Prospects with taus at LHCb, Belle II and more...

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In this talk

• $\tau$ LFV decays
• $B \to \tau$ LFV decays
• $b \to s\tau\tau$ decays

Not covered:
• LUV tests in $\tau$ decays
• Mass and Michel parameters
• $\tau$ g-2, EDM
• ...

Material stolen from different presentations (Alberto Luisano, Giampiero Mancinelli, Stéphane Monteil, Mogens Dam,.....)
Why caring about taus?

1) Anomalies seen in violation of LFU suggests a special role of the third family

- enhancements of $\tau \to \mu/e$ and $B \to \tau \mu/e$ LFV decays
- enhancements of $b \to s\tau\tau$ decays

D. Bečirević, N. Košnik, O. Sumensari, et R. Z. Funchal, « Palatable Leptoquark Scenarios for Lepton Flavor Violation in Exclusive $b\to s\ell_1\ell_2$ modes », arXiv:1608.07583
A. Crivellin, D. Müller, et T. Ota, « Simultaneous Explanation of R(D(∗)) and $b \to s\mu\mu$ : The Last Scalar Leptoquarks Standing », Journal of High Energy Physics, vol. 2017, n° 9, sept. 2017

Etc .........
Correlations between charged current anomalies and $b \to s \tau\tau$ decays, assuming NP contributions in $C_{9(')}^{\tau}$ and $C_{10(')}^{\tau}$
Interpretation of the anomalies in terms of vector leptoquarks

Why caring about taus?

2) $b \rightarrow \tau$ decays are much less well known than their $e/\mu$ counterparts

<table>
<thead>
<tr>
<th>Decays</th>
<th>SM prediction</th>
<th>Best 90% CL UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \tau e/\mu$</td>
<td>-</td>
<td>2.8/1.2 $10^{-5}$ [3][4]</td>
</tr>
<tr>
<td>$B_s \rightarrow \tau \mu$</td>
<td>-</td>
<td>3.4 $10^{-5}$ [4]</td>
</tr>
<tr>
<td>$B \rightarrow K \tau e/\mu$</td>
<td>-</td>
<td>3.0/4.8 $10^{-5}$ [5]</td>
</tr>
<tr>
<td>$B \rightarrow \pi \tau e/\mu$</td>
<td>-</td>
<td>7.5/7.2 $10^{-5}$ [5]</td>
</tr>
<tr>
<td>$B \rightarrow K^* \tau e/\mu$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$B^0 \rightarrow \tau\tau$</td>
<td>$(2.22\pm0.19) \times 10^{-8}$ [1]</td>
<td>1.6 $10^{-3}$ [6]</td>
</tr>
<tr>
<td>$B_s \rightarrow \tau\tau$</td>
<td>$(7.73\pm0.49) \times 10^{-7}$ [1]</td>
<td>5.2 $10^{-3}$ [6]</td>
</tr>
<tr>
<td>$B \rightarrow K^* \tau\tau$</td>
<td>$(0.98\pm0.10) \times 10^{-7}$ [2]</td>
<td>-</td>
</tr>
<tr>
<td>$B \rightarrow K\tau\tau$</td>
<td>$(1.20\pm0.12) \times 10^{-7}$ [2]</td>
<td>2.25 $10^{-3}$ [7]</td>
</tr>
</tbody>
</table>

3) Tau is the heaviest lepton, giving access to many LFV decays, an ideal probe for NP, different types of coupling can be tested.

Main players

Belle II
Physics data taking started in 2019
Expect 50 x Belle statistics by 2027

LHCb
Recorded ~9fb-1
Current upgrade I ongoing to increase peak luminosity by factor 5
Upgrade II under discussion

Expected luminosity profile

HL-LHC
$\tau$ LFV decays
Current limits at few $10^{-8}$ dominated by Belle

In $\mu \rightarrow e$ transitions, limits are at $10^{-13}$ level!
Tau LFV at B factories

