

HINTS OF STERILE NEUTRINOS FROM

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu} ?$$

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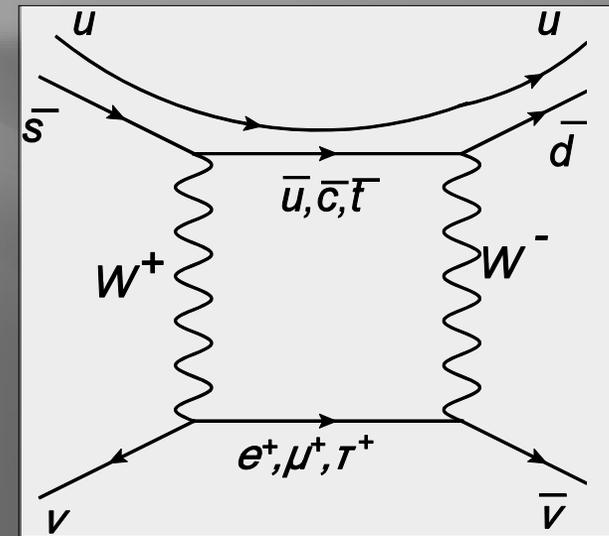
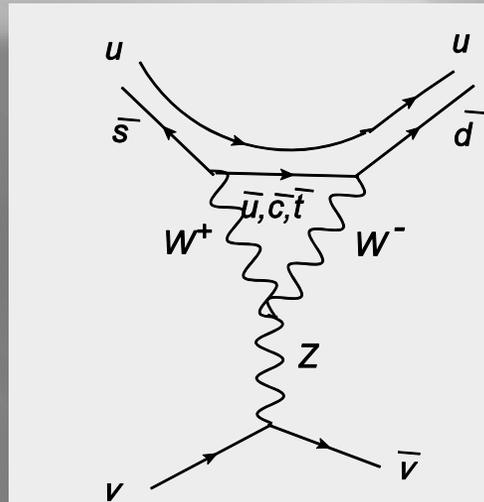
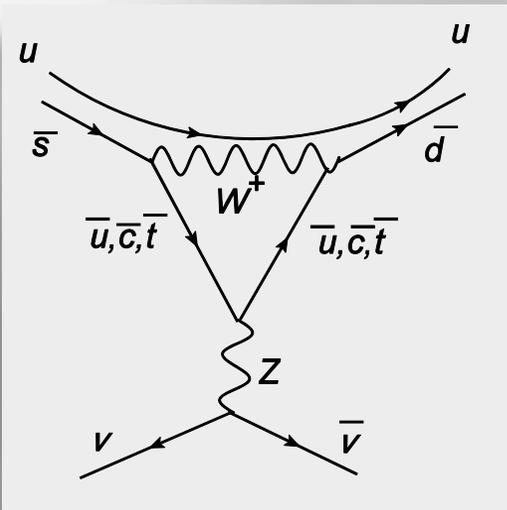
Chennai

Work in collaboration with Sanjoy Mandal and N. G. Deshpande



Rare Decay Modes : $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, $K_L \rightarrow \pi^0 \nu\bar{\nu}$

- ❖ Both decays are FCNC processes that proceed via Z penguin and box diagrams.
- ❖ Theoretically very clean.
- ❖ Sensitive to New Physics, which can appear through virtual effects in the loop diagrams.



Flavour: A tool for Probing High Scales of New Physics

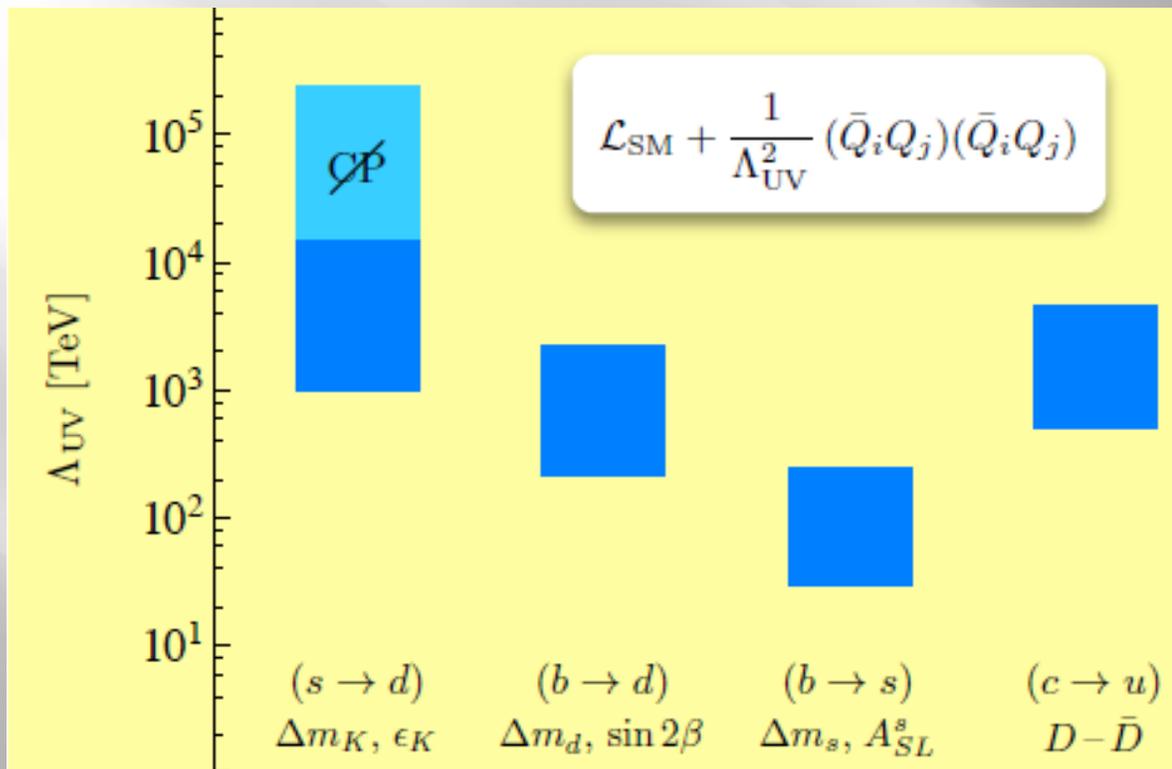
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^d (\text{SM fields})$$

FCNC and CPV rates are generally smallest in the Kaon system.

In principle all of the suppression mechanisms of the SM can be absent in BSM scenarios, so that large deviations can be predicted.

However such large deviations have not been observed! \Rightarrow

NP must also involve some kind of suppression of FCNC effects, or can arise only at very high scales



What's special about these modes?

