Accomplishments and mysteries in quark flavour physics (KM50), 10 Feb. 2023

Status of Lepton Flavour Universality Violation in $b \to sll$ data

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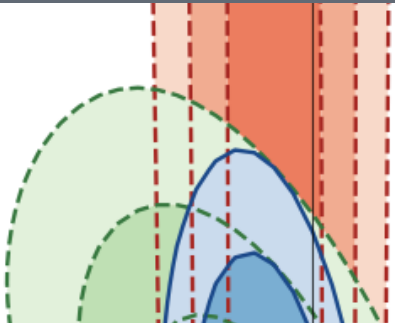


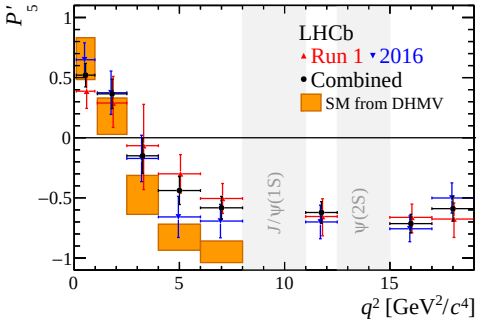
The $b \to s\ell\ell$ anomalies

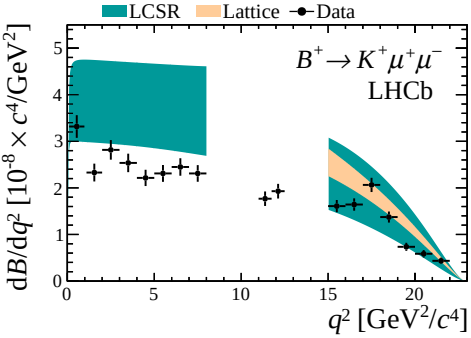
$b \to s\,\mu^+\mu^-$ anomaly

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

- Angular observables in $B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^-$ 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





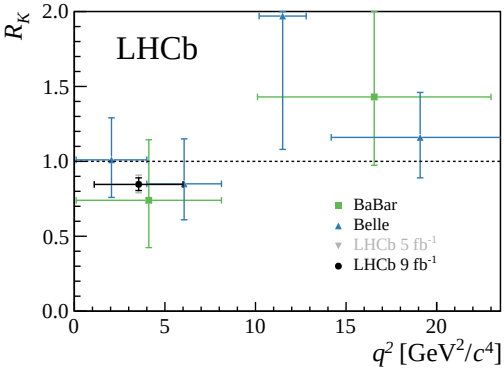
*: based on hadronic assumptions on which there is no theory consensus yet

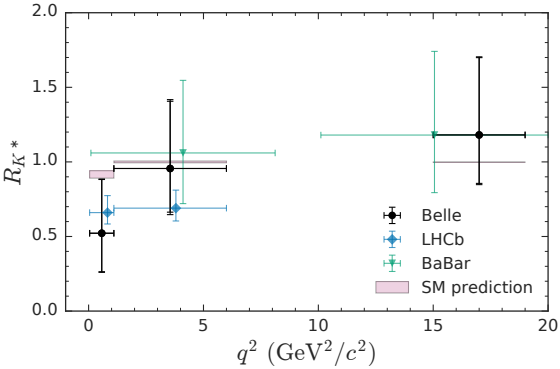
LFU violation in $b \to s\,\ell^+\ell^-$ decays (up to Dec. 2022)

Measurements of lepton flavour 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

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



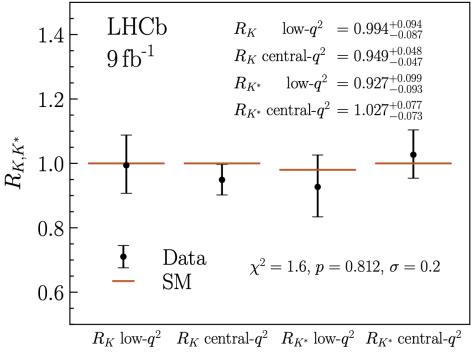


LFU violation in $b \to s\,\ell^+\ell^-$ decays

New LHCb measurement of the LFU ratios $R_K^{[0.1,1.1]}$, $R_K^{[1.1,6]}$, $R_{K^*}^{[0.1,1.1]}$, $R_{K^*}^{[1.1,6]}$

LHCb, arXiv:2212.09152, arXiv:2212.09153.

