Lepton Flavor Violation in Long-baseline Experiments

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1. Introduction

⋆ Status for neutrino parameters

“Allowed Regions”

$$\left\{\begin{array}{l}\sin^2 2\theta_{23}\\ |\delta m^2_{31}|\end{array}\right. \sim \left\{\begin{array}{l}0.9-1\\ (1.5-4)\times 10^{-3}\mathrm{eV}^2\end{array}\right.$$

Atmospheric neutrino anomaly $(\mu \leftrightarrow \tau)$

$$\left\{\begin{array}{l}\sin^2 2\theta_{12}\\ \delta m^2_{21}\end{array}\right. \sim \left\{\begin{array}{l}0.5-1\\ (1-20)\times 10^{-5}\mathrm{eV}^2\end{array}\right. \quad \text{Large MSW}$$

Solar neutrino deficit + KamLAND $(e \leftrightarrow \mu, \tau)$

“Upper Limit”

$$\sin^2 2\theta_{13} < 0.1$$

Chooz experiment

no constraint on CP/Majorana phase

○ **Lepton mixing**

$$\Updownarrow$$

Non conservation of Lepton Flavor Number

2. Models without lepton flavor

∘ Models for lepton mixings and neutrino masses

$\Longrightarrow$

Non conservation of Lepton Flavor Number

∘ Seasaw + SUSY (+SUSY breaking terms in high energy)

$\Longrightarrow$ Borzumati & Masiero, Hisano *et. al*

Large Lepton Flavor Violation

$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\mu \leftrightarrow e$ conversion etc.

∘ (Dirac) Neutrino Yukawa couplings

$$W = f_\nu^{ji} \bar{N}_j L_i H_u$$

$$\Downarrow$$

LFV in the charged-lepton

even if universal scalar mass(m_0^2) at GUT scale(M_G)

$$\mu \frac{d(m_{\tilde{L}}^2)_{ij}}{d\mu} = \left(\mu \frac{d(m_{\tilde{L}}^2)_{ij}}{d\mu}\right)_{\mathrm{MSSM}} + \frac{1}{16\pi^2}\left[m_{\tilde{L}}^2 f_\nu^\dagger f_\nu + f_\nu^\dagger f_\nu m_{\tilde{L}}^2 + 2(f_\nu^\dagger m_{\tilde{\nu}}^2 f_\nu + \tilde{m}_{H_u}^2 f_\nu^\dagger f_\nu + A_\nu^\dagger A_\nu)\right]_{ij}$$

SUSY breaking $m_{\tilde{L}}^2$ scalor lepton doublet

$m_{\tilde{\nu}}^2$ right-handed sneutrino

$\tilde{m}_{H_u}^2$ doublet Higgs

$$V^{Dirac\dagger} f_\nu^{ij} U^{Dirac} = \mathrm{diag}(f_{\nu 1}, f_{\nu 2}, f_{\nu 3})$$

Approximately (a_0:: universal A term)

$$(m^2_{\tilde{L}})_{ij} \simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}(f_\nu^\dagger f_\nu)_{ij}\log\frac{M_G}{M_R}$$
$$\simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}\sum_k U^{Dirac}_{ik}U^{Dirac*}_{jk}|f_{\nu k}|^2\log\frac{M_G}{M_R}$$

Note U^{Dirac}_{ij} **is relevant.**

$$\tau \to \mu\gamma \Leftrightarrow (m^2_{\tilde{L}})_{32}$$
$$\mu \to e\gamma \Leftrightarrow (m^2_{\tilde{L}})_{21}$$

