A New Strategy for Direct Measurement of Majorana Effective Neutrino Masses

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- References:

  - D. Delepine, V. G. Macias, S. Khalil and G. L. Castro, ``A new strategy for probing the Majorana neutrino CP violating phases and masses," arXiv:0908.2158 [hep-ph].

  - D.Delepine, V.G. Macias, S. Khalil and G. Lopez Castro, ``QFT results for neutrino oscillations and New Physics," Phys.Rev. D 79, 093003 (2009) [arXiv:0901.1460 [hep-ph]].

Outlines:

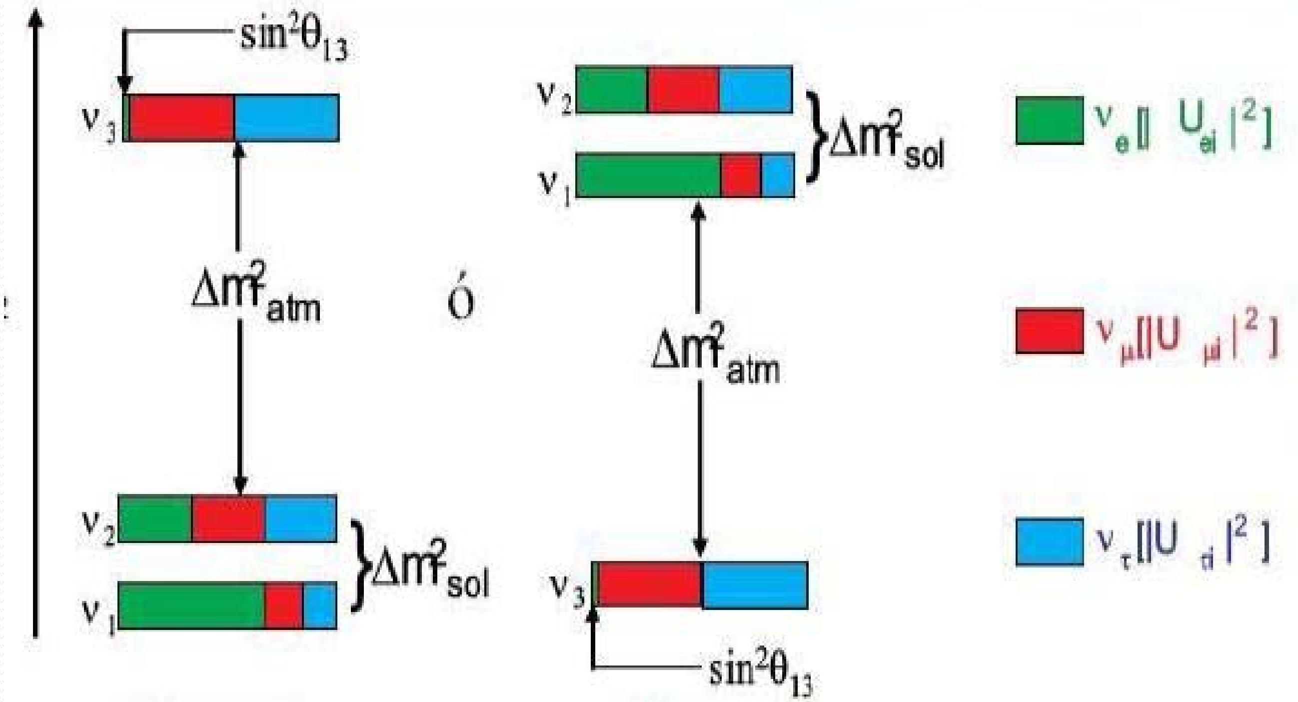
- Introduction: Neutrino masses and mixing status
- New Physics and Neutrino Oscillations: Usual Approach.
- Beyond Factorization:
  A. Neutrino-Neutrino oscillations.
  B. Neutrino-Antineutrino oscillations.
  C. Application to MINOS results.
- Conclusions

