HINTS OF STERILE NEUTRINOS FROM $K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}$?

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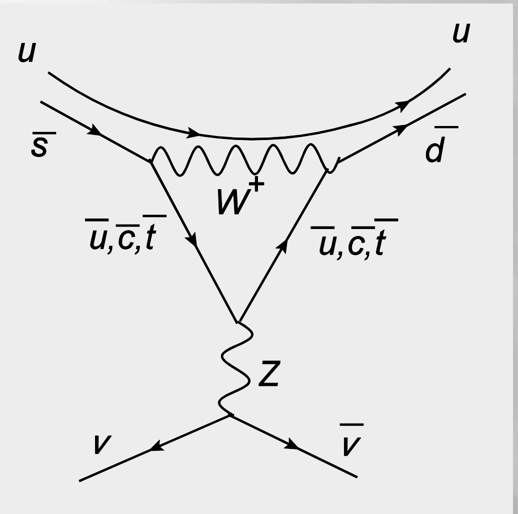
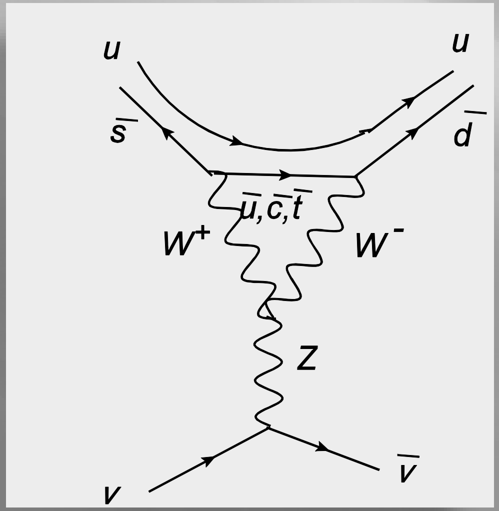
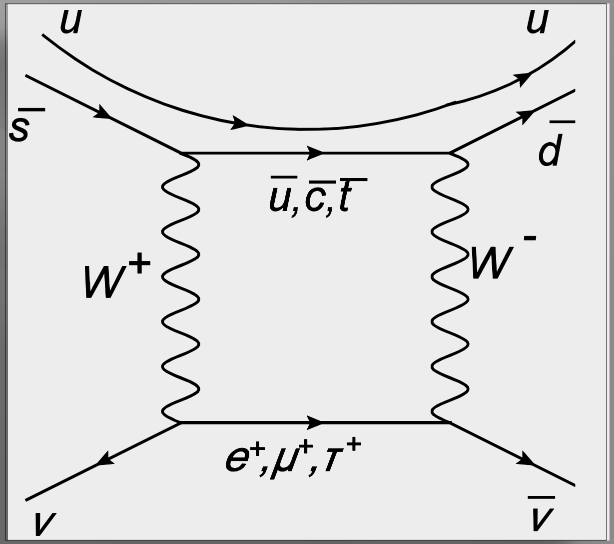
Work in collaboration with Sanjoy Mandal and N. G. Deshpande

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

- ***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.***

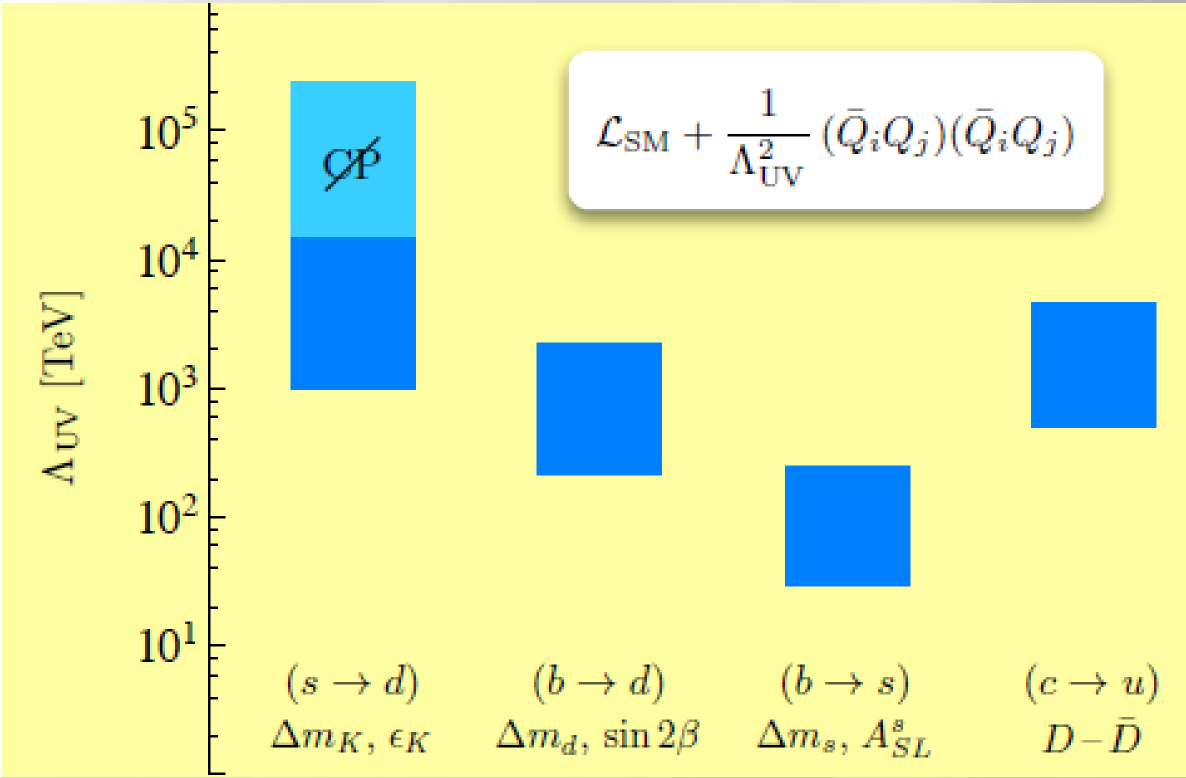






Flavour: A tool for Probing High Scales of New Physics

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



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 → d transitions being 2 orders of magnitude smaller than for b → {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

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$
$$BR(K_L \to \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

