Sensitivity for four-body tau-lepton decays at Belle and Belle II experiments

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Introduction

In the charged lepton sector Lepton Flavor Violation (LFV) is heavy suppress in the Standard Model

$$\ell_\alpha \to \ell_\beta < 10^{-54}$$

Example of lepton flavor conservation is a muon decay

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

Example of charged lepton flavor violation is a neutrinoless muon decay

$$\mu^- \to e^- \gamma$$

But we can also consider LFV from the Lepton Number Violation ($|\Delta L| = 2$)

$$\tau^- \to h^+ \ell^- \ell^- \nu_\tau$$

Introduction

Looking for lepton-number-violating (LNV) signals to prove that neutrinos are their antiparticles (or not), i.e. elucidate if neutrinos are Majorana particles (or Dirac ones).

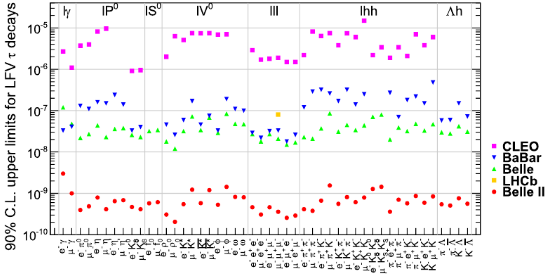


Figure 1: Upper limits[1].

[1] The Belle II Physics Book, 1808.10567

Introduction

Four-body $|\Delta L| = 2$ decays of the τ lepton[2], with an intermediate on-shell Majorana neutrino N with a kinematically allowed mass $(m_h + m_\ell) \leq m_N \leq (m_\tau - m_\ell)$ (We consider the N lifetime of $\tau_N = 40, 300$ ps).

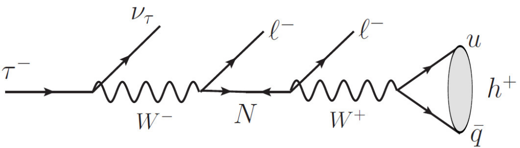


Figure 2: Event diagram.

[2] Castro, G. López and Quintero, N., Lepton number violating four-body tau lepton decays

This allows us to extract the limits on $|V_{\ell N}|^2$ without any additional assumption on the relative size of the mixing matrix elements. Based in the sensitivity of Belle II we can constrain the parameter space (m_N, $|V_{\ell N}|^2$).

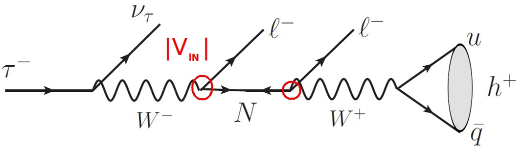


Figure 3: Mixing parameter, $|V_{\ell N}|^2$.

Four-body $|\Delta L| = 2$ decays of τ lepton

These processes occur via the intermediate on-shell Majorana neutrino through the leptonic decay $\tau^- \to \nu_\tau \ell^- N$ followed by the subsequent semileptonic decay $N \to \ell^- h^+$. Then, the decays are splitted into two subprocesses and the corresponding branching fraction can be expressed in the factorized form

$$BR(\tau^- \to h^+ \ell^- \ell^- \nu_\tau) = BR(\tau^- \to \nu_\tau \ell^- N) \times \Gamma(N \to \ell^- h^+)\tau_N/\hbar \quad (1)$$

Four-body $|\Delta L| = 2$ decays of τ lepton

Where we can provide a rough estimation of the expected number of events at the SuperKEKB[3], namely Belle II experiment and its predecessor Belle[4] for $h = \pi$),

$$
\begin{aligned}
BR(\tau^- \to h^+ \ell^- \ell^- \nu_\tau) \;&=\; BR(\tau^- \to \nu_\tau \ell^- N) \\
&\quad \times \Gamma(N \to \ell^- h^+) \tau_N / \hbar
\end{aligned}
\tag{2}
$$

[3] Abe, T., Belle II Technical Design Report

[4] Bevan, A. J., The Physics of the B Factories

The Belle Collaboration has measured the detection efficiency of τ decay modes to be $2.73 \pm 0.10\%$ for $\tau^- \to \pi^- e^+ e^- \nu_\tau$ and $4.14 \pm 0.16\%$ for $\tau^- \to \pi^- \mu^+ \mu^- \nu_\tau$[5]. This measurement includes

- Trigger
- Tracking
- Reconstruction
- Particle identification, and
- Selection efficiency

In the case of $\tau^- \to \pi^+ \mu^- \mu^- \nu_\tau$ detection efficiency we consider the same as $\tau^- \to \pi^- \mu^+ \mu^- \nu_\tau$ decays.

