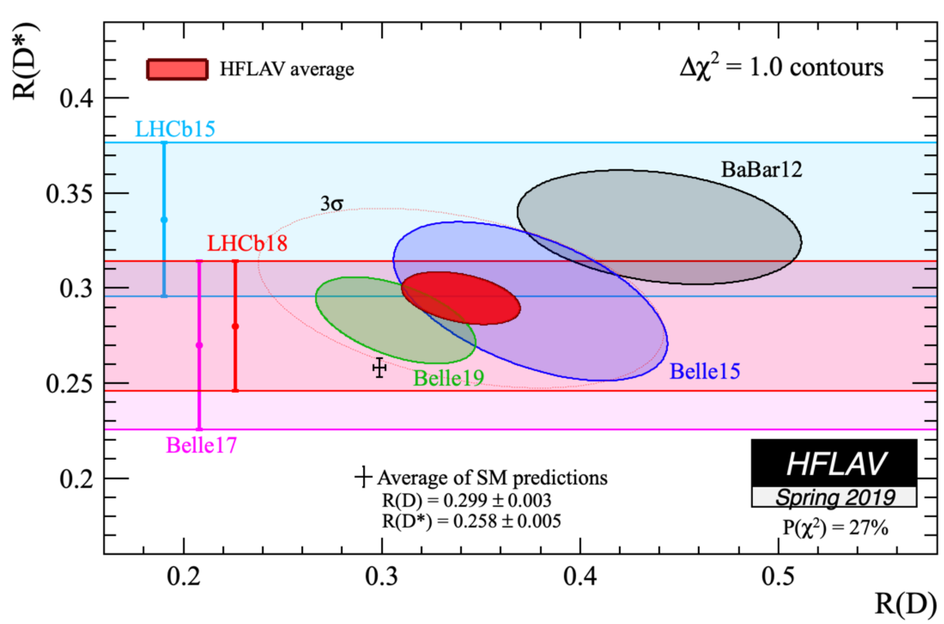
- Tensions in FCNC decay rate ratios $R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$



deviations$\sim 2-3\sigma$: Anomalies!!

- Exciting discrepancies observed in charged current B decays also

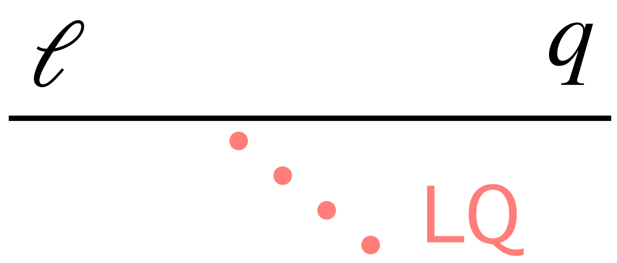




$$R(D^{(*)}) \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$

Leptoquarks



Idea from '70s: R-parity violating SUSY, GUTs

Mediators	Spin	Interaction terms	Operators
$S_3(\bar{3},3,1/3)$	0	$+\overline{Q^c}\, Y_{S_3}\, i\tau_2\, \boldsymbol{\tau}\cdot\mathbf{S_3}\, L$	$\mathcal{O}^V_{LL}$
$\tilde{R}_2(3,2,1/6)$	0	$-\bar{d}_R\, Y_{\tilde{R}_2}\, \tilde{R}_2^T\, i\tau_2 L + \overline{Q}\, Z_{\tilde{R}_2}\, \tilde{R}_2\, \nu_R$	$\mathcal{O}^V_{RL}$, $\mathcal{O}^V_{LR}$, $\mathcal{O}^{S,T}_{LL}$, $\mathcal{O}^{S,T}_{RR}$
$S_1(\bar{3},1,1/3)$	0	$+\overline{Q^c}\, i\tau_2\, Y_{S_1} L\, S_1 + \overline{u^c_R}\, \tilde{Y}_{S_1}\, S_1\, e_R + \overline{d^c_R}\, Z_{S_1}\, S_1\, \nu_R$	$\mathcal{O}^{S,V,T}_{RR}$, $\mathcal{O}^{S,V,T}_{LL}$
$U^\mu_3(3,3,2/3)$	1	$+\overline{Q}\, \gamma^\mu \tau^a\, Y_{U_1} L\, U^a_{1\mu}$	$\mathcal{O}^V_{LL}$
$V^\mu_2(\bar{3},2,5/6)$	1	$+\overline{d^c_R}\, \gamma^\mu Y_{V_2} V^T_{2\mu} i\tau_2\, L + \overline{Q^c_L}\, \gamma^\mu \tilde{Y}_{V_2} i\tau_2\, V_{2\mu} e_R$	$\mathcal{O}^S_{RL}$
$\bar{U}^\mu_1(3,1,-1/3)$	1	$+\bar{d}_R\, Z_{\bar{U}_1}\, \gamma^\mu \bar{U}_{1\mu}\, \nu_R$	$\mathcal{O}^V_{RR}$

S_3 :

1st generation couplings stringently constrained from Kaon, lepton data

$$\left(\begin{array}{c|cc} & & \\ \hline & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{array}\right)$$

$\times$ $b \to c\tau\bar{\nu}$: $\mathscr{P}^V_{LL}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from $B^0_s - \bar{B}^0_s$

S_3 :

1st generation couplings stringently constrained from Kaon, lepton data

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

✗ $b \to c\tau\bar{\nu}$: $\mathscr{P}^V_{LL}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from $B_s^0 - \bar{B}_s^0$

✓ $b \to s\mu\mu$: $C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.41^{+0.07}_{-0.07}$

$$Y^{32}_{S_3} Y^{22}_{S_3} = 0.0028 \pm 0.0005\,, \qquad |Y^{32}_{S_3}| \leq 1.33$$

S_3 :

1st generation couplings stringently constrained from Kaon, lepton data

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

✗ $b \to c\tau\bar{\nu}: \mathscr{P}^{V}_{LL}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from $B^0_s - \bar{B}^0_s$

✓ $b \to s\mu\mu$: $C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.41^{+0.07}_{-0.07}$

$$Y^{32}_{S_3} Y^{22}_{S_3} = 0.0028 \pm 0.0005\,, \qquad |Y^{32}_{S_3}| \leq 1.33$$

$b \to s\nu\bar{\nu}$: C^{V}_{LL}

➡ Only ~2% enhancement in R^{ν}_{K} with $Y^{22} Y^{32}$

S_3 :

1st generation couplings stringently constrained from Kaon, lepton data

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

$b \to c\tau\bar{\nu}$: $\mathscr{P}^V_{LL}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from $B_s^0 - \bar{B}_s^0$

$b \to s\mu\mu$: $C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.41^{+0.07}_{-0.07}$

$$Y^{32}_{S_3} Y^{22}_{S_3} = 0.0028 \pm 0.0005\,, \qquad |Y^{32}_{S_3}| \leq 1.33$$