- ❖ *Exceptionally suppressed : Besides being 4th order in weak coupling, CKM elements lead to $s \rightarrow d$ transitions being 2 orders of magnitude smaller than for $b \rightarrow \{d, s\}$ transitions*
- ❖ *Exceptionally theoretically clean: Hadronic matrix elements can be accurately related using chiral perturbation theory to those of charged semileptonic decays.*
- ❖ *Accurate calculations of the loop contributions with NLO EW corrections, NNLO QCD corrections to charm loop contributions etc. have been done (Thanks to Buras et al!)*
- ❖ *Only uncertainty in the branching ratio prediction is in the CKM elements which are expected to be more accurately known with data from BelleII, LHCb and with improved lattice estimates.*

Theoretical Estimates

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

$$BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

Current Exp. values

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3 \pm 11.5) \times 10^{-11}$$

$$BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 2.6 \times 10^{-8}$$

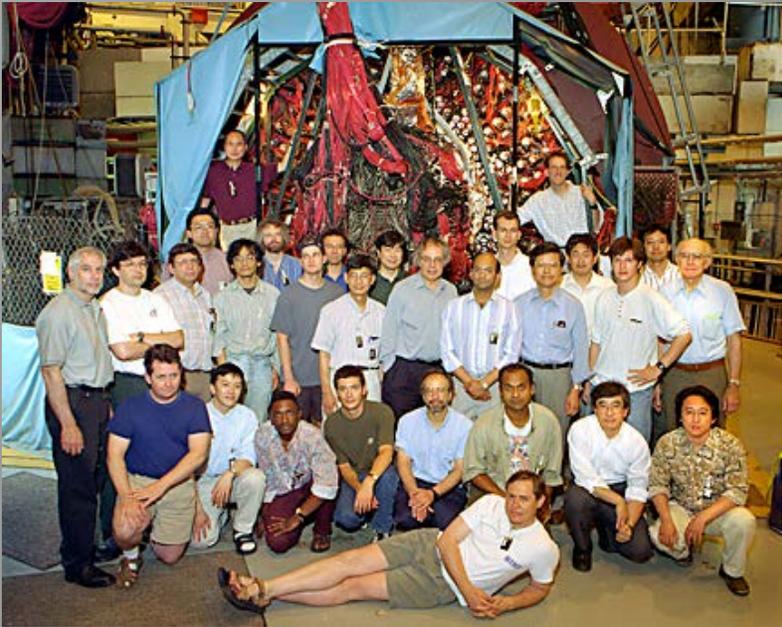


NA62

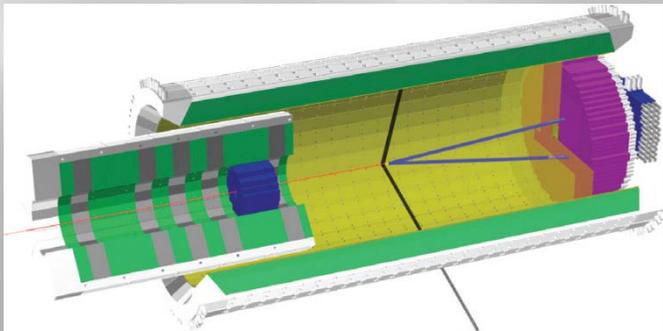
Experiments



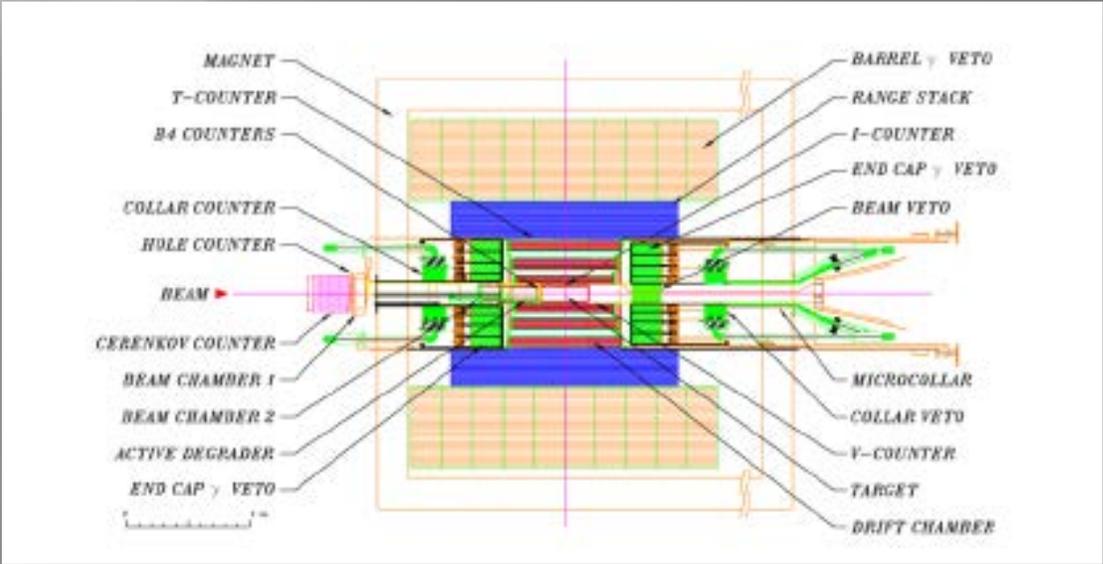
E949



ORKA



KOTO



Earlier Suggestions for Search for Massive Neutrinos via this Mode

VOLUME 53, NUMBER 24 PHYSICAL REVIEW LETTERS 10 DECEMBER 1984

Neutrino-Mass Limits from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Decay

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 (Received 27 September 1984)

The present limit on the mass of the tau neutrino ($m_\nu < 143$ MeV), obtained from tau decay, may be lowered significantly from a study of the pion spectrum in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. We show that if $m_\nu \geq 50$ MeV then the pion spectrum differs significantly from its value when all neutrinos are massless. Our results are also applicable to any new massive neutrino with $50 \leq m_\nu \leq 150$ MeV.

PACS numbers: 14.60.Gh, 11.30.Pb, 13.20.Es

Are all neutrinos massless, or do they all have tiny (eV or smaller) masses? Is there a hierarchy of masses among them, with large (megaelectronvolt or even higher) values for the third—or higher generation—neutrinos? The answers to these important questions are still shrouded in both theoretical and experimental uncertainties. It is therefore very useful to search for experimental signatures of massive neutrinos in as many mass regimes as possible. Unfortunately most searches involve unknown mixings among neutrinos. The least stringent experimental limit is for the τ neutrino: $m_\nu < 143$ MeV¹ from τ decays. It is very difficult to use τ decays to push this limit down much further.

Here we suggest the use of the proposed $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiments² to set limits on—or observe—the τ neutrino mass from the present experimental limit down to 50 MeV or so, depending on the experimental rate and resolution. The results are independent of mixing among neutrinos of different generations; uncertainties involving the yet undetermined Kobayashi-Maskawa angles and possible quantum chromodynamics corrections are factored into a total multiplicative constant which does not affect the shape of the pion spectrum discussed here.

The Feynman diagrams for the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the standard model involve loops: box diagrams and a flavor-changing Z vertex. For the i th generation the effective Lagrangian for the relevant quark transition is given by

$$\mathcal{L}_i = -\frac{G_F \alpha}{\sqrt{2} \pi \sin^2 \theta_w} \hat{D}_i [\bar{\nu}_i \gamma_\mu (1 - \gamma_5) s] [\bar{v}_i \gamma^\mu (1 - \gamma_5) u] . \quad (1)$$

The effective Lagrangian for $K^+(k) \rightarrow \pi^+(p) \nu_i(q_1) \bar{\nu}_i(q_2)$ is then

$$\mathcal{L}_i = -\frac{G_F \alpha}{\sqrt{2} \pi \sin^2 \theta_w} \hat{D}_i [f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu] [\bar{\nu}_i \gamma_\mu (q_1) \nu_i(q_2)] . \quad (2)$$

where $q^2 = (k-p)^2$, and $f_\pm(q^2)$ are form factors measured in K_{S1} and K_{S2} decays. \hat{D}_i is defined in Ref. 3, and may include QCD corrections as prescribed in Ref. 4. For $m_i \ll M_w$, as is assumed here, where i is the neutrino's charged weak partner, \hat{D}_i is independent of the generation label i , and will be denoted hereafter by \hat{D} . Therefore the differential width, where E_π is the pion energy in the rest frame of the decaying kaon, becomes

$$\frac{d\Gamma}{dE_\pi} = \frac{G_F^2 \alpha^2 \hat{D}^2 \lambda}{(2\pi)^3 M_K^2 \sin^4 \theta_w} \sum \left[1 - \frac{4m_i^2}{q^2} \right] \left\{ f_+^2 m_i^2 q^2 + 2f_+ f_- (m_i^2 - m_\pi^2) + f_-^2 \left[2m_i^2 (m_i^2 + m_\pi^2) - q^2 (m_i^2 + 2m_\pi^2) + (m_i^2 - m_\pi^2 - q^2)^2 \right] \right. \\ \left. - \frac{2}{3q^2} \left[\frac{1}{3q^2} m_i^2 \lambda^2 + m_i^2 \lambda^2 + m_\pi^2 \lambda^2 + 4q^2 m_i^2 m_\pi^2 \right] \right\} . \quad (3)$$

