ON THE SIGNIFICANCE OF THE FLAVOUR ANOMALIES:

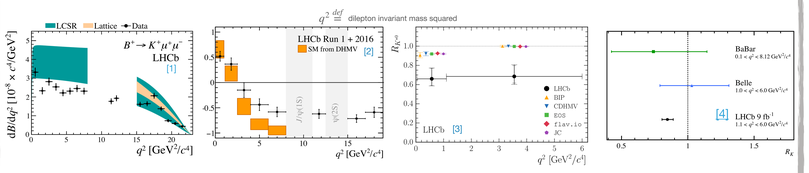
A general EFT description of $b \to s\ell\ell$ lepton universality ratios

Gino Isidori[1], Davide Lancierini[1], Abhijit Mathad[1], Patrick Owen[1], Nicola Serra[1] and Rafael Silva Coutinho[1]

Physik-Institut, Universität Zürich, CH-8057 Zurich, Switzerland

(1) Motivation:

- Recent experimental results on $b \to s\ell\ell$ measurements have shown a pattern of deviations with respect to Standard Model (SM) predictions:



- Aim to give robust determination of combined statistical significance of these experimental results.
- Among these results, lepton flavour universality (LFU) ratios are particularly interesting thanks to their small SM uncertainty. [5],[6]

$$R_X \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(H_b \to X_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(H_b \to X_s e^+e^-)}{dq^2} dq^2} \qquad (1)$$

Where H_b is a b-hadron, and X_s represents a well defined hadronic system with strangeness such that the transition satisfies $\Delta B = \Delta S$

- Aim to include any LFU ratio in global $b \to s\ell\ell$ fits, even in absence of precise knowledge of the underlying hadronic structure.

(2) The EFT framework:

- Alternative hypothesis to test with respect to the SM: Short-distance interaction of New Physics (NP) origin, connecting the b and s quarks with a dilepton pair.

- SM and NP effects in $b \to s\ell\ell$ transitions are described by means of an effective Lagrangian containing only light SM fields.

$$\Delta\mathcal{L}^{b\to s\ell\ell}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V^*_{ts} V_{tb} \sum_i C_i \mathcal{O}_i + \text{h.c.}$$

Operators: long-distance (encode QCD non-perturbative effects)

Wilson Coefficients: short-distance (SM and NP effects)

- Only difference between SM and NP cases is a larger number of effective operators in a generic NP case.
- Dimension-six operators with non-vanishing tree-level matrix element are:

$$\mathcal{O}^\ell_9 = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}^\ell_{10} = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,$$
$$\mathcal{O}^{\ell\prime}_9 = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}^{\ell\prime}_{10} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,$$
$$\mathcal{O}^\ell_{\hat{S}} = (\bar{s}_L b_R)(\bar{\ell}_R\ell_L)\,, \qquad \mathcal{O}^{\ell\prime}_{\hat{S}} = (\bar{s}_R b_L)(\bar{\ell}_L\ell_R)\,.$$

Dipole operators, $\mathcal{O}^{(\prime)}_7$, are not included as they:
- Do not describe a local interaction
- Are strongly constrained by [7],[8].

(3) Method for a global significance estimate:

- To evaluate the global significance of the NP hypothesis in the $b \to s\ell\ell$ system we adopt as the test statistic the log likelihood ratio:

$$\Delta\chi^2 = -2\log\frac{\mathcal{L}(X|\Delta\hat{C}^U_9, C^{\text{SM}}_i)^*}{\mathcal{L}(X|\hat{C}_i)}$$

- SM Pseudo-experiments (PE) are generated, varying the measurement according to the experimental uncertainty.
- For each PE the full set of C_i is fitted [13] and the $\Delta\chi^2$ between the best fit $\hat{C}_i$ and the SM prediction $(\Delta\hat{C}^U_9, C^{SM}_i)$ is calculated.
- Data are fitted in the same way as PE and the $\Delta\chi^2$ distribution is used to calculate the p-value.

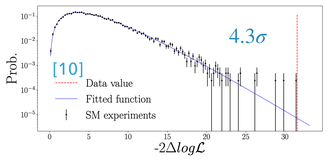
* Note on hadronic uncertainties:

We separate non-local contributions due to intermediate charm states from non-universal NP contributions:

$$C^e_i = C^{\text{SM}}_i + \Delta C^U_i\,,$$
$$C^\mu_i = C^{\text{SM}}_i + \Delta C^U_i + \Delta C^\mu_i$$

And adopt a conservative attitude towards theoretical uncertainties treating $\Delta\hat{C}^U_9$ as a SM nuisance parameter

- Using this set of observables, we obtain:
  - R_K, R_{K^*} [4] [3]
  - $B^0_s \to \mu^+\mu^-$ [9]
  - Angular distributions [2] in $B^0 \to K^{*0}\mu^+\mu^-$



(4) Extension to a generic LFU ratio:

Adopting a basis of chirally projected operators, in the limit of massless leptons, the generic R_X ratio (1) can be expressed as [12]:

$$R_X = \frac{\left\{|C^\mu_L|^2 + |C^{\mu\prime}_L|^2 + \text{Re}\left[\langle\eta^0_X\rangle C^{\mu*}_L C^{\mu\prime}_L + C^*_7\left(\langle\eta^{77}_X\rangle C_7 + \langle\eta^{79}_X\rangle C^\mu_L + \langle\eta^{79\prime}_X\rangle C^{\mu\prime}_L\right)\right]\right\} + \left\{L \to R\right\}}{\left\{|C^e_L|^2 + |C^{e\prime}_L|^2 + \text{Re}\left[\langle\eta^0_X\rangle C^{e*}_L C^{e\prime}_L + C^*_7\left(\langle\eta^{77}_X\rangle C_7 + \langle\eta^{79}_X\rangle C^e_L + \langle\eta^{79\prime}_X\rangle C^{e\prime}_L\right)\right]\right\} + \left\{L \to R\right\}} \qquad (2)$$

Where $C^{\ell\,(\prime)}_{L/R} = C^{\ell\,(\prime)}_9 \mp C^{\ell\,(\prime)}_{10}$, and $\langle\eta^i_X\rangle$ channel dependent nuisance parameters

- Eq. (2) implies that $R_X \sim 1 + O(1\%)$(QED) in any model with LU Wilson Coefficients i.e.: $|R_X - 1| \neq 1$ only if $|\Delta C_i| \neq 0$, for some i:

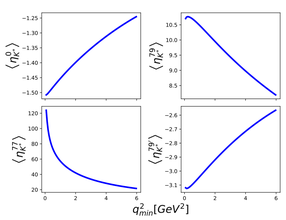
$$\Delta C_i = C^\mu_i - C^e_i\,, \qquad i = L, L', R, R'$$

- Since

$$|C^{\text{SM}}_L| = O(10) \gg |C^{\text{SM}}_7|, |C^{\text{SM}}_R|,$$
$$|C^{\ell\prime}_{L,R}|^{\text{SM}} = 0\,,$$

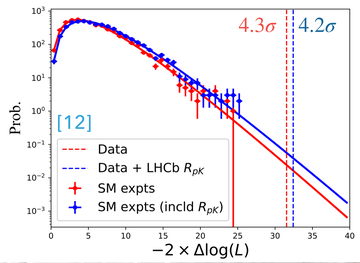
Large NP effects in R_X can arise only from non-vanishing $|\Delta C_i|$ interfering with the SM amplitude.

- Matrix element positivity implies $|\eta^0_X(q^2)| \leq 2$
- Boundaries on $\langle\eta^{7,i}_X\rangle$ parameters are determined from $B^0 \to K^{*0}\mu^+\mu^-$ channel where the impact of the dipole operator is maximal [12],[13]



(5) Global combination of current measurements

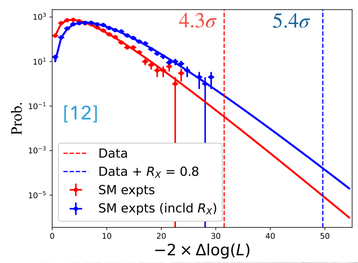
- Following the outlined method [9] we make use of Eq. (2) to add to the combination the LFU ratio R_{pK} which has been measured by the LHCb collaboration [11].
- The inclusion of R_{pK} causes as small reduction of in significance of the NP hypothesis from 4.3σ to 4.2σ.



(6) Inclusion of future measurements: two scenarios

- We estimate the impact on the significance of future measurements such as R_{pK}, $R_{K\pi\pi}$ and $R_{K\pi}$ with 9fb^{-1}.
- Uncertainties are obtained by scaling luminosity and centre of mass energy.

Scenario	NP Significance
Current data	$4.3\ \sigma$
Current data + $R_X = 0.8$	$5.4\ \sigma$
Current data + $R_X = 1.0$	$3.8\ \sigma$



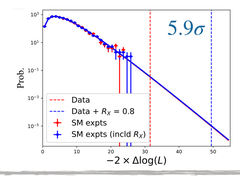
(7) Conclusions:

Two novel tools have been introduced:

- A method to evaluate the global significance for the NP interpretation of $b \to s\ell\ell$ flavour anomalies.
- The possibility to include any LFU ratio in global fits, treating the hadronic uncertainties as nuisance parameters.

These have allowed us to draw the following conclusions:

- Given the existing LFU measurements, the global significance of 4.2σ for the NP hypothesis in the $b \to s\ell\ell$ system is remarkable, even when adopting a highly conservative theory approach.
- This new approach allows to include hypothetical new measurements of $R_{K\pi\pi}$ and $R_{K\pi}$ or extrapolation to full dataset of the already published ones such as R_{pK} in assessing the global significance.



- When including the full set of observables, the hypothetical perfect knowledge of the hadronic nuisance parameters would translate in a marginal increase of significance ($5.4\sigma \to 5.9\sigma$), providing confirmation that they play a minor role in our approach.

References:

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[4] LHCb collaboration, Test of lepton universality in beauty-quark decays
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[12] Isidori et al., A general effective field theory description of b → sl+l− lepton universality ratios
[13] D. Straub et al. flavio: a Python package for flavour and precision phenomenology in the Standard Model and beyond