Neutrino masses

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Physics of the Standard Model and Beyond

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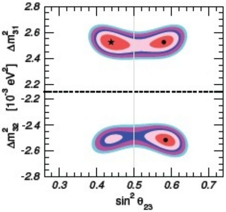
Outline

What do we know about neutrino parameters?

Current status of neutrino parameters

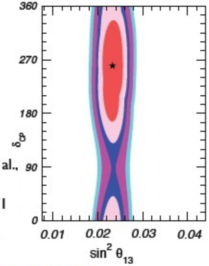


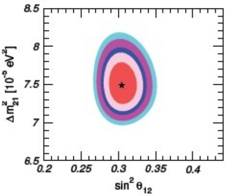
3 sizable mixing angles

2 mass squared differences

NuFit 3.0: M. C. Gonzalez-Garcia et al., 1611.01514

See also F. Capozzi et al., 1703.04471





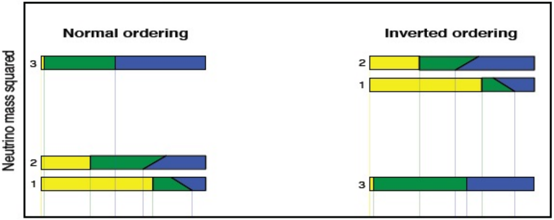
- neutrinos have mass
- neutrinos mix

First evidence of physics beyond the Standard Model.

What do we know about neutrino parameters?

Neutrino masses

$\Delta m_s^2 \ll \Delta m_A^2$ implies at least 3 massive neutrinos.



Fractional flavour content of mass eigenstates

$$m_1 = m_{\min} \qquad m_3 = m_{\min}$$
$$m_2 = \sqrt{m_{\min}^2 + \Delta m_{\rm sol}^2} \qquad m_1 = \sqrt{m_{\min}^2 + |\Delta m_{\rm A}^2| - \Delta m_{\rm sol}^2/2}$$
$$m_3 = \sqrt{m_{\min}^2 + \Delta m_{\rm A}^2 + \Delta m_{\rm sol}^2/2} \qquad m_2 = \sqrt{m_{\min}^2 + |\Delta m_{\rm A}^2| + \Delta m_{\rm sol}^2/2}$$

Measuring the masses requires:

- the mass scale: $m_{\min}$
- the mass ordering. There is a hint in favour of NO based mainly on atmospheric events.

F. Capozzi et al., 1703.04471; See also SK, talks at ICHEP 2016 and NOW 2016

What do we know about neutrino parameters?

Phenomenology questions for the future

- **What is the nature of neutrinos? Dirac vs Majorana?**
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

What do we know about neutrino parameters?

Phenomenology questions for the future

- **What is the nature of neutrinos? Dirac vs Majorana?**

  Neutrinoless dbeta decay

- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.

- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.

  LBL: T2K, NOvA, DUNE, T2HK, ESSnuSB, Daedalus, nuFACT..., PINGU, ORCA, INO, JUNO

- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?

  reactor SBL and MBL, atm, LBL, ...

- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects? MINOS+, MicroBooNE, SoLid, ...

Outline

The nature of neutrinos: Dirac vs Majorana

Dirac neutrino: four components

particle: spin up/down   anti-particle: spin up/down

$$\left(\nu_L \xrightarrow{CPT} (\nu^c)_R \xleftrightarrow{Lorentz} (\nu^c)_L \xrightarrow{CPT} \nu_R \right)_D$$

Majorana neutrino: just two components

Neutral particles can be their own anti-particle (Majorana 1937)

example: neutral pion (neutral kaon is not) !

Majorana neutrino is its own antiparticle

spin up/down

$$\left(\nu_L \underset{Lorentz}{\overset{CPT}{\rightleftarrows}} \nu_R \right)_M$$

The nature of neutrinos: Dirac vs Majorana

Dirac Neutrino

◇ Neutrino and Antineutrino are distinct particles.
(like their charged lepton partners)

◇ Flavor lepton number is not conserved but total lepton number is conserved.

