Neutrino Flavor Models

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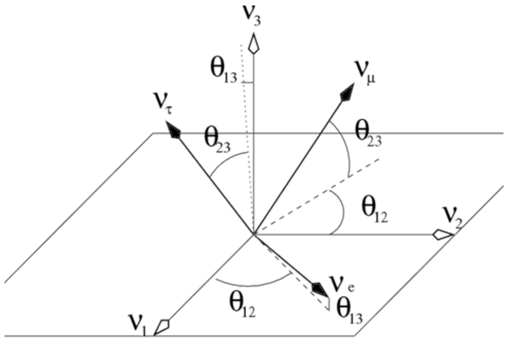
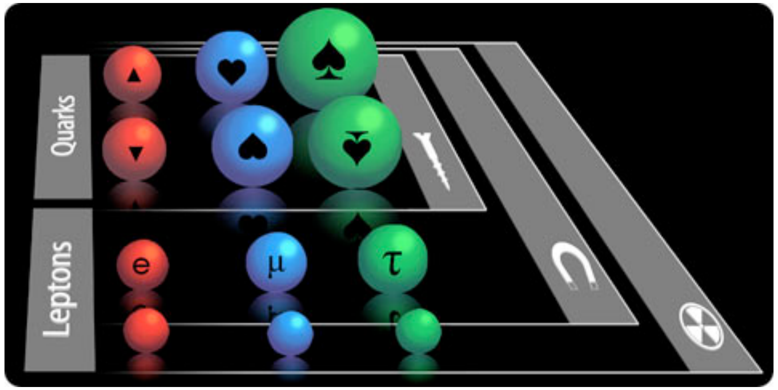
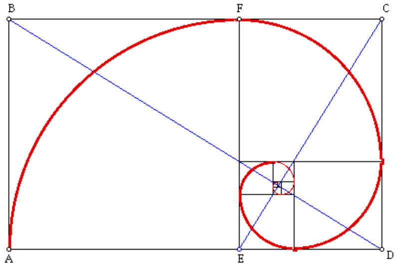
International Workshop for the Next Generation Nucleon Decay and Neutrino Detector (NNN15) and Unification Day 2 (UD2)

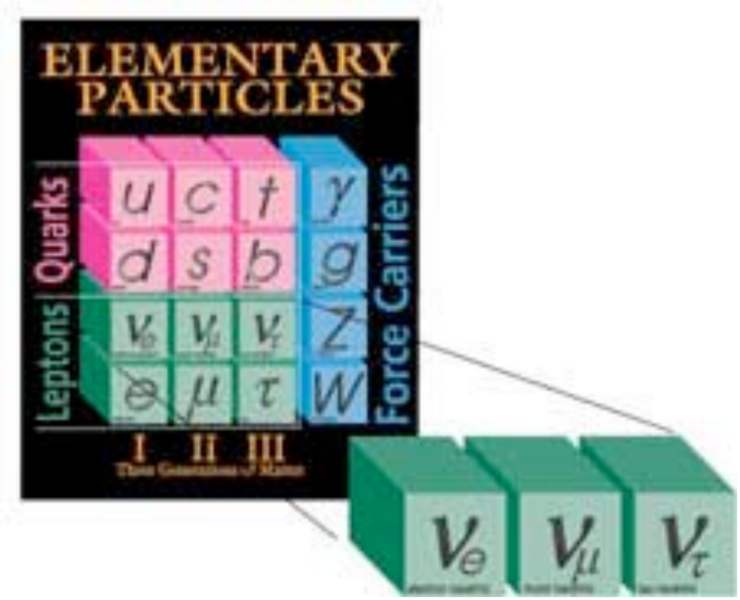






Discovery of Neutrino Oscillations:

$$\mathcal{P}_{\nu_\alpha \to \nu_\beta}(L) = \sum_{ij} \mathcal{U}_{i\alpha}\mathcal{U}^*_{i\beta}\mathcal{U}^*_{j\alpha}\mathcal{U}_{j\beta} e^{-\frac{i\Delta m^2_{ij} L}{2E}}$$



surprises, confusion, excitement for beyond SM physics theory!

3 Neutrino "Reference" Picture:

data (w/exceptions*) consistent with 3 ν mixing picture

intriguing pattern of masses, mixings: paradigm shift for SM flavor puzzle

Of course — the picture may not be this "simple"!

Many Questions Remain

- **How many light neutrinos?**

Anomalies: LSND, MiniBooNE, Gallium, Reactor

eV-scale sterile neutrinos? But tension still with all oscillation data

For now restrict to 3-family neutrino models only

SM $\longrightarrow$ νSM

- **Still, many questions:**

Nature of neutrino mass suppression? Majorana? Dirac?

