Type-II Dirac neutrino seesaw in a flavour model

Mario Lamprea

Institute of Physics, UNAM

in collab. with C. Bonilla, E. Peinado and J. W. F. Valle

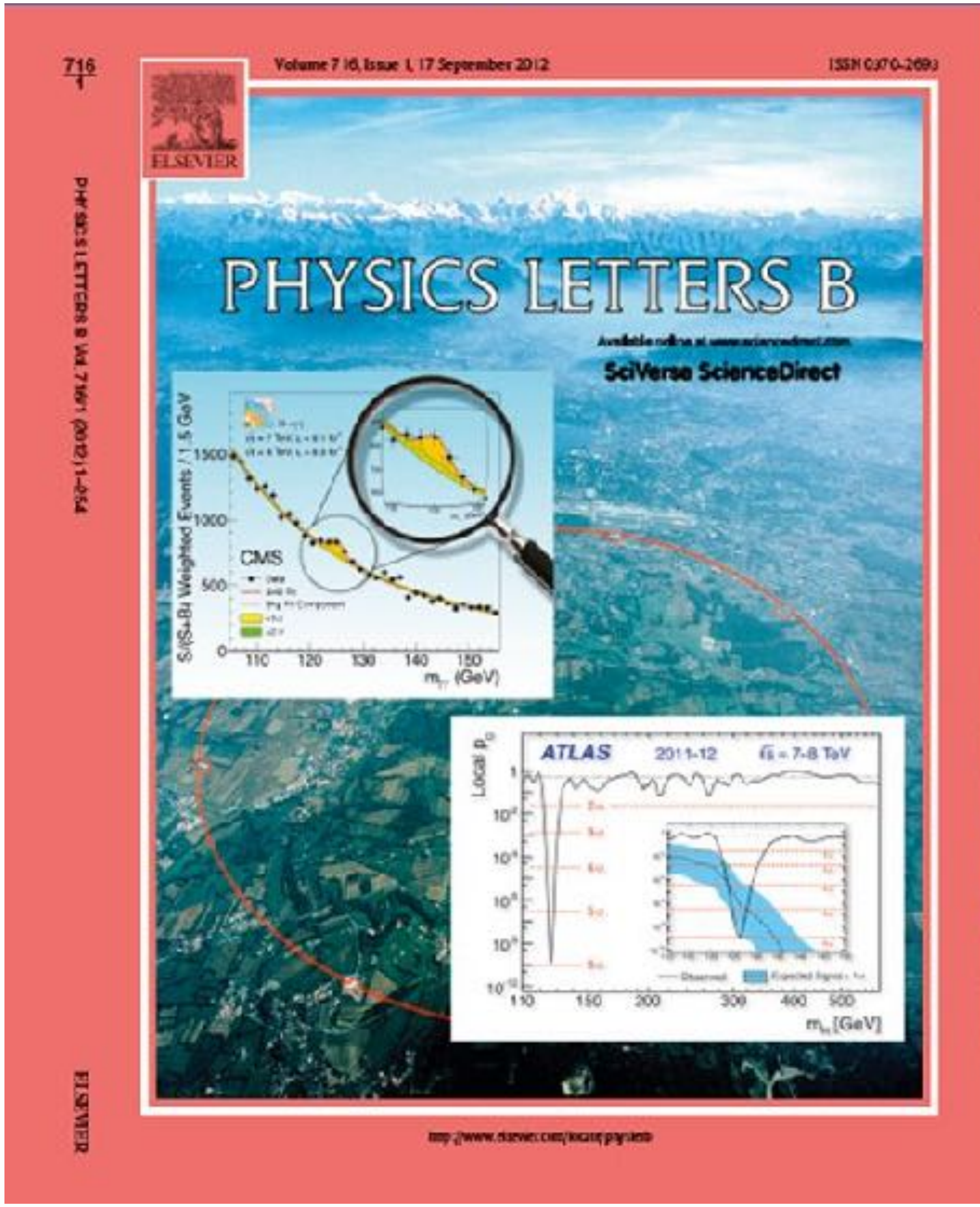
Reunion anual - DPyC - ICN

Mexico city, May 30th

Introduction

Standar Model is complete

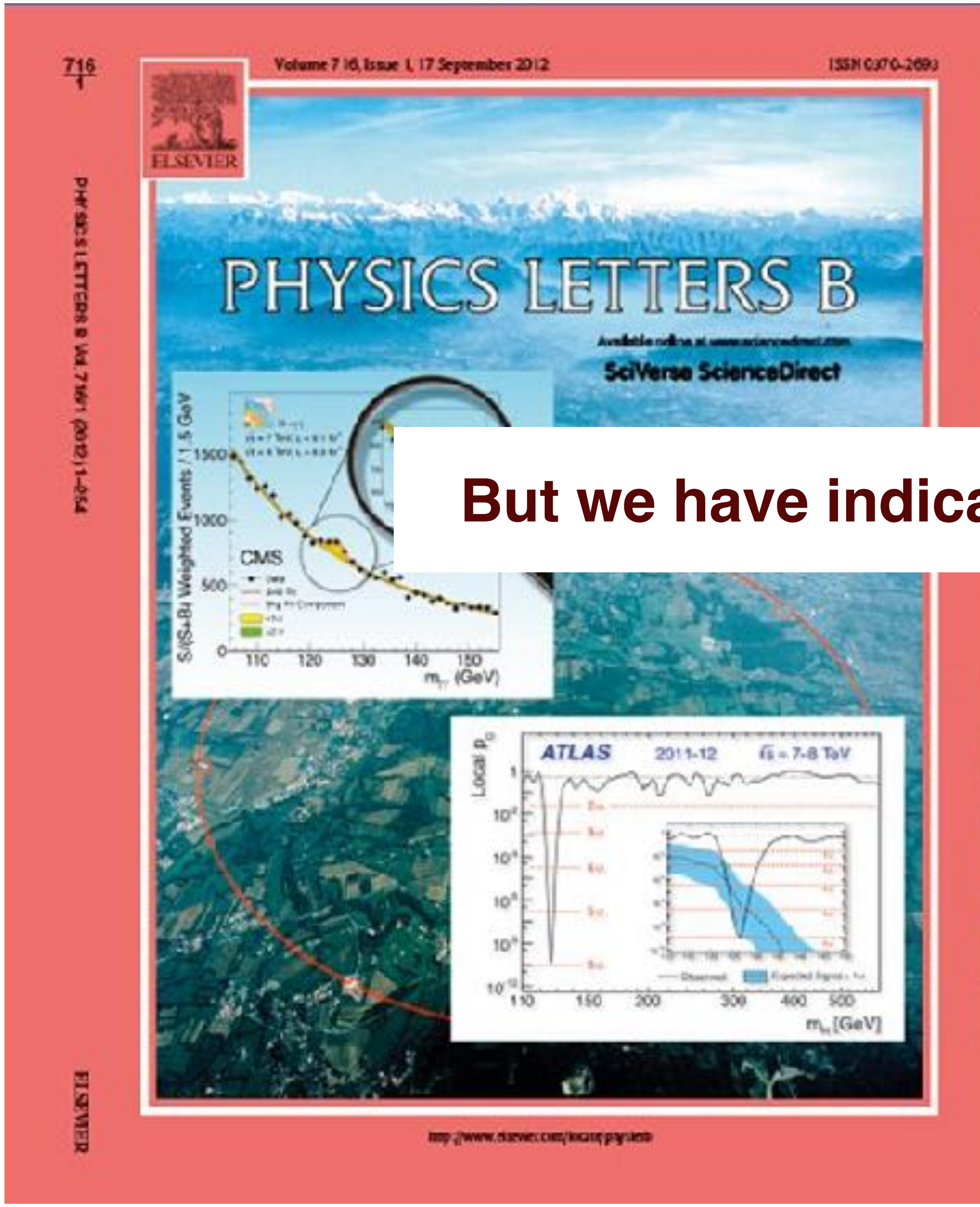
Discovery of the last SM particle



4 Jul 2012, CERN
Francois Englert & Peter Higgs

Introduction

Standar Model is complete



But we have indications of new physics

4 Jul 2012, CERN
Francois Englert & Peter Higgs

Introduction

Remain open questions in SM (some of them):

Neutrino oscillations (origin of the neutrino masses)

Evidence of *dark matter* (gravitation)

The *asymmetry matter-antimatter* of the universe (BAU)

Introduction

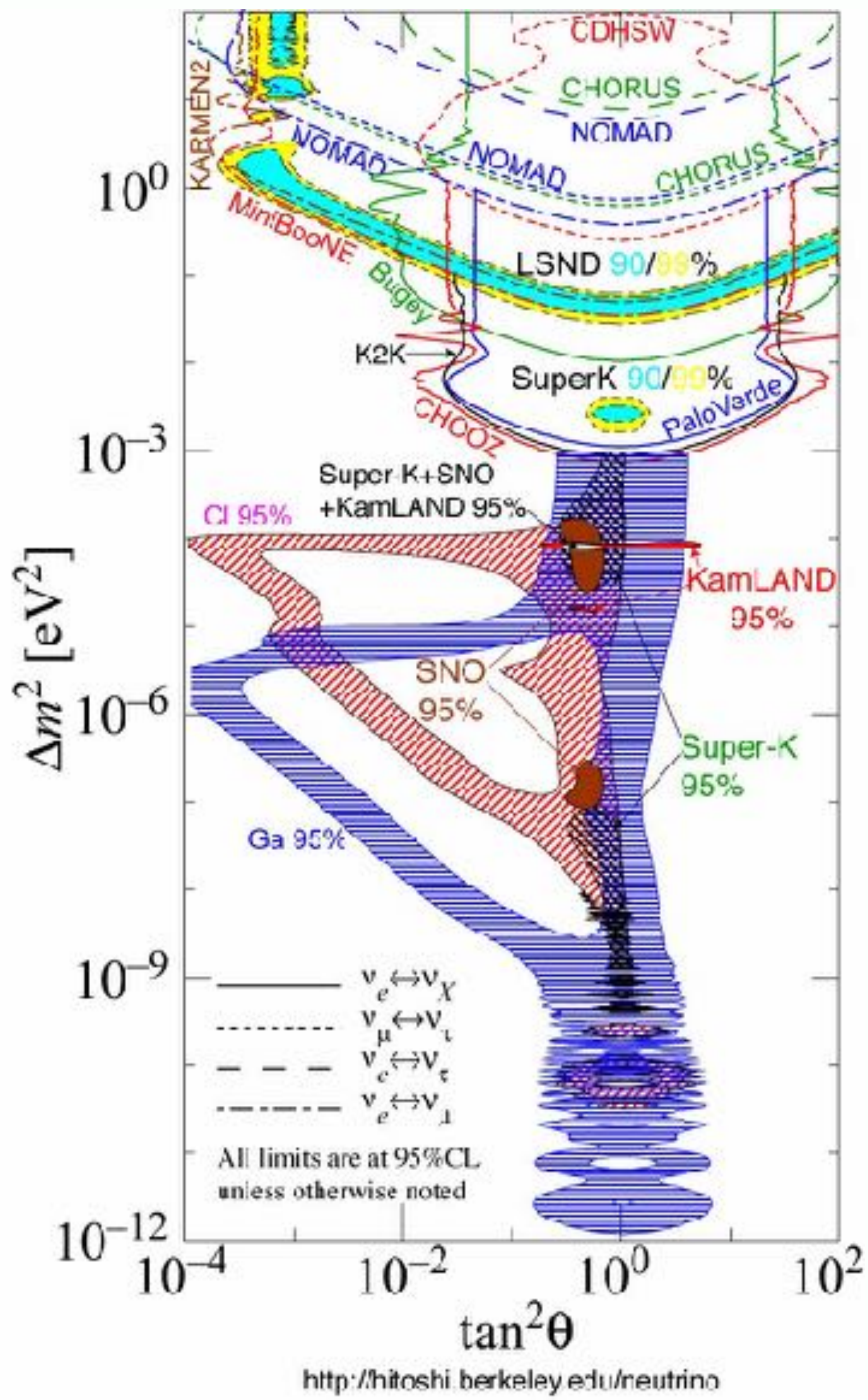
Neutrinos

- There are **tree massless** neutrinos in the **SM**.

Introduction

Neutrinos

- There are **tree massless** neutrinos in the **SM**.
- But neutrino oscillations are *evidence* of their **masses** and **mixing**.



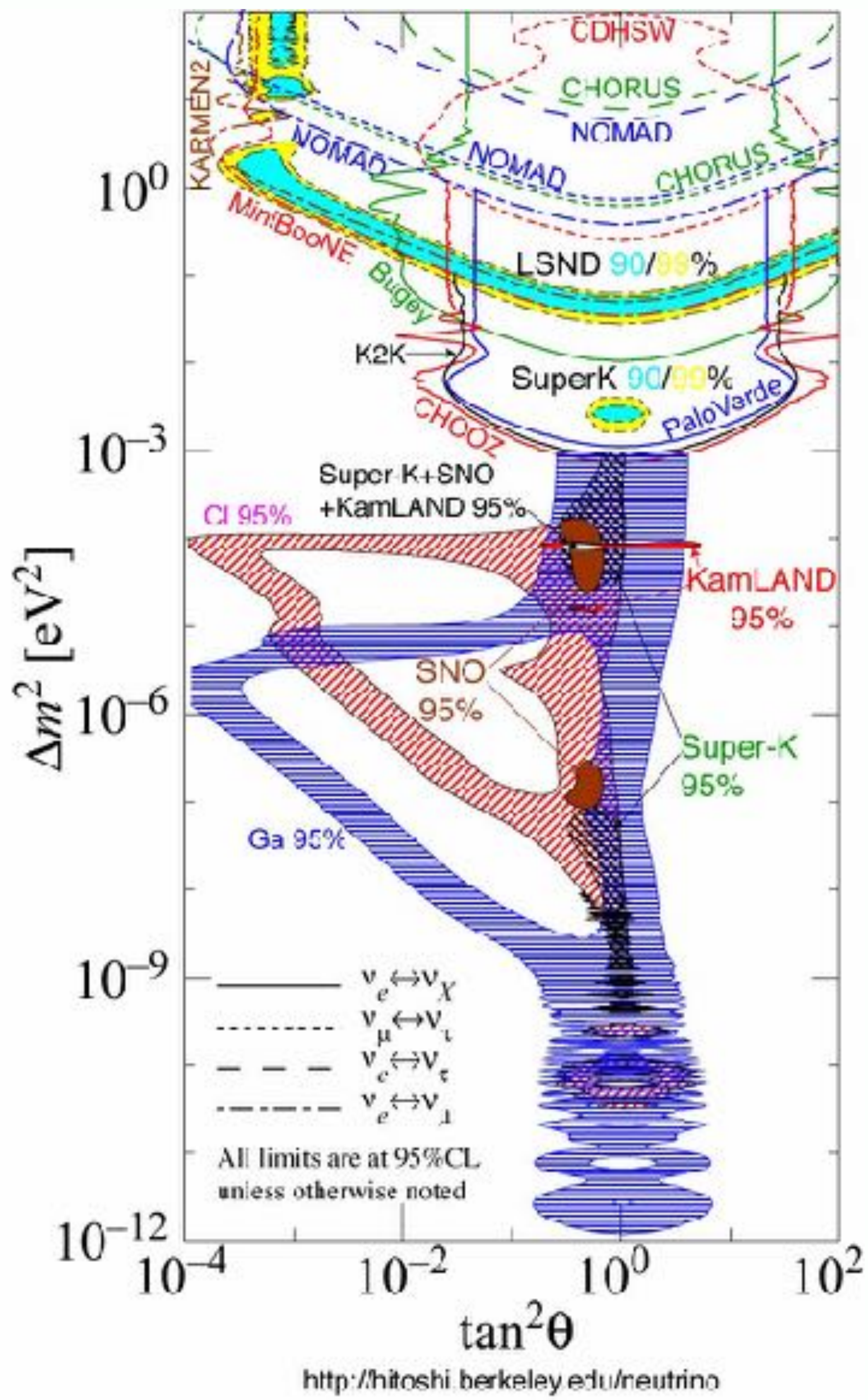
Measurements of oscillation parameters

Introduction

Neutrinos

- There are **tree massless** neutrinos in the **SM**.
- But neutrino oscillations are *evidence* of their **masses** and **mixing**.

  Two square mass differences, at least two masses are non-zero.



