Sterile neutrinos in flavor violating processes

Gela Devidze

High Energy Physics Institute
Tbilisi State University
Tbilisi, Georgia

Fifth Autumn School & Workshop of RTN
"Physics of the Standard Model and Beyond“
25-30 *September 2017, Tbilisi*

Content

- Motivation
- Oscillation
- Discovery possibility
- summary

The observation of neutrino oscillations provides a clear evidence of the existence of physics beyond the SM.

The neutrinos can be either Majorana or Dirac particles

They can induce flavor violation

Neutrinoless double beta decays

Specific scattering processes

Rare decays

For neutrinos with masses, neutrino oscillations were predicted. . Oscillations of active (light) neutrinos were later observed

Oscillations of active (light) neutrinos were later observed , with the conclusion that the first three neutrinos have nonzero but light masses.

The oscillations are sensitive only to mass differences

Neutrinoless double beta decays and rare decays can help with the determination of the absolute mass of the light neutrinos (The best present upper bounds on the absolute masses of the light neutrinos are obtained from cosmology 0.23 eV)

The light neutrino masses can be produced via the seesaw mechanism
The light neutrinos in these seesaw scenarios have masses $\sim M_D^2 / M_R$ (<<1 eV),
(with M_D being an electroweak scale or lower; the heavy neutrinos are very heavy, with masses $M_R >> 1$ TeV, their mixing with active neutrino flavors being very suppressed $\sim M_D / M_R$ (<<1).

Other seesaw scenarios exist where the heavy neutrinos have lower masses $M_N \leq 1$ TeV, and even $M_N \leq$ 1 GeV ; their mixing with the standard model flavors may be less suppressed than in the original scenarios.

sterile neutrinos can have very different observable effects

- keV-scale sterile neutrinos can be dark matter candidates

- Above 10^9 GeV, they could explain the observed baryonic asymmetry of the Universe through high scale leptogenesis

- Sterile neutrinos in the range MeV-GeV have been introduced in minimal models like the νMSM and lead to visible effects in meson decays.

- Evidence of neutrino oscillations --- Neutrinos are massive:
- $m_1 , m_2 , m_3 \; : \; \Delta m^2_{12} \sim 10^{-5} eV^2 \qquad \Delta m^2_{23} \sim 10^{-3} eV^2$
- Bounds from Astrophysics/Cosmology: $\sum m(\nu_i) < O(10^{-1}) eV$
- ...but in the Standard Model (SM), neutrinos are massless!!!
  one enter physics Beyond the SM!!!

New open questions:

- Why neutrino masses are so small?
- Are massive neutrinos Majorana or Dirac fermions?

Why are Neutrino Masses so small?

- Consider Dirac masses (due to Yukawa couplings):

$$L_y = y_e(\bar{\nu}_L, \bar{e}_L)\begin{pmatrix}\Phi^+\\ \phi^0\end{pmatrix} e_R \qquad y_e \frac{v}{\sqrt{2}} \bar{e}_L e_R$$

- To include a Dirac neutrino mass, we need an extra field: ν_R

$$L_y = y_\nu(\bar{\nu}_L, \bar{e}_L)\begin{pmatrix}\Phi^0\\ -\phi^-\end{pmatrix} \nu_R \qquad y_\nu \frac{v}{\sqrt{2}} \bar{\nu}_L \nu_R$$

- ...but R is \sterile" under all SM interactions (except the Yukawa term)...

- a Majorana term is allowed: $L_y = y_\nu \bar{L}\phi^c \nu_R + \frac{1}{2} M \bar{\nu}_R^c \nu_R$
- We get a \seesaw" Mass matrix:

$$(\bar{\nu}_L, \bar{\nu}_R^c)\begin{pmatrix}0 & m_D\\ m_D^T & M\end{pmatrix}\begin{pmatrix}\nu_L^c\\ \nu_R\end{pmatrix}$$

Many possible scenarios for seesaw:

Type 1 : $$\left(\bar{\nu}_L, \bar{\nu}_R^c\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Masses: $m_{light} \sim \dfrac{m_D^2}{M}$, $m_{heavy} \sim M$

Mixing: $\nu_e \sim \nu_{light} + \sin\theta N_h$, $\sin\theta \sim \dfrac{m_D}{M}$