Neutrino masses and mixing status (I)

parameter	Ref. [1] best fit$\pm 1\sigma$	Ref. [1] 3σ interval	Ref. [2] (MINOS updated) best fit$\pm 1\sigma$	Ref. [2] (MINOS updated) 3σ interval
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.05–8.34	$7.67^{+0.22}_{-0.21}$	7.07–8.34
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$\pm 2.40^{+0.12}_{-0.11}$	$\pm(2.07–2.75)$	-2.39 ± 0.12 $+2.49 \pm 0.12$	$-(2.02–2.79)$ $+(2.13–2.88)$
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.25–0.37	$0.321^{+0.023}_{-0.022}$	0.26–0.40
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.36–0.67	$0.47^{+0.07}_{-0.06}$	0.33–0.64
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.056	0.003 ± 0.015	≤ 0.049

Ref[1]:T. Schwetz, M. Tortola and J.W. F. Valle, New J. Phys. 10 (2008) 113011 [arXiv:0808.2016].
Ref[2]: M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rept. 460 (2008) 1 [arXiv:0704.1800].

Neutrino masses and mixing status (II)



$$s_{13} << s_{23} << s_{12} << 1 \qquad\qquad s_{13} << s_{12} < s_{23} \sim 1$$

$$|U_{CKM}| \approx \begin{pmatrix} 1 & 0{,}2 & 0 \\ 0{,}2 & 1 & 0{,}04 \\ 0{,}01 & 0{,}04 & 1 \end{pmatrix} \qquad |U_{MNS}| \approx \begin{pmatrix} 0{,}8 & 0{,}55 & 0 \\ 0{,}4 & 0{,}8 & 0{,}7 \\ 0{,}4 & 0{,}8 & 0{,}7 \end{pmatrix}$$

New Physics in Neutrino oscillations:

- Usually the effect of New Physics (NP) are taken into account assuming factorization of the amplitudes:

$$A_{SO}(I \to F) = A_S(\pi^{\pm} \to \nu_{\mu}^{\mp} \mu^{\pm}) A_P(\nu_{\mu} \overrightarrow{osc}\, \nu_e) A_d(\nu_e^{\mp} + N \to N' + e^{\pm})$$

- Assuming NP given by: $L_{eff} = \lambda(V_{ud})(\bar{\nu}_e \gamma^{\alpha} P_L \mu)(\bar{d}\gamma_{\alpha} P_L u) + h.c.$

$$A_{NP}(I \to F) = A_S(\pi^{\pm} \to \mu^{\pm} \nu_e^{\mp}) A_p(\nu_e \overrightarrow{no\, osc}\, \nu_e) A_d(\nu_e^{\mp} + N \to N' + e^{\pm})$$