Measurements of oscillation parameters

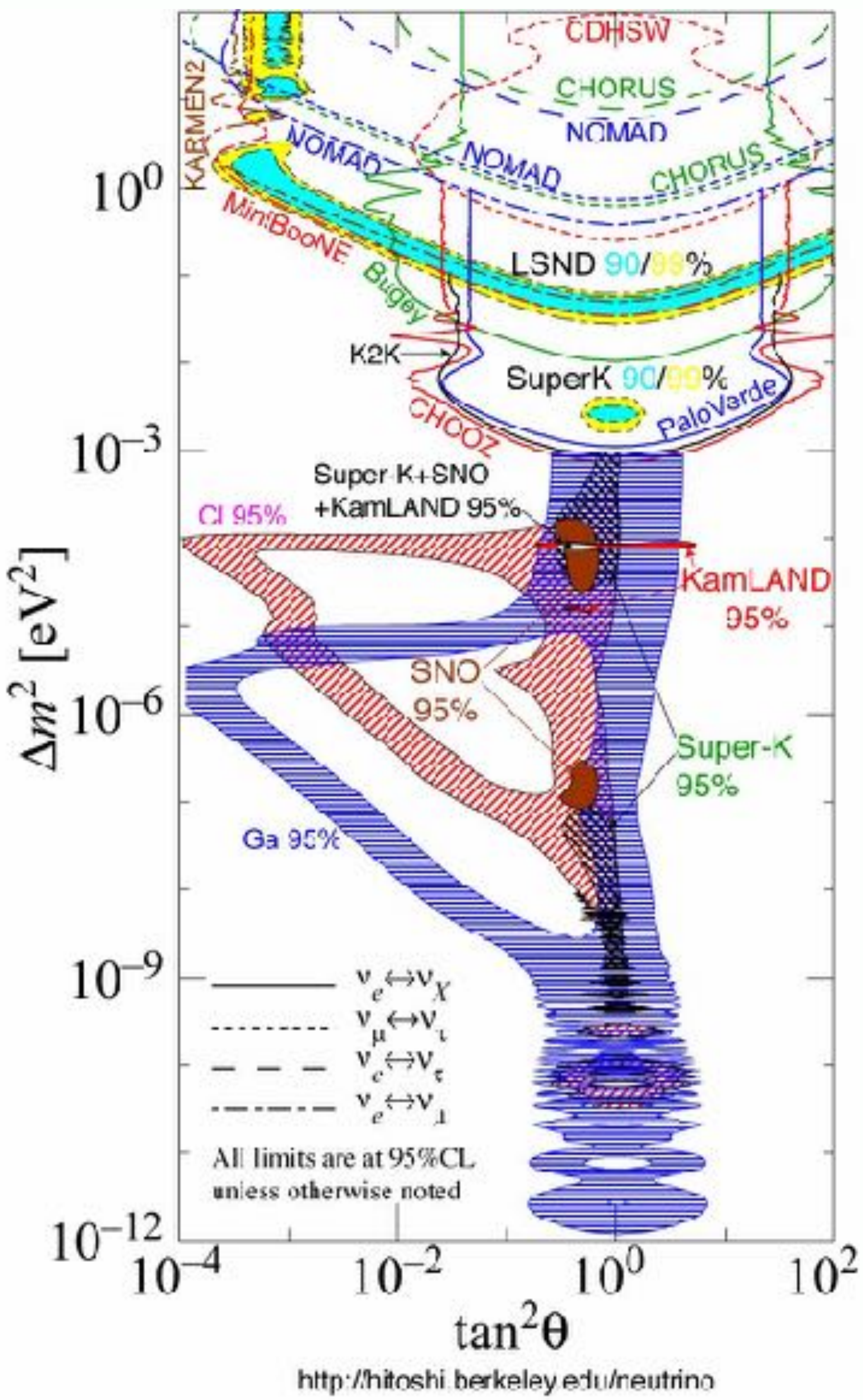
Introduction

Neutrinos

- There are **tree massless** neutrinos in the **SM**.
- But neutrino oscillations are *evidence* of their **masses** and **mixing**.

  Two square mass differences, at least two masses are non-zero.

  Still allowed both mass orderings: **NO** & **IO**.

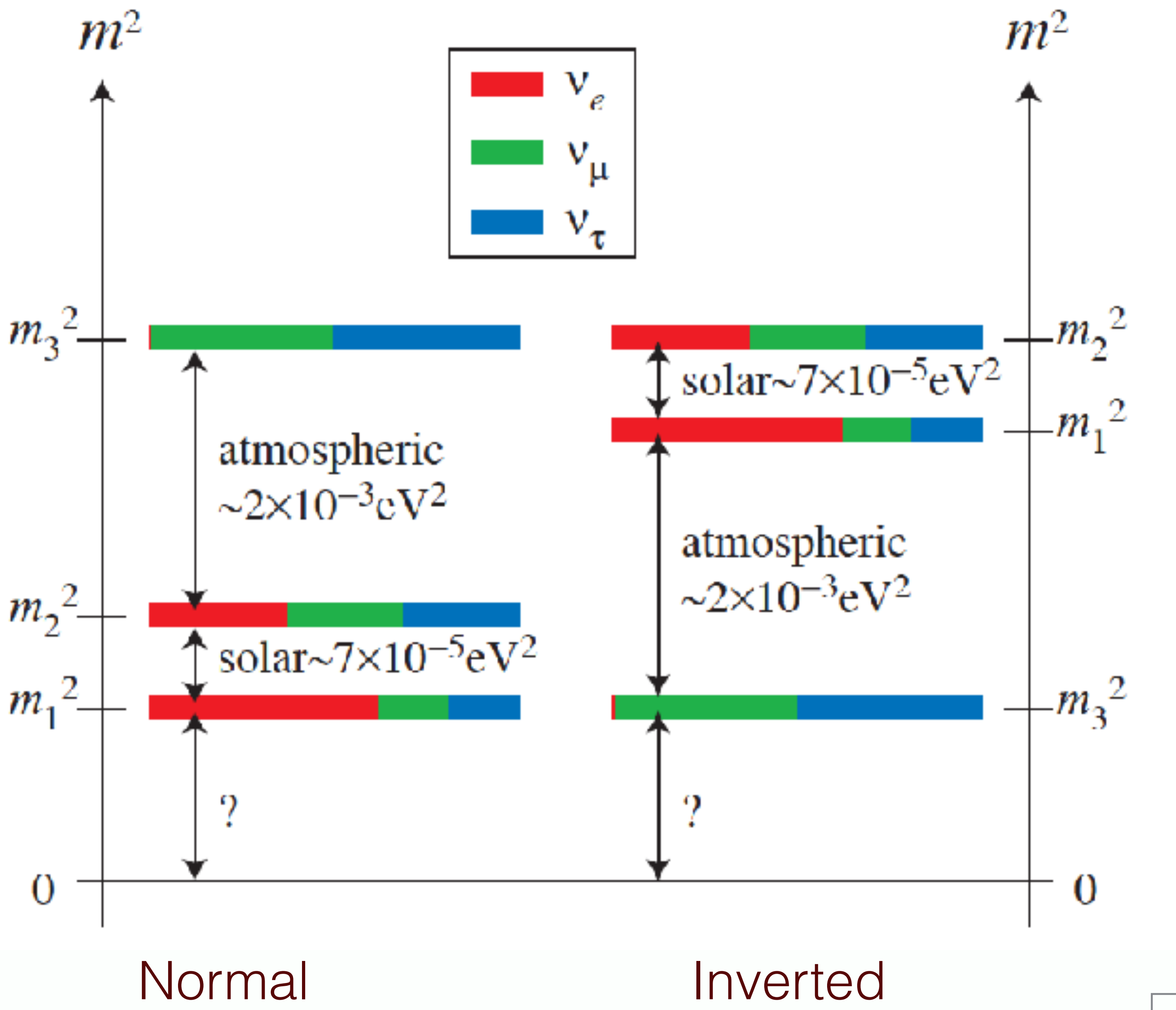


Measurements of oscillation parameters

Introduction

Neutrinos

Neutrino oscillations status

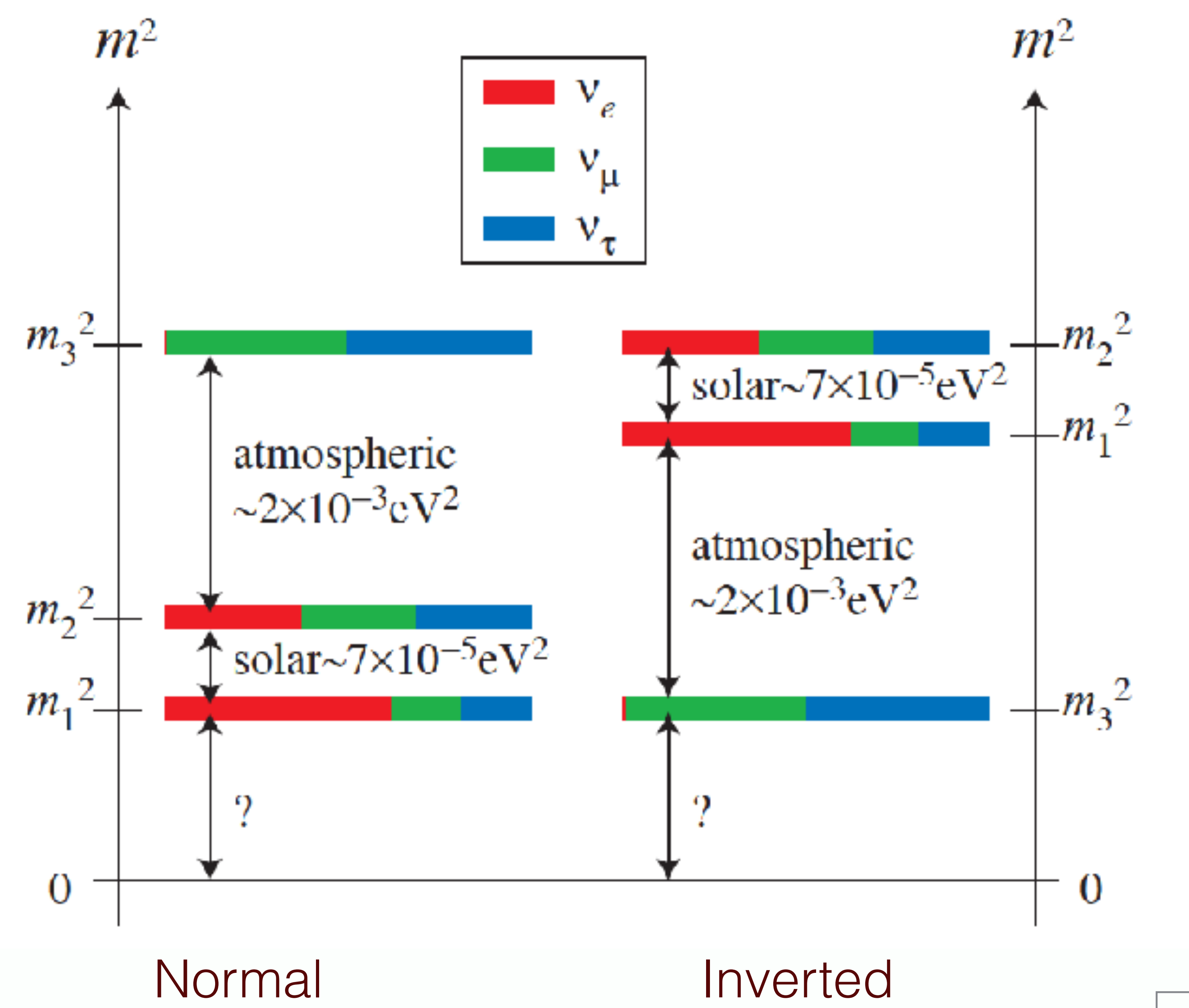


[S. King, 2016]

Introduction

Neutrinos

Neutrino oscillations status



In addition to a CP phase.

[S. King, 2016]

Introduction

Neutrinos

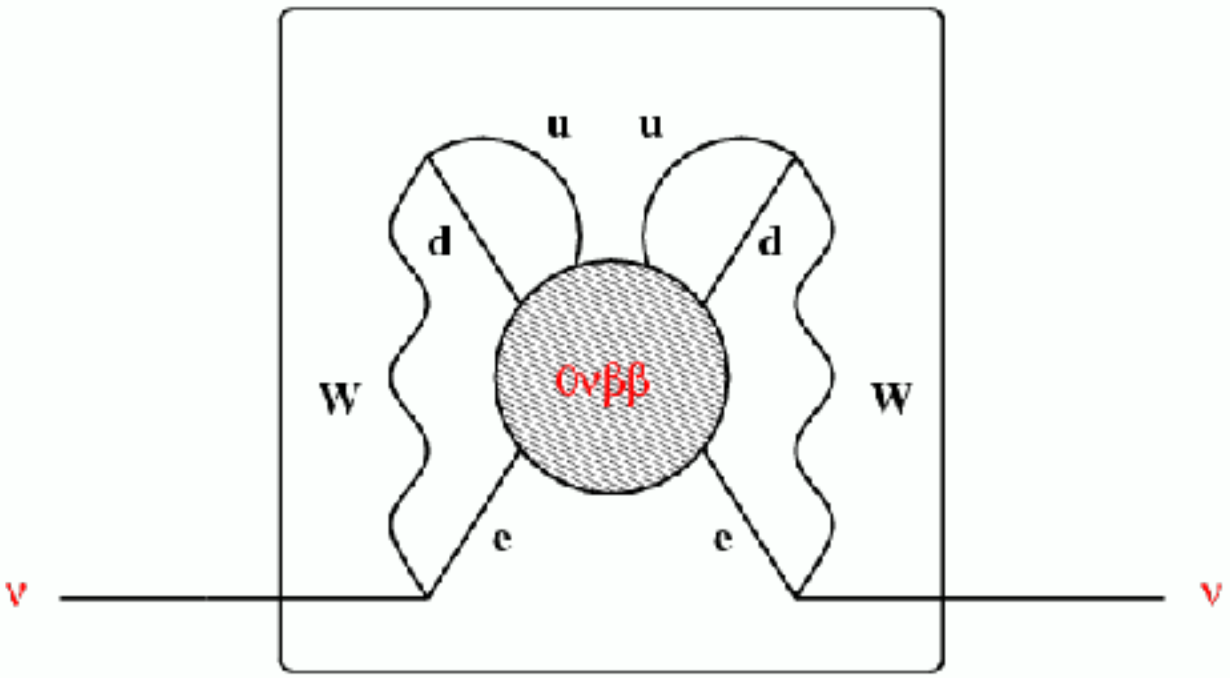
- There are **tree massless** neutrinos in the **SM**.

- But neutrino oscillations are *evidence* of their **masses** and **mixing**.

  Two square mass differences, at least two masses are non-zero.

  Still allowed both mass orderings: **NO** & **IO**.

- Nature of neutrinos: **Dirac** or **Majorana** fermions (can be proved by some proceses with $\Delta L = 2$, as **0νββ** via **blackbox theorem**).



Black box theorem

Introduction

Neutrinos

- There are **tree massless** neutrinos in the **SM**.

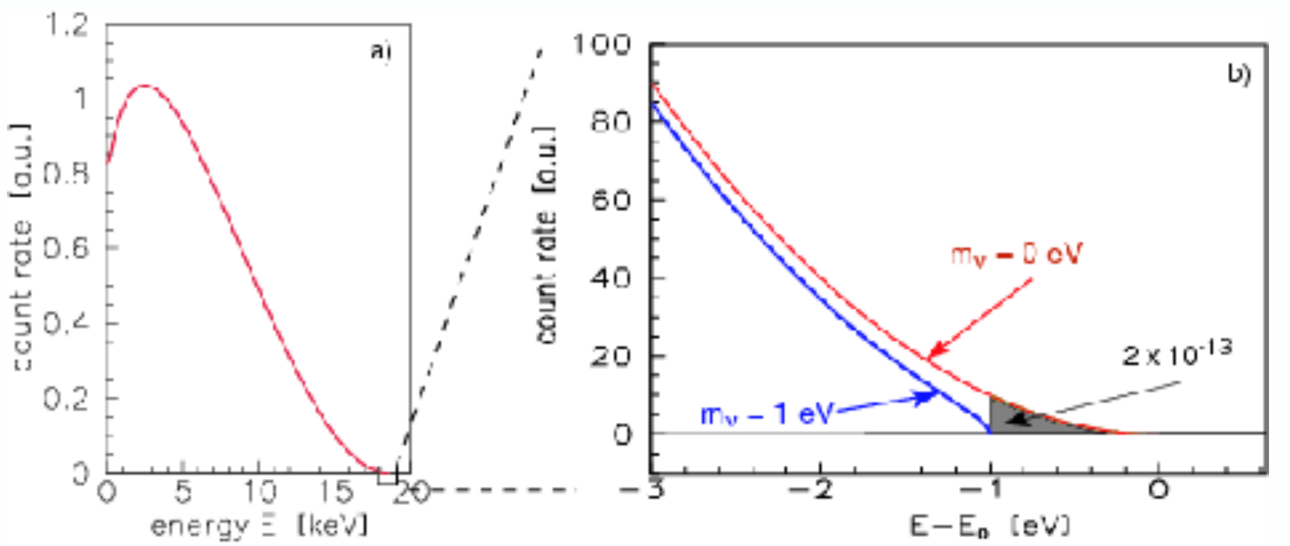
- But neutrino oscillations are *evidence* of their **masses** and **mixing**.

