Portorož 2021: Physics of the Flavourful Universe, 22 September 2021

Anomalies in rare *B* decays after Moriond 2021

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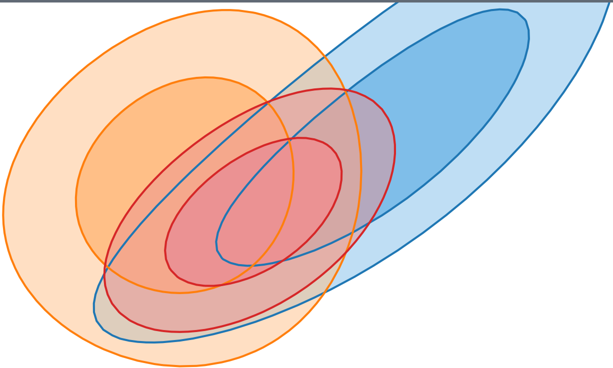
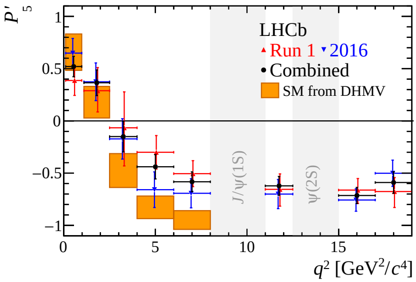


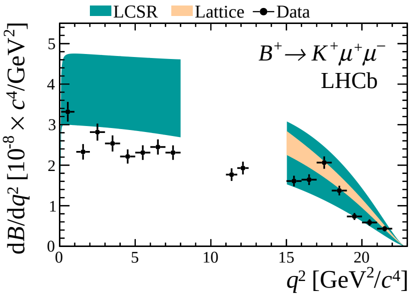
The $b \to s\ell\ell$ anomalies

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



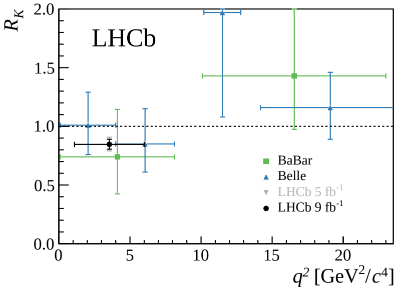


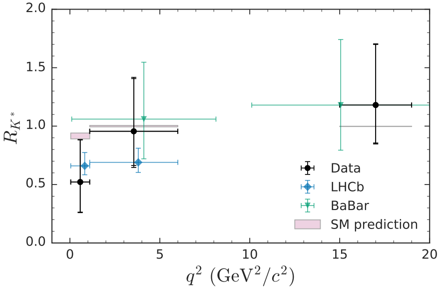
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

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

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

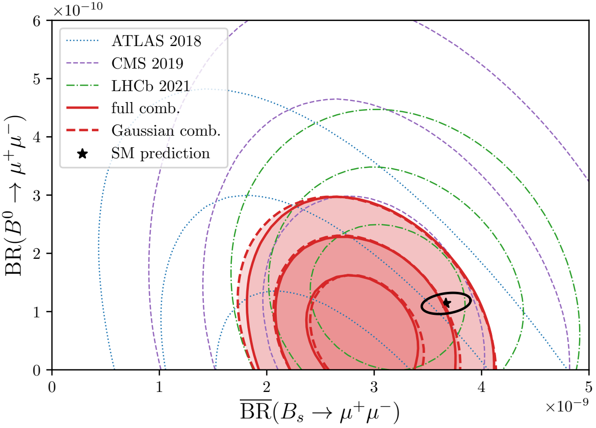




Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

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

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



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

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

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

- **Hadronic operators**:

