Tests of Lepton Flavour- / Number-
Violation
Conservation and Universality
at Belle II

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Ami Rostomyan
(for the Belle II collaboration)
**Lepton flavour conservation**

Conservation of the individual lepton-flavour and the total lepton numbers within the SM ($m_\nu = 0$)

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

⇒ The observation of neutrino oscillations as a first sign of LFV beyond the SM!
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**What about the charged leptons?**

- The charged LFV processes can occur through oscillations in loops
- Unmeasurable small rates \((10^{-54}-10^{-49})\) for all the LFV \(\mu\) and \(\tau\) decays

\[
B(\ell_1 \rightarrow \ell_2 \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\ell_1 i}^* U_{\ell_2 i} \left( \frac{\Delta m_{i1}^2}{M_W^2} \right)^2 \right|^2.
\]
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Observation of LFV will be a clear signature of the NP!

→ Charged LFV enhanced in many NP models ($10^{-10}$ - $10^{-7}$)
Lepton flavour conservation

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The observation of neutrino oscillations as a first sign of LFV beyond the SM!

What about the charged leptons?

No success in searches so far!
Lepton number conservation

Within the SM ($m_\nu = 0$), conservation of the individual lepton-flavour and the total lepton numbers

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⇒ The observation of neutrino oscillations as a first sign of LFV beyond the SM!

Are neutrinos Dirac ($|\Delta L| = 0$) or Majorana ($|\Delta L| = 2$) particles?
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Within the SM \((m_\nu = 0)\), conservation of the individual lepton-flavour and the total lepton numbers

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- Heavily suppressed LNV \(\tau\)-decay rates within the \(\nu\)SM

\[ \langle m \rangle^2_{\ell_1 \ell_2} = \left| \sum_{m=1}^{3} U_{\ell_1 m} U_{\ell_2 m} m_{\nu m} \right|^2, \]
Lepton number conservation

Within the SM \((m_\nu = 0)\), conservation of the individual lepton-flavour and the total lepton numbers

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\[
\langle m \rangle_{\ell_1 \ell_2}^2 = \left| \sum_{m=1}^{3} U_{\ell_1 m} U_{\ell_2 m} m_\nu_m \right|^2,
\]

- Unmeasurable decay rates with high NP scale, for example in models with heavy right-handed neutrinos

\[
\left| \sum_{m'=4}^{3+n} \frac{V_{\ell_1 m'} V_{\ell_2 m'}}{m_{N m'}} \right|^2,
\]
Lepton number conservation

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Observation of LNV will hint at light NP scale!

- NP models with light (0.1 - 5 GeV) right-handed Majorana neutrinos

- Significant enhancement of the $\tau$ decay rates

- G.L. Castro, N. Quntero (2013) -
Lepton number conservation

Within the SM ($m_\nu = 0$), conservation of the individual lepton-flavour and the total lepton numbers

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The observation of neutrino oscillations as a first sign of LFV beyond the SM!

Are neutrinos Dirac ($|\Delta L| = 0$) or Majorana ($|\Delta L| = 2$) particles?

No answer yet!
**Lepton universality**

Within the SM, the coupling of leptons to W bosons is flavour-independent: $g_e = g_\mu = g_\tau$

Identical decays involving electrons, muon or taus
Lepton universality

Within the SM, the coupling of leptons to W bosons is flavour-independent: $g_e = g_\mu = g_\tau$

![Diagram showing lepton decays](image)

Identical decays involving electrons, muon or taus

- differences due to lepton masses
- easy to account for in predictions
- for example:

$$R(D^*) = \frac{BR(B \rightarrow D^*\tau\nu)}{BR(B \rightarrow D^*\ell\nu)} \text{ with } \ell = e, \mu$$
Lepton universality

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Discovery of lepton flavour non-universality is a key signature of NP!
Lepton universality

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Identical decays involving electrons, muon or taus

- differences due to lepton masses
- easy to account for in predictions
- for example:
  \[
  R(D^*) = \frac{\mathcal{B}R(B \rightarrow D^* \nu)}{\mathcal{B}R(B \rightarrow D^* \ell \nu)} \quad \text{with} \quad \ell = e, \mu
  \]

Discovery of lepton flavour non-universality is a key signature of NP!

