SUSY 2021

$B \to K\nu\bar{\nu}$ *measurements and beyond the standard model theories*

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Alexander von Humboldt Stiftung/Foundation

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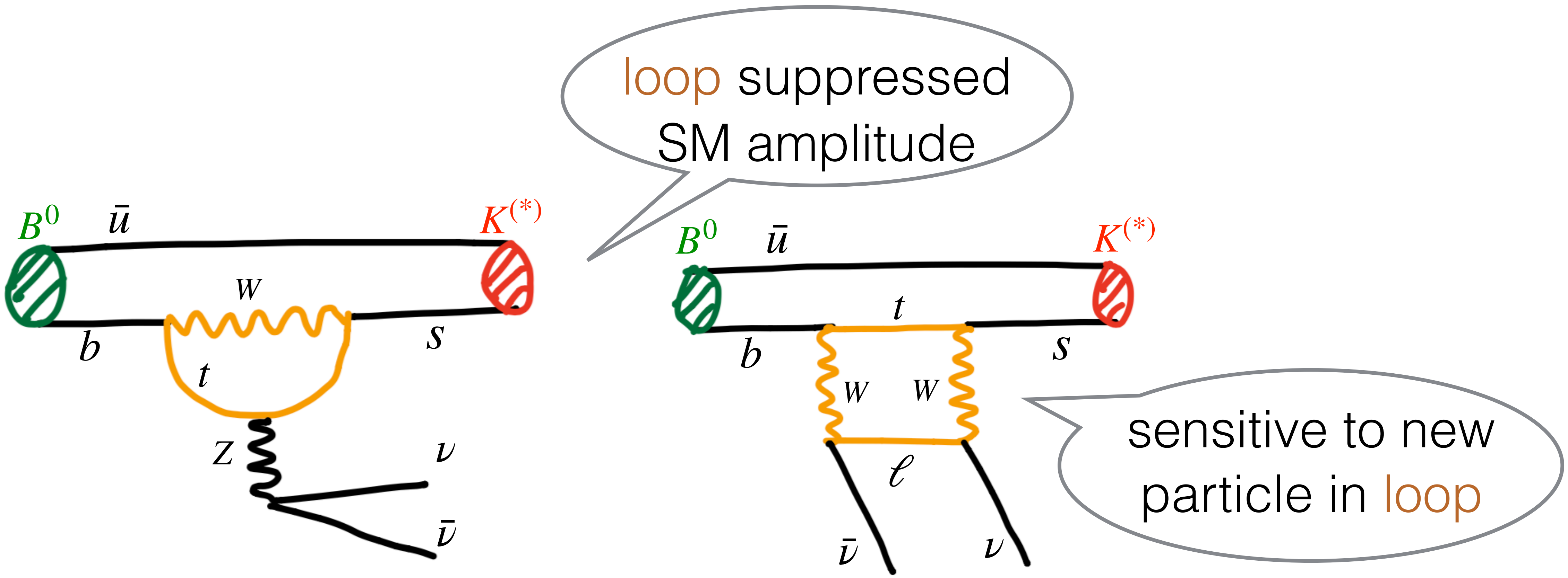
Outline

- Introduction
- New Physics analysis
  - Leptoquark
  - Heavy Z'
- Summary

Introduction



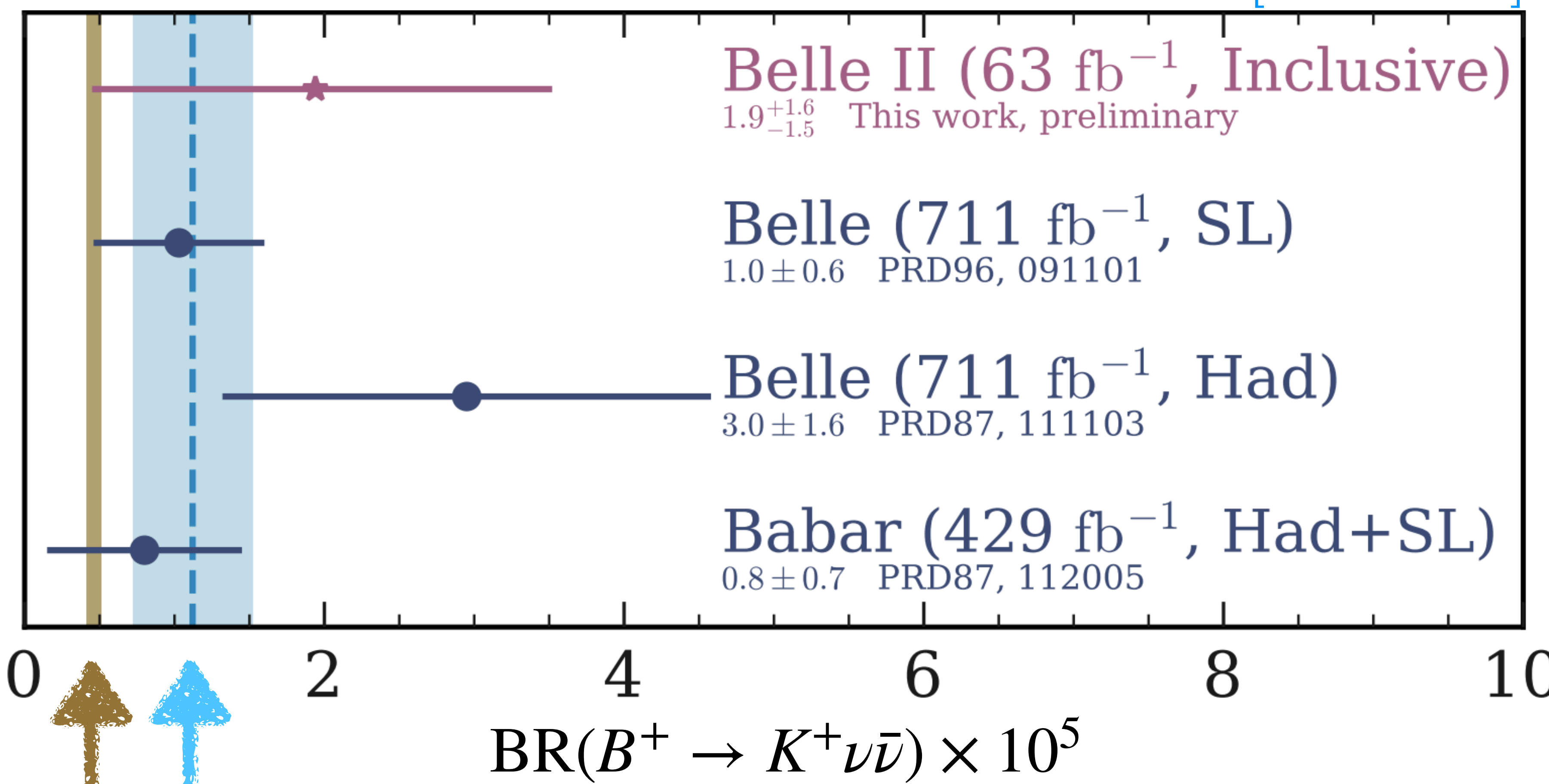
- [x] Theoretically much cleaner than $B \to K^* \ell^- \ell^+$

