Rare $B$ decays with final state including $\tau$ leptons

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Introduction

Why rare $B$ decays with $\tau$?

- Rare decays are good probes to search for physics beyond the SM
- Recent hints of LFU stressed the importance of the 3rd family

<table>
<thead>
<tr>
<th></th>
<th>$\mu\mu$ (ee)</th>
<th>$\tau\tau$</th>
<th>$\nu\nu$</th>
<th>$\tau\mu$</th>
<th>$\mu\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to s$</td>
<td>$R_K, R_{K^*}$</td>
<td>$B \to K^{(*)}\tau\tau$</td>
<td>$B \to K^{(*)}\nu\nu$</td>
<td>$B \to K \tau\mu$</td>
<td>$B \to K \mu\epsilon$</td>
</tr>
<tr>
<td></td>
<td>$O(20%)$</td>
<td>$\to 100\times SM$</td>
<td>$O(1)$</td>
<td>$\to \sim 10^{-6}$</td>
<td>$??$</td>
</tr>
<tr>
<td>$b \to d$</td>
<td>$B_d \to \mu\mu$</td>
<td>$B \to \pi \tau\tau$</td>
<td>$B \to \pi \nu\nu$</td>
<td>$B \to \pi \tau\mu$</td>
<td>$B \to \pi \mu\epsilon$</td>
</tr>
<tr>
<td>$B \to \pi \mu\mu$</td>
<td>$\to 100\times SM$</td>
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<tr>
<td>$B_s \to K^{(*)}\mu\mu$</td>
<td>$O(20%)$</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

G. Isidori, LHCb Implication WS (2017)
## Status of some relevant decay modes

<table>
<thead>
<tr>
<th>Modes</th>
<th>SM prediction</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \tau^+\tau^-$</td>
<td>$(2.22 \pm 0.19) \times 10^{-8}$ [1]</td>
<td>$&lt; 1.6 \times 10^{-3}$ [3]</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \tau^+\tau^-$</td>
<td>$(7.73 \pm 0.49) \times 10^{-7}$ [1]</td>
<td>$&lt; 5.2 \times 10^{-3}$ [3]</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\tau^+\tau^-$</td>
<td>$(1.20 \pm 0.12) \times 10^{-7}$ [2]</td>
<td>$&lt; 2.3 \times 10^{-3}$ [4]</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0}\tau^+\tau^-$</td>
<td>$(0.98 \pm 0.10) \times 10^{-7}$ [2]</td>
<td>-</td>
</tr>
<tr>
<td>$B^0 \rightarrow \tau^\pm e^\mp / \tau^\pm \mu^\mp$</td>
<td>-</td>
<td>$&lt; 2.8 \times 10^{-5}$ / $&lt; 2.2 \times 10^{-5}$ [5]</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \tau^\pm e^\mp / \tau^\pm \mu^\mp$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+\tau^\pm e^\mp / \pi^+\tau^\pm \mu^\mp$</td>
<td>-</td>
<td>$&lt; 7.5 \times 10^{-5}$ / $&lt; 7.2 \times 10^{-5}$ [6]</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\tau^\pm e^\mp / K^+\tau^\pm \mu^\mp$</td>
<td>-</td>
<td>$&lt; 3.0 \times 10^{-5}$ / $&lt; 4.8 \times 10^{-5}$ [6]</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0}\tau^\pm e^\mp / K^{*0}\tau^\pm \mu^\mp$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


This talk:

Current searches for $B^0_{(s)} \rightarrow \tau^+\tau^-$, $B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$ and $B^0 \rightarrow K^{*0}\tau^\pm \mu^\mp$ at LHCb
Some BSM predictions

Models proposed to explain the flavour anomalies
Very large enhancements may occur!

B. Capdevila et al., PRL 120, 181802 (2018)

A. Crivellin et al., JHEP09(2017)040

M. Bordone et al., arXiv:1805.09328
Rare $B$ decays with final state including $\tau$

- **Challenging search:**
  always at least a missing neutrino in the final state

- **Tau decay modes**
  - one-prong decays
    \[
    \tau^- \to e^- \bar{\nu}_e \nu_\tau; \mathcal{B} = \sim 17% \\
    \tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau; \mathcal{B} = \sim 17% \\
    \tau^- \to \pi^- \nu_\tau; \mathcal{B} = \sim 11% \\
    \tau^- \to \rho^- \nu_\tau; \mathcal{B} = \sim 22% 
    \]
  - three-prong decays
    \[
    \tau^- \to \pi^- \pi^+ \pi^- \nu_\tau; \mathcal{B} = \sim 9% \\
    \tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau; \mathcal{B} = \sim 5% 
    \]

- **BaBar & Belle (II) can constraint the kinematic of the decay using the information of the other $B$ and the centre of mass energy of the beam**
  Can use the one-prong decays, accessing $\sim 70\%$ of the $\tau$ decays