Smaller f_ν is preferable

○ f_ν **is related with neutrino Majorana mass matrix**

$$M_\nu = -v_u^2 f_\nu^T M_R^{-1} f_\nu$$

M_ν M_R : **fixed** $\Longrightarrow$ f_ν **determined**

e.g. $M_R = M_r I$

$$M_\nu = U^*_{MNS}\begin{pmatrix} m_{\nu 1} & 0 & 0 \\ 0 & m_{\nu 2} & 0 \\ 0 & 0 & m_{\nu 3}\end{pmatrix} U^\dagger_{MNS} = -\frac{v^2\sin^2\beta}{M_r}f_\nu^T f_\nu$$

$$f_\nu = \begin{pmatrix} \sqrt{m_{\nu 1}} & 0 & 0 \\ 0 & \sqrt{m_{\nu 2}} & 0 \\ 0 & 0 & \sqrt{m_{\nu 3}}\end{pmatrix} U^\dagger_{MNS} \times \frac{\sqrt{M_r}}{v\sin\beta}$$

up to Majorana phase

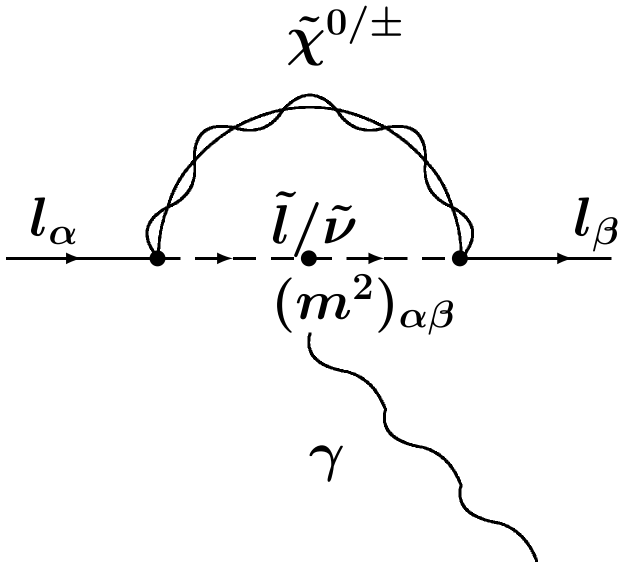
$$\Longrightarrow U^{Dirac} = U_{MNS}$$

In normal hierarchy,

$$
\begin{aligned}
(m^2_{\tilde{L}})_{\alpha\beta} &\simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}(U_{MNS})_{\alpha k}(U_{MNS})^*_{\beta k}|f_{\nu k}|^2 \log\frac{M_G}{M_R} \\
&\simeq -\frac{(6+a_0^2)m_0^2}{16\pi^2}(U_{MNS})_{\alpha 3}(U_{MNS})^*_{\beta 3}|f_{\nu 3}|^2 \log\frac{M_G}{M_R} \\
&= -\frac{(6+a_0^2)m_0^2}{16\pi^2}(U_{MNS})_{\alpha 3}(U_{MNS})^*_{\beta 3}(3.5+\log\frac{\frac{M_G}{10^{16.3}\mathrm{GeV}}}{\frac{M_R}{10^{15}\mathrm{GeV}}}) \\
&\times\ 0.8\times\frac{m^2_{\nu 3}/5*10^{-2}\mathrm{eV}}{v^2/250^2\mathrm{GeV}^2}\frac{M_r/10^{15}\mathrm{GeV}}{\sin^2\beta}
\end{aligned}
$$

$f_{\nu 3}\sim O(1) \Leftrightarrow M_r \sim 10^{15}$ GeV

$$\Gamma(l_\alpha \to l_\beta\gamma) \propto \left\{(m^2_{\alpha\beta})\right\}^2 \propto M_r^2$$



From dim. analysis and coupling counting

$$\frac{\Gamma(l_\alpha \to l_\beta \gamma)}{\Gamma(l_\alpha \to l_\beta \nu_\alpha \nu_{\bar{\beta}})}$$

$$\simeq \frac{1}{G_F^2}\left(\frac{m^2_{\alpha\beta}}{m_S^4}\right)^2 \times g^6$$

$$= \left\{\frac{(6+a_0^2)m_0^2}{16\pi^2} U_{\alpha 3} U^*_{\beta 3} \log \frac{M_G}{M_R}\right\}^2 f^2_{\nu 3} \frac{g^4}{G_F^2 m_S^4} g^2$$

