Private Note on CC LFV Search at Near Detector

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We discuss the possibilities of search for the lepton flavour violating deep inelastic scattering $\nu_\mu N \to \tau^- X$ at a near detector in future neutrino oscillation experiments.

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Contents

I. REMEMBRANCE AND RECENT WORKS

We are interested in the LFV process $\nu_\mu N \xrightarrow{\text{CC}} \tau X$ at a beam front of a neutrino oscillation experiment (and maybe also at the far site). This work can be positioned as a sequel to our paper[1] in which we thought about a search for the charged lepton flavour violating process $\mu N \xrightarrow{\text{NC}} \tau X$ at the beam dump of a muon storage ring. The main difficulty in the search was the miss-identification of the signal (tau-induced muon) with a huge number of muons which are induced by the electromagnetic interaction. With the CC process, we expect to avoid this difficulty.

Let us remember a bit on the charged LFV (NC) process. The charged lepton process $\mu N \to \tau X$ is originally proposed by Ref.[2], in which the authors introduced the effective interactions for the process and pointed out that the coupling of the scalar mediation was only loosely constrained from the flavour violating tau lepton decays. In our study[1], we specified the model as the SUSY-based two Higgs doublet model (type III). There is also a paper on this topic[3]. The authors assumed the leptoquark mediation behind the effective interaction and showed that the interaction which couples to the both first and second generation quarks were loosely constrained only by the $\nu_\mu N \to \tau X$ search at the neutrino experiments NOMAD/CHORUS (Actually, the LFV CC process has been considered and been experimentally tested in the neutrino oscillation experiments!). The authors also thought about the experimental setup to detect tau leptons and the method of the background rejection.

The detection of the CC LFV interactions has been recently studied in the context of the neutrino oscillation experiments (see e.g., Ref.[4–7]. For the current bounds, see Ref.[8]). Although the authors of Ref.[4] were interested in the same interactions as ours, they did not consider the tau detection at the near detector. They tried to find the interaction as a non-standard oscillation signal in the ν_μ disappearance channel at the near and the far detectors[1]. The paper Ref.[5] dealt with the implementation of near detectors into the realistic simulation of neutrino oscillation experiments. I think that the paper included the most advanced treatment of a near detector of a neutrino oscillation

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[1] For the NSI in matter (ϵ^m), the neutrino factory without tau detection is enough for the tau-associated NSI[9]. Here, we expect that the tau detection (especially at a near site) may help to find the NSI in source and detection ($\epsilon^{s,d}$).

experiment. Although the main interest of the paper was the impact of a near detector on the standard oscillation parameter search, the authors also mentioned the NSI search at the near site, which is basically the same as what we want to do. However, in Refs.[5–7], the author did not touch to the concrete method to detect tau leptons and assumed an imaginary OPERA-like detector. Maybe, we should specify the detector setup and clarify the method to detect the tau lepton, and also make a (toy) simulation for checking the background reduction etc.

II. THEORETICAL ASPECTS

We are interested in the search for the lepton flavour violating charged current process $\nu_\mu N \to \tau^- X$ at a near detector in a neutrino oscillation experiment. Here, let us specify the situation a little bit concrete: We will search for the process at a near detector in a pion-decay based muon neutrino beam (superbeam) experiment, i.e.,

$$\text{Source: } \pi^+ \to \mu^+ \nu \tag{1}$$

$$\text{Detection: } \quad \nu N \to \tau^- X. \tag{2}$$

This series of the processes can be described by the following exotic effective four-fermion interactions which are parametrized with the same way as the neutrino non-standard interactions at source and detection[10, 11]:

$$\mathscr{L}_{\text{SM}} = \frac{G_F}{\sqrt{2}} V_{ud}^* [\bar{\nu}^\alpha \gamma^\rho (1-\gamma^5) \ell_\alpha][\bar{d}\gamma_\rho (1-\gamma^5) u], \tag{3}$$

$$\begin{aligned}\mathscr{L}_{\text{NSI}} =& \frac{G_F}{\sqrt{2}} V_{ud}^* (\mathcal{E}^{V\mp A})_\beta{}^\alpha [\bar{\nu}^\beta \gamma^\rho (1-\gamma^5) \ell_\alpha][\bar{d}\gamma_\rho (1\mp\gamma^5) u] \\ &+ \frac{G_F}{\sqrt{2}} V_{ud}^* (\mathcal{E}^{S\mp P})_\beta{}^\alpha [\bar{\nu}^\beta (1+\gamma^5) \ell_\alpha][\bar{d}(1\mp\gamma^5) u] \\ &+ \frac{G_F}{\sqrt{2}} V_{ud}^* (\mathcal{E}^{T})_\beta{}^\alpha [\bar{\nu}^\beta \sigma^{\rho\sigma} \ell_\alpha][\bar{d}\sigma_{\rho\sigma} u],\end{aligned} \tag{4}$$

where the parameter $\mathcal{E}$ is defined as the ratio between the coupling of the non-standard interactions and that of the charged current interaction in the standard model (SM), which is shown in Eq.(3).

With the exotic interactions shown in Eq.(4), there are two ways to induce the LFV process described by Eqs.(1) and (2).