  Two square mass differences, at least two masses are non-zero.

  Still allowed both mass orderings: **NO** & **IO**.

- Nature of neutrinos: **Dirac** or **Majorana** fermions (can be proved by some proceses with $\Delta L = 2$, as **0νββ** via **blackbox theorem**).

- **Unknown** the **absolute mass scale** (hierarchy). There are some bounds from the Tritium β decay ($m_{\nu e} \lesssim 2$ eV) & from the Cosmology ($\sum m_\nu \lesssim 0.23$ eV).



e- energy spectrum, Katrin exp.

Introduction

Neutrinos

- There are **tree massless** neutrinos in the **SM**.

- But neutrino oscillations are *evidence* of their **masses** and **mixing**.

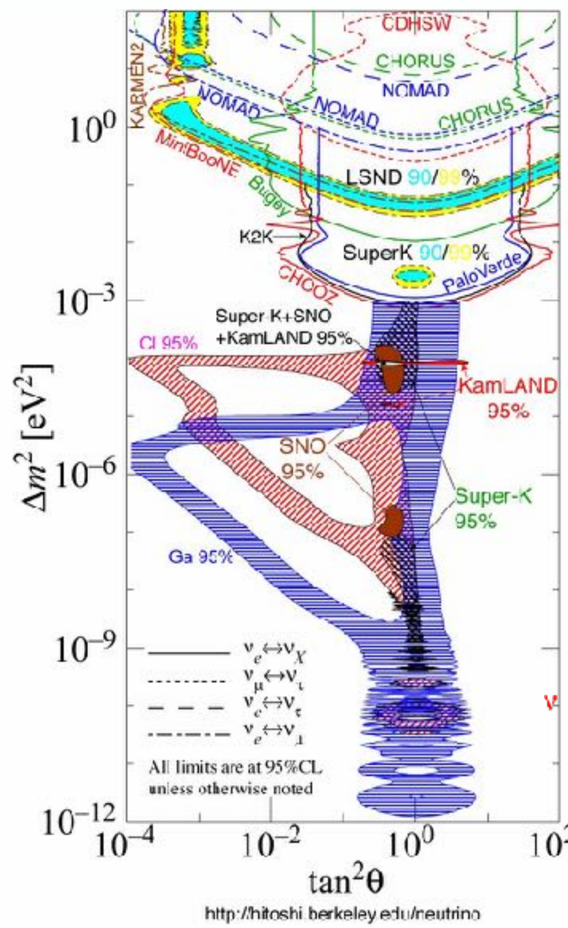
  Two square mass differences, at least two masses are non-zero.

  Still allowed both mass orderings: **NO** & **IO**.

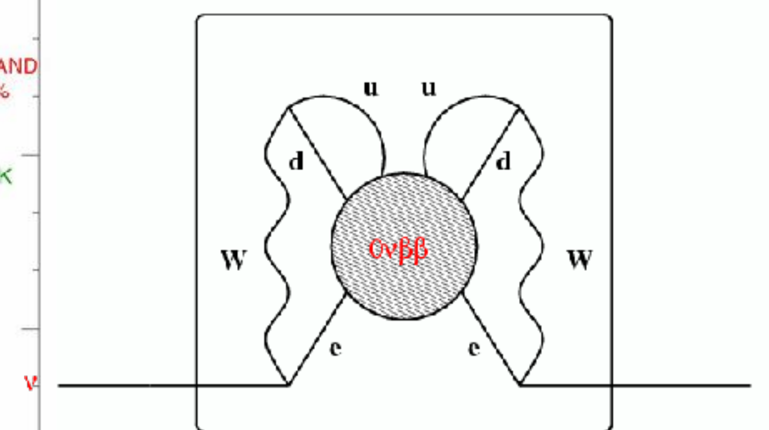
- Nature of neutrinos: **Dirac** or **Majorana** fermions (can be proved by some proceses with $\Delta L = 2$, as **0νββ** via **blackbox theorem**).

- **Unknown** the **absolute mass scale** (hierarchy). There are some bounds from the Tritium β decay ($m_{\nu e} \lesssim 2$ eV) & from the Cosmology ($\sum m_\nu \lesssim 0.23$ eV).

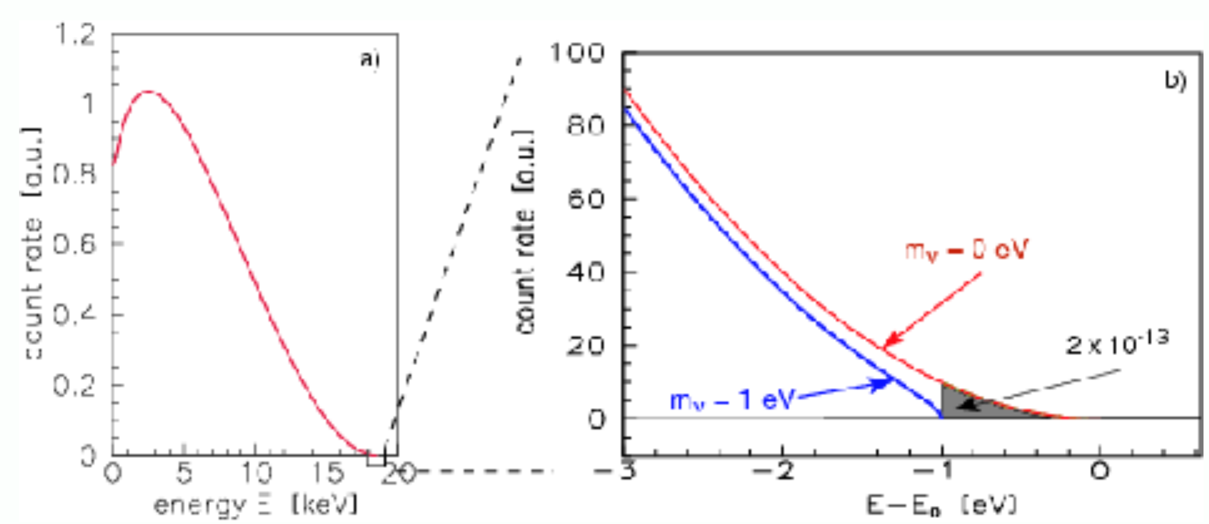
- The existence of **neutrino masses** *are* evidence of **physics BSM**.



Bounds in solar angle



Black box theorem



e- energy spectrum, Katrin

Introduction

Neutrinos

- Dirac and Majorana **mass terms**:

$$-\mathcal{L} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_L^c \end{pmatrix} \begin{pmatrix} m_M & m_D \\ m_D & m_s \end{pmatrix} \begin{pmatrix} \nu_R^c \\ \nu_R \end{pmatrix} + h.c.$$

$$-\mathcal{L}_D = m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) \qquad -\mathcal{L}_M = \frac{m_M}{2}(\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L) \qquad -\mathcal{L}_S = \frac{m_S}{2}(\bar{\nu}_L^c \nu_R + \bar{\nu}_R \nu_L^c)$$

Introduction

Neutrinos

- Dirac and Majorana **mass terms**:

$$-\mathcal{L} = \frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_L^c\end{pmatrix}\begin{pmatrix} m_M & m_D \\ m_D & m_s \end{pmatrix}\begin{pmatrix}\nu_R^c \\ \nu_R\end{pmatrix} + h.c.$$

$$-\mathcal{L}_D = m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) \qquad -\mathcal{L}_M = \frac{m_M}{2}(\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L) \qquad -\mathcal{L}_S = \frac{m_S}{2}(\bar{\nu}_L^c \nu_R + \bar{\nu}_R \nu_L^c)$$

- Lepton mixing matrix (**PMNS**): From *mismatch* between *mass* and *interaction* (flavour) eigenstates.

$$U = V_L^{l\dagger} V_L^{\nu}$$

Neutrinos

- Dirac and Majorana **mass terms**:

$$-\mathcal{L} = \frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_L^c\end{pmatrix}\begin{pmatrix}m_M & m_D \\ m_D & m_s\end{pmatrix}\begin{pmatrix}\nu_R^c \\ \nu_R\end{pmatrix} + h.c.$$

$$-\mathcal{L}_D = m_D(\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L) \qquad -\mathcal{L}_M = \frac{m_M}{2}(\bar{\nu}_L\nu_R^c + \bar{\nu}_R^c\nu_L) \qquad -\mathcal{L}_S = \frac{m_S}{2}(\bar{\nu}_L^c\nu_R + \bar{\nu}_R\nu_L^c)$$

- Lepton mixing matrix (**PMNS**): From *mismatch* between *mass* and *interaction* (flavour) eigenstates.

$$U = V_L^{l\dagger}V_L^{\nu}$$

For 3 light **Dirac** neutrinos (**3 mixing angles, 1 CP phase**)

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

Introduction

Neutrinos

- Dirac and Majorana **mass terms**:

$$-\mathcal{L} = \frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_L^c\end{pmatrix}\begin{pmatrix}m_M & m_D \\ m_D & m_s\end{pmatrix}\begin{pmatrix}\nu_R^c \\ \nu_R\end{pmatrix} + h.c.$$

$$-\mathcal{L}_D = m_D(\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L) \qquad -\mathcal{L}_M = \frac{m_M}{2}(\bar{\nu}_L\nu_R^c + \bar{\nu}_R^c\nu_L) \qquad -\mathcal{L}_S = \frac{m_S}{2}(\bar{\nu}_L^c\nu_R + \bar{\nu}_R\nu_L^c)$$

- Lepton mixing matrix (**PMNS**): From *mismatch* between *mass* and *interaction* (flavour) eigenstates.

$$U = V_L^{l\dagger}V_L^{\nu}$$

For 3 light **Dirac** neutrinos (**3 mixing angles, 1 CP phase**)

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

Majorana neutrinos (**2** additional **CP phases**)

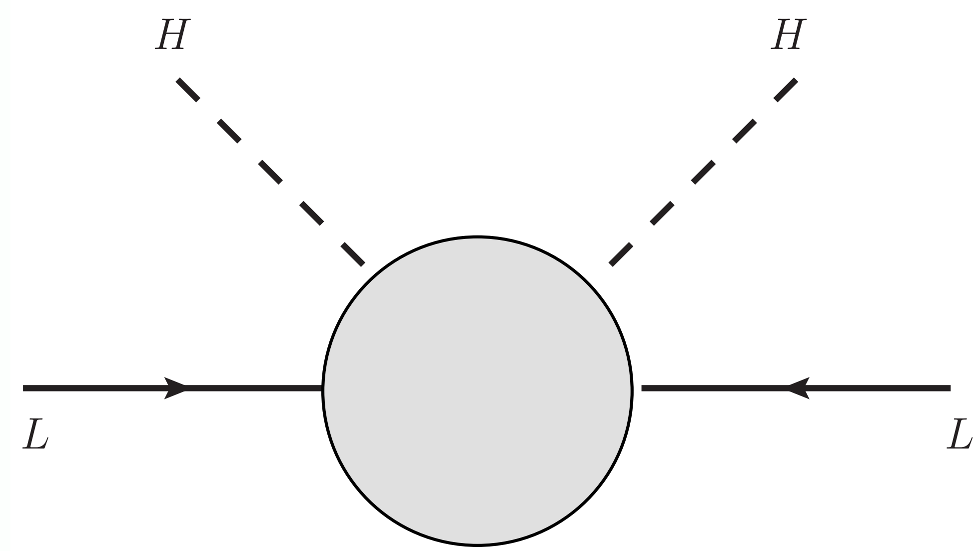
$$U_M = U_D D_M \qquad D_M = \mathrm{diag}(1, e^{i\lambda_2}, e^{i\lambda_3})$$

Introduction

Neutrinos

Mechanism for **mass** generation of **Majorana** LH neutrinos trough the *dimension 5* or *Weinberg operator* ($\Delta L = 2$).

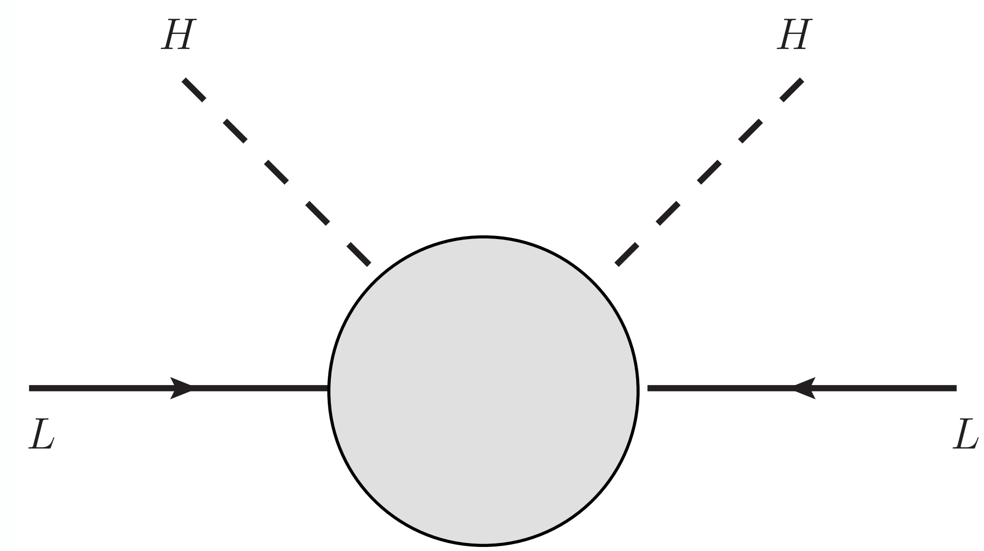
$$\mathcal{O}_5 = \frac{g}{\mathcal{M}}(\bar{L}^c \sigma_2 H)(H^T \sigma_2 L)$$



Neutrinos

Mechanism for **mass** generation of **Majorana** LH neutrinos trough the *dimension 5* or *Weinberg operator* (ΔL = 2).

$$\mathcal{O}_5 = \frac{g}{\mathcal{M}}(\bar{L}^c\sigma_2 H)(H^T\sigma_2 L)$$



$$m_e \simeq \mathcal{O}(1\,eV)$$

$$g \simeq \mathcal{O}(10^{-2} - 1)$$

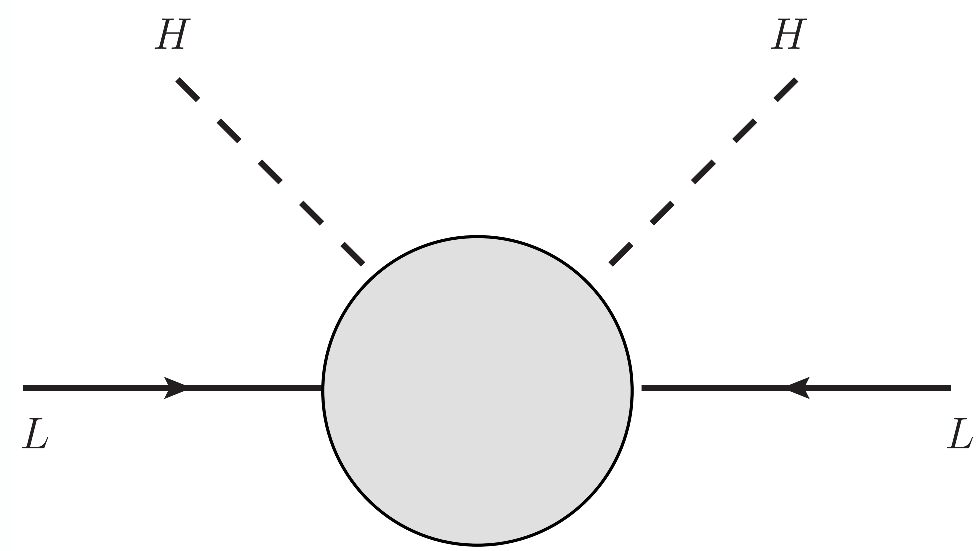
$$\mathcal{M} \simeq 10^{13-15}\ GeV$$

Introduction

Neutrinos

Mechanism for **mass** generation of **Majorana** LH neutrinos trough the *dimension 5* or *Weinberg operator* ($\Delta L = 2$).

