Overview on Neutrino Mass Models and their Predictions

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Where Do We Stand?

- Exciting Time in ν Physics: recent hints of large θ_{13} from T2K, MINOS, Double CHOOZ
- Latest 3 neutrino global analysis (including T2K and MINOS):

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

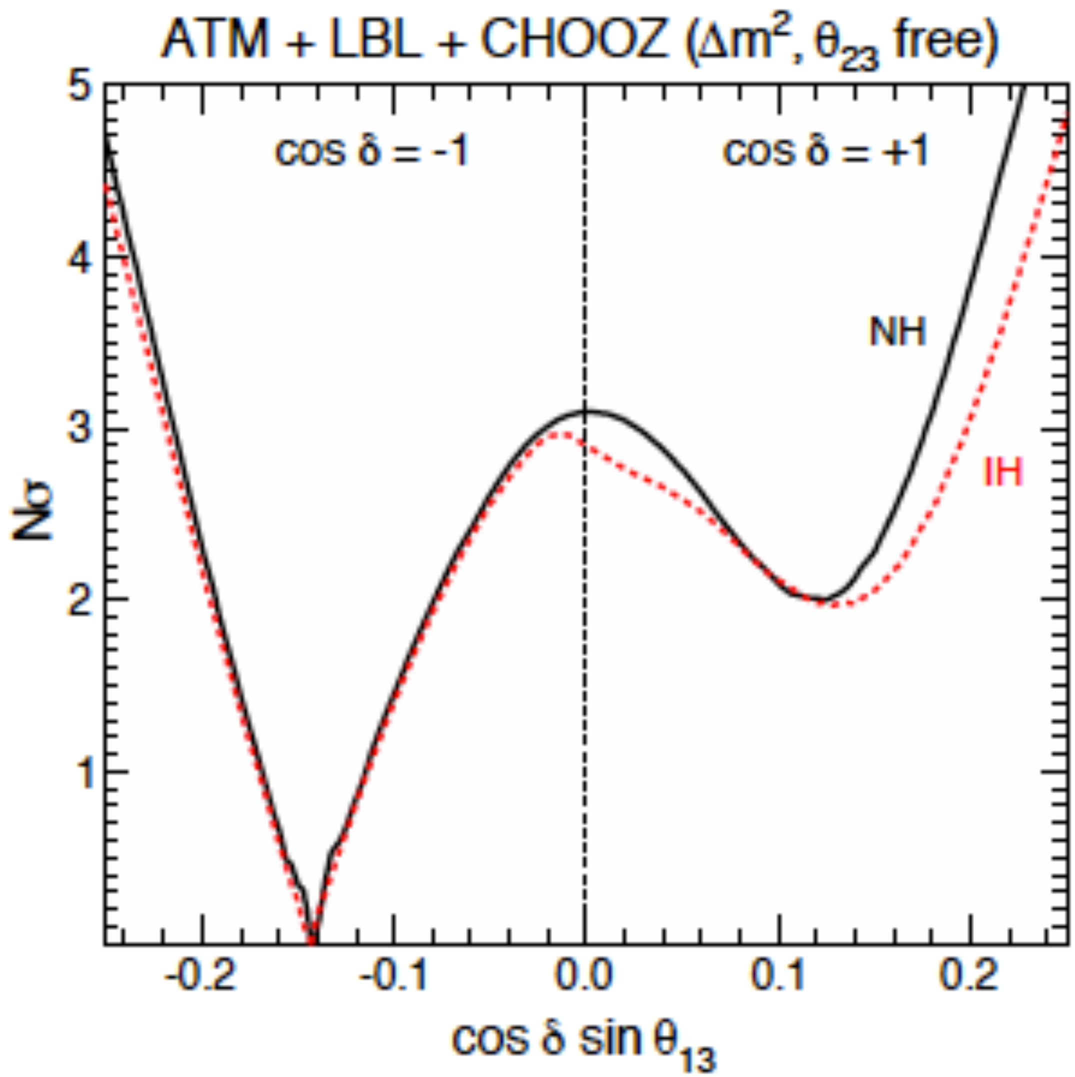
Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028