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PHYSICAL REVIEW D VOLUME 32, NUMBER 7 RAPID COMMUNICATIONS 1 OCTOBER 1985

Rapid Communications

Majorana neutrinos and photons from kaon decay

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 (Received 18 June 1985)

We discuss the suggestion by Deshpande and Eilam of putting bounds on the ν_τ mass from the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. We show that the Dirac or Majorana nature of the ν_τ can make a significant difference in the pion energy spectrum. We also discuss the relative importance of the $K^+ \rightarrow \pi^+ \nu_\tau \bar{\nu}_\tau$ mode, λ , being the photon.

Recently, Deshpande and Eilam¹ have pointed out that the shape of the pion spectrum from the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is sensitive to the mass of the ν neutrino if the latter lies in the range of tens of MeV. Hence this decay can be employed to improve on the present available upper limit² for m_{ν_τ} , viz., 143 MeV.

Since experiments are now being planned to look for such decay modes,³ we wish to point out that the analysis of the data will also sensitively depend on the nature of the ν_τ , viz., whether it is a Dirac or a Majorana particle. The reason for such dependence is twofold. Firstly, a Majorana neutrino is identical with its antiparticle. So, the final state contains two identical particles in the Majorana case. This gives a symmetry factor 1/2! in the calculation of the decay rate. Secondly, in the Dirac case the right-handed component of the neutrinos, ν_{Ri} , are singlets of SU(2)_L × U(1)_Y, and hence do not interact with W and Z bosons. In the Majorana case, on the other hand, a right-handed neutrino forms an SU(2)_L doublet with the right-handed component of a charged antilepton. So they have gauge interactions as well. If we take them into account, the effective leptonic current, which is simply $\bar{\nu}_i \gamma^\mu (1 - \gamma_5) \nu_i$ for the Dirac case, becomes

$$\bar{\nu}_i \gamma^\mu (1 - \gamma_5) \nu_i - \bar{\nu}_i \gamma^\mu (1 + \gamma_5) \nu_i - 2\bar{\nu}_i \gamma^\mu \nu_i$$

for the Majorana case.

To discuss both the Dirac and the Majorana cases, we write the effective Lagrangian for

$$K^+(k) \rightarrow \pi^+(p) \nu_i(q_1) \bar{\nu}_i(q_2)$$

as

$$\mathcal{L}_i = \frac{G_F \alpha}{\sqrt{2} \pi \sin^2 \theta_w} \hat{D}_i [f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu] \times [\bar{\nu}_i \gamma_\mu (q_1) \nu_i(q_2)] . \quad (1)$$

where $q = k - p = q_1 = q_2$ are form factors known from K_{S1} and K_{S2} decays, and \hat{D}_i is a factor coming from the diagrams⁴ and is independent of the generation label i if all the charged leptons are much lighter than the W boson, which is true for three generations. As explained earlier,

$$a = -b = 1 \text{ for Dirac neutrinos} , \quad (2a)$$

$$a = 0, b = -2 \text{ for Majorana neutrinos} . \quad (2b)$$

It is now straightforward to calculate the differential decay rate in the rest frame of the kaon. Denoting by E_π the pion energy in this frame, we get

$$\frac{d\Gamma}{dE_\pi} = \frac{1}{\pi^2} \frac{1}{(2\pi)^3} \frac{1}{m_K} \left[\frac{G_F \alpha \hat{D}_i^2}{\sin^4 \theta_w} \right] |p| \sqrt{1 - 4m_\pi^2/q^2} \times [f_+^2 + 2f_+ f_- + f_-^2] . \quad (3)$$

where $|p|$ is the number of identical particles in the final state (2 for Majorana, 1 for Dirac), m_K is the mass of ν_i , and

$$F_+ = 2q^2 m_i^2 / q^4 , \quad (4a)$$

$$F_- = -2(m_i^2 - m_\pi^2) m_i^2 / q^4 , \quad (4b)$$

$$F_0 = \frac{4}{3} m_i^2 |p|^2 (q^2 + p^2) + \frac{8}{3} \frac{m_i^2 p^2 m_\pi^2}{q^4} (q^2 - 2p^2) + \frac{2m_i^2 (m_i^2 - m_\pi^2)^2}{q^4} p^2 . \quad (4c)$$

A few comments are in order. Firstly, for the Dirac case, our Eq. (3) agrees with Eq. (3) of Ref. 1. Secondly, for massless neutrinos, the only term which survives in Eq. (4) is the first term of F_+ . This result can be traced back to the fact that in the $m_i \rightarrow 0$ limit only the term involving f_+ in the leptonic current contributes in Eq. (1). The depen-

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Pre-Nu Oscillations Discovery



Sterile Neutrinos

- *Cosmology gives upper bounds on the sum of active neutrino masses*
- *Neutrinos of masses above few eV have to be then necessarily gauge singlets*
- *Possible existence of singlet neutrinos with masses in eV to GeV range has been invoked in various models of neutrino masses.*
- *LSND, MiniBoone, Reactor anomalies*
- *Possible Dark Matter Candidates*
- *Hints from Cosmology*
- *Important to perform Extensive lab searches*



Decay Rate Evaluation for SM

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} \sum_{\ell=e,\mu,\tau} (V_{cs}^* V_{cd} X_{NL}^\ell + V_{ts}^* V_{td} X(x_t)) (\bar{s}d)_{V-A} (\bar{\nu}_\ell \nu_\ell)_{V-A}.$$

For, $K^+(k) \rightarrow \pi^+(p) \nu(q_1) \bar{\nu}(q_2)$ with $q^2 = (k - p)^2$,

the hadronic part, involves the measured $K \rightarrow \pi$ form factors and has the form:

$$f_+(q^2)(k + p)_\mu + f_-(k - p)_\mu$$

Leptonic part:

$$\bar{\nu}_l(q_1) \gamma^\mu (1 - \gamma_5) \nu_l(q_2)$$

$$\frac{d\Gamma_{SM}}{dE_\pi}(K^+ \rightarrow \pi^+ \bar{\nu} \nu) = \frac{1}{(2\pi)^5} \left(\frac{G_F \alpha}{\sin^2 \Theta_W} \right)^2 \frac{8}{3} \left[(D_1 X_{NL}^e + D_2)^2 + (D_1 X_{NL}^\mu + D_2)^2 + (D_1 X_{NL}^\tau + D_2)^2 \right] |\vec{P}|^3 f_+^{K^+2} m_K,$$

with

$$D_1 = \frac{1}{2} V_{cs}^* V_{cd}, \quad D_2 = \frac{1}{2} V_{ts}^* V_{td} X(x_t), \quad |P| = \sqrt{E_\pi^2 - m_\pi^2}.$$

