GDR-InF annual workshop, Sommières, 4 November 2019

B-decay discrepancies after Moriond 2019

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Outline

1. *B*-decay discrepancies
2. New physics interpretations
   - $b \to s\ell\ell$ in the weak effective theory
   - The global picture in the Standard Model effective field theory (SMEFT)
   - Simplified leptoquark model
3. Conclusions

Based on:

Jason Aebischer, Wolfgang Altmannshofer, Diego Guadagnoli, Méril Reboud, PS, David M. Straub [arXiv:1903.10434]

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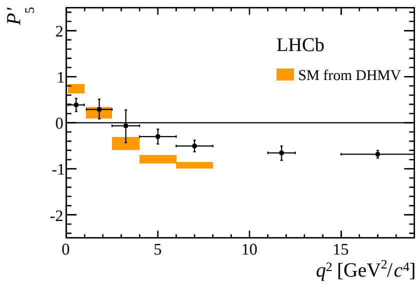
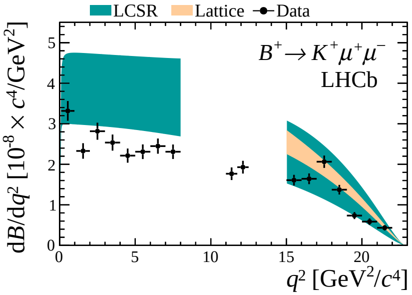
$b \to s\,\mu^+\mu^-$ anomaly

Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ:

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:1512.04442
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$.
  LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731

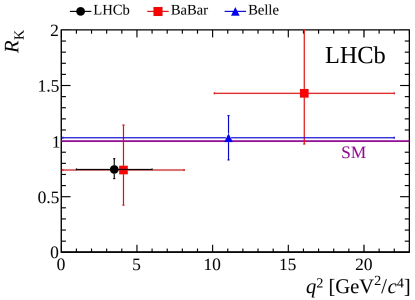


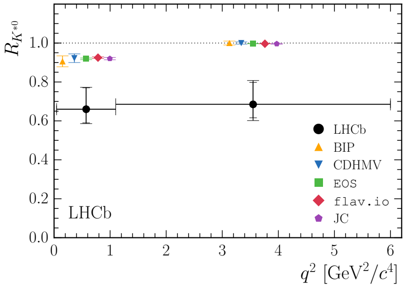


Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavour universality (LFU) ratios $R_K^{[1,6]}$, $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ showed deviations from SM by about 2.5σ each. LHCb, arXiv:1406.6482, arXiv:1705.05802

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$

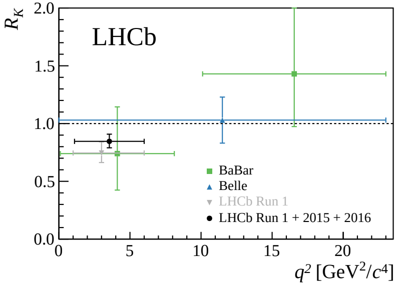


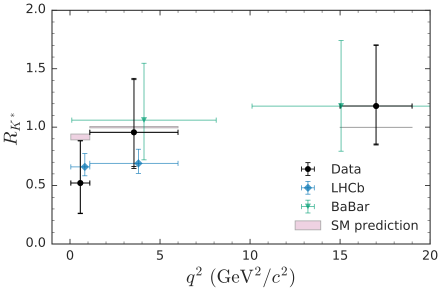


Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

New results at Moriond 2019

- Updated measurement of $\mathbf{R_K}$ **by LHCb** — LHCb, arXiv:1903.09252
- New measurement of $\mathbf{R_{K^*}}$ **by Belle** — Belle, arXiv:1904.02440





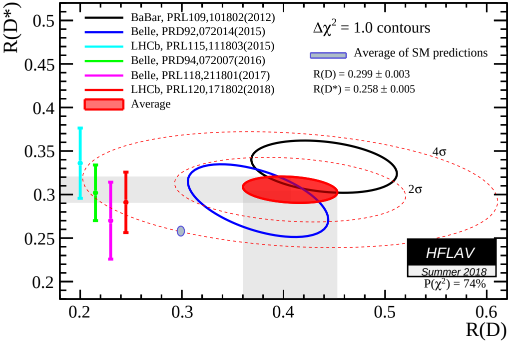
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb showed combined deviation from SM by 3.8σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

