SM tests in rare B decays with \textit{tau} leptons in the final state

Giampiero Mancinelli (CPPM)

Towards the Ultimate Precision in Flavour Physics
Warwick, April 17\textsuperscript{th} 2018
Disclaimer

Does not mean PRELIMINARY

It means:
UNOFFICIAL, take with a lot of grano salis, a good guessestimate, do not share, do not write a paper based on it, do not, really
**LF[U]V with B→τX decays**

- *Lepton Flavor* is (accidentally) conserved in the SM
  
  - Neutrino oscillations → LFV → extension of SM (O(10\(^{-40}\)) → unobservable)... worse, 10\(^{-54}\), in the charged lepton sector
  
  - LFU maybe just a low-energy property:
    - the different families may well have a very different behavior at high energies (explanation for their very different masses?).
  
  - Recent convincing (?) and coherent evidences of Lepton Flavor Universality violations in measurement by LHCb/Belle/BaBar
    - b → c charged currents: τ vs. light leptons (μ, e) \([R_D, R_{D^*}, R_{\text{J/ψ}}]\)
    - b → s neutral currents: μ vs. e \([R_{\text{K}}, R_{\text{K}^*} (+ P_5 \text{ etc})]\)
  
  - Most BSM → allow (large) charged LF[U]V (exp 3\(^{rd}\) generation)

- LFV observation in the charged sector → New Physics
Crivellin, Mueller, Ota
arxiv:1703.09226
FCNC with $B \rightarrow \tau X$ decays

- **FCNC $b \rightarrow sll$**
  
  - New physics lurking in boxes and loops (sensitivity $\sim 10$s of TeV)
  - Extensively studied ($l$=e,µ)
  - $\tau$ final states
    - more complex experimentally
    - in principle offer **unique window** to new observables
      - Sizable mass $\rightarrow$ access to RH and LH couplings
      - Angular variables including those related to $\tau$ polarization
      - Comparison with sister processes with $e$ or $\mu$ $\rightarrow$ test of LFU
**ττ Enhancements**

![Graph showing ττ Enhancements](image)

- Capdevila, Crivellin, Descotes-Genon, Matias
  - arXiv 1712.01919

- Alonso, Grinstein, Camalich
  - arXiv 1505.05164
Exciting $\tau$-imes

Gino Isidori (IW, Nov 2017) → idea: at high energies the 3 families are charged under 3 independent gauge groups (gauge bosons carry a flavor index)

If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables:

<table>
<thead>
<tr>
<th>$b \to s$</th>
<th>$m\mu ,(ee)$</th>
<th>$\tau\tau$</th>
<th>$\nu\nu$</th>
<th>$\tau\mu$</th>
<th>$\mu e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to d$</td>
<td>$B_d \to m\mu$</td>
<td>$B \to \pi \tau\tau$</td>
<td>$B \to \nu\nu$</td>
<td>$B \to \pi \tau\mu$</td>
<td>$B \to \mu e$</td>
</tr>
<tr>
<td>$s \to d$</td>
<td>long-distance pollution</td>
<td>$K \to \pi \nu\nu$</td>
<td>$K \to \nu\nu$</td>
<td>$K \to \mu e$</td>
<td></td>
</tr>
</tbody>
</table>

- $R_K, R_{K^*}$
- $O(20\%)$
- $100\times$SM
- $O(1)$
- $\sim 10^{-6}$
- $\sim 10^{-7}$
- $???
## Summary of relevant modes

