Neutrino Oscillations as Vacuum Birefringence

Flavour waves through the quantum vacuum:
A theory of oscillations

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1. Introduction

Neutrino oscillations are experimentally established.

However, their description within quantum theory is subtle.

Standard superposition assumption:

$$|\nu_\ell\rangle = \sum_k U^*_{\ell k}|\nu_k(m_k)\rangle$$

where $m_i \neq m_j$ for $i \neq j$.

But different masses define different superselection sectors. So coherent superpositions are forbidden!

What, then, is the oscillating one-particle neutrino?

2. Our approach

Asymptotic one-particle neutrinos are massless with definite energy, momentum and flavour.

Bilinear interactions with the Higgs vev induce forward coherent scattering in vacuum.

In analogy with circular birefringence, the neutrino wave function experiences the vacuum as a refractive medium leading to flavour oscillations.

3. Mechanism: Vacuum refraction of coherent flavour waves

Coherent forward scattering in the Higgs quantum vacuum builds an oscillating flavour wave.

Higgs quantum vacuum
Refractive medium for flavour waves

3a. Production

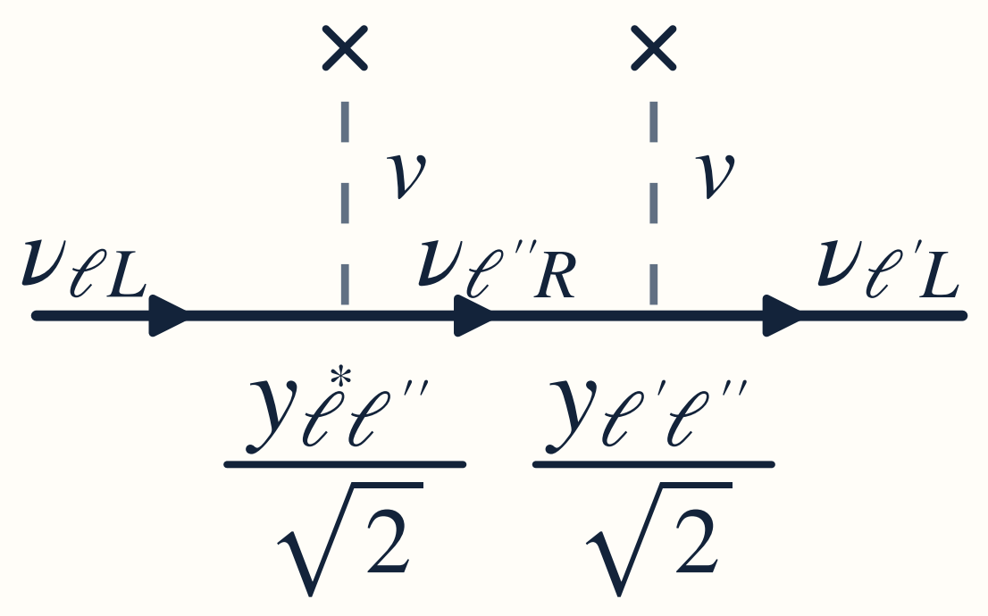
At the weak vertex ν_e is massless

$$|\nu_e(E = |\mathbf{p}|, m = 0)\rangle$$

3b. Coherent forward scattering in vacuum

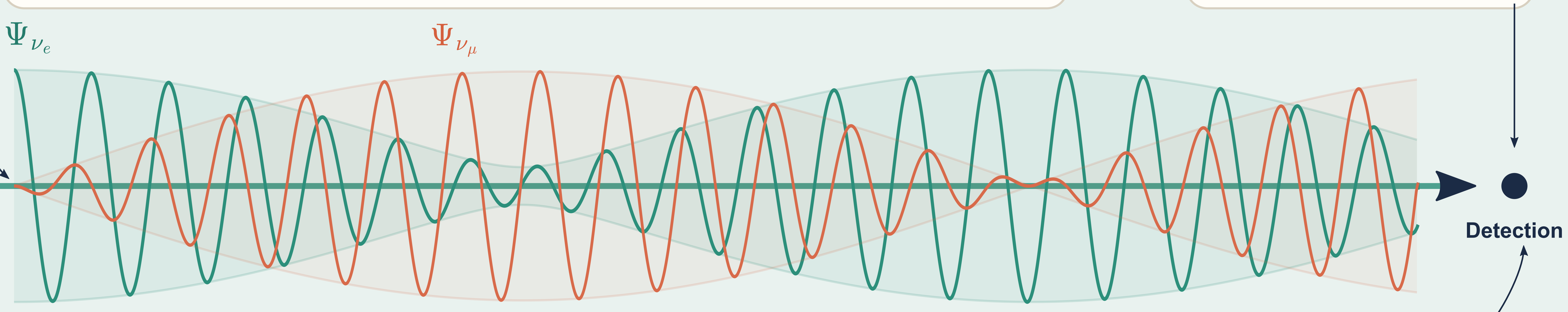
Higgs-vev bilinear induces forward scattering amplitude