If $m_S \sim O(100)$ GeV and $M_r \sim 10^{14\sim 15}$ GeV,

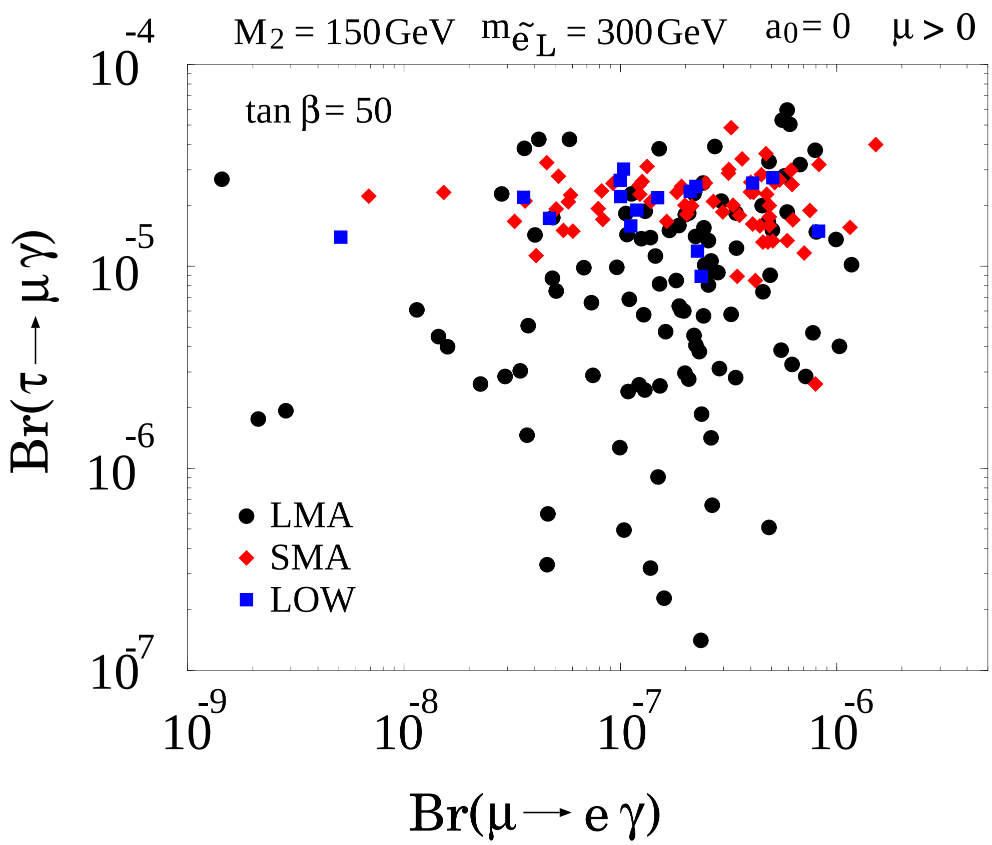
$\Longrightarrow O(10^{-3})$ **(or Br $\sim O(10^{-4})$)**

