Limits on effective Majorana neutrino mass from rare Kaon decays

Xiang Liu

1. Neutrino mixing
2. Neutrinoless double-beta decay ($0\nu2\beta$) & Effective Majorana neutrino mass
3. Rare Kaon decays & limits on effective mass
4. Limits from other processes
5. Conclusion

GERDA-CRESST seminar 03/03/06

Neutrino mixing (I)

mass states : ν_i $i =$ 1, 2, 3 flavor states : ν_α $\alpha = e, \mu, \tau$

For 3 Neutrino Mixing

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix} \begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ 0 & 1 & 0 \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix} \begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\left(\frac{1}{2}\phi_2\right)} & 0 \\ 0 & 0 & e^{i\left(\frac{1}{2}\phi_3+\delta\right)} \end{bmatrix}$$

Atmospheric(23) Unknown(13) Solar(12) Majorana phases (only if ν's are majorana)

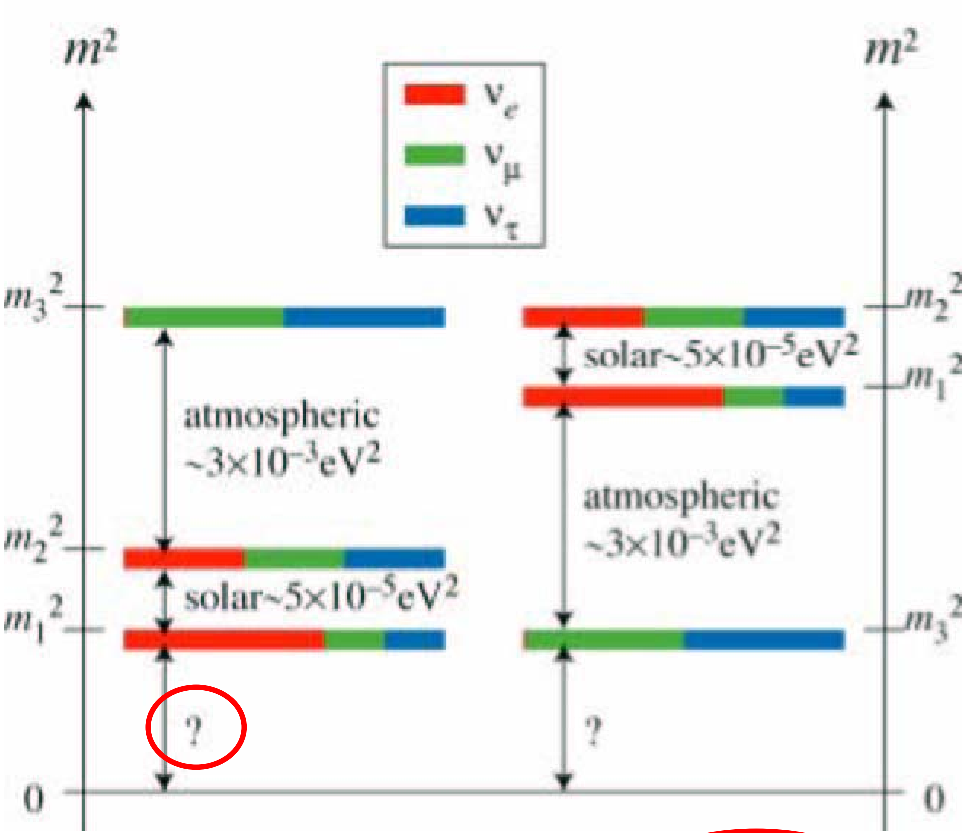
$c \equiv \cos\theta \quad s \equiv \sin\theta$

δ, ϕ: CP phase ϕ: Majorana phase

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

Oscillation probabilities do not depend on ϕ_2 , ϕ_3

Neutrino mixing (II)



normal hierarchy or inversed?

2-3 mixing:
$\delta m_a^2 \sim 2.5\times10^{-3}\,\mathrm{eV}^2$ $\theta a \sim 45°$

1-2 mixing:
$\delta m_s^2 \sim 6\times10^{-5}\,\mathrm{eV}^2$ $\theta s \sim 33°$

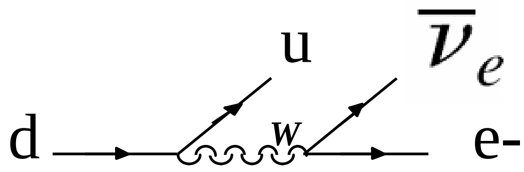
1-3 mixing:
θ_{13} very small

Absolute mass?
Mass hierarchy?
Majorana or Dirac?

