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

Sébastien Descotes-Genon

[based on 1712.01919, B. Capdevila, A. Crivellin, SDG, L. Hofer, Q. Matias]

Laboratoire de Physique Théorique
CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

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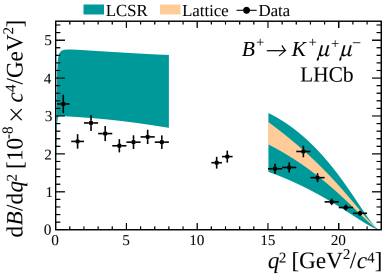
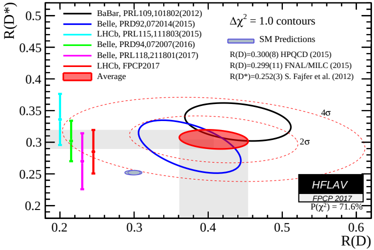
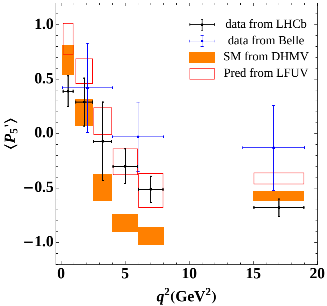
B-anomalies







- deviations in $b \to s\mu^+\mu^-$ and $b \to c\tau^-\bar{\nu}_\tau$
- can be analysed in EFT or model approaches
- “immediate” link between anomalies in a given model
- but possible to correlate in EFT ?

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

Effective Hamiltonian analyses of $R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\bar{\nu}_\ell)}$ and $R_{J/\psi}$

- 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]

favours NP contribution to SM operator $[\bar{c}\gamma^\mu P_L b][\bar{\tau}\gamma_\mu P_L \nu_\tau]$ leading to

$$R_{J/\psi}/R_{J/\psi}^{\mathrm{SM}} = R_D/R_D^{\mathrm{SM}} = R_{D^*}/R_{D^*}^{\mathrm{SM}}$$

which agrees well with the current measurements

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

If NP from a scale much larger than the electroweak symmetry breaking scale, NP contributions from $SU_L(2)$ invariant operators

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

involving Q and L left-handed quark and lepton doublets

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

Consequences of NP contributions to $b \to c\tau^-\bar{\nu}_\tau$

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

Recent studies of $i = j = k = l = 3$ in interaction basis

- in agreement with $U(2)$ symmetry for first two generations
- once reexpressed in terms of mass eigenstates, contributions to $b \to c\tau^-\bar{\nu}_\tau$ and $b \to s\mu^+\mu^-$
- constraints from $B \to K(^*)\nu\nu$ and from LFV decays ($t \to c$ transitions not constraining)

[Glashow, Guadagnoli, Lane; Battacharya et al; Butazzo et al]

But $b\bar{b} \to \tau^+\tau^-$ at odds with

- Z and τ decays through RGE [Feruglio, Paradisi, Pattori]
- direct LHC searches in $\tau^+\tau^-$ final state [Faroughy, Greljo, Kamenik]

other operators to explain $b \to c\tau^-\bar{\nu}_\tau$?

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

Let us take the basis of mass eigenbasis for d, ℓ, ν_ℓ (with $m_\nu = 0$)

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

$$\text{with} \qquad Q_i = \begin{pmatrix} V^*_{ji} u_j \\ d_i \end{pmatrix} \qquad L_i = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}$$

NP in FCCC $b \to c\tau^- \bar{\nu}_\tau$ from $\mathcal{O}^{(3)}_{k333}$ $\qquad C_{k3} \equiv C_{k333}$

$$C^{(3)}\mathcal{O}^{(3)} \quad \to \quad C^{(3)}_{13}\,(2V_{cd}[\bar{c}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\nu_\tau]) + C^{(3)}_{23}\,(2V_{cs}[\bar{c}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\nu_\tau]) + C^{(3)}_{33}\,(2V_{cb}[\bar{c}_L\gamma_\mu b_L][\bar{\tau}_L\gamma^\mu\nu_\tau]) \,.$$

- $C^{(3)}_{33}$ already excluded from previous discussion
- $C^{(3)}_{13}$ would contribute even more dominantly to $b \to u\tau^- \bar{\nu}_\tau$ (V_{ud} instead of V_{cd}), i.e., $\mathrm{Br}(B^- \to \tau^- \bar{\nu}_\tau)$: large contribution excluded

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

- $\mathcal{O}_{2333}$ remaining as a possibility for FCCC $b \to c\tau^-\bar{\nu}_\tau$
- implication for FCNCs: $b \to s\nu\bar{\nu}$ and $b \to s\ell^+\ell^-$
- $\mathrm{Br}(B \to K\nu\bar{\nu})$ rules out 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)

Looking at both FCCC and FCNC contributions from $\mathcal{O}_{2333}$ operators

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

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

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

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

leading to NP under the form

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

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

Correlating $b \to c\tau^-\bar{\nu}_\tau$ and $b \to s\tau\tau$

$$H_{\rm eff}(b \to s\tau\tau) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_a C_a O_a$$