- $\sigma_{\tau\tau} = 0.9 \text{ nb} \sim \sigma_{bb}$ : B factories are also $\tau$ factories
- Reconstruct the entire events (sometimes only leptonic or one prong decays of $\tau$ tag are used)
- Use variables related to event topology to suppress B backgrounds
- Background evaluated from sidebands in $m_\tau$ and $\Delta E = E_{\text{CM}}^{\text{sig}} - E_{\text{CM}}^{\text{beam}}$ variables

Belle $\tau \to \mu\gamma$

PLB 666 16-22 (2008)
Prospects for Belle II

- Most of LFV analyses are background free, expected limits scale as luminosity
- This may not be the case for $\tau \to \mu/\gamma$ due to higher beam induced backgrounds than in Belle
  Dedicated MC analysis showed that this can be mitigate
- Improved photon position reconstruction in ECL also helps

![Rotated signal region ($\tau \to \mu \gamma$)](image)

Signal region, background free
(Belle II physics book, arXiv:1808.10567)
From HL-LHC and HE-LHC opportunities arXiv:1812.07638
Tau LFV at LHC

- $\sigma_{\tau\tau}$ at the LHC about 5 orders of magnitude larger than at Belle II
- Reconstruct only $\tau$ decay products (no tagging)
- Fit $m_\tau$ in bins of a multivariate classifier

- Use $\tau$ produced from $D_s \rightarrow \tau \nu$ (LHCb) and/or $W \rightarrow \tau \nu$ (ATLAS)
- LHCb normalises to $D_s \rightarrow \phi (\rightarrow \mu\mu) \pi$ channel / ATLAS estimates the number of $\tau$ produced from MC
- Only $\tau \rightarrow \mu\mu\mu$ and $\tau \rightarrow \rho\mu\mu$ studied so far

\[ JHEP 02(2015)121 \quad EPJC 76(2016)232 \]
Prospects for HL-LHC

- ATLAS will benefit from improved tracking and trigger system
- CMS will benefit from the upgraded muon system with better coverage $|\eta|=2.4 \rightarrow 2.8$
- LHCb Upgrade 1 will enable a better trigger efficiency. Improved calorimeters in Upgrade II will help reducing background from $D_s \rightarrow \eta(\rightarrow \mu\mu\gamma)\mu\nu$ events
Prospects for HL-LHC

Opportunities in flavour physics at the HL-LHC and HE-LHC, arxiv:1812.07638

<table>
<thead>
<tr>
<th>$\text{BR}(\tau \to 3\mu)$ (90% CL limit)</th>
<th>Ref.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.8 \times 10^{-7}$</td>
<td>ATLAS [429]</td>
<td>Actual limit (Run 1)</td>
</tr>
<tr>
<td>$4.6 \times 10^{-8}$</td>
<td>LHCb [428]</td>
<td>Actual limit (Run 1)</td>
</tr>
<tr>
<td>$3.3 \times 10^{-8}$</td>
<td>BaBar [417]</td>
<td>Actual limit</td>
</tr>
<tr>
<td>$2.1 \times 10^{-8}$</td>
<td>Belle [423]</td>
<td>Actual limit</td>
</tr>
<tr>
<td>$3.7 \times 10^{-9}$</td>
<td>CMS HF-channel at HL-LHC</td>
<td>Expected limit (3000 fb$^{-1}$)</td>
</tr>
<tr>
<td>$6 \times 10^{-9}$</td>
<td>ATLAS W-channel at HL-LHC</td>
<td>Expected limit (3000 fb$^{-1}$)</td>
</tr>
<tr>
<td>$2.3 \times 10^{-9}$</td>
<td>ATLAS HF-channel at HL-LHC</td>
<td>Expected limit (3000 fb$^{-1}$)</td>
</tr>
<tr>
<td>$\mathcal{O}(10^{-9})$</td>
<td>LHCb at HL-LHC</td>
<td>Expected limit (300 fb$^{-1}$)</td>
</tr>
<tr>
<td>$3.3 \times 10^{-10}$</td>
<td>Belle-II [196]</td>
<td>Expected limit (50 ab$^{-1}$)</td>
</tr>
</tbody>
</table>
τ → μμμ @ tauFV

- "A fixed target experiment to search for flavour violation in tau decays"
- Proposal discussed in the 'physics beyond collider' workshops organized at CERN (here) and ESPP
- Beam dump experiment located at the SPS, upstream of SHiP

In SHiP:

Instead, design dedicated experiment upstream of SHiP, with thin, distributed targets, to bleed off ~2% of the beam intended for SHiP → 2 mm of tungsten (this value also set by upper limit of data rates in VELO).