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)		

Current Global Fit: $\theta_{13} \neq 0$ at 3σ

Cautions!! Different global fit analyses assume different error correlations among experiments ⇒ different results

Global Fit Including T2K/MINOS Results



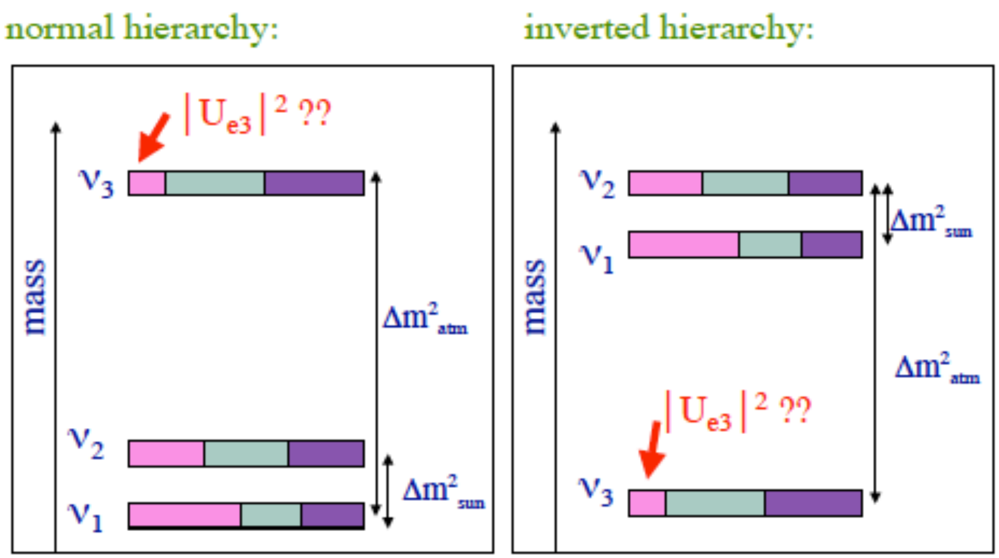
Fogli, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028

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

constraint on leptonic Dirac CP phase from global fit, albeit not statistically significant

Where Do We Stand?

- The known knowns:



What's Next?
Reactor Exp: Double CHOOZ, Daya Bay, Reno
Long Baseline Exp: MINOS, NOvA, T2K, LBNE...

The known unknowns:

- 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?

The unknown unknowns?

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)

    for a review, see e.g. M.-C. C, J.R. Huang, MPLA (2011)
- TeV scale new physics (extra dimension, 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); de Gouvea, Murayama (2003)
  - near degenerate spectrum, large mixing
  - predictions strongly depend on choice of statistical measure
- family symmetry: there's a structure, expansion parameter (~~symmetry~~ effect)
  - mixing result from dynamics of underlying symmetry
  - for leptons only (normal or inverted)
  - for quarks and leptons: quark-lepton connection ↔ GUT (normal)

- In most part of this talk: assume 3 generations, no LSND/MiniBoone/Reactor Anomaly
  - 4th generation model: (3+3) consistent with experiments including MiniBoone

    Hou, Lee, arXiv:1004.2359
  - sterile neutrinos: tension between fit to oscillation data and cosmology

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)

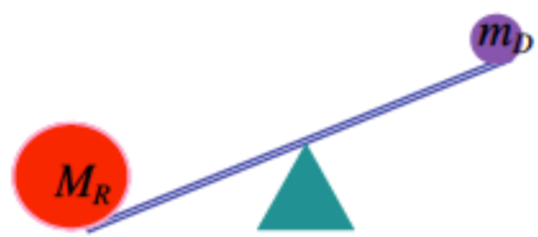
$\nu_R \nu_R$ mass term allowed

- 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 $m_D \sim m_t \sim 180\ GeV$

