Neutrino Oscillation Physics Discussions

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Where Do We Stand?

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

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

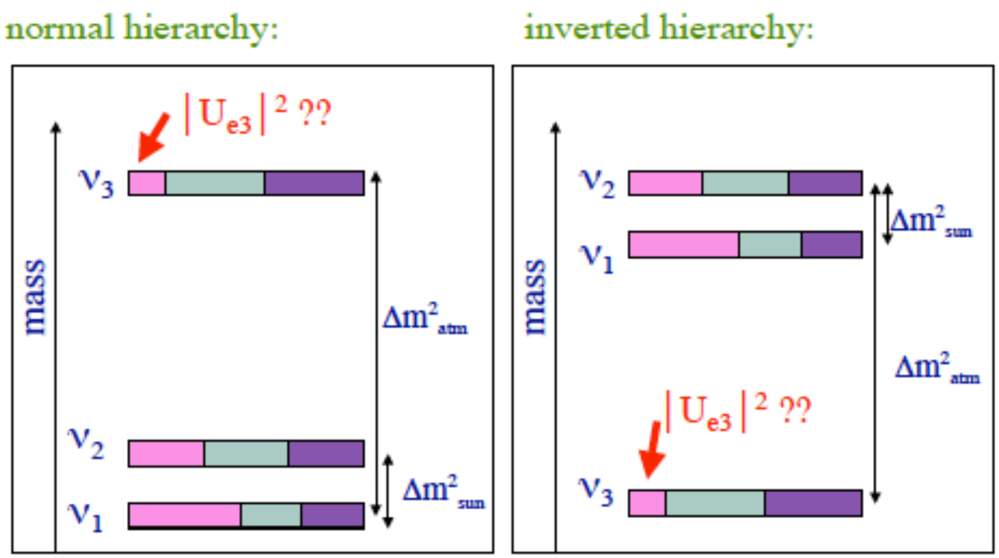
Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno, 2012

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}\ \mathrm{eV}^2$ (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$ (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$ (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

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

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 $\nu_{\mu,\tau}$)
- 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)
- 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/ 3 fairly large mixing angles
- neutrino anarchy: no parametrically small number
  - near degenerate spectrum, large mixing
  - predictions strongly depend on choice of statistical measure

Hall, Murayama, Weiner (2000); de Gouvea, Murayama (2003)

- family symmetry: there's a structure, expansion parameter (~~symmetry~~ effect)
  - mixing determined by dynamics of underlying symmetry
  - for leptons only (normal or inverted)
  - for quarks and leptons: quark-lepton connection ↔ GUT (normal)

Questions to be discussed

- precision in oscillation parameters needed to distinguish different models
  - theoretical frameworks; testable predictions
  - robustness of the model predictions?
    - theoretical uncertainties

⇒ Talk by Michael Ratz

- constraining the three neutrino paradigm
  - implications for new interactions

⇒ Talk by Jacobo Lopez-Pavon

Small Neutrino Mass: Seesaw Mechanism

- Mixture of light fields and heavy fields

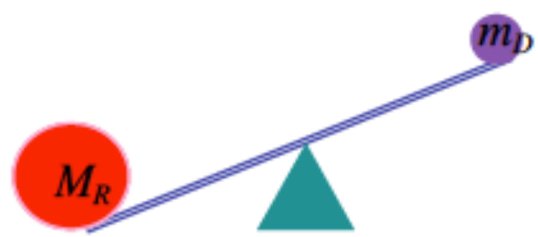
Yanagida, 1979; Gell-Mann, Ramond, Slansky, 1979; Mohapatra, Senjanovic, 1981

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

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

$\nu_R \nu_R$ mass term allowed

- Smallness of neutrino masses suggest a high mass scale



- Diagonalize the mass matrix:

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

$$m_{heavy} \sim M_R$$

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 !!)