$b \to s\nu\bar{\nu}$: C^V_{LL}

Only ~2% enhancement in R^ν_K with $Y^{22} Y^{32}$

However allowed range of Y^{23}, Y^{33} together with Y^{22}, Y^{32} explaining $b \to s\mu\mu$ anomalies give $R^\nu_K = 2.4 \pm 3.6$

$\tilde{R}_2$:

$$\left(\begin{array}{c|cc} & & \\ \hline & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{array}\right)$$

$b \to s\mu\mu$: $C'_9 = -C'_{10}$

$R_K^{[1,6]}$ tension slightly reduced

$R_{K^*}^{[1,6]} > 1$ disagreement

$\tilde{R}_2$:

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix} + \overbrace{\begin{pmatrix} & & \\ & Z^{22} & Z^{23} \\ & Z^{32} & Z^{33} \end{pmatrix}}^{\text{RHN coupling}}$$

$b \to c\tau\bar{\nu}$: $\mathscr{P}^S_{LL} = -4\mathscr{P}^T_{LL}$

$b \to s\nu\bar{\nu}$: C^S_{LL} generated with RHN
No interference with SM

$b \to s\mu\mu$: $C'_9 = -C'_{10}$

$R_K^{[1,6]}$ tension slightly reduced

$R_{K^*}^{[1,6]} > 1$ disagreement

$\tilde{R}_2$:

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix} + \overbrace{\begin{pmatrix} & & \\ & Z^{22} & Z^{23} \\ & Z^{32} & Z^{33} \end{pmatrix}}^{\text{RHN coupling}}$$

$b \to c\tau\bar{\nu}$: $\mathcal{P}^S_{LL} = -4\mathcal{P}^T_{LL}$

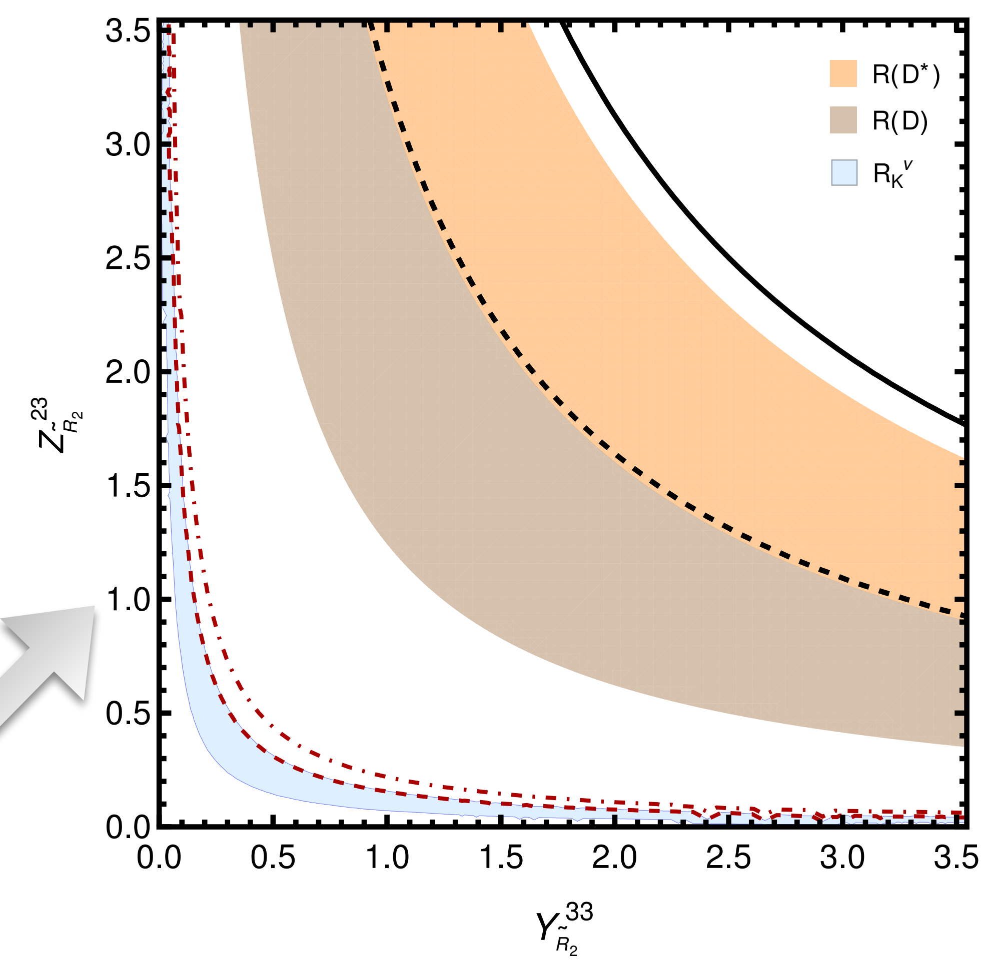
$b \to s\nu\bar{\nu}$: C^S_{LL} generated with RHN
No interference with SM

$b \to s\mu\mu$: $C_9' = -C_{10}'$

$R_K^{[1,6]}$ tension slightly reduced

$R_{K^*}^{[1,6]} > 1$ disagreement

Region explaining $R(D^{(*)})$ is completely excluded by R_K^ν



S_1 :

$b \to s\mu\mu$: No tree-level contribution, 1-loop effect requires large couplings incompatible with other data

LH only

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

$b \to c\tau\bar{\nu}$: $\mathscr{P}^{V}_{LL}$

$$R(D^{(*)}) \sim 1.04\, R(D^{(*)})_{\rm SM}$$

Large Y^{23}, Y^{33} values forbidden from $B_s^0 - \bar{B}_s^0$ & $Z \to \tau\tau$

$b \to s\nu\bar{\nu}$: C^{V}_{LL} → $R_K^{\nu} = 2.46 \pm 1.22$

S_1 :

$b \to s\mu\mu$: No tree-level contribution, 1-loop effect requires large couplings incompatible with other data

LH only

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

✗ $b \to c\tau\bar{\nu}$: $\mathscr{P}^{V}_{LL}$

$R(D^{(*)}) \sim 1.04\, R(D^{(*)})_{\rm SM}$

Large Y^{23}, Y^{33} values forbidden from $B_s^0 - \bar{B}_s^0$ & $Z \to \tau\tau$

$b \to s\nu\bar{\nu}$: C^{V}_{LL} ⇨ $R_K^{\nu} = 2.46 \pm 1.22$

$+$

$$\begin{pmatrix} & & \\ & \tilde{Y}^{22} & \tilde{Y}^{23} \\ & \tilde{Y}^{32} & \tilde{Y}^{33} \end{pmatrix}$$