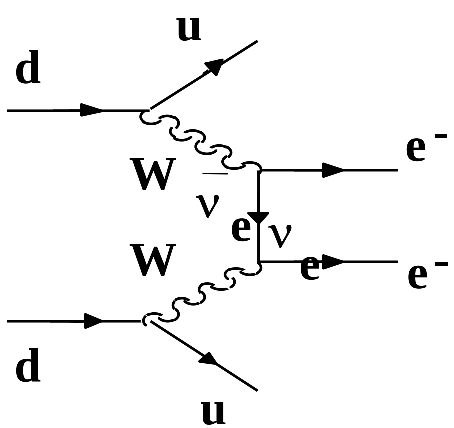
Sterile ? θ_{13} ? δ ?….

Neutrinoless double-beta decay ($0\nu 2\beta$)

β decay: (A,Z) => (A,Z+1) + e- + $\overline{\nu}_e$



If Majorana ν, (ν= anti ν)



0ν - $\beta\beta$ decay

(A,Z) => (A,Z+2) + 2 e$^-$ ($\Delta L=2$)

$$(T^{0\nu}_{1/2})^{-1} \sim G*M* \langle m_{ee}\rangle^2$$

G: phase-space integral
M: nuclear matrix elements
$\langle m_{ee}\rangle$: effective Majorana ν_e mass

$$\langle m_{ee}\rangle = \left| \Sigma V_{ei}^2 \, m_i \right|$$

$\langle m_{ee}\rangle \rightarrow$ absolute ν mass
$\rightarrow$ hierarchy

Effective Majorana ν mass

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

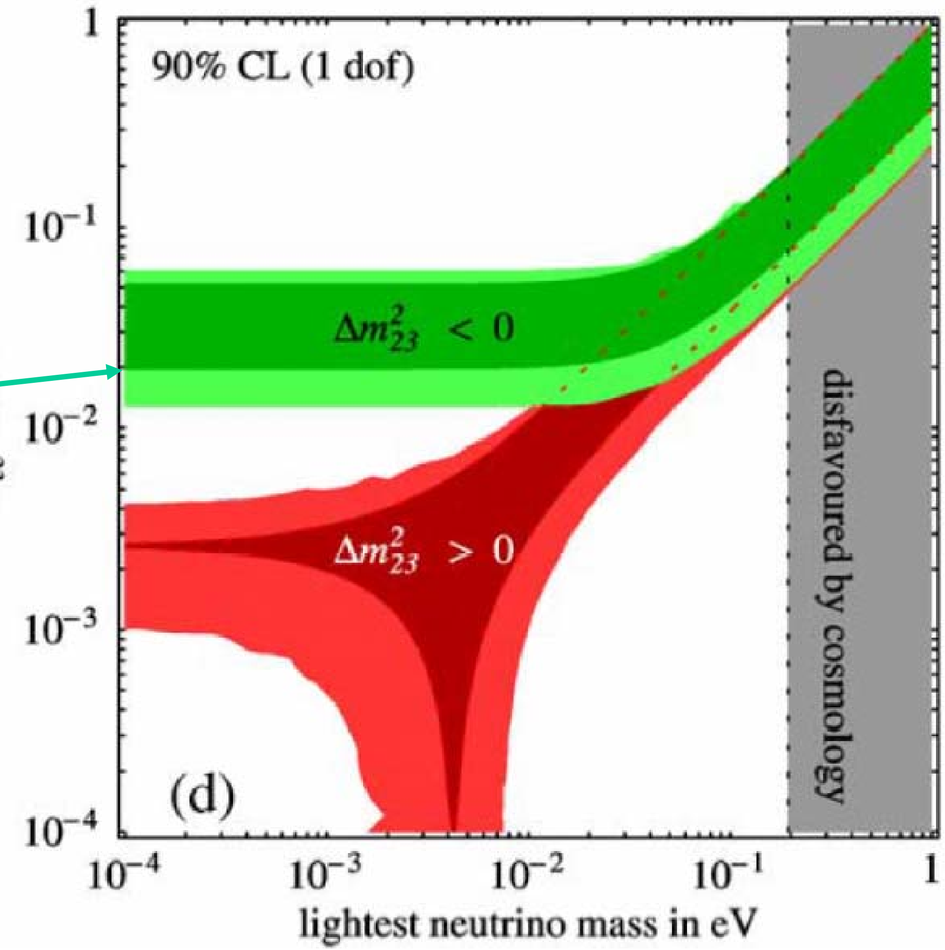
Assume $m_1 \cong m_2 = m_0 >> m_3$, $\theta_{13}=0$