$$f_+^{K^+}(t) = f_+^{K^+}(0) \left(1 + \frac{\lambda_+^{K^+} t}{m_{\pi^+}^2} \right); \quad f_0^{K^+}(t) = f_+^{K^+}(0) \left(1 + \frac{\lambda_0^{K^+} t}{m_{\pi^+}^2} \right),$$

where t=momentum transfer to the pion. and

$$f_0^{K^+} = f_+^{K^+} + \frac{f_-^{K^+} t}{(m_{K^+}^2 - m_{\pi_0}^2)}.$$



Decay Rate in presence of a singlet heavier Neutrino

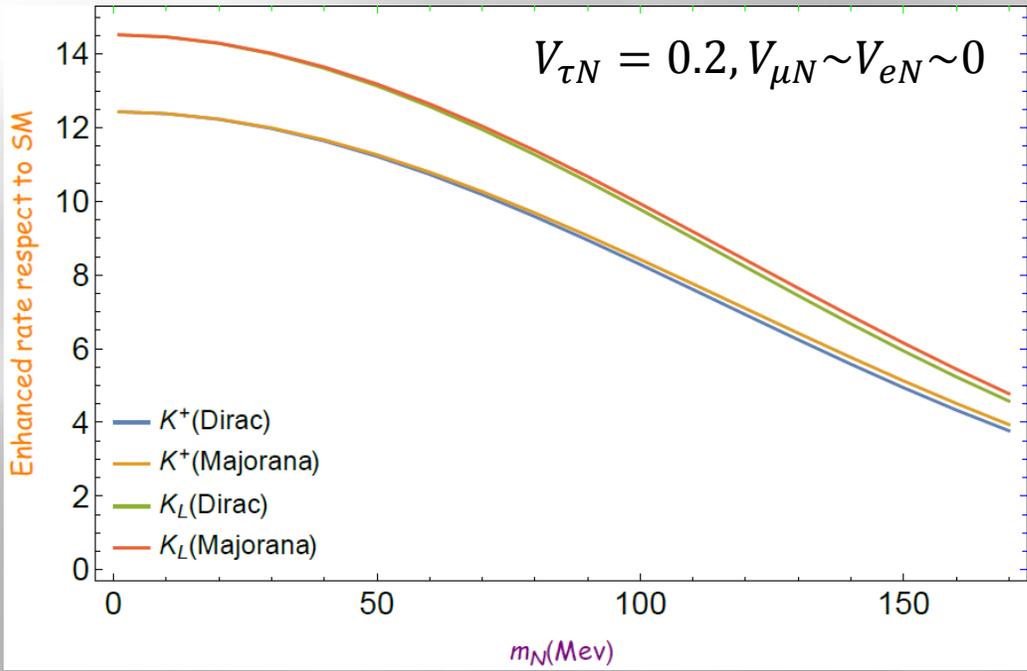
$$\nu_e = \sum_{j=1}^3 U_{ej} \nu_j + V_{eN} N$$

$$U^\dagger U + V^\dagger V = 1$$

In the literature, approximation made:

$U^\dagger U$ will be of order $\sim \mathcal{O}(1)$ and $V^\dagger V \sim \mathcal{O}\left(\frac{m_\nu}{m_N}\right)$

This mixing allows the decay modes $K^+ \rightarrow \pi^+ \nu \bar{N}$, $K^+ \rightarrow \pi^+ \bar{\nu} N$ and $K^+ \rightarrow \pi^+ N \bar{N}$ as well



Reasonable, however, is used even if the mixing elements are varied from 0 to 1



In fact Unitarity will imply the Massless neutrino rate has to be changed as:

$$\frac{d\Gamma}{dE_\pi}(K^+ \rightarrow \pi^+ \bar{\nu}\nu) = \frac{1}{(2\pi)^5} \left(\frac{G_F \alpha}{\sin^2 \Theta_W} \right)^2 \frac{8}{3} \\ (D_1 X_{NL}^e + D_2)^2 \left[(1 - |V_{eN}|^2)^2 + (1 - |V_{\mu N}|^2)^2 + (1 - |V_{\tau N}|^2)^2 \right] \\ |\vec{P}|^3 f_+^{K^+2} m_K,$$

$$\frac{d\Gamma}{dE_\pi}(K^+ \rightarrow \pi^+ \nu \bar{N}) = \frac{1}{(2\pi)^5 m_K} \left(\frac{G_F \alpha}{\sin^2 \Theta_W} \right)^2 \\ (D_1 X_{NL}^e + D_2)^2 (|V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2 - |V_{eN}|^4 - |V_{\mu N}|^4 - |V_{\tau N}|^4) \\ \frac{1}{6} \left(1 - \frac{m_N^2}{q^2} \right) |\vec{P}| \left(f_+^{K^+2} F_+ + f_+^{K^+} f_-^{K^+} F_{+-} + f_-^{K^+2} F_- \right),$$

$$F_+ = 16 \left(1 + \frac{m_N^2}{q^2} - \frac{1}{2} \frac{m_N^4}{q^4} \right) m_K^2 |\vec{P}|^2 - 6m_N^4 \frac{(m_K^2 - m_\pi^2)^2}{q^4} \\ + 6m_N^2 (m_K^2 + m_\pi^2 + 2m_K E_\pi) \\ F_{+-} = 12m_N^2 (m_K^2 - m_\pi^2) - 12m_N^4 \frac{(m_K^2 - m_\pi^2)}{q^2} \\ F_- = 6m_N^2 q^2 - 6m_N^4.$$

$$\frac{d\Gamma}{dE_\pi}(K^+ \rightarrow \pi^+ \bar{N} N) = \frac{1}{n!} \frac{1}{(2\pi)^5 m_K} \left(\frac{G_F \alpha}{\sin^2 \Theta_W} \right)^2$$

$$(D_1 X_{NL}^e + D_2)^2 (|V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2)^2$$

$$|\vec{P}| \sqrt{\left(1 - \frac{4m_N^2}{q^2}\right)} \left(f_-^{K^+} F'_- + 2f_+^{K^+} f_-^{K^+} F'_{+-} + f_+^{K^+} F'_+ \right),$$

