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

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Outline

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2. EFT approach for $b \to c\ell\nu$ and $b \to s\tau\tau$
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$B$-anomalies: $b \rightarrow s \mu \mu$

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

- **2013:** $1fb^{-1}$ dataset LHCb found $3.7\sigma$ (w.r.t. SM pred).
- **2015:** $3fb^{-1}$ dataset LHCb found $3\sigma$ (w.r.t. SM pred) in 2 bins.
- Belle confirmed it in a bin $[4,8]$ few months ago.
**B-anomalies: \( b \rightarrow s\mu\mu \)**

- **BR(\( B \rightarrow K \mu\mu \))** small compared to SM predictions.
- Deviations in **BR(\( B_s \rightarrow \phi \mu\mu \))**.
- Several systematic low-recoil small tensions in **BR_\mu**.
- **LFUV ratios** \( R_K \) & \( R_{K^*} \).
Global analysis of $b \rightarrow s \ell\ell$ data

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

- **1D Hypothesis:**
  \[ C_{9\mu} \rightarrow 5.8\sigma \]
  \[ C_{9\mu} = -C_{10\mu} \rightarrow 5.3\sigma \]
  \[ C_{9\mu} = -C_{9'\mu} \rightarrow 5.4\sigma \]

- **2D Hypothesis:**
  \[ (C_{9\mu}, C_{10\mu}) \rightarrow 5.7\sigma \]
  \[ (C_{9\mu}, C_{9'\mu}) \rightarrow 5.6\sigma \]
  \[ (C_{9\mu}, C_{10'\mu}) \rightarrow 5.7\sigma \]

- **6D Hypothesis:**
  \[ (C_{7'}, C_{9'\mu}, C_{10'\mu}) \rightarrow 5.0\sigma \]
Experimental Status

**EFT Approach**

**Implications**

**Conclusions**

### $B$-anomalies: $b \to c\ell\bar{\nu}$

#### 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).

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[Image of a graph showing $R(D^*)$ vs R(D) with contours and data points.]

[Image of a graph showing $R(J/\psi)$ vs R(J/\psi) with data points and error bars.]
EFT approach for $b \rightarrow c\ell\nu$ transitions

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

- 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]

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

⇒ Leading to

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

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,

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

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

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

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

$\Rightarrow$ $b$ transitions with lepton 3-generation final states $\Rightarrow j = k = l = 3$.

$\Rightarrow$ Notation: $\mathcal{O}_{ij33}^{(1,3)} \equiv \mathcal{O}_{ij}^{(1,3)}$ & $C_{ij33}^{(1,3)} \equiv C_{ij}^{(1,3)}$. 
Which operator(s) to explain $R_{D(*)}$?

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

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

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

- **Constraints on $C_{33}^{(3)}$:**
  - $\Rightarrow$ Contributions to $b \rightarrow c\tau^- \bar{\nu}_\tau$ and $b \rightarrow s\mu^+ \mu^-$.  
    [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 $b \rightarrow c\tau^- \bar{\nu}_\tau \Rightarrow$ CKM suppression.
  - $\Rightarrow$ Potential dominant contributions to very SM-like $b \rightarrow u\tau^- \bar{\nu}_\tau$ and $b \rightarrow d\tau^+ \tau^-$ transitions ($V_{ud} \leftrightarrow V_{cd}$) $\Rightarrow$ i.e. $\text{Br}(B^- \rightarrow \tau^- \bar{\nu}_\tau)$.
    [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 $b \to s\nu\bar{\nu}$

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

\[
C^{(1)}O^{(1)} \rightarrow C_{23}^{(1)} [(\bar{s}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu \tau_L) + (\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_\tau\gamma^\mu \nu_\tau)],
\]

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

$\Rightarrow$ Constraints from FCNCs: $b \to s\nu\bar{\nu}$.

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

Combining FCCC and FCNC contributions from $O_{23}$ operators,

$\Rightarrow C_{23}^{(1)} \sim C_{23}^{(3)}$ 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),

\[
2C_{23} [((\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu \nu_\tau) + (\bar{s}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu \tau_L)]
\]
Correlation between $b \rightarrow c \tau^{-}\bar{\nu}_{\tau}$ and $b \rightarrow s \tau^{+}\tau^{-}$

**b → sτ⁺τ⁻ Effective Hamiltonian**

\[
\mathcal{H}_{\text{eff}}^{b \rightarrow s\tau\tau} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum C_i O_i
\]

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

\[
\begin{aligned}
\mathcal{H}_{\text{eff}}^{b \rightarrow s\tau\tau} &\rightarrow -(4G_F/\sqrt{2}) V_{tb} V_{ts}^* \frac{\alpha}{4\pi}(C_9^{\text{SM}} + C_9^{\tau\tau}) \\
\mathcal{H}_{\text{eff}}^{b \rightarrow c\tau\nu} &\rightarrow (4G_F V_{cb}/\sqrt{2})(1 + \epsilon_L)
\end{aligned}
\]

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

- Process independent: $R_X/R_X^{\text{SM}}$ for all $X = D, D^*, J/\psi$
- Multiplicative factor very large leading to $\Delta = O(100)$

With the relevant effective operators,

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

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

- Still within the bounds derived in [Bobeth, Haisch] on $(\tau\tau)(\bar{s}b)$ operators
- SM negligible: $C_{9(10)}^{\text{SM}} \sim (-)4$ at $\mu = O(m_b)$
Following our previous result,

\[
\text{Br} \left( B_s \to \tau^+ \tau^- \right) = \left( \frac{\Delta}{C_{10}^{\text{SM}}} \right)^2 \text{Br} \left( B_s \to \tau^+ \tau^- \right)_{\text{SM}},
\]

\[
\text{Br} \left( B \to K \tau^+ \tau^- \right) = (8.8 \pm 0.8) \times 10^{-9} \Delta^2,
\]

\[
\text{Br} \left( B \to K^* \tau^+ \tau^- \right) = (10.1 \pm 0.8) \times 10^{-9} \Delta^2,
\]

\[
\text{Br} \left( B_s \to \phi \tau^+ \tau^- \right) = (9.1 \pm 0.5) \times 10^{-9} \Delta^2.
\]

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 \( \text{Br} \)) nor \( c \bar{c} \) continuum.
- Integrating over whole allowed kinematic range.
- Typical enhancement by \( 10^3 \) compared to SM value.
Illustrating the correlation

\[
\begin{align*}
\text{Br}(B_s \rightarrow \tau^+ \tau^-)_{\text{LHCb}} & \leq 6.8 \times 10^{-3}, \\
\text{Br}(B \rightarrow K\tau^+ \tau^-)_{\text{Babar}} & \leq 2.25 \times 10^{-3}.
\end{align*}
\]
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 $\tau$ polarisation discussed in [Kamenik et al]
Thank you