Searching for NP in $b \to s\tau\tau$ decays

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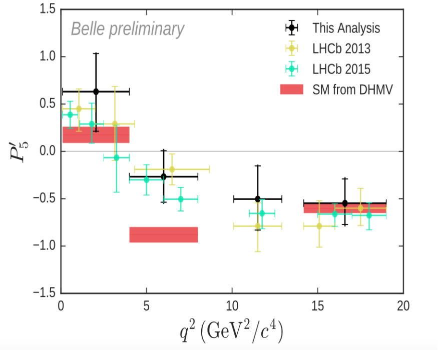
Outline

1. Experimental status. B-anomalies
2. EFT approach for $b \to c\ell\nu$ and $b \to s\tau\tau$
3. Implications for branching ratios
4. Conclusions

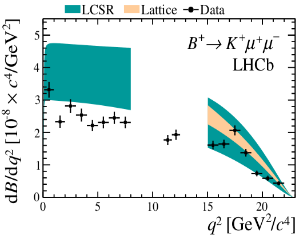
B-anomalies: $b \to s\mu\mu$

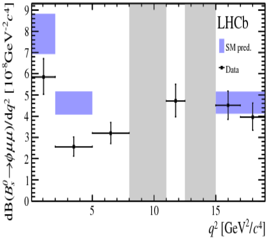
Recently, the field of semi-leptonic rare B decays has been providing some interesting anomalies.

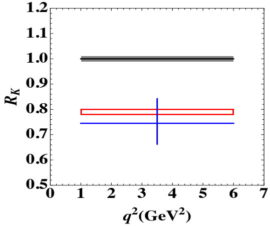


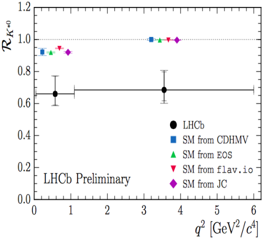
- 2013: 1fb^{-1} dataset LHCb found 3.7σ (w.r.t. SM pred).
- 2015: 3fb^{-1} dataset LHCb found 3σ (w.r.t. SM pred) in 2 bins.
- Belle confirmed it in a bin [4,8] few months ago.

B-anomalies: $b \to s\mu\mu$







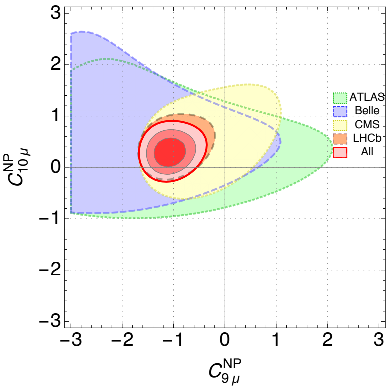


- $BR(B \to K\mu\mu)$ small compared to SM predictions.
- Deviations in $BR(B_s \to \phi\mu\mu)$.
- Several systematic low-recoil small tensions in BR_μ.
- LFUV ratios R_K & R_{K^*}.

Global analysis of $b \to s\ell\ell$ data

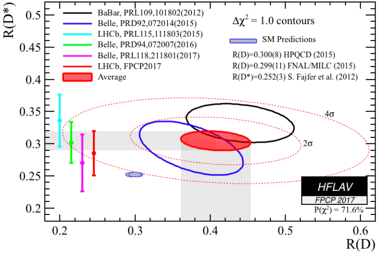
Global analysis of all the data available on $b \to s\ell\ell$ ($\ell = \mu, e$) suggest very significant signals of NP in the muon sector, especially in $C_{9\mu}$.

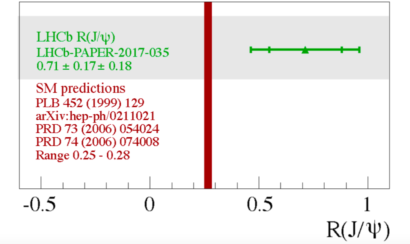
- 1D Hypothesis:
  - $\Rightarrow$ $C_{9\mu} \to 5.8\sigma$
  - $\Rightarrow$ $C_{9\mu} = -C_{10\mu} \to 5.3\sigma$
  - $\Rightarrow$ $C_{9\mu} = -C_{9'\mu} \to 5.4\sigma$
- 2D Hypothesis:
  - $\Rightarrow$ $(C_{9\mu}, C_{10\mu}) \to 5.7\sigma$
  - $\Rightarrow$ $(C_{9\mu}, C_{9'\mu}) \to 5.6\sigma$
  - $\Rightarrow$ $(C_{9\mu}, C_{10'\mu}) \to 5.7\sigma$
- 6D Hypothesis:
  - $\Rightarrow$ $(C_{7(')}, C_{9(')\mu}, C_{10(')\mu},) \to 5.0\sigma$