- If $m_D \sim 100 \ GeV$ (natural) $$\begin{cases} M \sim 10^{14} GeV \\ \nu_e \sim \nu_{light} + 10^{-12} N_h \end{cases}$$
- If $m_D \sim 1 \ MeV$ $$\begin{cases} M \sim 100 \ TeV \\ \nu_e \sim \nu_{light} + 10^{-8} N_h \end{cases}$$
- Y = 2, $SU(2)_L$ triplet Higgs: Type II seesaw
- Y = 0, SU(2)L triplet fermion: Type III seesaw
- Most scenarios imply:
  - Neutrinos are Majorana fermions
  - Extra neutrinos (usually heavier)

Standard neutrinos and Extra neutrinos

- In the SM: 3 massless, left-handed, neutrinos: ν_e , ν_μ , ν_τ associated with the 3 charged leptons (and their antiparticles):
- The Weak Interactions conserve each Lepton Flavor separately.

- Massive neutrinos: ν_1 , ν_2 , ν_3 : each flavor is a mixture of all 3 mass eigenstates:

$$\nu_l = U_{l1}\nu_1 + U_{l2}\nu_2 + U_{l3}\nu_3 \qquad\qquad l = e,\ \mu,\ \tau$$

- ...and if there are extra neutrinos (sterile under the SM and usually heavier in seesaw models): N_j , j = 1; 2; 3; …, then there are more admixtures:

$$\nu_l = \sum_{i=1,2,3} U_{li}\nu_i + \sum_j U_{lN_j} N_j$$

- Neutrino oscillation experiments - U_{li} are large, i.e. *O(1)*.
- No evidence of *Nj* so far: experiments only give upper bounds on U_{lN} .

Can charged leptons oscillate?

- Lets analyse the quantum-mechanical uncertainty processes where we can produce more than one lepton: $\pi^{\pm} \longrightarrow l^{\pm}\nu$, $W^{\pm} \to l_a^{\pm}\nu \; (l_a = e,\, \mu,\, \tau)$

CASE 1

$$\sigma_{m^2} < m_\mu^2 - m_e^2$$

In this case we would
know (exactly!) which
Lepton was produced

CASE 2

$$\sigma_{m^2} > m_\mu^2 - m_e^2$$

In this case it is (in principle)
impossible to determine
which lepton was produced

Estimating the mass uncertainty

From $m^2 = E^2 - p^2$ we have:

$$\sigma_{m^2} = \left[(2E\sigma_E)^2 + (2p\sigma_p)^2\right]^{1/2}$$

$$\sigma_E \simeq \Gamma_\pi = \Gamma_\pi^0/\gamma \qquad \sigma_p \simeq [(p/E)\tau_\pi]^{-1} = (E/p)\Gamma_\pi$$

$$\sigma_{m^2} \simeq 2\sqrt{2}\, E\sigma_E$$

Estimating the mass uncertainty in pion decay

- Lets consider pion decays: $\pi^{\pm} \longrightarrow l^{\pm}\nu$

- From the pion rest-frame decay width $\Gamma^0_\pi = 2.5 \cdot 10^{-8}$ eV

$$\sigma_{m^2} \simeq 2\sqrt{2}\,\bar{E}\,\Gamma^0_\pi \simeq 2\sqrt{2} \cdot 90 \text{ MeV} \cdot 2.5 \cdot 10^{-8} \text{ eV}$$

$$\sigma_{m^2} \simeq 6.4 \text{ eV}^2$$

$$\sigma_{m^2} < m^2_\mu - m^2_e \simeq (106 \text{ MeV})^2$$

(for neutrinos → 7.6×10^{-5} eV)

No charged lepton oscillation.

- Similar approach can be applied to kaon decays, leading tothe same results.

Estimating the mass uncertainty in W decay

- Lets consider W decay $W^{\pm} \to l_a^{\pm} \nu \; (l_a = e,\, \mu,\, \tau)$
- From the W rest-frame decay width, $\Gamma^0_{W \to l_a \nu} \simeq \dfrac{G_F m_W^3}{6\sqrt{2}\pi} \simeq 230 \;\; \mathrm{MeV}$

$$\begin{aligned} \sigma_{m^2} &\sim 2\sqrt{2}\, E \sigma_E \simeq 2\sqrt{2} \cdot 40 \text{ GeV} \cdot 230 \text{ MeV} \\ \sigma_{m^2} &\simeq (5 \text{ GeV})^2 \end{aligned}$$

$$\sigma_{m^2} \gg m_\mu^2 - m_e^2 \qquad \sigma_{m^2} > m_\tau^2 - m_\mu^2 \simeq (1.77 \text{ GeV})^2$$

- **Charged lepton oscillation!**

- All three leptons are produced coherently in W decays.

