

Anomalies and Precision in the Belle II Era - Workshop

New physics implications of $B \rightarrow K\nu\bar{\nu}$

Rusa Mandal
Universität Siegen

on arXiv: 2107.01080

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

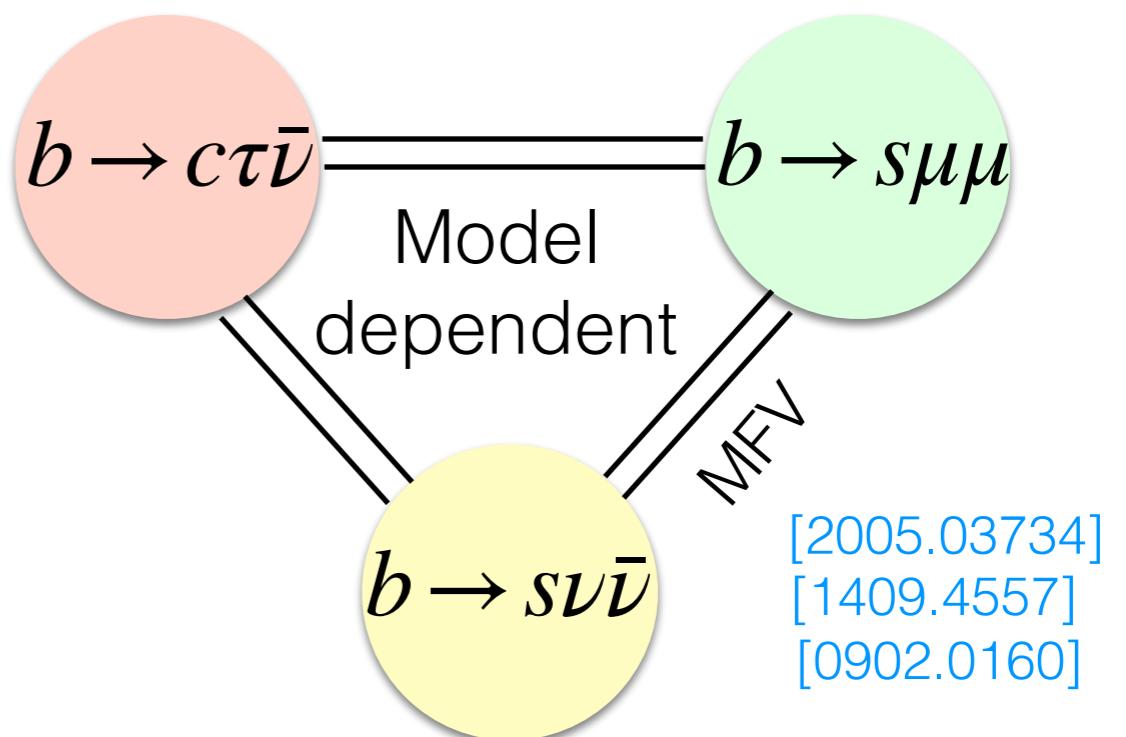
Outline

- Introduction

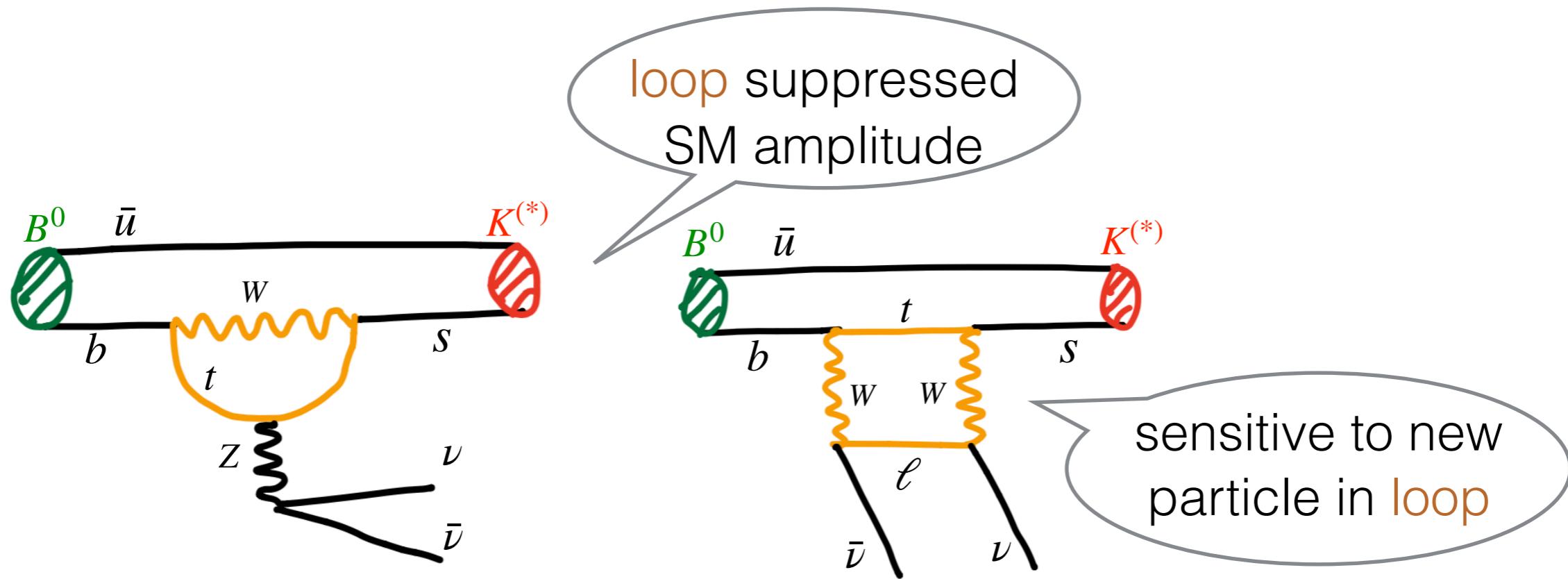
- New Physics analysis

- ▶ Leptoquarks
- ▶ Heavy Z'

- Summary



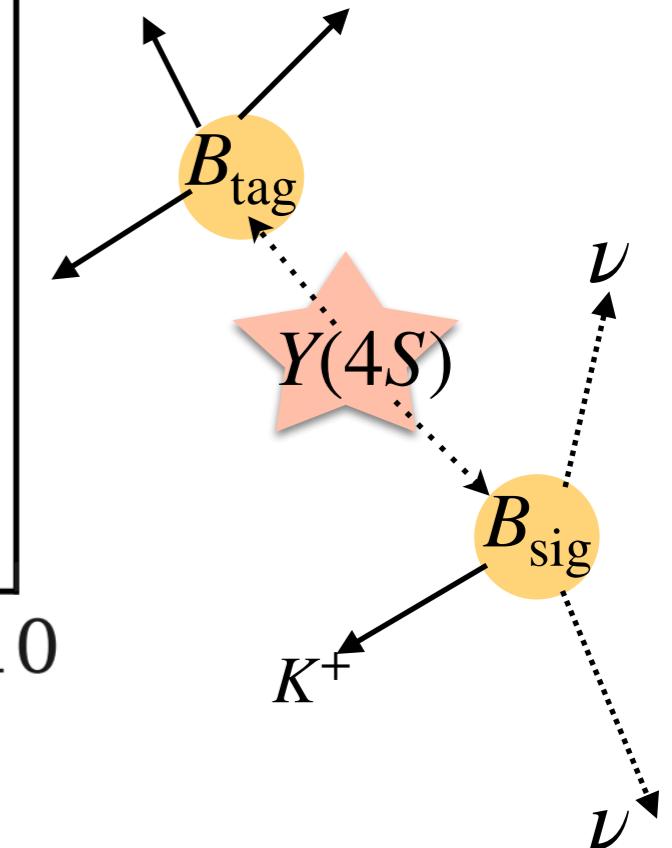
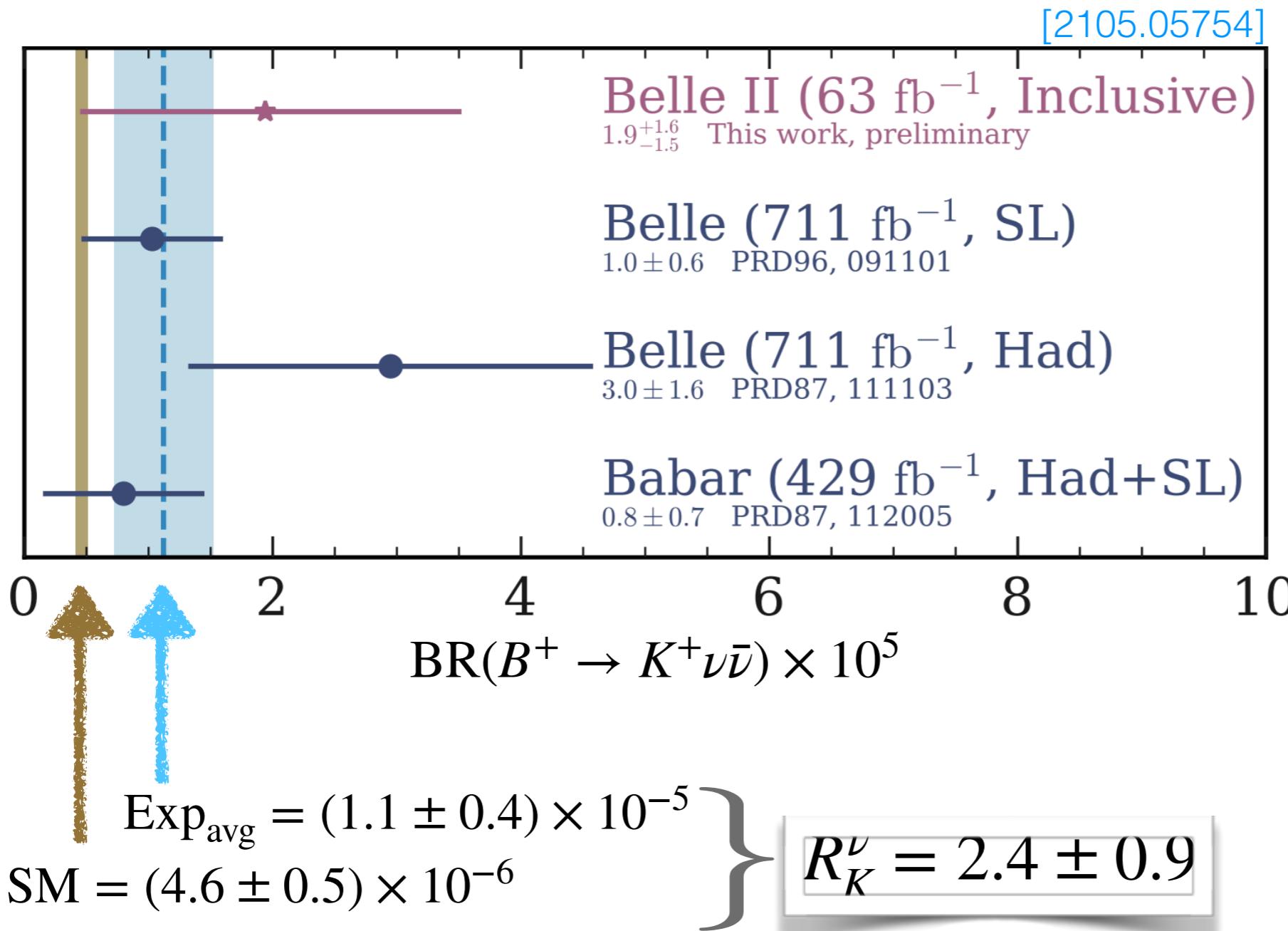
Introduction