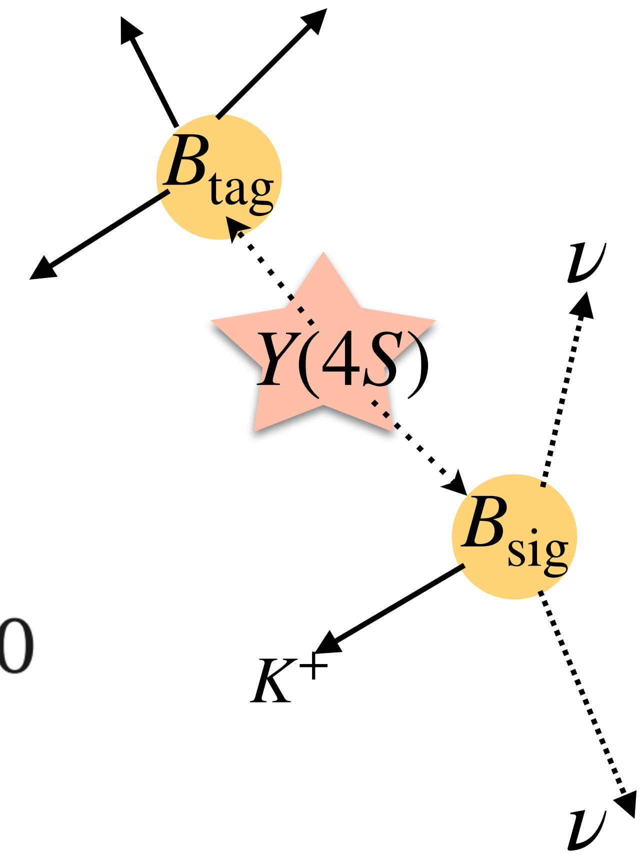
- [ ] Experimentally quite challenging due to two missing neutrinos—— No signal has been observed so far

Introduction

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

[2105.05754]





$$\mathrm{Exp_{avg}} = (1.1 \pm 0.4) \times 10^{-5}$$
$$\mathrm{SM} = (4.6 \pm 0.5) \times 10^{-6}$$

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

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

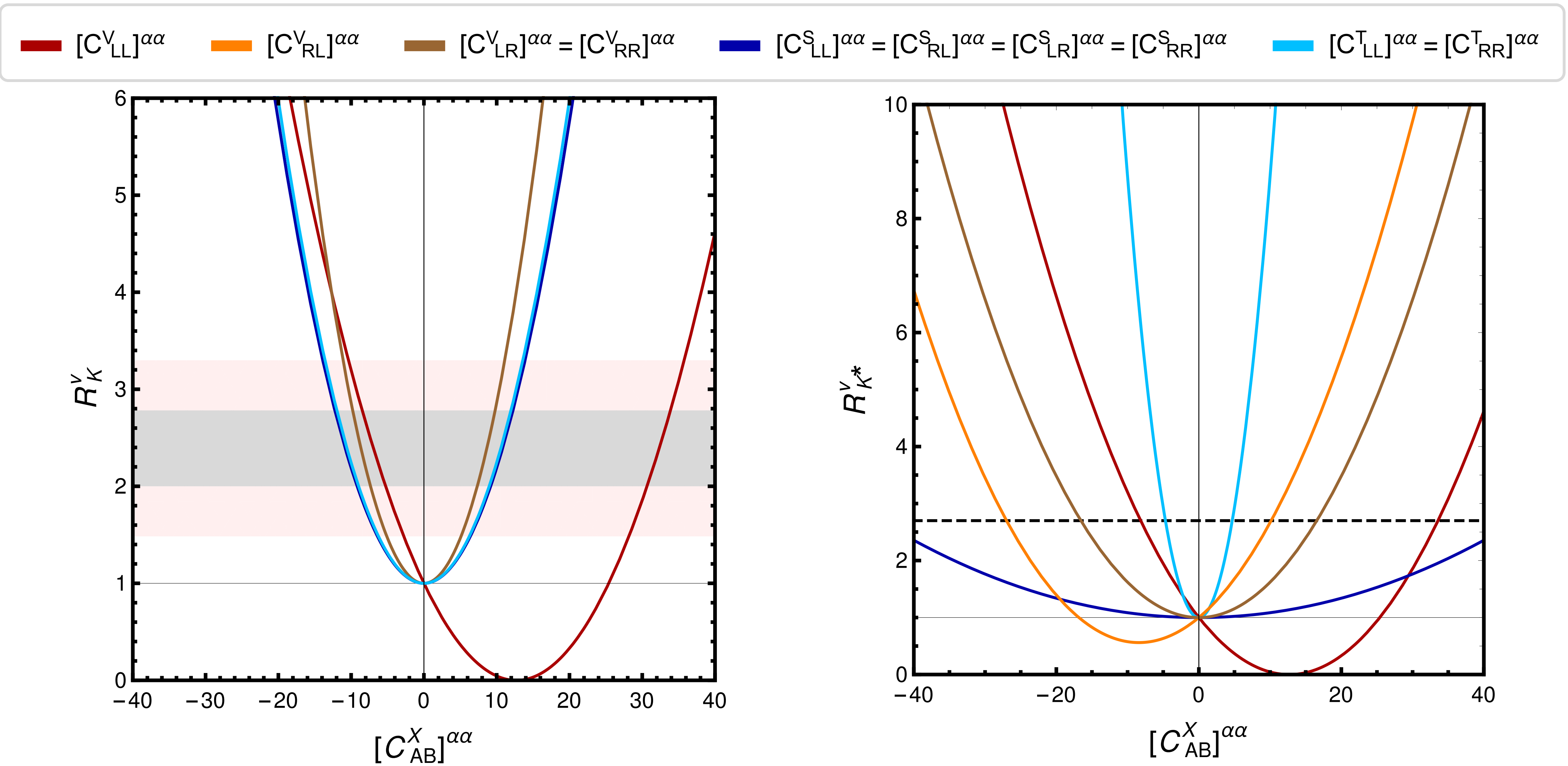
$C_{LL}^{\rm SM} = -2X_t/s_w^2$ = -12.7

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

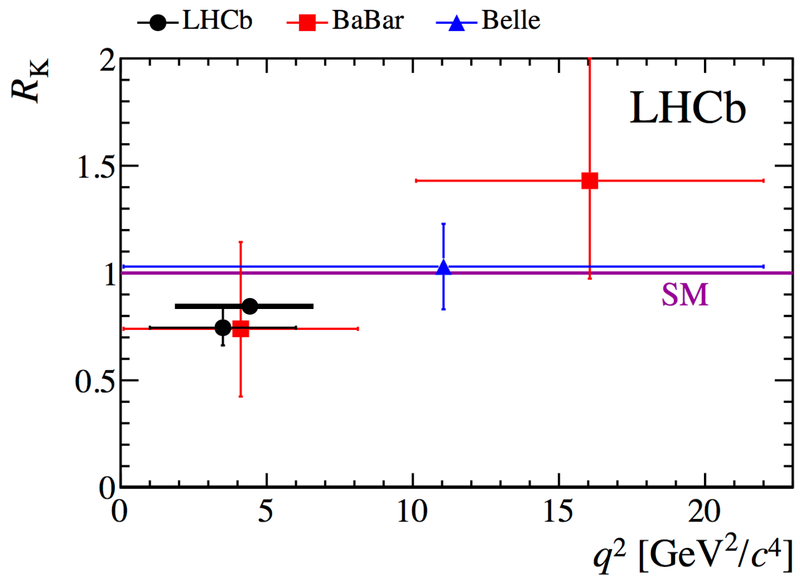


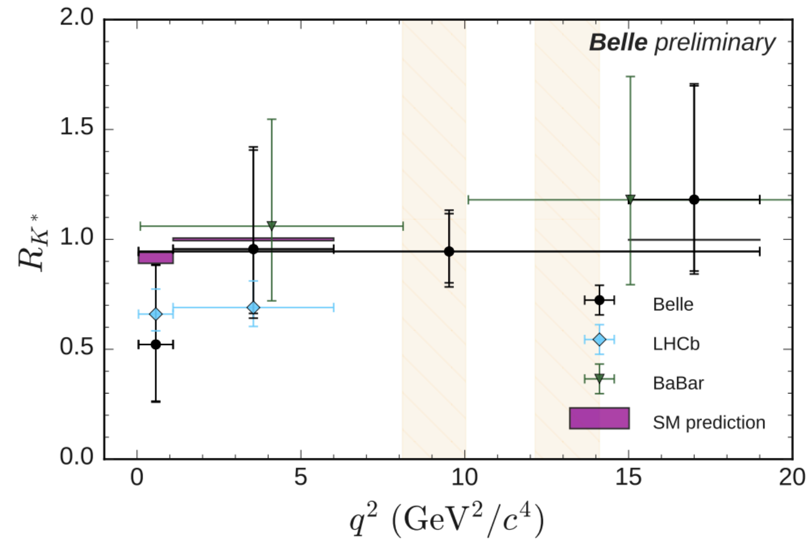
Variation with individual Wilson coefficients