- Observability → emitted state should preserve its coherence until detection.

- Coherence loss → due to the different group velocities of each mass-eigenstates, in the mixed state.

- Coherence length for W decays

In rest:

$$(\Delta v_g)_{\mathrm{min}} \simeq 2\frac{m_\mu^2 - m_e^2}{m_W^2}$$

$$(x_{\mathrm{coh}})_{\mathrm{max}} \simeq [\Gamma^0_{W\to l_a\nu}(\Delta v_g)_{\mathrm{min}}]^{-1} \simeq 2.5\times 10^{-8}\ \mathrm{cm}$$

In flight: $(x_{\mathrm{coh}})_{\mathrm{max}} \to \gamma^3 (x_{\mathrm{coh}})_{\mathrm{max}}$

For $(x_{\mathrm{coh}})_{\mathrm{max}}$ >1m , $\gamma \gtrsim 1600$ and $E_W \gtrsim 130\ \mathrm{TeV}$

The condition of having a coherent emission of charged leptons in a decay process and the condition that the leptons keep their coherence over a macroscopic distance L tend to put conflicting constraints on the size of the charged leptons’ wave packet.

$$L < \frac{4\sqrt{2}\,E^3}{(\Delta m^2_{\mu e})^2} \simeq 8.9 \times 10^{-10} \left(\frac{E}{\mathrm{GeV}}\right)^3 \ \mathrm{cm}$$

for $L \gtrsim 1\, m$ $E_{leptons} > 4.8\ TeV$

- Lets compare with the observability of the neutrinos oscillation:

for $L \gtrsim 1\, km$ $E_\nu \gtrsim 20\,\mathrm{eV}$

- Meaning: the charged lepton oscillations are “a little bit difficult to observe”.

Assume very heavy sterile neutrinos N_i exist and consider their decay into a charged lepton and charged Higgs boson:

$$N_i \to e_i^- + \Phi^+$$

We want to find out under what conditions the produced charged lepton state e_i is a coherent superposition of the mass eigenstates e_α ,

The decays are caused by the Yukawa coupling Lagrangian $L_Y = Y_{ai} \bar{L}_a N_{Ri} \Phi + h.c.$

for the rest-frame decay width of N_i we find $\Gamma_i^0 \simeq \alpha_i M_i$ $\left(\alpha_i \equiv \frac{(Y^+Y)_{ii}}{16\pi} \right)$

$$x_{coh} < 1.4 \times 10^{-15} cm \ \ (M_i / GeV)^3$$

Thus, for N_i decays in flight the condition of macroscopic coherence length puts a lower bound only on the energy of the sterile neutrinos, so that they can be relatively light.

If the condition for the coherent creation of the charged lepton state in the decay is satisfied and this state is detected through the inverse decay process before it loses its coherence, it may exhibit oscillations: a mass eigenstate sterile neutrino N_j different from N_i can be produced in the detection process, meaning that the state e_i has oscillated into e_j .

- Charged lepton states produced in the decays of heavy sterile neutrinos can be coherent superpositions of e, μ and τ.

$$N_i \rightarrow e_i^- + \Phi^+ \qquad\qquad \Phi^\pm \rightarrow N_i + e_i^\pm$$

- The roles of neutrinos and charged leptons reversed as compared to the usual situation because of sterile neutrinos being much heavier than the charged leptons.

- Charged leptons e, μ and τ do not oscillate into each other because they are mass eigenstates. Since in β decays and muon decays the production of $\mu^{\pm}$ and $\tau^{\pm}$ is kinematically forbidden, the are no charged lepton oscillations associated with these processes.

- Charged leptons born in $\pi^{\pm}$ and $K^{\pm}$ decays are produced incoherently, i.e. are either $\mu^{\pm}$ or $e^{\pm}$, but not their linear superpositions. Therefore they do not oscillate.