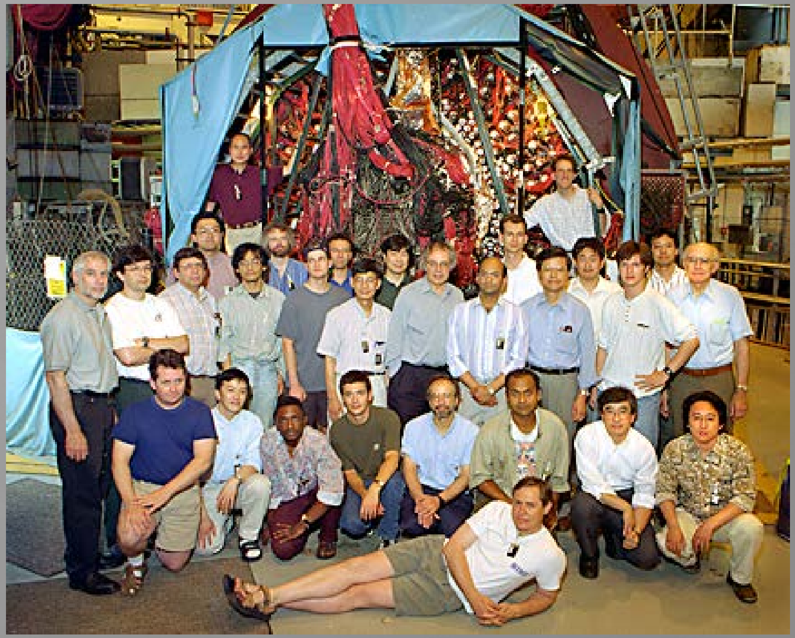
Current Exp. values

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (17.3 \pm 11.5) \times 10^{-11}$$
$$BR(K_L \to \pi^0 \nu \bar{\nu}) \leq 2.6 \times 10^{-8}$$

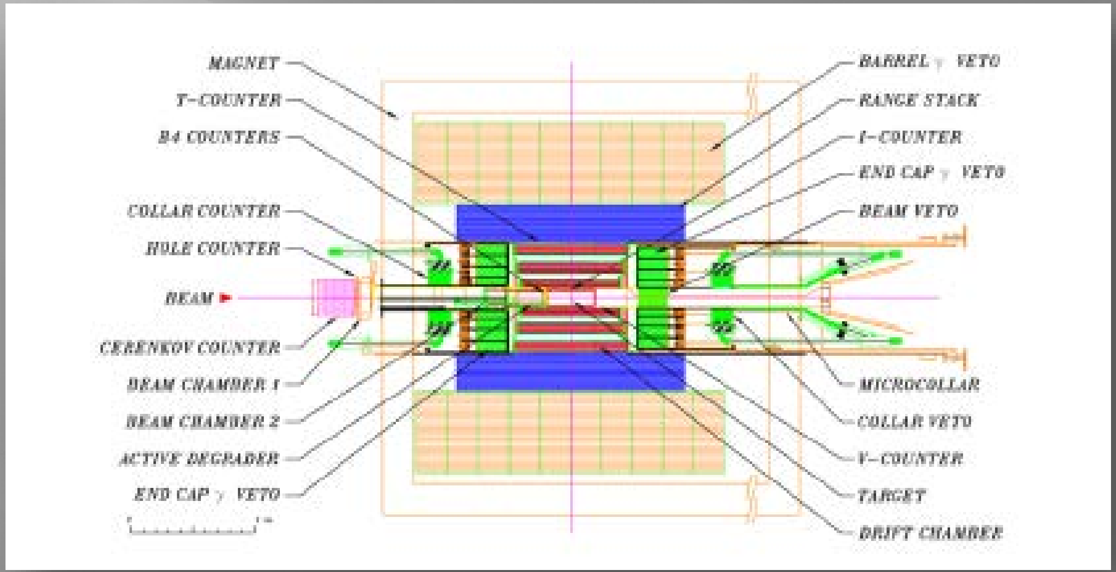
Experiments

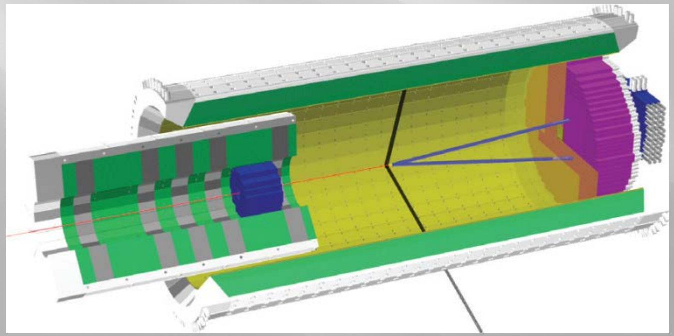
NA62

E949



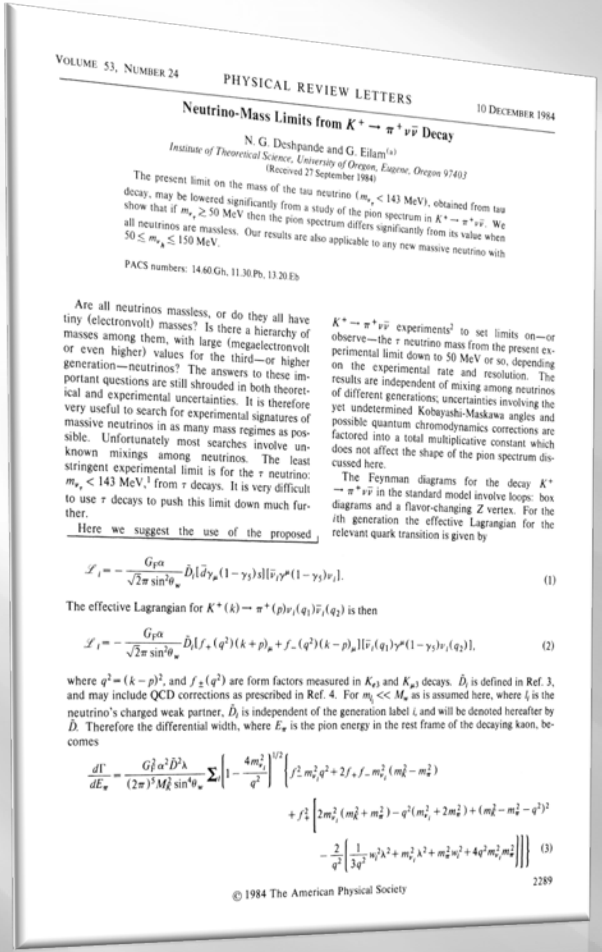
ORKA





KOTO

Earlier Suggestions for Search for Massive Neutrinos via this Mode



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

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The present limit on the mass of the tau neutrino ($m_{\nu_\tau} < 143$ MeV), obtained from tau decay, may be lowered significantly from a study of the pion spectrum in $K^+ \to \pi^+ \nu\bar{\nu}$. We show that if $m_{\nu_\tau} \geq 50$ 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 $50 \leq m_{\nu_x} \leq 150$ MeV.