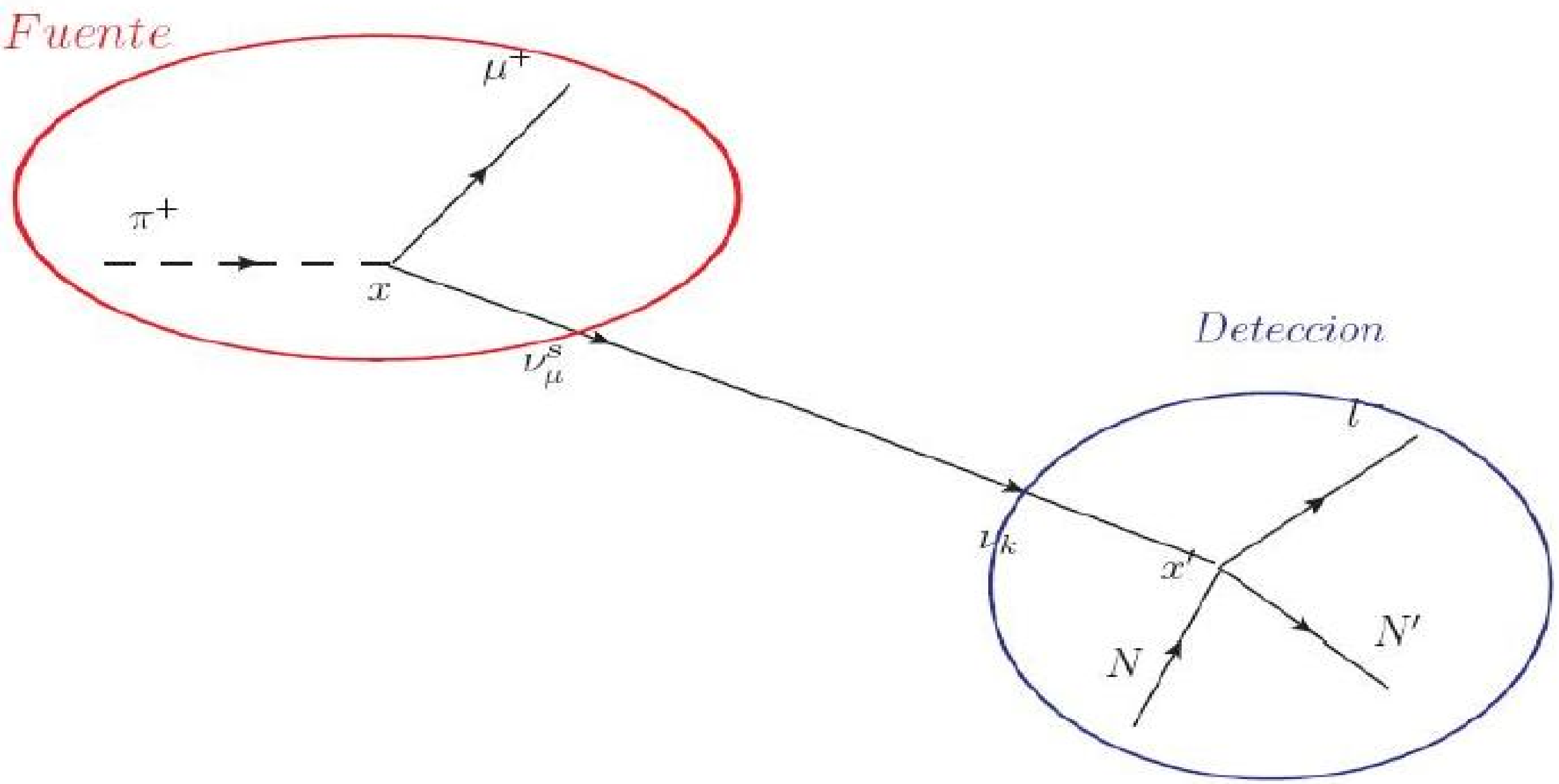
$$\Rightarrow \quad P(I \to F) = |A_{SO}|^2 + 2Re(A_{SO}^* A_{NP}) + |A_{NP}|^2$$

$$2Re(A_{SO}^* A_{NP}) = \Gamma \times 2\Re\left(\frac{\lambda}{2\sqrt{2}G_F} A_p^*(\nu_{\mu} \overrightarrow{osc}\, \nu_e) A_p(\nu_{\mu} \overrightarrow{no\, osc}\, \nu_{\mu})\right) \times \sigma$$

T. Ota, J. Sato. PhysRevD.71.096004; M. Glez.-García, Y. Grossman, A. Gusso, Y. Nir. PhysRevD.71.096004

Beyond Factorization using QFT (I)

$$\pi(p_1) \to \mu^+(p_2) \quad + \quad \nu_\mu^s(p)$$
$$\hookrightarrow \quad \nu_l^d(p) + N(p_N) \to N'(p_{N'}) + l(p_l)\ .$$



Beyond Factorization using QFT (II)

- Assuming Left-handed light neutrinos, the most general Hamiltonian responsable of New Physics is given by:

$$
\begin{aligned}
\mathscr{H} = 2\sqrt{2}G_F V_{ud}[& C_1^k(\bar{\mu}\gamma^\alpha P_L \nu_k)(\bar{u}\gamma_\alpha P_L d) \\
& + C_2^k(\bar{\mu}\gamma^\alpha P_L \nu_k)(\bar{u}\gamma_\alpha P_R d) \\
& + C_3^k(\bar{\mu} P_L \nu_k)(\bar{u} P_L d) \\
& + C_4^k(\bar{\mu} P_L \nu_k)(\bar{u} P_R d) \\
& + C_{5(R,L)}^k(\bar{\mu}\sigma^{\alpha\beta} P_L \nu_k)(\bar{u}\sigma_{\alpha\beta} P_{(R,L)} d)]
\end{aligned}
$$

$$
\begin{aligned}
T_{\nu_\mu - \nu_l} = \int d^4x\, d^4x' \sum_k e^{i(p_l + p_N + p_{N'})\cdot x'} \frac{G_F V_{ud}}{\sqrt{2}} (J_{NN'})_\mu \\
\times \bar{u}_l(p_l)\gamma^\mu(1-\gamma_5)\Delta_\nu^{lk}(x'-x) O^k v(p_2) e^{i(p_2 - p_1)\cdot x}
\end{aligned}
$$