[BC, Crivellin, Descotes-Genon, Matias, Virto]

B-anomalies: $b \to c\ell\nu$





$b \to c\ell\nu$ LFU ratios

$$R_X = \frac{Br(B \to X\tau\nu)}{Br(B \to X\ell\bar{\nu}_\ell)}$$

with $X = D, D^*, J/\psi$

- R_D & R_{D^*} HFLAV combination of Belle, Babar & LHCb data $\Rightarrow \sim 4\sigma$ (w.r.t. SM pred).
- LHCb measured $R_{J/\psi}$ $\Rightarrow \sim 2\sigma$ (w.r.t. SM pred).

EFT approach for $b \to c\ell\nu$ transitions

$b \to c\tau\nu$ Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{b\to c\tau\nu} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+\epsilon_L)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_\tau) + \text{right handed} + \text{tensors} + \text{scalars} + \ldots\Big] + \text{hc}$$

- not too large contributions to B_c lifetime [Alonso, Grinstein, Camalich]
- q^2 distribution of R_{D^*} [Freytsis et al; Celis et al; Ivanov et al]

$\Rightarrow$ NP contributions to SM operator $(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_\tau)$ are favoured.

$\Rightarrow$ Leading to

$$\frac{R_{J/\psi}}{R_{J/\psi}^{\text{SM}}} = \frac{R_D}{R_D^{\text{SM}}} = \frac{R_{D^*}}{R_{D^*}^{\text{SM}}} = (1+\epsilon_L)^2$$

agrees well with the current experimental data!

[Bernlochner, Ligeti, Papucci, Robinson, Ruderman; Watanabe; Dutta; Alok et al.]

Gauge generation of effective operators

Assuming NP generates these contributions from a scale much larger than the electroweak symmetry breaking scale, two $SU(2)_L$-operators drive the effect,

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

with $Q(L)$ the left-handed quark(lepton) doublets and $C^{(1,3)}_{ijkl}$ the corresponding WCs. [Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

After EWSB, $\mathcal{O}^{(1,3)}_{ijkl}$ contribute to $b \to c(s)$ processes with τ-leptons and τ-neutrinos in the final state.

- $\Rightarrow$ b transitions with lepton 3-generation final states $\Rightarrow$ $j = k = l = 3$.
- $\Rightarrow$ Notation: $\mathcal{O}^{(1,3)}_{ij33} \equiv \mathcal{O}^{(1,3)}_{ij}$ & $C^{(1,3)}_{ij33} \equiv C^{(1,3)}_{ij}$.

Which operator(s) to explain $R_{D^{(*)}}$?

Working in the mass eigenbasis for d, ℓ, ν_ℓ (assuming $m_{\nu_\ell} = 0$),

$$Q_i = \begin{pmatrix} V_{ji}^* u_j \\ d_i \end{pmatrix} \qquad L_i = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}$$

Four operators could provide a solution for $R_{D^{(*)},J/\psi}$: $\mathcal{O}_{33}^{(3)}$, $\mathcal{O}_{13}^{(3)}$ & $\mathcal{O}_{23}^{(1,3)}$.