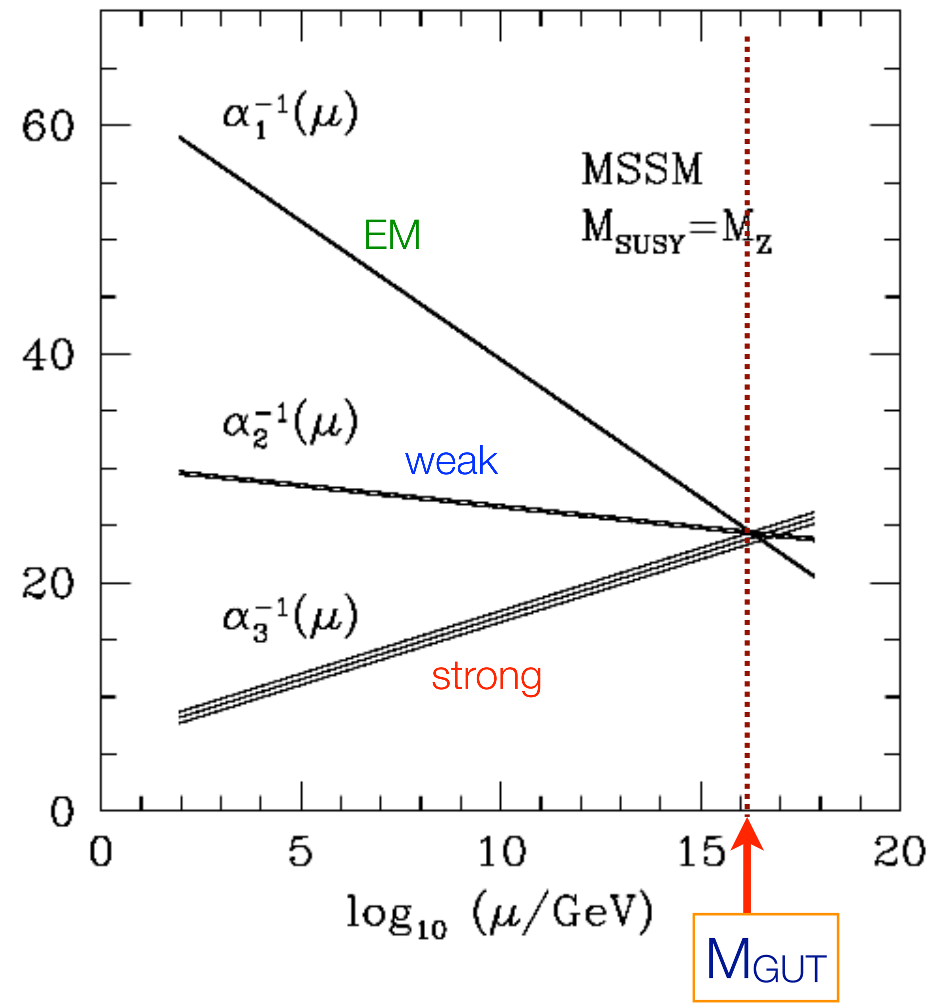
Grand Unification

- 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

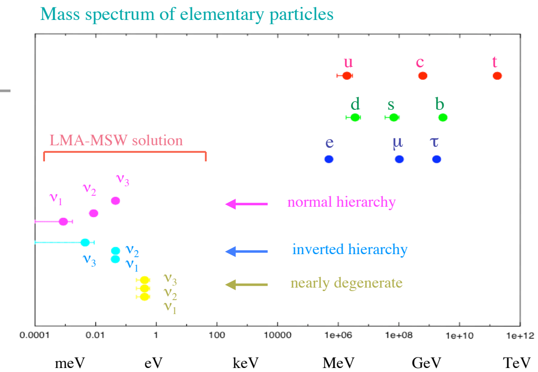
$$m_\nu \sim (\Delta m^2_{atm})^{1/2},\ m_D \sim m_{top}$$

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

coupling constants run!