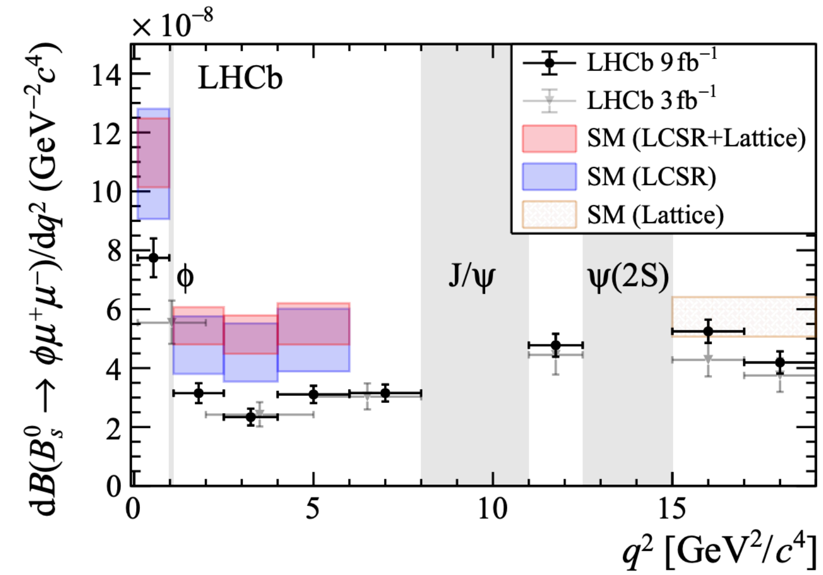
All operators can achieve the expected range

B-anomalies

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







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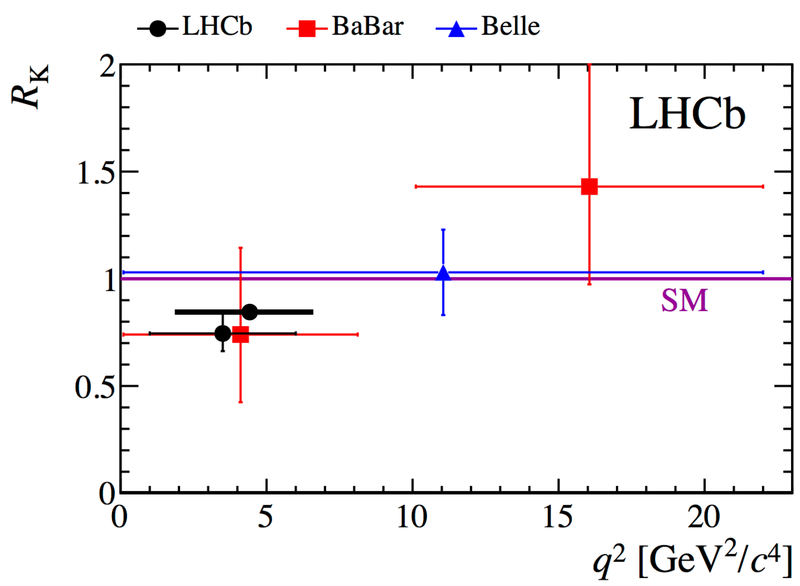
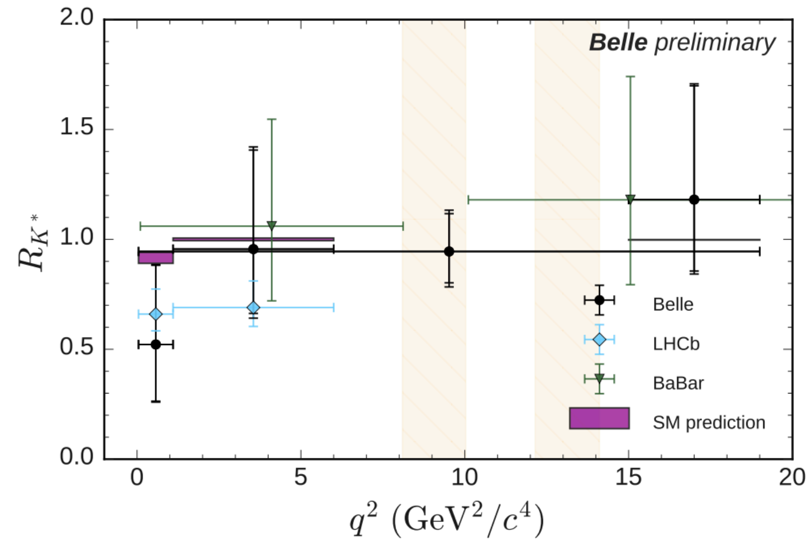
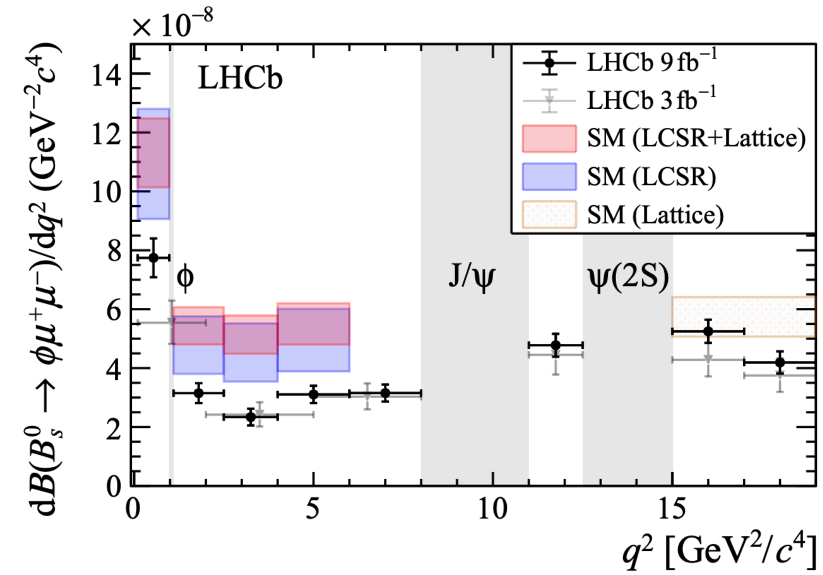
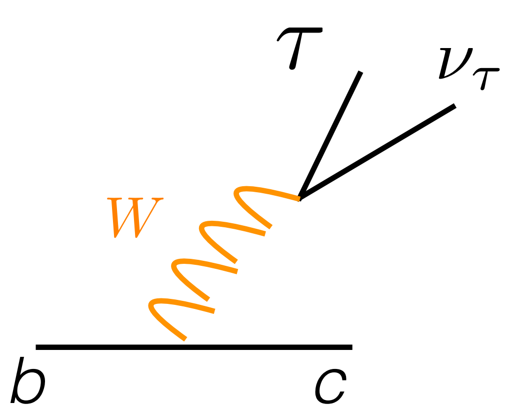
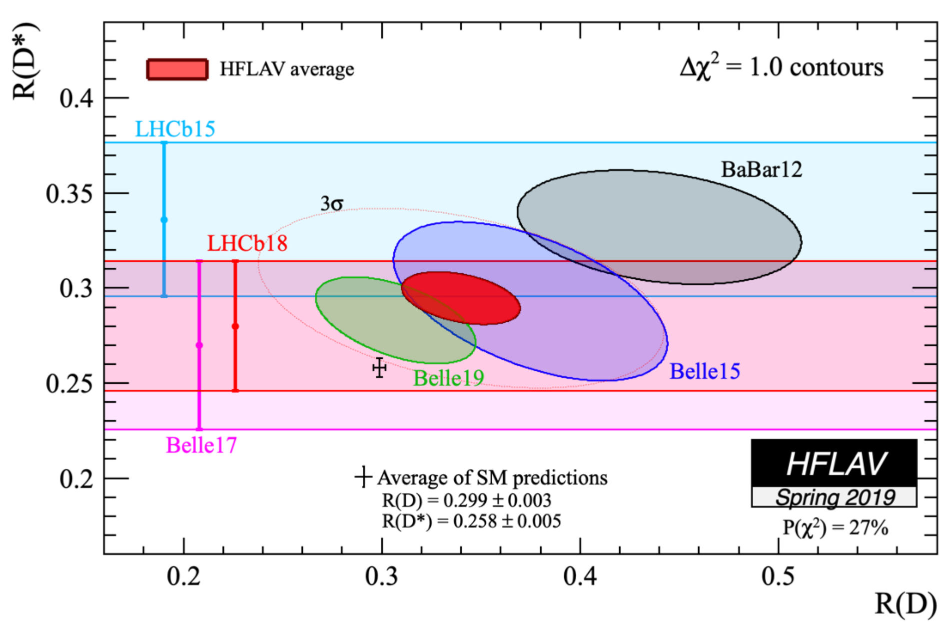