for $\tau \to \mu\gamma$

○ Bottom up approach

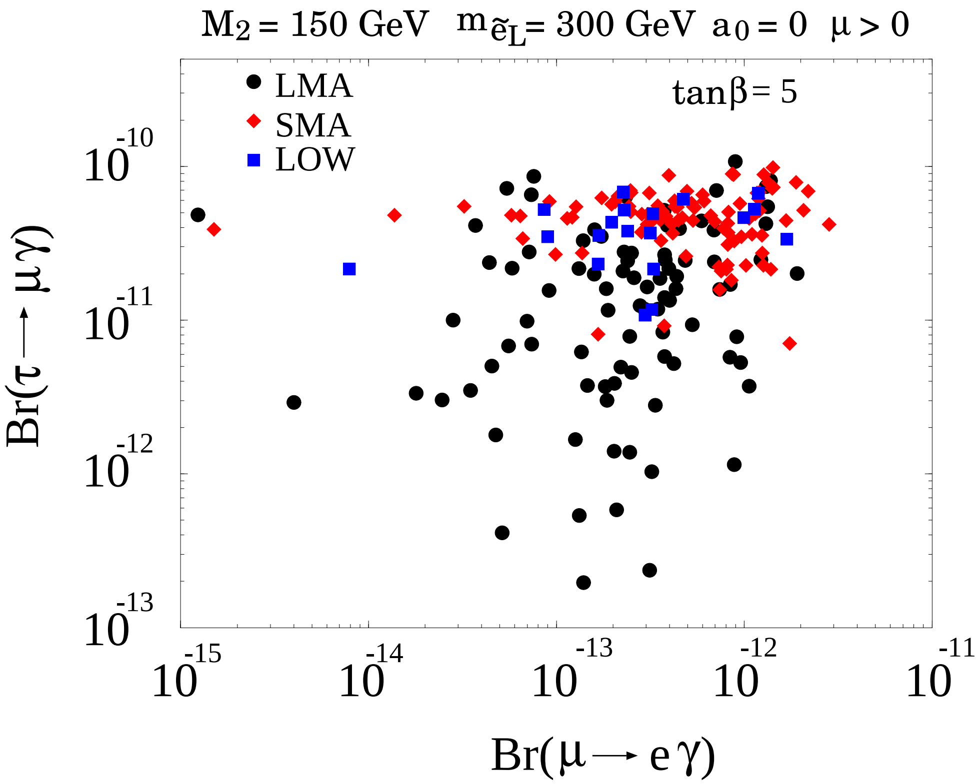
1. M_{ν_L} :fixed within constraint
2. Decomppose into M_{ν_R} and $M^{Dirac}(f_\nu)$

Example $M_r \sim 10^{14\sim 15}$ GeV Sato and Tobe



$\Longrightarrow$ If you love higher M_r scale, take top down approach: models with approppreately small $(f_\nu^\dagger f_\nu)_\alpha^\beta$

For smaller, say $M_r = 10^{12\sim13}$ GeV



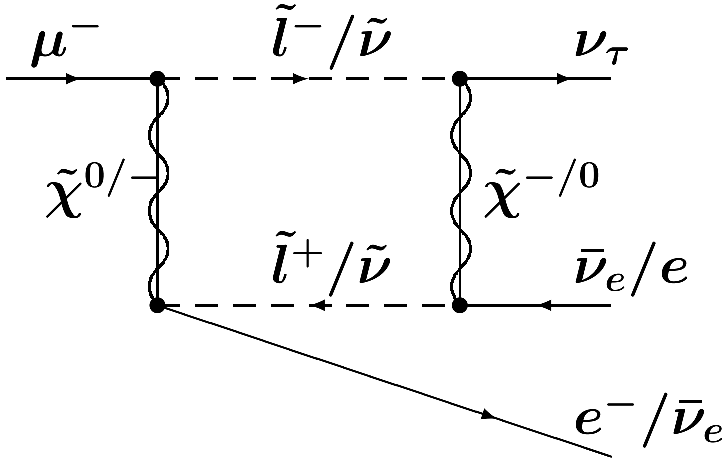
Bottom up approch, i.e. $M_r = 10^{13\sim14}$ GeV :O.K.