1. The pion at the source decays into a tau neutrino through an exotic interaction, and it hits the detector and makes a tau lepton:

$$\text{Source: } \pi^+ \xrightarrow{(\mathcal{E})_\tau{}^\mu} \mu^+ \nu_\tau \tag{5}$$

$$\text{Detection: } \quad \nu_\tau N \xrightarrow{\text{SM CC}} \tau^- X. \tag{6}$$

2. The muon neutrino produced by the pion decay at the beam source hits the detector and makes a tau lepton through an exotic interaction:

$$\text{Source: } \pi^+ \xrightarrow{\text{SM CC}} \mu^+ \nu_\mu \tag{7}$$

$$\text{Detection: } \quad \nu_\mu N \xrightarrow{(\mathcal{E}^\dagger)_\tau{}^\mu} \tau^- X. \tag{8}$$

Therefore, the flavour structures which concern with the process are only

$$(\mathcal{E})_\tau{}^\mu \text{ for source and } (\mathcal{E})_\mu{}^\tau \text{ for detection.} \tag{9}$$

They are, in general, independent and complex parameters. If we have the both of them, two non-standard amplitudes interfere with each other, and we have a chance to see the combination of the CP violating phases of the new physics parameters.

A. Examples of model

In this subsection, we will see some examples of the theoretical motivation for the effective interactions Eq.(4).

1. *TeV seesaw, Inverse seesaw: $(V-A)$*

If a model includes some neutral fermions which mix with neutrinos, the PMNS matrix should be extended and consequently 3×3 part of the PMNS matrix for the active neutrinos will be non-unitary. One of the typical example is the ordinal seesaw mechanism with right-handed neutrinos which have the masses of $M\sim\mathcal{O}(10^{10})$ GeV. However, the non-unitarity in this framework is negligible (suppressed by the large scale M). There are some attempt to set the heavy right-handed neutrino scale on the TeV scale — *TeV seesaw*, and one of its implementation is called *the inverse seesaw*[12–14]. The neutral fields which mix with the neutrinos can also be neutralinos in R-parity violating SUSY, KK-modes in extra dimension model, and so on. There is a number of studies on the extended seesaw mechanism.

Here, we follow the simple scenario with right-handed singlet/triplet fermions adopted in Sec.2.1/Sec.2.3 in Ref.[15]. If we have such fermions and form Yukawa interaction with the lepton doublet (Eqs.(6) and (48) in Ref.[15]), we have the non-unitary PMNS matrix N (Eqs.(18) and (65) in Ref.[15]). The modified gauge interactions are shown in Eqs.(15) and (59) in Ref.[15][2]. Note that in the singlet case, the neutral current interaction with charged leptons does not change from the SM case (see $\mathcal{L}_{NC}$ of Eq.(15) in Ref.[15]), i.e., when we take singlet right-handed neutrinos, we do not have the correlation between the CC LFV process $\nu_\mu N\to\tau^- X$ and the NC LFV process $\mu^- N\to\tau^- X$. The $\mathcal{E}$ parameter can be expressed with the parameters of Ref.[15] as

$$({\mathcal{E}^{V-A}})_\beta{}^\alpha=\delta_{\beta\alpha}-\frac{1}{2}(\epsilon^{N\dagger})_{\beta\alpha}\ \text{in Ref.[15] for singlet,} \tag{10}$$

$$({\mathcal{E}^{V-A}})_\beta{}^\alpha=\delta_{\beta\alpha}+\frac{1}{2}(\epsilon^{\Sigma\dagger})_{\beta\alpha}\ \text{in Ref.[15] for triplet.} \tag{11}$$

The total amplitude of the series of the processes described by Eqs.(1) and (2) is written as

$$\begin{aligned}
\mathscr{A}_{\text{signal}}=&\sum_\alpha\langle\tau^-X|\mathrm{i}\mathscr{L}|N\rangle|\nu_\alpha\rangle\langle\nu_\alpha|\langle\mu^+|\mathrm{i}\mathscr{L}|\pi^+\rangle\\
=&\langle\tau^-X|\mathrm{i}\mathscr{L}_{\text{SM}}|N\rangle|\nu_\tau\rangle\langle\nu_\tau|\langle\mu^+|\mathrm{i}\mathscr{L}_{\text{NSI}}|\pi^+\rangle+\langle\tau^-X|\mathrm{i}\mathscr{L}_{\text{NSI}}|N\rangle|\nu_\mu\rangle\langle\nu_\mu|\langle\mu^+|\mathrm{i}\mathscr{L}_{\text{SM}}|\pi^+\rangle\\
&+\sum_\alpha\langle\tau^-X|\mathrm{i}\mathscr{L}_{\text{NSI}}|N\rangle|\nu_\alpha\rangle\langle\nu_\alpha|\langle\mu^+|\mathrm{i}\mathscr{L}_{\text{NSI}}|\pi^+\rangle\\
=&\left[({\mathcal{E}^{V-A}})_\tau{}^\mu+({\mathcal{E}^{V-A\dagger}})_\tau{}^\mu\right]\langle\mu^-X|\mathrm{i}\mathscr{L}_{\text{SM}}|N\rangle|\nu_\mu\rangle\langle\nu_\mu|\langle\mu^+|\mathrm{i}\mathscr{L}_{\text{SM}}|\pi^+\rangle+\mathcal{O}(\mathcal{E}^2),
\end{aligned} \tag{12}$$