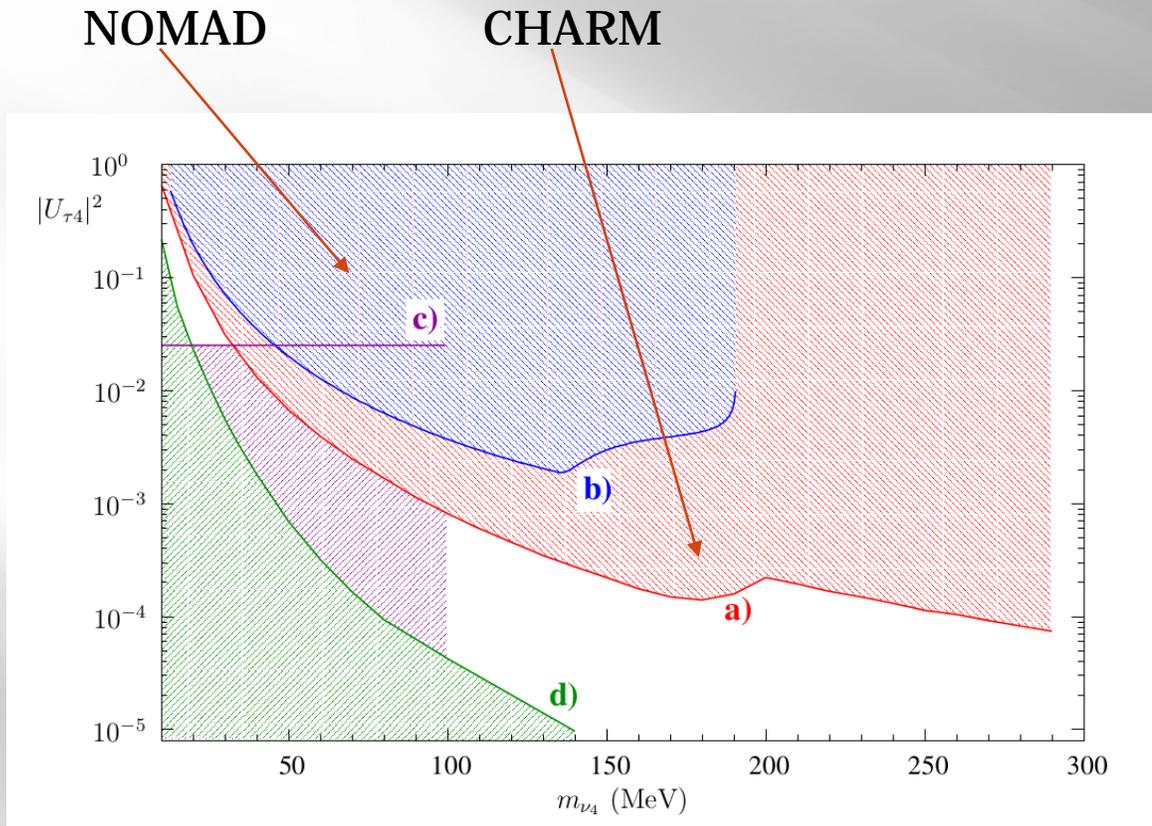
Will Distinguish Dirac and Majorana

$$F'_- = 2q^2 m_N^2$$

$$F'_{+-} = 2(m_K^2 - m_\pi^2) m_N^2$$

$$F'_+ = \frac{8}{3} m_K^2 |\vec{P}|^2 - \frac{8}{3} \frac{m_K^2 m_N^2 |\vec{P}|^2}{q^2} + \frac{2m_N^2 (m_K^2 - m_\pi^2)^2}{q^2}$$

Existing Bounds



$$|V_{eN}|^2, |V_{\mu N}|^2 < 10^{-5}, 10^{-6}$$

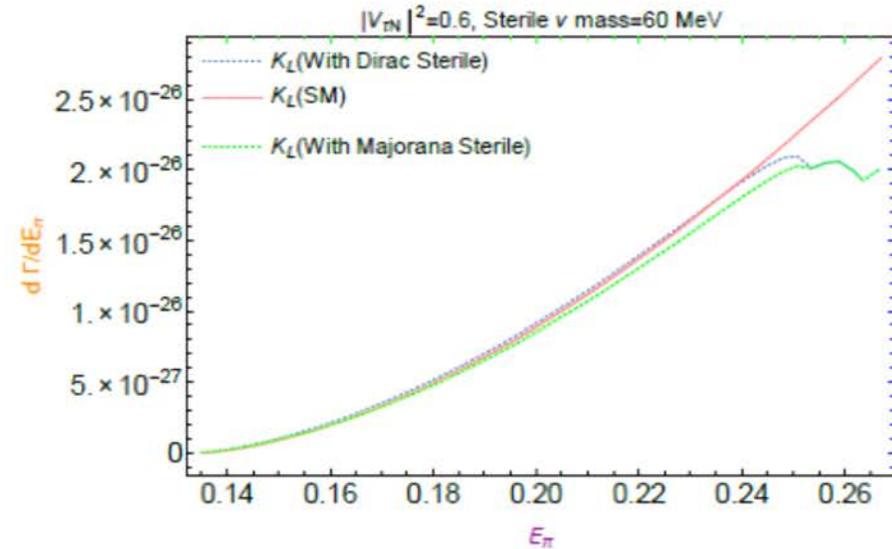
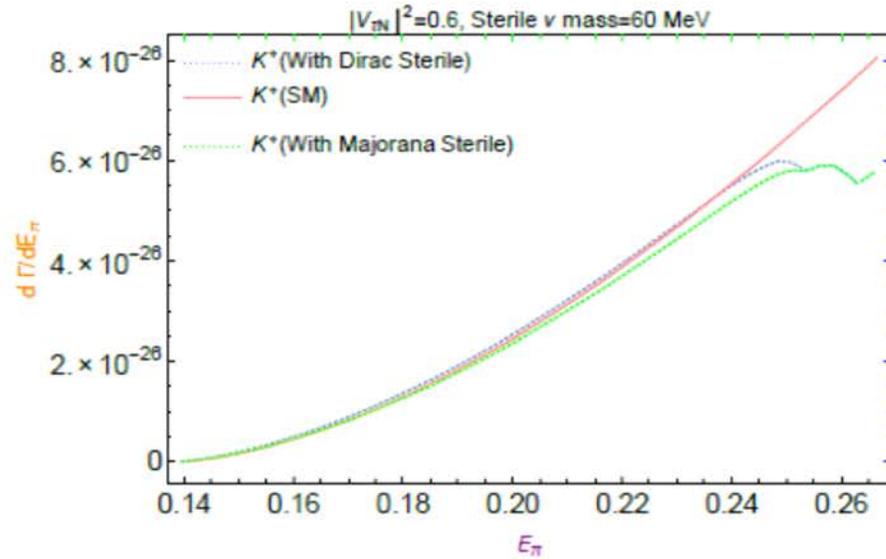
Neutrinoless double beta decay, peak searches in Kaon, Pion leptonic decays.

