Beyond the Flavour Anomalies, 1 April 2020

Global Fits of Flavour Anomalies

Presented by Sébastien Descotes-Genon & Peter Stangl

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

LAPTh
Laboratoire d'Annecy-le-Vieux de Physique Théorique

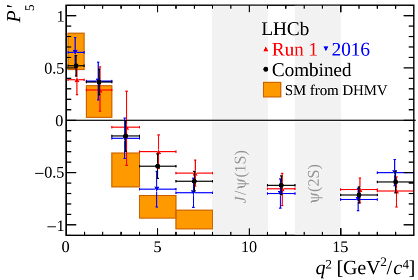
Outline

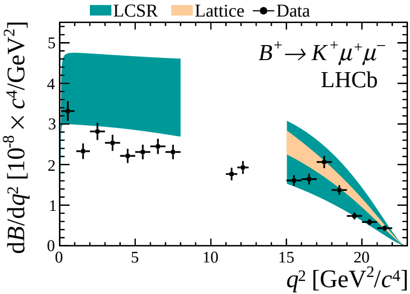
Flavour Anomalies

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

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

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:2003.04831
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$. LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731



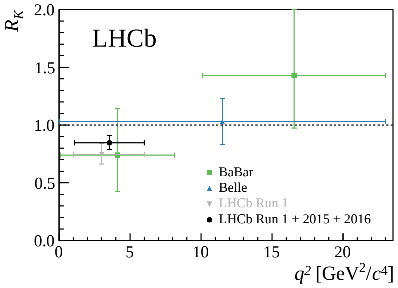


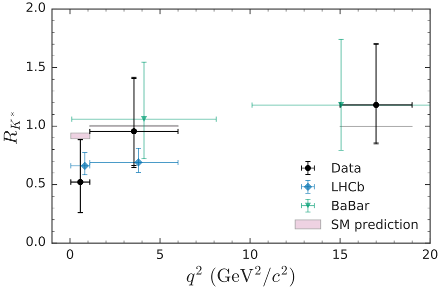
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

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

LHCb, arXiv:1705.05802, arXiv:1903.09252
Belle, arXiv:1904.02440, arXiv:1908.01848

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





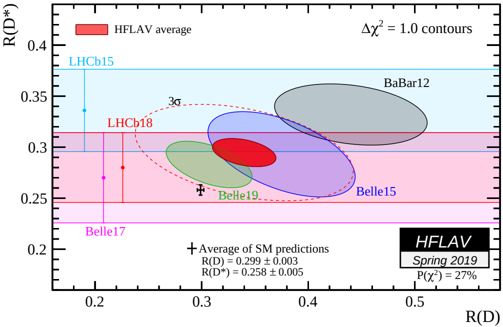
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

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

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

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

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

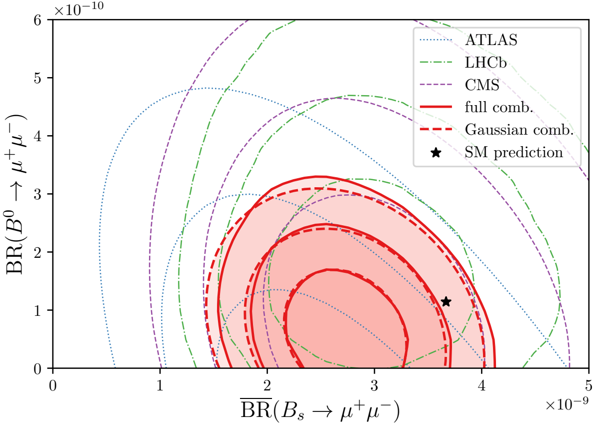


HFLAV, hflav.web.cern.ch

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

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

LHCb, arXiv:1703.05747
CMS, arXiv:1910.12127
ATLAS, arXiv:1812.03017



Theoretical Framework

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

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

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

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

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

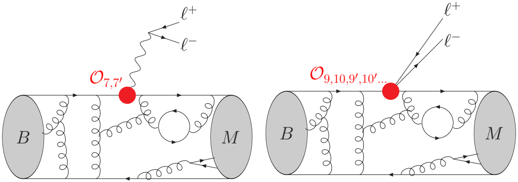
- Not considered here
  - Dipole operators: strongly constrained by radiative decays. e.g. [arXiv:1608.02556]
  - Four quark operators: dominant effect from RG running above m_B. Jäger, Leslie, Kirk, Lenz [arXiv:1701.09183]

Two sources of hadronic uncertainties for exclusive

$$A(B \to M\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu)\bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$

Two sources of hadronic uncertainties for exclusive

$$A(B \to M\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu)\bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



Form factors (local)

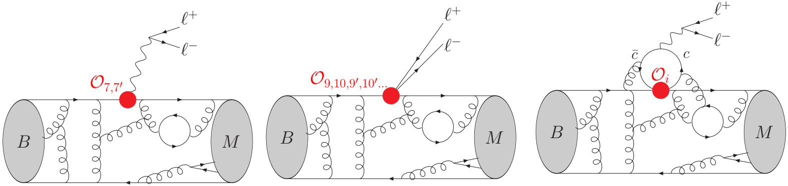
- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu} P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

Two sources of hadronic uncertainties for exclusive

$$A(B \to M\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu)\bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



Form factors (local) Charm loop (non-local)

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu} P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

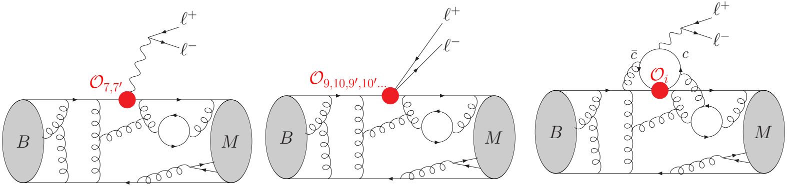
$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

- Non-local contributions (charm loops): hadronic contribs.

T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

Two sources of hadronic uncertainties for exclusive

$$A(B \to M\ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu)\bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$



Form factors (local) Charm loop (non-local)

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu}P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$
$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

- Non-local contributions (charm loops): hadronic contribs.