where $\mathscr{L}_{\text{SM}}$ is the SM CC four-fermion effective interaction Lagrangian Eq.(3), and $\mathscr{L}_{\text{NSI}}$ is the non-standard neutrino interactions which violate the lepton flavour as shown in Eq.(4). At the final step, we neglect the effect of the charged lepton mass in the final state of the DIS process $\nu N\to\ell X$. The rate of this process is calculated as the square of the amplitude, that is

$$\begin{aligned}
|\mathscr{A}_{\text{signal}}|^2=&\left|({\mathcal{E}^{V-A}})_\tau{}^\mu+({\mathcal{E}^{V-A\dagger}})_\tau{}^\mu\right|^2\left|\langle\mu^-X|\mathrm{i}\mathscr{L}_{\text{SM}}|N\rangle|\nu_\mu\rangle\right|^2\left|\langle\nu_\mu|\langle\mu^+|\mathrm{i}\mathscr{L}_{\text{SM}}|\pi^+\rangle\right|^2+\mathcal{O}(\mathcal{E}^3)\\
=&\left|({\mathcal{E}^{V-A}})_\tau{}^\mu+({\mathcal{E}^{V-A\dagger}})_\tau{}^\mu\right|^2\Gamma(\pi^+\xrightarrow{\text{SM CC}}\mu^+\nu_\mu)\sigma(\nu_\mu N\xrightarrow{\text{SM CC}}\mu^-X)+\mathcal{O}(\mathcal{E}^3).
\end{aligned} \tag{13}$$

The ratio between the event and the SM CC event is simply expressed with the parameter $\mathcal{E}$ as[3]

$$\frac{N_{\text{signal}}}{N_{\text{SM CC}}}=\frac{|\mathscr{A}_{\text{signal}}|^2}{|\mathscr{A}_{\text{SM CC}}|^2}=\left|({\mathcal{E}^{V-A}})_\tau{}^\mu+({\mathcal{E}^{V-A\dagger}})_\tau{}^\mu\right|^2. \tag{14}$$

In the massless limit of leptons, the signal and the SM CC events take the same energy dependence — the ratio becomes just a constant in energy. The constraints to the parameter $\mathcal{E}$ associated with the tau and mu flavours are given in Refs.[18] and [15]. The results are summarized at Eq.(81) and Eq.(123) in Ref.[15].

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[2] There is an attempt to solve the NuTeV anomaly with this modified gauge interactions, see Ref.[16, 17]

[3] When we have the flavour diagonal element of the parameter $\mathcal{E}$, the *observed* CC rate is shifted from the calculated rate in the SM. Here we do not take into account it.

$$\frac{N_{\rm signal}}{N_{\rm SM\ CC}} = \left|(\mathcal{E}^{V-A})_{\tau}{}^{\mu} + (\mathcal{E}^{V-A\dagger})_{\tau}{}^{\mu}\right|^2 = |(NN^\dagger)_{\tau\mu}|^2 \text{ in Ref.[15] } \lesssim 1.0\cdot 10^{-4} \text{ for singlet,} \tag{15}$$

$$\lesssim 1.4\cdot 10^{-6} \text{ for triplet.} \tag{16}$$

A large value of the parameter $\mathcal{E}$ such as 10^{-3} is motivated by the inverse seesaw scenario (see e.g., Appendix C in Ref.[15]). The parameter $\mathcal{E}$ should be correlated to the neutrino mass texture[6, 7, 19], LFV processes[15, 18], non-standard neutrino oscillation signal[20–24], the leptogenesis scenario[25, 26], and also the collider signature of right-handed neutrinos[27–30].

2. Leptoquarks: $(V-A)$, $(S\mp P)$, T

Leptoquarks are the way often taken to understand the effective interactions with leptons and quarks, which could be remnants of GUT theories. Among the list of the leptoquarks shown in the original paper[31], the relevant ones for the process are

$$S_1, \quad S_3, \quad V_2, \quad R_2, \quad U_1. \tag{17}$$

Please see Ref.[32] also, in which the authors studied the effects of leptoquarks in a neutrino oscillation experiment (but flavour diagonal part).

Here, let us see some examples in the following.

1. **S_1 mediation with g_{1L}**

   When we introduce the interaction with the scalar leptoquark S_1,

$$\mathscr{L}_{F=2} = (g_{1L})^{\alpha}\overline{Q^c}\mathrm{i}\tau^2 L_\alpha S_1 + \text{H.c.}, \tag{18}$$