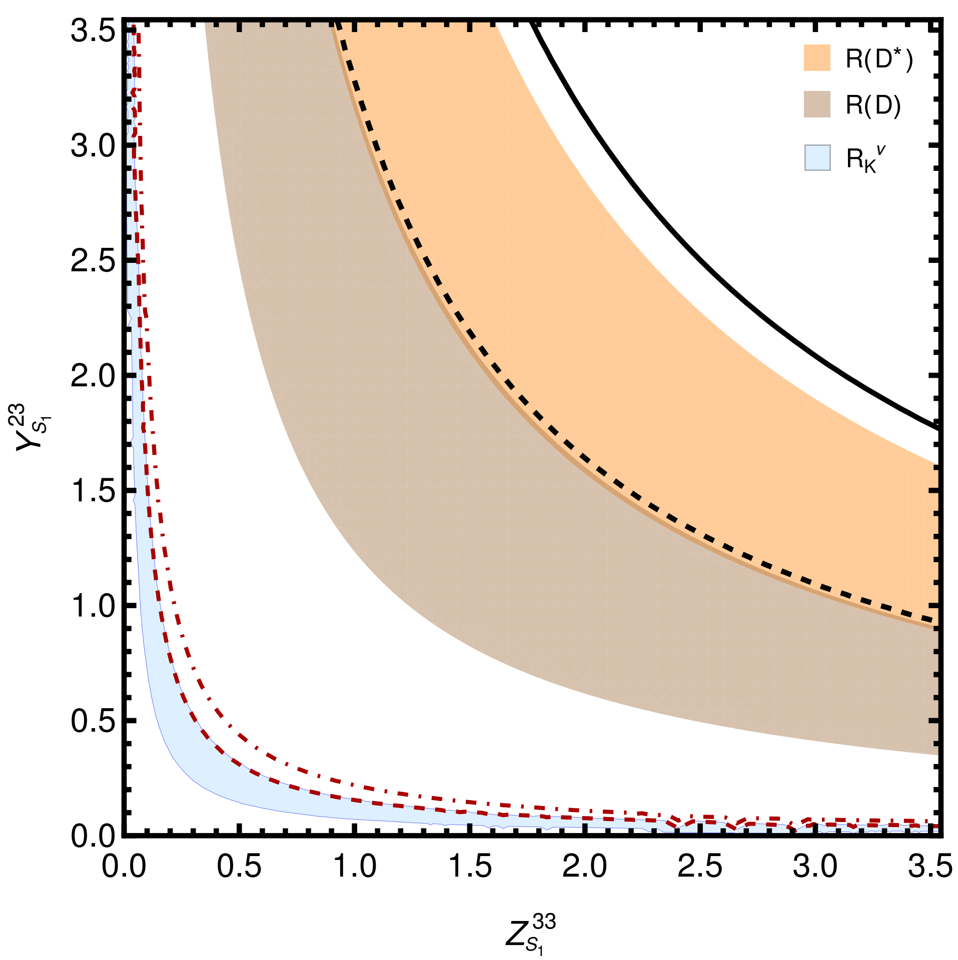
LH+RH

✓ $b \to c\tau\bar{\nu}$: $\mathscr{P}^{V}_{LL}, \mathscr{P}^{S}_{LL} = -4\mathscr{P}^{T}_{LL}$

$b \to s\nu\bar{\nu}$: C^{V}_{LL} ⇨ $R_K^{\nu} = 2.35 \pm 1.97$

S_1 :

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix} + \overbrace{\begin{pmatrix} & & \\ & Z^{22} & Z^{23} \\ & Z^{32} & Z^{33} \end{pmatrix}}^{\text{RHN coupling}} \longrightarrow \; b \to c\tau\bar{\nu}: \quad \mathscr{P}^S_{RR} = -4\mathscr{P}^T_{RR}$$



$b \to s\nu\bar{\nu}$: C^S_{RR} generated with RHN

No interference with SM

Region explaining $R(D^{(*)})$ is completely excluded by R^{ν}_K

Vector leptoquarks

Full UV model is needed for reliable estimates of loop induced processes

U_3^μ :

$$\begin{pmatrix} & \\ & \begin{matrix} Y^{22} & Y^{23} \\ Y^{32} & Y^{33} \end{matrix} \end{pmatrix}$$

$b \to c\tau\bar{\nu} : \mathscr{P}^V_{LL}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from R_K^ν

Vector leptoquarks

Full UV model is needed for reliable estimates of loop induced processes

$U_3^\mu :$

$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

✘ $b \to c\tau\bar{\nu} : \mathscr{P}_{LL}^{V}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from R_K^ν

✔ $b \to s\mu\mu$: $C_9^{\rm NP} = -C_{10}^{\rm NP}$

$b \to s\nu\bar{\nu}$: C_{LL}^{V} ⇒ $R_K^\nu \simeq 2.4$

Vector leptoquarks

Full UV model is needed for reliable estimates of loop induced processes

U_3^μ :

$$\left(\begin{array}{c|cc} & & \\ \hline & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{array}\right)$$

✗ $b \to c\tau\bar{\nu}: \mathscr{P}^V_{LL}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from R_K^ν

✓ $b \to s\mu\mu$: $C_9^{\rm NP} = -C_{10}^{\rm NP}$

$b \to s\nu\bar{\nu}$: C^V_{LL} ⇨ $R_K^\nu \simeq 2.4$

V_2^μ :

$$\left(\begin{array}{c|cc} & & \\ \hline & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{array}\right) + \left(\begin{array}{c|cc} & & \\ \hline & \tilde{Y}^{22} & \tilde{Y}^{23} \\ & \tilde{Y}^{32} & \tilde{Y}^{33} \end{array}\right)$$

$b \to c\tau\bar{\nu}: \mathscr{P}^V_{RL}$ ⇨ ✓ $R(D)$ ✗ $R(D^*)$

Differs in form factor dependence

Vector leptoquarks

Full UV model is needed for reliable estimates of loop induced processes

U_3^μ :

$$\begin{pmatrix} & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

$b \to c\tau\bar{\nu}$: $\mathscr{P}^V_{LL}$

Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are excluded from R_K^ν

$b \to s\mu\mu$: $C_9^{\rm NP} = -C_{10}^{\rm NP}$

$b \to s\nu\bar{\nu}$: $C_{LL}^V \Rightarrow R_K^\nu \simeq 2.4$

V_2^μ :

$$\begin{pmatrix} & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix} + \begin{pmatrix} & \\ & \tilde{Y}^{22} & \tilde{Y}^{23} \\ & \tilde{Y}^{32} & \tilde{Y}^{33} \end{pmatrix}$$

