Explaining the Flavor Anomalies with Leptoquarks

XXVII International Workshop on Deep Inelastic Scattering and Related Subjects

Francesco Saturnino

Albert Einstein Center for Fundamental Physics
Institute for Theoretical Physics
University of Bern

Turin
April 11, 2019

UNIVERSITÄT BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

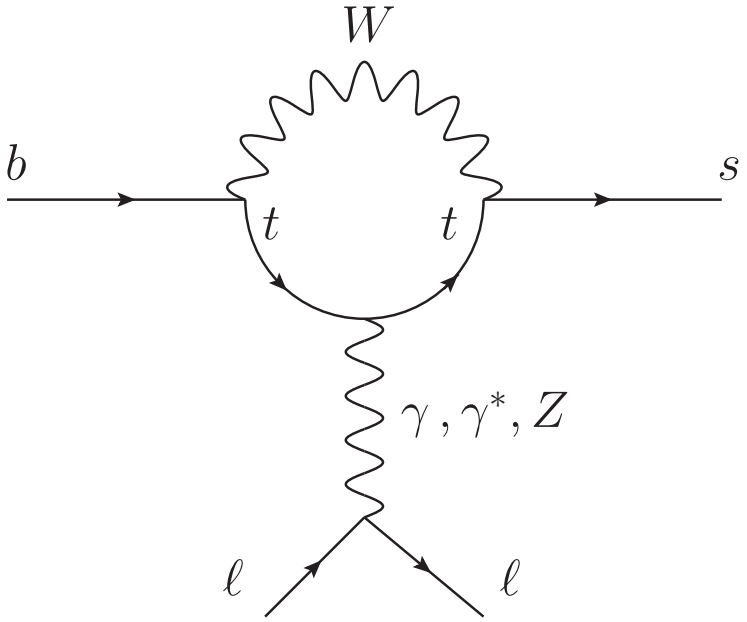
Outline

- Introduction: Flavor Anomalies in B-Decays
  - $b \to s\mu\mu$
  - $b \to c\tau\nu$
  - Explanation
- Pati-Salam Leptoquark
  - Phenomenology
  - Loop-Effects
- Conclusion

Flavor Anomalies: B-decays in the SM

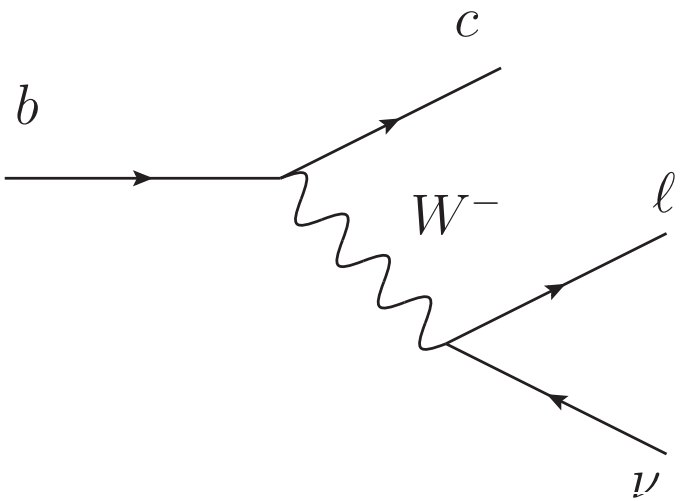
$\boldsymbol{b \to s\ell\ell}$

- Loop and CKM suppressed
- Lepton Flavor Universal (LFU)



$\boldsymbol{b \to c\ell\nu}$

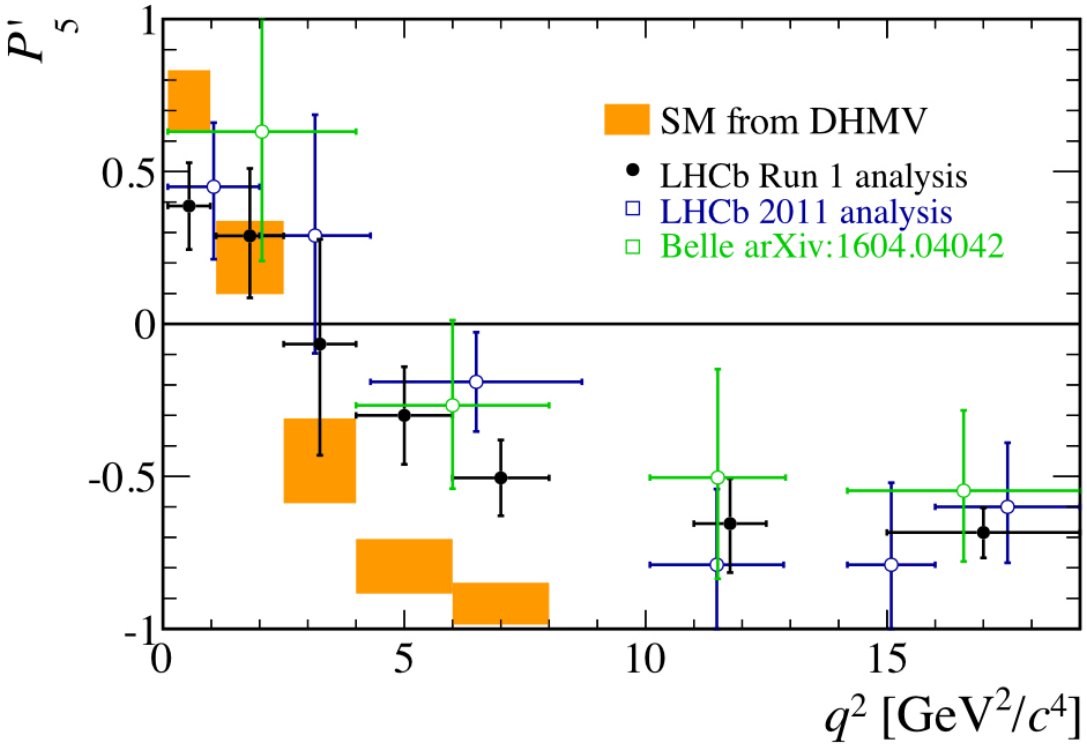
- Tree-level decay
- LFU (at amplitude)



Flavor Anomalies: $b \to s\mu\mu$

P_5': Angular observable in $B \to K^*\mu\mu$, defined to reduce hadronic uncertanties [Descotes-Genon, Hurth, Matias, Virto, 1303.5794]

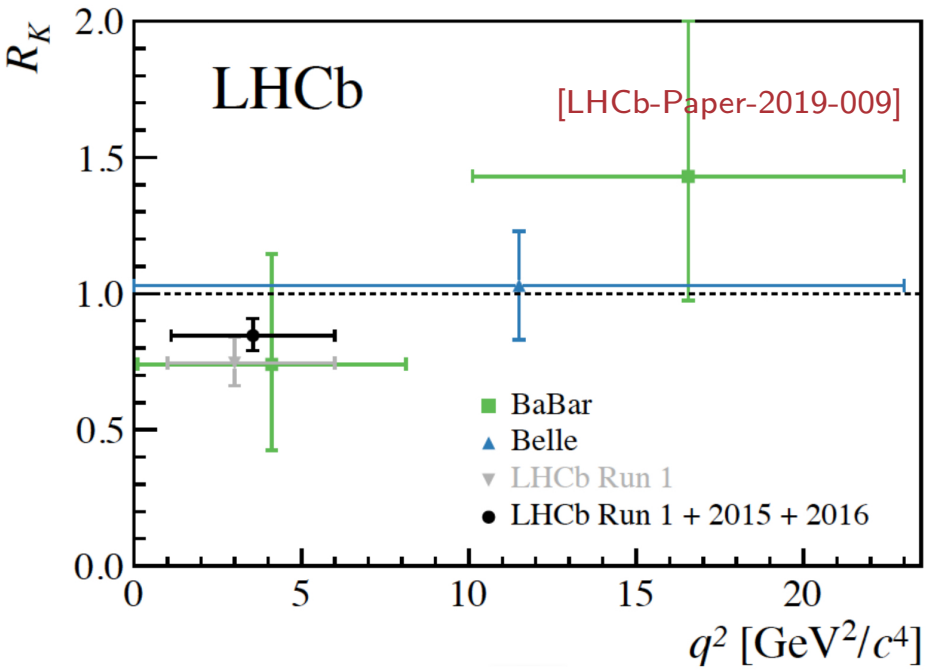
- LHCb found 3σ deviation from SM $\Rightarrow$ Confirmed by Belle
- 2σ tension in branching ratio of $B_s \to \phi\mu\mu$

