Flavour Anomalies — Hints for BSM physics in expected and unexpected places

Danny van Dyk

Technische Universität München

Planck 2021
June 29th, 2021

Overview

Contents

- this is not a comprehensive discussion of the flavour anomalies (substantial tensions shy of $5\,\sigma$ individually)
  - aiming for an overview of a (subjective) selection of flavour anomalies
  - off the menu: $(g-2)_\mu$, Cabibbo anomaly, ...
  - provide an idea of current status of and complexity behind the flavour anomalies
- concentrating on longstanding b anomalies

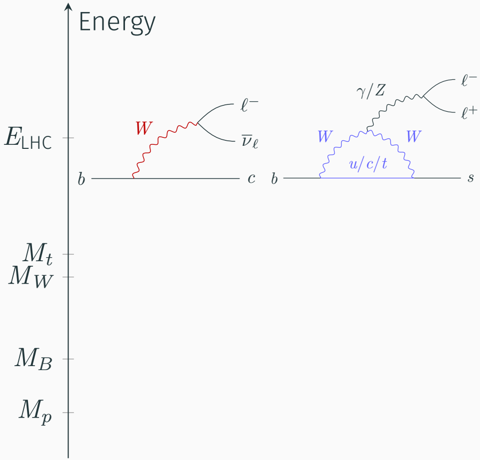
  $b \to c\tau^-\overline{\nu}$ driven by BaBar '12 & LHCb '15&'18 measurements

  $b \to s\mu^+\mu^-$ driven by LHCb '13...'21 analyses (& consistent with ATLAS, Belle, CMS)
- more in-depth discussions Wednesday afternoon
  - B anomalies at LHCb — M. Patel
  - Belle (II) status and prospects — Th. Kuhr
  - $(g-2)_\mu$ — A. Schreckenberger
  - BSM interpretation — M. Blanke

Framework

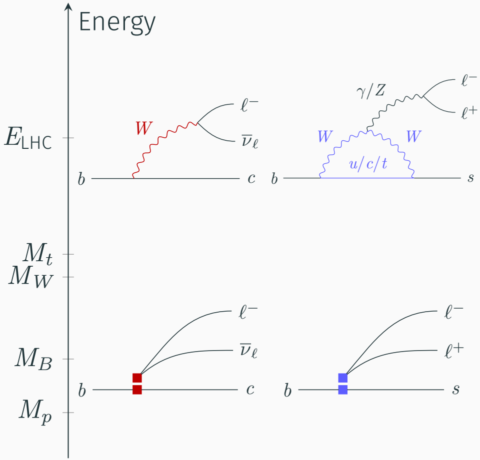
- theory predictions for b decays require an elaborate framework
- multiscale problem: m_t, m_W, m_b, Λ_{had}
- divide and conquer
  - introduce weak effective theory (WET) to separate m_t, m_W from other scales m_b, Λ_{had}
  - use renormalization group equations to understand WET at low scale $\simeq m_b$
  - compute hadronic matrix elements
    - from lattice QCD (if possible)
    - in power expansion of Λ_{had}/m_b using HQET & SCET
    - in QCD sum rules

- low-energy description of the SM and BSM models
- removes W and t, Z fields



Framework — Weak Effective Theory

- low-energy description of the SM and BSM models
- removes W and t, Z fields
- introduces dim-6 effective operators
  - dim-8 surpressed by $m_b^2/m_W^2 \sim 0.4\%$



$$\mathcal{L}^{\text{eff}} = \sum_i \mathcal{C}_i \times [\overline{s}\,\Gamma_i\,b] \times [\overline{\ell}\,\tilde{\Gamma}_i\,\nu] + \sum_j \mathcal{C}_j \times [\overline{s}\,\Gamma_j\,b] \times [\overline{\ell}\,\tilde{\Gamma}_j\,\ell]$$

$b \to c\tau^-\overline{\nu}$

- 10 operators per lepton flavour
- reduces to 5 if left-handed neutrinos assumed
  - very manageable in fits

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

- 10 $b \to s\ell\ell$ operators per lepton flavour
- additional operators required for consistent descr. at $O(\alpha_e)$
- $b \to s\{\gamma, g, \overline{q}q\}$ can all contribute to $b \to s\ell^+\ell^-$ processes
  - $b \to s\bar{q}q$ operators are presently not varied in $b \to s\mu^+\mu^-$ fits

To probe BSM physics, we need accurate knowledge of SM contributions!

