

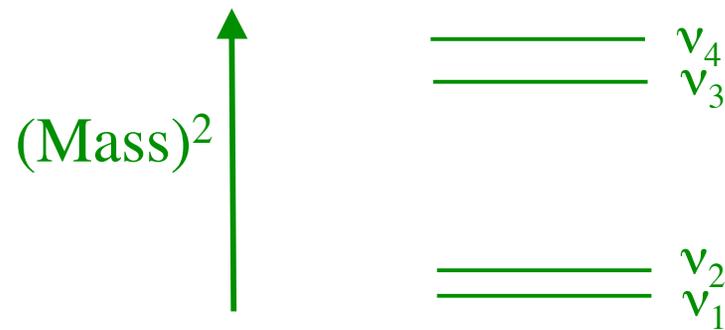
Neutrino Oscillation in Vacuum

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Let Us Assume Neutrino Masses and Leptonic Mixing

Neutrino mass —

There is some spectrum of 3 or more neutrino mass eigenstates ν_i :



$$\text{Mass}(\nu_i) \equiv m_i$$

Leptonic mixing —

When $W^+ \rightarrow l_\alpha^+ + \nu_\alpha$,

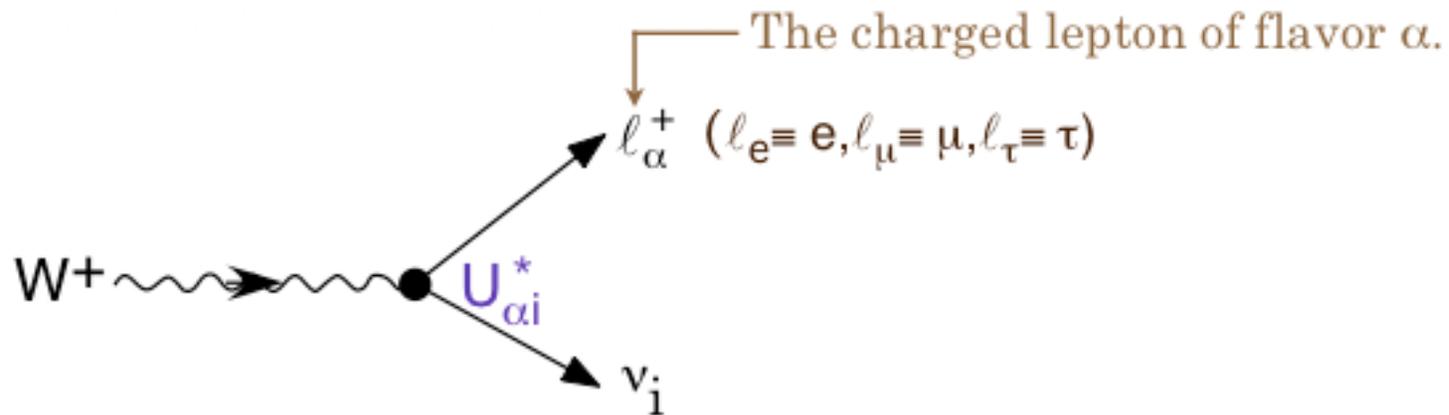
$l_e \equiv e, l_\mu \equiv \mu, l_\tau \equiv \tau$
 $e, \mu, \text{ or } \tau$

the produced neutrino state $|\nu_\alpha\rangle$ is

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle .$$

Neutrino of flavor α Neutrino of definite mass m_i
Leptonic Mixing Matrix

Another way to look at W decay:



A given l_{α}^{+} can be accompanied by *any* ν_i .

$$\text{Amp}(W^{+} \rightarrow l_{\alpha}^{+} + \nu_i) = U_{\alpha i}^{*}$$

The neutrino state $|\nu_{\alpha}\rangle$ produced together with l_{α}^{+}

$$\text{is } |\nu_{\alpha}\rangle = \sum_i U_{\alpha i}^{*} |\nu_i\rangle .$$

According to the Standard Model, extended to include neutrino mass and leptonic mixing —

- The number of different ν_i is the same as the number of different ℓ_α (3).
- The mixing matrix U is 3 x 3 and unitary:
$$UU^\dagger = U^\dagger U = 1.$$

Some models include “sterile” neutrinos — neutrinos that experience none of the known forces of nature except gravity.

In such models, there are $N > 3$ ν_i , and U is $N \times N$, but still unitary.

The Standard Model (SM) description of neutrino *interactions* (not masses or leptonic mixing) is well-confirmed.

We will assume it is true, and extend it to include mixing.