T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

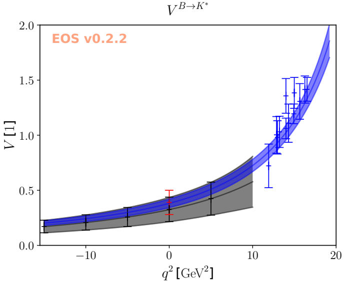
- Overal agreement about both contributions, using various tools

Hadronic uncertainties: form factors

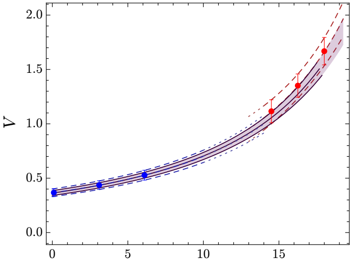
3 form factors for K, 7 form factors for K^* and ϕ

- low recoil: lattice QCD [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: Light-Cone Sum Rules (B-meson or light-meson DAs)

[Khodjamirian, Mannel, Pivovarov, Wang; Bharucha, Straub, Zwicky; Gubernari, Kokulu, van Dyk]



B-meson LCSR + lattice



Light-meson LCSR + lattice

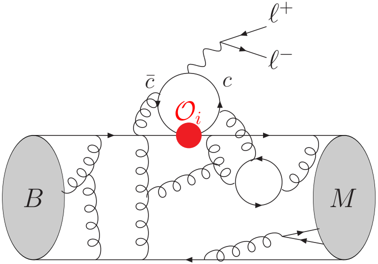
- correlations among the form factors needed
  - known from direct determination and/or combined fit to low and large recoils [PS]
  - recovered from EFT with $m_b \to \infty + O(\alpha_s) + O(1/m_b)$ [SDG]

[Jäger, Camalich; Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]

- optimised observables P_i to reduce the impact of form factor uncertainties

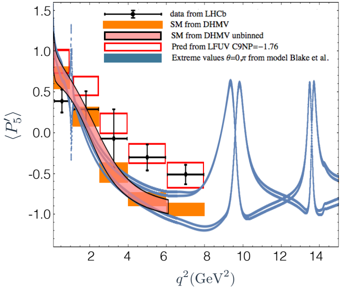
Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- depends on q^2, lepton univ.
- quark-hadron duality approx at large q^2 (syst of few %)



Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- depends on q^2, lepton univ.
- quark-hadron duality approx at large q^2 (syst of few %)

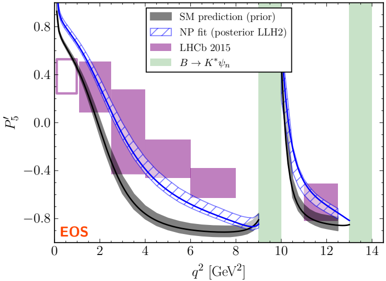


Several approaches agree at low-q^2

- LCSR estimates [Khodjamirian, Mannel, Pivovarov, Wang; Gubenari, Van Dyk]
- order of magnitude estimate for the fits (LCSR or Λ/m_b), check with bin-by-bin fits [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]

Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- depends on q^2, lepton univ.
- quark-hadron duality approx at large q^2 (syst of few %)



Several approaches agree at low-q^2

- LCSR estimates [Khodjamirian, Mannel, Pivovarov, Wang; Gubenari, Van Dyk]
- order of magnitude estimate for the fits (LCSR or Λ/m_b), check with bin-by-bin fits [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]
- fit of q^2-parametrisation to the data [Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli; Capdevila, SDG, Hofer, Matias]
- dispersive representation + $J/\psi, \psi(2S)$ data [Bobeth, Chrzaszcz, van Dyk, Virto]

Setup

- PS: Global likelihood from **smelli** python package for comparing theory predictions to experimental data Aebischer, Kumar, PS, Straub, arXiv:1810.07698
- SDG: Likelihood taking into account experimental and theoretical uncertainties and correlations in Gaussian approximation

[Algueró, Capdevila, Crivellin, SDG, Masuan Matias, Novoa-Brunet, Virto]

Two statistical quantities of interest to asses a NP scenario/hypothesis

- *p*-value of a given hypothesis: $\chi^2_{\rm min}$ considering N_{dof} (in %)
  goodness of fit: does the hypothesis give an overall good fit ?
  and if not, can we exclude it ?
- $\text{Pull}_{\rm SM}$: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{min}$ considering N_{dof} (in σ units)
  metrology: how well does the hypothesis solve SM deviations ?

Analysis Inputs

Experimental inputs

- R_K, R_{K^*} (large- and low-recoil bins)
- $B \to K^* \mu\mu$ (Br and ang obs)
- $B \to K^* ee$ (ang obs)
- $B_s \to \phi\mu\mu$ (Br and ang obs)
- $B^+ \to K^+ \mu\mu$, $B^0 \to K^0 \mu\mu$ (Br and ang obs)
- $B \to X_s\gamma$,$B \to X_s\mu\mu$,$B_s \to \mu\mu$,$B_s \to \phi\gamma$, $B \to K^*\gamma$ (Br)

including LHCb, ATLAS, CMS, Babar and Belle data whenever available

- SDG: No inclusion of additional observables that are not directly related to $b \to s\ell\ell$ and $b \to s\gamma$ (would require extra assumption on NP model)
- PS: **Global likelihood** contains many other observables not directly sensitive to considered Wilson coefficients
- PS: Theory **correlations with $\Delta F = 2$ observables** have an effect on the fit

Theoretical inputs

SDG:

- Form factors: B-meson DA LCSR + lattice + EFT for correlations
- Charm-loop corrections: Perturbative contribution + magnitude of of long-distance contrib inspired by [Khodjamirian, Mannel, Pivovarov, Wang]
- Quark-duality violation at high q^2: 10% effect at the level of the amplitude
- $Br(B_s \to \mu\mu)$ modified to include latest corrections from [Misiak ; Beneke, Bobeth, Szafron]

PS:

- Form factors: For B to light vector meson from [Bharucha, Straub, Zwicky], for $B \to K$ from [Gubernari, Kokulu, van Dyk]
- Non-factorizable effects parametrized as in [Bharucha, Straub, Zwicky], [Altmannshofer, Straub], compatible with [Khodjamirian, Mannel, Pivovarov, Wang], [Bobeth, Chrzaszcz, van Dyk, Virto]
- Additional parametric uncertainties (e.g. CKM) based on [flavio v2.0] with default settings

Results

1D Scenarios for $\mathcal{C}_{i\mu}$ [2020]

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

- LFUV fit: R_K, R_{K^*}, $Q_{4,5}$, $B_s \to \mu\mu$, $b \to s\gamma$
- All : all $b \to s\ell\ell$ and $b \to s\gamma$ observables
- Pull_{SM} in σ units increased compare to [2019]
- p-value of SM hyp decreased from 11% to 1.4% (2.5σ) for the fit “All"

Scenarios with a single Wilson coefficients

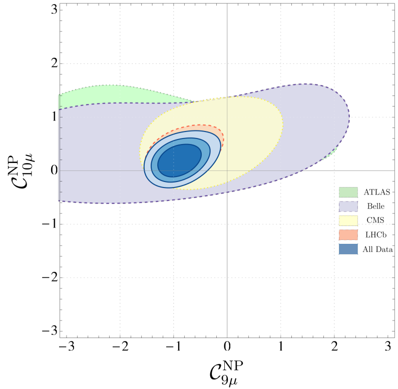
Coefficient	type	best fit	1σ	$\text{pull}_{1D} = \sqrt{\Delta\chi^2}$
$\boldsymbol{C_9^{bs\mu\mu}}$	$\boldsymbol{L \otimes V}$	-0.93	$[-1.07, -0.79]$	**6.2σ**
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.14$	$[-0.02, +0.31]$	0.9σ
$\boldsymbol{C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes A}$	$+0.71$	$[+0.58, +0.84]$	**5.7σ**
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-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	$[-0.61, -0.46]$	**6.9σ**

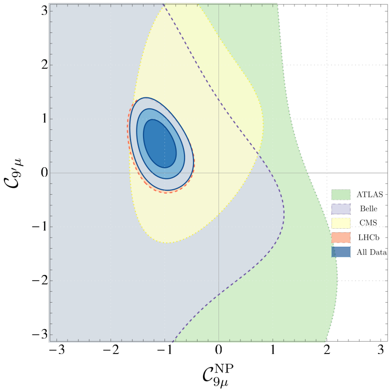
Only small pull for

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

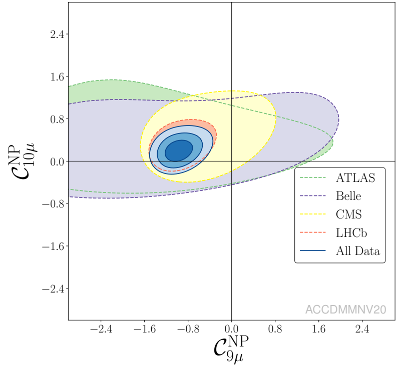
see also similar fits by other groups:
Ciuchini et al., arXiv:1903.09632 Datta et al., arXiv:1903.10086
Kowalska et al., arXiv:1903.10932 Arbey et al., arXiv:1904.08399

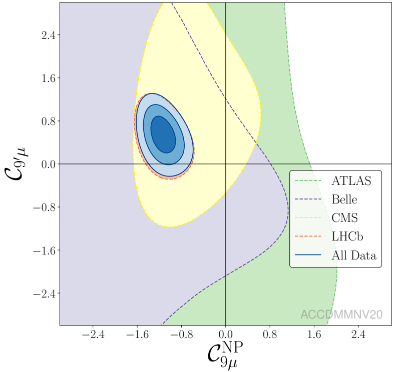
2D Scenarios for $\mathcal{C}_{i\mu}$ [2019]





2D Scenarios for $\mathcal{C}_{i\mu}$ [2020]





2D and 6D Scenarios for $\mathcal{C}_{i\mu}$ [2020]

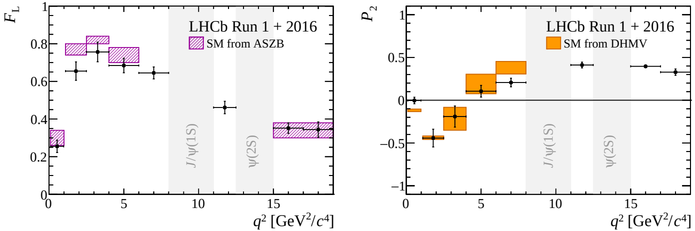
	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{10\mu}^{\text{NP}})$	(-0.98,0.19)	6.2	39.8 %	(-0.31,0.44)	3.2	70.0 %
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{9'\mu})$	(-1.14,0.55)	6.5	47.4 %	(-1.86,1.20)	3.5	81.2 %
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{10'\mu})$	(-1.17,-0.33)	6.6	50.3 %	(-1.87,-0.59)	3.7	89.6 %
$(\mathcal{C}_{9\mu}^{\text{NP}}=-\mathcal{C}_{9'\mu},\mathcal{C}_{10\mu}^{\text{NP}}=\mathcal{C}_{10'\mu})$	(-1.10,0.28)	6.5	48.9 %	(-1.69,0.29)	3.5	82.4 %
$(\mathcal{C}_{9\mu}^{\text{NP}},\mathcal{C}_{9'\mu}=-\mathcal{C}_{10'\mu})$	(-1.17,0.23)	6.6	51.1 %	(-2.05,0.50)	3.8	91.9 %

- Right-handed currents appear quite naturally
- No change in the hierarchy of scenarios

	$\mathcal{C}_7^{\text{NP}}$	$\mathcal{C}_{9\mu}^{\text{NP}}$	$\mathcal{C}_{10\mu}^{\text{NP}}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.00	-1.13	+0.20	+0.00	+0.49	-0.10
1 σ	$[-0.02,+0.02]$	$[-1.30,-0.96]$	$[+0.05,+0.37]$	$[-0.01,+0.02]$	$[+0.04,+0.95]$	$[-0.33,+0.14]$
2 σ	$[-0.03,+0.04]$	$[-1.46,-0.78]$	$[-0.09,+0.57]$	$[-0.03,+0.04]$	$[-0.39,+1.45]$	$[-0.55,+0.41]$

