Theory of ν – masses and mixing

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Lepton mixing: What is behind?

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R. Davis in 80ies: "Models of neutrino masses are so numerous that they can compose the Dark Matter in the Universe"

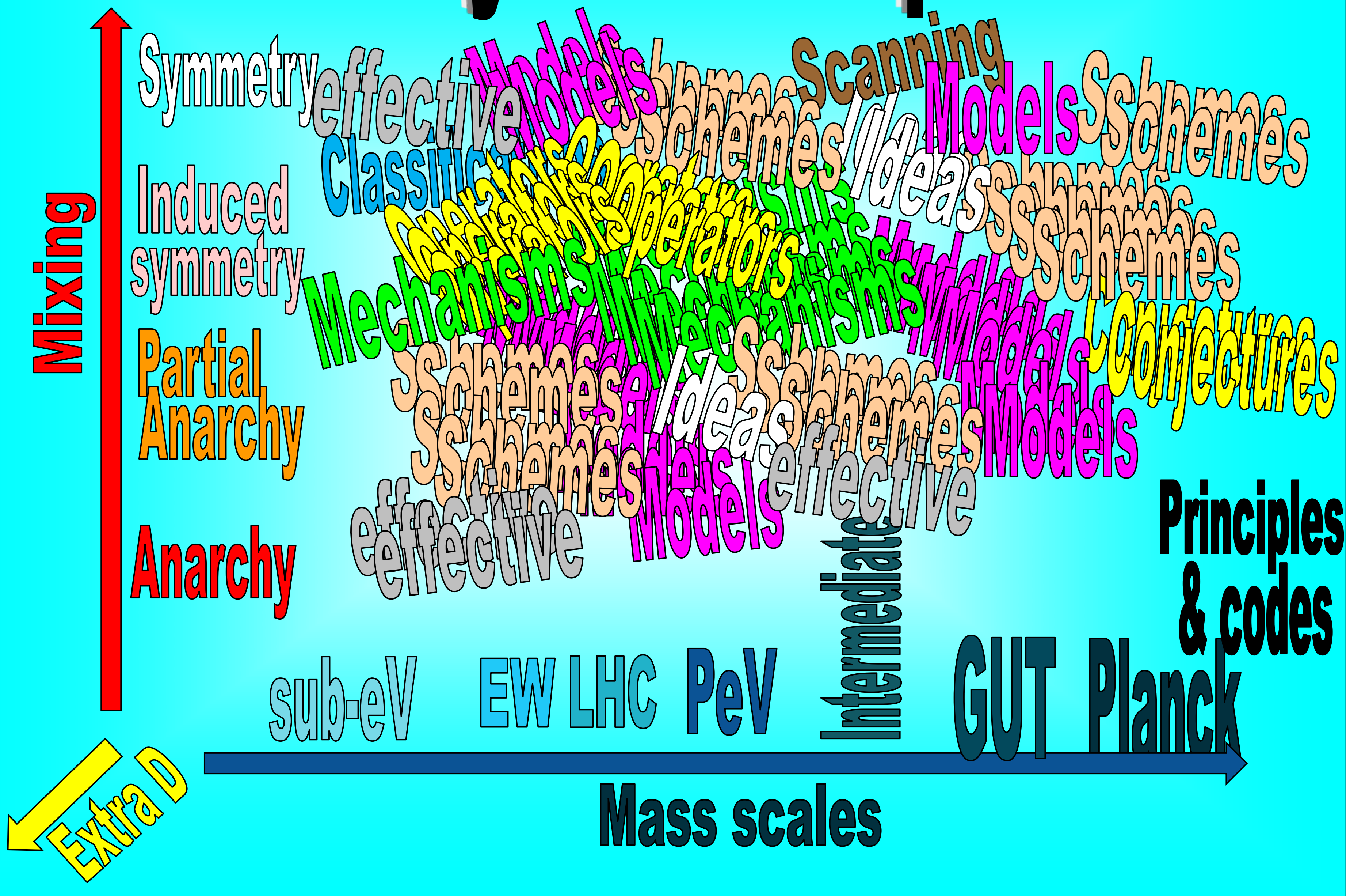
This can not be true: with present number of models the Universe would be overclosed many times contradicting observations

Davis's remark on ν models- DM connection has new turn now:

- joint models of neutrino masses and dark matter
- understanding neutrino properties can steam from the Dark sector of theory or
- neutrino mass can be sourced by DM

"Theory" Landscape

Multi dimensional



What is the problem?

No theory of flavor, in general

No theory of quark masses and mixing

No physics BSM has been discovered yet at LHC …
Especially no SUSY → UV completion issue.

What is the hope?

Neutrinos are the key

Less ambitious:

It is the neutrino that sheds the light on all these problems

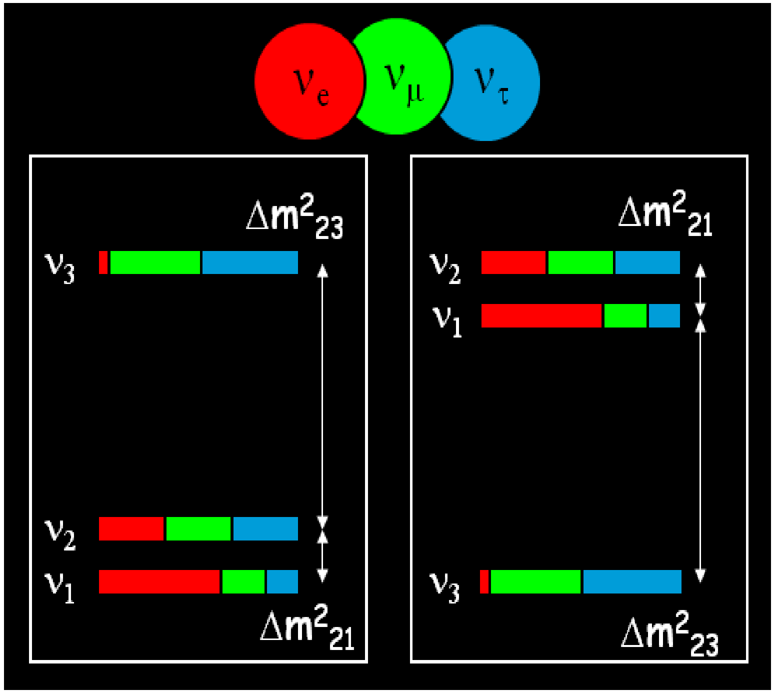
Understand at least the difference of neutrino mass and mixing from quark mixing and masses

What we really know

3ν - paradigm

All well established/confirmed results fit well a framework

- three neutrinos
  - with interactions described by the standard model
  - with masses and mixing
- negligible feedback of neutrino mass generation on the standard model



The theory?

$$\frac{1}{\Lambda} LLHH$$

S. Weinberg

Large scale of new physics

Violation of universality, Unitarity?

or maybe: $h\, L \bar{\nu}_R\, H$

With very small coupling h <<< 1

That's all?
Will we learn more?

Outline

I. Data and interpretation: bottom-up

II. Origins of ν - mass and mechanisms of generation

III. Mixing and flavor symmetries

IV. Models of neutrino mass. Connections

I. Data and interpretation bottom-up

Definitions and parameterization

Dirac and Majorana masses

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

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

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

corresponds to Majorana neutrino:

$\nu_M{}^C = e^{i\alpha} \nu_M \qquad \nu_M = \nu_L + e^{-i\alpha} \nu_L{}^C$ α 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 $\beta\beta_{0\nu}$ $\Gamma \sim m_L{}^2$

Vacuum mixing

$$\nu_f = U_{PMNS}\, \nu_m$$

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

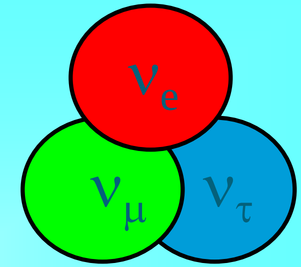
SM definition of flavor states may differ from "physical" ones, if e.g. …

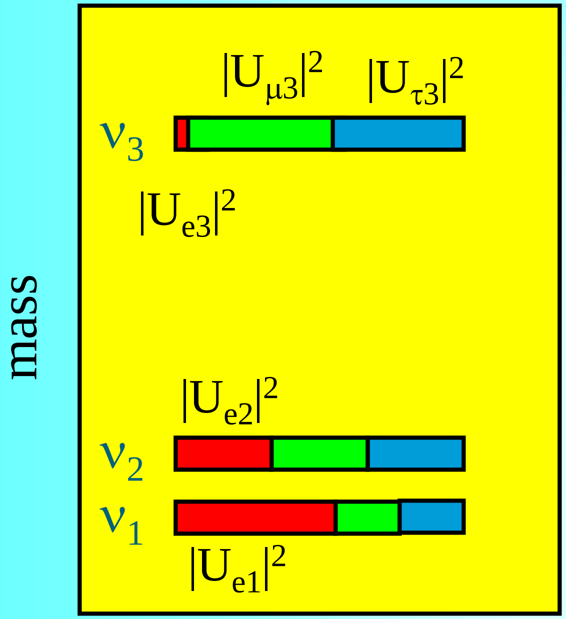
New heavy neutral leptons mix with neutrinos

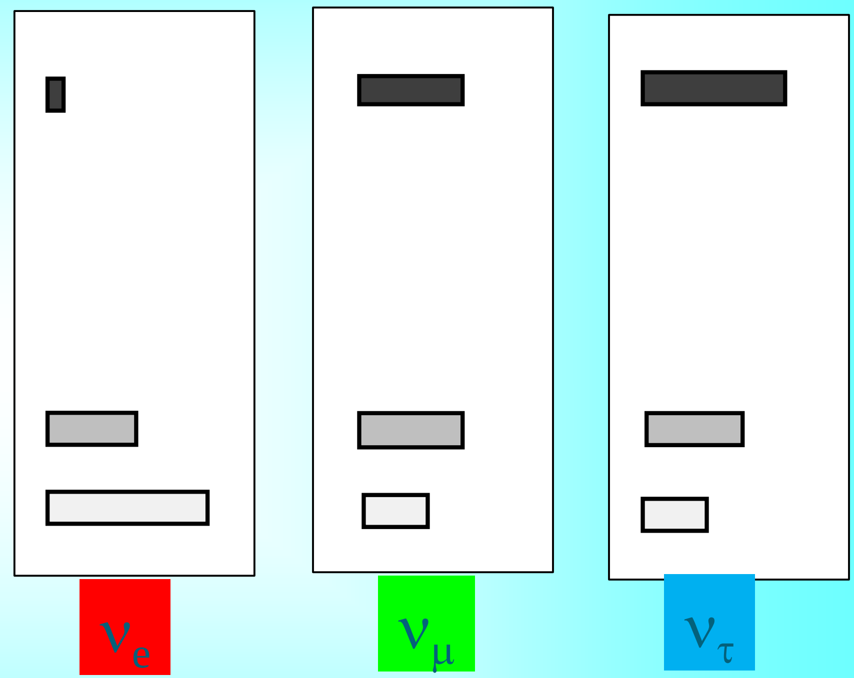
Physical flavor states produced e.g. in beta, pion, muon decays depend on kinematics of the process

Mixing

Dual role







Flavor content of mass states

Mass content of flavor states

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

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

Standard parametrization

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

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

Dirac phase matrix

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

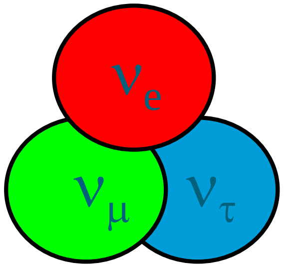
$I_M = \mathrm{diag}\,(1,\ e^{i\alpha_{21}/2},\ e^{i\alpha_{31}/2})$ - matrix of Majorana phases

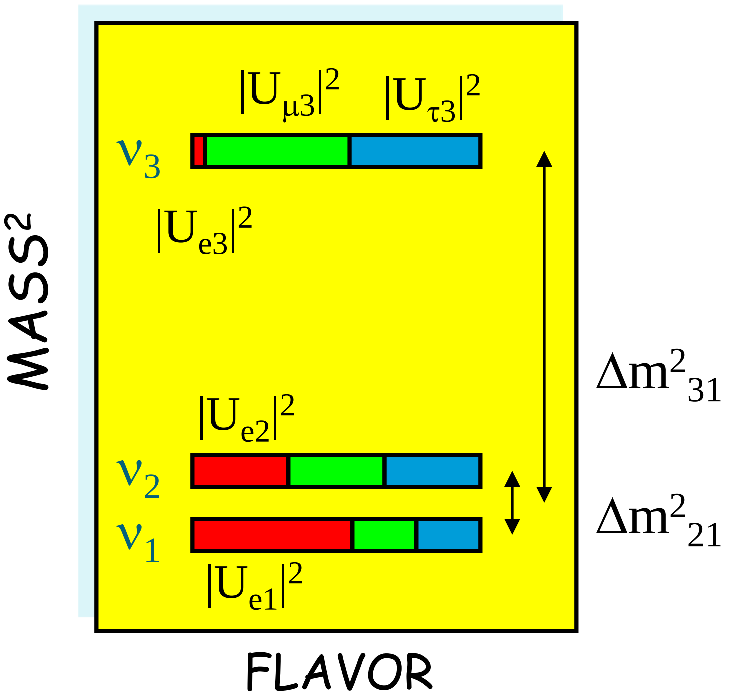
Not unique parametrization

Convenient for phenomenology, especially for oscillations in matter

Insightful for theory?

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

$$\tan^2\theta_{12} = |U_{e2}|^2 \; / \; |U_{e1}|^2$$

$$\sin^2\theta_{13} = |U_{e3}|^2$$

$$\tan^2\theta_{23} = |U_{\mu 3}|^2 \; / \; |U_{\tau 3}|^2$$

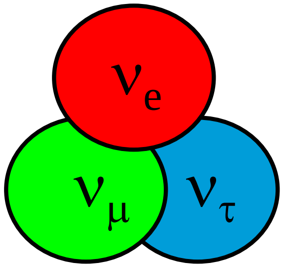
Mixing matrix:

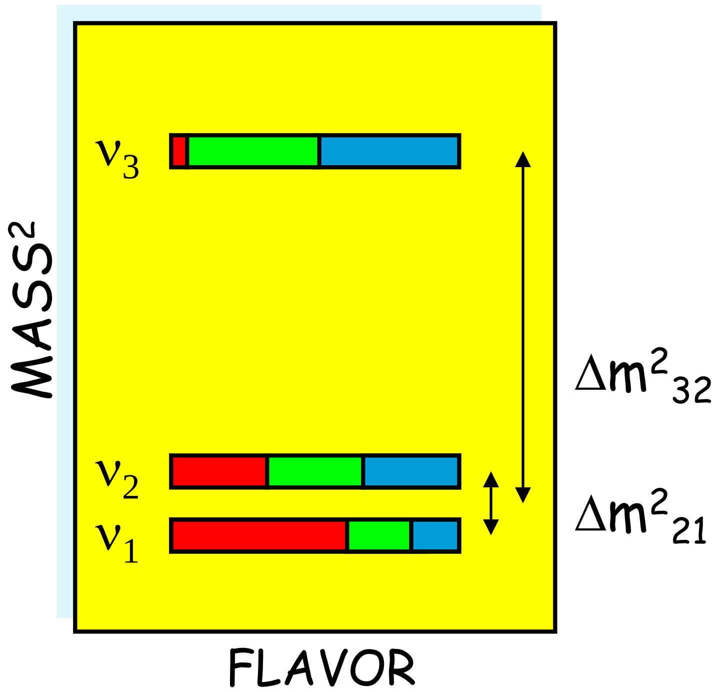
$$\nu_f = U_{PMNS}\, \nu_{mass}$$

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

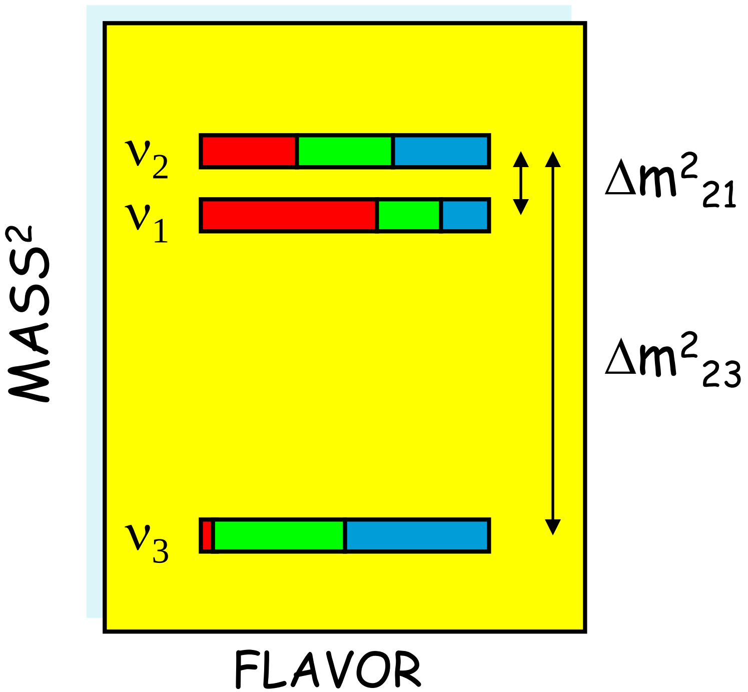
$$U_{PMNS} = U_{23} I_\delta U_{13} I_{-\delta} U_{12}$$

Mass Ordering





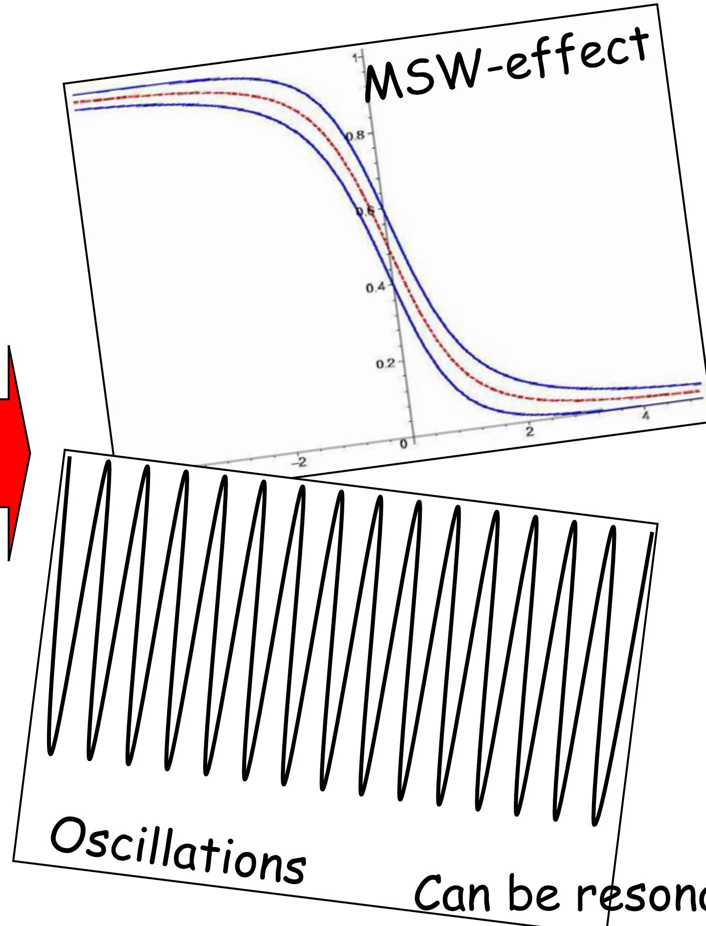
Normal mass ordering



Inverted mass ordering

Measurements

MINOS
T2K
NOvA
Solar neutrinos
KamLAND
Double Chooz
Daya Bay
RENO
NEOS
Atmospheric neutrinos
SK
DeepCore
Antares