$$|<m_{\beta\beta}>| \simeq m_0 \sqrt{1 - \sin^2 2\theta_\odot \sin^2\left(\frac{\Delta\alpha}{2}\right)}$$

$\Delta\alpha = \phi 2 - \phi 3$

$$|<m_{\beta\beta}>| \geq m_0 \cos 2\theta_\odot$$

(~20meV)

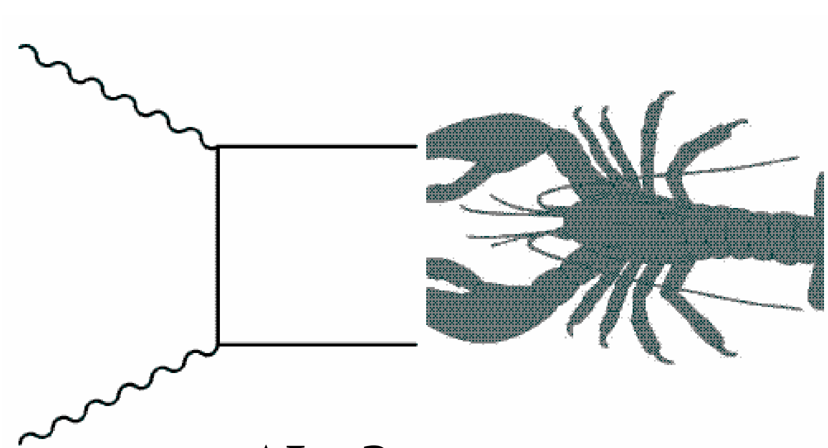


There also exists Meμ, Mμμ, Mlτ…

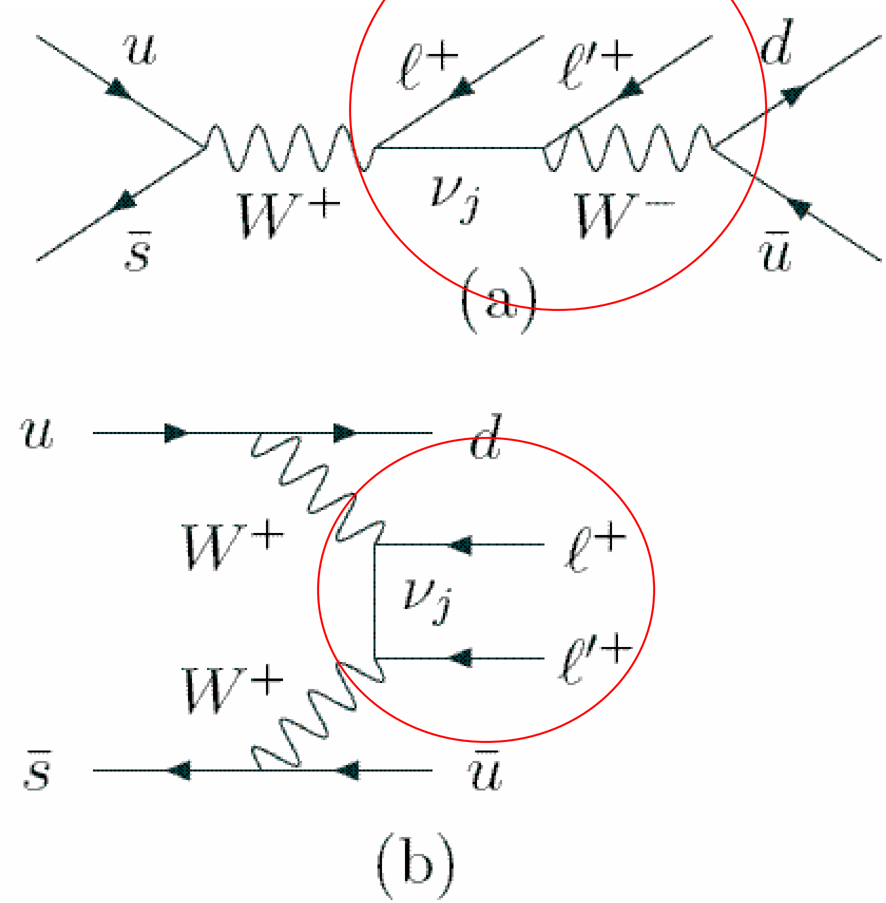
$<m_{e\mu}> = |\Sigma V_{ei} V_{\mu i} m_i|$