Pion Energy Spectrum

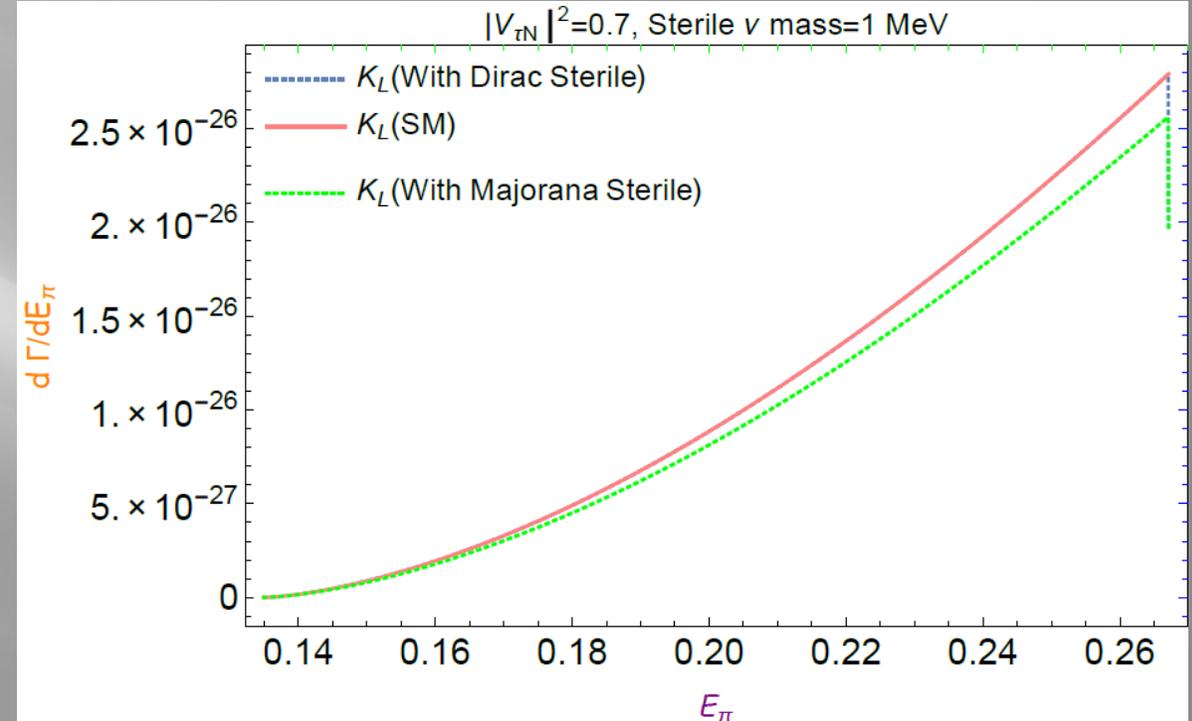
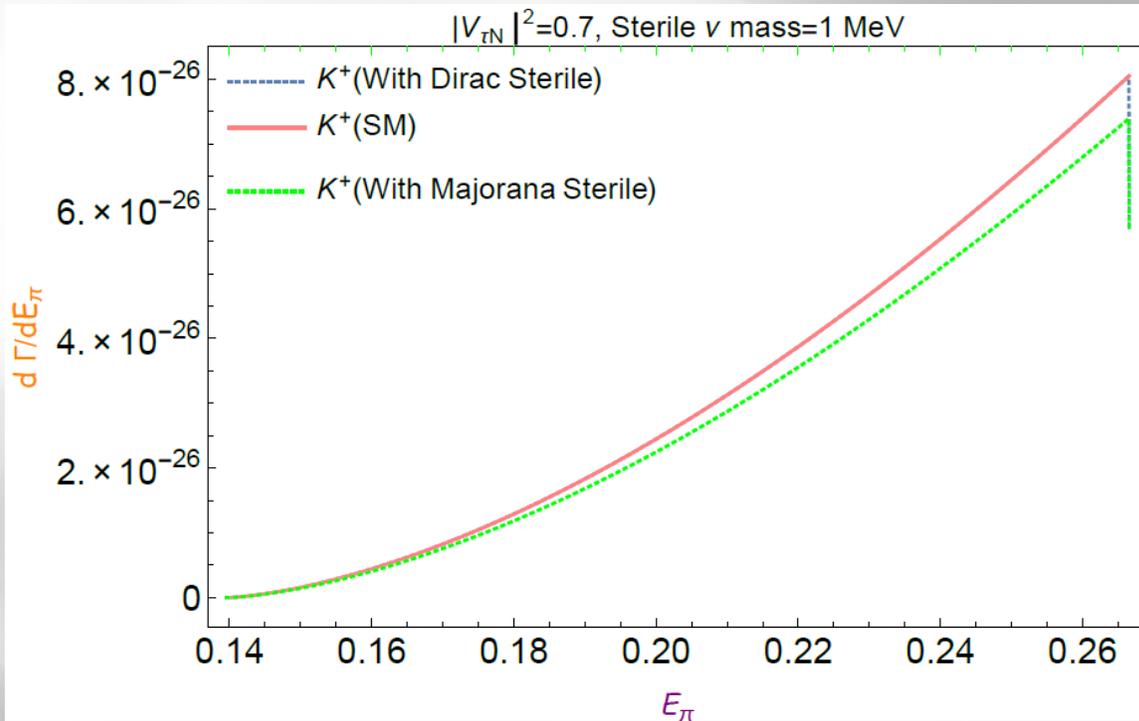
$$\frac{d\Gamma}{dE_\pi} = \frac{d\Gamma}{dE_\pi} (K^+ \rightarrow \pi^+ \nu \bar{\nu}) + \frac{d\Gamma}{dE_\pi} (K^+ \rightarrow \pi^+ \nu \bar{N}) + \frac{d\Gamma}{dE_\pi} (K^+ \rightarrow \pi^+ \bar{\nu} N) + \frac{d\Gamma}{dE_\pi} (K^+ \rightarrow \pi^+ N \bar{N}).$$

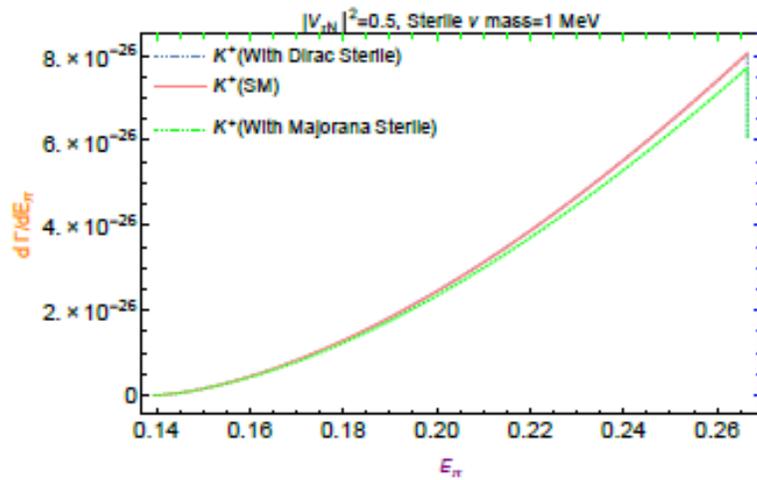
Large Mass and Large Mixing (Unrealistic!)