Can be resonantly enhanced in matter

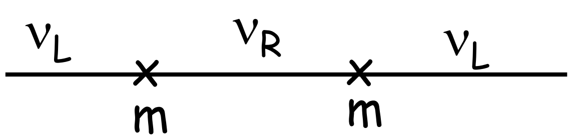
Δm^2

θ

Oscillations and masses

Oscillations and adiabatic conversion test the dispersion relations and not neutrino masses

$$p_i = \sqrt{E_i^2 - m_i^2}$$



In oscillations: no change of chirality, so e.g. V, A interactions with medium can reproduce effect of mass. Also interactions with scalar fields

It is consistency of results of many experiments in wide energy ranges and different environment: vacuum, matter with different density profiles that makes explanation of data without mass almost impossible.

proof of non-zero neutrino mass

Kinematical methods: distortion of the beta decay spectrum near end point - KATRIN

Neutrinoless double beta decay

Cosmology, Large scale structure of the Universe

Probing Nature of neutrino mass

Determination of masses, mass squared differences from processes at different conditions

Searches for dependence of mass on external variables:

Vacuum – media with different densities, fields

Solar – KamLAND: Δm_{21}^2

2-3 mixing: T2K - NOvA

Energies (in medium, or if Lorentz is violated)

Epochs (red shifts)

MAVAN

Momentum transfer

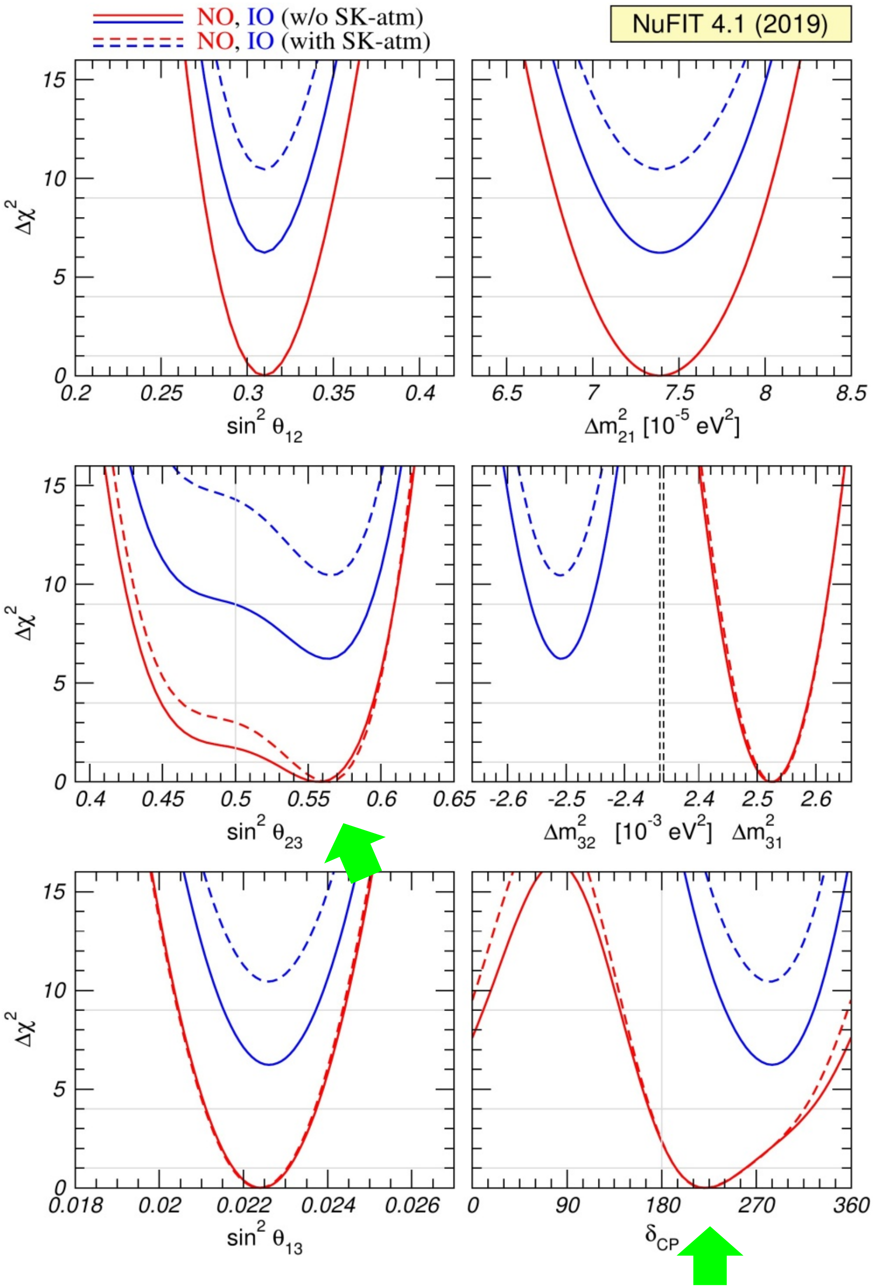
Virtuality: On shell – off shell

Neutrinoless Double beta decay – unique?

Global 3nu analysis

Esteban, Ivan et al.
arXiv:1811.05487 [hep-ph]

NuFIT 4.1 (2019), www.nu-fit.org



$\Delta\chi 2$ profiles minimized with respect to all undisplayed parameters.

The red (blue) curves correspond to Normal (Inverted) Ordering. Solid (dashed) curves are without (with) adding the tabulated SK-atm $\Delta\chi 2$.

Mass-squared splitting:
Δm_{31}^2 for NO and Δm_{31}^2 for IO

Global 3nu analysis

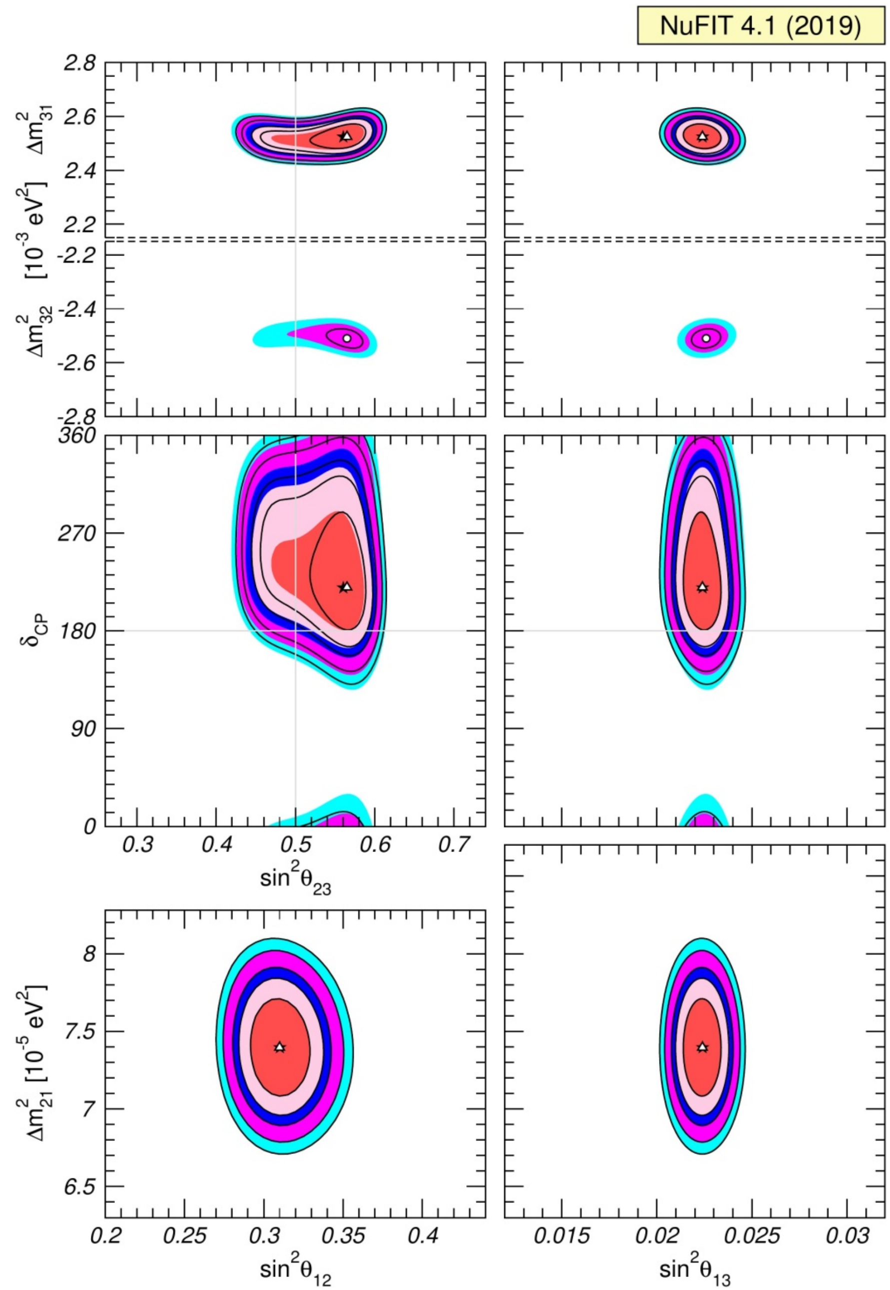
Esteban, Ivan et al. 1811.05487 [hep-ph]

NuFIT 4.1 (2019), www.nu-fit.org

The two-dimensional projection of the allowed six-dimensional region after minimization with respect to the undisplayed parameters.

The regions in the four lower panels are obtained from Δχ2 minimized with respect to the mass ordering.

Contours correspond to 1σ, 90%, 2σ, 99%, 3σ CL (2 dof). Coloured regions (black contour curves) are without (with) adding the tabulated SK-atm Δχ2.



Summarizing results

Data are in a very good agreement with 3ν framework

Data are internally consistent within error bars
Over determined: different experiments are sensitive to the same parameters

Some tensions:

Solar vs. KamLAND OK within experimental uncertainties

UNKNOWNS:

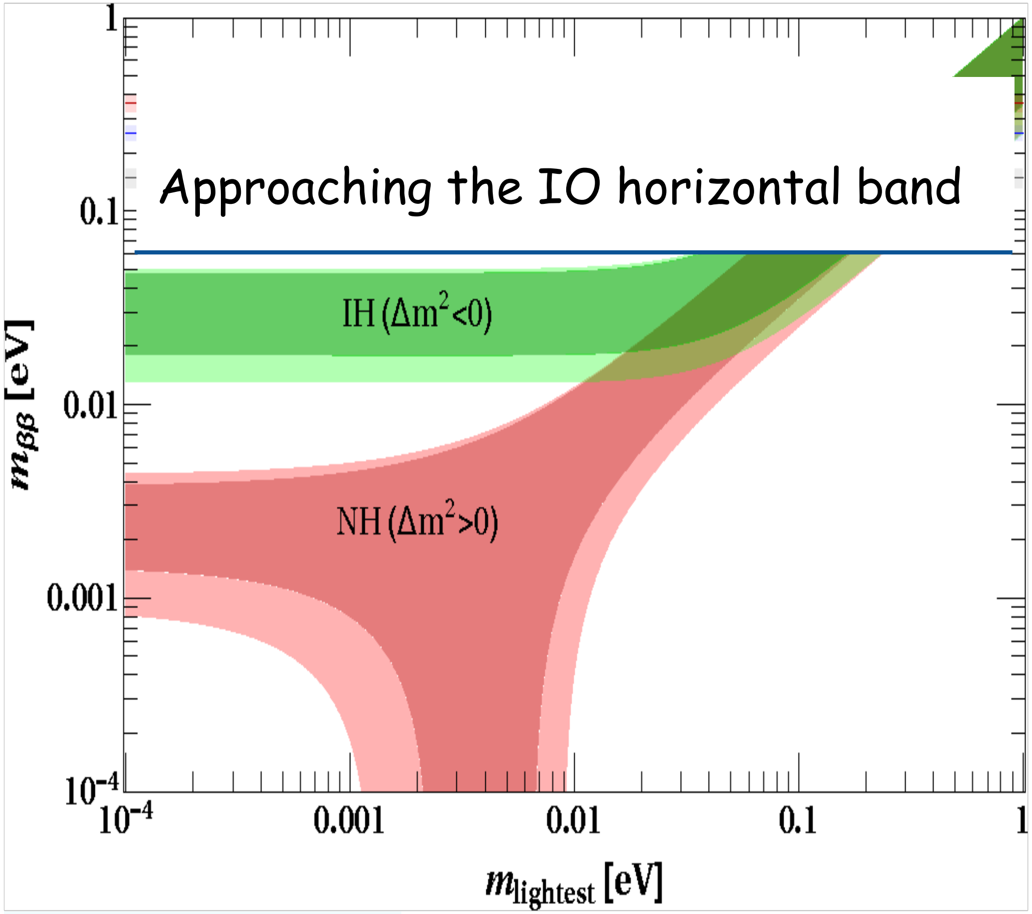
- CP-phase: best fit value deviates from $3\pi/2$, π and $3\pi/2$ are equally plausible.
- Mass ordering: NO is favored by 2 – 3 σ, $\Delta\chi^2 = 7.5$
- Deviation of 2-3 mixing from maximal at 1.5σ, second (high) octant is preferable

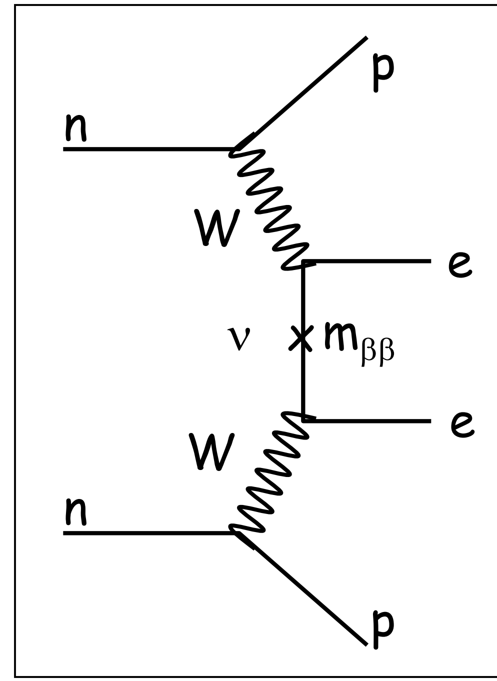
ANOMALIES:

LSND, MiniBooNE, Reactor, Gallium: Oscillations into steriles, new interactions, new particles – can dramatically affect our considerations

ββ0ν – decay results

$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\phi}$

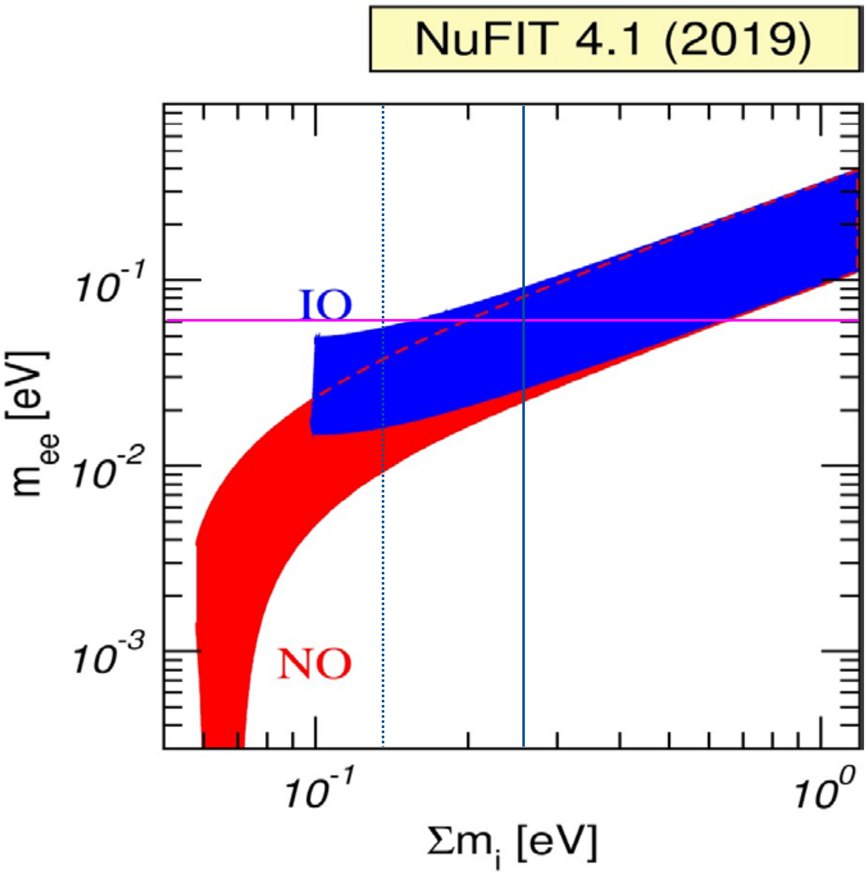




90% CL upper bound on $m_{\beta\beta}$ depending on NME

KamLAND-Zen	(61 – 165) meV	*A.Gando, et al, 1605.02889 [hep-ex]*
EXO-200	(93 – 286) meV	*G. Anton et al. 1906.02723 [hep-ex]*
CUORE	(110 – 520) meV	*S. Dell'Oro et al. 1905.07667 [nucl-ex]*
GERDA	(110 – 260) meV	

Bounds on masses



Allowed regions at 2σ (2 dof) obtained by projecting the results of the global analysis of oscillation data (w/o SK-atm) over the plane (Σm_ν, m_{ee}). The region for each ordering is defined with respect to its local minimum

Cosmology: $\Sigma_i m_i$ < 0.12 - 0.26 eV

A. Loureiro et al, 1811.02578 [astro-ph.CO]

Observations and Implications

What these results show, hint?

Regularities?

Relations?

Smallness of mass?