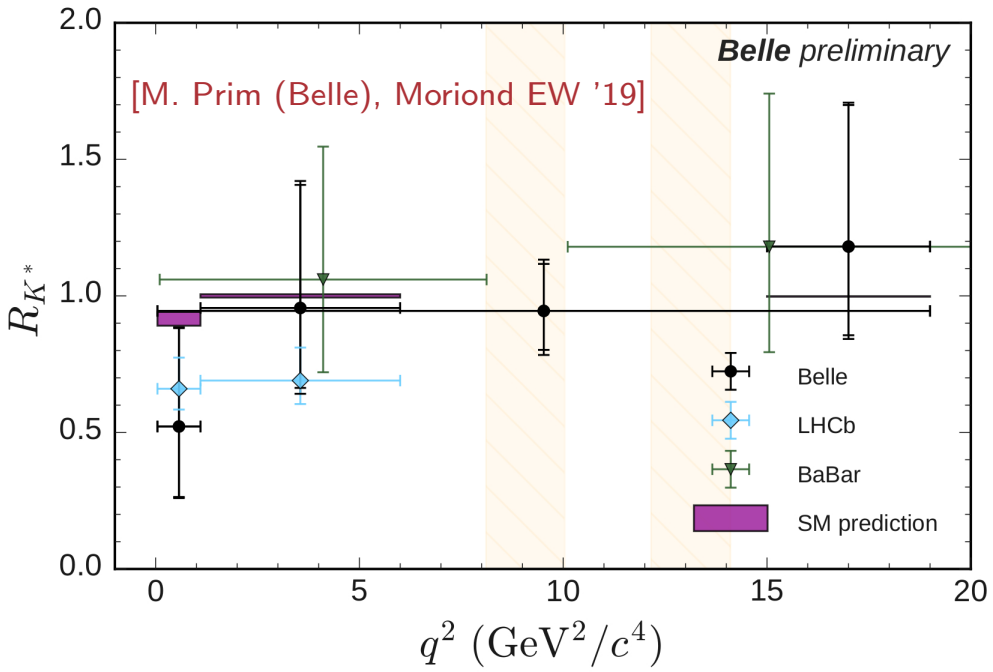


How reliable are SM predictions (hadronic uncertanties)?

Flavor Anomalies: $b \to s\mu\mu$

$$R(K^{(*)}) = \frac{\mathrm{Br}[B \to K^{(*)}\mu\mu]}{\mathrm{Br}[B \to K^{(*)}ee]} \qquad \text{Test of LFU}$$





- Very clean SM prediction of LFU
- $R(K)$ from 2.6σ now at 2.5σ from SM
- $R(K^*)$ from Belle compatible with SM but also with previous measurements

Flavor Anomalies: $b \to s\mu\mu$

Combining all 150+ $b \to s\ell\ell$ measurements: Global fits still match data significantly better than SM (pull $> 5\sigma$)

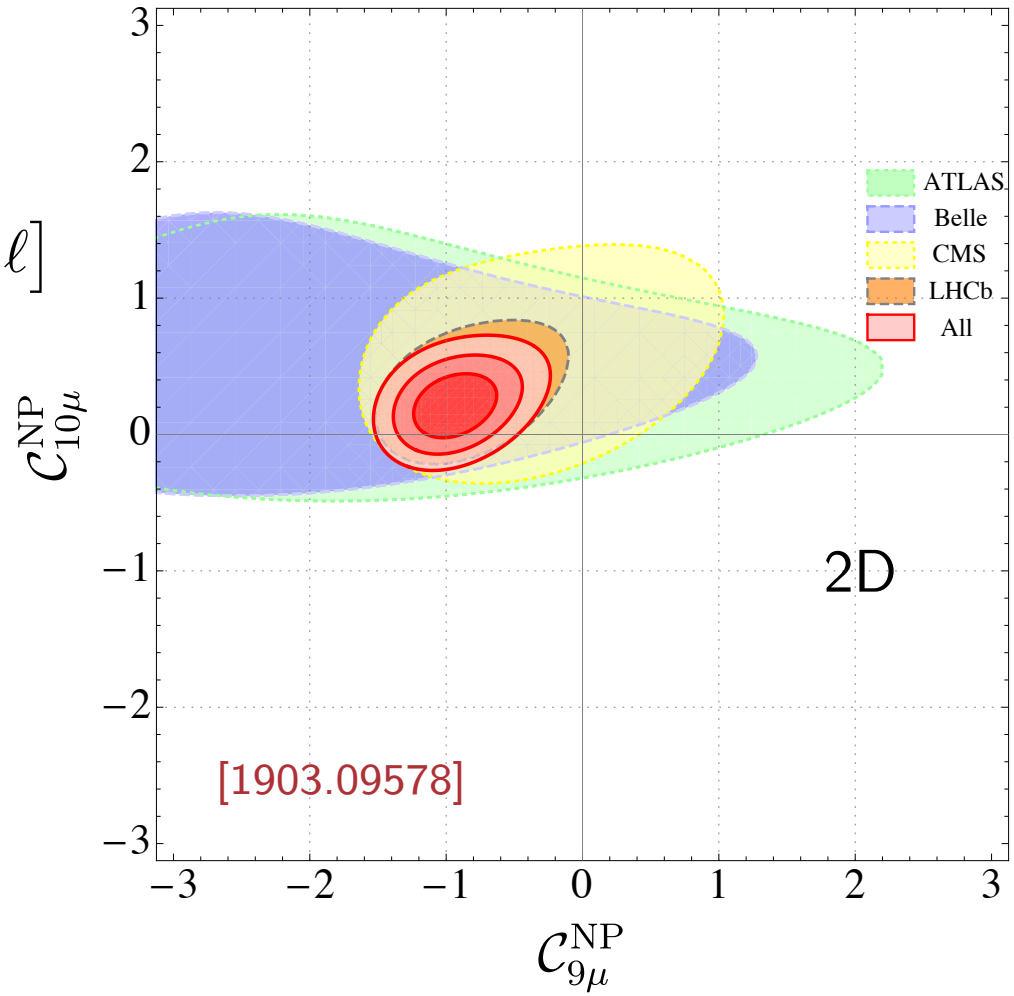
Relevant operators:

$$\mathcal{O}_9^{(\prime)} = [\bar{s}\gamma^\mu P_L(P_R)b]\,[\bar{\ell}\gamma_\mu\ell]$$
$$\mathcal{O}_{10} = [\bar{s}\gamma^\mu P_L b]\,[\bar{\ell}\gamma_\mu\gamma_5\ell]$$

Good fit to data (1D):