- Pull_{SM}: 5.1 [2019] $\to$ 5.8σ [2020]
- *p*-value: 81.6% [2019] $\to$ 46.8% [2020]

Comments on the $B \to K^* \mu\mu$ data



New data from LHCb

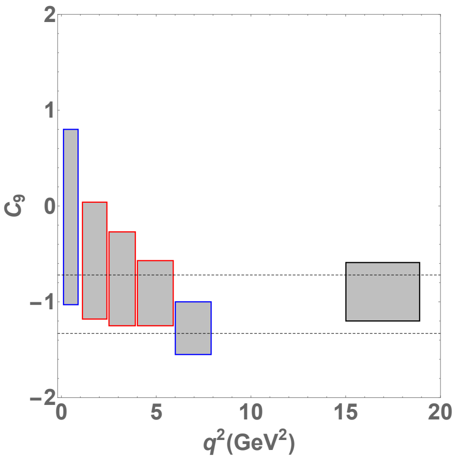
- uncertainty reduced by $30-50\%$ (in particular $[1.1, 2.5]$ and $[2.5, 4]$)
- new average value for F_L in the bin $[2.5, 4]$ more than 4σ below 1, helping the discussion in terms of optimised observables P_i

Excellent consistency

- new tensions with respect to the SM in $\langle P_3 \rangle_{[1.1,2.5]}$, $\langle P_6' \rangle_{[6,8]}$ and $\langle P_8' \rangle_{[1.1,2.5]}$
- enhanced tension for other observables such as the first bin of $P_{1,2}$
- tension in first bin of P_5' decreased, in better agreement with theory (see later)

Solve earlier tensions of the fit discussed in [Algueró, Capdevila, SDG, Masjuan Matias]

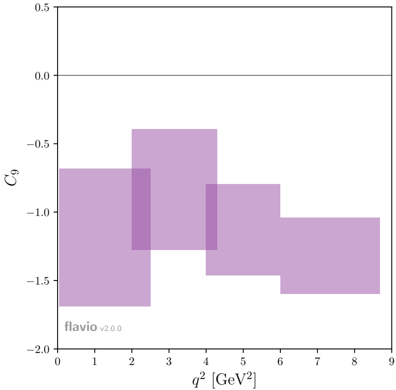
Consistency of the results over the q^2 range



Sanity check possible for the $C_{9\mu}$ NP hypothesis

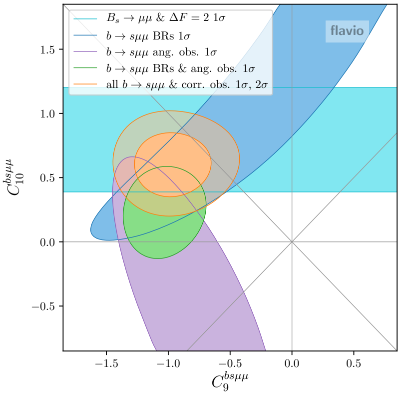
- $B \to K^* \mu\mu$ Br + ang obs + $B_s \to \mu\mu$ + $B \to X_s \mu\mu$ + $b \to s\gamma$
- $C_{9\mu}^{\rm NP}$ fitted separately for each bin
- Good agreement with global fit (2σ range)
- No indication of a q^2 variation
- In particular, agreement between low and large recoils with very different theoretical approaches and systematics

Consistency of the results over the q^2 range



- Finding also **good agreement with q^2-independent C_9** considering data on $B \to K^* \mu\mu$ from LHCb, ATLAS, CMS, CDF (different binning)

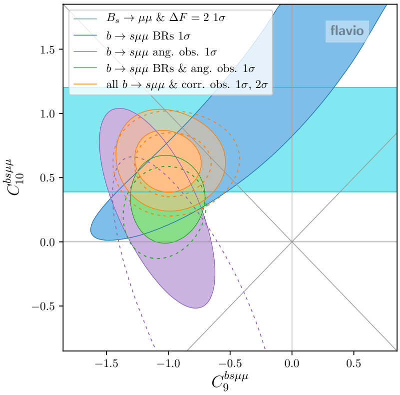
Scenarios with two Wilson coefficients



WET at 4.8 GeV

- **[2019]**: Angular obs. slightly disfavour positive $C_{10}^{bs\mu\mu}$, but overall good agreement between different sectors

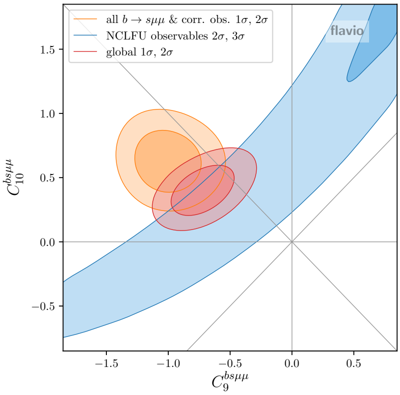
Scenarios with two Wilson coefficients



WET at 4.8 GeV

- **[2019]**:
  Angular obs. slightly disfavour positive $C_{10}^{bs\mu\mu}$, but overall good agreement between different sectors
- **[2020]**:
  Angular obs. slightly favour positive $C_{10}^{bs\mu\mu}$, agreement increased

Scenarios with two Wilson coefficients



WET at 4.8 GeV

- **[2019]**:
  Angular obs. slightly disfavour positive $C_{10}^{bs\mu\mu}$, but overall good agreement between different sectors
- **[2020]**:
  Angular obs. slightly favour positive $C_{10}^{bs\mu\mu}$, agreement increased
- **Global likelihood**:
  - Tension between fits to R_K & R_{K^*} and $b \to s\mu\mu$ observables in C_9 direction $\Rightarrow$ **LFU C_9**?
  - Purely left-handed $\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$ yields very good fit to experimental data

