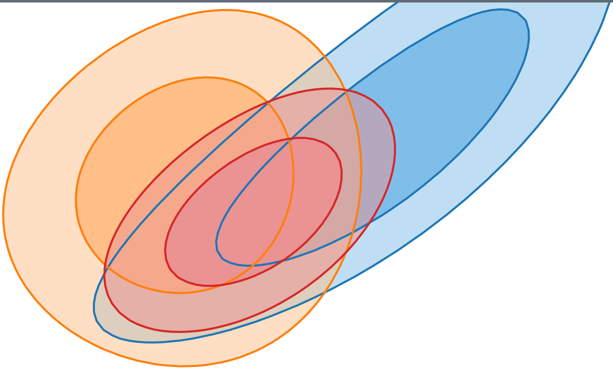
LF(U)V Workshop, Zürich, 4 July 2022

From the global $b \to s\ell\ell$ fit to models of new physics

Peter Stangl AEC & ITP University of Bern

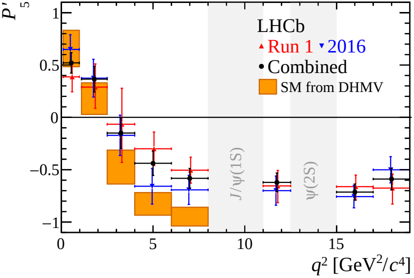


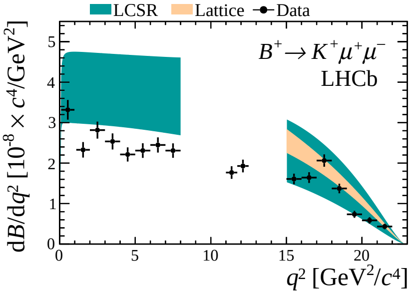
The $b \to s\ell\ell$ anomalies

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

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

- Angular observables in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:2003.04831, arXiv:2012.13241
- 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, arXiv:2105.14007





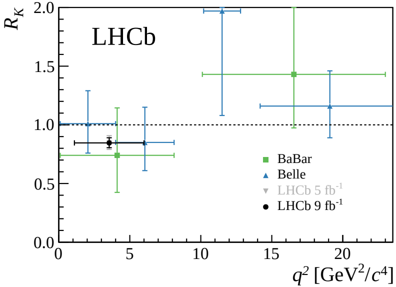
*: based on hadronic assumptions on which there is no theory consensus yet

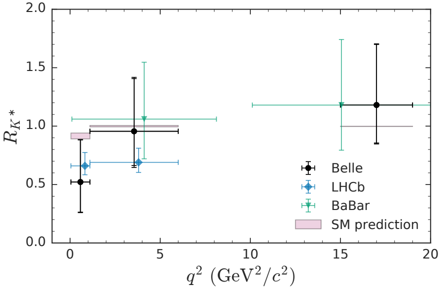
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavor universality (LFU) ratios $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$, $R_K^{[1,6]}$ show deviations from SM by 2.3, 2.5, and 3.1σ.

LHCb, arXiv:1705.05802, arXiv:2103.11769
Belle, arXiv:1904.02440, arXiv:1908.01848

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

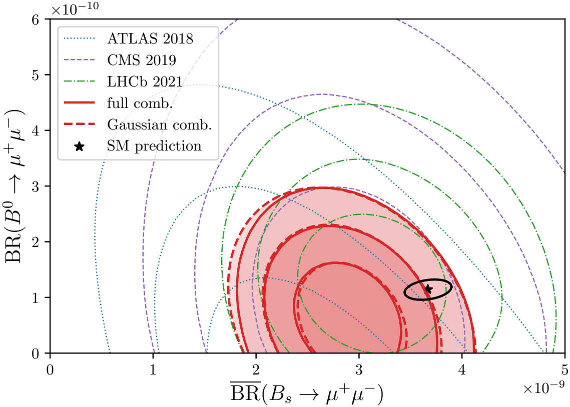




Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

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

ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127
LHCb, arXiv:2108.09283, arXiv:2108.09284
Altmannshofer, PS, arXiv:2103.13370



*: depends on parameters like V_{cb} but tension persists in V_{cb}-free ratio $\mathcal{B}(B_s \to \mu^+\mu^-)/\Delta M_s$

Bobeth, Buras, arXiv:2104.09521

The $b \to c\ell\nu$ anomalies

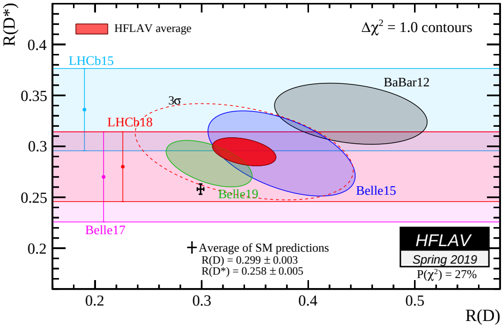
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by about 3-4σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529, arXiv:1904.08794

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

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



HFLAV, hflav.web.cern.ch

Theoretical Framework

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

- Effective Hamiltonian at scale m_b: $\mathcal{H}_{\text{eff}}^{bs\ell\ell} = \mathcal{H}_{\text{eff, sl}}^{bs\ell\ell} + \mathcal{H}_{\text{eff, had}}^{bs\ell\ell}$
- **Semileptonic operators**: ($\mathcal{N} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \approx (34\text{ TeV})^{-2}$)

$$\mathcal{H}_{\text{eff, sl}}^{bs\ell\ell} = -\mathcal{N}\left(C_7^{bs} O_7^{bs} + C_7'^{bs} O_7'^{bs} + \sum_{\ell} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i'^{bs\ell\ell} O_i'^{bs\ell\ell} \right) \right) + \text{h.c.}$$

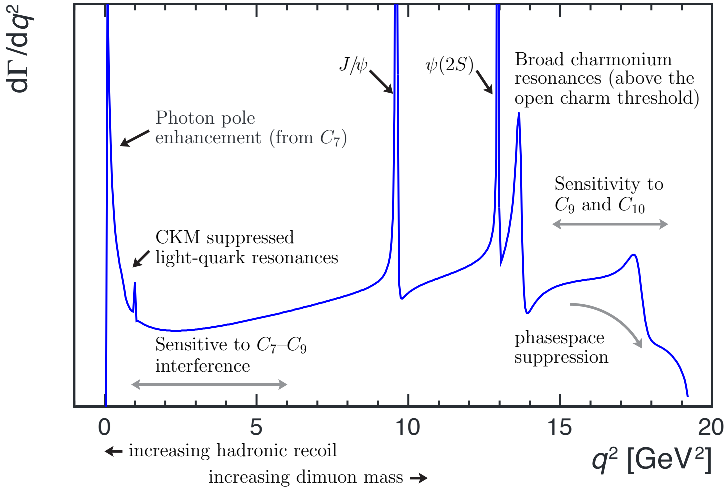
$$\begin{aligned}
O_9^{(\prime)bs\ell\ell} &= (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)\,, & C_9^{\text{SM}} &\approx -4.1\\
O_{10}^{(\prime)bs\ell\ell} &= (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, & C_{10}^{\text{SM}} &\approx +4.2\\
O_7^{(\prime)bs} &= \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu} P_{R(L)} b)\, F^{\mu\nu}\,, & C_7^{\text{SM}} &\approx -0.3\\
O_S^{(\prime)bs\ell\ell} &= m_b(\bar{s}P_{R(L)} b)(\bar{\ell}\ell)\,, & &\\
O_P^{(\prime)bs\ell\ell} &= m_b(\bar{s}P_{R(L)} b)(\bar{\ell}\gamma_5\ell)\,. & &
\end{aligned}$$

