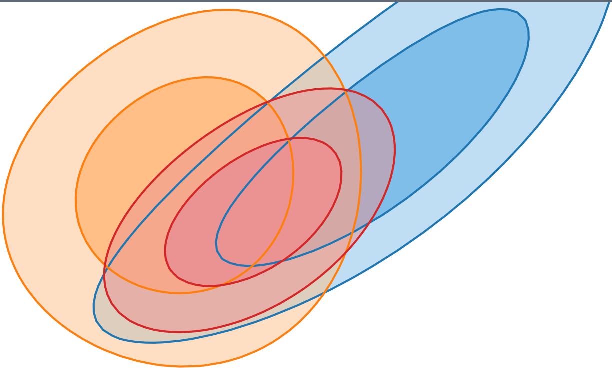
IPA2022: Interplay between Particle and Astroparticle physics 2022, Vienna, 6 September 2022

Flavour anomalies and possible interpretations

Peter Stangl AEC & ITP University of Bern

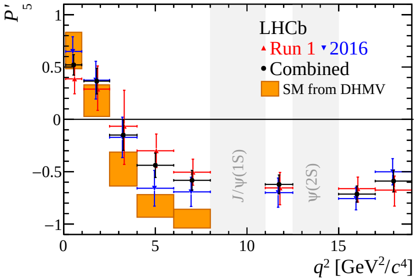


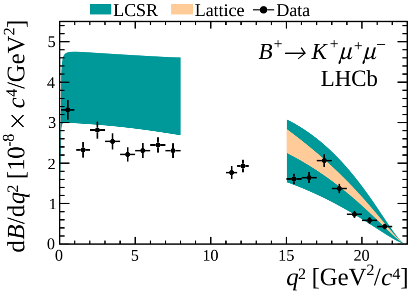
The $b \to s\ell\ell$ anomalies

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





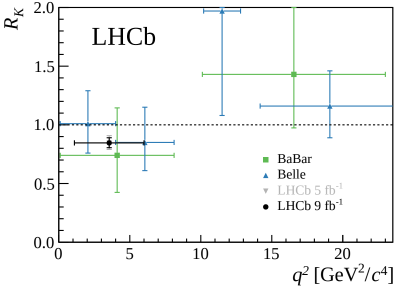
*: based on hadronic assumptions on which there is no theory consensus yet

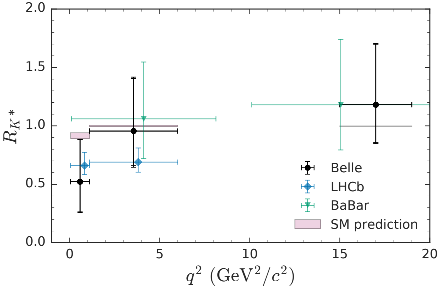
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

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

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





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

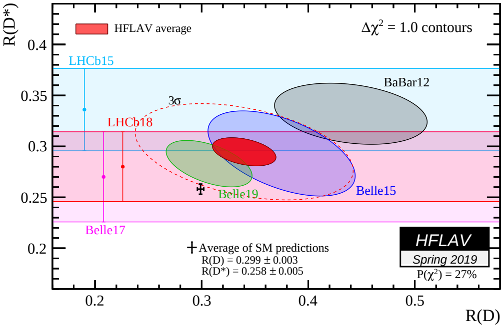
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

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

$b \to s\ell\ell$ Theory 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**: ($\mathcal{N} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \approx (34\ \text{TeV})^{-2}$)

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

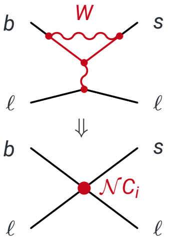
$$O_9^{(\prime)bs\ell\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad C_9^{\text{SM}} \approx -4.1$$

$$O_{10}^{(\prime)bs\ell\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad C_{10}^{\text{SM}} \approx +4.2$$

$$O_7^{(\prime)bs} = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b)\, F^{\mu\nu}\,, \qquad C_7^{\text{SM}} \approx -0.3$$

$$O_S^{(\prime)bs\ell\ell} = m_b (\bar{s} P_{R(L)} b)(\bar{\ell}\ell)\,,$$

$$O_P^{(\prime)bs\ell\ell} = m_b (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)\,.$$



- **Hadronic operators**:

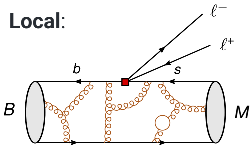
$$\mathcal{H}_{\text{eff, had}}^{bs\ell\ell} = -\mathcal{N}\frac{16\pi^2}{e^2}\left(C_8^{bs} O_8^{bs} + C_8^{\prime bs} O_8^{\prime bs} + \sum_{i=1..6} C_i^{bs\ell\ell} O_i^{bs} \right) + \text{h.c.}$$

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

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

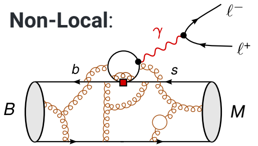
$$\mathcal{M}(B \to M\ell\ell) = \langle M\ell\ell | \mathcal{H}_{\text{eff}}^{bs\ell\ell} | B \rangle$$
$$= \mathcal{N}\Big[(\mathcal{A}_V^\mu + \mathcal{H}^\mu)\, \bar{u}_\ell \gamma_\mu v_\ell + \mathcal{A}_A^\mu\, \bar{u}_\ell \gamma_\mu \gamma_5 v_\ell + \mathcal{A}_S\, \bar{u}_\ell v_\ell + \mathcal{A}_P\,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

Local:



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

Non-Local:

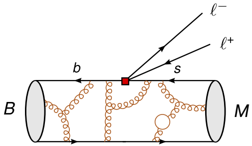


$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2} \sum_{i=1..6,8} C_i \int dx^4 e^{iq\cdot x} \langle M | T\{ j^\mu_{\text{em}}(x), O_i(0)\} | B \rangle$$

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

- **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**:
  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

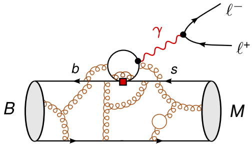
  - low q^2: **Light-cone sum rules** (LCSR)

    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; Gubernari, Reboud, van Dyk, Virto, arXiv:2206.03797

"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: $\mathcal{H}_{\text{eff}}^{bs\ell\ell} = \mathcal{H}_{\text{eff, SM}}^{bs\ell\ell} + \mathcal{H}_{\text{eff, NP}}^{bs\ell\ell}$

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

- 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

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 $\sim$ 200 observables $\Rightarrow$ **global** $b \to s\ell\ell$ analysis

Setup

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

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

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

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

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

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

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- $\Delta\chi^2$ and pull

Altmannshofer, PS, arXiv:2103.13370

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

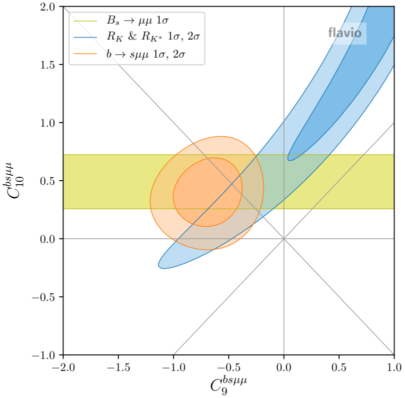
Results

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

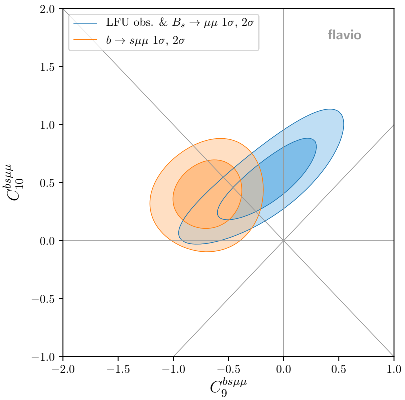
Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	$\mathbf{3.3\sigma}$	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	$\mathbf{5.1\sigma}$
$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	$\mathbf{4.7\sigma}$	$+0.54^{+0.12}_{-0.12}$	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
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.55^{+0.13}_{-0.13}$	$\mathbf{3.8\sigma}$	$-0.35^{+0.08}_{-0.08}$	$\mathbf{4.6\sigma}$	$-0.39^{+0.07}_{-0.07}$	$\mathbf{5.6\sigma}$
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



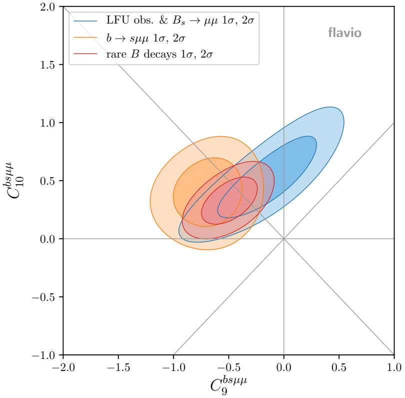
WET at 4.8 GeV

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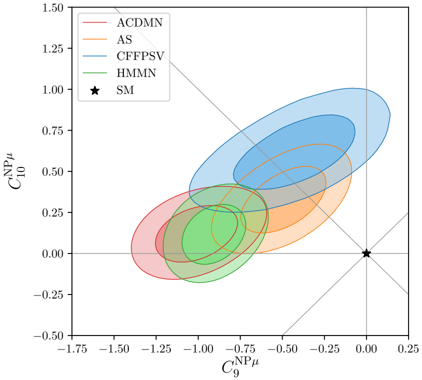
possible connection to $b \to c\ell\nu$ anomalies
see backup slides

