A Search for R-Parity Violated Scalar Tau-neutrino (ν_τ) at the Future Circular Collider

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Abstract

Future Circular Collider is one of the next generation energy-frontier proton-proton colliders with 100 TeV center of mass energy and promising very high luminosity. FCC will be an extraordinary machine for searching Beyond the Standard Model physics because of its very high center of mass energy and luminosity. Searching supersymmetric particles via R-parity violated interactions could be listed in promising BSM physics at the FCC. Scalar tau neutrino is one of the most interesting predictions. A search for $\tilde{\nu}_\tau$ neutrino decaying into $e\mu$ final state via R-parity violated interactions has been conducted at the FCC-pp. It is seen from this research that FCC-pp will be able to discover $\tilde{\nu}_\tau$ up to 28.8 TeV, observe 32.0 TeV and exclude 34.5 TeV mass values by taking $\lambda'_{311} = 0.11$ and $\lambda_{312} = \lambda_{321} = 0.07$ at $L_{int} = 17500 \text{ fb}^{-1}$. FCC-pp, also, will allow to examine very low values of the Yukawa coupling constants which cause R-parity violation interactions. It is obviously seen that FCC-pp will give an opportunity for detailed research on scalar tau neutrino production and decay via R-parity violated interactions.

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I. INTRODUCTION

The theory of supersymmetry (SUSY) provides general form of the space-time symmetries in quantum field theory that allows transformation bosons into fermions and vice versa [1–3]. In other words, a new fermionic and bosonic partner for each elementary Standard Model (SM) fermions and bosons exists as well as an additional Higgs boson doublet. These new particles are called gluino, gaugino, sleptons, squarks and higgsino. R-parity is a basic concept of baryon (B) and lepton (L) number conservation in particle interactions. R-parity quantum number is described as $R = (-1)^{3(B-L)+2S}$ [3] or equivalently $R = (-1)^{3B+L+2S}$ [4] where S is spin quantum number. R-parity quantum number can be ±1 that if $R = +1$, particles are called R-even particles and include the SM particles, else $R = -1$ means R-odd particles and include supersymmetric particles. The conservation of R-parity in collision or decay processes has fundamental consequences on supersymmetric phenomenology: supersymmetric particles have to be produced in pairs which generally unstable particles decay into lightest states. At the end of the process, a heavy unstable supersymmetric particle decays into the lightest supersymmetric particles (LSP) which must be in stable state due to R-parity invariance. R-parity, however, is not conserved in such a states called R-parity violation (RPV) that allows to LSP decay into SM particles. RPV can lead to important phenomenological potential at particle physics [4–18].

Right handed sneutrinos are considered as LSP [4, 19, 20] so if RPV occurs, sneutrinos decay into ordinary SM particles. Consequently, sneutrinos can be observed by searching final state SM particles. Then, plenty of experimental collaboration have been doing research on sneutrinos via considering RPV interactions [21–30]. The most recent ATLAS experiment results showed that mass limits of $\tilde{\nu}_\tau$ for $e\mu$, $e\tau$, and $\mu\tau$ final states in pp collision are 3.4, 2.9, and 2.6 TeV, respectively. Coupling constants were taken as $\lambda'_{311} = 0.11$ and $\lambda_{312} = \lambda_{321} = 0.07$ [30]. Lastly, CMS collaboration introduced experimental results that $\tilde{\nu}_\tau$ mass are excluded below 1.7 and 3.8 TeV for $e\mu$ final state in pp collision while coupling constants were taken as $\lambda_{312} = \lambda_{321} = \lambda'_{311} = 0.01$ and 0.1, respectively [29].

In this work, we researched resonant production of stau-neutrino ($\tilde{\nu}_\tau$) in pp collisions at Future Circular Collider (FCC) with $\sqrt{s} = 100$ TeV for $e\mu$ final state via both producing and decaying with R-parity violation (RPV) interactions. Following sections are basic parameters of FCC in section II, super potential, decay width and cross section in section III, signal
and background analysis in section IV and conclusion in section V.