Special

comparing within generation:

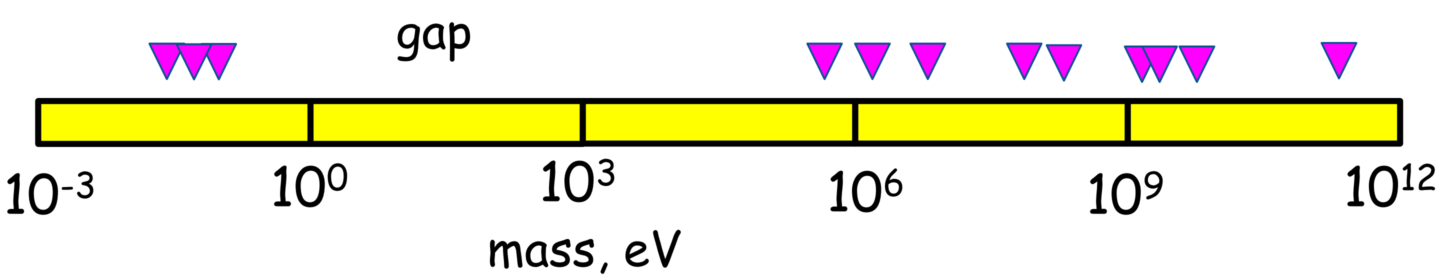
$$\frac{m_3}{m_\tau} \sim 3\ 10^{-11}$$

Similar for other generations
if spectrum is hierarchical

Normal?

Neutrinos: no clear generation structure and correspondence light flavor – light mass, especially if the mass hierarchy is inverted or spectrum is quasi-degenerate

$$\frac{m_3}{m_e} \sim 3\ 10^{-6} \qquad \frac{m_e}{m_t} \sim 3\ 10^{-6}$$

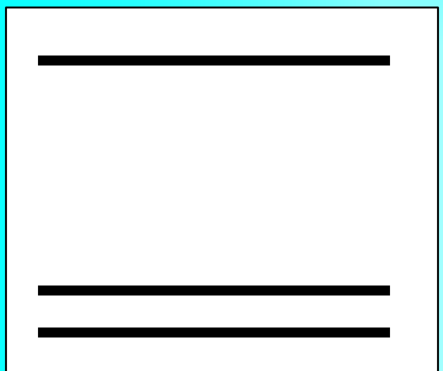


Neutrino Mass Ordering

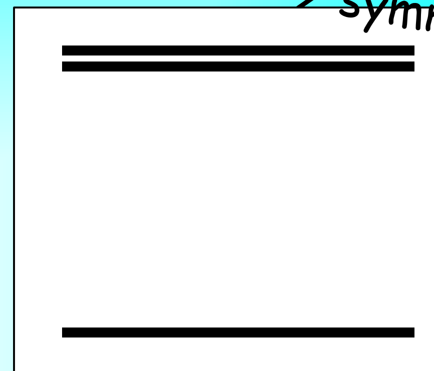
Fundamental:
principle, symmetry

Accidental: selection of
values of parameters

Quasi-degenerate
→ symmetry



Correlation of masses
of neutrinos and
charged leptons
in weak interactions:
Light likes light,
heavy – likes heavy



$$\frac{m_2}{m_3} \sim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} = 0.18$$

$$\theta \sim \sqrt{\frac{m_2}{m_3}}$$

the weakest
hierarchy

$$\frac{\Delta m}{m} \sim \frac{\Delta m_{21}^2}{2\,\Delta m_{32}^2} = 1.6\ 10^{-2}$$

but 1-2 mixing strongly
deviates from maximal

Similar to quark spectrum

rescaling

See-saw

Quark-lepton
symmetry

Unification

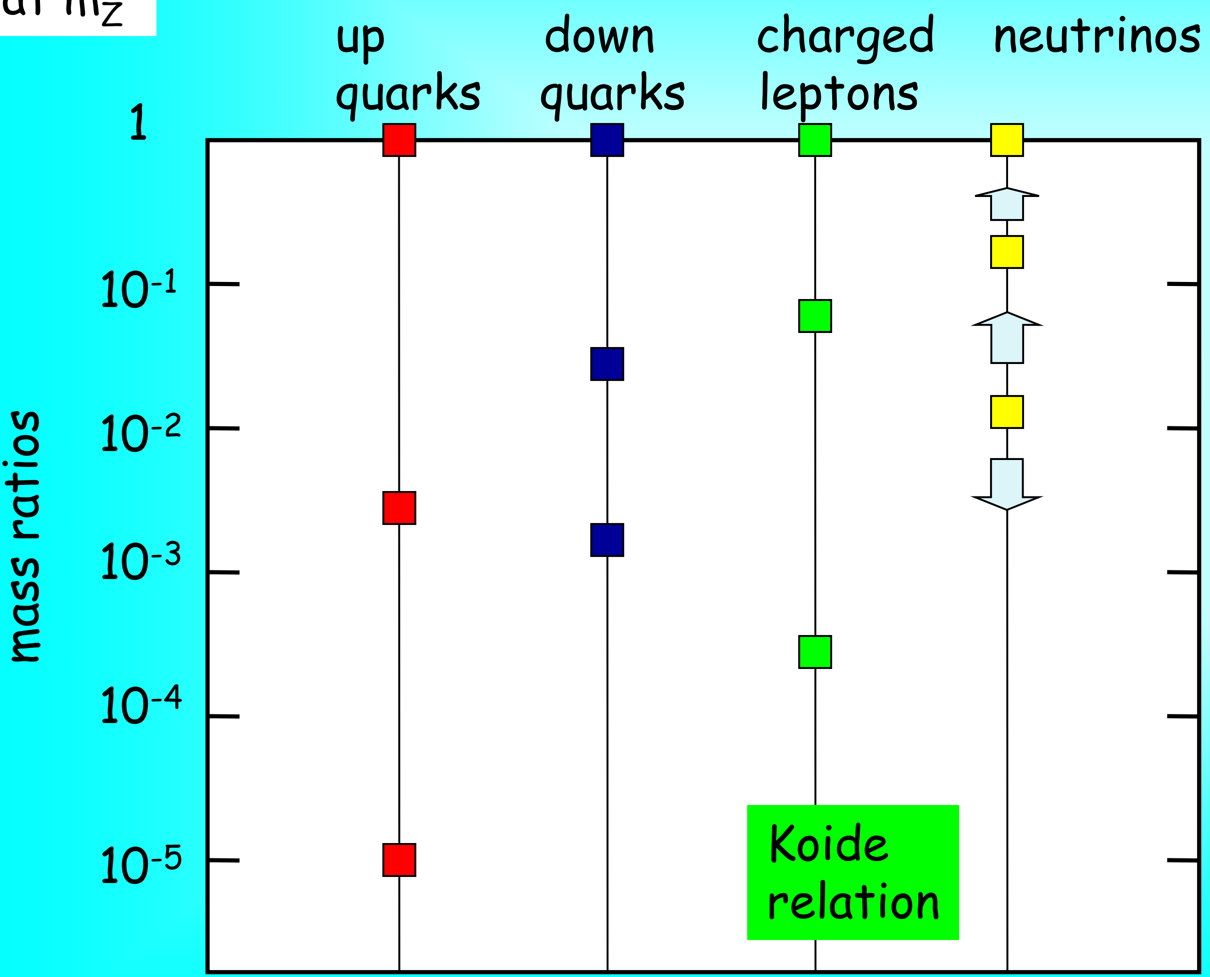
Pseudo-Dirac + 1 Majorana

Flavor symmetries

Broken $L_e - L_\mu - L_\tau$ symmetry

Mass hierarchies

at m_Z



$$\frac{m_2}{m_3} \geqslant \sqrt{\frac{\Delta m_{21}{}^2}{\Delta m_{32}{}^2}}$$

~ 0.18

Neutrinos have the weakest mass hierarchy (if any) among fermions

Related to large lepton mixing?

$m_u \, m_t = m_c{}^2$

$\sin\theta_C \sim \sqrt{m_d/m_s}$ Gatto–Sartori–Tonin relation

TBM mixing: zero order approximation?

As the reference point

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

L. Wolfenstein

P. F. Harrison
D. H. Perkins
W. G. Scott

ν_3 is bi-maximally mixed

ν_2 is tri-maximally mixed

$U_{tbm} = U_{23}(\pi/4)\, U_{12}(\theta_{12})$

$\sin^2\theta_{12} = 1/3$

- maximal 2-3 mixing
- zero 1-3 mixing
- no CP-violation

Uncertainty related to sign of 2-3 mixing:

$\theta_{23} = \pi/4 \rightarrow -\pi/4$

Mixing and mass matrices

Origin of mixing:
off-diagonal mass matrices

$M_l \neq M_\nu$

Diagonalization: → **Mixing matrix** → **Mass spectrum**

$M_l = U_{lL} m_l^{diag} U_{lR}^+$

$m_l^{diag} = (m_e, m_\mu, m_\tau)$

$M_\nu = U_{\nu L} m_\nu^{diag} U_{\nu L}^T$ for Majorana neutrinos

$m_\nu^{diag} = (m_1, m_2, m_3)$

CC in terms of mass eigenstates: $\bar{l} \gamma^\mu (1 - \gamma_5) U_{PMNS} \nu_{mass}$

→ $U_{PMNS} = U_{lL}^+ U_{\nu L}$

Flavor basis: $M_l = m_l^{diag}$ $U_{PMNS} = U_{\nu L}$

The TBM- mass matrix

Mixing from diagonalization of mass matrix in the flavor basis

$$m_{TBM} = U_{TBM}\, m^{diag}\, U_{TBM}{}^{T}$$

$$m^{diag} = \mathrm{diag}\,(|m_1|,\ |m_2| e^{i2\alpha},\ |m_3| e^{i2\beta})$$

$$m_{TBM} = \begin{pmatrix} a & b & b \\ \ldots & \frac{1}{2}(a+b+c) & \frac{1}{2}(a+b-c) \\ \ldots & \ldots & \frac{1}{2}(a+b+c) \end{pmatrix}$$

$a = (2m_1 + m_2)/3$, $b = (m_2 - m_1)/3$, $c = m_3$

The matrix has S_2 permutation symmetry $\nu_\mu \leftrightarrow \nu_\tau$

Mixing is determined by relations between the matrix elements:

$$m_{12} = m_{13} \qquad m_{22} = m_{33} \qquad m_{11} + m_{12} = m_{22} + m_{23}$$

Eigenvalues –by absolute values of elements

Deviations & observations

Deviations from TBM

bf

$\delta(\sin\theta_{12}) = -0.017$

$|\delta(\sin\theta_{23})| = 0.035$

$\delta(\sin\theta_{13}) = \sin\theta_{13} = 0.15$

Certain hierarchy of deviations = additional rotations

Problematic for a number of models, require further assumptions/ complications

Deviation from maximal 1-2 mixing:

$\delta(\sin\theta_{12}) = 0.15$

$\Rightarrow$ $\delta(\sin\theta_{12}) = \delta(\sin\theta_{13}) = \sin\theta_{13}$

1-3 mixing is in agreement with prediction

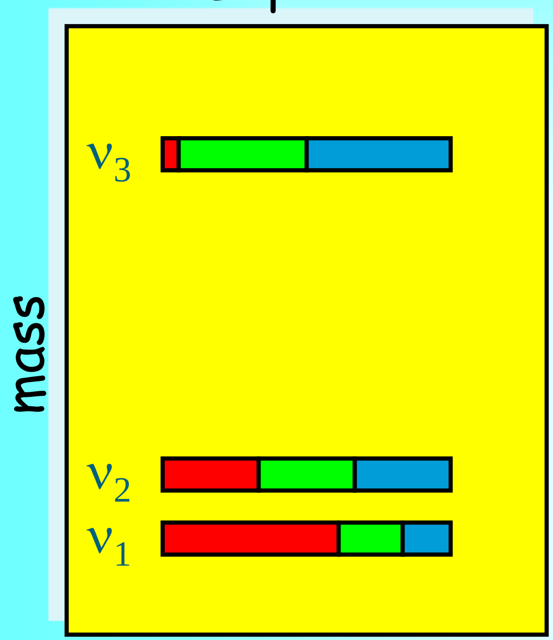
$\theta_{13} \sim \frac{1}{\sqrt{2}}\theta_C$

$\sin^2\theta_{13} \sim \frac{1}{2}\sin^2\theta_C$

θ_C Cabibbo angle

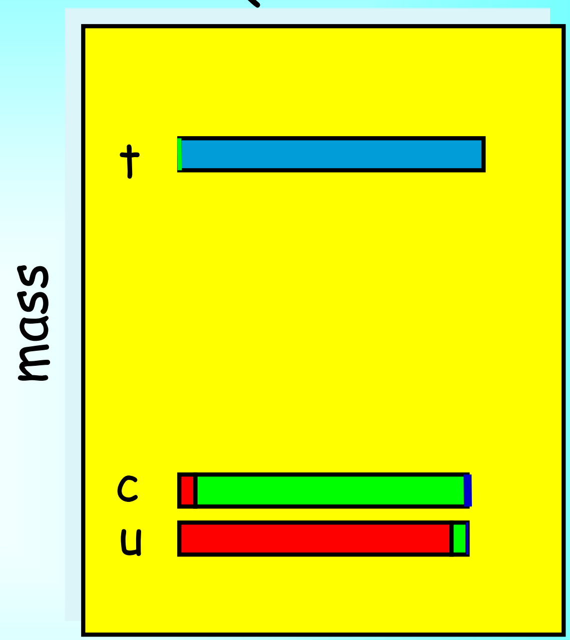
Leptons versus quarks

Leptons



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

Quarks



$U_d = V_{CKM}^{+}\,U$ $\quad U = (u, c, t)$

Mixings of quarks and leptons are strongly different but still related

Observation:

$\theta_{12}^{l} + \theta_{12}^{q} \sim \pi/4$

$\theta_{23}^{l} + \theta_{23}^{q} \sim \pi/4$

Sum up to maximal mixing angle
kind of complementarity

Quark-lepton complementarity

based on relations:

$\theta^l_{12} + \theta^q_{12} \sim \pi/4$ $\theta^l_{23} + \theta^q_{23} \sim \pi/4$

A.S.
M. Raidal
H. Minakata

``Lepton mixing = bi-maximal mixing – quark mixing"

Implications

Quark-lepton symmetry

Existence of structure which produces bi-maximal mixing

Grand Unification or family symmetry

See-saw? Properties of the RH neutrinos

Bi-maximal mixing

Another zero order reference structure

$$U_{bm} = \begin{pmatrix} \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \sqrt{\frac{1}{2}} \\ \frac{1}{2} & -\frac{1}{2} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

F. Vissani
V. Barger et al

Two maximal rotations

$$U_{bm} = U_{23}^{m} U_{12}^{m}$$

- maximal 2-3 mixing
- zero 1-3 mixing
- maximal 1-2 mixing
- no CP-violation

In general: lepton mixing

The data are in very good agreement with the ansatz

$$U_{PMNS} = U_{CKM}^{+} U_{X}$$

$$U_{CKM}^{+} = V_{CKM}$$

$$U_{X} = U_{TBM} \text{ or } U_{BM}$$

This
- reproduces QLC approximately
- can be realized in the seesaw type I
- gives prediction for 1-3 mixing

13-mixing

$$\sin\theta_{13} \sim \sqrt{\tfrac{1}{2}}\,\sin\theta_C$$

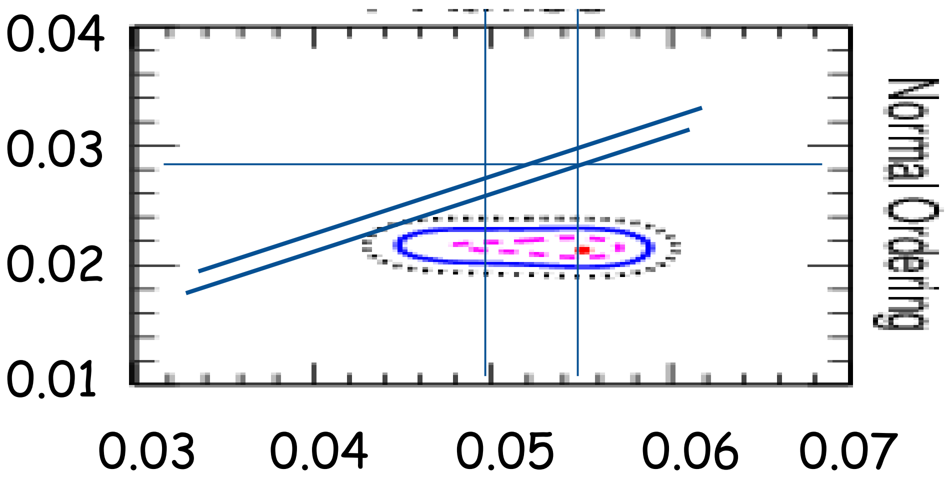
- Phenomenological level — C. Giunti, M. Tanimoto
- From QLC (Quark-Lepton Complementarity) — H. Minakata, A Y S
- From TBM-Cabibbo scheme — S. F. King et al

Now accuracy of measurements permits detailed comparison

Experimental status

From global fit *F. Capozzi, et al. Prog.Part.Nucl.Phys. 102 (2018) 48, arXiv:1804.09678 [hep-ph]*

for $\sin^2\theta_C$



$\sin^2\theta_{13}$

$\sin^2\theta_{23}$

~ 20% deviation in $\sin^2\theta_{13}$

can be due to deviation of $\theta_{12}{}^{l}$ from θ_C

Renormalization (RGE) effects from GUT scales to low energies

$$\sin^2\theta_{13} = \sin^2\theta_{23}\,\sin^2\theta_C\,(1 + O(\lambda^2))$$

lines: predictions from QLC

Implications

- Quarks and leptons know about each other,
  Q L unification, GUT or/and
  Common flavor symmetries

- Some additional physics is involved in the lepton sector
  which explains smallness of neutrino mass and difference
  of the quark and lepton mixing patterns

But may be ... 1-3 mixing of different origin

``Naturalness" : absence of fine tuning of mass matrix

Connecting solar and atmospheric neutrino sectors

$$\sin^2\theta_{13} = O(1)\frac{\Delta m_{21}{}^2}{\Delta m_{32}{}^2}$$

0.75

E. K. Akhmedov, G.C. Branco, M.N. Rebelo Phys.Rev.Lett. 84 (2000) 3535, [hep-ph/9912205]

Very small 1-3 mixing would be something special (symmetry)

Yet another "normal" relation:

almost the same relation in the quark and lepton sectors

$$\sin^2\theta_{13} = C \sin^2\theta_{12}\sin^2\theta_{23}$$

K. Patel, A. Y. S.

C_q = 0.380 +/- 0.020 C_l = 0.407 +/- 0.033

Similar structure of the mass matrices → Abelian symmetry

II. Mechanisms of neutrino mass generation

Nature of neutrino mass

is the neutrino mass of
the same origins as masses
of other particles?