Origin of Mass Hierarchy and Mixing

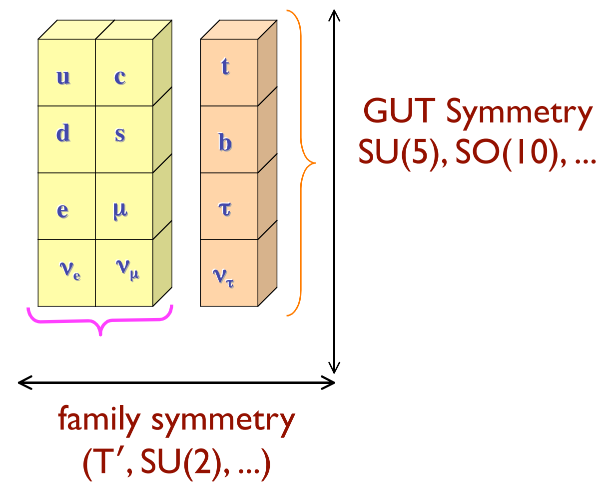


- In the SM: 22 physical quantities which seem unrelated
- Question arises whether these quantities can be related
- No fundamental reason can be found in the framework of SM
- less ambitious aim ⇒ reduce the # of parameters by imposing symmetries
  - SUSY Grand Unified Gauge Symmetry
    - GUT relates 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

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, Montanino, Palazzo, Rotunno, 2012

$$\sin^2\theta_{atm} = 0.386\ (0.331 - 0.637) \qquad \sin^2\theta_{\odot} = 0.307\ (0.259 - 0.359)$$

$$\sin^2\theta_{13} = 0.0241\ (0.0169 - 0.0313)$$

- Tri-bimaximal Mixing Pattern

Harrison, Perkins, Scott (1999)

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

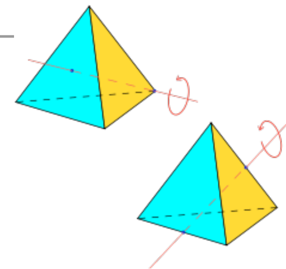
$$\sin^2\theta_{\text{atm, TBM}} = 1/2 \qquad \sin^2\theta_{\odot,\text{TBM}} = 1/3$$

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

- Leading Order: TBM (from symmetry) + Corrections/contributions (dictated by symmetry)

An Example: a SUSY SU(5) x T´ Model

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



- 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

Predictions: a SUSY SU(5) x T´ Model

- Charged Fermion Sector (7 parameters)

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

$k \rightarrow V_{cb}$, $b \rightarrow V_{ub}$

spinorial representations ⇒ complex CGs
⇒ CPV in quark sector

quark CP phase: γ = 45.6 degrees

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

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

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

⇓

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

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

Predictions: a SUSY SU(5) x T´ Model

- 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´

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

neutrino mixing angle

1/2

quark mixing angle

complex CGs: leptonic Dirac CPV

δ = 227 degrees

⇒ connection between leptogenesis & leptonic CPV at low energy

- sum rule among absolute 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

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

Other Possibilities: Beyond TBM

- Tri-bimaximal Mixing Accidental or NOT? Albright, Rodejohann (2009); Abbas, Smirnov (2010)

- Dodeca Mixing Matrix from D_{12} Symmetry

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

leading order:

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

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

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)