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

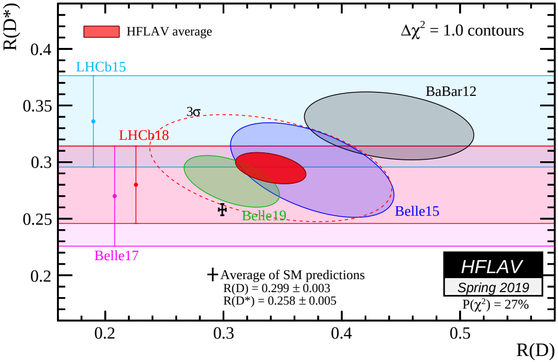


HFLAV, arXiv:1612.07233

Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

New results at Moriond 2019

- Updated measurements of $\mathbf{R_D}$ **and** $\mathbf{R_{D^*}}$ **by Belle** — Belle, arXiv:1904.08794



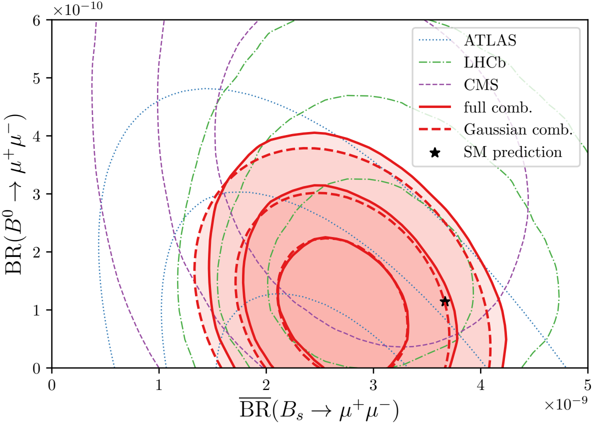
HFLAV, hflav.web.cern.ch

see talks by Adam Morris and Dawid Gerstel and discussion session on R_D and R_{D^*}

Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

Measurements of BR($B_{s,d} \to \mu^+\mu^-$) by LHCb, CMS, and ATLAS show combined deviation from SM by about 2σ.

LHCb, arXiv:1703.05747
CMS, arXiv:1307.5025
ATLAS, arXiv:1812.03017



Outline

Setup

- Global likelihood from **smelli** python package for comparing theory predictions to experimental data Aebischer, Kumar, PS, Straub, arXiv:1810.07698
- Quantify agreement between theory and experiment by likelihood L, $\Delta\chi^2$, and pull

$$\text{pull}_{1\text{D}} = 1\sigma \cdot \sqrt{\Delta\chi^2}\,, \qquad \text{where } -\frac{1}{2}\Delta\chi^2 = \ln L(\vec{0}) - \ln L(\vec{C}_{\text{best fit}})\,.$$

$$\text{pull}_{2\text{D}} = 1\sigma, 2\sigma, 3\sigma, \ldots \quad \text{for} \quad \Delta\chi^2 \approx 2.3, 6.2, 11.8, \ldots$$

- New physics scenarios in effective field theories:
  - **Weak Effective Theory (WET)** at scale m_b
  - **Standard Model Effective Field Theory (SMEFT)** at scale 2 TeV
- **Simplified leptoquark model** matched to SMEFT at 2 TeV

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$b \to s\ell\ell$ in the weak effective theory

- Effective Hamiltonian at scale m_b: $\mathcal{H}_{\text{eff}}^{bs\ell\ell} = \mathcal{H}_{\text{eff, SM}}^{bs\ell\ell} + \mathcal{H}_{\text{eff, NP}}^{bs\ell\ell}$

$$\mathcal{H}_{\text{eff, NP}}^{bs\ell\ell} = -\mathcal{N} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i'^{bs\ell\ell} O_i'^{bs\ell\ell} \right) + \text{h.c.}$$

- Operators considered here ($\ell = e, \mu$)

$$\begin{aligned}
O_9^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, & O_9'^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,\\
O_{10}^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, & O_{10}'^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,\\
O_S^{bs\ell\ell} &= m_b(\bar{s} P_R b)(\bar{\ell}\ell)\,, & O_S'^{bs\ell\ell} &= m_b(\bar{s} P_L b)(\bar{\ell}\ell)\,,\\
O_P^{bs\ell\ell} &= m_b(\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)\,, & O_P'^{bs\ell\ell} &= m_b(\bar{s} P_L b)(\bar{\ell}\gamma_5 \ell)\,.
\end{aligned}$$