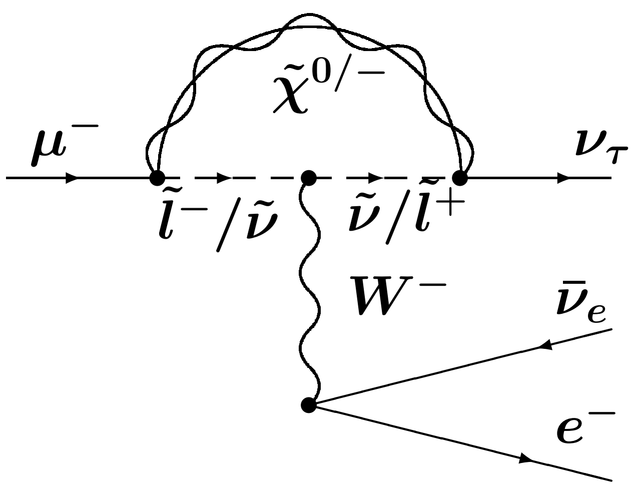
$\Longrightarrow$

$(f_\nu^\dagger f_\nu)_\alpha^\beta$ **could be as large as 0.1 or more**

3. LFV Interaction in Neutrino Oscillation

∘ Examples of LFV in Muon Decay





W attached at ino line ,etc.

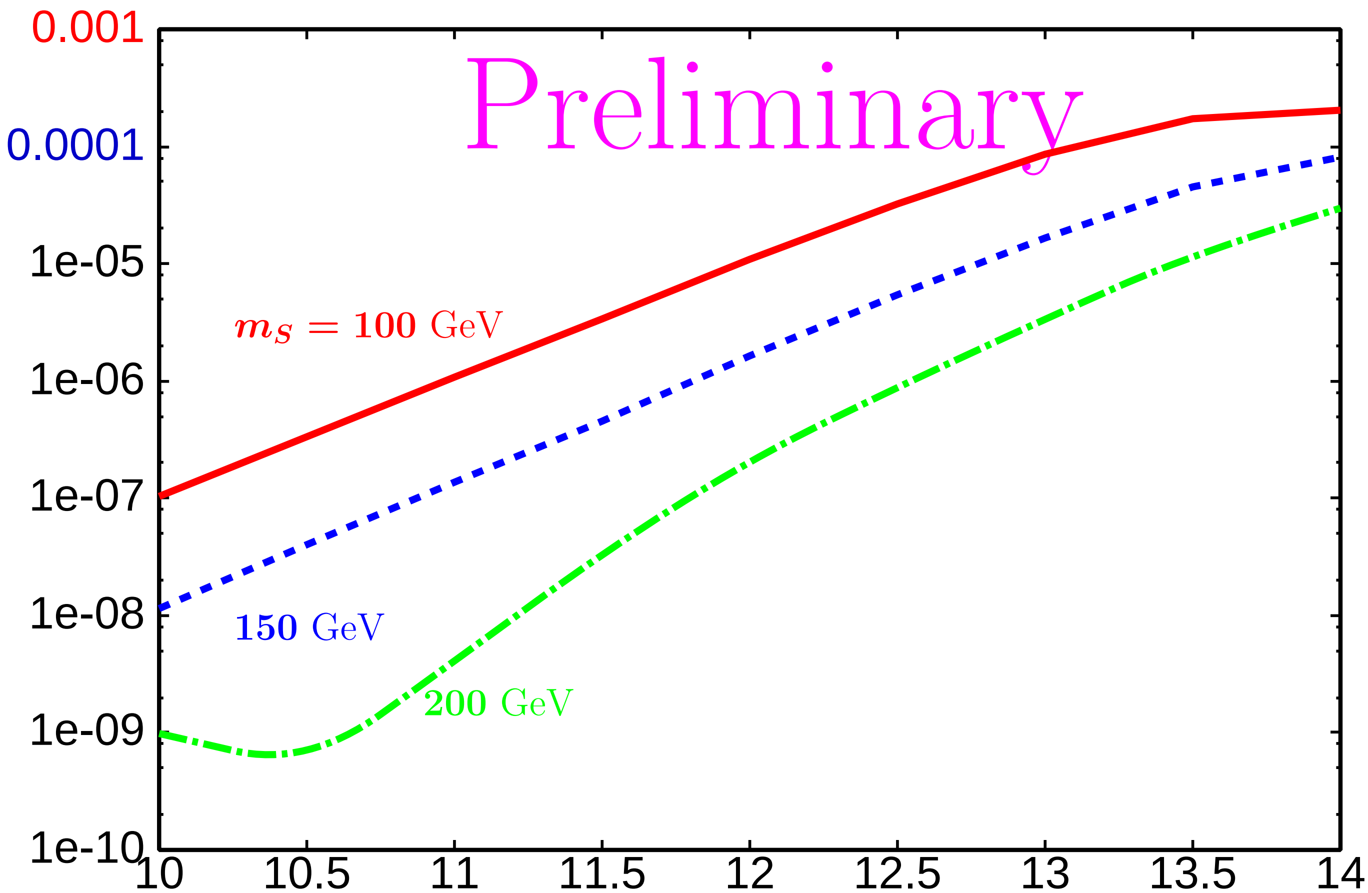
$$Amp(\mu^- \to \nu_\tau e^- \bar{\nu}_e) \simeq \frac{1}{(4\pi)^2} g^4 \frac{1}{m_S^2} \frac{(m^2)_{\mu\tau}}{m_S^2},$$