- Exciting discrepancies observed in charged current B decays also





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

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

B-anomalies

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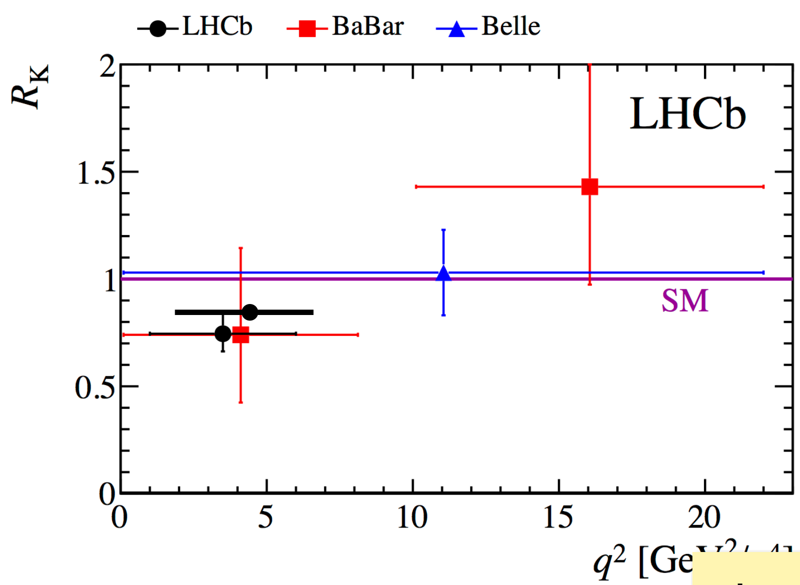
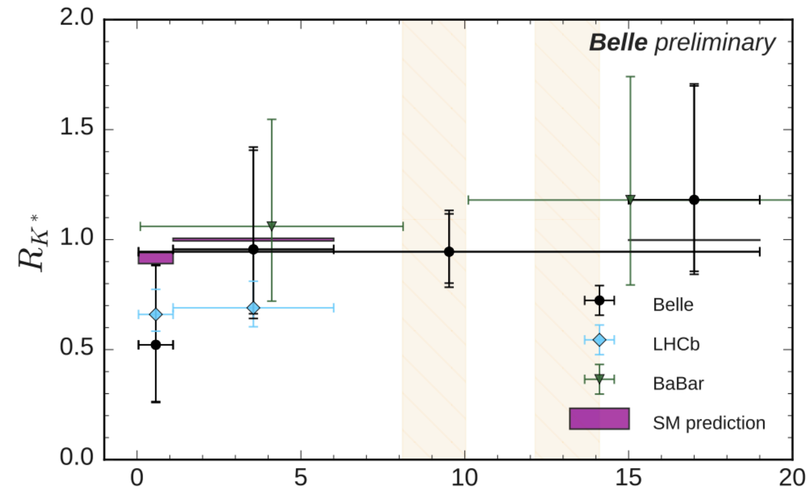
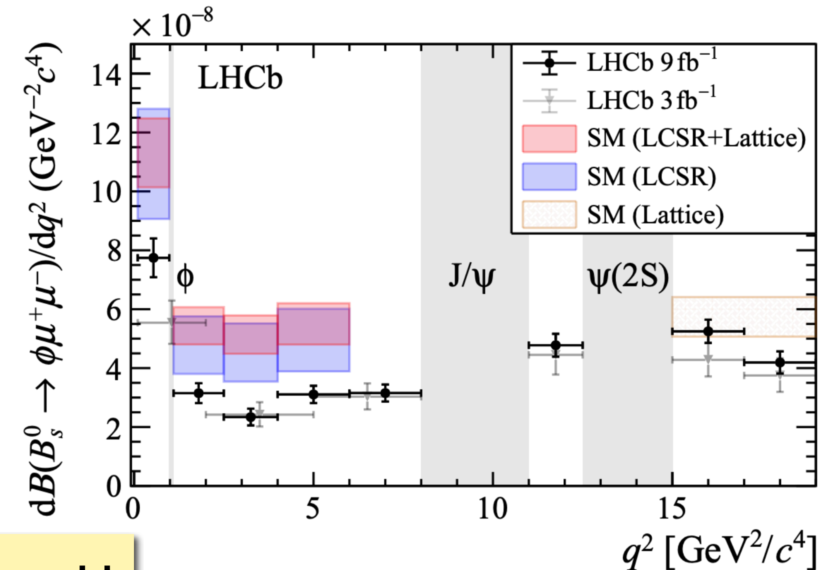
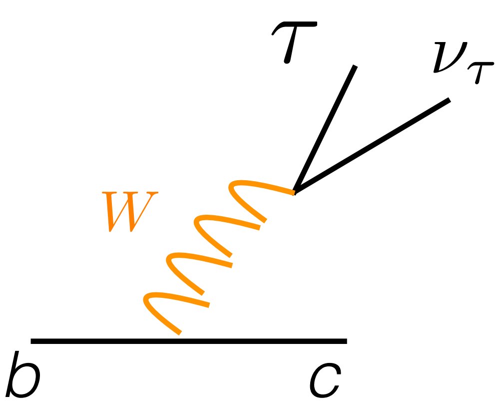