- For charged leptons produced in $W^{\pm}$ decays the coherence production condition is satisfied. However, for $W^{\pm}$ decays at rest the coherence is lost over microscopic distances because of the wave packet separation. For decays in flight with $E_W \geq 100$ TeV the coherence lengths can formally take macroscopic values; yet, the coherence effects in the charged lepton sector are unobservable even in this case because the standard charged-current weak interactions cannot provide a measurement of the composition of the initially produced as well as of the evolved charged lepton state.

- Charged lepton states produced in the decays of heavy sterile neutrinos can be coherent superpositions of e, μ and τ. They can maintain their coherence over macroscopic distances provided that their energies exceed a few hundred TeV. Such charged lepton states could oscillate, and their oscillations could lead to observable consequences.

Electroweak Precision Tests

The presence of heavy neutral fermions affects processes below their mass threshold due to their mixing with standard neutrinos and significant bounds can be set by precision electroweak data.

- The $\mu-e$ universality test, done by comparing the decay rate of pions into $e\nu$ and $\mu\nu$, can be used to constrain the ratio $\frac{1-|U_{e4}|^2}{1-|U_{\mu4}|^2}$

for $m_4 > m_\pi$. The analysis of experimental data leads to $(1-|U_{\mu4}|^2 /(1- |U_{e4}|^2) = 1.0012\pm0.0016$, which implies $|U_{e4}|^2 < 0.004$ for the least conservative case of $|U_{\mu4}|^2 = 0$.

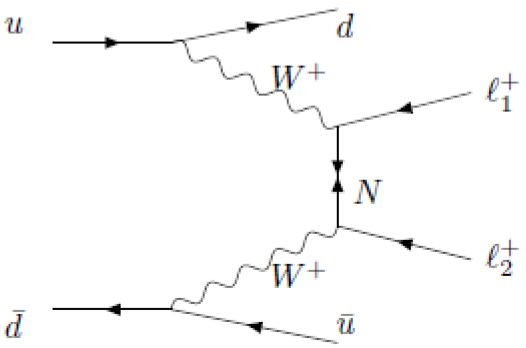
- limits on the parameters characterizing heavy sterile neutrinos can be obtained from searches for flavour changing neutral current processes such as $\mu \to e\gamma$, $\mu \to ee+e-$ and $\mu - e$ conversion
- The most well studied among $\Delta L = 2$ processes is neutrinoless double beta decay ($0\nu\beta\beta$) and the constraints from it deserve special attention. For heavy neutrinos with mass, $m \gg 1$ GeV, the bound is

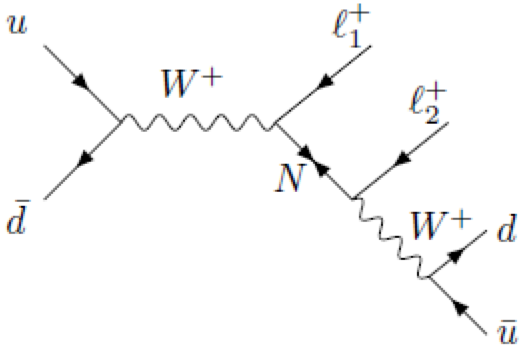
$$\sum_N \frac{|U_{eN}|^2}{m_N} < 5\cdot 10^{-5}\, TeV^{-1}$$

- The constraint above is very strong and makes it impossible to observe at colliders the like-sign dilepton signature with electrons $e^\pm e^\pm$

Heavy neutrino searches at the LHC

- In accelerator-based experiments, neutrinos in the final state are undetectable, so it is desirable to look for Lepton Flavor Violating processes with charged leptons in the final state.
- Caveat: Other physics (TeV-scale SUSY, extra-dimensions, etc.) may contribute to some flavorchanging processes as well.
- For $m_N > M_W$ the rates decrease with m_N : masses must be less than TeV.
- Heavy-to light mixings U_{lN} must be large enough.
- Most favorable processes: equal sign dileptons ($\Delta L = 2$):





Heavy neutrino searches at the LHC

- For $m_N > M_W$ the most favorable processes: equal sign dileptons ($\Delta L = 2$):

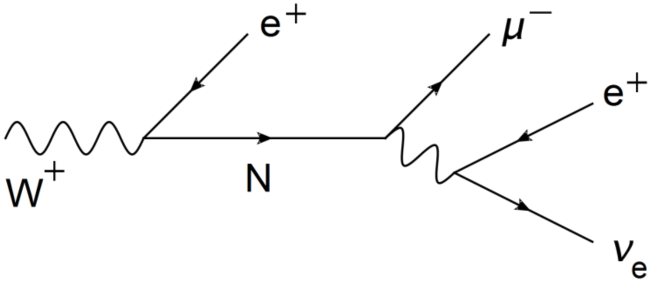
$$PP \to \mu^{\pm}\mu^{\pm} jj \qquad PP \to e^{\pm}e^{\pm} jj$$