- $C_9 = -C_{10}$ (purely LH)
- C_9 only
- $C_9 = -C_9'$

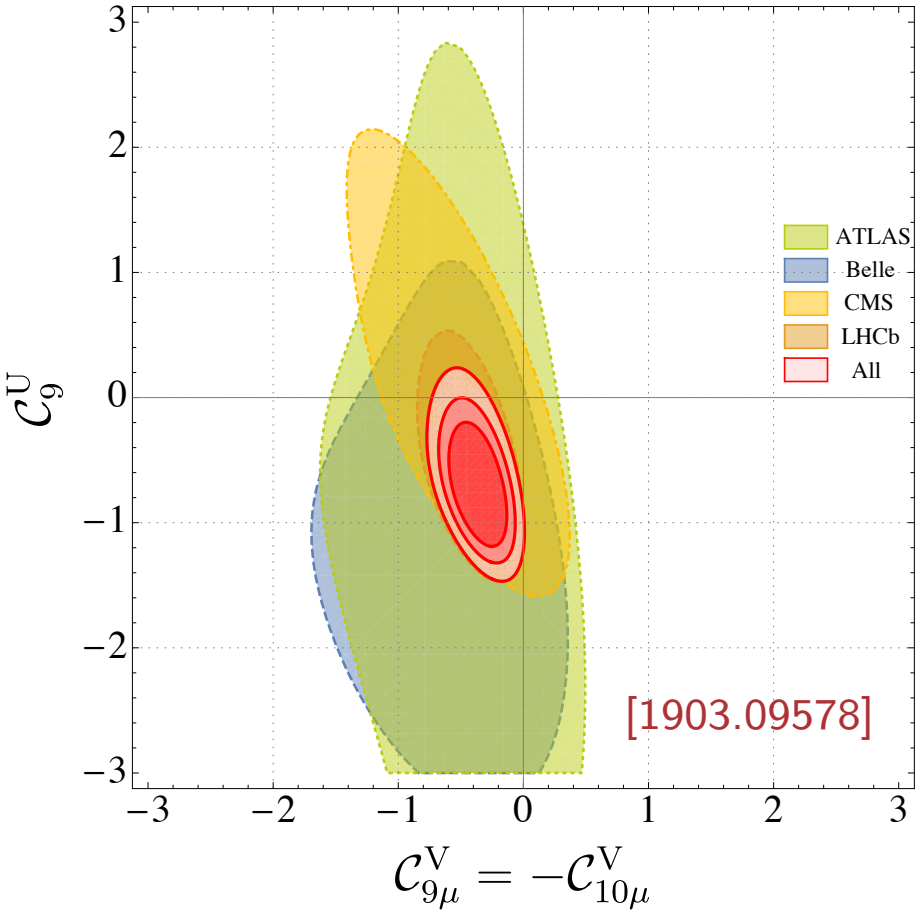
[Aebischer et al. 1903.10434]
[Algueró et al., 1903.09578]