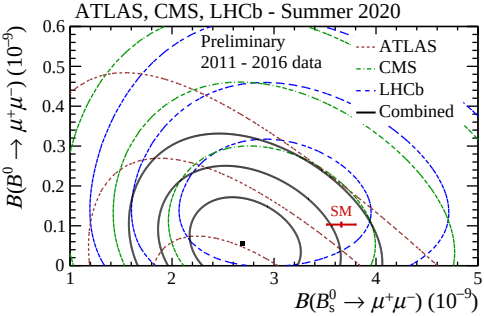
- sample of B meson decays in pp collisions collected between 2011 and 2018 (integrated luminosity of 9 fb^{-1})
- new modelling of residual backgrounds due to misidentified hadronic decays
- deviations from SM by ~ -0.0, $+1.1$, $+0.5$ and -0.4σ

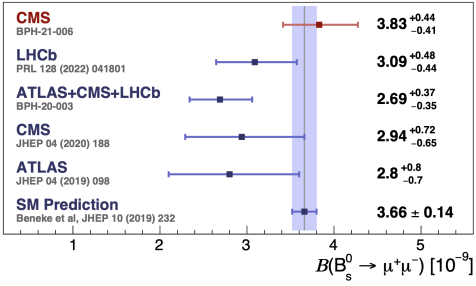


Leptonic modes $B_{s,d} \to \mu^+\mu^-$

Measurements of $\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$ by LHCb, CMS, and ATLAS show deviations of only about $\sim 1\sigma$ with respect to SM predictions*

ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127,**2212.10311**
LHCb, arXiv:1703.05747,2108.09283





ATLAS update missing $\Rightarrow$ full Run 1 + Run 2 LHC combination

*: depends on parameters like V_{cb}

Bobeth, Buras, arXiv:2104.09521

Theoretical Framework

$b \to s\ell\ell$ in the Weak Effective Theory

- Effective Hamiltonian at scale m_b: $\mathcal{H}_{\text{eff, sl}} = \mathcal{H}_{\text{eff, sl}} + \mathcal{H}_{\text{eff, had}}$

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

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

$$O_7^{(\prime)} = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b)\, F^{\mu\nu}\,, \quad O_9^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)\,, \quad O_{10}^{(\prime)\ell} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,.$$

$$C_7^{\text{SM}} \simeq -0.3\,, \qquad C_9^{\text{SM}} \simeq 4\,, \qquad C_{10}^{\text{SM}} \simeq -4\,.$$

Not considered here: (pseudo)scalar $O_{P,S}$ vanish in SM, could appear at dim. 6 in SMEFT (and tensor O_T only at dim. 8 in SMEFT)

- **Hadronic operators**:

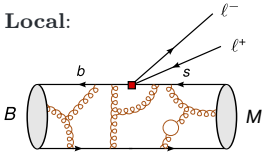
$$\mathcal{H}_{\text{eff, had}} = -\mathcal{N} \frac{16\pi^2}{e^2} \left(C_8 O_8 + C_8' O_8' + \sum_{i=1,\ldots,6} C_i O_i \right) + \text{h.c.}$$

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

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

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

Local:

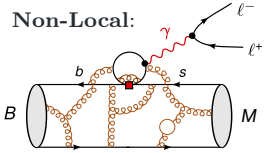


$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2}\,C_7\langle M|\bar{s}\,\sigma^{\mu\nu}q_\nu\,P_R\,b|B\rangle + C_9\langle M|\bar{s}\,\gamma^\mu\,P_L\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_A^\mu = C_{10}\langle M|\bar{s}\,\gamma^\mu\,P_L\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

$$\mathcal{A}_{S,P} = C_{S,P}\langle M|\bar{s}\,P_R\,b|B\rangle + (P_L \leftrightarrow P_R, C_i \to C_i')$$

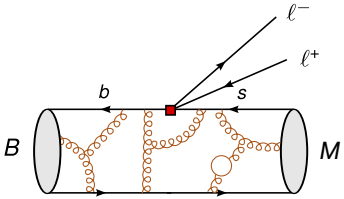
Non-Local:



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

- **Wilson coefficients** $C_i = C_i^{\rm SM} + C_i^{\rm NP}$:
  perturbative, short-distance physics (q^2 independent), well-known in SM, parameterise heavy NP
- **local** and **non-local hadronic matrix elements**:
  non-perturbative, long-distance physics (q^2 dependent), **main source of uncertainty**