- Search by ATLAS at $\sqrt{s} = 8$ TeV with 20.3 fb^{-1} pp collisions:
- Found no signal above background: bounds on $|U_{eN}|$ and $|U_{\mu N}|$ for m_N = 100-500 GeV.
- lowest near m_N = 100 GeV: $|U_{eN}|^2 = 0.029$ and : $|U_{\mu N}|^2 = 0.0028$.

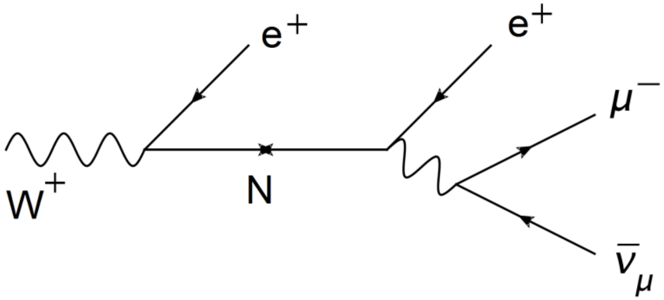
- Search by CMS at $\sqrt{s} = 8$ TeV with 19.7 fb^{-1} pp collisions:
- Found no signal above background; bounds $|U_{\mu N}|$ for m_N = 100-500 GeV.
- lowest near m_N = 100 GeV: $|U_{\mu N}|^2 = 0.0047$.

sterile Neutrinos ligther than M_W

- the purely leptonic W decays $W^+ \to e^+\mu^-e^+\nu_e$ and $W^+ \to e^+e^-\mu^-\bar{\nu}_\mu$ (or their charge conjugates), induced by sterile neutrinos with mass below M_W in the intermediate state.
- the first mode is induced by both Dirac or Majorana neutrinos, the second mode is induced only by Majorana neutrinos, as it violates lepton number



- Lepton Number Conserving (LNC) mode;
  caused by both Majorana and Dirac N:



Lepton Number Violating (LNV) mode:
caused by Majorana N only:

- one could distinguish between these two processes, thus distinguishing the Dirac or Majorana character of the sterile neutrinos, by studying the muon spectrum in the decays.

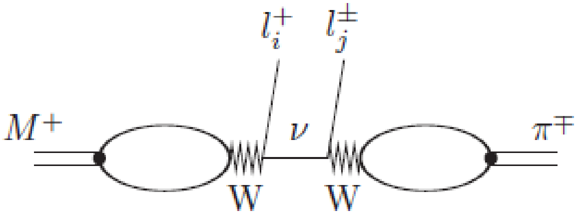
- If the neutrino is Majorana, both LNV and LNC decays will be induced, with a relative proportion that depends on the ratio of mixings $|U_{Ne}|^2 / |U_{N\mu}|^2$, but if the neutrino is Dirac, only the LNC process will occur. Therefore, a way to distinguish the Dirac vs. Majorana character of the heavy neutrino is to observe which of these two processes occur.

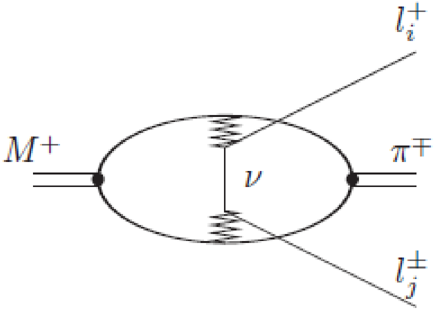
- Difficulties: On the one hand, in an actual experiment, the LNC and LNV processes cannot be distinguished by their final particles, because the only different one is the neutrino (a muon or electron neutrino),which goes undetected. On the other hand, the LNC and LNV processes cannot be distinguished by their rate,because they have exactly the same expression in terms of m_N , differing only in the mixing elements, which is still to date an unknown global factor. However, we find that the two processes can be distinguished by the energy spectrumof the muon (i.e. the opposite sign lepton). In the LNC process, the spectrum rises continuously with energy, all the way to the endpoint, while in the LNV process, the spectrum reaches a maximum at an intermediate energy and then gradually drops to zero at the endpoint.

