Lepton number violation in $\tau^- \rightarrow \pi^+ \mu^- \bar{\mu} \nu_\tau$ at Belle II experiment

D. Rodríguez Pérez, P. L. M. Podesta Lerma, Isabel Domínguez Jiménez

Universidad Autónoma de Sinaloa, Facultad de Ciencias Físico-Matemáticas, Av. de las Américas y Blvd. Universitarios, Cd. Universitaria, CP 80000, Cln, Sinaloa, México
E-mail: davidrope@uas.edu.mx

Abstract. The nature of neutrino masses is one of many questions opened about the Standard Model (SM) of elementary particles. The existence of lepton number violating processes, where it changes by two units implies the presence of a (heavy) Majorana neutrino. High precision measurements are essential to this kind of searches. In the B factory experiment Belle II is possible to find these kind of processes, we implemented the simulation and reconstruction of $\tau^- \rightarrow \pi^+ \mu^- \bar{\mu} \nu_\tau$ using belle2 software bas2f to investigate the feasibility of this channel.

1. Introduction
The SM is the current theory of fundamental particles and their interactions, which was created based on observations and theoretical predictions through several years. In this theory all the elementary matter particles are fermions, interacting among themselves by the exchange of gauge bosons and the mass is generated by the Higgs mechanism.

But, despite its tremendous success in describing the basic forces of nature many fundamental questions remain unanswered within the SM. Thus, considering the open questions that in the SM remain unanswered, it is fair to conclude that the present theory is an extremely successful but phenomenological description of subatomic processes at the energy scales up to $O(1 \text{ TeV})$, several issues remain to be explained such as the mass hierarchy, the nature of the neutrino, the nature of dark matter and dark energy, the absence of hierarchy and the validity of the SM up to higher energy scales, several approaches had been proposed such as supersymmetry, WIMPs, and Majorana neutrinos, the last one is the one we will use to try to extend our understanding of neutrinos.

At the energy frontier the main representatives are the ATLAS and the CMS experiments at the Large Hadron Collider (LHC) at CERN [1]. The second is the rate/precision frontier, exemplified by the LHCb experiment at the LHC and the Belle II experiment at SuperKEKB [2].

At the energy frontier, the LHC experiments will be able to discover new particles produced in proton-proton collisions at a center-of-mass energy of up to 14 TeV if there is any. Since the constituent gluons or quarks interact in these collisions, only a fraction of the center-of-mass energy available to produce such new particles, and the mass reach is limited to $O(1 \text{ TeV}/c^2)$. 
Sensitivity to the direct production of a specific new particle depends on the cross section and on the size of the data sample.

At the rare/precision frontier, the observable signatures of new particles or processes can be obtained through measurements of flavor physics reactions at lower energies and evidence of a deviation from the SM prediction. An observed discrepancy can be interpreted in terms of NP models. This is the approach of Belle II.

2. Lepton number violation

Experiments with neutrinos [3] [4] have questioned the SM, since this one considers that neutrinos are massless. Solar neutrino experiments [5] show that they oscillate from a definite flavor to another through long distances, thus the most reasonable explanation is that neutrinos should have mass. However, these neutrino oscillations don’t give information about absolute neutrino masses. Thus, there exist different mechanisms to obtain neutrino masses. The requirement of lepton number violation is necessary to generate neutrino masses in the case of Majorana nature.

The double-$\beta$ decay process without neutrinos [6] is the most studied process that violates the lepton number by two units. Until now, it has not been observed. But besides of the neutrinoless double beta decay, other processes had been searched at LHCb at CERN [1], BaBar at the SLAC [7] and Belle at KEKB [8]. They had imposed limits in the branching fraction to different decays, see Figure 1.

![Figure 1. Branching fraction limits in channels where $\Delta L = 2$.](image)

The Majorana neutrino mass ($m_N$) in the range of $\sim (100 \text{ GeV} - 1 \text{ TeV})$ can explain the suppressed channels. However, the $m_N$ is not determined and other cases can exist. In particular, when $m_N$ in the range of $\sim (\text{MeV to few GeV})$ the branching fractions can be enhanced for decays to four bodies (for more details see [9]). We focus in semi-leptonic decays, specifically on $\tau^+ \rightarrow \pi^+ \mu^- \mu^- \nu_\tau$ channel. We will study the feasibility of searching this channel in the Belle II detector.