$$\mathcal{L}_{int} = -\,\bar{\nu}_{\ell' L} M_{\ell'\ell} \nu_{\ell R} + h.c. \implies$$



$$\implies \nu_\ell \to \nu_{\ell'}$$

with same E, same p and possible change of flavour.



3c. Multiple scattering builds the oscillating flavour wave

$$\Psi(0,0) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \implies \Psi(x,t) = \begin{pmatrix} \Psi_{\nu_e}(x,t) \\ \Psi_{\nu_\mu}(x,t) \end{pmatrix}$$

3d. Coherent wave equation

The coherent flavour wave obeys a relativistic flavour-mixing wave equation.

$$\boxed{[\nabla^2 + E^2 n^2(x,E)]\Psi(x,t) = 0}$$

3e. Refractive index matrix

The refractive index matrix leads to flavour mixing and a difference in phase accumulation.

$$n^2(x,E) = \begin{pmatrix} n^2_{ee}(x,E) & n^2_{e\mu}(x,E) \\ n^2_{\mu e}(x,E) & n^2_{\mu\mu}(x,E) \end{pmatrix}$$

3f. Detection probability

The flavour-wave components give the detection amplitude and probability:

$$\mathcal{A}_{\nu_\ell \to \nu_{\ell'}}(L,t) = \Psi_{\nu_{\ell'}}(L,t)$$

$$P_{\nu_\ell \to \nu_{\ell'}}(L,t) = |\Psi_{\nu_{\ell'}}(L,t)|^2$$

4. Recovered phenomenology

✓ **4a. Standard vacuum oscillation probabilities**

$$P_{\nu_\ell \to \nu_{\ell'}}(L,E) = \sum_{i,j} U_{\ell' i} U^*_{\ell' j} U^*_{\ell i} U_{\ell j} e^{\underbrace{i\Delta n_{ij} EL}_{-i\Delta m^2 L/2E}}$$

✓ **4b. Matter effect and resonance**

$$n^2(E) = n^2_{vac}(E) + n^2_{matter}(x,E) \implies$$

Matter changes the refractive-index matrix.
Can resonantly maximize mixing

✓ **4c. Adiabatic conversion**

$$\gamma = \frac{E\Delta n}{2\,|\partial_x \theta_m|} \gg 1 \implies \Psi_i(x) \sim \exp\left[iE\int_0^x n_i(x')dx'\right]$$

5. What is different?

One flavour wave
Not a superposition of particles with different masses.

One group velocity
Verifiable in time-of-flight measurements.

$$v_g = \left(\frac{\partial(\bar{n}(E)E)}{\partial E}\right)^{-1} = \frac{1}{1 + \frac{\overline{m^2}}{2E^2}}$$

Coherence is manifest
No wave-packet separation of different mass states.

Refractive mass—not kinematic
Testable in direct kinematic-mass measurements.

6. Conclusions

Vacuum refraction gives a QFT-compatible mechanism for flavour oscillations.

Known phenomenology is recovered:
vacuum oscillations, MSW resonance, adiabatic conversion.

Distinctive and falsifiable
via time-of-flight, coherence tests and direct kinematic-mass measurements.

References

[1] M. Oksanen, N. Stirling and A. Tureanu, Phys. Lett. B 865, 139461 (2025); arXiv:2411.14348 [hep-ph]. →

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