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

$$C_{9'(10')}^{\tau\tau} = 0\,, \quad C_{9(10)}^{\tau\tau} \approx C_{9(10)}^{\rm SM} - (+)\Delta\,, \quad \Delta = \frac{2\pi}{\alpha}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{\rm SM}}} - 1\right)$$

- Correlation between $C_{9,10}^{\tau\tau}$ and Wilson coefficients for R_X
- Involves $R_X/R_X^{\rm SM}$ identical 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: $C_9^{SM} \simeq 4.1$, $C_{10}^{SM} \simeq -4.3$ at $\mu = O(m_b)$

Branching ratios

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

For the last three branching ratios

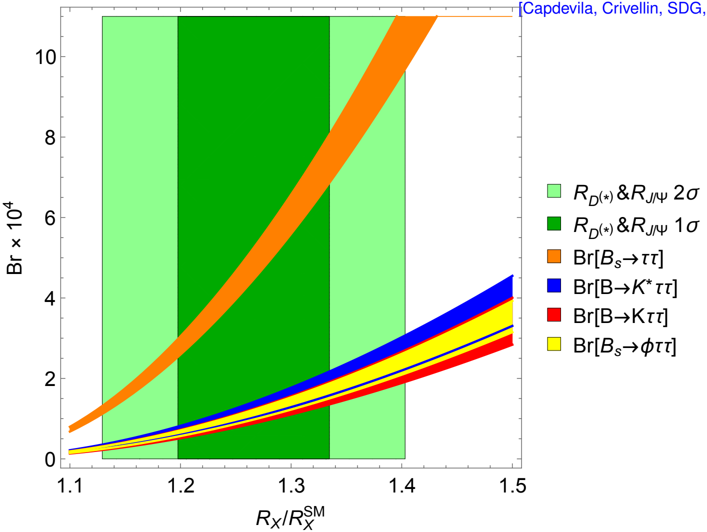
- Neglecting the SM short-distance contribution
- Neglecting the SM long-distance contribution: taking into account neither $\psi(2S)$ (at most a few 10^{-6} to Br) nor $c\bar{c}$ continuum
- Integrating over whole allowed kinematic range
- Typical enhancement by 10^3 compared to SM value

Experimentally

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

Illustrating the correlation

[Capdevila, Crivellin, SDG, Hofer, Matias]



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

If $b \to s\tau^+\tau^-$ not dominated by NP

- then SM contribution cannot be neglected : same form factors and $c\bar{c}$ contribution as in previous works [Capdevila, Crivellin, SDG, Matias, Virto]
- q^2-range leaving out $\psi(2S)$ to allow for quark-hadron duality (10%)
- fit to determine dependence on NP contribution to $C^{\tau\tau}_{9,10,9',10'}$

$$10^7 \times \mathrm{Br}\left(B \to K\tau^+\tau^-\right)^{[15,22]} =$$
$$\left(1.20 + 0.15\,C_9^{\rm NP} - 0.42\,C_{10}^{\rm NP} + 0.15\,C_9' - 0.42\,C_{10}' + 0.04\,C_9^{\rm NP}C_9' \right.$$
$$\left. +0.10\,C_{10}^{\rm NP}C_{10}' + 0.02\,C_9^{\rm NP\,2} + 0.05\,C_{10}^{\rm NP\,2} + 0.02\,C_9'^{\,2} + 0.05\,C_{10}'^{\,2}\right)$$
$$\pm\left(0.12 + 0.02\,C_9^{\rm NP} - 0.04\,C_{10}^{\rm NP} + 0.01\,C_9' - 0.04\,C_{10}' \right.$$
$$\left. +0.01\,C_{10}^{\rm NP}C_{10}' + 0.01\,C_{10}^{\rm NP\,2} + 0.08\,C_{10}'^{\,2}\right),$$

$$10^7 \times \mathrm{Br}\left(B \to K^*\tau^+\tau^-\right)^{[15,19]} =$$
$$\left(0.98 + 0.38\,C_9^{\rm NP} - 0.14\,C_{10}^{\rm NP} - 0.30\,C_9' + 0.12\,C_{10}' - 0.08\,C_9^{\rm NP}C_9' \right.$$
$$\left. -0.03\,C_{10}^{\rm NP}C_{10}' + 0.05\,C_9^{\rm NP\,2} + 0.02\,C_{10}^{\rm NP\,2} + 0.05\,C_9'^{\,2} + 0.02\,C_{10}'^{\,2}\right)$$
$$\pm\left(0.09 + 0.03\,C_9^{\rm NP} - 0.01\,C_{10}^{\rm NP} - 0.03\,C_9' - 0.01\,C_9^{\rm NP}C_9' \right.$$
$$\left. -0.01\,C_9'C_{10}' + 0.01\,C_9'^{\,2} - 0.01\,C_{10}'^{\,2}\right),$$

Outlook

$R_{D^{(*)}}$ 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 Z, τ and direct searches

$\Longrightarrow b \to s\tau^+\tau^-$ 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]

Thanks for your attention !