- Neutrino
- Antineutrino

Dirac Mass Term

◇ Need to have a right-handed neutrino.
(Not in the Standard Model)

- Mass term like e, μ, τ.

Majorana Neutrino

◇ Neutrinos and Antineutrinos are the same particles
(This can only happen since Neutrinos have no charge!)

◇ Lepton number is not conserved

Neutrino $\Leftrightarrow$ Antineutrino

Majorana Mass Term

New type of mass.

The nature of neutrinos: Dirac vs Majorana

Dirac Neutrino

Majorana Neutrino

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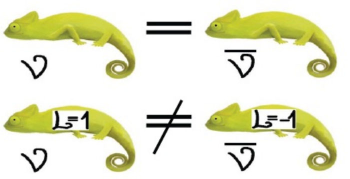
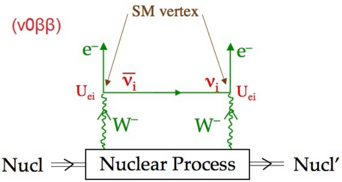


The nature of neutrinos is linked to the conservation of The the Lepton number (L). This information is crucial in understanding the Physics BSM: with or without L-conservation?

Outline

How to test the nature of neutrinos

Neutrinoless double beta decay, $(A, Z) \to (A, Z+2) + 2e$, tests the nature of neutrinos. It violates L by 2 units.



The half-life time depends on neutrino properties

$$[T_{0\nu}^{1/2}(0^+ \to 0^+)]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 |\langle\ m\ \rangle|^2$$

$$|\langle\ m\ \rangle| \equiv |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\rho} + m_3|U_{e3}|^2 e^{i\sigma}|$$

U_{ei} Mixing angles (known) and ρ, σ CPV phases(unknown)

How to test the nature of neutrinos

Predictions for Neutrinoless double beta decay

The predictions for $|\langle\ m\rangle|$ depend on the neutrino mass spectrum

- NH $(m_1 \sim\ m_2 << m_3) : |\langle\ m\ \rangle| \sim 1 - 5\ meV$
- IH $(m_3 << m_1 \sim\ m_2) : 10\ meV < |\langle\ m\ \rangle| < 50\ meV$
- QD $(m_1 \sim\ m_2 \sim\ m_3) : 44\ meV < |\langle\ m\ \rangle| < m_1$

Outline

What type of masses neutrinos can have

Neutrino masses in the SM lagrangian

A mass term for a fermion connects a left-handed field with a right-handed one. For example the usual Dirac mass

$$m_\psi(\overline{\psi}_R\psi_L + h.c.) = m_\psi\overline{\psi}\psi$$

Recall: In the standard model, $\nu_{\beta R}$ (the RH neutrino) doesnt exist, therefore neutrinos are massless.

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Solution: Introduce ν_R for Dirac masses

Dirac masses

This is the simplest case. We assume that we have two independent Weyl fields: ν_L and ν_R

and we can write down the term as above.

$$m_\nu(\overline{\nu}_R\nu_L + h.c.) = m_\nu\overline{\nu}\nu$$

What type of masses neutrinos can have

Dirac Neutrino mass term

We could simply put in $\nu_{\beta R}$ (sterile neutrino)

$-\mathcal{L}_{mass} = \sum_{\alpha\beta} M_{\alpha\beta} \left(\overline{\nu}_{\alpha L} \nu_{\beta R}\right) + h.c.$

$M_{\alpha\beta} = \frac{\upsilon}{\sqrt{2}} \lambda_{\alpha\beta}$

The coupling $\lambda_{\alpha\beta}$ doesnt have to be diagonal and in general it isnt. To find the physical fields, those of definite mass, we need to diagonalize $M_{\alpha\beta}$.