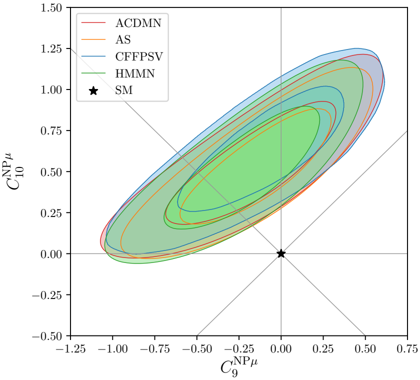
Global fit in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ plane prefers negative $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$

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

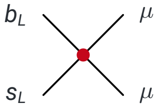
New particles to explain $b \to s\ell\ell$ anomalies

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

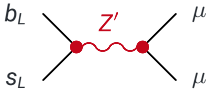
Global fits suggest

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

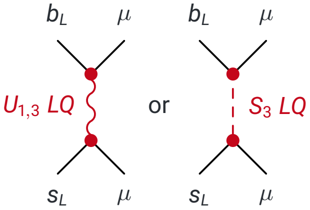
$$O_9^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)\,, \quad O_{10}^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



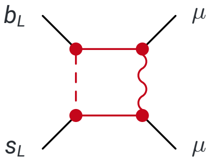
$$\sim \frac{C_9^\mu - C_{10}^\mu}{(34\,\text{TeV})^2}$$



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



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



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

Conclusions

Conclusions

- Discrepancies in numerous $b \to s\ell\ell$ observables can be **consistently explained by NP**
- Fits show preference for NP contributions to $\boldsymbol{C_9^\mu}$ and/or $\boldsymbol{C_{10}^\mu}$
- Different fits with different setups, inputs and statistical frameworks show **remarkable agreement**
- Main source of theory uncertainty in global fit 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

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

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

- AS (Altmannshofer, PS), arXiv:2103.13370

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

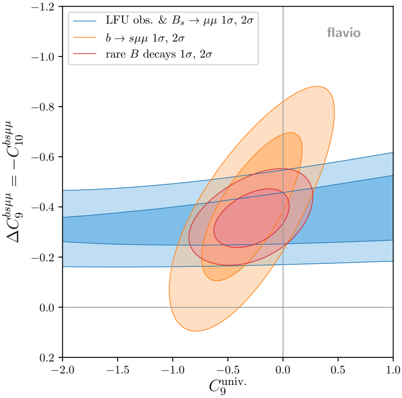
- HMMN (Hurth, Mahmoudi, Martínez-Santos, Neshatpour), arXiv:2104.10058

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

* 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



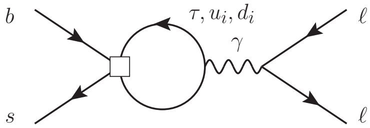
WET at 4.8 GeV

- 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:

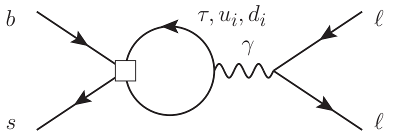


Bobeth, Haisch, arXiv:1109.1826
Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068

RG effect in SMEFT

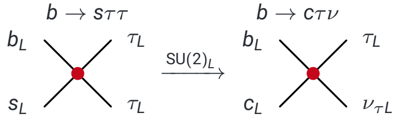
RG effects require scale separation

- Consider **SMEFT**



Possible operators:

- $[O_{lq}^{(3)}]_{3323} = (\bar{l}_3\gamma_\mu\tau^a l_3)(\bar{q}_2\gamma^\mu\tau^a q_3)$:
  Might 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 $[C_{lq}^{(1)}]_{3323} \approx [C_{lq}^{(3)}]_{3323}$

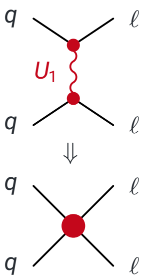
Buras et al., arXiv:1409.4557

- ***U_1* vector leptoquark** $(\mathbf{3},\mathbf{1})_{2/3}$ couples LH fermions

