Lepton polarization asymmetry in $B_s^* \rightarrow l^+l^-$ decays

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Outline

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- Why $B_s^* \to l^+ l^-$
- Branching ratio of $B_s^* \to \mu^+ \mu^-$ and NP effects
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- $B_s^* \to \tau^+ \tau^-$ in SM
- Correlation between $b \to c \tau \bar{\nu}$ and $b \to s \tau^+ \tau^-$
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- Conclusions
Discrepancies in $b \rightarrow s\mu^+\mu^-$

1. $B \rightarrow K^*\mu^+\mu^-$: In the measurements of $B \rightarrow K^*\mu^+\mu^-$ the main discrepancy is in the angular observable $P'_5$ at 4σ level [R. Aaij et al., JHEP(2016)].

2. $B^0_S \rightarrow \phi\mu^+\mu^-$: The measured branching ratio and angular analysis of $B^0_S \rightarrow \phi\mu^+\mu^-$ by LHCb collaboration has discrepancy at 3.5σ [R. Aaij et al., JHEP(2013)].

3. $R_K$: The ratio $R_K = \mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+e^+e^-)$ has been measured by LHCb collaboration [R. Aaij et al., PRL(2014)] with result

$$R_K^{exp} = 0.745 \pm 0.097.$$ 

and prediction of $R_K$ in SM is $R_K^{SM} = 1 \pm 0.01$. So $R_K^{exp}$ differs from $R_K^{SM}$ by 2.6σ.

4. $R_{K^*}$: The ratio $R_{K^*} \equiv \Gamma(B^0 \rightarrow K^{*0}\mu^+\mu^-)/\Gamma(B^0 \rightarrow K^{*0}e^+e^-)$ [R Aaij et. al. JHEP (2017)] has been measured by LHCb collaboration in two different $q^2$ ranges, $(0.045 \leq q^2 \leq 1.1 \text{ GeV}^2)$ (low $q^2$) and $(1.1 \leq q^2 \leq 6.0 \text{ GeV}^2)$ (central $q^2$), differ from the SM prediction of $\simeq 1$ [Hiller et al. PRD (2004)] by 2.2-2.4σ and 2.4-2.5σ respectively.

$\implies R_K$ and $R_{K^*}$ indicate towards Lepton Flavour Universality (LFU) violation.

$\implies$ Hints towards the presence of New Physics (NP) in $b \rightarrow s\mu^+\mu^-$ transition.
Why $B_s^* \rightarrow \mu^+\mu^-$

The $B_s^*$, is a vector meson with quark content $b\bar{s}$.

- $B_s^* \rightarrow \mu^+\mu^-$ decay is induced by $b \rightarrow s\mu^+\mu^-$ hence provides alternative observable to discriminate between various NP solutions.
- $B_s^* \rightarrow \mu^+\mu^-$ decay is induced by $b \rightarrow s\mu^+\mu^-$ which is FCNC interaction hence highly suppressed.
- This decay mode is theoretically very clean, depends only on decay constant of $B_s^*$.
- Compared to the pseudoscalar B meson, the purely leptonic decays of the vector $B_s^*$ are not chirally suppressed and are sensitive to different combinations of the underlying weak effective operators.
- The main uncertainty stems from the unmeasured and theoretically not well known $B_s^*$ width.

These properties make it a golden decay channel to probe new physics in $b \rightarrow s\mu^+\mu^-$ sector [Grinstein, Camalich, PRL(2016)].
Effective Hamiltonian for $b \rightarrow s\mu^+\mu^-$ process is given by

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ C_{7\text{eff}}^0 O_7 + C_{9\text{eff}}^0 O_9 + C_{10} O_{10} \right]$$

where,

$$O_7 = \frac{2i m_b (p_{\mu^+}^{\nu} + p_{\mu^-}^{\nu})}{(p_{\mu^+} + p_{\mu^-})^2} \left[ \bar{s} \sigma_{\mu\nu} P_R b \right] \left[ \bar{\mu} \gamma^{\mu} \mu \right],$$

$$O_9 = \left[ \bar{s} \gamma^{\mu} P_L b \right] \left[ \bar{\mu} \gamma_{\mu} \mu \right],$$

$$O_{10} = \left[ \bar{s} \gamma^{\mu} P_L b \right] \left[ \bar{\mu} \gamma_{\mu} \gamma_{5\mu} \right]$$

and $C_{7,9}^\text{eff}$ and $C_{10}$ are the Wilson Coefficients (WCs). The effect of the operators $O_i$, $i = 1 - 6, 8$ can be embedded in redefined effective Wilson coefficients as $C_7(\mu) \rightarrow C_7(\mu, q^2)$ and $C_9(\mu) \rightarrow C_9(\mu, q^2)$. 
$\mathcal{B}(B^*_s \rightarrow \mu^+ \mu^-)$ in SM