$b \to c\tau^-\overline{\nu}$

- matching at tree-level
- only one non-zero coefficient
- no QCD-induced scale evolution
- e.m. radiative corrections under control [A. Sirlin '90]

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

- matching starts at one-loop [Adel,Yao hep-ph/9308349]
- QCD-induced scale dependence
- NNLO QCD matching [Greub et al. hep-ph/9703349] [Bobeth et al. hep-ph/9910220]
- partial NNLL evolution [Chetyrkin et al. hep-ph/9612313] [Bobeth et al. hep-ph/0312090] [Gorbahn,Haisch hep-ph/0411071] [Gorbahn et al. hep-ph/0504194]

- working dominantly to leading order in α_e

$\Rightarrow$ matrix elements of semileptonic operators factorize

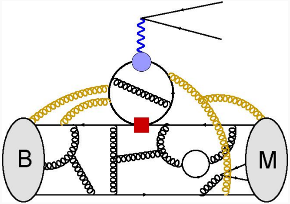
- hadronic matrix elements are discussed in terms of scalar-valued hadronic form factors

$b \to c\tau^-\overline{\nu}$ & $b \to s\mu^+\mu^-$

- number of indep. form factors depends on hadrons involved
- 3 for $P \to P\ell\ell'$
  e.g. $\overline{B} \to D\tau^-\overline{\nu}$ or $B \to K\mu^+\mu^-$
- 7 for $P \to V\ell\ell'$
  e.g. $\overline{B} \to D^*\tau^-\overline{\nu}$ or $B \to K^*\mu^+\mu^-$
- ≥ 10 for baryonic processes

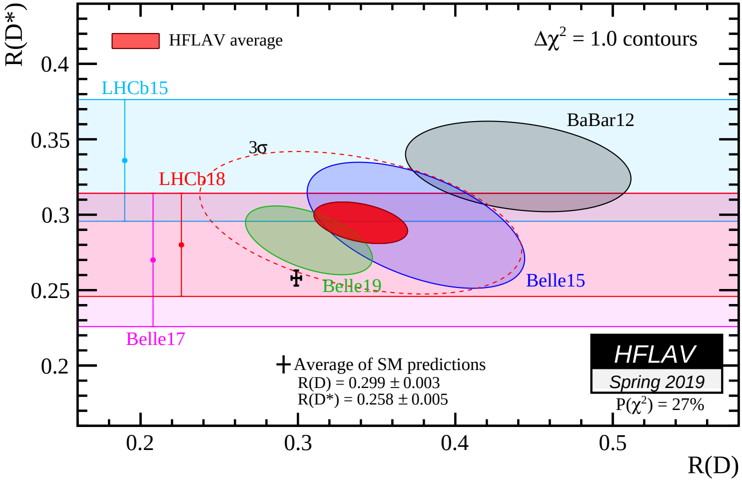
$b \to s\mu^+\mu^-$ only

- non-local contributions pollute local $b \to s\mu^+\mu^-$ interactions
- dominant: intermediate on-shell vector $\overline{c}c$



$b \to c\tau^- \overline{\mu}$

Test of Lepton-Flavour Universality (LFU) [HFLAV 1909.12524]



why is the SM prediction so precise?