- Earliest start date: 2026-2027 (2030 more realistic)
- $B(\tau \rightarrow \mu \mu \mu)$ UL down to $\sim 10^{-10}$
- Other $\tau \rightarrow 3l$, kaon and charm decays can be studied
τ → μμμ @ Super Tau/Charm Factory

- SCT factroy project at BINP, Novosibirsk
- Input to the ESPP here, workshop held in december 2018 at LAL
- E from 2 to 6 GeV, L = 10^{35} cm^{-2}s^{-1}, polarized e- beam
- Begin data taking in 2029-2030
- 10^{10} taus produced per year at max ττ cross section

- Similar project in China (HIEPA)
- Many LFV modes and other tau measurements possible
\( \tau \rightarrow \mu \mu \mu \rightarrow Z \text{ peak} \)

- FCC-ee at CERN, running at Z peak: 15x10\(^{10}\) tau pairs
- Start date \( \approx 2039 \)
- Dedicated study gives a limit at 2 \( 10^{-9} \) on \( \tau \rightarrow e/\mu \gamma \) and \(<10^{-10}\) on \( \tau \rightarrow 3\ell \)

- CEPC in China, running at Z peak: 3x10\(^{10}\) tau pairs
- Could be approved in 2022

Talk by M. Dam at TAU 2018

Smear with assumed FCC-ee detector resolutions:
- Muon momentum [GeV]
  \[ \sigma(p_T) = 2 \times 10^{-5} \times p_T \oplus 1 \times 10^{-3} \]
- Photon ECAL energy [GeV]
  \[ \sigma(E/E) = 0.165/\sqrt{E} \oplus 0.010/E \oplus 0.011 \]
- Photon ECAL spatial resolution
  \[ \sigma(x) = \sigma(y) = (6/E \oplus 2) \text{ mm} \]

From this, determine FCC-ee effective detector resolution for \( \tau \rightarrow \mu \gamma \)

\[ \sigma(m_{\gamma \mu}) = 26 \text{ MeV}; \quad \sigma(E_{\gamma \mu}) = 850 \text{ MeV} \]
Indicative benchmarks

Estimates from A. Lusiani shown at the Grenada symposium
Green are published
Red are reliable estimate based on dedicated studies
Orange are estimates with less solid fundations
$B \rightarrow \tau$ decays
B→τ LFV at B factories

- Dominated by Babar
- Reconstruct the entire event using hadronic tagging → signal B momentum is known, τ mass indirectly reconstructed

\[ \vec{p}_\tau = -\vec{p}_{\text{tag}} - \vec{p}_h - \vec{p}_l, \]
\[ E_\tau = E_{\text{beam}} - E_h - E_l, \]
\[ m_\tau = \sqrt{E_\tau^2 - |\vec{p}_\tau|^2}, \]

**B^+ → h^+τl (h=K,π)**
- Use one prong tau decay
- Normalized to B+ → D(*)l+nu
- Signal yield determined from the reconstructed tau mass distribution (cut and count)

**B^0 → τl**
- Use one and three prong tau decay
- Signal yield determined fitting l momentum in signal frame

342 fb⁻¹
**b → sττ at B factories**

- Only one published analysis by Babar on $B^+ \rightarrow K^+\tau\tau$
- Use hadronic tagging and leptonic $\tau$ decays only
- Selection based on MLP
- Cut and count analysis, compare observed events with expected background yield:
  - Combinatorial from mES sidebands
    \[ m_{ES} = \sqrt{(E_{CM}^s/2 - p_{D_{tag}}^2)} \]
  - Peaking (with correct tag) from MC, crosschecked on $B \rightarrow D \text{lnu}$ control sample