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$U^{\dagger} M V = m_{diag}$

$\nu_{\alpha L} = \sum_i U_{\alpha i}\nu_{iL}$; $\nu_{\alpha R} = \sum_i V_{\alpha i}\nu_{iR}$

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$M_{\alpha\beta}$ and $U_{\alpha i}$

Flavor Lepton number violate.

U is the mixing matrix which enters in neutrino oscillations.

So the form of the mass matrix determines the mixing pattern.

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$-\mathcal{L}^{D}_{mass} = \sum_i \overline{\nu}_{iL} m_i \nu_{iR} + h.c.$

This conserves total lepton number!

$\nu_L \rightarrow \ e^{i\alpha}\ \nu_L$

What type of masses neutrinos can have

Dirac Neutrino mass term

It follows that

$$\lambda_\nu \sim \frac{\sqrt{2} m_\nu}{\nu_H} \sim \frac{0.2\ eV}{200 GeV} \sim 10^{-12}$$

Tiny couplings!

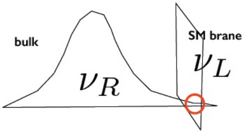
1. why the coupling is so small????
2. why the mixings are large? (instead of small as in the quark sector)
3. why neutrino masses have at most a mild hierarchy if they are not quasi-degenerate? instead of what happens to quarks?
4. Dirac masses are strictly linked to lepton number conservation. But this is an accidental global symmetry. Should it be conserved at high scales?

What type of masses neutrinos can have

There are models which address the problem of the smallness of the couplings.

Extra-D models

In these models all gauge-interacting fields are in the SM brane. Right-handed neutrinos are singlets and therefore will be in the bulk.



The overlap of the wavefunctions (which are normalised) of the left-handed and right-handed neutrinos leads to a small Yukawa coupling.

See e.g. Arkani-Hamed et al., 2002; Grossman and 49 Neubert, 2000. Models with warped extra-D....

What type of masses neutrinos can have

Majorana Neutrino mass term

Other possibility: Since neutrinos have electric charge = 0, neutrinos could be Majorana particles, i.e. be their own antiparticles $(\nu = \nu^C)$

We use the fact that

$$(\nu_L)^C = (\nu^C)_R$$

then the mass term is

Majorana mass term for left-handed neutrinos:

$-\mathcal{L}^M_{mass,L} = \frac{1}{2} m_L \overline{(\nu_L)^C} \nu_L \; + h.c.$

Majorana mass term for right-handed neutrinos:

$-\mathcal{L}^M_{mass,R} = \frac{1}{2} m_R \overline{(\nu_R)^C} \nu_R \; + h.c.$

NOTE: Majorana mass terms break lepton conservation by 2 units.

$\nu_L \to \; e^{i\alpha} \; \nu_L \qquad \Rightarrow \qquad \mathcal{L}^M_{mass} \to \; e^{2\; i\alpha} \mathcal{L}^M_{mass}$

What type of masses neutrinos can have

Diagonalize a Majorana mass term

If there are several fields, there will be a Majorana mass matrix. We can show that it is symmetric.

$$M_M = M_M^T$$

In fact:

$$\begin{aligned} &\nu_L^T M_M C^{-1} \nu_L = (\nu_L^T M_M C^{-1} \nu_L)^T \\ &= -\nu_L^T M_M^T C^{-1,T} \nu_L = \nu_L^T M_M^T C^{-1} \nu_L \end{aligned}$$

This implies that only one unitary mixing matrix is required to diagonalise it

$$M_M = (U^\dagger)^T \; m_{diag} U^\dagger$$

What type of masses neutrinos can have

Dirac + Majorana masses

If we have both the left-handed and right-handed neutrinos, we can write down three mass terms:

- a Dirac mass term
- a Majorana mass term for the left-handed neutrinos
- a Majorana mass term for the right-handed neutrinos.