   we obtain the following effective four fermion interactions,

$$\begin{aligned}
\mathrm{i}\mathscr{L}_{\rm eff} =& -\mathrm{i}\frac{(g_{1L}^*)_\tau(g_{1L})^\mu}{4M_{S_1}^2}\left[(\overline{L}^\tau\gamma^\rho L_\mu)(\overline{Q}\gamma_\rho Q) - (\overline{L}^\tau\gamma^\rho\vec{\tau}L_\mu)(\overline{Q}\gamma_\rho\vec{\tau}Q)\right] \\
=& -\mathrm{i}\frac{(g_{1L}^*)_\tau(g_{1L})^\mu}{8M_{S_1}^2}\Big[[\bar{\nu}^\tau\gamma^\rho(1-\gamma^5)\nu_\mu][\bar{d}\gamma_\rho(1-\gamma^5)d] + [\bar{\tau}\gamma^\rho(1-\gamma^5)\mu][\bar{u}\gamma_\rho(1-\gamma^5)u] \\
& - [\bar{\tau}\gamma^\rho(1-\gamma^5)\nu_\mu][\bar{u}\gamma_\rho(1-\gamma^5)d] - [\bar{\nu}^\tau\gamma^\rho(1-\gamma^5)\mu][\bar{d}\gamma_\rho(1-\gamma^5)u]\Big].
\end{aligned} \tag{19}$$

   We have again the $(V-A)(V-A)$ Lorenz structure, and the ratio between the signal and the SM CC event becomes a constant in energy. The coupling is constrained by the flavour violating tau lepton decay. The typical size can be read from Ref.[33],

$$\frac{G_F V_{ud}^*}{\sqrt{2}}(\mathcal{E}^{V-A})_\tau{}^\mu = \frac{G_F V_{ud}}{\sqrt{2}}(\mathcal{E}^{V-A\dagger})_\tau{}^\mu = \frac{(g_{1L}^*)_\tau(g_{1L})^\mu}{8M_{S_1}^2} \lesssim \frac{1}{(10[\text{TeV}])^2}. \tag{20}$$

   From this, we can roughly estimate the ration between the signal and SM CC event, which may be

$$\frac{N_{\rm signal}}{N_{\rm SM\ CC}} = \left|(\mathcal{E}^{V-A})_\tau{}^\mu + (\mathcal{E}^{V-A})_\tau{}^\mu\right|^2 \lesssim 10^{-6}. \tag{21}$$

   More accurate number will be shown in somewhere.

2. **V_2 mediation with g_{2L} and g_{2R}**

   Let us see another example in which we will have an effective interaction with the other Lorentz structure than $(V-A)(V-A)$. Here we take the interactions with the vector leptoquark V_2,

$$\mathscr{L}_{F=2} = \left[(g_{2L})^\alpha\overline{d_R^c}\gamma^\rho L_\alpha + (g_{2R})^\alpha\overline{Q^c}\gamma^\rho e_{R\alpha}\right]V_{2\rho} + \text{H.c.}. \tag{22}$$

This mediates the $(S-P)$ type effective interaction,

$$\begin{aligned}
\mathrm{i}\mathscr{L}_{\text{eff}} =& \mathrm{i}\frac{2(g_{2L}^*)_\mu (g_{2R})^\tau}{M_V^2}(\bar{L}^\mu \mathrm{P}_R \tau)(\bar{d}\mathrm{P}_L Q) + \mathrm{i}\frac{2(g_{2L}^*)_\tau (g_{2R})^\mu}{M_V^2}(\bar{L}^\tau \mathrm{P}_R \mu)(\bar{d}\mathrm{P}_L Q) + \text{H.c.} \\
=& \mathrm{i}\frac{(g_{2L}^*)_\mu (g_{2R})^\tau}{2M_V^2}\Big[[\bar{\nu}^\mu(1+\gamma^5)\tau][\bar{d}(1-\gamma^5)u] + [\bar{\mu}(1+\gamma^5)\tau][\bar{d}(1-\gamma^5)d]\Big] \\
&+ \mathrm{i}\frac{(g_{2L}^*)_\tau (g_{2R})^\mu}{2M_V^2}\Big[[\bar{\nu}^\tau(1+\gamma^5)\mu][\bar{d}(1-\gamma^5)u] + [\bar{\tau}(1+\gamma^5)\mu][\bar{d}(1-\gamma^5)d]\Big] + \text{H.c.}.
\end{aligned} \tag{23}$$

We can read off the parameters $\mathcal{E}^{S-P}$ from this effective Lagrangian, which are

$$(\mathcal{E}^{S-P})_\mu{}^\tau = \frac{\sqrt{2}}{G_F V_{ud}^*}\frac{(g_{2L}^*)_\mu (g_{2R})^\tau}{2M_V^2}, \qquad (\mathcal{E}^{S-P})_\tau{}^\mu = \frac{\sqrt{2}}{G_F V_{ud}^*}\frac{(g_{2L}^*)_\tau (g_{2R})^\mu}{2M_V^2}. \tag{24}$$

Although the bound for the scalar part of the effective interactions is rather slack[33], we have to take into account the stringent constrained to the pseudo-scalar part, and finally the typical size of the signal should roughly be the same as Eq.(21). However, there is a crucial difference from the (S_1 mediated) $(V-A)$ type interaction: The energy and angular dependence of the signal event should differ from those of the SM CC event because of their Lorentz structure. It may be helpful to discriminate the signal from backgrounds.