[4] Observation of $\tau^- \to \pi^- \nu_\tau e^+ e^-$ and search for $\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$, PhysRevD.100.071101

Expected experimental sensitivity at Belle and Belle II

$$N_{\rm exp}^{\rm Belle/Belle\,II} = \sigma(ee \to \tau\tau){\rm BR}(\tau^- \to \pi^+\ell^-\ell^-\nu_\tau) \times \epsilon_D^{\rm Belle}(\tau^- \to \pi^+\ell^-\ell^+\nu_\tau) \times \mathcal{L}_{\rm int}^{\rm Belle/Belle\,II}, \quad (3)$$

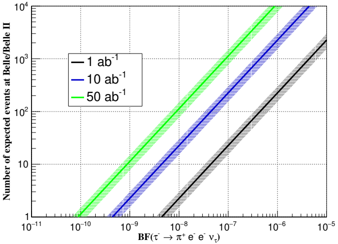


Figure 4: $BR(\tau^- \to \pi^+ e^- e^- \nu_\tau)$.

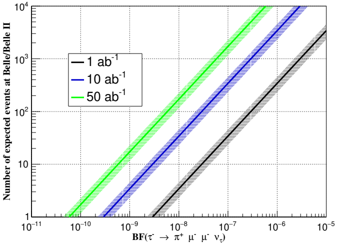


Figure 5: $BR(\tau^- \to \pi^+ \mu^- \mu^- \nu_\tau)$.

Bounds on the parameter space $(m_N, |V_{\ell N}|^2)$

In the analysis of the next section, we will take a branching fraction of the order of 10^{-9} as the conservative and accessible to Belle II and the limit for Belle. We explore the constraints on the $(m_N, |V_{\ell N}|^2)$ plane that can be achieved from the experimental searches on $\tau^- \to X^+ \ell^- \ell^- \nu_\tau$.

$$|V_{\ell N}|^2 = \left[\frac{BR(\tau^- \to X^+ \ell^- \ell^- \nu_\tau)\hbar}{\overline{\overline{BR}}(\tau^- \to \nu_\tau \ell^- N) \times \overline{\Gamma}(N \to \ell^- X^+)\tau_N} \right]^{1/2} \quad (4)$$

The experimental non-observation of $|\Delta L| = 2$ processes can be reinterpreted as bounds on the parameter space of a heavy sterile neutrino $(m_N, |V_{\ell N}|^2)$.

Bounds on the parameter space $(m_N, |V_{\ell N}|^2)$

We will consider the heavy neutrino lifetime of $\tau_N = 40$ ps, which corresponds to an average flight distance of up to 12 mm, well inside the Belle II vertex detector[1].

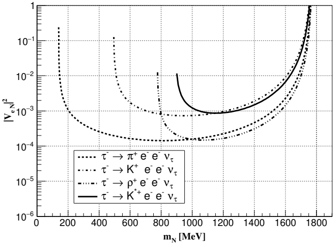


Figure 6: $\tau^- \to h^+ e^- e^- \nu_\tau$.

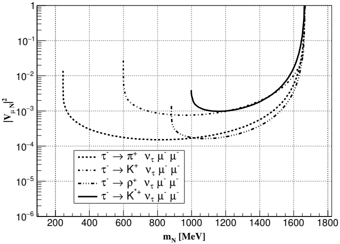


Figure 7: $\tau^- \to h^+ e^- e^- \nu_\tau$.

We will consider the heavy neutrino lifetime of $\tau_N = 300$ ps, which corresponds to an average flight distance of up to 90 mm, just inside the Belle II vertex detector[1].