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

Are all neutrinos massless, or do they all have tiny (electronvolt) 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: $m_{\nu_\tau} < 143$ MeV,[1] 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 $K^+ \to \pi^+ \nu\bar{\nu}$ experiments[2] 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 $K^+ \to \pi^+ \nu\bar{\nu}$ in the standard model involve loops: box diagrams and a flavor-changing Z vertex. For the ith generation the effective Lagrangian for the relevant quark transition is given by

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

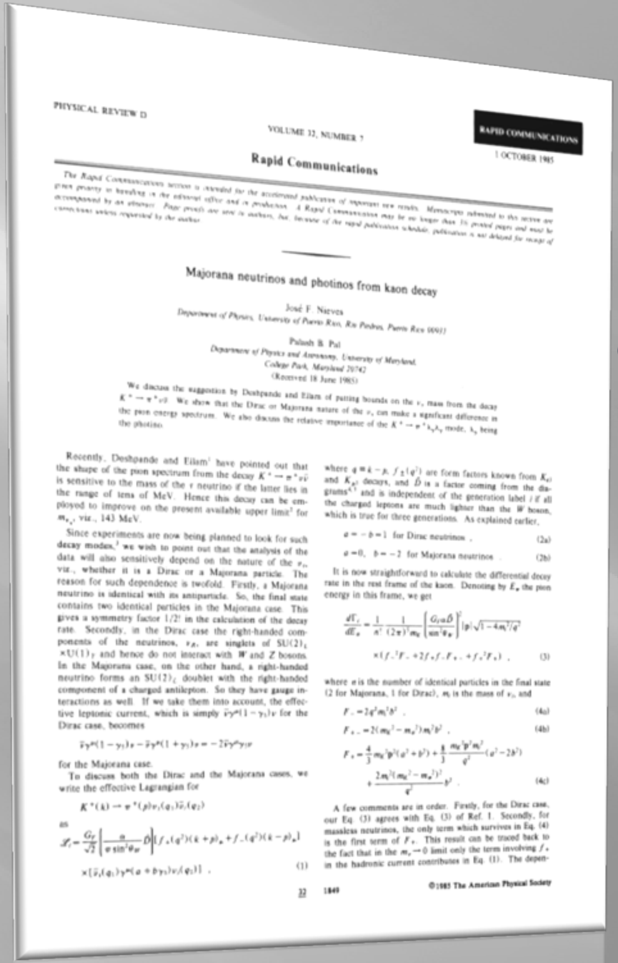
The effective Lagrangian for $K^+(k) \to \pi^+(p)\nu_i(q_1)\bar{\nu}_i(q_2)$ is then

$$\mathcal{L}_i = -\frac{G_F \alpha}{\sqrt{2}\pi \sin^2\theta_w} \tilde{D}_i [f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu][\bar{\nu}_i(q_1)\gamma^\mu(1-\gamma_5)\nu_i(q_2)], \quad (2)$$

where $q^2 = (k-p)^2$, and $f_\pm(q^2)$ are form factors measured in K_{e3} and $K_{\mu 3}$ decays. $\tilde{D}_i$ is defined in Ref. 3, and may include QCD corrections as prescribed in Ref. 4. For $m_{l_i} \ll M_w$ as is assumed here, where l_i is the neutrino's charged weak partner, $\tilde{D}_i$ is independent of the generation label i, and will be denoted hereafter by $\tilde{D}$. Therefore the differential width, where E_π is the pion energy in the rest frame of the decaying kaon, becomes

$$\frac{d\Gamma}{dE_\pi} = \frac{G_F^2 \alpha^2 \tilde{D}^2 \lambda}{(2\pi)^5 M_K^2 \sin^4\theta_w} \sum_i \left[1 - \frac{4m_{\nu_i}^2}{q^2}\right]^{1/2} \Big\{ f_-^2 m_{\nu_i}^2 q^2 + 2 f_+ f_- m_{\nu_i}^2 (m_K^2 - m_\pi^2) + f_+^2 \left[2m_{\nu_i}^2(m_K^2+m_\pi^2) - q^2(m_{\nu_i}^2 + 2m_K^2) + (m_K^2 - m_\pi^2 - q^2)^2\right] - \frac{2}{q^2}\left[\frac{1}{3q^2} w_i^2 \lambda^2 + m_{\nu_i}^2 \lambda^2 + m_K^2 w_i^2 + 4 q^2 m_{\nu_i}^2 m_K^2\right] \Big\} \quad (3)$$

2289



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

Rapid Communications

Majorana neutrinos and photinos from kaon decay

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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

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

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

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

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

Leptonic part:

$$\overline{\nu_l}(q_1)\gamma^\mu(1-\gamma_5)\nu_l(q_2)$$

$$\frac{d\Gamma_{SM}}{dE_\pi}(K^+ \to \pi^+\bar{\nu}\nu) = \frac{1}{(2\pi)^5}\left(\frac{G_F\alpha}{sin^2\Theta_W}\right)^2 \frac{8}{3}$$
$$\left[(D_1X^e_{NL} + D_2)^2 + (D_1X^\mu_{NL} + D_2)^2 + (D_1X^\tau_{NL} + D_2)^2\right]$$
$$|\vec{P}|^3\, {f_+^{K^+}}^2 m_K,$$