Effective Majorana ν mass is a matrix

Rare Kaon decay



$\Delta L=2$



$K^+ \rightarrow \pi^- \mu^+ \mu^+$ $\rightarrow \pi^- e^+ e^+$ $\rightarrow \pi^- \mu^+ e^+$

$$BR(K^+ \to \pi^- \mu^+ \mu^+) \sim 10^{-(13\pm 2)} r_{\mu\mu} \left| \sum_j U^2_{\mu j} f(m_{\nu_j}/(100\ \mathrm{MeV}) \right|^2$$

$r_{ee}=1$, $r_{\mu\mu}=0.2$, $f(x)=x$ if $(x<<1)$

Experiments

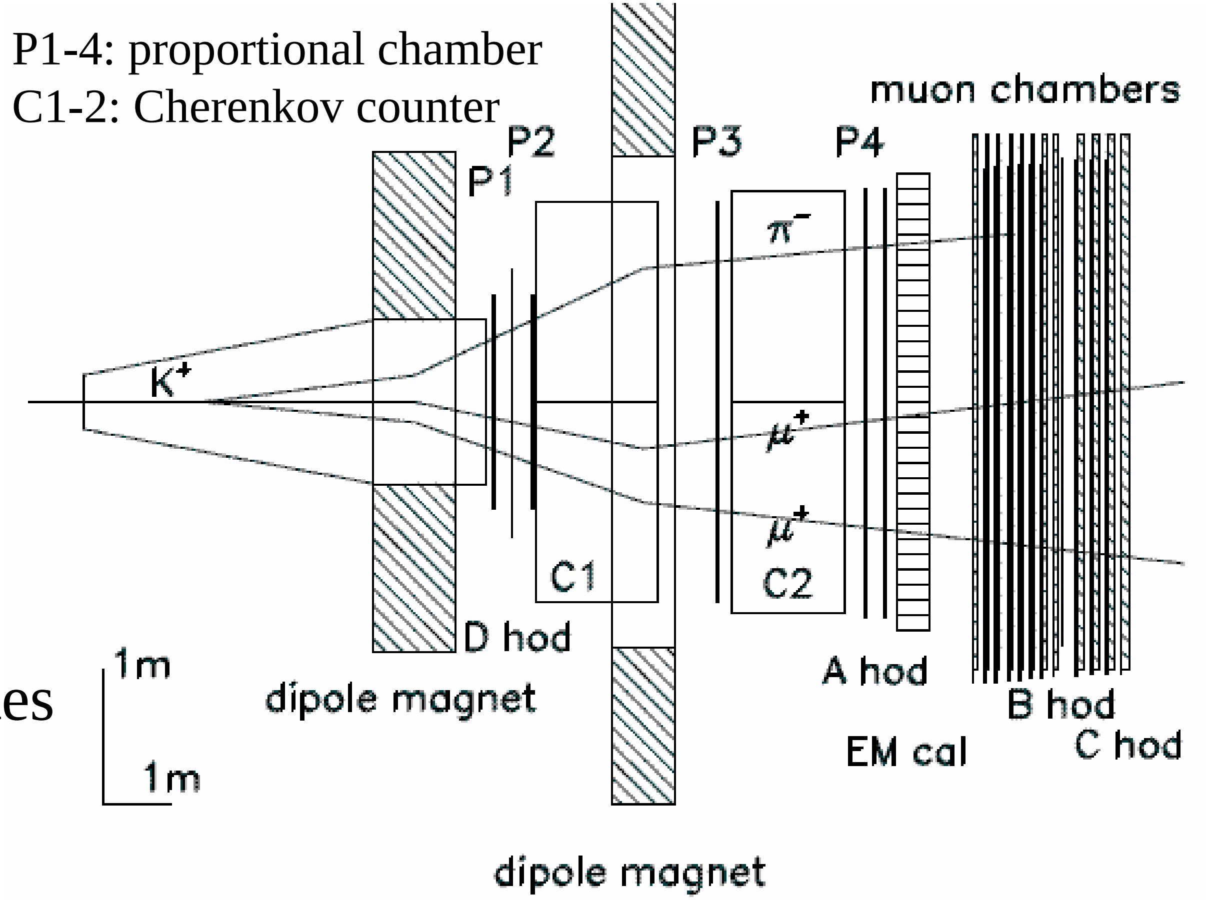
E865 at BNL

hep-ex/0006003

Designed to search
K+ → π+ μ+ e-

Data collected 1997.
~ 400 π- μ+ μ+ candidates

P1-4: proportional chamber