The SM amplitude for $B^*_s \rightarrow l^+ l^-$ decay is given by

$$ \mathcal{M}_{SM} = -\alpha_{em} G_F \frac{f_{B^*_s} V_{ts}^* V_{tb} m_{B^*_s}}{2\sqrt{2}\pi} \epsilon^\mu \left[ (C_9^{\text{eff}} + \frac{2m_b f_{B^*_s}^T}{m_{B^*_s} f_{B^*_s}} C_7^{\text{eff}}) (\bar{l} \gamma_\mu l) + C_{10} (\bar{l} \gamma_\mu \gamma_5 l) \right]. $$

Therefore, the SM decay rate is found to be

$$ \Gamma_{SM} = \frac{\alpha_{em}^2 G_F^2 f_{B^*_s}^2 m_{B^*_s}^3}{96\pi^3 |V_{ts} V_{tb}|^2} \sqrt{1 - 4m_l^2/m_{B^*_s}^2} \left[ \left( 1 + \frac{2m_l^2}{m_{B^*_s}^2} \right) \left| C_9^{\text{eff}} + \frac{2m_b f_{B^*_s}^T}{m_{B^*_s} f_{B^*_s}} C_7^{\text{eff}} \right|^2 + \left( 1 - \frac{4m_l^2}{m_{B^*_s}^2} \right) |C_{10}|^2 \right]. $$

Assuming the total decay width of $B^*_s$ is comparable to the dominant decay $B^*_s \rightarrow B_s \gamma$. Using $\Gamma(B^*_s \rightarrow B_s \gamma) = 0.10 \pm 0.05$ KeV, the SM branching fraction for $B^*_s \rightarrow \mu^+ \mu^-$ is [Kumar, Saini, Gangal, Das, PRD(2017)]

$$ \mathcal{B}(B^*_s \rightarrow \mu^+ \mu^-) = (1.26 \pm 0.63) \times 10^{-11} $$
New Physics effects in $B(B_s^* \rightarrow \mu^+\mu^-)$

The effective Hamiltonian in the presence of vector and axial-vector NP operators is given by

$$\mathcal{H}_{\text{eff}}(b \rightarrow s\mu^+\mu^-) = \mathcal{H}_{SM} + \mathcal{H}_{VA},$$

where $\mathcal{H}_{VA}$ is

$$\mathcal{H}_{VA} = \frac{\alpha G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \left[ C_{9}^{NP} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu) + C_{10}^{NP} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu\gamma_5) + C_9'^{NP} (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu) + C_{10}'^{NP} (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu\gamma_5) \right]$$


→ Two NP solutions [Alok et al PRD(2017)]:

▸ NP in the form of only vector operator: $C_{9}^{NP} < 0$

▸ NP in the form of vector and axial-vector operators: $C_{9}^{NP} = -C_{10}^{NP} < 0$

→ None of the vector and axial-vector NP solutions can be distinguished by the branching ratio of $B_s^* \rightarrow \mu^+\mu^-$. [Kumar, Saini, Gangal, Das, PRD(2017)]

→ Look for new observable to pin down the NP → Lepton polarization asymmetry!
Lepton longitudinal polarization asymmetry

The lepton longitudinal polarization asymmetry is defined as [Handoko, Kim and Yoshikawa, PRD (2002)]

\[
\mathcal{A}_{LP}^{\pm} = \frac{[\Gamma(s_{l-}, s_{l+}) + \Gamma(s_{l-}, s_{l+})] - [\Gamma(s_{l-}, s_{l+}) + \Gamma(s_{l-}, s_{l+})]}{[\Gamma(s_{l-}, s_{l+}) + \Gamma(s_{l-}, s_{l+})] + [\Gamma(s_{l-}, s_{l+}) + \Gamma(s_{l-}, s_{l+})]}
\]

In the dilepton rest frame, these unit polarization vectors are

\[
s_{l\pm}^{\alpha} = \left( \frac{|\vec{p}_{l}|}{m_l}, \pm \frac{E_{l}}{m_l} \frac{\vec{p}_{l}}{|\vec{p}_{l}|} \right)
\]