with

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

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

where t=momentum transfer to the pion. and

$$f_0^{K^+} = f_+^{K^+} + \frac{f_-^{K^+}t}{(m^2_{K^+} - m^2_{\pi^0})}.$$

Decay Rate in presence of a singlet heavier Neutrino

$$\nu_\ell = \sum_{j=1}^{3} U_{\ell j}\nu_j + V_{\ell N} N$$

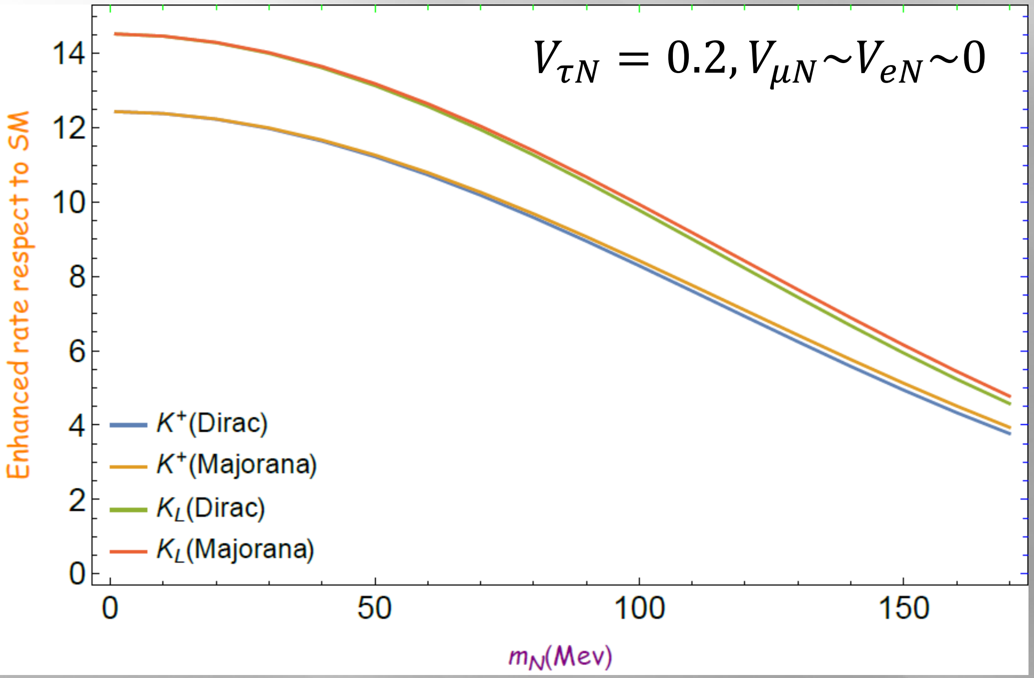
$$U^\dagger U + V^\dagger V = 1$$

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

In the literature, approximation made:

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

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:

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

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

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

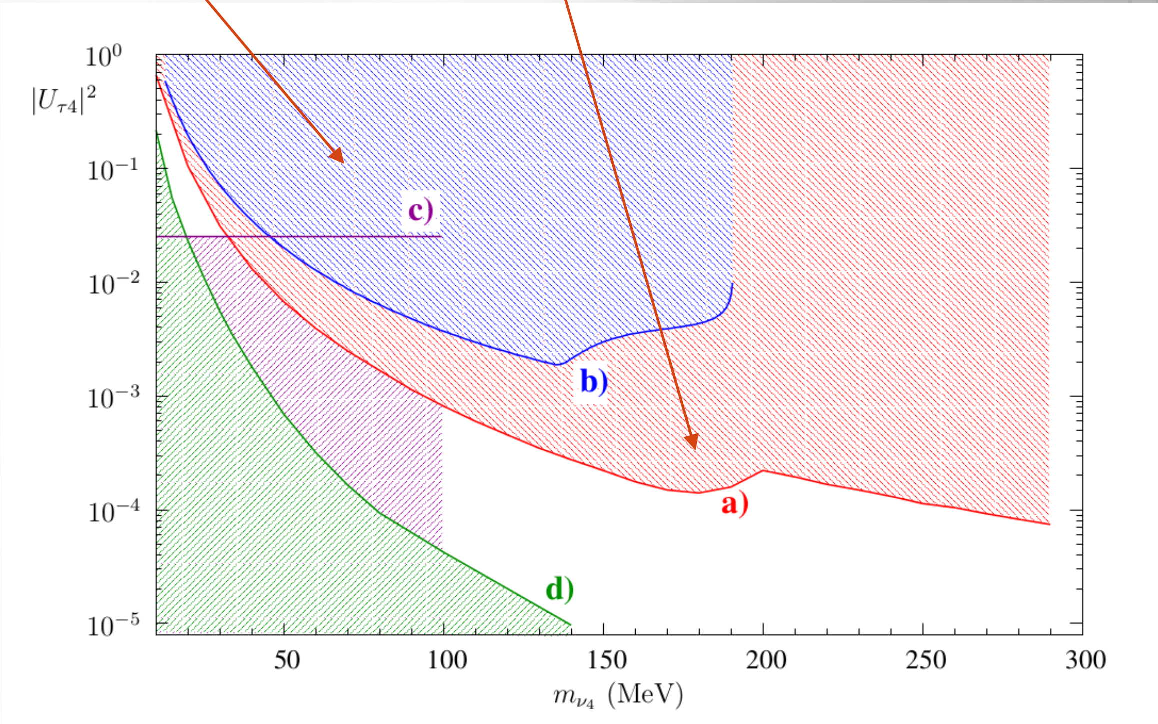
$$\frac{d\Gamma}{dE_\pi}(K^+ \to \pi^+ \bar{N} N) = \frac{1}{n!} \frac{1}{(2\pi)^5 m_K} \left(\frac{G_F \alpha}{sin^2 \Theta_W} \right)^2$$
$$(D_1 X^e_{NL} + D_2)^2 \left(| V_{eN} |^2 + | V_{\mu N} |^2 + | V_{\tau N} |^2 \right)^2$$
$$| \vec{P} | \sqrt{\left(1 - \frac{4m_N^2}{q^2}\right)} \left(f_-^{K^+ 2} F'_- + 2 f_+^{K^+} f_-^{K^+} F'_{+-} + f_+^{K^+ 2} F'_+ \right),$$

Will Distinguish Dirac and Majorana

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

Existing Bounds

NOMAD CHARM



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

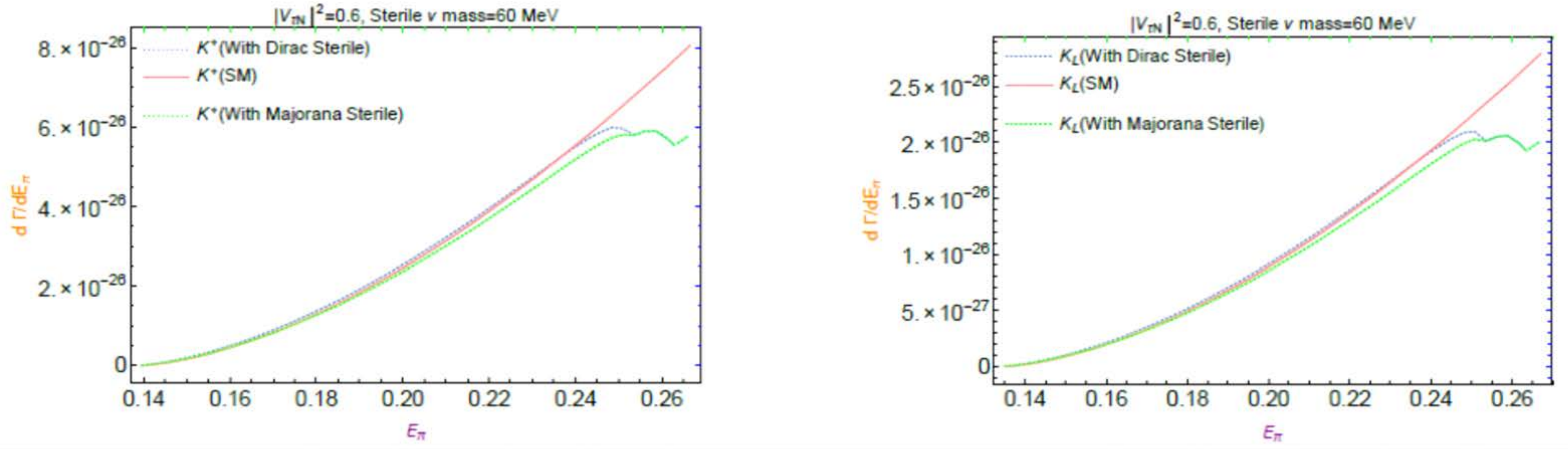
Neutrinoless double beta decay, peak searches in Kaon, Pion leptonic decays.