$b \to c\tau\bar{\nu}$: $\mathscr{P}^V_{RL} \Rightarrow R(D)\ \ R(D^*)$

Differs in form factor dependence

$b \to s\mu\mu$: $C_S = -C_P, C'_S = C'_P$

$b \to s\nu\bar{\nu}$: $C_{LL}^V \Rightarrow R_K^\nu \simeq 2.4$

Leptoquarks

Mediators	Spin	R_K	R_{K^*}	$R(D)$	$R(D^*)$	R_K^ν
$S_3(\bar{3}, 3, 1/3)$	0	✓	✓	✗	✗	✓
$\tilde{R}_2(3, 2, 1/6)$	0	✓	✗ $R_{K^*}^{[1,6]} > 1$	— no effect —		no effect
+ RHN				✗	✗ ←	✓
$S_1(\bar{3}, 1, 1/3)$	0	— no effect —		✓	✓	✓
+ RHN				✗	✗ ←	✓
$U_3^\mu(3, 3, 2/3)$	1	✓	✓	✗	✗ ←	✓
$V_2^\mu(\bar{3}, 2, 5/6)$	1	✗	✗	✓	✗	✓
$\bar{U}_1^\mu(3, 1, -1/3)$	1	— no effect —		— no effect —		✓

Heavy Z' :

- Neutral current $\mathcal{L}(Z') = \sum_{i,j,\psi_L} \Delta_L^{ij} \bar{\psi}_L^i \gamma^\mu P_L \psi_L^j Z'_\mu + \sum_{i,j,\psi_R} \Delta_R^{ij} \bar{\psi}_R^i \gamma^\mu P_R \psi_R^j Z'_\mu$

$b \to s\mu\mu$: LH couplings $C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}} = \frac{v^2}{M_{Z'}^2} \frac{\pi}{\alpha_{\mathrm{EM}} V_{tb} V_{ts}^*} \Delta_L^{sb} \Delta_L^{\mu\mu}$

Stringently constrained from tree-level contribution to $B_s^0 - \bar{B}_s^0$

$$\Delta_L^{sb} = (8.5 \pm 6.4) \times 10^{-3}, \qquad \Delta_L^{\mu\mu} = 2.00 \pm 0.95$$

$$R_K^\nu = 1.05 \pm 0.03$$

Heavy Z' :

- Neutral current $\mathcal{L}(Z') = \sum_{i,j,\psi_L} \Delta_L^{ij} \bar{\psi}_L^i \gamma^\mu P_L \psi_L^j Z'_\mu + \sum_{i,j,\psi_R} \Delta_R^{ij} \bar{\psi}_R^i \gamma^\mu P_R \psi_R^j Z'_\mu$

$b \to s\mu\mu$: LH couplings $C_9^{\rm NP} = -C_{10}^{\rm NP} = \frac{v^2}{M_{Z'}^2} \frac{\pi}{\alpha_{\rm EM} V_{tb} V_{ts}^*} \Delta_L^{sb} \Delta_L^{\mu\mu}$

Stringently constrained from tree-level contribution to $B_s^0 - \bar{B}_s^0$

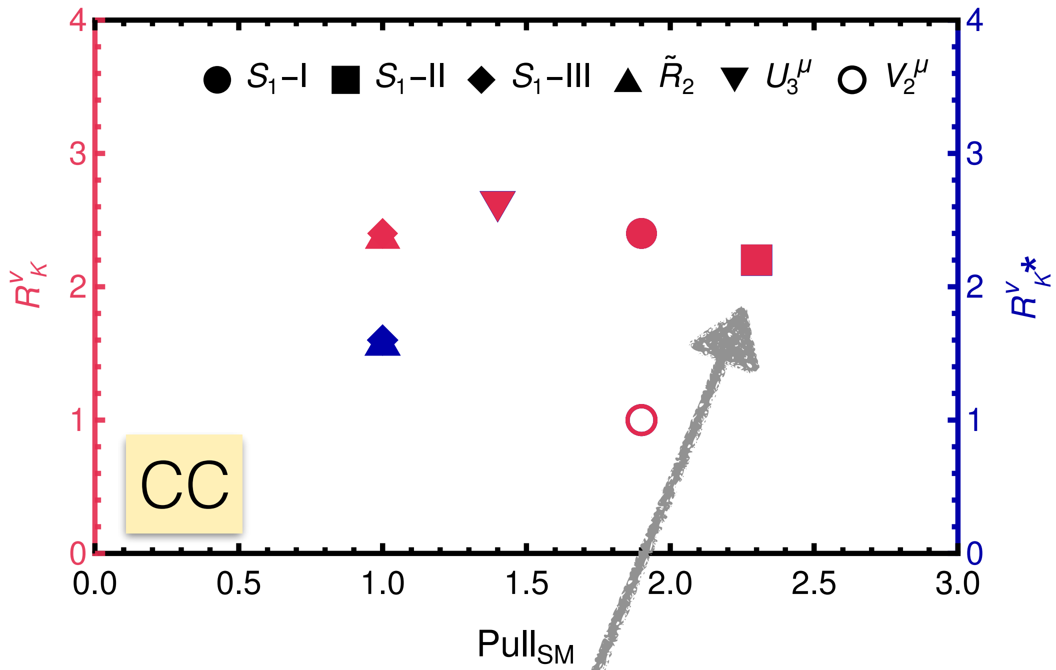
$\Delta_L^{sb} = (8.5 \pm 6.4) \times 10^{-3}, \qquad \Delta_L^{\mu\mu} = 2.00 \pm 0.95$

$R_K^\nu = 1.05 \pm 0.03$

$b \to s\mu\mu$: LH + RH couplings $C_9^{\rm NP} = -C_{10}^{\rm NP}$ & $C'_9 = -C'_{10}$

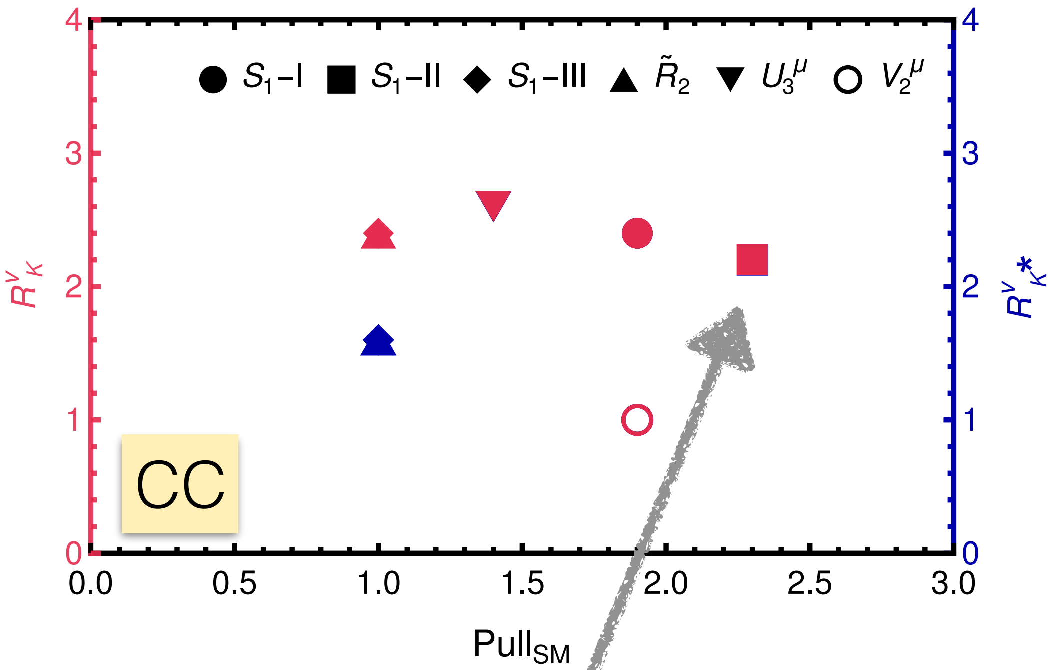
No new contribution to $R_K^\nu \simeq 1.1$