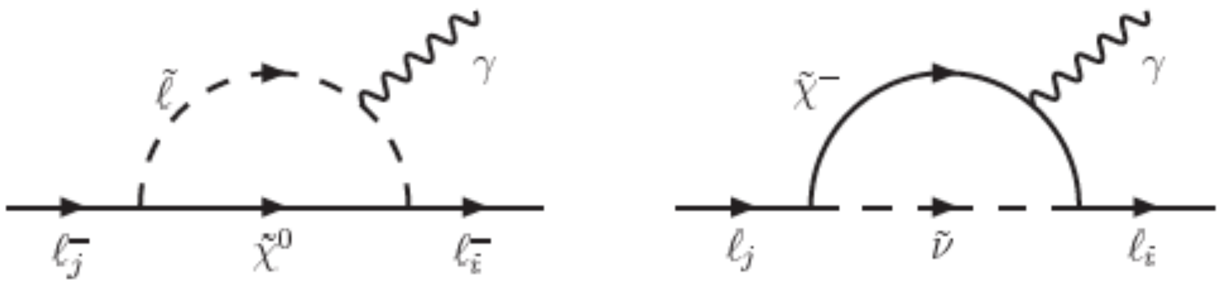
$\Phi = (1 + \sqrt{5}) / 2 = 1.62$

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

Correlations: Charged Lepton Flavor Violation

- SUSY GUTs: Lepton flavor violating charged lepton decays



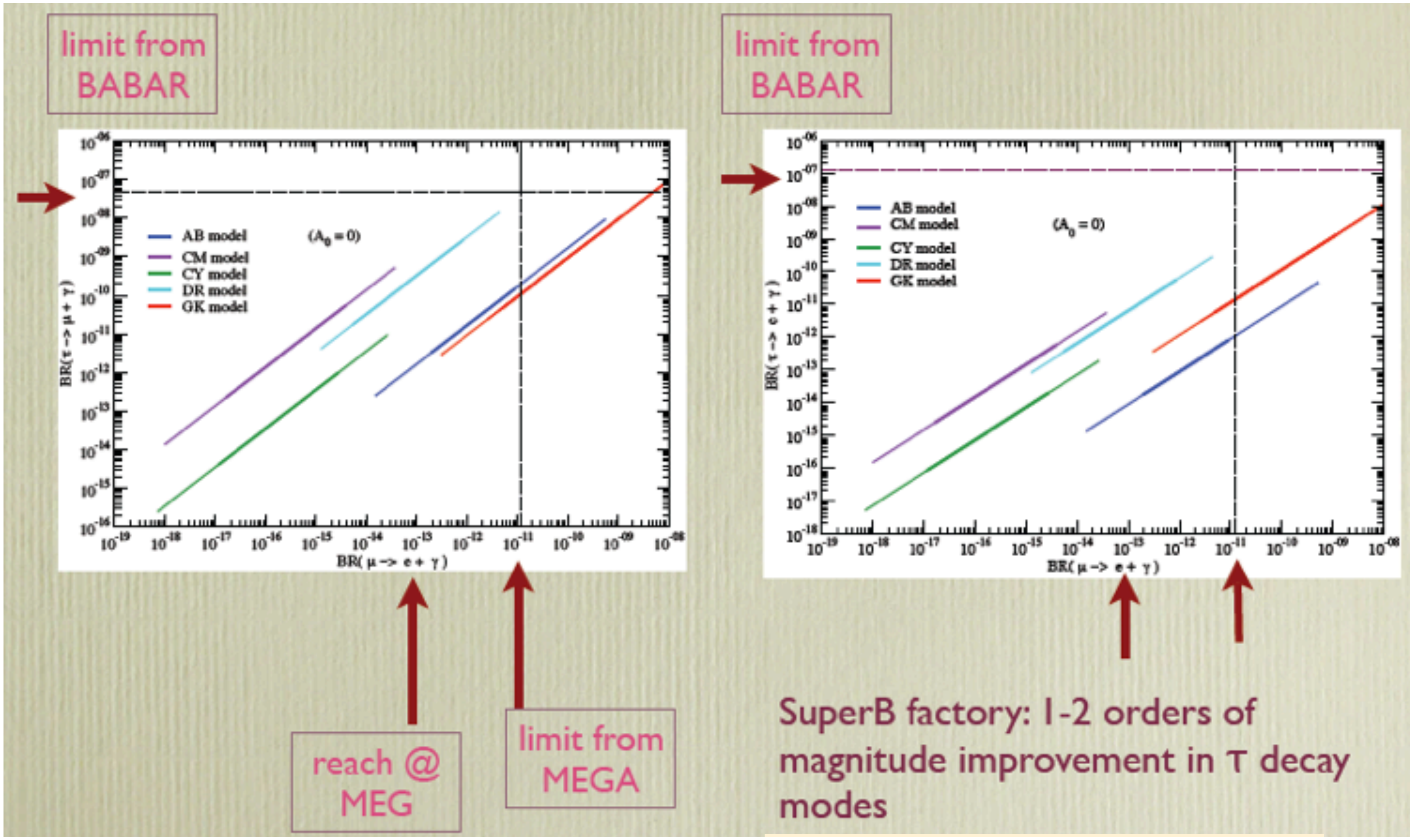
  - individual branching fraction: strong dependence on soft SUSY parameters

  - correlations between branching fractions: strong dependence on flavor structure

Correlations: Charged Lepton Flavor Violation

- five viable SUSY SO(10) models with dark matter constraints:

C.H. Albright, M.-C.C (2008)