Pion Energy Spectrum

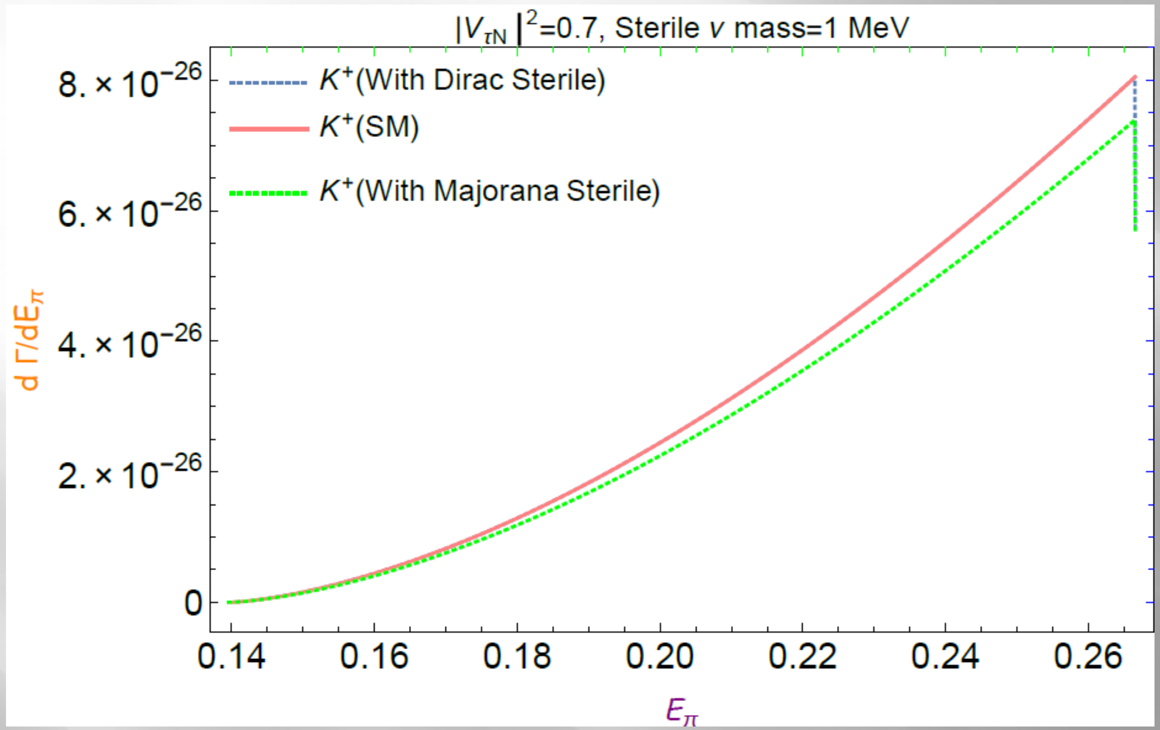
$$\frac{d\Gamma}{dE_\pi} = \frac{d\Gamma}{dE_\pi}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) + \frac{d\Gamma}{dE_\pi}\left(K^+ \to \pi^+ \nu\bar{N}\right) + \frac{d\Gamma}{dE_\pi}\left(K^+ \to \pi^+ \bar{\nu}N\right) + \frac{d\Gamma}{dE_\pi}\left(K^+ \to \pi^+ N\bar{N}\right).$$

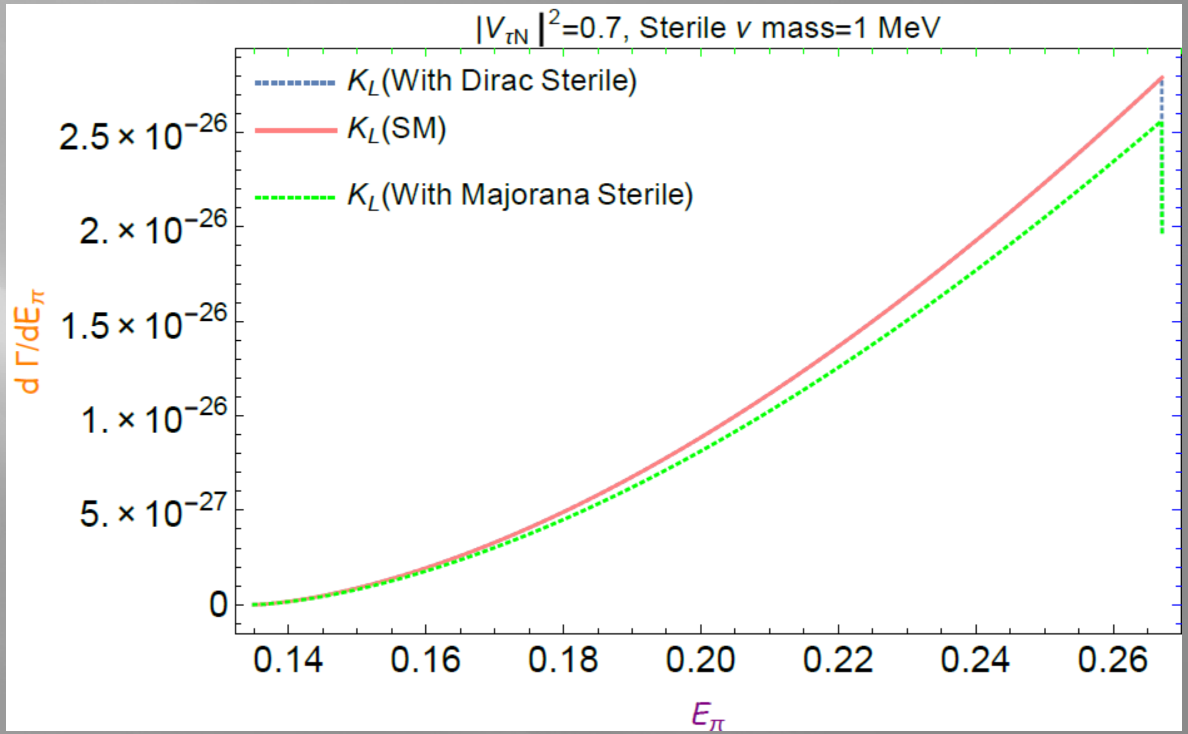
Large Mass
and
Large Mixing
(Unrealistic!)