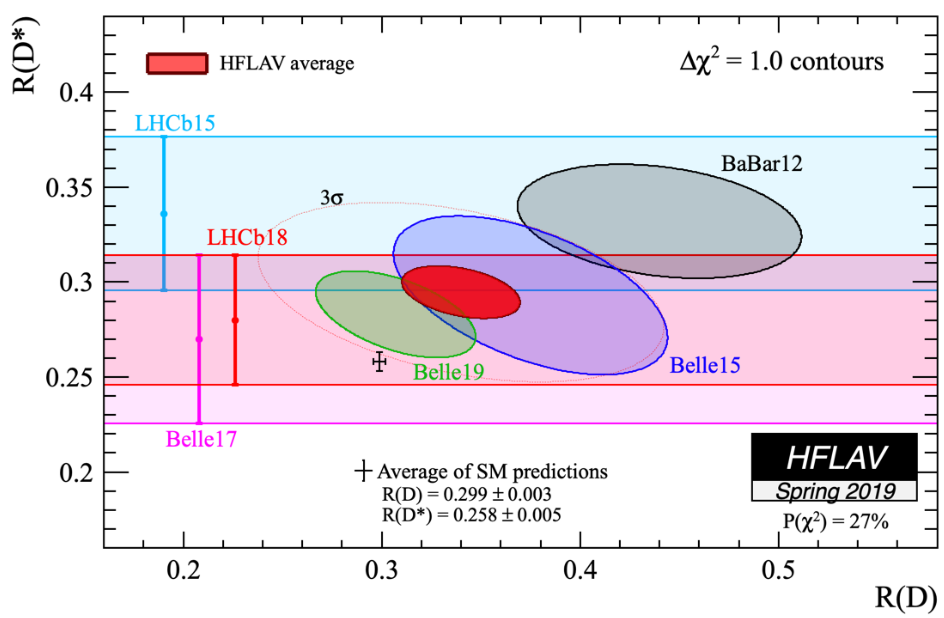




deviations$\sim 2-3\sigma$: Anomalies!!

- Exciting discrepancies observed in charged current B decays also





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

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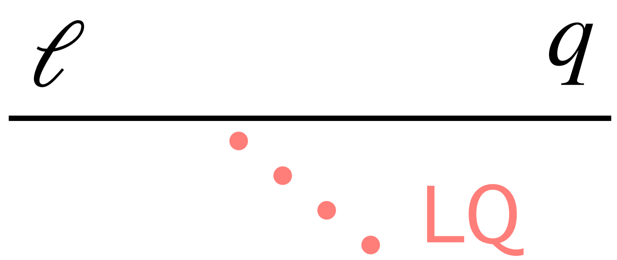
Leptoquarks



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

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

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

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

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

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

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

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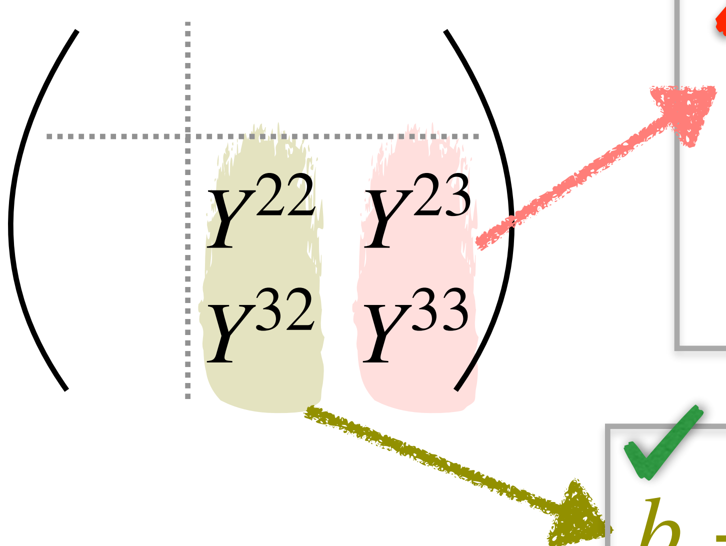

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$b \to s\nu\bar{\nu}$: C^{V}_{LL}

➡ Only ~2% enhancement in R_K^{ν} 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 $R_K^{\nu} = 2.4 \pm 3.6$

$\tilde{R}_2$:

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

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

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

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

$\tilde{R}_2$:

RHN coupling

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

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

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

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

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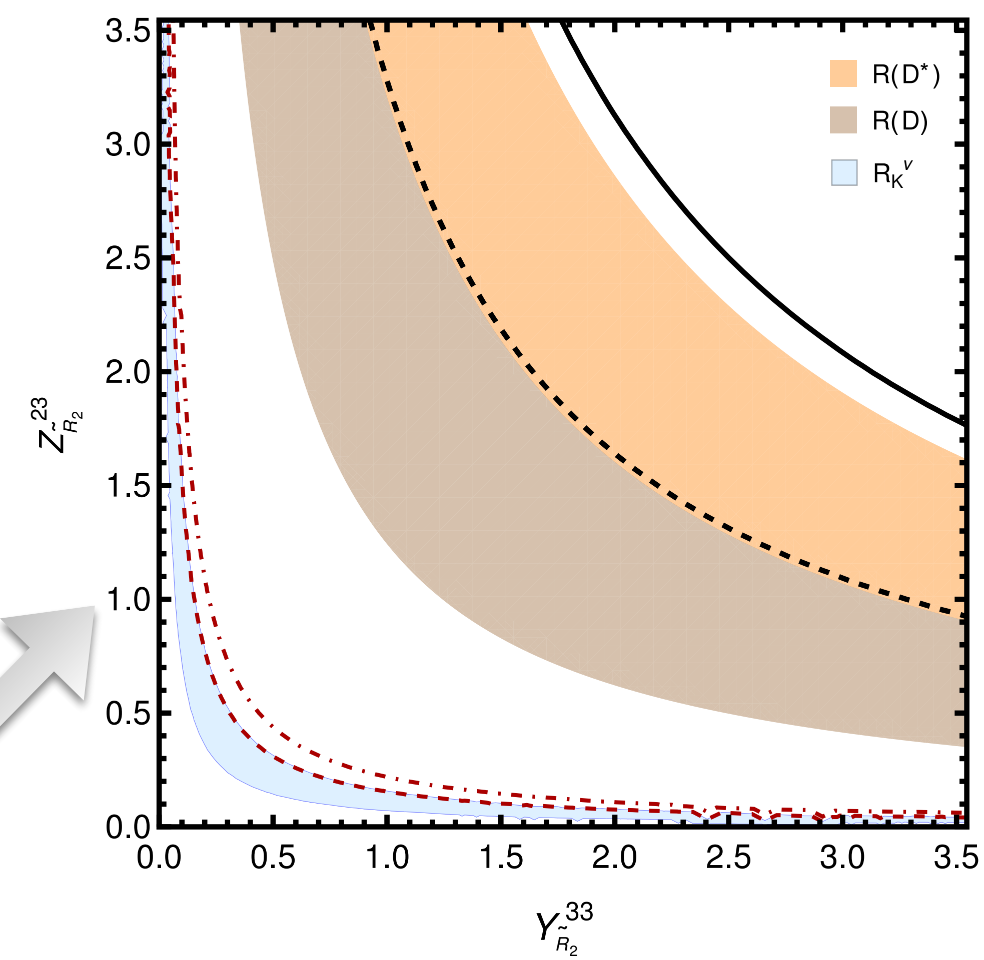
Region explaining $R(D^{(*)})$ is completely excluded by R_K^ν



S_1 :

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

LH only

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

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

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} ⇒ $R^\nu_K = 2.46 \pm 1.22$

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+

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

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} ⇒ $R^\nu_K = 2.35 \pm 1.97$