- **Not possible in hadron collider, even less with a forward detector**
  In LHCb: focus on the three-prong decays, allowing to reconstruct the $\tau$ decay vertex
\[ B^{0}_{(s)} \rightarrow \tau^{+}\tau^{-} \]

LHCb Run 1 - published

PRL 118, 251802 (2017)
$B^{0}_{(s)} \rightarrow \tau^{+}\tau^{-}$ decay reconstruction

PRL 118, 251802 (2017)

- Imposing $B$, $\tau$, $\nu$ mass constraints, the $\tau$'s momenta can be computed analytically → original method developed by J. Charles & A. Morda (A. Morda thesis)
  - approximations in the resolution + detector resolution → many events w/o real solutions
  - intermediate quantities associated with the method → used to discriminate signal from background
$B^{0}_{(s)} \rightarrow \tau^{+}\tau^{-}$ classification and selection

PRL 118, 251802 (2017)

Exploit: $\tau^{-} \rightarrow a_1^{-}(1260)\nu_{\tau} \rightarrow \rho(770)\pi^{-}\nu_{\tau} \rightarrow \pi^{-}\pi^{+}\pi^{-}\nu_{\tau}$

Selection:

- Isolation variables (track & composite, neutral, vertex)
- Multivariate classifier (NN) trained using the background region
$B_{(s)}^0 \to \tau^+ \tau^-$ fit strategy

PRL 118, 251802 (2017)

- 1-dimensional histogram fit to the output of a neural network (flat output for signal between 0 and 1)
- signal templates from simulation (\(\hat{N}_{SR}^{\text{sim}}\) and \(\hat{N}_{CR}^{\text{sim}}\))
- background template from data control region (\(\hat{N}_{CR}^{\text{data}}\))
$B^{0}_{(s)} \rightarrow \tau^{+}\tau^{-}$ fit model

PRL 118, 251802 (2017)

Events fraction in the 3 categories:

<table>
<thead>
<tr>
<th></th>
<th>simulated signal</th>
<th>selected candidates (data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>16%</td>
<td>7%</td>
</tr>
<tr>
<td>Control</td>
<td>58%</td>
<td>47%</td>
</tr>
<tr>
<td>Background</td>
<td>13%</td>
<td>37%</td>
</tr>
</tbody>
</table>

Fit model:

$$\mathcal{N}_{\text{data}}^{\text{SR}} = s \times \hat{\mathcal{N}}_{\text{sim}}^{\text{SR}} + f_b \times \left( \mathcal{N}_{\text{data}}^{\text{CR}} - s \times \epsilon^{\text{CR}} \times \hat{\mathcal{N}}_{\text{sim}}^{\text{CR}} \right)$$

- $s$: signal yield (free)
- $f_b$: background normalisation (free)
- $\epsilon^{\text{CR}}, \epsilon^{\text{SR}}$: signal efficiencies in the control and signal regions (from simulation)
$B^0_s \rightarrow \tau^+ \tau^-$ fit to data

PRL 118, 251802 (2017)

With background only model:

Nominal fit:

$s = -23 \pm 71$

- compatible with the background only hypothesis
- set an upper limit on $B$ using $B^0 \rightarrow D^+ D_s^-$ as a normalisation mode
$B^0_{(s)} \to \tau^+\tau^-$ limits on branching fractions

PRL 118, 251802 (2017)

Two independent fits, one for $B^0_s$ and another for $B^0$

$B^0_s \to \tau^+\tau^-$:

$B^0 \to \tau^+\tau^-$:

$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \cdot 10^{-3} @ 95\%$ CL

$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \cdot 10^{-3} @ 95\%$ CL
$B^{0}_{(s)} \rightarrow \tau^{+} \tau^{-}$ prospects

- **LHCb:**
  - Presented results are using only Run 1 data
    - $B(B^{0} \rightarrow \tau^{+} \tau^{-}) < 6.8 \cdot 10^{-3} @ 95\%$ CL
    - $B(B^{0} \rightarrow \tau^{+} \tau^{-}) < 2.1 \cdot 10^{-3} @ 95\%$ CL
  - Adding the $\tau^{-} \rightarrow \mu^{-} \bar{\nu}_{\mu} \nu_{\tau}$ mode:
    - no significant improvement to the expected limit
  - **Future reaches** (Physics case for an LHCb Upgrade II)
    - $B(B^{0}_{s} \rightarrow \tau^{+} \tau^{-}) \lesssim 1.3 \cdot 10^{-3}$ after LHCb Upgrade I
    - $B(B^{0}_s \rightarrow \tau^{+} \tau^{-}) \lesssim 5 \cdot 10^{-4}$ after LHCb Upgrade II