Local matrix elements



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

$$\mathcal{A}_A^\mu = C_{10} \langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \rightarrow C_i')$$

$$\mathcal{A}_{S,P} = C_{S,P} \langle M|\bar{s}\, P_R\, b|B\rangle + (P_L \leftrightarrow P_R, C_i \rightarrow C_i')$$

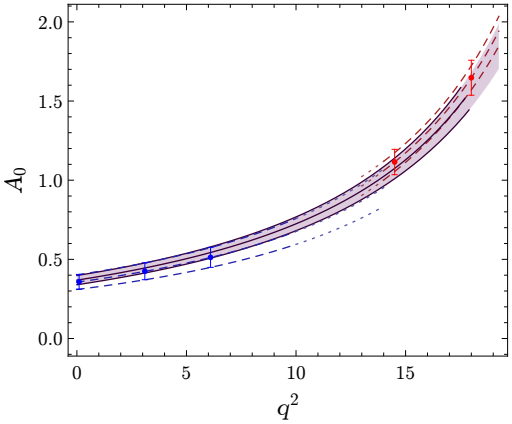
- $\langle M|\bar{s}\,\Gamma_i\, b|B\rangle$ matrix elements are parameterised by:
  - **3 form factors** for each **spin zero** final state $M = \boldsymbol{K}$
  - **7 form factors** for each **spin one** final state $M = \boldsymbol{K^*}, \boldsymbol{\phi}$
- Determination of form factors
  - high 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 (LCSR)

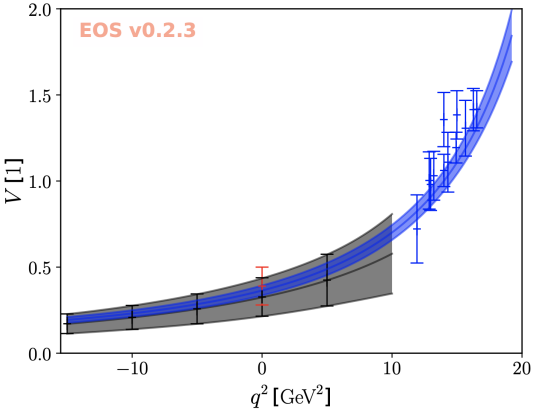
    Ball, Zwicky, arXiv:hep-ph/0406232
    Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
    Bharucha, Straub, Zwicky, arXiv:1503.05534
    Gubernari, Kokulu, van Dyk, arXiv:1811.00983
  - low + high q^2: Combined fit to **continuum methods + lattice**

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

Form factors $B \to V$ $(V = K^*, \phi)$



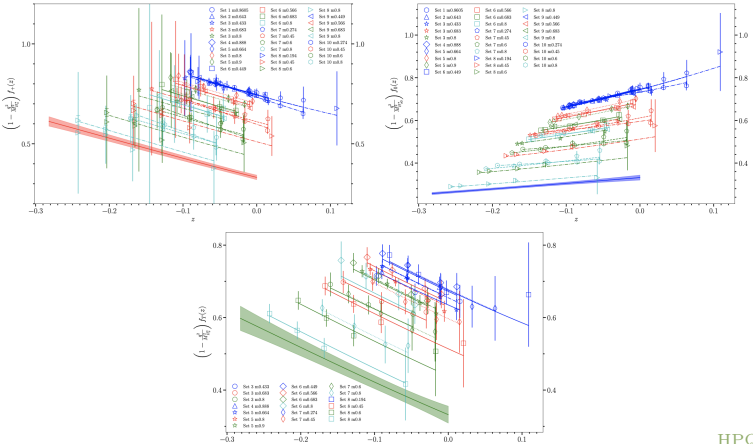
Bharucha, Straub, Zwicky, arXiv:1503.05534



Gubernari, Kokulu, van Dyk, arXiv:1811.00983

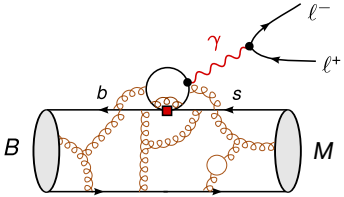
Form factors $B \to K$

- Lattice QCD calculation of the $B \to K$ form factors **across the full physical** q^2 range
  - ⇒ highly improved staggered quark (HISQ) formalism (valence quarks)
  - ⇒ gluon field configurations by MILC
  - ⇒ first fully relativistic calculation, using the heavy-HISQ method