Hint for NP with \(~4\sigma~\)
The role of $\tau$ leptons in the quest

NP may favour the third generation!?
The role of $\tau$ leptons in the quest

NP may favour the third generation!?

The only lepton that decays into hadrons

[$\ell = e$ or $\mu$]

states with no lepton
flavour number

.signal side

-> a large variety of LFV and LNV semi-leptonic
decays ($\tau \to \ell h(h)$), in addition to radiative
($\tau \to \ell \gamma$) and leptonic decays ($\tau \to \ell \ell \ell$)

-> $\tau \to \mu$ and $\tau \to e$: test of the lepton flavour
structure
The role of τ leptons in the quest

NP may favour the third generation!?  

The only lepton that decays into hadrons

\[ \ell = e \text{ or } \mu \]  

states with no lepton flavour number

- a large variety of \textbf{LFV} and \textbf{LNV} semi-leptonic decays (\( \tau \rightarrow \ell h(h) \)), in addition to radiative (\( \tau \rightarrow \ell \gamma \)) and leptonic decays (\( \tau \rightarrow \ell \ell \ell \))
- \( \tau \rightarrow \mu \) and \( \tau \rightarrow e \): test of the lepton flavour structure

\[ \ell \quad h \quad h \]  

\[ e^+ \quad \tau \quad e^- \]  

\[ \nu_\tau \quad \text{tag side} \]

\[ \text{signal side} \]

B mesons decay into e, μ, τ leptons

\[ B \rightarrow \ell \nu \]  

\[ B \rightarrow D^* \ell \nu \]  

\[ B \rightarrow K(\ast) \ell \ell \]  

\[ B \rightarrow \ell \ell \]  

\[ B_s \rightarrow \ell \ell \]  

\[ B \rightarrow W^- \nu \]  

\[ \rightarrow \text{modes used to test the lepton flavour universality} \]

\[ e^+ \rightarrow \gamma(4S) \rightarrow e^- \]

\[ B \rightarrow W^+ H^+ \rightarrow \nu \ell^+ \]

\[ \bar{b} \rightarrow W^+ X^+ \rightarrow \mu^+ \]

\[ s \rightarrow W^- \nu \rightarrow \mu^- \]
The role of $\tau$ leptons in the quest

**NP may favour the third generation!?!**

**The only lepton that decays into hadrons**

$\ell = e$ or $\mu$

- states with no lepton flavour number

- $\ell = e$ or $\mu$

- $h = \text{higgs boson}$

$\tau$ signal side

$\tau$ tag side

- $e^+$

- $e^-$

$\nu_\tau$

- $\tau \to \mu$ and $\tau \to e$: test of the lepton flavour structure

- a large variety of LFV and LNV semi-leptonic decays ($\tau \to \ell h(h)$), in addition to radiative ($\tau \to \ell \gamma$) and leptonic decays ($\tau \to \ell \ell \ell$)

**B mesons decay into e, $\mu$, $\tau$ leptons**

- loops used to test the lepton flavour universality

**TREE**

$B \to \ell \nu$

$B \to D^* \ell \nu$

**LOOP**

$B \to \ell \ell$

$B_s \to \ell \ell$

$B \to K^{(*)} \ell \ell$

Test the SM in a variety of ways

Ami Rostomyan

30th Rencontres de Blois, Blois, France
Neutrinos on the tag or signal side

Not possible to fully reconstruct the full event

e^+e^- annihilation data is ideal for missing energy channels

- the kinematics of the initial state is precisely known
- the neutrino energy can be determined precisely
The progress of $\tau$ LFV and LNV searches

... mostly occurred at the B-factories

- immense amount of $e^+e^-$ annihilation data (BaBar $\rightarrow$ 531 fb$^{-1}$, Belle $\rightarrow$ 1000 fb$^{-1}$)
- large cross section of pairwise $\tau$-lepton production ($X$-section = 0.9 nb for $e^+e^- \rightarrow \tau^+\tau^-$ at 10.58 GeV
  
  X-section = 1.1 nb for $e^+e^- \rightarrow BB$ at 10.58 GeV)

The upper limits reached for $\tau$ decays approached the regions sensitive to NP.
Belle II @ SuperKEKB

New facility to search for physics beyond the SM by studying B, D and $\tau$ decays