Note on the difference in the Lorentz structure:
The $S-P$ interaction in a pion decay gets the enhancement factor (see Eq.(21) in Ref.[34]),

$$\omega_\mu = \frac{m_\pi}{m_\mu}\frac{m_\pi}{m_u + m_d}. \tag{25}$$

Since the amplitude for the detection process takes the different energy dependences depending on its Lorentz structure, we cannot simply factor out it as we did in Eq.(12). The rate of the process is calculated to be

$$\begin{aligned}
|\mathscr{A}_{\text{signal}}|^2 =& \Big|\omega_\mu (\mathcal{E}^{S-P})_\tau{}^\mu \langle \tau^- X|\mathrm{i}\mathscr{L}_{\text{SM}}|\nu_\tau N\rangle + (\mathcal{E}^{S-P\dagger})_\tau{}^\mu \langle \tau^- X|\mathrm{i}\mathscr{L}_{S-P}|\nu_\mu N\rangle\Big|^2 \big|\langle \nu_\mu \mu^+|\mathrm{i}\mathscr{L}_{\text{SM}}|\pi^+\rangle\big|^2 \\
=& \Big|\omega_\mu (\mathcal{E}^{S-P})_\tau{}^\mu \langle \tau^- X|\mathrm{i}\mathscr{L}_{\text{SM}}|\nu_\tau N\rangle + (\mathcal{E}^{S-P\dagger})_\tau{}^\mu \langle \tau^- X|\mathrm{i}\mathscr{L}_{S-P}|\nu_\mu N\rangle\Big|^2 \Gamma(\pi^+ \to \mu^+\nu_\mu),
\end{aligned} \tag{26}$$

where $\mathscr{L}_{S-P}$ is the effective Lagrangian with the $S-P$ Lorentz structure, which is shown in Eq.(4) but the parameter $\mathcal{E}$ is factored out,

$$\mathscr{L}_{S-P} = \frac{G_F}{\sqrt{2}}V_{ud}^*[\bar{\nu}^\mu(1+\gamma^5)\tau][\bar{d}(1-\gamma^5)u] + \text{H.c.}. \tag{27}$$

Finally, the ratio between the signal and the SM CC event can be written as

$$\frac{N_{\text{signal}}}{N_{\text{SM CC}}} = \frac{\big|\omega_\mu (\mathcal{E}^{S-P})_\tau{}^\mu \langle \tau^- X|\mathrm{i}\mathscr{L}_{\text{SM}}|\nu_\tau N\rangle + (\mathcal{E}^{S-P\dagger})_\tau{}^\mu \langle \tau^- X|\mathrm{i}\mathscr{L}_{S-P}|\nu_\mu N\rangle\big|^2}{|\langle \mu^- X|\mathrm{i}\mathscr{L}_{\text{SM}}|\nu_\mu N\rangle|^2}. \tag{28}$$

In the massless limit of leptons and partons, the interference term disappears, and it can be reduced to

$$\frac{N_{\text{signal}}}{N_{\text{SM CC}}} = \omega_\mu^2 \left|(\mathcal{E}^{S-P})_\tau{}^\mu\right|^2 + \left|(\mathcal{E}^{S-P\dagger})_\tau{}^\mu\right|^2 \frac{|\langle \tau^- X|\mathrm{i}\mathscr{L}_{S-P}|\nu_\mu N\rangle|^2}{|\langle \mu^- X|\mathrm{i}\mathscr{L}_{\text{SM}}|\nu_\mu N\rangle|^2} \tag{29}$$

$$= \omega_\mu^2 \left|(\mathcal{E}^{S-P})_\tau{}^\mu\right|^2 + \left|(\mathcal{E}^{S-P\dagger})_\tau{}^\mu\right|^2 \frac{\int \mathrm{d}x\mathrm{d}y\,[xf_d(x)y^2 + xf_{\bar{u}}(x)y^2]}{4\int \mathrm{d}x\mathrm{d}y\,[xf_d(x) + xf_{\bar{u}}(x)(1-y)^2]} \tag{30}$$

The cross sections with a proton are calculated to be

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y}(\nu P \xrightarrow{V-A} \ell X) = \frac{G_F^2|V_{ud}|^2}{\pi}s\left[xf_d(x) + xf_{\bar{u}}(x)(1-y)^2\right], \tag{31}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y}(\nu P \xrightarrow{S-P} \ell X) = \frac{G_F^2|V_{ud}|^2}{4\pi}s\left[xf_d(x)y^2 + xf_{\bar{u}}(x)y^2\right]. \tag{32}$$

The result for the $(V-A)$ type interaction can be found in a textbook, e.g., Eq.(17.35) in Peskin and Schroeder. The derivation will be written somewhere.