$\overline{B} \to D^{(*)}$ Form Factors are Special

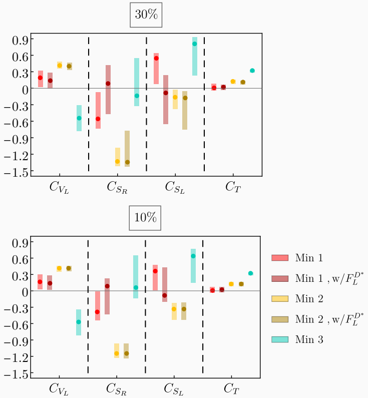
- heavy-quark expansion very effective if both quark flavours b and c are heavy [Isgur,Wise '89]
- simultaneous expansion in α_s up to NLO and $\Lambda_{\text{had}}/m_{b,c}$ up to 2nd power [Falk,Neubert hep-ph/9209268 & hep-ph/9209269]
- precice lattice QCD results for $\overline{B}_{(s)} \to D_{(s)}$ form factors in large parts of phase space [FNAL/MILC 1503.07237; HPQCD 1505.03925]
- first lattice QCD results for $\overline{B}_{(s)} \to D_{(s)}$ form factor [HPQCD 2105.11433; FNAL/MILC 2105.14019]
- consistent picture of all theory inputs to NLO & 2nd power [Bordone et al. 1908.09398 & 1912.09335]

Interpretation

global fit to $b \to c\tau^-\overline{\nu}$ data [Murgui et al. 1904.09311]

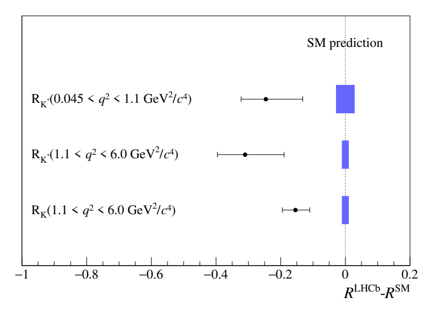
- measurements
  - R_D, R_{D^*}
  - D^* polarisation (optional)
- assumptions:
  - $\Gamma(B_c^- \to \tau^-\overline{\nu})/\Gamma(B_c^-) < X\%$
  - semi-tau. width cannot dominate $\Gamma(B_c^-)$ [Alonso et al. 1611.06676]
  - no r.h. $b \to c$ vector current, since it is lepton-flavour universal

[Cata,Jung 1505.05804]



- global fits need updating, due to new measurements and predictions
  - $R_{J/\psi}$ from semileptonic B_c decays
- LHCb is working hard on new measurements
  - R_D / combined $R_D \& R_{D^*}$ measurements
  - R_{Λ_c} will test complementary WET constraints [Böer et al. 1907.12554]
- Belle II in excellent position to contribute in near future
- a lot of work before LFU violation can be claimed!
  - anomalies tend to vanish
  - theory under good control; need more measurements!

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

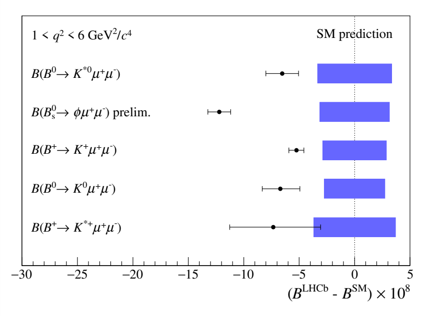


- SM predictions ~ 1 if $1\,\text{GeV}^2 \leq q^2 = m_{\ell\ell}^2 \leq 6\,\text{GeV}^2$
- LHCb meas. consistently below, with $\geq 3\,\sigma$ tensions in R_K

see talk by M. Patel

$$R_X \equiv \frac{\langle \mathcal{B}(B \to X\mu^+\mu^-)\rangle_{1,6}}{\langle \mathcal{B}(B \to Xe^+e^-)\rangle_{1,6}}$$

Anomalies in Plots

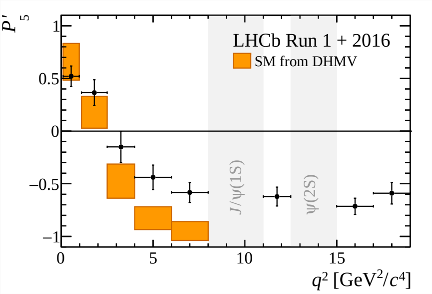


$$\langle \mathcal{B}(B \to X\mu^+\mu^-)\rangle_{1,6}$$

- SM predictions ~ 1 if $1\,\mathrm{GeV}^2 \leq q^2 = m_{\ell\ell}^2 \leq 6\,\mathrm{GeV}^2$
- LHCb meas. consistently below, with $\geq 3\,\sigma$ tensions in R_K

  see talk by M. Patel

- larger th. uncertainties for $\mathcal{B}$
- muonic $\mathcal{B}$ systematically below SM pred.



representing full kinematic distribution of $B \to K^*(\to K\pi)\mu^+\mu^-$

- SM predictions ~ 1 if $1\,\text{GeV}^2 \leq q^2 = m^2_{\ell\ell} \leq 6\,\text{GeV}^2$
- LHCb meas. consistently below, with $\geq 3\,\sigma$ tensions in R_K

see talk by M. Patel

- larger th. uncertainties for $\mathcal{B}$
- muonic $\mathcal{B}$ systematically below SM pred.