- **Hadronic operators**:

$$\mathcal{H}_{\text{eff, had}}^{bs\ell\ell} = -\mathcal{N}\frac{16\pi^2}{e^2}\left(C_8^{bs} O_8^{bs} + C_8'^{bs} O_8'^{bs} + \sum_{i=1..6} C_i^{bs\ell\ell} O_i^{bs} \right) + \text{h.c.}$$

$$\text{e.g.}\quad O_1^{bs} = (\bar{s}\gamma_\mu P_L T^a c)(\bar{c}\gamma^\mu P_L T^a b)\,, \quad O_2^{bs} = (\bar{s}\gamma_\mu P_L c)(\bar{c}\gamma^\mu P_L b)\,.$$

Cartoon: q^2 dependence of $B \to K^* \ell^+ \ell^-$

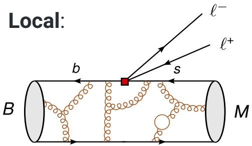


Blake, Lanfranchi, Straub, arXiv:1606.00916

Theory of $B \to M\ell\ell$ decays ($M = K, K^*, \phi$)

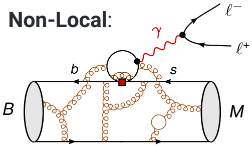
$$\begin{aligned}\mathcal{M}(B\to M\ell\ell) &= \langle M\ell\ell|\mathcal{H}_{\text{eff}}^{bs\ell\ell}|B\rangle \\ &= \mathcal{N}\Big[\,(\mathcal{A}_V^\mu + \mathcal{H}^\mu)\,\bar u_\ell\gamma_\mu v_\ell + \mathcal{A}_A^\mu\,\bar u_\ell\gamma_\mu\gamma_5 v_\ell + \mathcal{A}_S\,\bar u_\ell v_\ell + \mathcal{A}_P\,\bar u_\ell\gamma_5 v_\ell\Big]\end{aligned}$$

Local:



$$\begin{aligned}\mathcal{A}_V^\mu &= -\frac{2im_b}{q^2}\,C_7\langle M|\bar s\,\sigma^{\mu\nu}q_\nu\,P_R\,b|B\rangle + C_9\langle M|\bar s\,\gamma^\mu\,P_L\,b|B\rangle \\ &\quad + (P_L \leftrightarrow P_R, C_i \to C_i') \\ \mathcal{A}_A^\mu &= C_{10}\langle M|\bar s\,\gamma^\mu\,P_L\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i') \\ \mathcal{A}_{S,P} &= C_{S,P}\langle M|\bar s\,P_R\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')\end{aligned}$$

Non-Local:

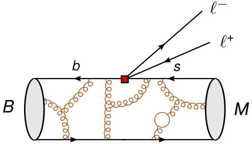


$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2}\sum_{i=1..6,8} C_i\int dx^4 e^{iq\cdot x}\langle M|T\{j^\mu_{\mathrm{em}}(x), O_i(0)\}|B\rangle$$

$$j^\mu_{\mathrm{em}} = \sum_q Q_q\,\bar q\gamma^\mu q$$

- **Wilson coefficients $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$**:
  perturbative, short-distance (q^2-independent), parameterize heavy new physics
- **local** and **non-local** **hadronic matrix elements**: see talk by Marzia Bordone
  non-perturbative, long-distance (q^2-dependent), **main source of uncertainty**

Local matrix elements



$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2} C_7 \langle M|\bar{s}\,\sigma^{\mu\nu} q_\nu\, P_R\, b|B\rangle + C_9 \langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle$$
$$+ (P_L \leftrightarrow P_R, C_i \to C_i')$$
$$\mathcal{A}_A^\mu = C_{10} \langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$
$$\mathcal{A}_{S,P} = C_{S,P} \langle M|\bar{s}\, P_R\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

- Matrix elements $\langle M|\bar{s}\,\Gamma_i\, b|B\rangle$ can be parameterized by:
  - **3 form factors** for each **spin zero** final state, $M = \boldsymbol{K}$
  - **7 form factors** for each **spin one** final state, $M = \boldsymbol{K}^*, \phi$

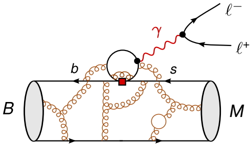
- Determination of form factors
  - high q^2: **Lattice QCD**

    HPQCD, arXiv:1306.2384
    Fermilab, MILC, arXiv:1509.06235
    Horgan, Liu, Meinel, Wingate, arXiv:1310.3722, arXiv:1501.00367
  - low q^2: **Light-cone sum rules** (LCSR)

    Bharucha, Straub, Zwicky, arXiv:1503.05534
    Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
    Gubernari, Kokulu, van Dyk, arXiv:1811.00983
    Ball, Zwicky, arXiv:hep-ph/0406232
  - low + high q^2: Combined fit **LCSR + lattice**

    Bharucha, Straub, Zwicky, arXiv:1503.05534
    Gubernari, Kokulu, van Dyk, arXiv:1811.00983
    Altmannshofer, Straub, arXiv:1411.3161

Non-local matrix elements



$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2} \sum_{i=1..6,8} C_i \int dx^4 e^{iq\cdot x} \langle M | T\{ j^\mu_{\rm em}(x), O_i(0)\} | B\rangle$$

$$j^\mu_{\rm em} = \sum_q Q_q\, \bar{q}\gamma^\mu q$$

- Contributions at low q^2 from QCD factorization (QCDF)
  Beneke, Feldmann, Seidel, arXiv:hep-ph/0106067
- **Beyond-QCDF** contributions **the main source of uncertainty**
- Non-local contributions can mimic New Physics in C_9
- Several approaches to estimate beyond-QCDF contributions at low q^2
  - fit of sum of resonances to data — Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
  - direct fit to angular data — Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli, arXiv:1512.07157
  - Light-Cone Sum Rules estimates — Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945; Gubernari, van Dyk, Virto, arXiv:2011.09813
  - analyticity + experimental data on $b \to sc\bar{c}$ — Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305; Gubernari, van Dyk, Virto, arXiv:2011.09813

“Cleanliness” of $b \to s\ell\ell$ observables in the SM

	parametric uncertainties	local hadr. matrix elements	non-local hadr. matrix elements
$\mathcal{B}(B \to M\ell\ell)$	✗	✘	✘
angular observables	✓	✗	✘
$\overline{\mathcal{B}}(B_s \to \ell\ell)$	✗	✓	✓ (N/A)
LFU observables	✓	✓	✓

New physics interpretation of $b \to s\ell\ell$ anomalies

New physics in $b \to s\ell\ell$ 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 ($\ell = e, \mu$)

$$O_9^{(\prime)bs\ell\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \,,$$
$$O_{10}^{(\prime)bs\ell\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \,.$$

- Not considered here
  - Scalar operators: can only reduce tension in $B_s \to \mu\mu$
  - Dipole operators: strongly constrained by radiative decays

    e.g. Paul, Straub, arXiv:1608.02556
  - Four quark operators: dominant effect from RG running above m_B

    Jäger, Leslie, Kirk, Lenz, arXiv:1701.09183

Setup

- Quantify agreement between theory and experiment by χ^2 function

$$\chi^2(\vec{C}) = \left(\vec{O}_{\rm exp} - \vec{O}_{\rm th}(\vec{C})\right)^{\rm T} \left(C_{\rm exp} + C_{\rm th}\right)^{-1} \left(\vec{O}_{\rm exp} - \vec{O}_{\rm th}(\vec{C})\right) .$$

- **theory errors** and **correlations** in covariance matrix $\boldsymbol{C}_{\rm th}$
- **experimental errors** and available **correlations** in covariance matrix $\boldsymbol{C}_{\rm exp}$
- Theory errors depend on new physics (NP) Wilson coefficients $\boldsymbol{C}_{\rm th}(\vec{\boldsymbol{C}})$
- $\Delta\chi^2$ and pull

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

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

- New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV

Setup

- Quantify agreement between theory and experiment by χ^2 function

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- Theory errors depend on new physics (NP) Wilson coefficients $\boldsymbol{C}_{\rm th}(\vec{\boldsymbol{C}})$ *NEW*

Altmannshofer, PS, arXiv:2103.13370

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- New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV

Observables in global $b \to s\ell\ell$ analysis

- Inclusive decays
    - $B \to X_s \ell^+ \ell^-$ ($\mathcal{B}$)
- Exclusive leptonic decays
    - $B_{s,d} \to \ell^+ \ell^-$ ($\mathcal{B}$)
- Exclusive semileptonic decays
    - $B^{(0,+)} \to K^{(0,+)} \ell^+ \ell^-$ ($\mathcal{B}_\mu$, R_K, angular observables)
    - $B^{(0,+)} \to K^{*(0,+)} \ell^+ \ell^-$ ($\mathcal{B}_\mu$, $R_{K^{*0}}$, angular observables)
    - $B_s \to \phi \mu^+ \mu^-$ ($\mathcal{B}$, angular observables)
    - $\Lambda_b \to \Lambda \mu^+ \mu^-$ ($\mathcal{B}$, angular observables)
- Fits include ~ 200 observables $\Rightarrow$ **global** $b \to s\ell\ell$ analysis

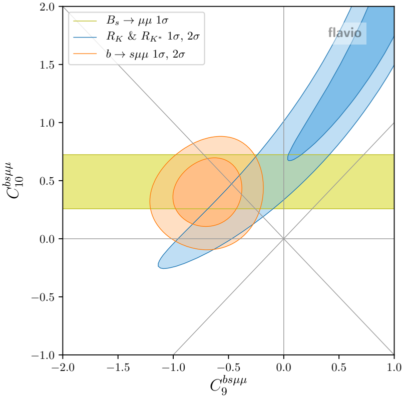
Results of global fit

based on Altmannshofer, PS, arXiv:2103.13370 (+ $B_s \to \phi\mu^+\mu^-$ angular observables, LHCb arXiv:2107.13428)
see also similar fits by other groups:
Geng et al., arXiv:2103.12738 Algueró et al., arXiv:2104.08921 Hurth et al., arXiv:2104.10058
Ciuchini et al., arXiv:2110.10126 Alok et al., arXiv:1903.09617, Datta et al., arXiv:1903.10086,
Kowalska et al., arXiv:1903.10932, D'Amico et al., arXiv:1704.05438, Hiller et al., arXiv:1704.05444, …

Scenarios with a single Wilson coefficients

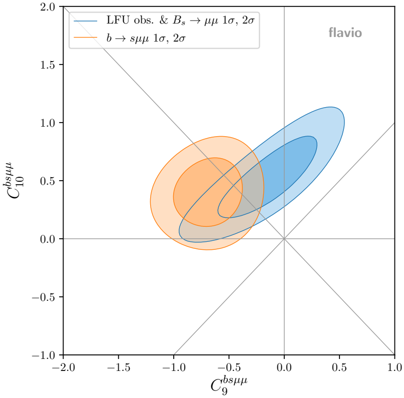
	$b \to s\mu\mu$		LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull	best fit	pull
$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	**3.3σ**	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	**5.1σ**
$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	**4.7σ**	$+0.54^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.15^{+0.24}_{-0.24}$	0.6σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.19^{+0.13}_{-0.13}$	1.5σ
$C_{10}^{\prime bs\mu\mu}$	$-0.09^{+0.15}_{-0.15}$	0.6σ	$+0.07^{+0.11}_{-0.13}$	0.5σ	$+0.04^{+0.10}_{-0.09}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.16^{+0.14}_{-0.14}$	1.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$+0.05^{+0.11}_{-0.11}$	0.5σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.55^{+0.13}_{-0.13}$	**3.8σ**	$-0.35^{+0.08}_{-0.08}$	**4.6σ**	$-0.39^{+0.07}_{-0.07}$	**5.6σ**
C_9^{bsee}			$+0.74^{+0.20}_{-0.19}$	4.1σ	$+0.75^{+0.20}_{-0.19}$	4.1σ
C_{10}^{bsee}			$-0.67^{+0.17}_{-0.18}$	4.2σ	$-0.66^{+0.17}_{-0.18}$	4.3σ
$C_9^{\prime bsee}$			$+0.36^{+0.18}_{-0.17}$	2.1σ	$+0.40^{+0.19}_{-0.18}$	2.3σ
$C_{10}^{\prime bsee}$			$-0.32^{+0.16}_{-0.16}$	2.1σ	$-0.31^{+0.15}_{-0.16}$	2.1σ
$C_9^{bsee} = C_{10}^{bsee}$			$-1.39^{+0.26}_{-0.26}$	4.0σ	$-1.28^{+0.24}_{-0.23}$	4.1σ
$C_9^{bsee} = -C_{10}^{bsee}$			$+0.37^{+0.10}_{-0.10}$	4.2σ	$+0.37^{+0.10}_{-0.10}$	4.3σ

Scenarios with two Wilson coefficients



WET at 4.8 GeV

Scenarios with two Wilson coefficients



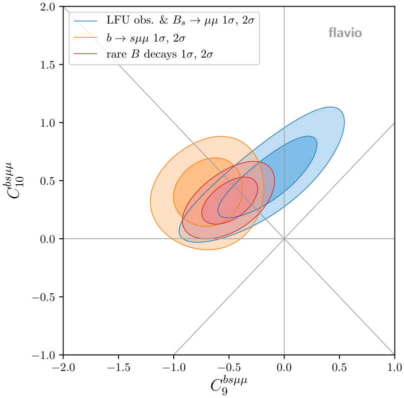
WET at 4.8 GeV

Combination of $B_s \to \mu^+\mu^-$ and LFU observables ($R_K, R_{K^*}, D_{P_{4',5'}}$)