$$\mathcal{O}_5 = \frac{g}{\mathcal{M}}(\bar{L}^c \sigma_2 H)(H^T \sigma_2 L)$$



- *Completion* of this dim-5 operator:

$$m_e \simeq \mathcal{O}(1\, eV)$$

$$g \simeq \mathcal{O}(10^{-2} - 1)$$

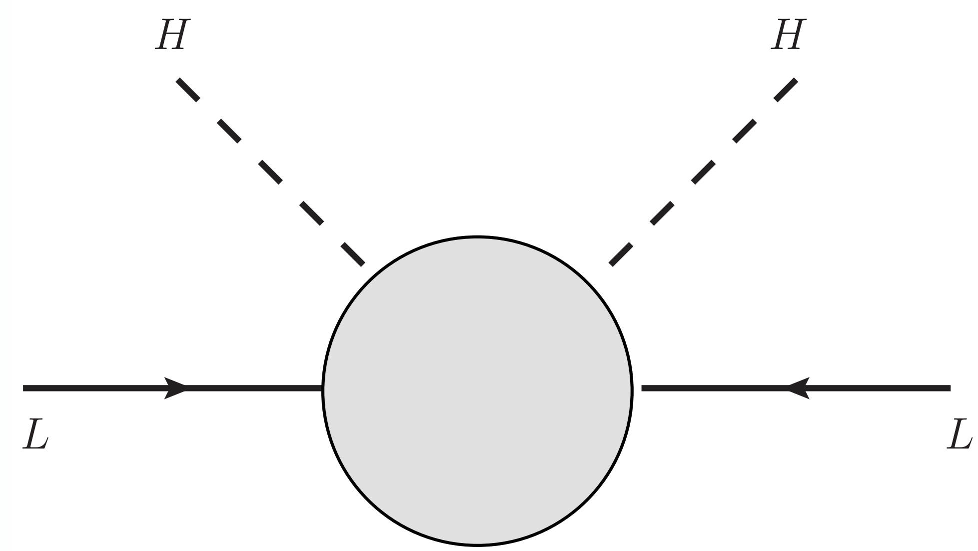
$$\mathcal{M} \simeq 10^{13-15}\ GeV$$

Introduction

Neutrinos

Mechanism for **mass** generation of **Majorana** LH neutrinos trough the *dimension 5* or *Weinberg operator* ($\Delta L = 2$).

$$\mathcal{O}_5 = \frac{g}{\mathcal{M}} (\bar{L}^c \sigma_2 H)(H^T \sigma_2 L)$$



- *Completion* of this dim-5 operator:

  At **tree level** by heavy mediator (seesaw type I, II & III).

$$m_e \simeq \mathcal{O}(1\, eV)$$

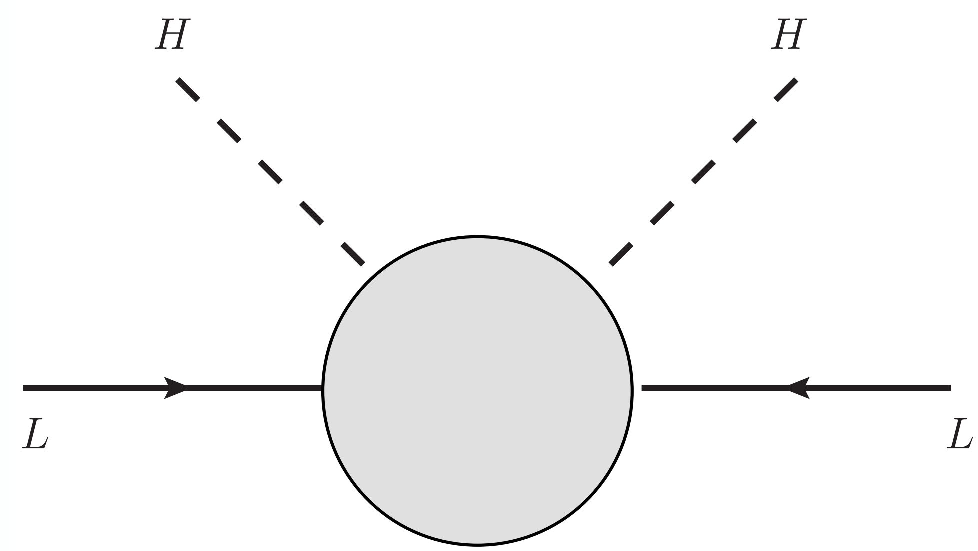
$$g \simeq \mathcal{O}(10^{-2} - 1)$$

$$\mathcal{M} \simeq 10^{13-15}\ GeV$$

Neutrinos

Mechanism for **mass** generation of **Majorana** LH neutrinos trough the *dimension 5* or *Weinberg operator* ($\Delta L = 2$).

$$\mathcal{O}_5 = \frac{g}{\mathcal{M}}(\bar{L}^c \sigma_2 H)(H^T \sigma_2 L)$$



- *Completion* of this dim-5 operator:

  At **tree level** by heavy mediator (seesaw type I, II & III).

  Other ways, as **radiative processes** (loop suppression of the LH neutrino masses)

$$m_e \simeq \mathcal{O}(1\, eV)$$

$$g \simeq \mathcal{O}(10^{-2} - 1)$$

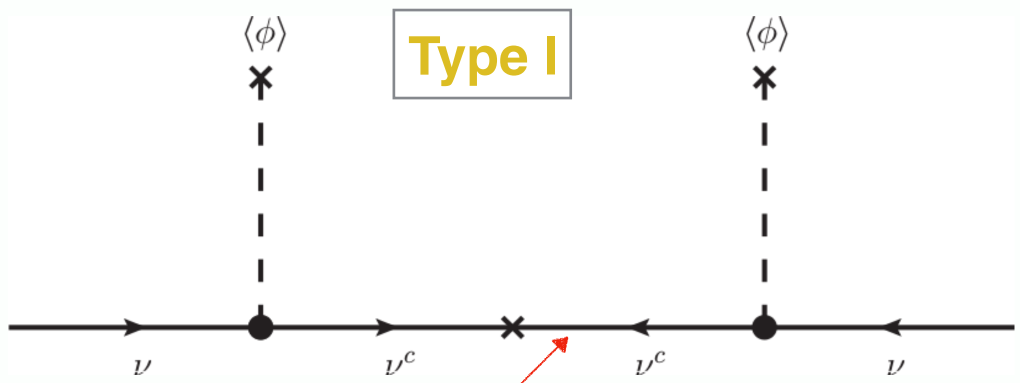
$$\mathcal{M} \simeq 10^{13-15}\ GeV$$

Introduction

Neutrinos

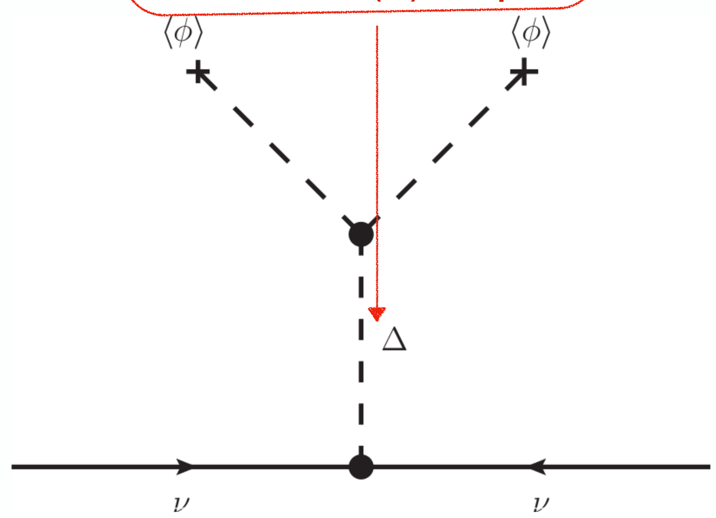
Seesaw models:

Type I



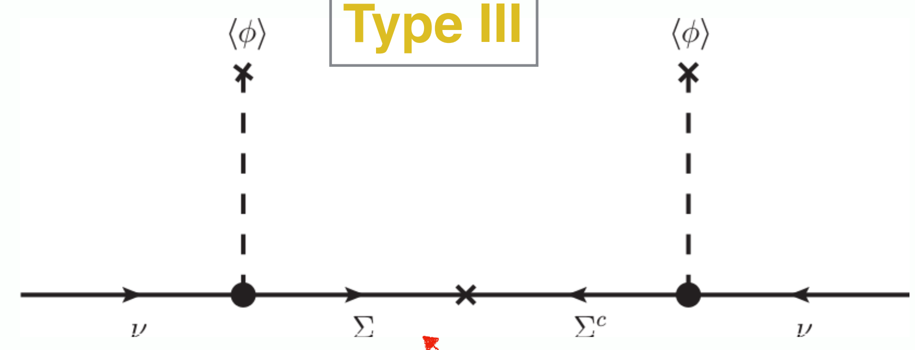
Heavy RH Neutrinos

Scalar SU(2)$_L$ triplet



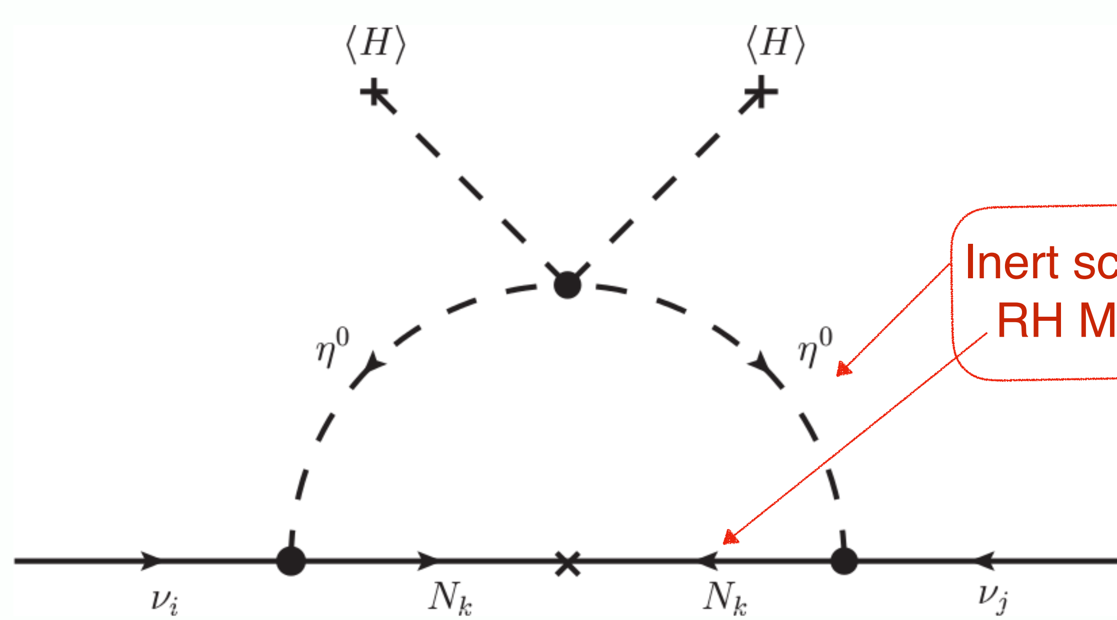
Type II

Type III



Fermionic SU(2)$_L$ Triplet

Radiative models:



Inert scalar SU(2)$_L$ doublet
RH Majorana Neutrinos

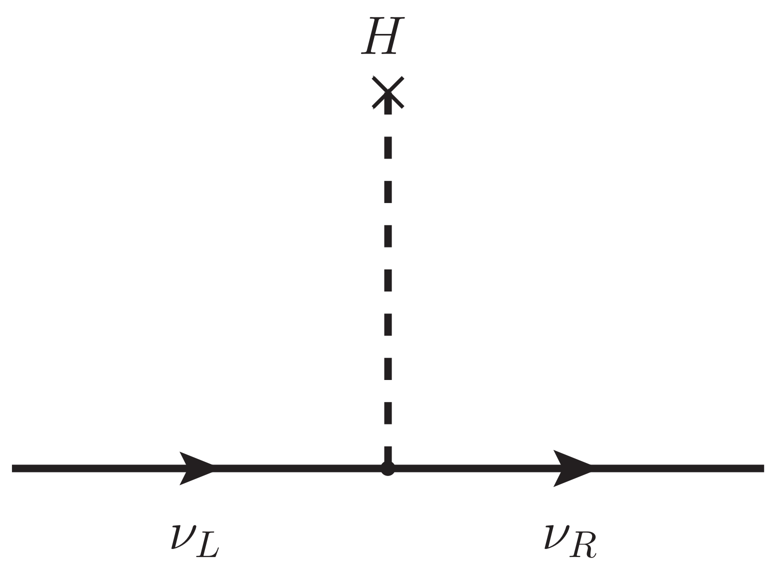
Scotogenic
[E. Ma, 2006]

Introduction

Neutrinos

In analogy with **quarks** and **charged leptons** in the **SM**.
Mass term for **Dirac neutrinos** (RH neutrinos $\mathbf{\nu_R}$ *added*).

$$-\mathcal{L} = y_D \bar{L} H \nu_R + \text{h.c.}$$

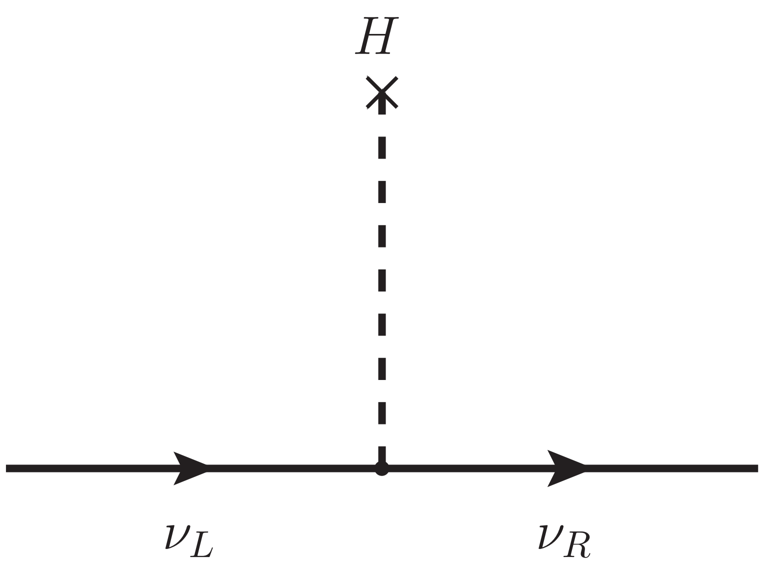


Introduction

Neutrinos

In analogy with **quarks** and **charged leptons** in the **SM**.
Mass term for **Dirac neutrinos** (RH neutrinos **ν_R** *added*).

$$-\mathcal{L} = y_D \bar{L} H \nu_R + \text{h.c.}$$



Assuming Yukawa coupling of quark top of order 1.

$$y_D \sim \mathcal{O}(10^{-12})$$ For a Dirac neutrino.

$$y_e \sim \mathcal{O}(10^{-6})$$ For the lightest charged lepton (e^-).

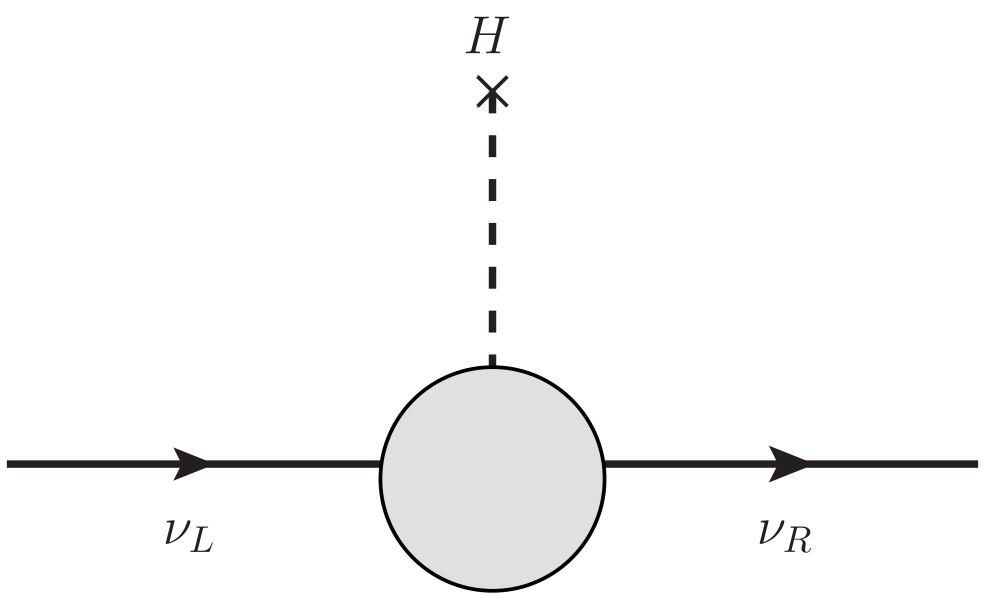
Seems **unnatural** the **Yukawa** coupling for a **Dirac** neutrino

Introduction

Neutrinos

In analogy with **quarks** and **charged leptons** in the **SM**.
Mass term for **Dirac neutrinos** (RH neutrinos **ν_R** *added*).

$$-\mathcal{L} = y_D \bar{L} H \nu_R + \text{h.c.}$$



Assuming Yukawa coupling of quark top of order 1.