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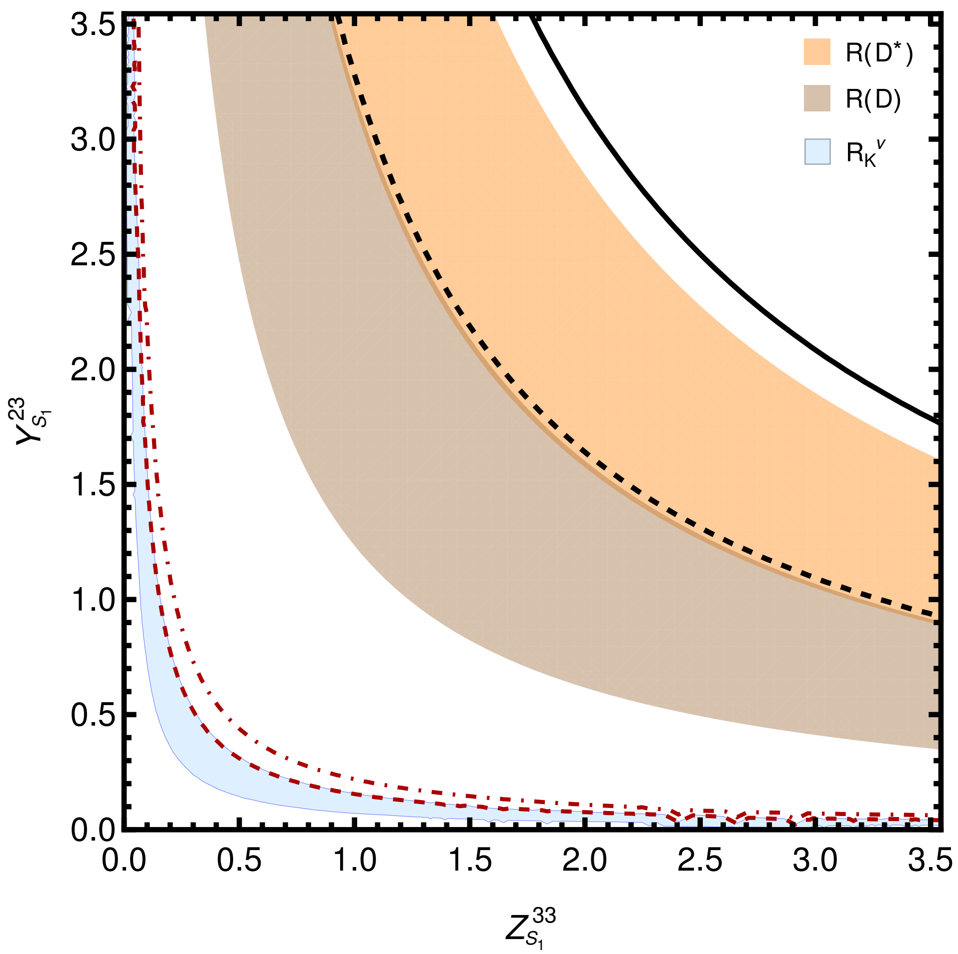

$b \to s\nu\bar{\nu}$: C^S_{RR} generated with RHN
No interference with SM

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 :

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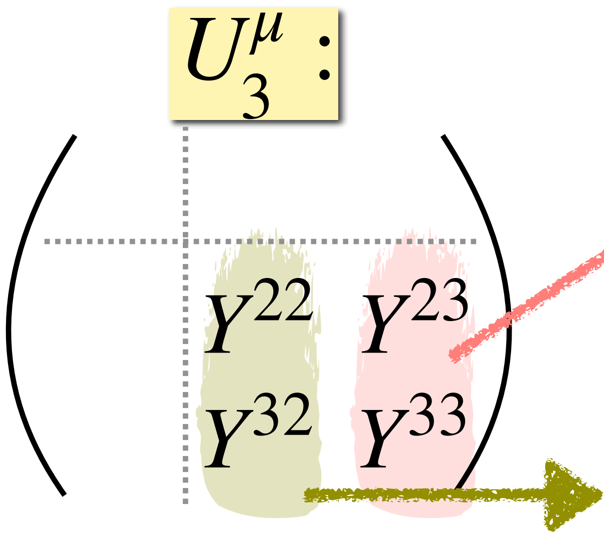

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✓ $b \to s\mu\mu$: $C_9^{\rm NP} = -C_{10}^{\rm NP}$

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

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V_2^μ :

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

Differs in form factor dependence

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

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

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 ⟶ $R_K^\nu \simeq 2.4$

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 $B_s^0 - \bar{B}_s^0$

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

$R_K^\nu = 1.05 \pm 0.03$

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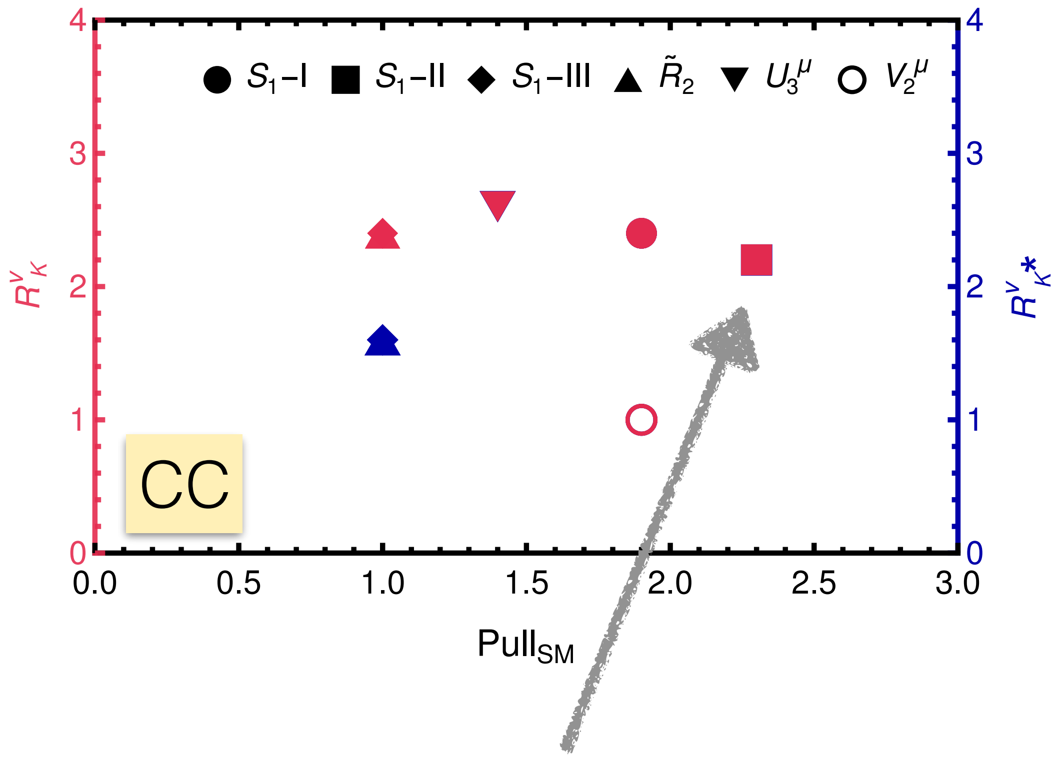
$R_K^\nu = 1.05 \pm 0.03$