Two aspects

Similar to cosmological constant

Smallness:

Suppression wrt. the EW scale

Why there is no usual scale Dirac masses?

No RH component → Dirac mass can not be formed

symmetry

See-saw or multi-singlet mechanisms
- suppression only
-finite contribution negligible

Finite value

Mechanisms unrelated to suppression of usual Dirac masses

Seesaw type II

Radiative mechanisms

see-saws type-I does both things simultaneously:

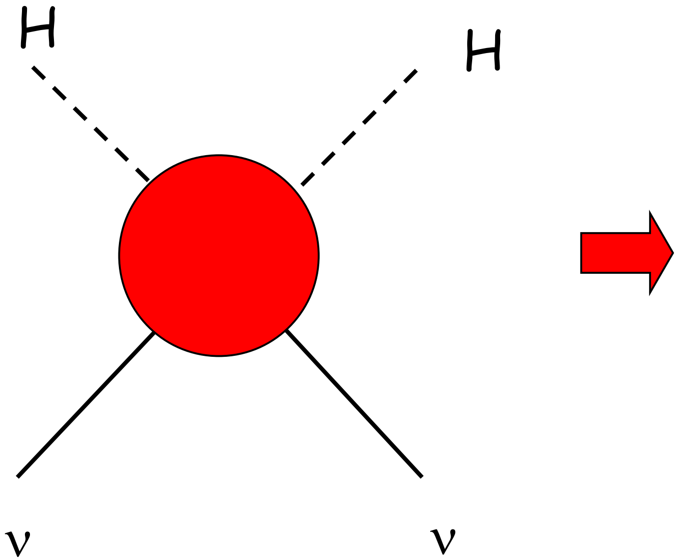
incomplete suppression

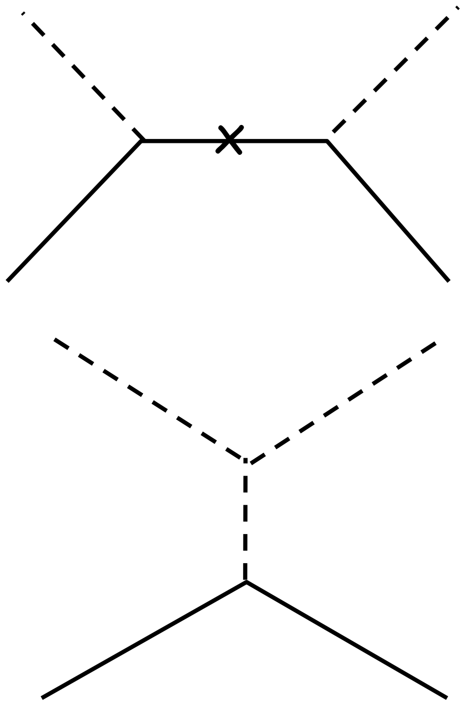
D5 operator

S. Weinberg

If no new particles at the EW scale, after decoupling of heavy degrees of freedom →
set of non-renormalizable operators

$$\frac{1}{\Lambda} \; L\,L\,H\,H$$

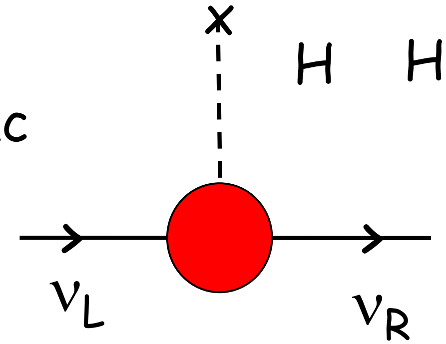




Neutrino mass and EW Symmetry breaking

Dirac

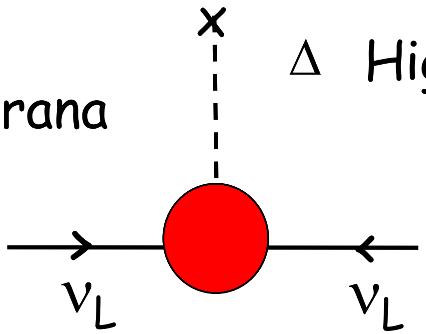
Higgs doublet



$m_D = h \langle H \rangle$

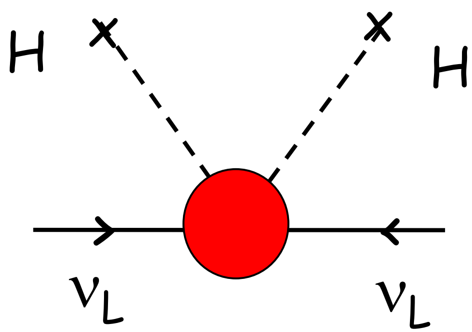
Majorana

Higgs triplet



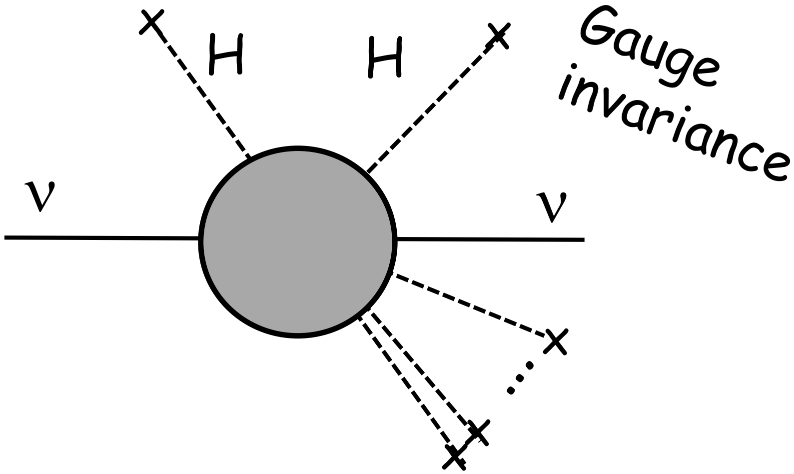
$m_L = f \langle \Delta \rangle$

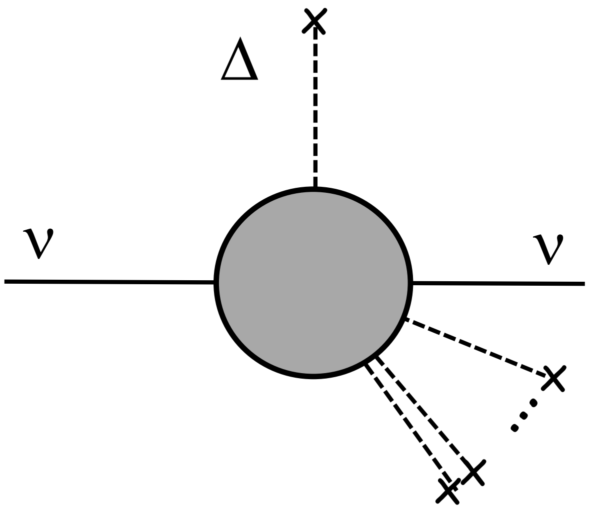
Elementary or composite operator with $I_W = 1$



$m_L = f \langle H \rangle \langle H \rangle$

Origins of (finite) mass





Similarly for Dirac neutrinos

Hard mass related to the EW scale

small effective coupling

small induced VEV formed by large VEV's (seesaw II)

Soft mass

VEV created at small scales

melting at T ~ VEV

MAVAN

Environment dependent masses; relic neutrinos

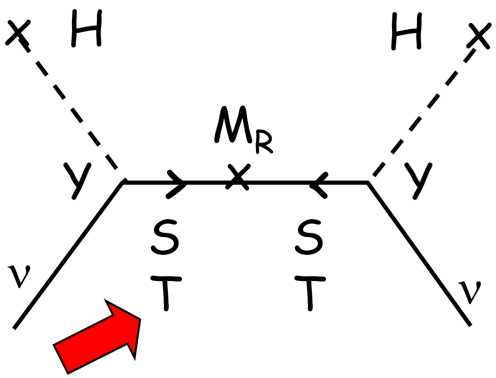
Gravitationally induced mass

Melting couplings

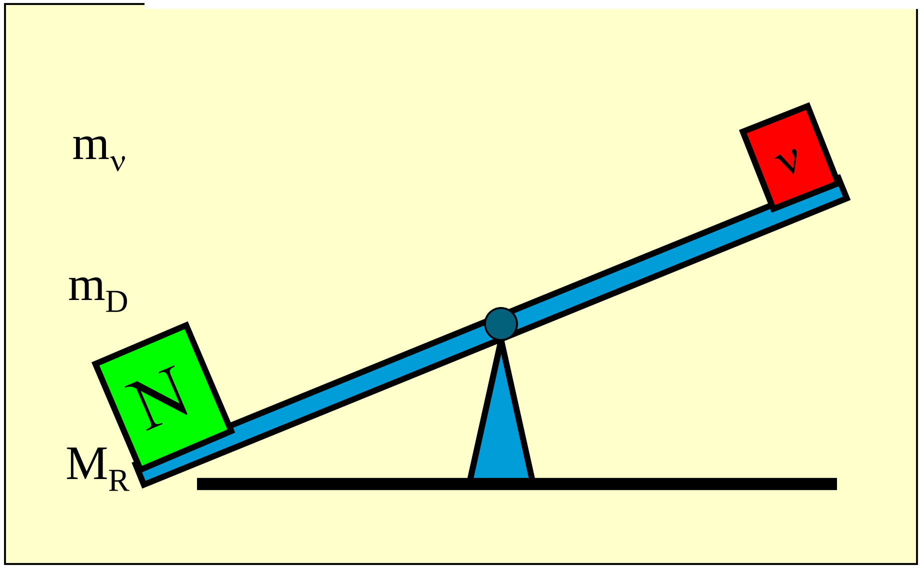
See-saw

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

Type 1



$m_D = Y\langle H \rangle$



Type 3 (SU(2) triplet intermediate state)

R Foot, H Lew, X G He, G C Joshi

Mass matrix:

$$\begin{array}{c c} & \begin{array}{cc} \nu & N \end{array} \\ \begin{array}{c} \nu \\ N \end{array} & \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \end{array}$$

if $M_R \gg m_D$ ⇒ $m_\nu = - m_D^T M_R^{-1} m_D$

$M_R \sim 10^{14}$ GeV

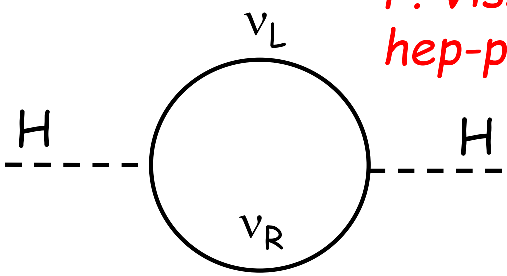
High scale line: the problem

Simplest seesaw implies new physical scale

$$M_R \sim m_D^2 / m_\nu \sim 10^{14}\ \text{GeV} \ll M_{Pl}$$

(Another indication: unification of gauge couplings)

ν_R



F. Vissani hep-ph/9709409

J Elias-Miro et al, 1112.3022 [hep-ph]

$$\delta m_H^2 \sim \frac{y^2}{(2\pi)^2} M_R^2 \log(q/M_R)$$

$$\sim \frac{M_R^3 m_\nu}{(2\pi v)^2} \log(q/M_R)$$

New physics below Planck scale $M_R < 10^7$ GeV

Small Yukawas, Leptogenesis ?

M. Fabbrichesi

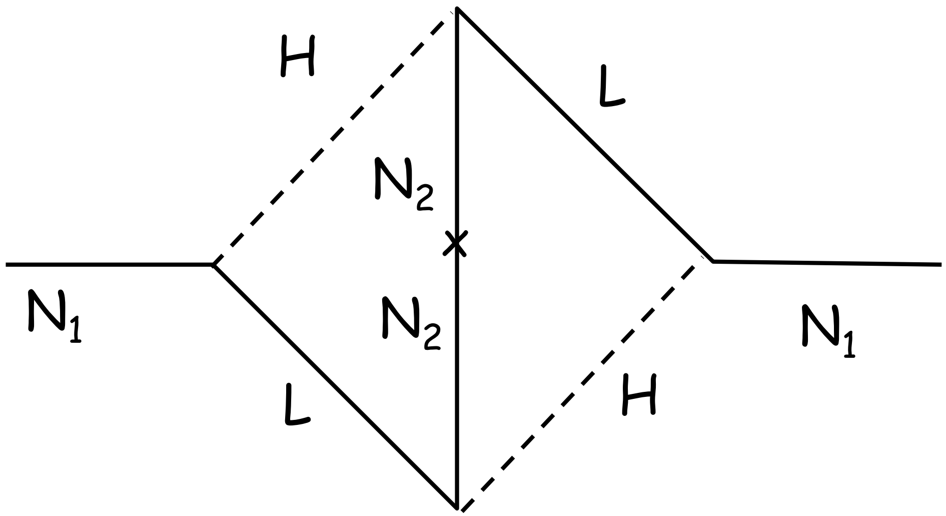
Cancellation?

"Partial" SUSY?

Planck-scale lepton number violation

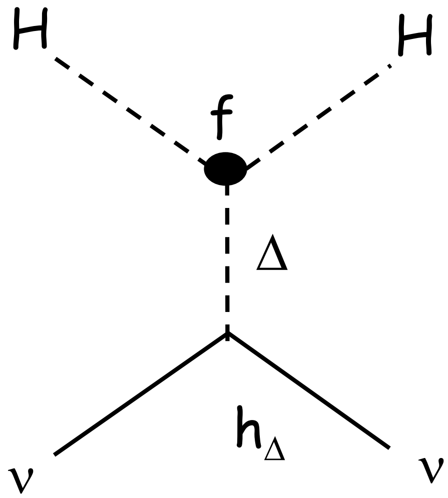
A Ibarra,et al
1802.09997 [hep-ph]

$M_2 \sim M_{Pl}$



$$M_1 \sim M_2 \frac{4\, y_1^2\, y_2^2}{(16\,\pi^2)^2} \,\mathrm{Log}\, M_2 / M_{Pl}$$ $\sim 10^{14}$ GeV

See-saw type-II



M. Magg and C. Wetterich
G. Lazarides, Q Shafi and C Wetterich
R. Mohapatra, G. Senjanovic,

Seesaw for VEV's:

$$\langle\Delta\rangle = \langle H\rangle^2 f/M_\Delta^2$$

$$m_\nu = h_\Delta \langle\Delta\rangle = h\, f \langle H\rangle^2 / M_\Delta^{\ 2}$$

Natural smallness of VEV

Light triplet?

Double Seesaw

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

R.N. Mohapatra
J. Valle

Beyond SM:
many heavy singlets
...string theory

$\mu = M_S$

μ - scale of B-L violation

→ $m_\nu = m_D^T M_D^{-1T} \mu M_D^{-1} m_D$

$\mu = 0$ massless neutrinos

violation of universality,
unitarity

$\mu << M_D$ Inverse seesaw

lower the scales of neutrino
mass generation

$\mu >> M_D$ Cascade seesaw

explains intermediate scale
for the RH neutrinos

$\mu \sim M_{Pl}$, $M \sim M_{GU}$ → $M \sim M_{GU}^2/M_{Pl} \sim 10^{-14}$ GeV

Screening of Dirac structures

A.Y.S
M. Lindner,
M.A. Schmidt
A.Y.S

$d = M_D^{-1} m_D$ ➡ $m_\nu = d^T M_S d$

screening factor

1. Complete screening of the Dirac structure

$m_D = A M_D$ as a consequence of symmetry $A = v_{EW}/V_{GUT}$

$d = A I$ ➡ $m_\nu = A^2 M_S$

Light neutrino mass matrix is determined by the heaviest one M_S

2. Partial screening of the Dirac structure

m_D , M_D = diag ➡ d = diagonal e.g. d = diag (a, 1, 1)

Affect mixing

$d = U_{23}^{max}$ or U_ω

S belong to Hidden sector

Linear Seesaw

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & m_L^T \\ m_D & 0 & M_D^T \\ m_L & M_D & 0 \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

E. Witten,
E . K. Akhmedov et al

$$m_\nu = m_D^T M_D^{-1} m_L + m_L^T M_D^{-1T} m_D$$

Linear in m_L - can produce weaker hierarchy than the double or inverse seesaw

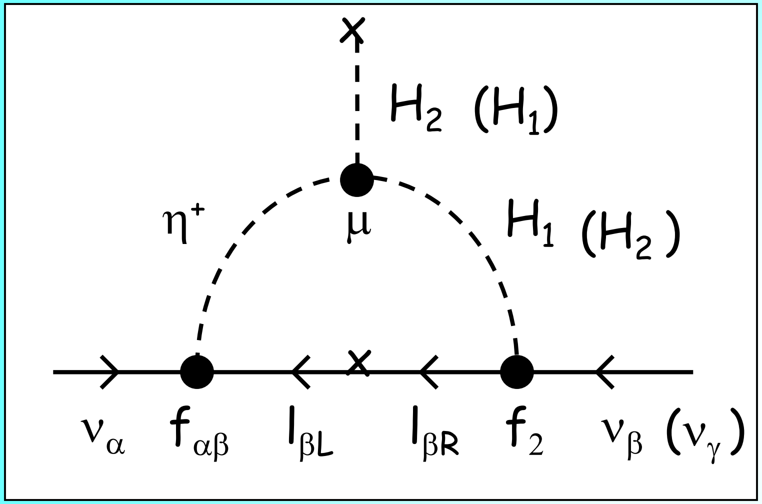
if ~ μ nonzero – both linear and double seesaw contributions

$$\frac{m_\nu^{lin}}{m_\nu^{dss}} = \frac{m_L M_D}{m_D \mu}$$

for $m_L = m_D$ linear seesaw dominates over the inverse seesaw

Zee-mechanism

No RH neutrinos
new bosons: singlet η^+, doublet H_2



$$m_\nu = A\,[(f\,m^2 + m^2 f^T) - v(\cos\beta)^{-1}(f\,m\,f_2 + f_2{}^T m\, f^T)]$$

$$A = \sin 2\theta_Z \ \ln(M_2/M_1)/(8\pi^2 v \tan\beta)$$

$$m = (m_e, m_\mu, m_\tau)$$

If only H_1 couples with leptons

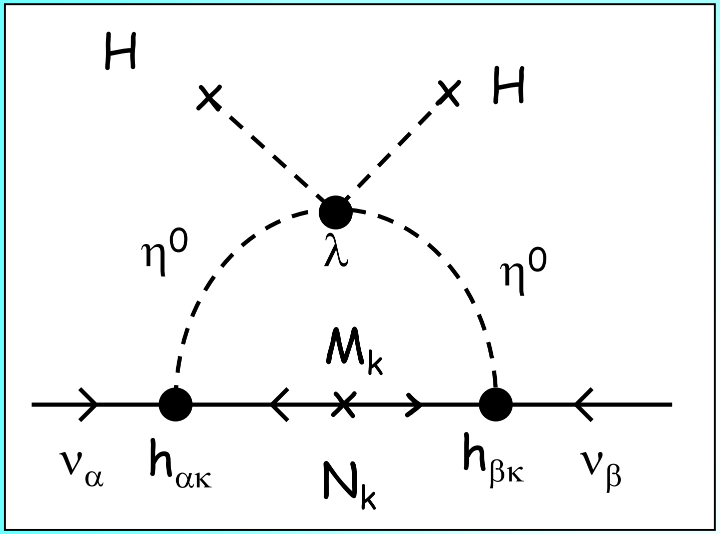
$$\begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ & 0 & m_{\mu\tau} \\ & & 0 \end{pmatrix}$$