- LFU obs. & $B_s \to \mu\mu$:
  very clean theory prediction, insensitive to universal $C_9^{\text{univ.}}$
- $b \to s\mu\mu$ sensitive to univ. coeff. possibly afflicted by underestimated hadr. uncert.
- Agreement between $b \to s\mu\mu$ observables and R_K & R_{K^*} could be further improved by **LFU** contribution to $\boldsymbol{C_9^{\text{univ.}}}$

possible connection to $b \to c\ell\nu$ anomalies
see backup slides

Scenarios with two Wilson coefficients



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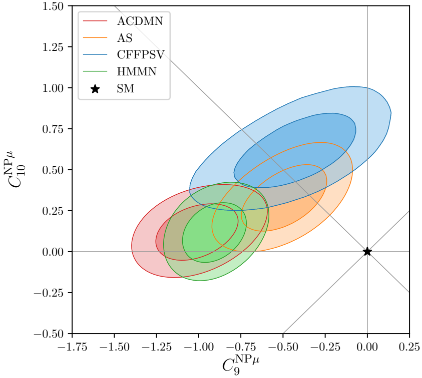
possible connection to $b \to c\ell\nu$ anomalies
see backup slides

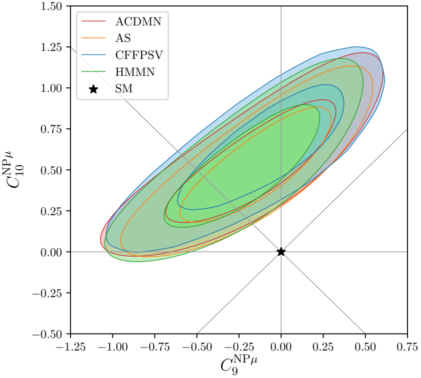
Global fit in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ plane prefers negative $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$

Robustness of global fits

Capdevila, Fedele, Neshatpour, PS



global fit



fit to LFU observables + $B_s \to \mu\mu$

ACDMN (Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet), arXiv:2104.08921
AS (Altmannshofer, PS), arXiv:2103.13370
CFFPSV (Ciuchini, Fedele, Franco, Paul, Silvestrini, Valli), arXiv:2011.01212
HMMN (Hurth, Mahmoudi, Martínez-Santos, Neshatpour), arXiv:2104.10058

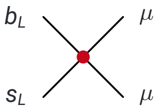
New particles to explain $b \to s\ell\ell$ anomalies

New particles to explain $b \to s\ell\ell$ anomalies

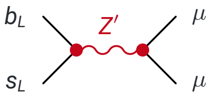
Global fits suggest

$$\boldsymbol{C_9^\mu - C_{10}^\mu \approx -0.7, \qquad 0 \gtrsim \frac{C_{10}^\mu}{C_9^\mu} \gtrsim -1}$$

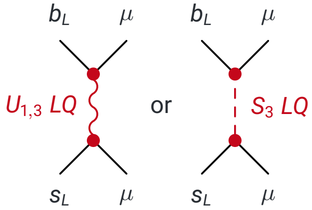
$$O_9^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)\,, \quad O_{10}^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



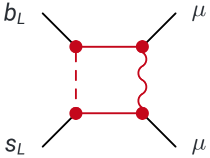
$$\sim \frac{C_9^\mu - C_{10}^\mu}{(34\,\text{TeV})^2}$$



$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2}$$

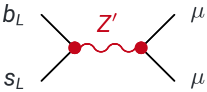


$$\sim \frac{g_{b\mu}\, g_{s\mu}}{m_{LQ}^2}$$

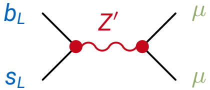


$$\sim \frac{g_b\, g_s\, g_{\mu,1}\, g_{\mu,2}}{16\,\pi^2\, m_{\text{NP}}^2}$$

Z'

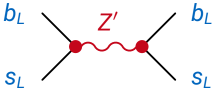


Z': Constraints from B_s-$\bar{B}_s$ mixing



$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2} \sim \frac{1}{(36\,\text{TeV})^2}$$

$\rightarrow$



$$\sim \frac{g_{bs}^2}{m_{Z'}^2} \lesssim \frac{\left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| \Big/ 10\%}{(244\,\text{TeV})^2}$$

$$\left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| \approx 10\%$$

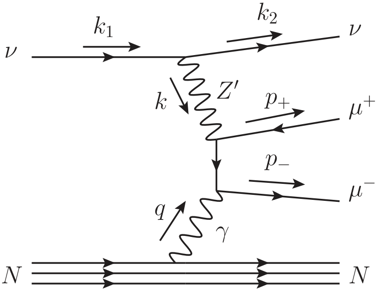
$$\Downarrow$$

$$\frac{1}{5\,\text{TeV}} \lesssim \frac{g_{\mu\mu}}{m_{Z'}}$$

Ways around:

- imaginary part of g_{bs} → constraints from *CP* violating observables
- Z' coupling to $(\bar{s}\gamma_\mu P_R b)$ → constraint from $R_K \approx R_{K^*}$
- …

Z': Constraints from neutrino trident production



Altmannshofer, Gori, Pospelov, Yavin, arXiv:1406.2332

- $\mu^+\mu^-$ production induced by neutrino in Coulomb field of heavy nucleus
- Cross section with Z' contribution

$$\frac{\sigma}{\sigma_{SM}} \simeq \frac{1+\left(1+4\,s_W^2+2\,v^2\,\frac{g_{Z'}^2}{m_{Z'}^2}\right)^2}{1+\left(1+4\,s_W^2\right)^2}$$

$$\Downarrow$$

$$\frac{g_{\mu\mu}}{m_{Z'}} \lesssim \frac{1}{0.5\,\text{TeV}}$$

Z': Constraints from B_s-$\bar{B}_s$ mixing and neutrino trident

Example: Gauged $L_\mu - L_\tau$

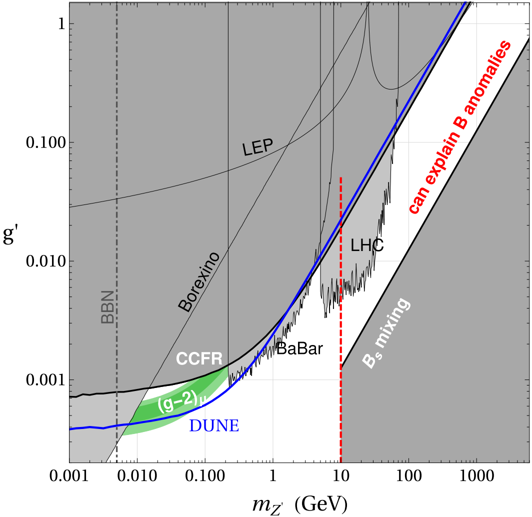
Combined constraints from

- B_s-$\bar{B}_s$ mixing

$$\frac{1}{5\,\text{TeV}} \lesssim \frac{g_{\mu\mu}}{m_{Z'}}$$

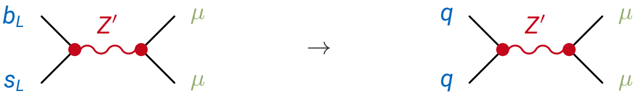
- neutrino trident production

$$\frac{g_{\mu\mu}}{m_{Z'}} \lesssim \frac{1}{0.5\,\text{TeV}}$$



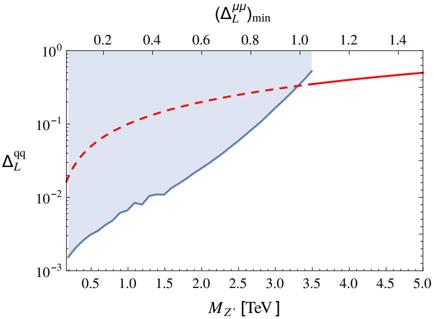
Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank, arXiv:1902.06765