- Theoretically much cleaner than $B \rightarrow K^* \ell^- \ell^+$
- 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%



Hamiltonian

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

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


SM FCNC contribution

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

Includes light right-handed neutrinos

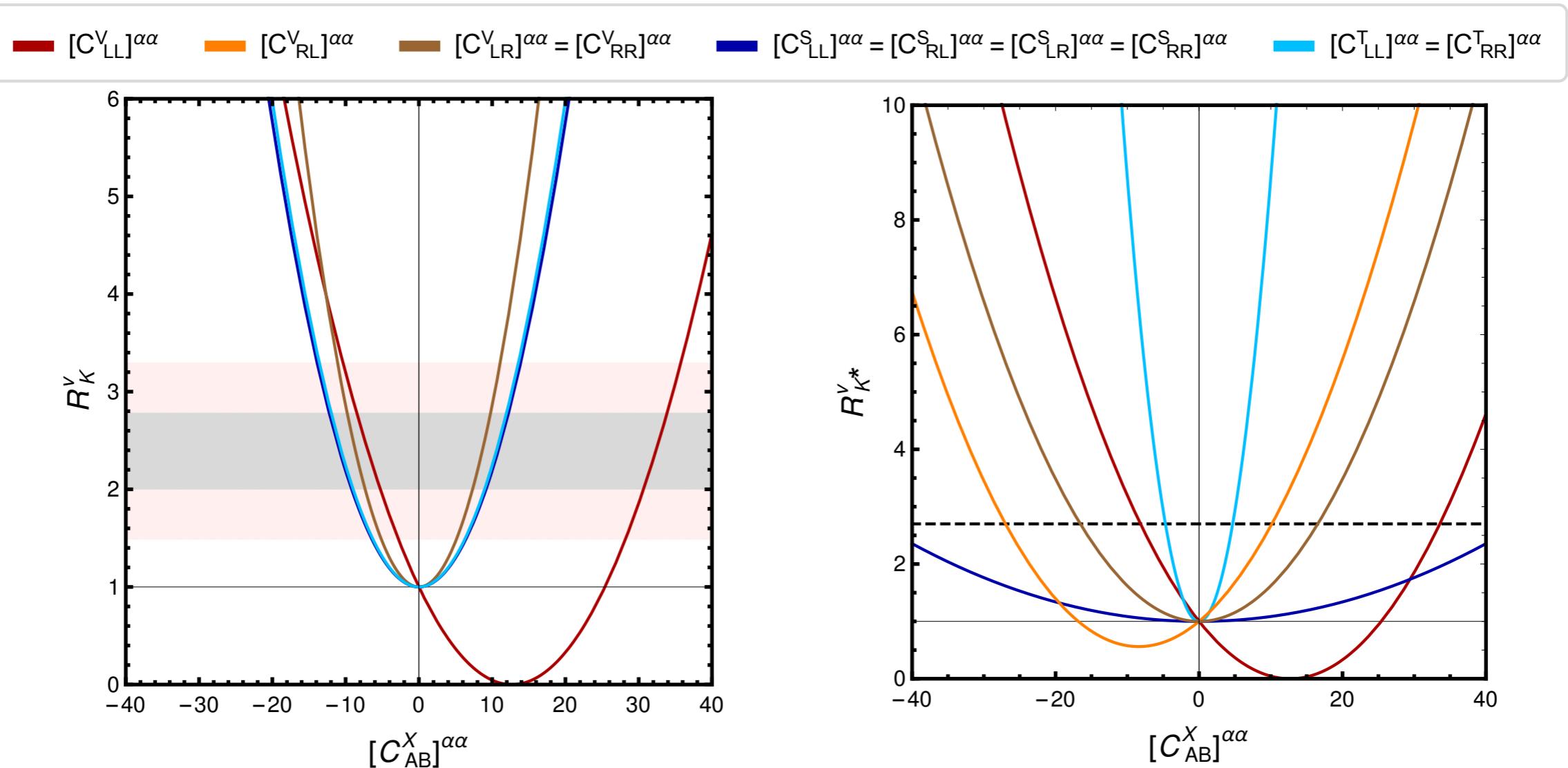
$$[\mathcal{O}_{AB}^V]^{\alpha\beta} \equiv (\bar{s} \gamma^\mu P_A b) (\bar{\nu}^\alpha \gamma_\mu P_B \nu^\beta),$$

$$[\mathcal{O}_{AB}^S]^{\alpha\beta} \equiv (\bar{s} P_A b) (\bar{\nu}^\alpha P_B \nu^\beta),$$

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

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

Hamiltonian



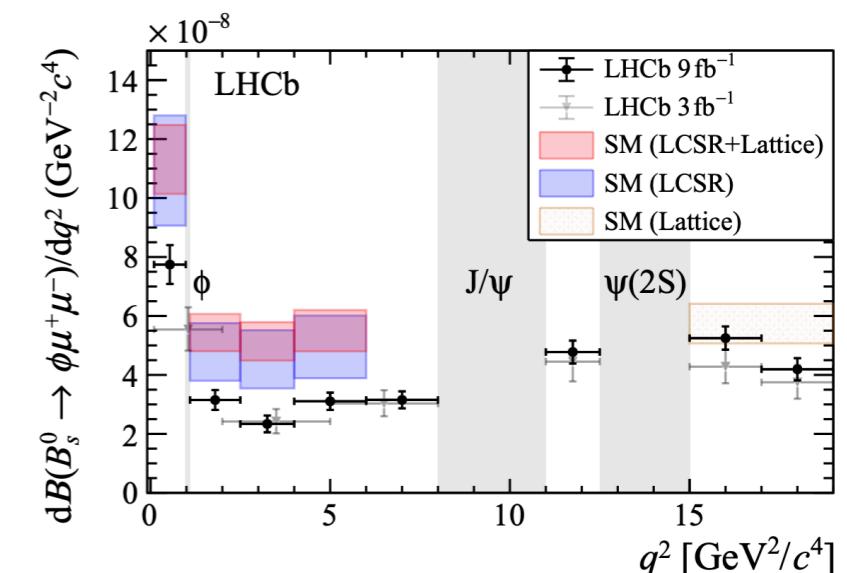
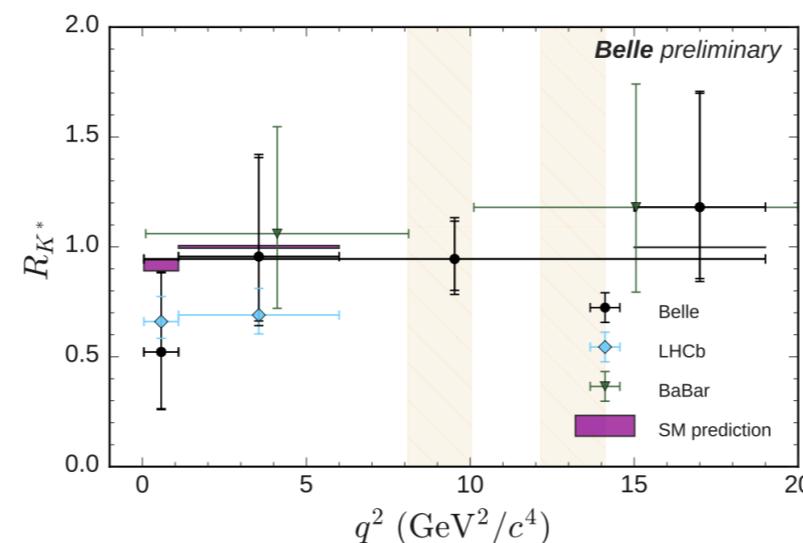
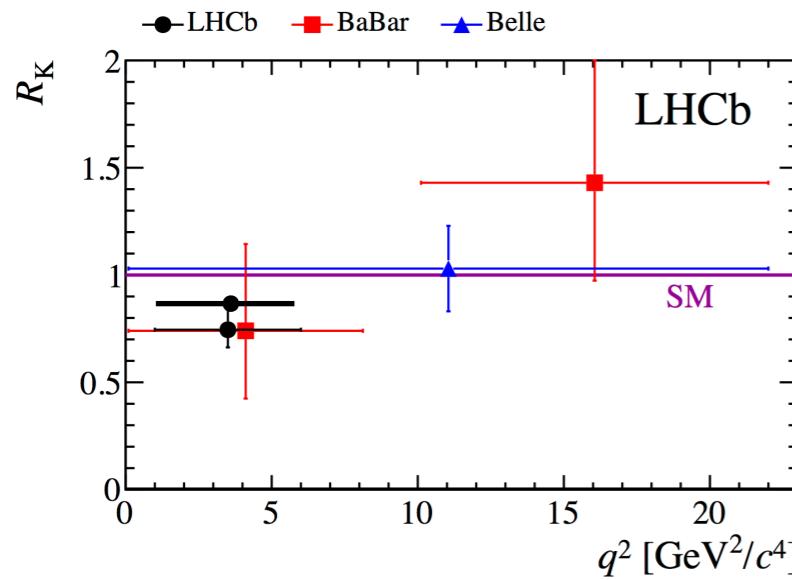
Variation with individual Wilson coefficients