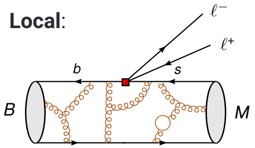
$$\mathcal{H}_{\text{eff, had}}^{bs\ell\ell} = -\mathcal{N}\frac{16\pi^2}{e^2}\left(C_8^{bs} O_8^{bs} + C_8^{\prime bs} O_8^{\prime bs} + \sum_{i=1..6} C_i^{bs\ell\ell} O_i^{bs} \right) + \text{h.c.}$$

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 ($M = K, K^*, \phi$)

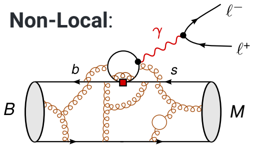
$$\mathcal{M}(B \to M\ell\ell) = \langle M\ell\ell|\mathcal{H}_{\text{eff}}^{bs\ell\ell}|B\rangle$$
$$= \mathcal{N}\Big[\left(\mathcal{A}_V^\mu + \mathcal{H}^\mu\right)\bar{u}_\ell\gamma_\mu v_\ell + \mathcal{A}_A^\mu\,\bar{u}_\ell\gamma_\mu\gamma_5 v_\ell + \mathcal{A}_S\,\bar{u}_\ell v_\ell + \mathcal{A}_P\,\bar{u}_\ell\gamma_5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

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:

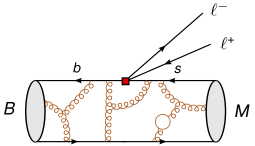


$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2}\sum_{i=1..6,8} C_i\int dx^4 e^{iq\cdot x}\langle M|T\{j^\mu_{\text{em}}(x), O_i(0)\}|B\rangle$$

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

- **Wilson coefficients**:
  perturbative, short-distance UV physics, parameterize heavy new physics
- **local** and **non-local** **hadronic matrix elements**:
  non-perturbative, **main source of uncertainty**

Form factors



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

- Not all $\langle M|\bar{s}\,\Gamma_i\, b|B\rangle$ matrix elements independent:
  - **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

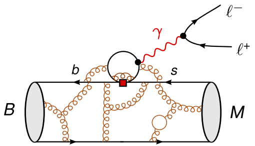
  - low q^2: **Continuum methods** (e.g. Light-cone sum rules)

    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 **continuum + 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 for $q^2 < 6\ \text{GeV}^2$ from QCD factorization (QCDF)

  Beneke, Feldmann, Seidel, arXiv:hep-ph/0106067

- **Beyond-QCDF** contributions **the main source of uncertainty**
- Could mimic new physics in C_9 (but in general q^2 and helicity dependent)

  e.g. Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli, arXiv:1512.07157

- Several compatible approaches to treat beyond-QCDF contributions at low q^2
  - Light-Cone Sum Rules estimates — Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945; Gubernari, van Dyk, Virto, arXiv:2011.09813
  - fit of sum of resonances to data — Blake, Egede, Owen, Pomery, Petridis, arXiv:1709.03921
  - analyticity + experimental data on $b \to s c\bar{c}$ — Bobeth, Chrzaszcz, van Dyk, Virto, arXiv:1707.07305
  - order of magnitude estimate parameterized as polynomial in q^2

    Descotes-Genon, Hofer, Matias, Virto, arXiv:1407.8526, arXiv:1510.04239
    Arbey, Hurth, Mahmoudi, Neshatpour, arXiv:1806.02791
    Altmannshofer, Straub, arXiv:1411.3161

Uncertainties of observables

- $B \to K\mu\mu$, $B \to K^*\mu\mu$, and $B_s \to \phi\mu\mu$ **branching fractions**:
  fully affected by uncertainties from form factors and non-local matrix elements
- **Angular observables**:
  reduced impact of form factor uncertainties
- $B_s \to \mu\mu$ **branching fraction**
  Small uncertainties (no hadron in final state, B_s decay constant from lattice)
- **LFU observables**
  Tiny hadronic uncertainties in SM (but can be larger in the presence of new physics)

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

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

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

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

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

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

Setup

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

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

- **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 Wilson coefficients $\boldsymbol{C}_{\rm th}(\vec{\boldsymbol{C}})$ *NEW*

  Altmannshofer, PS, arXiv:2103.13370
- $\Delta\chi^2$ and pull

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

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

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

New data in 2021

- LFU ratio R_K LHCb, arXiv:2103.11769
- $B_s \to \mu^+\mu^-$ branching ratio LHCb, arXiv:2108.09283, arXiv:2108.09284
- $B_s \to \phi\mu^+\mu^-$ branching ratios LHCb, arXiv:2105.14007
- $B_s \to \phi\mu^+\mu^-$ angular observables LHCb, arXiv:2107.13428 included here for the first time!

Results

based on Altmannshofer, PS, arXiv:2103.13370

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:2011.01212   Datta et al., arXiv:1903.10086   Kowalska et al., arXiv:1903.10932

Scenarios with a single Wilson coefficients

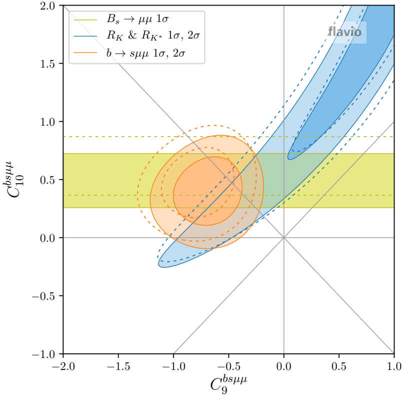
Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	$\mathbf{3.3\sigma}$	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	$\mathbf{5.1\sigma}$
$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	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 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 $C_9^{bs\mu\mu}$

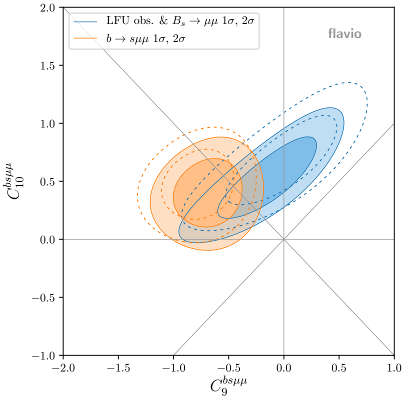
Scenarios with two Wilson coefficients



WET at 4.8 GeV

- **New 2021 data**:
  - $\boldsymbol{R_K}$: smaller uncertainty
  - $\boldsymbol{B_s \to \mu\mu}$: smaller uncertainty, better agreement with $b \to s\mu\mu$
  - $\boldsymbol{b \to s\mu\mu}$: smaller uncertainty, better agreement with $R_{K^{(*)}}$

Scenarios with two Wilson coefficients

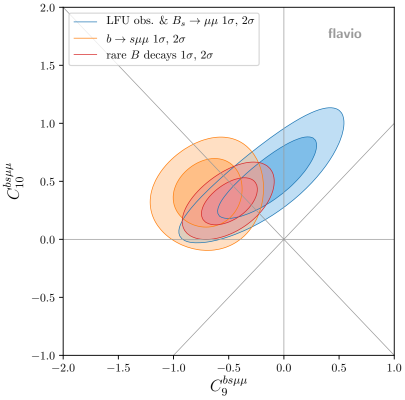


WET at 4.8 GeV

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.
- **New 2021 data**:
  - **LFU obs. &** $\boldsymbol{B_s \to \mu\mu}$: smaller uncertainty, better agreement with $b \to s\mu\mu$
  - $\boldsymbol{b \to s\mu\mu}$: smaller uncertainty, better agreement with LFU obs. & $B_s \to \mu\mu$

Scenarios with two Wilson coefficients

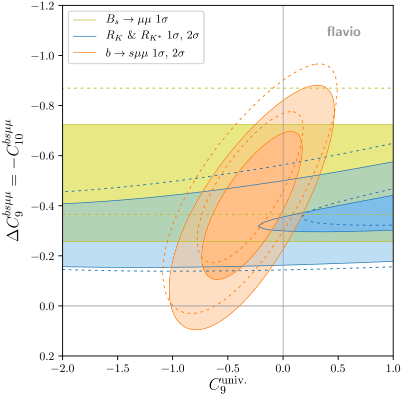


WET at 4.8 GeV

- Global fit in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ plane prefers negative $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$
- Tension between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*} could be reduced by **LFU** contribution to $\boldsymbol{C_9}$

Scenarios with two Wilson coefficients

- **New 2021 data**:
  smaller uncertainty, better agreement between R_K & R_{K^*} and $B_s \to \mu\mu$, smaller best-fit value of $C_9^{\text{univ.}}$



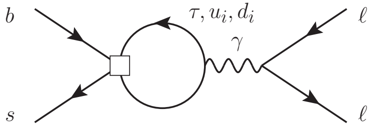
WET at 4.8 GeV

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

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

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

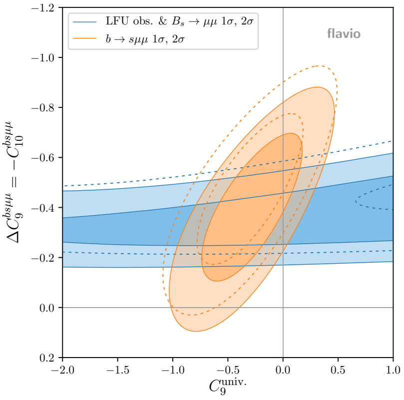
- Slight preference for **non-zero $C_9^{\text{univ.}}$**
  - could be mimicked by hadronic effects
  - can arise from RG effects:



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

Scenarios with two Wilson coefficients

- **New 2021 data**:
  smaller uncertainty, better agreement between R_K & R_{K^*} and $B_s \to \mu\mu$,
  smaller best-fit value of $C_9^{\text{univ.}}$



WET at 4.8 GeV

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

$$C_9^{bsee} = C_9^{bs\tau\tau} = C_9^{\text{univ.}}$$
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scenario first considered in
Algueró et al., arXiv:1809.08447

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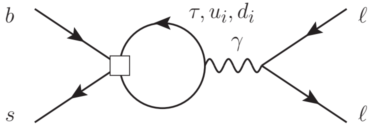

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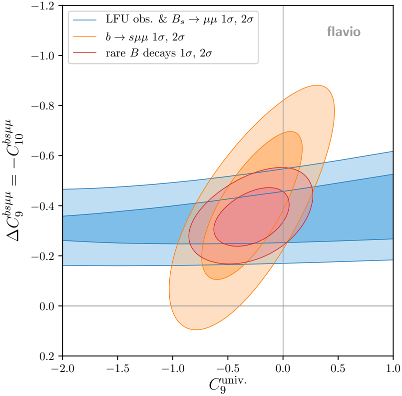

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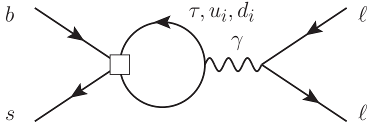

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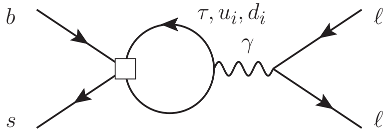
RG effect in SMEFT

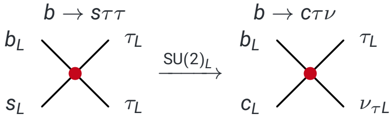
RG effects require scale separation

- 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

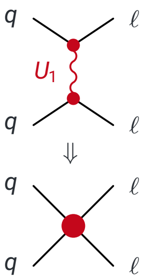
- ***U_1* vector leptoquark** $(\mathbf{3}, \mathbf{1})_{2/3}$ couples LH fermions

see talks by
Claudia Cornella,
Darius Faroughy,
Ivan Nišandžić

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

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

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



Conclusions

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- Updated measurements of R_K and $\text{BR}(B_s \to \mu\mu)$, and $B_s \to \phi\mu\mu$ branching ratios and angular observables.

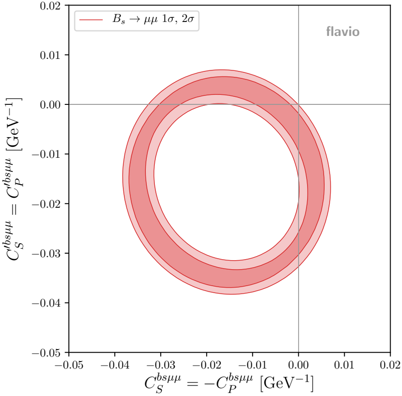
- New physics in the single muonic Wilson coefficients $\boldsymbol{C_9^{bs\mu\mu}}$, $\boldsymbol{C_{10}^{bs\mu\mu}}$, and $\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$ gives clearly better fit to data than SM ($\text{pull}_{1D} \gtrsim 5\sigma$).

- Slight tension between $R_{K^{(*)}}$ and $b \to s\mu\mu$ in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ scenario can be reduced by **lepton flavor universal $\boldsymbol{C_9^{\text{univ.}}}$** (possible connection to charged current $b \to c\tau\nu$ anomalies in $R_{D^{(*)}}$).

- Many more **experimental updates** on $b \to s\ell\ell$ anomalies expected soon not only from **LHCb** but also **ATLAS** and **CMS**, and eventually **Belle II**.

Backup slides

Scenarios with two Wilson coefficients

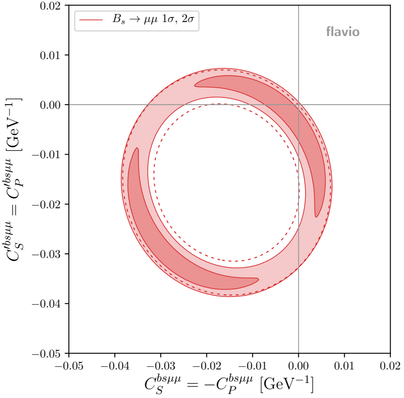


WET at 4.8 GeV

Constraint on scalar coefficients

- **Before Moriond 2021**

Scenarios with two Wilson coefficients



WET at 4.8 GeV

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  - Region corresponding to mass eigenstate rate asymmetry $A_{\Delta\Gamma} = -1$ excluded at 1σ

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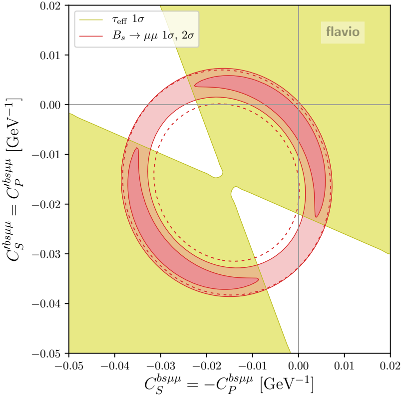

WET at 4.8 GeV

Constraint on scalar coefficients

- **After Moriond 2021**:
  - Region corresponding to mass eigenstate rate asymmetry $A_{\Delta\Gamma} = -1$ excluded at 1σ
  - Clear effect of new, more precise measurement of effective $B_s \to \mu\mu$ lifetime $\tau_{\rm eff}$

The global picture in the SMEFT

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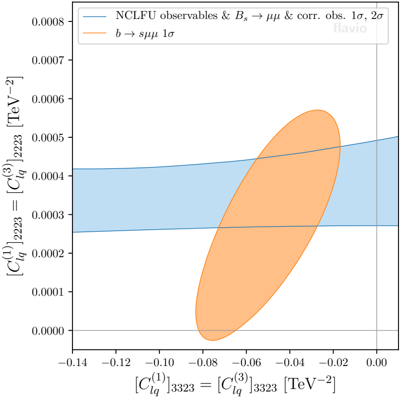

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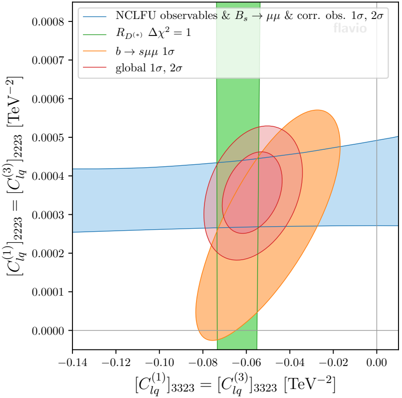

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  Very good agreement between $R_{D^{(*)}}$, $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanations

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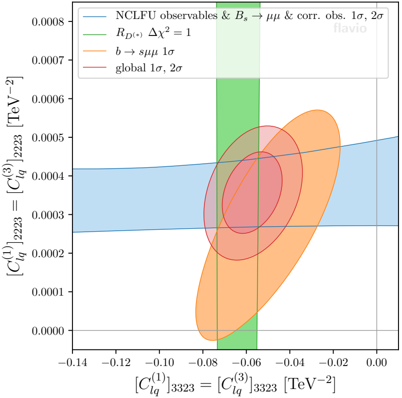

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- $R_{D^{(*)}}$ **explanation**:
  Very good agreement between $R_{D^{(*)}}$, $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanations
- **Only a simple SMEFT scenario**
  ⇒ Consider explicit models that yield this coefficients
  ⇒ Good candidate: U_1 **Leptoquark**

Correlation effects in the global likelihood

Slightly different results by different groups

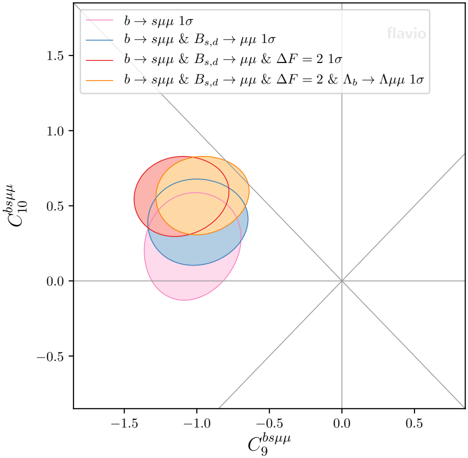
Descotes-Genon, PS, Talk at Beyond the Flavour Anomalies
https://conference.ippp.dur.ac.uk/event/876/

	All			LFUV		
1D Hyp.	$1\,\sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	$1\,\sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	$[-1.19, -0.88]$	6.3	37.5 %	$[-1.25, -0.61]$	3.3	60.7 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	$[-0.59, -0.41]$	5.8	25.3 %	$[-0.50, -0.28]$	3.7	75.3 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{9'\mu}$	$[-1.17, -0.87]$	6.2	34.0 %	$[-2.15, -1.05]$	3.1	53.1 %

Coefficient	type	best fit	1σ	$\mathrm{pull}_{1\mathrm{D}} = \sqrt{\Delta\chi^2}$
$\boldsymbol{C_9^{bs\mu\mu}}$	$\boldsymbol{L \otimes V}$	-0.93	$[-1.07, -0.79]$	$\boldsymbol{6.2\sigma}$
$C_9'^{bs\mu\mu}$	$R \otimes V$	$+0.14$	$[-0.02, +0.31]$	0.9σ
$\boldsymbol{C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes A}$	$+0.71$	$[+0.58, +0.84]$	$\boldsymbol{5.7\sigma}$
$C_{10}'^{bs\mu\mu}$	$R \otimes A$	-0.20	$[-0.29, -0.08]$	1.7σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.15$	$[+0.02, +0.29]$	1.2σ
$\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes L}$	-0.53	$[-0.61, -0.46]$	$\boldsymbol{6.9\sigma}$