Z': Constraints from $pp \to \mu\mu$

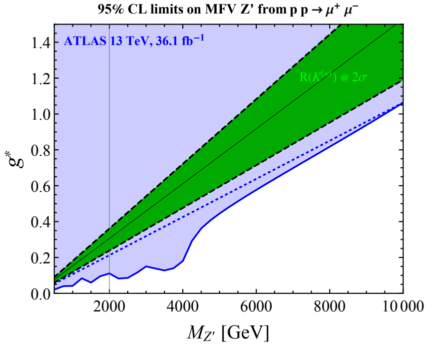


- Direct searches for a Z' resonance
- Searches for quark-lepton contact interactions

Z': Constraints from $pp \to \mu\mu$



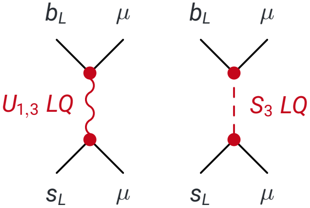
Altmannshofer, Straub, arXiv:1411.3161



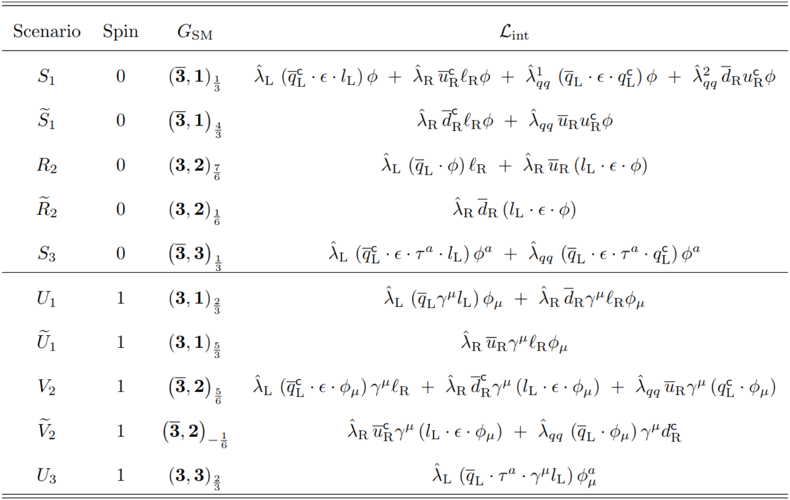
Greljo, Marzocca, arXiv:1704.09015

- Couplings to light quarks must be suppressed for $m_{Z'} < 4.5\,\text{TeV}$
- MFV-like Z'-quark couplings already excluded

Leptoquarks



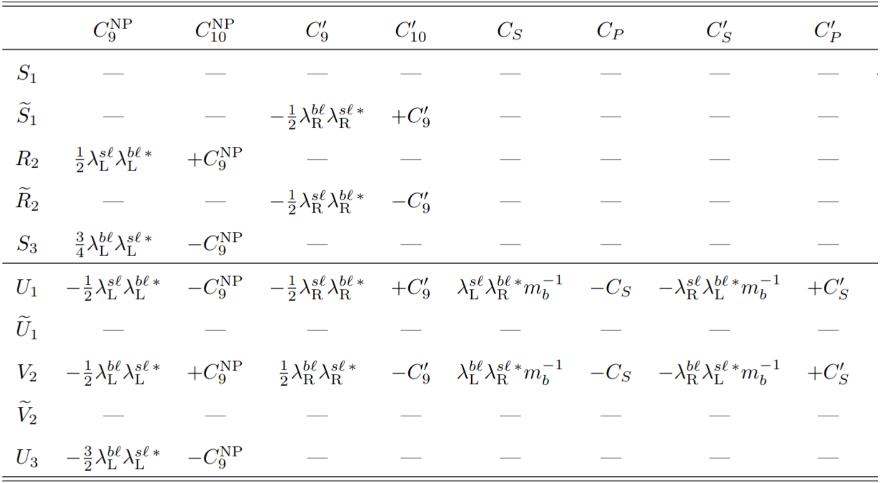
Overview of Leptoquarks



Scenario	Spin	G_{SM}	$\mathcal{L}_{\mathrm{int}}$
S_1	0	$(\overline{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$	$\hat{\lambda}_{\mathrm{L}}\,(\overline{q}_{\mathrm{L}}^{\mathsf{c}}\cdot\epsilon\cdot l_{\mathrm{L}})\,\phi \;+\; \hat{\lambda}_{\mathrm{R}}\,\overline{u}_{\mathrm{R}}^{\mathsf{c}}\ell_{\mathrm{R}}\phi \;+\; \hat{\lambda}_{qq}^{1}\,(\overline{q}_{\mathrm{L}}\cdot\epsilon\cdot q_{\mathrm{L}}^{\mathsf{c}})\,\phi \;+\; \hat{\lambda}_{qq}^{2}\,\overline{d}_{\mathrm{R}}u_{\mathrm{R}}^{\mathsf{c}}\phi$
$\widetilde{S}_1$	0	$(\overline{\mathbf{3}},\mathbf{1})_{\frac{4}{3}}$	$\hat{\lambda}_{\mathrm{R}}\,\overline{d}_{\mathrm{R}}^{\mathsf{c}}\ell_{\mathrm{R}}\phi \;+\; \hat{\lambda}_{qq}\,\overline{u}_{\mathrm{R}}u_{\mathrm{R}}^{\mathsf{c}}\phi$
R_2	0	$(\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$\hat{\lambda}_{\mathrm{L}}\,(\overline{q}_{\mathrm{L}}\cdot\phi)\,\ell_{\mathrm{R}} \;+\; \hat{\lambda}_{\mathrm{R}}\,\overline{u}_{\mathrm{R}}\,(l_{\mathrm{L}}\cdot\epsilon\cdot\phi)$
$\widetilde{R}_2$	0	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$\hat{\lambda}_{\mathrm{R}}\,\overline{d}_{\mathrm{R}}\,(l_{\mathrm{L}}\cdot\epsilon\cdot\phi)$
S_3	0	$(\overline{\mathbf{3}},\mathbf{3})_{\frac{1}{3}}$	$\hat{\lambda}_{\mathrm{L}}\,(\overline{q}_{\mathrm{L}}^{\mathsf{c}}\cdot\epsilon\cdot\tau^{a}\cdot l_{\mathrm{L}})\,\phi^{a} \;+\; \hat{\lambda}_{qq}\,(\overline{q}_{\mathrm{L}}\cdot\epsilon\cdot\tau^{a}\cdot q_{\mathrm{L}}^{\mathsf{c}})\,\phi^{a}$
U_1	1	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$\hat{\lambda}_{\mathrm{L}}\,(\overline{q}_{\mathrm{L}}\gamma^{\mu}l_{\mathrm{L}})\,\phi_{\mu} \;+\; \hat{\lambda}_{\mathrm{R}}\,\overline{d}_{\mathrm{R}}\gamma^{\mu}\ell_{\mathrm{R}}\phi_{\mu}$
$\widetilde{U}_1$	1	$(\mathbf{3},\mathbf{1})_{\frac{5}{3}}$	$\hat{\lambda}_{\mathrm{R}}\,\overline{u}_{\mathrm{R}}\gamma^{\mu}\ell_{\mathrm{R}}\phi_{\mu}$
V_2	1	$(\overline{\mathbf{3}},\mathbf{2})_{\frac{5}{6}}$	$\hat{\lambda}_{\mathrm{L}}\,(\overline{q}_{\mathrm{L}}^{\mathsf{c}}\cdot\epsilon\cdot\phi_{\mu})\,\gamma^{\mu}\ell_{\mathrm{R}} \;+\; \hat{\lambda}_{\mathrm{R}}\,\overline{d}_{\mathrm{R}}^{\mathsf{c}}\gamma^{\mu}\,(l_{\mathrm{L}}\cdot\epsilon\cdot\phi_{\mu}) \;+\; \hat{\lambda}_{qq}\,\overline{u}_{\mathrm{R}}\gamma^{\mu}\,(q_{\mathrm{L}}^{\mathsf{c}}\cdot\phi_{\mu})$
$\widetilde{V}_2$	1	$(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\hat{\lambda}_{\mathrm{R}}\,\overline{u}_{\mathrm{R}}^{\mathsf{c}}\gamma^{\mu}\,(l_{\mathrm{L}}\cdot\epsilon\cdot\phi_{\mu}) \;+\; \hat{\lambda}_{qq}\,(\overline{q}_{\mathrm{L}}\cdot\phi_{\mu})\,\gamma^{\mu}d_{\mathrm{R}}^{\mathsf{c}}$
U_3	1	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$\hat{\lambda}_{\mathrm{L}}\,(\overline{q}_{\mathrm{L}}\cdot\tau^{a}\cdot\gamma^{\mu}l_{\mathrm{L}})\,\phi_{\mu}^{a}$