<table>
<thead>
<tr>
<th>Decays</th>
<th>SM prediction</th>
<th>Experimental measurement or upper limit (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to \tau e$ / $B \to \tau \mu$</td>
<td>-</td>
<td>$2.8 \times 10^{-5}$ / $2.2 \times 10^{-5}$ [4]</td>
</tr>
<tr>
<td>$B_s \to \tau e$ / $B_s \to \tau \mu$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$B \to K \tau e$ / $B \to K \tau \mu$</td>
<td>-</td>
<td>$3.0 \times 10^{-5}$ / $4.8 \times 10^{-5}$ [1]</td>
</tr>
<tr>
<td>$B \to \pi \tau e$ / $B \to \pi \tau \mu$</td>
<td>-</td>
<td>$7.5 \times 10^{-5}$ / $7.2 \times 10^{-5}$ [1]</td>
</tr>
<tr>
<td>$B \to K^* \tau e$ / $B \to K^* \tau \mu$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$B \to \tau \tau$</td>
<td>$(2.22 \pm 0.19) \times 10^{-8}$</td>
<td>$1.6 \times 10^{-3}$ [2]</td>
</tr>
<tr>
<td>$B_s \to \tau \tau$</td>
<td>$(7.73 \pm 0.49) \times 10^{-7}$</td>
<td>$5.2 \times 10^{-3}$ [2]</td>
</tr>
<tr>
<td>$B \to K^* \tau \tau$</td>
<td>$(0.98 \pm 0.10) \times 10^{-7}$</td>
<td>-</td>
</tr>
<tr>
<td>$B \to K \tau \tau$</td>
<td>$(1.20 \pm 0.12) \times 10^{-7}$</td>
<td>$2.3 \times 10^{-3}$ [3]</td>
</tr>
<tr>
<td>$B \to \tau \nu$</td>
<td>$(7.7 \pm 0.6) \times 10^{-5}$</td>
<td>$(1.06 \pm 0.19) \times 10^{-4}$ [5]</td>
</tr>
<tr>
<td>$B \to \pi \tau \nu$</td>
<td>$(9.35 \pm 0.38) \times 10^{-5}$</td>
<td>$2.5 \times 10^{-4}$ [6]</td>
</tr>
</tbody>
</table>

LHCb (and Belle II) challenges
Neutrinoes and Mass reconstruction

- LHCb challenge (no $4\pi$ coverage)
  - $\tau$ decay modes
    - $3\pi\nu$ (9.0%), $\mu\nu\nu$ (17.4%), (+3$\pi\pi^0\nu$?)
- Missing Mass reconstruction
  - Visible mass (Mvis)
  - Corrected mass (MCM)
  - (partial) Anal. reconstruction
    - $B_{(s)} \rightarrow \tau\tau$ ($3\pi,3\pi$)
      - Analytical (partial) : some important discriminating variables
    - MCM, Mvis in NN
- Belle II
  - Other B fully reconstructed (had or SL tag)
    - Cost in statistics (still factor ~2 better than Belle)
  - Or using untagged reconstruction
    - Cost in background (still overall better reach expected)
Background characterization

- Same Sign (SS) Data
  - Limitations (e.g. when $B^0$ signal has $n$ charged tracks in the final state $\rightarrow$ no exclusive events with $n$ tracks can be part of SS data)
- Exclusive MC samples (most with D decays)
  - Large number of exclusive modes
- Generic MC bbbar samples very tiny in LHCb
  - Trick to get exclusives from generic MC
    - using other side of MC signal samples
- Combinatorial background
  - High mass SS data sidebands (BDT)
  - “Dalitz” plane ($\tau \rightarrow 3\pi\nu$)
Isolation variables

- Lots of custom made variables (BDT of)
  - Track (&composite) isolations (Cut and BDT based)
  - Neutral isolations
  - Vertex isolations

Input isolation variables to a BDT for $B \rightarrow ... \tau$

[not an exhaustive sample]

Signal

Background
Multivariate approaches

- You can find them (BDT, NN, ...) everywhere just like parsley in good Italian dishes:
  - Preselection MVA (often Isolation-based)
  - Selection MVA(s)
  - Specific backgrounds MVA ($B_{(s)} \rightarrow \tau\tau$)
    - Combinatorics, signal-(un)like, semileptonic D decays, hadronic D decays...
  - Fit a final MVA (alone or in 2D simultaneous fit with some B mass variable)

- Variables validation (MC/Data) on control channels
  - typically the ones used for BR normalization

- Dalitz variables used in MVA or not depending on bg control region used
Control samples/regions and fits

- **Estimation of background component in signal region of the fit**
  - If B Mass reconstructible
    - Use same sign to validate shape, fit opposite sign
    - Estimate/eliminate peaking backgrounds
  - Otherwise, no sidebands to control background
    - Control samples and/or regions are crucial: e.g. Dalitz plane regions – Dalitz models (Tauola/BaBar)
      - Hard to validate that background has the same behavior (MVA) in signal and control regions
      - Unblind part of signal region for low MVA values (background dominated)
      - Fit keeping into account signal component in control region
      - Fit toy studies with SS data
      - Normally LHCb can’t distinguish $B_s$ and $B_d$
    - **Belle II can... but limited integrated luminosity at the $\Upsilon(5s)$**
$B_{(s)} \rightarrow \tau \tau$ (LHCb)