C1-2: Cherenkov counter



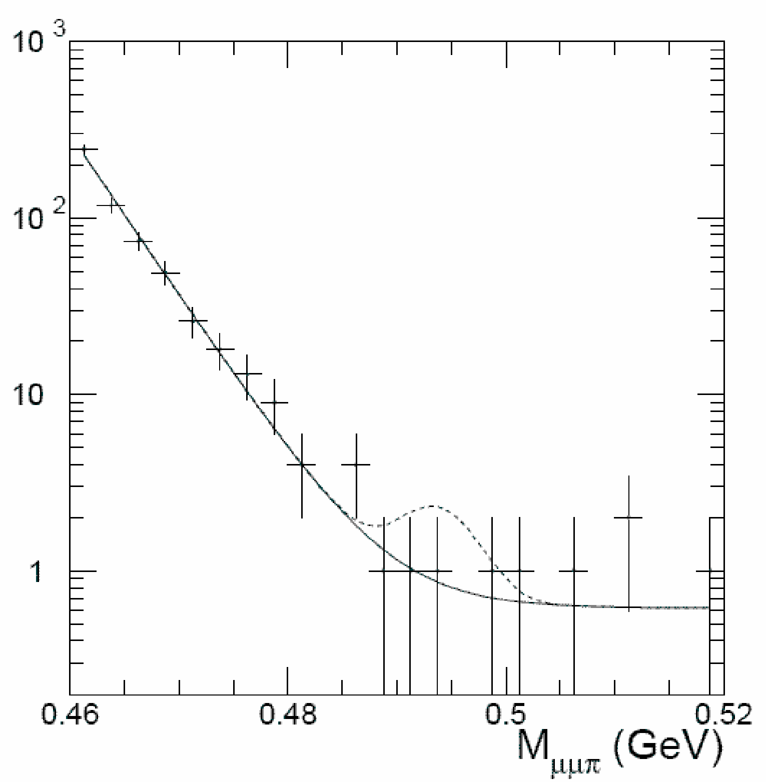
Experiments & results

hep-ex/0006003

$$Br(K^+ \to \mu^+\mu^+\pi^-) < 3.0 \times 10^{-9} (90\% \mathrm{C.L.})$$

K+ → π- μ+ μ+

→Mμμ<500GeV



$$Br(K^+ \to e^+e^+\pi^-) < 6.4 \times 10^{-10}$$

$$\cancel{Br(K^+ \to \pi^+e^+\mu^-) < 5.2 \times 10^{-10}}$$

$$Br(K^+ \to \mu^+e^+\pi^-) < 5.0 \times 10^{-10}$$

→Mee<~1GeV

Observe 5, expected background 5.3

Limits from other $\Delta L=2$ processes

Rare D&B decays: $D^+ \rightarrow \pi^- \mu^+ \mu^+$,

$B^+ \rightarrow K^- \mu^+\mu^+$, etc.