- Not considered here
  - Dipole operators: strongly constrained by radiative decays. e.g. [arXiv:1608.02556]
  - Four quark operators: dominant effect from RG running above m_B.
    Jäger, Leslie, Kirk, Lenz [arXiv:1701.09183]

Scenarios with a single Wilson coefficients

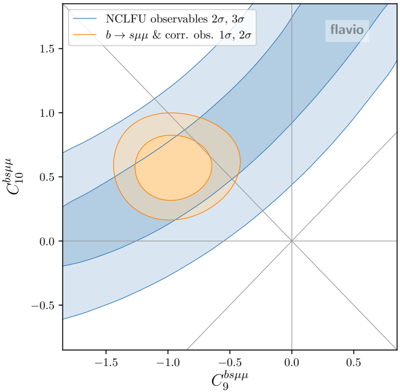
Coefficient	type	best fit	1σ	$\text{pull}_{1D} = \sqrt{\Delta\chi^2}$
$\boldsymbol{C_9^{bs\mu\mu}}$	$\boldsymbol{L \otimes V}$	-0.97	$[-1.12, -0.81]$	**5.9σ**
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.14$	$[-0.03, +0.32]$	0.8σ
$\boldsymbol{C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes A}$	$+0.75$	$[+0.62, +0.89]$	**5.7σ**
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-0.24	$[-0.36, -0.12]$	2.0σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.20$	$[+0.06, +0.36]$	1.4σ
$\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes L}$	-0.53	$[-0.61, -0.45]$	**6.6σ**

Only small pull for

- Coefficients with $\ell = e$ (cannot explain $b \to s\mu\mu$ anomaly)
- Scalar coefficients (can only reduce tension in $B_s \to \mu\mu$)

see also similar fits by other groups:
Algueró et al., arXiv:1903.09578 Ciuchini et al., arXiv:1903.09632 Datta et al., arXiv:1903.10086
Kowalska et al., arXiv:1903.10932 Arbey et al., arXiv:1904.08399

Scenarios with two Wilson coefficients



WET at 4.8 GeV

- **Before Moriond 2019**: Very good agreement between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*}

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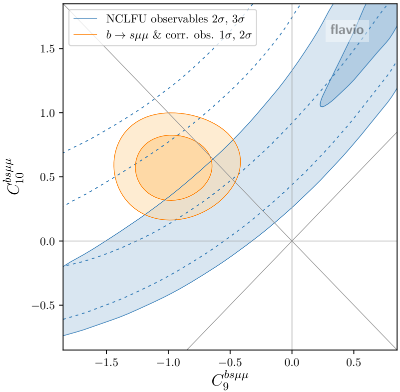

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- **After Moriond 2019**: Updated R_K measurement by LHCb and new R_{K^*} measurement by Belle closer to SM value LHCb, arXiv:1903.09252 Belle, arXiv:1904.02440

  Tension between fits to R_K & R_{K^*} and $b \to s\mu\mu$ observables in C_9 direction

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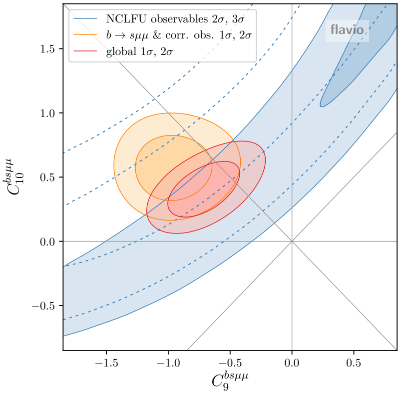

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  Updated R_K measurement by LHCb and new R_{K^*} measurement by Belle closer to SM value LHCb, arXiv:1903.09252 Belle, arXiv:1904.02440

  Tension between fits to R_K & R_{K^*} and $b \to s\mu\mu$ observables in C_9 direction
- **Global likelihood**:
  Contribution to purely left-handed $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ yields very good fit to experimental data