$$-\mathcal{L}_{mass}^{D+M} = M^D\ \overline{\nu}_L \nu_R + \frac{1}{2} M_L^M \overline{(\nu_L)^C} \nu_L + \frac{1}{2} M_R^M \overline{(\nu_R)^C} \nu_R\ + h.c.$$

What type of masses neutrinos can have

$$-\mathcal{L}^{D+M}_{mass} = M^D\ \overline{\nu}_L\nu_R + \frac{1}{2}M^M_L\overline{(\nu_L)^C}\nu_L + \frac{1}{2}M^M_R\overline{(\nu_R)^C}\nu_R\ + h.c.$$

and one can use $\overline{\nu^C_L}(M^D)^T\nu^C_R = \overline{\nu}_R\ M^D\ \nu_L$

We start by rewriting $-\mathcal{L}^{D+M}_{mass} = \frac{1}{2}\overline{(\psi_L)^C}\mathcal{M}\psi_L + h.c.$

with $\psi \equiv \begin{pmatrix} \nu_L \\ \nu^C_R \end{pmatrix}$ and $\mathcal{M} \equiv \begin{pmatrix} M^M_L & (M^D)^T \\ M^D & M^M_R \end{pmatrix}$

What type of masses neutrinos can have

$$-\mathcal{L}_{mass}^{D+M} = M^D\ \overline{\nu}_L \nu_R + \frac{1}{2} M_L^M \overline{(\nu_L)^C} \nu_L + \frac{1}{2} M_R^M \overline{(\nu_R)^C} \nu_R\ + h.c.$$

and one can use $\overline{\nu_L^C} (M^D)^T \nu_R^C = \overline{\nu}_R\ M^D\ \nu_L$

We start by rewriting $-\mathcal{L}_{mass}^{D+M} = \frac{1}{2} \overline{(\psi_L)^C} \mathcal{M} \psi_L + h.c.$

with $\psi \equiv \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix}$ and $\mathcal{M} \equiv \begin{pmatrix} M_L^M & (M^D)^T \\ M^D & M_R^M \end{pmatrix}$

Then, we need to diagonalise the full mass matrix, and we find the Majorana massive states, in analogy to what we have done for the Majorana mass case.

The difference is that

$$\chi \equiv \nu_{iL} + \nu_{iL}^C \Rightarrow\ \chi = \chi^C$$

$$\nu_{iL} = U_j \nu_L + U_k \nu_R^C$$

U_j Not unitary and U_k Mixing between mass states and sterile neutrinos

Outline

Models of neutrino masses BSM

See-saw type I

General case: both Dirac and Majorana mass terms

$\rightarrow$ See-saw Mechanism an explanation of $m_\nu << m_\ell, m_q$

$$-\mathcal{L}^{tot}_{mass} = \mathcal{L}^{D}_{mass} + \mathcal{L}^{M}_{mass}$$

Mixing between active neutrinos and heavy neutrinos will emerge but it will be typically very small

$$M_R >> M_D \begin{array}{l} \nearrow m_{light} \simeq M_D^T M_R^{-1} M_D \\ \searrow m_{heavy} \simeq M_R \end{array}$$

No SM principle prevents M_R from being large but we expect M_D to be of the same order of the mass of the quarks and charged leptons.

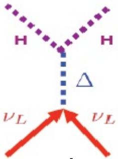
$$m_{light} \sim \frac{1GeV^2}{10^{10}GeV} \sim 0.1eV \qquad \tan\ 2\theta = \frac{2M_D}{M_R}$$

Models of neutrino masses BSM

See-saw type II

We introduce a Higgs triplet which couples to the Higgs and left handed neutrinos. It has hypercharge 2.

$$-\mathcal{L}_\Delta \propto \; y_\Delta \; L^T \; C^{-1} \; \sigma_i \; \Delta_i \; L + h.c.$$



with, $\quad \Delta_i = \left(\begin{array}{c} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{array} \right)$

Once the Higgs triplet gets a vev, Majorana neutrino masses arise: $m_\nu \sim \; y_\Delta \; \nu_\Delta$

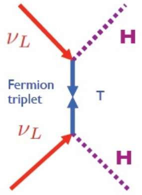
The component of the Higgs triplet could tested directly at the LHC.