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

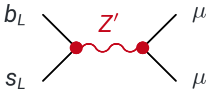
- Generates **semi-leptonic operators at tree-level**

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

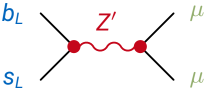


More on new particles to explain $b \to s\ell\ell$ anomalies

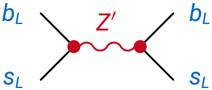
Z'



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



$\rightarrow$



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

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

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

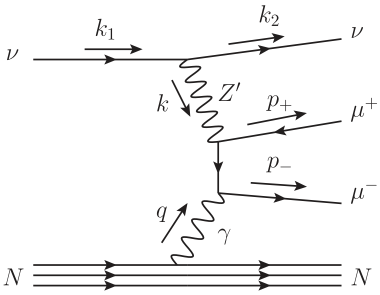
$$\Downarrow$$

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

Ways around:

- imaginary part of g_{bs} $\rightarrow$ constraints from *CP* violating observables
- Z' coupling to $(\bar{s}\gamma_\mu P_R b)$ $\rightarrow$ 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 $L_\mu - L_\tau$

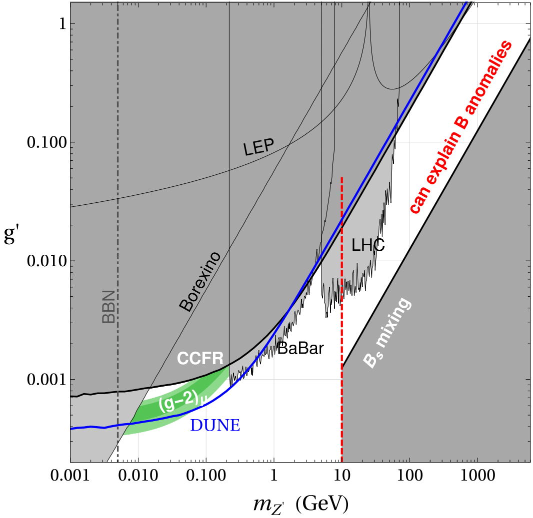
Combined constraints from

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

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

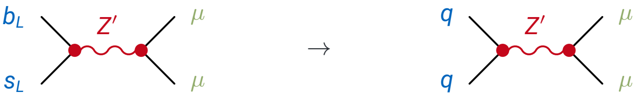
- neutrino trident production

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



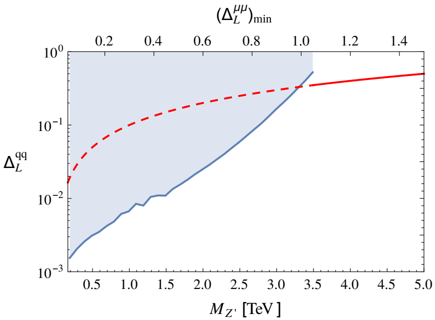
Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank, arXiv:1902.06765

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

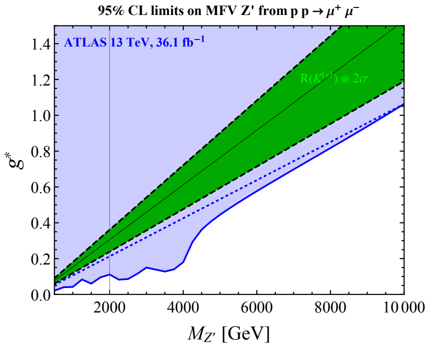


- Direct searches for a Z' resonance
- Searches for quark-lepton contact interactions