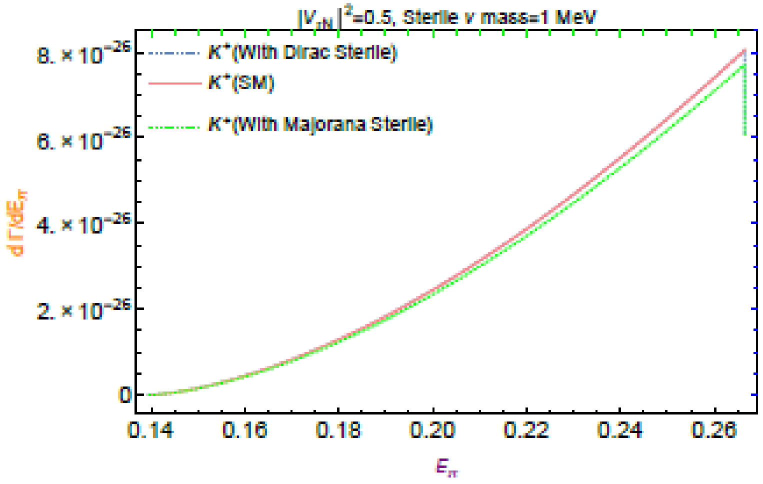
The two Kinks



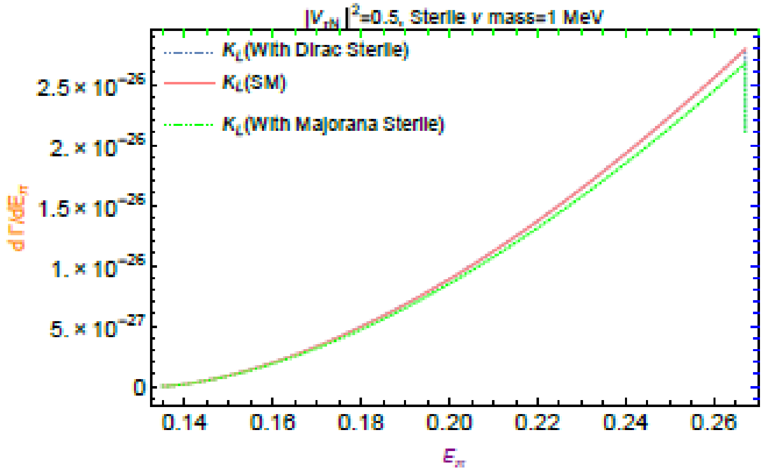
More Realistic Case



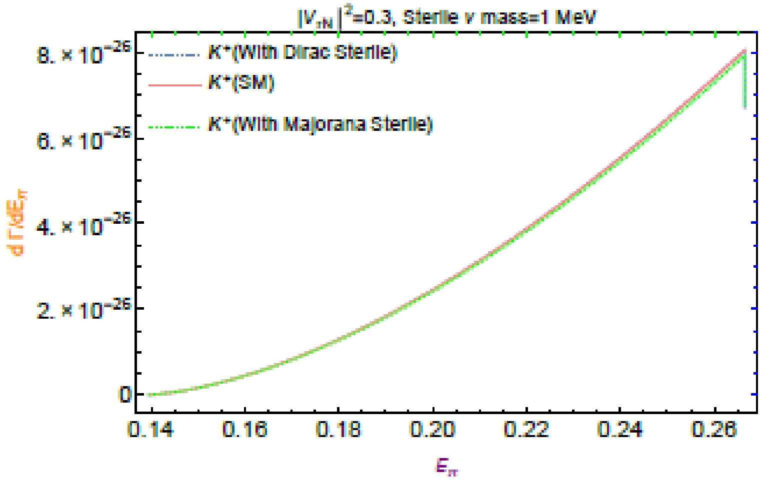



$|V_{\tau N}|^2$=0.5, Sterile ν mass=1 MeV
K^+(With Dirac Sterile)
K^+(SM)
K^+(With Majorana Sterile)
dΓ/dE$_\pi$
E_π

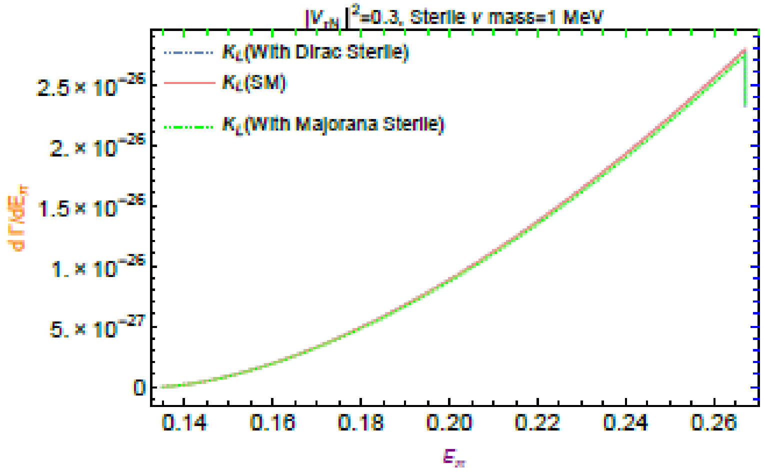
(c)


$|V_{\tau N}|^2$=0.5, Sterile ν mass=1 MeV
K_L(With Dirac Sterile)
K_L(SM)
K_L(With Majorana Sterile)
dΓ/dE$_\pi$
E_π

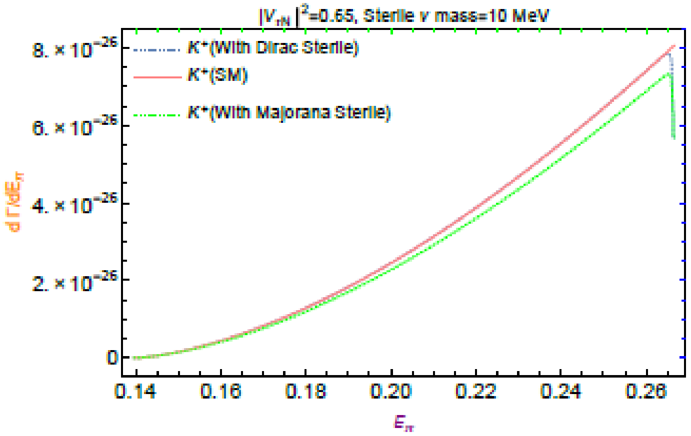
(d)