Beyond Factorization using QFT (III)

- with

$$O^k \equiv \frac{G_F}{\sqrt{2}} V_{ud}(1+\gamma_5) f_\pi \left(\frac{-i m_\pi^2}{m_u + m_d} (C_3^k - C_4^k) - i (C_1^k - C_2^k) \not{p}_\pi \right)$$

- The neutrino propagator:

$$\triangle_\nu^{lk}(x' - x) = \sum_i U_{li} U_{ki}^* \int \frac{d^3 p}{(2\pi)^3} \left(\frac{e^{-iE(t'-t)} e^{i\vec{p}\cdot(\vec{x'}-\vec{x})} (\not{p} + m)}{2E_{\nu_i}} - \frac{e^{iE(t'-t)} e^{-i\vec{p}\cdot(\vec{x'}-\vec{x})} (\not{p} - m)}{2E_{\nu_i}} \right)$$

Beyond Factorization using QFT (IV)

- Let's assume to have neutrino quasi-elastic scattering on nucleons:

$$(J_{NN'})_\mu = \overline{u}_{N'}(p_{N'})\gamma_\mu(g_V + g_A\gamma_5)u_N(p_N)$$

$$g_V = g_V(q^2 = 0) = 1 \text{ y } g_A = g_A(q^2 = 0) \approx -1{,}27.$$

$$|T_{\nu_\mu^s - \nu_l}(t)|^2 \equiv \sum_{q,k,i,j} (B_q^* m_\mu - m_\pi A_q^*)(B_k m_\mu - m_\pi A_k) U_{li}^* U_{ki} U_{lj} U_{qj}^* \frac{e^{-i\tau(E_{\nu_i} - E_{\nu_j})}}{E_{\nu_i} E_{\nu_j}} F(P,M) \,,$$

$$B_k \equiv -i(C_1^{k*} - C_2^{*k}) \qquad A_k = \frac{-im_\pi^2}{m_u + m_d}(C_3^{k*} - C_4^{k*})$$

$$F(P,M) = (2\pi)^4 \delta^4(p_l + p_N + p_{N'} + p_2 - p_1)(G_F|V_{ud}|)^4 |f_\pi|^2 32(g_a^2 + 1) m_N^2 (m_\mu^2 - m_\pi^2) E_l(E_2 - E_p)$$

Beyond Factorization using QFT (V)

- CP asymmetry assuming that the only sources of CP violation comes from (S-P)x(S+P) terms:

$$N(\tau) \propto \Re\left(\sum_{i,j,k,q} A_k B_q^* U_{li}^* U_{ki} U_{lj} U_{qj}^* e^{-it\left(E_{\nu_i} - E_{\nu_j}\right)} \right) - \Re\left(\sum_{i,j,k,q} A_k^* B_q U_{li} U_{ki}^* U_{lj}^* U_{qj} e^{-it\left(E_{\nu_i} - E_{\nu_j}\right)} \right)$$

