Neutrinos Physics: Theory

Lisa L. Everett
U. Wisconsin, Madison

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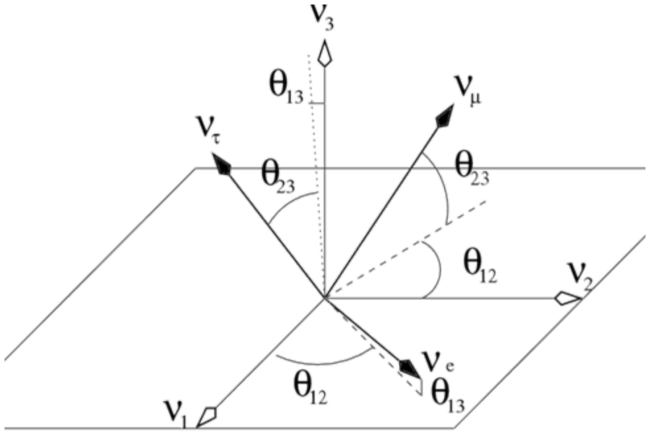
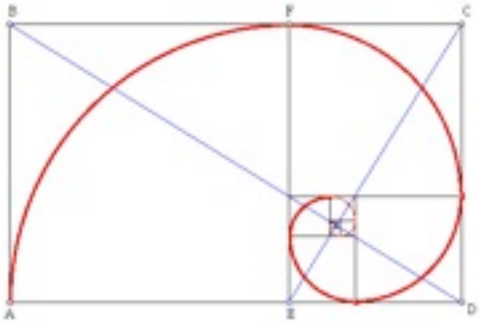
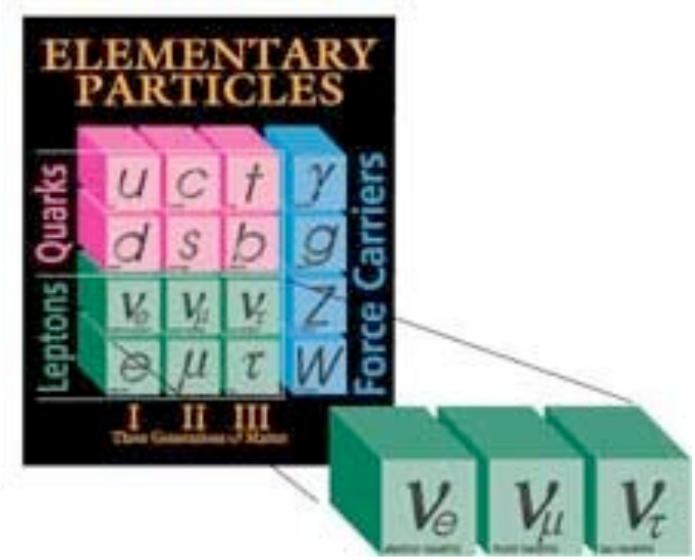




Main Theme



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!

“Reference Picture”:

data (except LSND) consistent with 3ν mixing picture

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

Challenges to the Reference Picture

LSND, Recent results from MINOS, MiniBooNE, reactor neutrino anomaly

differences b/w $\nu, \overline{\nu}$ modes! suggestions of sterile neutrinos, NSI’s,...

If robust, potentially profound implications...

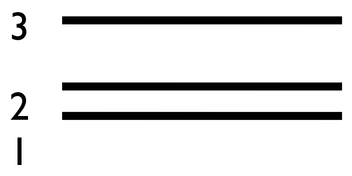
The Reference Picture: Neutrino Masses+ Mixings

Assume: 3 neutrino mixing

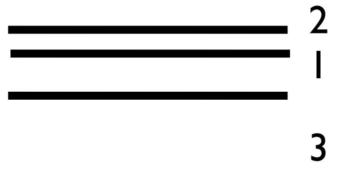
fits: Schwetz, Tortola, Valle 1103.0734

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2 \theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2 \theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2 \theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

Normal Hierarchy (upper line)



Inverted Hierarchy (lower line)



Cosmology (WMAP): $\sum_i m_i < 0.7\,\mathrm{eV}$

The Reference Picture: Lepton Mixing

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

Pontecorvo
Maki, Nakagawa,
Sakata

"Dirac" phase

"Majorana" phases

Rewriting...

Solar: $\theta_{12} = 34.0^\circ \pm 1.0$

Atmospheric: $\theta_{23} = 45.6^\circ \pm 3.5$

Reactor: $\theta_{13} = 5.7^{\circ}{}^{+2.2}_{-2.1}$

2 large

1 small

No constraints on CP violation

Hints for nonzero θ_{13} !

~2008: slight tension noted b/w datasets in global fits Fogli et al,...

June 2011: new results for $\nu_\mu \to \nu_e$

T2K $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ (90% c.l.) 1108.2822

disfavor zero reactor angle at 2.5σ

MINOS disfavor zero reactor angle at 1.7σ

updated global fit: claims evidence now at $> 3\sigma$ Fogli et al., '11,...

For Comparison: Quark Mixing

Cabibbo; Kobayashi, Maskawa

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

Cabibbo angle θ_c

Mixings:

$$\left.\begin{aligned} \theta_{12}^{\mathrm{CKM}} &= 13.0^\circ \pm 0.1^\circ \\ \theta_{23}^{\mathrm{CKM}} &= 2.4^\circ \pm 0.1^\circ \\ \theta_{13}^{\mathrm{CKM}} &= 0.2^\circ \pm 0.1^\circ \end{aligned}\right\}$$

3 small angles

CP violation:

$$J \equiv \mathrm{Im}(\mathcal{U}_{\alpha i}\mathcal{U}_{\beta j}\mathcal{U}_{\beta i}^{*}\mathcal{U}_{\alpha j}^{*})$$

Jarlskog; Dunietz, Greenberg, Wu

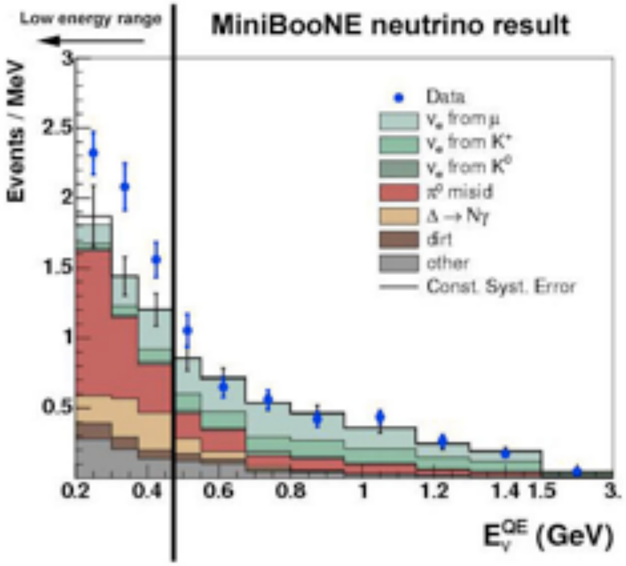
$$J_{\mathrm{CP}}^{(\mathrm{CKM})} \simeq \sin 2\theta_{12}^{\mathrm{CKM}} \sin 2\theta_{23}^{\mathrm{CKM}} \sin 2\theta_{13}^{\mathrm{CKM}} \sin \delta_{\mathrm{CKM}}$$

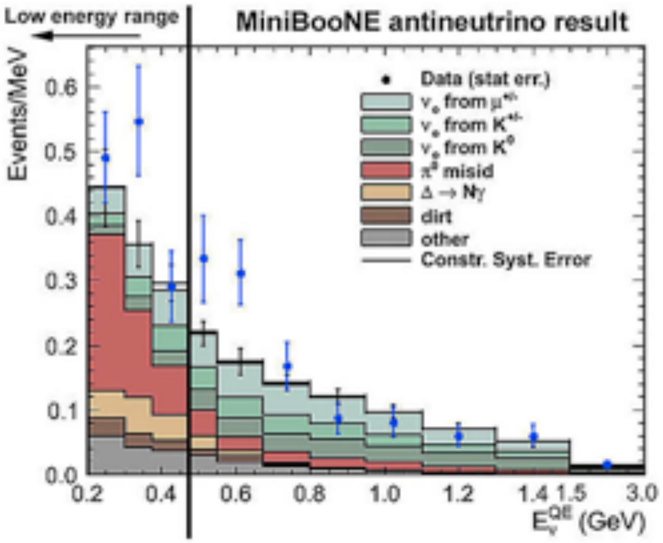
$$J \sim 10^{-5} \qquad \delta_{\mathrm{CKM}} = 60^\circ \pm 14^\circ$$

O(1) CP-violating phase

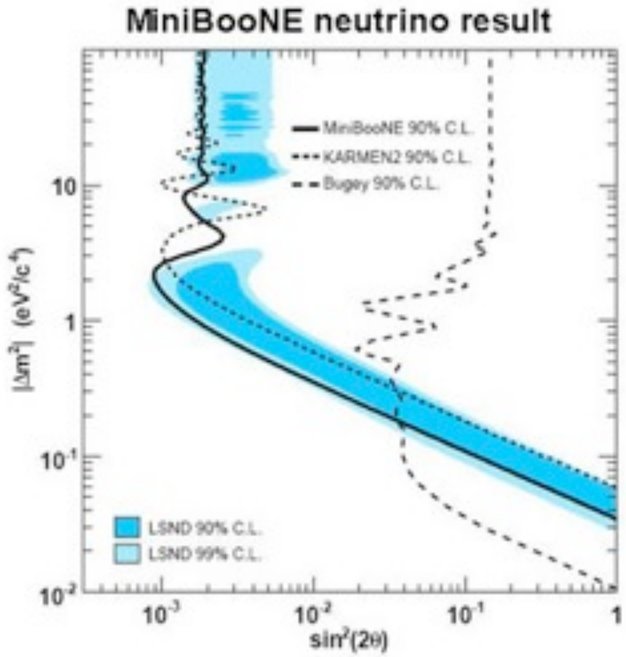
Challenge to the Reference Picture: MiniBooNE

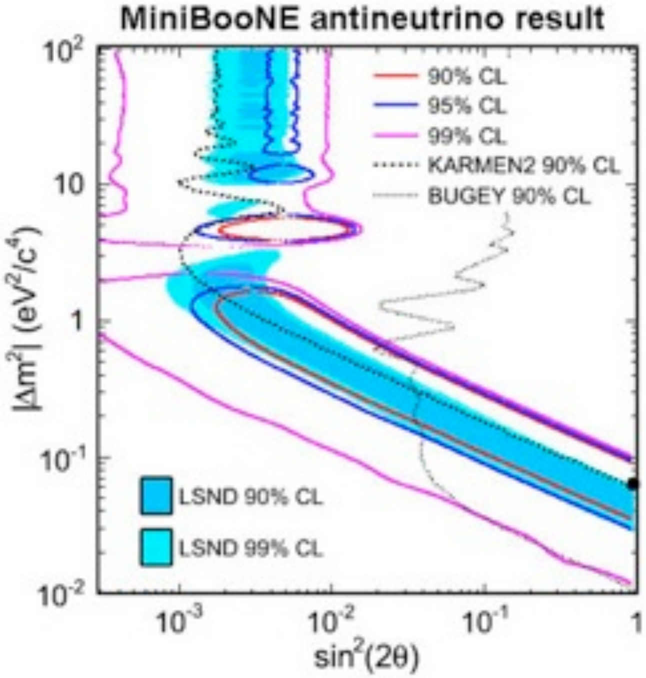
1007.1150


MiniBooNE neutrino result


MiniBooNE antineutrino result

(exclusion region)

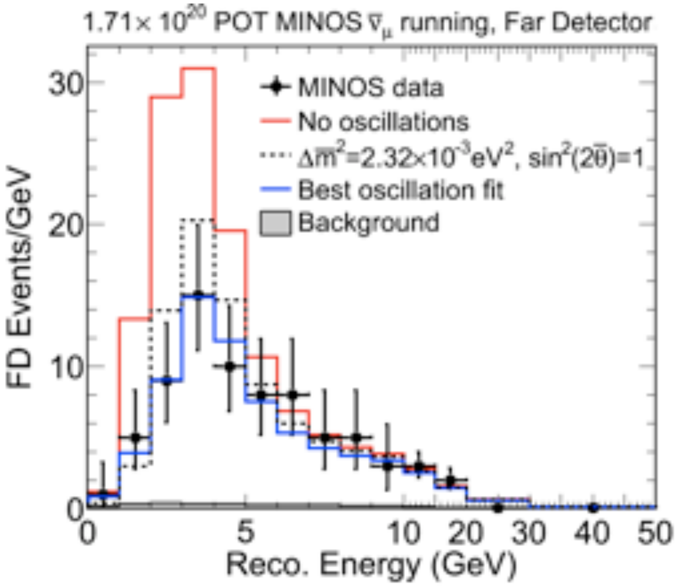

MiniBooNE neutrino result

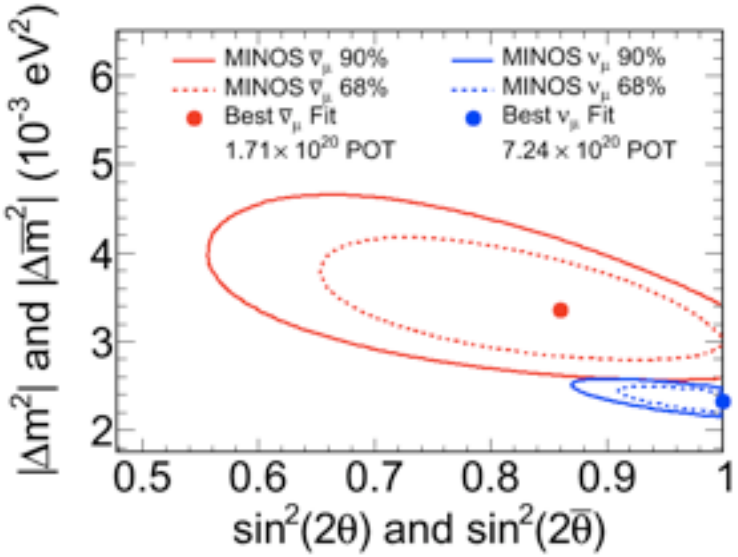

MiniBooNE antineutrino result

(MiniBooNE allowed regions)

Challenge to the Reference Picture: MINOS

1104.0344





$$\Delta m^2_{32} = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} > 0.91$$

90% c.l.

$$\Delta \overline{m}^2_{32} = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\overline{\theta}_{23} = 0.86 \pm 0.11$$

Challenge to the Reference Picture: reactor ν anomaly

recent improvement to calculation of reactor $\overline{\nu}_e$ flux

new prediction is 3% higher

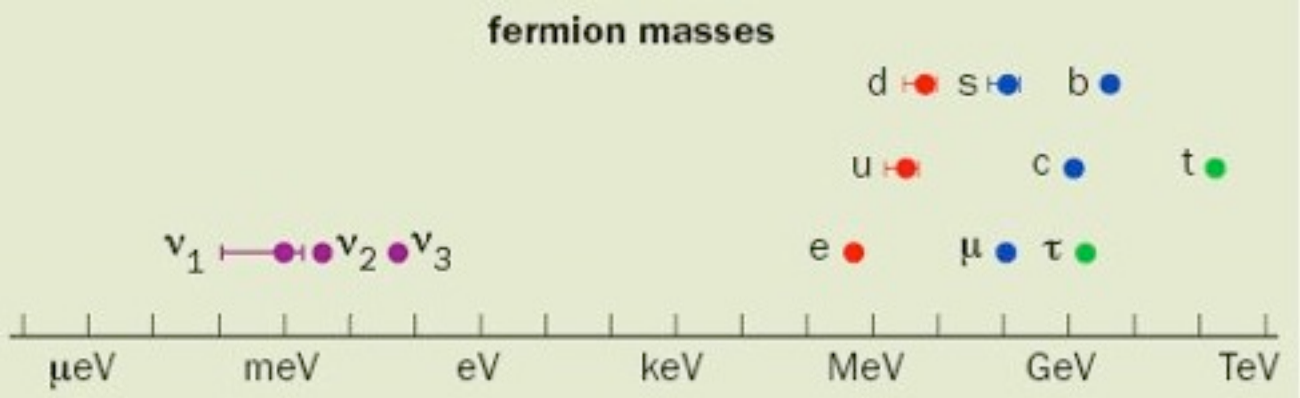
Mueller et al., 1101.2663

deficit of $\overline{\nu}_e$ at all oscillation searches at reactors!

Theoretical Implications: Reference Picture

Shifts in the paradigm for addressing SM flavor puzzle:

- Suppression of neutrino mass scale



- Mixing Angles quarks small, leptons 2 large, 1 small

Strikingly different flavor patterns for quarks and leptons!

implications for quark-lepton unification?

Mass Generation

Quarks, Charged Leptons

"natural" mass scale tied to electroweak scale

Dirac mass terms, parametrized by Yukawa couplings

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

t quark: O(1) Yukawa coupling

rest: suppression (flavor symmetry)

Neutrinos

beyond physics of Yukawa couplings!

Options: Dirac

or Majorana

Majorana first:

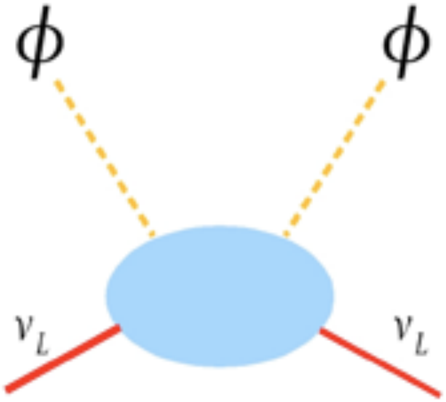
advantages: naturalness, leptogenesis, $0\nu\beta\beta$

SM at NR level: Weinberg dim 5 operator

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

(if $\lambda \sim O(1)$ $\Lambda \gg m \sim O(100\,\mathrm{GeV})$ ... but a priori unknown)

Underlying mechanism: examples



Type I seesaw ν_R (fermion singlet)

Type II seesaw Δ (scalar triplet)

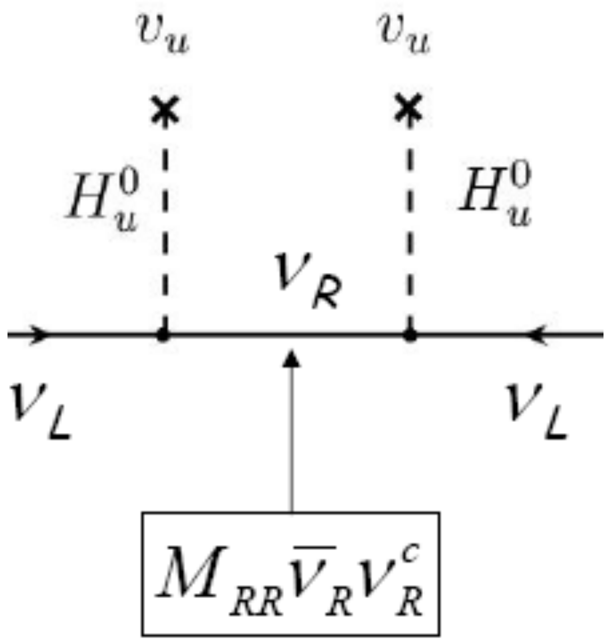
Type III seesaw Σ (fermion triplet)

+ variations

Prototype: Type I seesaw

Minkowski; Yanagida;
Gell-Mann, Ramond, Slansky;...

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, may be visible at LHC

see e.g. Fileviez Perez, Han et al., '08

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?

more difficult in general,
but suppression mechanisms exist.

e.g. large/warped 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. Everyone has a favorite scenario.

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

Leptons: Observed 2 large, 1 small pattern in $\mathcal{U}_{\rm MNSP} = \mathcal{U}_e \mathcal{U}_\nu^\dagger$ most intriguing possibility (for 3-family mixing)

Handwave a bit: in diagonal charged lepton basis

3 small angles ⟶ $\sim$ diagonal $\mathcal{M}_\nu$ (easy)

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

3 large angles ⟶ "anarchical" $\mathcal{M}_\nu$ (easy)

2 large, 1 small ⟶ fine-tuning, non-Abelian (harder)

Also suggests new focus: discrete (non-Abelian) family symmetries

good for lepton sector, not obviously ideal for quarks...

Proceed by noting that in some limit of flavor symmetry:

$$\mathcal{U}_{\mathrm{MNSP}} = \mathcal{U}_e \mathcal{U}_\nu^\dagger \sim \underset{\uparrow}{\mathcal{W}} + \underset{\uparrow}{\mathcal{O}(\lambda')}$$

"bare" mixing angles $(\theta_{12}^0, \theta_{13}^0, \theta_{23}^0)$ perturbation

Main theme: many theoretical starting points!

Perturbations: useful (and well-motivated in many scenarios) to take

$$\lambda' = \lambda \equiv \sin\theta_c$$

ideas of "Cabibbo haze" and quark-lepton complementarity (more shortly)

Datta, Everett, Ramond '05

Raidal '04, Minakata+Smirnov '04,
many, many others...

within the framework of quark-lepton unification,
Cabibbo-sized effects can "leak" into lepton sector

So in the lepton sector, classify models by $\mathcal{W}(\theta_{12}^0, \theta_{13}^0, \theta_{23}^0)$

Choose: $\theta_{23}^0 = 45^\circ$ $\theta_{13}^0 = 0^\circ$ (reasonable*)

Choices for "bare" solar angle θ_{12}^0 (historical ordering)

"bimaximal" mixing

requires large perturbations

$\theta_{12} = \theta_{12}^0 + \mathcal{O}(\lambda)$

"tri-bimaximal" mixing

exact, or are there corrections?

$$\left.\begin{array}{r}\text{"hexagonal" mixing}\\ \text{"golden ratio" mixing}\end{array}\right\}$$

need moderate perturbations

$\theta_{12} = \theta_{12}^0 + \mathcal{O}(\lambda^2)$

All obtainable from discrete non-Abelian family symmetries

Recent overview: Albright, Dueck, Rodejohann 1004.2798 (ADR)

Further enumeration of schemes: Rodejohann, Zhang, Zhou '11

*question: how will perturbations affect reactor angle θ_{13}

The dominant paradigm:

Tri-bimaximal (HPS) Mixing

Harrison, Perkins, Scott ’02

“bare” solar angle $\tan\theta^0_{12} = \frac{1}{\sqrt{2}}$ $\theta^0_{12} = 35.26^\circ$

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

(~Clebsch-Gordan coeffs!)

Meshkov; Zee,...

Readily obtained within many discrete subgroups of $SO(3),\ SU(3)$

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

↑

wins popularity contest

(100s of papers. Some key players: Ma, Altarelli and Feruglio, King, and many, many, many others

why? HPS via further breakdown to (simple) coset space

Bimaximal Mixing

"bare" solar angle $\theta_{12}^{0} = 45^\circ$ $\tan\theta_{12}^{0} = 1$

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

$$\theta_{12} = \theta_{12}^{0} + \mathcal{O}(\lambda) \sim \frac{\pi}{4} - \theta_c$$

"quark-lepton complementarity"

Raidal; Minakata, Smirnov; Frampton, Mohapatra; Xing; Ferrandis, Pakvasa; King; Ramond; Rodejohann, many, many others...

Also obtainable in discrete non-Abelian family symmetry framework.

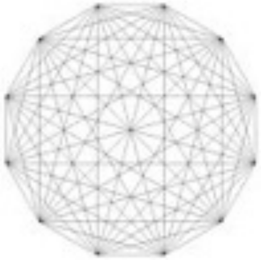
Large perturbations good for larger reactor angle (T2K hint)?

Recent resurgence in literature. Predict it will continue!!

Other intriguing schemes

Hexagonal Mixing:

"bare" solar angle $\tan\theta_{12}^0 = \frac{1}{\sqrt{3}}$ $\theta_{12}^0 = \pi/6$



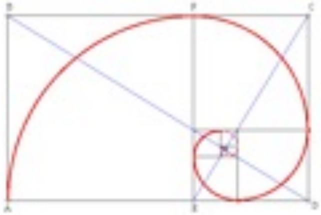
$$\mathcal{U}_{\rm MNSP}^{\rm (HM)} = \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

dihedral symmetry

$\mathcal{D}_{12}$ $\mathcal{D}_6$ ADR '10

Golden Ratio Mixing: 2 cases

$\phi = (1+\sqrt{5})/2$



GR1. "bare" solar angle $\tan\theta_{12} = \phi^{-1}$ $\theta_{12} = 31.72^\circ$

GR2. "bare" solar angle $\cos\theta_{12} = \frac{\phi}{2}$ $\theta_{12} = 36^\circ$

$$\mathcal{U}_{\rm MNSP}^{\rm (GR1)} = \begin{pmatrix} \sqrt{\frac{\phi}{\sqrt{5}}} & -\sqrt{\frac{1}{\sqrt{5}\phi}} & 0 \\ \frac{1}{\sqrt{2}}\sqrt{\frac{1}{\sqrt{5}\phi}} & \frac{1}{\sqrt{2}}\sqrt{\frac{\phi}{\sqrt{5}}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}}\sqrt{\frac{1}{\sqrt{5}\phi}} & \frac{1}{\sqrt{2}}\sqrt{\frac{\phi}{\sqrt{5}}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{U}_{\rm MNSP}^{\rm (GR2)} = \begin{pmatrix} \frac{\phi}{2} & -\frac{1}{2}\sqrt{\frac{\sqrt{5}}{\phi}} & 0 \\ \frac{1}{2}\sqrt{\frac{5}{2\phi}} & \frac{\phi}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2}\sqrt{\frac{5}{2\phi}} & \frac{\phi}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

GR1: Datta, Ling, Ramond '05; Kajiyama, Raidal, Strumia '07; Everett, Stuart '08, '11; Feruglio '11

GR2: Adulpravitchai, Blum, Rodejohann '09

Beyond the Reference Picture

Question: theoretical implications of distinct oscillation patterns for ν, $\overline{\nu}$?

Ideas proposed in previous contexts (e.g. LSND):

CPT violation (CPTV) Lorentz violation (LV)	Murayama, Yanagida '00 Barenboim et al. '01, Skaudhage '01, Bilenky et al., '01, Barger et al. '03, Kostelecky et al '03, Jacobson, Ohlsson '03,...
effective CPTV via enhanced matter effects due to nonstandard interactions/sterile neutrinos	Nelson, Walsh '07,...
effective LV (extra dimensions)	Pas, Pakvasa, Weiler '05
(decaying) sterile neutrino	Palomares-Ruiz, Pascoli, Schwetz '05
quantum decoherence	Farzan, Schwetz, Smirnov '08,...
...	

Beyond the Reference Picture:
CPT no longer a fundamental symmetry

CPTV ⟶ Lorentz Violation

much attention paid recently to this exciting possibility

e.g. MiniBooNe 1008.0906, Diaz, Kostelecky 1012.5985,
many others, lots of press/blog attention,...

Challenge: confining LV to neutrino sector

example: braneworld w/ bulk neutrinos + ghost condensation

Mukohyama, Park 1009.1251

question: theoretical motivation?

Beyond the Reference Picture: Effective CPTV

Non-Standard Interactions (NSI) w/ or w/o Sterile ν

Recent overview of NSIs w/o sterile neutrinos:

Kopp, Machado, Parke 1009.0014

Bottom line: can accommodate data, but some tension

NSI interactions must be ~electroweak

must avoid charged lepton NSI's (affects theory embedding)

Sterile neutrinos in eV rangle plus NSI's:

1+3 scheme +NSI — Akhmedov and Schwetz 1007.4171

2+3 scheme favored — Kopp, Maltoni, Schwetz 1103.4570

Can address new reactor neutrino anomaly. challenge for BBN?

New long-range forces as source of NSI's

Class of models with a new ultralight Abelian gauge boson

that is very weakly coupled (fifth force constraints)

sign of matter effect differs for $\nu, \bar{\nu}$

Joshipura, Mantry '03,
Nelson, Walsh '07
Pospelov '08,...

gauged symmetry: several examples

$B - L$ + eV-scale sterile ν

Englehardt, Nelson,
Walsh 1002.4452

$$L_\mu - L_\tau$$

Joshipura, Mohanty '03, ...,
Heeck, Rodejohann
1007.2655

$$B - L_e - 2L_\tau$$

Davoudiasl, Lee, Marciano
1102.5352

gauge boson extremely light and weakly coupled, e.g. for last 2

$$\alpha \sim 10^{-50} \qquad M_{Z'} \sim 10^{-18}\,\mathrm{eV}$$

motivation? tension with atmospheric ν

Theoretical Implications of eV-scale Sterile Neutrinos

suggested by LSND, MiniBooNE, reactor neutrino anomaly

n_s sterile neutrinos: $3(n_s+1)$ mixing angles

$2n_s+1$ Dirac phases

n_s+2 Majorana phases

see e.g. Barry, Rodejohann, Zhang 1105.3911

Global fits:

$n_s=1$ "2+2" strongly disfavored, "3+1" tension w/cosmology (3 at eV scale)

1+3 (1 at eV scale) better, but no possibility of CP violation in SBL

$n_s=2$ "3+2" tension w/cosmology (3 at eV scale), "2+3," "1+3+1" better

allows for CPV in SBL experiments

Kopp, Maltoni, Schwetz '11
Giunti et al. '11

Implications:

even 1 eV-scale sterile neutrino can have important impact on $0\nu\beta\beta$

can be implemented within Type I seesaw framework

relatively straightforward to incorporate in non-Abelian flavor models

Barry, Rodejohann, Zhang '11

Conclusions

Neutrino data has taken beyond SM physics theory on a wild ride, with no signs of stopping (may even get wilder!)

Bottom Line:

A number of ways to generate masses/mixings, all with advantages/disadvantages. “Favorites” are not the only options.

Improved data (esp. reactor angle) will greatly aid these efforts!

Challenges have emerged to the reference picture, suggesting new (and perhaps quite exotic) physics. Only hints now, but potentially very exciting if the hints remain w/ more data. New ideas needed!

Stay tuned!