Neutrinos
selected topics

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Landscape of the field

Solar neutrinos

Atmospheric neutrinos

Cosmic neutrinos

Supernova neutrinos

Collective oscillations

Mass hierarchy

CP-violation

2-3 mixing

Neutrinos &

LHC

Higgs physics

Dark matter

Grav. waves

Leptogenesis

Inflation

Absolute mass scale

Models of mass and mixing

Flavor symmetries

Neutrinos and unification

Nature of neutrinos

$\beta\beta0\nu$ - decays

Sterile neutrinos

Non-standard interaction

Violation of fundamental symmetries

Future detectors and experiments

3ν - paradigm

All well established/confirmed results fit well a framework

- three neutrinos
  - with interactions described by the standard model
    - with masses and mixing

New physics BSM behind

ν_R

Mechanism of neutrino mass generation has negligible effect (feedback) on Standard model structures and interaction

Higgs properties?

Content:

1. Masses, mixing and oscillations
2. Flavor transformations in matter
3. Phenomenology of neutrinos from various sources
4. Neutrino Mass hierarchy and CP-violation
5. Beyond the 3 neutrino paradigm
6. Towards the Underlying physics

The Nobel Prize in Physics 2015

Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

SNO Collaboration
Queen's University, Kingston, Canada

" for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Challenging Nobel citation

Oscillations or no-oscillations?

A.Y.S. 1609.02386 [hep-ph]

While Super-Kamiokande (SK), indeed, has discovered oscillations, SNO observed effect of the adiabatic (almost non-oscillatory) flavor conversion of neutrinos in the matter of the Sun.

Oscillations are irrelevant for solar neutrinos apart from small regeneration inside the Earth.

Both oscillations and adiabatic conversion do not imply masses uniquely and further studies were required to show that non-zero neutrino masses are behind the SNO results.

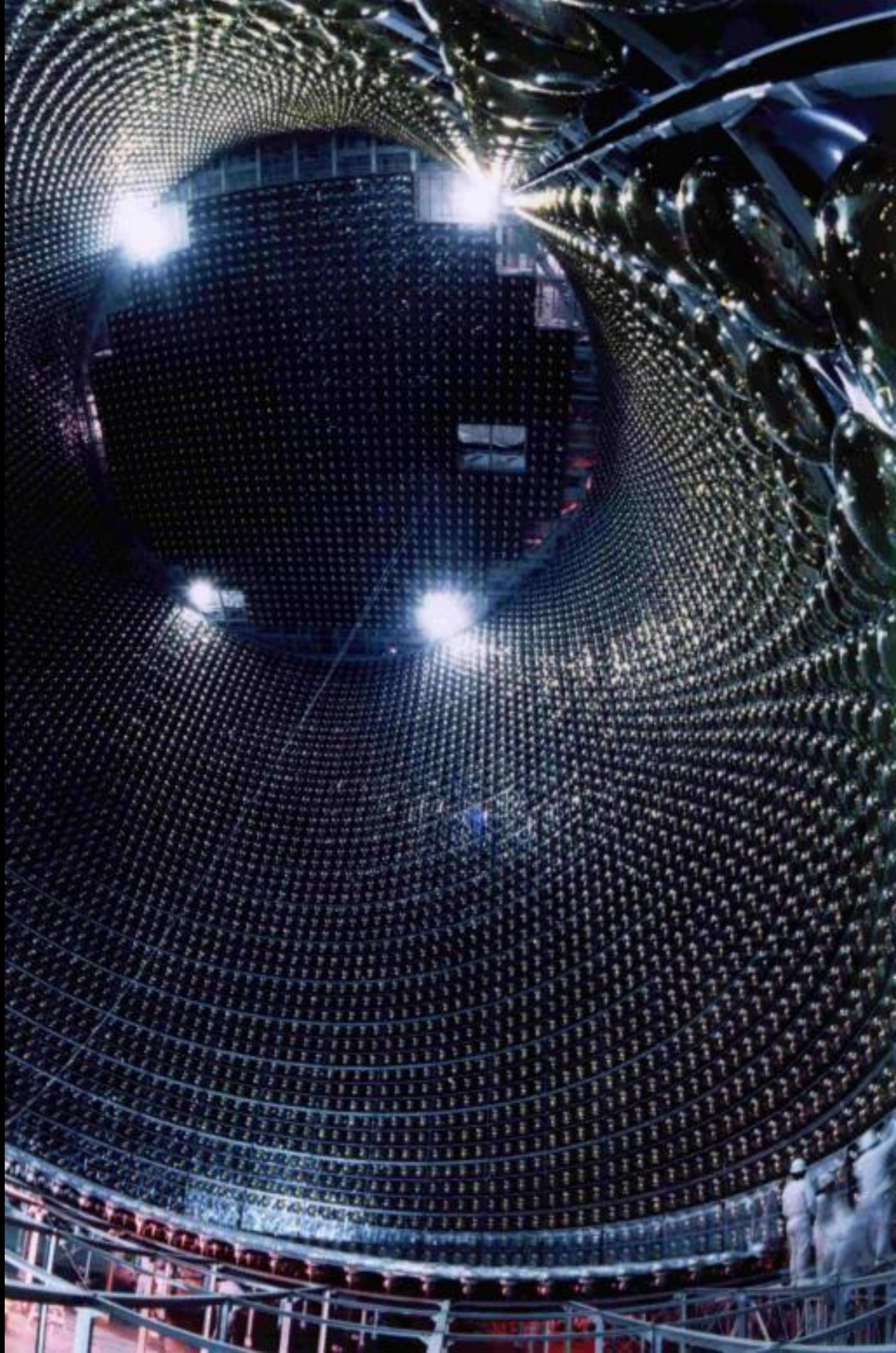
Science magazine, Dec. 2016, Adrian Cho:

"Did the Nobel committee get the physics wrong?"

Repubblica, Dec. 14 2016, E. Dusi:

"C'e un errore nel Nobel della fisica del 2015"

Masses, Mixing and Oscillations



Neutrinos in SM

SM definition of flavor states may differ from "physical" one if e.g. ...

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

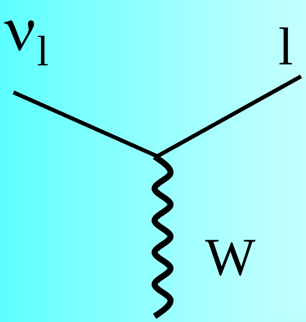
$I_W = 1/2$
$I_{3W} = 1/2$

Chiral components

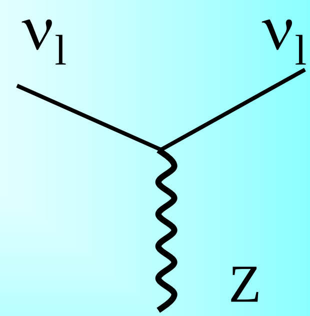
$\nu_L = \frac{1}{2}(1 - \gamma_5)\,\nu$

$\nu_R = \frac{1}{2}(1 + \gamma_5)\,\nu$?

$\nu_e \;\; \nu_\mu \;\; \nu_\tau$ neutrino flavor states, form doublets (charged currents) with definite charged leptons,



$l = e, \mu, \tau$



Neutral current interaction

$$\frac{g}{2\sqrt{2}}\,\bar{l}\,\gamma^\mu(1 - \gamma_5)\nu_l\,W^+_\mu + h.c.$$

$$\frac{g}{4}\,\bar{\nu}_l\,\gamma^\mu(1 - \gamma_5)\nu_l\,Z_\mu$$

Conservation of lepton numbers L_e, L_μ, L_τ

... New heavy neutral leptons mix with neutrinos

Dirac and Majorana neutrinos

Dirac mass term $- m_D \overline{\nu}_R \nu_L + h.c.$

Instead of independent RH component $\nu_R \rightarrow \nu_L{}^C$ $\quad \nu_L{}^C = C (\overline{\nu}_L)^T$ $\quad C = i\gamma_0 \gamma_2$ charge conjugate

$- \frac{1}{2} m_L \nu_L{}^T C \nu_L + h.c.$ → two component massive neutrino

corresponds to Majorana neutrino:

$\nu_M{}^C = e^{i\alpha} \nu_M$ $\quad \nu_M = \nu_L + e^{-i\alpha} \nu_L{}^C$ $\quad \alpha$ is the Majorana phase

$$- \frac{1}{2} m_M \overline{\nu}_M \nu_M = - \frac{1}{2} m_M e^{i\alpha} \nu_L{}^T C \nu_L + h.c.$$

No invariance under $\nu_L \rightarrow e^{i\alpha} \nu_L$

Lepton number of the mass operator: L = 2 and -2 (for h.c.)

mass term violates lepton number by $|\Delta L| = 2$

Processes with lepton number violation by $|\Delta L| = 2$ with probabilities $\quad \beta\beta_{0\nu}$ $\quad \Gamma \sim m_L{}^2$

Flavors and mixing

Flavor neutrino states:

ν_e ν_μ ν_τ

e μ τ

- correspond to certain charged leptons
- interact in pairs

Mass eigenstates

ν_1 ν_2 ν_3

m_1 m_2 m_3

Mixing

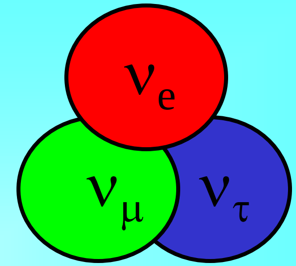
flavor is characteristic of interactions

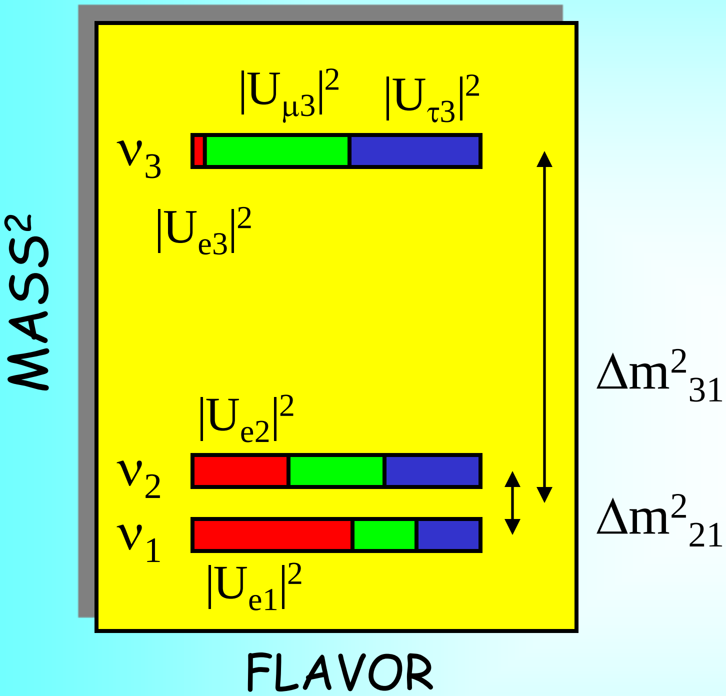
Flavor states $\neq$ Mass eigenstates

$n \rightarrow p + e^- + \bar{\nu}_e$

$\pi \rightarrow \mu + \nu_\mu$

Mixing angles





Normal mass hierarchy

$$\Delta m^2_{31} = m^2_3 - m^2_1$$
$$\Delta m^2_{21} = m^2_2 - m^2_1$$

Mixing determines the flavor composition of mass states

Mixing parameters

$$\tan^2\theta_{12} = |U_{e2}|^2 \;/\; |U_{e1}|^2$$
$$\sin^2\theta_{13} = |U_{e3}|^2$$
$$\tan^2\theta_{23} = |U_{\mu 3}|^2 \;/\; |U_{\tau 3}|^2$$

Mixing matrix:

$$\nu_f = U_{PMNS}\, \nu_{mass}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{PMNS} = U_{23} I_\delta U_{13} I_{-\delta} U_{12}$$

Standard parametrization

$U_{PMNS} = U_{23} I_{\delta} U_{13} I_{-\delta} U_{12}$

$I_{\delta} = \mathrm{diag}\,(1, \; 1, \; e^{i\delta})$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ s_{12}c_{23} + c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & - s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} + s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$, etc.

δ is the Dirac CP violating phase

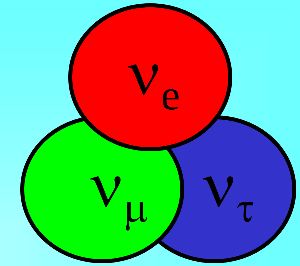
θ_{12} is the \`\`solar" mixing angle

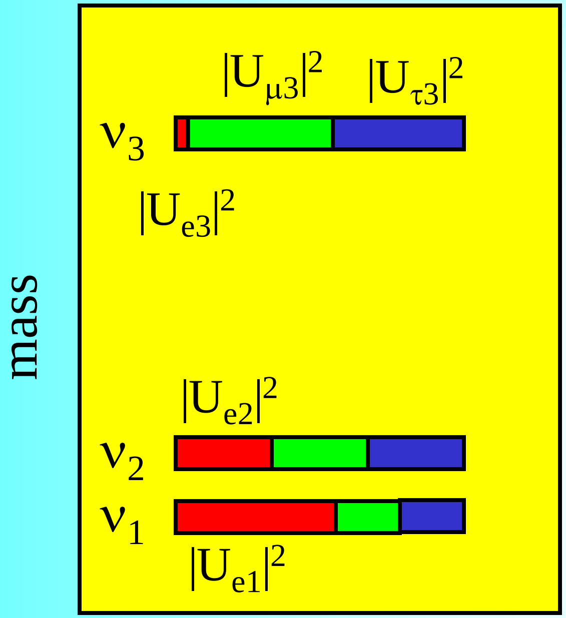
θ_{23} is the \`\`atmospheric" mixing angle

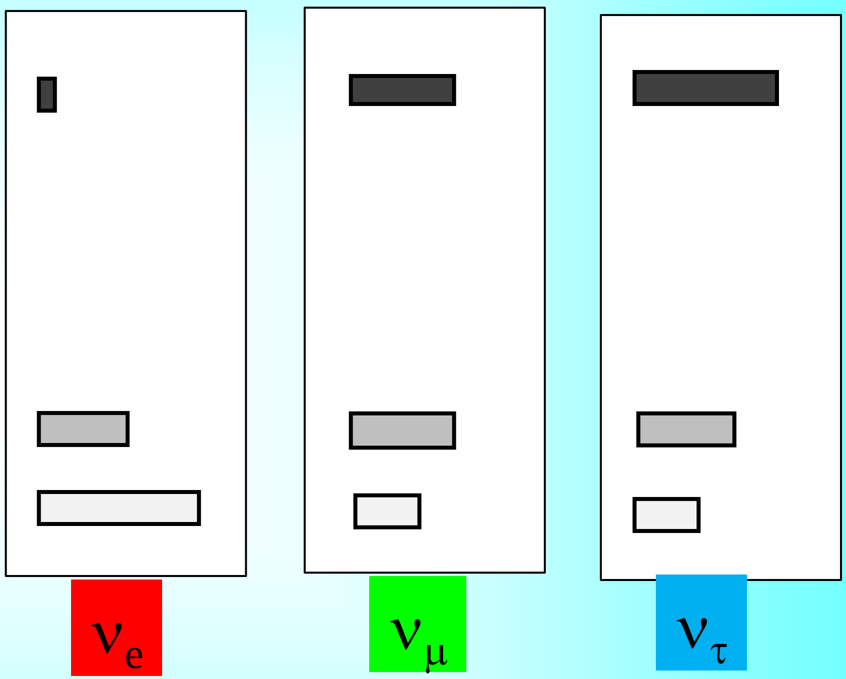
θ_{13} is the mixing angle determined by T2K, Daya Bay, CHOOZ, DC...

Mixing

Dual role







Flavor content of mass states

$$\nu_{mass} = U_{PMNS}^{+} \nu_f$$

Mass content of flavor states

$$\nu_f = U_{PMNS} \nu_{mass}$$

Who mixes neutrinos?

= creates certain (coherent) combinations of mass states

Mixing in CC → mixing in produced states

Non-trivial interplay of

Charged current weak interactions

Kinematics of specific reactions

Difference of the charged lepton masses

ν_e → $\beta-$ decays, energy conservation

ν_μ → $\pi-$ decays, chirality suppression

ν_τ → Beam dump, D - decay

Energy interval selection, loss of coherence

What about neutral currents?

Neutrino oscillations

B. Pontecorvo, 1957

"Mesonium and antimesonium"
Zh. Eksp.Teor. Fiz. 33, 549 (1957)
[Sov. Phys. JETP 6, 429 (1957)]

periodic transformation of one neutrino species (flavor) into another

- Consequence of mixing: production of mixed states
- effect of propagation of mixed states
- interference effect
- effect of the relative phase increase with time / distance :

Neutrino oscillations

THEORY:

Simple but not as simple as in most of textbooks (pointlike or plane wave)

BB

Conceptually wrong but gives correct final results for physically relevant situations

Wave packet picture (or QFT) should be used to avoid misconception.
Complications related to WP disappear in final result in physically relevant cases

…disappear in normalization

In principle:

Lagrangian

$$\frac{g}{2\sqrt{2}}\,\bar{l}\,\gamma^{\mu}(1-\gamma_5)\nu_l\,W^{+}_{\mu}$$

$$-\tfrac{1}{2}\,m_L\,\nu_L{}^{T}C\nu_L$$

$$-\,\bar{l}_L\,m_l\,l_R\;+\;h.c.$$

Starting from
the first principles

QFT

QM

Amplitudes,
probabilities
of processes

Observables,
number of
events, etc..

Actually not very simple

Quantum mechanics at macroscopic distances

What is the problem?

Set-up

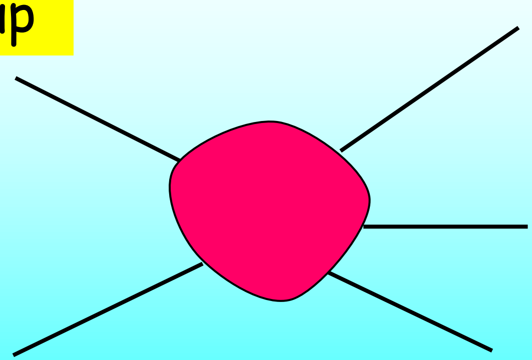
Formalism should be adjusted to specific physics situation

Initial conditions

Recall, the usual set-up

asymptotic states described by plane waves

- enormous simplification



single interaction region

Approximations

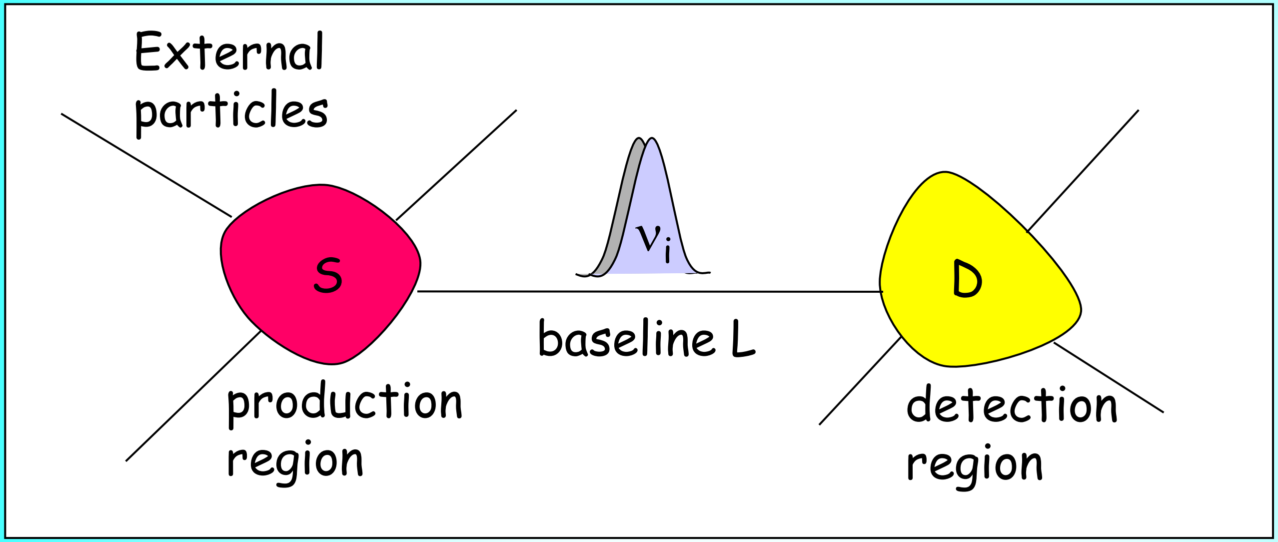
Approximations, if one does not want to consider whole history of the Universe to compute e.g. signal in Daya Bay

Truncating the process

Localizations

Of some initial and final particles

Oscillation set-up: localization



E. Akhmedov, A.S.

BB2

Finite space and time phenomenon

Two interaction regions in contrast to usual scattering problem : wave packets (wave functions) of external particles (e.g. nuclei) which determine localization

Neutrinos: propagators for mass states or as real particles on mass shell

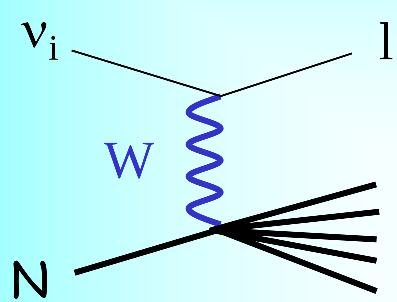
Interference of two amplitudes with exchange of ν_1 and ν_2

In terms of mass eigenstates

Without flavor states

$$\frac{g}{2\sqrt{2}} U_{PMNS}\Big|_{li} \bar{l}\,\gamma^{\mu}(1-\gamma_5)\,\nu_i\, W^{+}_{\mu} + \text{h.c.}$$

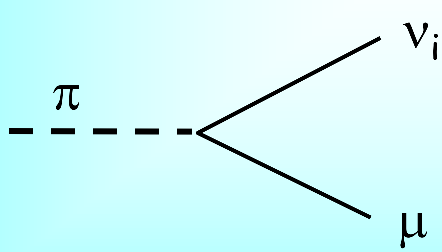
Scattering



interaction constant

Eigenstates of the Hamiltonian in vacuum

$\pi \rightarrow \mu\ \nu_i$



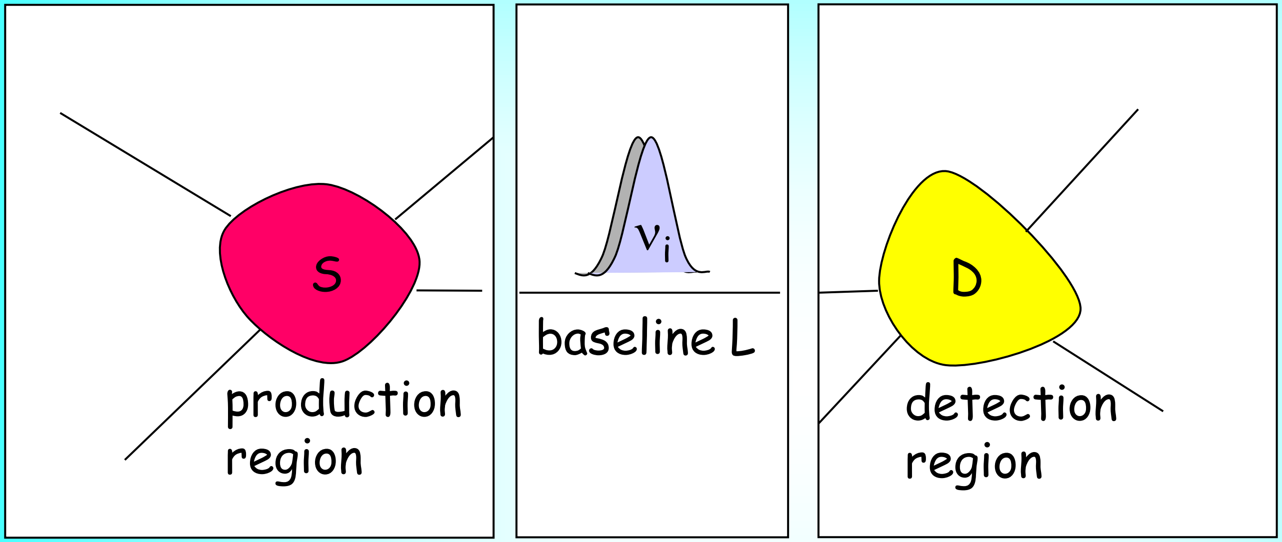
Lagrangian of interactions

wave functions of accompanying particles

compute the wave functions of neutrino mass eigenstates

Wave packets

Factorization



If oscillation effect in production/detection regions can be neglected

r_D , r_S << l_ν

⇒ **factorization**

Production, propagation and detection can be considered as three independent processes

Wave packets and oscillations

Suppose ν_α is produced in the source centered at x = 0, t = 0

After formation of the wave packet (outside the production region)

$$|\nu_\alpha(x,t)\rangle = \Sigma_k U_{\alpha k}^* \Psi_k(x, t)|\nu_k\rangle$$

$$\Psi_k \sim \int dp\, f_k(p - p_k)\, e^{ipx - iE_k(p)t}$$ - WF of k-mass state

$$E_k(p) = \sqrt{p^2 + m_k^2}$$ - dispersion relation

$f_k(p - p_k)$ - the momentum distribution function peaked at

p_k - the mean momentum

Expanding around mean momentum

describes spread of the wave packets

$$E_k(p) = E_k(p_k) + (dE_k/dp)\Big|_{p_k}(p - p_k) + (dE_k^2/dp^2)\Big|_{p_k}(p - p_k)^2 + ...$$

$$v_k = (dE_k/dp)\Big|_{p_k} = (p/E_k)\Big|_{p_k}$$ - *group velocity of* ν_k

Shape factor and phase factor

$E_k(p) = E_k(p_k) + v_k(p - p_k)$

(neglecting spread of the wave packets)

Inserting into $\Psi_k \sim \int dp\, f_k(p - p_k)\, e^{ipx - iE_k(p)t}$

$$\Psi_k \sim e^{ip_k x - iE_k(p_k)t}\, g_k(x - v_k t)$$

Phase factor

$$e^{i\phi_k}$$

$$\phi_k = p_k x - E_k t$$

Depends on mean characteristics p_k and corresponding energy:

$$E_k(p_k) = \sqrt{p_k^2 + m_k^2}$$

Shape factor

$$g_k(x - v_k t) = \int dp\, f_k(p)\, e^{ip(x - v_k t)}$$

Depends on x and t only in combination $(x - v_k t)$ and therefore describes propagation of the wave packet with group velocity v_k without change of the shape

Mixing & mixed states **

One needs to compute the state which is produced
i.e. compute

the shape factors $g_k(x - v_k t)$

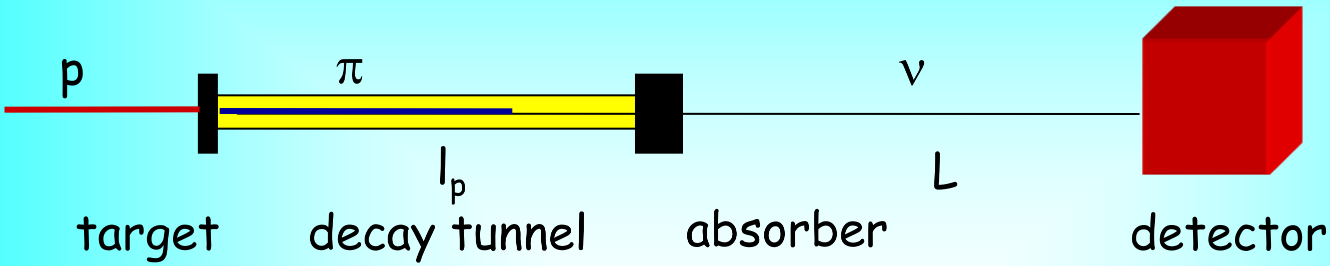
mean momenta p_k

- Fundamental interactions
- Kinematics
- characteristics of parent and accompanying particles

Process dependent

If heavy neutrinos are present but can not be produced for kinematical reasons, flavor states in Lagrangian differ from the produced states, etc..

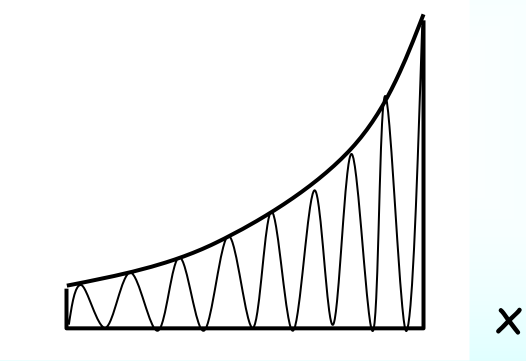
Neutrino wave packets **



D. Hernandez, AS

E. Kh Akhmedov,
D. Hernandez, AS
arXiv:1110.5453

ν wave packet



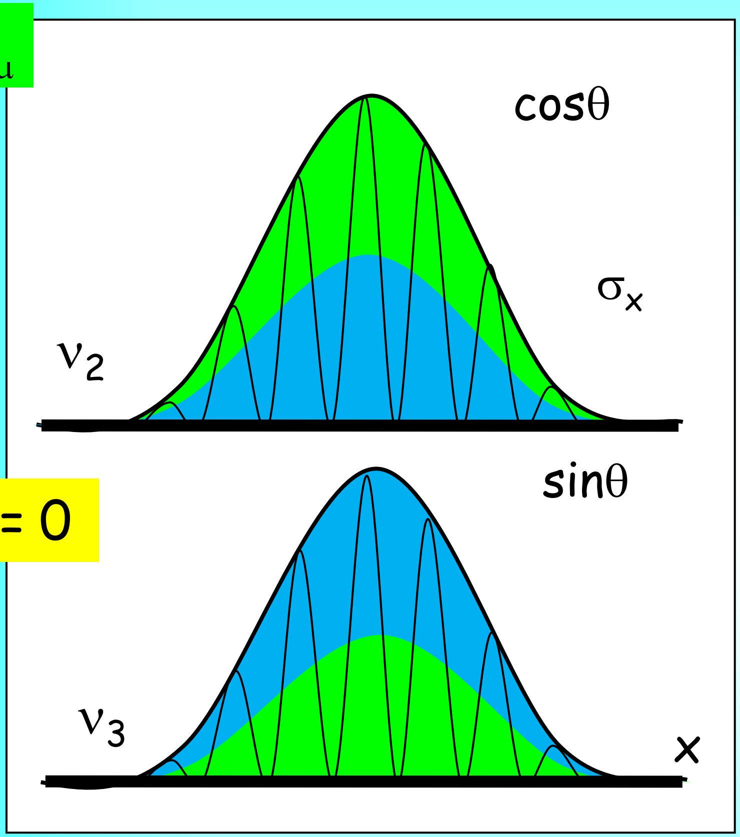
The length of the ν wave packet
emitted in the forward direction

$$\sigma = l_p \frac{v - v_\pi}{v_\pi}$$

Doppler effect

Mixing and wave packets

ν_μ



$\phi = 0$

					ϕ
ν_μ	= cosθ	ν_2	+ sinθ	ν_3	0
ν_τ	= - sinθ	ν_2	+ cosθ	ν_3	π

$e^{i\pi}$

differ by
- mass content
- phase difference

Inverting

$\nu_2 = \cos\theta\ \nu_\mu - \sin\theta\ \nu_\tau$

$\nu_3 = \cos\theta\ \nu_\tau + \sin\theta\ \nu_\mu$

Interference of the same flavor parts

k = 2,3

$$\Psi_k = g_k(x - v_k t)\ e^{i\phi_k}$$

Shape factor
v_k - group velocity

Phase factor
$\phi_k = p_k x - E_k t$

E_k and p_k - mean energy and momentum in packet

... for maximal mixing

$\theta = \pi/4$

$$\nu_\mu = (\nu_2 + \nu_3) / 2^{1/2}$$
$$\nu_\tau = (- \nu_2 + \nu_3) / 2^{1/2}$$

The difference in phase only, mass composition is the same!
Interaction of neutrino state depends on the phase difference between mass eigenstates

$$\nu(\phi) = (e^{i\phi} \nu_2 + \nu_3)/2^{1/2}$$

$$\nu(\phi) = \begin{cases} \nu_\mu & \phi = 0 \\ \nu_\tau & \phi = \pi \\ \nu_\mu , \nu_\tau & 0 < \phi < \pi \end{cases}$$

Flavor composition (interaction properties) depends on ϕ

Propagation

Additional phase difference due to difference of masses

$$|\nu(x,t)\rangle = \cos\theta\, g_2(x - v_2 t)\,|\nu_2\rangle + \sin\theta\, g_3(x - v_3 t)e^{i\phi}|\nu_3\rangle$$

$\phi = \phi_3 - \phi_2$ - oscillation phase changes with (x,t)

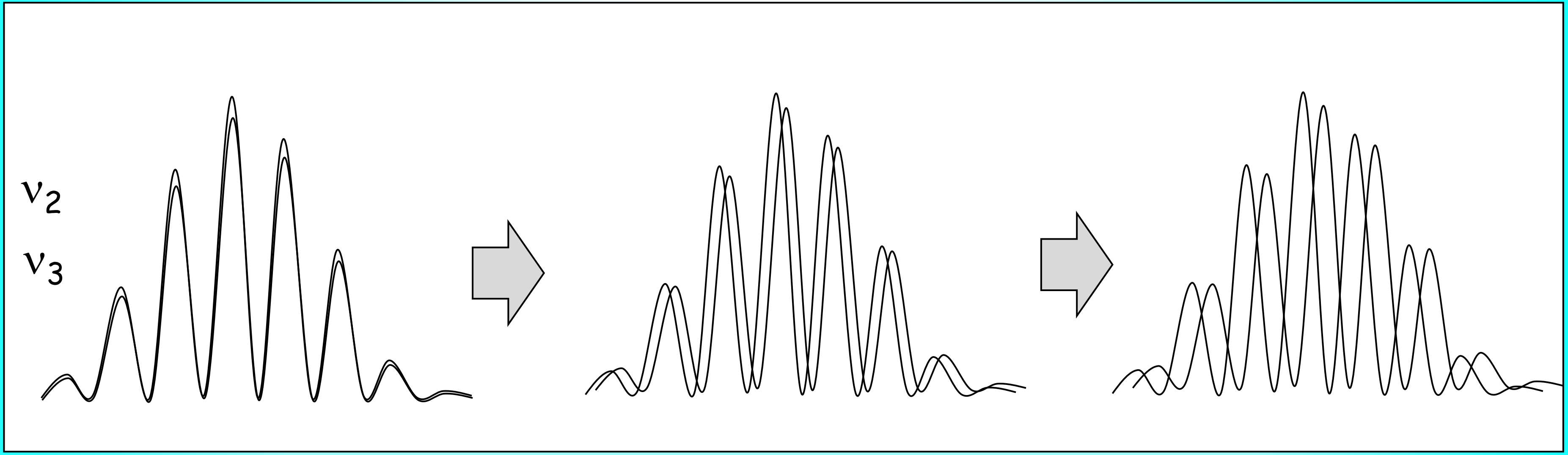
for $\phi \neq 0$ components ν_τ will not cancel → appearance of ν_τ

Oscillations

Difference of masses of ν_2 and ν_3 → Difference of phase velocities → Phase difference increase with distance

$$\phi = \frac{\Delta m^2 L}{2E}$$

$$\Delta m^2 = m_3^2 - m_2^2$$



distance

L

shift of oscillatory patterns

$\phi = 0$

ν_μ

Oscillation phase

$\phi = \phi_2 - \phi_1$ $\phi_i = - E_i t + p_i x$ $p_i = \sqrt{E_i^2 - m_i^2}$ Dispersion relation

$\phi = \Delta E t - \Delta p x$

These are averaged characteristics of WP

where

$$\Delta p = (dp/dE)\Delta E + (dp/dm^2)\Delta m^2 = 1/v_g \, \Delta E + (1/2p)\, \Delta m^2$$

group velocity

insert

$$\phi = (\Delta E/v_g)\,(v_g t - x) + \frac{\Delta m^2}{2E} x$$

standard oscillation phase

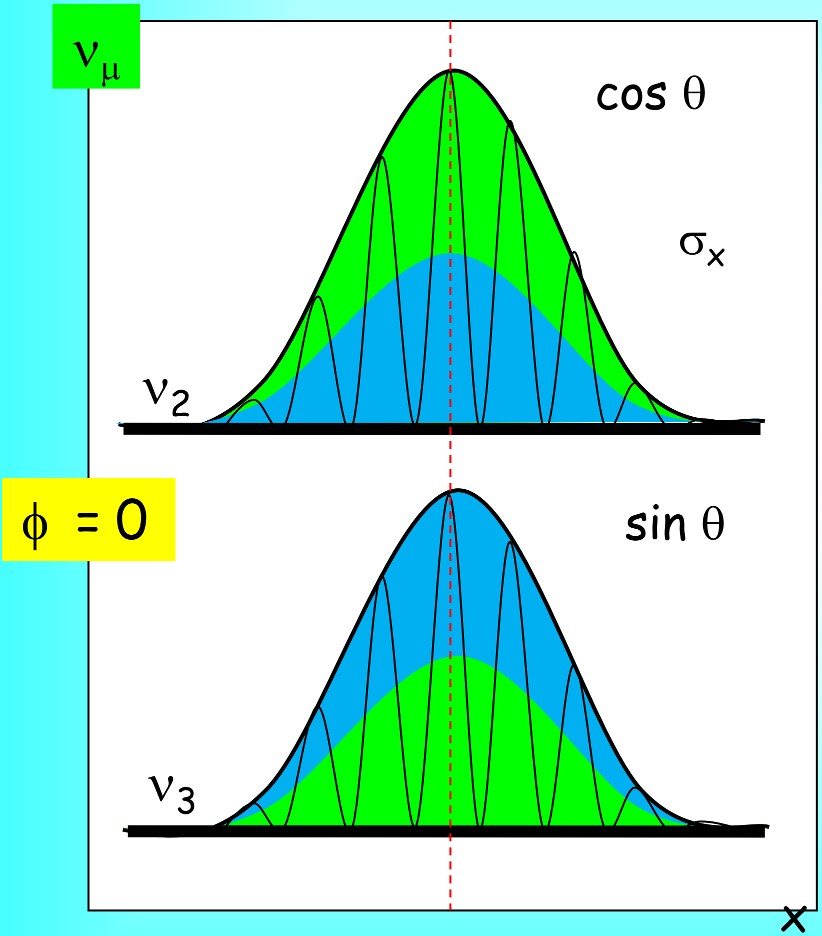
$\Delta E \sim \Delta m^2/2E$ $< \sigma_x$

Averaged energies

$\sigma_x \Delta m^2/2E$

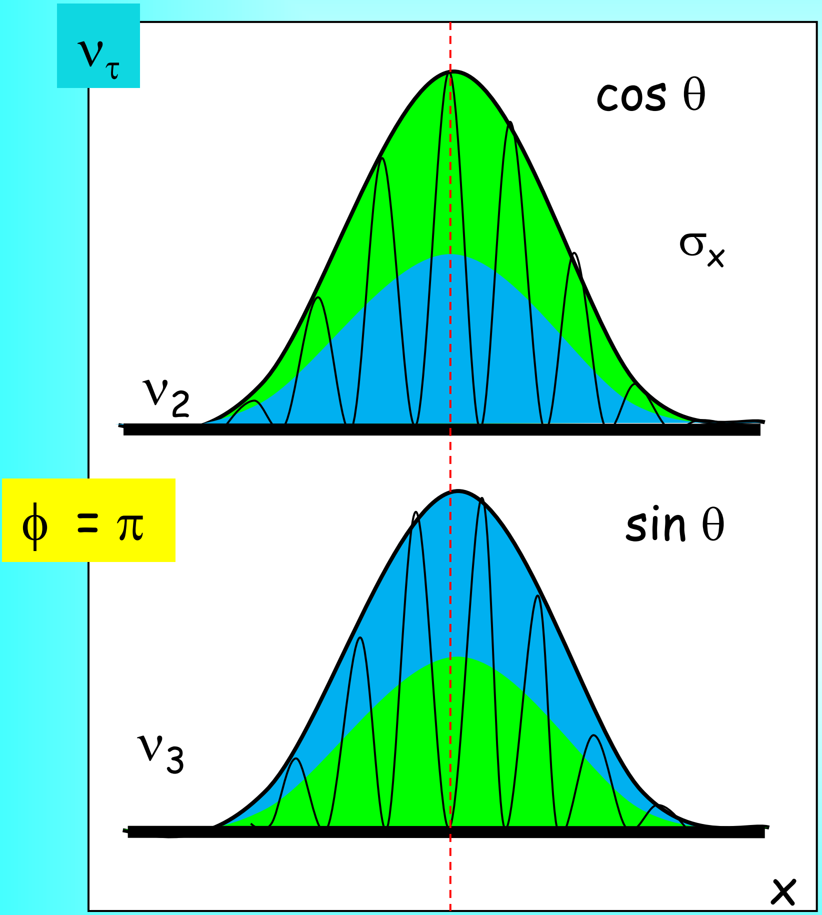
Oscillation effect over the size of WP usually- small → Phase difference along the wave packets is the same

Oscillations



- Destructive interference of the tau parts
- Constructive interference of muon parts

Oscillations



- Destructive interference of the muon parts
- Constructive interference of tau parts

Detection: **

As important as production
should be considered symmetrically with production

Detection effect can be included in
the generalized shape factors

$$g_k(x - v_k t) \rightarrow G_k(L - v_k t)$$

$x \rightarrow L$ - distance between central points of the production and detection regions

HOMEWORK...

Based on

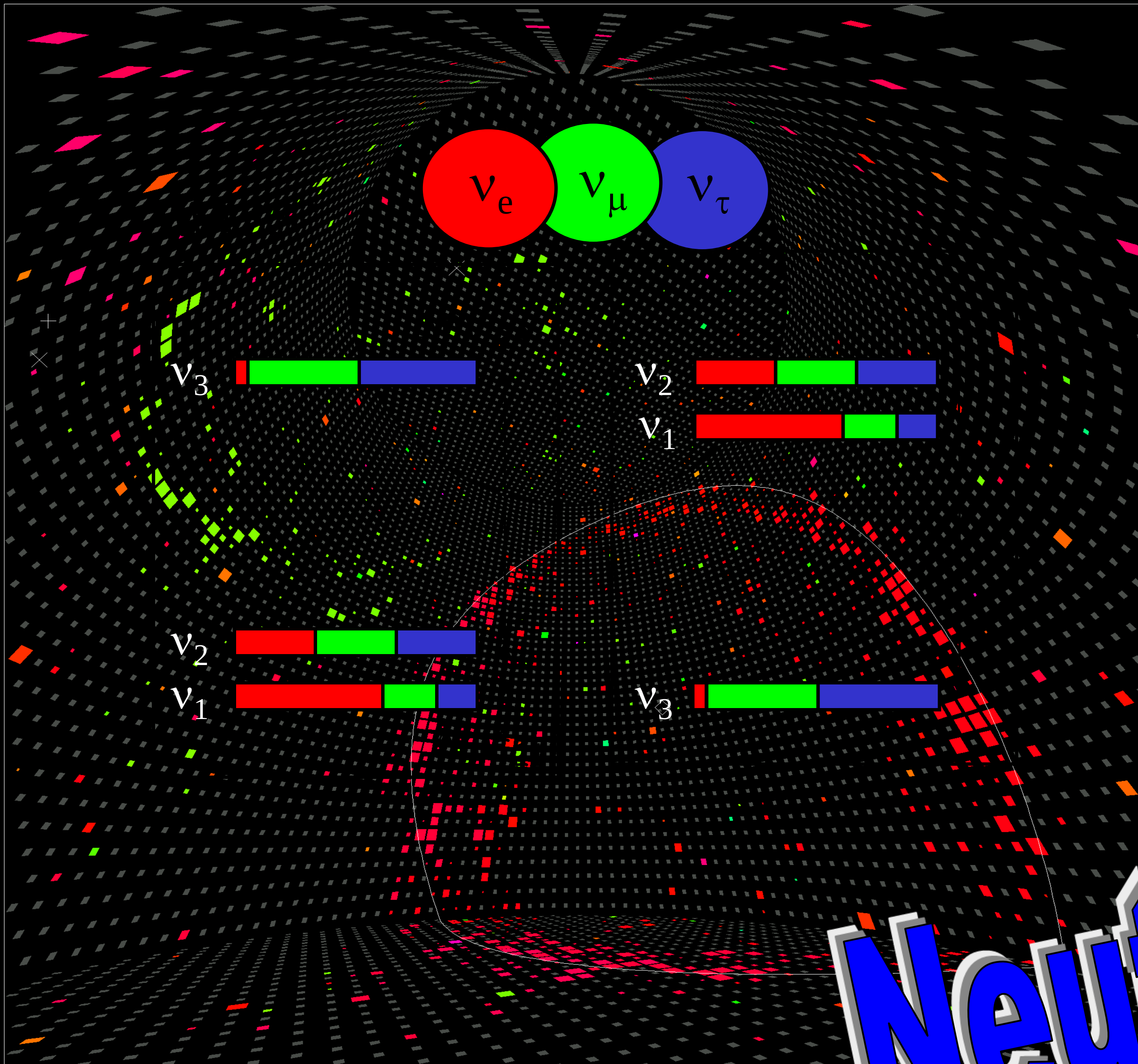
[1] Neutrino production coherence and oscillation experiments.
E. Akhmedov, D. Hernandez, A. Smirnov, JHEP 1204 (2012) 052,
arXiv:1201.4128 [hep-ph]

[2] Neutrino oscillations: Entanglement, energy-momentum conservation and QFT.
E.Kh. Akhmedov, A.Yu. Smirnov, Found. Phys. 41 (2011) 1279-1306
arXiv:1008.2077 [hep-ph]

[3] Paradoxes of neutrino oscillations.
E. Kh. Akhmedov, A. Yu. Smirnov Phys. Atom. Nucl. 72 (2009) 1363-1381
arXiv:0905.1903 [hep-ph]

[4] Active to sterile neutrino oscillations: Coherence and MINOS results.
D. Hernandez, A.Yu. Smirnov, Phys.Lett. B706 (2012) 360-366
arXiv:1105.5946 [hep-ph]

[5] Neutrino oscillations: Quantum mechanics vs. quantum field theory.
E. Kh. Akhmedov, J. Kopp, JHEP 1004 (2010) 008
arXiv:1001.4815 [hep-ph]



Neutrinos