Can not reconcile
two large mixings
one small mixing and
hierarchy of Δm^2

X-G He
P. Frampton, M. C. Oh
T. Yoshikawa

- inverse hierarchy of $f_{\alpha\beta}$
- $f_{\alpha\beta} < 10^{-4}$

Scotogenic mechanism



E. Ma, hep-ph 0601225

No RH neutrinos
new higgs doublet (η^+ , η^0)
and fermionic singlets N_k
odd under discrete symmetry Z_2

SM particles are Z_2 even

η^0 has zero VEV

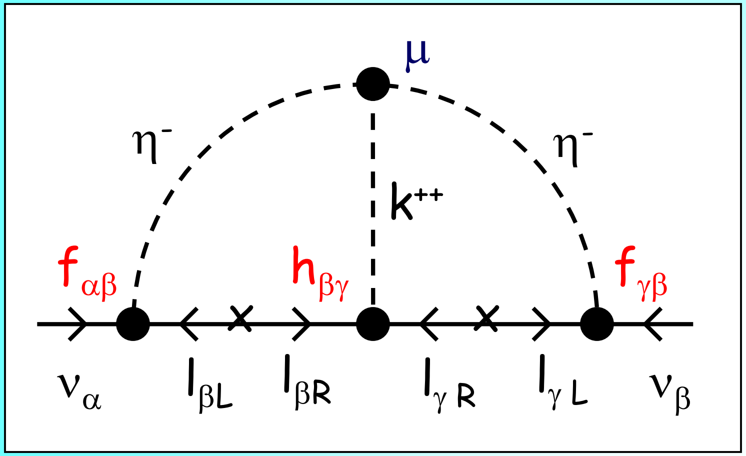
If H gives mass to
charged leptons leptons

If Z_2 is exact
η^0 or lightest N_k are stable and
can be Dark Matter particles

Neutrino mass – DM connection

Zee-Babu mechanism

K.S. Babu,
C. Macesanu



No RH neutrinos
new scalar singlets η^- and k^{++}

$m_\nu \sim 8\ \mu\ f\ m_l\ h\ m_l\ f\ I$

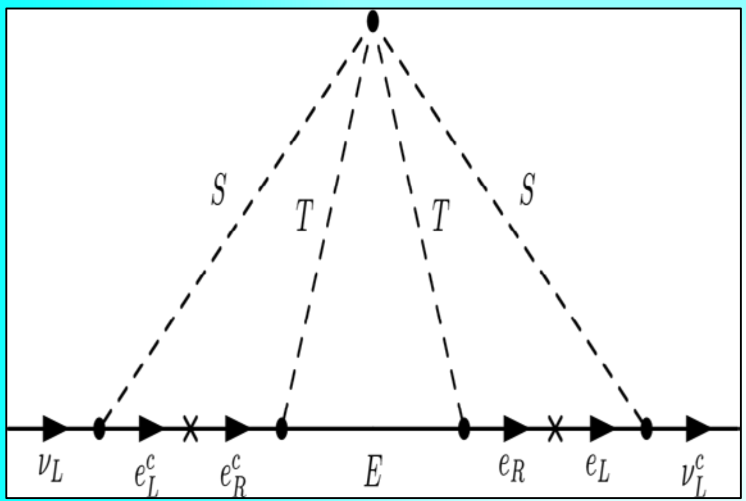
$m_l = \text{diag}\ (m_e, m_\mu, m_\tau)$

f and h are matrices of the couplings in the flavor basis

Features:
- the lightest neutrino mass is zero
- neutrino data require inverted hierarchy of couplings h
- f, h ~ 0.1

Testable:
- new charged bosons
- decays $\mu \to \gamma\ e$, $\tau \to 3\mu$ within reach of the forthcoming experiments

Three loops



A. Ahriche et al, 1404.2696 hep-ph

Z_2 symmetry

Classification of the effective operators
→ dressing
→ Multiloop mechanisms

S~(1,1,2) and *T*~(1,3,2) are scalars
E~(1,3,0) is a fermionic triplet.
There are three distinct diagrams with the sets {*T*+,*E*^{0} ,*T*−}, {*T*$^+$,(*E*+)c,*T*0} and {*T*0,*E*+,*T*−−} propagating in the inner loop.

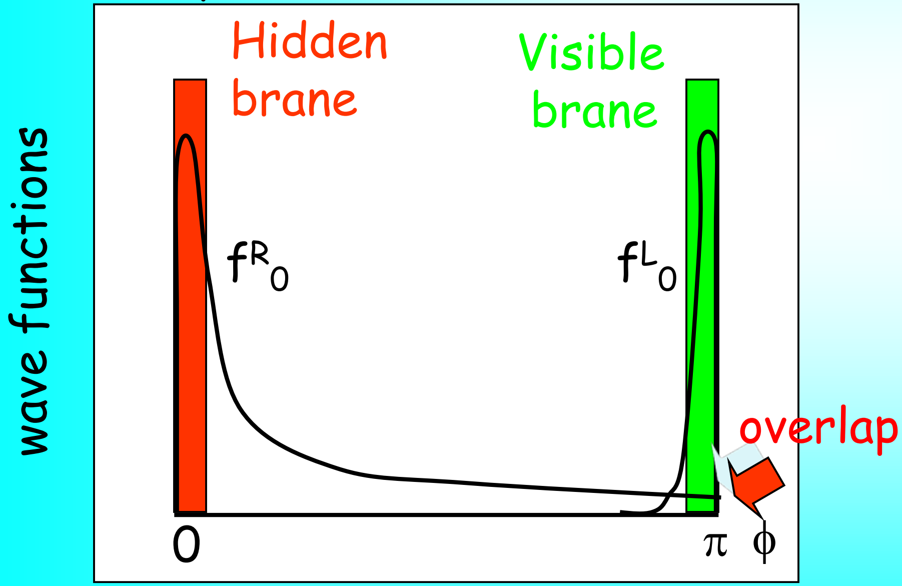
Overlap in extra dimensions

Right handed components are localized differently in extra dimensions

small Dirac masses due to overlap suppression:

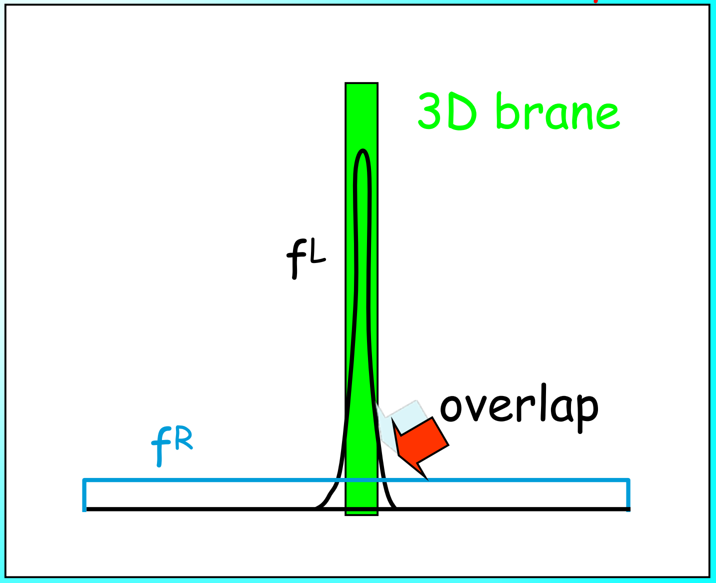
Warped extra D

Grossman Neubert



Flat extra D

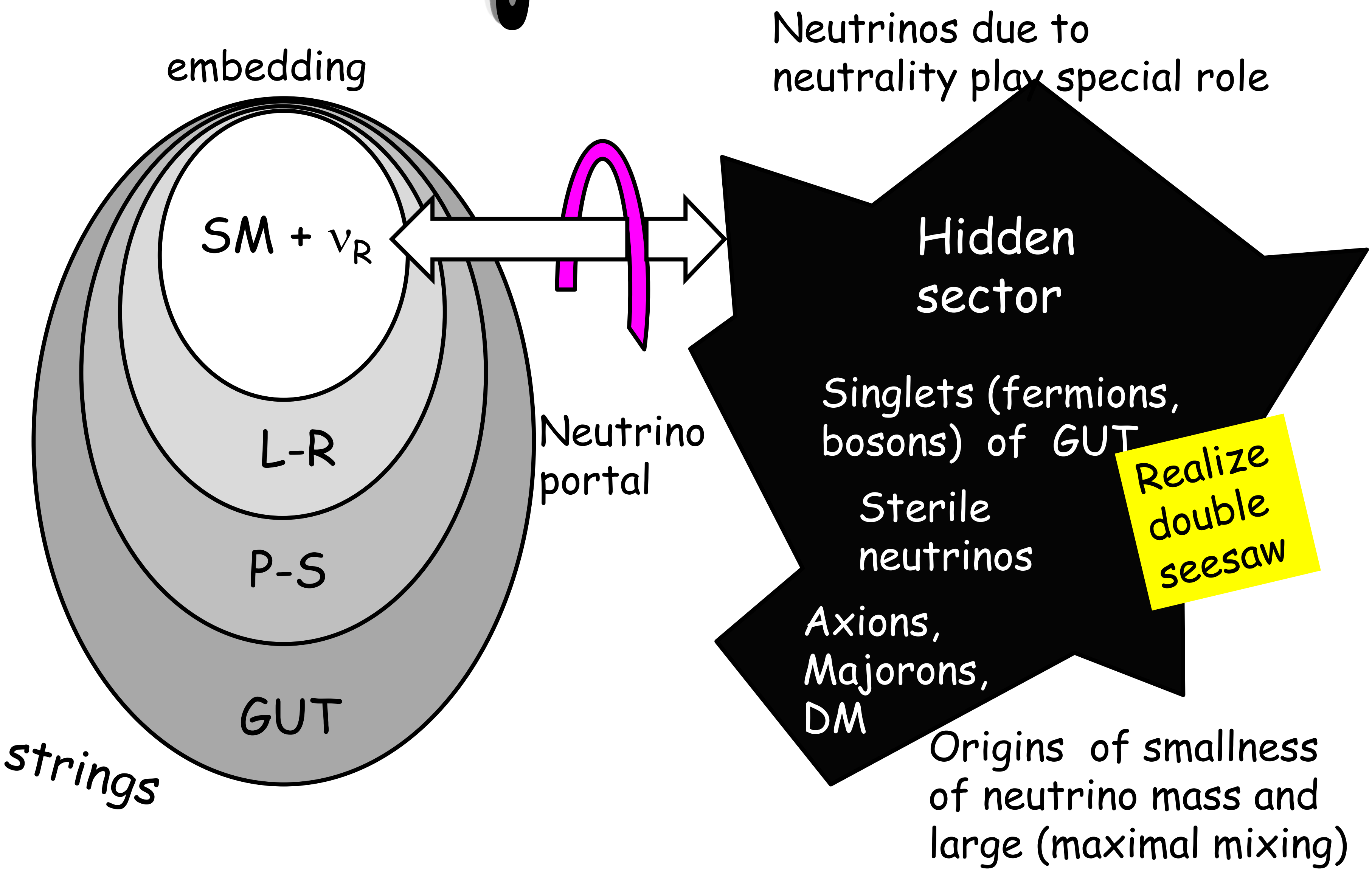
Arkani-Hamed, Dvali, Dimopoulos



$$m\,\varepsilon\,\overline{f^L}\,f^R \;+\; h.\,c.$$

amount of overlap in extra D

Mass and mixing from Hidden world



Neutrino portal

Neutrino are special

$\bar{L}H$ F

LH

ν_R

S

ν_R

S

Dark sector

via the portal:

Neutrino mass - seesaw
Large lepton mixing
Non Standard
Interactions

SM is well protected

Singlet of SM
symmetry
group

F - fermionic
operator

Non-local
interactions

Interactions which
violated fundamental
symmetries

Singlet of symmetry
group of hidden sector

$$\frac{1}{\Lambda^{n(F)\,-\,3/2}}\, L\, H\, F$$

Connection to the
Higgs portal: H^+H

Clockwork mechanism

A. Ibarra et all
1711.02070
[hep-ph]

fast rotation

slow rotation

Strong hierarchy (small quantities) without small parameters

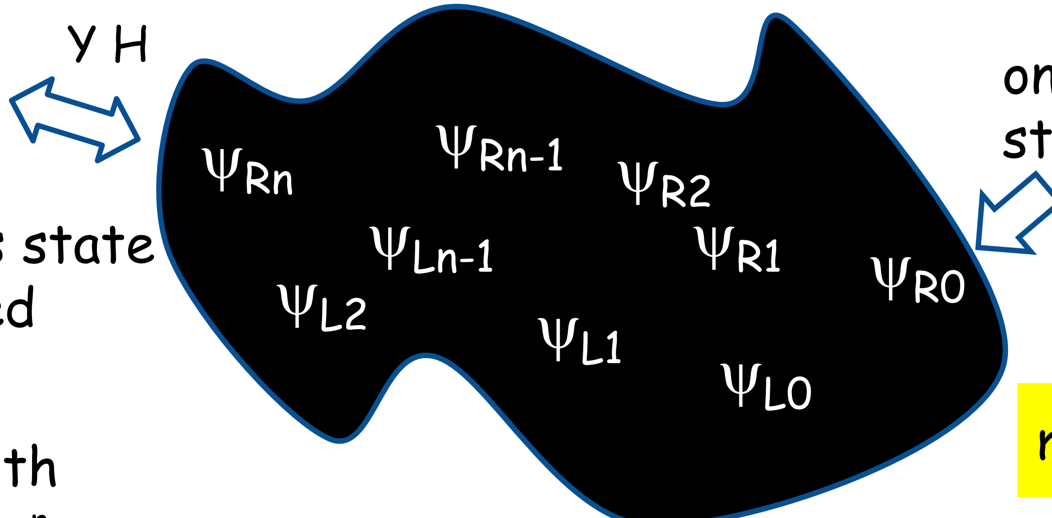
G. Giudice, et al

ψ_{L0}

It can be considered as special case neutrino mass with multiple RH neutrinos, or neutrino via hidden sector

Resembles generation due to extra dimension in deconstruction mode

ν_L



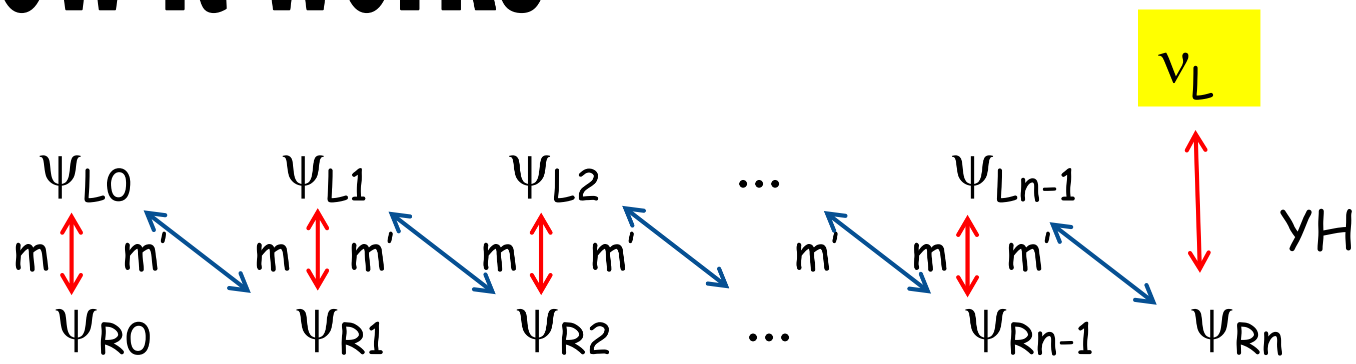
one massless state mostly here

Mixing of massless state in ψ_{Rn} is suppressed by factor q^n , $q > 1$

Yukawa coupling with massless state $Y q^{-n}$

$$m_\nu = \frac{1}{q^n} Y\langle H\rangle$$

How it works



$q = m'/m$ gear

$$\begin{matrix}\psi_{R0}\\ \psi_{R1}\\ \psi_{R2}\\ \cdots\\ \psi_{Rn}\end{matrix}\quad \begin{pmatrix} 1 & 0 & 0 & 0 & \cdots \\ -q & 1 & 0 & 0 & \cdots \\ 0 & -q & 1 & 0 & \cdots \\ \cdots & & & & \\ 0 \cdots & & & 0 & -q \end{pmatrix} \times \overset{\Sigma}{\begin{matrix} q^n \\ q^{n-1} \\ q^{n-2} \\ \cdots \\ 1 \end{matrix}}$$

Mixing of massless state in ψ_{Rn}

$1/N$

$m_\nu = Y\langle H\rangle/N$

Massless state

$$(q^n\, \psi_{R0} + q^{n-1}\, \psi_{R1} + q^{n-2}\, \psi_{R2} + \ldots + \psi_{Rn})/N$$

Normalization: $N^2 = \Sigma_{0\ldots n}\; q^{2j}$

Suppression factor

$$\frac{1}{q^n}\sqrt{\frac{q^2 - 1}{q^2 - q^{-2n}}}$$

Medium generated mass

Due to interactions with new light scalar fields

m_ν

Strongly restricted

Interactions with usual matter (electrons, quarks) due to exchange by very light mediator

Interactions with scalar field sourced by DM particles

Interaction with "Fuzzy" dark matter

Effective mass due to interactions with dark matter

$$L = - g_X \phi \bar{X} X - g_\nu \phi \bar{\nu}_L \nu_R + h.c.$$

H. Davoudiasl, et al
1803.0001 [hep-ph]

ϕ - very light scalar field producing long (astronomical) range forces

X – Dark matter particle (fermion of GeV mass scale) source of the scalar field

$$m_\nu = g_\nu \phi$$

From equation of motion for ϕ neglecting neutrino contribution to generation of ϕ

$$\phi = \frac{- g_X n_X}{m_\phi^2}$$

$$m_\nu = \frac{g_X g_\nu \rho_X}{m_\phi^2 m_X}$$

$m_\phi = 10^{-20} - 10^{-26}$ eV is mass of scalar

$n_X = \langle \bar{X} X \rangle$ is the number density of X

ρ_X - energy density of DM

$g_X = g_\nu = 10^{-19} \rightarrow m_\nu = 0.1$ eV

Mass depends on local density of DM and different in different parts of the Galaxy and outside

Interactions with fuzzy dark matter

A. Berlin,
B. 1608.01307 [hep-ph]

Ultra-light scalar DM, huge density ρ – as a classical field, solution

$$\phi(t, x) \sim \frac{\sqrt{2\rho(x)}}{m_\phi} \cos(m_\phi t)$$

Coupling to neutrinos $g_\phi \, \phi \, \nu_i \nu_j + \ldots$

gives contribution to neutrino mass and modifies mixing

Mass states oscillate

$\delta m(t) = g_\phi \, \phi(t)$ $\quad\quad$ $\Delta\theta_m(t) = g_\phi \, \phi(t) / \Delta m_{ij}$

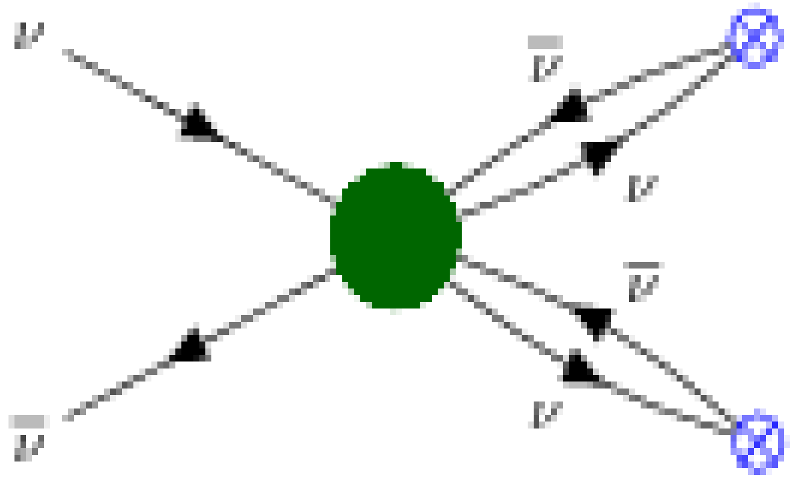
Neutrinos propagating in this field will experience time variations of mixing in time with frequency given by m_ϕ

Period ~ month, bounds from solar neutrinos, lab. experiments

Observable new effects (and not just renormalization of SM Yukawa and VEV) if the field has

- spatial dependence
- different sign for neutrinos and antineutrinos

Soft couplings and small VEV's



Neutrino mass generation through the condensate (crossed blue circles) via non-perturbative interaction (green circle).