All operators can achieve the expected range

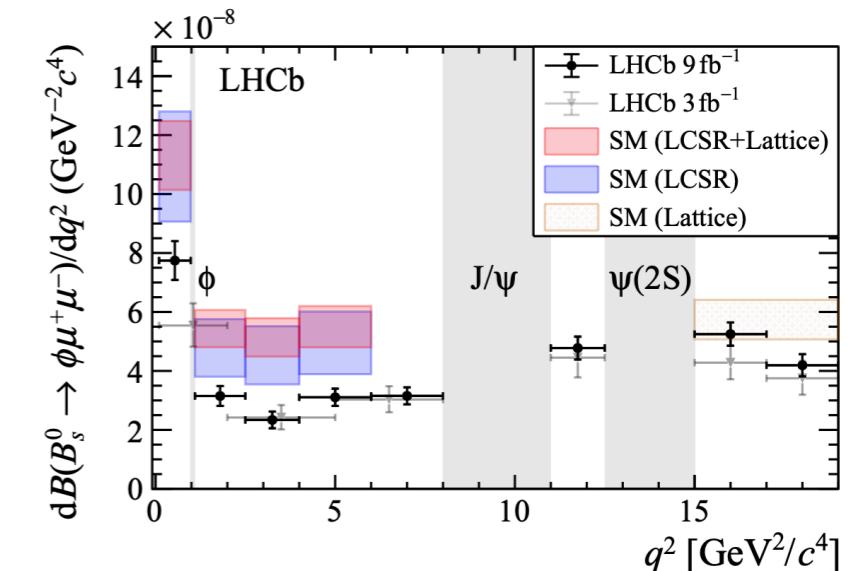
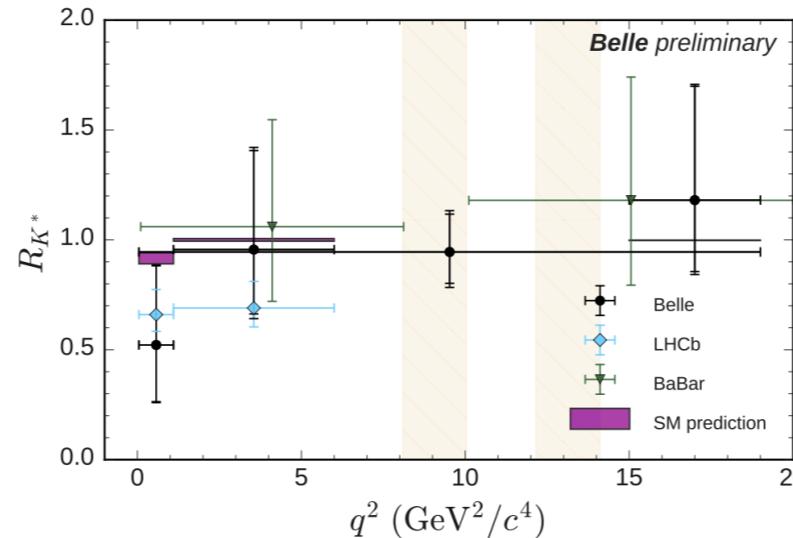
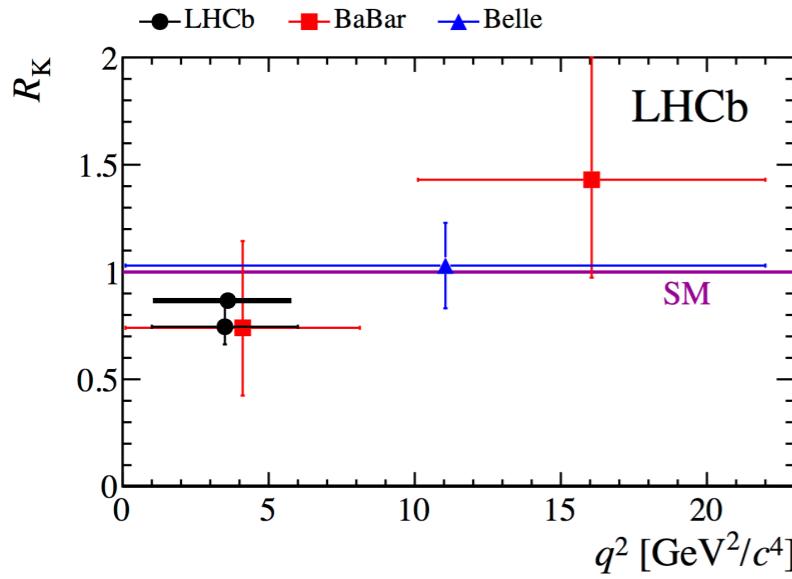
B-anomalies

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

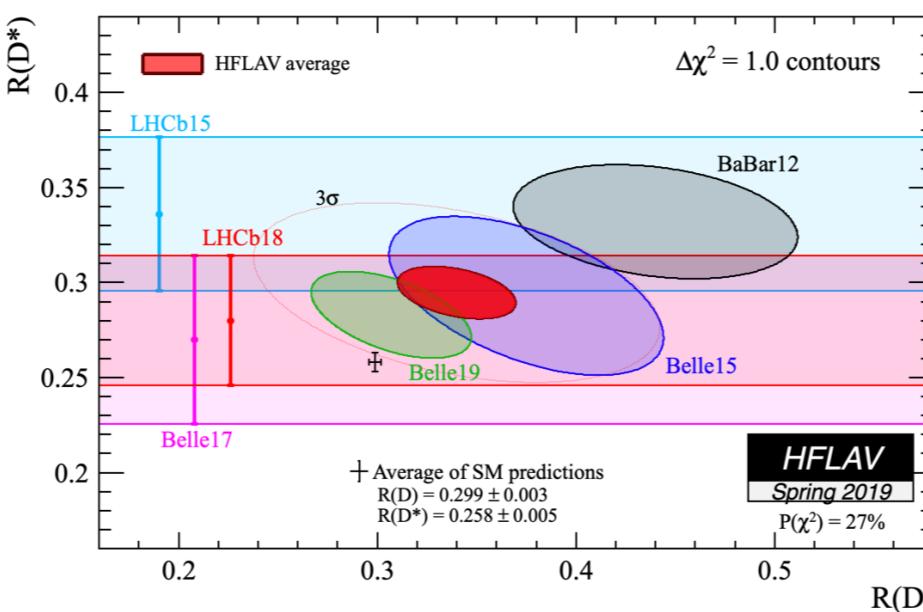
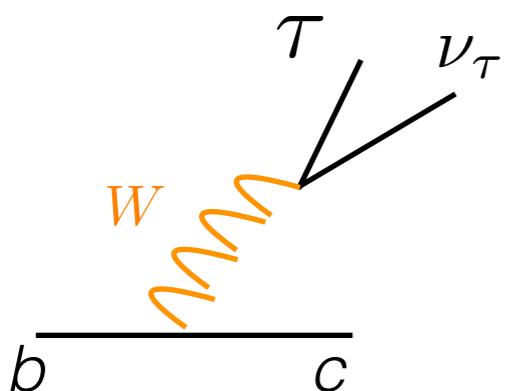


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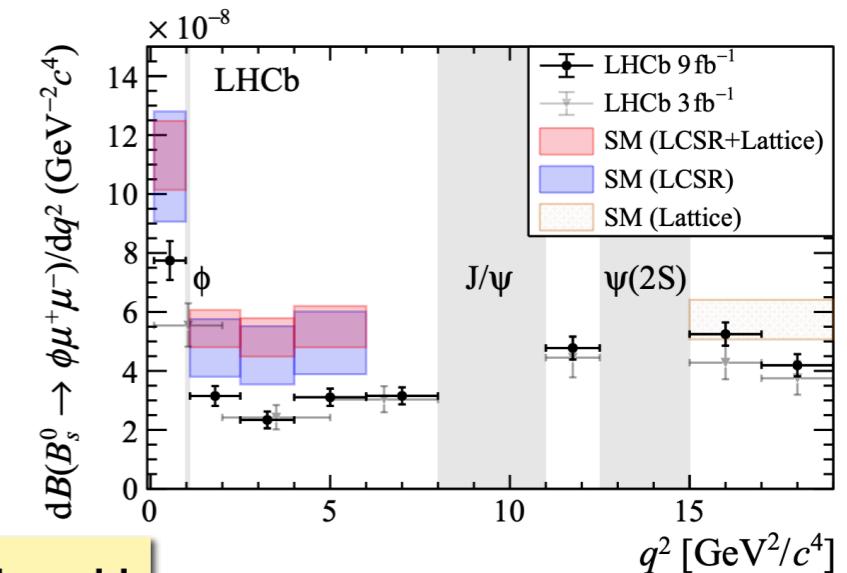
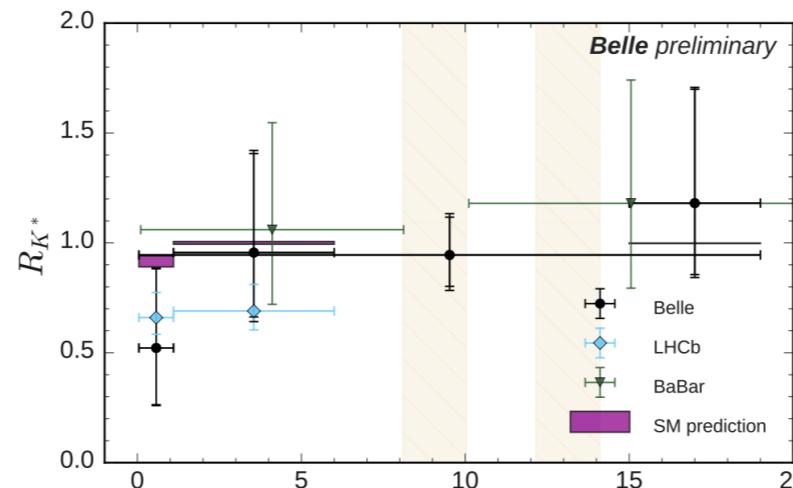
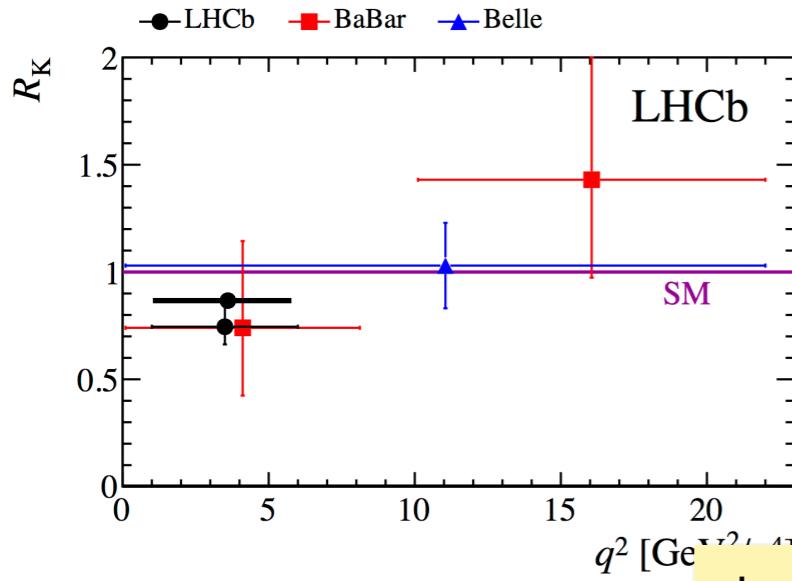
► Exciting discrepancies observed in charged current B decays also



$$R(D^{(*)}) \equiv \frac{\text{BR}(B \rightarrow D^{(*)}\ell\nu)}{\text{BR}(B \rightarrow D^{(*)}\ell\nu)} \quad \ell \in \{e, \mu\}$$