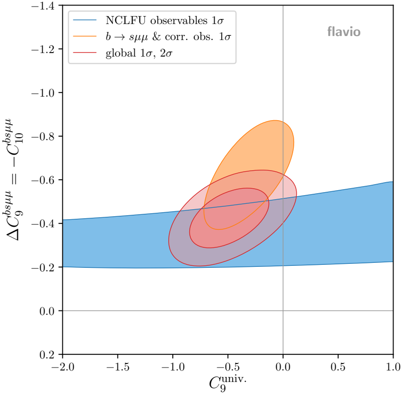
Scenarios with two Wilson coefficients

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

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

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

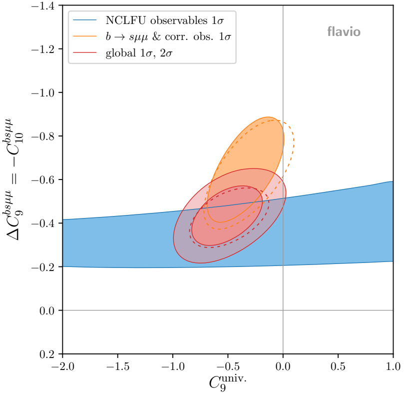
Scenarios with two Wilson coefficients



WET at 4.8 GeV

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

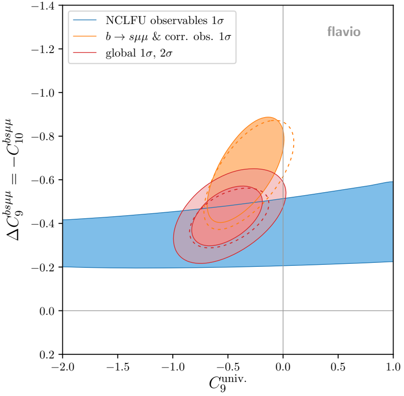
Scenarios with two Wilson coefficients



WET at 4.8 GeV

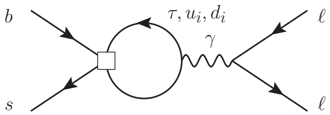
- **[2019]**:
  Preference for **non-zero $C_9^{\text{univ.}}$**
- **[2020]**:
  Preference for **non-zero $C_9^{\text{univ.}}$** slightly increased

Scenarios with two Wilson coefficients



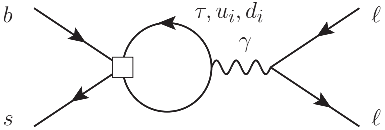
WET at 4.8 GeV

- **[2019]**:
  Preference for **non-zero $C_9^{\text{univ.}}$**
- **[2020]**:
  Preference for **non-zero $C_9^{\text{univ.}}$** slightly increased
- $C_9^{\text{univ.}}$ can arise from RG effects:



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

The global picture in the SMEFT



RG effects require scale separation

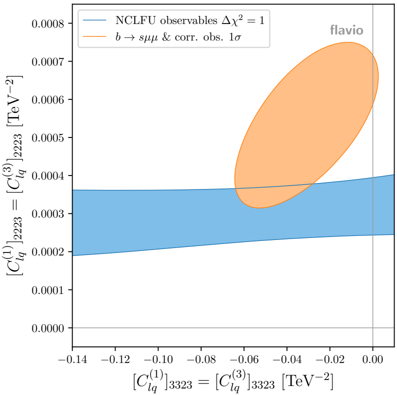
- Consider **SMEFT at 2 TeV**

Possible operators:

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

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

The global picture in the SMEFT

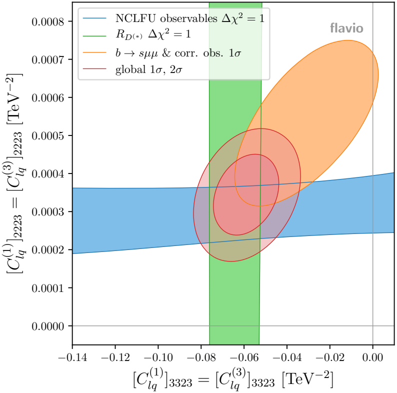


- **[2019]**: Clear preference for **non-zero** $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$

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

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

The global picture in the SMEFT

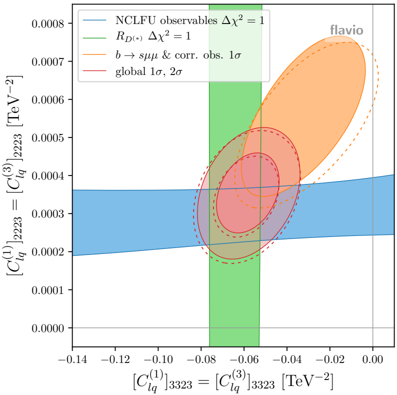


- **[2019]**: Clear preference for **non-zero** $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$
- $R_{D^{(*)}}$ **explanation**: Agreement with combined $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanation has improved

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

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

The global picture in the SMEFT

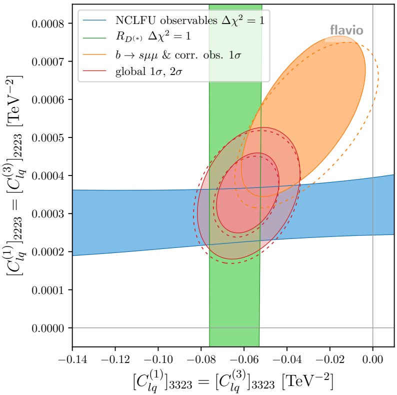


- **[2019]**:
  Clear preference for
  non-zero $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$
- $R_{D^{(*)}}$ **explanation**:
  Agreement with combined $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanation has improved
- **[2020]**:
  Prefernce for
  non-zero $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$
  slightly increased