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

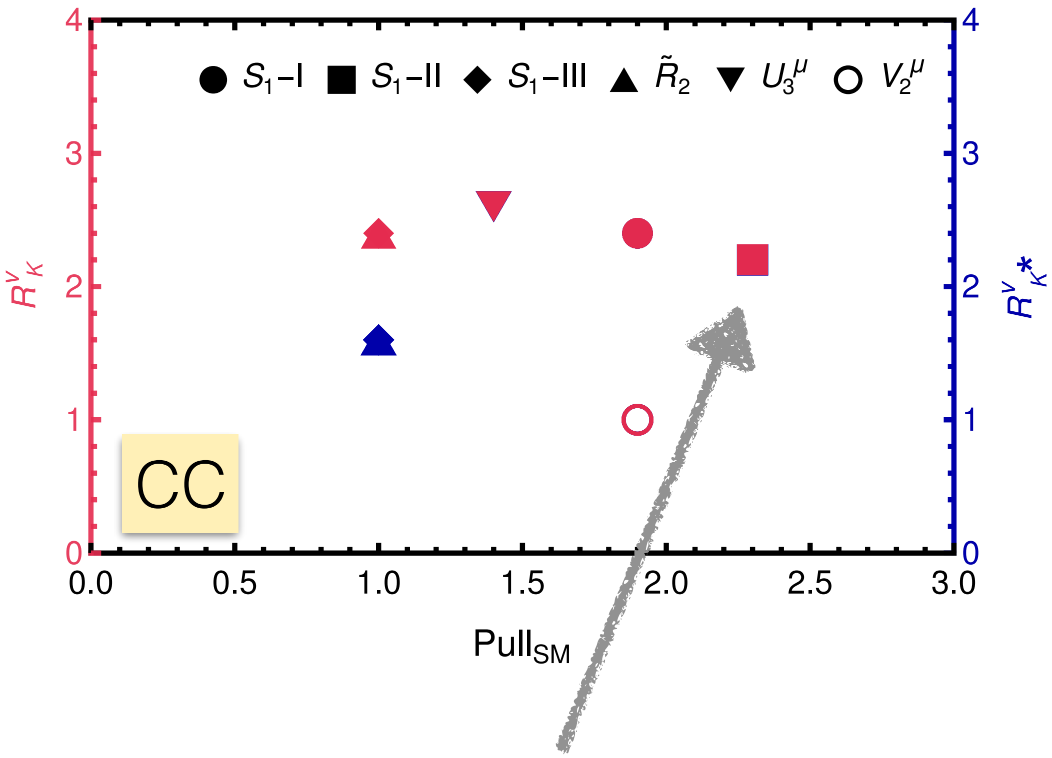
No new contribution to $R_K^\nu \simeq 1.1$