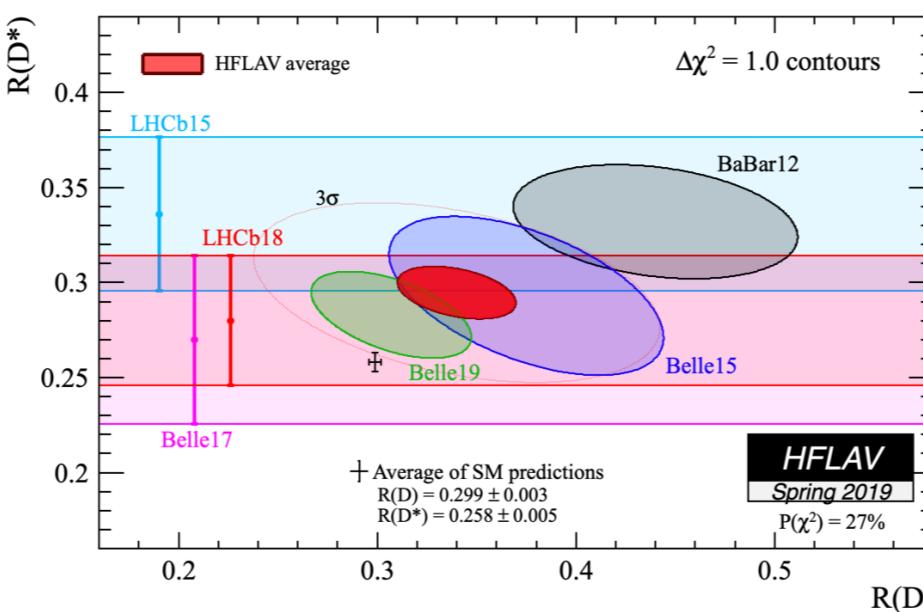
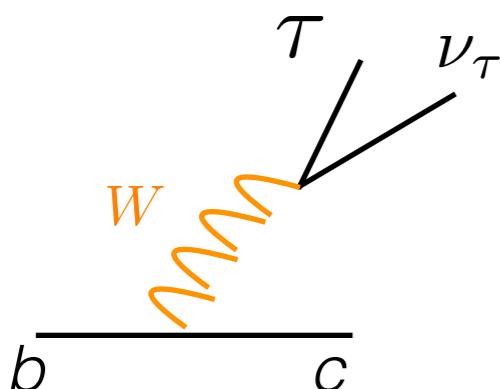
B-anomalies

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



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

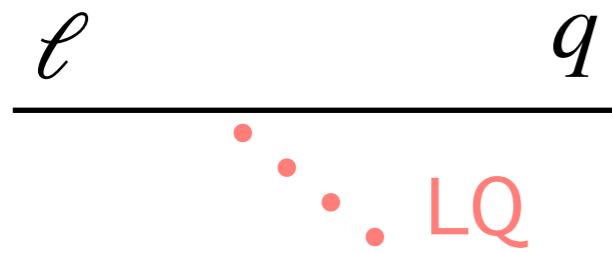
► Exciting discrepancies observed in charged current B decays also



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

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

Leptoquarks

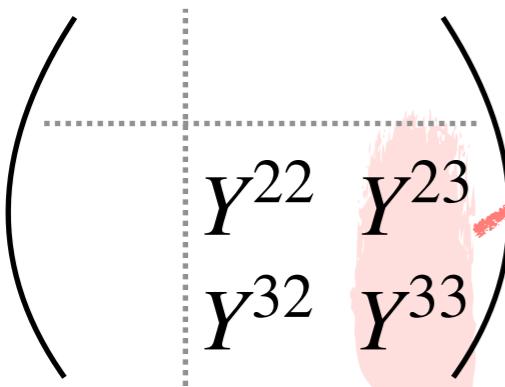


Idea from '70s: R-parity violating SUSY, GUTs

Mediators	Spin	Interaction terms	Operators
$S_3(\bar{3}, 3, 1/3)$	0	$+ \bar{Q}^c Y_{S_3} i\tau_2 \boldsymbol{\tau} \cdot \mathbf{S}_3 L$	\mathcal{O}_{LL}^V
$\tilde{R}_2(3, 2, 1/6)$	0	$- \bar{d}_R Y_{\tilde{R}_2} \tilde{R}_2^T i\tau_2 L + \bar{Q} Z_{\tilde{R}_2} \tilde{R}_2 \nu_R$	$\mathcal{O}_{RL}^V, \mathcal{O}_{LR}^V, \mathcal{O}_{LL}^{S,T}, \mathcal{O}_{RR}^{S,T}$
$S_1(\bar{3}, 1, 1/3)$	0	$+ \bar{Q}^c i\tau_2 Y_{S_1} L S_1 + \bar{u}_R^c \tilde{Y}_{S_1} S_1 e_R + \bar{d}_R^c Z_{S_1} S_1 \nu_R$	$\mathcal{O}_{RR}^{S,V,T}, \mathcal{O}_{LL}^{S,V,T}$
$U_3^\mu(3, 3, 2/3)$	1	$+ \bar{Q} \gamma^\mu \tau^a Y_{U_1} L U_{1\mu}^a$	\mathcal{O}_{LL}^V
$V_2^\mu(\bar{3}, 2, 5/6)$	1	$+ \bar{d}_R^c \gamma^\mu Y_{V_2} V_{2\mu}^T i\tau_2 L + \bar{Q}_L^c \gamma^\mu \tilde{Y}_{V_2} i\tau_2 V_{2\mu} e_R$	\mathcal{O}_{RL}^S
$\bar{U}_1^\mu(3, 1, -1/3)$	1	$+ \bar{d}_R Z_{\bar{U}_1} \gamma^\mu \bar{U}_{1\mu} \nu_R$	\mathcal{O}_{RR}^V

$S_3 :$

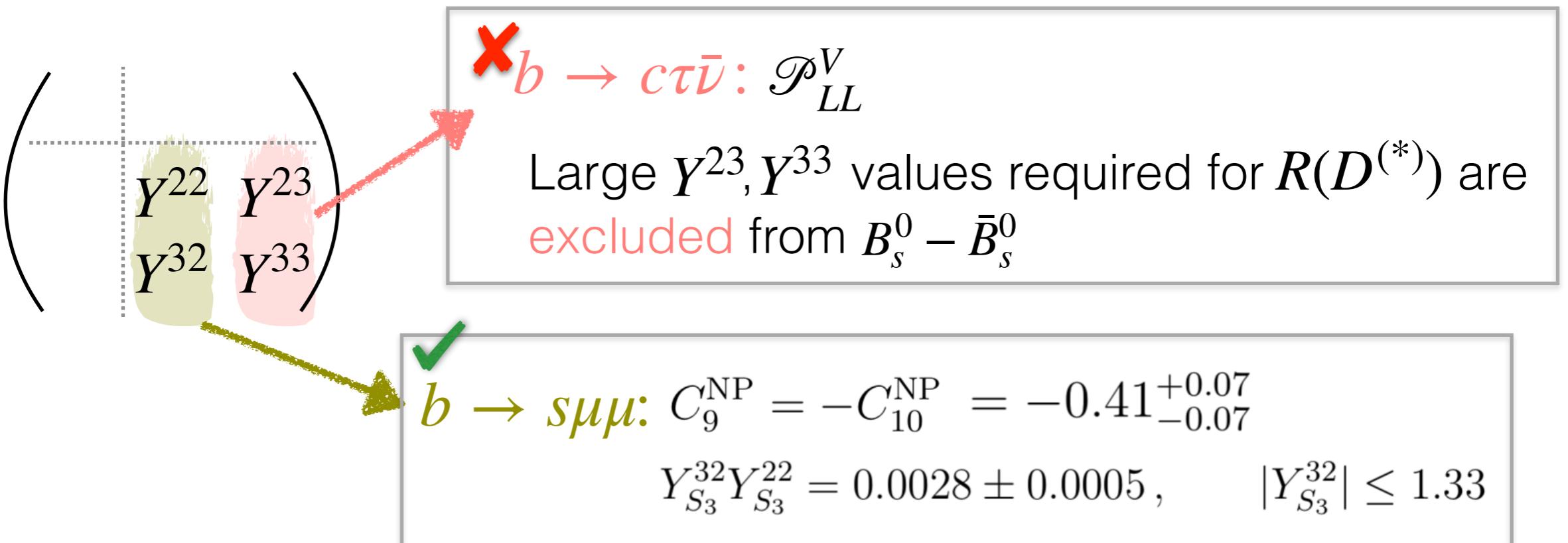
1st generation couplings stringently constrained from Kaon, lepton data



$\times b \rightarrow c\tau\bar{\nu} : \mathcal{P}_{LL}^V$
Large Y^{23}, Y^{33} values required for $R(D^{(*)})$ are
excluded from $B_s^0 - \bar{B}_s^0$