Small neutrino masses from gravitational θ-term

G. Dvali and L. Funcke, Phys.Rev. D93 (2016) no.11, 113002 arXiv:1602.03191 [hep-ph]

No $\beta\beta_{0\nu}$ decay due to large q^2 the vertex does not exist

$\beta\beta_{0\nu}$ decay - unique process where neutrinos are highly virtual

Certain generic features independent on specific scenario can be considered on phenomenological level

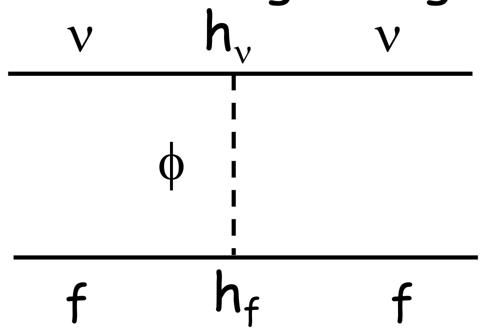
Back-up

Definitions and parameterization

Refraction due to long range forces

Light dark sector scalars, vectors …

Scattering via light mediators exchange:



$$A \sim \frac{h_\nu h_f}{q^2 - m_\phi^2}$$

With decrease of m_ϕ and the same decrease of h

refraction $(q^2 = 0) \sim h_\nu h_f / m_\phi^2$ does not change

inelastic scattering is suppressed as $h_\nu h_f / q^2$

Refraction effects dominate at small m_ϕ

Potential

$$V = \frac{h_\nu h_f}{m_\phi^2} n_f$$

in scalar case contributes to mass

number density of scatterers

EW - LHC scale

- No hierarchy problem (even without SUSY)
- testable at LHC, new particles at 0.1 – few TeV scale
- LNV decays

Low scale seesaw

νMSM

Low scale

L-R

$\not{R}_p$-SUSY

Neutralino as RH neutrino

Inverse seesaw

Radiative

One loop

Two loops

Three loops

Four loops

High dimensional operators

Radiative seesaw

Small VEV

Higgs Triplet

New Higgs doublets

Connection to Dark Matter

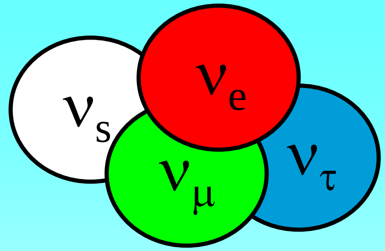
Remarks on sterile neutrinos

Most of discussion in 3 neutrino framework

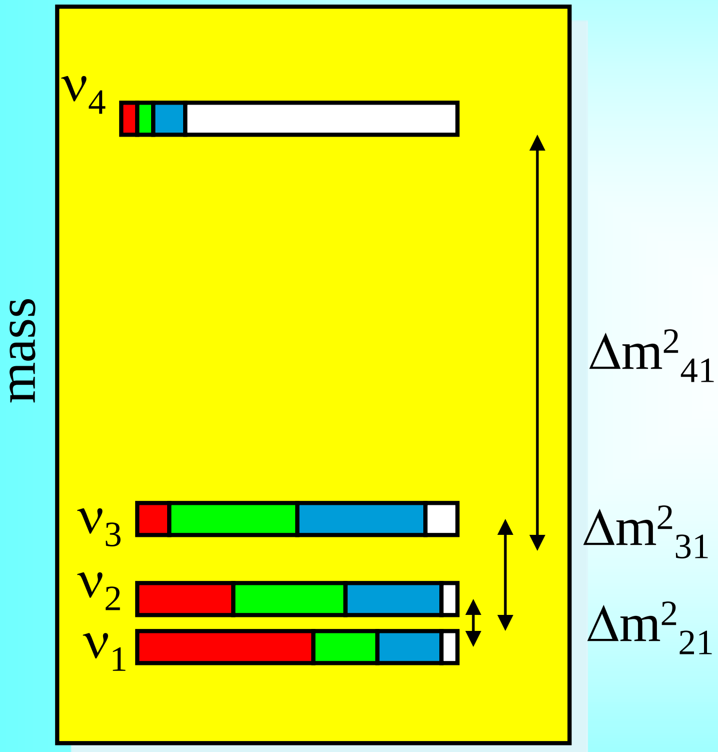
Rather plausible that new neutrino states exist

Depending on mass and mixing they may or may not affect our consideration significantly

(3 + 1) scheme



Interpretation



Strong perturbation of 3ν pattern:

$$m_{\alpha\beta}^{ind} \sim m_4 U_{\alpha 4} U_{\beta 4} \sim \sqrt{\Delta m_{32}^2}$$

Effect of possible sterile neutrinos can be neglected if

$$m_{\alpha\beta}^{ind} \ll \tfrac{1}{2}\sqrt{\Delta m_{21}^2} \sim 3\ 10^{-3}\ \text{eV}$$

$$|U_{\alpha 4}|^2 < 10^{-3}\,(1\ \text{eV}/m_4)$$

Large flavor mixing from steriles

Mass matrix

$$\begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_S \end{array} \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} & m_{eS} \\ \ldots & m_{\mu\mu} & m_{\mu\tau} & m_{\mu S} \\ \ldots & \ldots & m_{\tau\tau} & m_{\tau S} \\ \ldots & \ldots & \ldots & m_{SS} \end{pmatrix}$$

no contribution from S to $\beta\beta_{0\nu}$ decay, but S do contribute to oscillations

$$m_\nu = m_a + m_{ind}$$

eV scale seesaw

$$m_a = \begin{pmatrix} 0.2 & 0.4 & 0.4 \\ \ldots & 2.8 & 2.0 \\ \ldots & \ldots & 3.0 \end{pmatrix} 10^{-2}\ \text{eV}$$

$$m_{ind} = \frac{m_{SS}}{1\ \text{eV}} \begin{pmatrix} 2.0 & 2.0 & 4.5 \\ \ldots & 2.0 & 4.5 \\ \ldots & \ldots & 10.0 \end{pmatrix} 10^{-2}\ \text{eV}$$

produce dominant $\mu\tau$-block with small determinant

Enhance lepton mixing

Generate TBM mixing

m_{eS} $m_{\mu S}$ $m_{\tau S}$ may have certain symmetry

Summarizing results

Quark and Lepton Mixing

No immediate relations, equalities

Different mechanism of generation of masses of quarks and neutrinos

Partially connected

e.g. in seesaw type-II

Still some relations can be obtained within GUT since the same 126 contributes to quark masses

$\theta_{12}^{l} \sim \pi/2 - \theta_{12}^{q}$ $= \theta_C$

$\theta_{23}^{l} \sim \pi/2 - \theta_{23}^{q}$

QLC -relations

$\theta_{13}^{l} \sim \frac{1}{\sqrt{2}} \theta_C$

Predicted from QLC

Other quark mixing angles can be involved
But they give small corrections to these relations

Neutrino weak states

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

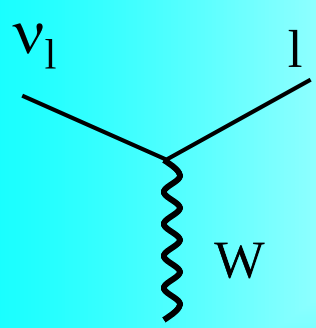
$I_W = 1/2$
$I_{3W} = 1/2$

Chiral components

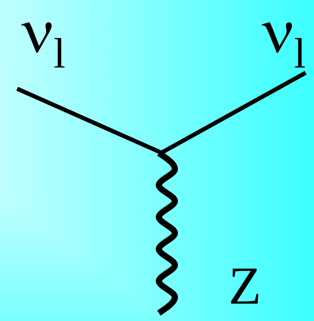
$$\nu_L = \tfrac{1}{2}(1 - \gamma_5)\,\nu$$

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

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



$l = e\,,\ \mu\,,\ \tau$



Neutral current interaction

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

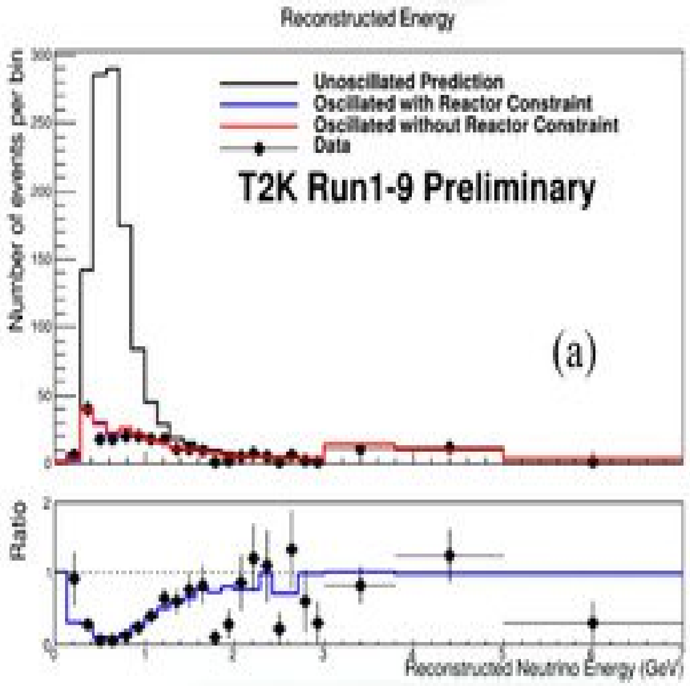
$$\frac{g}{4}\,\bar{\nu}_l\,\gamma^\mu(1 - \gamma_5)\nu_l\, Z_\mu$$

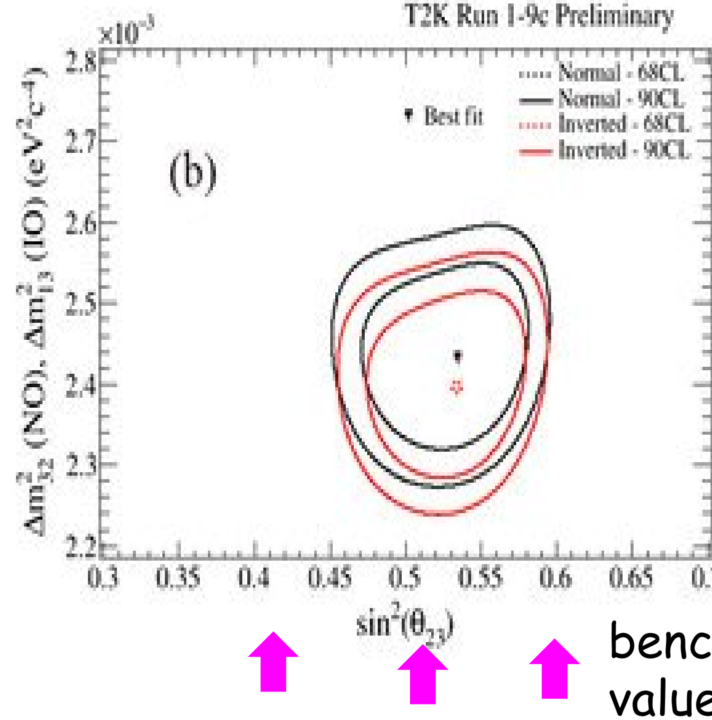
Conservation of lepton numbers L_e, L_μ, L_τ

T2K results

D. Karlen, (T2K Collaboration)
Universe **2019**, *5*(1), 21.

Update 2.2 → 2.6×10 ^{21} POT



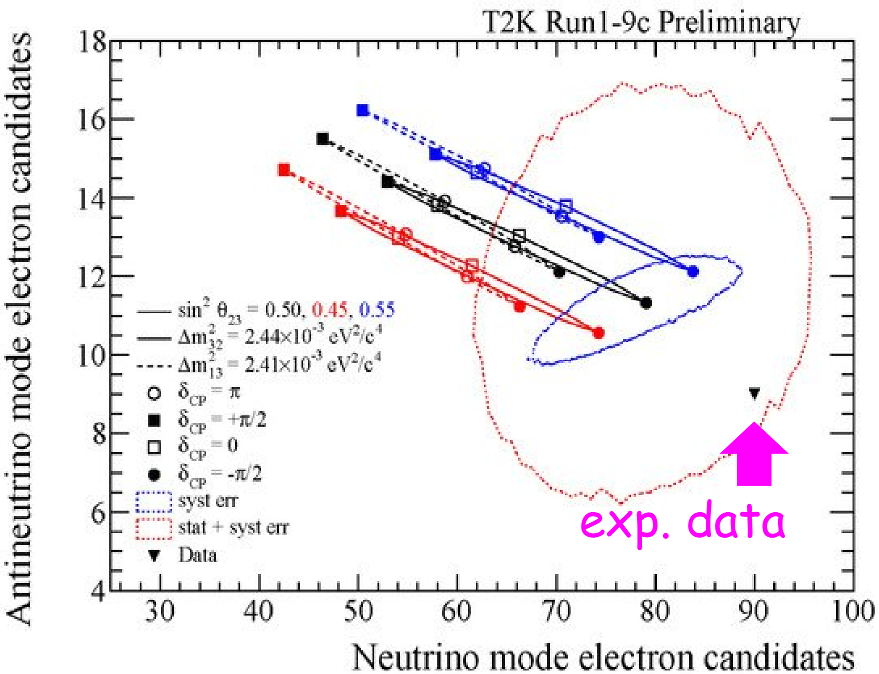


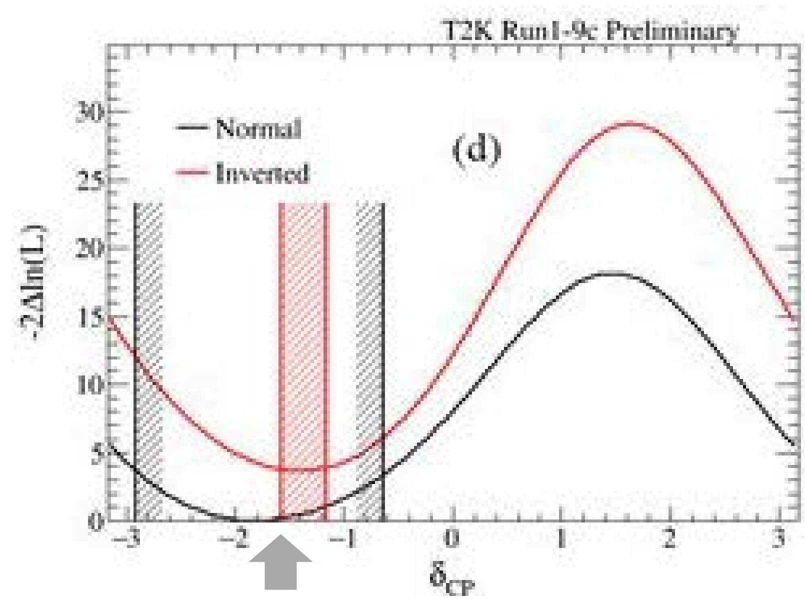
benchmark values

The rate of muon-neutrinos in the far detector. Data vs. expected rate for the best fit oscillation parameters.

Confidence intervals for the atmospheric oscillation parameters for the normal and inverted mass ordering .