Decay processes that violate the total lepton number $\Delta L = 2$ can be induced by the exchange of Majorana neutrinos. We consider a scenario where these decays are dominated by the
exchange of only one heavy neutrino, which produces an enhancement of the decay amplitude via the resonant mechanism and the high luminosity in the Belle II experiment allows to study the \( \tau^- \to \pi^+ \mu^- \mu^- \nu_\tau \) channel. The resonant contribution of a heavy Majorana neutrino to \( \Delta L = 2 \) four-body decays of \( \tau \) lepton provides additional information and complementary constrains on the parameter space of Majorana neutrino.

3. Belle II

The B factory experiment Belle II at the SuperKEKB [2] accelerator in Tsukuba, Japan, has confirmed the Kobayashi-Maskawa mechanism of CP violation in the SM. Furthermore, it has a rich physics program of \( \tau \) leptons. The aim of \( e^+e^- \) colliders is to accumulate 50 ab\(^{-1}\), corresponding to about 47 billion \( \tau^+\tau^- \) events, by the year 2022. This corresponds to 50 times the luminosity of its predecessor KEKB.

3.1. Accelerator

SuperKEKB uses the same two rings that were used by KEKB: a low-energy ring (LER) for positrons and a high-energy ring (HER) for electrons. These are located side by side 11 meters below the ground level in the TRISTAN tunnel, which has a circumference of around 3 km. However, the beam energies have been changed from the present values of 3.5 and 8.0 GeV to 4.0 and 7.0 GeV. In SuperKEKB the Nano-Beam scheme is used [2], in which the emittance growth due to intra-beam scattering and the short beam lifetime due to the Touschek effect and both are serious problems, particularly in the LER. The increase in the beam energy of the HER from 3.5 to 4.0 GeV helps mitigate these problems. The decrease in the beam energy of the HER from 8.0 to 7.0 GeV allows a lower emittance.

In the interaction region, the 7 GeV electrons in the HER and the 4 GeV positrons in the LER collide at one interaction point (IP) with a non-zero crossing angle of 83 mrad.

4. Luminosity

The center-of-mass (CM) energy corresponds to the mass of the \( \Upsilon(4S) \) resonance,

\[
E_{CM} = 2\sqrt{E_{HER}E_{LER}} = 10.58\text{GeV} \sim M_{\Upsilon(4S)}.
\]

The production cross section for \( \Upsilon(4S) \) (bound \( b\bar{b} \) state) at the CM is 1.1 nb, 1.3 nb for \( c\bar{c} \) pair production, and 2.1 nb for \( q\bar{q} \) pair production. Where \( q \) is a \( u, d, \) or \( s \) quark. Cross sections of various processes are summarized in Table 1.

| Process | \( \sigma \) [nb] |
|---------|-----------------|
| \( b\bar{b} \) | 1.1 |
| \( c\bar{c} \) | 1.3 |
| \( q\bar{q} \) \( (q = u, d, s) \) | 2.1 |
| \( \tau^+\tau^- \) | 0.93 |
| QED \( (25.551^\circ < \theta < 159.94^\circ) \) | 37.8 |
| \( \gamma\gamma \) | 11.1 |

Table 1. Cross-section for various processes in \( e^+e^- \) collisions at \( \sqrt{s} = 10.58 \) GeV. QCD refers to Bhabha and radiative Bhabha processes.
The rate of interaction in $e^+e^-$ collisions is proportional to the interaction cross section, $\sigma_{\text{interaction}}$:

$$\frac{dN_{\text{interaction}}}{dt} = \mathcal{L}_{e^+e^-}\sigma_{\text{interaction}},$$

(2)

where the coefficient $\mathcal{L}_{e^+e^-}$ is the luminosity of the accelerator and is a measure of the number of particles per unit area per unit time at the IP,

$$\mathcal{L}_{e^+e^-} = \nu n \frac{N_{e^+}N_{e^-}}{A}$$

(3)

here, $n$ is the number of bunches in the storage ring composed of $N_{e^+}$ positrons and $N_{e^-}$ electrons that collide $\nu$ times per second and $A$ is the overlapping area of the two colliding beams. The luminosity goal of SuperKEKB is $8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$, which is around 50 times as large as the peak luminosity achieved by the KEKB collider.

