Theory Predictions for Neutrino Oscillations

Mu-Chun Chen, University of California - Irvine

WIN 09, Relais San Clemente, Italy, September 14-19, 2009

Neutrino Mass beyond the SM

- SM: effective low energy theory with non-renormalizable terms
- new physics effects suppressed by powers of small parameter $\frac{M_W}{M}$
- neutrino masses generated by dim-5 operators

$$\frac{\lambda_{ij}}{M} H H L_i L_j \quad \Rightarrow \quad m_\nu = \lambda_{ij} \frac{v^2}{M}$$

λ_{ij} are dimensionless couplings; M is some high scale

- m_ν small: non-renormalizable terms (M is high)

lowest higher dimensional operator that probes high scale physics

- total lepton number and family lepton numbers broken
  - ➡ lepton mixing and CP violation expected
  - ➡ $\mu \to e \gamma$; $\tau \to \mu \gamma$; $\tau \to e \gamma$ decays ; μ - e conversion

Tri-bimaximal Neutrino Mixing

Schwetz, Tortola, Valle (Aug 2008)

- Neutrino Oscillation Parameters (2σ)

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

$$\sin^2\theta_{23} = 0.5^{+0.14}_{-0.12}, \qquad \sin^2\theta_{12} = 0.304^{+0.044}_{-0.032}$$

- indication for non-zero θ_{13}:

Bari group, June 2008

$$\sin^2\theta_{13} = 0.01^{+0.016}_{-0.011}\ (1\sigma)$$

consistent with $\theta_{13} = 0$

- Tri-bimaximal neutrino mixing:

Harrison, Perkins, Scott, 1999

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

$$\sin^2\theta_{\text{atm, TBM}} = 1/2 \qquad \sin\theta_{13,\text{TBM}} = 0.$$

$$\sin^2\theta_{\odot,\text{TBM}} = 1/3 \qquad \tan^2\theta_{\odot,\text{TBM}} = 1/2$$

$$\tan^2\theta_{\odot,\text{exp}} = 0.429$$

new KamLAND result: $\tan\theta^2_{\odot,exp} = 0.47^{+0.06}_{-0.05}$

Neutrino Mass Spectrum

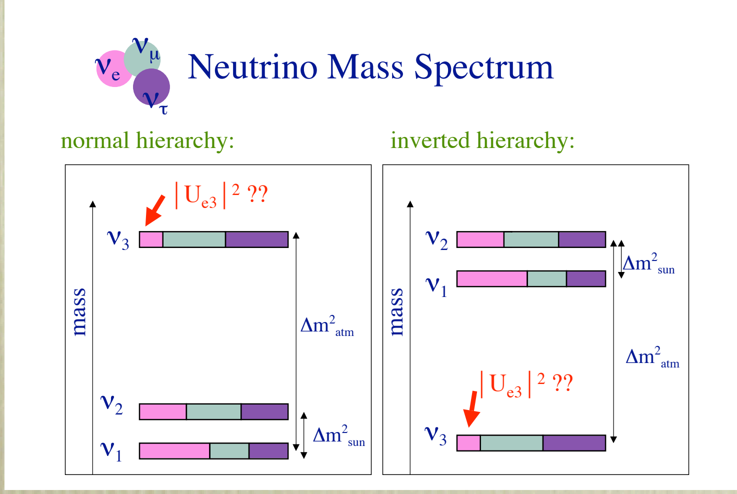
- search for absolute mass scale:
  - end point kinematic of tritium beta decays:

$$\text{Tritium} \rightarrow He^3 + e^- + \overline{\nu}_e$$

Mainz: $m_\nu < 2.2$ eV
KATRIN: increase sensitivity ~ 0.2 eV

  - WMAP + 2dFRGS + Lyα: $\sum(m_{\nu_i}) < (0.7\text{-}1.2)$ eV
  - neutrinoless double beta decay

current bound: $|<m>| < (0.19 - 0.68)$ eV (CUORICINO, Feb 2008)



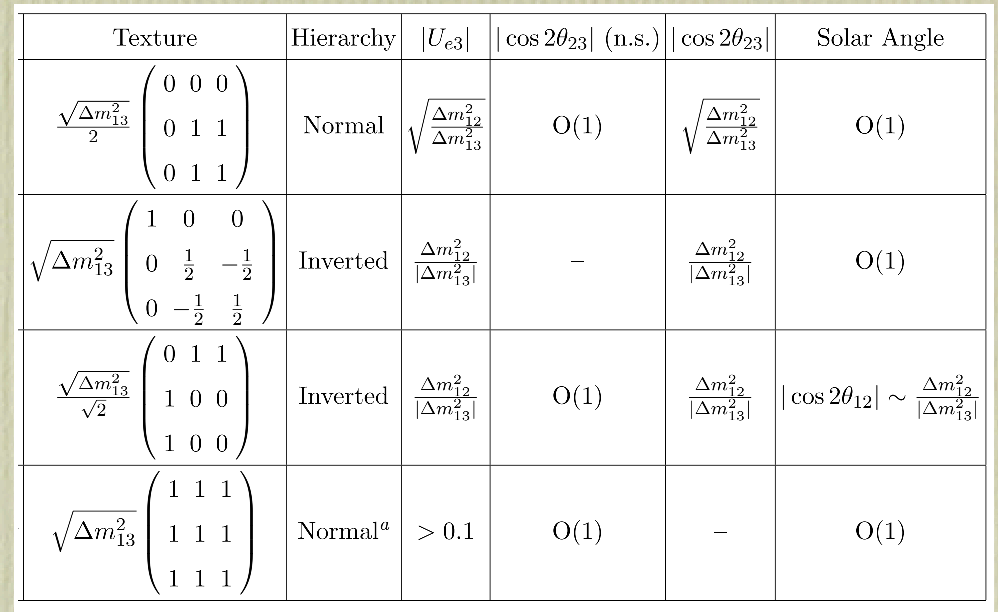
The known unknowns:

- How small is θ_{13}?
- $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?
- Neutrino mass hierarchy (Δm_{13}^2) ?
- CP violation in neutrino oscillations?