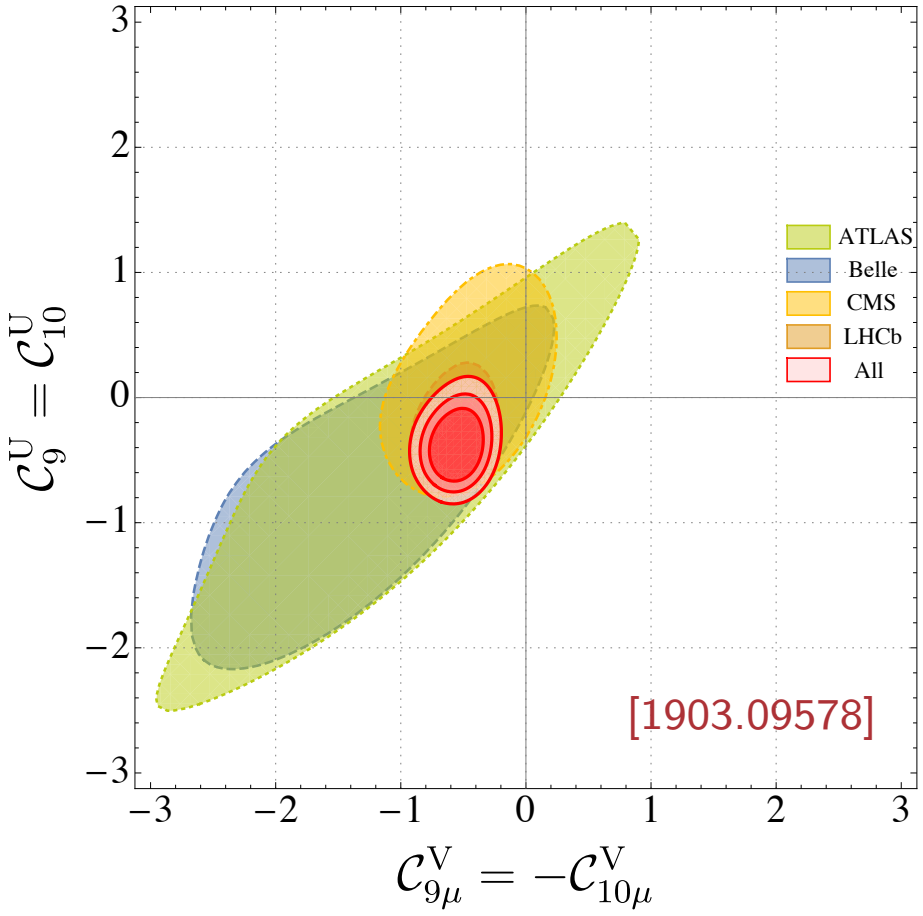


Here: LFUV NP only

Flavor Anomalies: $b \to s\mu\mu$: LFU vs. LFUV NP

Good fits also for LFUV+LFU NP

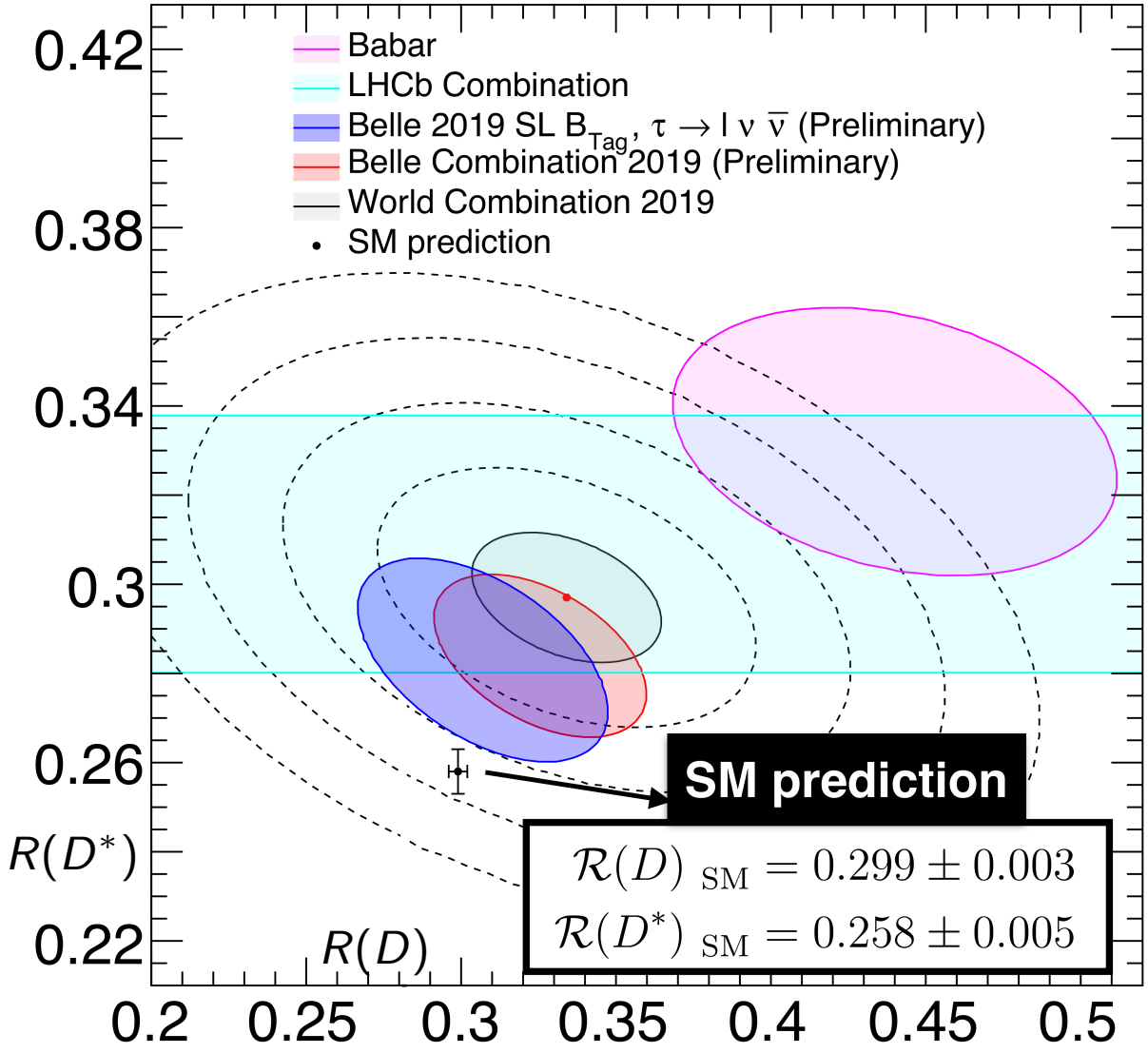




Flavor Anomalies: $b \to c\tau\nu$

$$R(D^{(*)}) = \frac{\mathrm{Br}[B \to D^{(*)}\tau\nu]}{\mathrm{Br}[B \to D^{(*)}\ell\nu]} \quad \ell = \{\mu, e\}$$

Test of LFU

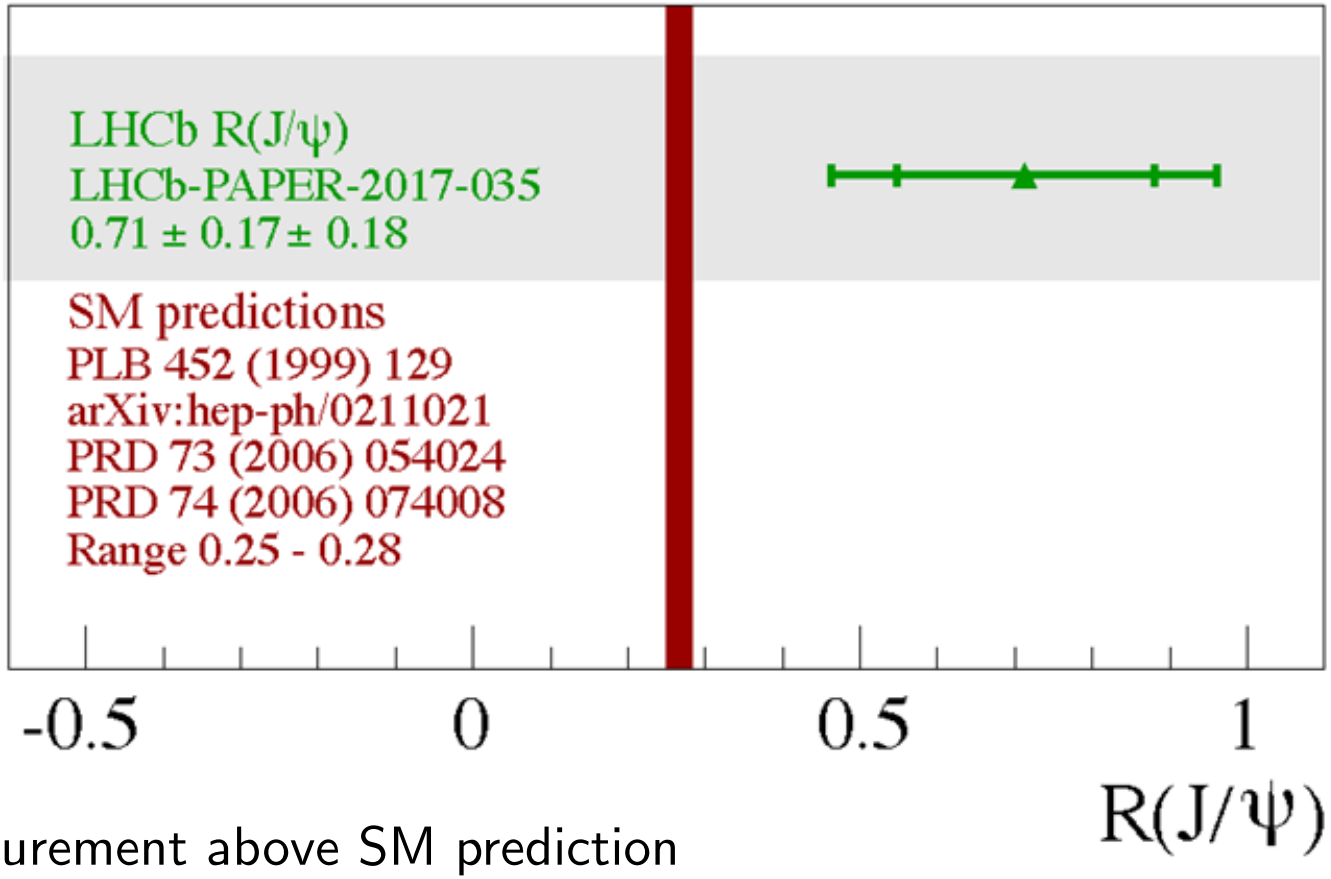


- All measurements above SM prediction
- Clean SM prediction of LFU
- World average now from 3.8σ to 3.1σ

[G. Caria (Belle), Moriond EW '19]

Flavor Anomalies: $b \to c\tau\nu$

$$R(J/\Psi) = \frac{\mathrm{Br}[B_c \to J/\Psi\, \tau\nu]}{\mathrm{Br}[B_c \to J/\Psi\, \mu\nu]}$$



Measurement above SM prediction (consistent with $R(D^{(*)})$)

Flavor Anomalies: Takeaway

- Hints for LFUV in
  - $b \to c\ell\nu$ (CC, τ vs μ/e)
  - $b \to s\ell\ell$ (NC, μ vs e)
- Newest experiments still neither proof nor disproof LFUV
- Solid theory for $R(D^{(*)})$, $R(K^{(*)})$
- Slight tension $b \to d\mu\mu$ and $b \to u\tau\nu$, consistent with $b \to s\mu\mu$ and $b \to c\tau\nu$
- Tensions in LFU observables: Reduction of hadronic uncertainties in SM predictions needed ($P5'$, $B_s \to \phi\mu\mu$)

Explaining the Anomalies

- 10-20% effect required at amplitude-level

$\boldsymbol{b \to s\ell\ell}$:

- Small NP contribution sufficient
- Possible models: Z', loop-effects from heavy scalars/fermions, Leptoquarks

$\boldsymbol{b \to c\tau\nu}$:

- Large NP contribution needed
- Possible models:
  - charged scalars
    $\Rightarrow$ Too large B_c lifetime and problems with direct searches/q^2-distributions
  - W'
    $\Rightarrow$ Strong constraints from direct LHC searches
  - Leptoquarks