Table from Christoph Niehoff, PhD thesis

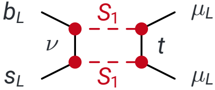
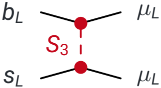
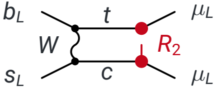
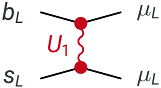
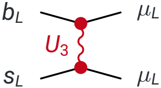
Leptoquark contributions to WET Wilson coefficients



	$C_9^{\rm NP}$	$C_{10}^{\rm NP}$	C_9'	C_{10}'	C_S	C_P	C_S'	C_P'
S_1	—	—	—	—	—	—	—	—
$\widetilde{S}_1$	—	—	$-\frac{1}{2}\lambda_{\rm R}^{b\ell}\lambda_{\rm R}^{s\ell\,*}$	$+C_9'$	—	—	—	—
R_2	$\frac{1}{2}\lambda_{\rm L}^{s\ell}\lambda_{\rm L}^{b\ell\,*}$	$+C_9^{\rm NP}$	—	—	—	—	—	—
$\widetilde{R}_2$	—	—	$-\frac{1}{2}\lambda_{\rm R}^{s\ell}\lambda_{\rm R}^{b\ell\,*}$	$-C_9'$	—	—	—	—
S_3	$\frac{3}{4}\lambda_{\rm L}^{b\ell}\lambda_{\rm L}^{s\ell\,*}$	$-C_9^{\rm NP}$	—	—	—	—	—	—
U_1	$-\frac{1}{2}\lambda_{\rm L}^{s\ell}\lambda_{\rm L}^{b\ell\,*}$	$-C_9^{\rm NP}$	$-\frac{1}{2}\lambda_{\rm R}^{s\ell}\lambda_{\rm R}^{b\ell\,*}$	$+C_9'$	$\lambda_{\rm L}^{s\ell}\lambda_{\rm R}^{b\ell\,*}m_b^{-1}$	$-C_S$	$-\lambda_{\rm R}^{s\ell}\lambda_{\rm L}^{b\ell\,*}m_b^{-1}$	$+C_S'$
$\widetilde{U}_1$	—	—	—	—	—	—	—	—
V_2	$-\frac{1}{2}\lambda_{\rm L}^{b\ell}\lambda_{\rm L}^{s\ell\,*}$	$+C_9^{\rm NP}$	$\frac{1}{2}\lambda_{\rm R}^{b\ell}\lambda_{\rm R}^{s\ell\,*}$	$-C_9'$	$\lambda_{\rm L}^{b\ell}\lambda_{\rm R}^{s\ell\,*}m_b^{-1}$	$-C_S$	$-\lambda_{\rm R}^{b\ell}\lambda_{\rm L}^{s\ell\,*}m_b^{-1}$	$+C_S'$
$\widetilde{V}_2$	—	—	—	—	—	—	—	—
U_3	$-\frac{3}{2}\lambda_{\rm L}^{b\ell}\lambda_{\rm L}^{s\ell\,*}$	$-C_9^{\rm NP}$	—	—	—	—	—	—

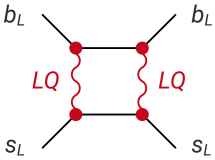
Table from Christoph Niehoff, PhD thesis

Leptoquarks: possible solutions for $b \to s\mu\mu$

Spin	G_{SM}	Name	Characteristic process	First time used for $b \to s\mu\mu$
0	$(\bar{3},1)_{1/3}$	S_1		Bauer, Neubert, arXiv:1511.01900
0	$(\bar{3},3)_{1/3}$	S_3		Hiller, Schmaltz, arXiv:1408.1627
0	$(3,2)_{7/6}$	R_2		Bečirević, Sumensari, arXiv:1704.05835
1	$(3,1)_{2/3}$	U_1		Barbieri et al., arXiv:1512.01560
1	$(3,3)_{2/3}$	U_3		Fajfer, Košnik, arXiv:1511.06024

Leptoquarks: B_s-$\bar{B}_s$ mixing loop-suppressed

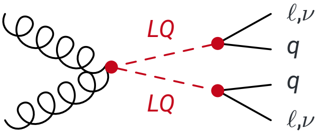
- Generic strong constraint on Z' models is loop-suppressed for leptoquark models



- Big advantage compared to Z'

Leptoquarks: direct constraints

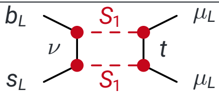
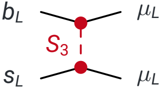
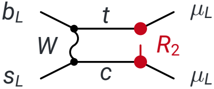
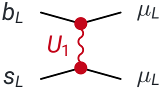
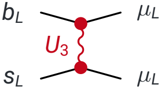
- QCD pair production
- Direct searches with $jj\ell\ell$ or $jj\nu\nu$ final states



Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\rm int}$ / Ref.
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1} [39]
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1} [40]
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV	140 fb^{-1} [42]
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV	140 fb^{-1} [44]

Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, arXiv:2103.12504

Leptoquarks: still viable solutions for $b \to s\mu\mu$

Spin	G_{SM}	Name	Characteristic process	$R_{K^{(*)}}$	
0	$(\bar{3},1)_{1/3}$	S_1		✗	requires too large couplings
0	$(\bar{3},3)_{1/3}$	S_3		✓	
0	$(3,2)_{7/6}$	R_2		✗	tension with LHC limits
1	$(3,1)_{2/3}$	U_1		✓	
1	$(3,3)_{2/3}$	U_3		✓	

cf. Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, arXiv:2103.12504

Model building challenges

Model building challenges

Single-particle tree-level explanation possible with neutral $\boldsymbol{Z'}$ vector boson, scalar $\boldsymbol{S_3}$ or vector $\boldsymbol{U_1}$ (or U_3) leptoquark.