- Constraints on $C_{33}^{(3)}$:
  - $\Rightarrow$ Contributions to $b \to c\tau^-\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$.
    [Glashow, Guadagnoli, Lane; Battacharya et al; Butazzo et al]
  - $\Rightarrow$ Proportional to V_{cb} $\Rightarrow$ $R_{D^{(*)}}$ requires a large $C_{33}^{(3)}$.
  - $\Rightarrow$ Conflict with bounds from electroweak precision data [Feruglio, Paradisi, Pattori].
  - $\Rightarrow$ Disfavoured by LHC searches in $\tau^+\tau^-$ final state [Faroughy, Greljo, Kamenik].
- Constraints on $C_{13}^{(3)}$:
  - $\Rightarrow$ Proportional to V_{cd} in $b \to c\tau^-\bar{\nu}_\tau$ $\Rightarrow$ CKM suppression.
  - $\Rightarrow$ Potential dominant contributions to very SM-like $b \to u\tau^-\bar{\nu}_\tau$ and $b \to d\tau^+\tau^-$ transitions ($Vud \leftrightarrow Vcd$) $\Rightarrow$ i.e. $\mathrm{Br}(B^- \to \tau^-\bar{\nu}_\tau)$.
    [Charles et al; Descotes-Genon, Koppenburg]
  - $\Rightarrow$ A large contribution is excluded.

Consequences for $b \to c\tau^-\bar{\nu}_\tau$ and $b \to s\tau^+\tau^-$ from $b \to s\nu\bar{\nu}$

$\Rightarrow$ $\mathcal{O}_{23}^{(1,3)}$ are the only remaining operators for the generation of $b \to c\tau^-\bar{\nu}_\tau$ FCCC able to explain $R_{D^{(*)}}$.

$$C^{(1)}\mathcal{O}^{(1)} \quad \to \quad C_{23}^{(1)}\left[(\bar{s}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\tau_L) + (\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_\tau\gamma^\mu\nu_\tau)\right],$$

$$C^{(3)}\mathcal{O}^{(3)} \quad \to \quad C_{23}^{(3)}\left[2V_{cs}(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_\tau) + (\bar{s}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\tau_L) - (\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_\tau\gamma^\mu\nu_\tau)\right]$$

- $\Rightarrow$ Constraints from FCNCs: $b \to s\nu\bar{\nu}$.
- $\Rightarrow$ $\mathrm{Br}(B \to K\nu\bar{\nu})$ excludes large effects in $b \to s\nu\bar{\nu}$ (SM : 4.2×10^{-6} [Buras et al], Babar bound $\leq 1.7 \times 10^{-5}$ at 90%CL)

Combining FCCC and FCNC contributions from $\mathcal{O}_{23}$ operators,

- $\Rightarrow$ $C_{23}^{(1)} \simeq C_{23}^{(3)}$ evades the $b \to s\nu\bar{\nu}$ constraint
- $\Rightarrow$ can be achieved with vector LQ $SU(2)$ singlet or with 2 scalar LQs

[Alonso, Grinstein Camalich; Calibbi, Crivellin, Ota, Müller]

$\Rightarrow$ Contributions to $b \to c\tau^-\bar{\nu}_\tau$ and $b \to s\tau^+\tau^-$ are naturally generated together in the combination (neglecting small CKM effects),

$$2C_{23}\left[(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_\tau) + (\bar{s}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\tau_L)\right]$$

Correlation between $b \to c\tau^-\bar{\nu}_\tau$ and $b \to s\tau^+\tau^-$

$b \to s\tau^+\tau^-$ Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{b\to s\tau\tau} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i \mathcal{O}_i$$

With the relevant effective operators,

$$O_{9(10)}^{\tau\tau} = \frac{\alpha}{4\pi}(\bar{s}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu(\gamma^5)\tau),$$
$$O_{9'(10')}^{\tau\tau} = \frac{\alpha}{4\pi}(\bar{s}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu(\gamma^5)\tau),$$

We impose the $SU(2)_L$ structure $C_9^{\tau\tau} = -C_{10}^{\tau\tau}$ that we observe in the SM and use that $C_{23}^{(1)} \simeq C_{23}^{(3)}$,

$$\left.\begin{array}{r} \mathcal{H}_{\text{eff}}^{b\to s\tau\tau} \to -(4G_F/\sqrt{2})V_{tb}V_{ts}^* \frac{\alpha}{4\pi}(C_9^{\text{SM}} + C_9^{\tau\tau}) \\ \mathcal{H}_{\text{eff}}^{b\to c\tau\nu} \to (4G_F V_{cb}/\sqrt{2})(1+\epsilon_L) \end{array}\right\} \Rightarrow C_{9(10)}^{\tau\tau} \simeq C_{9(10)}^{\text{SM}} - (+)\Delta$$

$$\Rightarrow \quad \Delta = \frac{2\pi}{\alpha}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{\text{SM}}}} - 1\right)$$