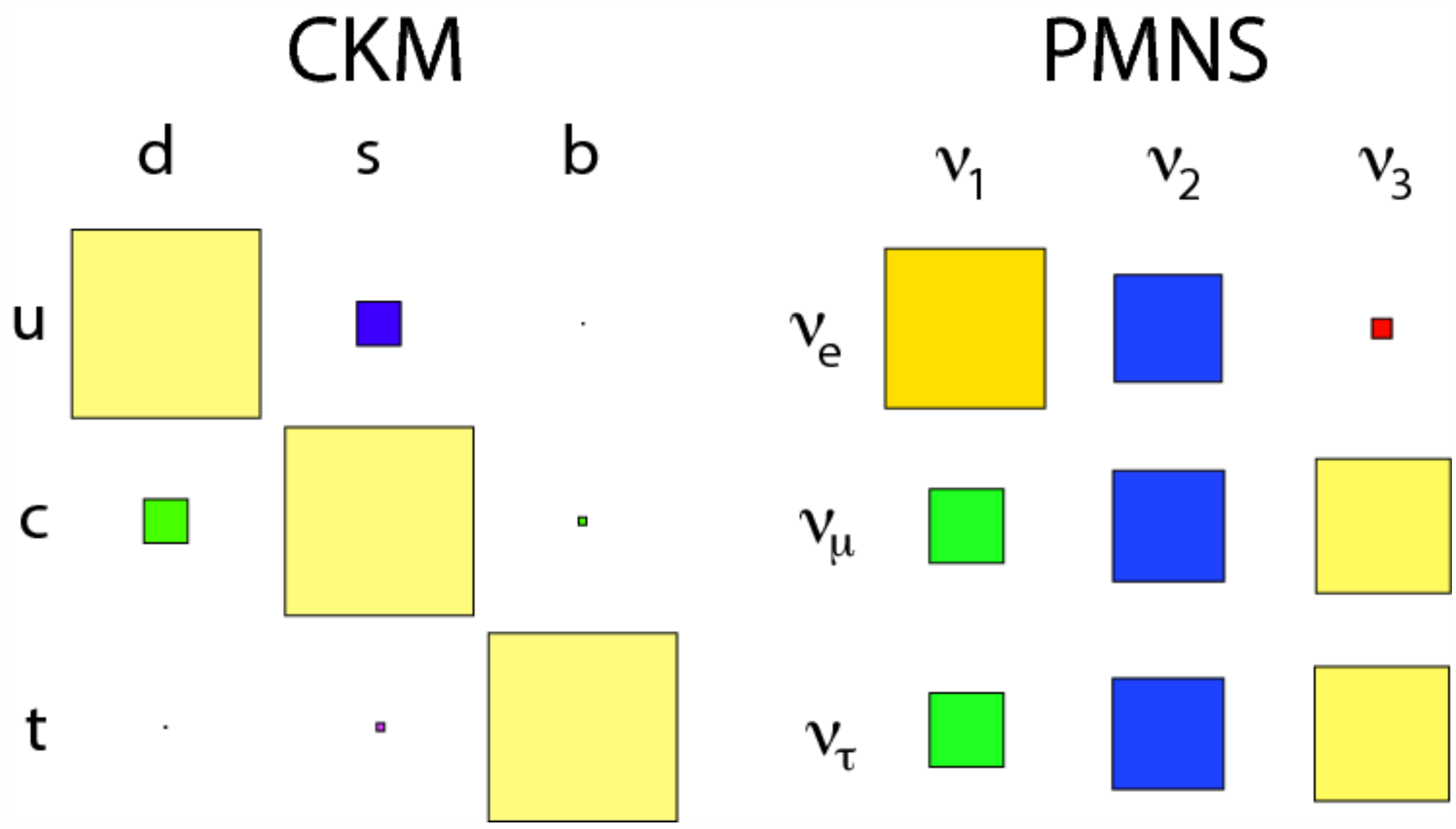
$$y_D \sim \mathcal{O}(10^{-12})$$ For a Dirac neutrino.

$$y_e \sim \mathcal{O}(10^{-6})$$ For the lightest charged lepton (e^-).

Seems **unnatural** the **Yukawa** coupling for a **Dirac** neutrino

Introduction

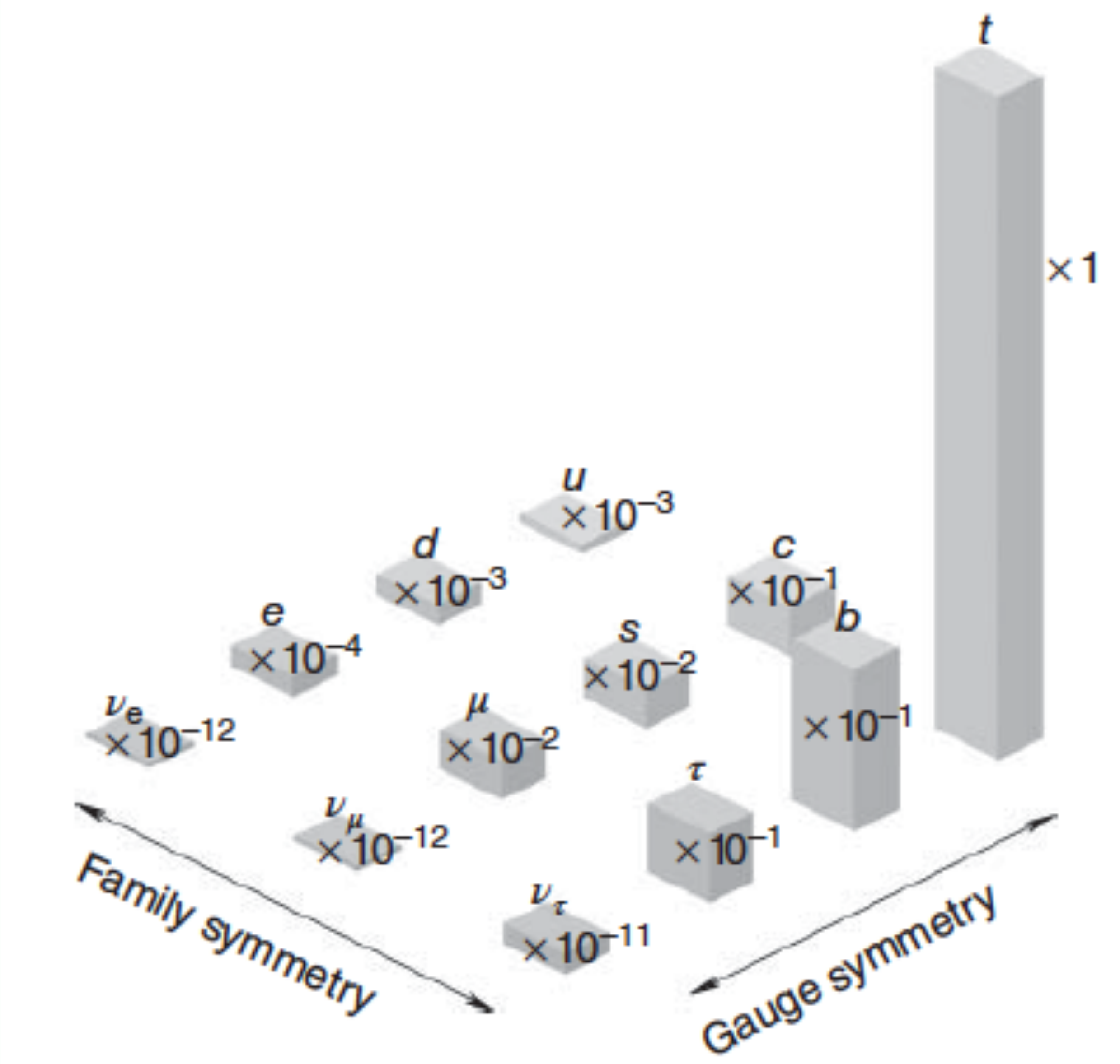
Disparity between the **quark** and **lepton mixing matrices**



[S. Stone, 2013]

Introduction

Disparity between the **quark** and **lepton masses.**



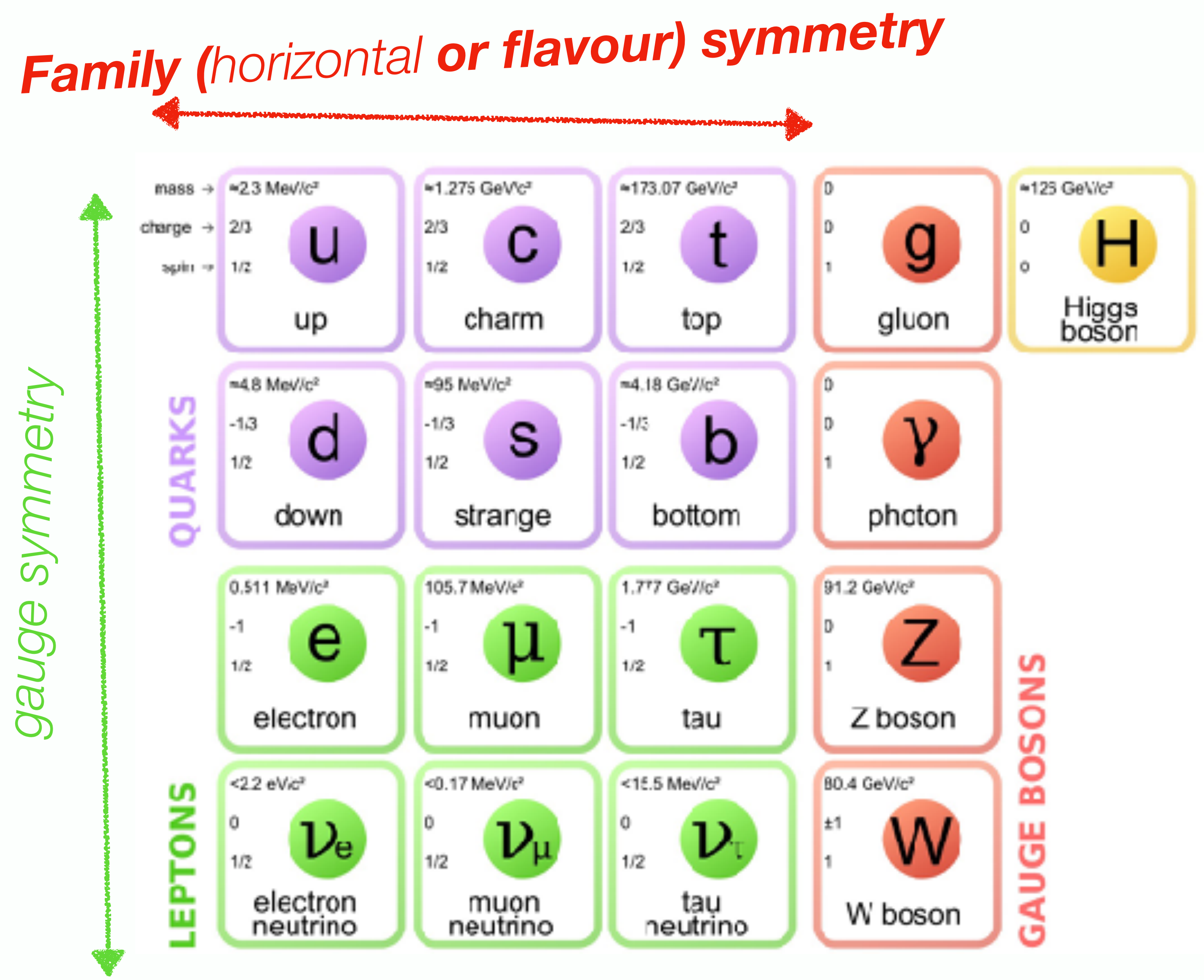
[J. Valle & J. Romão, 2015]

Introduction

Family symmetries

- They have been used to **reduce** the n° of **Yukawa couplings** and **correlations** among **observables**: masses, mixings & CP phases.

- Sometimes gives predictions, as certain mass matrix textures (TM, BM,TBM, BTM).



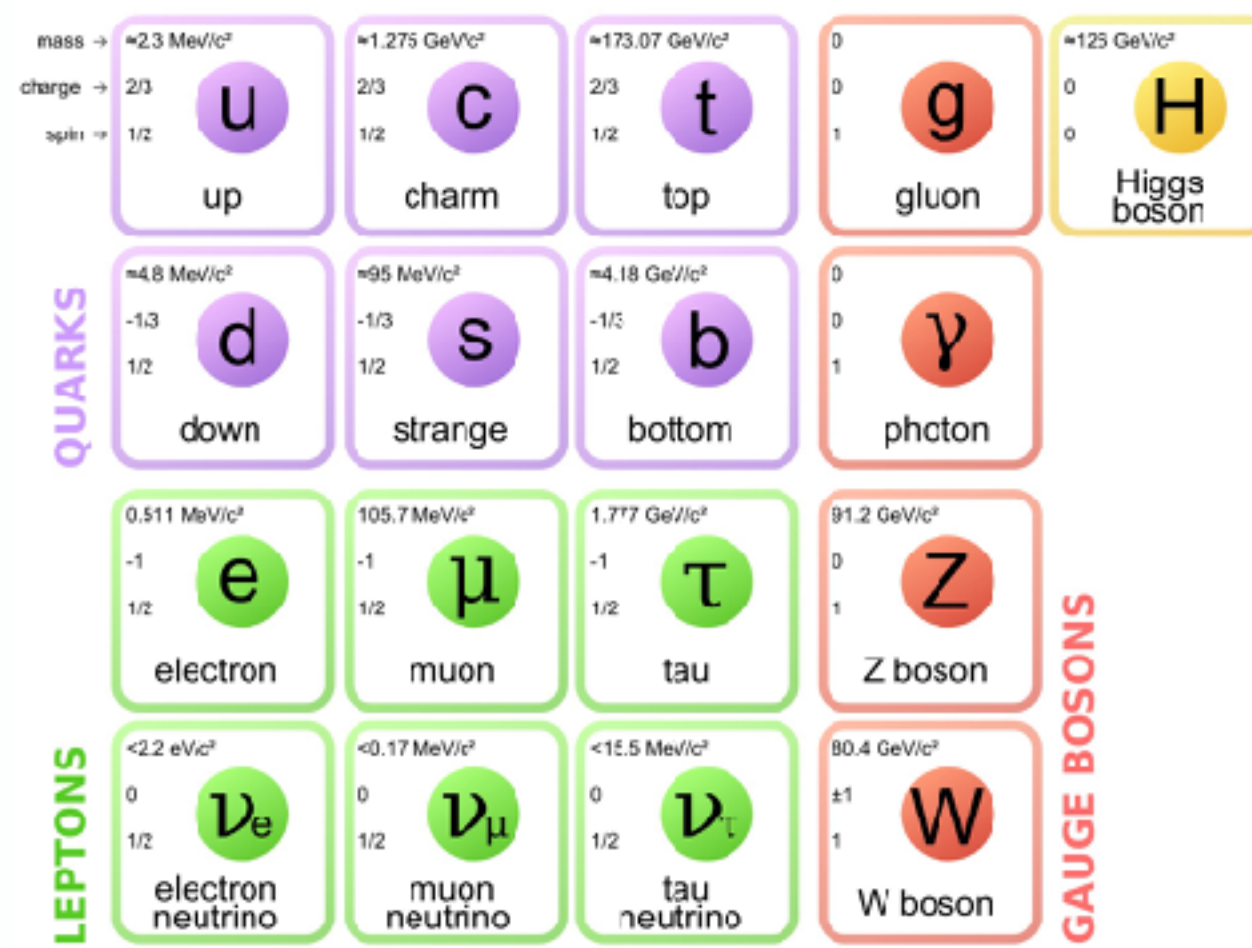
Introduction

Family symmetries

Non-Abelian finite groups of order < 32 constructed from direct products of Z, D, Q, S and T.