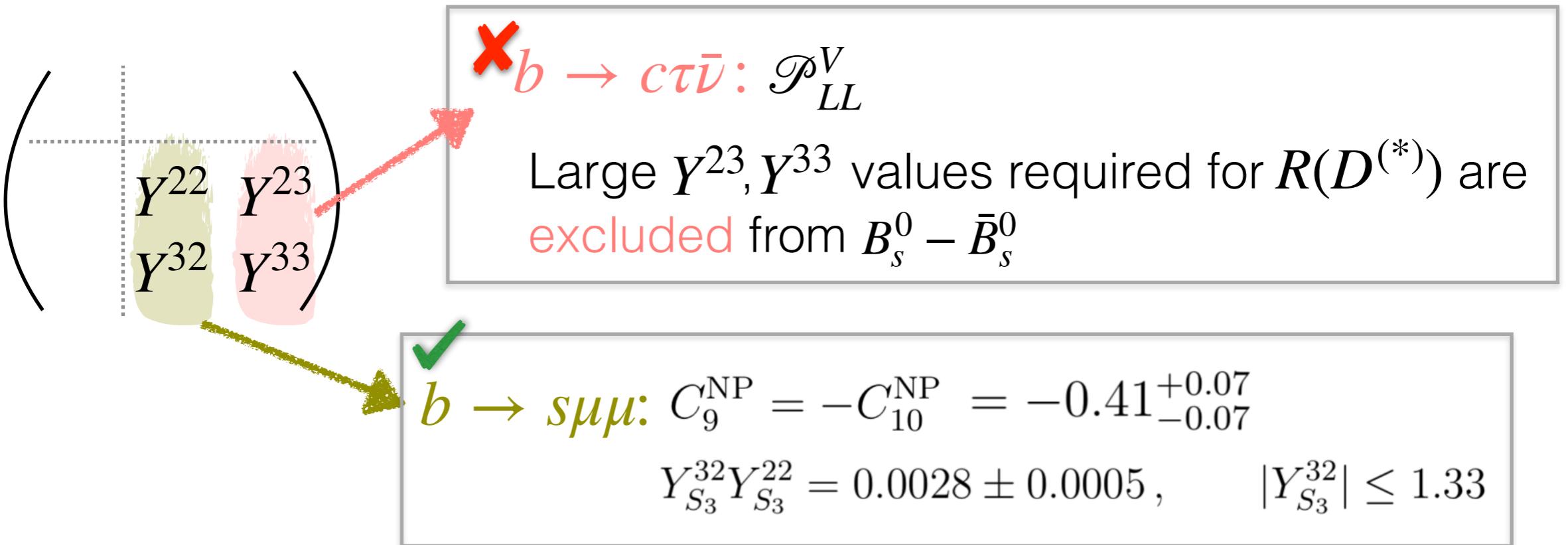
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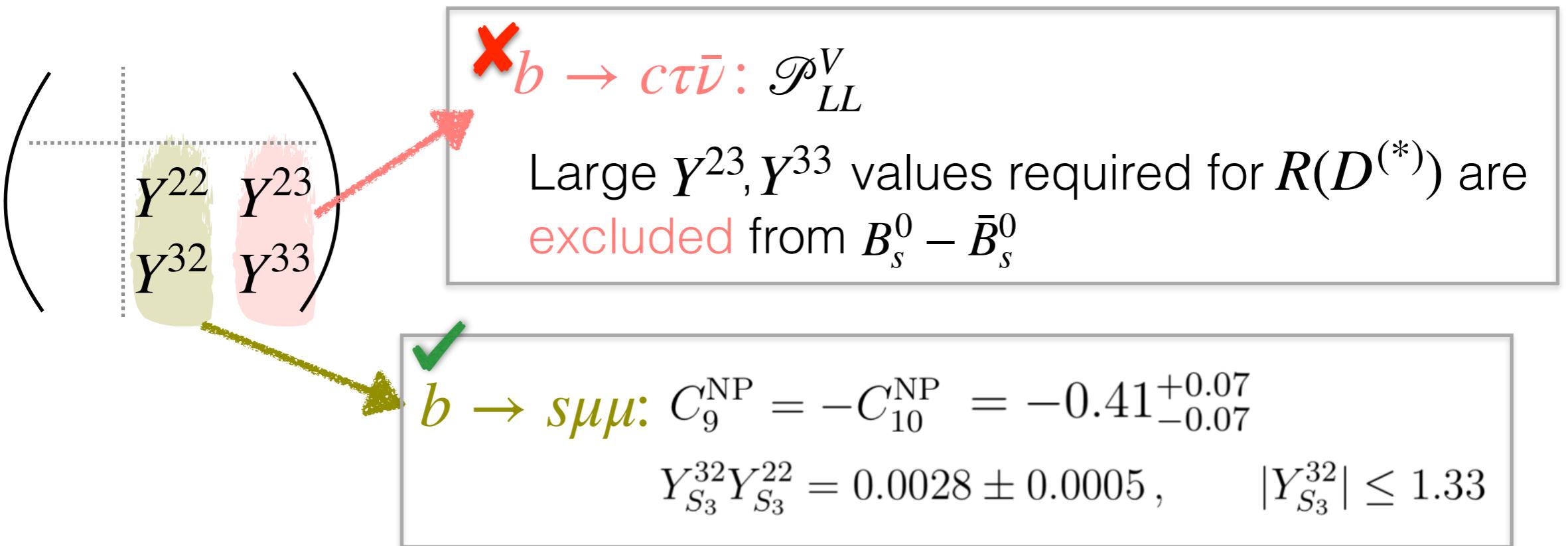


$b \rightarrow s\nu\bar{\nu}: C_{LL}^V$

→ Only $\sim 2\%$ enhancement in R_K^ν with $Y^{22}Y^{32}$

$S_3 :$

1st generation couplings stringently constrained from Kaon, lepton data



$b \rightarrow s\nu\bar{\nu}$: C_{LL}^V

→ 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 $b \rightarrow s\mu\mu$ anomalies give $R_K^\nu = 2.4 \pm 3.6$

$\tilde{R}_2 :$

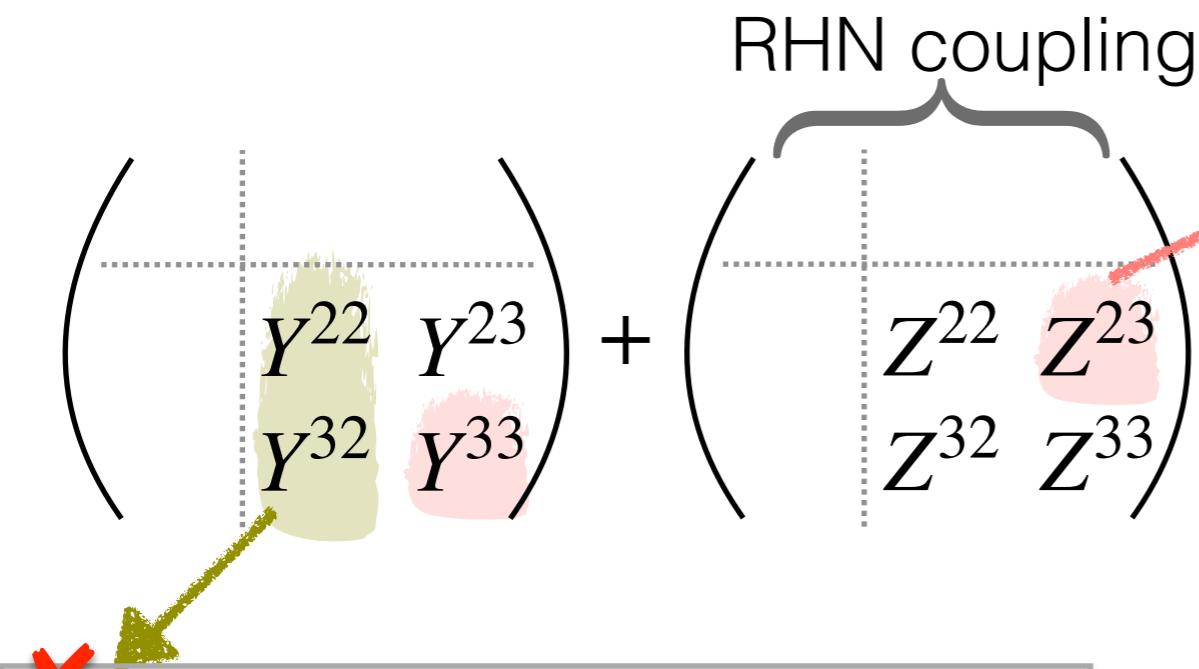
$$\begin{pmatrix} & & \\ & Y^{22} & Y^{23} \\ & Y^{32} & Y^{33} \end{pmatrix}$$

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

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

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

$\tilde{R}_2 :$

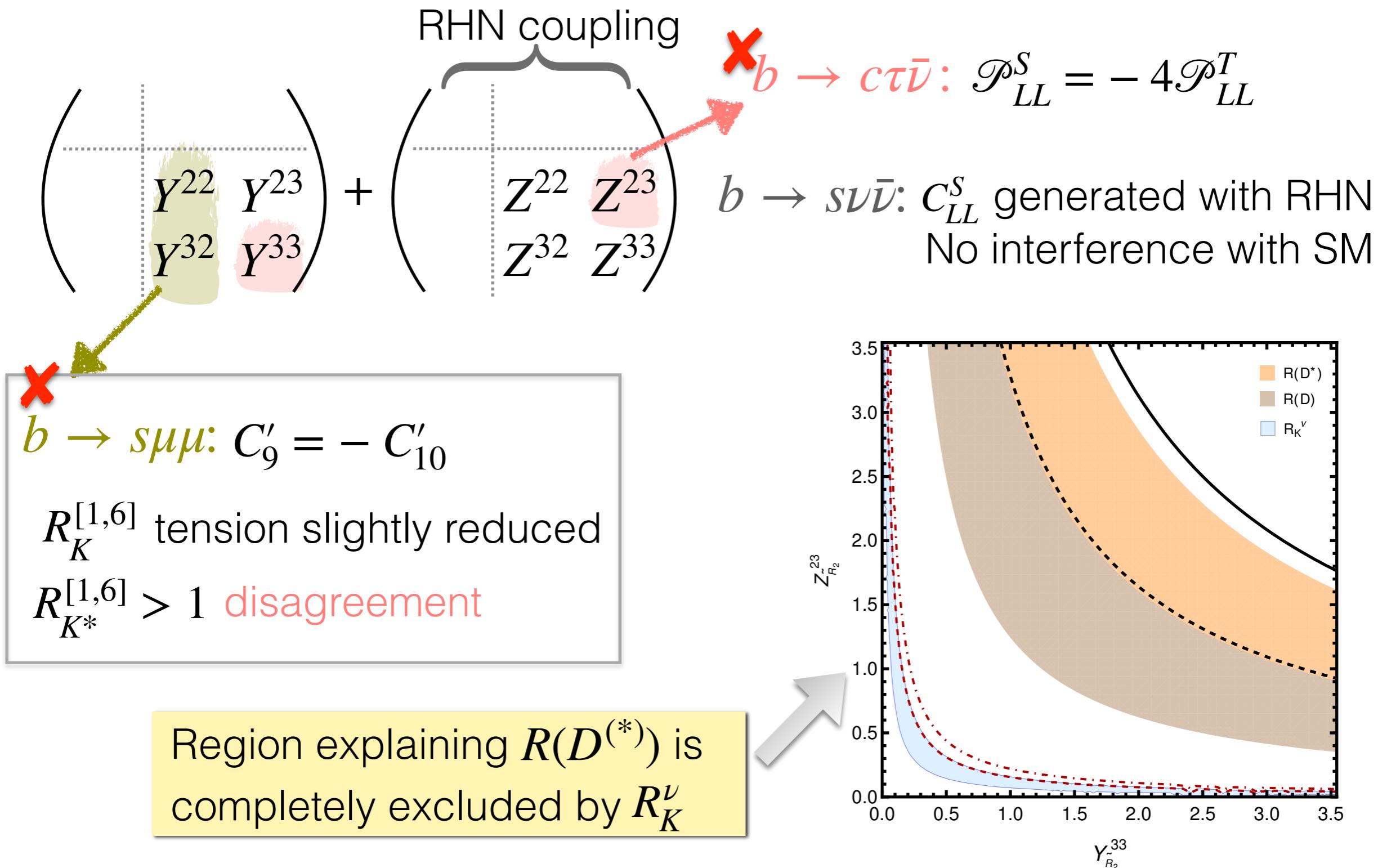


$$b \rightarrow c\tau\bar{\nu} : \mathcal{P}_{LL}^S = -4\mathcal{P}_{LL}^T$$

$b \rightarrow s\nu\bar{\nu}$: C_{LL}^S generated with RHN
No interference with SM

