Recent Developments in Neutrino Physics - from a Theoretical Perspective

Mu-Chun Chen
University of California at Irvine

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Neutrino Mass beyond the SM

- SM: effective low energy theory
- new physics effects suppressed by powers of new physics scale M

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \underbrace{\frac{\mathcal{O}_{5D}}{M} + \frac{\mathcal{O}_{6D}}{M^2}}_{} + \ldots$$

new physics effects

- neutrino masses generated by dim-5 operators -- lowest order higher dimensional operator

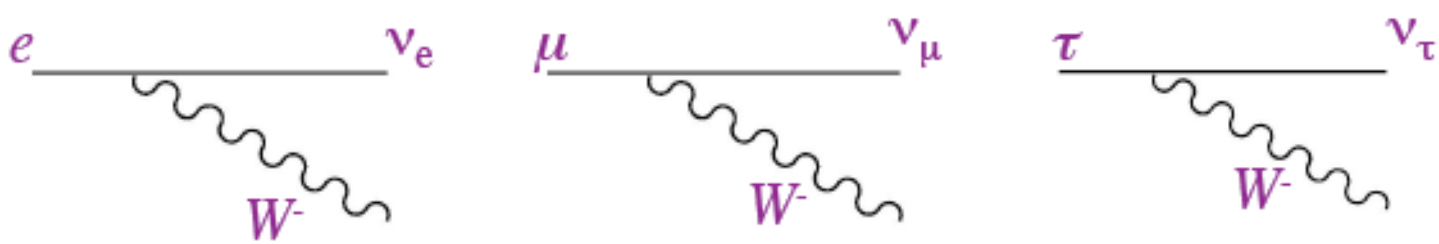
$$\frac{\lambda_{ij}}{M} H H L_i L_j \quad \Rightarrow \quad m_\nu = \lambda_{ij} \frac{v^2}{M}$$

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

- high M $\Rightarrow$ small m_ν
- total lepton number and individual family lepton numbers broken
  - lepton mixing expected
  - $\mu \rightarrow e\,\gamma$ (MEG @ PSI) ; μ - e conversion (Mu2e @ Fermilab) ;

What if Neutrinos Have Mass?

- Similar to the quark sector, there can be mismatch between mass eigenstates and weak eigenstates
- weak interactions eigenstates: ν_e, ν_μ, ν_τ



- mass eigenstates: ν_1, ν_2, ν_3
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

$$\begin{aligned} V^{\dagger}_{e,R} M_e V_{e,L} &= \mathrm{diag}(m_e, m_\mu, m_\tau) \\ V^{T}_{\nu,L} M_\nu V_{\nu,L} &= \mathrm{diag}(m_1, m_2, m_3) \end{aligned}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{MNS} = V^{\dagger}_{e,L} V_{\nu,L}$$

Leptonic Mixing Matrix

- Three neutrino case:
  - two mass differences: $\Delta m_a^2,\ \Delta m_s^2$

$$U_{MNS} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix}}_{\text{atm}} \underbrace{\begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ o & 1 & o \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix}}_{\text{reactor}} \underbrace{\begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{solar}} \underbrace{\begin{bmatrix} 1 & o & 0 \\ 0 & e^{i\left(\frac{1}{2}\phi_{12}\right)} & 0 \\ 0 & 0 & e^{i\left(\frac{1}{2}\phi_{13}+\delta\right)} \end{bmatrix}}_{\text{Majorana phases}}$$

  - three mixing angles: $c_a,\ c_s,\ c_x$
  - three CP phases: $\delta,\ \phi_{12},\ \phi_{13}$
    - CP violation in neutrino oscillation sensitive to Dirac phase, δ
    - neutrinoless double beta decay sensitive to Majorana phases, Φ_{12}, Φ_{13}

Compelling Evidences of Neutrino Oscillation

Details see Talk by Hiro Tanaka

Atmospheric Neutrinos:

SuperKamiokande (up-down asymmetry, L/E, θz dependence of μ-like events), K2K

dominant channel: $\nu_\mu \longrightarrow \nu_\tau$

next: MINOS, NOvA, T2K,...

Solar Neutrinos:

Homestake, Kamiokande, SAGE, GALLEX/GNO, SK, SNO, BOREXINO, KamLAND

dominant channel: $\nu_e \longrightarrow \nu_{\mu,\tau}$

next: BOREXINO, ...

“Anomalies”?

LSND Anomaly: if true ⇒ sterile ν with $\Delta m^2 \sim (0.1\text{-}1)\ \mathrm{eV}^2$

dominant channel: $\overline{\nu}_\mu \to \overline{\nu}_e$ (3.8σ excess)

re-calculation of pion production cross-section for $\overline{\nu}_e$ background:

excess reduced to 3σ A. Zhemchugov (HARP-CDP), ICHEP2010

MiniBoone: R. Van de Water @ Neutrino 2010

neutrino mode:

E < 475 MeV: unexplained 3σ e-like excess

E > 475 MeV: 2-neutrino fit inconsistent with LSND at 90% CL

anti-neutrino mode:

E < 475 MeV: small 1.3σ e-like excess

E > 475 MeV: an excess consistent with null at 3%;

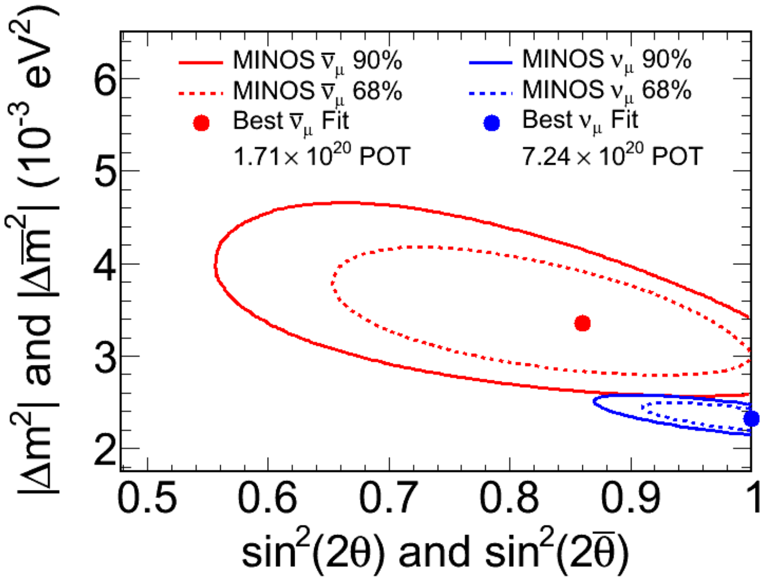
2-neutrino fit consistent with LSND at 99.4% CL

I.Bigi, 1982; Murayama, Yanagida, 2001

inconsistency between neutrino and anti-neutrino mode ⇒ CPT violation?

"Anomalies"?

MINOS:



arXiv:1103.0340; 1104.0344

consistent @ 2% CL

CPT violation?

Reactor Antineutrino Anomaly:

Mueller et al, arXiv:1101.2663; Mention, Fechner, Lasserre, Mueller, Lhuillier, Cribier, Letorneau, arXiv:1101.2755

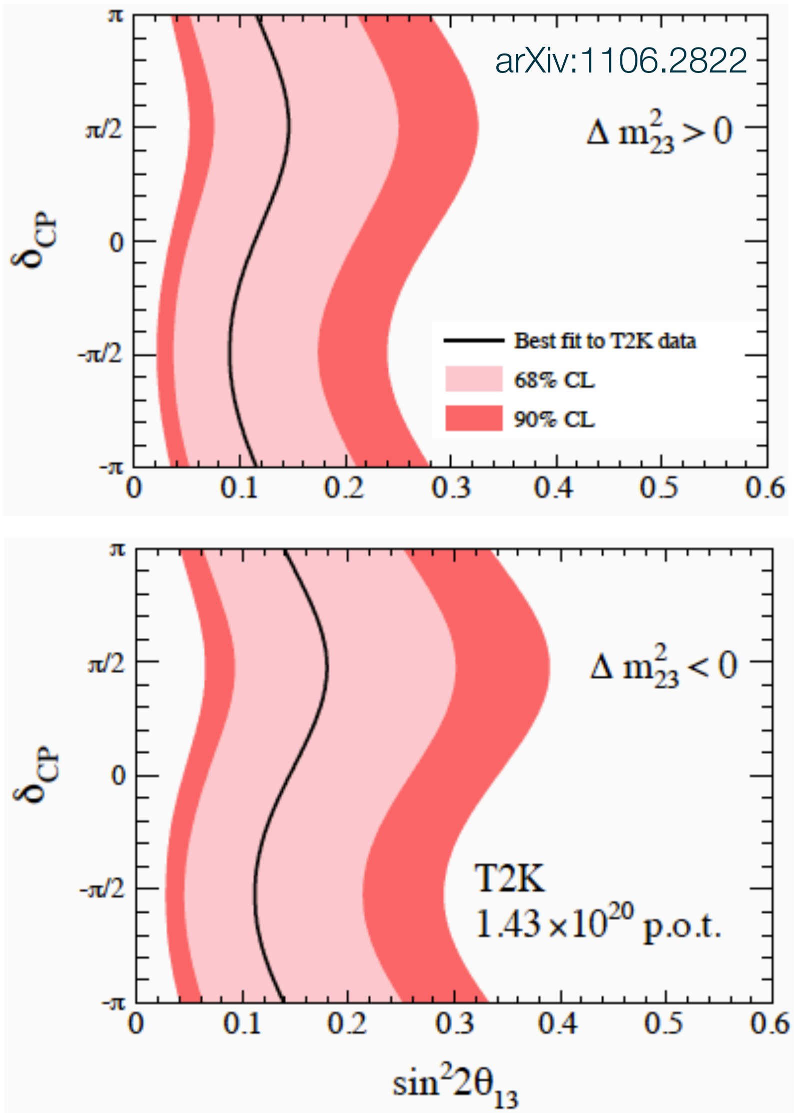
improved predictions for reactor anti-neutrino flux

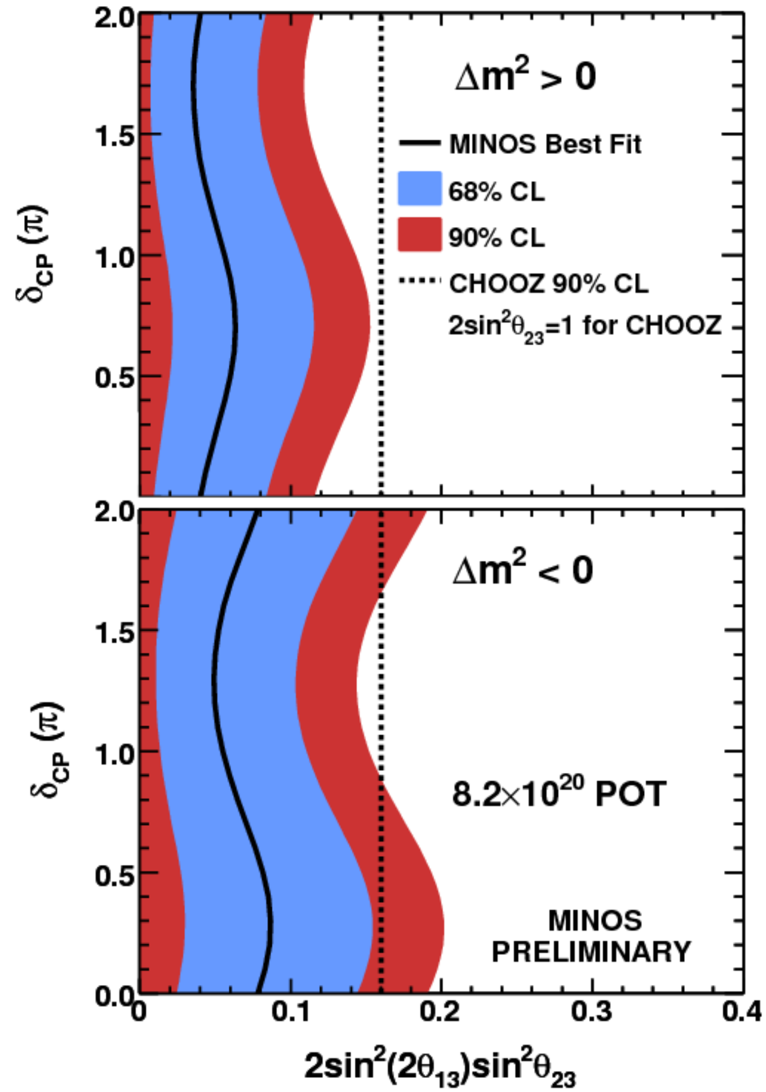
normalization shifted by +3%

sterile neutrino with $\Delta m^2 > (1.5)$ eV^2 and $\sin^2 2\theta = 0.14 \pm 0.08$ (cosmology?)

First Indication of $\theta_{13} \neq 0$

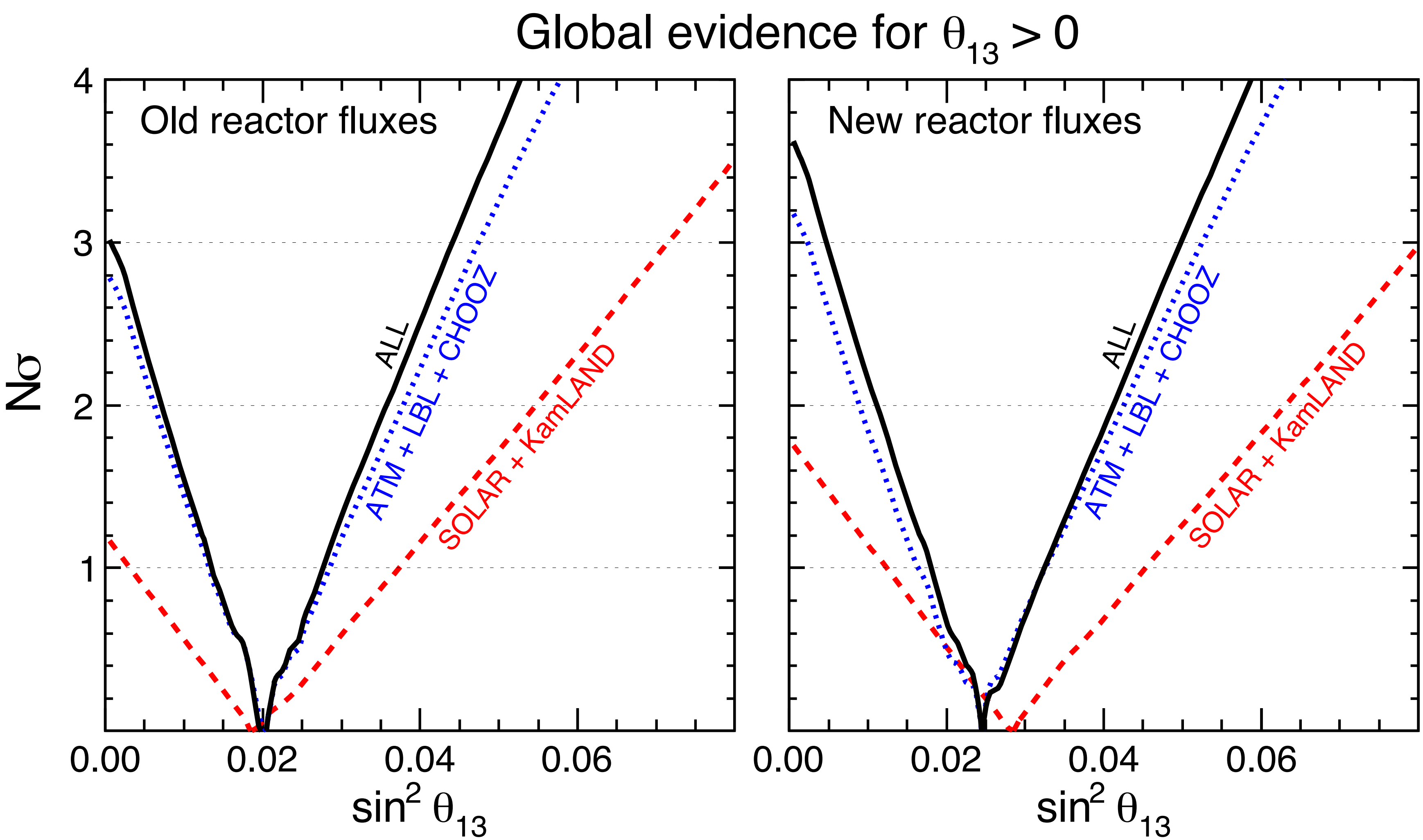
Details see Talk by Hiro Tanaka





Global Fit Including T2K/MINOS Results

Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028



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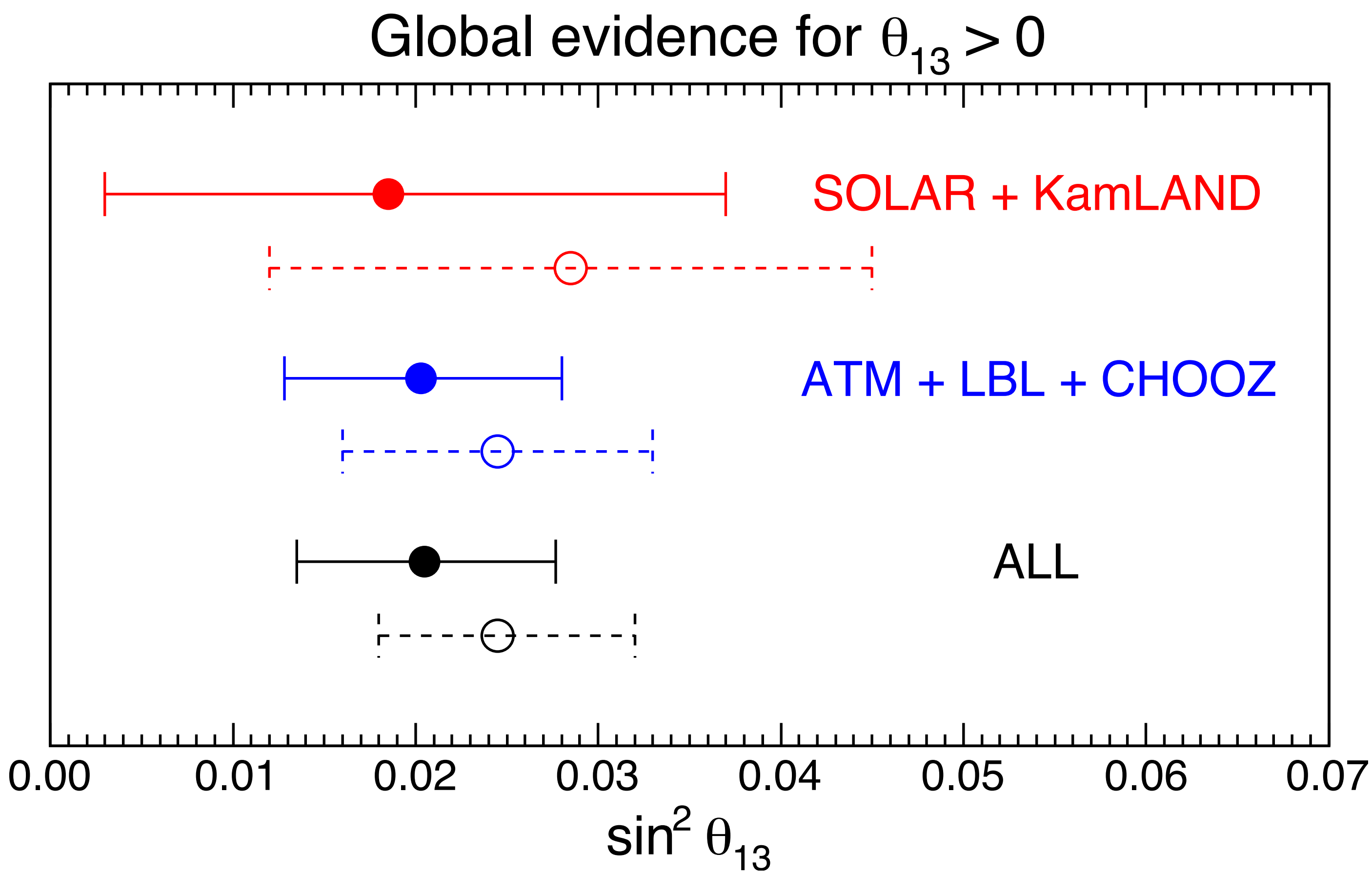

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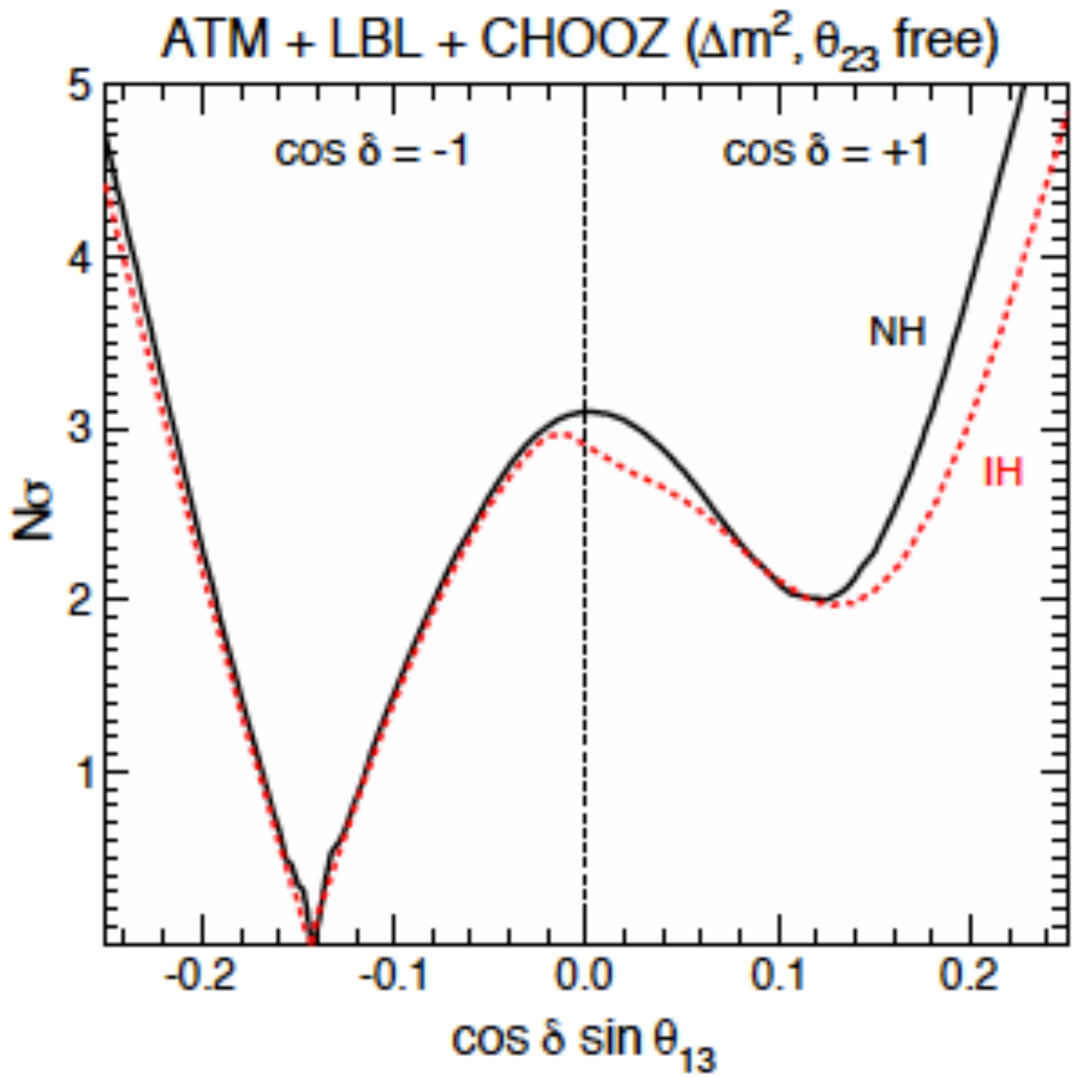


Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028

Consistent with SuperK Best Fit:
δ = 220 degrees
(Neutrino 2010)

Where Do We Stand?

- Latest 3 neutrino global analysis including atm, solar, reactor, LBL (T2K/MINOS) experiments:

Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028

$$P(\nu_a \to \nu_b) = \left|\langle \nu_b | \nu,\ t\rangle\right|^2 \simeq \sin^2 2\theta\ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306	0.021	0.42	2.35
		(0.312)	(0.025)		
1σ range	7.32 – 7.80	0.291 – 0.324	0.013 – 0.028	0.39 – 0.50	2.26 – 2.47
		(0.296 – 0.329)	(0.018 – 0.032)		
2σ range	7.16 – 7.99	0.275 – 0.342	0.008 – 0.036	0.36 – 0.60	2.17 – 2.57
		(0.280 – 0.347)	(0.012 – 0.041)		
3σ range	6.99 – 8.18	0.259 – 0.359	0.001 – 0.044	0.34 – 0.64	2.06 – 2.67
		(0.265 – 0.364)	(0.005 – 0.050)		

Generally: Different global fit analyses assume different error correlations among experiments ⇒ different results

Where Do We Stand?

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

$$m_{\nu_e} < 2.2 \text{ eV (95\% CL)} \quad \text{Mainz}$$
$$m_{\nu_\mu} < 170 \text{ keV}$$
$$m_{\nu_\tau} < 15.5 \text{ MeV}$$

KATRIN: increase sensitivity ~ 0.2 eV

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

  - WMAP + 2dFRGS + Lyα $\sum(m_{\nu_i}) < (0.36\text{-}1.5)$ eV Gonzalez-Garcia et al, arXiv:1006.3795
    - very model dependent
  - neutrinoless double beta decay
    - uncertainty in nuclear matrix element

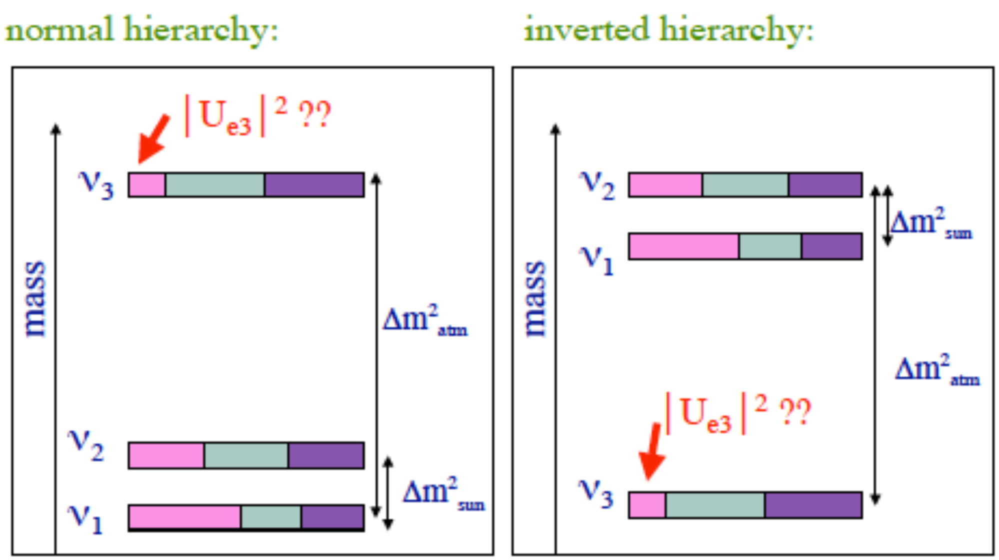
$$\text{current bound:} \quad |\langle m\rangle| \equiv \left|\sum_{i=1,2,3} m_i U_{ie}^2\right| < (0.19 - 0.68) \text{ eV} \quad (\text{CUORICINO, Feb 2008})$$

- Effective number of neutrinos:
  - WMAP7 + BAO: $N_{eff} = 4.34\,^{+0.86}_{-0.88}$ Komatsu et al, arXiv:1001.4538
  - BBN: $N_s < 1.2$ Mangano, Serpico, arXiv:1103.1261

resolved by Planck soon!

Neutrino Mass Spectrum

- two mass orderings compatible with data



<u>The known unknowns</u>:

- How small is θ_{13}? (ν_e component of ν_3)
- $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?

  (ν_3 composition of ν)
- neutrino mass hierarchy (Δm_{13}^2)?
- CP violation in neutrino oscillations?
- Majorana vs Dirac?

<u>What's Next?</u>

Reactor Exp: Double CHOOZ, Daya Bay, Reno

Long Baseline Exp: MINOS, NOvA, T2K, LBNE...

Theoretical Challenges

(i) Absolute mass scale: Why $m_\nu << m_{u,d,e}$?

- seesaw mechanism: most appealing scenario ⇒ Majorana
  - GUT scale (type-I, II) vs TeV scale (type-III, double seesaw)
- TeV scale new physics (extra dimension, extra U(1)) ⇒ Dirac or Majorana

(ii) Flavor Structure: Why neutrino mixing large while quark mixing small?

- seesaw doesn't explain entire mass matrix w/ 2 large, 1 small mixing angles
- neutrino anarchy: no parametrically small number Hall, Murayama, Weiner (2000)
  - near degenerate spectrum, large mixing
  - predictions strongly depend on choice of statistical measure
- family symmetry: there's a structure, expansion parameter (~~symmetry~~ effect)
  - leptonic symmetry (normal or inverted)
  - quark-lepton connection ↔ GUT (normal)

- In most part of this talk: assume 3 generations, no LSND/MiniBoone/Reactor Anomaly
  - MiniBoone anti-neutrino mode: excess in low energy region consistent with LSND
  - 4th generation model: (3+3) consistent with experiments including MiniBoone Hou, Lee, arXiv:1004.2359

Small Neutrino Mass: Seesaw Mechanism

Yanagida, 1979; Gell-Mann, Ramond, Slansky, 1979;
Mohapatra, Senjanovic, 1981

- Mixture of light fields and heavy fields

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

ν_R: sterile (singlet under ALL gauge groups in SM)

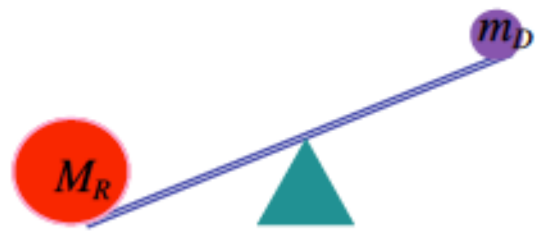
$\nu_R \nu_R$ mass term allowed

- Diagonalize the mass matrix:

$$m_\nu \sim m_{light} \sim \frac{m_D^2}{M_R} << m_D$$

$$m_{heavy} \sim M_R$$

- Smallness of neutrino masses suggest a high mass scale

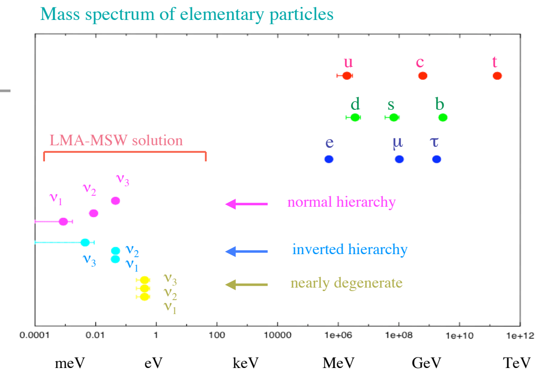


For $m_{\nu_3} \sim \sqrt{\Delta m^2_{atm}}$

If $m_D \sim m_t \sim 180 \;\; GeV$

$\Rightarrow$ $\boxed{M_R \sim 10^{15} \; GeV \;\; (\text{GUT !!})}$

Origin of Mass Hierarchy and Mixing



- In the SM: 22 physical quantities which seem unrelated
- Question arises whether these quantities can be related
- No fundamental reason can be found in the framework of SM
- less ambitious aim ⇒ reduce the # of parameters by imposing symmetries
  - Grand Unified Gauge Symmetry
    - GUT relates quarks and leptons
      - quarks & leptons reside in the same GUT multiplets
      - one set of Yukawa coupling for a given GUT multiplet ⇒ intra-family relations
  - Family Symmetry
    - relate Yukawa couplings of different families
      - inter-family relations
      - further reduce the number of parameters

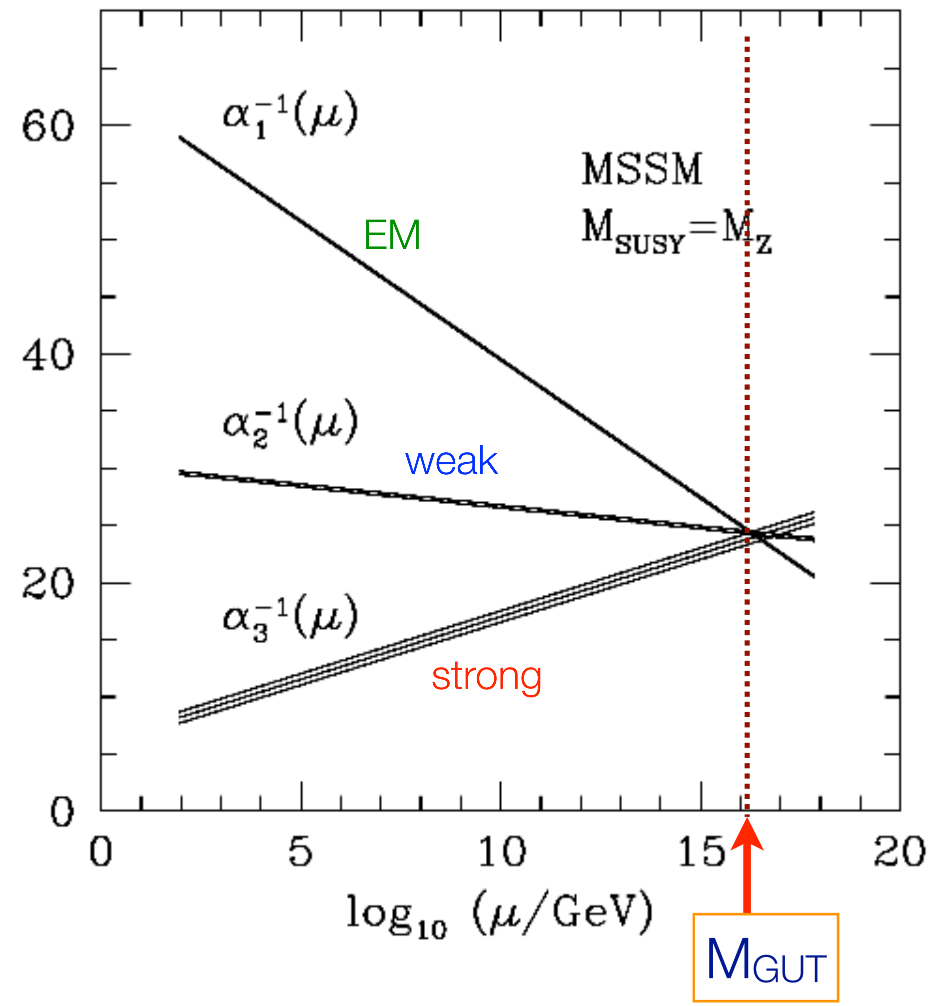
Grand Unification

- Motivations:
    - Electromagnetic, weak, and strong forces have very different strengths
    - But their strengths become the same at 10^{16} GeV if there is supersymmetry
    - To obtain

$$m_\nu \sim (\Delta m^2_{atm})^{1/2},\ m_D \sim m_{top}$$

$$M_R \sim 10^{15}\ \text{GeV}$$

coupling constants run!



Grand Unification

- Candidate GUT groups:
  - SU(5):
    - unify15 known fermions in each generation into a 10 + $\overline{5}$-dim representations
    - can add by hand an extra singlet as ν_R
  - SO(10):
    - unify15 known fermions in each generation into a 16-dim spinor representation ⇒ ν_R is predicted

    $16 = 10 + \overline{5} + 1$

charge quantization explained!

$$10 = (3,2,1/6) \sim \begin{bmatrix} u & u & u \\ d & d & d \end{bmatrix}$$
$$+ (3^*,1,-2/3) \sim (u^c, u^c, u^c)$$
$$+ (1,1,1) \sim e^c$$

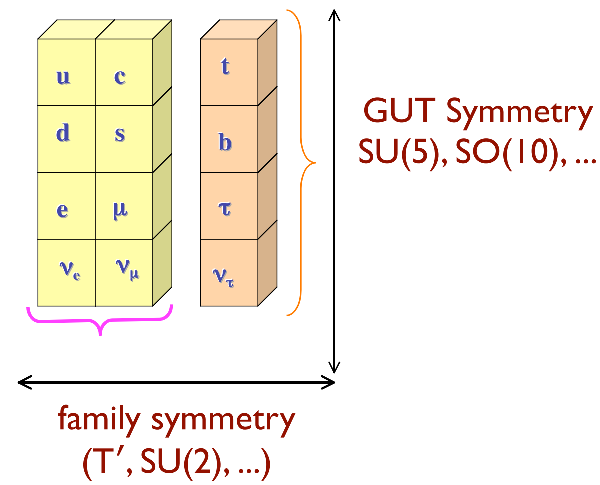
$$\overline{5} = (3^*,1,1/3) \sim (d^c, d^c, d^c)$$
$$+ (1,2,-1/2) \sim \begin{bmatrix} \nu \\ e \end{bmatrix}$$

$$16 = (3,2,1/6) \sim \begin{bmatrix} u & u & u \\ d & d & d \end{bmatrix}$$
$$+ (3^*,1,-2/3) \sim (u^c\ u^c\ u^c)$$
$$+ (3^*,1,1/3) \sim (d^c\ d^c\ d^c)$$
$$+ (1,2,-1/2) \sim \begin{bmatrix} \nu \\ e \end{bmatrix}$$
$$+ (1,1,1) \sim e^c$$
$$+ (1,1,0) \sim \nu^c$$

$$\begin{aligned}
u &: |\uparrow\downarrow\uparrow\uparrow\downarrow\rangle \\
u &: |\uparrow\downarrow\uparrow\downarrow\uparrow\rangle \\
u &: |\uparrow\downarrow\downarrow\uparrow\uparrow\rangle \\
d &: |\downarrow\uparrow\uparrow\uparrow\downarrow\rangle \\
d &: |\downarrow\uparrow\uparrow\downarrow\uparrow\rangle \\
d &: |\downarrow\uparrow\downarrow\uparrow\uparrow\rangle \\
u^c &: |\downarrow\downarrow\uparrow\downarrow\downarrow\rangle \\
u^c &: |\downarrow\downarrow\downarrow\uparrow\downarrow\rangle \\
u^c &: |\downarrow\downarrow\downarrow\downarrow\uparrow\rangle \\
d^c &: |\uparrow\uparrow\uparrow\downarrow\downarrow\rangle \\
d^c &: |\uparrow\uparrow\downarrow\uparrow\downarrow\rangle \\
d^c &: |\uparrow\uparrow\downarrow\downarrow\uparrow\rangle \\
e &: |\downarrow\uparrow\downarrow\downarrow\downarrow\rangle \\
\nu_e &: |\uparrow\downarrow\downarrow\downarrow\downarrow\rangle \\
e^c &: |\downarrow\downarrow\uparrow\uparrow\uparrow\rangle \\
\nu_e{}^c &: |\uparrow\uparrow\uparrow\uparrow\uparrow\rangle
\end{aligned}$$

Origin of Mass Hierarchy and Mixing

- Several models have been constructed based on
  - GUT Symmetry [SU(5), SO(10)] ⊕ Family Symmetry G_F
- Family Symmetries G_F based on continuous groups:
  - U(1)
  - SU(2)
  - SU(3)



- Recently, models based on discrete family symmetry groups have been constructed
  - A_4 (tetrahedron)
  - T´ (double tetrahedron)
  - S_3 (equilateral triangle)
  - S_4 (octahedron, cube)
  - A_5 (icosahedron, dodecahedron)
  - Δ_{27}
  - Q4

Motivation: Tri-bimaximal (TBM) neutrino mixing

What does the data tell us?

- Neutrino Oscillation Parameters $P(\nu_a \to \nu_b) = \left|\langle \nu_b | \nu,\ t\rangle\right|^2 \simeq \sin^2 2\theta\ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$

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

- Latest Global Fit (3σ) Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028

$$\sin^2\theta_{atm} = 0.42\ (0.34 - 0.64)\ ,\ \sin^2\theta_{\odot} = 0.306\ (0.259 - 0.359)$$

$$\sin^2\theta_{13} = 0.021\ (0.001 - 0.044)$$

- Tri-bimaximal Mixing Pattern Harrison, Perkins, Scott (1999)

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

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

$$\sin\theta_{13,\text{TBM}} = 0.$$

Best fit value using atm data only

$\Rightarrow \theta_{13} = 0$ Wendell et al (2010)

Models for Tri-bimaximal Mixing

- Neutrino mass matrix

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

solar mixing angle NOT fixed

μ-τ symmetry: Petcov; Fukuyama, Nishiura; Mohapatra, Nussinov; Ma, Raidal; ...

S_3: Kubo, Mondragon, Mondragon, Rodriguez-Jauregui; Araki, Kubo, Paschos; Mohapatra, Nasri, Yu; ...

D_4: Grimus, Lavoura; ...

- If A + B = C + D $\Rightarrow$ $\tan^2\theta_{12} = 1/2$ TBM pattern
  - mass matrix M diagonalized by U_{TBM}

$$U^T_{TBM}\, M\, U_{TBM} = diag(m_1, m_2, m_3)$$

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

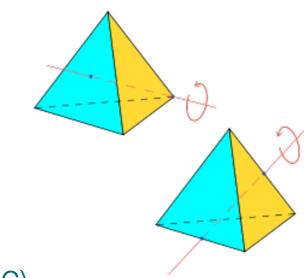
A_4: Ma, Rajasekaran; Altarelli, Feruglio; ...

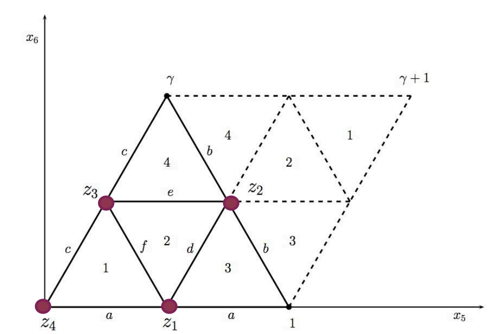
$Z_3 \times Z_7$: Luhn, Nasri, Ramond; ...

Double Tetrahedral T´ Symmetry

- Smallest Symmetry to realize TBM ⇒ Tetrahedral group A_4 Ma, Rajasekaran (2004)
  - even permutations of 4 objects

    S: (1234) → (4321), T: (1234) → (2314)
  - invariance group of tetrahedron
  - can arise from extra dimensions: 6D → 4D Altarelli, Feruglio (2006)
  - does NOT give quark mixing





- Double Tetrahedral Group T´ Frampton, Kephart (1995); M.-C.C., K.T. Mahanthappa PLB652, 34 (2007); 681, 444 (2009)
  - inequivalent representations

A4: $1,\ 1',\ 1'',\ 3$ (vectorial) ⟶ TBM for neutrinos

other: $2,\ 2',\ 2''$ (spinorial) ⟶ 2 +1 assignments for charged fermions

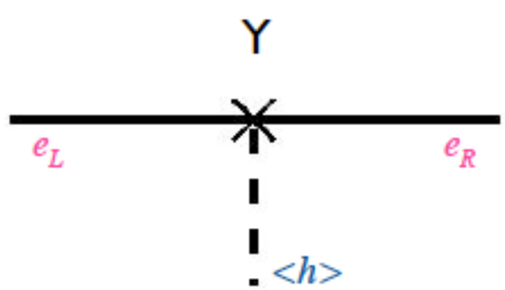
  - complex CG coefficients when spinorial representations are involved

CP Violation

- CP violation ⇔ complex mass matrices

$$\overline{U}_{R,i}(M_u)_{ij}Q_{L,j} + \overline{Q}_{L,j}(M_u^\dagger)_{ji}U_{R,i} \xrightarrow{\mathcal{CP}} \overline{Q}_{L,j}(M_u)_{ij}U_{R,i} + \overline{U}_{R,i}(M_u)^*_{ij}Q_{L,j}$$

- Conventionally, CPV arises in two ways:
  - Explicit CP violation: complex Yukawa coupling constants Y
  - Spontaneous CP violation: complex scalar VEVs <h>

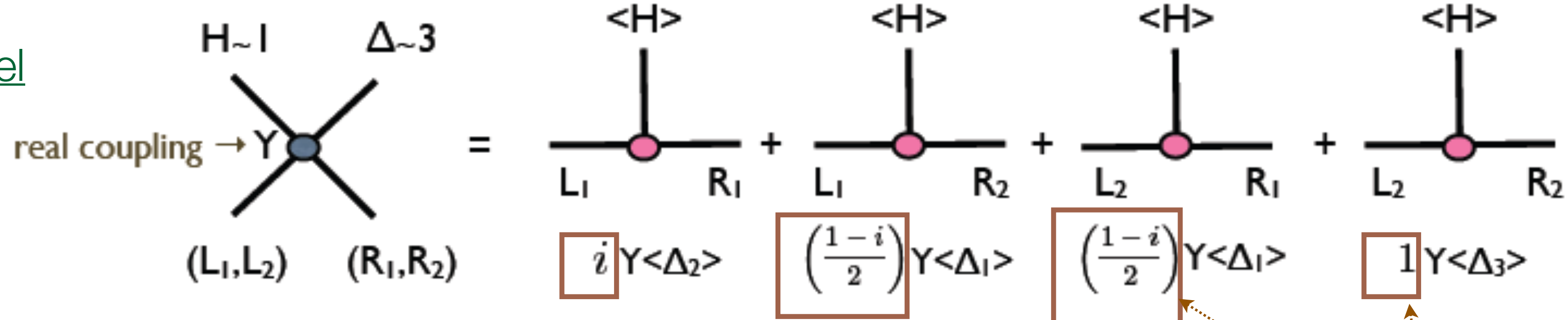


A Novel Origin of CP Violation

M.-C.C., K.T. Mahanthappa
Phys. Lett. B681, 444 (2009)

- Complex CG coefficients in T´ ⇒ explicit CP violation
  - real Yukawa couplings, real scalar VEVs
  - CPV in quark and lepton sectors purely from complex CG coefficients
  - no additional parameters needed ⇒ extremely predictive model!

a toy model



- scalar potential: Z_3 symmetry ⇒ $\langle\Delta_1\rangle = \langle\Delta_2\rangle = \langle\Delta_3\rangle \equiv \langle\Delta\rangle$ real
- complex effective mass matrix

CGs of T´

$$\begin{array}{cc} & \begin{array}{cc} L_1 & L_2 \end{array} \\ M = & \left(\begin{array}{cc} i & \frac{1-i}{2} \\ \frac{1-i}{2} & 1 \end{array}\right) Y\langle\Delta\rangle \end{array} \quad (R_1 \; R_2)$$

The Model

M.-C.C, K.T. Mahanthappa
Phys. Lett. B652, 34 (2007); Phys. Lett. B681, 444 (2009)

- Symmetry: SUSY SU(5) x T´ x Z_{12} x Z_{12}

	SU(5)	T'	
$10(Q,\, u^c,\, e^c)_L$	:	$(T_1,T_2) \sim 2$, $T_3 \sim 1$	1: (N1,N2,N3) ~ 3
$\overline{5}(d^c, \ell)_L$	:	$(F_1, F_2, F_3) \sim 3$	

- Superpotential: only 10 operators allowed

(7+2) parameters fit 22 masses, mixing angles, CPV measures

$$\mathcal{W}_{\rm Yuk} = \mathcal{W}_{TT} + \mathcal{W}_{TF} + \mathcal{W}_{\nu}$$

spinorial representations ⇒ complex CGs

⇒ CPV in quark & charged lepton sector

$$\mathcal{W}_{TT} = y_t H_5 T_3 T_3 + \frac{1}{\Lambda^2} H_5 \left[y_{ts} T_3 T_a \psi\zeta + y_c T_a T_b \phi^2 \right] + \frac{1}{\Lambda^3} y_u H_5 T_a T_b \phi'^3$$

up type quarks

$$\mathcal{W}_{TF} = \frac{1}{\Lambda^2} y_b H'_{\overline{5}} \overline{F} T_3 \phi\zeta + \frac{1}{\Lambda^3} \left[y_s \Delta_{45} \overline{F} T_a \phi\psi\zeta' + y_d H_{\overline{5}'} \overline{F} T_a \phi^2 \psi' \right]$$

down type quarks & charged leptons

$$\mathcal{W}_{\nu} = \lambda_1 NNS + \frac{1}{\Lambda^3} \left[H_5 \overline{F} N \zeta\zeta' \Big(\lambda_2 \xi + \lambda_3 \eta \Big) \right]$$

neutrino masses

Λ : scale above which T' is exact

Reality of Yukawa couplings: ensured by degrees of freedom in field redefinition

Model Predictions

M.-C.C, K.T. Mahanthappa
Phys. Lett. B652, 34 (2007); Phys. Lett. B681, 444 (2009)

- Resulting neutrino mass matrices

$$M_{RR} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} S_0 \qquad M_D = \begin{pmatrix} 2\xi_0 + \eta_0 & -\xi_0 & -\xi_0 \\ -\xi_0 & 2\xi_0 & -\xi_0 + \eta_0 \\ -\xi_0 & -\xi_0 + \eta_0 & 2\xi_0 \end{pmatrix} \zeta_0 \zeta_0' v_u$$

only vector representations
⇒ all CG are real

⇒ Majorana phases: 0 or π

- seesaw mechanism: effective neutrino mass matrix

$$U_{TBM}^T M_\nu U_{TBM} = \mathrm{diag}((3\xi_0 + \eta_0)^2, \eta_0^2, -(-3\xi_0 + \eta_0)^2) \frac{(\zeta_0 \zeta_0' v_u)^2}{S_0}$$

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

Form diagonalizable:
-- no adjustable parameters
-- neutrino mixing from CG coefficients!

General conditions for form diagonalizability:
M.-C.C., S.F. King, JHEP0906, 072 (2009)

- mass sum rule among 3 masses

$$m_2^2 - m_1^2 = (\eta_0^4 - (3\xi_0 + \eta_0)^4) \frac{(\zeta_0 \zeta_0' v_u)^2}{S_0} > 0$$

$$m_3^2 - m_1^2 = -24 \eta_0 \xi_0 (9\xi_0^2 + \eta_0^2) \frac{(\zeta_0 \zeta_0' v_u)^2}{S_0}$$

normal hierarchy predicted

Model Predictions

M.-C.C, K.T. Mahanthappa
Phys. Lett. B652, 34 (2007); Phys. Lett. B681, 444 (2009)

spinorial representations ⇒ complex CGs
⇒ CPV in quark sector

- Charged Fermion Sector (7 parameters)

$$M_u = \begin{pmatrix} ig & \frac{1-i}{2}g & 0 \\ \frac{1-i}{2}g & g+(1-\frac{i}{2})h & k \\ 0 & k & 1 \end{pmatrix} y_t v_u \qquad M_d,\ M_e^T = \begin{pmatrix} 0 & (1+i)b & 0 \\ -(1-i)b & (1,-3)c & 0 \\ b & b & 1 \end{pmatrix} y_b v_d \phi_0$$

V_{cb} V_{ub}

$$\boxed{\theta_c \simeq \left|\sqrt{m_d/m_s} - e^{i\alpha}\sqrt{m_u/m_c}\right| \sim \sqrt{m_d/m_s},} \Rightarrow \boxed{\theta_{12}^e \simeq \sqrt{\frac{m_e}{m_\mu}} \simeq \frac{1}{3}\sqrt{\frac{m_d}{m_s}} \sim \frac{1}{3}\theta_c}$$

Georgi-Jarlskog relations ⇒ $V_{d,L} \neq I$
SU(5) ⇒ $M_d = (M_e)^T$
⇒ corrections to TBM related to θ_c

- Neutrino Sector (2 parameters)

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

$$\boxed{\theta_{13} \simeq \theta_c/3\sqrt{2}}$$

CGs of SU(5) & T′

$$\boxed{\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,TBM} + \frac{1}{2}\theta_c\cos\delta}$$

neutrino mixing angle

1/2

quark mixing angle

complex CGs: leptonic Dirac CPV
(the only non-zero leptonic CPV phase)

prediction for Majorana phases: 0, π

⇒ connection between leptogenesis & CPV in neutrino oscillation

correction accounts for discrepancy between exp best fit value and TBM prediction for solar angle

Numerical Results

- Experimentally: $m_u : m_c : m_t = \theta_c^{7.5} : \theta_c^{3.7} : 1 \qquad m_d : m_s : m_b = \theta_c^{4.6} : \theta_c^{2.7} : 1$
- Model Parameters at M_{GUT}:

$$M_u = \begin{pmatrix} ig & \frac{1-i}{2}g & 0 \\ \frac{1-i}{2}g & g + (1-\frac{i}{2})h & k \\ 0 & k & 1 \end{pmatrix} y_t v_u$$

$$\frac{M_d}{y_b v_d \phi_0 \zeta_0} = \begin{pmatrix} 0 & (1+i)b & 0 \\ -(1-i)b & c & 0 \\ b & b & 1 \end{pmatrix}$$

$$\begin{aligned} b &\equiv \phi_0 \psi_0' / \zeta_0 = 0.00304 \\ c &\equiv \psi_0 \zeta_0' / \zeta_0 = -0.0172 \\ k &\equiv y' \psi_0 \zeta_0 = -0.0266 \\ h &\equiv \phi_0^2 = 0.00426 \\ g &\equiv \phi_0'^3 = 1.45 \times 10^{-5} \end{aligned}$$

$y_t = 1.25$

$y_b \phi_0 \zeta_0 \simeq m_b / m_t \simeq 0.011$

7 parameters in charged fermion sector

predicting: 9 masses, 3 mixing angles, 1 CP Phase; all agree with exp within 3σ

- CKM Matrix and Quark CPV measures:

CPV entirely from CG coefficients

$$|V_{CKM}| = \begin{pmatrix} 0.974 & 0.227 & 0.00412 \\ 0.227 & 0.973 & 0.0412 \\ 0.00718 & 0.0408 & 0.999 \end{pmatrix}$$

$$\begin{aligned} A &= 0.798 \\ \bar{\rho} &= 0.299 \\ \bar{\eta} &= 0.306 \end{aligned}$$

$$\begin{aligned} \beta &\equiv \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = 23.6^o, \ \sin 2\beta = 0.734 \ , \\ \alpha &\equiv \arg\left(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) = 110^o \ , \\ \gamma &\equiv \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = \delta_q = 45.6^o \ , \\ J &\equiv \mathrm{Im}(V_{ud}V_{cb}V_{ub}^*V_{cs}^*) = 2.69 \times 10^{-5} \ , \end{aligned}$$

Direct measurements @ 3σ (ICHEP2010)

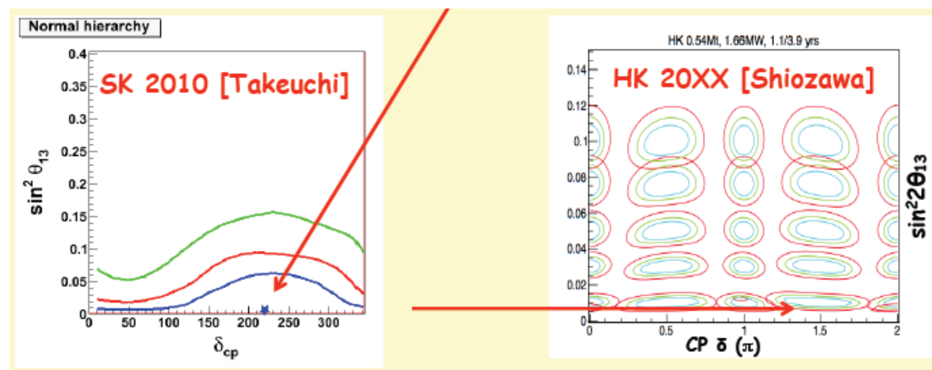
$$\begin{aligned} \sin 2\beta &= 0.672^{+0.069}_{-0.07} \\ \gamma\ (\mathrm{deg}) &= 71^{+46}_{-45} \\ \alpha\ (\mathrm{deg}) &= 89^{+21}_{-13} \end{aligned}$$

Numerical Results

- Diagonalization matrix for charged leptons $\begin{pmatrix} 0.997e^{i177^o} & 0.0823e^{i131^o} & 1.31\times10^{-5}e^{-i45^o} \\ 0.0823e^{i41.8^o} & 0.997e^{i176^o} & 0.000149e^{-i3.58^o} \\ 1.14\times10^{-6} & 0.000149 & 1 \end{pmatrix}$
- MNS Matrix   Note that these predictions do NOT depend on η_0 and ξ_0

$$|U_{MNS}| = \begin{pmatrix} 0.838 & 0.542 & 0.0583 \\ 0.362 & 0.610 & 0.705 \\ 0.408 & 0.577 & 0.707 \end{pmatrix}$$

prediction for Dirac CP phase: δ = 227 degrees



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

$$J_\ell = -0.00967$$ Dirac phase the only non-vanishing leptonic CPV phase

$\Rightarrow$ connection between leptogenesis & CPV in neutrino oscillation

SuperK best fit: δ = 220 degrees

- Neutrino Masses: using best fit values for Δm^2

$$\xi_0 = -0.0791\,, \quad \eta_0 = 0.1707\,, \qquad S_0 = 10^{12}\ \mathrm{GeV}$$

$$|m_1| = 0.00134\ \mathrm{eV},\ |m_2| = 0.00882\ \mathrm{eV},\ |m_3| = 0.0504\ \mathrm{eV}$$

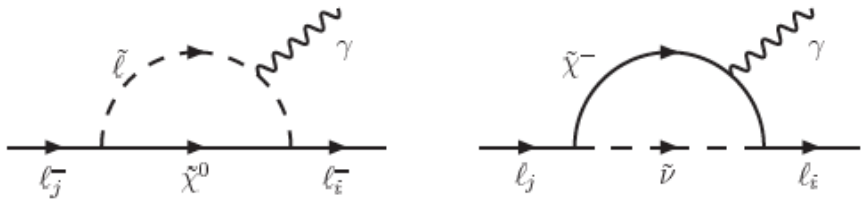
2 independent parameters in neutrino sector

- Majorana phases: $\alpha_{21} = \pi \qquad \alpha_{31} = 0.$

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

Predictions for LFV Radiative Decay

- SUSY GUTs: slepton-neutralino and sneutrino-chargino loop: Borzumati, Masiero (1986)



- CMSSM: at M_{GUT}, slepton mass matrices flavor blind
- RG evolution: generate off diagonal elements in slepton mass matrices
- dominant contribution: LL slepton mass matrix Hisano, Moroi, Tobe, Yamaguichi (1995)

$$BRji = \frac{\alpha^3}{G_F^2 m_s^8} |(m_{LL}^2)_{ji}|^2 \tan^2\beta$$

$$(m_{LL}^2)_{ji} = -\frac{1}{8\pi^2} m_0^2 (3 + A_0^2/m_0^2) Y_{jk}^\dagger \log\left(\frac{M_G}{M_k}\right) Y_{ki}$$

very model dependent

good approximation to full evolution effects:

$$m_s^8 \simeq 0.5 m_0^2 M_{1/2}^2 (m_0^2 + 0.6 M_{1/2}^2)^2$$

Petcov, Profumo, Takanishi, Yaguna (2003)

Predictions for LFV Radiative Decay

- in SUSY SU(5) x T' model:

M.-C.C., Mahanthappa, Meroni, Petcov, under preparation

  - degenerate RH masses
  - ratios of branching fractions depend on mixing & light neutrino masses

$$Y^{+}Y = \begin{pmatrix} 0.000122635 & 0.0000589172 & 0.000131458 \\ 0.0000589172 & 0.000941119 & 0.000720549 \\ 0.000131458 & 0.000720549 & 0.000936627 \end{pmatrix}$$

  - predicting $$Br(\mu \to e\gamma) < Br(\tau \to e\gamma) < Br(\tau \to \mu\gamma)$$

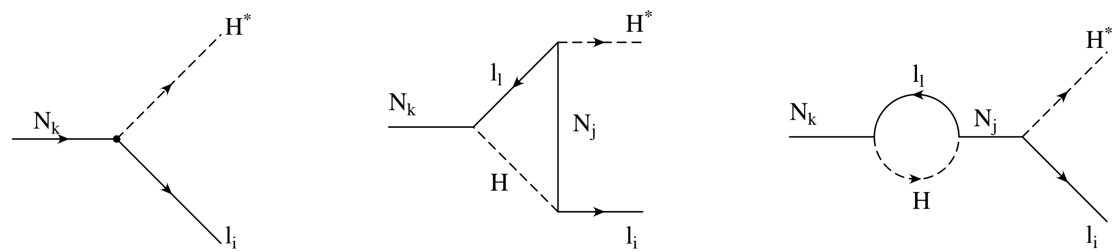
  - $m_0 = 50$ GeV, $M_{1/2} = 200$ GeV, $A_0 = 7m_0$:
    - $Br(\tau \to \mu + \gamma) = 1.38 \times 10^{-9}$
    - $Br(\tau \to e + \gamma) = 4.59 \times 10^{-11}$
    - $Br(\mu \to e + \gamma) = 9.23 \times 10^{-12}$

Sakharov's Conditions

- Necessary conditions for Bayogenesis [Matter-Antimatter Asymmetry]
  - baryon number violation
  - CP violation
  - out-of-equilibrium
- CP violation in quark sector gives too small baryon number asymmetry
- neutrino oscillation opens up new possibility
  - leptogenesis: require leptonic CP phase   Fukugita, Yanagida, 1986

Leptogenesis

- RH heavy neutrino decay: Fukugita, Yanagida, '86; Luty, '92; Covi, Roulet, Vissani, '96; Flanz et al, '96; Plumacher, '97; Pilaftsis, '97; Buchmuller, Plumacher, '98
  - quantum interference of tree-level & one-loop diagrams ⇒ primordial lepton number asymmetry ΔL



  - asymmetry (RH neutrino N_i decay into lepton of flavor α) Pascoli, Petcov, Riotto, 2006

$$\epsilon_{i\alpha} = \frac{[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})]}{\sum_\alpha [\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})]}$$

$$= -\frac{3M_i}{16\pi v^2} \frac{\mathrm{Im}(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{i\beta} R_{i\rho})}{\sum_\beta m_\beta |R_{i\beta}|^2}$$

$m = \mathrm{diag}(m_1, m_2, m_3)$ (light neutrino masses)

$M = \mathrm{diag}(M_1, M_2, M_3)$ (RH neutrino masses)

$R = vM^{-1/2} h U m^{-1/2}$ R: phases in RH sector

R: high energy parameters
U: low energy information

depend on parameters in both high energy (i.e. RH neutrinos) & low energy (i.e. effective light neutrinos) sectors

- EW non-perturbative effects:
  ΔL → ΔB

Leptogenesis ↔ Low Energy Observables

- three flavors distinguished by Yukawa interactions:
- Y_τ, Y_μ, Y_e equilibrium at temperatures below 10^{12}, 10^9, 10^6 GeV, respectively
- Flavor effect: Abada, Davidson, Josse-Michaux, Losada, Riotto, 2006; Nardi, Nir, Roulet, Racker, 2006
  - $T \sim M_1 > 10^{12}$ GeV: Y_e, Y_μ, Y_τ out of equilibrium ⇒ 1 flavor regime

$$\epsilon_i \equiv \sum_\alpha \epsilon_{i\alpha} = -\frac{3M_i}{16\pi v^2}\frac{\mathrm{Im}(\sum_\rho m_\rho^2 R_{i\rho}^2)}{\sum_\beta m_\beta |R_{i\beta}|^2}$$

only depend on high energy phases (R)

presence of low energy leptonic CPV (neutrino oscillation, neutrinoless double beta decay)

real R, complex U:

non-vanishing low energy CPV (h)

vanishing leptogenesis

$\not\leftrightarrow$ leptogenesis ≠ 0

- no model independent connection can exist

Leptogenesis ↔ Low Energy Observables

- leptogenesis at $T \sim M_1 < 10^{12}$ GeV:
  - flavors distinguishable ($T_{eq} = Y^2 M_{pl}$) ⇒ non-universal wash-out effects
    - $T \sim M_1 \sim (10^9 - 10^{12})$ GeV: Y_e, Y_μ out of equilibrium; Y_τ in equilibrium
      - 2 flavor regime: ($\varepsilon_e + \varepsilon_\mu$), ε_τ evolve independently
    - $T \sim M_1 \sim (10^6 - 10^9)$ GeV: Y_e, out of equilibrium; Y_μ, Y_τ in equilibrium
      - 3 flavor regime: ε_e, ε_μ, ε_τ evolve independently
  - asymmetry associated with each flavor

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{\alpha\beta}^* U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

$\boxed{\text{leptogenesis} \neq 0}$ ⇒ $\boxed{\text{low energy CPV} \neq 0}$

Connection in Specific Models

- models for neutrino masses:
  - additional symmetries or textures
  - reduce the number of parameters ⇒ connection can be established
- texture assumption (may be realized by symmetry)
  - models with 2 RH neutrinos (2 x 3 seesaw) Kuchimanchi & Mohapatra, 2002
  - sign of baryon asymmetry ↔ sign of CPV in ν oscillation Frampton, Glashow, Yanagida, 2002
- all CP come from a single source
  - models with spontaneous CP violation:
    - minimal LR model: only 1 physical leptonic CP phase M.-.C.C, Mahanthappa, 2005
    - SM + vectorial quarks + singlet scalar Branco, Parada, Rebelo, 2003
    - SCPV in SO(10): $<126>_{B-L}$ complex Achiman, 2004, 2008
  - SUSY SU(5) x T′ Model: M.-.C.C, Mahanthappa, 2009
    - geometrical origin of CP violation ⇒ only lepton Dirac CP phase ≠ 0

Leptogenesis in SUSY SU(5) x T′

M.-C.C, K.T. Mahanthappa, arXiv:1107.xxxx

- TBM from broken discrete symmetries through type-I seesaw E. Jenkins, A. Manohar, 2008
- exact TBM: $\sin\theta_{13} = 0 \;\Rightarrow\; J_{CP}^{lep} \propto \sin\theta_{13} = 0$ CP violation through Majorana phases: $\alpha_{21},\ \alpha_{31}$
- no leptogenesis as $\mathrm{Im}(hh^\dagger) = 0$
- true even when flavor effects included

In usual seesaw realization:
R = diagonal $\Rightarrow \varepsilon_{i\alpha} = 0$

Choubey, King, Mitra, 2010

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

$$R = vM^{-1/2}U_{\nu,R}M_D U_{\text{TBM}} m^{-1/2} \rightarrow \text{real, non-diagonal (12) block}$$

Dirac CPV phase ⇒ non-vanishing lepton number asymmetry

Radiatively induced RH neutrino mass splitting ⇒ resonant enhanced asymmetry ⇒ sufficient for observed baryon number asymmetry

Dirac phase the only non-vanishing leptonic CPV phase
⇒ connection between leptogenesis & low energy CPV

Sum Rules: Quark-Lepton Complementarity

Quark Mixing

mixing parameters	best fit	3σ range
θ^q_{23}	2.36^o	2.25^o - 2.48^o
θ^q_{12}	12.88^o	12.75^o - 13.01^o
θ^q_{13}	0.21^o	0.17^o - 0.25^o

Lepton Mixing

mixing parameters	best fit	3σ range
θ^e_{23}	42.8^o	35.5^o - 53.5^o
θ^e_{12}	34.4^o	31.5^o - 37.6^o
θ^e_{13}	5.6^o	$\leq 12.5^o$

measuring leptonic mixing parameters to the precision of those in quark sector

- QLC-I

  (BM)

  $\theta_c + \theta_{sol} \cong 45^o$ Raidal, '04; Smirnov, Minakata, '04

  $\theta^q_{23} + \theta^e_{23} \cong 45^o$

  improved $\delta\theta_{12}$ from SNO+, SuperK possible

- QLC-II

  (TBM)

  $\tan^2\theta_{sol} \cong \tan^2\theta_{sol,TBM} + (\theta_c / 2) * \cos \delta_e$

  $\theta^e_{13} \cong \theta_c / 3\sqrt{2}$ Ferrandis, Pakvasa; King; Dutta, Mimura; M.-C.C., Mahanthappa

- testing these sum rules could be a more robust way to distinguish different models

Other Possibilities

- Tri-bimaximal Mixing Accidental or NOT? Albright, Rodejohann (2009); Abbas, Smirnov (2010)
  - current data precision: TBM can be accidental ⇒ open up other possibilities
- Golden Ratio for solar angle

$\tan^2\theta_{sol} = 1/\Phi^2 = 0.382$, ($1.4\sigma$ below best fit)

$\Phi = (1 + \sqrt{5}) / 2 = 1.62$

Datta, Ling, Ramond, '03;
Z2 x Z2: Kajiyama, Raidal, Strumia, '07;
A5: Everett, Stuart, '08; ...

- Dodeca Mixing Matrix from D_{12} Symmetry J. E. Kim, M.-S. Seo, arXiv:1005.4684 [hep-ph]

leading order:

$\theta_c = 15^o$, $\theta_{sol} = 30^o$, $\theta_{atm} = 45^o$

$$V_{\rm PMNS} = U_l^\dagger U_\nu = \begin{pmatrix} \cos\frac{\pi}{6} & \sin\frac{\pi}{6} & 0 \\ -\frac{1}{\sqrt{2}}\sin\frac{\pi}{6} & \frac{1}{\sqrt{2}}\cos\frac{\pi}{6} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}}\sin\frac{\pi}{6} & \frac{1}{\sqrt{2}}\cos\frac{\pi}{6} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\left.\begin{array}{r} 12 = 360^o / 30^o \;\Rightarrow Z_{12} \\ 15^o \Rightarrow Z_2 \end{array}\right\} Z_{12} \times Z_2 = D_{12}$$

$\theta_c + \theta_{sol} = 45^o$ (not from GUT symmetry)

breaking of D_{12} :

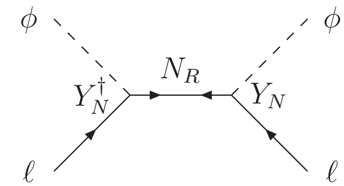
$\theta_c = 15^o \rightarrow 13.4^o$

$\theta_{sol} = 30^o + O(\varepsilon)$, $\theta_{13} = O(\varepsilon)$

TeV Scale Seesaw Models

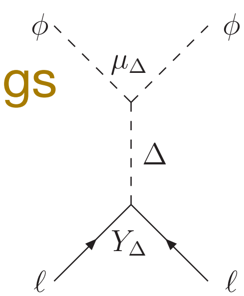
For a recent review:
M.-C. C., J.R. Huang, arXiv:1105.3188

- Without new interactions:
    - type-I seesaw   Kersten, Smirnov, 2007
        - RH neutrino produced by gauge interaction
        - production cross section suppressed by heavy-light mixing
        - generally decouple from collider physics



- type-II seesaw
    - TeV scale doubly charged Higgs ⇔ small couplings
    - unique signatures: $\Delta^{++} \to e^+e^+,\ \mu^+\mu^+,\ \tau^+\tau^+$
        - produced through gauge interaction
        - independent of light-heavy mixing
        - 300 fb^{-1} for $M_\Delta \sim 600$ GeV at LHC

Perez, Han, Huang, Li, Wang, '08; ...



Han, Mukhopadhyaya, Si, Wang, '07;
Akeroyd, Aoki, Sugiyama, '08; ...

TeV Scale Seesaw Models

- With new interactions:
  - SUSY LR Model:
    - TeV Scale W_R ⇔ small Yukawa
    - tested via searches for W_R
    - production independent of light-heavy mixing
    - LHC: W_R up to (3-4) TeV , ν_R in (100-1000) GeV range

Azuleos et al 06; del Aguila et al 07, Han et al 07; Chao, Luo, Xing, Zhou, '08; ...

- More Naturally: inverse seesaw or higher dimensional operators or Extra Dim
  - SO(10): adjoint fermions + inverse seesaw
  - inverse seesaw
  - adjoint SU(5)
  - higher dimensional effective operators
  - TeV Scale Extra Dimension

TeV Scale Seesaw Models

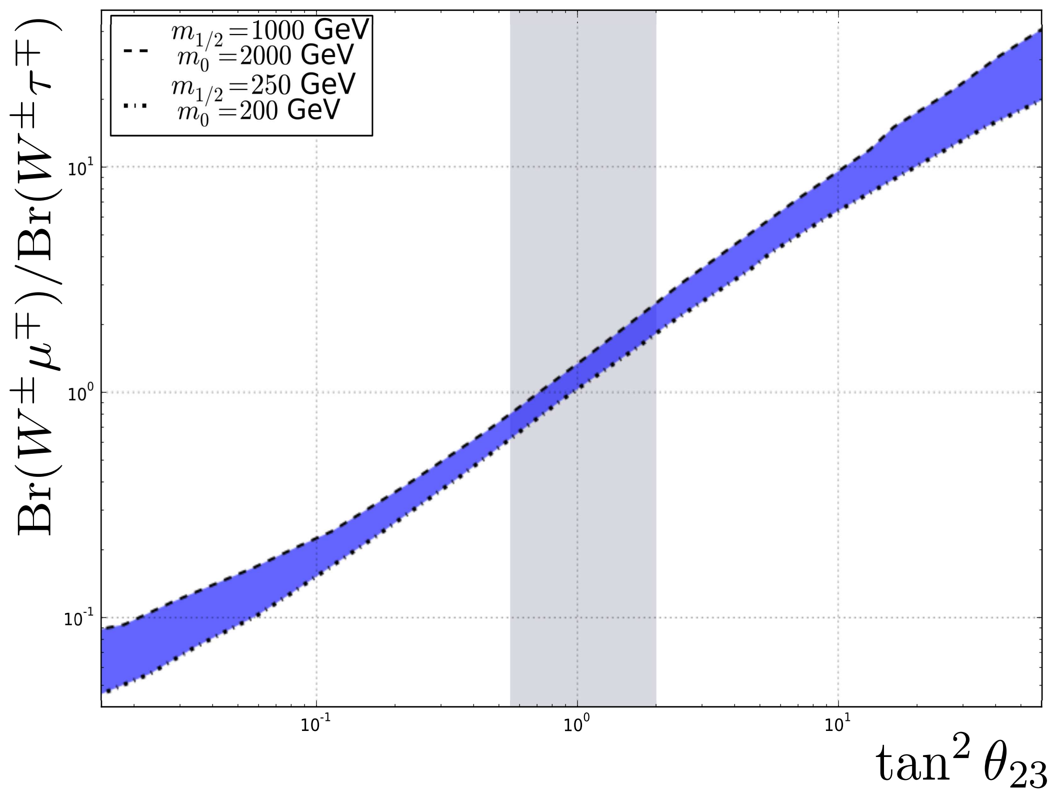
de Campos, Eboli, Hirsch, Margo, Porod, Restrepo, Valle, 2010

- MSSM with bi-linear R-Parity Violation

$$\mathcal{W}_R = \epsilon_i \hat{L}_i \hat{H}_u$$

- mixing angle ↔ neutralino decay:

$$\tan^2\theta_{\rm atm} \simeq \frac{BR(\tilde{\chi}^0_1 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}^0_1 \to \tau^\pm W^\mp)}$$



TeV Scale Seesaw and Non-anomalous U(1)

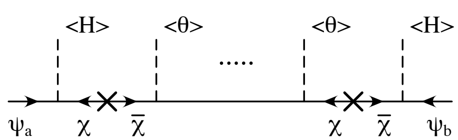
M.-C. C., de Gouvea, Dobrescu (2006)

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

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

- neutrino masses generated by very high dimensional operators

$$m_{LL} \sim \left(\frac{\langle\phi\rangle}{M}\right)^p \frac{HHLL}{M} \to M \sim TeV, \quad \text{for large } p \qquad \frac{\langle\phi\rangle}{M} \sim \text{not too small} \quad \sim 0.1$$



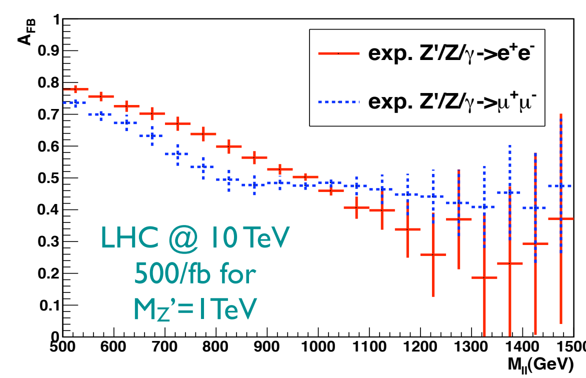
$\Lambda \sim$ TeV!

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

- anomaly cancellation: relate flavorful fermion charges

  ⇒ predict mass hierarchy and mixing
- neutrinos can either be Dirac or Majorana
- TeV scale Z′: probing flavor sector at LHC

M.-C. C., J.-R. Huang (2009)



Prediction for Sparticle Spectrum

M.-C. C., J.-R. Huang (2010)

- predict testable (RG invariant) mass sum rules in AMSB among sparticles at colliders

$$\bar{m}^2_{Q_i} + \bar{m}^2_{u^c_i} + \bar{m}^2_{H_u} = (m^2_{Q_i} + m^2_{u^c_i} + m^2_{H_u})_{AMSB} \; (i = 1,2,3)$$
$$\bar{m}^2_{Q_i} + \bar{m}^2_{d^c_i} + \bar{m}^2_{H_d} = (m^2_{Q_i} + m^2_{d^c_i} + m^2_{H_d})_{AMSB} \; (i = 1,2,3)$$
$$\bar{m}^2_{L_i} + \bar{m}^2_{e^c_i} + \bar{m}^2_{H_d} = (m^2_{L_i} + m^2_{e^c_i} + m^2_{H_d})_{AMSB} \; (i = 1,2,3)$$

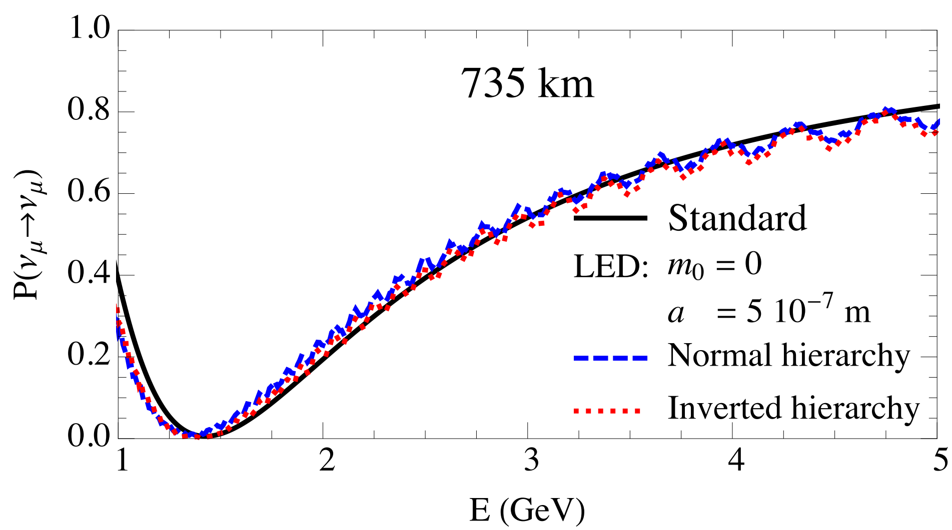
functions of gauge couplings, Yukawa couplings and gravitino mass ($m_{3/2}$)

Flavor Physics at the Collider

Constraints on Extra Dimension

Machado, Nunokawa, Zukanovich Funchal, 2011

- Set-up: 1 large extra dimension
  - 3 RH neutrinos propagate in bulk
  - SM lepton doublets & Higgs: confined to SM brane
  - naturally small Dirac mass due to volume suppression
- mixing between active neutrinos and KK modes:



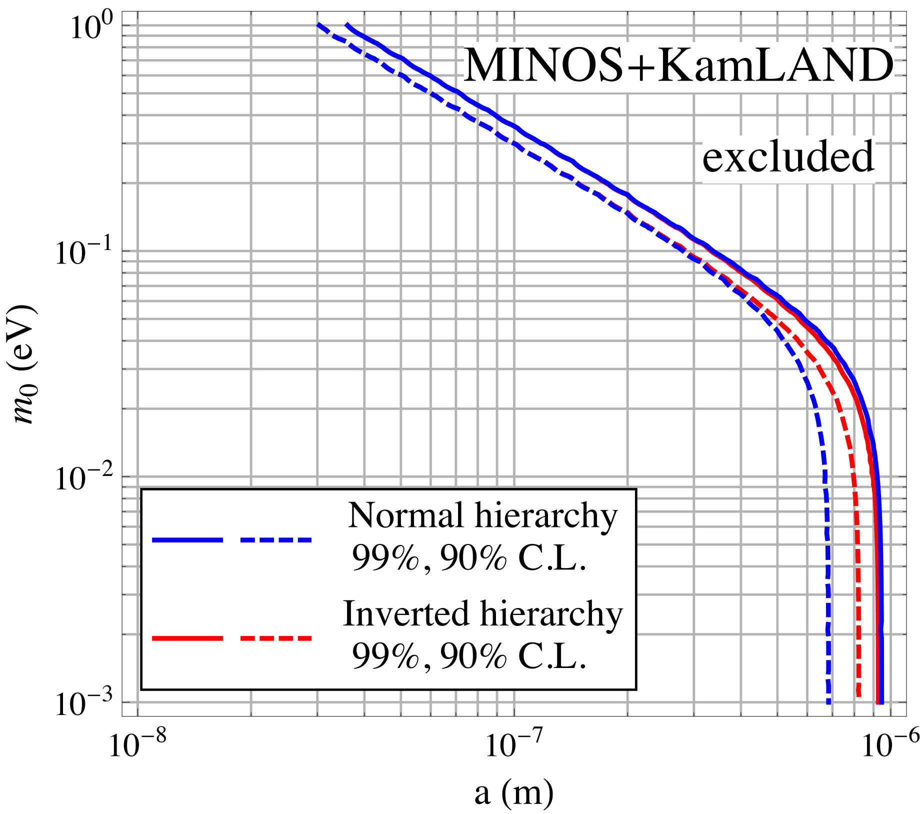
$$P(\nu_\alpha^{(0)} \to \nu_\beta^{(0)}; L) = \left| \sum_{i,j,k} \sum_{N=0}^{\infty} U_{\alpha i} U_{\beta k}^{*} W_{ij}^{(0N)*} W_{kj}^{(0N)} \exp\left(i \frac{\lambda_j^{(N)2} L}{2Ea^2} \right) \right|^2$$

- shift in oscillation minima
- global reduction of survival probabilities
- extra wiggles

Constraints on Extra Dimension

- constraints from neutrino experiments

Machado, Nunokawa, Zukanovich Funchal, 2011



current table top experiment:

$a < 2 \times 10^{-4}$ m

Curing FCNC Problem: Family Symmetry vs MFV

- low scale new physics severely constrained by flavor violation
- Minimal Flavor Violation

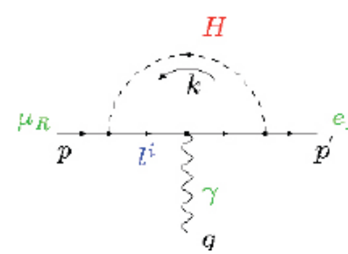
D'Ambrosio, Giudice, Isidori, Strumia (2002);
Cirigliano, Grinstein, Isidori, Wise (2005)

  - assume Yukawa couplings the only source of flavor violation

- Example: Warped Extra Dimension

$$\psi_{(0)} \sim e^{(1/2-c)ky}$$

  - wave function overlap ⇒ naturally small Dirac neutrino mass
  - non-universal bulk mass terms (c) ⇒ FCNCs at tree level ⇒ Λ > O(10) TeV
    - FCNCs: present even in the limit of massless neutrinos
      - tree-level: μ-e conversion, μ→3e, etc
    - charged current
      - one-loop: μ→e+γ, τ→e+γ, τ→μ+γ



  - fine-tuning to get large mixing and mild mass hierarchy for neutrinos

Curing FCNC Problem: Family Symmetry vs MFV

- Two approaches:
  - Minimal Flavor Violation in RS

    quark sector: A. Fitzpatrick, G. Perez, L. Randall (2007)
    lepton sector: M.-C.C., H.B. Yu (2008)

$$C_e = aY_e^\dagger Y_e, \quad C_N = dY_\nu^\dagger Y_\nu, \quad C_L = c(\xi Y_\nu Y_\nu^\dagger + Y_e Y_e^\dagger)$$

  - T´ symmetry in the bulk for quarks & leptons:

    M.-C.C., K.T. Mahanthappa, F. Yu (PLB2009);
    A4 for leptons: Csaki, Delaunay, Grojean, Grossmann

    - TBM neutrino mixing: common bulk mass term, no tree-level FCNCs
    - TBM mixing and masses decouple: no fine-tuning
    - realistic masses and mixing angles in quark sector
    - no tree-level FCNCs in lepton sector and 1-2 family of quark sector

- Family Symmetry: alternative to MFV to avoid FCNCs in TeV scale new physics
  - many family symmetries violate MFV ⇒ possible new FV contributions

Conclusions

- current data consistent with TBM mixing
- finite group family symmetry T´ x SU(5):
  - group theoretical origin of mixing
  - CP violation from complex CG coefficients
  - QLC: $$\boxed{\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,TBM} + \frac{1}{2}\theta_c\cos\delta}$$ $$\boxed{\theta_{13} \simeq \theta_c/3\sqrt{2}}$$

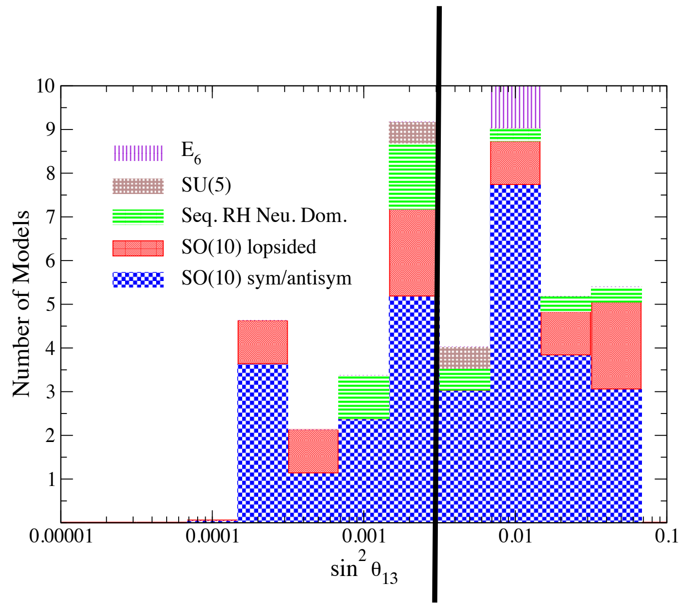
quark CP phase: γ = 45.6 degrees

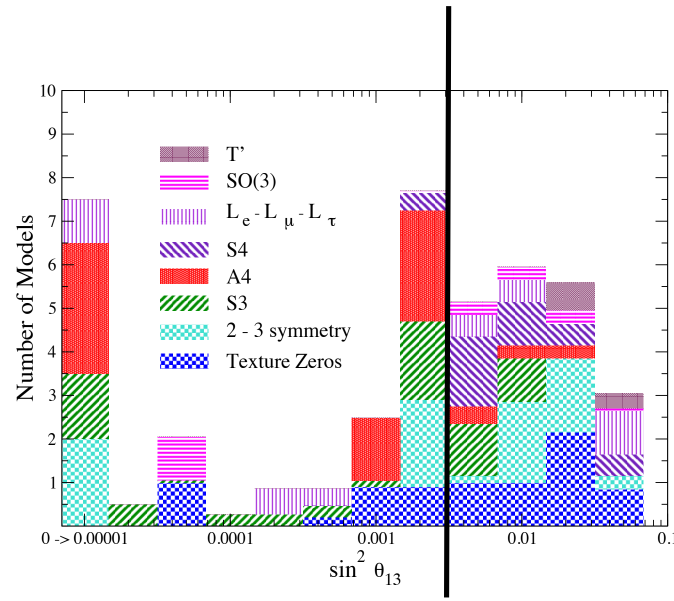
δ = 227 degrees

- More precise measurements of oscillation parameters important for pinning down the underlying new physics
- New interactions (gauge symmetry, extra dimensions, SUSY): may probe flavor sector at colliders
- If T2K result holds up ⇒ large deviation from TBM
  - Future data will tell!

Backup

- If T2K result holds up ⇒





C.H. Albright (2009); updates from M.-C. C., C. H. Albright (2006)