Explaining the Anomalies: Combined Explanation

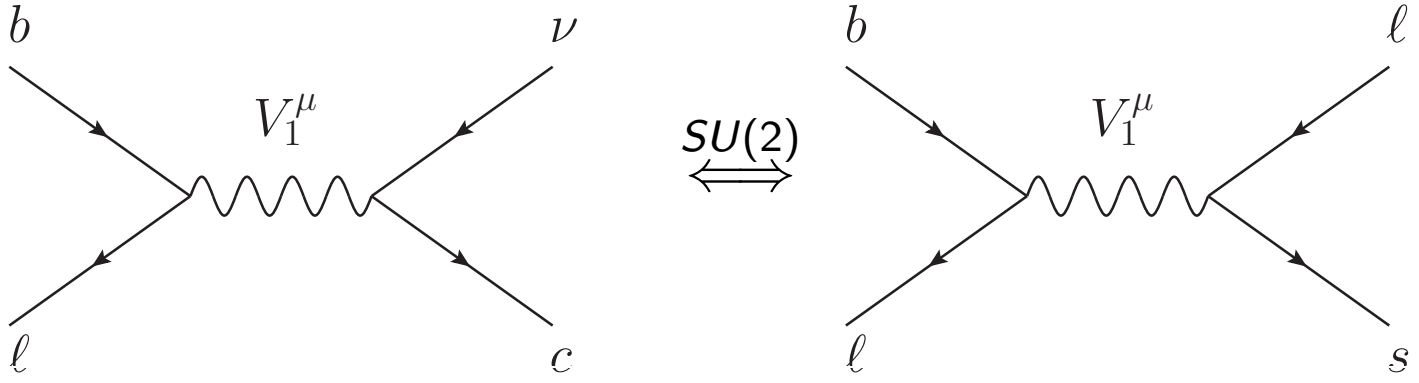
The Vector Leptoquark $SU(2)$-singlet is a prime candidate to address both anomalies simultaneously:

- Left-handed (i.e $C_9 = -C_{10}$) effect in $b \to s\mu\mu$
- Left-handed vector current in $R(D)$ and $R(D^*)$
- No tree-level effect in $b \to s\nu\nu$
- No proton decay
- Originally arising in the Pati-Salam model
  [Pati, Salam, Phys. Rev. D10, 275 (1974)]
- Pati-Salam does not work at TEV-scale ($K \to \pi\mu e$, $K_L \to \mu e$) $\Rightarrow$ Challenging UV-completion

Vector Leptoquark: Possible UV completions

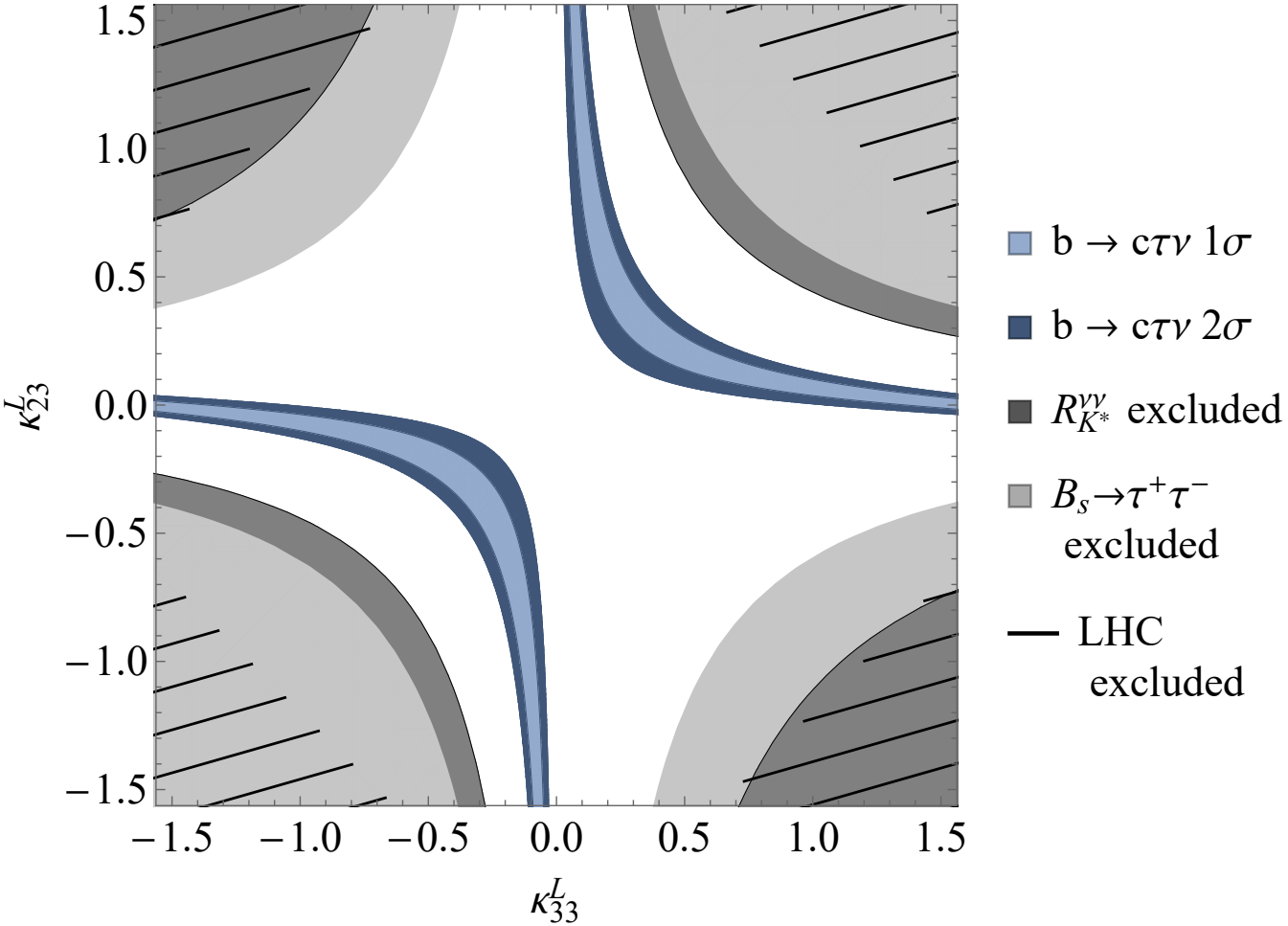
- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_Y$ + vector-like fermions
  [Di Luzio, Greljo, Nardecchia, 1708.08450]
- $SU(4) \times U(2)_L \times SU(2)_R$ + vector-like fermions
  [Calibbi, Crivellin, Li, 1709.00692]
- $SU(4)^3$ [Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368]
- $SU(4) \times U(2)_L \times SU(2)_R$ including scalar LQs and light right-handed neutrinos [Heeck, Teresi, 1808.07492]
- $SU(8)$ [Matsuzaki, Nishiwaki, Yamamoto, 1806.02312]
- $SU(4) \times U(2) \times SU(2)_R$ in extra dims [Blanke, Crivellin,1801.07256]
- Composite LQ model [Barbieri, Murphy, Senia, 1611.04930]

Explaining the Anomalies: Combined Explanation



$$\left(\bar{3}, 1, -\frac{4}{3}\right) \qquad \mathcal{L}_{\text{int}} = \kappa_{fi} \bar{Q}_f \gamma_\mu L_i \, V_1^{\mu\dagger}$$

$b \to c\tau\nu$: Only $(\bar{b}\,\tau)$ and $(\bar{c}\,\nu_\tau)$ couplings needed



[Crivellin, Greub, Müller, FS, 1807.02068]

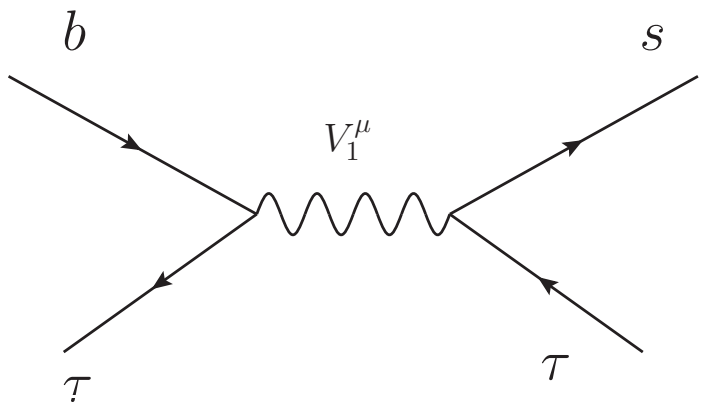
– LHC exclusion from $pp \to \tau\tau$ [Faroughy, Greljo, Kamenik, 1609.07138]