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

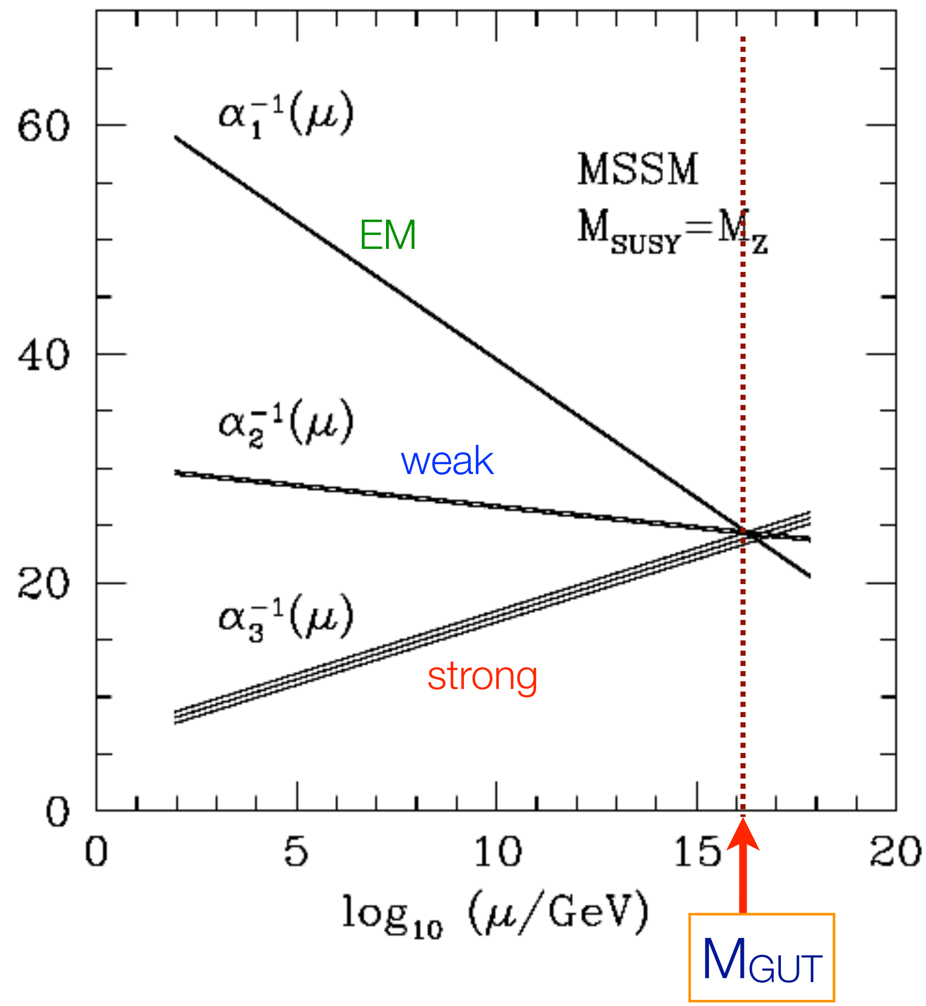
Grand Unification

- 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

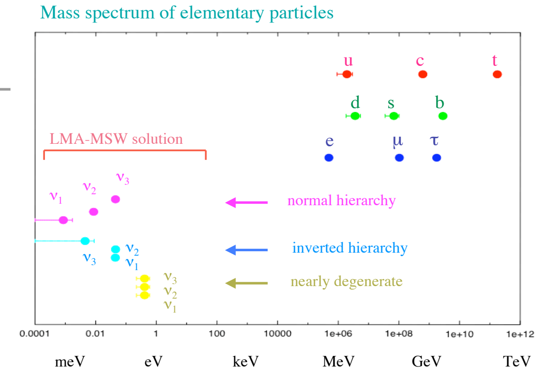
$$m_\nu \sim (\Delta m^2_{atm})^{1/2},\ m_D \sim m_{top}$$

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

coupling constants run!