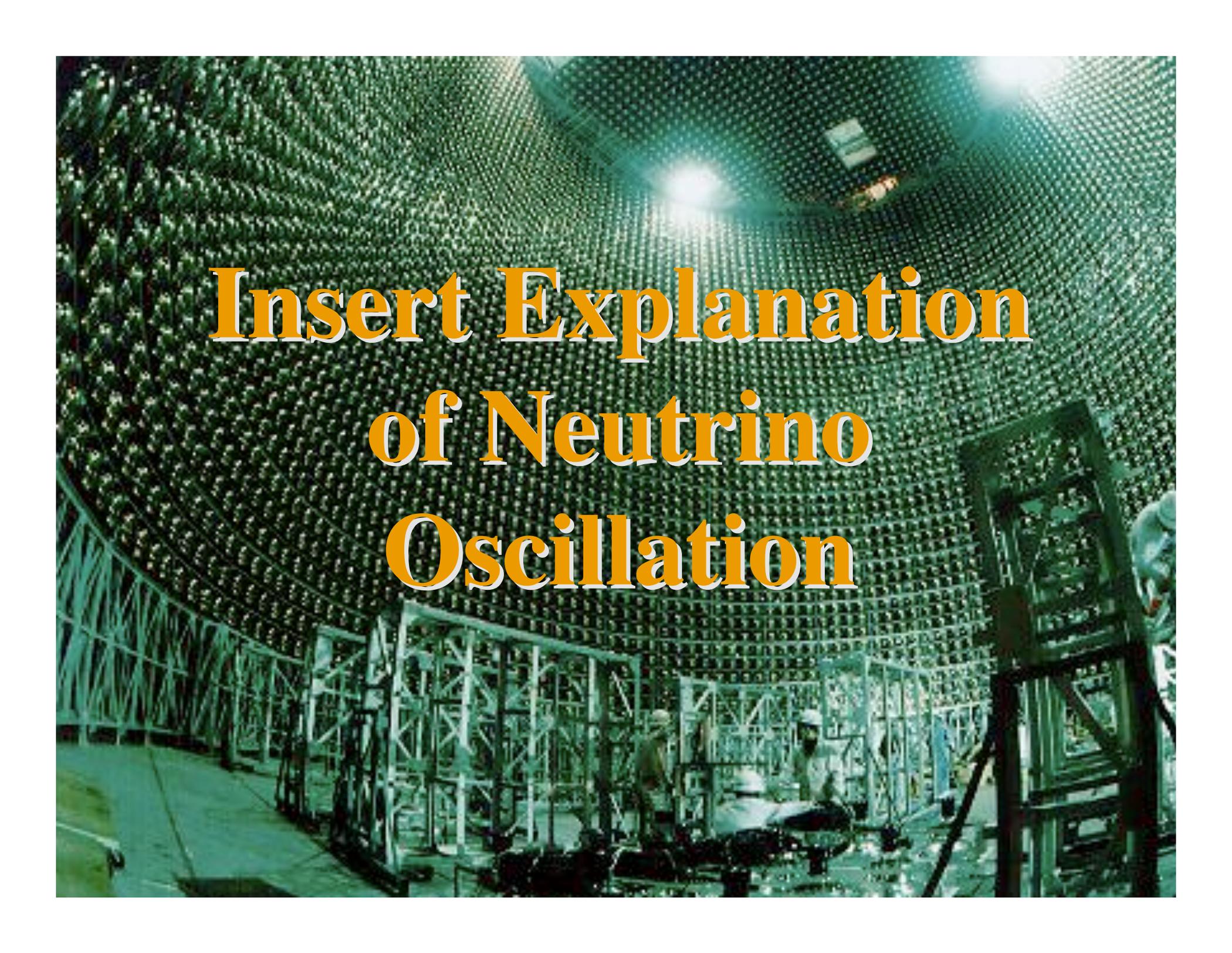
For the lepton couplings to the W boson, we then have —

$$L_{SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \left(\bar{\ell}_{L\alpha} \gamma^\lambda \nu_{L\alpha} W_\lambda^- + \bar{\nu}_{L\alpha} \gamma^\lambda \ell_{L\alpha} W_\lambda^+ \right)$$

Left-handed

$$= -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\bar{\ell}_{L\alpha} \gamma^\lambda U_{\alpha i} \nu_{Li} W_\lambda^- + \bar{\nu}_{Li} \gamma^\lambda U_{\alpha i}^* \ell_{L\alpha} W_\lambda^+ \right)$$

Taking mixing into account

The image shows the interior of a large, cylindrical particle detector. The walls are covered in a dense, green, grid-like pattern of small, square-shaped elements. The structure is supported by a complex network of metal beams and scaffolding. Several bright lights are visible, creating a high-contrast environment. The overall color scheme is dominated by green and blue tones.

Insert Explanation of Neutrino Oscillation