ON THE SIGNIFICANCE OF THE FLAVOUR ANOMALIES: A general EFT description of $b \to s\ell\ell$ lepton universality ratios

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(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]

- 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.

\[
\Delta L_{\text{eff}} = \frac{4 G_F}{4\pi} \alpha V_{tb} V_{ts} \sum_i C_i Q_i + \text{h.c.}
\]

- 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:

\[
C_{1} = (\bar{s}_L b_L)(\bar{\nu}_e \nu_e), \quad C_{10} = (\bar{s}_L b_L)(\bar{\nu}_\tau \nu_\tau), \quad C_{13} = (\bar{s}_L b_L)(\bar{\nu}_\mu \nu_\mu), \quad C_{15} = (\bar{s}_L b_L)(\bar{\nu}_\tau \nu_e).
\]

- Where $Q_i$ is a linear combination of $C_{i}$, and the $(\bar{\nu}_\mu \nu_\mu)$ channel dependent nuisance parameters.
- Eq. (2) implies that $R_{\ell\ell} = 1 + \cal{O}(\Lambda^{4}/\Lambda^{2})$ in any model with LU Wilson Coefficients i.e.: $|C_{1} - 1| \leq 1$ only if $|\Delta C_{1}| \leq 1$ for some $i$.

- $\Delta C_{1} = |C_{1} - 1|$, $i = \ell L', R, R'$

- Large NP effects in $R_{\ell\ell}$ can arise only from non-vanishing $|\Delta C_{1}|$ interfering with the SM amplitude.

(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 the test statistic the log likelihood ratio:

\[
\Delta \chi^2 = -2 \log \frac{L(X|C_1) L_{\text{SM}}}{L(X|\hat{C}_1)}
\]

- SM-Pseudo-experiments (PE) are generated, varying the measurement according to the experimental uncertainty.
- For each PE the full set of $C_{1}$ is fitted [13] and the $\Delta \chi^2$ between the best fit $C_{1}$ and the SM prediction $\Delta(C_{1}^{\text{SM}})$ is calculated.
- Data are fitted in the same way as PE and the $\Delta \chi^2$ distribution is used to calculate the p-value.

- Using this set of observables, we obtain:
- $R_{\ell\ell}, \hat{R}_{\ell\ell}$
- $B_{\ell \ell} \to \nu\mu$
- Angular distributions [2]

(4) Extension to a generic LFU ratio:

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

\[
R_{X} = \frac{\sum_{\ell=L'}^{L',R,R'} R_{\ell\ell} C_{i}^{X} + R_{\ell\ell}^{R} C_{i}^{X} + CSi + CI(\ell) + C_{i}^{i} + C_{i}^{R}}{\sum_{\ell=L'}^{L',R,R'} R_{\ell\ell}^{R} C_{i}^{X} + R_{\ell\ell}^{R} C_{i}^{X} + CSi + CI(\ell) + C_{i}^{i} + C_{i}^{R}}
\]

Where $C_{i}^{X} = C_{i}^{X} + C_{i}^{X}$, and $(\gamma\ell)$ channel dependent nuisance parameters.

- $R_{X} = 1 + \cal{O}(\Lambda^{4}/\Lambda^{2})$(QED)

(5) Global combination of current measurements

- Following the outlined method we make use of Eq. (2) to add to the combination the LFU ratio $R_{\ell\ell}$, which has been measured by the LHCb collaboration.
- The inclusion of $R_{\ell\ell}$ causes a 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 $R_{\ell\ell}$, $R_{\ell\ell}$, and $R_{\ell\ell}$ with 96σ.

- $\Delta(C_{1}^{\text{SM}})$ uncertainties are obtained by scaling luminosity and centre of mass energy.

(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 $R_{\ell\ell}$ and $R_{\ell\ell}$ or extrapolation to full dataset of the already published ones such as $R_{\ell\ell}$ 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 (3.4σ $\rightarrow$ 3.6σ), providing confidence that they play a minor role in our approach.

References:

[1] LHCb collaboration. Differential branching fractions and angular asymmetries of $B \to K\pi\ell^+\ell^-$ decay
[2] LHCb collaboration. Measurement of $C_{1}$ Averaged Observables in the $B \to K\ell^+\ell^-$ decay
[3] LHCb collaboration. Test of lepton universality with $B \to K\ell^+\ell^-$ decay
[4] LHCb collaboration. Strong constraints on the $b \to q\ell\ell$ photon polarization from 800 KeV–0.8 GeV–decays
[5] LHCb collaboration. Analysis of neutral B-meson decays into two muons
[6] Isidori et al., On the significance of new physics in $b \to s\ell\ell$–decays
[7] LHCb collaboration. Test of lepton universality with $B \to J/\psi K$–decays
[8] Isidori et al., A general effective field theory description of $b \to s\ell\ell$ leptonic universality ratios