Neutrino physics

Stéphane Lavignac (IPhT Saclay)

- neutrinos in the Standard Model
- massive neutrinos - Dirac versus Majorana
- flavour mixing - PMNS matrix
- neutrinos oscillations in vacuum and CP violation
- neutrino propagation in matter
- beta decay and neutrinoless double beta decay
- sterile neutrinos

2024 Asia-Europe-Pacific School of High-Energy Physics
Nakhon Pathom, Thailand, 12-25 June 2024

A few references (textbooks and reviews)

- M. Fukugita and T. Yanagida, *Massive neutrinos in physics and astrophysics*, Springer, 2003
- A. Strumia and F. Vissani, *Neutrino masses and mixings and…*, arXiv:hep-ph/0606054 (last update: April 2010)
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Neutrino physics
Lecture 1

Stéphane Lavignac (IPhT Saclay)

- neutrinos in the Standard Model
- flavour mixing - PMNS matrix
- neutrinos oscillations in vacuum
- the experimental evidence for neutrino oscillations
- CP violation and 3-flavour effects

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Neutrinos in the electroweak Standard Model

<u>Gauge group :</u> $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{\rm QED}$

(couplings) (g) (g') $(e = g \sin\theta_W)$

The spontaneous breaking of the electroweak gauge group leads to 2 massive gauge bosons (W±, Z) and 1 massless gauge boson (the photon γ)

<u>Fermions :</u> come in three generations (family replication)

LH fermions → SU(2) doublets $(T^3 = \pm 1/2)$ → couple to the W

RH fermions → SU(2) singlets $(T^3 = 0)$ → do not couple to the W

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \qquad Y = -1$$

$$e_R \quad \mu_R \quad \tau_R \qquad Y = -2$$

$$Q = T^3 + \frac{Y}{2}$$

Leptons from different generations are distinguished by their <u>flavour</u> (e, μ, τ), which labels the charged lepton mass eigenstates

Neutrinos are special fermions :

1) only weak interactions $\Rightarrow$ very small interaction rate (difficult to detect them; cosmic messengers)

2) no electric charge $\Rightarrow$ can be their own antiparticles (Majorana fermions)

$\overline{\nu} \neq \nu$	Dirac	lepton number is conserved
$\overline{\nu} = \nu$	Majorana	lepton number is violated

3) the SM as originally defined contains no RH neutrino, since only ν_L (or more precisely the left-helicity neutrino) has been observed [Goldhaber 1957]

$\Rightarrow$ neutrinos are massless in the SM

A fermion mass term involves both chiralities:

$$\mathcal{L}_{\rm mass} = -m\,\bar{\psi}\psi = -m\,(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \qquad \psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

[way out: Majorana mass term, but cannot be generated in the SM]

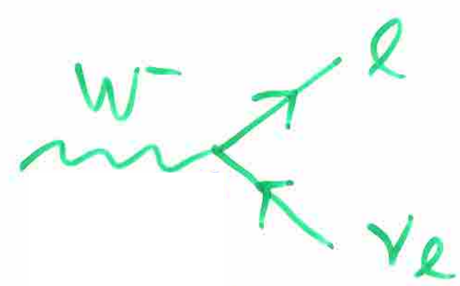
4) neutrinos are actually massive, but their masses are much smaller (< 1 eV) than the ones of charged leptons and quarks; also their mixing angles (PMNS matrix) are large, while those of the quarks (CKM matrix) are small

Neutrino interactions

Neutrinos only couple to the W and the Z bosons :

$$\mathcal{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=e,\mu,\tau} \bar{e}_{\alpha L}\gamma^\mu \nu_{\alpha L}$$

$$= \frac{g}{\sqrt{2}} W_\mu^- \left(\bar{e}_L\gamma^\mu\nu_{eL} + \bar{\mu}_L\gamma^\mu\nu_{\mu L} + \bar{\tau}_L\gamma^\mu\nu_{\tau L}\right)$$



$$\mathcal{L}_{\mathrm{NC}} = \frac{g}{2\cos\theta_W} Z_\mu \sum_{\alpha=e,\mu,\tau} \bar{\nu}_{\alpha L}\gamma^\mu \nu_{\alpha L}$$

$$= \frac{g}{2\cos\theta_W} Z_\mu \left(\bar{\nu}_{eL}\gamma^\mu\nu_{eL} + \bar{\nu}_{\mu L}\gamma^\mu\nu_{\mu L} + \bar{\nu}_{\tau L}\gamma^\mu\nu_{\tau L}\right)$$

θw = angle de Weinberg $\quad \sin^2\theta_W = \frac{g'^2}{g^2 + g'^2}$

Neutrinos only couple to the W and the Z bosons :

$$\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}}\, W_\mu^- \left(\bar{e}_L\gamma^\mu\nu_{eL} + \bar{\mu}_L\gamma^\mu\nu_{\mu L} + \bar{\tau}_L\gamma^\mu\nu_{\tau L}\right)$$

$$\mathcal{L}_{\rm NC} = \frac{g}{2\cos\theta_W}\, Z_\mu \left(\bar{\nu}_{eL}\gamma^\mu\nu_{eL} + \bar{\nu}_{\mu L}\gamma^\mu\nu_{\mu L} + \bar{\nu}_{\tau L}\gamma^\mu\nu_{\tau L}\right)$$

All SM interactions (including the charged lepton couplings to the photon and the Z , and their Yukawa couplings) preserve lepton number

$$L = \sum_{\alpha=e,\mu,\tau} \left(N_{e^-_\alpha} + N_{\nu_\alpha} - N_{e^+_\alpha} - N_{\bar{\nu}_\alpha}\right) = L_e + L_\mu + L_\tau$$

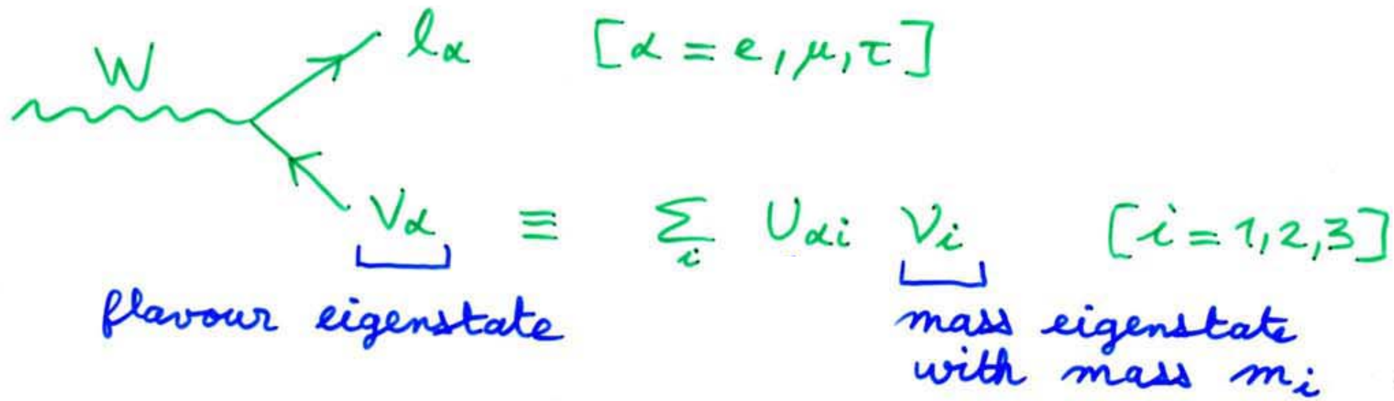
(accidental global symmetry of the SM; follows from gauge and Lorentz invariance + renormalizability; not a fundamental symmetry)

Thus e.g. $\pi^+ \to \mu^+\nu_\mu$ is allowed, but $\pi^+ \to \mu^+\bar{\nu}_\mu$ is forbidden

In the absence of neutrino masses, lepton flavour (i.e. the individual quantum numbers L_e, L_μ, L_τ) is also exactly conserved. Neutrino masses induce lepton flavour violating (LFV) transitions $\nu_\alpha \to \nu_{\beta\neq\alpha}$ (oscillations), but also LFV processes like $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$, which however are extremely suppressed in the absence of new physics [GIM mechanism]

Flavour mixing – PMNS matrix

When neutrinos are massive, possibility of flavour mixing : the neutrino to which a given charged lepton (e, μ or τ) couples via the W is not a mass eigenstate, but a coherent superpositions of mass eigenstates



Like in the quark sector, the origin of flavour mixing is the mismatch between the basis of gauge (or flavour) eigenstates and of mass eigenstates. The relative rotation is the lepton mixing matrix, known as PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

Physical parameters in $U_{\rm PMNS}$

U is a 3x3 unitary matrix ⇒ 3 mixing angles and 6 phases (not all physical)

$$\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}} W^-_\mu \sum_\alpha \bar{e}_{\alpha L} \gamma^\mu \nu_{\alpha L} = \frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha,i} \bar{e}_{\alpha L} \gamma^\mu U_{\alpha i} \nu_{iL}$$

(i) if neutrinos are Dirac fermions : analogous to quarks and CKM

can rephase the lepton fields $e_{\alpha L} \to e^{i\phi_\alpha} e_{\alpha L}$, $\nu_{iL} \to e^{i\phi_i} \nu_{iL}$ and absorb the phases in the PMNS matrix, so that CC interactions are unaffected

$$U_{\alpha i} \to e^{i(\phi_\alpha - \phi_i)} U_{\alpha i}$$

⇒ removes 2x3 - 1 = 5 relative phases ⇒ a single physical phase $\delta_{\rm PMNS}$

(i) if neutrinos are Majorana fermions : cannot rephase the neutrino fields, since this would affect the Majorana condition

$$U_{\alpha i} \to e^{i\phi_\alpha} U_{\alpha i}$$

⇒ removes only 3 phases ⇒ 3 physical phases : 1 "Dirac" phase $\delta_{\rm PMNS}$ and 2 "Majorana" phases

Standard parametrization of the PMNS matrix

Analogous to CKM: written as the product of three rotations with angles θ_{23}, θ_{13} and θ_{12}, the second (complex) rotation depending on the phase δ

$$U \;\equiv\; U_{23}U_{13}U_{12}P \;\equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} P$$

P is the unit matrix in the Dirac case, and a diagonal matrix of phases containing 2 independent phases ϕ_i in the Majorana case

$$c_{ij} = \cos\theta_{ij}\ ,\ \ s_{ij} = \sin\theta_{ij}$$

$$\theta_{ij} \in [0, \pi/2]\,, \quad \delta \in [0, 2\pi[\,, \quad \phi_i \in [0, \pi[$$

$\delta \neq 0, \pi \;\Rightarrow$ CP violation in oscillations: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar\nu_\alpha \to \bar\nu_\beta)$

The Majorana phases play a role only in $\Delta L = 2$ processes like neutrinoless double beta decay

Neutrino oscillations in vacuum and CP violation

Oscillations are a quantum-mechanical process due to neutrino mass and mixing. An (ideal) oscillation experiment involves 3 steps:

1) production of a pure flavour state at t = 0 (e.g. a ν_μ from $\pi^+ \to \mu^+ \nu_\mu$)

This flavour state is a coherent superposition of mass eigenstates determined by the PMNS matrix, e.g. in the 2 flavour case

$$|\nu(t=0)\rangle = |\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

2) propagation

Each mass eigenstate, being an eigenstate of the Hamiltonian in vacuum, evolves with its own phase factor $e^{-iE_i t}$ $\Rightarrow$ modifies the coherent superposition, which is no longer a pure flavour eigenstate:

$$|\nu(t)\rangle = -\sin\theta\, e^{-iE_1 t}|\nu_1\rangle + \cos\theta\, e^{-iE_2 t}|\nu_2\rangle$$

3) detection via a CC interaction which identifies a specific flavour

probability amplitude : $\langle\nu_e|\nu(t)\rangle = -\cos\theta\sin\theta e^{-iE_1 t} + \cos\theta\sin\theta e^{-iE_2 t}$

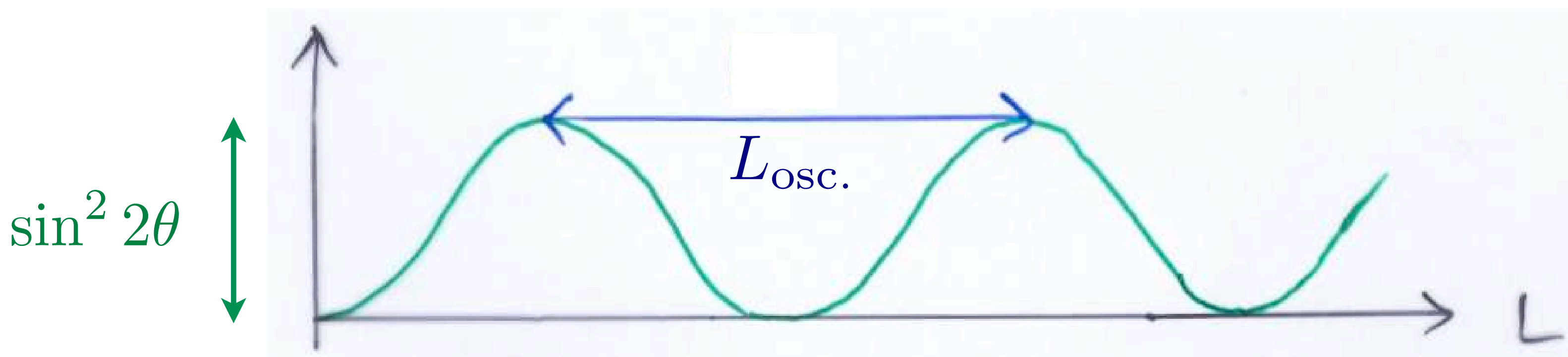
oscillation probability : $P(\nu_\mu \to \nu_e; t) = |\langle\nu_e|\nu(t)\rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{E_2 - E_1}{2}\, t\right)$

2-flavour oscillations in vacuum

Assuming ultra-relativistic neutrinos $L \simeq ct$, $m_i^2 \ll p^2$

$$E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \quad \Rightarrow \quad \frac{E_2 - E_1}{2} \simeq \frac{m_2^2 - m_1^2}{4p}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Amplitude of oscillations: $\sin^2 2\theta$

Oscillation length: $L_{\text{osc.}}(\text{km}) = 2.48\, E(\text{GeV})/\Delta m^2(\text{eV}^2)$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \Delta m^2 \equiv m_2^2 - m_1^2$$

The above derivation gives the correct oscillation probability, but is a bit oversimplified

The propagating mass eigenstates ν_i where described as plane waves with well-defined (and equal) momenta ($p_i = p$)

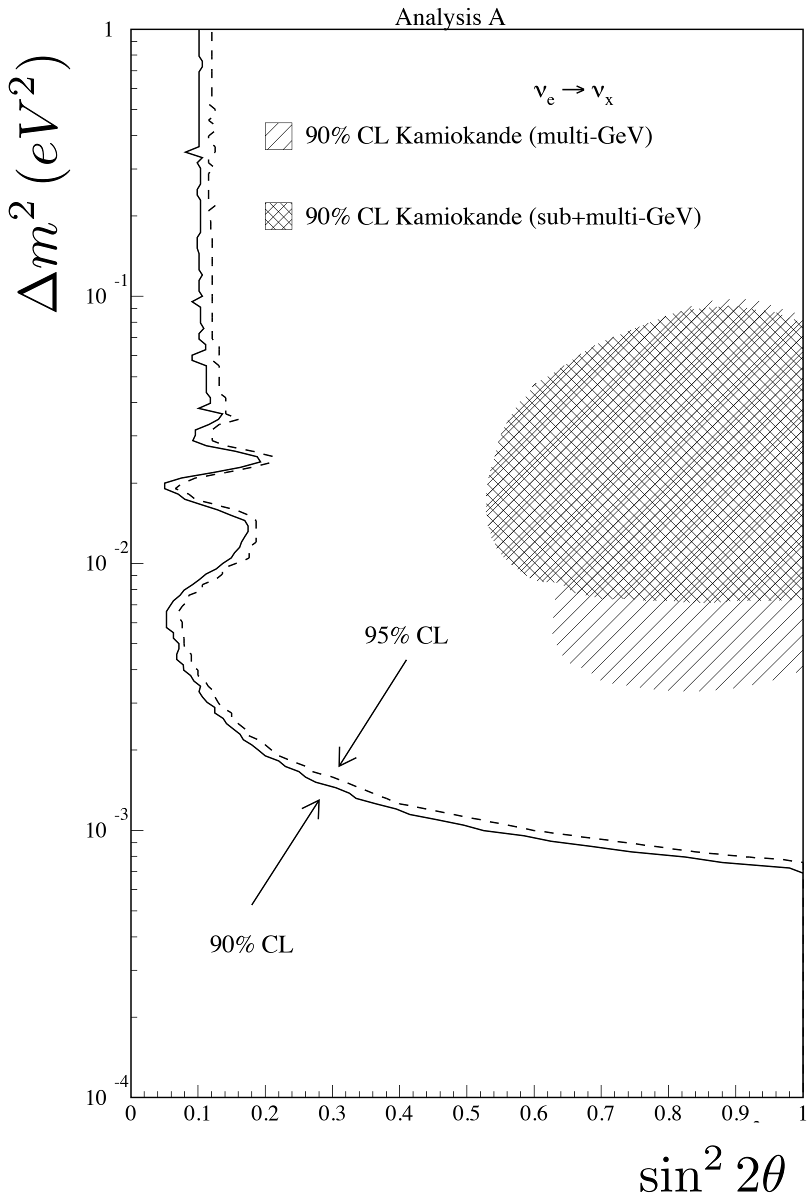
Should instead be described by wave packets with mean momenta p_i

Under appropriate coherence conditions at production and detection, and neglecting decoherence due to separation of the wave packets, the above oscillation formula is recovered (without the ad hoc assumption $p_i = p$)

[See e.g. Akhmedov and Smirnov, arXiv: 0905.1903 for details]

A typical exclusion curve (CHOOZ) :

$$P_{\text{th.}}(\bar{\nu}_e \to \bar{\nu}_e) \;=\; \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) <\; P_{\text{exp.}}$$



CHOOZ Collaboration, hep-ex/9907037

N-flavour oscillations in vacuum

$$\nu_\alpha(x) = \sum_i U_{\alpha i}\, \nu_i(x) \quad \textbf{(fields)} \quad \Rightarrow \quad |\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \quad \textbf{(states)}$$

and for antineutrinos $\quad |\bar{\nu}_\alpha\rangle = \sum_i U_{\alpha i}\, |\bar{\nu}_i\rangle$

1) production: $|\nu(t=0)\rangle = |\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$

2) propagation: $|\nu(t)\rangle = \sum_i U^*_{\alpha i}\, e^{-iE_i t} |\nu_i\rangle$

3) detection: $\langle \nu_\beta | \nu(t)\rangle = \sum_j U_{\beta j} \langle \nu_j | \nu(t)\rangle = \sum_i U_{\beta i} U^*_{\alpha i}\, e^{-iE_i t}$

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu(t)\rangle|^2 = \left|\sum_i U_{\beta i} U^*_{\alpha i}\, e^{-iE_i t}\right|^2$$

Assuming ultra-relativistic neutrinos, one obtains

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i<j} \mathrm{Re}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right)$$

$$+ \, 2 \sum_{i<j} \mathrm{Im}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ji} L}{2E}\right)$$

Oscillation probability = sum of oscillating terms with different « frequencies » $\Delta m^2_{ji} \equiv m^2_j - m^2_i$ and amplitudes (which depend on the θ_{ij} and Dirac-type CP-violating phases)

For $\alpha \neq \beta$, $P(\alpha \to \beta)$ is called appearance probability

$$P(\nu_\alpha \to \nu_\beta) \,=\, -\,4 \sum_{i<j} \mathrm{Re}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right)$$

$$+\,2 \sum_{i<j} \mathrm{Im}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ji} L}{2E}\right)$$

For antineutrinos, U → U* (δ → - δ) and the last term changes sign
if $\delta \neq 0, \pi \;\Rightarrow\; P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \,\neq\, P(\nu_\alpha \to \nu_\beta)$ ➞ CP violation

For $\alpha = \beta$ (disappearance or survival probability), the last term vanishes and the formula simplifies to

$$P(\nu_\alpha \to \nu_\alpha) \,=\, 1 - 4 \sum_{i<j} \left|U_{\alpha i} U_{\alpha j}\right|^2 \sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right)$$

No CP violation in disappearance experiments: $P(\nu_\alpha \to \nu_\alpha) \,=\, P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$

3-flavour oscillations

2 independent Δm^2: Δm^2_{32} (« atmospheric ») and Δm^2_{21} (« solar »)

U contains 3 mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and one phase δ

$$U \equiv U_{23}U_{13}U_{12} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

[omitting possible « Majorana » phases, which are relevant only for lepton number violating processes such as neutrinoless double beta decay, and have no effect on oscillations, since they cancel in in the combinations $U_{\alpha i}U^*_{\beta i}$]

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i<j} \mathrm{Re}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ji}L}{4E}\right)$$
$$+ 2 \sum_{i<j} \mathrm{Im}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ji}L}{2E}\right)$$

In many experiments, oscillations are dominated by a single Δm^2 and can be described to a good approximation as 2-flavour oscillations:

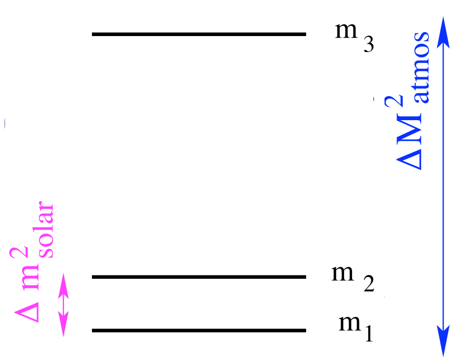
- solar neutrinos (*), LBL reactors ($\nu_e/\bar{\nu}_e$ disappearance) — $\Delta m^2_{21},\ \theta_{12}$ — $\Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\mathrm{eV}^2$
- atmospheric, LBL accelerators ($\nu_\mu/\bar{\nu}_\mu$ disappearance) — $\Delta m^2_{31},\ \theta_{23}$ — $|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$
- SBL reactor experiments ($\bar{\nu}_e$ disappearance) — $\Delta m^2_{31},\ \theta_{13}$ — $\sin^2\theta_{13} \simeq 0.022$

(*) matter effets dominate for high-energy solar neutrinos

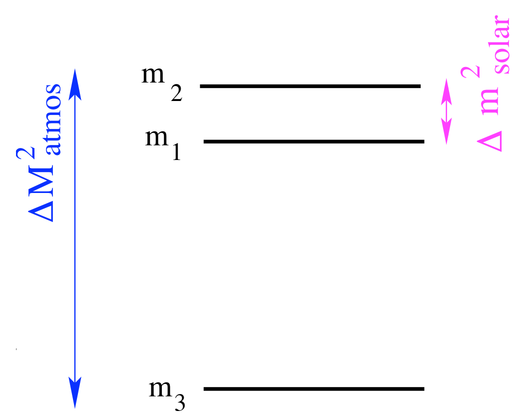
Notes : 1) θ_{13} is the only « small » leptonic angle $\theta_{13} < \theta_{12}, \theta_{23}$

2) $\Delta m^2_{21} \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$ [by convention, $\Delta m^2_{21} > 0$]

sign of Δm^2_{31} unknown $\Rightarrow$ two types of spectra allowed



Normal hierarchy
(normal ordering)
$\Delta m^2_{31} > 0$

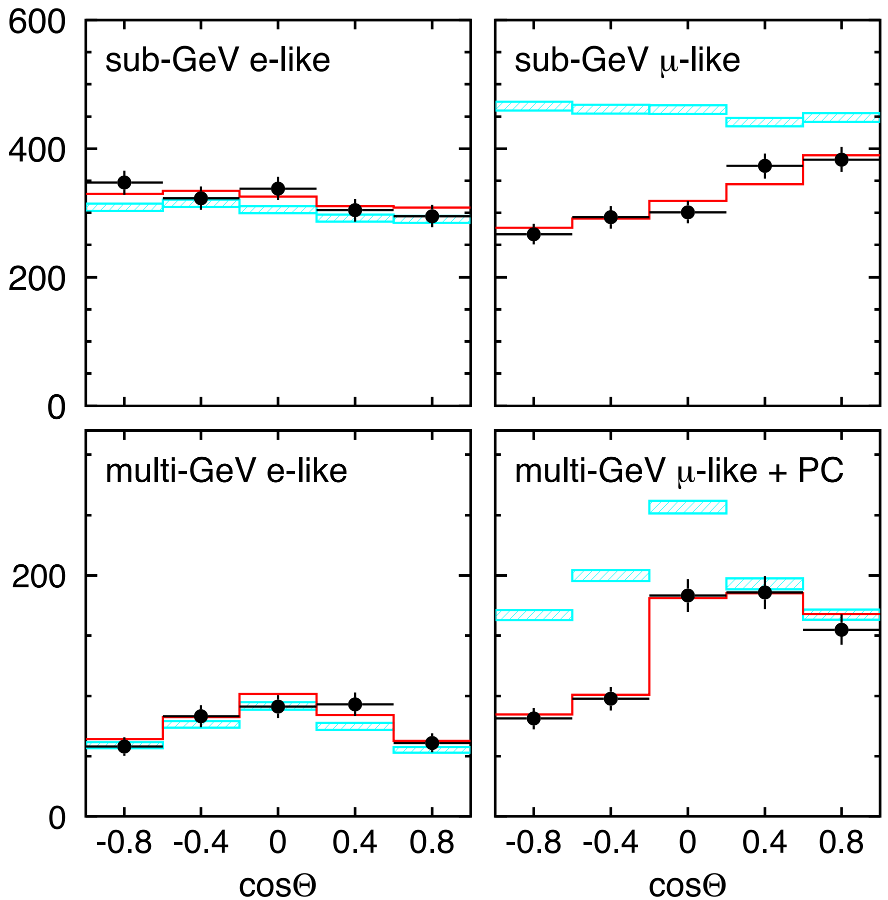


Inverted hierarchy
(inverted ordering)
$\Delta m^2_{31} < 0$

The experimental evidence for neutrino oscillations

The first evidences came from the observation of a deficit in the measured fluxes of solar and atmospheric neutrinos

<u>Atmospheric neutrinos</u> (Super-Kamiokande 1998)



[SK collaboration, Phys. Rev. D71 (2005) 112005]

produced by the interactions of cosmic rays in the atmosphere

deficit of upward-going muon neutrinos [Θ = zenith angle] interpreted as $\nu_\mu \to \nu_\tau$ oscillations

$$P^{2\nu}_{\mu\tau} = \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$$

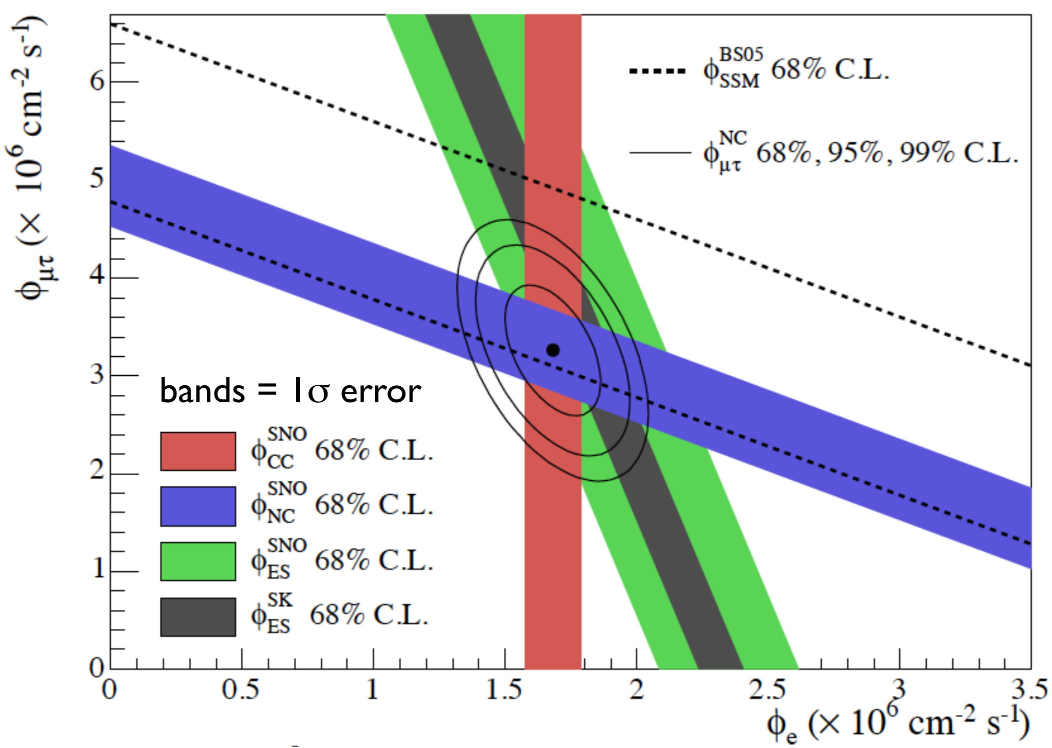
$$\theta_{23} \text{ close to } \pi/4$$

<u>Solar neutrinos</u> (SNO 2001-2002)

Deficit of ν_e with respect to solar model predictions observed by Homestake (1968-2002), GALLEX/SAGE, Kamiokande and Super-Kamiokande

SNO was able to measure the flux of electron neutrinos (Φ_e) via the charged current (W exchange) as well as the total flux $(\Phi_e + \Phi_{\mu\tau})$ via the neutral current (Z exchange), confirming both the deficit and the solar models

[SNO collaboration, Phys. Rev. C72 (2005) 055502]



interpretation :

$\nu_e \to \nu_\mu, \nu_\tau$ oscillations

[actually adiabatic flavour conversions in the matter of the Sun]

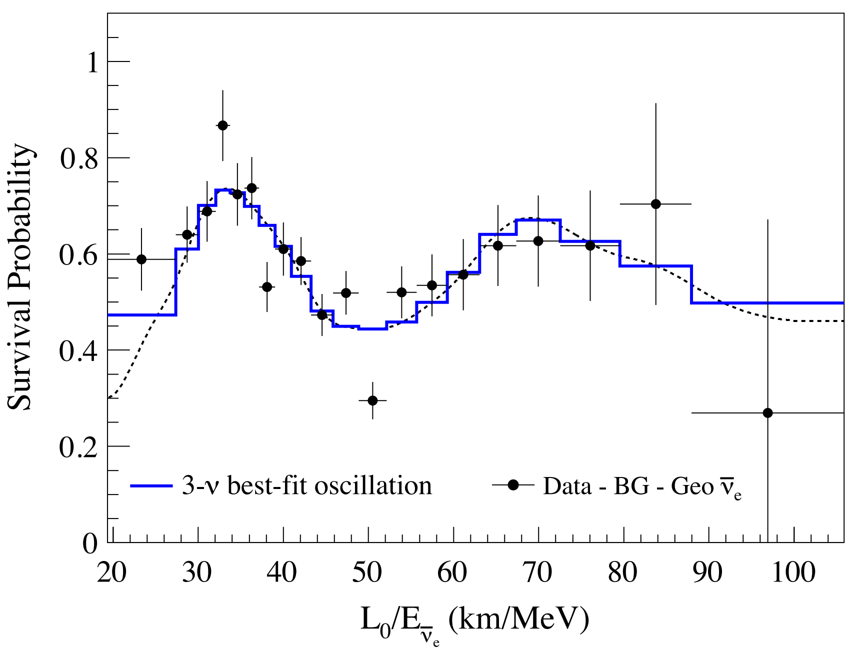
$$\Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\mathrm{eV}^2$$

$$\sin^2\theta_{12} \simeq 0.31$$

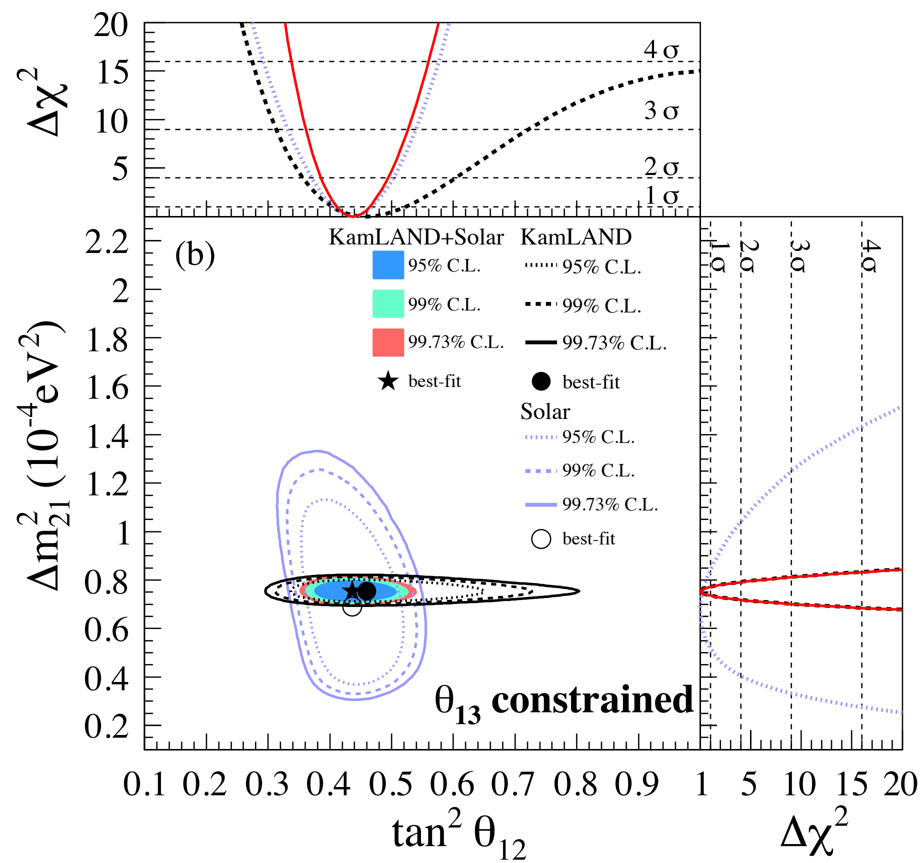
Solar neutrinos parameters confirmed by KamLAND (2002)

Long baseline reactor neutrino experiment in Japan: detector surrounded by 56 nuclear reactors with an average (flux-weighted) distance of 180 km

The oscillation pattern is clearly visible in KamLAND data (survival probability of electron antineutrinos as a function of L/E)



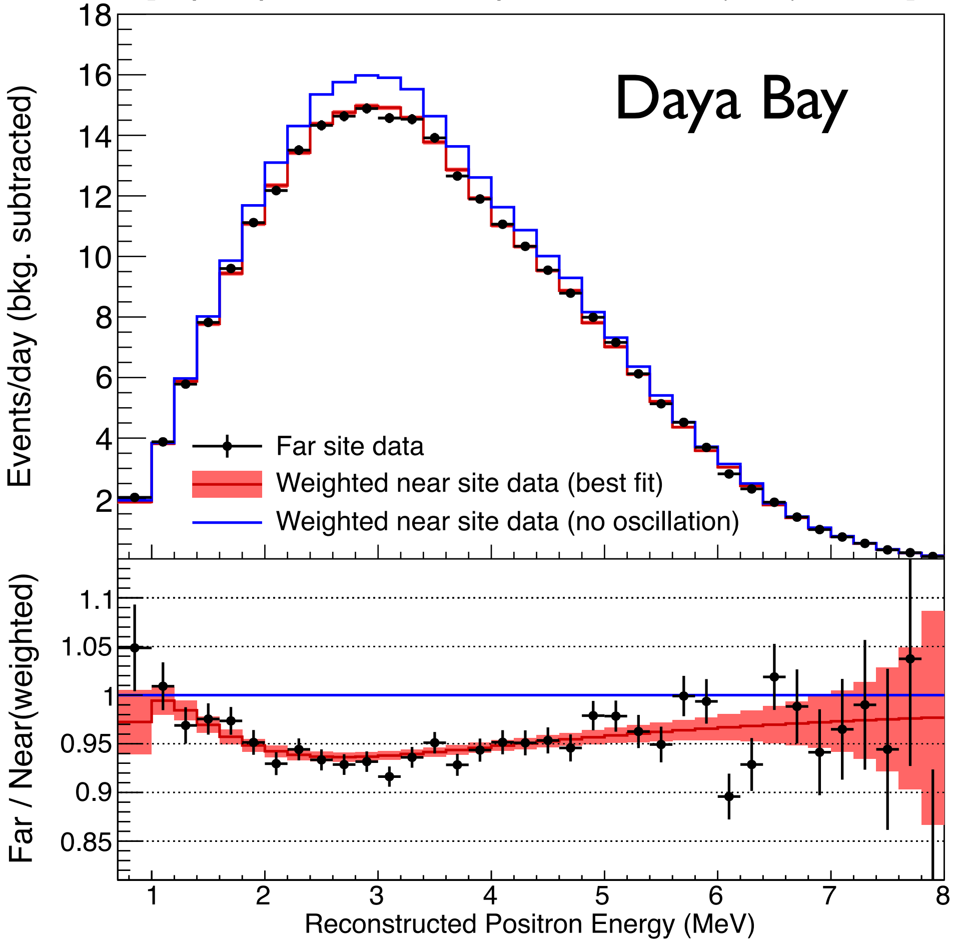
$$P_{ee}^{2\nu} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



Measurement of the third mixing angle (2011-2012)

Short baseline reactor neutrino experiments (Double Chooz, Day Bay, RENO) have observed a deficit of electron antineutrinos in their far detector (L around 1 km)

[Daya Bay collaboration, Phys. Rev. Lett. 115 (2015) 111802]



interpretation :

$\bar{\nu}_e \to \bar{\nu}_e$ disappearance

$$P_{ee}^{2\nu} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$|\Delta m_{31}^2| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{13} \simeq 0.022$$

CP violation in oscillations

$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ at leading order in Δm^2_{21} $(\alpha \neq \beta)$:

$$\Delta P_{\alpha\beta} = \pm 8\, J \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right), \qquad J \equiv \mathrm{Im}\left[U_{e1} U^*_{\mu 1} U^*_{e2} U_{\mu 2}\right]$$

Jarlskog invariant $\quad J = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\delta$

→ condition for CP violation : $\quad \delta \neq 0, \pi$

→ for CP violation to be observable, sub-dominant oscillations governed by Δm^2_{21} must develop $\Rightarrow$ long baseline oscillation experiments (> 100 km), also sensitive to matter effects (which can mimic a CP asymmetry)

CP violation is only possible in <u>appearance experiments</u> $(\alpha \neq \beta)$
e.g. electron (anti-)neutrino appearance in a muon (anti-)neutrino beam
$(\nu_\mu \to \nu_e,\, \bar{\nu}_\mu \to \bar{\nu}_e)$

Disappearance experiments, e.g. at reactors, have no sensitivity to δ, implying $P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$

3-flavour effects in oscillations

With growing experimental precision, neutrino oscillations become sensitive to 3-flavour effects (CP violation, sub-leading oscillations, interferences)

<u>Long baseline appearance experiments (T2K, NOvA, DUNE, HK) :</u>

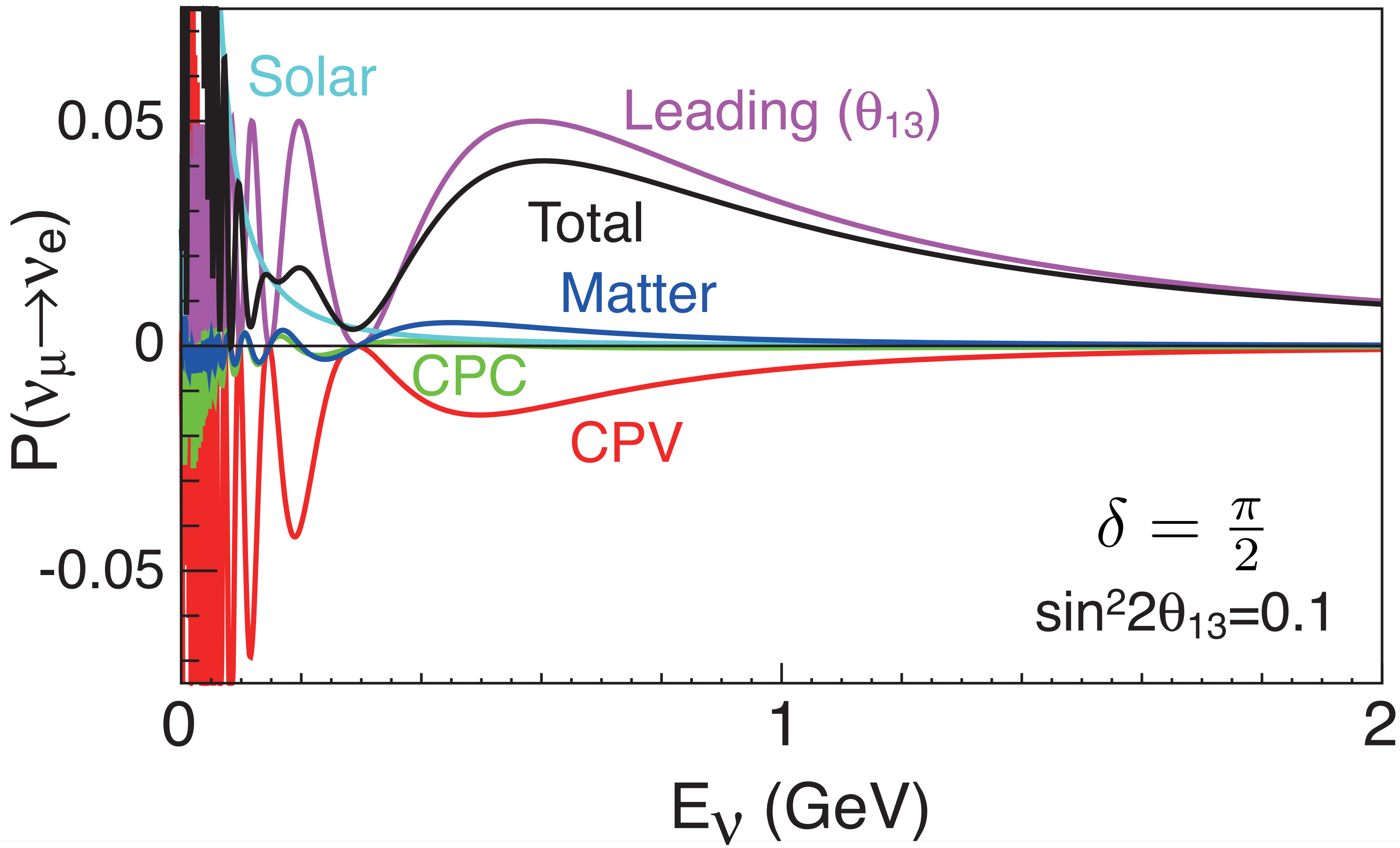
$$\begin{aligned} P(\nu_\mu \to \nu_e) \;\simeq\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cos^2\theta_{23}\sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) \\ & + \frac{1}{2}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\delta\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{2E}\right) \\ & - \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \end{aligned}$$

- first term: leading Δm^2_{31}-driven term, proportional to $\sin^2 2\theta_{13}$ and sensitive to the octant of θ_{23} (i.e. whether $\theta_{23} < \pi/4$ or $> \pi/4$)

- the third and fourth terms involve both Δm^2_{31} and Δm^2_{21} and are CP-even and CP-odd (changes sign for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations), respectively

- due to the long baseline, matter effects must be included (less important for T2K than for NOvA and DUNE)

Relative size of the different terms in the $\nu_\mu \to \nu_e$ oscillation probability for the long baseline accelerator experiment T2K (Japan, 295 km), in which matter effects are small

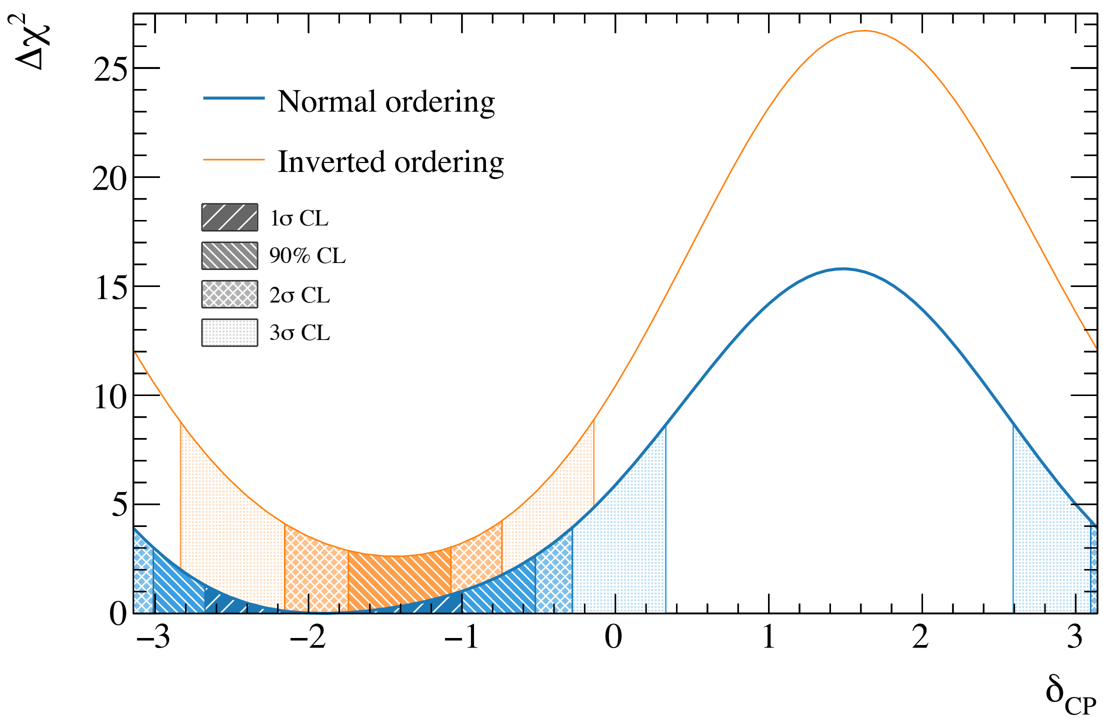


[arXiv:1412.4673]

First hints of CP violation at T2K

Long baseline accelerator experiment in Japan (295 km)

Observes more events in the neutrino mode $(\nu_\mu \to \nu_e)$ and less events in the antineutrino mode $(\bar{\nu}_\mu \to \bar{\nu}_e)$ than expected $\Rightarrow$ suggests CP violation (CP conservation excluded at more than 90% C.L.)



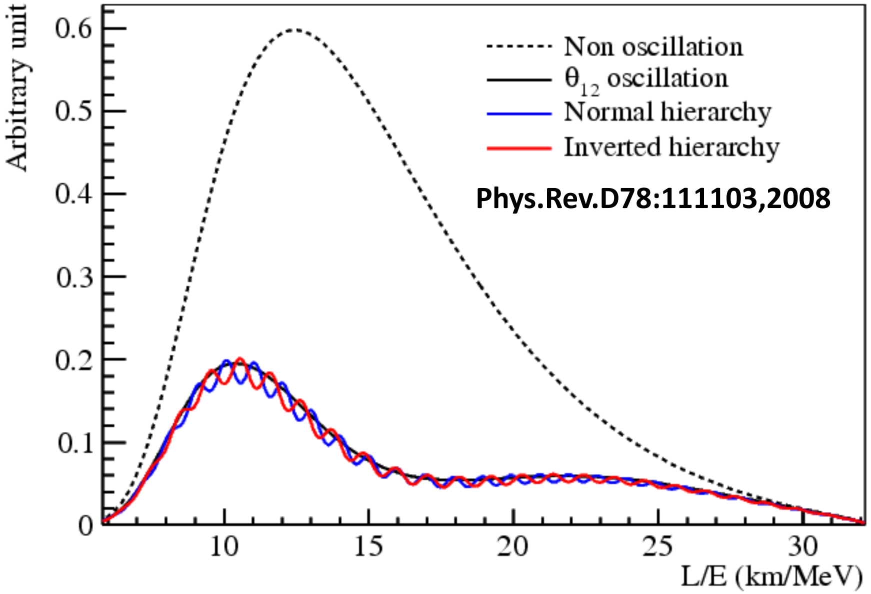
[T2K Coll., Eur. Phys. J. C 83 (2023)]

constraints from SBL reactor experiments imposed $(\Delta m^2_{31}, \theta_{13})$

The long baseline accelerator experiment NOvA (USA, 810 km) does not confirm the hint for CPV in the NO case – more data / new experiments needed

Long baseline reactor experiments ($\bar{\nu}_e \to \bar{\nu}_e$ disappearance) :

JUNO (China, 53 km) will be sensitive to oscillations governed by the 3 Δm^2



$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

subtle interference between the oscillations governed by Δm^2_{31} and Δm^2_{32}, which develop on top of the leading Δm^2_{21}-driven oscillations

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E} \qquad \cos^2\theta_{12} \simeq 0.7,\ \sin^2\theta_{12} \simeq 0.3$$

The distorsions of the antineutrino energy spectrum depend on the mass hierarchy $\Rightarrow$ can be used to determine the hierarchy (if the experiment reaches a sufficient energy resolution)

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$ for NH → the term with the largest amplitude (P_{31}) oscillates faster

$|\Delta m^2_{31}| < |\Delta m^2_{32}|$ for IH → the term with the smallest amplitude (P_{32}) oscillates faster