3. R-parity violating SUSY: $(S-P)$, $(V-A)$

A SUSY model without R-parity includes the following additional superpotential (see e.g., Eq.(2.2) in Ref.[35]),

$$\mathscr{W}_{\not R} = \frac{1}{2}\lambda_\gamma^{\alpha\beta}\hat{L}_\alpha\hat{L}_\beta\hat{E}^\gamma + \lambda_\gamma^{\prime\alpha\beta}\hat{L}_\alpha\hat{Q}_\beta\hat{D}^\gamma + \cdots . \tag{33}$$

From this superpotential, the R-parity violating Yukawa interactions are induced (Eqs.(2.7) and (2.8) in Ref.[35]),

$$\begin{aligned}\mathscr{L}_\lambda =& -\frac{1}{2}\lambda_\gamma^{\alpha\beta}\left[\tilde{\nu}_\alpha\bar{\ell}^\gamma \mathrm{P}_L\ell_\beta + \tilde{\ell}_{L\beta}\bar{\ell}^\gamma\mathrm{P}_L\nu_\alpha + \tilde{\ell}_R^{*\gamma}\overline{\nu^c}_\alpha\mathrm{P}_L\ell_\beta - (\alpha\to\beta)\right] + \text{H.c.},\\ \mathscr{L}_{\lambda'} =& -\lambda_\gamma^{\prime\alpha\beta}\left[\tilde{\nu}_\alpha\bar{d}^\gamma\mathrm{P}_L d_\beta + \tilde{d}_{L\beta}\bar{d}^\gamma\mathrm{P}_L\nu_\alpha + \tilde{d}_R^{*\gamma}\overline{\nu^c}_\alpha\mathrm{P}_L d_\beta - \tilde{\ell}_{L\alpha}\bar{d}^\gamma\mathrm{P}_L u_\beta - \tilde{u}_{L\beta}\bar{d}^\gamma\mathrm{P}_L\ell_\alpha - \tilde{d}_R^{*\gamma}\overline{\ell^c}_\alpha\mathrm{P}_L u_\beta\right] + \text{H.c.}.\end{aligned} \tag{34}$$

The left-handed slepton mediates the $(S-P)$ interaction (interactions with blue colour in Eq.(34))

$$\mathrm{i}\mathscr{L}_{\text{eff}} = \mathrm{i}\frac{(\lambda^*)_{i\mu}^{\tau}\lambda_1^{\prime i1}}{4M_{\tilde{\ell}_{Li}}^2}[\bar{\nu}^\mu(1+\gamma^5)\tau][\bar{d}(1-\gamma^5)u] + \mathrm{i}\frac{(\lambda^*)_{i\tau}^{\mu}\lambda_1^{\prime i1}}{4M_{\tilde{\ell}_{Li}}^2}[\bar{\nu}^\tau(1+\gamma^5)\mu][\bar{d}(1-\gamma^5)u] + \text{H.c.}. \tag{35}$$

Assuming the sneutrino mass is the same as the left-handed slepton mass, we can read the typical size of the coupling from the bound given in Ref.[35] (Eq.(6.104)),

$$(\mathcal{E}^{S-P})_\mu{}^\tau = \frac{\sqrt{2}}{G_F}\frac{(\lambda^*)_{i\mu}^{\tau}\lambda_1^{\prime i1}}{4M_{\tilde{\ell}_{Li}}^2} \lesssim 5.2\cdot 10^{-3}, \qquad (\mathcal{E}^{S-P})_\tau{}^\mu = \frac{\sqrt{2}}{G_F}\frac{(\lambda^*)_{i\tau}^{\mu}\lambda_1^{\prime i1}}{4M_{\tilde{\ell}_{Li}}^2} \lesssim 5.2\cdot 10^{-3}. \tag{36}$$

Although this should be updated, the typical size of the ratio between the signal and the SM CC events seems to be $\mathcal{O}(10^{-6})$ again. The NSI in the pion decay is enhanced by ω_μ^2, but I think, it is constrained from another process (with pion) and finally the ratio should not be as large as $\mathcal{O}(10^{-4})$ or so.

We also have the possibility to obtain the $(V-A)$ type interaction from the interactions shown with green colour in Eq.(34),

$$\mathrm{i}\mathscr{L}_{\text{eff}} = \mathrm{i}\frac{(\lambda')_i^{\alpha 1}(\lambda'^*)_{\beta 1}^{i}}{8M_{\tilde{d}_{Ri}}^2}[\bar{\nu}^\beta\gamma^\rho(1-\gamma^5)\ell_\alpha][\bar{d}\gamma^\rho(1-\gamma^5)u], \tag{37}$$

and

$$(\mathcal{E}^{V-A})_\beta{}^\alpha = \frac{\sqrt{2}}{G_F}\frac{(\lambda')_i^{\alpha 1}(\lambda'^*)_{\beta 1}^{i}}{8M_{\tilde{d}_{Ri}}^2}, \tag{38}$$

which is expected to be constrained by the lepton flavour violating tau decay at the same level as the S_1 leptoquark mediation. I will check the precise number.

4. Two Higgs doublet model type III: $(S\mp P)$

If the both two of the Higgs doublets couple to the lepton doublets (so-called type III two Higgs doublet model), the Higgs bosons can mediate the lepton flavour violating processes.