The two Kinks

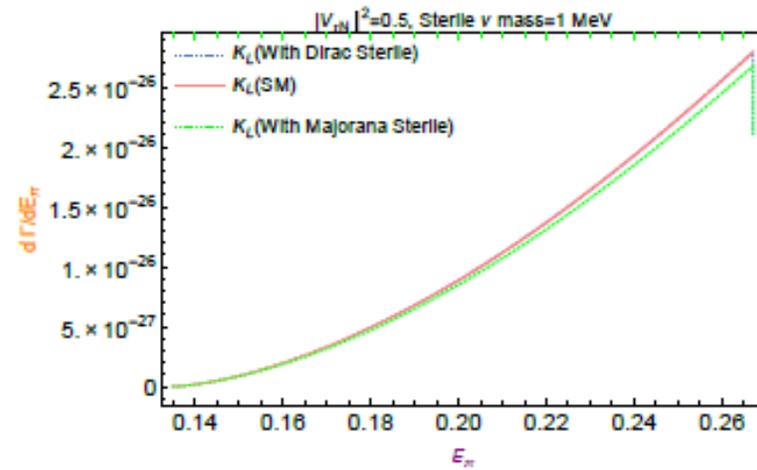


More Realistic Case

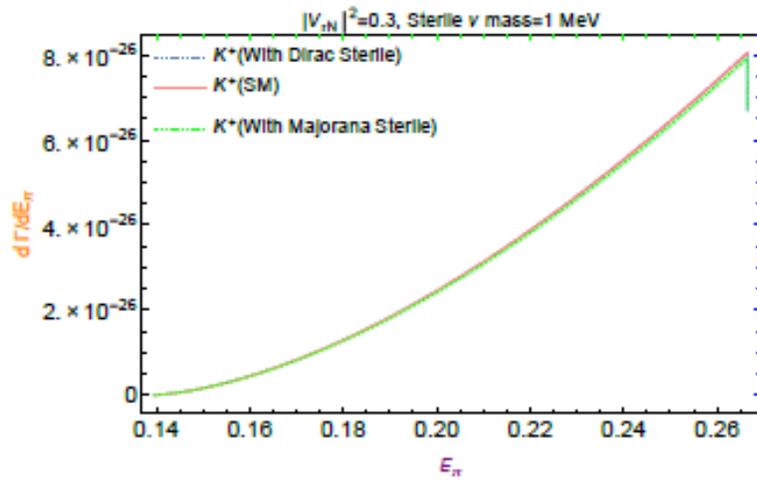




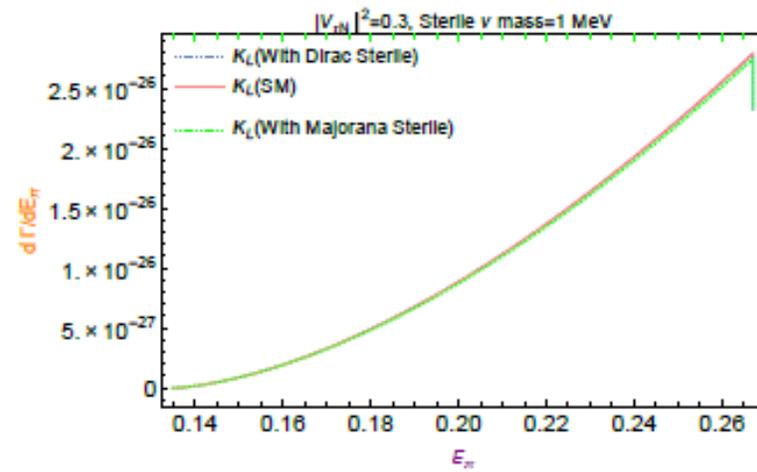
(c)



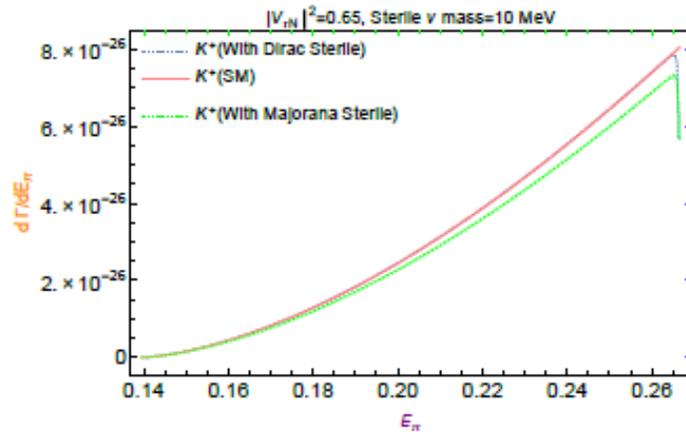
(d)



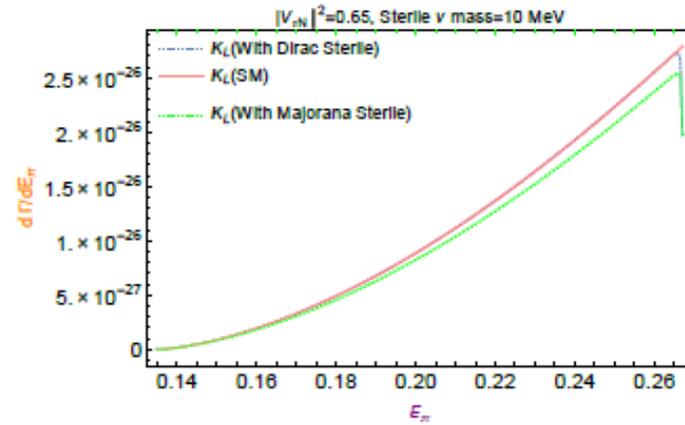
(e)



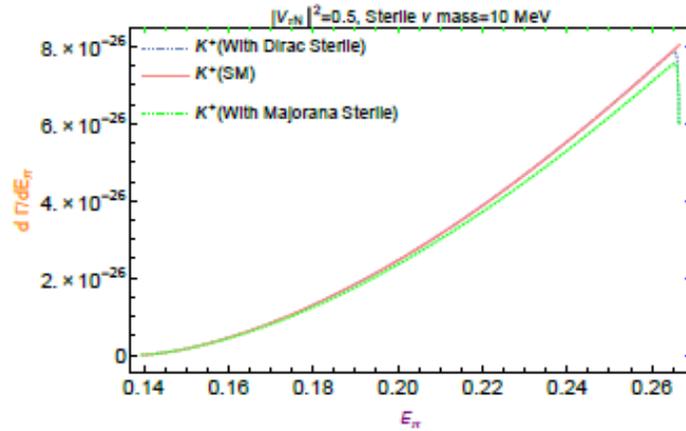
(f)



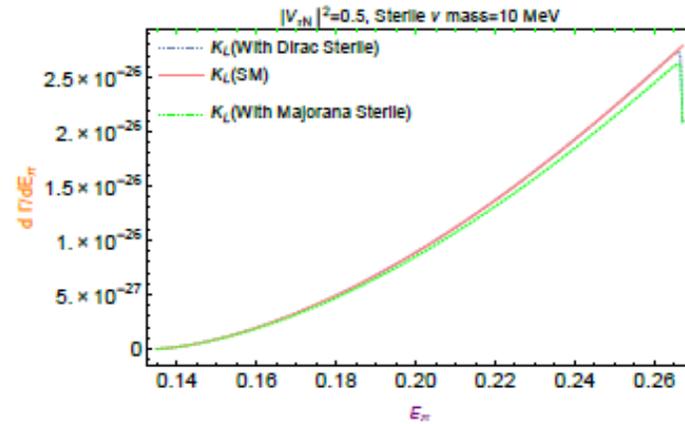
(g)



(h)



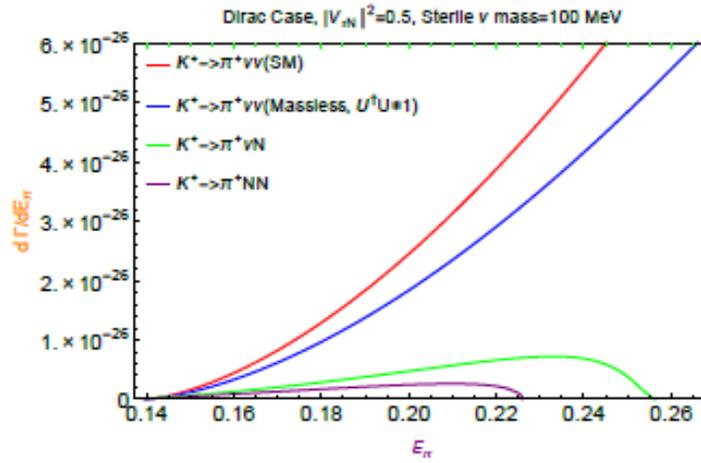
(i)



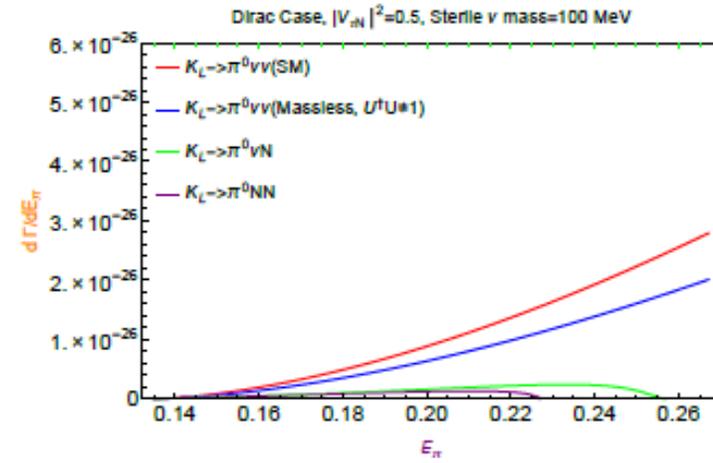
(j)