**SuperKEKB** – major upgrade of the KEKB
- an asymmetric electron-positron collider
- collisions near and at $Y(nS)$
- smaller interaction point
- increased currents

First beams and commissioning in 2016

**Belle II detector** – upgraded Belle detector
- improved tracking efficiency, particle identification
- smarter software and more precise algorithms
- rolled in April 2017
- First recorded events in April 2018

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Ami Rostomyan
First recorded events

exp 3, run 125, event 223
April 26, 2018
First collisions: first peaks

Mass peaks for charged tracks and photons

Data accumulation is on going
Plans for Belle II

Phase 1: first beams
- no detector over interaction region,
- study the beam properties

Phase 2: first collisions
- no PXD detector
- instead BEAST II (radiation monitoring system)
- understand backgrounds
- establish nano-beam scheme and reach KEKB luminosity

Phase 3: first physics with full detector
- luminosity milestones:
  - 1ab⁻¹ after 1 year
  - 5ab⁻¹ mid of 2020
  - 50ab⁻¹ by 2025

More details are given in Isabelle Ripp-Baudot’s presentation
40 times higher luminosity comes at the cost of higher machine induced backgrounds

Beam background

Use the timing information from calorimeter to reduce the background
Suppression of beam background

The beam backgrounds are expected to be 10-20 higher

- small number of daughter particles from $\tau$ LFV decay
- $\tau$ LFV searches more complicated compared to Belle
- feasibility studies using MC samples in more contaminated environment

Energy-based cuts to reduce the background

Background-free search (even with high beam BG)
Two independent variables:

\[ \Delta E = E_{\mu\gamma}^{CM} - E_{\text{beam}}^{CM} \quad M_{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2} \]

- For signal \( \Delta E \) close to 0 and \( M_{\mu\gamma} \) close to \( \tau \) mass

Main background sources:

- \( \tau \to \mu\nu\nu \)
- \( \tau \to e\nu\nu \)
  \( + \gamma \)
- \( \tau \to \pi\nu \)
- \( e^+e^- \to ee(\mu\mu)\gamma \)
- \( e^+e^- \to \text{continuum} \)

Background suppression:

- event topology
- back-to-back production: thrust value close to 1
- missing momentum towards the tag hemisphere
- relation between the missing momentum and missing mass
- total visible energy
- …
Fig. 4: Figs. 4(a) and (b) for signal events in the signal region.

In an LFV analysis, in order to evaluate the signal yield, two independent variables are defined in the CM frame, e.g.

\[ \Delta E = E_{\mu\gamma}^{\text{CM}} - E_{\text{beam}}^{\text{CM}} \]

\[ M_{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2} \]

- For signal \( \rightarrow \Delta E \) close to 0 and \( M_{\mu\gamma} \) close to \( \tau \) mass

\[ \Delta E \] (GeV)
\[ M_{\text{inv}} (\text{GeV}/c^2) \]

\[ \Delta E \text{ of } \tau \] (GeV)

\[ \text{Invariant mass of } \tau \] (GeV)

\[ \text{BGx0} \]
\[ \text{BGx1} \]

Perspectives at Belle II

LFV and LNV $\tau$ decays

- One of factors pushing up the sensitivity of probes is the increase of the luminosity

- Equally important is the increase of the signal detection efficiency
  - high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

The searches at Belle II will push the current bounds further by more than one order of magnitude
Perspectives at Belle II

Semi-tauonic B decays (example)

\[ R(D^*) = \frac{\text{Br}(B \to D^{(*)}\tau\nu)}{\text{Br}(B \to D^{(*)}l\nu)} \quad (l=e, \mu) \]

- Current experimental results limited by statistics
- 1ab\(^{-1}\) (KEKB) \(\rightarrow\) 50ab\(^{-1}\) (SuperKEKB)
- LHCb experiment continues in parallel
- BelleII can confirm/deny this anomaly
Outlook

- SuperKEKB is completing the commissioning phase and first collisions achieved
- Phase 2 data taking has been started
- First data is available already
- The data with the full detector installed will start in early 2019
- Belle II will probe the New Physics in many channels with neutrinos in the final state
- Belle II will be the major player in \( \tau \) physics in the near future
- Very exciting times are ahead!