$|V_{\tau N}|^2$=0.3, Sterile ν mass=1 MeV
K^+(With Dirac Sterile)
K^+(SM)
K^+(With Majorana Sterile)
dΓ/dE$_\pi$
E_π

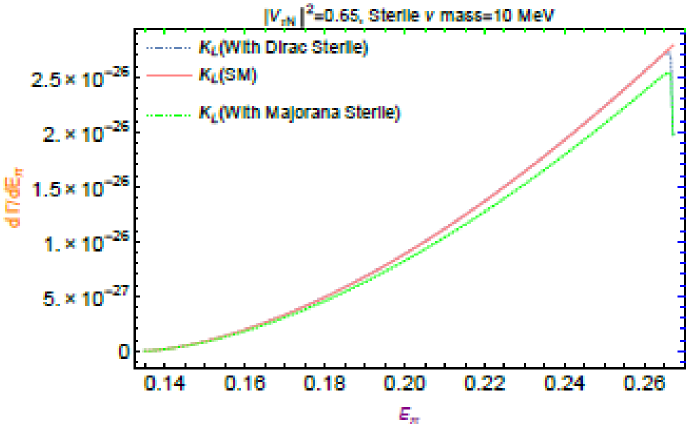
(e)


$|V_{\tau N}|^2$=0.3, Sterile ν mass=1 MeV
K_L(With Dirac Sterile)
K_L(SM)
K_L(With Majorana Sterile)
dΓ/dE$_\pi$
E_π

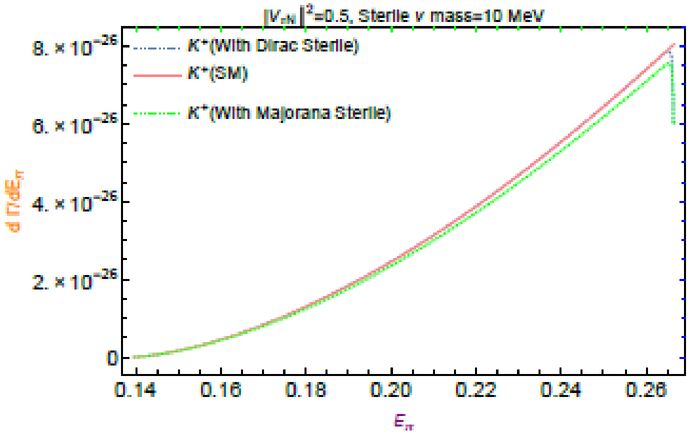
(f)



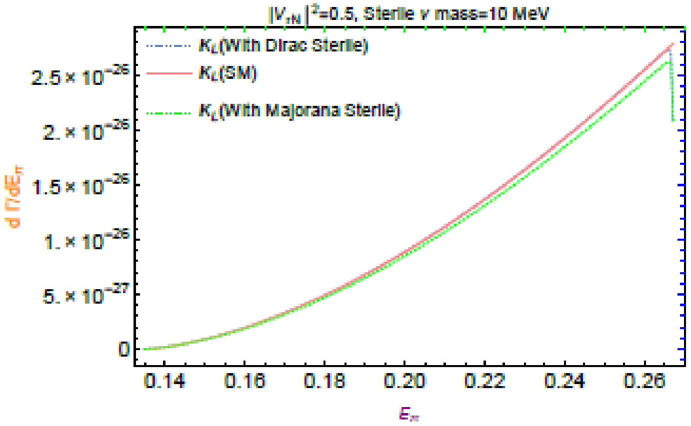
(g)



(h)



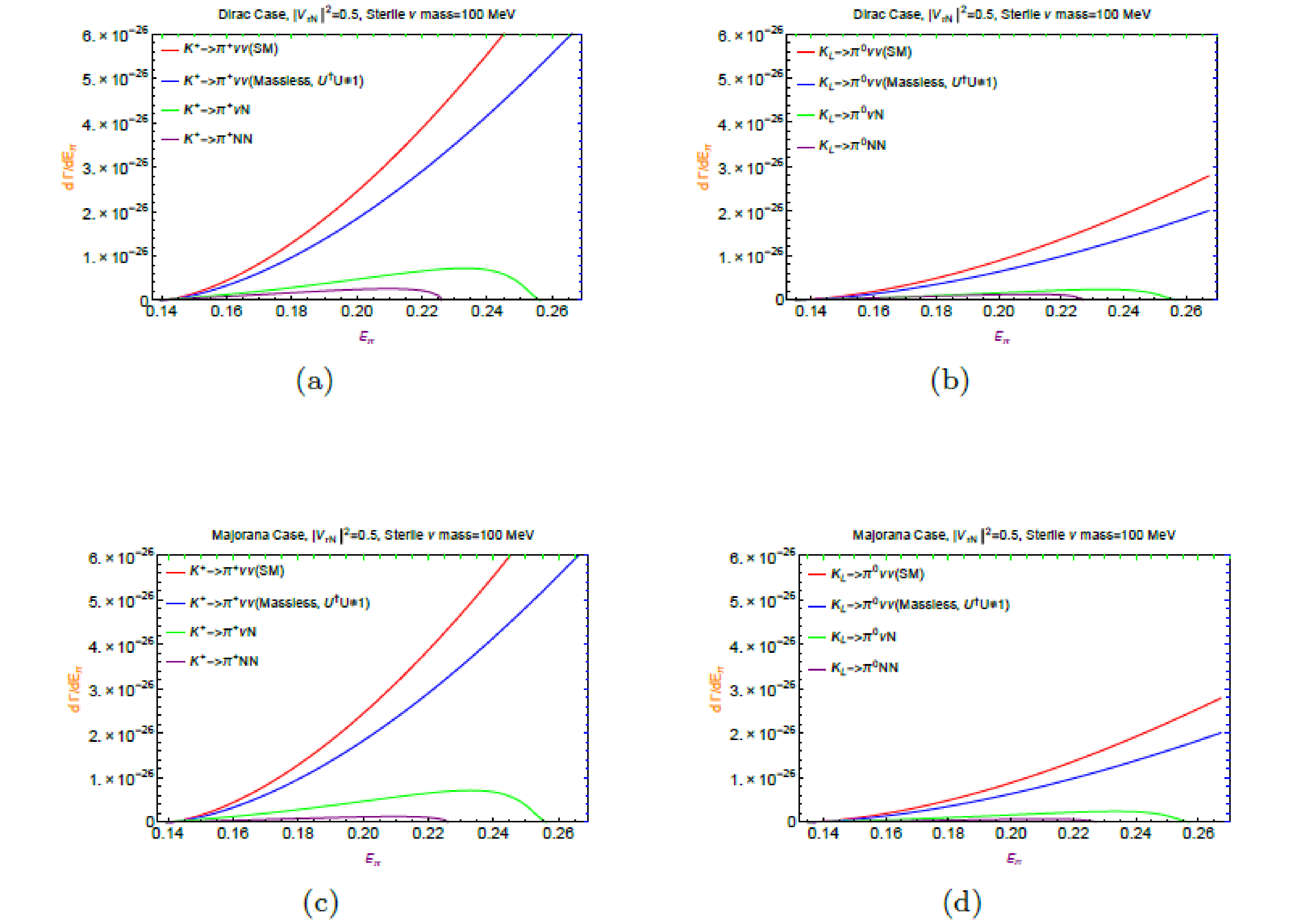
(i)