– QCD corrections weaken LHC bounds [Aebischer, Crivellin, Greub, 1811.08907]

$$\kappa_{fi} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \kappa_{23} \\ 0 & 0 & \kappa_{33} \end{pmatrix}$$

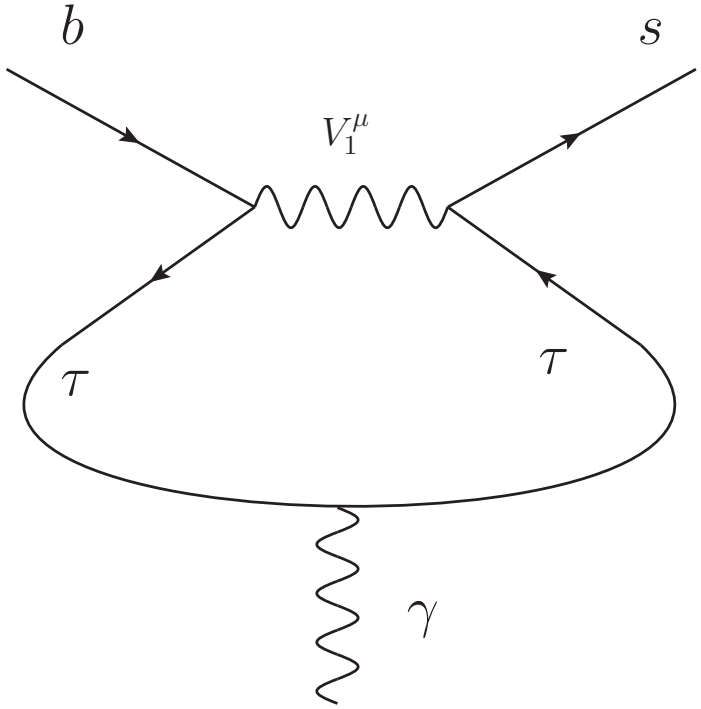
$$R^{\nu\nu}_{K^{(*)}} = \frac{\mathrm{Br}[B \to K^{(*)}\nu\nu]}{\mathrm{Br}[B \to K^{(*)}\nu\nu]_{SM}} < 3.9\ (2.7)$$

$(\bar{c}\,\nu_\tau)$-coupling also induces $(\bar{s}\,\tau)$-coupling $\Rightarrow$ Generates loop-effects:



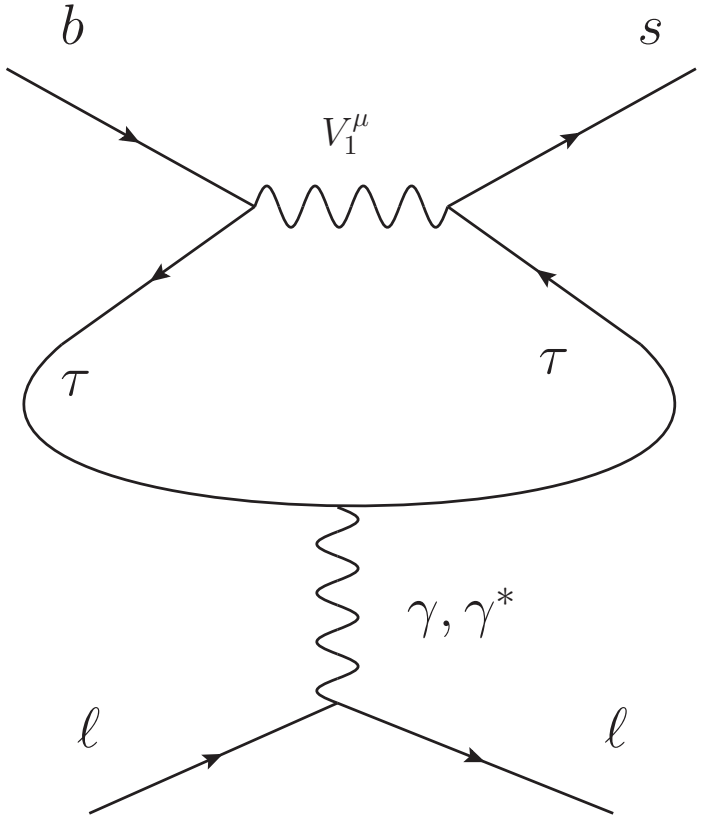
$\Rightarrow$ Large effect in $b \to s\tau\tau$:
Enhancement of $\mathrm{Br}[B_s \to \tau\tau]$ by $\sim 10^3$

$(\bar{c}\,\nu_\tau)$-coupling also induces $(\bar{s}\,\tau)$-coupling $\Rightarrow$ Generates loop-effects:



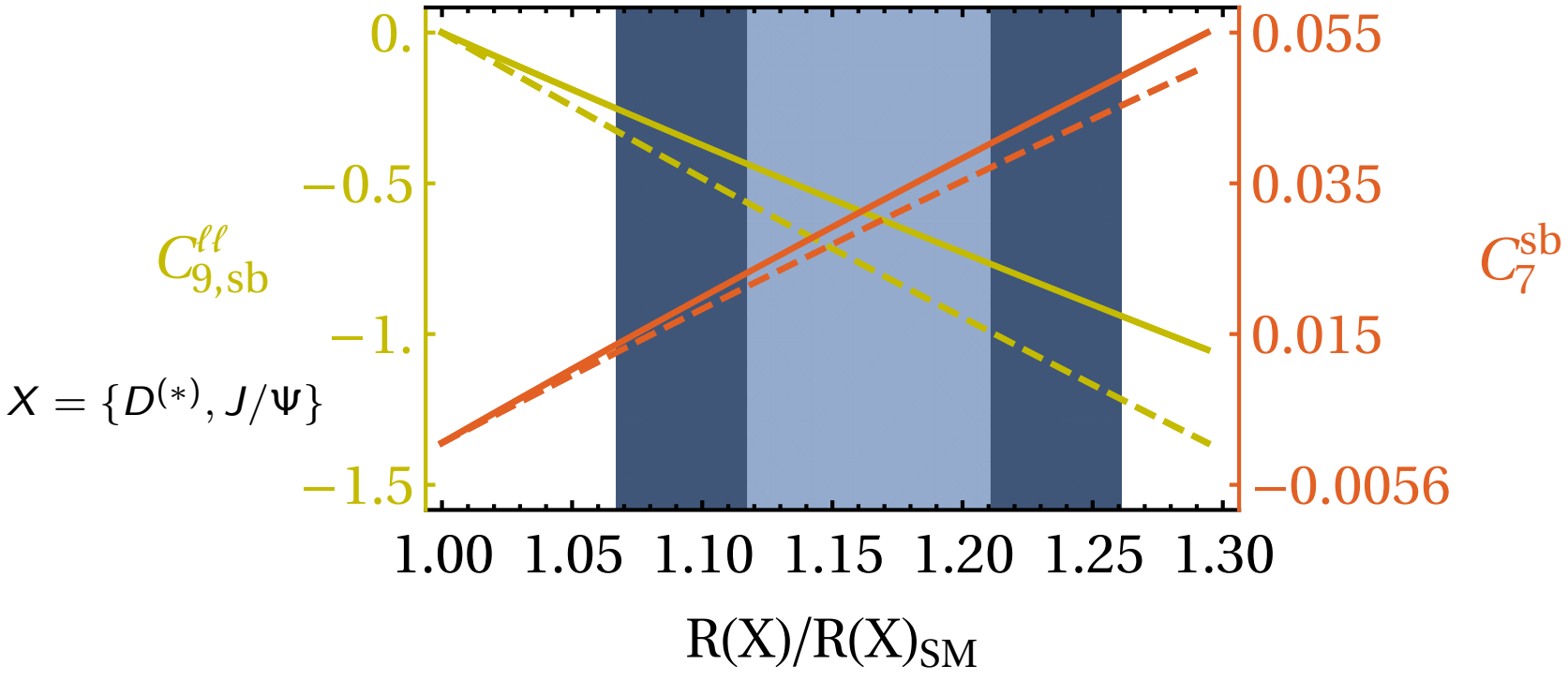
$\Rightarrow$ Effects in C_7

$(\bar{c}\,\nu_\tau)$-coupling also induces $(\bar{s}\,\tau)$-coupling $\Rightarrow$ Generates loop-effects:



$\Rightarrow$ Effects in C_7 and C_9

Loop-Effects in C_7 and C_9

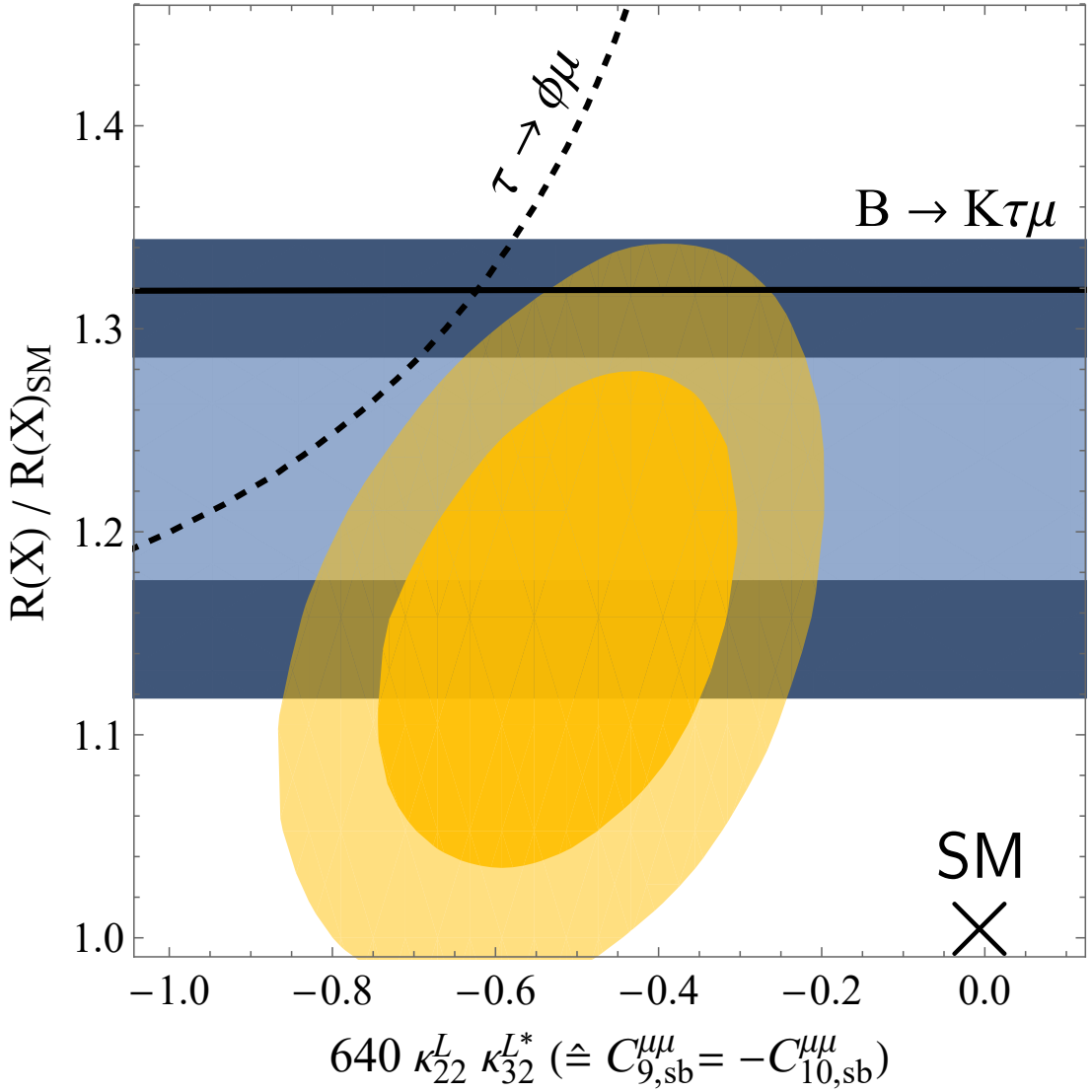


$b \to s\gamma$: $-0.01 < C_7 < 0.05 \Rightarrow$ perfect agreement

[Capdevila, Crivellin, Descote-Genon, Matias, Virto, 1704.053402]

This only explains flavor conserving quantities (like P_5'), but not LFUV like $R(K^{(*)})$.

Allow $b \to s\mu\mu$ at tree-level with small couplings to address $R(K^{(*)})$



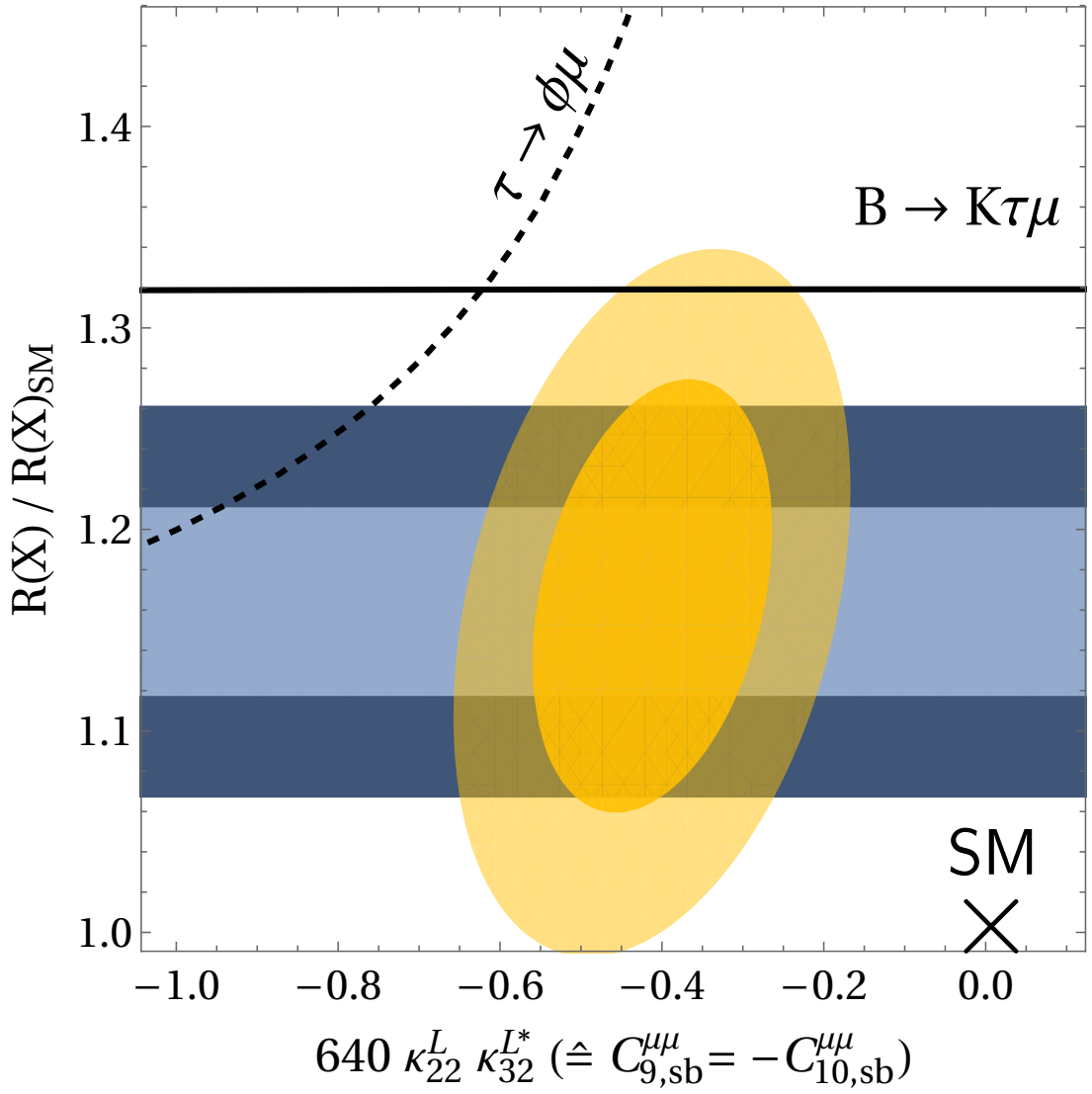
Thanks to B. Capdevila for model-specific fit!