- In Standard Model: $B_q^{\ *} = i\delta_{\mu q}$

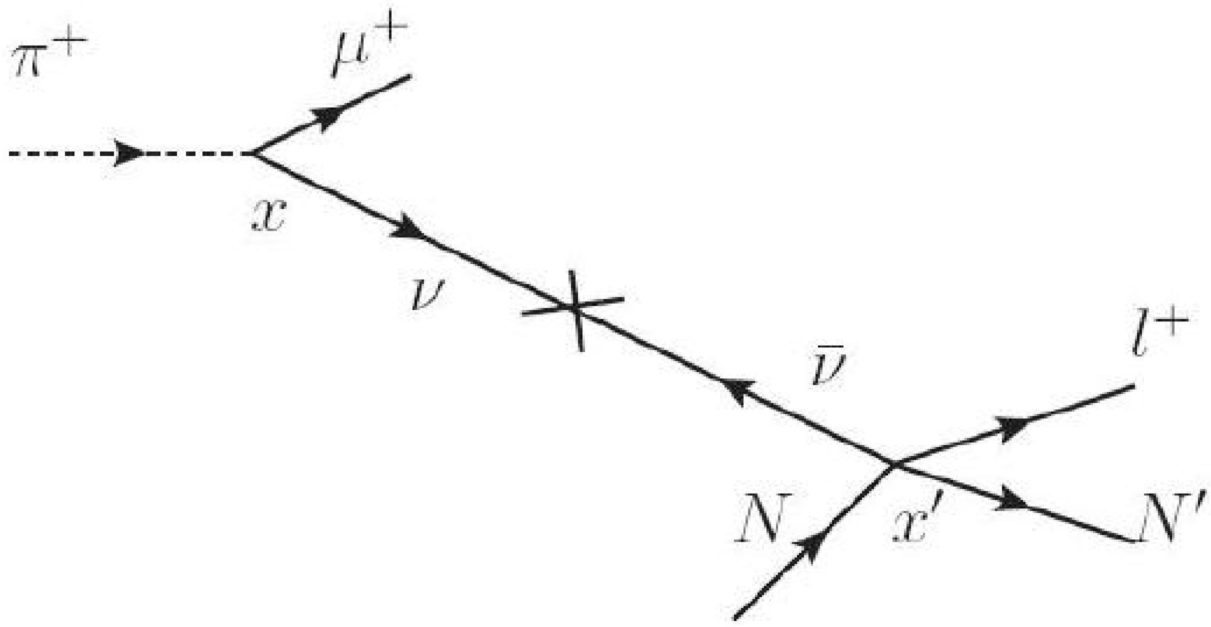
- It is interesting that in this case, one recovers factorization:

$$a_{CP} = \frac{\left|\left\langle \nu_l \,|\, \nu_\mu(t) \right\rangle\right|^2 - \left|\left\langle \overline{\nu}_l \,|\, \overline{\nu}_\mu(t) \right\rangle\right|^2}{\left|\left\langle \nu_l \,|\, \nu_\mu(t) \right\rangle\right|^2 + \left|\left\langle \overline{\nu}_l \,|\, \overline{\nu}_\mu(t) \right\rangle\right|^2}$$

$$\left|\nu_\mu(t)\right\rangle \equiv \sum_i \varepsilon_{k\mu} U_{ki} e^{iE_{\nu_i} t} \left|\nu_i\right\rangle \quad with \quad \varepsilon_{k\mu} = A_k$$

Neutrino-Antineutrino oscillations (I)

$$\begin{aligned}\pi(p_1 \to \mu^+(p_2) \quad &+ \quad \nu_\mu^s(p) \\ &\hookrightarrow \quad \bar{\nu}_l^d(p) + N(p_N) \to N(p_{N'}) + l^+(p_l)\end{aligned}$$



Neutrino-Antineutrino oscillations (II)

$$
\begin{aligned}
T_{\nu_k-\bar{\nu}_l}(t) \;=\; & (2\pi)^4\delta^4(p_l + p_N + p_{N'} + p_2 - p_1)(G_F V_{ud})^2 (J_{NN'})_\mu \\
& \times f_\pi \sum_i \bar{v}_l(p_l)\gamma^\mu(1+\gamma_5)\mathbf{p}_\pi v(p_2) \\
& \times \lambda_i U_{li} U_{\mu i}(m_{\nu_i}) \frac{e^{-it(E_{\nu_i}-E)}}{2E_{\nu_i}}
\end{aligned}
$$