C_9 vs. $C_9 = -C_{10}$ with global likelihood

Likelihood contours for different sets of observables taken into account



- **Most groups** doing fits of $b \to s\ell\ell$ observables **do not include $\Delta F = 2$** obs.: They do not depend on $b \to s\ell\ell$ Wilson coefficients
- In **global likelihood**, **$\Delta F = 2$** obs. naturally **included** (global!)
- Choice whether to include them or not: **clear difference** in $C_{10}^{bs\mu\mu}$ direction (red contour vs. blue contour)
- This explained the differences between the different groups!

Why does the inclusion of $\Delta F = 2$ observables has such an impact on the fit in the $C_{10}^{bs\mu\mu}$ direction if **$\Delta F = 2$ observables do not depend on $C_{10}^{bs\mu\mu}$**?

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$\Delta F = 2$ observables do not depend on $C_{10}^{bs\mu\mu}$?

Theory correlations...

Correlations in a toy example

- Correlations for observables O_1, O_2 (uncertainties $\sigma_{1,2}$, correlation coeff. ρ):

$$-2\ln\mathcal{L}(O_1,O_2)=\frac{1}{1-\rho^2}\left(\frac{D_1^2}{\sigma_1^2}+\frac{D_2^2}{\sigma_2^2}-2\rho\frac{D_1\,D_2}{\sigma_1\,\sigma_2}\right)\,,\qquad D_{1,2}=(O_{1,2}-\hat{O}_{1,2})$$

- If $D_1(C_{10})$ depends on C_{10} and D_2 is constant in C_{10}, then $\Delta\ln\mathcal{L}$ between $C_{10}=0$ and $C_{10}=\tilde{C}_{10}$ yields

$$\Delta\ln\mathcal{L}\propto\frac{D_1^2(0)-D_1^2(\tilde{C}_{10})}{\sigma_1^2}-2\,\rho\,D_2\frac{D_1(0)-D_1(\tilde{C}_{10})}{\sigma_1\,\sigma_2}$$

- First term is present whether we include O_2 or not (up to $\frac{1}{1-\rho^2}$ prefactor)
- **Second term makes a difference**
  - if $\rho\neq 0$, i.e. $\boldsymbol{O_1}$ **and** $\boldsymbol{O_2}$ **are correlated**
  - if $D_2\neq 0$, i.e. experimental estimate $\boldsymbol{\hat{O}_2}$ **shows deviation from SM prediction** O_2

Correlations in the global likelihood

The same is true for $\Delta F = 2$ observables, in particular ϵ_K:

- theory predictions of ϵ_K and $BR(B_s \to \mu\mu)$ are correlated, $BR(B_s \to \mu\mu)$ depends on C_{10}
- experimental estimate of ϵ_K shows deviation from SM prediction

Should we include $\boldsymbol{\Delta F = 2}$ observables in $b \to s\ell\ell$ fit or not?

Two different assumptions:

- **Including them** and only varying C_{10} means we assume all other Wilson Coefficients $C_i = 0$, i.e. we fix the SM point in these directions
- **Excluding them** is (nearly) equivalent to setting certain $C_i \neq 0$ such that theory prediction and experimental estimate of $\Delta F = 2$ observables agree

Bayesian approach: marginalise over “nuisance coefficients” C_i

- **Including them** and only varying C_{10} corresponds to prior on C_i strongly peaked around SM value $C_i = 0$
- **Excluding them** is equivalent to flat prior that allows the posterior for C_i to be peaked around $C_i \neq 0$

What can we learn from this?

- There are different assumptions we can make by including or excluding certain observables
- It is not obvious if there is a “correct” one, but we should be aware of the differences
- The $\Delta\chi^2$ values between best-fit point and SM point can be different and one has to think about what “SM point” actually means if one does not fix $C_i = 0$