- $b \to c\tau\nu\ 1\sigma$
- $b \to c\tau\nu\ 2\sigma$
- $b \to s\ell^+\ell^-\ 1\sigma$
- $b \to s\ell^+\ell^-\ 2\sigma$
- $\kappa^L_{33} = 0.5 = 2.5\ \kappa^L_{32}$
- $\kappa^L_{33} = 0.5 = 25\ \kappa^L_{32}$

$$\kappa_{fi} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & \kappa_{23} \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$$

[Crivellin, Greub, Müller, FS, 1807.02068]

Allow $b \to s\mu\mu$ at tree-level with small couplings to address $R(K^{(*)})$



Thanks to B. Capdevila for model-specific fit!

- $b \to c\tau\nu\ 1\sigma$
- $b \to c\tau\nu\ 2\sigma$
- $b \to s\ell^+\ell^-\ 1\sigma$
- $b \to s\ell^+\ell^-\ 2\sigma$
- $\kappa^L_{33} = 0.5 = 2.5\ \kappa^L_{32}$
- $\kappa^L_{33} = 0.5 = 25\ \kappa^L_{32}$

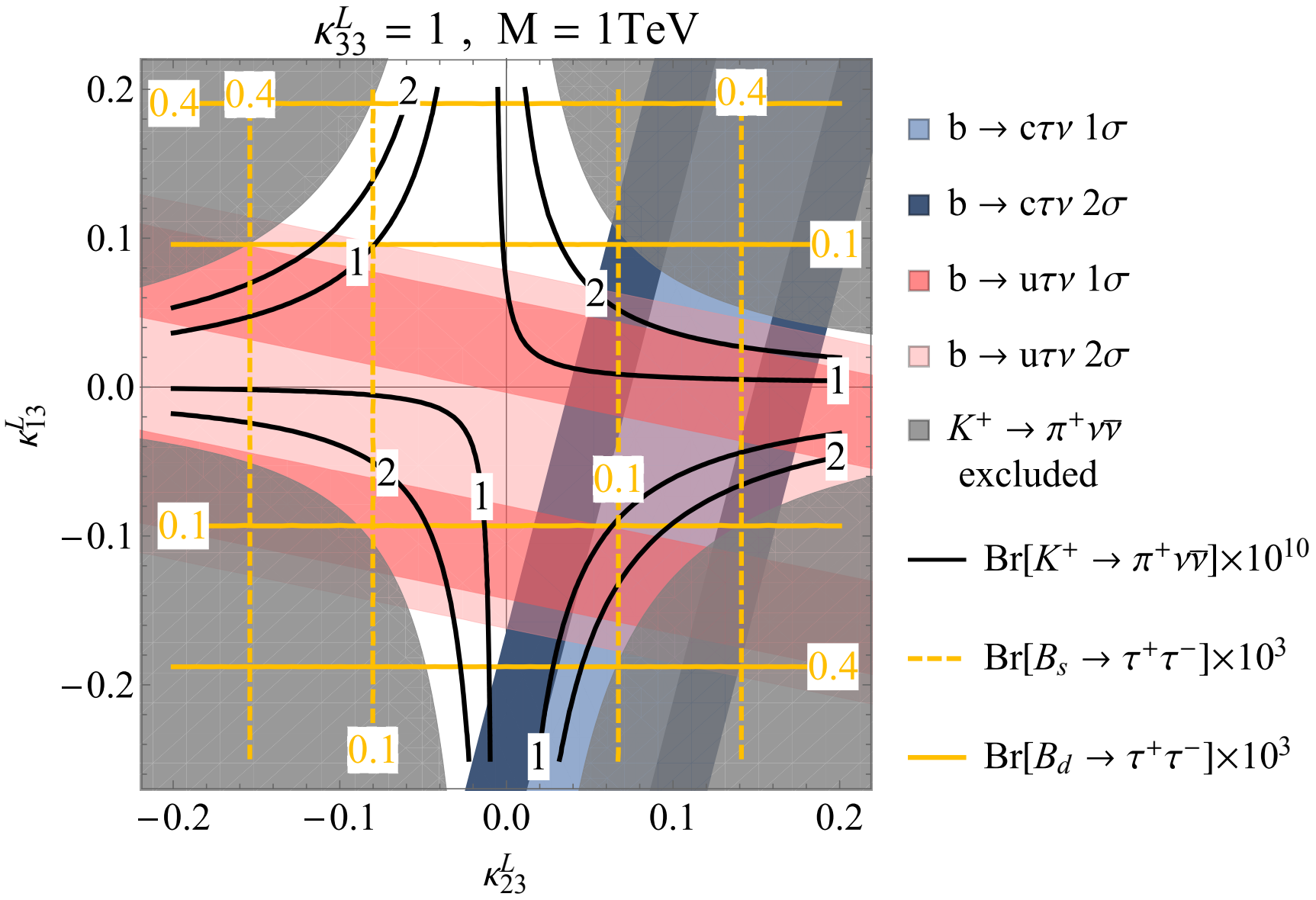
$$\kappa_{fi} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & \kappa_{23} \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$$

[Crivellin, Greub, Müller, FS, 1807.02068]

Conclusion

- Vector Leptoquark singlet is a prime candidate to address the flavor anomalies
- LFUV in $b \to s\ell\ell$ and $b \to c\ell\nu$ experimentally still not (dis)proofed
- Global fits show that LFU+LFUV NP is compatible with the flavor anomalies
- Explanation of $R(D^{(*)})$ requires a generic flavor structure:
  - Huge $b \to s\tau\tau$ enhancement $\Rightarrow$ Strong predictions
  - Sizable loop-effects in $b \to s\ell\ell$ and $b \to s\nu\nu$
- Explaining $R(D^{(*)})$ with the VLQ leads to the right size in loop-effects

Backup



Couplings to first generatoin quarks are allowed

Strong effects in $B_{s(d)} \to \tau\tau$

Observable	Experiment	SM	Prediction
$\mathrm{Br}[B_s \to \tau\tau]$	$\leq 6.8 \times 10^{-3}$ (LHCb)	$(7.73 \pm 0.5) \times 10^{-7}$	$\mathcal{O}(10^{-4})$
$\mathrm{Br}[B_d \to \tau\tau]$	$\leq 2.1 \times 10^{-3}$ (LHCb) $(7.73 \pm 0.5) \times 10^{-7}$ (Belle)	$(2.22 \pm 0.2) \times 10^{-8}$	$\mathcal{O}(10^{-4})$