Signal region: both $\tau$ in 5
Control region: one $\tau$ in (4,5,8) and the other in (4,8)
Background region: at least one $\tau$ in (1,3,7,9)

Using as well variables coming from the full reconstruction of $B \rightarrow \tau^+\tau^-$, developed by A. Mordá and J. Charles (theorist at CPT)
**B_{(s)} \to \tau \tau** (LHCb)

\[
N_{\text{data}}^{\text{SR}} = s \times \hat{N}_{\text{sim}}^{\text{SR}} + f_b \times \left( N_{\text{data}}^{\text{CR}} - s \cdot \frac{\varepsilon_{\text{CR}}}{\varepsilon_{\text{SR}}} \hat{N}_{\text{sim}}^{\text{CR}} \right)
\]

\[\text{BR}(B \to \tau \tau) < 2.1 \times 10^{-3} \quad @ \ 95\% \ CL\]

\[\text{BR}(B_s \to \tau \tau) < 6.8 \times 10^{-3} \quad @ \ 95\% \ CL\]

- 3\pi\nu\mu\nu
- Harder (B, D semileptonic backgrounds)
- Not clear a comparable limit can be reached

\[\text{BR}(B_{(s)} \to \tau \tau) \sim \%\]


R. Alonso, arxiv:1505.05164
C. Bobeth and U. Haisch, APP B44 (2013) 127 arxiv:1109.1826
Other work in progress in LHCb

$B_d \rightarrow K^\tau \tau$

- 100xSM possible (if anomalies due to NP, G. Isidori)
- Mass reconstructable in principle, but low efficiency for physical solutions
  - $3\pi\nu$, $3\pi\nu$, and $3\pi\nu$, $\mu\nu\nu$

$B_{(s)} \rightarrow \tau \mu$

- Analysis in good shape™ (internal review, but still blind)
  - $\tau \rightarrow 3\pi\nu$
- Mass reconstructable analytically
- Publication hoped before 10/18

$B_d \rightarrow K^\tau \mu$

- BR~$10^{-6}$ possible
  - $\tau \rightarrow 3\pi\nu$ ($\mu$ mode considered)

$(B_s^{**} \rightarrow K)B_u \rightarrow K\tau \mu$

- BR~$10^{-6}$ possible
- $B^{**}$ chain: Full mass reconstruction, in principle

REM !!! these modes are possible at Belle II as well... see following slides
\[ B_u \rightarrow \tau \nu \] (Belle I+II)

- In the SM:
  \[ B(B^+ \rightarrow \tau^+ \nu) = \frac{G_F^2 m_B m_{\tau}^2}{8\pi} \left[ 1 - \frac{m_{\tau}^2}{m_B^2} \right]^2 f_B^2 |V_{ub}|^2 \tau_{B+} \]
  - Using \(|V_{ub}|_{\text{excl}} = (3.55 \pm 0.12) \times 10^{-3}\), \(f_B = (186 \pm 4)\) MeV
  - \(B(B^+ \rightarrow \tau^+ \nu) = (0.77 \pm 0.06) \times 10^{-4}\)
- BaBar / Belle WA:
  - \(B(B^+ \rightarrow t^+ n) = (1.06 \pm 0.19) \times 10^{-4}\)
  - Measurement statistically limited
  - Syst: DT/MC disagreement, efficiency estimations, pdfs in final fit

- Belle II extrapolations based on Belle results (SL and hadronic tag) + Belle II full MC:

<table>
<thead>
<tr>
<th>tag</th>
<th>uncertainty (%)</th>
<th>5 ab(^{-1})</th>
<th>50 ab(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadronic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stat.</td>
<td>13.0</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Syst.</td>
<td>6.8</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>14.7</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>semileptonic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stat.</td>
<td>8.5</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Syst.</td>
<td>8.7</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>12.2</td>
<td>5.3</td>
<td></td>
</tr>
</tbody>
</table>