Origin of Mass Hierarchy and Mixing

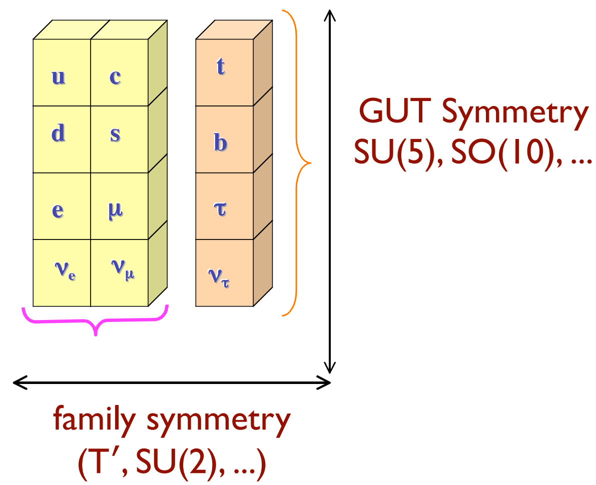


- In the SM: 22 physical quantities which seem unrelated
- Question arises whether these quantities can be related
- No fundamental reason can be found in the framework of SM
- less ambitious aim ⇒ reduce the # of parameters by imposing symmetries
  - SUSY Grand Unified Gauge Symmetry
    - GUT relates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

⇒ Experimentally testable correlations among physical observables

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}
  - Q_4

Motivation: Tri-bimaximal (TBM) neutrino mixing

Discussion on Discrete gauge anomaly:
Araki, Kobayashi, Kubo, Ramos-Sanchez, Ratz, Vaudrevange (2008)

Tri-bimaximal Neutrino Mixing

- 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)

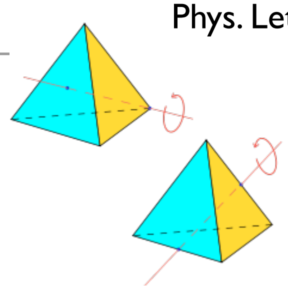
$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

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

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

An Example: a SUSY SU(5) x T´ Model

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



- Double Tetrahedral Group T´
  - may arise from extra dimensions
- Symmetries ⇒ 9 parameters in Yukawa sector ⇒ 22 physical observables
  - neutrino mixing angles from group theory (CG coefficients)
  - TBM: misalignment of symmetry breaking patterns
    - neutrino sector: T' → G_{TST2} , charged lepton sector: T' → G_T
  - GUT symmetry ⇒ deviation from TBM related to quark mixing θ_c
  - **complex CG's of T´ ⇒ Novel Origin of CP Violation**

    M.-C.C, K.T. Mahanthappa, Phys. Lett. B681, 444 (2009)
    - CP violation in both quark and lepton sectors entirely from group theory
    - connection between leptogenesis and CPV in neutrino oscillation
- family symmetry: forbid Higgsino mediated proton decay

Predictions: a SUSY SU(5) x T´ Model

M.-C.C, K.T. Mahanthappa
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- Charged Fermion Sector (7 parameters)

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

V_{cb}

$$M_d,\ M_e^T = \begin{pmatrix} 0 & (1+i)b & 0 \\ -(1-i)b & (1,-3)c & 0 \\ b & b & 1 \end{pmatrix} y_b v_d \phi_0$$

V_{ub}

spinorial representations ⇒ complex CGs
⇒ CPV in quark sector

quark CP phase: γ = 45.6 degrees

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

$$m_d \simeq 3 m_e \qquad m_\mu \simeq 3 m_s$$

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

$$\theta_{12}^e \simeq \sqrt{\frac{m_e}{m_\mu}} \simeq \frac{1}{3}\sqrt{\frac{m_d}{m_s}} \sim \frac{1}{3}\theta_c$$

SU(5) ⇒ $M_d = (M_e)^T$
⇒ corrections to TBM related to θ_c

Predictions: a SUSY SU(5) x T´ Model

M.-C.C, K.T. Mahanthappa
Phys. Lett. B652, 34 (2007);
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- Neutrino Sector (2 parameters):