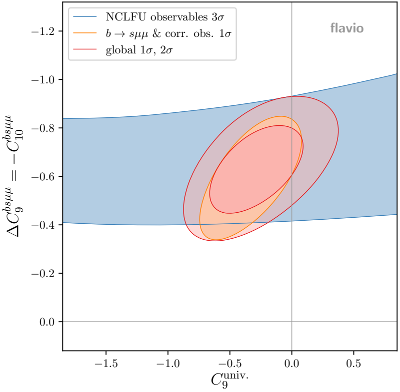
Scenarios with two Wilson coefficients

- **LFU contribution** only affects $b \to s\mu\mu$ observables
- Tension between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*} could be reduced by **LFU** contribution to $\boldsymbol{C_9}$
- Perform two-parameter fit in space of $\boldsymbol{C_9^{\text{univ.}}}$ and $\boldsymbol{\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$:

$$C_9^{bsee} = C_9^{\text{univ.}} \qquad C_{10}^{bsee} = 0$$
$$C_9^{bs\mu\mu} = C_9^{\text{univ.}} + \Delta C_9^{bs\mu\mu} \qquad C_{10}^{bs\mu\mu} = -\Delta C_9^{bs\mu\mu}$$
$$C_9^{bs\tau\tau} = C_9^{\text{univ.}} \qquad C_{10}^{bs\tau\tau} = 0$$

scenario first considered in
Algueró et al., arXiv:1809.08447

Scenarios with two Wilson coefficients



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- **Before Moriond 2019**: Fit compatible with $C_9^{\text{univ.}} = 0$ and only contribution to $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$

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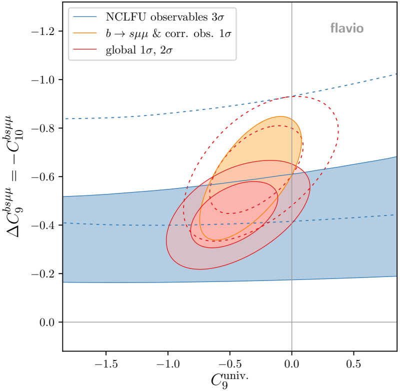

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- **After Moriond 2019**:
  Preference for **non-zero $C_9^{\text{univ.}}$**

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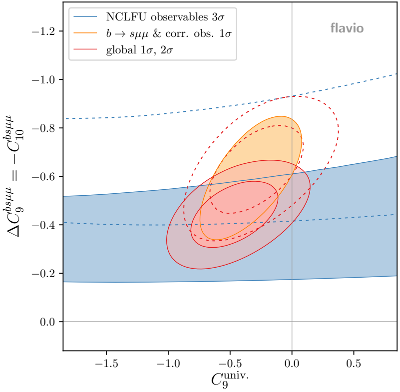

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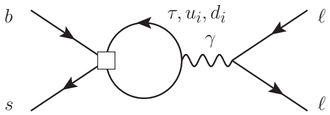
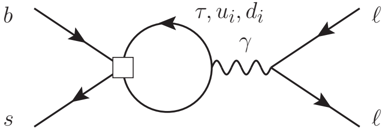
- **After Moriond 2019**: Preference for **non-zero $C_9^{\text{univ.}}$**
- $C_9^{\text{univ.}}$ can arise from RG effects:



Bobeth, Haisch, arXiv:1109.1826
Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068

Outline

The global picture in the SMEFT



RG effects require scale separation

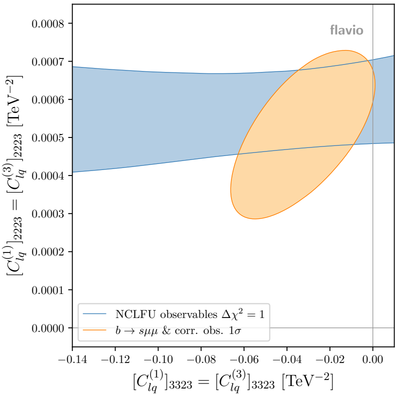
- Consider **SMEFT at 2 TeV**

Possible operators:

- $[O_{lq}^{(3)}]_{3323} = (\bar{l}_3 \gamma_\mu \tau^a l_3)(\bar{q}_2 \gamma^\mu \tau^a q_3)$:
  Can also **explain $R_{D^{(*)}}$ anomalies!**
- $[O_{lq}^{(1)}]_{3323} = (\bar{l}_3 \gamma_\mu l_3)(\bar{q}_2 \gamma^\mu q_3)$:
  Strong constraints from $B \to K\nu\nu$ require $[C_{lq}^{(1)}]_{3323} \approx [C_{lq}^{(3)}]_{3323}$