We assume the following structure of the Yukawa interactions which is also motivated from the models like MSSM (see e.g. Refs.[36–38]),

$$-\mathscr{L}_{\text{Yukawa}} = \overline{\ell_R}^a\left[(Y_\ell)_a\delta_a^b(\Phi_1)_i + \left[Y_{\ell a}(\epsilon^L)_a{}^b + (\epsilon^R)_a{}^b Y_{\ell b}\right](\Phi_2)_i\right](\mathrm{i}\tau^2)^{ij}(L_b)_j. \tag{39}$$

After the re-diagonalization of the mass matrix for charged leptons, we obtain the flavour violating interactions

$$-\mathscr{L}_{\text{LFV}} = \frac{\sqrt{2}m_\tau}{v\cos^2\beta}\left[(\kappa^L)_\tau{}^\beta\bar{\tau}\mathrm{P}_L\nu_\beta + (\kappa^R)_\beta{}^\tau\bar{\ell}^\beta\mathrm{P}_L\nu_\tau\right]H^- + (\text{neutral Higgs}) + \text{H.c.}, \tag{40}$$

where

$$(\kappa^{L/R})_\alpha{}^\beta \simeq \frac{(\epsilon^{L/R})_\alpha{}^\beta}{\left[1+[(\epsilon^L)_\tau{}^\tau + (\epsilon^R)_\tau{}^\tau]\tan^2\beta\right]} \simeq (\epsilon^{L/R})_\alpha{}^\beta. \tag{41}$$

As shown in Fig.A.19 (c) in Ref.[39], we have the following Higgs-quark-quark coupling

$$\mathscr{L}_{udH^\pm} = \frac{1}{\sqrt{2}v}\left[(m_d \tan\beta + m_u \cot\beta)(\bar{u}d) + (m_d \tan\beta - m_u \cot\beta)(\bar{u}\gamma^5 d)\right] H^+ \tag{42}$$

The effective four fermion interaction for the detection process $\nu_\mu N \to \tau X$ is

$$\mathrm{i}\mathscr{L}_{\text{eff}} = -\mathrm{i}\frac{1}{2M_{H^\pm}^2}\frac{m_\tau}{v^2\cos^2\beta}(\kappa^L)_\tau{}^\mu[\bar{\tau}(1-\gamma^5)\nu_\mu]\Big[m_{di}\tan\beta[\bar{u}^i(1+\gamma^5)d_i] + m_{ui}\cot\beta[\bar{u}^i(1-\gamma^5)d_i]\Big], \tag{43}$$

and we also have the effective interaction which affects the pion decay process at the neutrino beam source,

$$\mathrm{i}\mathscr{L}_{\text{eff}} = -\mathrm{i}\frac{1}{2M_{H^\pm}^2}\frac{m_\tau}{v^2\cos^2\beta}(\kappa^R)_\mu{}^\tau[\bar{\mu}(1-\gamma^5)\nu_\tau]\Big[(m_{di}\tan\beta)(\bar{u}^i(1+\gamma^5)d_i) + m_{ui}\cot\beta(\bar{u}^i(1-\gamma^5)d_i)\Big], \tag{44}$$

and the parameter $\mathcal{E}^{S\mp P}$ can be read off from these Lagrangians, which are

$$(\mathcal{E}^{S-P})_\tau{}^\mu = \frac{\sqrt{2}}{2G_F M_{H^\pm}^2}\frac{m_\tau m_{di}\tan\beta}{v^2\cos^2\beta}(\kappa^{R\dagger})_\tau{}^\mu, \qquad (\mathcal{E}^{S+P})_\tau{}^\mu = \frac{\sqrt{2}}{2G_F M_{H^\pm}^2}\frac{m_\tau m_{ui}\cos\beta}{v^2\cos^2\beta}(\kappa^{R\dagger})_\tau{}^\mu, \tag{45}$$

$$(\mathcal{E}^{S-P\dagger})_\tau{}^\mu = \frac{\sqrt{2}}{2G_F M_{H^\pm}^2}\frac{m_\tau m_{di}\tan\beta}{v^2\cos^2\beta}(\kappa^{L})_\tau{}^\mu, \qquad (\mathcal{E}^{S-P\dagger})_\tau{}^\mu = \frac{\sqrt{2}}{2G_F M_{H^\pm}^2}\frac{m_\tau m_{ui}\cot\beta}{v^2\cos^2\beta}(\kappa^{L})_\tau{}^\mu. \tag{46}$$

Although these LFV parameters are constrained in a large parameter region by $\tau \to \mu\gamma$ in THDM, the strongest bound in the SUSY-like limit is given by $\tau \to \mu\eta$[40] (Eq.(22) in Ref.[36]),

$$(\mathcal{E}^{S-P})_\tau{}^\mu \lesssim 5.9 \cdot 10^{-3}\left[\frac{m_{di}}{\text{GeV}}\right]. \tag{47}$$

The bound for down quarks is $\mathcal{O}(10^{-6})$. For strange quarks, the coupling is enhanced by the Yukawa coupling, and the bound becomes

$$(\mathcal{E}^{S-P})_\tau{}^\mu \lesssim 5.9 \cdot 10^{-4}. \tag{48}$$

III. EXPERIMENTAL ASPECTS

- Backgrounds,
- Oscillation events as fake LFV signals

$$P_{\nu_\mu\to\nu_\tau} = \sin^2 2\theta_{23}\sin^2\frac{\Delta m_{31}^2 L}{4E} \sim \left[\frac{\Delta m_{31}^2 L}{4E}\right]^2 = 1.0\cdot 10^{-7}\left[\frac{10[\text{GeV}]}{E}\right]^2\left[\frac{L}{1[\text{km}]}\right]^2. \tag{49}$$

- Method of τ detection,
  - OPERA-like — A huge number of CC muon exposes emulsion films
  - ICARUS-like — Is it still realistic possibility?
  - Decay muon track, Statistical cut Ref.[3]
- Method of Background cut,