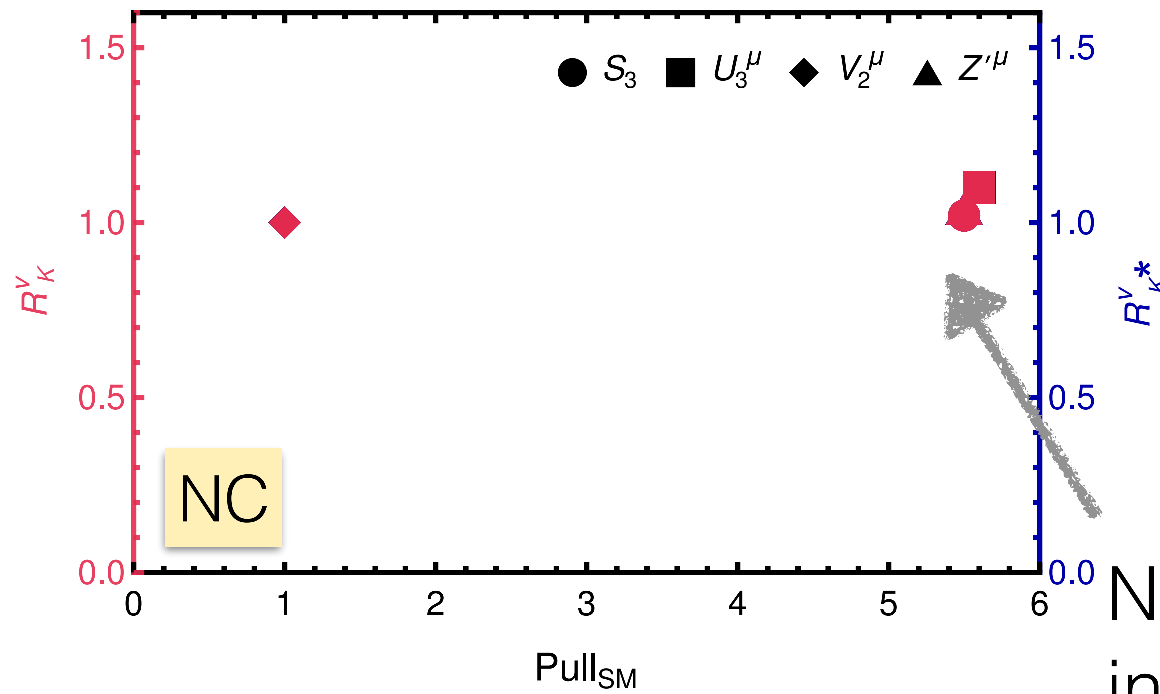
Comparison



S_1 with three non-vanishing couplings

Comparison

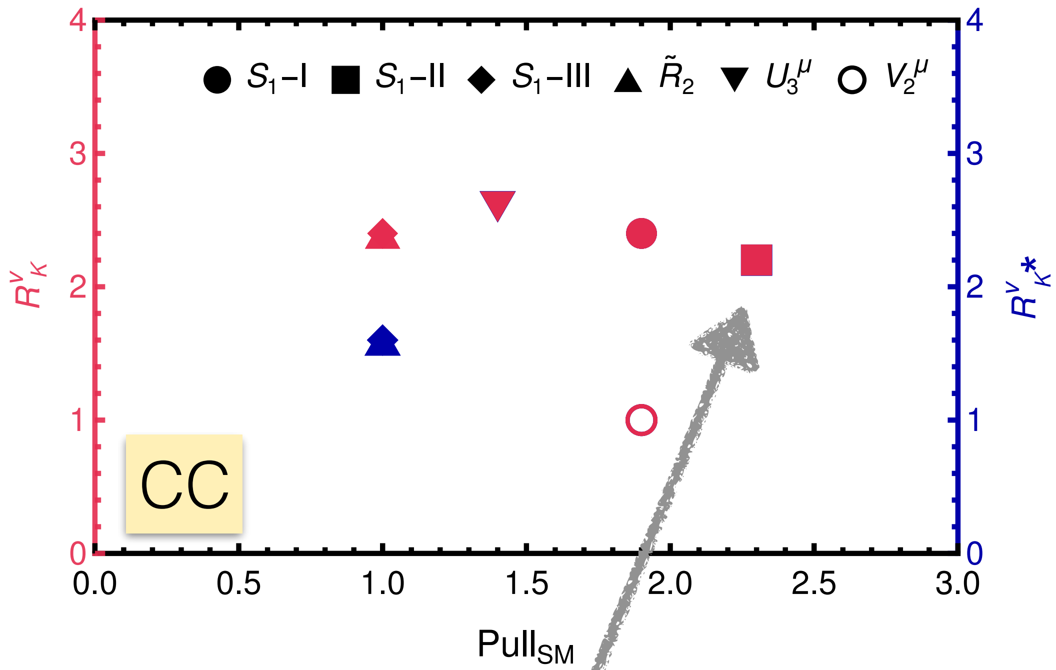


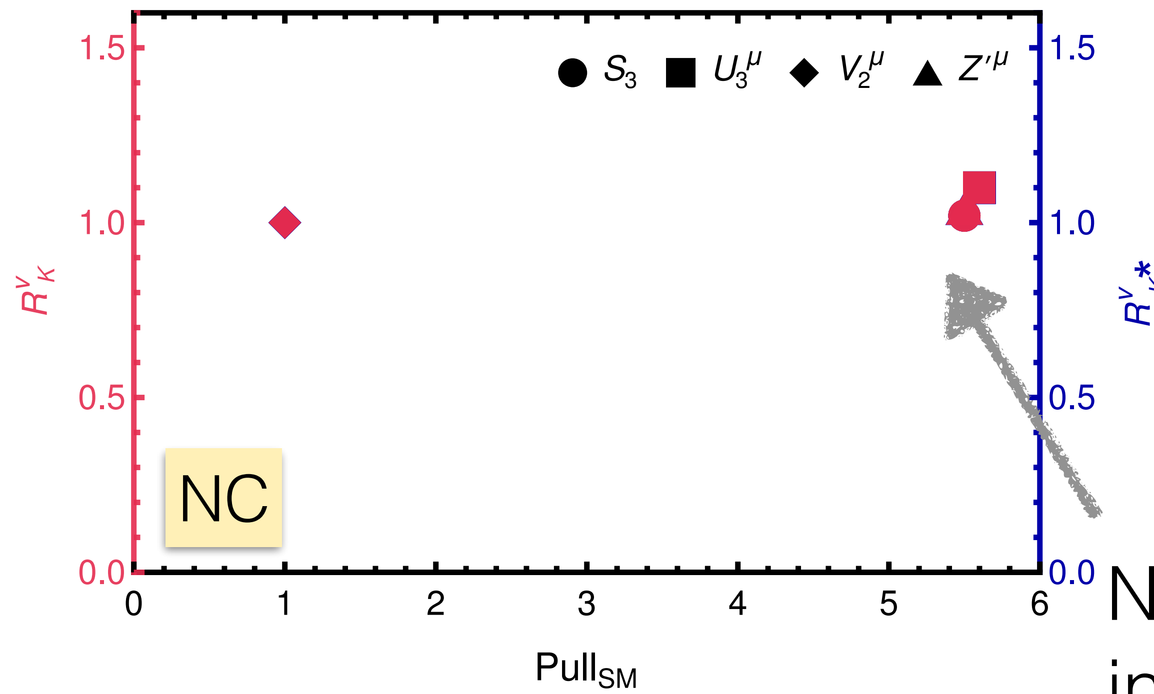


No excess in R_K^ν

S_1 with three non-vanishing couplings

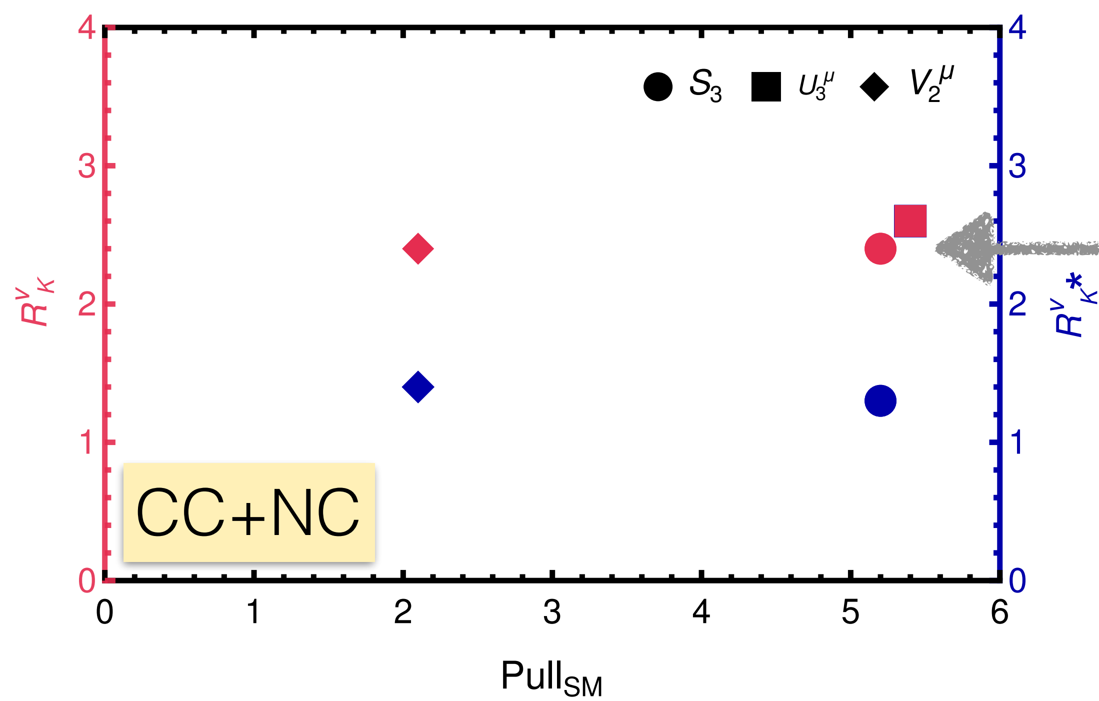
Comparison





No excess in R_K^ν

S_1 with three non-vanishing couplings



S_3 & U_3^μ can show desired enhancement

Summary

- Experimental challenges might be overcome with inclusive tag technique@Belle II — expecting signal soon?!

- Possibilities to connect the indicated excess with both NC and CC *B*-anomalies in `simplified' models