contribution of heavy sterile neutrino to the semileptonic LNV and LFV decays of τ and the pseudoscalar mesons $\tau \to l M_1 M_2$, $M_1^+ \to l_i^+ l_j^\pm M_2^\mp$

Neutrino interactions are represented by the SM Charged (CC) and Neutral Current (NC) Lagrangian terms

$$L = \frac{g_2}{\sqrt{2}} \sum_i V_{li} \bar{l} \gamma^\mu P_L \nu_i W_\mu^- + \frac{g_2}{2\cos\theta_W} \sum_{\alpha,i,j} V_{\alpha j} V_{\alpha i}^* \bar{\nu}_i \gamma^\mu P_L \nu_j Z_\mu \qquad l = e, \mu, \tau \qquad i = 1,\ldots,n+3$$





From the non-observation of these rare meson decay modes one can determine constraints on mixing parameters $|V_{l_1 4} V_{l_2 4}|$

For the various decay modes, the mixing parameters probed are $|V_{e4}|^2$, $|V_{e4}V_{\mu4}|$ and $|V_{\mu4}|^2$ depending on the final state leptons.

The most stringent constraints are from the mode $K^+ \to l_1^+ l_2^+ \pi^-$ with mixings of $O(10^{-9})$.

Lepton-Number Violating Tau Decays $\tau \to lM_1M_2$

A direct search for tau decays has been made at the BaBar detector.

The experimental limits for various decay modes are typically of the order of 10^{-7}

The most stringent bound on $|V_{e4}V_{\tau4}|$ is of $O(10^{-6})$ and comes from $\tau - \to e+\pi-\pi-$.

The most stringent bound on $|V_{\mu4}V_{\tau4}|$ is also of $O(10^{-6})$ and comes from $\tau- \to \mu+\pi-\pi-$.

- The observation of a LV process would show that neutrino is a Majorana particle unambiguously. Apart from light neutrinos, LV processes involving SM particles can receive a contribution from heavy Majorana neutrinos due to mixing. In fact, this contribution can be resonantly enhanced for appropriate masses of the heavy neutrino. In the absence of observation of LV interactions, the rates for these processes can constrain the mixing elements |Vℓ14Vℓ24| as a function of the mass m4 of the heavy Majorana neutrino.
- Amongst the rare meson decays, the K+ → ℓ + 1 ℓ + 2 π − decay mode currently gives the most sensitive experimental limits on |Vℓ14Vℓ24|. Potentially, these constraints are six orders of magnitude more stringent than the constraints from precision electroweak data which limit |Vℓ4| 2 to few times 10−3 . As the intermediate heavy sterile neutrino is a real particle which might exit the detector if the decay length is longer than the detector size, for very small mixing angles the bounds get weakened but are still much more stringent than the electroweak precision constraints
- In particular, many interesting processes of D, B decays have not even been experimentally probed as well as those with a τ lepton in the final state. Among the τ -decay modes the best limits come from τ − → ℓ +π −π −. The other τ -decay modes have sensitivity of order 10−3 to 10−5 . Again, the constraints from τ decay modes are competitive with or better than constraints from precision EW data by 2 to 3 orders of magnitude. The experimental bound on LV processes is expected to improve in the future.
- For the collider signals of heavy Majorana neutrinos we looked for the definitive lepton number violating like-sign dilepton production and no missing energy. Such signals have low backgrounds and have the potential for discovery of heavy Majorana neutrinos.

summary

Sterile neutrinos are well motivated.

rich phenomenology;

no direct evidence yet;

(probably) the best chans in mesons decays

- The phenomenology of sterile neutrinos in the processes, which can be searched for in laboratory experiments have been studied in the literature in different contexts and from complementary points of view
- Their resonant contributions to and meson decays have been studied . Another potential process to look for sterile Majorana neutrinos is like-sign dilepton production in hadron collisions . Possible implications of sterile neutrinos have been also studied in LFV muonium decay and high-energy muon electron scattering .
- Constraints on the sterile neutrino parameters have been derived .
- An interesting explanation of anomalous excess of events observed in the neutrino experiments has been recently proposed in terms of sterile neutrinos with masses from 40 MeV to 80MeV. An explanation comes out of their possible production in neutral current interactions of and subsequent radiative decay to light neutrinos.