  Buras et al., arXiv:1409.4557
- $[O_{qe}]_{2333} = (\bar{q}_2 \gamma_\mu q_3)(\bar{e}_3 \gamma^\mu e_3)$ cannot explain $R_{D^{(*)}}$
- Four-quark operators cannot explain $R_{D^{(*)}}$, models yielding large enough contributions already in tension with data

The global picture in the SMEFT



- **Before Moriond 2019**: Fit compatible with $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} = 0$ and only contribution to $[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223}$

$$[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} \quad \Rightarrow \quad C_9^{\text{univ.}} \quad \text{(RG effect)}$$

$$[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223} \quad \Rightarrow \quad \Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$$

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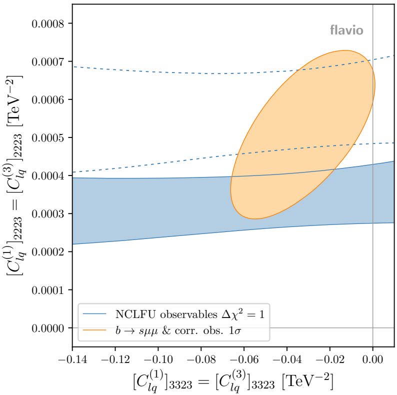

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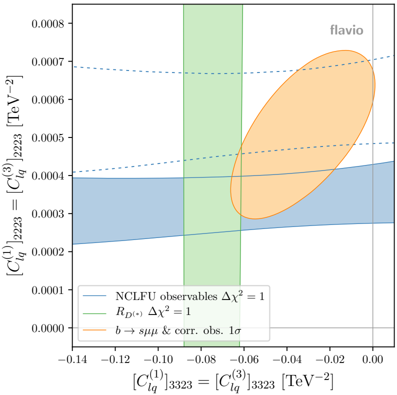

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  Agreement with combined $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanation has improved

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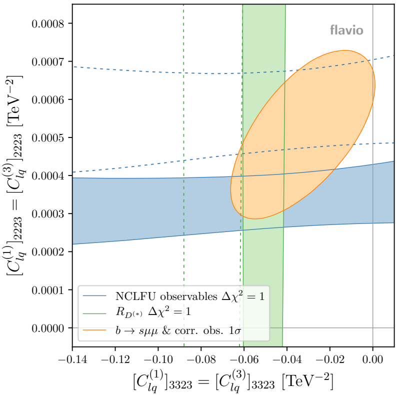

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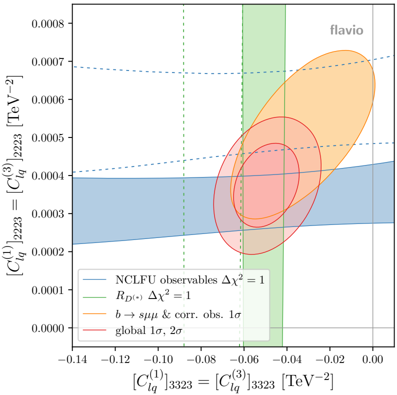

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Predictions from global likelihood in SMEFT scenario

Observable	1σ	SM
$R_{K^*}^{[0.045,1.1]}$	$0.88\,^{+0.01}_{-0.01}$	0.926 ± 0.004
$R_{K^*}^{[1.1,6.0]}$	$0.81\,^{+0.04}_{-0.04}$	0.9964 ± 0.0006
$R_{K^*}^{[0.1,8.0]}$	$0.83\,^{+0.04}_{-0.03}$	0.995 ± 0.002
$R_{K^*}^{[15,19]}$	$0.79\,^{+0.04}_{-0.04}$	0.99807 ± 0.00004
$R_{K}^{[1.0,6.0]}$	$0.80\,^{+0.04}_{-0.04}$	1.0008 ± 0.0003
$R_{\phi}^{[1.0,6.0]}$	$0.81\,^{+0.04}_{-0.04}$	0.9970 ± 0.0003
$\langle P_5' \rangle^{[4.0,6.0]}$	$-0.58\,^{+0.13}_{-0.12}$	-0.763 ± 0.072
R_D	$0.34\,^{+0.01}_{-0.01}$	0.303 ± 0.006
R_{D^*}	$0.29\,^{+0.01}_{-0.01}$	0.255 ± 0.004
$\overline{\text{BR}}(B_s \to \mu^+\mu^-)$	$2.98\,^{+0.20}_{-0.19} \times 10^{-9}$	$(3.67 \pm 0.16) \times 10^{-9}$
$\text{BR}(B^\pm \to K^\pm\tau^+\tau^-)$	$3.05\,^{+1.78}_{-1.06} \times 10^{-5}$	$(1.66 \pm 0.19) \times 10^{-7}$
$\overline{\text{BR}}(B_s \to \tau^+\tau^-)$	$1.41\,^{+0.80}_{-0.47} \times 10^{-4}$	$(7.78 \pm 0.33) \times 10^{-7}$