Frampton and Kephart, PRD64 (01)

order	groups
6	$S_3 \equiv D_3$
8	$D_4, Q = Q_4$
10	D_5
12	$D_6, Q_6, T \equiv A_4$
14	D_7
16	$D_8, Q_8, Z_2 \times D_4, Z_2 \times Q$
18	$D_9, Z_3 \times D_3$
20	D_{10}, Q_{10}
22	D_{11}
24	$D_{12}, Q_{12}, Z_2 \times D_6, Z_2 \times Q_6, Z_2 \times T, Z_3 \times D_4, Z_3 \times Q, Z_4 \times D_3, S_4$
26	D_{13}
28	D_{14}, Q_{14}
30	$D_{15}, D_5 \times Z_3, D_3 \times Z_5$



Family symmetries

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: **3**.

Introduction

Family symmetries

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: **3**.

Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1}, \quad \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3}, \quad \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2}, \quad \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3}, \quad \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

Introduction

Family symmetries

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1},\ \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3},\ \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2},\ \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3},\ \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

A_4 has two sub-groups Z_2, Z_3.

Two generators: $\boldsymbol{S}$, $\boldsymbol{T}$.

Introduction

Family symmetries

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: $\mathbf{3}$.

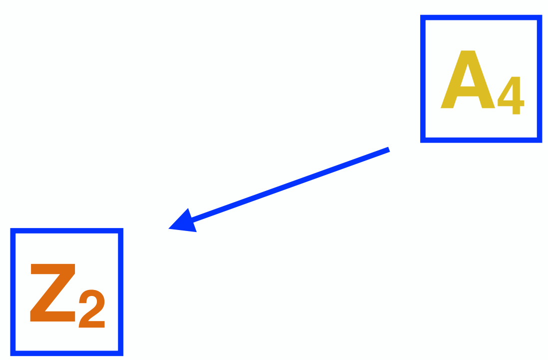
Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1},\ \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3},\ \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2},\ \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3},\ \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

A_4 has two sub-groups Z_2, Z_3.



Two generators: $\boldsymbol{S}$, $\boldsymbol{T}$.

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Generators in the a *3 dim.* rep. (with $\boldsymbol{S}$ *real* and *diagonal*).

Introduction

Family symmetries

Alternating group (A_4): Flavour symmetry group. [E. Ma, *et al.* '01]

Non-abelian, discrete group. It has:

Tree 1-dim. irreps.: $\mathbf{1_1}$, $\mathbf{1_2}$, $\mathbf{1_3}$.

One 3-dim. irrep.: **3**.

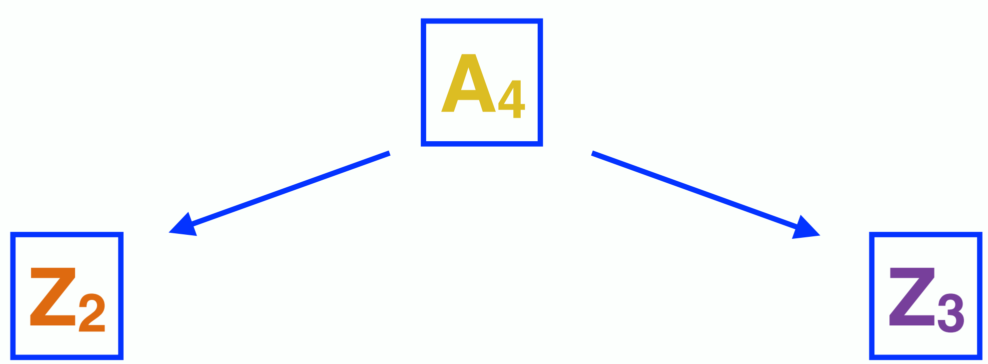
Product rule:

$$\mathbf{1_1} \otimes \mathbf{1_1} = \mathbf{1_1},\ \mathbf{1_2} \otimes \mathbf{1_2} = \mathbf{1_3},\ \mathbf{1_3} \otimes \mathbf{1_3} = \mathbf{1_2},$$

$$\mathbf{1_1} \otimes \mathbf{1_2} = \mathbf{1_2},\ \mathbf{1_1} \otimes \mathbf{1_3} = \mathbf{1_3},\ \mathbf{1_2} \otimes \mathbf{1_3} = \mathbf{1_1},$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1_1} \oplus \mathbf{1_2} \oplus \mathbf{1_3} \oplus \mathbf{3} \oplus \mathbf{3}.$$

A_4 has two sub-groups Z_2, Z_3.



Two generators: $\boldsymbol{S}$, $\boldsymbol{T}$.

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \qquad T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

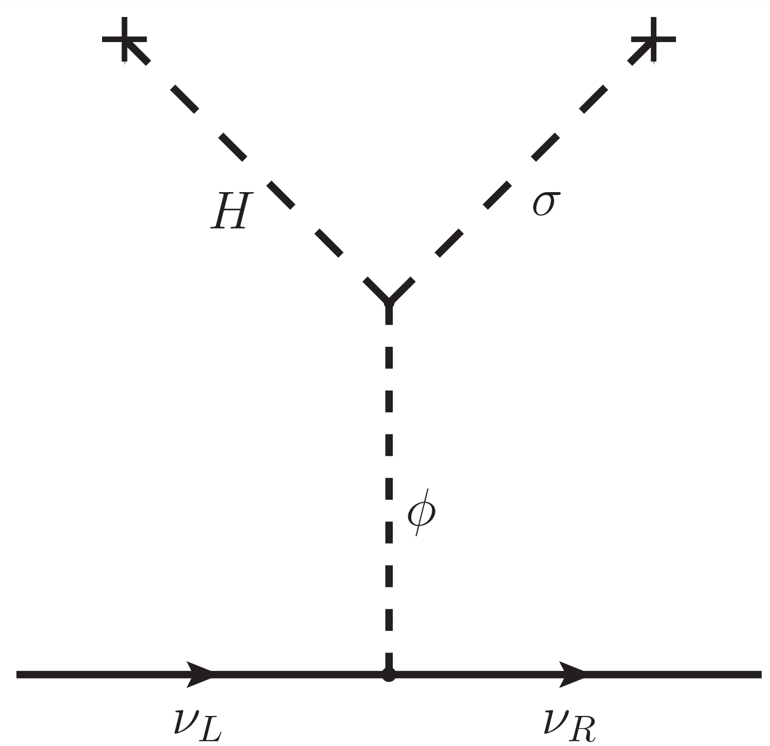
Generators in the a *3 dim.* rep. (with $\boldsymbol{S}$ *real* and *diagonal*).

Model

Enhancement of the **SM** symmetry

SM -> SMx$\mathbf{A_4}$x$\mathbf{Z_3}$x$\mathbf{Z_2}$

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



$$H^d = (H_1^d, H_2^d, H_3^d)$$

$$\phi = (\phi_1, \phi_2, \phi_3)$$

$$H_i^d = \begin{pmatrix} h_i^{d\,+} \\ h_i^{d\,0} \end{pmatrix}$$

$$\phi_i = \begin{pmatrix} \phi_i^0 \\ \phi_i^- \end{pmatrix}$$

$$\nu_R = (\nu_{R_1}, \nu_{R_2}, \nu_{R_3})$$

Higgs doublets

RH Neutrinos

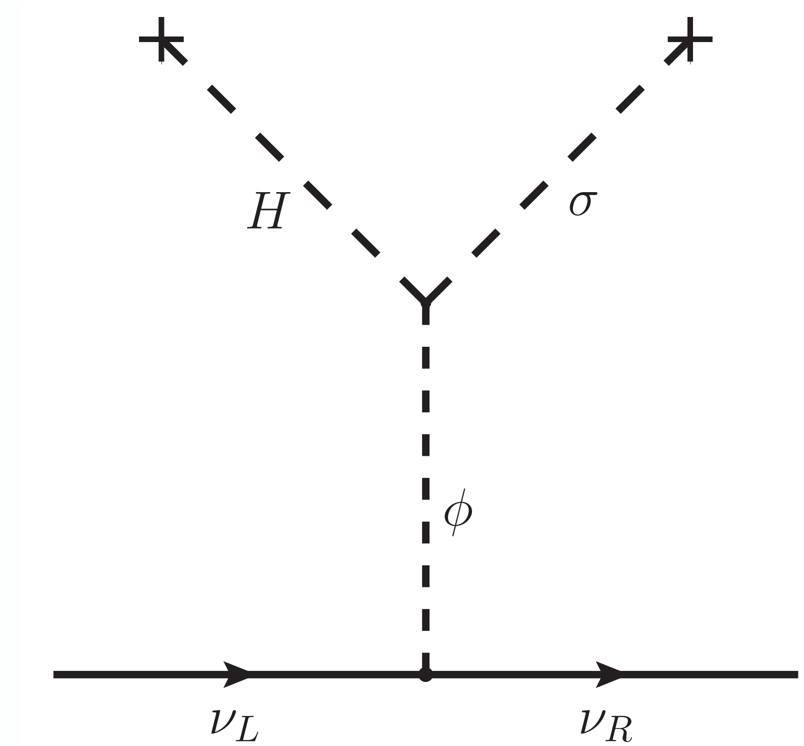
Flavon fields $\boldsymbol{\sigma_i}$

Model

Enhancement of the **SM** symmetry

SM -> SMx**A₄**x**Z₃**x**Z₂**

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



$$H^d = (H_1^d, H_2^d, H_3^d)$$

$$\phi = (\phi_1, \phi_2, \phi_3)$$

$$\nu_R = (\nu_{R_1}, \nu_{R_2}, \nu_{R_3})$$

$$\langle H^d \rangle = (v_{h_1^d}, v_{h_2^d}, v_{h_3^d})$$

$$\langle \phi \rangle = (v_{\phi_1}, v_{\phi_2}, v_{\phi_3}).$$

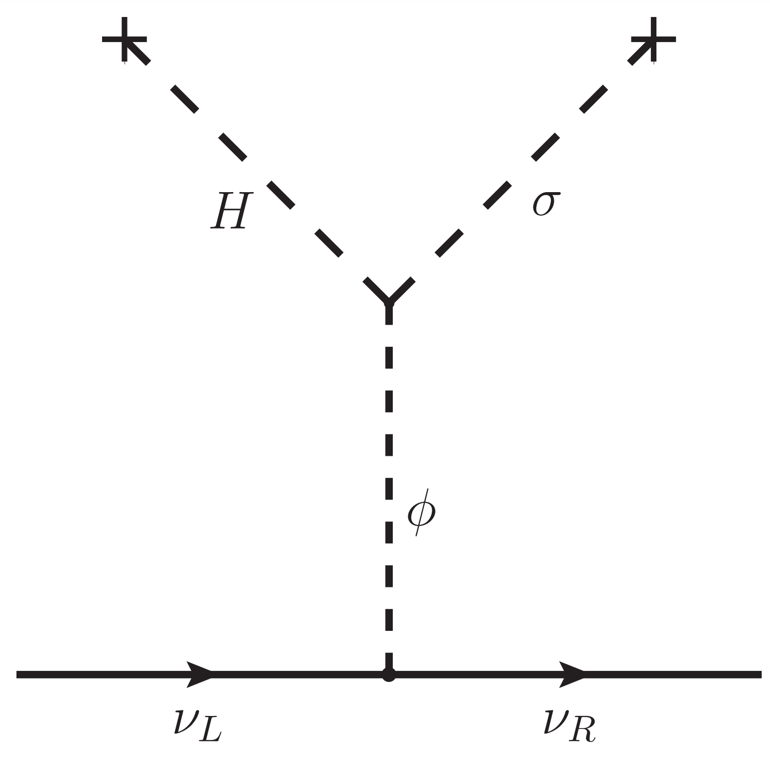
A₄ and Z₂ are **broken**.

Model

Enhancement of the **SM** symmetry

SM -> SMx**A4**x**Z3**x**Z2**

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



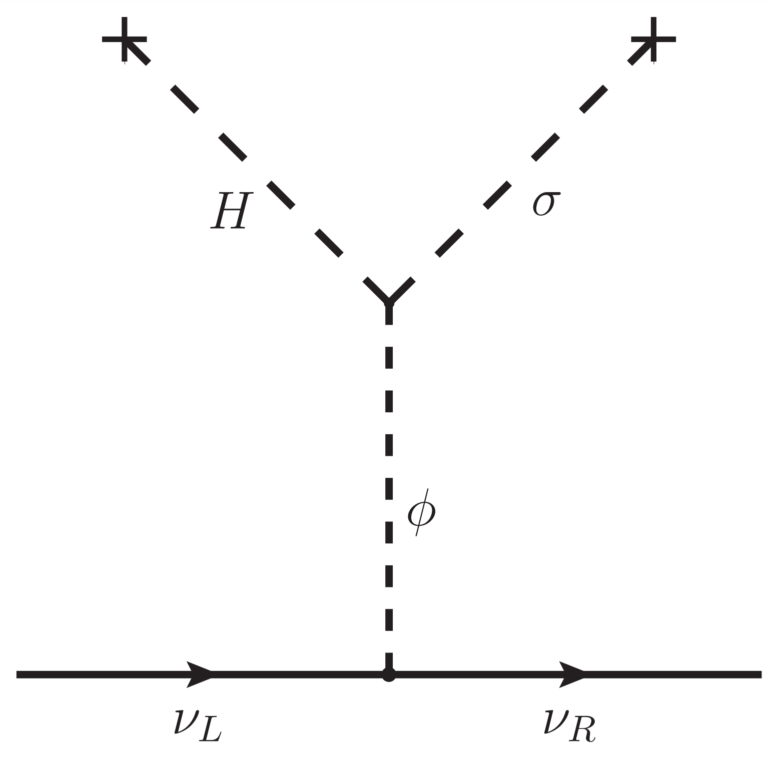
A4 gives the **flavour structure**

Model

Enhancement of the **SM** symmetry

SM -> SMx$\mathbf{A_4}$x$\mathbf{Z_3}$x$\mathbf{Z_2}$

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



A$_4$ gives the **flavour structure**

Z$_3$ forbids $M_R \nu_R \nu_R$

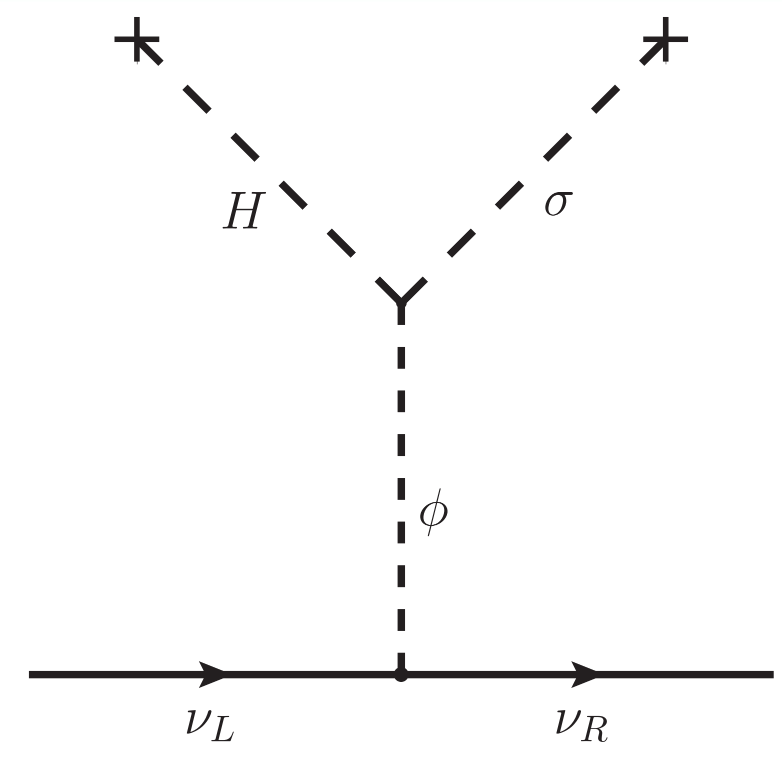
Maj. mass term RH

Model

Enhancement of the **SM** symmetry

SM -> SMxA_4xZ_3xZ_2

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



A4 gives the **flavour structure**

Z_3 forbids

$M_R \nu_R \nu_R$

$LH^d LH^d$

$L\tilde{\phi}L\tilde{\phi}$

$LH^d L\tilde{\phi}$

Maj. mass term RH

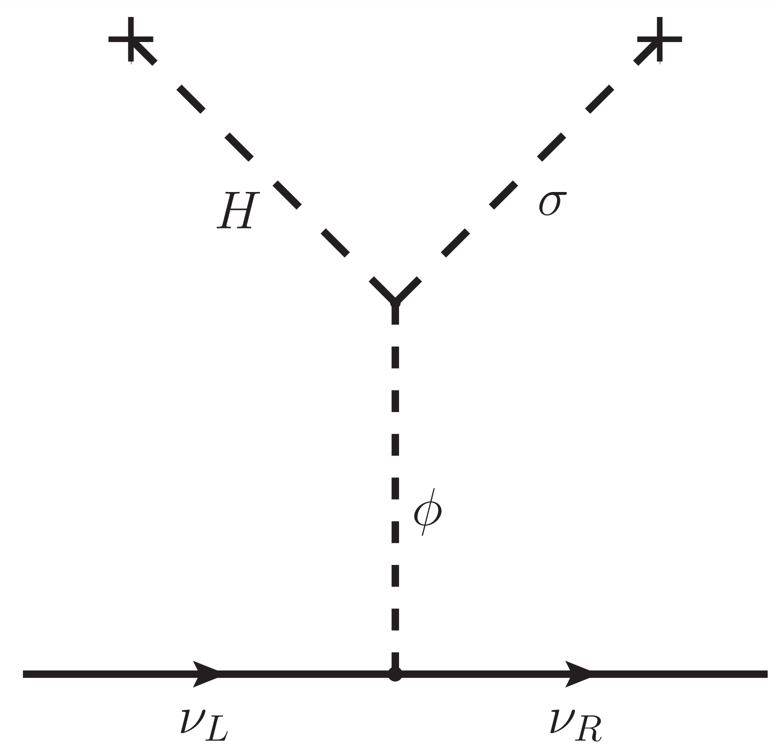
dim-5 Op.