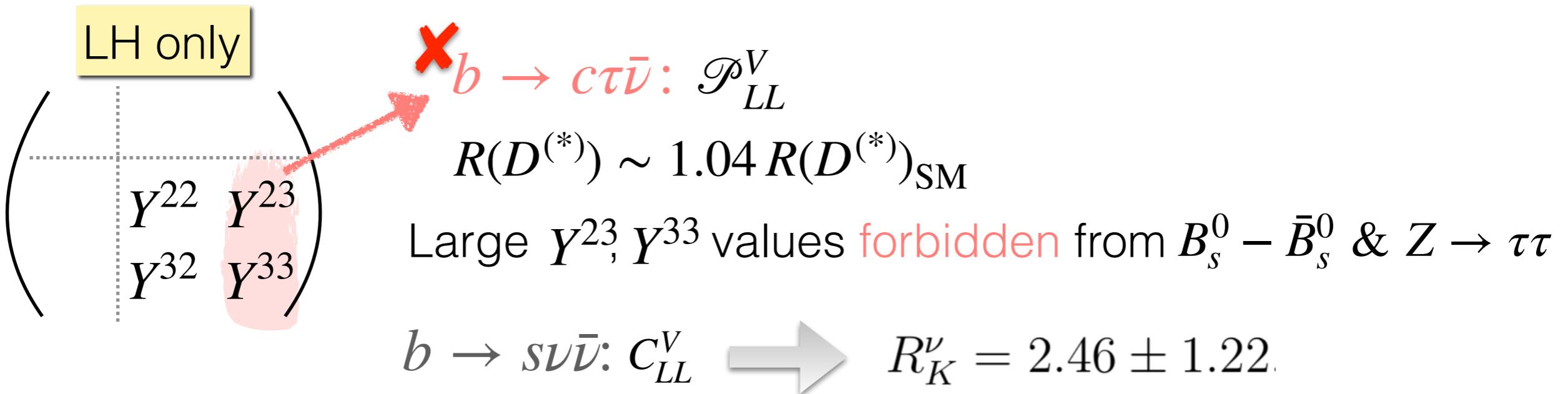
X
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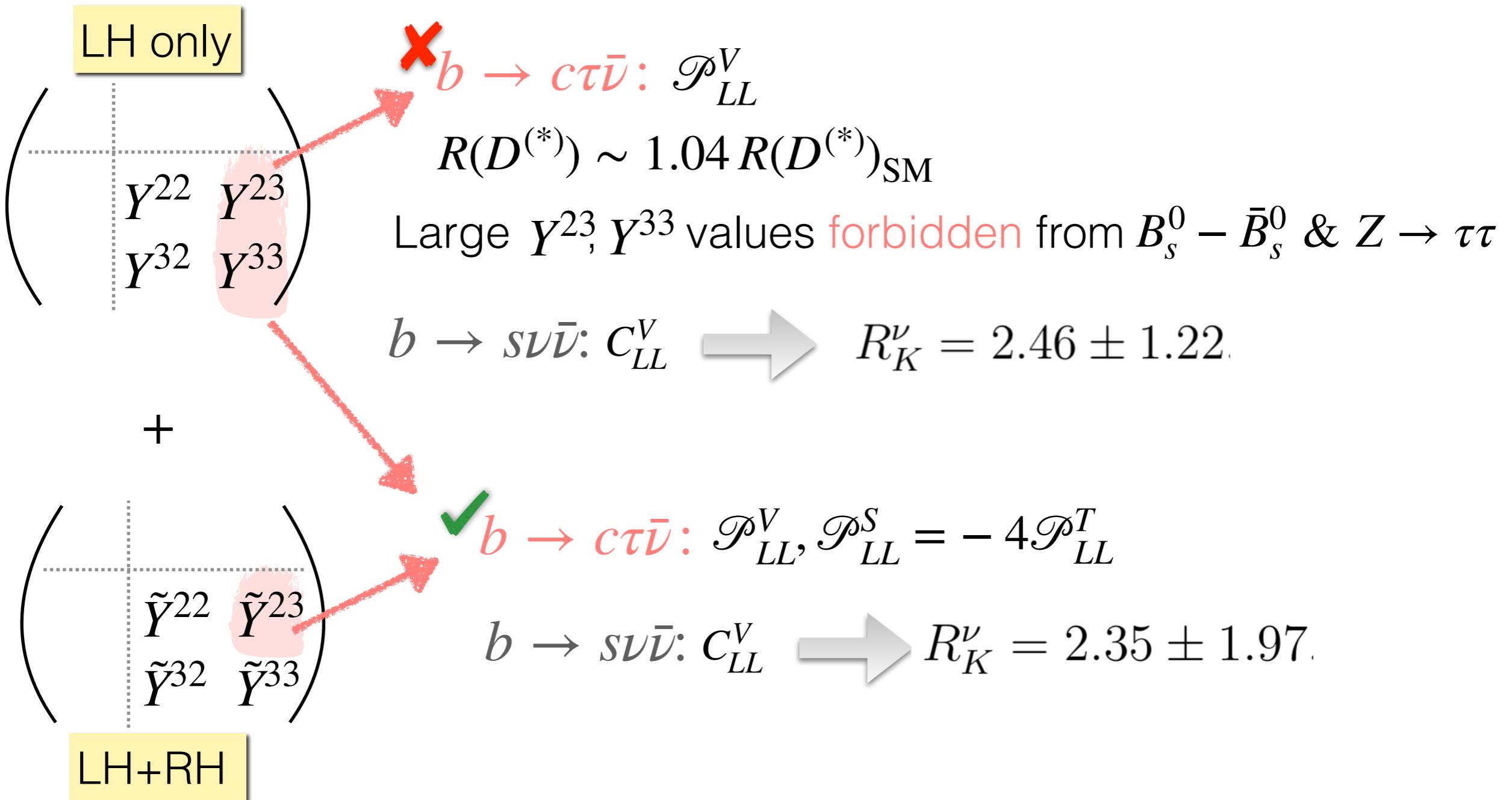
$S_1 :$

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

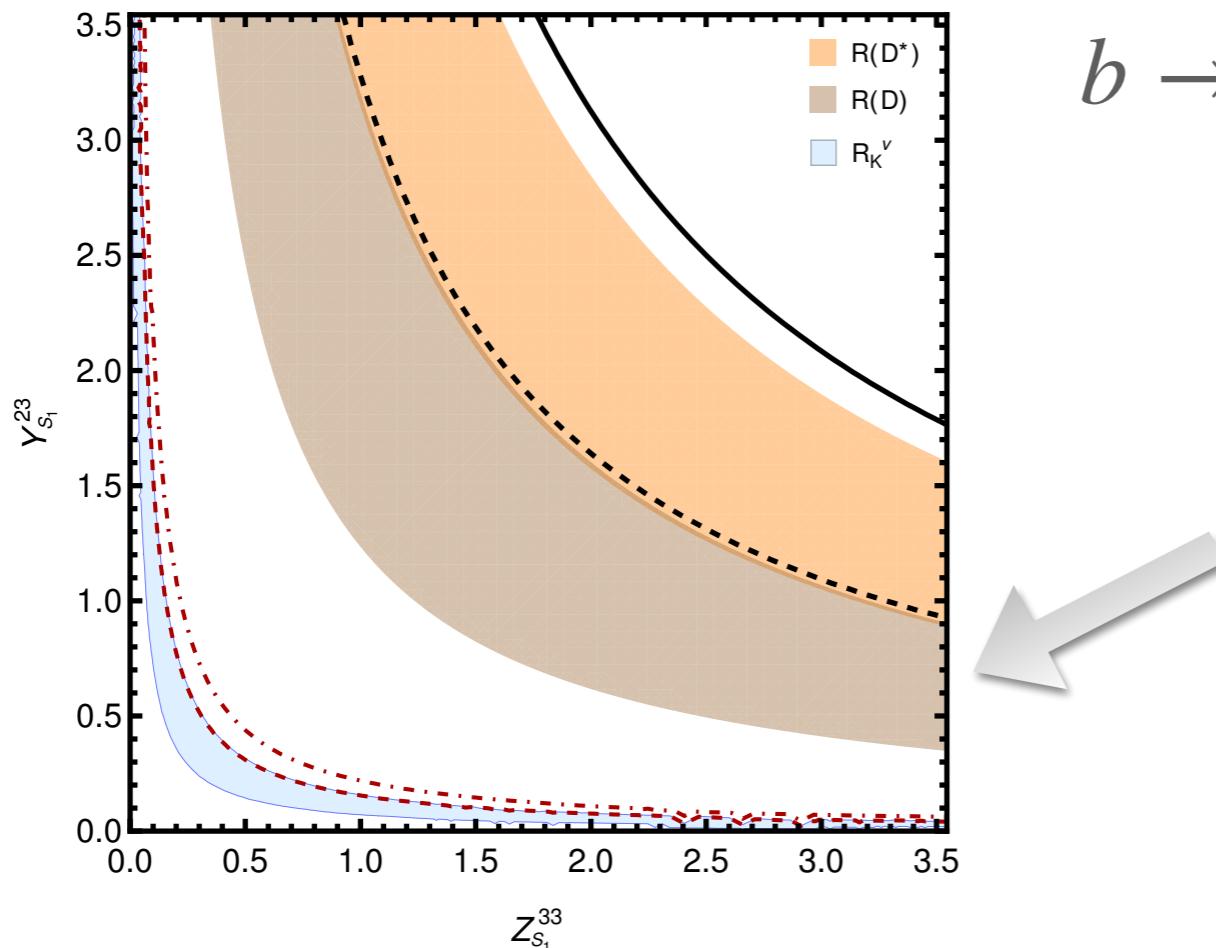
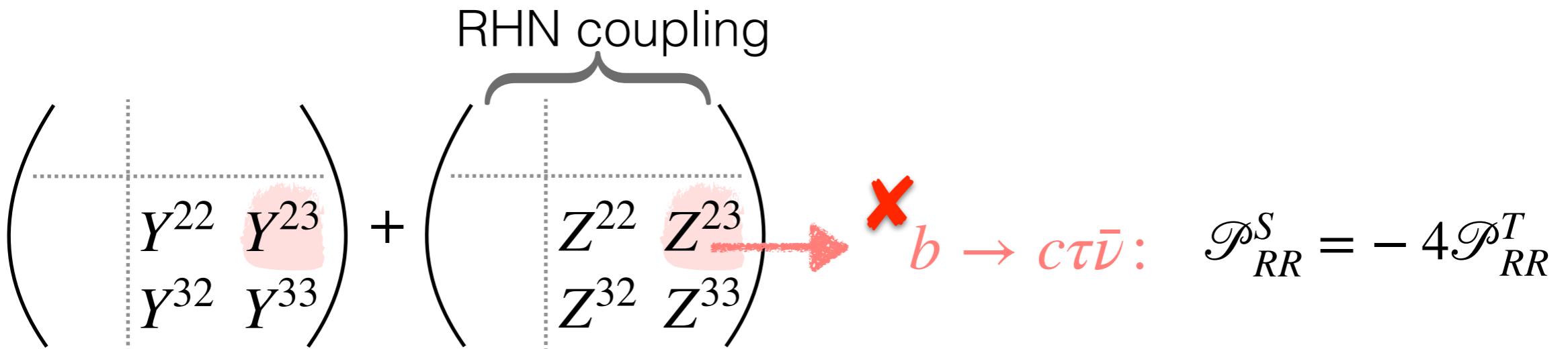