see parallel session on $b \to s\tau^+\tau^-$, talk by Olcyr Sumensari

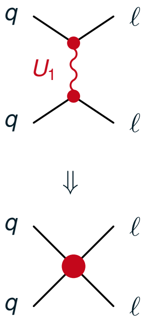
Outline

Simplified U_1-leptoquark model

see talk by Jonathan Kriewald

- **U_1 vector leptoquark** $(\mathbf{3},\mathbf{1})_{2/3}$ couples quarks and leptons

$$\mathcal{L}_{U_1} \supset g_{lq}^{ji} \left(\bar{q}^i \gamma^\mu l^j\right) U_\mu + \text{h.c.}$$



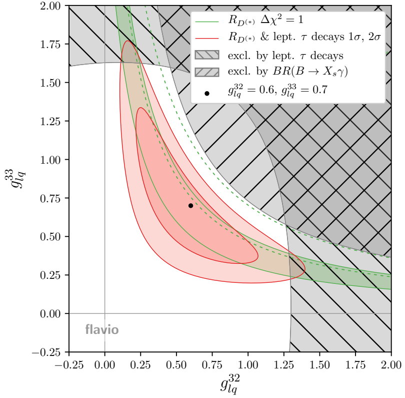
- Generates **semi-leptonic operators at tree-level**

$$[C_{lq}^{(1)}]_{ijkl} = [C_{lq}^{(3)}]_{ijkl} = -\frac{g_{lq}^{jk}\, g_{lq}^{il*}}{2M_U^2}$$

- And **dipole operators at one-loop**, e.g.
  $[O_{dV}]_{ij} = (\bar{q}_i \sigma^{\mu\nu} V_{\mu\nu} d_j)\varphi, \quad V \in \{W, B, G\}$:

$$[C_{dV}]_{23} = \kappa_V \frac{Y_b}{16\pi^2} \sum_i \frac{g_{lq}^{i2}\, g_{lq}^{i3*}}{M_U^2}, \qquad \kappa_W = \frac{g}{6}, \quad \kappa_B = \frac{-4\,g'}{9}, \quad \kappa_V = \frac{-5\,g_s}{12}$$

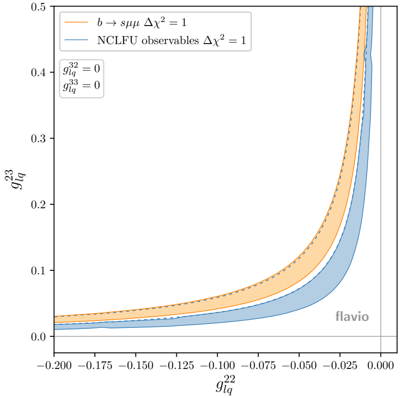
Simplified U_1-leptoquark model



- $R_{D^{(*)}}$ mostly depends on **tauonic couplings g_{lq}^{32}, g_{lq}^{33}**
- Dipole operators contribute to **$BR(B \to X_s\gamma)$**
- RG running contributes to **leptonic τ decays**
- Well defined allowed region for explaining $R_{D^{(*)}}$, select **benchmark point**

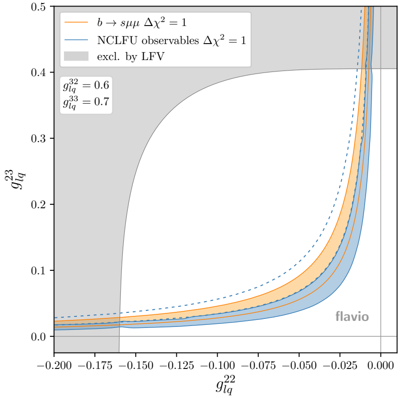
$$g_{lq}^{32} = 0.6, \qquad g_{lq}^{33} = 0.7$$