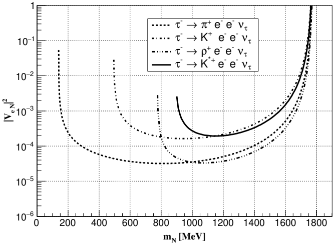


Figure 8: $\tau^- \to h^+ e^- e^- \nu_\tau$.

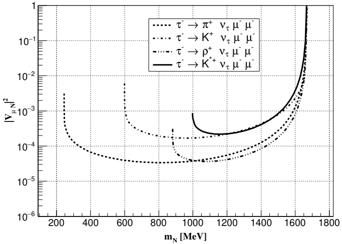
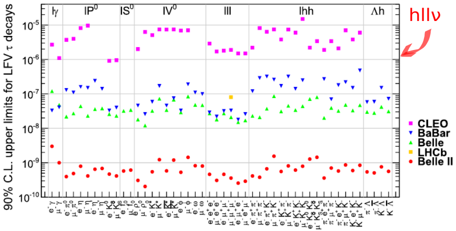


Figure 9: $\tau^- \to h^+ e^- e^- \nu_\tau$.

Summary

We have explored a τ search to track the possible signals of lepton-number-violation at the Belle and Belle II experiments (four-body $|\Delta L| = 2$ decays of the τ lepton).
We performed an exploratory study on the potential sensitivity that Belle II experiment that could achieve for these $|\Delta L| = 2$ processes as well as the limit for Belle experiment.
This to extract the limits on $|V_{\ell N}|^2$ without any additional assumption on the relative size of the mixing matrix elements.



Backup

The decay width for $\tau \to \nu \ell N$ can be written as

$$\Gamma(\tau \to \nu_\tau \ell N) = \frac{1}{4} \frac{G_F^2}{64 m_\tau^3 (2\pi)^3} |V_{\ell N}|^2 \int_{s_{12}^-}^{s_{12}^+} \int_{s_{13}^-}^{s_{13}^+} 64 (s_{12} - m_\ell^2 - m_\nu^2)(m_N^2 + m_\tau^2 - s_{12})\, ds_{13}\, ds_{12}, \quad (5)$$

and the $BR(\tau^- \to \nu_\tau \ell^- N)$ is then obtained dividing (5) by the total decay width of τ lepton, taken from *PhysRevD.98.030001*.

Table 1: Mass and decay constant mesons.

Particle	Mass[MeV]	f_h [MeV]
$\pi^\pm$	139.57	130.41
$K^\pm$	493.67	156.2
$\rho^\pm$	775.49	220
$K^{*\pm}$	891.66	217

The result for pseudoscalar mesons ($h = \pi, K$) is

$$\begin{aligned}\Gamma(N \to \ell^- h^+) &= \frac{G_F^2}{16\pi}|V_{uq}^{CKM}|^2|V_{\ell N}|^2 f_h^2 m_N \\ &\times\sqrt{\lambda(m_N^2, m_\ell^2, m_h^2)}\Bigg[\left(1-\frac{m_\ell^2}{m_N^2}\right)^2 \\ &-\frac{m_h^2}{m_N^2}\left(1+\frac{m_\ell^2}{m_N^2}\right)\Bigg],\end{aligned} \tag{6}$$

by the other hand, for vector mesons ($h = \rho, K^*$) we have

$$\begin{aligned}\Gamma(N \to \ell^- h^+) &= \frac{G_F^2}{16\pi}|V_{uq}^{CKM}|^2|V_{\ell N}|^2 f_h^2 m_N \\ &\times\sqrt{\lambda(m_N^2, m_\ell^2, m_h^2)}\Bigg[\left(1-\frac{m_\ell^2}{m_N^2}\right)^2 \\ &+\frac{m_h^2}{m_N^2}\left(1+\frac{m_\ell^2}{m_N^2}\right)-2\left(\frac{m_h^2}{m_N^2}\right)^2\Bigg],\end{aligned} \tag{7}$$

where f_h is the hadron decay constant, see Table 1.