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

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

The global picture in the SMEFT



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

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

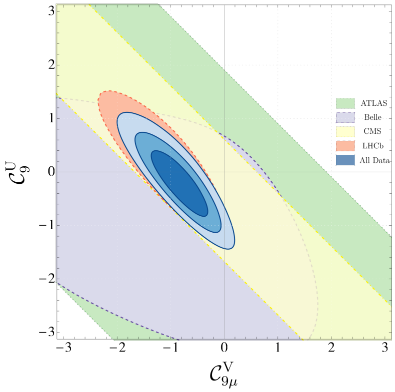
- **[2019]**: Clear preference for **non-zero** $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$
- $R_{D^{(*)}}$ **explanation**: Agreement with combined $R_{K^{(*)}}$ and $b \to s\mu\mu$ explanation has improved
- **[2020]**: Prefernce for **non-zero** $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$ slightly increased
- **Only a simple SMEFT scenario**
  $\Rightarrow$ Consider explicit models that yield this coefficients
  $\Rightarrow$ Good candidate: U_1 **Leptoquark**

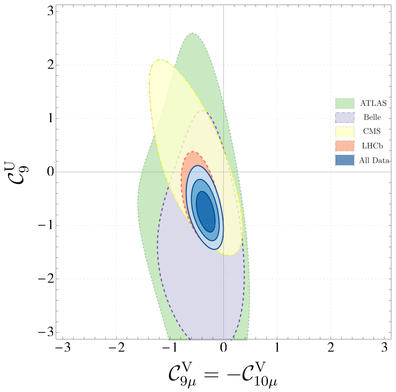
Scenarios for LFU and LFUV $\mathcal{C}_i$ [2019]

R_K and R_{K^*} support LFUV NP, but there could also be a LFU piece

$$\mathcal{C}_{ie} = \mathcal{C}_i^{\mathrm{U}} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\mathrm{U}} + \mathcal{C}_{i\mu}^{\mathrm{V}}$$

[Algueró, Capdevila, SDG, Masjuan, Matias]



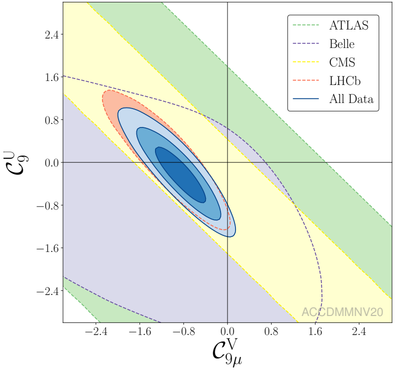


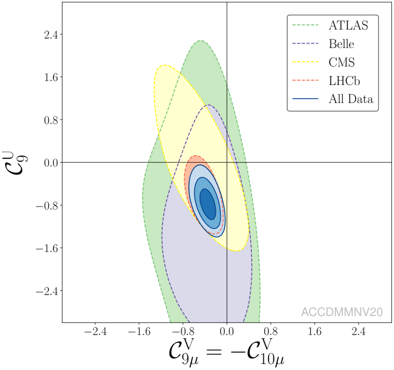
Scenarios for LFU and LFUV $\mathcal{C}_i$ [2020]

R_K and R_{K^*} support LFUV NP, but there could also be a LFU piece

$$\mathcal{C}_{ie} = \mathcal{C}_i^{\rm U} \qquad \mathcal{C}_{i\mu} = \mathcal{C}_i^{\rm U} + \mathcal{C}_{i\mu}^{\rm V}$$

[Algueró, Capdevila, SDG, Masjuan, Matias]





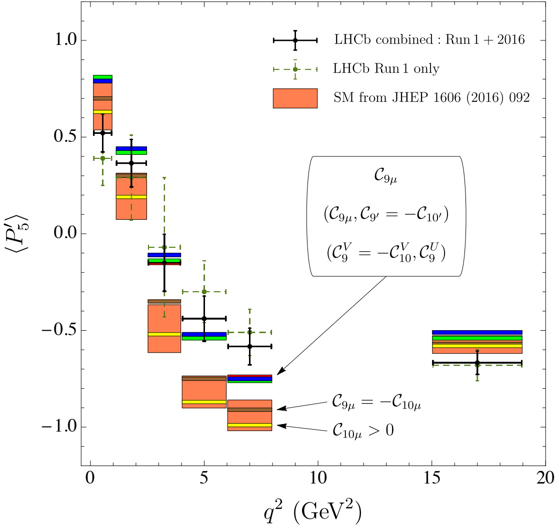
Scenarios for LFU and LFUV $\mathcal{C}_i$ [2020]

	Scenario	Best-fit point	1 σ	2 σ	Pull_{SM}	p-value
Sc. 5	$\mathcal{C}_{9\mu}^{\text{V}}$	-0.54	$[-1.06, -0.06]$	$[-1.68, +0.39]$	6.0	39.4 %
	$\mathcal{C}_{10\mu}^{\text{V}}$	$+0.58$	$[+0.13, +0.97]$	$[-0.48, +1.33]$		
	$\mathcal{C}_{9}^{\text{U}} = \mathcal{C}_{10}^{\text{U}}$	-0.43	$[-0.85, +0.05]$	$[-1.23, +0.67]$		
Sc. 6	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$	-0.56	$[-0.65, -0.47]$	$[-0.75, -0.38]$	6.2	41.4 %
	$\mathcal{C}_{9}^{\text{U}} = \mathcal{C}_{10}^{\text{U}}$	-0.41	$[-0.53, -0.29]$	$[-0.64, -0.16]$		
Sc. 7	$\mathcal{C}_{9\mu}^{\text{V}}$	-0.84	$[-1.15, -0.54]$	$[-1.48, -0.26]$	6.0	36.5 %
	$\mathcal{C}_{9}^{\text{U}}$	-0.25	$[-0.59, +0.10]$	$[-0.92, +0.47]$		
Sc. 8	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$	-0.34	$[-0.44, -0.25]$	$[-0.54, -0.16]$	6.5	48.4 %
	$\mathcal{C}_{9}^{\text{U}}$	-0.80	$[-0.98, -0.60]$	$[-1.16, -0.39]$		
Sc. 9	$\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}$	-0.66	$[-0.79, -0.52]$	$[-0.93, -0.40]$	5.7	28.4 %
	$\mathcal{C}_{10}^{\text{U}}$	-0.40	$[-0.63, -0.17]$	$[-0.86, +0.07]$		
Sc. 10	$\mathcal{C}_{9\mu}^{\text{V}}$	-1.03	$[-1.18, -0.87]$	$[-1.33, -0.71]$	6.2	41.5 %
	$\mathcal{C}_{10}^{\text{U}}$	$+0.28$	$[+0.12, +0.45]$	$[-0.04, +0.62]$		
Sc. 11	$\mathcal{C}_{9\mu}^{\text{V}}$	-1.11	$[-1.26, -0.95]$	$[-1.40, -0.78]$	6.3	43.9 %
	$\mathcal{C}_{10'}^{\text{U}}$	-0.29	$[-0.44, -0.15]$	$[-0.58, -0.01]$		
Sc. 12	$\mathcal{C}_{9'\mu}^{\text{V}}$	-0.06	$[-0.21, +0.10]$	$[-0.37, +0.26]$	2.1	2.2 %
	$\mathcal{C}_{10}^{\text{U}}$	$+0.44$	$[+0.26, +0.62]$	$[+0.09, +0.81]$		
Sc. 13	$\mathcal{C}_{9\mu}^{\text{V}}$	-1.16	$[-1.31, -1.00]$	$[-1.46, -0.83]$	6.2	49.2 %
	$\mathcal{C}_{9'\mu}^{\text{V}}$	$+0.56$	$[+0.27, +0.83]$	$[-0.02, +1.10]$		
	$\mathcal{C}_{10}^{\text{U}}$	$+0.28$	$[+0.08, +0.49]$	$[-0.11, +0.70]$		
	$\mathcal{C}_{10'}^{\text{U}}$	$+0.01$	$[-0.19, +0.22]$	$[-0.40, +0.42]$		