Models of neutrino masses BSM

see-saw type III

We introduce a fermionic triplet which has hypercharge 0.

$$-\mathcal{L}_T \propto \; y_T \, \overline{L}\sigma \; H.T + h.c.$$



with, $\quad T = \begin{pmatrix} T^0 & T^+ \\ T^- & -T^0 \end{pmatrix}$

$$m_\nu \simeq \; (-y_T)^T \; M_T^{-1} \; y_T \; \nu_H^2$$

Majorana neutrino masses are generated as in see-saw type I:
The component of the fermionic triplet have gauge interactions and can be produced at the LHC

Outline

Analyzing Data

Tri-bi maximall mixing

In the first experimental approximation:

$U \to U_{tri-bi\ \ maximall}$

L.Wolfenstein

P.F.Harrison

D.H. Perkins

W.G. Scott

Solar Neutrinos $\theta_{12} \simeq 32^\circ$

Atmospheric Neutrinos $\theta_{23} \simeq 45^\circ$

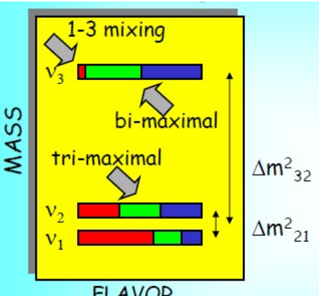
Reactor Neutrinos $\theta_{13} = 0$

$$U_{TBM} = \begin{pmatrix} -\sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}.$$

ν_2 is tri-maximally mixed.

ν_3 is bi-maximally mixed.

No CP violation.



Analyzing Data

The form of the mass matrix determines the mixing pattern.

magic matrix $\Rightarrow \nu_2$ is tri-maximally mixed.

the row sums and column sums are each equal to m_2.

$$M_\nu = \left(\begin{array}{ccc} a & b & c \\ d & e & a+b+c-d-e \\ b+c-e & a+c-d & d+e-c \end{array} \right)_{magic}$$

exact $\mu - \tau$ symmetry $\Rightarrow \nu_3$ is bi-maximally mixed.

$$M_\nu = \left(\begin{array}{ccc} A & B & B \\ B & C & D \\ B & D & C \end{array} \right)_{\mu \leftrightarrow \tau}$$

Discrete Family Symmetries: S_3, A_4, S_4 and ...

complex component of mass matrix$\Rightarrow$CP violation.

magic matrix and exact $\mu - \tau$ symmetry $\Leftrightarrow$ Tribimaximally mixing matrix

Analyzing Data

$$\color{red}{\text{DayaBy} \Longrightarrow \theta_{13} \neq 0}\; U_{TBM} = \begin{pmatrix} -\sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \color{red}{\rightsquigarrow} \color{blue}{0.15} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \color{red}{\rightsquigarrow} \color{blue}{0.62} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \color{red}{\rightsquigarrow} \color{blue}{0.78} \end{pmatrix}.$$

θ_{13} is small $\Rightarrow$ $\mu - \tau$ symmetry must be broken, may softly.

Analyzing Data

Perturbative approach

$M_\nu = M_0 + M_\delta$

M_0 is a magic matrix with exact $\mu - \tau$ symmetry

M_δ Must break $\mu - \tau$ symmetry $\Rightarrow \theta_{13} \neq 0$

Summary

- Neutrinos have masses and a wide experimental programme aims at measuring them.
- Neutrinos can be Dirac or Majorana particles. Neutrinoless double beta decay is the most sensitive test.
- Neutrino masses beyond the Standard Model: Dirac, Majorana and Dirac+Majorana masses
- We have looked at models of masses BSM: Dirac masses
  see saw type I
  see-saw type II
  see-saw type III

A few references

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