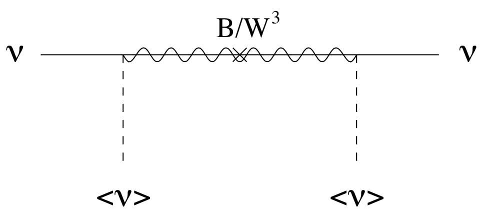


Correlations: Sparticle Decay and Mixing Angle

- MSSM with bi-linear R-Parity Violation   Kaplan, Nelson, 1999

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

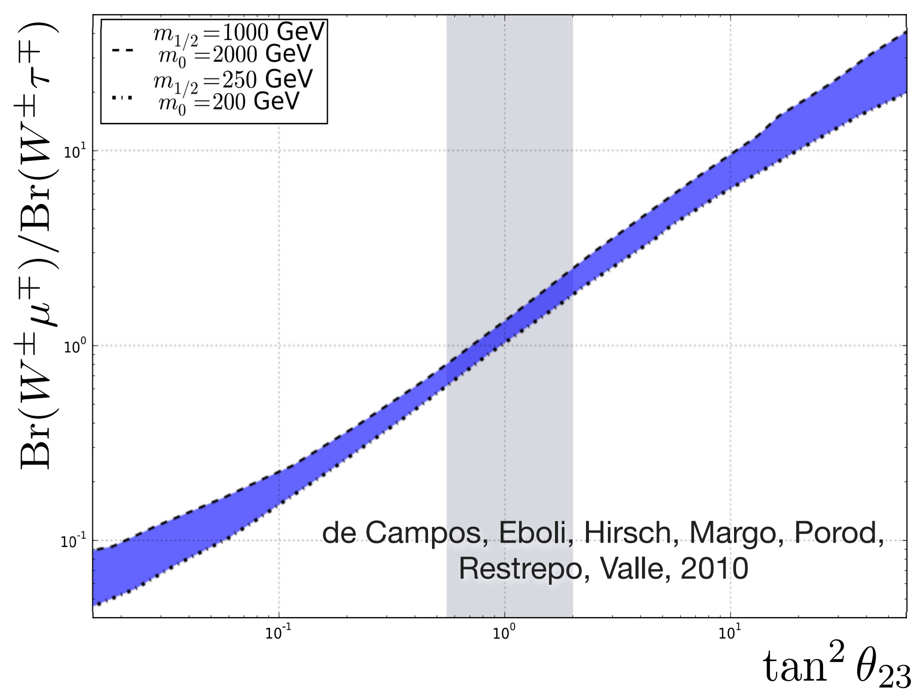
- mass generation for Δm_{atm}^2:



- mixing angle ↔ neutralino decay:

Mukhopadhyaya, Roy, Vissani, 1998

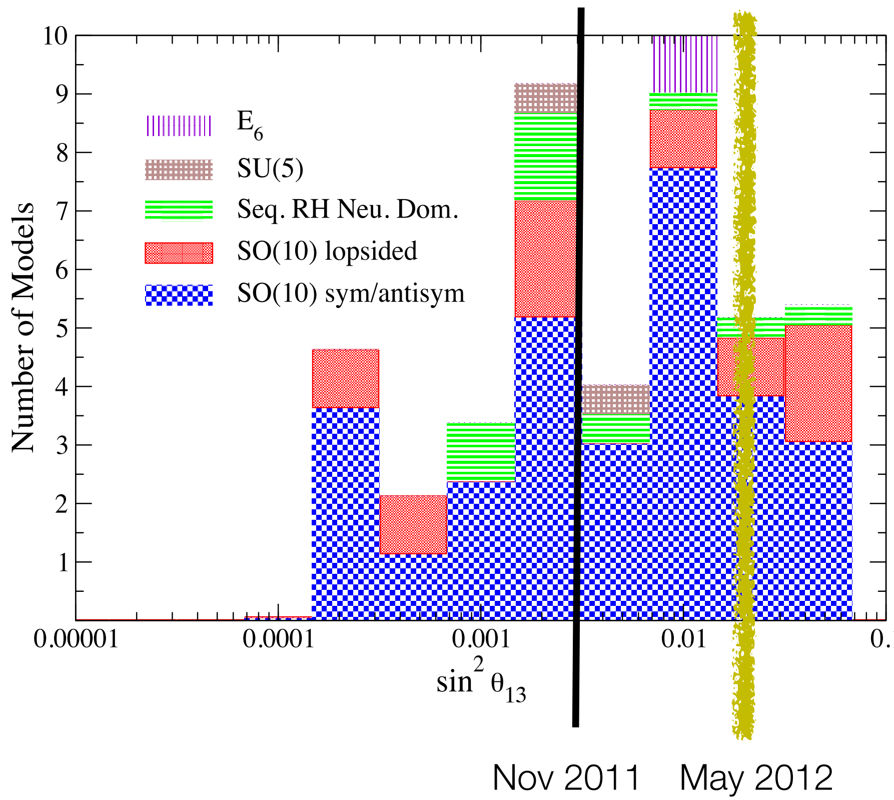
$$\tan^2\theta_{\rm atm} \simeq \frac{BR(\tilde{\chi}_1^0 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \to \tau^\pm W^\mp)}$$