Consistency of scenarios with $B \to K^* \mu\mu$ data

- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies

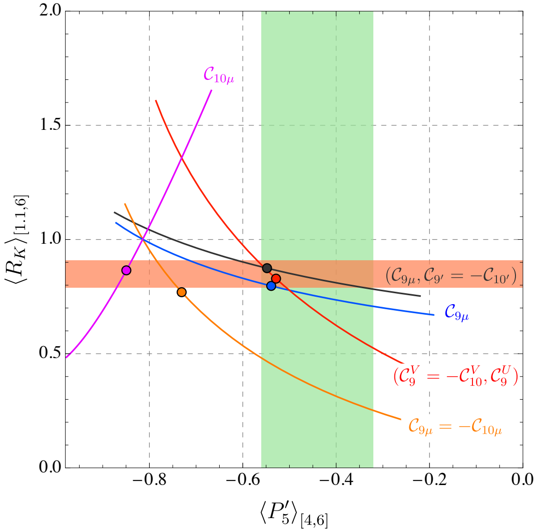
Consistency of scenarios with $B \to K^* \mu\mu$ data



- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies
- Reduction of the internal inconsistencies of the fit
  - for P_5'

for some of the scenarios

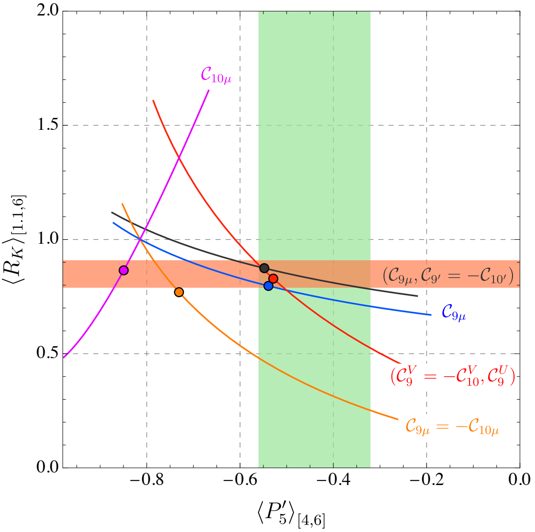
Consistency of scenarios with $B \to K^*\mu\mu$ data



- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies
- Reduction of the internal inconsistencies of the fit
  - for P_5'
  - between P_5' and R_K

  for some of the scenarios

Consistency of scenarios with $B \to K^*\mu\mu$ data



- Increase of significance for some scenarios (up to 0.8 σ), but same hierarchies
- Reduction of the internal inconsistencies of the fit
  - for P_5'
  - between P_5' and R_K

  for some of the scenarios
- p-value of SM decreased to 1.4%

An EFT interpretation: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

An EFT interpretation: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

- Two ops. with left-handed doublets

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu\vec{\sigma} Q_j][\bar{L}_k\gamma^\mu\vec{\sigma} L_l]$$

An EFT interpretation: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

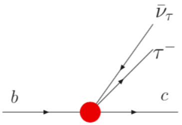
$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

- Two ops. with left-handed doublets

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu\vec{\sigma} Q_j][\bar{L}_k\gamma^\mu\vec{\sigma} L_l]$$

- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F for $b \to c\tau\nu$)



An EFT interpretation: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

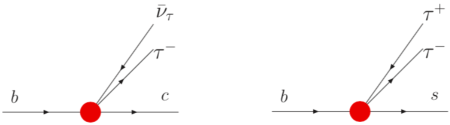
$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

- Two ops. with left-handed doublets

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu\vec{\sigma}Q_j][\bar{L}_k\gamma^\mu\vec{\sigma}L_l]$$

- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F for $b \to c\tau\nu$)
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$ [Capdevila, Crivellin, SDG, Hofer, Matias]
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K^{(*)}\nu\nu$, Z decays, direct production in $\tau\tau$



An EFT interpretation: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

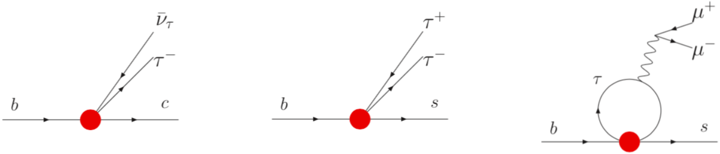
$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

- Two ops. with left-handed doublets

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu\vec{\sigma}Q_j][\bar{L}_k\gamma^\mu\vec{\sigma}L_l]$$

- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F for $b \to c\tau\nu$)
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$ [Capdevila, Crivellin, SDG, Hofer, Matias]
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K^{(*)}\nu\nu$, Z decays, direct production in $\tau\tau$
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\rm U}_9$



