Searching for heavy Majorana neutrinos in 
\[ \tau^- \rightarrow \pi^+ \mu^- \mu^- \nu_\tau \] at Belle II

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Abstract. A feasibility study is done concerning the lepton number violation decay channel 
\[ \tau^- \rightarrow \pi^+ \mu^- \mu^- \nu_\tau \]. Monte Carlo events are produced using phase space and the response of the detector is simulated. The observation will be a proof of the Majorana nature of the neutrinos.

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 \( O(1 \text{ TeV}) \).

The future experiments in high energy physics are designed to address the above questions about New Physics using complementary approaches. One approach is at the energy frontier with the main representatives being 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. Since the constituent gluons or quarks interact in these collisions, only a fraction of the center-of-mass energy is 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 it considers that neutrinos are massless. Solar neutrino experiments [5] show that they oscillate from a definite flavor to another through long distances, thus neutrinos should have mass. However, these neutrino oscillations don’t give information about absolute neutrino masses. Different mechanisms exist to obtain neutrino masses. The requirement of lepton number violation is necessary to generate neutrino masses in the case of Majorana nature.

Neutrinoless double beta decay [6] is the most studied process that violates the lepton number by two units. Until now, it has not been observed. Besides the neutrinoless double beta decay, other processes have been searched in LHCb at CERN [1], BaBar at SLAC [7] and Belle at KEKB [8]. They have imposed limits in the branching fraction to different decays, Figure 1.

![Figure 1. Branching fraction limits in channels where $\Delta L = 2$ [9].](image)

However, the Majorana neutrino mass ($m_N$) is not determined and we can consider it in the range of ~MeV to few GeV. Then, 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 possibility to search 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 $\tau^- \rightarrow \pi^+ \mu^- \mu^- \nu_\tau$ channel. The resonant contribution of a heavy Majorana neutrino to $\Delta L = 2$ four-body decays of $\tau$ lepton provide 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 correspond 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. The rate of interaction in $e^+e^-$ collisions is proportional to the interaction cross section, $\sigma_{\text{interaction}}$:

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

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,

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

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 40 times as large as the peak luminosity achieved by the KEKB collider.

5. Analysis
We produced the signal using the KKMC generator [10], $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$, with $\tau$ decaying to the signal mode $\tau^- \rightarrow \pi^+\mu^-\mu^-\nu\tau$, and the other decaying to all experimentally measured SM decay modes of the $\tau$, approximately 42 decays. A total of 50,000 events were generated for this decay.

Samples for a range of background events were produced by the Belle II collaboration; the generators used for each background process are given in Table 1. Initial state radiation (ISR) and final state radiation (FSR) of multiple photons is generated by KKMC and BABAYAGA@NLO[11] generators. Beam backgrounds are also taken into account and include radiative Bhabha, Touschek scattering and beam-gas interactions.
Table 1. Samples for a range of background events were produced by the Belle II collaboration; the generators used for each background process:

| Background process | Cross-section [nb] | Generator |
|--------------------|-------------------|-----------|
| $e^+ e^- \rightarrow B^+ B^-$ | 0.525 | EvtGen, PYTHIA |
| $e^+ e^- \rightarrow B^0 \bar{B}^0$ | 0.525 | EvtGen, PYTHIA |
| $e^+ e^- \rightarrow u\bar{u}$ | 1.61 | KKMC |
| $e^+ e^- \rightarrow d\bar{d}$ | 0.40 | KKMC |
| $e^+ e^- \rightarrow s\bar{s}$ | 0.38 | KKMC |
| $e^+ e^- \rightarrow c\bar{c}$ | 1.30 | KKMC |
| $e^+ e^- \rightarrow \tau\bar{\tau}$ | 1.30 | KKMC |

5.1. Reconstruction

Reconstruction of events can be separated into three sections: tracking, calorimeter reconstruction and particle identification. Tracking of charged particle is achieved using the innermost detectors, the VXD and the CDC. Pattern recognition algorithms are to collect all detector hits belonging to a single track, then a track candidate is created. Impact parameters can be determined through the VXD, and hence vertex positions of decaying particles can be calculated. A helical fit is applied to the track candidate, using track impact parameters combined with highly accurate measurements of charged track momenta from the CDC. The track is extrapolated from the CDC to the point-of-closest approach [2].

5.2. Event selection

Some selection criteria were applied to the reconstructed events removing the more obvious background components.

- $0.5 < M_{\pi^+\mu^-\mu^-} < 2.0$ GeV
- For particle identification,
  - $L(\pi) > 0.9$
  - $L(\mu) > 0.9$
- Tag side: One charged track.
- Signal side: Three charged tracks.

Taus are unstable particles, and will decay before reaching any of the Belle II detectors. Therefore, they must be reconstructed from the detection of their decay products. However, the neutrino can not be detected and it will be missing mass. The hemispheres are defined in the CM by the plane perpendicular to the thrust axis $\hat{n}$, defined as the unit vector in the direction of the thrust $T = \max \left[ \frac{\sum_i |\hat{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|} \right]$, where $\vec{p}_i$ is the momentum of the $i$-th particle.

These selection criteria will allow to have the control of background sample. For this purpose, we observe the two dimensional distribution of the $\Delta E$ and the missing mass of the $\tau$ candidate, where $\Delta E$ is the difference between the energy of $\tau$ candidate and the half energy of the system in the center-of-mass frame, as shown in Fig. 2.
6. Conclusions
We simulated the channel
\[ \tau^- \rightarrow \pi^+ \mu^- \mu^- \nu_\tau \]
which is a decay to four bodies and its branching fraction is enhanced with respect to decays to three bodies. This mode has not been measured before, we also simulated the possible source of background and from this study, we have found that is reasonable to look for this decay mode.

Forthcoming Research
Selection criteria could be optimised to increase signal efficiency through use of multivariate analysis techniques. Additional selection variables could be investigated and signal region analysis can be extended to utilise Mass and \( \Delta E \) resolutions and provide a statistics-motivated signal region.

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