- Process independent: R_X/R_X^{SM} for all $X = D, D^*, J/\psi$
- Multiplicative factor very large leading to $\Delta = O(100)$
- Still within the bounds derived in [Bobeth, Haisch] on $(\tau\tau)(\bar{s}b)$ operators
- SM negligible: $C_{9(10)}^{SM} \simeq (-)4$ at $\mu = O(m_b)$

Branching ratios

Following our previous result,

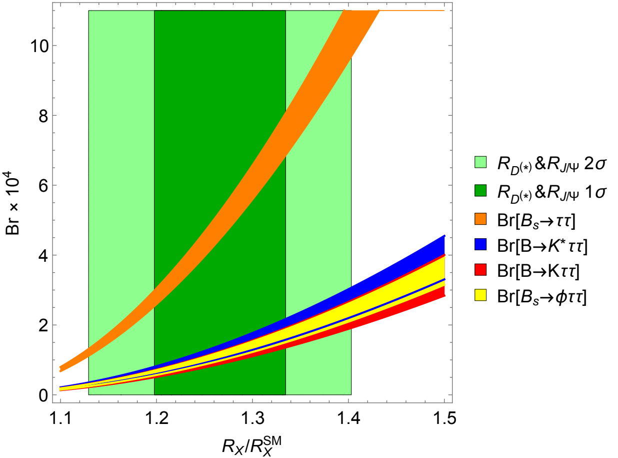
$$\begin{aligned}
\mathrm{Br}\left(B_s \to \tau^+\tau^-\right) &= \left(\frac{\Delta}{C_{10}^{\mathrm{SM}}}\right)^2 \mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{SM}} \, , \\
\mathrm{Br}\left(B \to K\tau^+\tau^-\right) &= (8.8 \pm 0.8) \times 10^{-9}\Delta^2 \, , \\
\mathrm{Br}\left(B \to K^*\tau^+\tau^-\right) &= (10.1 \pm 0.8) \times 10^{-9}\Delta^2 \, , \\
\mathrm{Br}\left(B_s \to \phi\tau^+\tau^-\right) &= (9.1 \pm 0.5) \times 10^{-9}\Delta^2 \, ,
\end{aligned}$$

For the last three branching ratios,

- Neglecting the SM short-distance contribution.
- Neglecting the SM long-distance contribution: taking into account neither $\psi(2S)$ (at most a few 10^{-6} to Br) nor $c\bar{c}$ continuum.
- Integrating over whole allowed kinematic range.
- Typical enhancement by 10^3 compared to SM value.

Illustrating the correlation

[BC, Crivellin, Descotes-Genon, Hofer, Matias]



$$\mathrm{Br}\left(B_s \to \tau^+\tau^-\right)_{\mathrm{LHCb}} \leq 6.8 \times 10^{-3}, \quad \mathrm{Br}\left(B \to K\tau^+\tau^-\right)_{\mathrm{Babar}} \leq 2.25 \times 10^{-3}.$$

Conclusions

$R_{D^{(*)}}$ and $b \to s\tau^+\tau^-$ correlated from fairly general assumptions,

- Deviations in $b \to c\tau^-\bar{\nu}_\tau$ decays from NP in left-handed four-fermion vector operator,
- NP due to physics from scale larger than electroweak scale,
- Contribution to $b \to s\nu_\tau\bar{\nu}_\tau$ is suppressed
- Pure 3rd-gen coupling disfavoured by precision data

$\Rightarrow$ $b \to s\tau^+\tau^-$ processes dominated by NP approximately three orders of magnitude larger than SM

$b \to s\tau^+\tau^-$ interesting processes by themselves

- $B \to K\tau^+\tau^-$, $B \to K^*\tau^+\tau^-$ and $B_s \to \phi\tau^+\tau^-$ branching ratios: SM and NP dependence on $C_9^{\tau\tau}$, $C_{10}^{\tau\tau}$, $C_{9'}^{\tau\tau}$ and $C_{10'}^{\tau\tau}$
- Other observables related to τ polarisation discussed in [Kamenik et al]

Thank you