But we need to **build UV-complete models**!

- Vector boson $\boldsymbol{Z'}$ or $\boldsymbol{U_1}$ **LQ**:
    - UV completion for massive vector boson: **gauge boson** or **composite state**
    - Quark-flavor violating coupling might require quarks mixing with **vector-like quarks**
    - **Find proper symmetry group** that **contains** $\boldsymbol{Z'}$ or $\boldsymbol{U_1}$ (gauged and gauge-anomaly free for gauge boson or global group for composite state)
      E.g. $\boldsymbol{G \supset U(1)'}$ **for** $\boldsymbol{Z'}$ or $\boldsymbol{G \supset SU(4)}$ **for** $\boldsymbol{U_1}$
- Scalar $\boldsymbol{S_3}$ **LQ**:
    - S_3 generically **couples** to **all lepton flavors** and to **diquarks**
    - Without protection mechanism: **excessive contributions** to **LFV** and **proton decay**!
    - Charge S_3 under **new** $\boldsymbol{U(1)}$ **symmetry** to forbid diquark couplings and allow only second-generation lepton couplings

      Hambye, Heeck, arXiv:1712.04871
      Davighi, Kirk, Nardecchia, arXiv:2007.15016

      $\Rightarrow$ Leptoquark coupling only to muons: "**muoquark**" Greljo, PS, Thomsen, arXiv:2103.13991

More model building challenges in interactive session by Javier Fuentes-Martin

Conclusions

Conclusions

- Discrepancies in numerous $b \to s\ell\ell$ observables can be **consistently explained by NP**

- Global fits show preference for NP contributions to $\boldsymbol{C_9^\mu}$ and/or $\boldsymbol{C_{10}^\mu}$

- Main source of theory uncertainties due to **non-local hadronic contributions**

- SM predictions of **LFU observables** very well under control

  $\Rightarrow$ experimental observation of discrepancy in these observables would be **clear sign of NP**

- Interpretation in terms of a single **new particle** possible:
  neutral $\boldsymbol{Z'}$ vector bosons, scalar $\boldsymbol{S_3}$ or vector $\boldsymbol{U_1}$ (or U_3) leptoquark

- **NP models** imply **effects in many other observables** in indirect (B_s-$\bar{B}_s$ mixing, LFV, etc.) and direct (e.g. $pp \to \ell\ell$, $pp \to jj\ell\ell$) searches.

Backup slides

p-value of the SM fit

p-value of the SM fit

p-value of goodness-of-fit from Wilks' theorem

$$p_{SM} = 1 - F(\chi^2_{SM}; n_{obs})$$

with $F(\chi^2; n_{obs})$ the χ^2 CDF and n_{obs} the number of independent observables (measurements of an observable by different experiments counted separately).

- ACDMN (Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet), arXiv:2104.08921

$$\begin{aligned} \textit{Global fit}: \ n_{\mathrm{obs}} &= 246 \quad \Rightarrow \quad p = 1.1\% \\ \textit{LFU fit}^*: \ n_{\mathrm{obs}} &= 22 \quad \Rightarrow \quad p = 1.4\% \end{aligned}$$

- AS (Altmannshofer, PS), arXiv:2103.13370

$$\begin{aligned} \textit{Global fit}: \ n_{\mathrm{obs}} &= 191 \quad \Rightarrow \quad p = 1.2\% \\ \textit{LFU fit}^*: \ n_{\mathrm{obs}} &= 21 \quad \Rightarrow \quad p = 0.5\% \end{aligned}$$

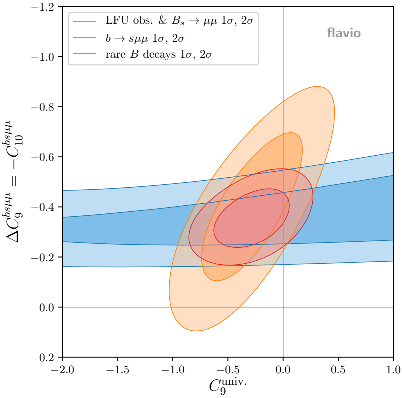
- HMMN (Hurth, Mahmoudi, Martínez-Santos, Neshatpour), arXiv:2104.10058

$$\begin{aligned} \textit{Global fit}: \ n_{\mathrm{obs}} &= 173 \quad \Rightarrow \quad p = 0.4\% \\ \textit{LFU fit}^*: \ n_{\mathrm{obs}} &= 7 \quad \Rightarrow \quad p = 0.02\% \end{aligned}$$

* LFU fit: all the measured LFU observables + $\mathcal{B}(B_s \to \mu^+\mu^-)$ (all groups)
+ effective $B_s \to \mu\mu$ lifetime + radiative decays + $\mathcal{B}(B_s \to X_s\mu^+\mu^-)$ (depending on the group)

Scenario with universal C_9

Scenarios with two Wilson coefficients



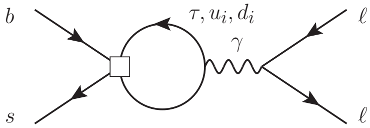
WET at 4.8 GeV

- Perform two-parameter fit in space of $\boldsymbol{C_9^{\text{univ.}}}$ and $\boldsymbol{\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$:

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

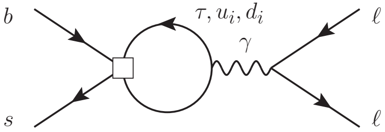
scenario first considered in
Algueró et al., arXiv:1809.08447

- Slight preference for **non-zero $\boldsymbol{C_9^{\text{univ.}}}$**
  - could be mimicked by hadronic effects
  - can arise from RG effects:



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

RG effect in SMEFT

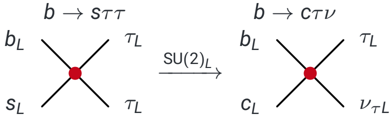


RG effects require scale separation

- Consider **SMEFT**

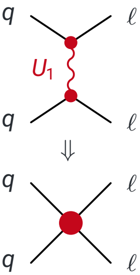
Possible operators:

- $[\boldsymbol{O_{lq}^{(3)}}]_{3323} = (\bar{\boldsymbol{l}}_3 \gamma_\mu \boldsymbol{\tau}^a \boldsymbol{l}_3)(\bar{\boldsymbol{q}}_2 \gamma^\mu \boldsymbol{\tau}^a \boldsymbol{q}_3)$:
  Might also **explain $\boldsymbol{R_{D^{(*)}}}$ anomalies!**