HPQCD, arXiv:2207.12468

Non-local matrix elements



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

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

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

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

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

Theory setup

Improved QCDF

Improved QCDF (iQCDF) approach: $m_b \to \infty$ and $E_{V,P} \to \infty$ ($V = K^*$, ϕ, $P = K$) decomposition of full form factors (FF)

$$F^{\text{Full}}(q^2) = F^{\infty}(\xi_\perp(q^2), \xi_\parallel(q^2)) + \Delta F^{\alpha_s}(q^2) + \Delta F^{\Lambda}(q^2)$$

where F stands for any FF (either helicity or transversity basis)

Charles et al; hep-ph/9901378
Beneke, Feldman; hep-ph/0008255
Descotes-Genon, Hofer, Matias, Virto; arXiv:1407.8526

- $m_b \to \infty$ and $E_{V,P} \to \infty$ symmetries: low-q^2 and LO in α_s and Λ/m_b

  $\Rightarrow$ **Dominant correlations** automatically taken into account (important for a maximal cancellation of errors)

  Capdevila, Descotes-Genon, Hofer, Matias; arXiv:1701.08672

- $\mathcal{O}(\alpha_s)$ corrections $\Rightarrow$ QCDF

$$\langle \ell^+\ell^- \bar{K}_i^* | \mathcal{H}_{\text{eff}} | \bar{B} \rangle = \sum_{a,\pm} C_{i,a}\xi_a + \Phi_{B,\pm} \otimes T_{i,a,\pm} \otimes \Phi_{K^*,a} \quad (i = \perp, \parallel, 0)$$

Beneke, Feldman; hep-ph/0008255
Beneke, Feldman, Seidel; hep-ph/0106067

- $\mathcal{O}(\Lambda/m_b)$ corrections $\Rightarrow$ $\Delta F^{\Lambda}(q^2) = a_F + b_F \dfrac{q^2}{m_B^2} + c_F \dfrac{q^4}{m_B^4}$

Jäger, Camalich; arXiv:1212.2263
Descotes-Genon, Hofer, Matias, Virto; arXiv:1407.8526

Estimating beyond QCDF contribution at low-q^2

- LO (factorisable) charm-loop contribution accounted for in the $Y(q^2)$ (perturbative) function,

$$C_9^{\rm eff}(q^2) = C_9^{\rm SM} + Y(q^2)$$

Buras, Münz; hep-ph/9501281
Krüger, Lunghi; hep-ph/0008210

- Estimate of the soft-gluon emission contribution at low q^2:

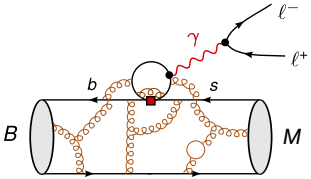
  ⇒ Calculations based on continuum methods

Khodjamirian, Mannel, Pivovarov, Wang; arxiv:1006.4945
Gubernari, van Dyk, Virto; arxiv:2011.09813

  ⇒ Shift in $C_9^{\rm eff}$. Order of magnitude for the shift estimated from theory calculations

$$C_{9\,i}^{\rm eff}(q^2) = C_9^{\rm eff}(q^2) + C_9^{\rm NP} + s_i \delta C_9^{{\rm LD},i}(q^2) \quad (i = \perp, \parallel, 0)$$

Descotes-Genon, Hofer, Matias, Virto; arxiv:1407.8526
Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239



Estimating beyond QCDF contribution at low-q^2

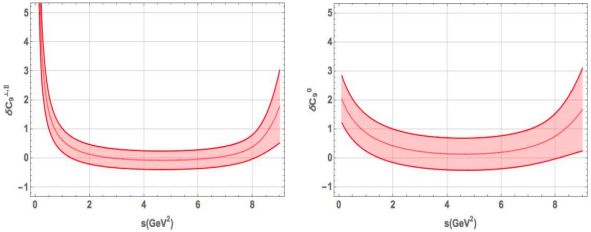
- Parameterisation for the long-distance contribution

$$\delta C_9^{\mathrm{LD},\perp}(q^2) = \frac{a^\perp + b^\perp q^2 (c^\perp - q^2)}{q^2 (c^\perp - q^2)} \qquad \delta C_9^{\mathrm{LD},\parallel}(q^2) = \frac{a^\parallel + b^\parallel q^2 (c^\parallel - q^2)}{q^2 (c^\parallel - q^2)}$$

$$\delta C_9^{\mathrm{LD},0}(q^2) = \frac{a^0 + b^0 (q^2 + s_0)(c^0 - q^2)}{(q^2 + s_0)(c^0 - q^2)}$$