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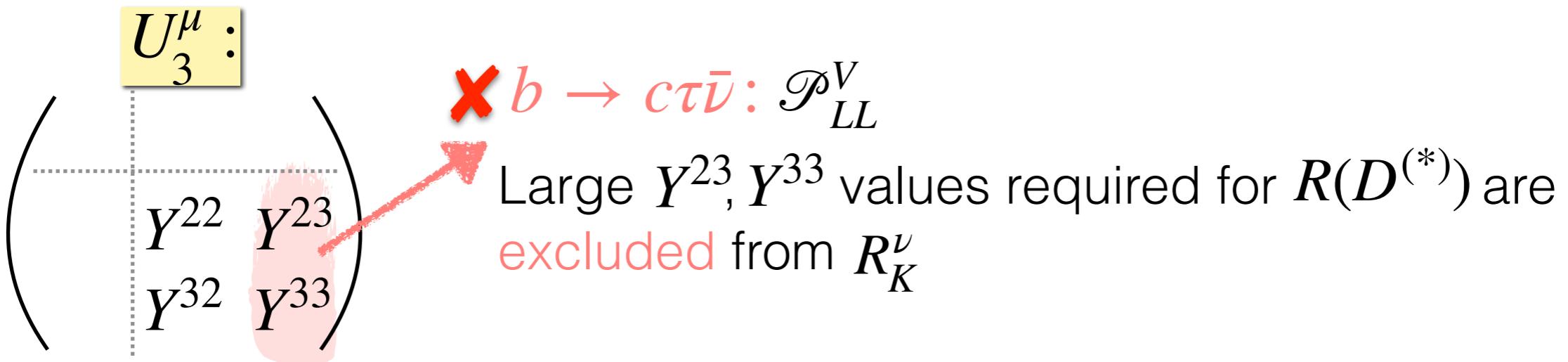


$b \rightarrow s\nu\bar{\nu}$: C_{RR}^S generated with RHN
No interference with SM

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

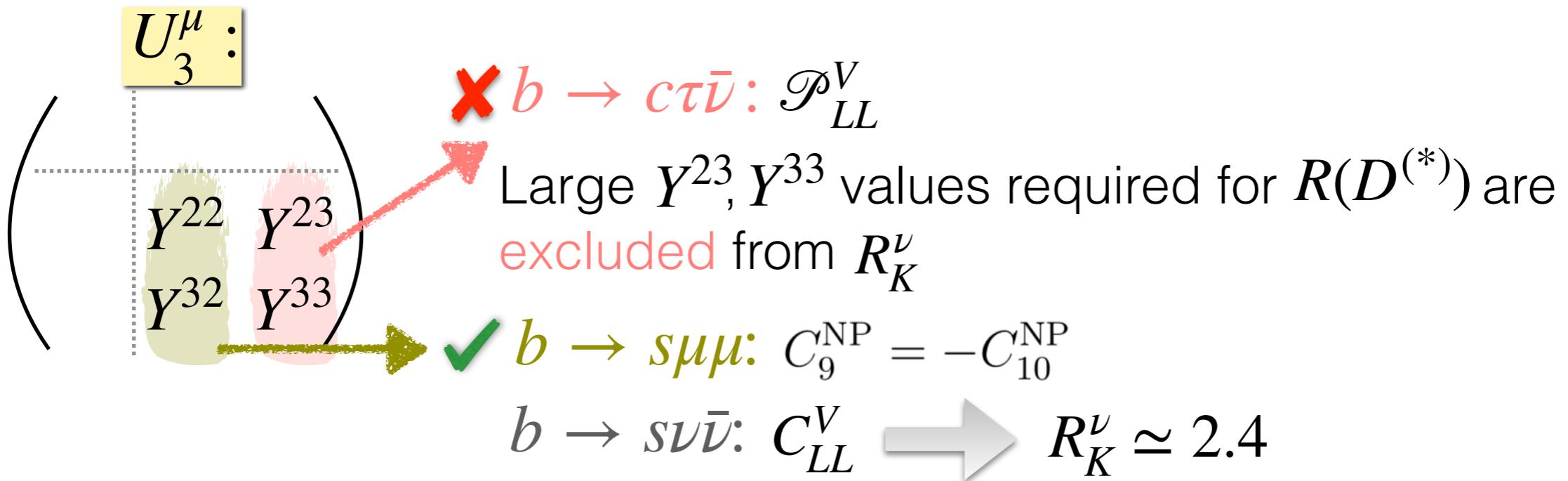
Vector leptoquarks

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



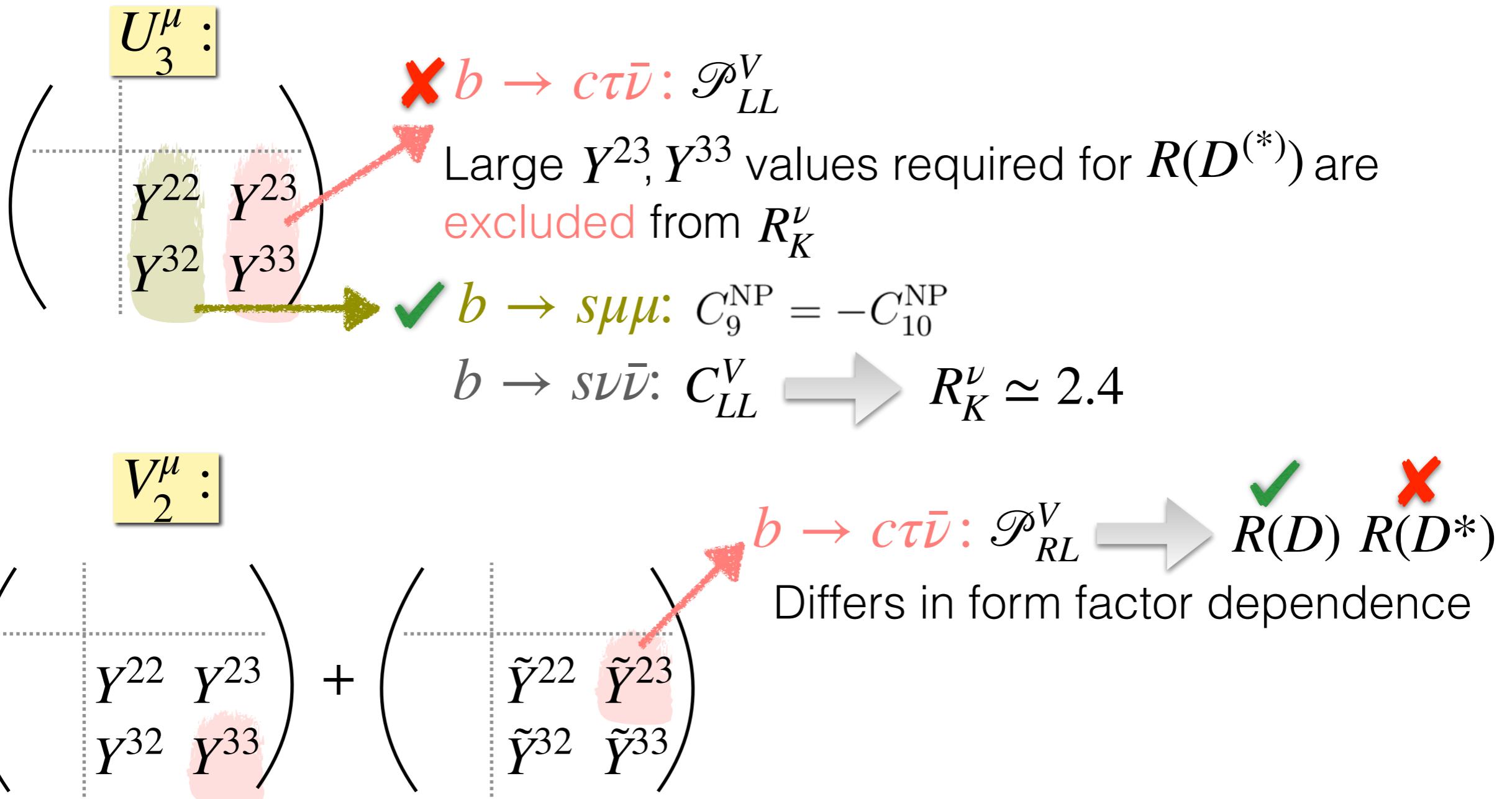
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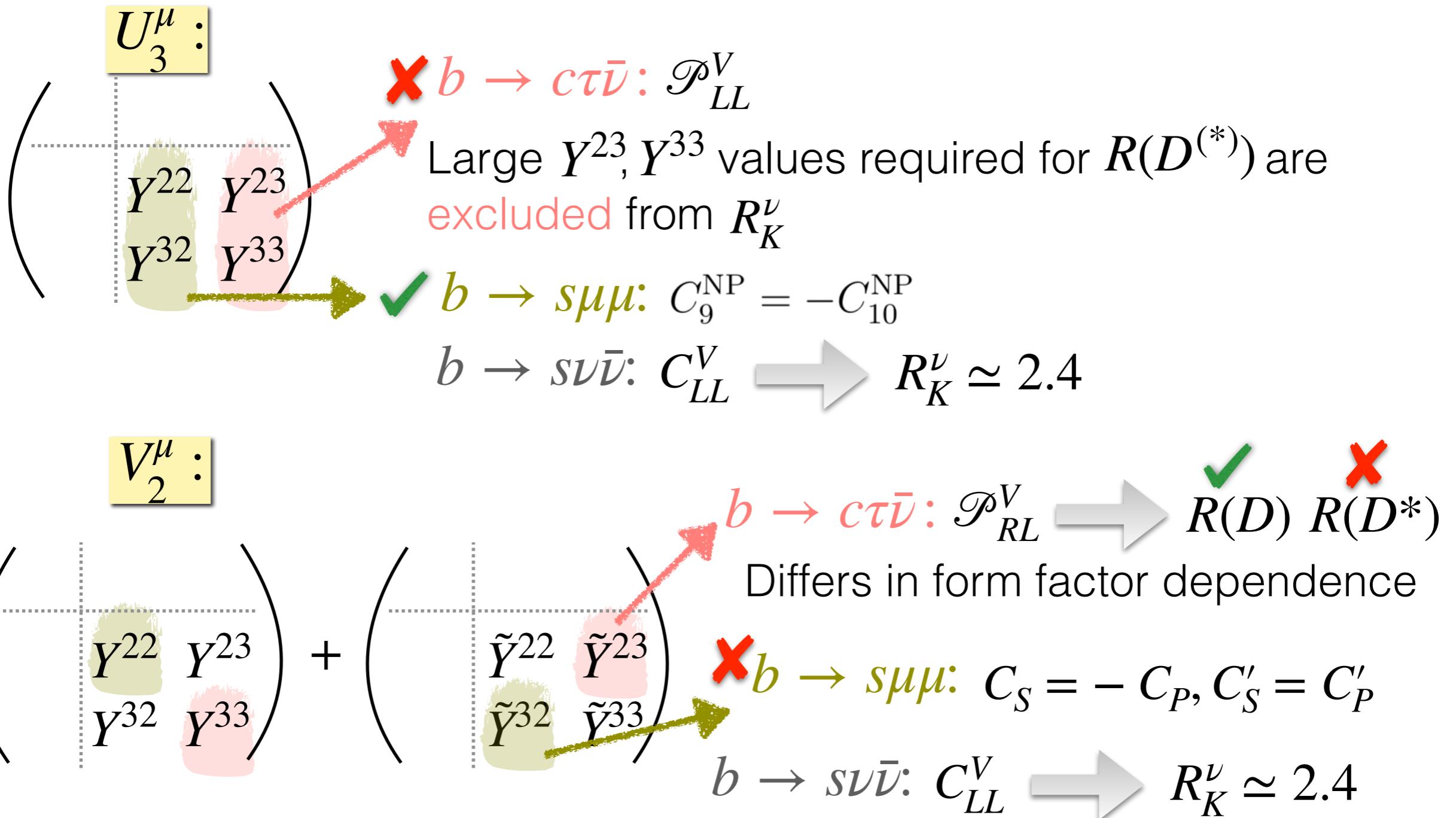
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Heavy Z' :