- angular observables compared in bins of q^2
- deviations significant and consistent with R_X, $\mathcal{B}$

- to LO in α_e, SM prediction differs from 1 only due to $4m_\mu^2/q^2$ factors
  - various groups agree on predictions

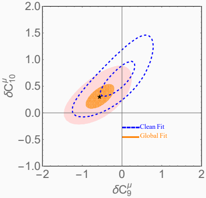
- radiative corrections
  - semi-analytic calculation of integrated R_K agree with *PHOTOS*-based simulation [Bordone,Isidori,Pattori 1605.07633]
  - double-differential distribution can suffer from large correction, requires more careful treatment compatible with current best practice [Isidori,Nabeebaccus,Zwicky 2009.00929]
  - no structure-dependent studies yet for rare semileptonic decays, but important insights gained from QED factorization studies for $B \to K\pi$ decays [Beneke,Bobeth,Szafron 1908.07011] [Beneke,Böer,Toelstede,Vos 2008.10615]

Branching Ratios

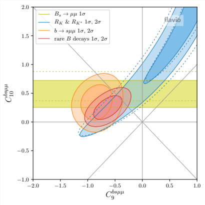
- large uncertaintes, since form factors contribute fully!
- largest deviations seen at small values of $1\,\text{GeV}^2 \leq q^2 \leq 6\,\text{GeV}^2$
  - current lattice QCD results limited to $q^2 \gtrsim 12\,\text{GeV}^2$
  - current th. predictions dominated by QCD light-cone sum rules (large uncertainties)
- first attempt to account for finite width in $K^* \to K\pi$

  [Descotes-Genon 1908.02267]
  - SM prediction grows by $\sim 20\%$, increasing tensions
  - effect cancels in ratios (LFU, ang. obs.)

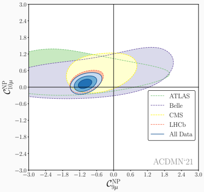
- normalization cancels hadronic form factors partially
  - theory correlations indispensable
  - using lattice QCD info if available, heavy-quark expansion if not
- major task: disentangle non-local contributions from WET coefficients C_7 & C_9
- non-local effects: using pertubative QCD at time-like momentum transfer below narrow charmonium resonances
  - a-posteriori tests seem to indicate that non-local effects are not driving the anomalies



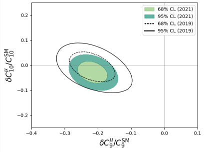
[Geng et al. 2103.12738]



[Altmannsh.,Stangl 2103.13370]

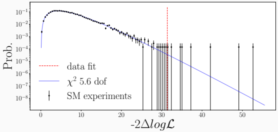


[Alguero++ 2104.08921]



[Hurth et al. 2104.10058]

- consistent interpretation, with scenario dependent tensions
- tension $> 5\,\sigma$ for all-operator fits to all data
- tension $\geq 4\,\sigma$ for fits to “clean” subset of data



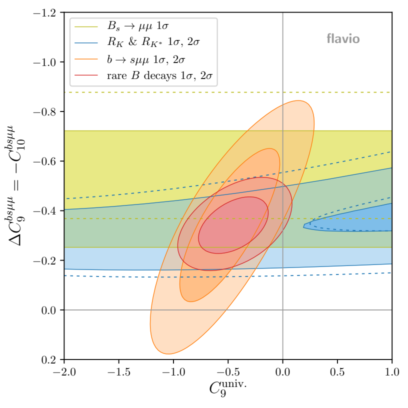
how to determine the significance?