Mass hierarchy? Lepton mixing angle pattern? CP violation?

Implications for BSM paradigms? Connections to other NP?

The Data: Fermion Masses

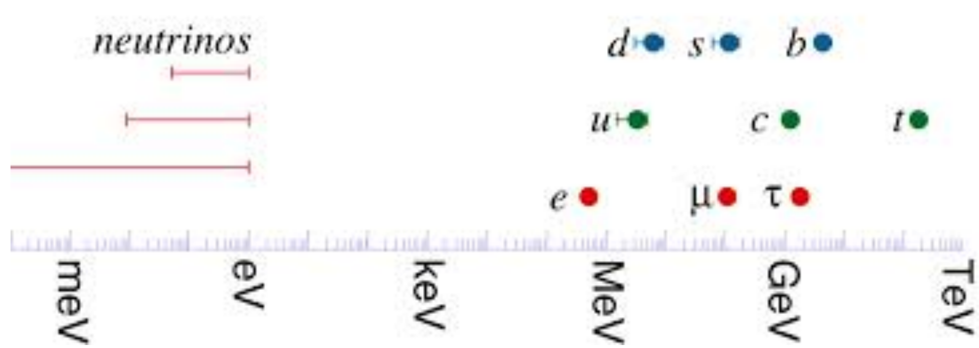
Quarks, charged leptons:

$m_u \simeq 1 - 4\,\mathrm{MeV}$ $\quad m_c \simeq 1\,\mathrm{GeV}$ $\quad m_t \simeq 175\,\mathrm{GeV}$

$m_d \simeq 4 - 8\,\mathrm{MeV}$ $\quad m_s \simeq 100\,\mathrm{MeV}$ $\quad m_b \simeq 5\,\mathrm{GeV}$

$m_e = 0.511\,\mathrm{MeV}$ $\quad m_\mu = 105\,\mathrm{MeV}$ $\quad m_\tau \simeq 1.8\,\mathrm{GeV}$

hierarchy!

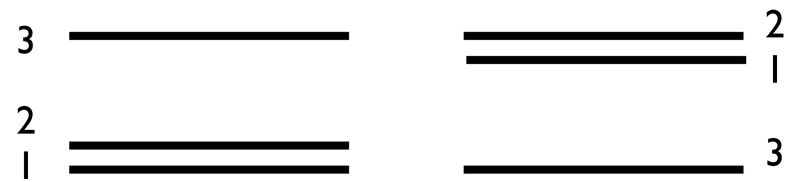


Neutrinos: $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

$$\Delta m^2_{\odot} = |\Delta m^2_{12}| \simeq 8 \times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{\oplus} = |\Delta m^2_{23}| \simeq 2 \times 10^{-3}\,\mathrm{eV}^2$$

Normal Hierarchy (NH) Inverted Hierarchy (IH)

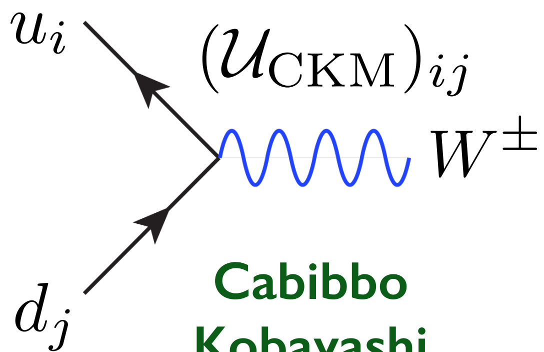


individual masses: only limits from direct searches, cosmology

The Data: Fermion Mixing

rotation matrices

Quarks:



Cabibbo
Kobayashi
Maskawa

$$\mathcal{U}_{\rm CKM} = \mathcal{R}_1(\theta_{23}^{\rm CKM})\mathcal{R}_2(\theta_{13}^{\rm CKM}, \delta_{\rm CKM})\mathcal{R}_3(\theta_{12}^{\rm CKM})$$

$\theta_{12}^{\rm CKM} = 13.0^\circ \pm 0.1^\circ \; = \theta_C$ **(Cabibbo angle)**

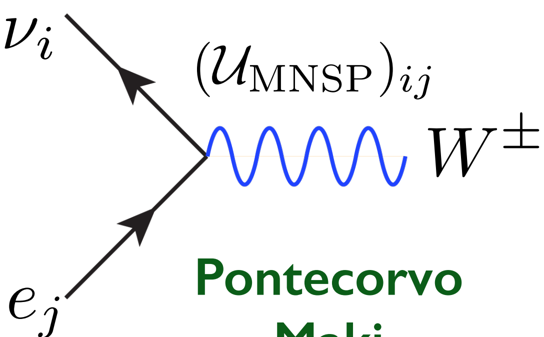
$\theta_{23}^{\rm CKM} = 2.4^\circ \pm 0.1^\circ$

$\theta_{13}^{\rm CKM} = 0.2^\circ \pm 0.1^\circ$

$\delta_{\rm CKM} = 60^\circ \pm 14^\circ$

3 "small" angles
1 large CP phase

Leptons:



Pontecorvo
Maki
Nakagawa
Sakata

$$\mathcal{U}_{\rm MNSP} = \mathcal{R}_1(\theta_{23})\mathcal{R}_2(\theta_{13}, \delta_{\rm MNSP})\mathcal{R}_3(\theta_{12})\mathcal{P}$$

phases (if Majorana)

NH; best fit +/-1sig (3sig range)

$\theta_{12} = 33.48^\circ{}^{+0.78^\circ}_{-0.75^\circ}$ $(31.29^\circ - 35.91^\circ)$

$\theta_{23} = 42.3^\circ{}^{+3.0^\circ}_{-1.6^\circ}$ $(38.2^\circ - 53.3^\circ)$

$\theta_{13} = 8.50^\circ{}^{+0.20^\circ}_{-0.21^\circ}$ $(7.85^\circ - 9.10^\circ)$

2 large angles,
1 "small" angle

fits from Gonzalez-Garcia et al. '14,
see also Forero et. al '14, Capozzi et al. '13

(Broad) Theoretical Implications

SM probes: only sensitive to subset of model parameters

Can only provide classes of viable models!
(need NP/precision measurements to distinguish)

<u>Basic categories:</u>

most important question (by far)

Majorana or Dirac neutrinos?

mechanism for suppressing neutrino mass scale

lepton mixing angles: symmetry or anarchy?

We're still in the very early stages of mapping out the theory space of acceptable models!

Mass Generation

Quarks, Charged Leptons

"natural" mass scale tied to electroweak scale

Dirac mass terms, parametrized by Yukawa couplings

$$Y_{ij} H \cdot \bar{\psi}_{Li} \psi_{Rj}$$

top quark: O(1) Yukawa coupling

rest: suppression (flavor symmetry)

Neutrinos beyond physics of Yukawa couplings!

Options: Dirac

Majorana

Majorana first:

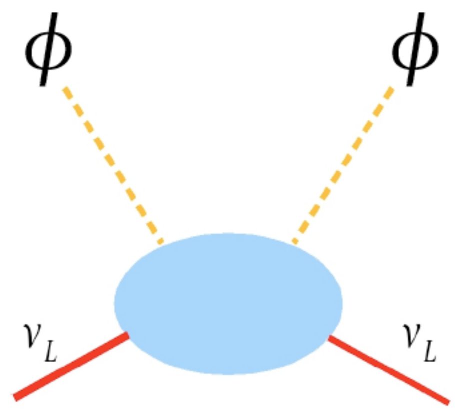
advantages: naturalness, leptogenesis, $0\nu\beta\beta$

SM at NR level: Weinberg dim 5 operator

$$\frac{\lambda_{ij}}{\Lambda} L_i H L_j H$$

(if $\lambda \sim O(1)$ $\quad \Lambda \gg m \sim O(100\,\mathrm{GeV})$ but wide range possible)

Underlying mechanism: examples



Type I seesaw ν_R (fermion singlet)

Type II seesaw Δ (scalar triplet)

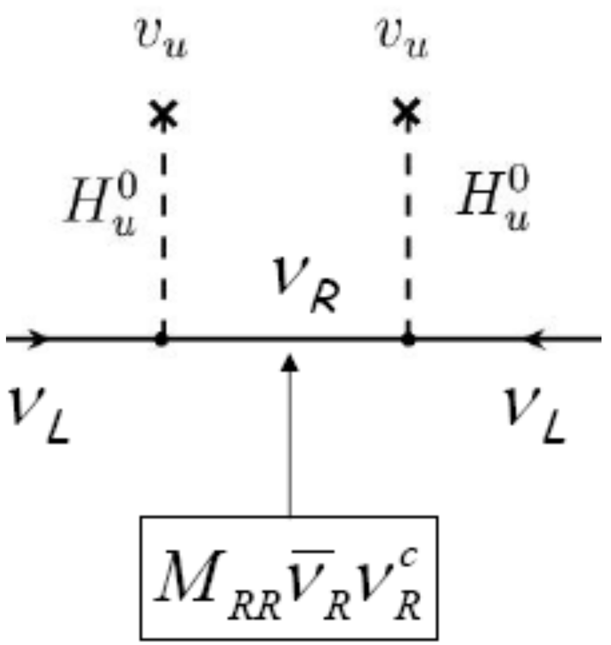
Type III seesaw Σ (fermion triplet)

+ variations

Prototype: Type I seesaw

Minkowski;Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;…

right-handed neutrinos: $Y_{ij} L_i \nu_{Rj} H + M_{R\,ij} \nu_{Ri} \nu^c_{Rj}$



$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$m \sim \mathcal{O}(100\,\mathrm{GeV})$

$M \gg m$

$$m_1 \sim \frac{m^2}{M} \qquad m_2 \sim M \gg m_1$$

$$\nu_{1,2} \sim \nu_{L,R} + \frac{m}{M} \nu_{R,L}$$

advantages: naturalness, connection to grand unification, leptogenesis,...

disadvantage: testability (even at low scales)

Different in Type II, III: new EW charged states — visible at LHC?

Many other ideas for Majorana neutrino masses...

more seesaws (double, inverse,...),
loop-induced masses (Babu-Zee, ...),
SUSY with R-parity violation, RS models,
higher-dimensional (>5) operators,...

What about Dirac masses?

Less intuitive, but suppression mechanisms exist…

extra dimensions, extra gauge symms (non-singlet ν_R),SUSY breaking,…

General themes:

Trade-off b/w naturalness and testability.
Much richer than quark and charged lepton sectors.

Lepton (and Quark) Mixing Angle Generation

Standard paradigm: spontaneously broken flavor symmetry

$$Y_{ij} H \cdot \bar{\psi}_{Li} \psi_{Rj} \longrightarrow \left(\frac{\varphi}{M}\right)^{n_{ij}} H \cdot \bar{\psi}_{Li} \psi_{Rj}$$

Froggatt, Nielsen

Quarks:

hierarchical masses, small mixings: continuous family symmetries

CKM matrix: small angles and/or alignment of left-handed mixings

$$\mathcal{U}_{\mathrm{CKM}} = \mathcal{U}_u \mathcal{U}_d^\dagger \sim 1 + \mathcal{O}(\lambda)$$

$$\lambda \sim \frac{\varphi}{M}$$

Wolfenstein parametrization: $\lambda \equiv \sin\theta_c = 0.22$

suggests Cabibbo angle (or some power) as a flavor expansion parameter

The Flavor Puzzle, Rejuvenated

Flavor puzzle of SM is notoriously difficult...

Still difficult in νSM, but more interesting --

One primary reason: two large mixing angles!

3-family models: handwave a bit (in diagonal charged lepton basis)

3 small angles $\longrightarrow$ $\sim$ diagonal $\mathcal{M}_\nu$
1 large, 2 small $\longrightarrow$ $\sim \mathrm{Rank}\mathcal{M}_\nu < 3$
("easy")

3 large angles $\longrightarrow$ anarchical $\mathcal{M}_\nu$
2 large, 1 small $\longrightarrow$ fine-tuning, non-Abelian
("harder")

Anarchy vs. Structure

The question: is θ_{13} large or small?

$$\theta_{13} \simeq 9^\circ \pm 1^\circ$$

New case for anarchy: de Gouvea and Murayama,...

Focus here on structure (symmetry):

Paradigm: discrete non-Abelian family symmetry

(e.g. some subgroup of SO(3) or SU(3), broken to some appropriate coset space)

One issue/challenge: many theoretical starting points

Role of Small (Cabibbo-sized) Corrections

Quark sector:

$$\mathcal{U}_{\mathrm{CKM}} \sim 1 + O(\lambda_C)$$

Cabibbo angle λ_C (or some power) as a flavor expansion parameter

Lepton sector:

$$\mathcal{U}_{\mathrm{MNSP}} \sim \mathcal{W} + O(\lambda')$$

$(\theta_{12}^0, \theta_{13}^0, \theta_{23}^0)$ **perturbations**

choice of "bare" mixing angles

Unification paradigm (broad sense): useful to take

$$\lambda' = \lambda_C$$

ideas of **quark-lepton complementarity** and **"Cabibbo haze"**

Raidal '04, Minakata+Smirnov, many others...
("haze" terminology from Datta, L.E., Ramond '05)

Long before measurement, conjecture that θ_{13} is a Cabibbo effect

$$\theta_{13} \sim \frac{\lambda_C}{\sqrt{2}} \sim \lambda_C \cos\theta_{23}^0$$

Ramond, others...

(general idea often called "charged lepton corrections") $\mathcal{U}_{\rm MNSP} \sim \mathcal{U}_{\rm CKM}^\dagger \mathcal{W}$

good fit to data, but nontrivial to implement...

one reason: now $\sim \lambda_C$ corrections floating around

The Flavor Puzzle in the νSM

Pre-Reactor Meas. most models: $\theta^0_{23} = 45^\circ$ $\theta^0_{13} = 0^\circ$

Choices for "bare" solar angle θ^0_{12}:

(i) within $\sim \lambda_C^2$ of exp:

tri-bimaximal mixing $\tan\theta^0_{12} = \frac{1}{\sqrt{2}}$ $\theta^0_{12} = 35.26^\circ$

"the beautiful matrix
with the ugly name"

Harrison, Perkins, Scott
(100s of papers…some key players
here at this meeting!)

others, such as golden ratio mixing $\phi = (1+\sqrt{5})/2$

$\tan\theta_{12} = \phi^{-1}$ $\theta_{12} = 31.72^\circ$ or $\cos\theta_{12} = \frac{\phi}{2}$ $\theta_{12} = 36^\circ$

Ramond; Kajiyama et al.;
LE+Stuart (+Ding); Feruglio et al.,...

Rodejohann et al.,...

(ii) within $\sim \lambda_C$ of exp: QLC idea of Raidal, Minakata/Smirnov,…

bimaximal mixing $\tan\theta^0_{12} = 1$

“Top-down” approach: detailed model-building

example: tri-bimaximal (TBM/HPS) mixing

$$\mathcal{U}_{\mathrm{MNSP}}^{(\mathrm{HPS})} = \begin{pmatrix} \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

(~Clebsch-Gordan coeffs!)

Meshkov; Zee,...

Obtained w/in many discrete non-Abelian subgroups of $SO(3),\, SU(3)$

$$\mathcal{G}_F = \mathcal{A}_4,\, \mathcal{S}_4,\, \mathcal{T}',\, \Delta(3n^2),\, \ldots$$

Many papers!!
many key players…

(note: details encoded in rather complicated flavon sector)

“Bottom-up” approach: residual symmetries

$$\mathcal{G}_F \longrightarrow \mathcal{G}_e \times \mathcal{G}_\nu$$

Lam; Ding et al.,…

pure group theory argument: e.g. “minimal” group S_4 **for TBM**

Post-Reactor Meas.

"Top-down" approach:

(1) Keep $\theta^0_{23} = 45^\circ \quad \theta^0_{13} = 0^\circ$

(i) within $\sim \lambda_C^2$ of exp: need to control corrections

TBM (or other mixing scenarios) as leading order framework

many papers...

(ii) within $\sim \lambda_C$ of exp: resurgence?

(2) Modify $\theta^0_{23} = 45^\circ \quad \theta^0_{13} = 0^\circ$

θ_{13} numerology? drop maximal θ_{23}?

"Bottom-up" approach:

larger groups? implications for CP violation?

Holthausen et al., King et al., Hagedorn et al., many others,...

CP Violation

Model-building: spontaneous v. explicit CP violation

Generalized CP transformations:

CP tmns as automorphisms Grimus, Rebelo '90's

for discrete groups: Holthausen et al., Chen et al.,…

family symmetry: $\phi \to \rho(g)\phi$

generalized CP: $\phi \to U\phi^*$ (not $\phi \to \phi^*$)

consistency condition $\longrightarrow$ $U\rho(g)^*U^{-1} = \rho(g')$

Moral: CP and family symmetries can be inextricably intertwined

Lots of recent work along these lines… see e.g. Ding et al.; Girardi et al.; L.E., Garon, Stuart; many others…

eV-scale Sterile Neutrinos?

If eV-scale sterile ν present, many implications:

mass hierarchies? $0\nu\beta\beta$ **GUT connections?**

mixing pattern and residual symmetries? CP?

example: $n_s = 1$ $\theta_{14} \sim \theta_{13}$ **same origin?**

Back to the drawing board!!

Conclusions and Outlook

The SM flavor puzzle is a difficult but intriguing problem —
we're just beginning to scratch its surface!

Most important question: Majorana or Dirac neutrinos?

New insights/approaches from the lepton data

Naturalness/testability tradeoff

Precision measurements/NP needed to distinguish models

Lots of ideas, lots of room for more

Stay tuned!