$$\frac{Amp(\mu^- \to \nu_\tau e^- \bar{\nu}_e)}{Amp(\mu^- \to \nu_\mu e^- \bar{\nu}_e)} \propto \frac{g^2}{(4\pi)^2} \frac{m_W^2}{m_S^2} \frac{10 \sim 30}{16\pi^2} (f^\dagger f)_{\mu\tau}$$
$$\sim O(10^{-4})$$

Cannot be ignored

Gonzalez-Garcia *et.al*, **Gago** *et.al*, **Ota** *et. al*

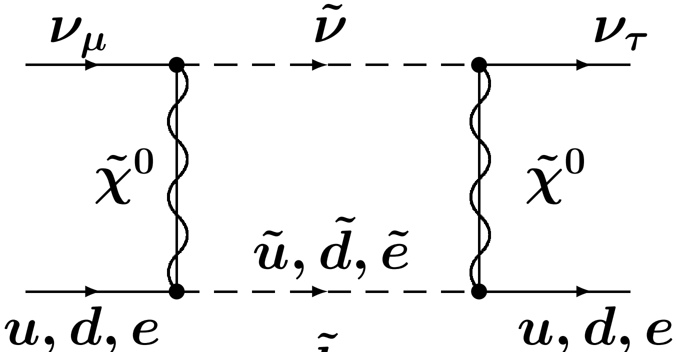
Ratio of LFV decay $\mu \to \nu_\tau \bar{\nu}_e e$ to Standard Model