[1] S. Kanemura, Y. Kuno, M. Kuze, and T. Ota, Phys. Lett. **B607**, 165 (2005), hep-ph/0410044.
[2] M. Sher and I. Turan, Phys. Rev. **D69**, 017302 (2004), hep-ph/0309183.
[3] S. N. Gninenko, M. M. Kirsanov, N. V. Krasnikov, and V. A. Matveev, Mod. Phys. Lett. **A17**, 1407 (2002), hep-ph/0106302.
[4] J. Kopp, M. Lindner, T. Ota, and J. Sato, Phys. Rev. **D77**, 013007 (2008), 0708.0152.
[5] J. Tang and W. Winter (2009), 0903.3039.

[6] M. Malinsky, T. Ohlsson, Z.-z. Xing, and H. Zhang (2009), 0905.2889.
[7] M. Malinsky, T. Ohlsson, and H. Zhang (2009), 0903.1961.
[8] C. Biggio, M. Blennow, and E. Fernandez-Martinez (2009), 0907.0097.
[9] J. Kopp, T. Ota, and W. Winter, Phys. Rev. **D78**, 053007 (2008), 0804.2261.
[10] Y. Grossman, Phys. Lett. **B359**, 141 (1995), hep-ph/9507344.
[11] M. C. Gonzalez-Garcia, Y. Grossman, A. Gusso, and Y. Nir, Phys. Rev. **D64**, 096006 (2001), hep-ph/0105159.
[12] M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. **B216**, 360 (1989).
[13] R. N. Mohapatra and J. W. F. Valle, Phys. Rev. **D34**, 1642 (1986).
[14] S. Nandi and U. Sarkar, Phys. Rev. Lett. **56**, 564 (1986).
[15] A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, and T. Hambye, JHEP **12**, 061 (2007), 0707.4058.
[16] W. Loinaz, N. Okamura, T. Takeuchi, and L. C. R. Wijewardhana, Phys. Rev. **D67**, 073012 (2003), hep-ph/0210193.
[17] W. Loinaz, N. Okamura, S. Rayyan, T. Takeuchi, and L. C. R. Wijewardhana, Phys. Rev. **D70**, 113004 (2004), hep-ph/0403306.
[18] S. Antusch, C. Biggio, E. Fernandez-Martinez, M. B. Gavela, and J. Lopez-Pavon, JHEP **10**, 084 (2006), hep-ph/0607020.
[19] W. Loinaz, N. Okamura, S. Rayyan, T. Takeuchi, and L. C. R. Wijewardhana, Phys. Rev. **D68**, 073001 (2003), hep-ph/0304004.
[20] S. Antusch, M. Blennow, E. Fernandez-Martinez, and J. Lopez-Pavon (2009), 0903.3986.
[21] T. Ohlsson and H. Zhang, Phys. Lett. **B671**, 99 (2009), 0809.4835.
[22] G. Altarelli and D. Meloni, Nucl. Phys. **B809**, 158 (2009), 0809.1041.
[23] S. Goswami and T. Ota, Phys. Rev. **D78**, 033012 (2008), 0802.1434.
[24] E. Fernandez-Martinez, M. B. Gavela, J. Lopez-Pavon, and O. Yasuda, Phys. Lett. **B649**, 427 (2007), hep-ph/0703098.
[25] W. Rodejohann (2009), 0903.4590.
[26] A. Pilaftsis and T. E. J. Underwood, Phys. Rev. **D72**, 113001 (2005), hep-ph/0506107.
[27] W. Rodejohann and K. Zuber, Phys. Rev. **D62**, 094017 (2000), hep-ph/0005270.
[28] J. Kersten and A. Y. Smirnov, Phys. Rev. **D76**, 073005 (2007), 0705.3221.
[29] F. del Aguila, J. A. Aguilar-Saavedra, and R. Pittau, JHEP **10**, 047 (2007), hep-ph/0703261.
[30] N. Haba, S. Matsumoto, and K. Yoshioka (2009), 0901.4596.
[31] W. Buchmuller, R. Ruckl, and D. Wyler, Phys. Lett. **B191**, 442 (1987).
[32] M. Honda, Y. Kao, N. Okamura, A. Pronin, and T. Takeuchi (2007), 0707.4545.
[33] D. Black, T. Han, H.-J. He, and M. Sher, Phys. Rev. **D66**, 053002 (2002), hep-ph/0206056.
[34] P. Herczeg, Phys. Rev. **D52**, 3949 (1995).
[35] R. Barbier et al., Phys. Rept. **420**, 1 (2005), hep-ph/0406039.
[36] S. Kanemura, T. Ota, and K. Tsumura, Phys. Rev. **D73**, 016006 (2006), hep-ph/0505191.
[37] P. Paradisi, JHEP **02**, 050 (2006), hep-ph/0508054.
[38] P. Paradisi, JHEP **08**, 047 (2006), hep-ph/0601100.
[39] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson (1989), *The Higgs Hunter's guide*, SCIPP-89/13.
[40] M. Sher, Phys. Rev. **D66**, 057301 (2002), hep-ph/0207136.