[Lancierini et al. 2104.05631]

- fitting a few-operator scenario is not a suitable way to establish significance of a tension
  - not invariant under reparametrization
- accounting for all operators similar to Look-Elsewhere Effect

[Lancierini et al. 2104.05631]

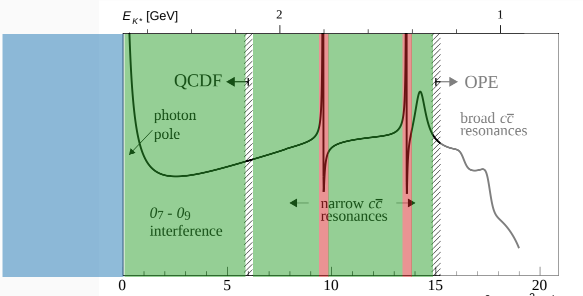
- recent conservative analysis yields global significance of $3.9\,\sigma$, despite large “trial factors“



[Altmannshofer,Stangl 2103.13370]

- ▶ several groups investigate both LFU and LFUV contrib.
- \+ tension larger than in μ-only assumption!
- – LFU part sensitive to non-local form factors
- ▶ accurate interpretation requires accurate predictions of non-local form factors

parametrize non-local effects [Bobeth et al. 1707.07305; Gubernari et al. 2011.09813]



[sketch from Blake, Gershon, Hiller 1501.03309]

- predict non-local form factors in timelike region
- extrapolate to spacelike region
- account for experimental measurements of hadronic decays
- global fit based on recent parametrization in prep.

[Gubernari,Reboud,DvD,Virto w.i.p.]

What's Next?

- LFU observables: th. very clean; e.m. radiative contributions seem under control
- confirmation seems to require measurements independent of LHCb ($\rightarrow$ Belle (II), ATLAS, CMS)

- overwhelming number of measurements for other observables, in a variety of q^2 and across LHC experiments and BaBar/Belle
- $\mathcal{B}$ & angular observables require further th. developments
  - theory uncertainties currently limiting factor in fit significances!

$$b \to c\overline{u}\{d, s\}$$

Hadronic Decays

- weak hadronic B decays notoriously difficult to predict
- exception: $\overline{B}^0 \to D^+ K^-$ and $\overline{B}_s \to D_s^+ \pi^-$ [Beneke et al. hep-ph/0006124]
  - four different quark flavours make this manageable (colour-allowed tree decay)
  - $\overline{B}_{(s)} \to D_{(s)}$ form factors from lattice QCD at high precision
  - in the SM no Λ_{had}/m_b absent; corrections start at $\Lambda_{\text{had}}^2/m_b^2$
- ratio of $\mathcal{B}$s is sensitive to f_s/f_d: ratio of B_s production over B^0 production
  - important input for measurements of $\overline{B}_s \to \mu^+\mu^-$, which enters global $b \to s\mu^+\mu^-$ fits

- ratios of $\mathcal{B}$ with identical flavour quantum numbers agree well with measurements

- however: absolute $\mathcal{B}$ show tensions in excess of 4σ

[Bordone et al. 2007.10338; Cai et al. 2103.04138]

- genuine puzzle; all explanations unlikely!
  - measurements biased toward smaller results by $\sim -30\%$
  - color- and doubly power-suppressed corrections cause $\sim -20\%$ shift at amplitude level
  - $\sim -20\%$ modification of four-quark four-flavour tree-level operators in the WET

Conclusion

Summary

- longstanding $b \to s\mu^+\mu^-$ anomalies make us #cautiouslyexcited
  - significances of the $b \to s\mu^+\mu^-$ anomalies have been increasing with growing data sets
  - LFU observables are limited by data set
  - non-LFU observables are limited by theory
    - non-local form factors single-largest syst. th. uncertainty
- $b \to c\tau^-\overline{\nu}$ anomalies seem stable
  - recent lattice QCD analyses (HPQCD, FNAL/MILC) pave road toward high-precision theory-only predictions for $\overline{B} \to D^*\tau^-\overline{\nu}$
  - looking forward to complementary measurements by LHC experiments and Belle II
- interesting puzzle in hadronic $b \to c\overline{u}\{d, s\}$ decays