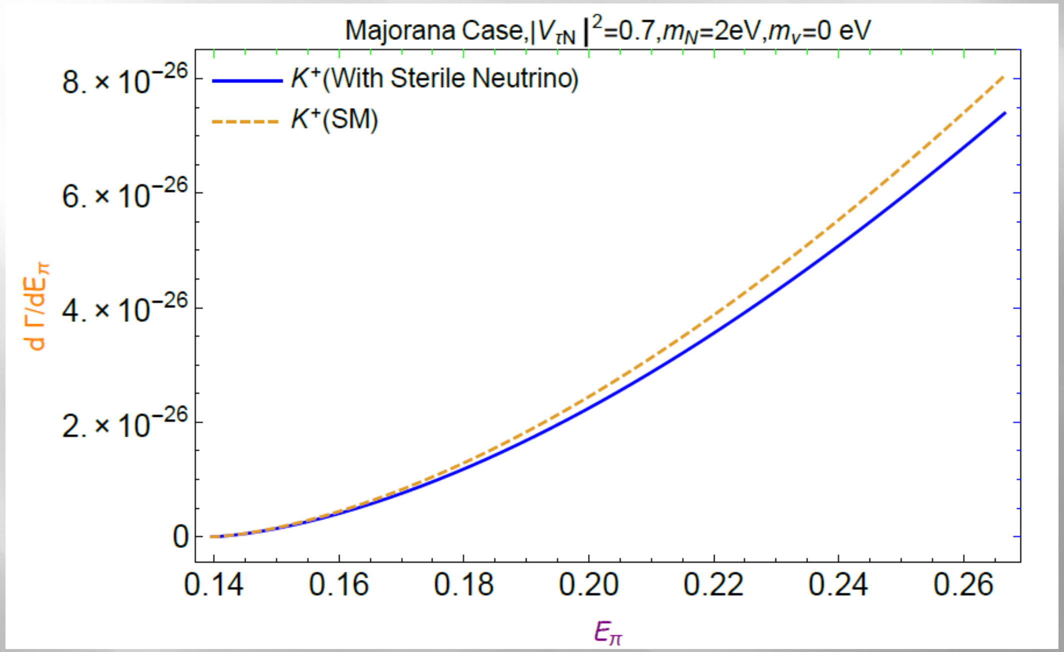
(j)

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

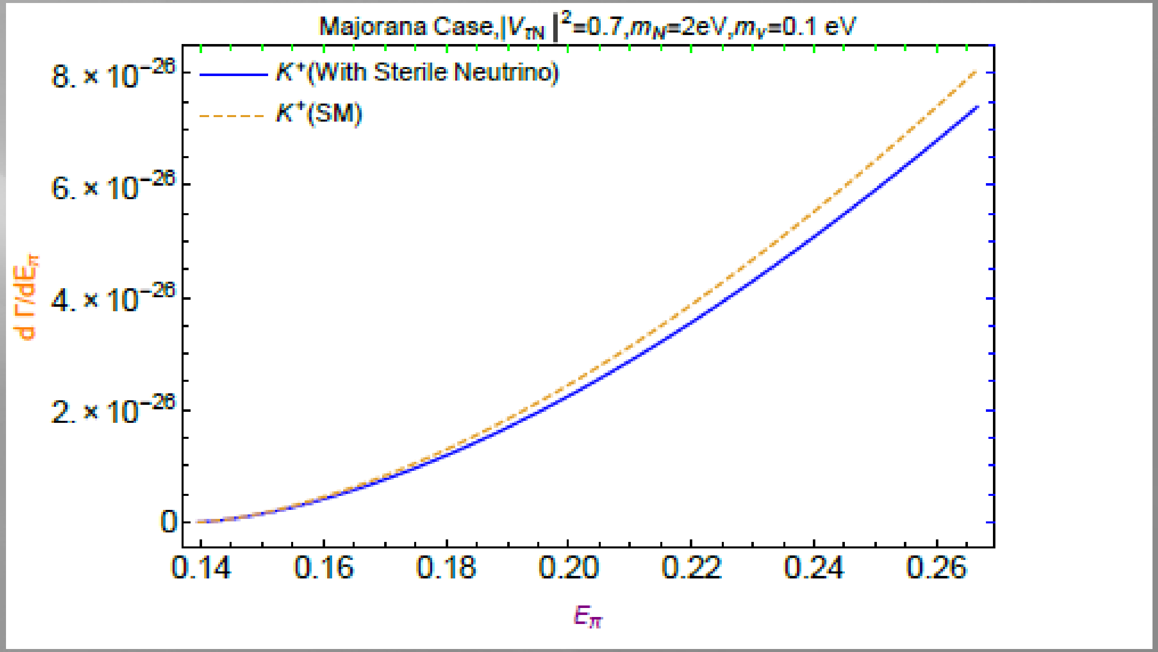
Individual Differential Decay Rate Contributions



$m_N = 2eV$



Majorana Case,$|V_{\tau N}|^2$=0.7,m_N=2eV,m_ν=0 eV
K^+(With Sterile Neutrino)
K^+(SM)
$8. \times 10^{-26}$
$6. \times 10^{-26}$
$4. \times 10^{-26}$
$2. \times 10^{-26}$
0
$d\Gamma/dE_\pi$
0.14
0.16
0.18
0.20
0.22
0.24
0.26
E_π



Majorana Case,$|V_{\tau N}|^2$=0.7,m_N=2eV,m_ν=0.1 eV
K^+(With Sterile Neutrino)
K^+(SM)
$8. \times 10^{-26}$
$6. \times 10^{-26}$
$4. \times 10^{-26}$
$2. \times 10^{-26}$
0
$d\Gamma/dE_\pi$
0.14
0.16
0.18
0.20
0.22
0.24
0.26
E_π

CONCLUSIONS

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