T2K results





The expected numbers of ν_e and $\overline{\nu}_e$ events for optimized systematic parameter values. The solid (dashed) ellipses are for NO (IO)

Jagged - expected 1σ regions for $\sin^2\theta_{23} = 0.5$, $\delta_{CP} = -\pi/2$ with different treatment of systematics: random with external data (blue) or Poisson random (red)

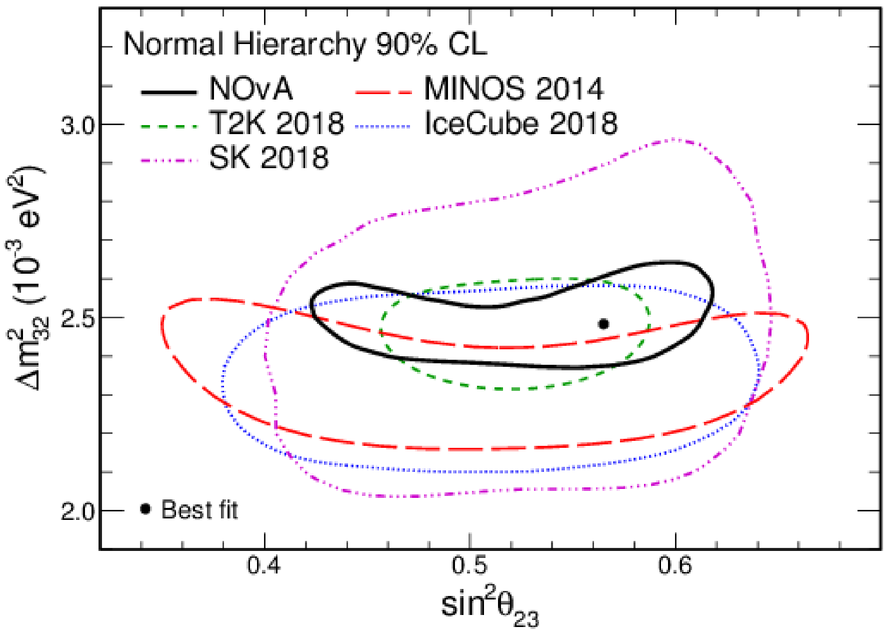
The frequentist 2σ confidence intervals on δ_{CP}

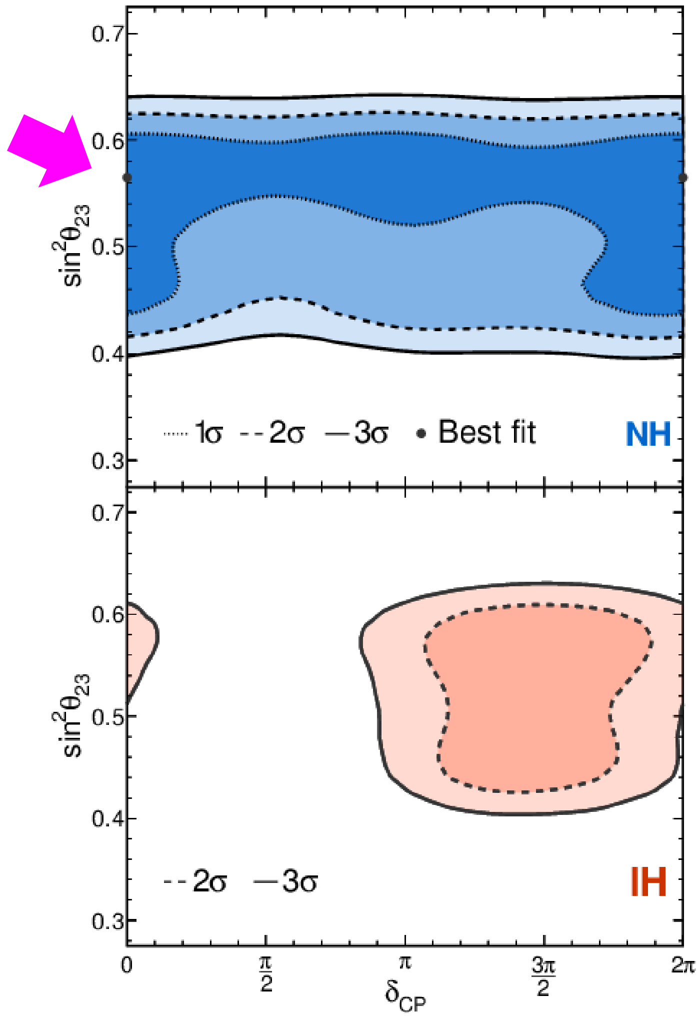
Best fit close to maximal CP violation

NOvA results

NOvA Collaboration (Acero, M.A. et al.) arXiv:1906.04907 [hep-ex]

First measurement of neutrino oscillation parameters using neutrinos and antineutrinos by NOvA

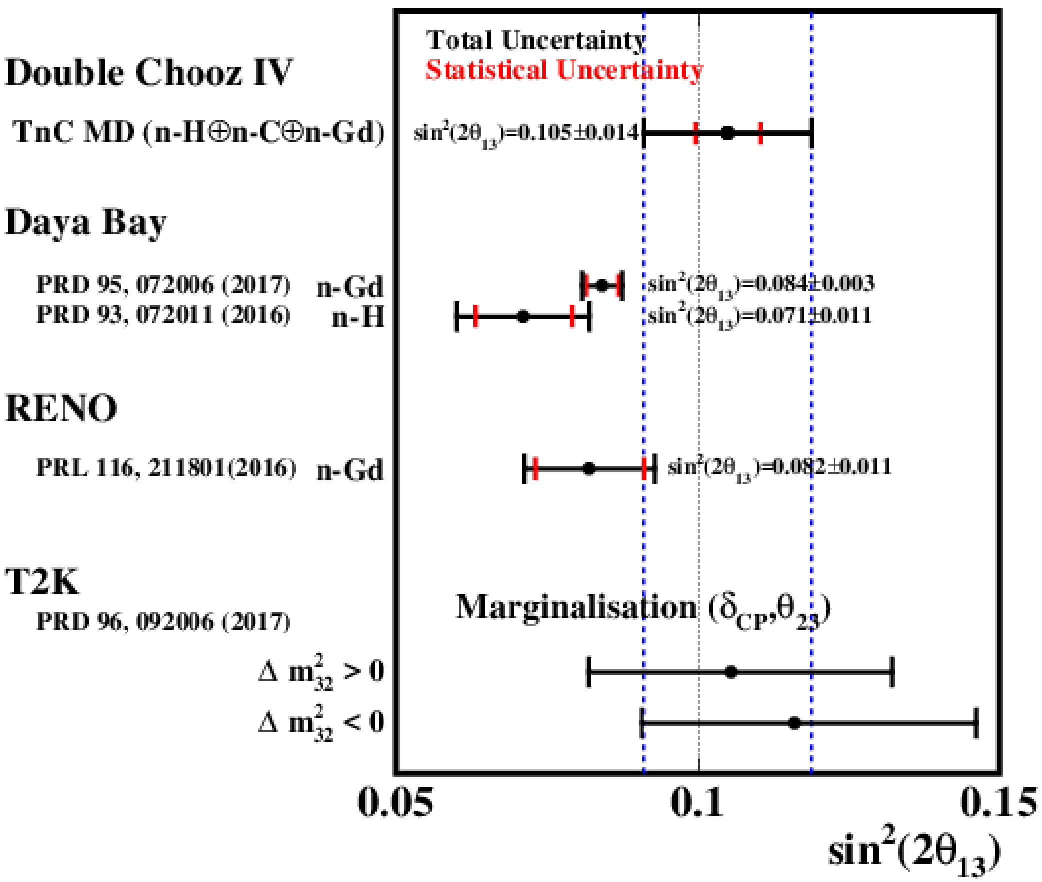




Best fit point (NO):
no CP violation, δ_{CP} = 0.
At 1σ any value is allowed

1-3 mixing from reactors

First Double Chooz θ13 Measurement via Total Neutron Capture Detection - Double Chooz Collaboration (de Kerret, H. et al.) arXiv:1901.09445 [hep-ex]



The most precise published reactor measurements of θ_{13} from DC MD TnC , DYB and RENO .

DC result shows a [25,48]% higher central value whose significance ranges [1.3,1,9]σ compared to other reactor measurements.

The T2K larger uncertainty is due to the marginalisation over θ_{23} and CP violation.

Atmospheric neutrinos

ANTARES: measurements of 2-3 mass and mixing

IceCube Deep Core: tentative attempts to extract mass hierarchy

ORCA: 2 strings employed

Super-Kamiokande -IV

Super-Kamiokande Collaboration (Jiang, M. et al.) PTEP 2019 (2019) no.5, 053F01, 1901.03230 [hep-ex]

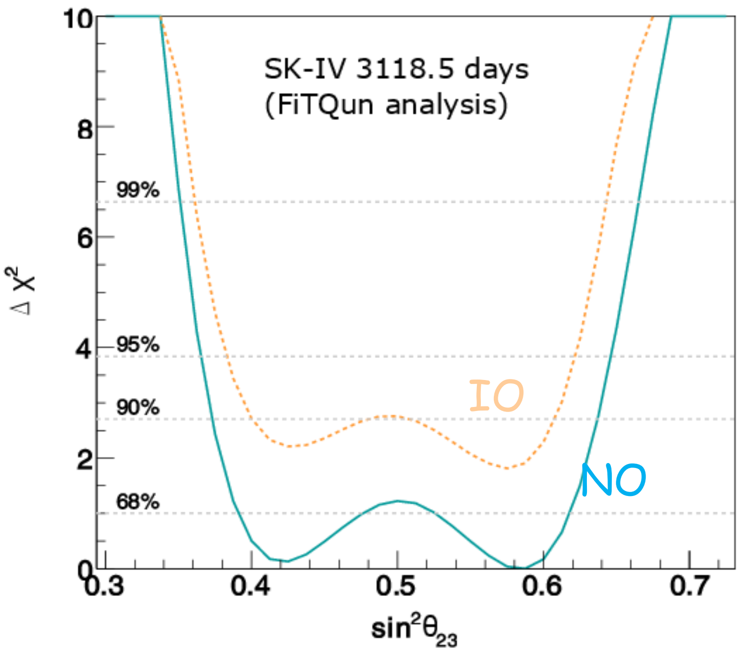
Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction

- A new event reconstruction algorithm based on a maximum likelihood method developed .
- Improves kinematic and particle identification capabilities,
- Enable to increase fiducial volume by 32%
- increase the sensitivity to the neutrino mass hierarchy.

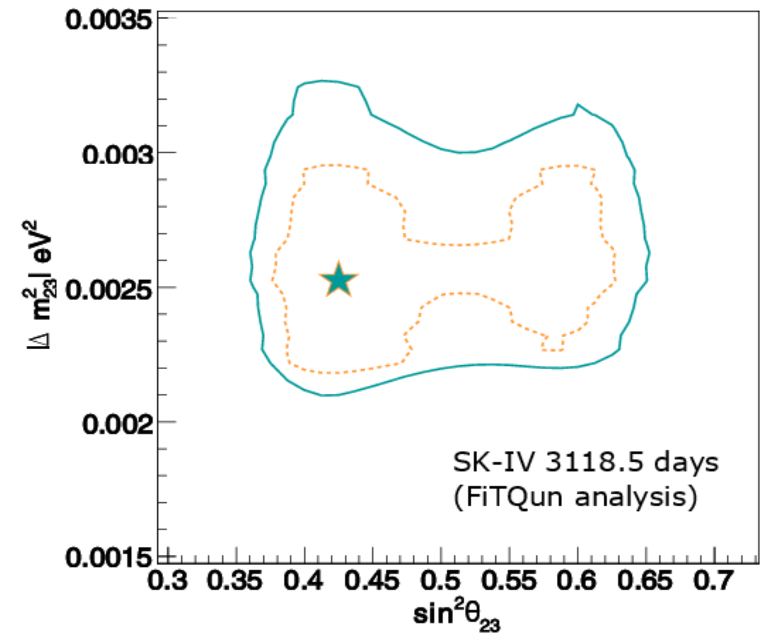
Super-Kamiokande results

Super-Kamiokande Collaboration (Jiang, M. et al.) PTEP 2019 (2019) no.5, 053F01, 1901.03230 [hep-ex]

253.9 kton·year exposure



Super-K constraint with no assumed bounds on 13 mixing



The best-fit value, (star) is the same for NO and IO. $\sin^2\theta_{13} = 0.0210 \pm 0.0011$. The contours - relative to the global bf.

Weak preference for the NO, disfavoring the IO at 74%

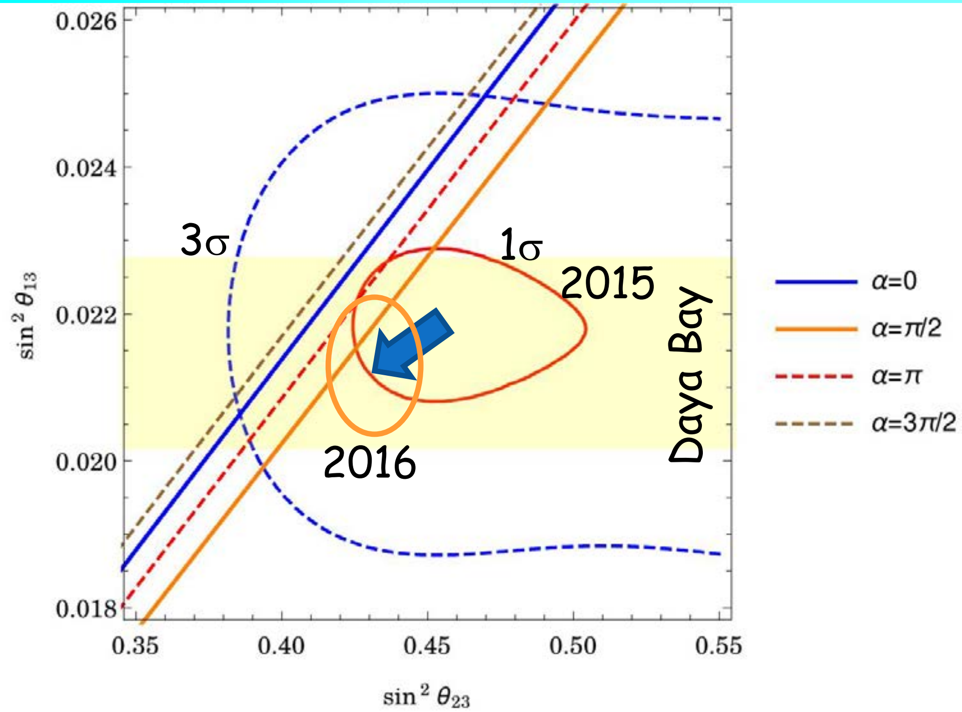
bf – substantial deviation from maximal: $\sin^2\theta_{23} = 0.42$.
At 1 maximal mixing and high octant are allowed

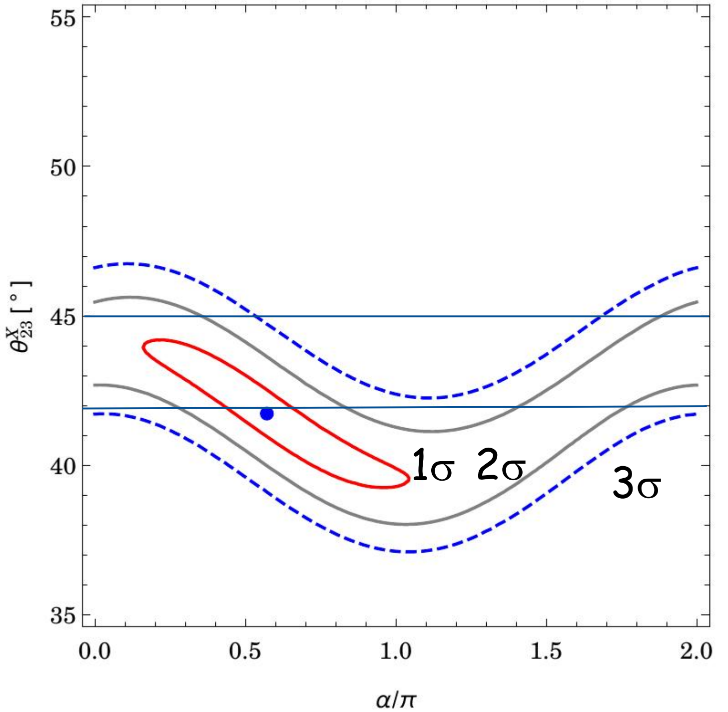
General relation

Normal mass ordering

$\sin^2\theta_{13} = \sin^2\theta_{23} \sin^2\theta_C (1 + O(\lambda^2))$

$\lambda = \sin \theta_C$





Dependence of 1-3 mixing on 2-3 mixing for different values of the phase α. Allowed regions from the global fit NuFIT 2015

Allowed values of parameters of U_X

Best fit value: $\theta^X_{23} = 42^0$

RGE effect from maximal mixing value at high scale

Summarizing results

NuFIT 4.1 (2019)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.244 \to 0.496 & 0.467 \to 0.678 & 0.646 \to 0.772 \\ 0.287 \to 0.525 & 0.488 \to 0.693 & 0.618 \to 0.749 \end{pmatrix}$$

$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.243 \to 0.490 & 0.473 \to 0.674 & 0.651 \to 0.772 \\ 0.295 \to 0.525 & 0.493 \to 0.688 & 0.618 \to 0.744 \end{pmatrix}$$

$$\text{TBM} \quad \begin{pmatrix} 0.866 & 0.577 & 0 \\ 0.408 & 0.577 & 0.707 \\ 0.408 & 0.577 & 0.707 \end{pmatrix}$$

But there are correlations between elements

Summarizing results

NuFIT 4.1 (2019)

without SK atmospheric data

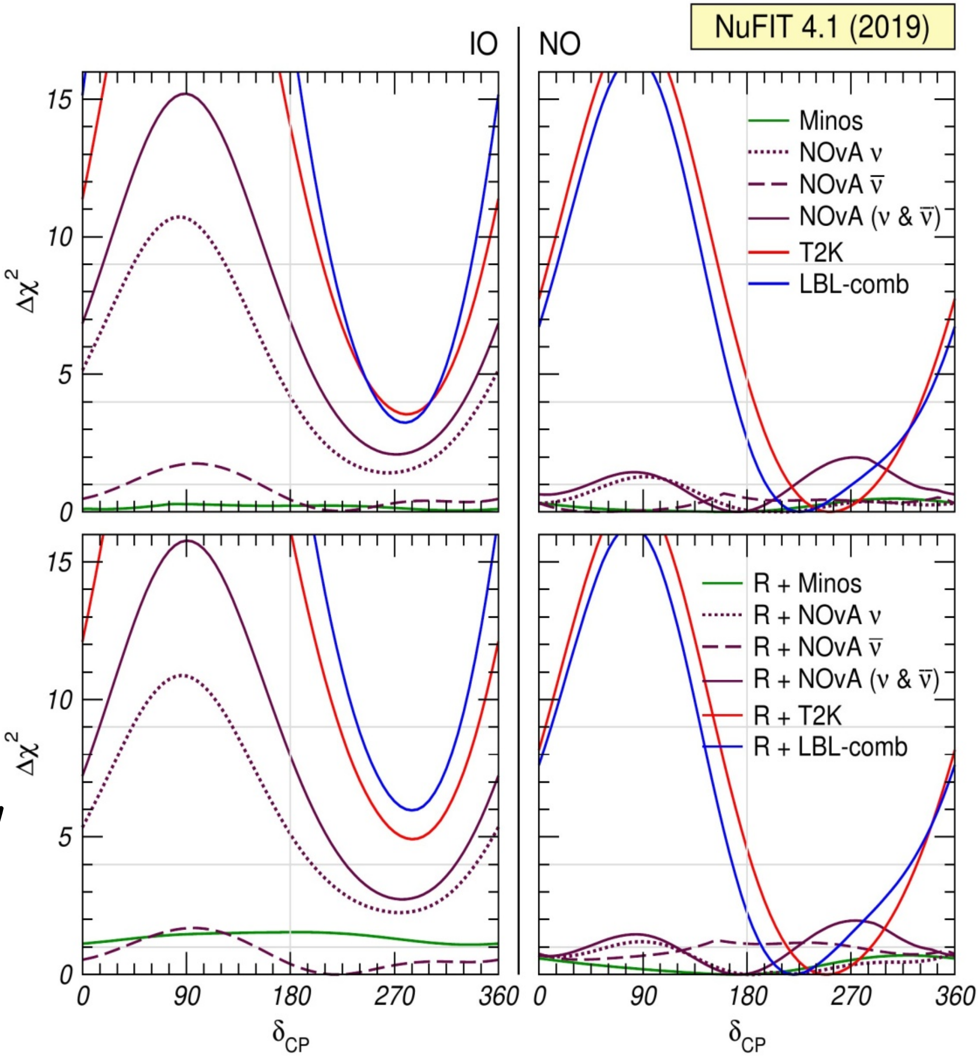
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

Summarizing results

Bounds on δ_{CP} from MINOS (green), NOvA (dark-redwood), T2K (red) and their combination (blue). Left (right) panels are for IO (NO); for each experiment $\Delta\chi^2$ is defined with respect to the global minimum of the two orderings. For NOvA we also show as dotted (dashed) lines the results obtained using only neutrino (antineutrino) data. The upper panels show the 1-dimensional $\Delta\chi^2$ from LBL accelerator experiments after imposing a prior on θ_{13} to account for reactor bounds. The lower panels show the corresponding determination when the full information of LBL and reactor experiments is used in the combination. In all panels solar and KamLAND data are included to constrain Δm^2_{21} and θ_{12}.