Simplified U_1-leptoquark model



- $R_{K^{(*)}}$ can be explained by **muonic couplings g_{lq}^{22}, g_{lq}^{23}**
- **Vanishing tauonic couplings**: Tension between fits to $R_{K^{(*)}}$ and $b \to s\mu\mu$ observables after Moriond 2019

Simplified U_1-leptoquark model



- $R_{K^{(*)}}$ can be explained by **muonic couplings g_{lq}^{22}, g_{lq}^{23}**
- **Vanishing tauonic couplings**: Tension between fits to $R_{K^{(*)}}$ and $b \to s\mu\mu$ observables after Moriond 2019
- Benchmark point explaining $R_{D^{(*)}}$,

$$g_{lq}^{32} = 0.6, \qquad g_{lq}^{33} = 0.7,$$

  implies non-zero $C_9^{\text{univ.}}$, $R_{K^{(*)}}$ and $b \to s\mu\mu$ in good agreement after Moriond 2019
- Constraint from **LFV observables**

Outline

Conclusions

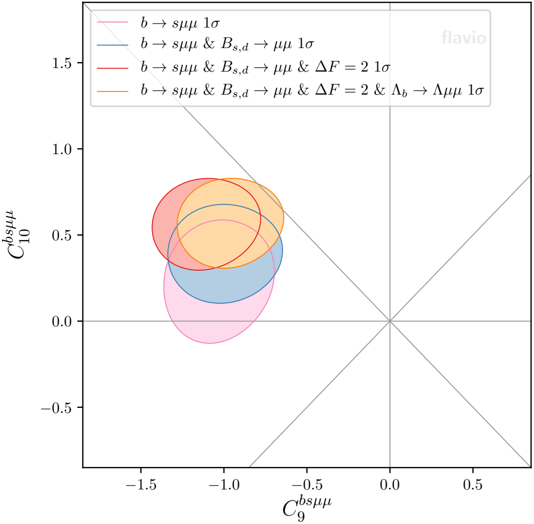
- New and updated measurements of $R_{K^{(*)}}$ and $R_{D^{(*)}}$ as well as $B_s \to \mu\mu$.
- New physics in the single muonic Wilson coefficients $C_9^{bs\mu\mu}$, $C_{10}^{bs\mu\mu}$, and $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ gives a clearly better fit to data than the SM (pull $\approx 6\sigma$).
- Slight tension between $R_{K^{(*)}}$ fit and $b \to s\mu\mu$ fit with only muonic Wilson coefficients can be reduced by lepton flavor universal $C_9^{\text{univ.}}$.
- Lepton flavor universal $C_9^{\text{univ.}}$ can be generated through RG effects from semi-tauonic Wilson coefficients that can explain $R_{D^{(*)}}$.
- U_1-leptoquark can generate these semi-tauonic Wilson coefficients in addition to semi-muonic ones that explain $R_{K^{(*)}}$.