II. FUTURE CIRCULAR COLLIDER

Currently, the Large Hadron Collider (LHC) that has 13 TeV center of mass energy provides proton-proton collisions at CERN. The Future Circular Collider (FCC) is a post-LHC project that is proposed as a new energy-frontier machine to be built at CERN (see Fig. 1).

| Parameters                        | Phase I | Phase II |
|-----------------------------------|---------|----------|
| Circumferences (km)               | 100     | 100      |
| Beam Energy (TeV)                 | 50      | 50       |
| Center of Mass Energy (TeV)       | 100     | 100      |
| Peak Luminosity \(10^{34} \text{cm}^{-2}\text{s}^{-1}\) | 5.1     | 29       |
| Integrated Luminosity \(fb^{-1}/yr\) | \(\geq 250\) | \(\geq 1000\) |
| Operation Time [years]            | 10      | 15       |
| Total Integrated Luminosity \(fb^{-1}\) | 2500    | 17500    |

FCC is designed with three options [31]: (a) a 100-TeV proton-proton collider (FCC-pp) [32, 33], (b) proton-electron collider (FCC-he) [34] and (c) electron-positron collider (FCC-ee) [35]. Center of mass energy will be 100 TeV for FCC-pp but the other two options have different scenarios such as FCC-ee might have center of mass energy between 61 and 350 GeV and FCC-he’s center of mass energy varies from 3.46 to 31.6 TeV [31, 36, 37]. Main collider tunnel is planned about 80 or 100 km circumferences near Geneva that allows to reach very high integrated luminosity per year in two phases. Integrated luminosity will be 250 \(fb^{-1}\) per year during the Phase I and 1000 \(fb^{-1}\) per year during the Phase II. FCC main parameters are summarized in Tab. I that total integrated luminosity depict cumulative values of the operation time for two phases: 2500 \(fb^{-1}\) (Phase I) and 17500 \(fb^{-1}\) (Phase I + Phase II). It seems that FCC will be a very high luminosity frontier machine that is going to play important role for new physics researches.
III. SUPERPOTENTIAL, DECAY WIDTH AND CROSS SECTION

Superpotential of RPV interactions for $\tau$ sneutrino is defined by Eq. 1 [4],

$$W_{RPV} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$ (1)

where: $\lambda_{ijk}$, $\lambda'_{ijk}$ and $\lambda''_{ijk}$ are Yukawa couplings for RPV, $i$, $j$ and $k$ are particle family indices; $L$ and $E$ denote $SU(2)$ doublet and singlet lepton superfields, respectively; $Q$ is a $SU(2)$ doublet quark superfield and $U$ and $D$ are $SU(2)$ singlet quark superfields. Additionally, it should be noted that the Yukawa couplings $\lambda_{ijk}$ and $\lambda'_{ijk}$ are lepton number violation and baryon number violation coefficients, respectively.

Figure 1. Future Circular Collider’s proposed layout.
Effective RPV interaction Lagrangians for the decays, $\tilde{\nu}_\tau \rightarrow e\mu$ and $\tilde{\nu}_\tau \rightarrow d\bar{d}$ are given by equations 2 and 3, respectively.

$$L_{\text{RPV}_{e\mu}} = -\frac{1}{2}\lambda_{321}\tilde{\nu}_{\tau L}\bar{e}_{R}\mu_{L} - \frac{1}{2}\lambda_{312}\tilde{\nu}_{\tau L}\bar{\nu}_{R}e_{L} + h.c. \quad (2)$$

$$L_{\text{RPV}_{d\bar{d}}} = -\frac{1}{2}\lambda'_{311}\tilde{\nu}_{\tau L}\bar{d}_{R}d_{L} + h.c. \quad (3)$$

![Figure 2. Total decay width channels for R-parity violated interactions.](image)

When decay width is calculated, all RPV decay channels are considered. Then, total decay widths with respect to $\tilde{\nu}_\tau$ mass was plotted in Fig. 2. Resonant production of the $\tilde{\nu}_\tau$ at FCC via RPV interactions is illustrated in Fig. 3 as Feynman diagrams. Undoubtedly, black dots represent the R-parity violation vertices.