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

- Seesaw mechanism:

$$U_{TBM}^T M_\nu U_{TBM} = \mathrm{diag}((3\xi_0 + \eta_0)^2, \eta_0^2, -(-3\xi_0 + \eta_0)^2) \frac{(\zeta_0 \zeta_0' v_u)^2}{s_0 \Lambda}$$

- Prediction for MNS matrix:

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

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

CGs of SU(5) & T´

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

complex CGs: leptonic Dirac CPV

δ = 227 degrees

⇒ connection between leptogenesis & leptonic CPV at low energy

neutrino mixing angle

1/2

quark mixing angle

- sum rule among absolute masses:

normal hierarchy predicted

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

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

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	$\leq 12.5^o$

- QLC-I (BM)
  $\theta_C + \theta_{sol} \cong 45^o$ Raidal, '04; Smirnov, Minakata, '04
  $\theta^q_{23} + \theta^e_{23} \cong 45^o$

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

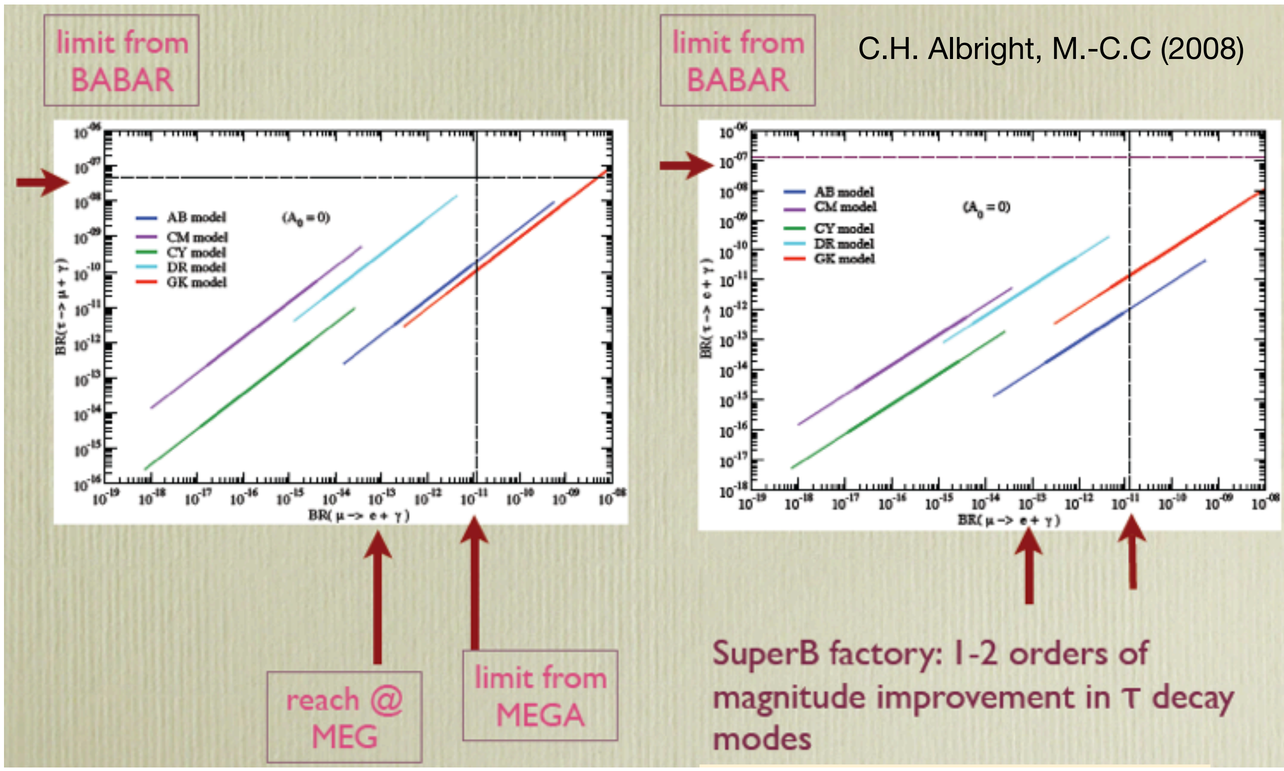
- QLC-II (TBM)
  $\tan^2\theta_{sol} \cong \tan^2\theta_{sol,TBM} + (\theta_C / 2) * \cos \delta_e$
  $\theta^e_{13} \cong \theta_C / 3\sqrt{2}$ Ferrandis, Pakvasa; King; Dutta, Mimura; M.-C.C., Mahanthappa

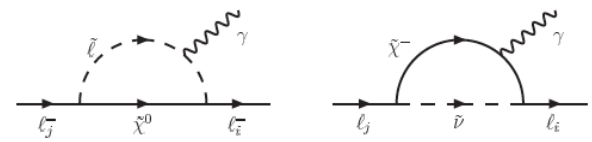
- testing sum rules: a *more* robust way to distinguish different classes of models

need improved $\delta\theta_{12}$ measurement

Correlations among other Observables

- SUSY GUTs: Lepton flavor violating charged lepton decays
  - five viable SUSY SO(10) models with dark matter constraints:





- individual branching fraction: strong dependence on soft SUSY parameters
- correlations between branching fractions: strong dependence on flavor structure

Correlations among other Observables

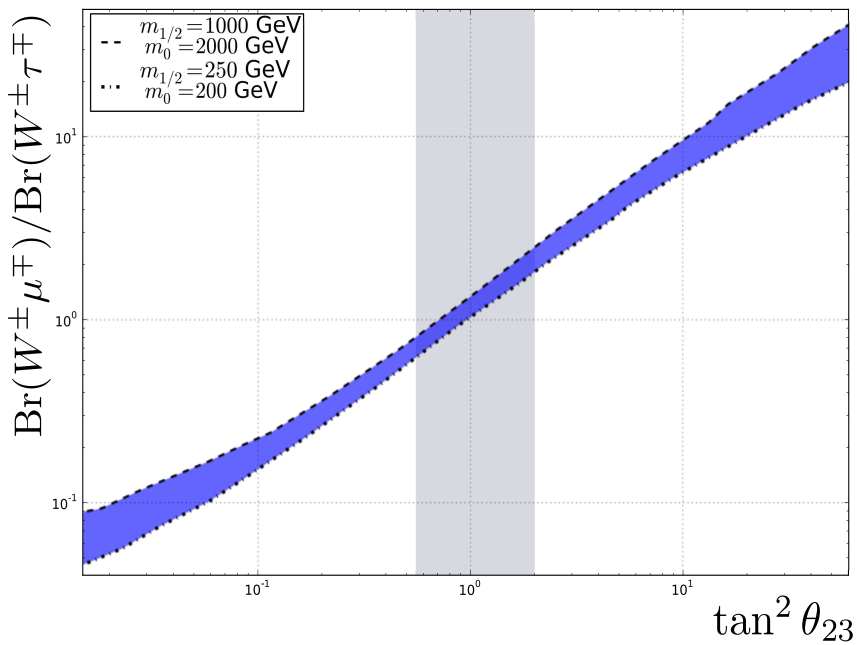
- MSSM with bi-linear R-Parity Violation

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

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

  - TeV scale mechanism for neutrino mass
  - mixing angle ↔ neutralino decay

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



"Large" Deviations from TBM

- Generically: corrections on the order of $(\theta_c)^2$ numerically
  - from charged lepton sector: through GUT relations
  - from neutrino sector: higher order contributions
- Modifying the Neutrino sector: Different symmetry breaking patterns
  - A4: group of order 12 ⇒ many subgroups
  - systematic study of breaking into other A4 subgroups
  - several solutions give realistic masses, $\theta_{13} \sim (5 - 10)^o$, $\theta_{23} - \pi/4 > 0$
  - more complicated flavon sector

M.-C.C, J. Huang, J. O'Bryan, A. Wijangco, F. Yu, under preparation

deviations correlated

- Modifying the charged lepton sector:
  - breaking the relation (based on single SU(5) CG): $\theta_{12}^e \simeq \sqrt{\frac{m_e}{m_\mu}} \simeq \frac{1}{3}\sqrt{\frac{m_d}{m_s}} \sim \frac{1}{3}\theta_c$
  - Georgi-Jarlskog relations achieved by combination of several SU(5) CGs
  - $\theta_{13} \sim (5 - 10)^o$ possible
  - more complicated SU(5) particle content

Antusch, Spinrath (2009); Antusch, Maurer (2011); Marzocca, Petcov, Romanino, Spinrath, (2011)

Other Possibilities: Beyond TBM

- Tri-bimaximal Mixing Accidental or NOT? Albright, Rodejohann (2009); Abbas, Smirnov (2010)
  - current data precision: TBM can be accidental ⇒ open up other possibilities
- Dodeca Mixing Matrix from D_{12} Symmetry

J. E. Kim, M.-S. Seo, (2010)

leading order:

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

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

breaking of D_{12} :

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

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

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

deviations correlated

- Golden Ratio for solar mixing 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 or A5: Kajiyama, Raidal, Strumia, '07; ...
D10: Adulpravitchai, Blum, Rodejohann, '09; ...

  - prediction for θ_{13} model/parameter dependent

Conclusions

- efforts at current and future experiments important
  - fundamental properties of neutrinos
  - underlying new physics for neutrino mass and mixing
- Example: a SUSY SU(5) x T´ Model
  - 9 parameters ⇒ 22 physical observables
  - group theoretical origin of mixing
  - CP violation from complex CG coefficients

quark CP phase: γ = 45.6 degrees

δ = 227 degrees

  - QLC sum rules:

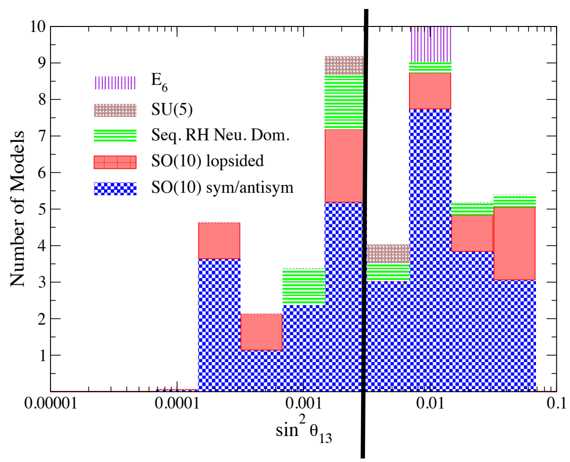
$$\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,TBM} + \frac{1}{2}\theta_c\cos\delta$$

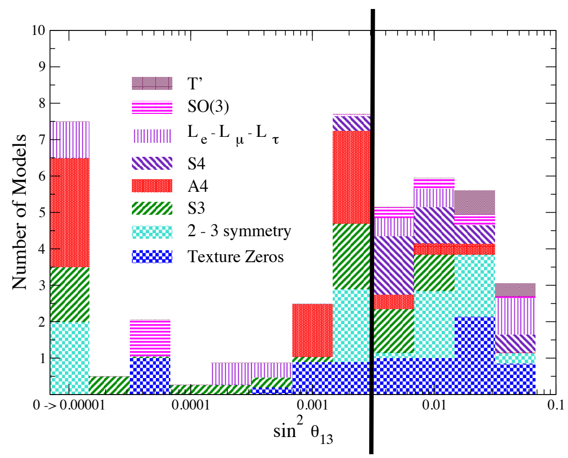
$$\theta_{13} \simeq \theta_c/3\sqrt{2}$$

  - normal hierarchy predicted
  - firm predictions for leptogenesis, 0νββ decay and LFV processes