For Higher masses, since the Mixing element $V_{\tau N}$ is more tightly constrained, the deviation from SM case is negligible

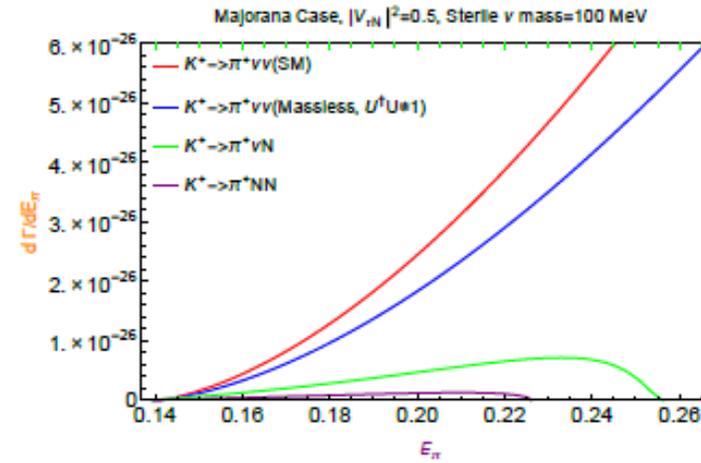
Individual Differential Decay Rate Contributions



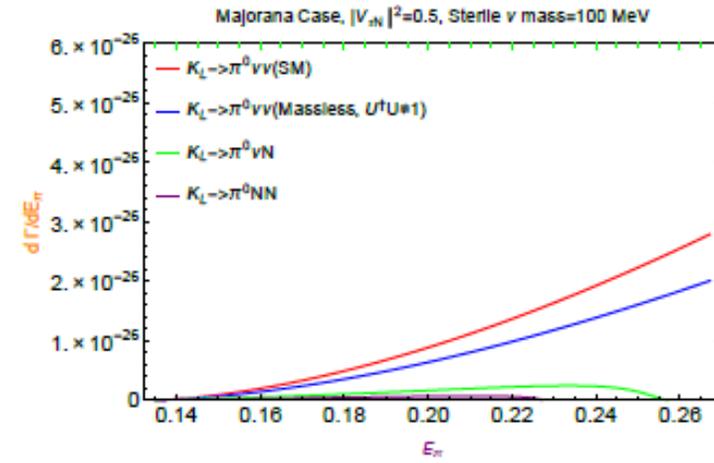
(a)



(b)

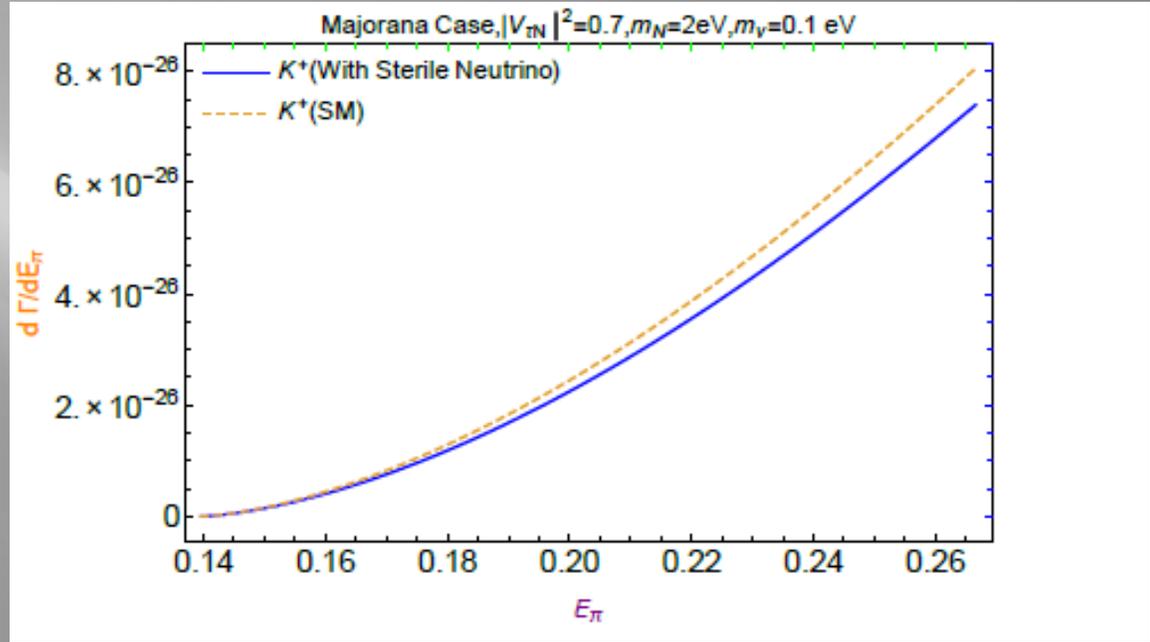
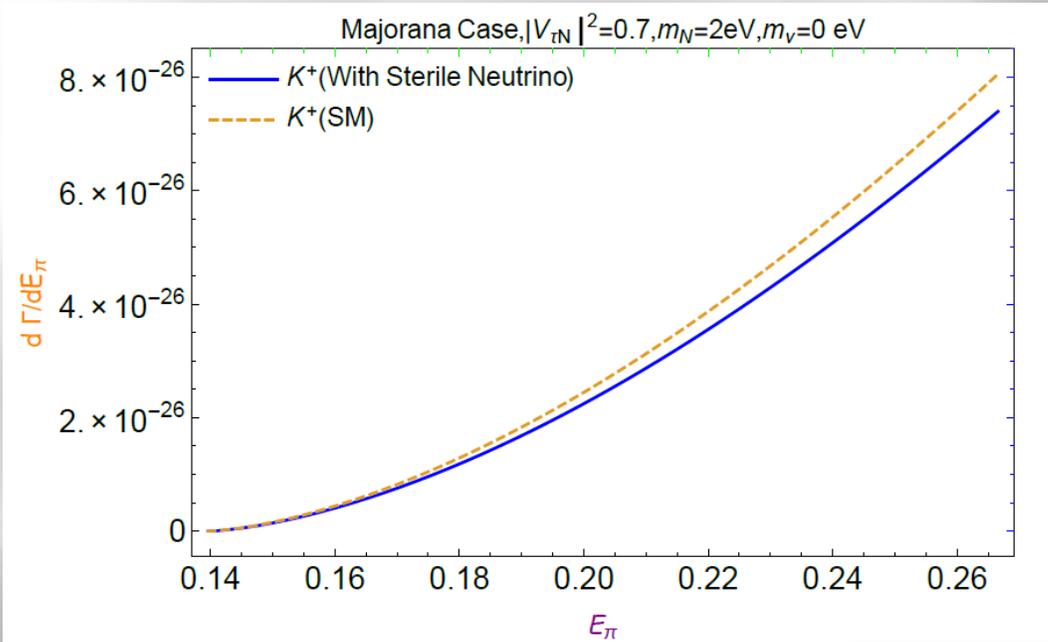


(c)



(d)

$$m_N = 2\text{eV}$$



CONCLUSIONS

The Rare decay modes $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, will be measured to 10% accuracy by NA62, ORKA can measure it to 5% accuracy. $K_L \rightarrow \pi^0 \nu \bar{\nu}$ will be observed by KOTO

The pion decay distributions can give some hints on presence of Majorana sterile neutrinos of small masses, from few eV to about 10 MeV