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



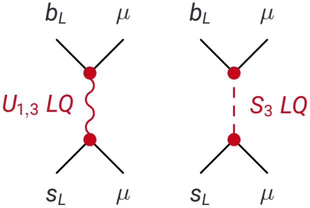
Altmannshofer, Straub, arXiv:1411.3161



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}	$\mathcal{L}_{\text{int}}$
S_1	0	$(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$	$\hat\lambda_{\text{L}}\,(\bar q_{\text{L}}^{\text{c}}\cdot\epsilon\cdot l_{\text{L}})\,\phi \;+\; \hat\lambda_{\text{R}}\,\bar u_{\text{R}}^{\text{c}}\ell_{\text{R}}\phi \;+\; \hat\lambda_{qq}^{1}\,(\bar q_{\text{L}}\cdot\epsilon\cdot q_{\text{L}}^{\text{c}})\,\phi \;+\; \hat\lambda_{qq}^{2}\,\bar d_{\text{R}} u_{\text{R}}^{\text{c}}\phi$
$\widetilde S_1$	0	$(\bar{\mathbf{3}},\mathbf{1})_{\frac{4}{3}}$	$\hat\lambda_{\text{R}}\,\bar d_{\text{R}}^{\text{c}}\ell_{\text{R}}\phi \;+\; \hat\lambda_{qq}\,\bar u_{\text{R}} u_{\text{R}}^{\text{c}}\phi$
R_2	0	$(\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$\hat\lambda_{\text{L}}\,(\bar q_{\text{L}}\cdot\phi)\,\ell_{\text{R}} \;+\; \hat\lambda_{\text{R}}\,\bar u_{\text{R}}\,(l_{\text{L}}\cdot\epsilon\cdot\phi)$
$\widetilde R_2$	0	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$\hat\lambda_{\text{R}}\,\bar d_{\text{R}}\,(l_{\text{L}}\cdot\epsilon\cdot\phi)$
S_3	0	$(\bar{\mathbf{3}},\mathbf{3})_{\frac{1}{3}}$	$\hat\lambda_{\text{L}}\,(\bar q_{\text{L}}^{\text{c}}\cdot\epsilon\cdot\tau^a\cdot l_{\text{L}})\,\phi^a \;+\; \hat\lambda_{qq}\,(\bar q_{\text{L}}\cdot\epsilon\cdot\tau^a\cdot q_{\text{L}}^{\text{c}})\,\phi^a$
U_1	1	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$\hat\lambda_{\text{L}}\,(\bar q_{\text{L}}\gamma^\mu l_{\text{L}})\,\phi_\mu \;+\; \hat\lambda_{\text{R}}\,\bar d_{\text{R}}\gamma^\mu\ell_{\text{R}}\phi_\mu$
$\widetilde U_1$	1	$(\mathbf{3},\mathbf{1})_{\frac{5}{3}}$	$\hat\lambda_{\text{R}}\,\bar u_{\text{R}}\gamma^\mu\ell_{\text{R}}\phi_\mu$
V_2	1	$(\bar{\mathbf{3}},\mathbf{2})_{\frac{5}{6}}$	$\hat\lambda_{\text{L}}\,(\bar q_{\text{L}}^{\text{c}}\cdot\epsilon\cdot\phi_\mu)\,\gamma^\mu\ell_{\text{R}} \;+\; \hat\lambda_{\text{R}}\,\bar d_{\text{R}}^{\text{c}}\gamma^\mu\,(l_{\text{L}}\cdot\epsilon\cdot\phi_\mu) \;+\; \hat\lambda_{qq}\,\bar u_{\text{R}}\gamma^\mu\,(q_{\text{L}}^{\text{c}}\cdot\phi_\mu)$
$\widetilde V_2$	1	$(\bar{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}$	$\hat\lambda_{\text{R}}\,\bar u_{\text{R}}^{\text{c}}\gamma^\mu\,(l_{\text{L}}\cdot\epsilon\cdot\phi_\mu) \;+\; \hat\lambda_{qq}\,(\bar q_{\text{L}}\cdot\phi_\mu)\,\gamma^\mu d_{\text{R}}^{\text{c}}$
U_3	1	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$\hat\lambda_{\text{L}}\,(\bar q_{\text{L}}\cdot\tau^a\cdot\gamma^\mu l_{\text{L}})\,\phi_\mu^a$

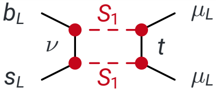
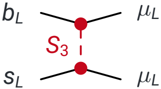
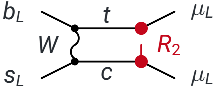
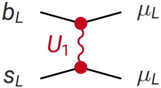
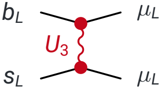
Table by Christoph Niehoff

Leptoquark contributions to WET Wilson coefficients

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

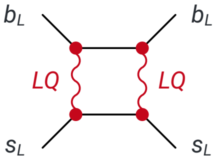
Table by Christoph Niehoff

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

Spin	G_{SM}	Name	Characteristic process	
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

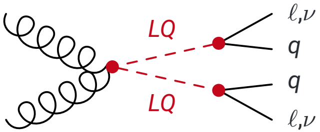
- Generic strong constraint on Z' models is loop-suppressed for leptoquark models



- Big advantage compared to Z'