$\Rightarrow$ We vary s_i in the range $[-1, 1]$

$\Rightarrow$ a^i, b^i, c^i parameters floated according to KMPW calculation



Khodjamirian, Mannel, Pivovarov, Wang, arXiv:1006.4945
Descotes-Genon, Hofer, Matias, Virto; arxiv:1407.8526
Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239

Summary theory framework

Theory status up to Dec. 2022

- Pseudoscalar channels: $B \to K\ell\ell$
  - ⇒ Local form factors: improved QCDf with KMPW LCSRs (low-q^2), Lattice QCD (high-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs
- Vector channels: $B \to \{K^*, \phi\}\,\ell\ell$
  - ⇒ Local form factors: improved QCDf with KMPW LCSRs (low-q^2), Lattice QCD (high-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs

Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239
Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921

Updated theory status

- Pseudoscalar channels: $B \to K\ell\ell$
  - ⇒ Local form factors: Lattice QCD (all-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs
- Vector channels: $B \to \{K^*, \phi\}\,\ell\ell$
  - ⇒ Local form factors: improved QCDf based on GKvD LCSRs (low-q^2), Lattice QCD (high-q^2)
  - ⇒ Non-local form factors: parametrisation based on KMPW LCSRs

Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; In Preparation

Non-negligible impact on $B \to K\ell\ell$ observables

Predictions with HPQCD'22 Form Factors			
$10^7 \times \mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 0.98]$	0.325 ± 0.025	0.29 ± 0.02	$+1.0$
$[1.1, 2]$	0.334 ± 0.025	0.21 ± 0.02	$+4.0$
$[2, 3]$	0.371 ± 0.028	0.28 ± 0.02	$+2.5$
$[3, 4]$	0.371 ± 0.028	0.25 ± 0.02	$+3.4$
$[4, 5]$	0.371 ± 0.028	0.22 ± 0.02	$+4.5$
$[5, 6]$	0.371 ± 0.030	0.23 ± 0.02	$+4.0$
$[6, 7]$	0.372 ± 0.033	0.25 ± 0.02	$+3.3$
$[7, 8]$	0.376 ± 0.043	0.23 ± 0.02	$+3.1$
$[15, 22]$	1.150 ± 0.161	0.85 ± 0.05	$+1.8$

HPQCD, arXiv:2207.12468
LHCb, arXiv:1403.8044

Fit setup

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

- Inclusive decays
  - $B \to X_s\gamma$ ($\mathcal{B}$)
  - $B \to X_s\ell^+\ell^-$ ($\mathcal{B}$)
- Exclusive leptonic decays
  - $B_{s,d} \to \ell^+\ell^-$ ($\mathcal{B}$; $\ell = \mu$, e)
- Exclusive radiative/semileptonic decays
  - $B \to K^*\gamma$ ($\mathcal{B}$, $S_{K^*\gamma}$, A_I)
  - $B^{(0,+)} \to K^{(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu$, R_{K^+}, R_{K_S}, angular observables)
  - $B^{(0,+)} \to K^{*(0,+)}\ell^+\ell^-$ ($\mathcal{B}_\mu$, $R_{K^{*0}}$, $R_{K^{*+}}$, angular observables)
  - $B_s \to \phi\mu^+\mu^-$ ($\mathcal{B}$, angular observables)
  - $\Lambda_b \to \Lambda\mu^+\mu^-$ ($\mathcal{B}$, angular observables) (not included)
- Fits might include ~ 250 observables $\Rightarrow$ **global** $b \to s\ell\ell$ analyses

Statistical framework

We parametrise the Wilson coefficients as,

$$C_i = C_i^{\rm SM} + C_i^{\rm NP} \quad (i = 7_\mu^{(\prime)}, 9_\mu^{(\prime)}, 10_\mu^{(\prime)},\, C_i^{\rm NP} \in \mathbb{R} \Rightarrow \text{no CPV})$$

Standard frequentist fit to the NP contributions to the Wilson coefficients,

$$\chi^2(C_i^{\rm NP}) = \left(\mathcal{O}^{\rm th}(C_i^{\rm NP}) - \mathcal{O}^{\rm exp}\right)_i Cov_{ij}^{-1} \left(\mathcal{O}^{\rm th}(C_i^{\rm NP}) - \mathcal{O}^{\rm exp}\right)_j$$

- Both **theory and experiment** contribute to the covariance matrix
  $\Rightarrow Cov = Cov^{\rm th} + Cov^{\rm exp}$
- Experimental covariance
  $\Rightarrow$ **Experimental correlations** between observables (if not provided, assumed uncorrelated). Assume gaussian errors (symmetrize if needed)
- Theoretical covariance
  $\Rightarrow$ Compute the **theoretical correlations** by performing a multivariate gaussian scan over all nuisance parameters
- $Cov = Cov(C_i)$
  $\Rightarrow$ **Mild** dependency $\Rightarrow Cov = Cov_{\rm SM} \equiv Cov(C_i = 0)$

Descotes-Genon, Hofer, Matias, Virto; arxiv:1510.04239
Capdevila, Crivellin, Descotes-Genon, Matias, Virto; arxiv:1704.05340

New Physics interpretation

1D NP fits

	Global (Jul. 2022)			
1D Hyp.	bfp	1σ	Pull_{SM}	p-value (%)
$C_{9\mu}^{\text{NP}}$	-0.67 (-1.01)	[-0.83,-0.52] $([-1.15, -0.87])$	4.5 (7.0)	19.6 (24.0)
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$	-0.19 (-0.45)	[-0.25, -0.12] $([-0.52, -0.37])$	3.0 (6.5)	9.5 (16.9)
$C_{9\mu}^{\text{NP}} = -C_{9\mu}^{\prime}$	-0.49 (-0.92)	[-0.67, -0.32] $([-1.07, -0.75])$	3.1 (5.7)	10.0 (8.2)
	LFUV			
1D Hyp.	bfp	1σ	Pull_{SM}	p-value (%)
$C_{9\mu}^{\text{NP}}$	-0.21 (-0.87)	$[-0.39, -0.04]$ $([-1.11, -0.65])$	1.2 (4.4)	92.4 (40.7)
$C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$	-0.08 (-0.39)	$[-0.15, -0.01]$ $([-0.48, -0.31])$	1.1 (5.0)	91.5 (73.5)
$C_{9\mu}^{\text{NP}} = -C_{9\mu}^{\prime}$	-0.04 (-1.60)	$[-0.26, 0.15]$ $([-2.10, -0.98])$	0.2 (3.2)	87.5 (8.4)

⇒ Substantial drop in significances

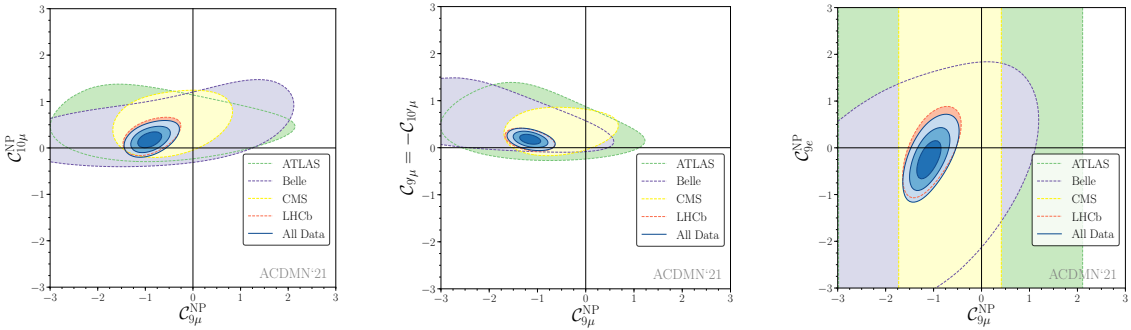
⇒ $C_{9\mu}^{\text{NP}}$ is the strongest signal for the Global fit

⇒ p-value for $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$ reduces significantly (less fit coherence: ang. obs. vs LFU ratios)

⇒ NP contributions to the WC compatible with SM values for the LFUV fit

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921
Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; In preparation