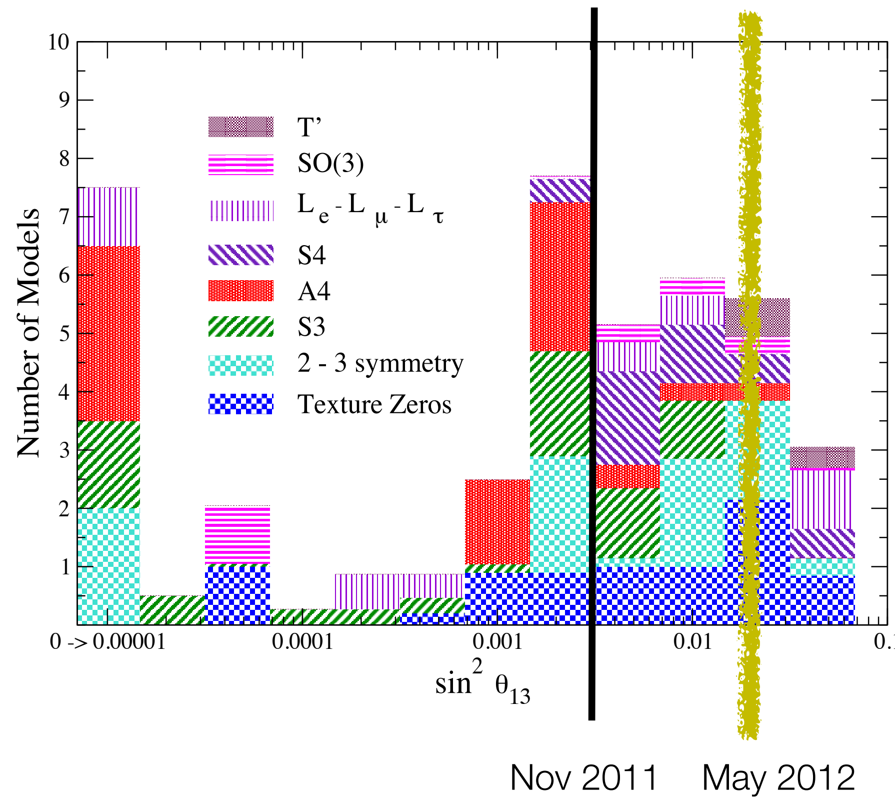


Conclusions

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

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

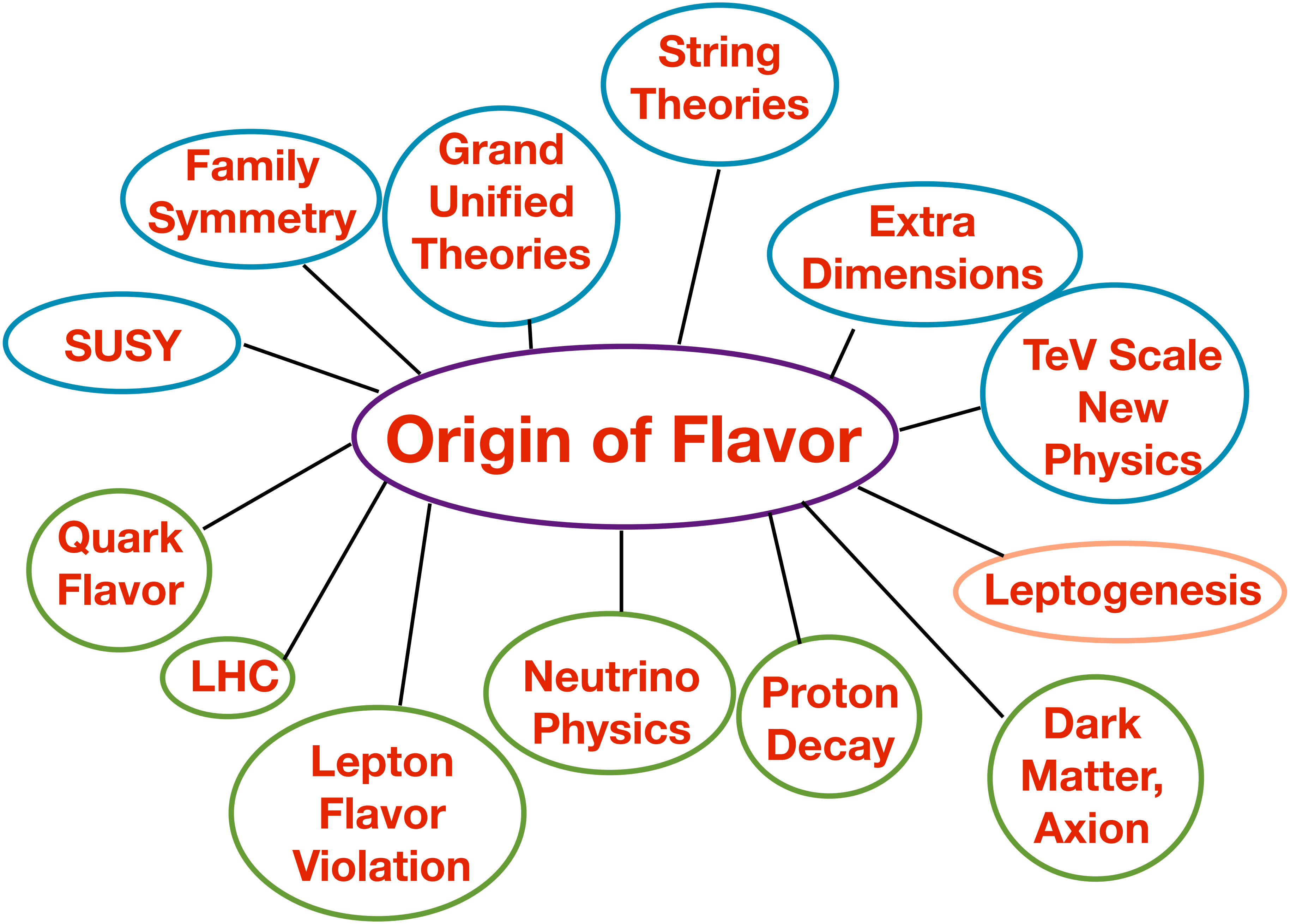




Conclusions

- we are not just testing a number, but rather a paradigm like in the case of CKM matrix

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

Discussion

Q: What accuracy do we need in oscillation parameters in order to distinguish different models?

Q: What precisions can be achieved experimentally in measuring θ_{13}, θ_{23}, θ_{12}?

Discussion

Q: Is Tri-bimaximal mixing pattern still viable?

Q: What precisions can be achieved experimentally in measuring θ_{13}, θ_{23}, θ_{12}? to exclude TBM pattern?

Q: Can we ever exclude it?

Discussion

Q: What precision do we need in CP phase?

Q: Given the large value of θ_{13}, what precision can be achieved experimentally in measuring the CP phase?

Discussion

Q: How seriously should we take the hints of sterile neutrinos (or something else) from LSND/MiniBooNE, reactor, radioactive source, or cosmological data?

Q: How far should we go and find out what is going on?

[B. Kayser @ GGI What's Nu?]

Discussion

Q: In what sense do we need to constrain the three neutrino paradigm? What type of new physics can we constrain?

Q: What experimental precision do we need to establish three neutrino paradigm?