Leptoquarks: direct constraints

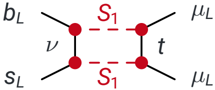
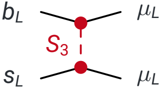
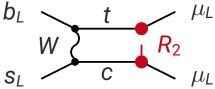
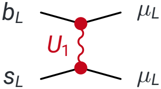
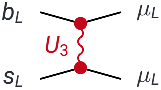
- QCD pair production
- Direct searches with $jj\ell\ell$ or $jj\nu\nu$ final states



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		X	requires too large couplings
0	$(\bar{3},3)_{1/3}$	S_3		✓	
0	$(3,2)_{7/6}$	R_2		X	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

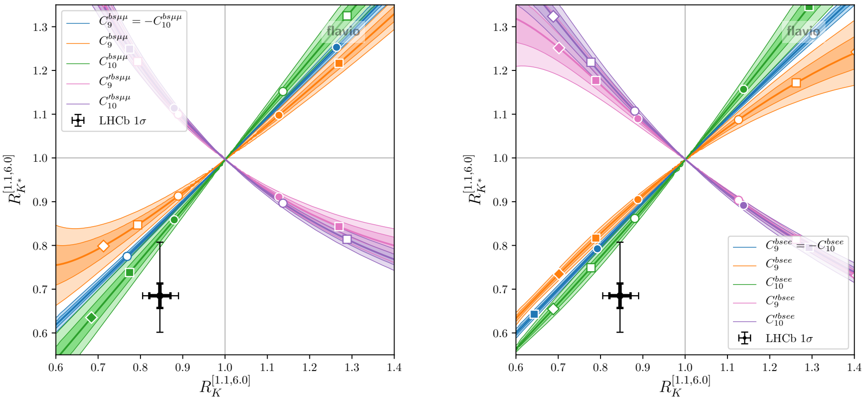
Theory uncertainties in presence of NP

Scenarios with a single Wilson coefficients

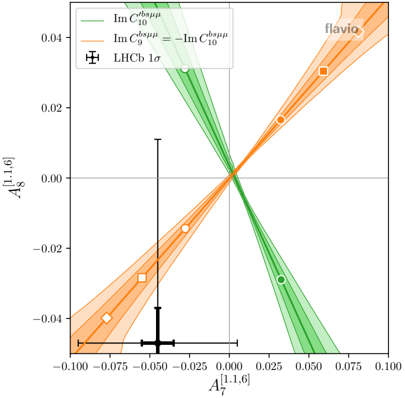
	Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
NP err.	$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	$\mathbf{3.3\sigma}$	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	$\mathbf{5.1\sigma}$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

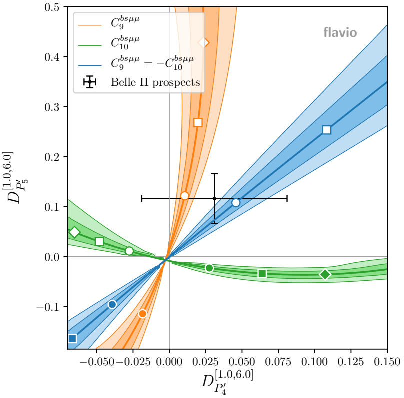
Visible effect of theory errors depending on new physics, in particular for $C_9^{bs\mu\mu}$

Theory uncertainties in presence of NP



Theory uncertainties in presence of NP





Parameterisation of beyond-QCDF contributions

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

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

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

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

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 $B_s \to \phi$

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

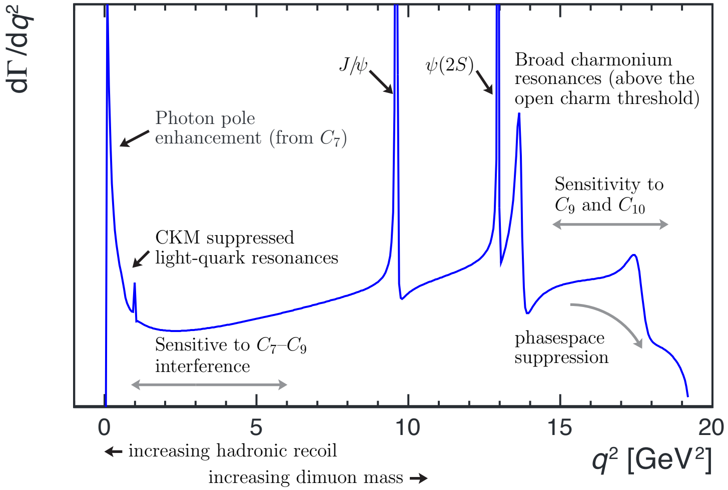
$$C_9^{\text{eff}}(q^2) \to C_9^{\text{eff}}(q^2) + c_\lambda \qquad \text{at high } q^2\,,$$