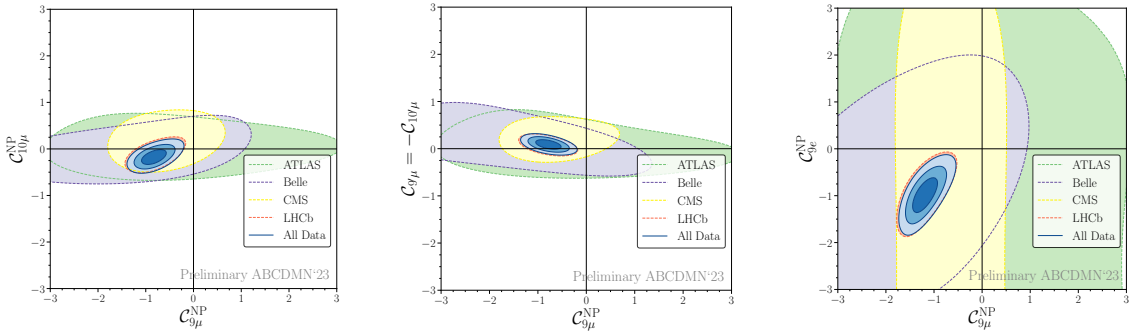
2D NP fits (up to Jul. 2022)



- 3σ regions experiment by experiment
- $\text{Pulls}_{\rm SM}$ (p-values): 6.8σ (25.6%), 7.1σ (31.8%) & 6.7σ (23.8%) (respectively)
- High significances for NP solutions with right-handed currents (RHC)
- $C_{9e}^{\rm NP}$ compatible with SM

Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; arxiv:2104.08921

Updated 2D NP fits



- 3σ regions experiment by experiment
- Pulls$_{\rm SM}$ (p-values): 4.4σ (21.6%), 4.3σ (20.5%) & 5.6σ (40.4%) (respectively)
- Drop in significance for NP solutions with RHC (compatible with SM)
- $C_{9e}^{\rm NP}$ increases. Compatible with LFU NP

Algueró, Biswas, Capdevila, Descotes-Genon, Matias, Novoa-Brunet; In Preparation

Are we overlooking LFU NP?

⇒ Rotation of the basis of operators with a **LFU-LFUV alignment** (instead of flavour)

$$C_{i\ell}^{\rm NP} = C_{i\ell}^{\rm V} + C_i^{\rm U} \quad (C_i^{\rm U} \text{ the same } \forall \ell)$$

where $i = 9, 10, 9', 10'$ and $\ell = e, \mu$ (trivial extension to $\ell = \tau$)

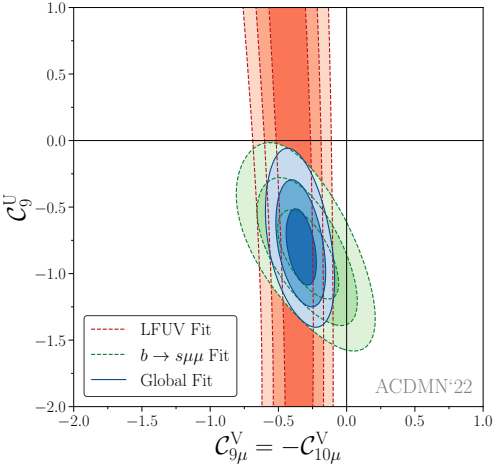
⇒ The NP parameter space can be equally described with $\{C_{i\mu}^{\rm NP}, C_{ie}^{\rm NP}\}$ or $\{C_{i\mu}^{\rm V}, C_i^{\rm U}\}$ ($C_{ie}^{\rm V} = 0$)

⇒ The LFU vs LFUV language generates non-obvious NP directions in the μ vs e language

$$\left\{ \begin{array}{l} C_{9\mu}^{\rm V} = -C_{10\mu}^{\rm V} \\ C_9^{\rm U} \end{array} \right. \Rightarrow \left\{ \begin{array}{l} C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} + C_{9e}^{\rm NP} \\ C_{9e}^{\rm NP} \end{array} \right.$$

Algueró, BC, Descotes-Genon, Masjuan, Matias; arxiv:1809.08447

NP fits with LFU contributions (up to Jul. 2022)

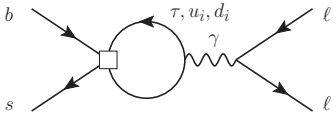


WET at 4.8 GeV

- Two-parameter fit in space of $C_{9\mu}^{\rm V} = -C_{10\mu}^{\rm V}$ and $C_9^{\rm U}$

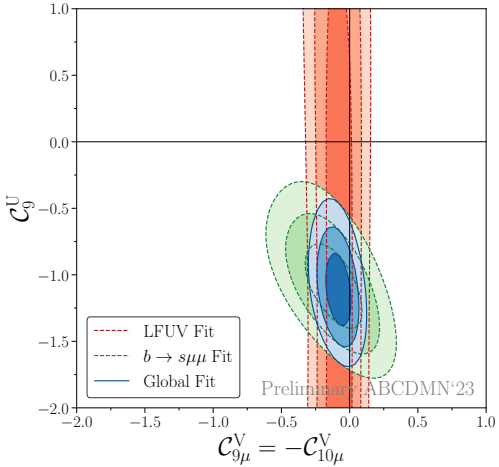
  scenario first considered in Algueró et al., arXiv:1809.08447