- **Belle II 5 ab$^{-1}$** (Belle II Physics book):
  - $B(B^{0}_{s} \rightarrow \tau^{+} \tau^{-}) \lesssim 8 \cdot 10^{-4}$ with 5 ab$^{-1}$ @ $\Upsilon(5S)$
  - $B(B^{0} \rightarrow \tau^{+} \tau^{-}) \lesssim 1 \cdot 10^{-4}$ with 50 ab$^{-1}$ @ $\Upsilon(4S)$
$B_{(s)}^0 \rightarrow \tau^\pm \mu^\mp$

LHCb Run 1 - on going analysis
\( B^0_{(s)} \rightarrow \tau^\pm \mu^\mp \)

on going analysis

- Easier than \( B^0_{(s)} \rightarrow \tau^+ \tau^- \)
  - only one missing neutrino
  - only 4 tracks
  - the muon points to the \( B \) vertex

- Enough constraints to compute the \( B \) mass
$B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$

ongoing analysis

- $B$ mass computed up to a 2-fold ambiguity (imposing the $\tau$ mass)
- $\sim 70\%$ of physical solution - less for background
- 1st solution gives largest separation between signal and background
$B^0_{(s)} \rightarrow \tau^\pm \mu^{\mp}$ strategy

on going analysis

Main backgrounds:

- combinatorics
- partially reconstructed $B$ decays

Backgrounds samples:

- same-sign candidates ($\tau^\pm \mu^\mp$)
  → selection optimisation
- simulation
  → qualitative studies
  - exclusive decays - non-exhaustive list
  - inclusive b-samples - statistically limited

Backgrounds rejection:

- multivariate classifiers
  including isolation variables
- dedicated cuts against peaking background (e.g. $B^0_{(s)} \rightarrow D^{(s)} (\rightarrow \mu^- \bar{\nu}_\mu \pi^+ \pi^- \pi^\mp)$)

Signal yield extraction:

- Simultaneous fit to the mass distributions in categories with different signal over background ratios
$B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$ prospects

- **LHCb:**
  - On going analysis using only Run 1 data
  - Subject of a thesis defended in September
  - **Expect** (Physics case for an LHCb Upgrade II)
    \[ \mathcal{B}(B^0_s \rightarrow \tau^\pm \mu^\mp) \lesssim \text{few} \ 10^{-5} \ 	ext{after Run 1&2} \]
    \[ \mathcal{B}(B^0_s \rightarrow \tau^\pm \mu^\mp) \lesssim \text{few} \ 10^{-6} \ 	ext{after LHCb Upgrade II} \]

- **Belle II 5 \text{ ab}^{-1}** (Belle II Physics book):
  - \[ \mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) \lesssim 1 \cdot 10^{-5} \ 	ext{with 50 \text{ ab}^{-1}} \]
$B^0 \rightarrow K^*^0 \tau^{\mp} \mu^{\pm}$

LHCb Run 1&2 - on going analysis
$B^0 \to K^{*0} \tau^\mp \mu^{\pm}$

ongoing analysis

Diagram:

- Comparison with $B^0_{(s)} \to \tau^\pm \mu^\mp$
  - 6 tracks! but:
  - only one missing neutrino
  - the $B$ decay vertex is reconstructed
$B^0 \rightarrow K^{*0} \tau^\mp \mu^\pm$ strategy

on going analysis

Mass reconstruction:
- use the corrected mass: $\sqrt{P_T^2 + M_{ch}^2} + P_T \rightarrow$

Background:
combinatorics + partially rec. $B$ decays
- suppressed using multivariate techniques

Simulated $B^0 \rightarrow K^{*0} \tau^\mp \mu^\pm$ decays

Signal yield extraction
- counting experiment
- background yield extracted from 2D control regions: $A = BC/D$
$B^0 \rightarrow K^{*0} \tau^\pm \mu^\mp$ prospects

- **LHCb:**
  - On going analysis using Run 1 data - updated soon with Run 2?
  - Subject of a thesis defended in September
  - Expect (Physics case for an LHCb Upgrade II)
    \[ \mathcal{B}(B^0 \rightarrow K^{*0} \tau^\pm \mu^\mp) \lesssim \text{few } 10^{-6} \] (Run 1&2)

- **Belle II 5 ab^{-1}** (Belle II Physics book):
  - \[ \mathcal{B}(B^0 \rightarrow \tau^\pm \mu^\mp) \lesssim 1 \cdot 10^{-5} \] with 50 ab^{-1}
Conclusions

- Many models proposed to explain the flavour anomalies predicts large enhancements for rate of rare $B$ decays with $\tau$ in the final state
- The searches for $B^0_{(s)} \to \tau^\pm \mu^\mp$ and $B^0 \to K^{*0} \tau^\pm \mu^\mp$ are well advanced
- Others are progressing ($B^+ \to K^+ \tau^\pm \mu^\mp$) or will start soon ($B^0 \to K^{*0} \tau^+ \tau^-$)
- Hope for more news in the near future ...