Model

Enhancement of the **SM** symmetry

SM -> SMx$\mathbf{A_4}$x$\mathbf{Z_3}$x$\mathbf{Z_2}$

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



$\mathbf{A_4}$ gives the **flavour structure**

$\mathbf{Z_3}$ forbids

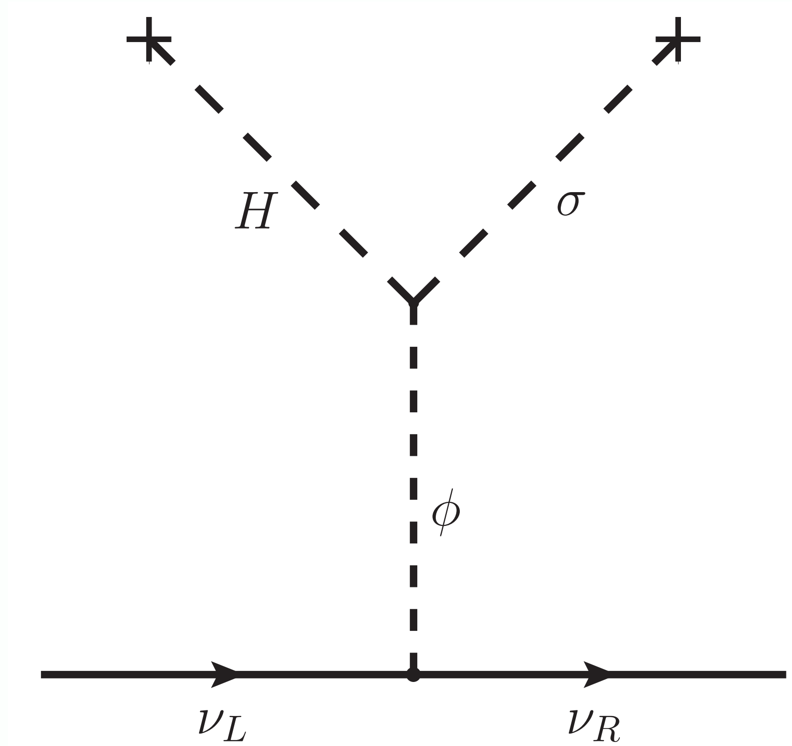
	LH^dLH^d	$\nu_R\nu_R\sigma^n$
$M_R\nu_R\nu_R$	$L\tilde{\phi}L\tilde{\phi}$	$(H^{d\dagger}H^d)^n$
	$LH^dL\tilde{\phi}$	$(\phi^\dagger\phi)^n$
Maj. mass term RH	dim-5 Op.	loop level Maj. masses

Model

Enhancement of the **SM** symmetry

SM -> SMx**A_4**x**Z_3**x**Z_2**

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



A_4 gives the **flavour structure**

Z_3 forbids

$M_R \nu_R \nu_R$

$LH^d LH^d$

$L\tilde{\phi}L\tilde{\phi}$

$LH^d L\tilde{\phi}$

$\nu_R \nu_R \sigma^n$

$(H^{d\dagger} H^d)^n$

$(\phi^\dagger \phi)^n$

Maj. mass term RH

dim-5 Op.

loop level Maj. masses

Z_2 forbids

$\bar{L}\,\tilde{\phi}\,\ell_R$

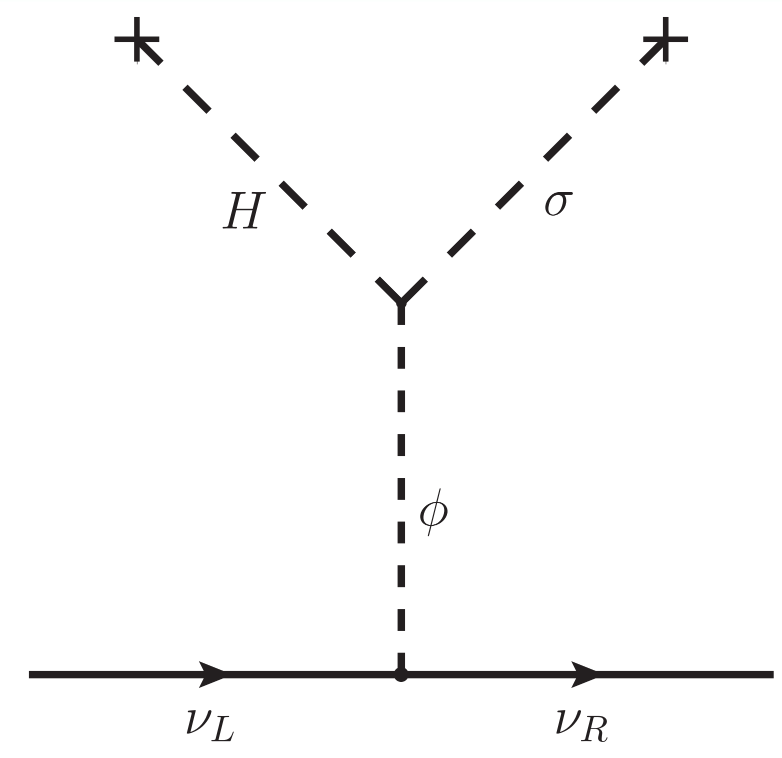
$\bar{L}\,\tilde{H}^d\,\nu_R$

Model

Enhancement of the **SM** symmetry

SM -> SMx**A_4**x**Z_3**x**Z_2**

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



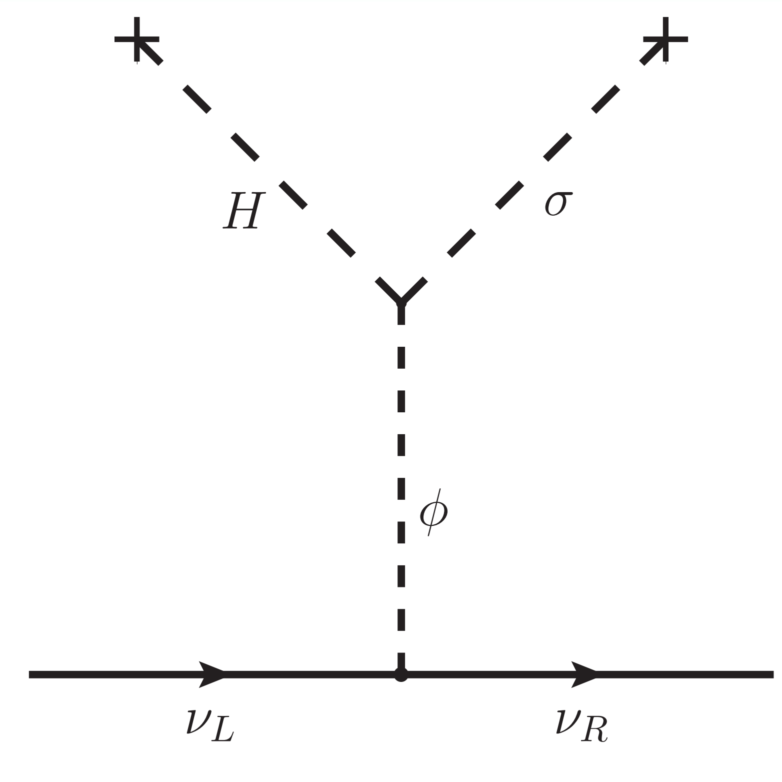
$$\mathcal{L}_Y \supset Y_\ell^i \left[\bar{L}, H^d\right]_{3_i} \ell_R + Y_\nu^i \left[\bar{L}, \phi\right]_{3_i} \nu_R + \text{h.c.}$$

ϕ acquires a **small** induced **vev**. [C. Bonilla et. al., 2016]

$$v_\Phi \approx \kappa v_H \left(\frac{1}{\lambda_{H\Phi}\frac{v_H^2}{v_\sigma^2} + \lambda_{\sigma\Phi} - 2\frac{\mu_\Phi^2}{v_\sigma^2}} \right) \qquad v_\sigma \gtrsim v_H \gg v_\Phi$$

Model

	$\bar{L}$	ℓ_R	ν_R	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,-1/2)$	$(1,-1)$	$(1,0)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$ or $\mathbf{1_i}$
$\mathbb{Z}_3$	ω^2	ω	ω	1	1	1
$\mathbb{Z}_2$	$+$	$+$	$-$	$+$	$-$	$-$



Complete model (inspired in [S. King, et al. (2013)])

	$\bar{Q}$	$\bar{L}$	u_{R_i}	d_R	ℓ_R	ν_R	H^u	H^d	ϕ	σ
$SU(2)_L \otimes U(1)_Y$	$(2,1/6)$	$(2,-1/2)$	$(1,2/3)$	$(1,-1/3)$	$(1,-1)$	$(1,0)$	$(2,-1/2)$	$(2,1/2)$	$(2,-1/2)$	$(1,0)$
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1_i}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}/\mathbf{1_i}$
Z_3	1	ω^2	1	1	ω	ω	1	1	1	1
Z_2	$+$	$+$	$+$	$+$	$+$	$-$	$+$	$+$	$-$	$-$
Z_2^d	$+$	$+$	$+$	$-$	$+$	$+$	$+$	$-$	$+$	$+$

Accounts for the **masses** and **mixings** of **quarks** and **leptons**

Model

Flavour structure provides the generalised **bottom-tau mass relation.**

$$\mathcal{L}_Y \supset Y_\ell^i \left[\bar{L}, H^d\right]_{3_i} \ell_R + \text{h.c.}$$

Mass matrix for **charged leptons** and **down type quarks.**

$$m_\ell = \begin{pmatrix} 0 & a_\ell \alpha_\ell e^{i\theta_\ell} & b_\ell \\ b_\ell \alpha_\ell & 0 & e^{i\theta_\ell} a_\ell \rho_\ell \\ a_\ell e^{i\theta_\ell} & b_\ell \rho_\ell & 0 \end{pmatrix}$$

with

$$a_\ell = v_{h_2^d}(Y_\ell^1 + Y_\ell^3) \qquad b_\ell = v_{h_2^d}(Y_\ell^2 + Y_\ell^4)$$

$$\alpha_\ell = v_{h_3^d}/v_{h_2^d} \qquad \rho_\ell = v_{h_1^d}/v_{h_2^d}$$

$$\langle H^d \rangle = (v_{h_1^d}, v_{h_2^d}, v_{h_3^d}) = v_{h_2^d}(\rho_\ell, 1, \alpha_\ell)$$

Unremovable **CP phase** θ_ℓ Set $\theta_\ell = 0$ **CPV** comes from **u-type quarks** and **neutrinos**

Model

Flavour structure provides the generalised **bottom-tau mass relation.**

$$\mathcal{L}_Y \supset Y_\ell^i \ \left[\bar{L}, H^d\right]_{3_i} \ell_R \ + \text{h.c.}$$

Mass matrix for **charged leptons** and **down type quarks.**

$$m_\ell = \begin{pmatrix} 0 & a_\ell \alpha_\ell e^{i\theta_\ell} & b_\ell \\ b_\ell \alpha_\ell & 0 & e^{i\theta_\ell} a_\ell \rho_\ell \\ a_\ell e^{i\theta_\ell} & b_\ell \rho_\ell & 0 \end{pmatrix}$$

Bi-unitary **invariants** of the **mass squared matrix** $M_\ell^2 = m_\ell m_\ell^\dagger$

$$\begin{aligned} \text{Tr} M_\ell^2 &= m_1^2 + m_2^2 + m_3^2, \\ \det M_\ell^2 &= m_1^2 m_2^2 m_3^2, \\ (\text{Tr} M_\ell^2)^2 - \text{Tr}(M_\ell^2)^2 &= 2m_1^2 m_2^2 + 2m_2^2 m_3^2 + 2m_1^2 m_3^2. \end{aligned}$$

Model

Flavour structure provides the generalised **bottom-tau mass relation.**

$$\mathcal{L}_Y \supset Y_\ell^i \ \left[\bar{L}, H^d\right]_{3_i} \ell_R \ + \text{h.c.}$$

Mass matrix for **charged leptons** and **down type quarks.**

$$m_\ell = \begin{pmatrix} 0 & a_\ell \alpha_\ell e^{i\theta_\ell} & b_\ell \\ b_\ell \alpha_\ell & 0 & e^{i\theta_\ell} a_\ell \rho_\ell \\ a_\ell e^{i\theta_\ell} & b_\ell \rho_\ell & 0 \end{pmatrix}$$

Bi-unitary **invariants** of the **mass squared matrix** $M_\ell^2 = m_\ell m_\ell^\dagger$

$$(b_\ell \rho_\ell)^2 \approx m_3^2,$$
$$(b_\ell^3 \rho_\ell \alpha_\ell)^2 \approx m_1^2 m_2^2 m_3^2,$$
$$(a_\ell b_\ell \rho_\ell^2)^2 \approx m_2^2 m_3^2.$$

assuming

$$\rho_\ell \gg \alpha_\ell$$
$$\rho_\ell \gg 1$$
$$b_\ell > a_\ell$$
$$\rho_\ell \gg \frac{b_\ell}{a_\ell}$$

Model

Flavour structure provides the generalised **bottom-tau mass relation.**

$$(b_\ell \rho_\ell)^2 \approx m_3^2,$$
$$(b_\ell^3 \rho_\ell \alpha_\ell)^2 \approx m_1^2 m_2^2 m_3^2,$$
$$(a_\ell b_\ell \rho_\ell^2)^2 \approx m_2^2 m_3^2.$$

Solving

$$\rho_\ell \gg \alpha_\ell$$
$$\rho_\ell \gg 1$$
$$b_\ell > a_\ell$$
$$\rho_\ell \gg \frac{b_\ell}{a_\ell}$$

$$a_\ell \approx \frac{m_2}{m_3}\sqrt{\frac{m_1 m_2}{\alpha_\ell}}$$

$$b_\ell \approx \sqrt{\frac{m_1 m_2}{\alpha_\ell}}$$

$$\frac{\rho_\ell}{\sqrt{\alpha_\ell}} \approx \frac{m_3}{\sqrt{m_1 m_2}}$$

Leading to

$$\frac{m_\tau}{\sqrt{m_e m_\mu}} = \frac{m_b}{\sqrt{m_d m_s}}$$

as

$$\rho_\ell = \rho_d$$
$$\alpha_\ell = \alpha_d$$

[S. Morisi, et al., 2016]

Results

No actual **perdition** for the **CKM**, but it can be **fitted in the model**.
However there are **predictions** for the LMM (**PMNS**).

$$\mathcal{L}_Y \supset Y_\nu^i \, \left[\bar{L}, \phi\right]_{3_i} \nu_R + \text{h.c.},$$

Neutrino mass matrix

$$m_\nu = \begin{pmatrix} 0 & a_\nu \alpha_\nu & b_\nu e^{i\theta_\nu} \\ b_\nu e^{i\theta_\nu} \alpha_\nu & 0 & a_\nu \rho_\nu \\ a_\nu & b_\nu e^{i\theta_\nu} \rho_\nu & 0 \end{pmatrix}$$

real Yukawas $a_\nu = v_{\phi_2}(Y_\nu^1 + Y_\nu^3)$ $b_\nu = v_{\phi_2}(Y_\nu^2 + Y_\nu^4)$

$\alpha_\nu = v_{\phi 3}/v_{\phi 2}$ $\rho_\nu = v_{\phi 1}/v_{\phi 2}$

θ_ν **CPV phase** lepton sector

Results

$$m_\nu = \begin{pmatrix} 0 & a_\nu \alpha_\nu & b_\nu e^{i\theta_\nu} \\ b_\nu e^{i\theta_\nu}\alpha_\nu & 0 & a_\nu \rho_\nu \\ a_\nu & b_\nu e^{i\theta_\nu}\rho_\nu & 0 \end{pmatrix}$$

Invariants of the **squared neutrino matrix** $M_\nu^2 = m_\nu m_\nu^\dagger$

$$\begin{aligned} (a_\nu^2 + b_\nu^2)(1+\alpha_\nu^2+\rho_\nu^2), &= m_1^2 + m_2^2 + m_3^2, \\ (a_\nu^6 + b_\nu^6 + 2a_\nu^3 b_\nu^3 \cos(3\theta_\nu))\alpha_\nu^2\rho_\nu^2, &= m_1^2 m_2^2 m_3^2, \\ a_\nu^2 b_\nu^2 (1+\alpha_\nu^4+\rho_\nu^4) + (a_\nu^4+b_\nu^4)(\rho_\nu^2+\alpha_\nu^2(1+\rho_\nu^2)) &= 2m_1^2m_2^2 + 2m_2^2m_3^2 + 2m_1^2m_3^2 \end{aligned}$$

Lepton mixing matrix (**PMNS**) $V = U_l^\dagger U_\nu$

Fixed by CKM fitting.