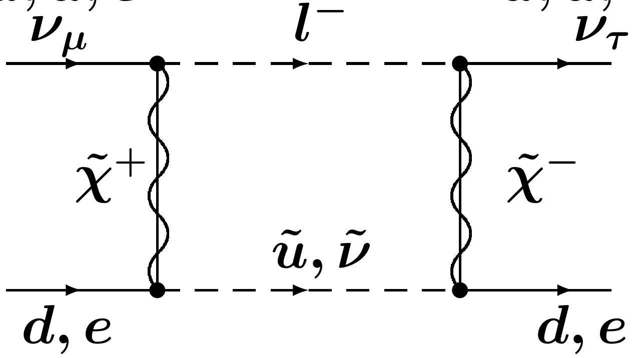


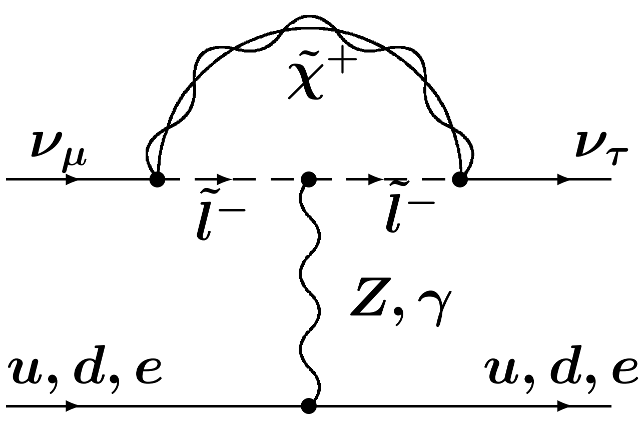
Simplest case

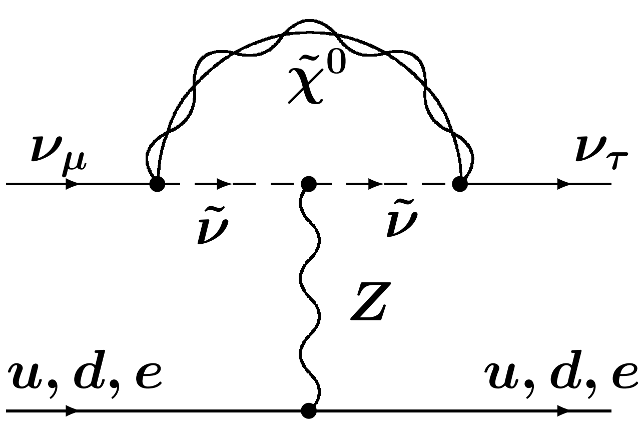
∘ **Similar effect in Propagation (Matter Effect) / Detection Processes**

Matter effect

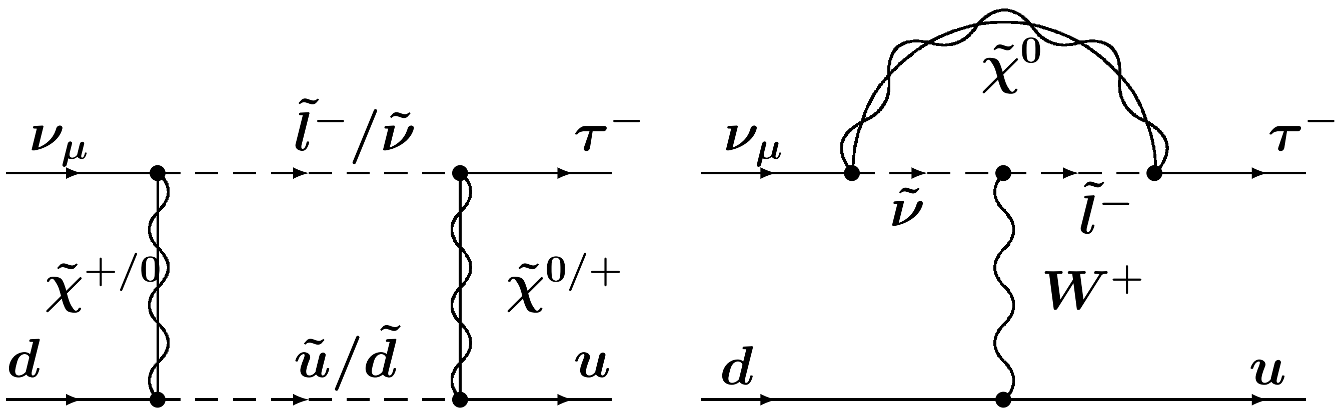








Detection Process



etc.

4. Summary and Discussion

4.1 Summary

∘ To explain neutrino oscillation, LFV in "fundamental" models must be large.

∘ These LFV effects can be reflected on low energy LFV phenomena.

SUSY+ν_R, R Parity Breaking scinario, etc.

∘ In neutrino oscillation experiments, these effects can be large, and may need to be included.

∘ τ appearance is important since large $\mu \leftrightarrow \tau$ mixing from atmospheric neutrino anomaly.

4.2 Discussion

∘ Comparison with direct measurement. Which is better ???

◇ One definite advantage : (Coherent) Matter effect

◇ Anyway there are !!

∘ ν_μ from π

◇ chiral enhancement

$\Longrightarrow$ much smaller LFV effect

Opera ? ICARUS ? and others ?? *cf* Ota and Sato