- $[\boldsymbol{O_{lq}^{(1)}}]_{3323} = (\bar{\boldsymbol{l}}_3 \gamma_\mu \boldsymbol{l}_3)(\bar{\boldsymbol{q}}_2 \gamma^\mu \boldsymbol{q}_3)$:
  Strong constraints from $B \to K\nu\nu$ require $[\boldsymbol{C_{lq}^{(1)}}]_{3323} \approx [\boldsymbol{C_{lq}^{(3)}}]_{3323}$

Buras et al., arXiv:1409.4557



- ***U*$_1$ vector leptoquark** $(\mathbf{3}, \mathbf{1})_{2/3}$ couples LH fermions

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

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

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

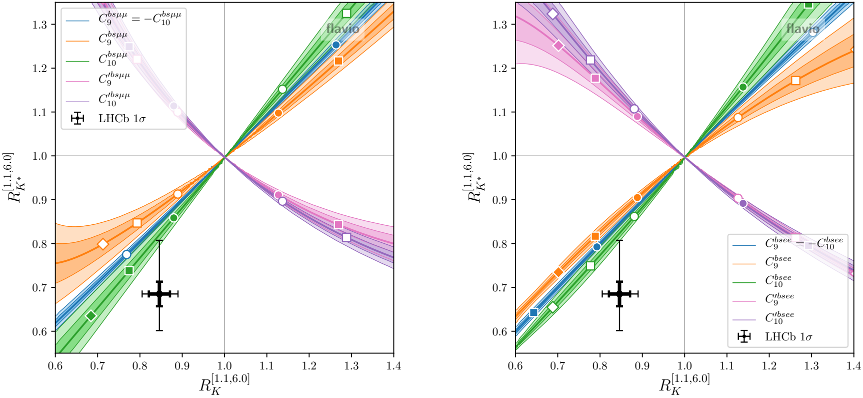
Theory uncertainties in presence of NP

Scenarios with a single Wilson coefficients

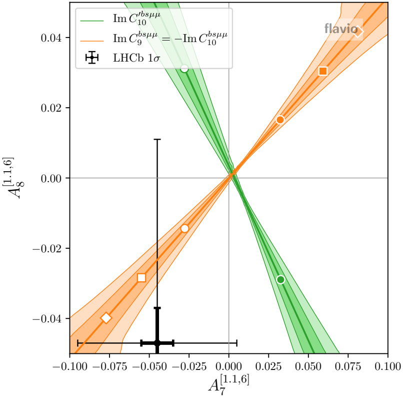
		$b \to s\mu\mu$		LFU, $B_s \to \mu\mu$		all rare B decays	
	Wilson coefficient	best fit	pull	best fit	pull	best fit	pull
NP err.	$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	**3.3σ**	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	**5.1σ**
	$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	**4.7σ**	$+0.54^{+0.12}_{-0.12}$	4.8σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.55^{+0.13}_{-0.13}$	**3.8σ**	$-0.35^{+0.08}_{-0.08}$	**4.6σ**	$-0.39^{+0.07}_{-0.07}$	**5.6σ**
SM err.	$C_9^{bs\mu\mu}$	$-0.83^{+0.22}_{-0.20}$	**3.6σ**	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.77^{+0.15}_{-0.15}$	**5.3σ**
	$C_{10}^{bs\mu\mu}$	$+0.45^{+0.21}_{-0.20}$	2.3σ	$+0.60^{+0.14}_{-0.14}$	**4.7σ**	$+0.54^{+0.12}_{-0.12}$	4.9σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.17}_{-0.18}$	**3.8σ**	$-0.35^{+0.08}_{-0.08}$	**4.6σ**	$-0.39^{+0.07}_{-0.07}$	**5.6σ**

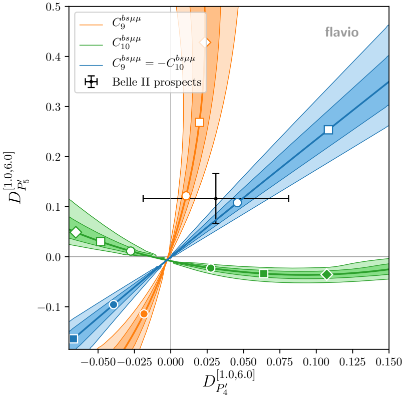
Visible effect of theory errors depending on new physics, in particular for $C_9^{bs\mu\mu}$

Theory uncertainties in presence of NP



Theory uncertainties in presence of NP





Parameterisation of beyond-QCDF contributions

Parameterisation of beyond-QCDF contributions for $B \to K$

$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + a_K + b_K(q^2/\,\text{GeV}^2) \quad \text{at low } q^2\,,$$

$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + c_K \quad \text{at high } q^2\,,$$

$$\begin{aligned} \text{Re}(a_K) &= 0.0 \pm 0.08\,, & \text{Re}(b_K) &= 0.0 \pm 0.03\,, & \text{Re}(c_K) &= 0.0 \pm 0.2\,, \\ \text{Im}(a_K) &= 0.0 \pm 0.08\,, & \text{Im}(b_K) &= 0.0 \pm 0.03\,, & \text{Im}(c_K) &= 0.0 \pm 0.2\,. \end{aligned}$$

1σ uncertainties enclose the effects considered in Khodjamirian et al. arXiv:1006.4945, Beylich et al. arXiv:1101.5118, Khodjamirian et al. arXiv:1211.0234

Parameterisation of beyond-QCDF contributions for $B \to K^*$ and $B_s \to \phi$

$$\begin{aligned} C_7^{\text{eff}}(q^2) &\to C_7^{\text{eff}}(q^2) + a_{0,-} + b_{0,-}(q^2/\,\text{GeV}^2) \\ C_7' &\to C_7' + a_+ + b_+(q^2/\,\text{GeV}^2) \end{aligned} \qquad \text{at low } q^2\,,$$

$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + c_\lambda \qquad \text{at high } q^2\,,$$

$$\begin{aligned}
\text{Re}(a_+) &= 0.0 \pm 0.004\,, & \text{Re}(b_+) &= 0.0 \pm 0.005\,, & \text{Re}(c_+) &= 0.0 \pm 0.3\,, \\
\text{Im}(a_+) &= 0.0 \pm 0.004\,, & \text{Im}(b_+) &= 0.0 \pm 0.005\,, & \text{Im}(c_+) &= 0.0 \pm 0.3\,, \\
\text{Re}(a_-) &= 0.0 \pm 0.015\,, & \text{Re}(b_-) &= 0.0 \pm 0.01\,, & \text{Re}(c_-) &= 0.0 \pm 0.3\,, \\
\text{Im}(a_-) &= 0.0 \pm 0.015\,, & \text{Im}(b_-) &= 0.0 \pm 0.01\,, & \text{Im}(c_-) &= 0.0 \pm 0.3\,, \\
\text{Re}(a_0) &= 0.0 \pm 0.12\,, & \text{Re}(b_0) &= 0.0 \pm 0.05\,, & \text{Re}(c_0) &= 0.0 \pm 0.3\,, \\
\text{Im}(a_0) &= 0.0 \pm 0.12\,, & \text{Im}(b_0) &= 0.0 \pm 0.05\,, & \text{Im}(c_0) &= 0.0 \pm 0.3\,.
\end{aligned}$$

1σ uncertainties enclose the effects considered in Khodjamirian et al. arXiv:1006.4945, Beylich et al. arXiv:1101.5118