<table>
<thead>
<tr>
<th></th>
<th>$e^+ e^-$</th>
<th>$\mu^+ \mu^-$</th>
<th>$e^+ \mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{bkg}^{i}$</td>
<td>49.4±2.4±2.9</td>
<td>45.8±2.4±3.2</td>
<td>59.2±2.8±3.5</td>
</tr>
<tr>
<td>$\epsilon_{\text{sig}} (\times 10^{-5})$</td>
<td>1.1±0.2±0.1</td>
<td>1.3±0.2±0.1</td>
<td>2.1±0.2±0.2</td>
</tr>
<tr>
<td>$N_{i_{\text{obs}}}$</td>
<td>45</td>
<td>39</td>
<td>92</td>
</tr>
<tr>
<td>Significance ($\sigma$)</td>
<td>-0.6</td>
<td>-0.9</td>
<td>3.7</td>
</tr>
</tbody>
</table>

**Combined upper limit:** $\text{BR} < 2.25 \times 10^{-3}$ at 90% CL

- Expected limit from Belle presented by S. Wehle: $3.2 \times 10^{-4}$ at 90% CL
Prospects for Belle II

• Improved tagging thanks to Full Event Interpretation tagging algorithm (arXiv:1807.08680)
  • Hierarchical approach
  • MVA-based
  • Highly tunable
  • Already used in Belle analyses

<table>
<thead>
<tr>
<th>Tag</th>
<th>FR$^{10}$ @ Belle</th>
<th>FEI @ Belle MC</th>
<th>FEI @ Belle II MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic $B^+$</td>
<td>0.28 %</td>
<td>0.49 %</td>
<td>0.61 %</td>
</tr>
<tr>
<td>Semileptonic $B^+$</td>
<td>0.67 %</td>
<td>1.42 %</td>
<td>1.45 %</td>
</tr>
<tr>
<td>Hadronic $B^0$</td>
<td>0.18 %</td>
<td>0.33 %</td>
<td>0.34 %</td>
</tr>
<tr>
<td>Semileptonic $B^0$</td>
<td>0.63 %</td>
<td>1.33 %</td>
<td>1.25 %</td>
</tr>
</tbody>
</table>

Other possible improvements:
• Use of semileptonic tagging, as e.g. in Belle $B \rightarrow h\nu\nu$ analysis (PRD 96(2017)091101)
• Use inclusive analysis (no tagging): for $B \rightarrow \tau \mu$, CLEO reached limit at $3.8 \times 10^{-5}$ with $10 \text{fb}^{-1}$! PRL93(2004)241802 (1.7x Babar)
• Additionnal tau modes
Prospects for Belle II


<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab$^{-1}$ (0.12 ab$^{-1}$)</th>
<th>Belle II 5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^+ \tau^+ \tau^-) \cdot 10^5$</td>
<td>&lt; 32</td>
<td>&lt; 6.5</td>
<td>&lt; 2.0</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow \tau^+ \tau^-) \cdot 10^5$</td>
<td>&lt; 140</td>
<td>&lt; 30</td>
<td>&lt; 9.6</td>
</tr>
<tr>
<td>$\text{Br}(B_{s0}^0 \rightarrow \tau^+ \tau^-) \cdot 10^4$</td>
<td>&lt; 70</td>
<td>&lt; 8.1</td>
<td>–</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^+ \tau^\pm e^\mp) \cdot 10^6$</td>
<td>–</td>
<td>–</td>
<td>&lt; 2.1</td>
</tr>
<tr>
<td>$\text{Br}(B^+ \rightarrow K^+ \tau^\pm \mu^\mp) \cdot 10^6$</td>
<td>–</td>
<td>–</td>
<td>&lt; 3.3</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow \tau^\pm e^\mp) \cdot 10^5$</td>
<td>–</td>
<td>–</td>
<td>&lt; 1.6</td>
</tr>
<tr>
<td>$\text{Br}(B^0 \rightarrow \tau^\pm \mu^\mp) \cdot 10^5$</td>
<td>–</td>
<td>–</td>
<td>&lt; 1.3</td>
</tr>
</tbody>
</table>
B→τ LFV at LHCb

- Only one public analysis, based on 3 fb⁻¹: \( B_{(s)} \rightarrow τ \mu \)
- Use \( τ \rightarrow πππν \) decays (\( τ \) decay vertex)
- B mass reconstruction possible with a 2-fold ambiguity