Conclusions

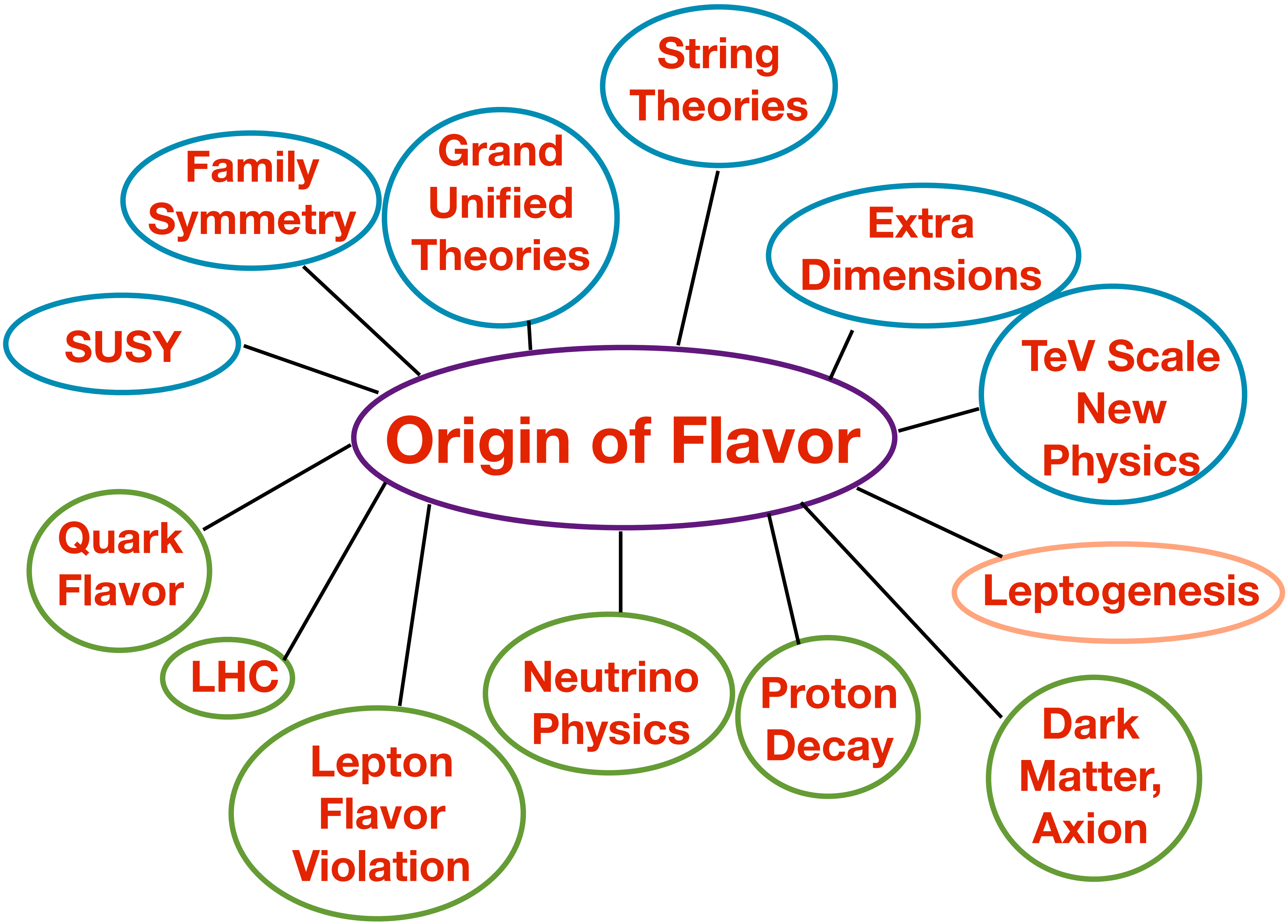
- precise measurements of oscillation parameters important for pinning down underlying new physics





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

- Testing correlations: robust way to distinguish different classes of models
  - correlations among neutrino mixing parameters
  - sum rules among quark and lepton mixing parameters
  - correlations among other flavor violating processes


Origin of Flavor
SUSY
Family Symmetry
Grand Unified Theories
String Theories
Extra Dimensions
TeV Scale New Physics
Leptogenesis
Dark Matter, Axion
Proton Decay
Neutrino Physics
Lepton Flavor Violation
LHC
Quark Flavor