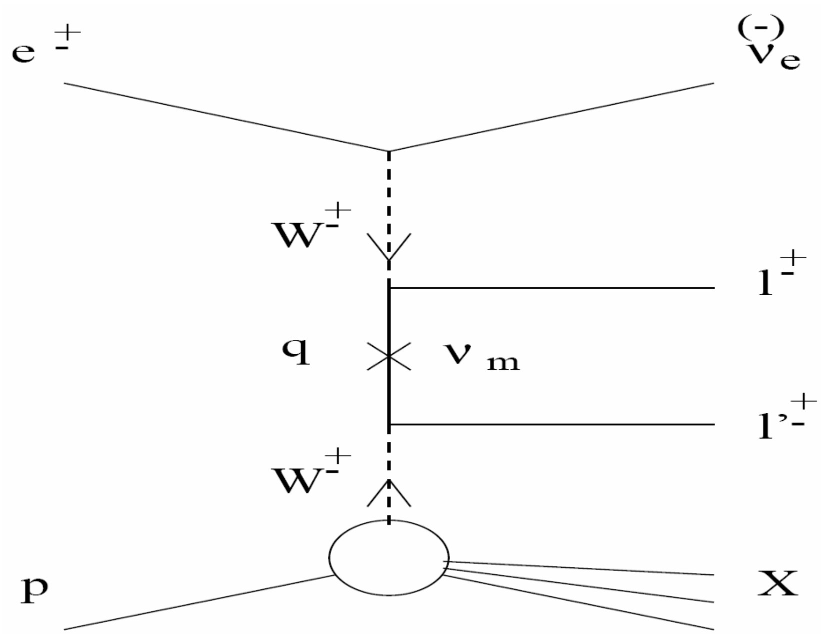
Muon capture: $\mu^- (A,Z) \rightarrow (A,Z-2)\, \mu^+$

Muon positron conversion: $\mu^- (A,Z) \rightarrow (A,Z-2)\, e^+$

(hep-ph/0005285)

Tri-muon production: $\nu_\mu N \rightarrow \mu^-\mu^+\mu^+ X$

Di-lepton at HERA: $ep \rightarrow \nu_e\, l\, l\, X$ ($ll= \mu\mu, \tau\tau, e\mu, e\tau$)



Results

$$\langle m_{\alpha\beta} \rangle = \begin{pmatrix} \langle m_{ee} \rangle & \langle m_{e\mu} \rangle & \langle m_{e\tau} \rangle \\ & \langle m_{\mu\mu} \rangle & \langle m_{\mu\tau} \rangle \\ & & \langle m_{\tau\tau} \rangle \end{pmatrix} \lesssim \begin{pmatrix} 2 \cdot 10^{-10} & 1.7(8.2) \cdot 10^{-2} & 4.2 \cdot 10^{3} \\ & 500 & 4.4 \cdot 10^{3} \\ & & 2.0 \cdot 10^{4} \end{pmatrix} \mathrm{GeV}.$$

Mee : $0\nu 2\beta$

Meμ: Muon positron conversion: μ^- (A,Z) $\rightarrow$ (A,Z-2) e^+

M$\mu\mu$: Rare Kaon deay, tri-muon production (<10E4GeV)

Mlτ: HERA dilepton production

Conclusion

Neutrino oscillation experiments →neutrinos have mass.

Searching for effective Majorana neutrino mass

→ Majorana or Dirac neutrino

→ absolute neutrino mass

→ hierarchy

$0\nu 2\beta$ is not the only way to measure effective mass (though it gives the most stringent limit).

Limits on rare Kaon decay ($K^+ \rightarrow \pi^- \mu^+ \mu^+$) → $M_{\mu\mu} < 500$GeV

Many processes with “Lobster diagram” ($\Delta L=2$) can be used to measure (set limit) on effective mass.

List of reading materials

Phenomenology:

hep-ph/0008080 Effective Majorana neutrino masses
(Zuber)

hep-ph/0003160 New limits on effective Majorana neutrino masses from rare kaon decays
(Zuber)

hep-ph/9911298 Bounds on effective Majorana neutrino masses at HERA
(Zuber)

hep-ph/0005285 Implications of improved upper bounds on $\Delta L=2$ Processes
(Littenberg, Shrock)

Phys. Rev. Lett. 68, 443-446 (1992) Upper bounds on lepton-number violating meson decays
(Littenberg, Shrock)

Experiments:

hep-ex/0512044 Rare Kaon Decays (Littenberg)

hep-ex/0006003 Search for Lepton Flavor Violations in K+ decays (E865)