Close to a diagonal

$$U_\nu^\dagger m_\nu V_\nu = D_\nu$$

$$U_\ell^\dagger m_\ell V_\ell = D_\ell$$

$$D = \mathrm{diag}\,(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

Results

Global Neutrino Fit [P. F. de Salas, et al., 2017]

parameter	best fit ± 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.56 ± 0.19	7.20–7.95	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.55 ± 0.04	2.47–2.63	2.43–2.67
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.47^{+0.04}_{-0.05}$	2.39–2.55	2.34-2.59
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/^\circ$	$34.5^{+1.1}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$ [a]	3.98–4.78 & 5.60–6.17	3.84–6.35
$\theta_{23}/^\circ$	41.0 ± 1.1	39.1–43.7 & 48.4–51.8	38.3–52.8
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.98^{+0.17}_{-0.15}$ [b]	4.09–4.42 & 5.61–6.27	3.89–4.88 & 5.22–6.41
$\theta_{23}/^\circ$	$50.7^{+1.0}_{-0.9}$	39.8–41.7 & 48.5–52.3	38.6–44.3 & 46.2–53.2
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$	1.98–2.31	1.89–2.39
$\theta_{13}/^\circ$	$8.44^{+0.18}_{-0.15}$	8.1–8.7	7.9–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.155^{+0.076}_{-0.092}$	1.98–2.31	1.90–2.39
$\theta_{13}/^\circ$	$8.44^{+0.15}_{-0.18}$	8.1–8.7	7.9–8.9
δ/π (NO)	$1.40^{+0.31}_{-0.20}$	0.85–1.95	0.00–2.00
$\delta/^\circ$	252^{+56}_{-36}	153–351	0–360
δ/π (IO)	$1.56^{+0.22}_{-0.26}$	1.07–1.97	0.00–0.17 & 0.83–2.00
$\delta/^\circ$	281^{+39}_{-47}	193–355	0–31 & 149–360

[a]There is a local minimum in the second octant, at $\sin^2\theta_{23}$=0.596 with $\Delta\chi^2 = 2.1$ with respect to the global minimum.
[b]There is a local minimum in the first octant, at $\sin^2\theta_{23}$=0.426 with $\Delta\chi^2 = 3.0$ with respect to the global minimum for IO.

TABLE I: Neutrino oscillation parameters summary determined from this global analysis. The ranges for inverted ordering refer to the local minimum of this neutrino mass ordering.

Results

Numerical scan in the parameter region taking as **inputs** the **3σ values** of the **neutrino oscillation parameters**.

Global fit data from [P. F. de Salas, et al., 2017]

Only consistent with the **IO**

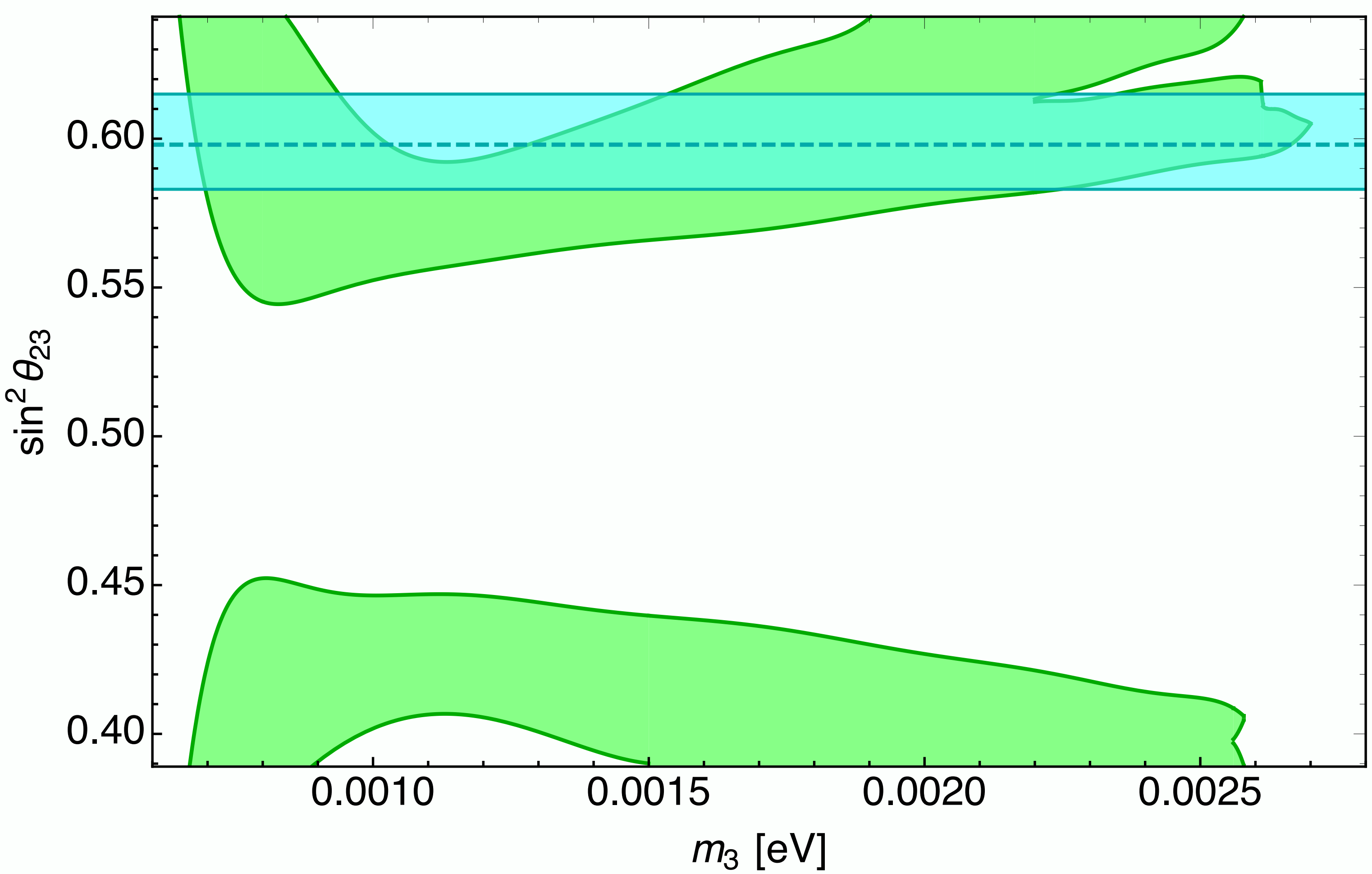


Figure 2. *The regions in the atmospheric mixing angle θ_{23} and the lightest neutrino mass m_3 plane allowed by current oscillation data are the shaded (green) areas, see text. The horizontal dashed line represents the best-fit value for $\sin^2\theta_{23}$, whereas the horizontal shaded region corresponds to the 1σ allowed region from Ref. [1].*

Results

Numerical scan in the parameter region taking as **inputs** the **3σ values** of the **neutrino oscillation parameters**.

Data from [P. F. de Salas, et al., 2017]

IO

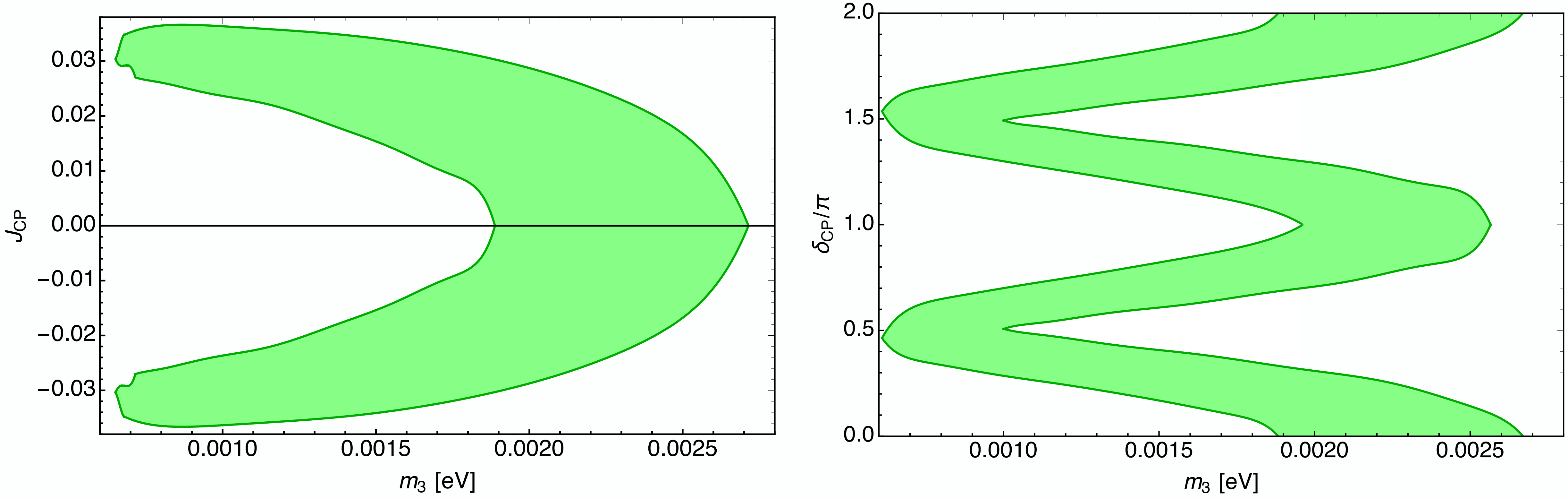


Figure 3. *Correlation between the CP violation and the lightest neutrino mass. Left: correlation between the Jarlskog invatiant and the lightest neutrino mass m_3 allowed by the current oscillation data from Ref. [1]. Right: We plot also the allowed region for the correlation between the the Dirac CP phase δ_{CP} and the lightest neutrino mass m_3.*

Results

Numerical scan in the parameter region taking as **inputs** the **3σ values** of the **neutrino oscillation parameters**.

Data from [P. F. de Salas, et al., 2017]

IO

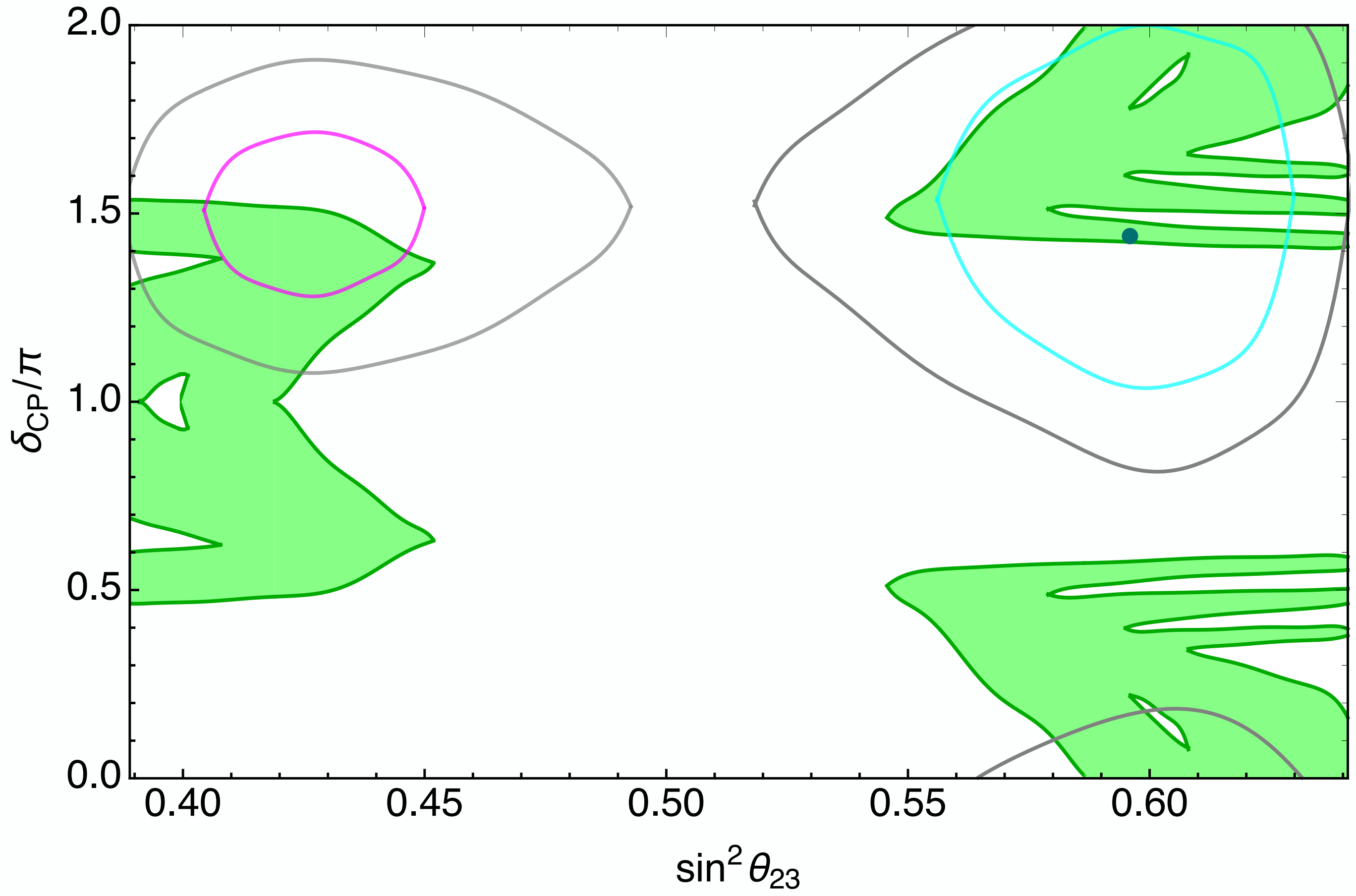


Figure 4. *The allowed regions of the atmospheric mixing angle and δ_{CP} are indicated in shaded (green). They result from a numerical scan keeping only those choices that lie within 3σ of their preferred best fit values Ref. [1]* The unshaded regions are 90 and 99%CL regions obtained directly in the unconstrained three–neutrino oscillation global fit [1].

Summary and Conclusions

We have propose a **SM extension** with underlying **A4 flavour symmetry**.

The **model addresses** both aspects of the flavour problem: the explanation of **mass hierarchies** of quark and leptons, as well as **restricting** the **structure** of the **lepton mixing matrix**.

The **model predicts** the **golden flavour-dependent bottom-tau mass relation**.

Summary and Conclusions

Requires an **IO** and **non-maximal atmospheric mixing** angle (Neither the preference for normal ordering nor the indication for an octant are currently statistically significant).

The **residual flavour symmetry forbids** the **Majorana mass terms** at **any order** and provides a **natural realisation** of a **type-II Dirac seesaw mechanism**.

The **CKM matrix**, although **no** definite **predictions** are made, the required CKM **matrix elements** can be adequately **described**. Then the **contribution to the neutrino mixing matrix** that comes **from** the **charged lepton sector** is **fixed**.

Gracias!