This work considers resonant $\tilde{\nu}_\tau$ generation via $\lambda'_{311}$ coupling at FCC-pp collider and $\tilde{\nu}_\tau$ decays into $e\mu$ final states via $\lambda_{312} = \lambda_{321}$ couplings. So, signal processes, $dd \rightarrow \tilde{\nu}_\tau + X \rightarrow e\mu + X$, were produced at leading order (LO) with MadGraph5_aMC@NLOv2.3.3 [38, 39] for numerical calculation, parton distribution function (PDF) was set as CTEQ6L1 [40, 41], renormalization and factorization scales were identified as $\tilde{\nu}_\tau$ mass, and $\lambda'_{311} = 0.11$ and $\lambda_{312} = \lambda_{321} = 0.07$ were taken as RPV Yukawa couplings. One can see from Fig. 4 that $\tilde{\nu}_\tau$...
could be produced up to roughly 30 TeV mass value when considering 10 events with 17500 $fb^{-1}$ luminosity value at the FCC-pp.

Figure 3. Feynman diagrams of the $d\bar{d} \to e\mu$ subprocess.

Figure 4. Resonant production cross section of $\tilde{\nu}_\tau$ in the FCC-pp at $\sqrt{s} = 100$ TeV.

IV. SIGNAL - BACKGROUND ANALYSIS

As it is mentioned in previous section, the signal processes were generated as $d\bar{d} \to \tilde{\nu}_\tau + X \to e\mu + X$ with analysis software, MadGraph5_aMC@NLOv2.3.3. The background
processes were comprised of two categories: irreducible and reducible backgrounds for $e\mu$ final states. Irreducible background is composed of final state particles with two different lepton flavors. Top pair production ($t\bar{t}$), single top ($tW$) and diboson ($WW, WZ, ZZ$) contribute to irreducible background. Consequence of mis-reconstruction of jets as lepton, $W$+jets and multi-jets and mis-reconstruction of photon as lepton, $W+\gamma$, the reducible background occurs which is neglected due to its small contribution to total background [28, 42, 43] for $e\mu$ final states. Numerical calculation of background and signal processes were computed by MadGraph5_aMC@NLOv2.3.3.

Figure 5. Transverse momentum plots for electron, positron, anti-muon and muon.

Transverse momentum ($P_T$), pseudorapidity ($\eta$) and invariant mass ($M_{\tilde{\nu}_\tau}$) distribution plots for $e\mu$ final states were produced to identify appropriate cuts that are created by MADANALYSIS 5 [44]. It is seen from Fig. 5 that selecting 1000 GeV transverse momentum cut for $e\mu$ final state particles is enough to make signal almost unchanged and to reduce background. Also, Fig. 6 shows that signal distributions of the $e\mu$ final state particles exceed the background between -2.5 and 2.5 $\eta$ values which coincide with CMS and ATLAS detector’s acceptances [29, 30]. For this reason, $|\eta| < 2.5$ region is chosen for analysis calculations. Then, as can be seen from Fig. 7, selecting $M_{\tilde{\nu}_\tau} - 1000 < M_{\tilde{\nu}_\tau} < M_{\tilde{\nu}_\tau} + 1000$ mass window is a proper cut to eliminate background effects. Additionally, $E_T^{miss} < 25$ GeV
are taken to suppress the first two generation neutrinos’ contribution to background that come from $W$ decays. Lastly, $\Delta R \geq 0.4$ cone angle cut is applied to $e\mu$ final states.

Eq. 4 was used for calculating statistical significances;

$$SS = \frac{\sigma_S}{\sqrt{\sigma_S + \sigma_B}} \sqrt{L_{\text{int}}}$$  \hspace{1cm} (4)$$

where, $\sigma_S$ and $\sigma_B$ denote signal and background cross section values, respectively and $L_{\text{int}}$ is an integrated luminosity value. Using Phase I and II luminosity values for 25 years operation time and Eq. 4 by applying cuts mentioned above, $\tilde{\nu}_\tau$ mass limits depending on luminosity was plotted in Fig. 8 for three confidence levels. As can be seen from Fig. 8, $\tilde{\nu}_\tau$ will be discovered up to nearly 29 TeV mass value for integrated luminosity equals to 17500 $fb^{-1}$ with taking $\lambda'_{311} = 0.11$ and $\lambda_{312} = \lambda_{321} = 0.07$.