Backup slides

New physics in individual Wilson coefficients

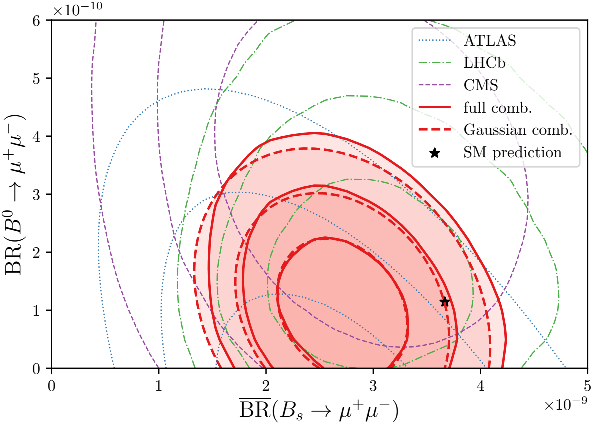
Coefficient	type	best fit	1σ	pull
$\boldsymbol{C_9^{bs\mu\mu}}$	$\boldsymbol{L \otimes V}$	-0.97	$[-1.12, -0.81]$	**5.9σ**
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.14$	$[-0.03, +0.32]$	0.8σ
$\boldsymbol{C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes A}$	$+0.75$	$[+0.62, +0.89]$	**5.7σ**
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-0.24	$[-0.36, -0.12]$	2.0σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.20$	$[+0.06, +0.36]$	1.4σ
$\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes L}$	-0.53	$[-0.61, -0.45]$	**6.6σ**
C_9^{bsee}	$L \otimes V$	$+0.93$	$[+0.66, +1.17]$	3.5σ
$C_9^{\prime bsee}$	$R \otimes V$	$+0.39$	$[+0.05, +0.65]$	1.2σ
C_{10}^{bsee}	$L \otimes A$	-0.83	$[-1.05, -0.60]$	3.6σ
$C_{10}^{\prime bsee}$	$R \otimes A$	-0.27	$[-0.57, -0.02]$	1.1σ
$C_9^{bsee} = C_{10}^{bsee}$	$L \otimes R$	-1.49	$[-1.79, -1.18]$	3.2σ
$C_9^{bsee} = -C_{10}^{bsee}$	$L \otimes L$	$+0.47$	$[+0.33, +0.59]$	3.5σ
$\left(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}\right) \times \text{GeV}$	$\bar{L}R \otimes \bar{R}L$	-0.006	$[-0.009, -0.003]$	2.8σ
$\left(C_S^{\prime bs\mu\mu} = C_P^{\prime bs\mu\mu}\right) \times \text{GeV}$	$\bar{R}L \otimes \bar{L}R$	-0.006	$[-0.009, -0.003]$	2.8σ

C_9 vs. $C_9 = -C_{10}$

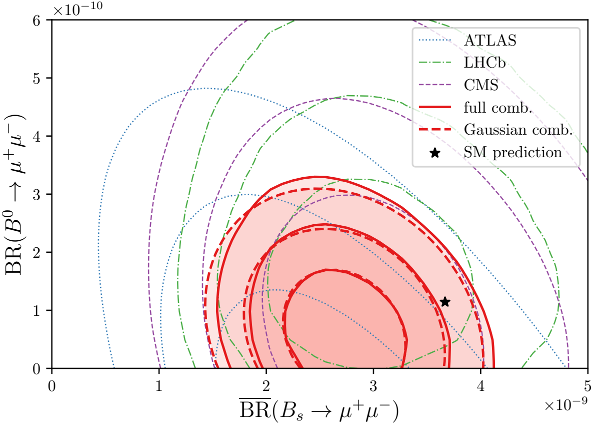


$b \to s\mu\mu$ 1σ
$b \to s\mu\mu$ & $B_{s,d} \to \mu\mu$ 1σ
$b \to s\mu\mu$ & $B_{s,d} \to \mu\mu$ & $\Delta F = 2$ 1σ
$b \to s\mu\mu$ & $B_{s,d} \to \mu\mu$ & $\Delta F = 2$ & $\Lambda_b \to \Lambda\mu\mu$ 1σ
flavio
1.5
1.0
0.5
0.0
−0.5
$C_{10}^{bs\mu\mu}$
−1.5
−1.0
−0.5
0.0
0.5
$C_9^{bs\mu\mu}$

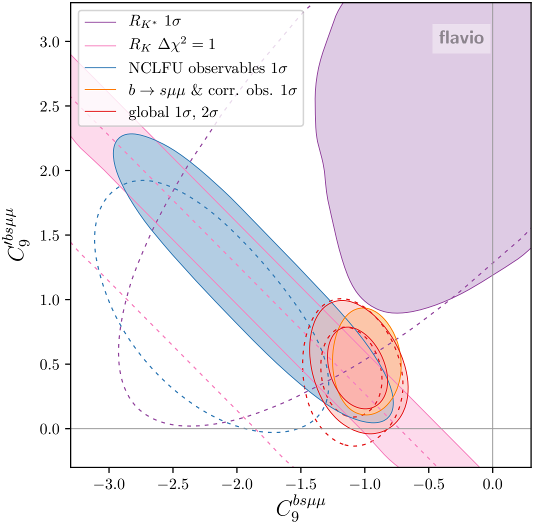
Combination of $B_{s,d} \to \mu^+\mu^-$ measurements



Combination of $B_{s,d} \to \mu^+\mu^-$ measurements



New physics in right-handed quark current



Direct contraints on U_1 leptoquark