- RHN explanations to $R(D^{(*)})$ are excluded for S_1 & $\tilde{R}_2$ by $B \to K^{(*)}\nu\bar{\nu}$

- Heavy Z' explaining $b \to s\mu\mu$ with minimal setup can not enhance R_K^ν

- S_1 explaining CC *B*-anomalies & S_3 in NC+CC framework can produce expected enhancement in R_K^ν

- Other links—Dark matter connection?! [1111.6402]

Summary

- Experimental challenges might be overcome with inclusive tag technique@Belle II — expecting signal soon?!

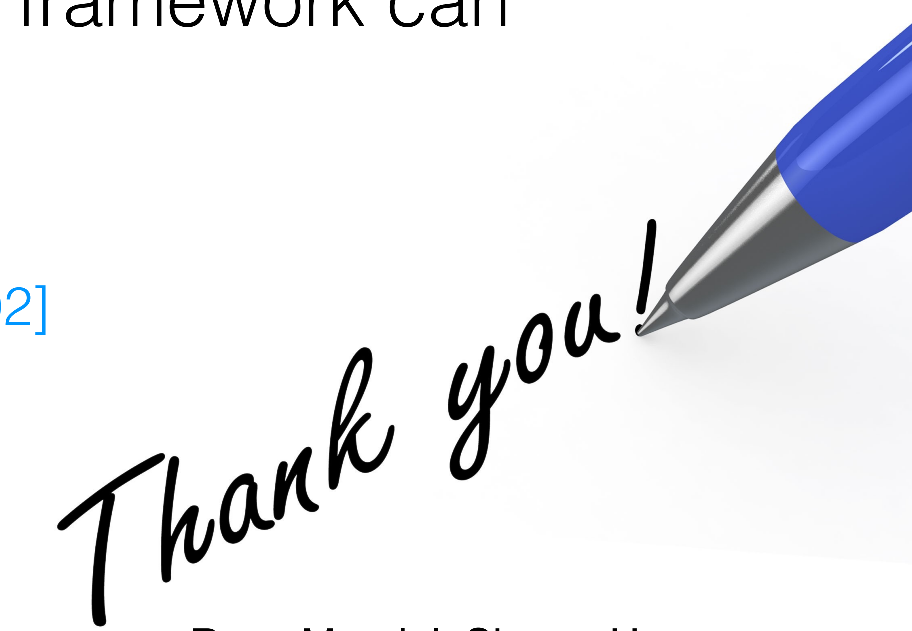
- Possibilities to connect the indicated excess with both NC and CC *B*-anomalies in `simplified' models