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

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

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

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



Blake, Lanfranchi, Straub, arXiv:1606.00916

$b \to c\ell\nu$ Theory Framework

$b \to c\ell\nu$ in the weak effective theory

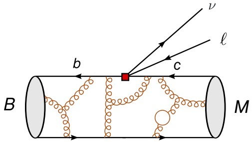
- Effective Hamiltonian at scale m_b: $\left(\mathcal{N}^{bc\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \approx (850\text{ GeV})^{-2}\right)$

$$\mathcal{H}_{\text{eff}}^{bc\ell\nu} = -\mathcal{N}^{bc\ell\nu} \sum_{\ell} \sum_{i=V_L,V_R,S_L,S_R,T} C_i^{bc\ell\nu} O_i^{bc\ell\nu} + \text{h.c.}$$

$$\begin{aligned}
O_{V_L}^{bc\ell\nu} &= (\bar{c}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu P_L \nu_\ell)\,, \qquad C_{V_L}^{\text{SM}} = 1 \\
O_{V_R}^{bc\ell\nu} &= (\bar{c}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu P_L \nu_\ell)\,, \\
O_{S_L}^{bc\ell\nu} &= (\bar{c}P_L b)(\bar{\ell}P_L \nu_\ell)\,, \\
O_{S_R}^{bc\ell\nu} &= (\bar{c}P_R b)(\bar{\ell}P_L \nu_\ell)\,, \\
O_{T}^{bc\ell\nu} &= (\bar{c}\sigma_{\mu\nu} P_L b)(\bar{\ell}\sigma^{\mu\nu} P_L \nu_\ell)\,.
\end{aligned}$$

Theory of $B \to M\ell\nu$ decays ($M = D, D^*$)

$$\mathcal{M}(B \to M\ell\nu) = \langle M\ell\nu|\mathcal{H}_{\text{eff}}^{bc\ell\nu}|B\rangle$$
$$= \mathcal{N}^{bc\ell\nu}\left[\mathcal{A}_V^\mu\,\bar{u}_\ell\gamma_\mu P_L v_\nu + \mathcal{A}_S\,\bar{u}_\ell P_L v_\nu + \mathcal{A}_T^{\mu\nu}\,\bar{u}_\ell\sigma_{\mu\nu}P_L v_\ell\right]$$



$$\mathcal{A}_V^\mu = C_{V_L}\langle M|\bar{c}\,\gamma^\mu\,P_L\,b|B\rangle + C_{V_R}\langle M|\bar{c}\,\gamma^\mu\,P_R\,b|B\rangle$$
$$\mathcal{A}_S = C_{S_L}\langle M|\bar{c}\,P_L\,b|B\rangle + C_{S_R}\langle M|\bar{c}\,P_R\,b|B\rangle$$
$$\mathcal{A}_T^{\mu\nu} = C_T\langle M|\bar{c}\,\sigma^{\mu\nu}P_L\,b|B\rangle$$

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

Hadronic matrix elements

$\langle M|\bar{c}\,\Gamma_i\,b|B\rangle$ matrix elements can be parameterized by:

- **3 form factors** for **spin zero** final state, $M = \boldsymbol{D}$
- **7 form factors** for **spin one** final state, $M = \boldsymbol{D^*}$

Form factor parameterisations:

- **BGL**, **BCL**: model-independent, based on unitarity and analyticity
  Boyd, Grinstein, Lebed, arXiv:hep-ph/9504235, arXiv:hep-ph/9705252
  Bourrely, Caprini, Lellouch, arXiv:0807.2722
- Different **form factors related** by Heavy Quark Symmetry (HQS), **Heavy Quark Effective Theory (HQET)** provides α_s and $1/m_{b,c}$ corrections
  - **CLN**: $\mathcal{O}(\alpha_s, 1/m_{b,c})$ Caprini, Lellouch, Neubert, arXiv:hep-ph/9712417
    (+) small set of parameters
    (−) Numerical coefficients introduced in 1997 when theory error estimates not needed due to large experimental uncertainties - not acceptable anymore with current experimental precision
  - Recent **HQET parameterisations**

    Proper error treatment — Bernlochner, Ligeti, Papucci, Robinson, arXiv:1703.05330

    Higher-order corrections $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$ — Bordone, Jung, van Dyk, arXiv:1908.09398; Jung, Straub, arXiv:1801.01112