Within the SM, \(\mathcal{A}_{LP}^{\pm}\) becomes

\[
\mathcal{A}_{LP}^{\pm}|_{SM} = \mp \frac{2\sqrt{1 - 4m_{l}^2/m_{B_s^*}^2} \Re \left[ \left( C_{9}^{\text{eff}} + \frac{2m_b f_{B_s^*}^{T}}{m_{B_s^*} f_{B_s^*}^{T}} C_{7}^{\text{eff}} \right) C_{10}^{*} \right]}{\left( 1 + 2m_{l}^2/m_{B_s^*}^2 \right) \left| C_{9}^{\text{eff}} + \frac{2m_b f_{B_s^*}^{T}}{m_{B_s^*} f_{B_s^*}^{T}} C_{7}^{\text{eff}} \right|^2 + \left( 1 - 4m_{l}^2/m_{B_s^*}^2 \right) |C_{10}|^2}.
\]
$A_{LP}(\mu)$ within New Physics

The effective Hamiltonian in the presence of vector and axial-vector NP operators is given by

$$\mathcal{H}_{\text{eff}}(b \to s l^+ l^-) = \mathcal{H}_{\text{SM}} + \mathcal{H}_{\text{VA}},$$

where $\mathcal{H}_{\text{VA}}$ is

$$\mathcal{H}_{\text{VA}} = \frac{\alpha_{\text{em}} G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \left[ C_{9}^{NP} (\bar{s} \gamma^\mu P_L b)(\bar{l} \gamma_{\mu} l) + C_{10}^{NP} (\bar{s} \gamma^\mu P_L b)(\bar{l} \gamma_{\mu} \gamma_5 l) 
+ C_{9}^{NP} (\bar{s} \gamma^\mu P_R b)(\bar{l} \gamma_{\mu} l) + C_{10}^{NP} (\bar{s} \gamma^\mu P_R b)(\bar{l} \gamma_{\mu} \gamma_5 l) \right].$$

In the presence of NP, $A_{LP}^{\pm}$ becomes

$$A_{LP}^{\pm}|_{NP} = \mp \frac{2 \sqrt{1 - 4m_l^2/m_{B^*_s}^2}}{(1 + 2m_l^2/m_{B^*_s}^2)} \text{Re} \left[ (C + C_{9}^{NP} + C_{9}^{NP}) (C_{10} + C_{10}^{NP} + C_{10}^{NP})^* \right] \frac{\left| C + C_{9}^{NP} + C_{9}^{NP} \right|^2 + \left(1 - 4m_l^2/m_{B^*_s}^2 \right) \left| C_{10} + C_{10}^{NP} + C_{10}^{NP} \right|^2}{\left| C_{9}^{NP} + C_{10}^{NP} + C_{10}^{NP} \right|^2}$$

Here $C = \left( C_{9}^{\text{eff}} + \frac{2m_b f_{B^*_s}^T}{m_{B^*_s} f_{B^*_s}} C_{7}^{\text{eff}} \right)$.
$A_{LP}(\mu)$ Predictions

The SM prediction of muon longitudinal polarization asymmetry is

$$A_{LP}^+(\mu)|_{SM} = -A_{LP}^-(\mu)|_{SM} = 0.9955 \pm 0.0003$$

$\Rightarrow$ Two types of NP solutions to $b \rightarrow s \mu^+\mu^-$ anomalies [Capdevila, Crivellin, Descotes-Genon, Matias and Virto, JHEP(2018), Alok, Bhattacharya, Datta, Kumar, Kumar and London, PRD(2017)]

(I) $C_9^{NP} < 0$

(II) $C_9^{NP} = -C_{10}^{NP} < 0$

$\Rightarrow$ A third possible solution is $C_9^{NP} = C_9^{NP} < 0$ is largely rejected because it predicts $R_K = 1$, in disagreement with experiment.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NP WCs</th>
<th>$A_{LP}^+(\mu) = -A_{LP}^-(\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>0</td>
<td>$0.9955 \pm 0.0003$</td>
</tr>
<tr>
<td>(I) $C_9^{NP}$</td>
<td>$-1.25 \pm 0.19$</td>
<td>$0.8877 \pm 0.0312$</td>
</tr>
<tr>
<td>(II) $C_9^{NP} = -C_{10}^{NP}$</td>
<td>$-0.68 \pm 0.12$</td>
<td>$0.9936 \pm 0.0057$</td>
</tr>
</tbody>
</table>