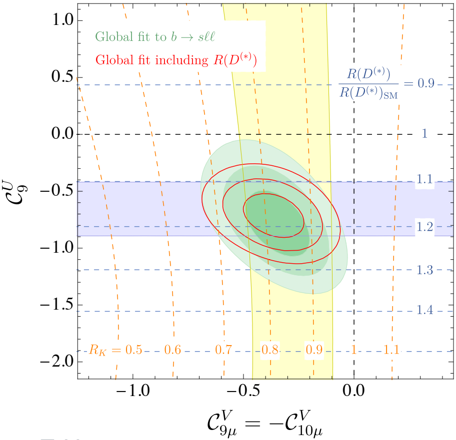
An EFT interpretation: *B* anomalies

Scenario LFU + LFUV NP (Sc 8)

- $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$ from small $\mathcal{O}_{2322}$ $[b \to s\mu\mu]$
- $\mathcal{C}_9^{\rm U}$ from radiative corr from large $\mathcal{O}_{2333}$ $[b \to c\tau\nu$ and $b \to s\mu\mu]$

Generic flavour struct and NP at scale Λ

$$\mathcal{C}_9^{\rm U} \approx 7.5 \left(1 - \sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)};\rm SM}}}\right) \times \left(1 + \frac{\log(\Lambda^2/(1\,\mathrm{TeV}^2))}{10.5}\right)$$



- Agreement with (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV
- Scenario 8 has Pull$_{rmSM}$ of 7.4 σ once R_{D^*} included
- Huge ehhancement of $b \to s\tau\tau$ modes $O(10^{-4})$ [Capdevila, Crivellin, SDG, Hofer, Matias]

$$\mathrm{Br}(B_s \to \tau^+\tau^-)_{\rm LHCb} \leq 6.8\times10^{-3}, \quad \mathrm{Br}(B \to K\tau^+\tau^-)_{\rm Babar} \leq 2.25\times10^{-3}$$

Conclusions

Conclusions

New $B \to K^* \mu\mu$ data a very reassuring confirmation of the situation in $b \to s\ell\ell$

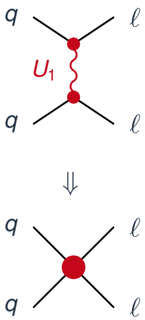
- Increased consistency between $B \to K^* \mu\mu$ data and the rest of the global fit, in particular between R_K and P_5'
- Increase in the pull_{SM} of the favoured scenarios, no change in hierarchy of scenarios
- Possibility of right-handed currents in several favoured scenarios
- Possibility of LFU contributions, in good agreement with simple EFT interpretations combining $b \to c\ell\nu$ and $b \to s\ell\ell$ anomalies
- Significant decrease of the p-value of the SM

Backup slides

Simplified U_1-leptoquark model

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

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



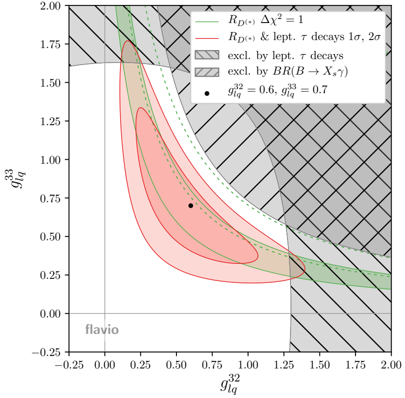
- Generates **semi-leptonic operators at tree-level**

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

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

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

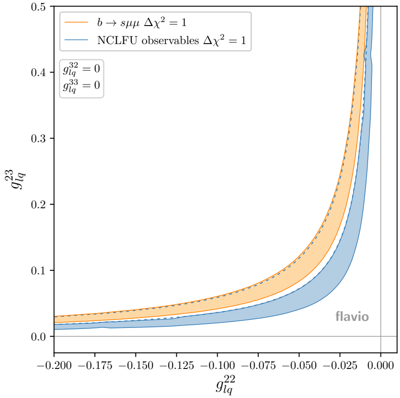
Simplified U_1-leptoquark model



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

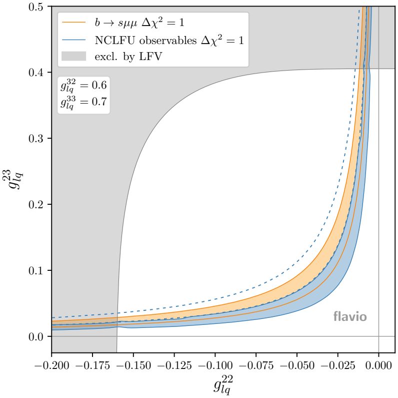
$$g_{lq}^{32} = 0.6, \qquad g_{lq}^{33} = 0.7$$

Simplified U_1-leptoquark model



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

Simplified U_1-leptoquark model

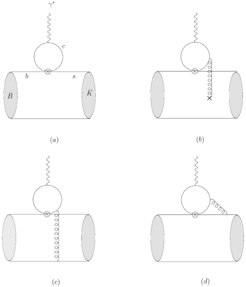


- $R_{K^{(*)}}$ can be explained by **muonic couplings g_{lq}^{22}, g_{lq}^{23}**
- **Vanishing tauonic couplings**: Tension between fits to $R_{K^{(*)}}$ and $b \to s\mu\mu$ observables after Moriond 2019
- Benchmark point explaining $R_{D^{(*)}}$,

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

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

Pending questions



- Estimate of soft-gluon $c\bar{c}$ contribution from Light-Cone Sum Rules
  - Several $c\bar{c}$ contributions, with hard and soft gluons (hard to estimate)
  - Soft-gluon correction from LCSR smaller than thought ? [Gubernari, Van Dyk]
  - Impact on contribution to be worked out (not used at face value in fits)

- Narrow-width approx for form factors
  - Not problem for K or ϕ, but for K^* ?
  - Lattice QCD : other collaborations ?
  - K^*-meson LCSR: not able to catch the effect (need to use $K\pi$ DAs)
  - B-meson LCSR: universal 10% effect, increasing SM discrepancy

[Khodjamirian, SDG, Virto]