- RHN explanations to $R(D^{(*)})$ are excluded for S_1 & $\tilde{R}_2$ by $B \to K^{(*)}\nu\bar{\nu}$

- Heavy Z' explaining $b \to s\mu\mu$ with minimal setup can not enhance R_K^{ν}

- S_1 explaining CC *B*-anomalies & S_3 in NC+CC framework can produce expected enhancement in R_K^{ν}

- Other links—Dark matter connection?! [1111.6402]



Back ups

Charged current

$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left(\mathcal{Q}_{LL}^{V\alpha\beta} \delta_{\alpha\beta} + \sum_{\substack{X=S,V,T \\ A,B=L,R}} \mathcal{P}_{AB}^{X\alpha\beta} \, \mathcal{Q}_{AB}^{X\alpha\beta} \right)$$

$$\begin{aligned}
\mathcal{Q}_{AB}^{V\alpha\beta} &\equiv (\bar{c}\,\gamma^\mu P_A b)\left(\bar{\ell}^\alpha \gamma_\mu P_B \nu^\beta\right) \,, \\
\mathcal{Q}_{AB}^{S\alpha\beta} &\equiv (\bar{c}\,P_A b)\left(\bar{\ell}^\alpha P_B \nu^\beta\right) \,, \\
\mathcal{Q}_{AB}^{T\alpha\beta} &\equiv \delta_{AB}\;(\bar{c}\,\sigma^{\mu\nu} P_A b)\left(\bar{\ell}^\alpha \sigma_{\mu\nu} P_B \nu^\beta\right)
\end{aligned}$$

SMEFT matching

$$\mathcal{P}_{LL}^{V\alpha\beta} = +\frac{v^2}{\Lambda^2} \sum_{m=1}^{3} \frac{V_{2m}}{V_{cb}} [\mathcal{C}_{lq}^{(3)}]^{m3\alpha\beta} \,,$$

$$\mathcal{P}_{LL}^{S\alpha\beta} = -\frac{v^2}{2\Lambda^2 V_{cb}} [\mathcal{C}_{lequ}^{(1)*}]^{23\alpha\beta} \,,$$

$$\mathcal{P}_{LL}^{T\alpha\beta} = -\frac{v^2}{2\Lambda^2 V_{cb}} [\mathcal{C}_{lequ}^{(3)*}]^{23\alpha\beta} \,,$$

$$\mathcal{P}_{RL}^{S\alpha\beta} = +\frac{v^2}{2\Lambda^2} \sum_{m=1}^{3} \frac{V_{2m}}{V_{cb}} [\mathcal{C}_{ledq}^{*}]^{m3\alpha\beta} \,.$$

Running factors: $\mathcal{P}_{AB}^{S(T)}(m_b) = 1.67(0.84) \times \mathcal{P}_{AB}^{S(T)}(\Lambda = \mathcal{O}(\mathrm{TeV}))$

Neutral current

- Hamiltonian and relevant operators for $b \to s\mu\mu$

$$\mathcal{H}^{\text{eff}} = \frac{-4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu)\mathcal{O}_i(\mu)\,,$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\mu\nu}P_R b\right) F^{\mu\nu}$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\mu}\gamma^\mu \mu\right)$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\mu}\gamma^\mu \gamma_5 \mu\right)$$

New contribution to (axial)vector currents

$$C_9 \to C_9 + C_9^{\text{NP}}$$

$$C_{10} \to C_{10} + C_{10}^{\text{NP}}$$

$$\mathcal{C}_9^{ij\alpha\beta} = -\,\mathcal{C}_{10}^{ij\alpha\beta} = -\,\frac{v^2}{M^2}\frac{\pi}{\alpha_{\text{EM}} V_{td_j} V_{td_i}^*}\left([\mathcal{C}_{lq}^{(3)}]^{ij\alpha\beta} + [\mathcal{C}_{lq}^{(1)}]^{ij\alpha\beta}\right)$$

$$[\mathcal{C}_{lq}^{(1)}]^{ij\alpha\beta} = -\frac{1}{4}(3\,|g_3|^2 \tilde{S}_{QL}^{j\beta}\tilde{S}_{QL}^{*i\alpha} + |g_1|^2 S_{QL}^{j\beta} S_{QL}^{*i\alpha})$$

$$[\mathcal{C}_{lq}^{(3)}]^{ij\alpha\beta} = -\frac{1}{4}(|g_3|^2 \tilde{S}_{QL}^{j\beta}\tilde{S}_{QL}^{*i\alpha} - |g_1|^2 S_{QL}^{j\beta} S_{QL}^{*i\alpha})\,,$$

Model independent bound

Assuming SM sensitivity with full Belle-II data — bounds on EFT Wilson coefficients [2111.04327]