Neutrino-Antineutrino oscillations (III)

$$|T_{\nu_\mu-\bar{\nu}_l}(t)|^2 = (2\pi)^4\delta^4(p_l+p_N+p_{N'}+p_2-p_1)(G_V)^2|f_\pi|^2$$
$$\times\sum_{i,j}\lambda_i\lambda_j^* U_{li}U_{lj}^* U_{\mu i}U_{\mu j}^* e^{-it\triangle E_{\nu_{ij}}}\frac{m_{\nu_i}m_{\nu_j}}{4E_{\nu_i}E_{\nu_j}}m_N 64(g_a-1)^2(m_\mu^2-m_\pi^2)$$
$$\times(E_2-E_p)\left(((1+\frac{m_N}{(E_2-E_p)}G(g_a))k_1\cdot p_2-2m_N F(g_a)E_2)\frac{m_\mu^2}{(m_\mu^2-m_\pi^2)}\right.$$
$$\left.-\frac{1}{2}m_\mu^2-2F(g_a)E_l m_N\frac{(m_\mu^2+m_\pi^2)}{(m_\mu^2-m_\pi^2)}\right)$$

$$F(g_a)=\frac{g_a^2+1}{(g_a-1)^2},\ G(g_a)=\frac{g_a+1}{g_a-1}$$

At this point, the term kl.p2 breaks the factorization assumption as it depends on the angle between the momentum of the muon and of the lepton going out at detection.

Neutrino-Antineutrino oscillations (IV)

- If the hypothesis that neutrino and antineutrino interactions with nucleons are identical, CP asymmetry is independent of the breaking of factorization :

$$a_{CP} \propto \frac{\sum_{i>j} \Im\left(\lambda_i \lambda_j^* U_{li} U_{\mu i} U_{lj}^* U_{\mu j}^*\right) m_i m_j \sin\left(\frac{\Delta m_{ij}^2}{2E}\right)}{\sum_{i>j} \Re\left(\lambda_i \lambda_j^* U_{li} U_{\mu i} U_{lj}^* U_{\mu j}^*\right) m_i m_j \sin^2\left(\frac{\Delta m_{ij}^2}{4E}\right)}$$

- Assuming 2 generations, one gets:

$$a_{\bar{\nu}_e \to \nu_\mu} = \frac{2 m_1 m_2 \sin\left(\frac{\Delta m^2 L}{2E}\right) \sin\xi}{m_1^2 + m_2^2 - 2 m_1 m_2 \cos\left(\frac{\Delta m^2 L}{2E}\right) \cos\xi}$$

Application to MINOS results:

MINOS observes **no appearance** of $\bar{\nu}_\mu$ in the NuMI beam

→

Result: limit fraction, α, of events transitioning from ν_μ to $\bar{\nu}_\mu$:

- α < 0.026 (90% C.L.)

See, http://theory.fnal.gov/jetp/talks/Hartnell.pdf

$$P(\nu_\mu - \bar{\nu}_\mu) < 0.026\ (90\%\ \text{c.l.}).$$

→

$$\left| \sum_i U_{\mu i}^2 \frac{m_{\nu_i}}{E_{\nu_i}} e^{itE_{\nu_i}} \right|^2 \lesssim 0.001$$

→

$$\begin{aligned} 0.001 \times E_\nu^2 &\gtrsim |\langle m_{\mu\mu} \rangle|^2 \\ &- 4\,\mathrm{Re}\left(U_{\mu 2}^2 U_{\mu 3}^{*2}\right) m_{\nu_2} m_{\nu_3} \sin^2 \frac{\gamma}{2} \\ &- 2\,\mathrm{Im}\left(U_{\mu 2}^2 U_{\mu 3}^{*2}\right) m_{\nu_2} m_{\nu_3} \sin\gamma\ . \end{aligned}$$

$$\gamma = \frac{\Delta m_{23}^2 L(km)}{2E_\nu (GeV)}$$

$$|\langle m_{\mu\mu} \rangle| \lesssim 109\ \text{MeV}$$

Conclusions:

- If Majorana neutrinos do exist, $\Delta L = 2$ *processes like* neutrino-antineutrino oscillations can occur. The production of leptons with same charges at the production and detection vertices of neutrinos will be a clear manifestation of these processes.
- The time evolution probability of the whole process is not factorizable into production, oscillation and detection probabilities, as is the case in neutrino oscillations.
- For very short times of propagation of neutrinos, the observation of *muon+ muon + events would lead to a direct bound* the effective mass of muon Majorana neutrinos.
- Neutrino experiments aiming to measure neutrino-antineutrino oscillations with different short- and long-baseline setups can be useful to get direct and complementary constraints on the masses and phases of Majorana neutrinos.