- Significant preference for **non-zero** $C_9^{\rm U}$
- This scenario is one of the most successful NP solutions to solve the $b \to s\ell\ell$ anomalies
  - ⇒ $\text{Pull}_{\rm SM} = 7.2\sigma$
  - ⇒ It successfully describes, with optimal internal consistency, $b \to s\mu\mu$ angular data + LFU ratios
  - ⇒ Could be mimicked by hadronic effects
  - ⇒ Can arise from RG effects:



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

NP fits with LFU contributions

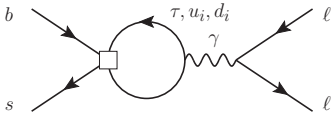


WET at 4.8 GeV

- Two-parameter fit in space of $C_{9\mu}^{\rm V} = -C_{10\mu}^{\rm V}$ and $C_9^{\rm U}$

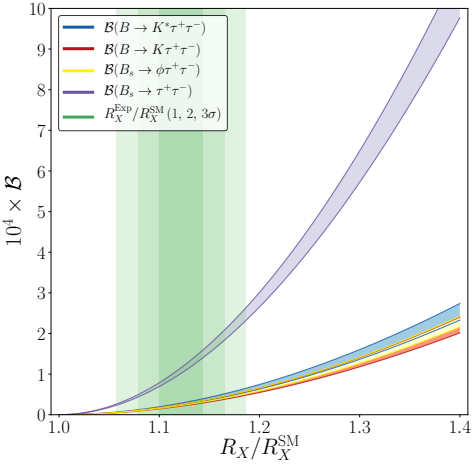
  scenario first considered in Algueró et al., arXiv:1809.08447

- Large **non-zero** $C_9^{\rm U}$ but LFUV compatible with 0
- This scenario is one of the most successful NP solutions to solve the $b \to s\ell\ell$ anomalies
  - ⇒ $\text{Pull}_{\rm SM} = 5.6\sigma$
  - ⇒ It successfully describes, with optimal internal consistency, $b \to s\mu\mu$ angular data + LFU ratios
  - ⇒ Could be mimicked by hadronic effects
  - ⇒ Can arise from RG effects:



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

$b \to s\tau\tau$ as a proof of universal NP



⇒ $b \to s\tau\tau$ channles are enhanced under the presence of $C_9^{\rm U}$

⇒ $C_9^{\rm U}$ of the size of the contribution from the correlation between $b \to s\ell\ell$ and $b \to c\ell\nu$

⇒ Typical enhancement by 10^2-10^3 compared to SM value.

Capdevila, Crivellin, Descotes-Genon, Hofer, Matias; arxiv:1712.01919

Conclusions

Conclusions

- Important tensions in the inner structure of the fit:
  - ⇒ LFU ratios are SM-like
  - ⇒ $B \to K^{(*)}\mu\mu$ and branching ratios for $B \to K\mu\mu$ continue to deviate with high significance
- Substantial reduction on the significance of the most preferred NP scenarios
  - ⇒ $C_{9\mu}^{\rm NP}$ continues to be the WC where most of the NP signal is encapsulated
  - ⇒ LFUV components are mostly suppressed
  - ⇒ High significances for scenarios with universal NP $C_9^{\rm U}$
- Exploit the correlations among $b \to s\ell\ell$ and $b \to c\ell\nu$ and $b \to s\tau\tau$ to test the nature of $C_9^{\rm U}$: either NP or hadronic effects (or a combination)

Thank you!

Backup slides

Consistency over q^2

Testing the q^2 dependence of $C_9^{\rm NP}$ by means of data:

- Fit to $B \to K^* \mu^+ \mu^-$ ($\mathcal{B}$'s + Ang. obs) + $B_s \to \mu^+ \mu^-$ + $B \to X_s \mu^+ \mu^-$ + $b \to s\gamma$
- $C_9^{\rm NP}$ bin-by-bin fit (assuming KMPW-like $\delta C_9^{{\rm LD},i}(q^2)$)
- Good agreement with global fit (2σ range)
- No indication of a strong q^2 dependence
- Consistency large and low recoil (different theo. treatments)