>5\(\sigma\) significance
Consistent with SM at 2\(\sigma\)

2.6 ab\(^{-1}\) to reach a 5\(\sigma\) single experiment discovery
LHCb Phase II

- **Improvements for tau leptons:**
  - Better Ecal → better neutral isolation algorithms
  - Tracking stations in the magnet → ~30% more efficiency for $B \rightarrow \tau\tau$
  - Hadronic trigger improvements (up to factors 2 for hadronic tau decays)
  - Mass reconstruction methods depend heavily on the error on the primary and the tau decay vertices, hence any improvement in the tracking system will be highly valuable.

- **Added difficulties:**
  - Isolation variables and high pile-up
    - recoverable in principle, but needs MC/data nPV agreement
Perspectives LHCb

- \( B_S \to \tau\tau \)

- \( B_S \to \tau\mu \)

Only luminosity gain

Adding muonic mode and improved upgrade had trigger and tracking and better analysis


\( B_S \to \tau\tau \sim 10^{-3} \) (MI, MLFV)


\( B_S \to \tau\tau \sim 5 \times 10^{-4} \) (MAX, LQ)

Only luminosity gain

Adding \( \pi\pi\pi\pi^0 \) mode and improved upgrade trigger and tracking and better analysis


\( B_S \to \tau\mu \sim 10^{-6} \) (Z')


\( B_S \to \tau\mu \sim 3 \times 10^{-6} \) (MAX, LQ)
# Belle II / LHCb Perspectives (prel)

<table>
<thead>
<tr>
<th>Decays</th>
<th>SM prediction</th>
<th>BELLE II limit reach 5 ab-1 (90% CL)</th>
<th>BELLE II limit reach 50 ab-1 (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B→τe / B→τµ</td>
<td>-</td>
<td>1.6 $10^{-5}$ / 1.3 $10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>B_s→τe / B_s→τµ</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>B→Kτe / B→Kτµ</td>
<td>-</td>
<td>2.1 $10^{-6}$ / 3.3 $10^{-6}$</td>
<td></td>
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<tr>
<td>B→ττ</td>
<td>(2.22±0.19) $10^{-8}$</td>
<td>3.0 $10^{-4}$</td>
<td>9.6 $10^{-5}$</td>
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<td>B_s→ττ</td>
<td>(7.73±0.49) $10^{-7}$</td>
<td>8.1 $10^{-4}$</td>
<td>-</td>
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<tr>
<td>B→Kττ</td>
<td>(1.20±0.12) $10^{-7}$</td>
<td>6.5 $10^{-5}$</td>
<td>2.0 $10^{-5}$</td>
</tr>
<tr>
<td>B→τν</td>
<td>(7.7±0.6) $10^{-5}$</td>
<td>Error ~0.7 $10^{-5}$</td>
<td>Error ~0.3 $10^{-5}$</td>
</tr>
<tr>
<td>R_τπ→π[τ/ν]ν</td>
<td>0.641 ± 0.016</td>
<td>±0.23</td>
<td>±0.09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decays</th>
<th>SM prediction</th>
<th>LHCb RUN3 (95% CL)</th>
<th>LHCb RUN5 (95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B→τµ</td>
<td>-</td>
<td>1.0 $10^{-6}$</td>
<td>2.6 $10^{-7}$</td>
</tr>
<tr>
<td>B_s→τµ</td>
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Synergy in B → τ ± τ −: BELLE II → better understanding of intermediate resonance structure of the τ → π − π + π − ν τ decay
- exploited in LHCb analysis to define a region with higher signal sensitivity, and control → possible syst limitation

G. Mancinelli (CPPM)
Conclusions

- Lot’s of work on B rare decays into tau leptons

- Motivated by...
  - LFUV anomalies
  - Boredom with muons?
  - Feeling crazy?

- Very challenging
  - Missing energy (neutrinos)
  - High level and variety of (exclusive) backgrounds

- Not possible to just turn the crank
  - Handmade (work of artisans!) analyses, made from scratch
  - Longer time
  - Small groups of people. Highly formative.
  - Isolations and other tools/selections, MVAs, creative control samples

- Analysis improvements/upgrades needed to get to much more interesting regimes