- Signal yield obtained from a fit to the mass in 4 bins of a BDT
- Limited Bs and Bd signal separation
  - Bs signal fit, assuming no B0 contribution
- BR normalised to the \( B^0 \rightarrow D^- (\rightarrow K^+π^-π^-)π^+ \) mode
- First limit on Bs mode, best limit on \( B^0 \) mode
$b \rightarrow s\tau\tau$ at LHCb

- Only one analysis on $B_{(s)} \rightarrow \tau\tau$
- Analysis complicated by the fact that we have no indication about the $B$ decay vertex
- But using $\tau \rightarrow \pi\pi\pi\nu$ we can access to the 2 $\tau$ decay vertex
- Signal yield obtained from a fit to a NN,
- Background taken from CR region based on $\tau$ Dalitz plane
- First limit on $B_s$ mode, best limit on $B^0$ mode
Prospects at LHCb

- More data (~6 fb\(^{-1}\) for Run2) and modes to analyze!
- Will benefit from higher trigger efficiency from Upgrade I and additional tracking stations from LS3 (+ further possible tracking improvements)
- \(B \rightarrow \tau \mu\) : unofficial estimates from G. Mancinelli (SM@LHC 2019)

<table>
<thead>
<tr>
<th>Decays</th>
<th>LHCb RUN3 (95% CL)</th>
<th>LHCb RUN5 (95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B \rightarrow \tau \mu)</td>
<td>1-2 (10^{-6})</td>
<td>4-7 (10^{-7})</td>
</tr>
<tr>
<td>(B_s \rightarrow \tau \mu)</td>
<td>5-9 (10^{-6})</td>
<td>1-3 (10^{-6})</td>
</tr>
</tbody>
</table>

- Ongoing analysis of \(B \rightarrow K^* \tau \mu\)
  - 6 tracks in the final state but B decay vertex known
  - Expect limit at few \(10^{-6}\) for Run1+Run2

- Work in progress on a method using \((B_s^* \rightarrow K)B_u \rightarrow K\tau \mu\), full mass reconstruction possible
Prospects at LHCb

• $B_{(s)} \rightarrow \tau \tau$ :
  • Feasibility study using final state ($3\pi, \mu$) but unfortunately not competitive with ($3\pi, 3\pi$)
  • Limits at few $10^{-4}$ reachable with Run4 or Run5

![Graph showing limits on $B(B_s^0 \rightarrow \tau^+ \tau^-)$ with years 2011-2036, indicating improvements over time.]

Assuming a factor 4 improvement thanks to trigger, tracking and analysis reoptimization.
Prospects at FCC-ee

- Dedicated study for $B \to K^{*}\tau\tau$ analysis
- Make use of partial reconstruction technique to solve the kinematic of the decay
- Assume detector performance similar to ILD
- At baseline luminosity, assuming SM BR more than 1000 events observables!

- Other $B \to \tau$ decays should be feasible

Backgrounds: (pink - $DsK^{*}\tau\nu\nu$ and $DsDsK^{*}$) [signal in red+green].
Conclusion

• We start to master taus!

• Many interesting results will come from Belle II and LHCb in the coming years (and possibly others in a longer time scale)

• In 2028, the picture could be:
First $\tau @$ Belle II
Main $\tau$ decays

<table>
<thead>
<tr>
<th>$\tau$ decay</th>
<th>BF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^+ \rightarrow \mu^+ \nu\nu$</td>
<td>$17.39\pm0.04$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow e^+ \nu\nu$</td>
<td>$17.82\pm0.04$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \nu$</td>
<td>$10.82\pm0.05$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \pi^0 \nu$</td>
<td>$25.49\pm0.09$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \pi^0 \pi^0 \nu$</td>
<td>$9.26\pm0.10$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \nu$</td>
<td>$9.31\pm0.05$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \nu$</td>
<td>$4.62\pm0.05$</td>
</tr>
</tbody>
</table>

One prong ~81% of decays

three prong ~14% of decays

Leptonic ~35% of decays

hadronic
Before LHCb $B \to \tau \mu$: