Neutrino Masses and Mixing: New Symmetry of Nature?

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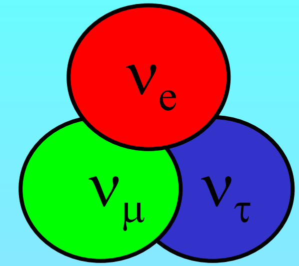
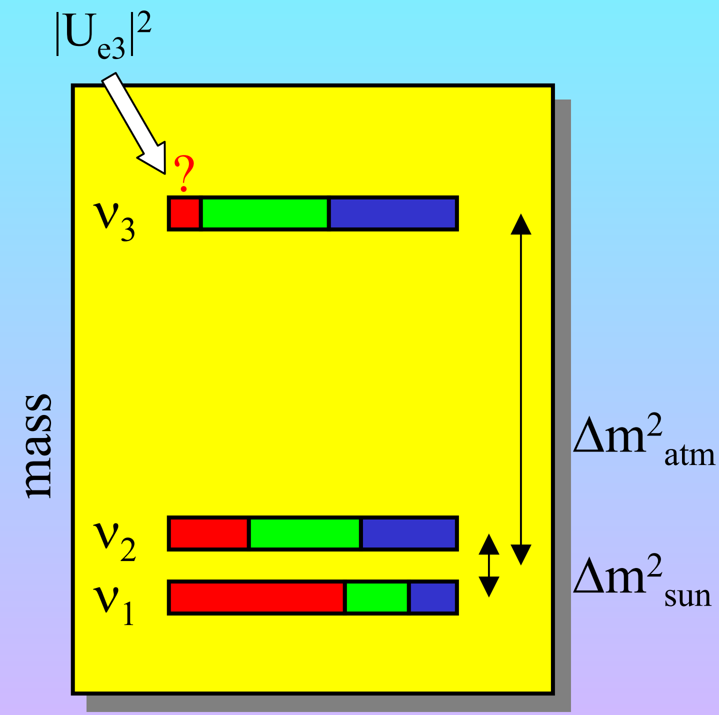
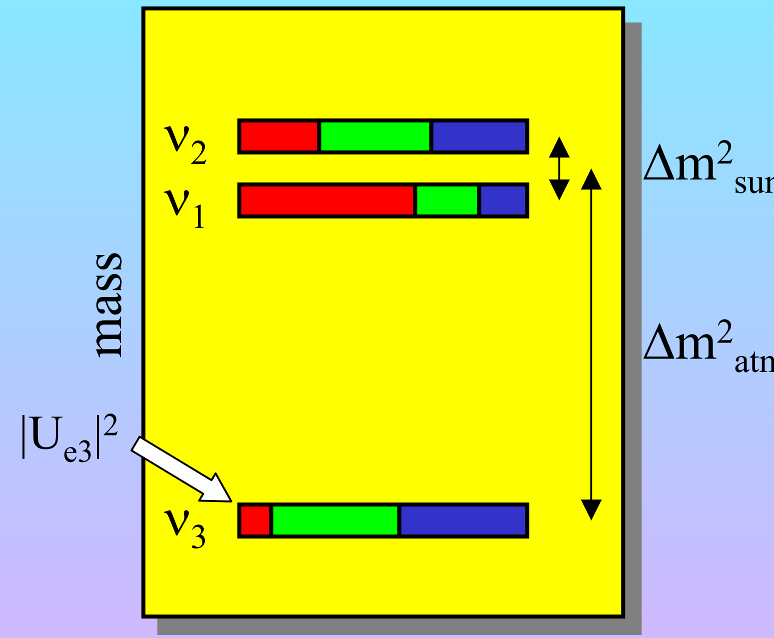
- Summary of results
- New symmetry of nature?
- Symmetry case
- No-symmetry case
- Flavor symmetry or quark-lepton symmetry?

Mass spectrum and mixing





Normal mass hierarchy (ordering)



Inverted mass hierarchy (ordering)

- Type of mass spectrum: with Hierarchy, Ordering, Degeneracy ➡ absolute mass scale
- Type of the mass hierarchy: Normal, Inverted
- $U_{e3} = ?$

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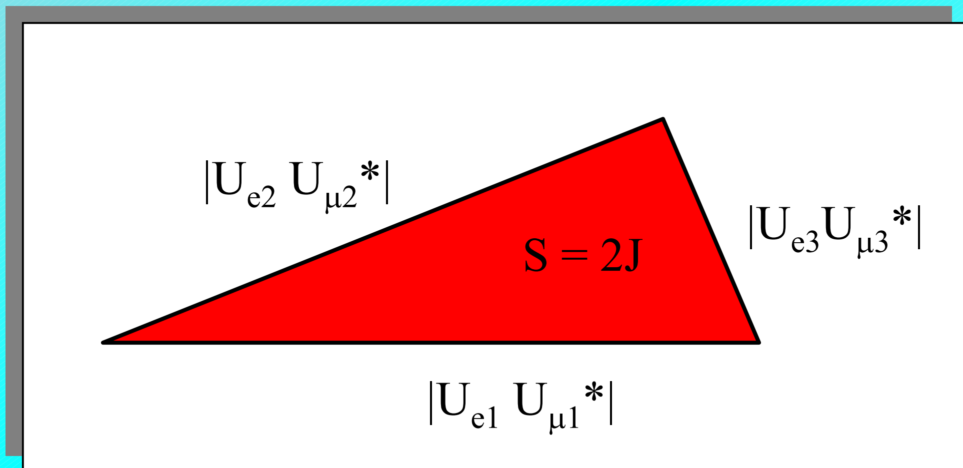
Leptonic Unitarity Triangle

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.78 - 0.88 & 0.47 - 0.62 & 0.0 - 0.23 \\ 0.18 - 0.55 & 0.40 - 0.73 & 0.57 - 0.82 \\ 0.19 - 0.55 & 0.41 - 0.75 & 0.55 - 0.82 \end{pmatrix}$$

Global fit of the oscillation data 3σ

M.C. Gonzalez-Garcia ,



- $|U_{e3}| = 0.16$
- nearly best fit values of other angles

Y. Farsan, A.S.

Can we reconstruct the triangle?
Can we use it to determine the CP-violating phase?

$$J = s_{12}\, c_{12}\, s_{13}\; c_{13}^2\, s_{23}\, c_{23} \sin\delta$$

Problem: coherence (we deal with coherent states and not mass eigenstates of neutrinos)

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Main features

- Heaviest mass: $m_h > \sqrt{\Delta m_{23}^2} > 0.04$ eV $\Rightarrow$ $\boxed{m_h \sim (0.04 - 0.4)\ \text{eV}}$

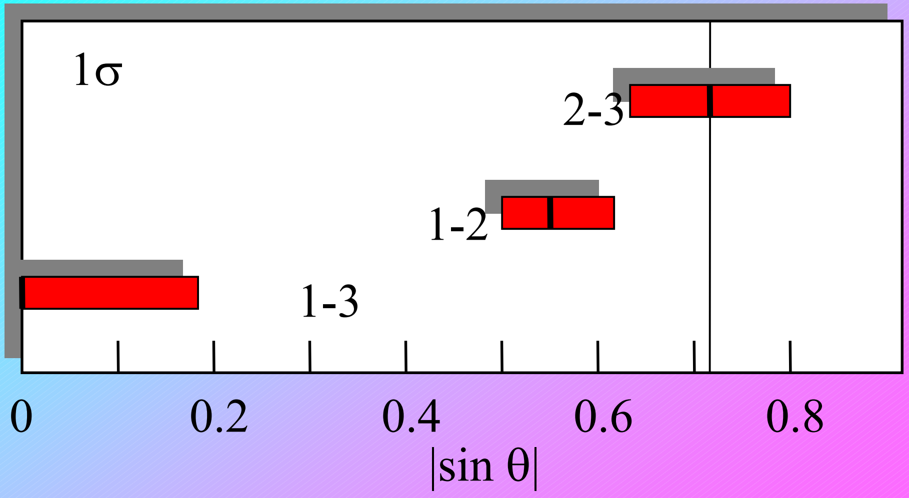
- Hierarchy of mass squared differences: $\boxed{|\Delta m_{12}^2 / \Delta m_{23}^2| = 0.01 - 0.15}$

- No strong hierarchy of masses: $|m_2/m_3| > \sqrt{|\Delta m_{12}^2 / \Delta m_{23}^2|} = 0.18^{+0.22}_{-0.08}$

- Bi-large or large-maximal mixing between neighboring families (1- 2) (2- 3):

$$\boxed{\theta_{12} + \theta_C = \theta_{23} \sim 45^o}$$

- bi-maximal + corrections?



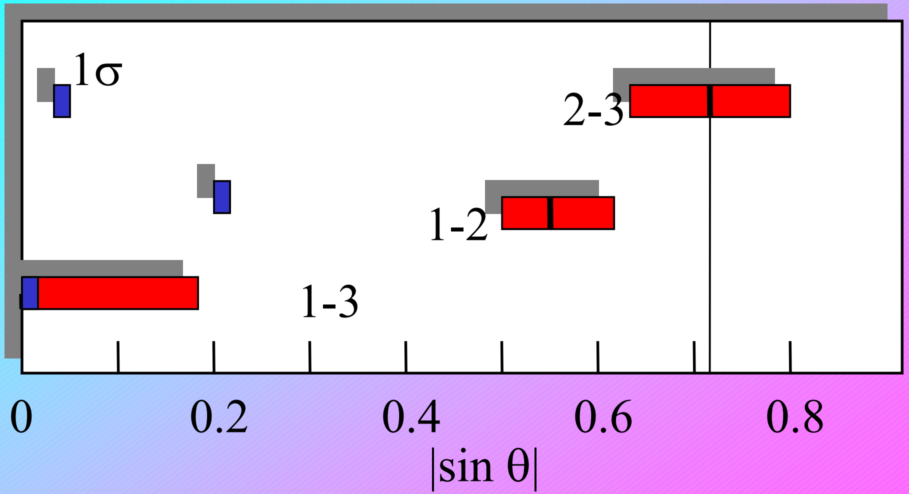
Quarks and Leptons

Mixing	Quarks	Leptons
1-2, θ_{12}	13^o	32^o
2-3, θ_{23}	2.3^o	45^o
1-3, θ_{13}	$\sim 0.5^o$	$<13^o$

$$\theta_{12} + \theta_C = \theta_{23} \sim 45^o$$

Hierarchy of mass:

- Neutrinos $|m_2 / m_3| > 0.18$
- Charged leptons $|m_\mu / m_\tau| = 0.06$
- Down quarks $|m_s / m_b| \sim 0.02 - 0.03$
- Up-quarks $|m_c / m_t| \sim 0.005$



New Symmetry of Nature?

What can testify ?

Maximal or close to maximal 2-3 mixing

Degenerate or partially degenerate spectrum

Very small 1 -3 mixing

$|0.5 - \sin^2\theta_{23}| \ll \sin^2\theta_{23}$

$\Delta m \ll m$

$\theta_{13} \ll \theta_{12} \times \theta_{23}$

2ν data fit:
Best fit value:
$\sin^2 2\theta_{23} = 1.0$

$\sin^2 2\theta_{23} > 0.91$, 90% CL

$m_1 = m_2 = m_3$

$m_3 = m_2 \ll m_1$
(inverted hierarchy) ?

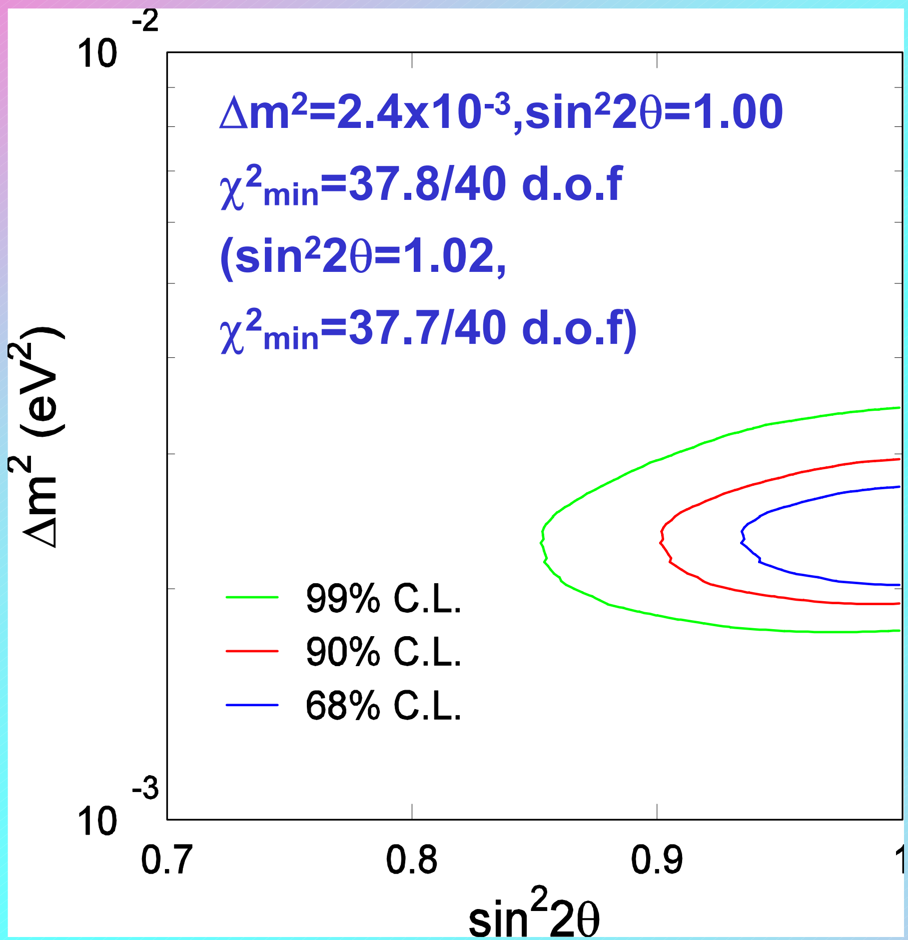
Oscillation parameters

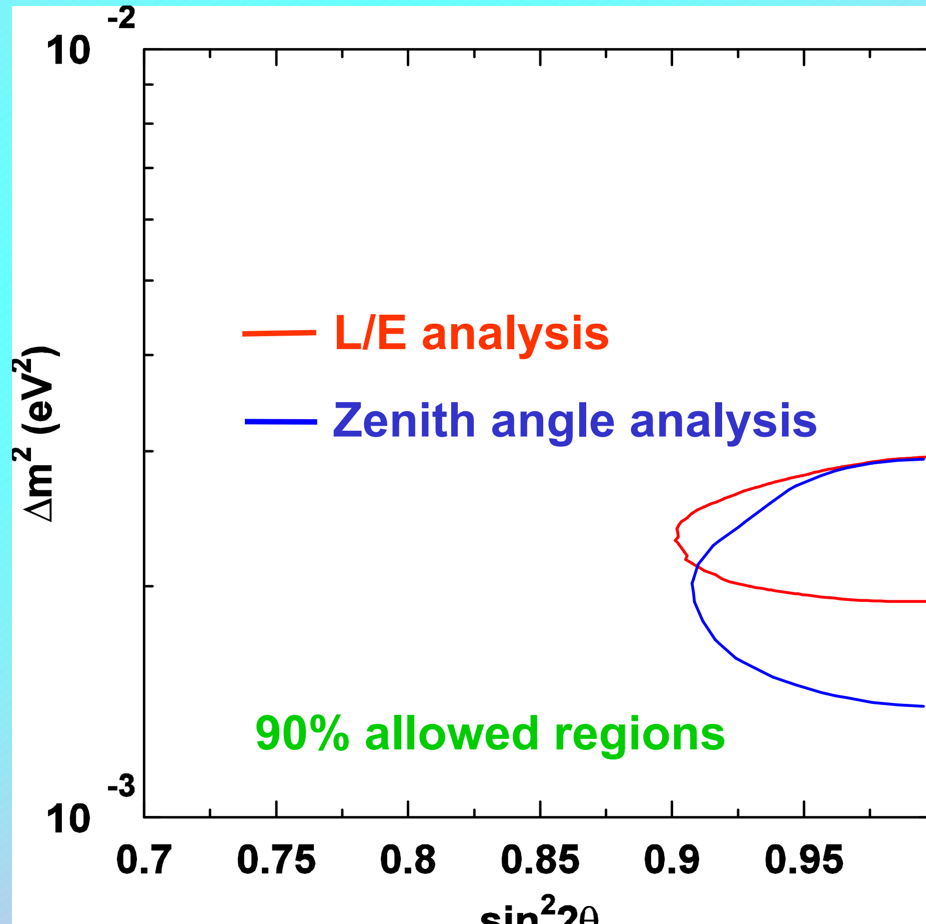
SuperKamiokande

Preliminary

$1.9\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2

$0.90 < \sin^2 2\theta$ at 90% C.L.



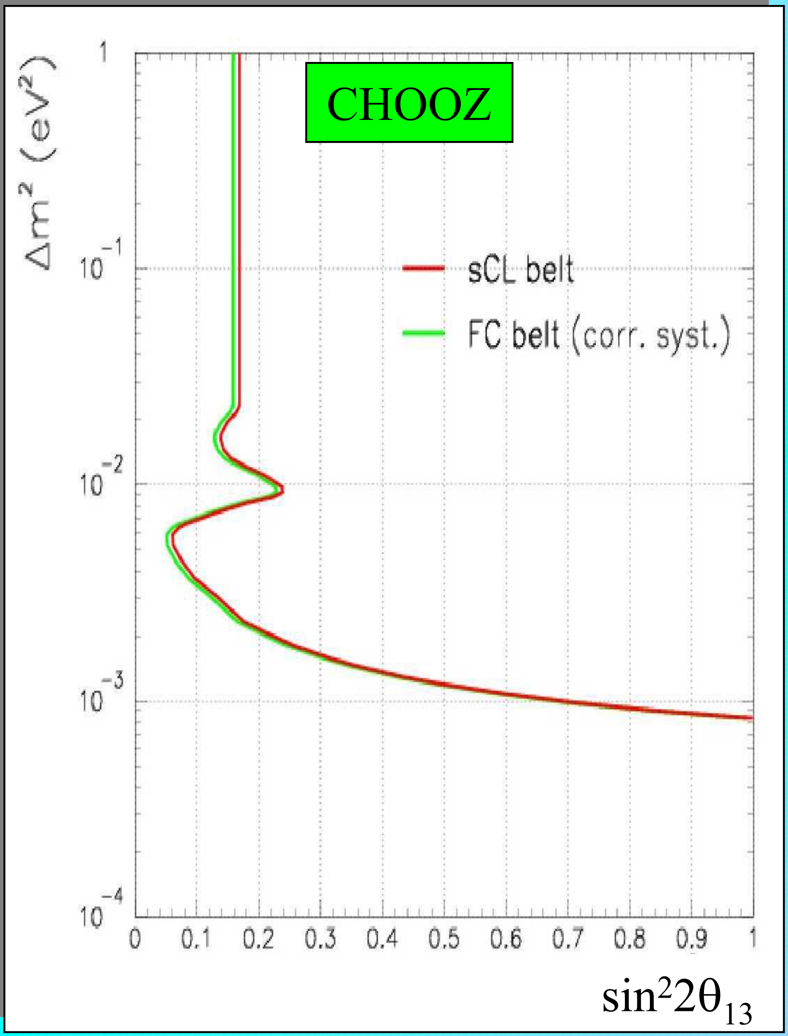


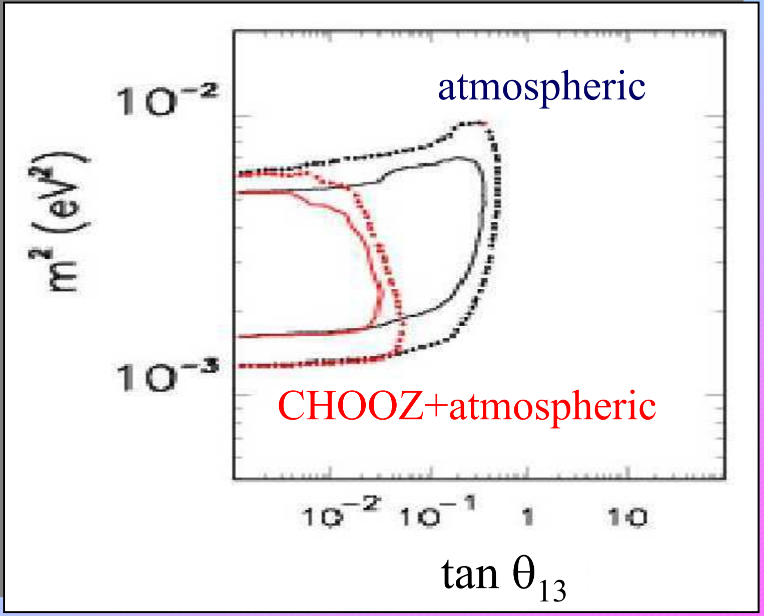
U_e3

$U_{e3} = \sin\theta_{13}\, e^{-i\delta}$
$= \langle \nu_e \mid \nu_3 \rangle$

Has important implications for phenomenology and theory:

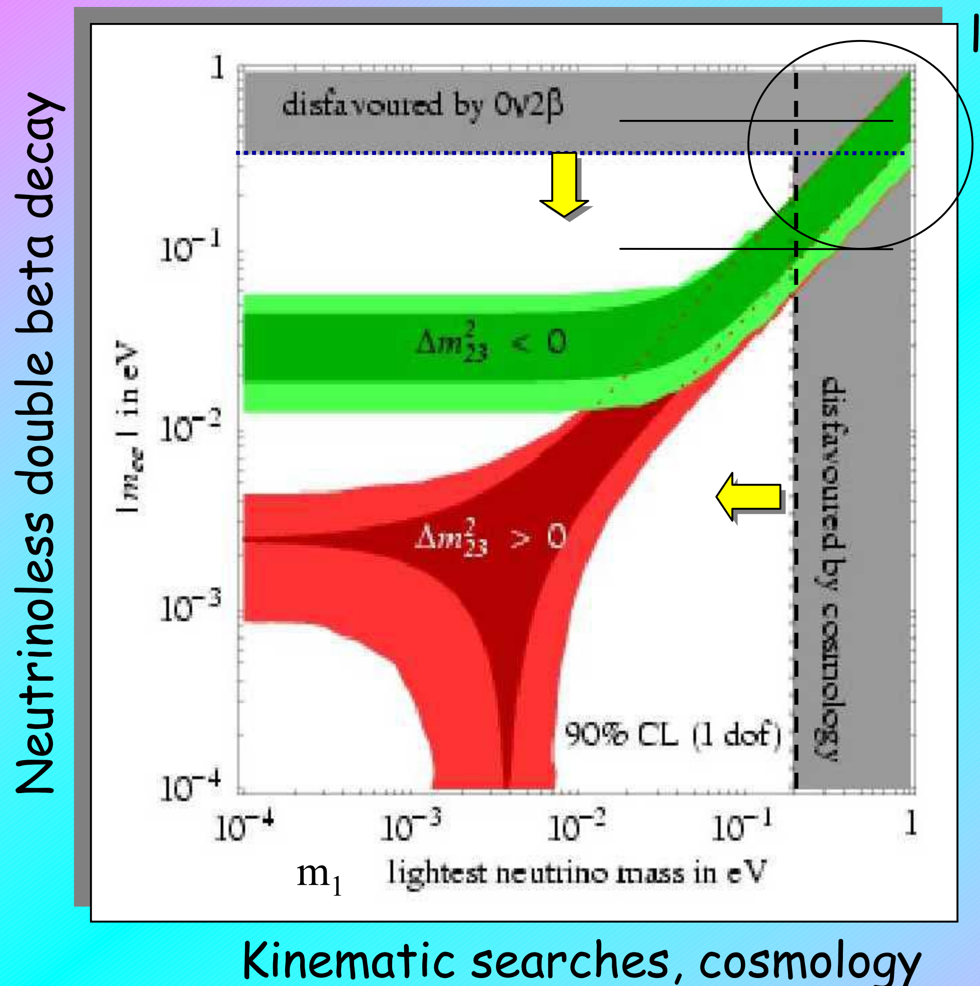
- supernova neutrinos: can lead to O(1) effect;
- atmospheric neutrinos (resonance enhancement, parametric effects);
- allows to establish mass hierarchy;
- LBL experiments;
- CP-violations requires U_{e3} = 0;
- key test of models of large lepton mixing

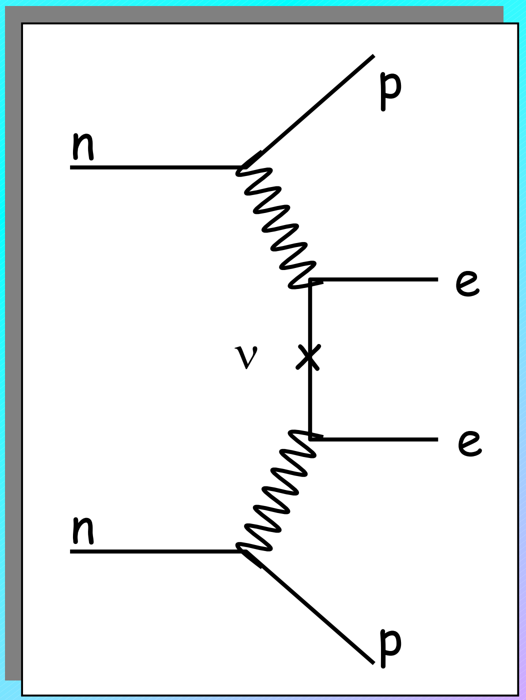




Absolute scale of mass

F. Feruglio, A. Strumia, F. Vissani





$$m_{ee} = \Sigma_k U_{ek}^2 m_k e^{i\phi(\kappa)}$$

Both cosmology and
double beta decay
have similar sensitivities

Degenerate spectrum

$\Delta m/m_0 \sim \Delta m_{atm}{}^2/2m_0{}^2$ ⇒ Degenerate: $m_0 >$ (0.08 - 0.10) eV

- Large or maximal mixing ⇔ Mass degeneracy

- Cosmology: m_0 = 0.20 +/- 10 eV

  Large scale structure analysis including X-ray galaxy clusters

  S.W Allen, R.W. Schmidt, S. L. Bridle

- Heidelberg-Moscow result
  77.7 kg y
  4.2σ effect

  $m_i > m_{ee}$ at least for one mass eigenstate

  m_{ee} = (0.29 - 0. 60) eV (3σ)

  m_{ee}(b.f.) = 0.44 eV

  H. Klapdor-Kleingrothaus, et al.

Relations?

Degeneracy of mass spectrum

Deviation of 2-3 mixing from maximal

Symmetry which leads to maximal 2-3 mixing e.g. Permutations, Z_2 can give $\sin\theta_{13} = 0$

?

1-3 mixing

Violation of the symmetry

$D_{23} \neq 0$

$\sin\theta_{13} \neq 0$

Large mixing and Degeneracy

Degeneracy parameter: $\delta_{23} = \Delta m/m = \Delta m^2/2m^2$

Deviation from maximal mixing: $D_{23} = 0.5 - \sin^2\theta_{23}$

Degeneracy vs. deviation.

examples

1). $\begin{pmatrix} 0 & 1 \\ 1 & \varepsilon \end{pmatrix}$ ⇒ $D_{23} = \delta_{23}$

2). $\begin{pmatrix} 1 & \varepsilon \\ \varepsilon & 1 \end{pmatrix}$ ⇒ $D_{23} = 0$, $\delta_{23} = 2\varepsilon$ maximal mixing, arbitrary mass split

3). $\begin{pmatrix} \varepsilon & 1 \\ 1 & -\varepsilon \end{pmatrix}$ ⇒ $D_{23} = \varepsilon/2$, $\delta_{23} = 0$ arbitrary mixing zero mass split

For $m = 0.25$ eV: $\delta_{23} = 0.03$, $D_{23} \sim 0.1$ will exclude the possibility 1).

Simple relation is absent due to presence of

- third neutrino
- Majorana phases

⇒ Smaller δ_{21} is associated to larger D_{21}

Two extreme cases

Quasi-degenerate spectrum

- New symmetry
  SO(3), A_4, Z_2 , ...
- Quark -lepton symmetry?

S Barshay,
M. Fukugita,
T. Yanagida
...

Hierarchical Spectrum

- No particular symmetry
- Deviation from maximal mixing
- Quark-lepton analogy/symmetry

Symmetry case

In the flavor basis: $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$

$$m_\nu = m_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} + \delta m$$

$\delta m \ll m_0$

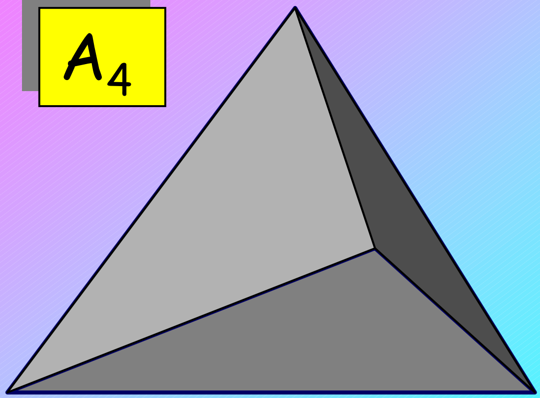
Features:

- Degenerate spectrum: $m_1 = m_2 = - m_3$
- Maximal or near maximal 2-3 mixing
- Opposite CP parities of ν_2 and ν_3
  ν_2 and ν_3 form pseudo-Dirac pair
- Neutrinoless double beta decay: $m_{ee} \sim m_0$
- Most of the oscillation parameters are not imprinted in to the dominant structure: all Δm^2 the as well as 1-2 and 1-3 mixings are determined by δm.
- δm is due to the radiative corrections?

Symmetry

E. Ma,
G. Rajasekaran
K.S. Babu,
J. Valle

A_4



Symmetry group of even permutations of 4 elements

Symmetry of tetrahedron: (4 faces, 4 vertices)

→ Plato's fire

Irreducible representations: $\underline{3}$, $\underline{1}$, $\underline{1'}$, $\underline{1''}$

- Transformations under A_4 — $(\nu_i\,,\ e_i) \sim \underline{3}$ $(u_i\,,\ d_i) \sim \underline{3}$ $(i = 1, 2, 3)$ $H_{1,2} \sim \underline{1}$

  $u_1^c, d_1^c, e_1^c \sim \underline{1}$ $u_2^c, d_2^c, e_2^c \sim \underline{1'}$ $u_3^c, d_3^c, e_3^c \sim \underline{1''}$

- New heavy quarks leptons and Higgs are introduced — U_i, U_1^c, D_i, D_1^c, E_i, E_1^c, N_i^c, χ_i $\sim \underline{3}$

- Explicit asymmetry of charged fermions and neutrino sector:

  no ν_i^c and N_i → Leads to different mixing of quarks and leptons

Model: quarks and leptons

- Problem to include leptons and quarks in unique model
  Symmetry between leptons and quarks is explicitly broken

- Neutral and charge lepton sectors are different:

Extra symmetries required (e.g. Z_3)

H_1: e_i — E_i^c ----- E_i — e_1^c $\quad \langle \chi_i \rangle$

M_E

A_4 is broken

H_2: ν_i — N_i^c

M_N

$i = 1, 2, 3$

Majorana mass

- Seesaw
- Mixing - from the charged leptons in the symmetry basis

Mixing of quarks: $U_L^+ U_L = I$

Mixing of leptons: $U_L^T U_L = M_0$

$$U_L = \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix}$$

- Oscillation parameters are determined by δm
  - an additional theory independent on A_4 required

$\omega = \exp(-2i\pi/3)$

- Masses and mixing angles are unrelated

Do we really see a symmetry?

1). The only serious indication is nearly maximal 2-3 mixing:

$\sin^2 2\theta_{23} > 0.91, \quad 90\ \%\ CL$

2). $\sin^2 2\theta_{23}$ is a ``bad'' parameter from theoretical point of view

$\sin^2\theta_{23}$ is better, but for this parameter:

$\sin^2\theta_{23} = \quad (0.35 - 0.65) \quad 90\ \%\ CL$ ⇒

Relative deviation from maximal mixing (1/2) can be large

$\Delta\sin^2\theta_{23} / \sin^2\theta_{23} \sim \quad 0.7$

3). The atmospheric neutrino results may provide some hint that the mixing is not maximal

Excess of the e-like events (?)

Three neutrino analysis of data is needed

LMA oscillations of atmospheric neutrinos

Excess of the e-like events in sub-GeV

$$\frac{F_e}{F_e^0} - 1 = P_2 (r\, c_{23}^2 - 1)$$

``screening factor"

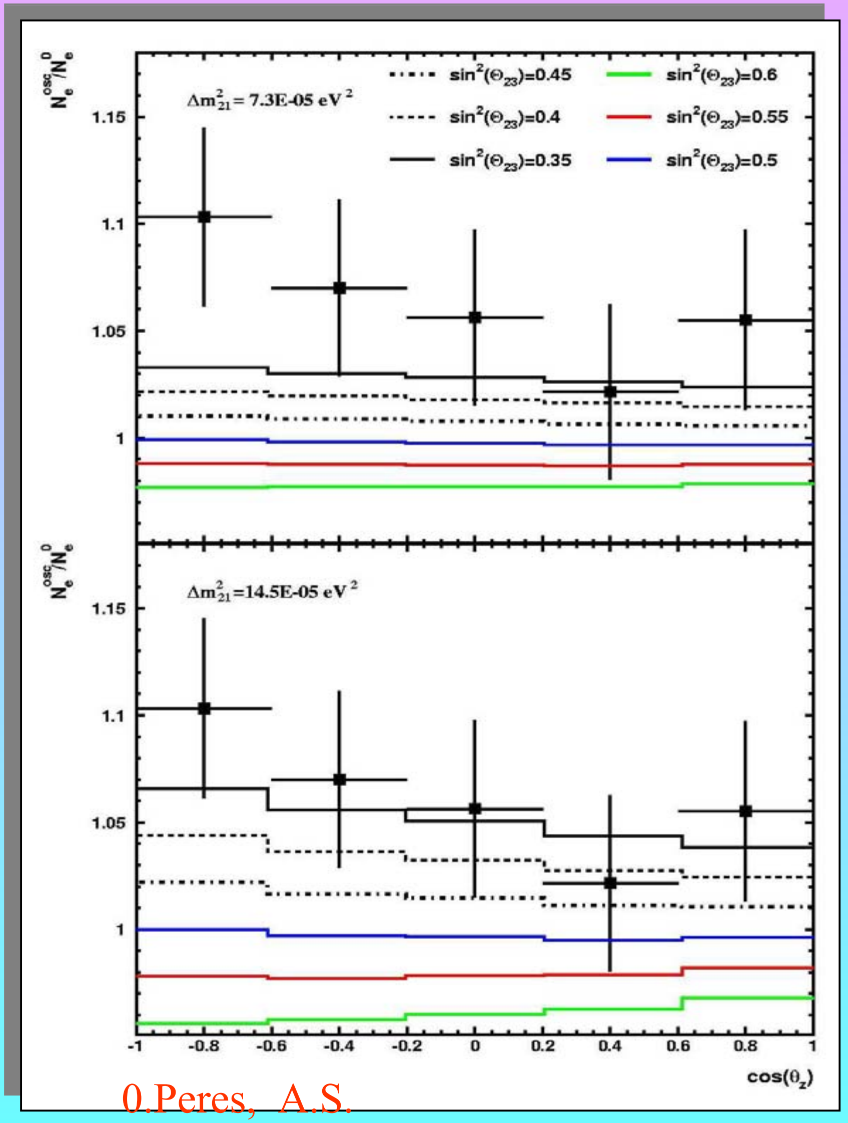
$P_2 = P(\Delta m^2_{12}, \theta_{12})$ is the 2ν transition probability

In the sub-GeV sample $r = F_\mu^0 / F_e^0 \sim 2$

The excess is zero for maximal 23- mixing

Searches of the excess can be used to restrict deviation of the 2-3 mixing from maximal

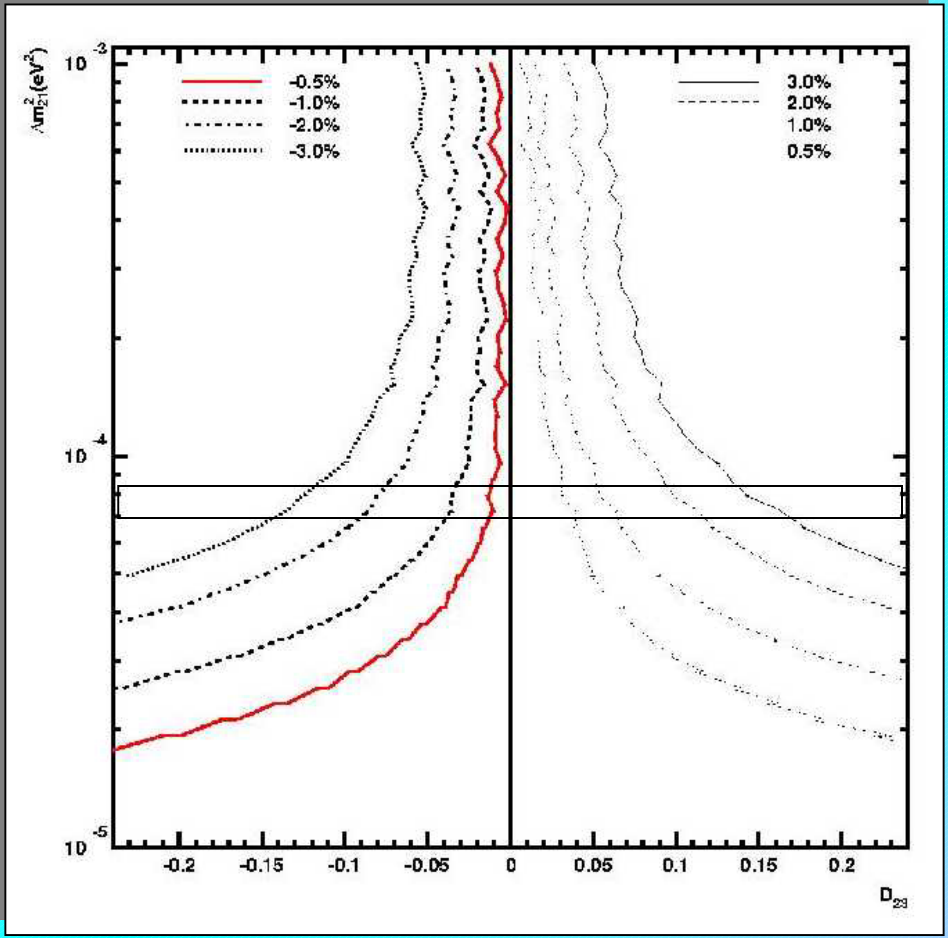
Zenith angle dependences of the e-like events



0.Peres, A.S.

Measuring 2-3 mixing

O. Peres & A.S.



$D_{23} = 0.5 - \sin^2\theta_{23}$

Contours of constant excess of the e-like events in %

KamLAND: 10% accuracy in measurements of Δm^2

Ambiguity related to $\sin\theta_{13}$

$\sin^2 2\theta = 0.91 \Rightarrow \sin^2\theta = 0.35$

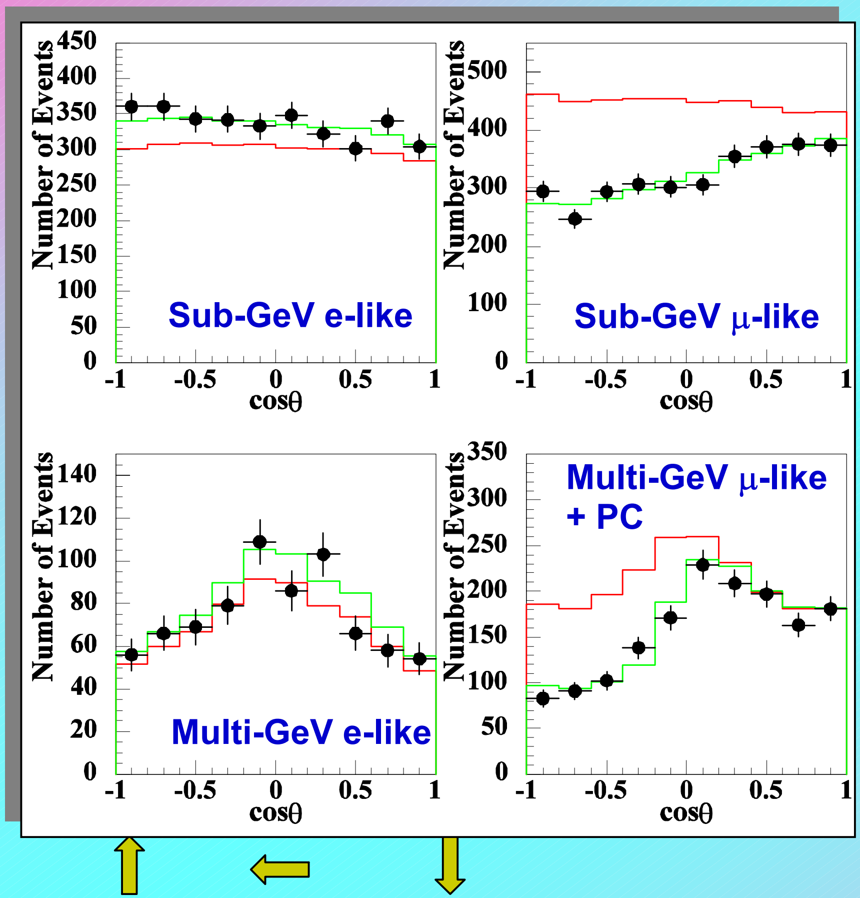
important theoretical implications

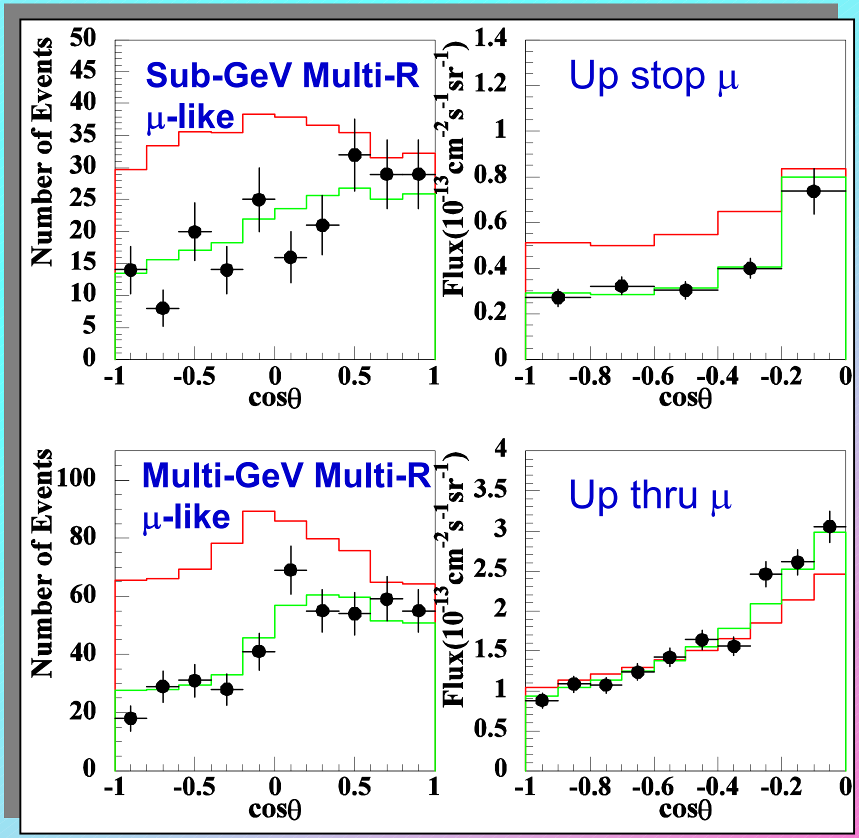
Still significant deviation of the 2-3 mixing from maximal is possible

Zenith angle distributions

$\nu_\mu \leftrightarrow \nu_\tau$

Best fit
$\sin^2 2\theta=1.0$, $\Delta m^2=2.0\times10^{-3}$ eV^2
Null oscillation

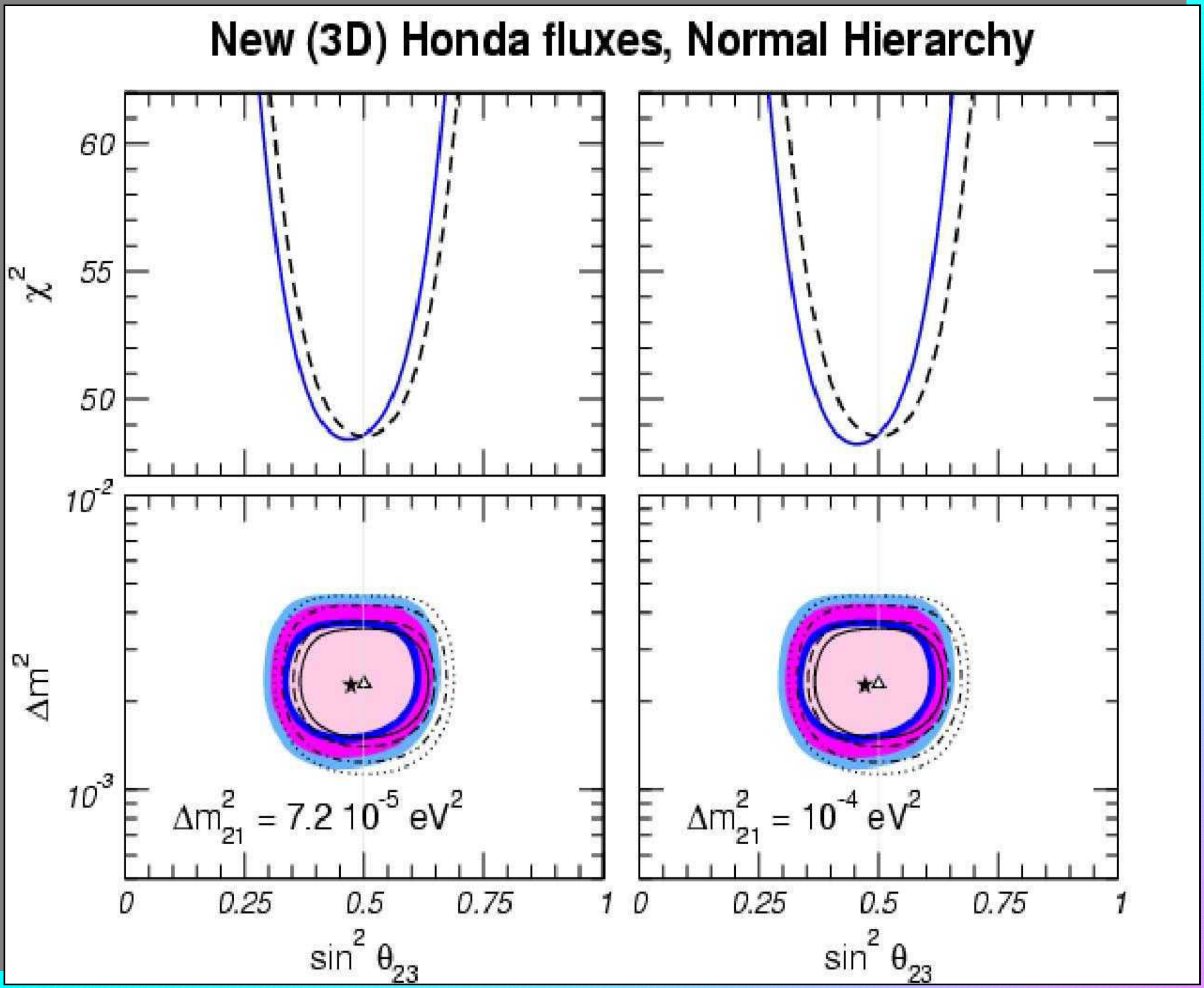




~13000km ~500km ~15km

SuperKamiokande

Deviation of 2-3 mixing from maximal



$\Delta m^2 = 0$

$\Delta m^2 \neq 0$

$\sin^2\theta_{23} = 0.45 - 0.47$

M. C. Gonzalez-Garcia
M. Maltoni, A.S.

"No-symmetry" approach

I. Dorsner, A. S

2-3 mixing differs from maximal one

No special symmetry for neutrinos or leptons

Approximate quark-lepton symmetry (analogy, correspondence)

Family structure, weak interfamily connections
no large mixing in the original mass matrices

All quark and lepton mass matrices have similar structure with ``flavor alignment"

$\theta_{ij} \sim \sqrt{m_i/m_j}$

$\theta_{atm} = 36 - 38^0$

Seesaw mechanism of neutrino mass generation

Large lepton mixing is the artifact of seesaw

Quark-Lepton symmetry

- Quarks-Lepton symmetry is realized in terms of the mass matrices (matrices of the Yukawa couplings).
- For the Dirac mass matrices of all quarks and leptons:

$$Y_U \sim Y_D \sim Y_{\nu D} \sim Y_L \sim Y_0$$

(implies large tan β)

Specifically: $Y_f = Y_0 + \Delta Y_f$ $\quad (Y_0)_{ij} \ll (\Delta Y_f)_{ij}$ $\quad f = U, D, L, \nu D$

- Y_0 is ``unstable'': det $(Y_0) \sim 0$ (as well as determinants of sub-matrices)

⇒ small perturbations produce significant change of masses and and mixings

Assume:

$$Y = \begin{pmatrix} a_{11}\,\varepsilon^4 & a_{12}\,\varepsilon^3 & a_{13}\,\varepsilon^2 \\ a_{21}\,\varepsilon^3 & a_{22}\,\varepsilon^2 & a_{23}\,\varepsilon \\ a_{31}\,\varepsilon^2 & a_{32}\,\varepsilon & 1 \end{pmatrix}$$

$\varepsilon \sim 0.2 - 0.3$

$|a_{ij}| = 1 + O(\varepsilon)$

- Observables (masses and mixings) appear as small perturbations of the dominant structure given by Y_0.

See-saw

Enhances (by factor ~ 2) the mixing which comes from diagonalization of the neutrino mass matrix

Leads to smallness of neutrino masses

Changes the relative sign of ``rotations" which diagonalize mass matrices of the charge leptons and neutrinos

For the RH neutrino mass matrix we take for simplicity the same form

$M_R \sim Y_0$

Seesaw

Smallness of neutrino masses

T. Yanagida
M. Gell-Mann, P. Ramond, R. Slansky
S. L. Glashow
R.N. Mohapatra, G. Senjanovic

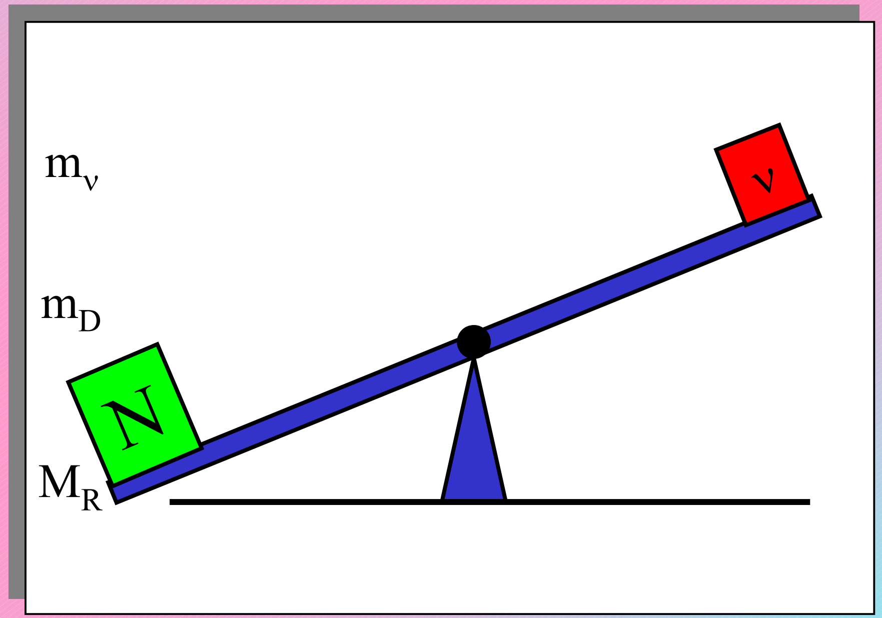
- $$N^T Y L H + \frac{1}{2} N^T M_R N + \text{h.c.}$$

$L = (\nu,\ l)^T \qquad N = (\nu_R)^c$

$$\Rightarrow \quad \begin{array}{c} \nu \\ N \end{array} \begin{pmatrix} 0 & m_D \\ m_D{}^T & M_R \end{pmatrix} \qquad m_D = Y\langle H\rangle$$

If $M_R \gg m_D$

$$\Rightarrow \quad m_\nu = -\ m_D{}^T M_R{}^{-1} m_D$$



Neutrality
$Q_{EM} = 0$,
$Q_c = 0$

$\Rightarrow$

Smallness of neutrino mass

- Zero charges
  -> can have Majorana mass
- Right handed components:
  singlets of the SM symmetry group
  -> mass is unprotected by symmetry
  can be large -- at the scale of lepton number violation

Flipping the sign of rotation

quark mixing:

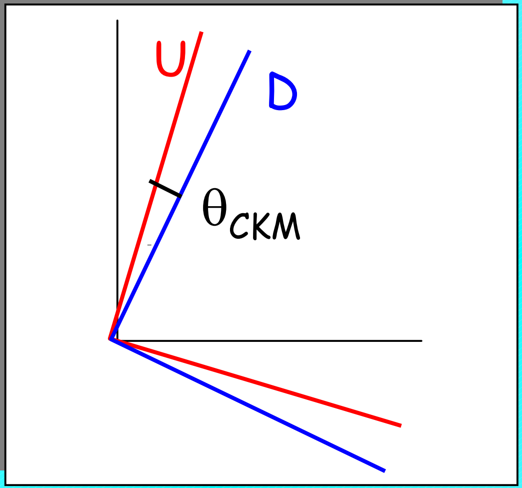
$V_{CKM} = U(up)^{+} U(down)$

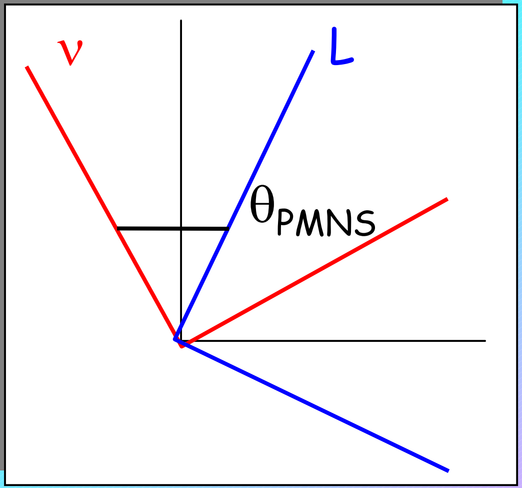
lepton mixing:

$V_{P-MNS} = U(\nu)^{+} U(l)$

For quarks the up and down rotations cancel each other leading to small mixing whereas for leptons they sum up producing large mixing

S. Barshay





It is the see-saw leads to flip of the sign of rotation which diagonalizes the neutrino mass matrix

changes the sign of the 23-elements

leads to m(22) > m(33)

Enhances 22 and 23 elements

Expansion parameter

ε is determined by inequality of masses of the s-quark and the muon (one would expect $m_\mu = m_s$ in the case of exact q-l symmetry)

$m_s/m_b = k_q \varepsilon^3$

$m_\mu / m_\tau = k_L \varepsilon^3$

$k_f \varepsilon \sim a_{22} - a_{23}{}^2$

These mass ratios can be reproduces for $a_{ij} = 1 + O(\varepsilon)$ if

$\varepsilon > 0.25$

An example with m_22 > m_33

- $\varepsilon \sim 0.26$

- $|a_{ij}(l)| = \begin{pmatrix} 1.00 & 0.91 & 1.01 \\ \dots & 1.26 & 0.74 \\ \dots & \dots & 1.00 \end{pmatrix}$ $\quad |a_{ij}(D)| = \begin{pmatrix} 1.00 & 1.26 & 1.00 \\ \dots & 1.09 & 1.05 \\ \dots & \dots & 1.00 \end{pmatrix}$

$|a_{ij}(M)| = \begin{pmatrix} 1.0000 & 1.0026 & 1.0000 \\ \dots & 1.0005 & 1.0007 \\ \dots & \dots & 1.0000 \end{pmatrix}$

For quarks deviations of $|a_{ij}|$ from 1 are smaller than 15%

- $m_1 = 0.0017$ eV
- $m_{ee} = 0.001 - 0.004$ eV
- $|\sin^2\theta_{13}| = 0.005$

Generically $|\sin^2\theta_{13}| \sim \varepsilon^4$

- Masses of the RH neutrinos:

$M_1 = 1.2\ 10^{10}$ GeV
$M_2 = 5.8\ 10^{10}$ GeV
$M_3 = 8.8\ 10^{14}$ GeV

Strong hierarchy: seesaw enhancement of 23-mixing

An example with changed sign of m_23

- $\varepsilon \sim 0.26$
- $|a_{ij}(l)| = \begin{pmatrix} 1.00 & 0.91 & 1.01 \\ \ldots & 1.26 & 0.74 \\ \ldots & \ldots & 1.00 \end{pmatrix}$ $|a_{ij}(D)| = \begin{pmatrix} 1.00 & 1.21 & 1.00 \\ \ldots & 0.80 & 1.09 \\ \ldots & \ldots & 1.00 \end{pmatrix}$

  $|a_{ij}(M)| = \begin{pmatrix} 1.00 & 1.13 & 1.00 \\ \ldots & 1.26 & 1.13 \\ \ldots & \ldots & 1.00 \end{pmatrix}$

- $m_1 = 0.0039$ eV
- $m_{ee} = 0.001 - 0.004$ eV
- $|\sin^2\theta_{13}| \sim 0.01$
- Masses of the RH neutrinos:

  $M_1 = 2.9\ 10^8$ GeV
  $M_2 = 2.4\ 10^{11}$ GeV
  $M_3 = 3.7\ 10^{14}$ GeV

Implications

No special symmetry for neutrinos of for lepton sector

Y_0 can be reproduced with U(1) family symmetry and charges q, q + 1, q + 2 charges, if unut charge is associated with one degree of ε (a la Froggatt-Nielsen)

Violation of the symmetry appears at the level $\varepsilon^2 - \varepsilon^3 \sim (1 - 3)\, 10^{-2}$

If the flavor symmetry is at GU scale its violation can come e.g. from the string scale

Conclusions

One of the main results is an amazing pattern of the lepton mixing which differs strongly from the quark mixing

The key question to the underlying physics is if there is a new (different from quark) symmetry behind neutrino mass spectrum and mixing

- maximal (near) maximal 2-3 mixing
- degenerate spectrum
- probably, small 1-3 mixing

New symmetry of Nature, which is realized (manifest itself) in the properties of neutrinos or lepton sector.

?

Nothing special: weakly broken quark-lepton symmetry; family structure, small interfamily mixing. Large lepton mixing - artifact of the seesaw mechanism

Neutrinos can shed some light on the fermoion mass problem in general. Hint: flavor alignment, $\varepsilon \sim 0.25$, ``unstable" mass matrices, U(1)

Priorities