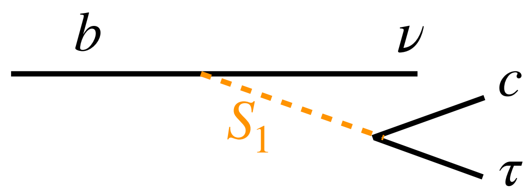
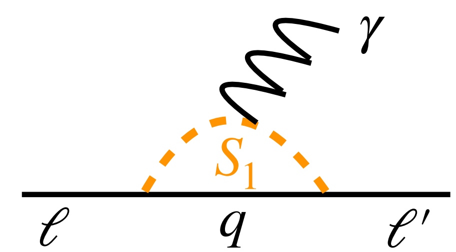
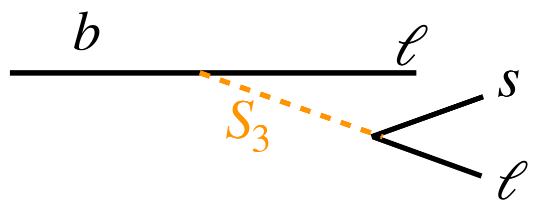
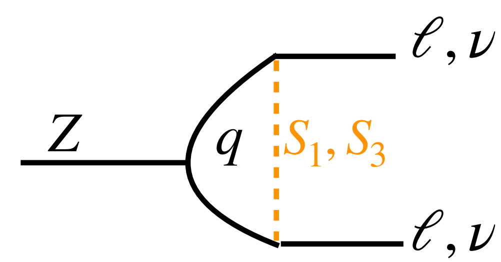
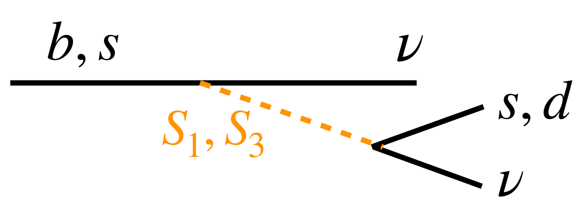
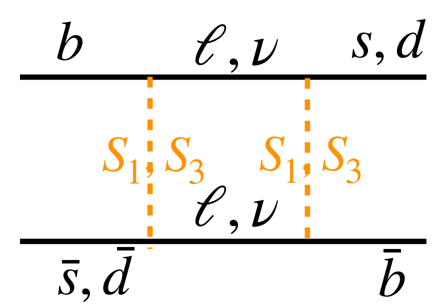
Operator	Current Bound: Value [TeV^{-2}]	Current Bound: NP scale [TeV]	Current Bound: Observable	Future Sensitivity (50 ab^{-1}): Value [TeV^{-2}]	Future Sensitivity (50 ab^{-1}): NP scale [TeV]	Future Sensitivity (50 ab^{-1}): Observable
$\mathcal{O}^{\rm VLL,NP}_{\nu d,\alpha\alpha sb}$	0.03	6	$B \to K^*\nu\nu$	0.022	7	$B \to K\nu\nu$ $B \to K^*\nu\nu$
$\mathcal{O}^{\rm VLR}_{\nu d,\alpha\alpha sb}$	0.021	7	$B \to K\nu\nu$	0.002	25	$B \to K\nu\nu$ $B \to K^*\nu\nu$
$\mathcal{O}^{\rm VLL}_{\nu d,\gamma\delta sb}$	0.017	8	$B \to K^*\nu\nu$	0.006	13	$B \to K\nu\nu$ $B \to K^*\nu\nu$
$\mathcal{O}^{\rm SLL}_{\nu d,\gamma\gamma sb}$	0.012	10	$B \to K\nu\nu$	0.002	25	$B \to K\nu\nu$
$\mathcal{O}^{\rm SLL}_{\nu d,\gamma\delta sb}$	0.009	10	$B \to K\nu\nu$	0.002	25	$B \to K\nu\nu$
$\mathcal{O}^{\rm TLL}_{\nu d,\gamma\delta sb}$	0.003	20	$B \to K^*\nu\nu$	0.0009	35	$B \to K^*\nu\nu$

Differential distribution

$$
\begin{aligned}
\frac{d\Gamma}{dq^2}(B\to K\nu\bar\nu) \;&=\; \frac{G_F^2|V_{tb}V_{ts}^*|^2\alpha_{\rm EM}^2}{192\times 16\pi^5 m_B^3}\, q^2\,\lambda_K^{1/2}(q^2)\times\\
&\times\sum_{\alpha=1}^{3}\sum_{\beta=1}^{3}\Bigg[\Big(|C_{LL}^{\rm SM}\delta_{\alpha\beta}+[C_{LL}^{V}]^{\alpha\beta}+[C_{RL}^{V}]^{\alpha\beta}|^2+|[C_{LR}^{V}]^{\alpha\beta}+[C_{RR}^{V}]^{\alpha\beta}|^2\Big)(H_V^s)^2\\
&\qquad+\frac{3}{2}\Big(|[C_{RL}^{S}]^{\alpha\beta}+[C_{LL}^{S}]^{\alpha\beta}|^2+|[C_{RR}^{S}]^{\alpha\beta}+[C_{LR}^{S}]^{\alpha\beta}|^2\Big)(H_S^s)^2\\
&\qquad+8\Big(|[C_{LL}^{T}]^{\alpha\beta}|^2+|[C_{RR}^{T}]^{\alpha\beta}|^2\Big)(H_T^s)^2\Bigg]\,,
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\Gamma}{dq^2}(B\to K^*\bar\nu\nu) = &\frac{G_F^2|V_{tb}V_{ts}^*|^2\alpha_{\rm EM}^2}{192\times 16\pi^5 m_B^3}\, q^2\,\lambda_{K^*}^{1/2}(q^2)\times\\
\times &\sum_{\alpha=1}^{3}\sum_{\beta=1}^{3}\left|C_{LL}^{\rm SM}\delta_{\alpha\beta}+[C_{LL}^{V}]^{\alpha\beta}\right|^2\left(H_{V,+}^2+H_{V,-}^2\right)\\
&+\left|C_{LL}^{\rm SM}\delta_{\alpha\beta}+[C_{LL}^{V}]^{\alpha\beta}-[C_{RL}^{V}]^{\alpha\beta}\right|^2 H_{V,0}^2\\
&-4\,{\rm Re}\left[\left(C_{LL}^{\rm SM}\delta_{\alpha\beta}+[C_{LL}^{V}]^{\alpha\beta}\right)[C_{RL}^{V*}]^{\alpha\beta}\right]H_{V,+}H_{V,-}\\
&+\left(\left|[C_{RL}^{V}]^{\alpha\beta}\right|^2+\left|[C_{LR}^{V}]^{\alpha\beta}\right|^2+\left|[C_{RR}^{V}]^{\alpha\beta}\right|^2\right)\left(H_{V,+}^2+H_{V,-}^2\right)\\
&+\left|[C_{LR}^{V}]^{\alpha\beta}-[C_{RR}^{V}]^{\alpha\beta}\right|^2 H_{V,0}^2-4{\rm Re}\left[[C_{LR}^{V}]^{\alpha\beta}\,[C_{RR}^{V*}]^{\alpha\beta}\right]H_{V,+}H_{V,-}\\
&+\frac{3}{2}\left(\left|[C_{RL}^{S}]^{\alpha\beta}-[C_{LL}^{S}]^{\alpha\beta}\right|^2+\left|[C_{RR}^{S}]^{\alpha\beta}-[C_{LR}^{S}]^{\alpha\beta}\right|^2\right)H_S^2\\
&+8\left(\left|[C_{LL}^{T}]^{\alpha\beta}\right|^2+\left|[C_{RR}^{T}]^{\alpha\beta}\right|^2\right)\left(H_{T,+}^2+H_{T,-}^2+H_{T,0}^2\right)\,.
\end{aligned}
$$

B anomalies

Tree		One-loop	
$b \to c\tau\bar{\nu}$		$\tau \to \mu\gamma$ $\mu \to e\gamma$	
$b \to s\ell\ell$		$Z \to \tau\tau$ $Z \to \nu\bar{\nu}$	
$B \to K^{(*)}\nu\bar{\nu}$ $K^+ \to \pi^+\nu\bar{\nu}$		ΔM_d ΔM_s	
$K_L \to \mu^{\pm}e^{\mp}$