Determination of form factors

- Choose form factor parameterisations
- Fit form factor parameters to input data from
  - **Experiments** (assume absence of new physics)
    Belle, arXiv:1510.03657, arXiv:1702.01521, arXiv:1809.03290
    LHCb, arXiv:2001.03225, arXiv:2003.08453
  - **Lattice QCD**
    FNAL/MILC 2105.14019, arXiv:1503.07237
    HPQCD arXiv:1505.03925
  - **Light-cone sum rules** (LCSR)
    Bharucha, Straub, Zwicky, arXiv:1503.05534
    Gubernari, Kokulu, van Dyk, arXiv:1811.00983
  - **Combined fits**
    Bernlochner, Ligeti, Papucci, Robinson, arXiv:1703.05330
    Jung, Straub, arXiv:1801.01112
    Bordone, Jung, van Dyk, arXiv:1908.09398
    Martinelli, Simula, Vittorio, arXiv:2105.08674

Theory uncertainties of $R_{D^{(*)}}$

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)} \qquad \ell \in \{e, \mu\}$$

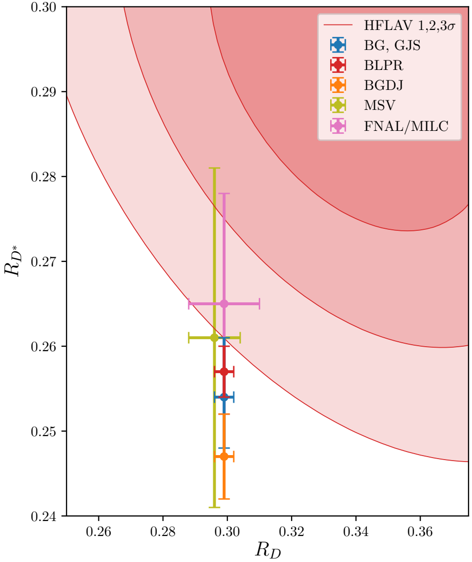
- Cancellation of parametric uncertainties (in particular from V_{cb}) in ratio
- In SM, $BR(B \to D^{(*)}e\nu) \approx BR(B \to D^{(*)}\mu\nu)$, but because of **large τ mass**

$$BR(B \to D^{(*)}\tau\nu) \not\approx BR(B \to D^{(*)}\ell\nu) \qquad \ell \in \{e, \mu\}$$

$\Rightarrow$ form factor uncertainties do not cancel
$\Rightarrow$ precise form factor determination important for $R_{D^{(*)}}$ theory predictions

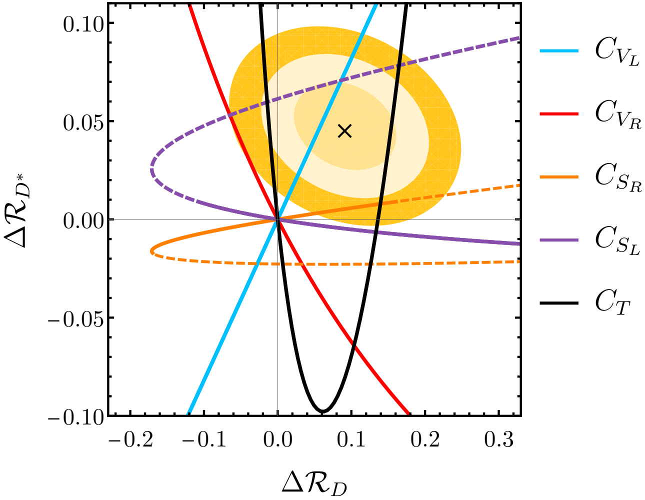
Theory predictions of $R_{D^{(*)}}$

	R_D	R_{D^*}
BG, GJS	0.299 ± 0.003	$0.254^{+0.007}_{-0.006}$
BLPR	0.299 ± 0.003	0.257 ± 0.003
BGDJ	0.299 ± 0.003	0.247 ± 0.005
MSV	0.296 ± 0.008	0.261 ± 0.020
FNAL/MILC	0.299 ± 0.011	0.265 ± 0.013



Bigi, Gambino (BG), arXiv:1606.08030
Gambino, Jung, Schacht (GJS), arXiv:1905.08209
Bernlochner, Ligeti, Papucci, Robinson (BLPR), arXiv:1703.05330
Bordone, Gubernari, Jung, van Dyk (BGDJ), arXiv:1912.09335
Martinelli, Simula, Vittorio (MSV), arXiv:2105.08674
FNAL/MILC, arXiv:1503.07237, arXiv:2105.14019
HFLAV, hflav.web.cern.ch

New physics scenarios for $R_{D^{(*)}}$



Murgui, Peñuelas, Jung, Pich, arXiv:1904.09311