Yukawa coupling coefficients, $\lambda'_{311}$, $\lambda_{312}$ and $\lambda_{321}$ can take different values other than 0.11 and 0.07. In numerical calculations, those values were considered but taking equal all $\lambda'_{311}$, $\lambda_{312}$ and $\lambda_{321}$ each other, for 5, 10 and 15 TeV mass values of the $\tilde{\nu}_\tau$, the coupling coefficients were scanned with whole integrated luminosities. Fig. 9 shows that if $\tilde{\nu}_\tau$ mass value is 5 TeV, $\tilde{\nu}_\tau$ will be discovered with 250 $fb^{-1}$ integrated luminosity and $\lambda'_{311} = \lambda_{312} = \lambda_{321} \geq 0.0093$. If $\tilde{\nu}_\tau$ mass value is not 5 TeV, $\tilde{\nu}_\tau$ will be excluded with $\lambda'_{311} = \lambda_{312} = \lambda_{321} \geq 0.0045$ for
Figure 7. Signal and background processes invariant mass distributions for $e\mu$ final states with 1 TeV transverse momentum cut for final leptons.

Table II. Yukawa couplings constant limits at different integrated luminosities.

| $M_{\tilde{\nu}_\tau}$ (TeV) | 5   | 10  | 15  |
|-------------------------------|-----|-----|-----|
| $\mathcal{L}_{int}(fb^{-1})$  | 250 | 17500 | 250 | 17500 | 250 | 17500 |
| $\lambda_{311}' = \lambda_{312} = \lambda_{321}$ | $\geq 0.0045$ | $\geq 0.0013$ | $\geq 0.014$ | $\geq 0.0024$ | $\geq 0.038$ | $\geq 0.005$ |
|                              | $\geq 0.0061$ | $\geq 0.0015$ | $\geq 0.021$ | $\geq 0.0032$ | $\geq 0.057$ | $\geq 0.007$ |
|                              | $\geq 0.0093$ | $\geq 0.0020$ | $\geq 0.035$ | $\geq 0.0048$ | $\geq 0.096$ | $\geq 0.012$ |

$\mathcal{L}_{int} = 250 fb^{-1}$. Coupling constants limits are summarized in Tab. II for Phase I + II upper and lower integrated luminosity values.

V. SUMMARY AND CONCLUSIONS

A search for RPV $\tilde{\nu}_\tau$ neutrino decaying into $e\mu$ final state has been carried out at the FCC-pp with its planned very high luminosity two phases over 25 years operation time. Let us remind that in numerical calculation $\lambda_{311}' = 0.11$ and $\lambda_{312} = \lambda_{321} = 0.07$ were chosen and distribution cuts were applied. As it can be seen at end of the first year of the Phase I ($\mathcal{L}_{int} = 250 fb^{-1}$), $\tilde{\nu}_\tau$ will be discovered ($5\sigma$), observed ($3\sigma$) and excluded up to 15.8, 17.8 and 21.2 TeV mass values, respectively. On the other hand, at the end of the whole 25 years
Yukawa coupling constants, $\lambda_{311}', \lambda_{312}$ and $\lambda_{321}$, could have values instead of 0.11 or 0.07. According to Yukawa coupling constant search over whole luminosity spectra of the FCC (see Fig. 9 and Tab. II), $\tilde{\nu}_\tau$ discovery at 5 TeV will be occur if $\lambda_{311}', \lambda_{312}$ and $\lambda_{321}$ coupling constants $\geq 0.0020$ at 17500 $fb^{-1}$ integrated luminosity. On the other hand, exclusion limits of the coupling constants are $\lambda_{311}' = \lambda_{312} = \lambda_{321} \geq 0.0013$ at the same mass value and integrated luminosity.

It is obviously seen from the results of this work, if the $\tilde{\nu}_\tau$ is exist as expected by BSM models, the next generation energy-frontier machine, FCC-pp has a great potential to observe this SUSY particle via examining RPV interactions. Additionally, FCC-pp gives another opportunity to examine $\tilde{\nu}_\tau$ via RPV interactions at very low Yukawa coupling constants.
Figure 9. Yukawa coupling constants limits for 5, 10 and 15 TeV scalar tau neutrino masses.

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