Need for Precision Measurements

- current data post two challenges:
  - why $m_\nu << m_{u,d,l}$
  - why lepton mixing large while quark mixing small
- To answer the first question => Seesaw mechanism: most appealing scenario
- Seesaw: not sufficient to explain the whole mass matrix with mass hierarchy and two large and one small mixing angles
  - ✳ flavor symmetry: there is a structure
    - Possible symmetries show up only in the lepton sector
    - Connection between quark and lepton sectors (GUT symmetry)
- These scenarios have drastically different predictions
- To tell these models apart: Precision measurements important

possible textures:



Texture	Hierarchy	$\lvert U_{e3}\rvert$	$\lvert\cos 2\theta_{23}\rvert$ (n.s.)	$\lvert\cos 2\theta_{23}\rvert$	Solar Angle
$\frac{\sqrt{\Delta m^2_{13}}}{2}\begin{pmatrix}0&0&0\\0&1&1\\0&1&1\end{pmatrix}$	Normal	$\sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$	O(1)	$\sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$	O(1)
$\sqrt{\Delta m^2_{13}}\begin{pmatrix}1&0&0\\0&\frac{1}{2}&-\frac{1}{2}\\0&-\frac{1}{2}&\frac{1}{2}\end{pmatrix}$	Inverted	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	–	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	O(1)
$\frac{\sqrt{\Delta m^2_{13}}}{\sqrt{2}}\begin{pmatrix}0&1&1\\1&0&0\\1&0&0\end{pmatrix}$	Inverted	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	O(1)	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	$\lvert\cos 2\theta_{12}\rvert \sim \frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$
$\sqrt{\Delta m^2_{13}}\begin{pmatrix}1&1&1\\1&1&1\\1&1&1\end{pmatrix}$	Normal^a	> 0.1	O(1)	–	O(1)

Altarelli, Feruglio, Masina, 02; Hall, Murayama, Weiner; Sato, Yanagida; Barbieri et al; ...

leptonic family symmetry:

Symmetry breaking	θ_{13}	$\theta_{23} - \pi/4$
none	0	0
μ-τ sector only	$\sim \Delta m^2_{12} / \Delta m^2_{31}$	$\leq 8^o$
e-sector only	$\sim \sqrt{\Delta m^2_{12} / \Delta m^2_{31}}$	$\leq 4^o$
dynamical	$\sim \sqrt{\Delta m^2_{12} / \Delta m^2_{31}}$	large

R. N. Mohapatra ('04)

$\sim \sqrt{\Delta m^2_{12}/\Delta m^2_{31}}$

$\sim \Delta m^2_{12}/\Delta m^2_{31}$

SO(10) GUT

- RH neutrino accommodated in the model

$$16 = \bar{5} + 10 + \underset{\swarrow \; \nu_R}{\textcircled{1}}$$

$$16 = (3, 2, 1/6) \sim \begin{bmatrix} u & u & u \\ d & d & d \end{bmatrix}$$

$$+ (3^*, 1, -2/3) \sim (u^c \;\; u^c \;\; u^c)$$

$$+ (3^*, 1, 1/3) \sim (d^c \;\; d^c \;\; d^c)$$

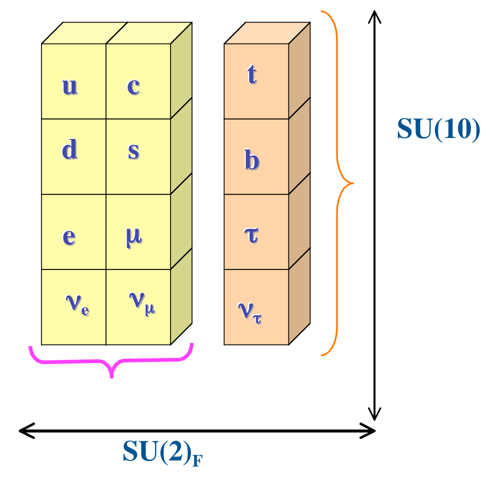
$$+ (1, 2, -1/2) \sim \begin{bmatrix} \nu \\ e \end{bmatrix}$$

$$+ (1, 1, 1) \sim e^c$$

$$+ (1, 1, 0) \sim \nu^c$$

- Natural for seesaw: offer both ingredients, i.e. RH neutrino & heavy scale neutrino oscillation strongly support SO(10)!!
- Quark & Leptons reside in the same GUT multiplets
- One set of Yukawa coupling for a given GUT multiplet
  - ➡ SO(10) relates quarks and leptons (intra-family relations)
  - ➡ reduce # of parameters in Yukawa sector

Models Based on SUSY SO(10)



- large neutrino mixing from neutrino sector

$$U_{MNS} = U_{e,L}^{+} U_{\nu,L}$$

SO(10) GUT + SU(2) family symmetry

Barbieri, Hall, Raby, Romanino; ...

$SO(10) \to SU(4) \times SU(2)_L \times SU(2)_R$
$\to SU(3) \times SU(2)_L \times U(1)_Y$

- symmetric mass matrices: M.-C.C & K.T. Mahanthappa

Up-type quarks ⇔ Dirac neutrinos

Down-type quarks ⇔ charged leptons

$$\text{seesaw} \quad \Rightarrow \quad M_\nu \sim \begin{pmatrix} 0 & 0 & * \\ 0 & 1 & 1 \\ * & 1 & 1 \end{pmatrix}$$

12 parameters accommodate 22 fermion masses, mixing angles and CP phases in both quark and lepton sectors

- prediction for θ_{13}:

$$\sin\theta_{13} \sim \left(\frac{\Delta m^2_{sun}}{\Delta m^2_{atm}}\right)^{1/2} \sim O(0.1) \Rightarrow \text{LMA}$$

continuous family symmetries: to get bi-maximal (TBM) ⇒

specific values for parameters (couplings)

Tri-bimaximal Neutrino Mixing

- Neutrino mass matrices:

$$M = \begin{pmatrix} A & B & B \\ B & C & D \\ B & D & C \end{pmatrix} \longrightarrow \quad \sin^2 2\theta_{23} = 1 \qquad \theta_{13} = 0$$

solar mixing angle NOT fixed

  - S3 Mohapatra, Nasri, Yu, 2006; ...
  - D4 Grimus, Lavoura, 2003; ...
  - μ-τ symmetry Fukuyama, Nishiura, '97; Mohapatra, Nussinov, '99; Ma, Raidal, '01; ...

- if A+B = C + D $\longrightarrow \quad \tan^2\theta_{12} = 1/2$ TBM pattern

  - A4 Ma, '04; Altarelli, Feruglio, '06; .....
  - Z3 × Z7 Luhn, Nasri, Ramond, 2007

[Other discrete groups: Hagedorn, Lindner, Plentinger; Chen, Frigerio, Ma; and many others...]

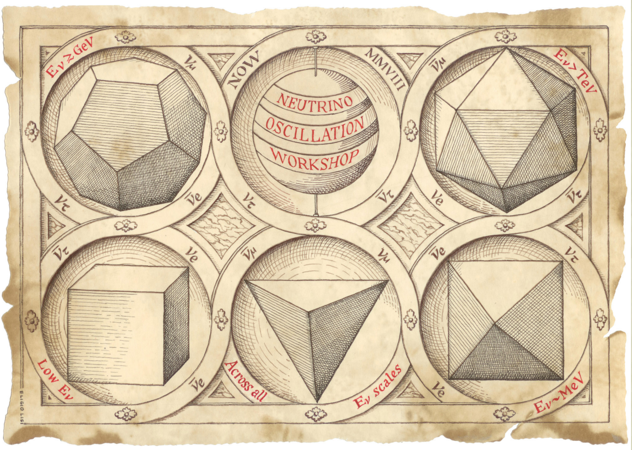
recent claim: S4 unique group for TBM [C.S. Lam, 2008]

Perfect Geometric Solids & Family Symmetries

solid	faces	vert.	Plato	Hindu	sym.
tetrahedron	4	4	fire	Agni	A_4
octahedron	8	6	air	Vayu	S_4
cube	6	8	earth	Prithvi	S_4
icosahedron	20	12	water	Jal	A_5
dodecahedron	12	20	quintessence	Akasha	A_5

From E. Ma, talk at WHEPP-9, Bangalore

A5



A5

आकाश

S4

S4

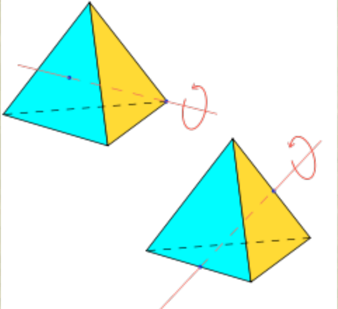
A4

Non-abelian Finite Family Symmetry

- TBM mixing matrix: can be realized in finite group family symmetry based on A4 Ma & Rajasekaran, '01
- even permutations of 4 objects

  S: (1234) → (4321)

  T: (1234) → (2314)



- invariance group of Tetrahedron
- orbifold compactification:

  6D → 4D on T2/Z2

Altarelli, Feruglio, '06

- Deficiencies:
  - does NOT give rise to CKM mixing: $V_{ckm} = 1$
  - does NOT explain mass hierarchy
  - all CG coefficients real

The Double Tetrahedral T′ Symmetry

- consider double covering of A_4
- Classified as a candidate family symmetry that can arise from Type-II B String theories

Frampton, Kaphart, 1995, 2001

- can account for quark sector:

Carr, Frampton, '07; Feruglio, Hedgedorn, Lin, Merlo, '07

exist in A_4: $1,\ 1',\ 1'',\ 3$ ⟶ TBM for neutrinos

not in A_4: $2,\ 2',\ 2''$ ⟶ 2 +1 assignments for quarks

- Combined with GUT: T′ x SU(5) GUT

M.-C.C & K.T. Mahanthappa
Phys. Lett. B652, 34 (2007)

  - only 9 operators allowed: highly predictive model
  - all 22 masses, mixing angles (CKM & MNS) and CPV measures are "accommodated"
    - lepton mixing
    - CPV in quark and lepton sectors

$\Big\}$ CG coefficients of T′ & SU(5)
⇒ pure geometrical in origin!

✳ In RS warped extra dimension: prevent tree-level FCNCs in both quark and lepton sectors

M.-C.C, K.T. Mahanthappa, F.Yu, arXiv:0907.3963

Group Theory of T′

- generators:

$$S^2 = R,\ T^3 = 1,\ (ST)^3 = 1,\ R^2 = 1$$

R=1: 1, 1′, 1″, 3 (vector)
R= -1: 2, 2′, 2″ (spinorial)

- generators: in 3-dim representations, T-diagonal basis

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2\omega & 2\omega^2 \\ 2\omega^2 & -1 & 2\omega \\ 2\omega & 2\omega^2 & -1 \end{pmatrix} \qquad T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix}$$

★ complex CG coefficients in T′

complexity cannot be avoided
by different basis choice

- spinorial x spinorial ⊃ vector:

$$2 \otimes 2 = 2' \otimes 2'' = 2'' \otimes 2' = 3 \oplus 1 \qquad 3 = \begin{pmatrix} \left(\frac{1-i}{2}\right)(\alpha_1\beta_2 + \alpha_2\beta_1) \\ i\alpha_1\beta_1 \\ \alpha_2\beta_2 \end{pmatrix}$$

J. Q. Chen & P. D. Fan,
J. Math Phys 39, 5519 (1998)

- spinorial x vector ⊃ spinorial:

$$2 \otimes 3 = 2 \oplus 2' \oplus 2'' \qquad 2 = \begin{pmatrix} (1+i)\alpha_2\beta_2 + \alpha_1\beta_1 \\ (1-i)\alpha_1\beta_3 - \alpha_2\beta_1 \end{pmatrix}$$

A Novel Origin of CP Violation

M.-C.C., K.T. Mahanthappa, arXiv:0904.1721

- Conventionally:
  - Explicit CP violation: complex Yukawa couplings
  - Spontaneous CP violation: complex Higgs VEVs

★ complex CG coefficients in T′ ⇒ explicit CP violation

  - real Yukawa couplings, real Higgs VEVs
  - CP violation in both quark and lepton sectors determined by complex CG coefficients
  - no additional parameters needed ⇒ extremely predictive model!!

Tri-bimaximal Mixing from Family Symmetry

- fermion charge assignments:

$$\begin{pmatrix} \ell_1 \\ \ell_2 \\ \ell_3 \end{pmatrix}_L \sim 3, \quad e_R \sim 1, \quad \mu_R \sim 1'', \quad \tau_R \sim 1' \qquad \xi \sim 3, \quad \eta \sim 1 \qquad \langle \xi \rangle = \xi_0 \Lambda \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

- SM Higgs ~ singlet under T′
- operator for neutrino masses: $\frac{HHLL}{M} \left(\frac{\langle \xi \rangle}{\Lambda} + \frac{\langle \eta \rangle}{\Lambda} \right)$
- TBM neutrino mixing from CG coefficients

Form diagonalizable!

-- no adjustable parameters
-- neutrino mixing from CG coefficients!

$$M_\nu = \frac{\lambda v^2}{M_x} \begin{pmatrix} 2\xi_0 + u & -\xi_0 & -\xi_0 \\ -\xi_0 & 2\xi_0 & u - \xi_0 \\ -\xi_0 & u - \xi_0 & 2\xi_0 \end{pmatrix} \qquad V_\nu = U_{\text{TBM}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$$V_\nu^{\text{T}} M_\nu V_\nu = \text{diag}(u + 3\xi_0, \, u, \, -u + 3\xi_0) \frac{v_u^2}{M_x}$$

General conditions for Form Diagonalizablility
in seesaw: M.-C. C, S. F. King, 2009

- charged lepton mass matrix in non-GUT model: diagonal
- in SU(5) model: corrections to TBM due to GUT relations $\langle \phi \rangle = \phi_0 \Lambda \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$
  - corrections at leading order in terms of θ_c and CG only

M.-C.C & K.T. Mahanthappa
Phys. Lett. B652, 34 (2007); arXiv:0904.1721

Quark and Lepton Mixing Matrices

M.-C.C & K.T. Mahanthappa
Phys. Lett. B652, 34 (2007);
arXiv:0904.1721

- CKM mixing matrix:

$$M_u = \begin{pmatrix} i\phi_0'^3 & \frac{1-i}{2}\phi_0'^3 & 0 \\ \frac{1-i}{2}\phi_0'^3 & \phi_0'^3 + (1-\frac{i}{2})\phi_0^2 & y'\psi_0\zeta_0 \\ 0 & y'\psi_0\zeta_0 & 1 \end{pmatrix} y_t v_u \qquad M_d = \begin{pmatrix} 0 & (1+i)\phi_0\psi_0' & 0 \\ -(1-i)\phi_0\psi_0' & \psi_0 N_0 & 0 \\ \phi_0\psi_0' & \phi_0\psi_0' & \zeta_0 \end{pmatrix} y_b v_d \phi_0,$$

V_{cb}

V_{ub}

$$\boxed{\theta_c \simeq \left|\sqrt{m_d/m_s} - e^{i\alpha}\sqrt{m_u/m_c}\right| \sim \sqrt{m_d/m_s},}$$

Georgi-Jarlskog relations ⇒ $V_{d,L} \neq I$

SU(5) ⇒ $M_d = (M_e)^T$

⇒ corrections to TBM related to θ_c

- MNS matrix:

$$M_e = \begin{pmatrix} 0 & -(1-i)\phi_0\psi_0' & \phi_0\psi_0' \\ (1+i)\phi_0\psi_0' & -3\psi_0 N_0 & \phi_0\psi_0' \\ 0 & 0 & \zeta_0 \end{pmatrix} y_b v_d \phi_0 \Longrightarrow \boxed{\theta_{12}^e \simeq \sqrt{\frac{m_e}{m_\mu}} \simeq \frac{1}{3}\sqrt{\frac{m_d}{m_s}} \sim \frac{1}{3}\theta_c}$$

$$U_{\rm MNS} = V_{e,L}^\dagger U_{\rm TBM} = \begin{pmatrix} 1 & -\theta_c/3 & * \\ \theta_c/3 & 1 & * \\ * & * & 1 \end{pmatrix} \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$$\boxed{\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,TBM} + \frac{1}{2}\theta_c\cos\delta} \qquad \boxed{\theta_{13} \simeq \theta_c/3\sqrt{2}}$$

new QLC relation!

leptonic Dirac CP phase ⇐ complex CG

Quark-Lepton Complementarity

lepton mixing

parameter	Best-fit value	3σ range
θ_{12}	33.2^o	$28.7^o - 38.1^o$
θ_{23}	45^o	$35.7^o - 55.6^o$
θ_{13}	2.6^o	$0 - 12.5^o$

quark mixing

parameter	Best-fit value	3σ range
θ_c	12.88^o	$12.75^o - 13.01^o$
θ_{23}^q	2.36^o	$2.25^o - 2.48^o$
θ_{13}^q	0.21^o	$0.17^o - 0.25^o$

$$\boxed{\theta_{12} + \theta_c = 45^o}$$

Raidal, '04; Smirnov & Minakata, '04

quark-lepton complementarity relation

↕

quark-lepton unification?

more generally:

$$\theta_{12} + \theta_C \left(\underbrace{\frac{1}{\sqrt{2}} + \frac{\theta_C}{4}}_{k} \right) \simeq \frac{\pi}{4}$$

Plentinger, Seidl, Winter, 08; Frampton, Matsuzaki, 08; King 05; King Antusch, 05

RG effects: $\Delta\theta_c \sim \theta_c^4$

MSSM: normal hierarchy $\Delta\theta_{12} < 0.1°$ Schmidt & Smirnov, '06

Motivate measurements of neutrino mixing angles to at least the accuracy of the measured quark mixing angles

Numerical Results

M.-C.C & K.T. Mahanthappa
Phys. Lett. B652, 34 (2007);
arXiv:0904.1721

- diagonalization matrix for charged leptons:

$$\begin{pmatrix} 0.997e^{i177^o} & 0.0823e^{i131^o} & 1.31\times 10^{-5}e^{-i45^o} \\ 0.0823e^{i41.8^o} & 0.997e^{i176^o} & 0.000149e^{-i3.58^o} \\ 1.14\times 10^{-6} & 0.000149 & 1 \end{pmatrix}$$

- MNS Matrix:

$$|m_1| = 0.0156 \text{ eV}, \quad |m_2| = 0.0179 \text{ eV}, \quad |m_3| = 0.0514 \text{ eV}$$

$$\begin{pmatrix} 0.838 & 0.542 & 0.0583e^{-i227^o} \\ -0.385-0.0345e^{i227^o} & 0.594-0.0224e^{i227^o} & 0.705 \\ 0.384-0.0346e^{i227^o} & -0.592-0.0224e^{i227^o} & 0.707 \end{pmatrix} \rightarrow |U_{MNS}| = \begin{pmatrix} 0.838 & 0.542 & 0.0583 \\ 0.362 & 0.610 & 0.705 \\ 0.408 & 0.577 & 0.707 \end{pmatrix}$$

$$\longrightarrow \quad \sin^2 2\theta_{atm} = 1, \quad \tan^2\theta_\odot = 0.419, \quad |U_{e3}| = 0.0583$$

prediction for Dirac CP phase: δ = 227 degrees

$$J_\ell = -0.00967$$

Note that these predictions do NOT depend on u_o and ξ_o

- neutrino masses: using best fit values for Δm^2

2 parameters in neutrino sector

$$u_0 = -0.0593, \quad \xi_0 = 0.0369, \quad M_X = 10^{14} \text{ GeV}$$

$$|m_1| = 0.0156 \text{ eV}, \quad |m_2| = 0.0179 \text{ eV}, \quad |m_3| = 0.0514 \text{ eV}$$

$$\alpha_{21} = \pi \qquad \alpha_{31} = 0.$$

predicting: 3 masses,
3 mixing angles, 3 CP Phases;
both θ_{sol} & θ_{atm} agree with exp

Neutrino Mass Sum Rule

- sum rule among three neutrino masses: $m_1 - m_3 = 2m_2$
- including CP violation:

$$\begin{aligned} m_1 &= u_0 + 3\xi_0 e^{i\theta} \\ m_2 &= u_0 \\ m_3 &= -u_0 + 3\xi_0 e^{i\theta} \end{aligned}$$

$$\begin{aligned} \Delta m^2_{atm} &\equiv |m_3|^2 - |m_1|^2 = -12u_0\xi_0 \cos\theta \\ \Delta m^2_{\odot} &\equiv |m_2|^2 - |m_1|^2 = -9\xi_0^2 - 6u_0\xi_0 \cos\theta \end{aligned}$$

- leads to sum rule

$$\Delta m^2_{\odot} = -9\xi_0^2 + \frac{1}{2}\Delta m^2_{atm} \longrightarrow \Delta m^2_{atm} > 0$$

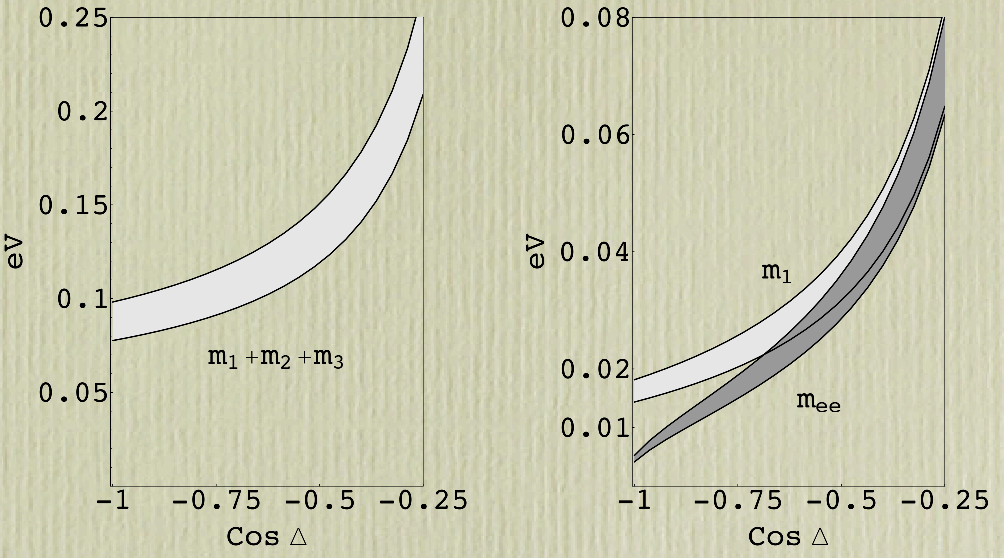
normal hierarchy predicted!!

- constraint on Majorana phases:

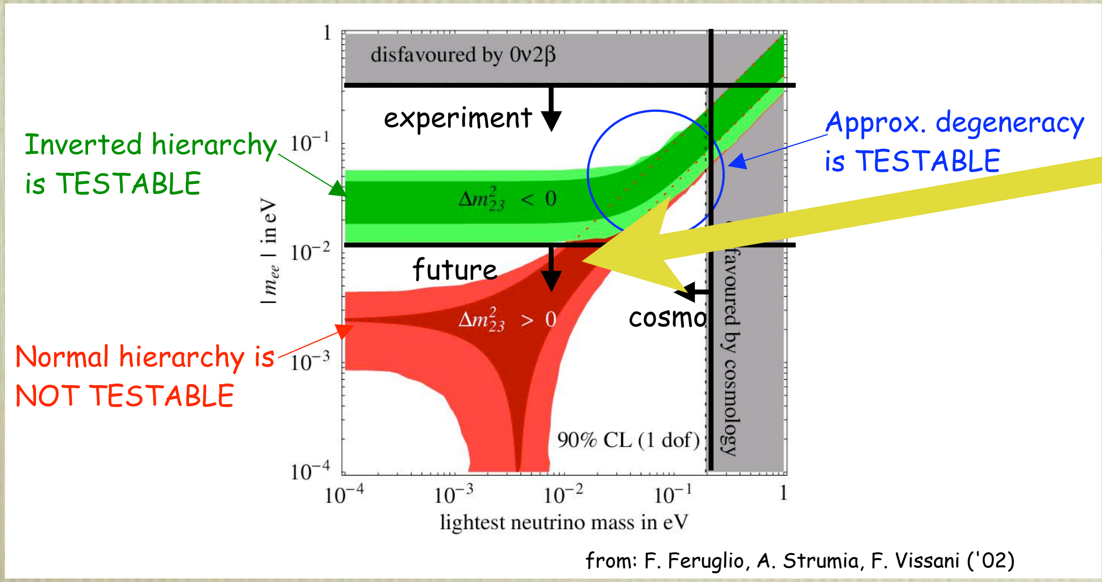
$$0 > \cos\theta > -\frac{3}{2}\frac{\xi_0}{u_0}$$

- mass sum rule:
  - ➡ large neutrino-less double beta decay matrix element
  - ➡ large sum of three absolute masses (cosmology)

Models with Tri-bimaximal Neutrino Mixing



For A4: Altarelli et al, 2006



Inverted hierarchy is TESTABLE

Approx. degeneracy is TESTABLE

Normal hierarchy is NOT TESTABLE

from: F. Feruglio, A. Strumia, F. Vissani ('02)

prediction in
A_4 and T′ models

TBM ⟷ Leptogenesis

- TBM from broken discrete symmetries through type-I seesaw

  E. Jenkins, A. Manohar, 2008

  - ➡ exact TBM mixing

    $\sin\theta_{13} = 0 \;\Rightarrow\; J_{CP}^{lep} \propto \sin\theta_{13} = 0$

    CP violation through Majorana phases: $\alpha_{21},\ \alpha_{31}$

  - ➡ no leptogenesis as $Im(y_D y_D^\dagger) = 0$
  - ➡ true even when flavor effects included
  - corrections to TBM pattern due to high dim operators

    small symmetry breaking parameter $\eta \ll 1$:

    $\sin\theta_{13} \sim \eta \sim 10^{-2},\ \epsilon \sim 10^{-6}$ can be generated

- SU(5) x T′ model: corrections to TBM from charged lepton sector

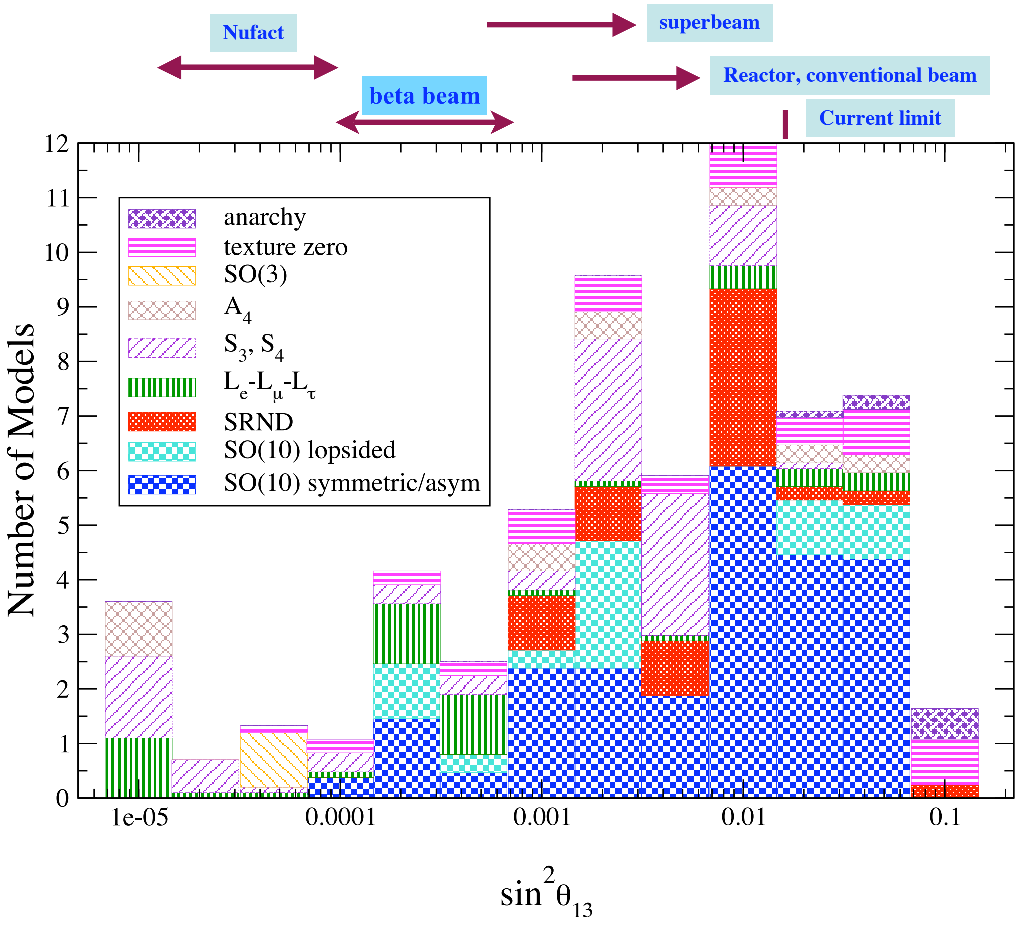
  M.-C.C., K.T. Mahanthappa, under preparation

  - without flavor effects ⇒ $\epsilon = 0$
  - with flavor effects ⇒ $\epsilon \sim 10^{-6}$ right amount for leptogenesis
  - Dirac phase the only non-vanishing leptonic CPV phase

    ⇒ connection between leptogenesis & low energy CPV

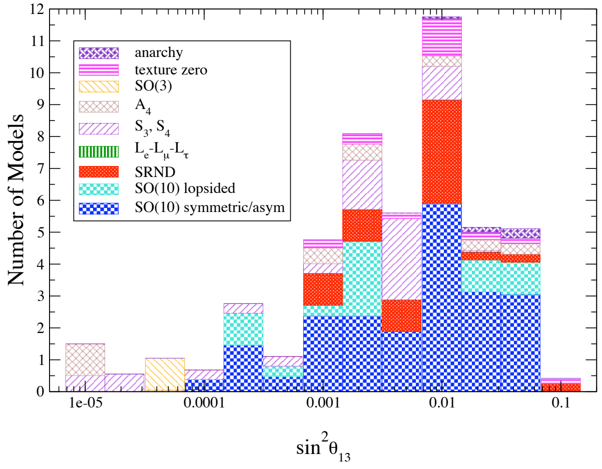
Distinguishing Models

C. Albright & M.-C.C, 2006

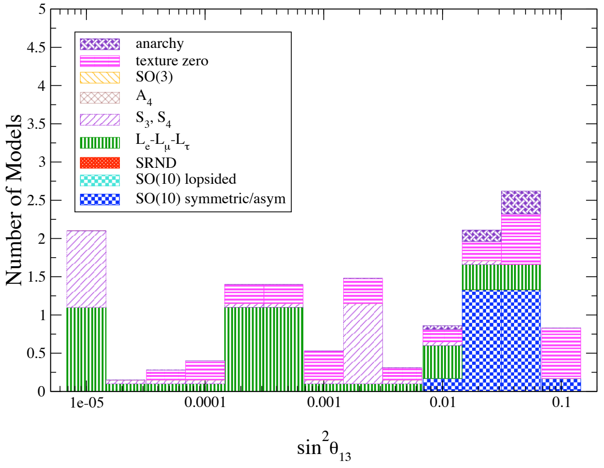


	$\sin^2 2\theta_{13}$	$\sin\theta_{13}$
current limit	10^{-1}	0.16
reactor	10^{-2}	0.05
Conventional beam	10^{-2}	0.05
superbeam	3×10^{-3}	2.7×10^{-2}
Neutrino factory	$(5\text{-}50) \times 10^{-5}$	$(3.5\text{-}11) \times 10^{-3}$

Models with Normal Hierarchy



Models with Inverted Hierarchy

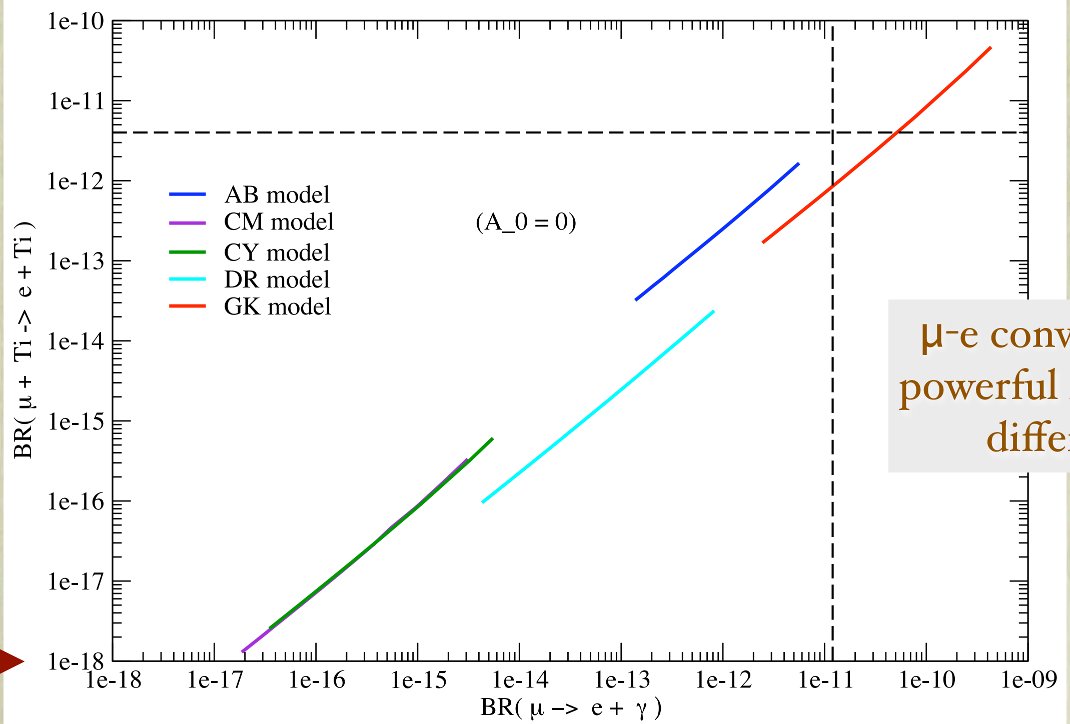


LFV Rare Processes

C. Albright & M.-C.C, 2008

predictions for LFV processes in five viable SUSY SO(10) models:

-- assuming MSUGRA boundary conditions
-- including Dark Matter constraints from WMAP (lower bound on predictions)



μ-e conversion could be powerful in distinguishing different models

sensitivity of proposed MECO-type exp

reach at MEG

TeV Scale Seesaw

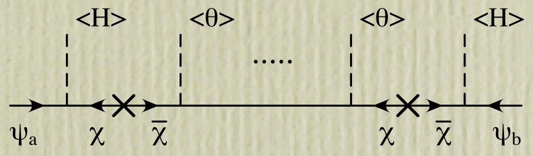
M.-C.C, A. de Gouvea, B. Dobrescu, 2006

- SM x U(1)$_{NA}$ + 3 ν_R: charged under U(1)$_{NA}$ symmetry, broken by <ϕ>
- U(1)$_{NA}$ forbids usual dim-4 Dirac operator and dim-5 Majorana operator

$$m_{LL} \sim \frac{HHLL}{M} \rightarrow M \sim 10^{14}\ GeV$$

- neutrino masses generated by very high dimensional operators

$$m_{LL} \sim \left(\frac{\langle\phi\rangle}{M}\right)^p \frac{HHLL}{M} \rightarrow M \sim \ TeV, \quad \text{for large } p \qquad\qquad \frac{\langle\phi\rangle}{M} \sim \text{not too small}$$



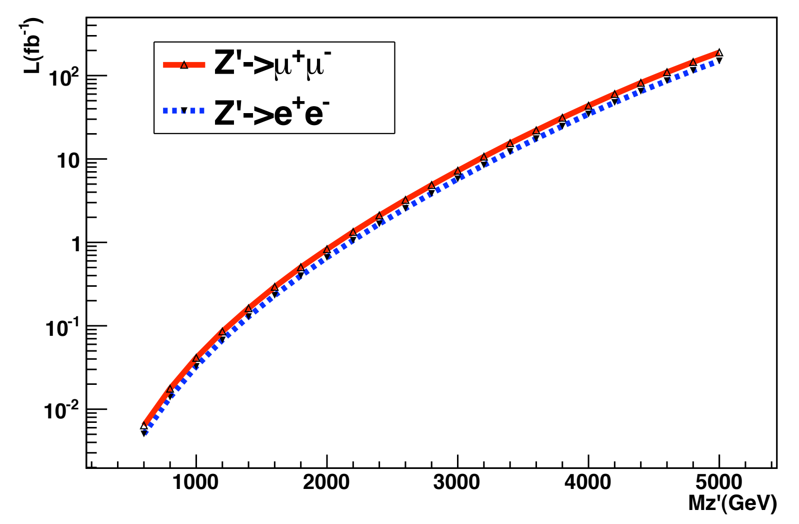
low seesaw scale achieved with all couplings ~ O(1)

- anomaly cancellations: charges of different families of fermions related => predict flavor mixing
- Through couplings to Z': can probe neutrino sector at colliders

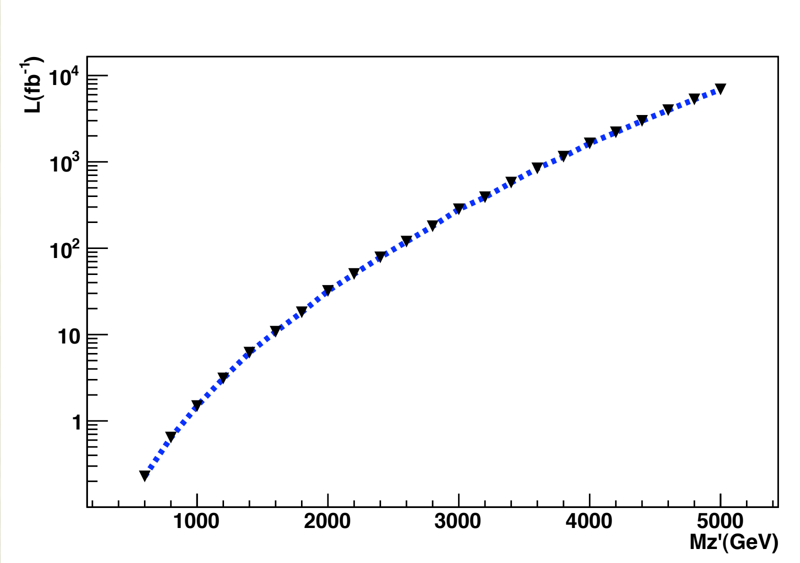
LHC Potential

M.-C.C, J.R. Huang, under preparation

lepton charges: $q_e = -55/8$, $q_\mu = q_\tau = 49/8$

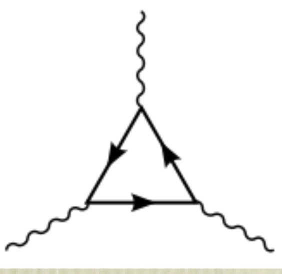


Integrated Luminosity needed for 5σ discovery



Integrated Luminosity needed for 5σ distinction

Non-anomalous v.s. Anomalous U(1)



- anomaly cancellations: relating charges of different fermions
  - $[U(1)]^3$ condition generally difficult to solve
- most models utilized anomalous U(1):
  - mixed anomaly: cancelled by Green-Schwarz mechanism
  - $[U(1)]^3$ anomaly: cancelled by exotic fields besides RH neutrinos
  - U(1) broken at fundamental string scale
  - earlier claim that U(1) has to be anomalous to be compatible with SU(5) while giving rise to realistic fermion mass and mixing patterns

constraints not as stringent

L.E. Ibanez, G.G. Ross 1994

- non-anomalous U(1) can be compatible with SUSY SU(5) while giving rise to realistic fermion mass and mixing patterns
  - no exotics other than 3 RH neutrinos
  - U(1) also forbids Higgs-mediated proton decay

M.-C.C, D.R.T. Jones, A. Rajaraman, H.B. Yu, 2008

Conclusion

- finite group family symmetry: group theoretical origin for mixing and CP violation
- Predictions of existing models for θ_{13}: 0 - current bound
- Precision measurements for the θ_{13} and mass hierarchy can tell different scenarios apart:
    - leptonic family symmetry vs GUT
    - inverted hierarchy, small 1-3 mixing => lepton symmetry
    - large 1-3 mixing => inconclusive
- deviation from maximal θ_{23} may tell how symmetry is broken
- May probe other interesting relations: e.g.
    - quark-lepton complementarity: $\theta_{12} + \theta_c = 45^o$
    - new quark-lepton complementarity: $\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,TBM} + \frac{1}{2}\theta_c \cos\delta$
- LFV rare processes can be a robust test

Precision Measurements Indispensable!!