5. Reconstruction

The main problem in reconstructing the channel is the background: we have two kinds of background combinatorial and contamination from other physics decays that have similar topology as a first approximation we generated three samples one for signal and two for background. We used the KKMC as the generator and the Belle II software called basf2 to simulate the detector response. We generate 50K events for each one of the channels listed in table. The cuts we used are invariant mass window of the tau candidate 1.0 GeV $< M_{\tau} < 1.9$ GeV probability of identification in this case is the global probability, for the muon $\text{PID}_\mu > 20\%$ and for the pion $\text{PID}_\pi > 80\%$, since the muons have to travel all the detector and need to be identified in the KLM. And finally a beam constraint $M_{bc} \leq 4$ GeV. The reconstructed candidates for each channel are also showed in the table 2. In the figure 2 we showed the result for the signal for some variables. Similar results are obtained for the other two channels. With this we see that combinatorial background is quite low as expected, since this is the ideal case.

| Channel | Reconstructed events | expected BR |
|---------|----------------------|-------------|
| $\tau^- \rightarrow \pi^+\mu^-\mu^-\nu_\tau$ | 11680 | $< 10^{-3}\%$ |
| $\tau^- \rightarrow \pi^+\mu^-\mu^-\nu_\tau$ | 10834 | $\sim 10^{-6}\%$ |
| $\tau^- \rightarrow \pi^+\pi^-\pi^-\nu_\tau$ | 11116 | $9.31 \pm 0.06\%$ |

Table 2. Reconstructed events; mass, PID and $M_{bc}$ cuts are used.

We used the background events and look for contamination, we called them false signals. The used cuts in these searches were the same that we used to find the simulated signal: 1.0 GeV $< M < 1.9$ GeV invariant mass window to reconstruct $\tau$’s; PID at $\geq 80\%$ and $\geq 20\%$ for $\pi$’s and $\mu$’s, respectively; and $M_{bc} \leq 4.0$ GeV. The results are in Figure 3

6. Conclusions

In Belle II will be possible to determine the neutrino nature. If neutrinos are Majorana particles we can use it to search violation of leptonic number process.

We simulated the $\tau^- \rightarrow \pi^+\mu^-\mu^-\nu_\tau$ which is a decay to four bodies and its branching fraction is enhanced with respect to decays to three bodies. The feasibility study of this decay in Belle II has been started and looks like very promising, more studies need to be done to find all sources of background and the understanding of them will determine the reach of this search for new physics.
Figure 2. Transverse momentum (top), pseudorapidity (middle) and polar angle (bottom) for the decay channel $\tau^- \rightarrow \pi^+ \mu^- \mu^- \nu_\tau$ with an invariant mass window of $1.0 \text{ GeV} < M_\tau < 1.9 \text{ GeV}$, PID ($\mu > 20\%$, $\pi > 80\%$), $M_{bc} \leq 4 \text{ GeV}$, using 11,991 reconstructed events (blue) and 11,680 simulated events (red).
Figure 3. Transverse momentum (top), pseudorapidity (middle) and polar angle (bottom) for the decay channel \((\tau^-) \rightarrow \pi^\pm \mu^- \mu^- \nu_\tau\) with an invariant mass window of \(1.0 \text{ GeV} < M_\tau < 1.9 \text{ GeV}\), PID \((\mu > 20\%, \pi > 80\%)\), \(M_{bc} \leq 4 \text{ GeV}\), using 2,825 for background 1 (blue) and 537 for background 2 (red).
References

[1] Brning O S, Collier P, Lebrun P, Myers S, Ostojic R, Poole J and Proudlock P 2004 *LHC Design Report* (Geneva: CERN) URL https://cds.cern.ch/record/782076

[2] Belle group P D I 2010 *Belle II, Technical Design Report*

[3] Mann A K and Primakoff H 1977 *Phys. Rev. D* **15**(3) 655–665 URL http://link.aps.org/doi/10.1103/PhysRevD.15.655

[4] Frati W, Gaisser T K, Mann A K and Stanev T 1993 *Phys. Rev. D* **48**(3) 1140–1149 URL http://link.aps.org/doi/10.1103/PhysRevD.48.1140

[5] Kuo T K and Pantaleone J 1990 *Phys. Rev. D* **41**(12) 3842–3845 URL http://link.aps.org/doi/10.1103/PhysRevD.41.3842

[6] Bilenky S M 2010 690–715 ISSN 1063-7796 (*Preprint* hep-ex/0105044) URL http://arxiv.org/abs/1001.1946

[7] Aubert B *et al.* (BaBar) 2002 *Nucl. Instrum. Meth.* **A479** 1–116 (*Preprint* hep-ex/0105044)

[8] Sagawa H 1996 *Il Nuovo Cimento A* **109** 1055–1060 ISSN 0369-3546 URL http://dx.doi.org/10.1007/BF02823846

[9] Quintero N 2014 *Estudios de violación del número leptónico en procesos resonantes inducidos por un neutrino de mayorana* Ph.D. thesis