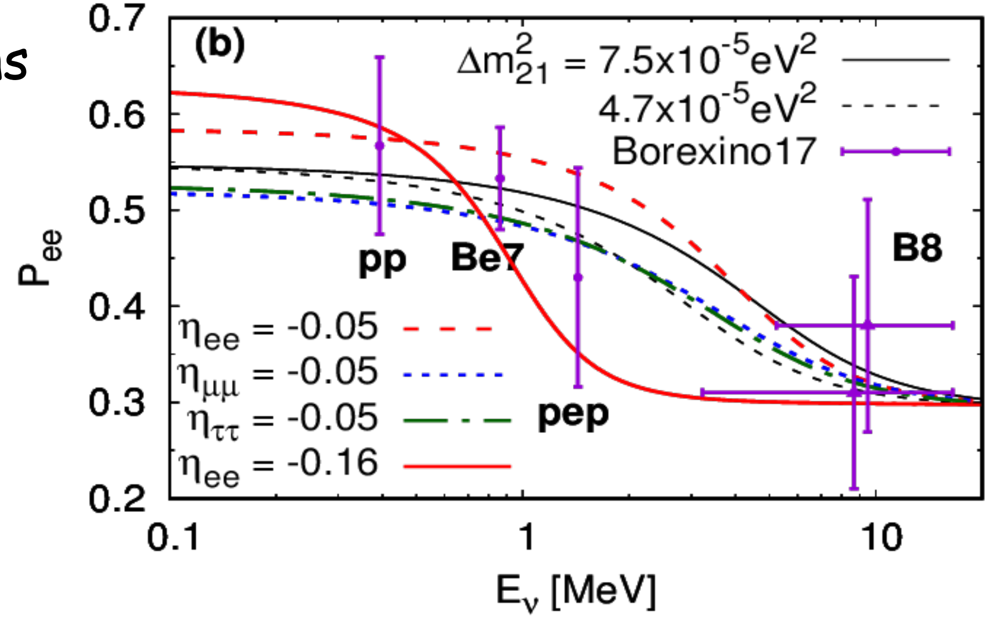


Refraction due to very light scalar mediator

Shao-Feng Ge, S. Parke, 1812.08376 [hep-ph]

Neutrino scattering on electrons via very light scalar exchange

The solar neutrino conversion probabilities with scalar NSIs vs. Borexino results.



To satisfy bounds on h_ν h_e (especially from searches of 5th force:

$$1/m_\phi >> R_{Earth}$$

→ strong suppression of the potential $V = V_0\, m_\phi R_{Earth}$

To avoid bounds – cancellations in 5^{th} force experiments – not shown if this is possible

After more than 40 years of theoretical studies, thousands of papers written we are not far from the beginning: "ground zero" determined by experimental measurements

Big temptation to give such lectures as collection of jokes, if not one point

Enormous efforts in determination of matrix elements, cross-sections, systematics, backgrounds...

And all this is to measure neutrino parameters

Determination of neutrino parameters is not the end of story

We measure neutrino parameters to establish the underlying physics.

In spite of scepticism searches for true theory of mass and mixing is the must

High scale seesaw, unification

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

q – l similarity: $m_D \sim m_q \sim m_l$

Lepton number violation

$M_R \sim$
- $M_{GUT} \sim 10^{16}$ GeV — for the heaviest in the presence of mixing
- 10^8 - 10^{14} GeV — $\frac{M_{GUT}^2}{M_{Pl}}$ double seesaw
- 10^{16} - 10^{17} GeV — many heavy singlets (RH neutrinos) ...string theory $N \sim 10^2$

In favor

Gauge coupling unification

Leptogenesis

Seesaw sector is responsible for inflation (scalar which breaks B-L and gives masses of RH neutrinos), dark matter

Double Seesaw

R.N. Mohapatra
J. Valle

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & M_S \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

M_S - scale of B-L violation

$M_S \sim M_{Pl}$, $M_D \sim M_{GU}$

$\Rightarrow$ $m_\nu = m_D^T M_D^{-1T} M_S M_D^{-1} m_D$

$M_S >> M_D$

$M_R = M_D^T M_S^{-1} M_D$

can be very hierarchical

Important feature:

if $m_D = A M_D$ $\Rightarrow$ $m_\nu \sim M_S$

hierarchical Dirac structures disappear

More than usual see-saw?

Scale of see-saw

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

q – l similarity: $m_D \sim m_q \sim m_l$

for one third generations $M_R \sim 2\ 10^{14}$ GeV

M_R - hierarchy

$$M_R = - m_D^{diag} (m_{TBM})^{-1} m_D^{diag}$$

Quadratic hierarchy

Flavor structure

Difficult to reproduce

Can be explained in the framework of double seesaw

Double Seesaw

R.N. Mohapatra
J. Valle

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & M_S \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$M_S >> M_D$

M_S - scale of B-L violation

RH neutrinos get mass via see-saw

$$M_R = M_D^T M_S^{-1} M_D$$

This explains

1. strong mass hierarchy $M_D \sim m_D$ and M_S has no strong hierarchy
2. intermediate scale of masses if $M_S \sim M_{Pl}$, $M_D \sim M_{GU}$
3. Flavor structure:

→ $m_\nu = m_D^T M_D^{-1T} M_S M_D^{-1} m_D$

if $m_D = A\ M_D$ → $m_\nu \sim M_S$ may have certain symmetries

A.Y.S
M. Lindner, M.A. Schmidt A.Y.S

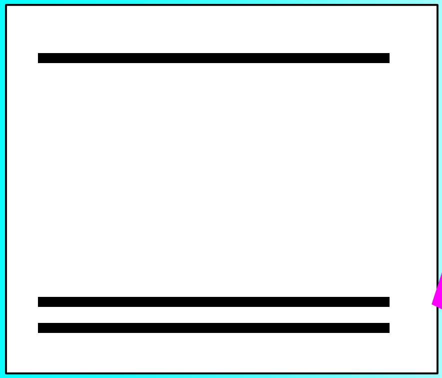
Mass and Mixing

In general

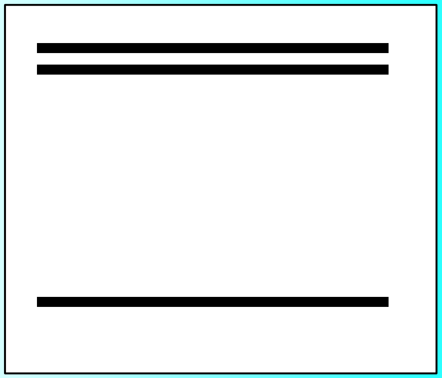
Maximal mixing ⇔ degeneracy of masses

This works for 1-2 Sector for both hierarchies:

Charged Lepton mixing explains deviation from maximal



Still degeneracy is possible



quark sector relation Still possible

2-3 mixing is close to maximal but 2-3 mass splitting is large. Complete degeneracy is disfavored by cosmology

$$\theta \sim \sqrt{\frac{m_2}{m_3}}$$

Simple symmetries → degeneracy, massless states

Standard parametrization

$U_{PMNS} = U_{23} I_\delta U_{13} I_{-\delta} U_{12}$ $\quad$ $I_\delta = \mathrm{diag}(1, 1, e^{i\delta})$

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

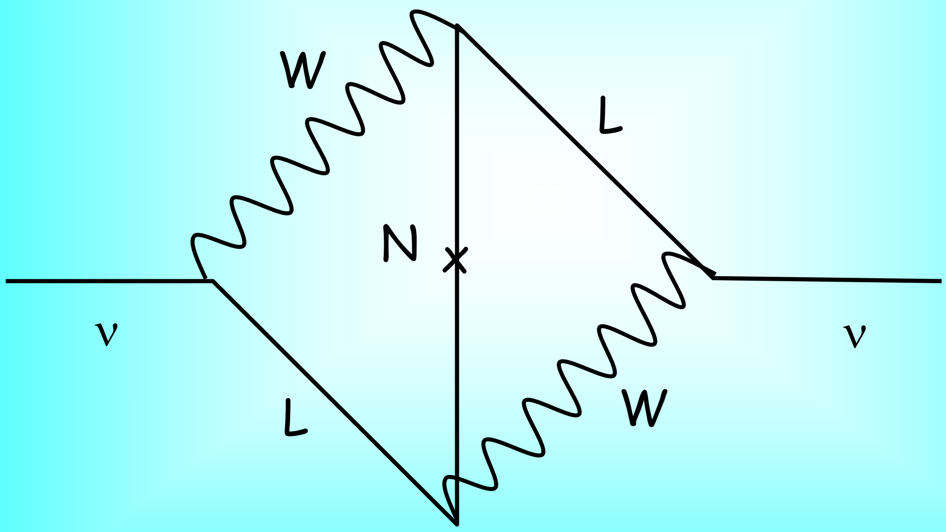
$c_{12} = \cos\theta_{12}$, etc.

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 reactor mixing angle

Summarizing results

Definitions and parameterization

Two loop mechanism

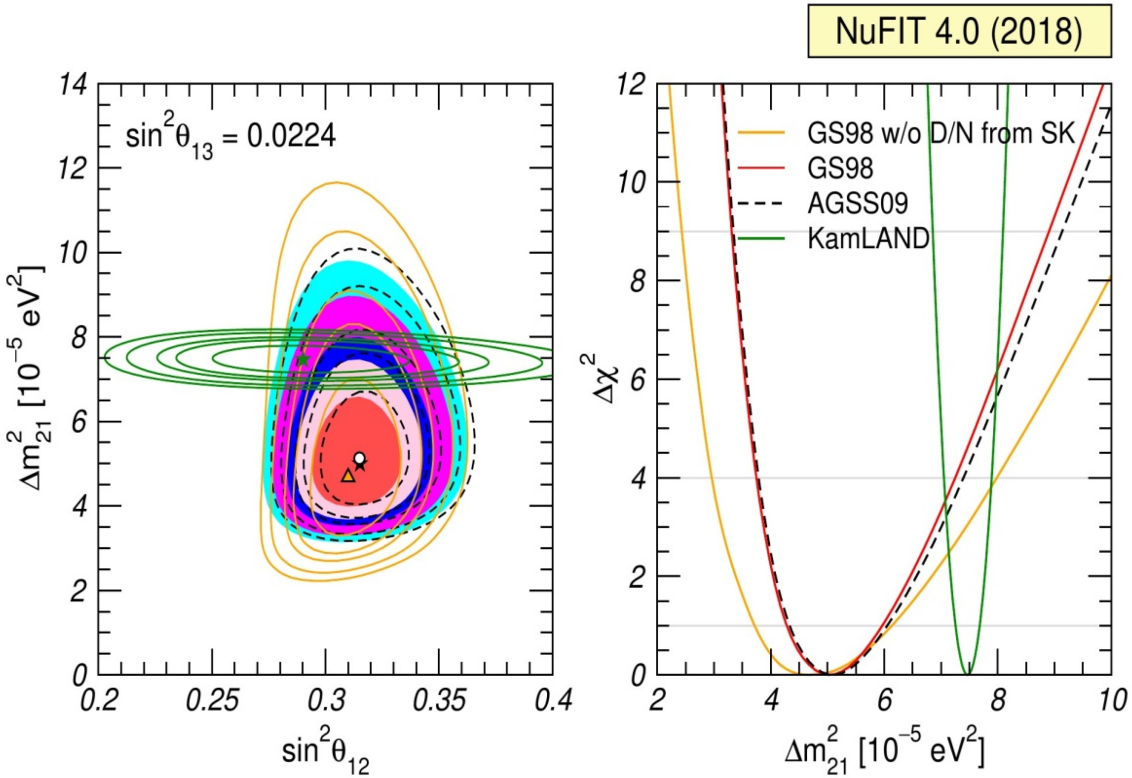


K S Babu, E Ma

If usual neutrinos mix with heavy Majorana lepton N

4th generation of fermions → main contribution

Solar neutrinos: Δm_{21}^2 - tension



Origin of tension:
- Absence of the upturn of spectrum (SNO, SK)
- 50% larger than expected D-N asymmetry for the bf Δm_{21}^2

Yellow lines - without the DN effect

68%, 90%, 95%, 99%, 3σ CL contours

Contours for solar models with different metallicity) also with and without DN effect

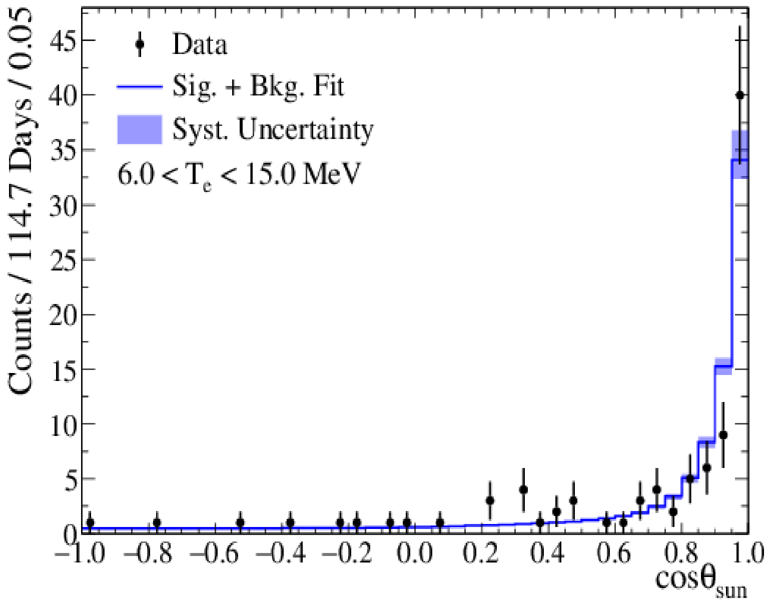
tension starts to disappear?

Solar neutrinos SNO+ results

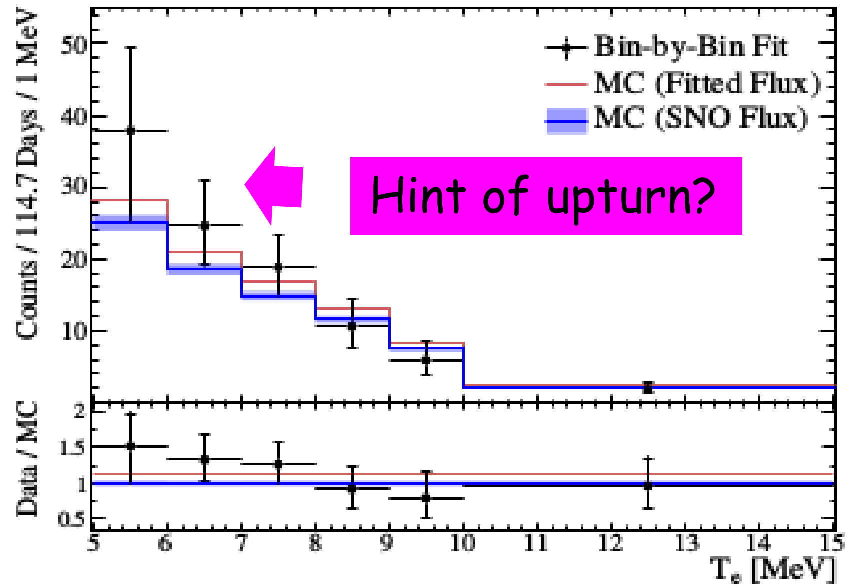
SNO+ Collaboration (Anderson, M. et al.)
Phys.Rev. D99 (2019) no.1, 012012
1812.03355 [hep-ex]

Water phase: Measurement of the 8B solar neutrino flux in SNO+ with very low backgrounds S/B ~ 4, E > 6 MeV

114.7 days of data



Distribution of event directions wrt. solar direction



The extracted event rate as function of reconstructed electron kinetic energy

69.2 kt-day dataset

Flux: 2.53 [-0.28+0.31(stat) -0.10+0.13(syst)] x 10^{-6} cm^{-2} s^{-1}

Deviations from TBM

$D_{13} = 0 - \sin^2\theta_{13}$ $D_{12} = 1/3 - \sin^2\theta_{12}$ $D_{23} = \frac{1}{2} - \sin^2\theta_{23}$

Deviations – consequences of symmetry
(complicated groups) → "direct"

Deviations - violation of (simple) symmetries → "semi-direct"

"Sum rules"

Ref. Nothing fundamental model dependent

Deviations related to mass ratios?

$Z_2 \times Z_2$ - TBM

Z_2 - only one column in the mixing matrix is fixed, e.g. TBM_1

Quark and Lepton Mixing

Patterns of mixing are strongly different

Un connected	Partially connected	Fully connected
Different mechanism of generation of masses of quarks and neutrinos	QLC -relations	by symmetry: difficult to realize

e.g. in seesaw type-II

$$\theta_{12}^{l} \sim \pi/2 - \theta_{12}^{q}$$ $= \theta_C$

$$\theta_{23}^{l} \sim \pi/2 - \theta_{23}^{q}$$

$$\theta_{13}^{l} \sim \frac{1}{\sqrt{2}} \theta_C$$ Predicted from QLC

In general:

$$U_{PMNS} = U_{CKM}^{+} U_X$$

$$U_{CKM} = V_{CKM}$$

Bi-maximal or TBM matrix