$\Rightarrow$ The prediction of $A_{LP}(\mu)$ for scenario (I) deviates from the SM at the level of $3.4\sigma$ where as $A_{LP}(\mu)$ for the scenario (II) is consistent with the SM.
The SM prediction of the branching ratio of $B_s^* \rightarrow \tau^+ \tau^-$ is

$$\mathcal{B}(B_s^* \rightarrow \tau^+ \tau^-) = (6.87 \pm 4.23) \times 10^{-12},$$

whereas the $\tau$ longitudinal polarization asymmetry is obtained to be

$$A_{LP}^+(\tau)|_{SM} = -A_{LP}^-(\tau)|_{SM} = 0.8860 \pm 0.0006.$$

$\Rightarrow$ New Physics in $b \rightarrow s \tau^+ \tau^-$?
$\Rightarrow$ It can come from $b \rightarrow c \tau \bar{\nu}$. [Capdevila, Crivellin, Descotes-Genon, Hofer, Matias, PRL(2018)]
Discrepencies in $b \rightarrow c\tau\bar{\nu}$

1. The current world average of the ratio $R_D = \mathcal{B}(B \rightarrow D\tau\bar{\nu})/\mathcal{B}(B \rightarrow D\{e/\mu\}\bar{\nu})$, measured by BaBar and Belle, deviates $2.3\sigma$ from the SM prediction [HFAG 2017].

2. There is a series of measurements of the ratio $R_{D^*} = \mathcal{B}(B \rightarrow D^*\tau\bar{\nu})/\mathcal{B}(B \rightarrow D^*\{e/\mu\}\bar{\nu})$ by BaBar, Belle and LHCb experiments. Recent world average of $R_{D^*}$ shows a discrepancy to the SM prediction at a level of $3.4\sigma$. Including the correlation, current experimental world averages of $R_{D^*}$ show a $\sim 4\sigma$ deviation from the SM predictions [HFAG 2017].

3. The measured value of $R_{J/\psi} = \mathcal{B}(B \rightarrow J/\psi\tau\bar{\nu})/\mathcal{B}(B \rightarrow J/\psi\mu\bar{\nu})$ by LHCb collaboration, is $1.7\sigma$ away from its SM prediction [R Aaij, PRL (2017)].

$\implies$ These ratios are an indication of LFU violation in the charged current sector. $\implies$ Hints towards the presence of New Physics (NP) in $b \rightarrow c\tau\bar{\nu}$ transition.
Correlation bwtwn $b \to c \tau \bar{\nu}$ and $b \to s \tau^+ \tau^-$

Together, the hint of new physics in $b \to c \tau \bar{\nu}$ and $b \to s \mu^+ \mu^-$ transitions, motivate the possibility of LFU violating effects in $b \to s \tau^+ \tau^-$. In such situation NP can be at tree level in the form of vector ($O_9$) and axial-vector ($O_{10}$). [Capdevila, Crivellin, Descotes-Genon, Hofer, Matias, PRL(2018)]

This tree level new physics also affects the branching ratio and $A_{LP}(\tau)$ of $B_s^* \to \tau^+ \tau^-$. In this model, the Wilson coefficients of $b \to s \tau^+ \tau^-$ transition can be written as

$$C^{\tau \tau}_9 = C^{SM}_9 - \Delta,$$

$$C^{\tau \tau}_{10} = C^{SM}_{10} + \Delta,$$

where $\Delta = \frac{2\pi}{\alpha} \frac{V_{cb}}{V_{tb}V_{ts}^*} \left( \sqrt{\frac{R_X}{R^{SM}_X}} - 1 \right) \sim O(100)$.

The ratio $R_X/R^{SM}_X \simeq 1.22 \pm 0.06$ is the weighted average of current experimental values of $R_D$, $R_{D^*}$ and $R_{J/\psi}$. 
NP effects in $B_s^* \to \tau^+\tau^-$

$\mathcal{B}(B_s^* \to \tau^+\tau^-)$ can be enhanced up to $10^{-9}$ which is about three orders of magnitude larger than its SM prediction.

It can be seen from the plot that $A_{LP}(\tau)$ is suppressed by about 5% in comparison to its SM value.
Conclusions

- Two scenarios (I) $C_9^{NP} < 0$ and (II) $C_9^{NP} = -C_{10}^{NP} < 0$ provide a good fit to all $b \rightarrow s\mu^+\mu^-$ data.

- $A_{LP}(\mu)$ is same as the SM asymmetry in scenario (II) but is smaller by 11% in scenario (I). However its experimental measurement would be a challenging task.

- The present data in $R_{D(*)}, J/\psi$ sector imply about three orders of magnitude enhancement in the branching ratio of $B_s^* \rightarrow \tau^+\tau^-$ whereas a suppression in $A_{LP}(\tau)$ as compared to their SM predictions.

- In case of $A_{LP}(\tau)$, it may be possible for LHCb to reconstruct $\tau$ where $\tau$ decays into multiple hadrons.

Thank You