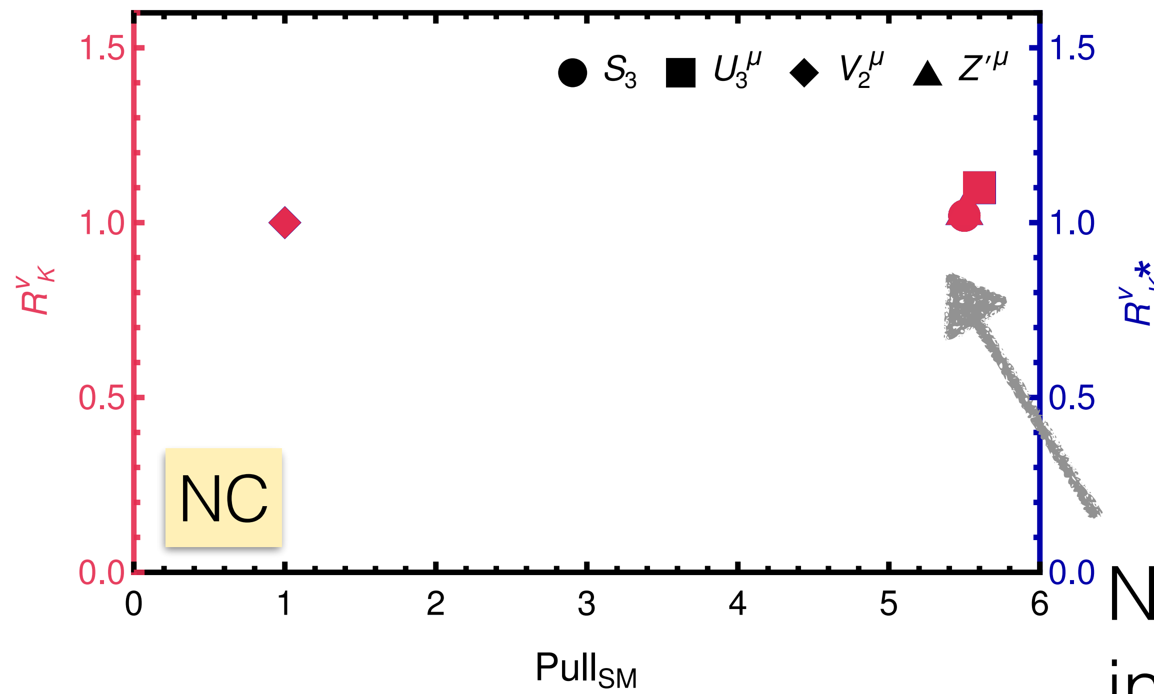
Comparison



S_1 with three non-vanishing couplings

Comparison





No excess in R_K^ν

S_1 with three non-vanishing couplings

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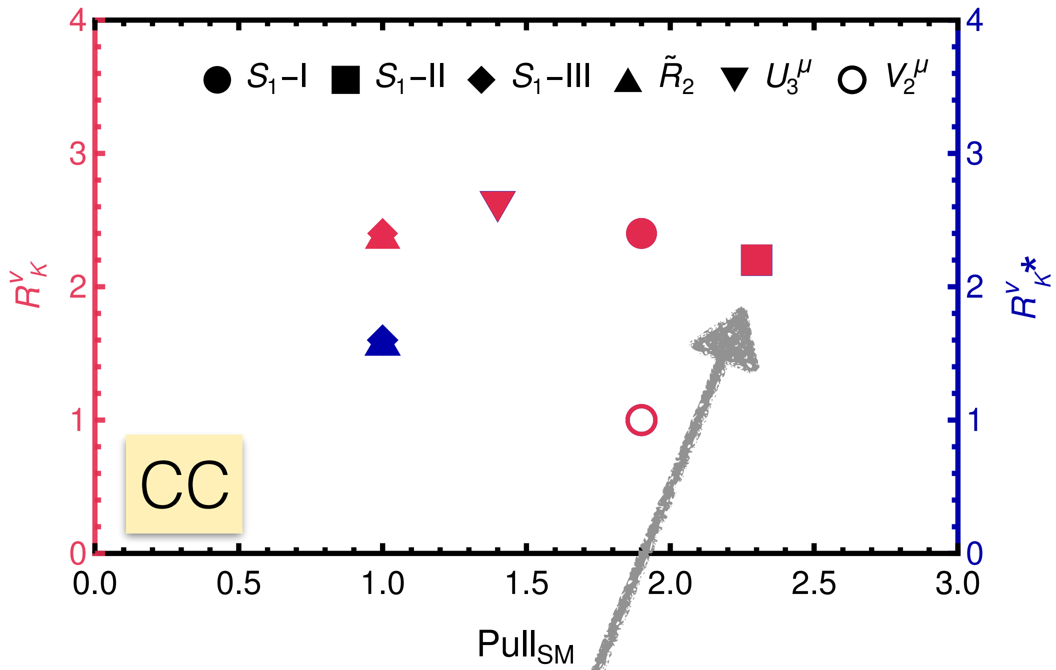
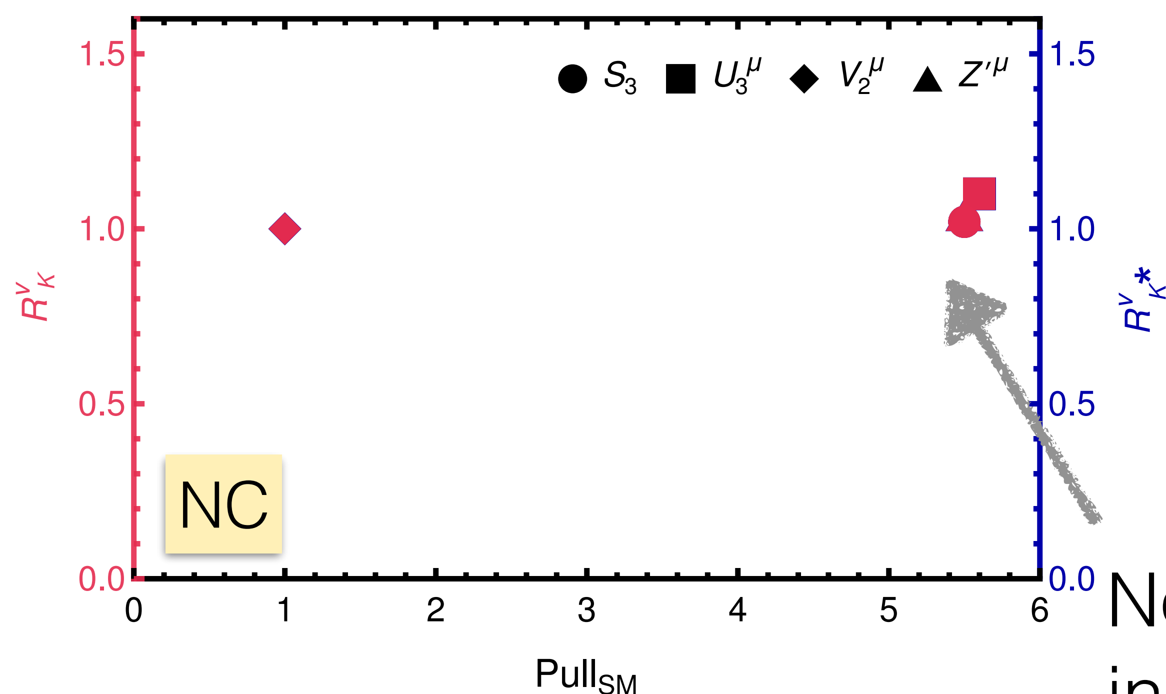
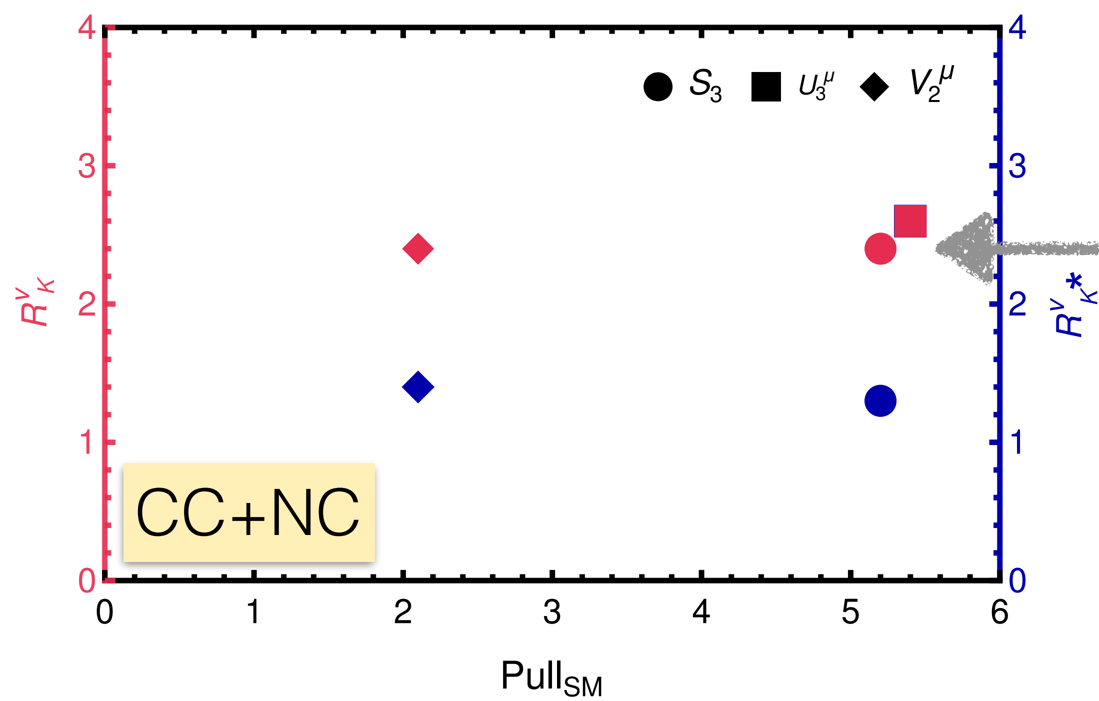




No excess in R_K^ν

S_1 with three non-vanishing couplings



S_3 & U_3^μ can show desired enhancement

Summary

- $B \to K^{(*)}\nu\bar{\nu}$ are important probe for new physics
- Experimental challenges might be overcome with inclusive tag technique@Belle II — expecting signal soon?!
- 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}

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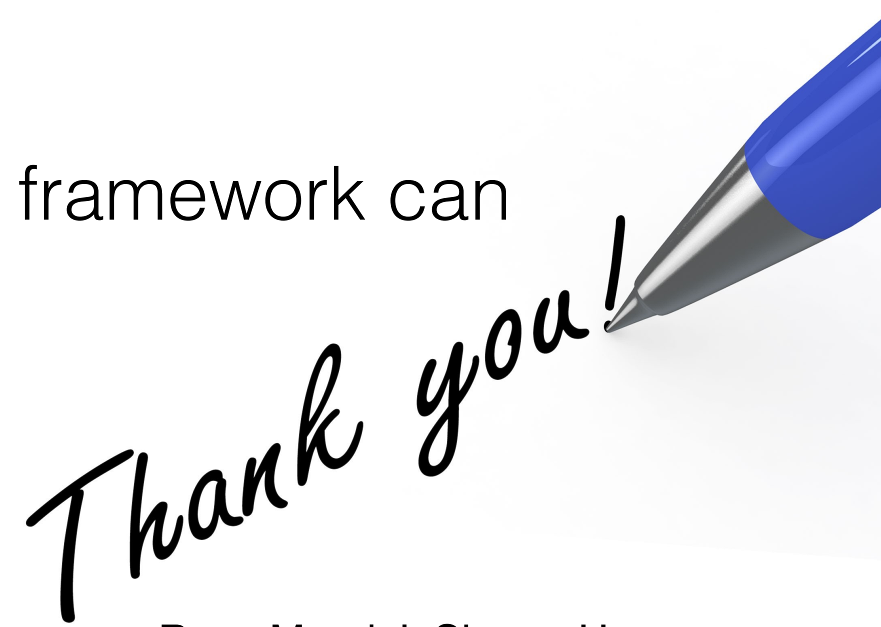

Back ups

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

$$\begin{aligned}
\mathcal{P}_{LL}^{V\alpha\beta} &= + \frac{v^2}{\Lambda^2} \sum_{m=1}^{3} \frac{V_{2m}}{V_{cb}} [\mathcal{C}_{lq}^{(3)}]^{m3\alpha\beta} , \\
\mathcal{P}_{LL}^{S\alpha\beta} &= - \frac{v^2}{2\Lambda^2 V_{cb}} [\mathcal{C}_{lequ}^{(1)*}]^{23\alpha\beta} , \\
\mathcal{P}_{LL}^{T\alpha\beta} &= - \frac{v^2}{2\Lambda^2 V_{cb}} [\mathcal{C}_{lequ}^{(3)*}]^{23\alpha\beta} , \\
\mathcal{P}_{RL}^{S\alpha\beta} &= + \frac{v^2}{2\Lambda^2} \sum_{m=1}^{3} \frac{V_{2m}}{V_{cb}} [\mathcal{C}_{ledq}^{*}]^{m3\alpha\beta} .
\end{aligned}$$

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

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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

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

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

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

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

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

B anomalies