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

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

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

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

$R_K^\nu = 1.05 \pm 0.03$

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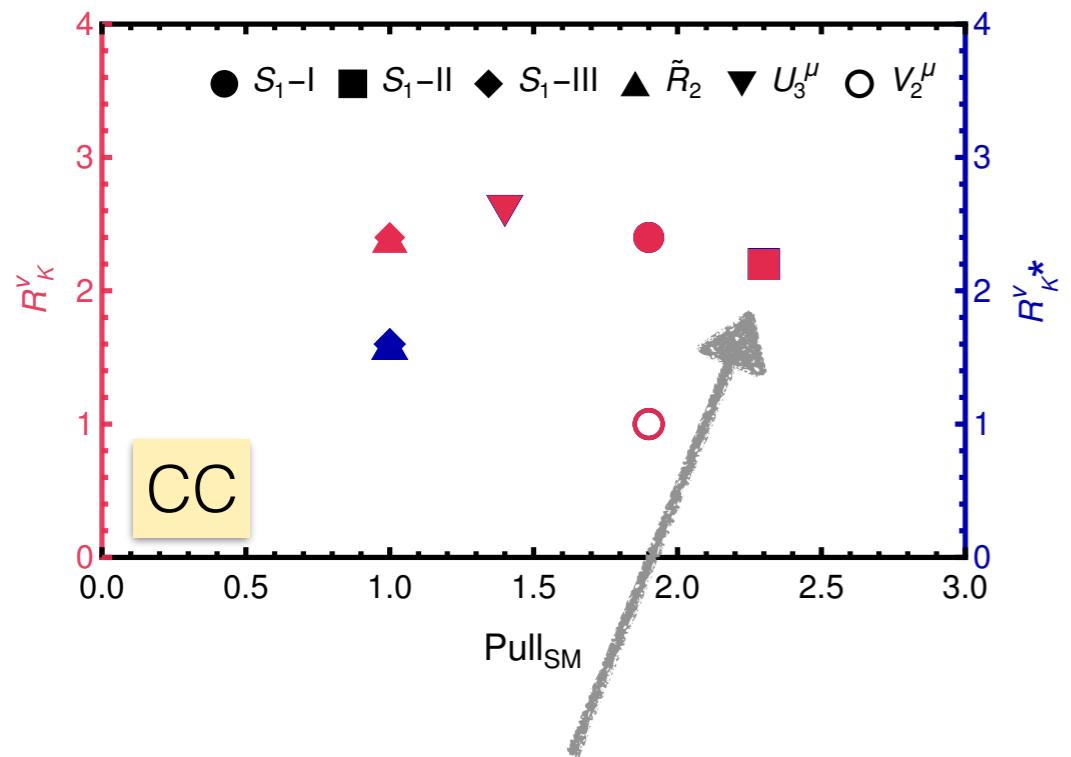
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$R_K^\nu = 1.05 \pm 0.03$

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

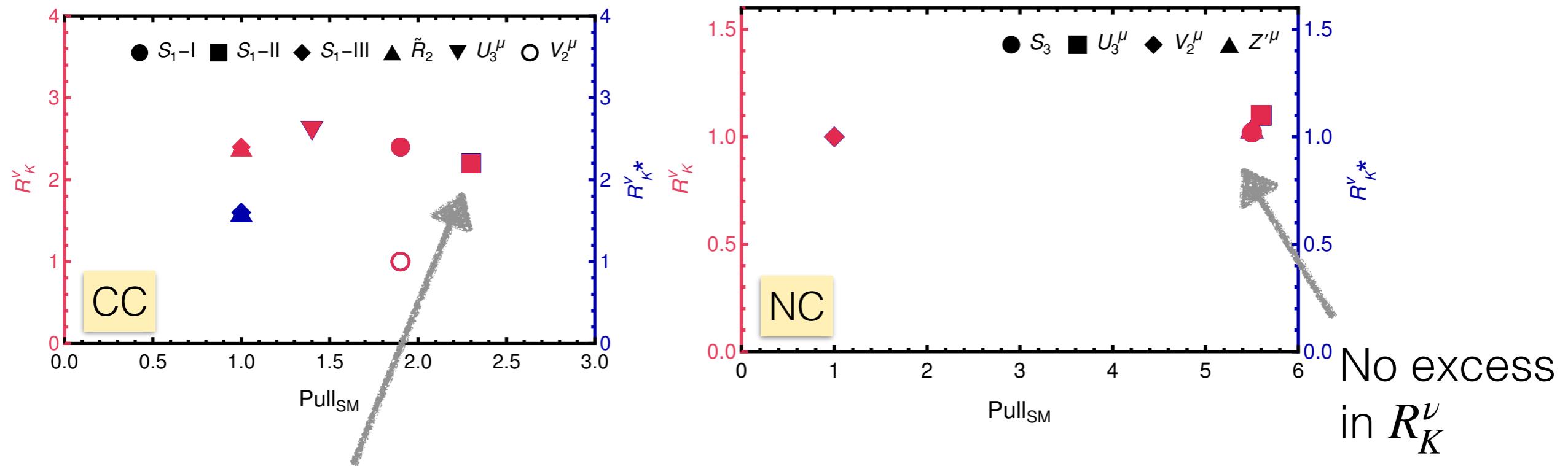
→ No new contribution to $R_K^\nu \simeq 1.1$

Comparison



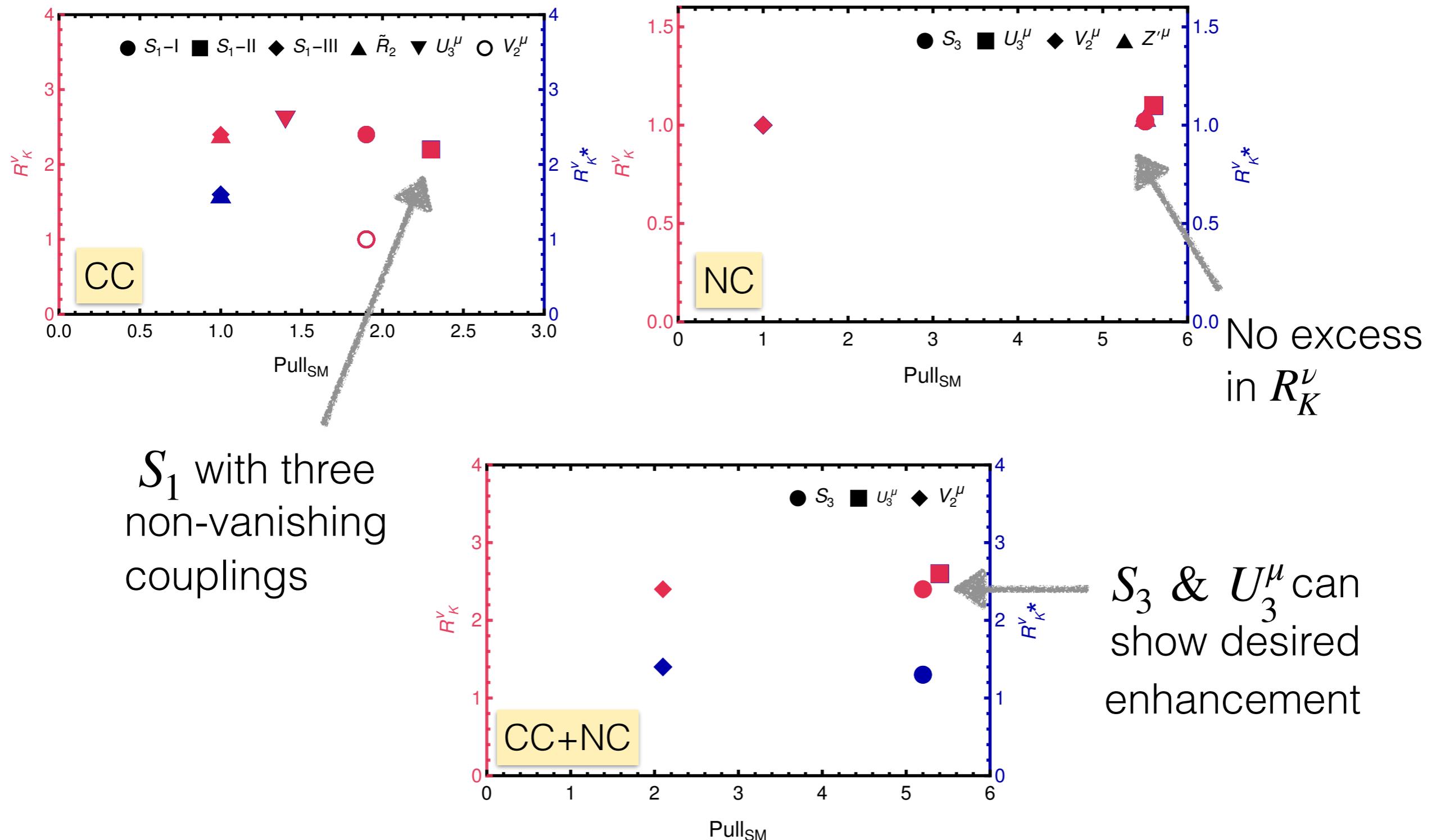
S_1 with three
non-vanishing
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Comparison



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Comparison



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 $B \rightarrow K^{(*)}\nu\bar{\nu}$
- ▶ Heavy Z' explaining $b \rightarrow s\mu\mu$ 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]

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Thank you!

Back ups

Charged current

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



SMEFT matching

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

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

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

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

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

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

Neutral current

► Hamiltonian and relevant operators for $b \rightarrow s\mu\mu$

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

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

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

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

New contribution to
(axial)vector currents

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

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

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

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

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

B anomalies