Phenomenology and Models

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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 [GS98, Bari group, AGSS09] (1σ) Gonzalez-Garcia, Maltoni, Salvado (2010)

$$\sin^2\theta_{23} = 0.463(0.415\text{–}0.530), \quad \sin^2\theta_{12} = 0.319(0.303\text{–}0.335), \quad \sin\theta_{13} = 0.127(0.072\text{–}0.165)$$

$$\Delta m^2_{21} = 7.59 \pm 0.20 \ \times 10^{-5}\ \text{eV}^2 \qquad \Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11 \ \times 10^{-3}\ \text{eV}^2 \\ +2.46 \pm 0.12 \ \times 10^{-3}\ \text{eV}^2 \end{cases}$$ (Global Minima)

- Tri-bimaximal Mixing Pattern Wolfenstein (1978); 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)

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 this talk: assume 3 generations, no LSND
  - 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

Origin of Flavor Mixing and Mass Hierarchy

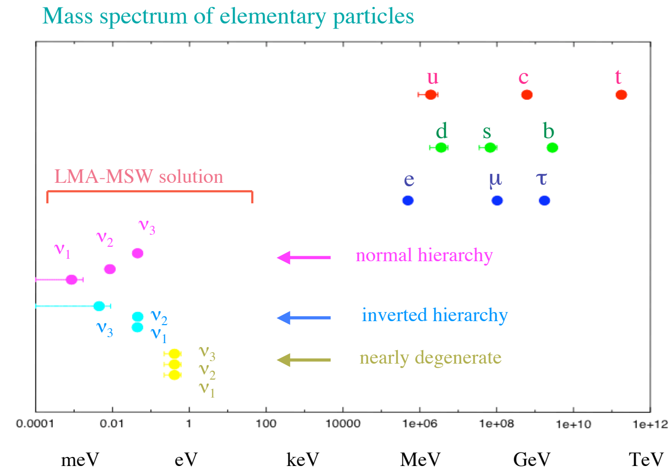
- SM: 22 arbitrary parameters in Yukawa sector
- No foundamental orgin found or suggested
- Reduce number of parameters
  - Grand Unification
    - seesaw scale ~ GUT scale
    - quarks and leptons unified
    - 1 coupling for entire multiplet

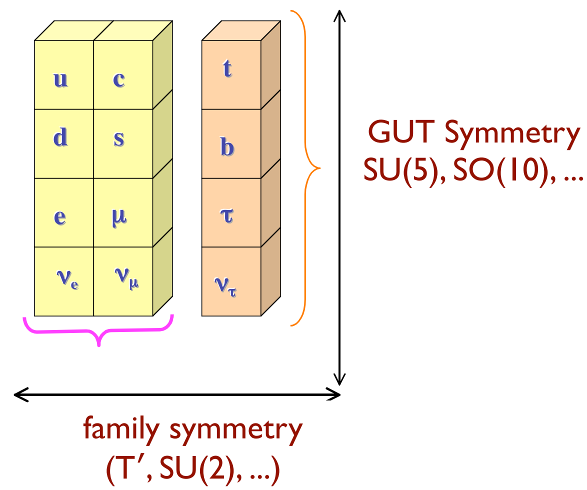
  ⇒ intra-family relations (e.g. SO(10))

  Up-type quarks ⇔ Dirac neutrinos

  Down-type quarks ⇔ charged leptons
  - Family Symmetry

  ⇒ inter-family relations (flavor structure)





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}

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

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

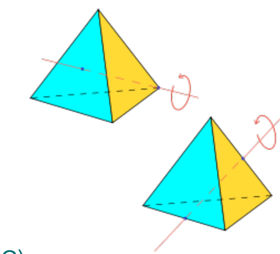
A_4: Ma, Rajasekaran; Altarelli, Feruglio; ...

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

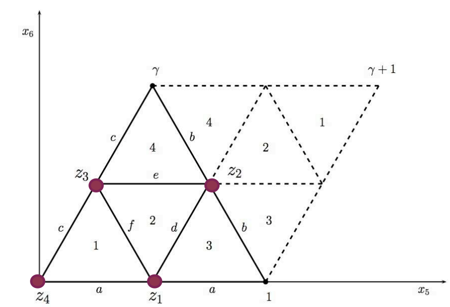
Double Tetrahedral T´ Symmetry

- Smallest Symmetry to realize TBM ⇒ Tetrahedral group A4 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, Kaphart (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

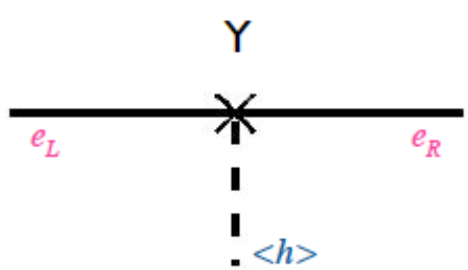
  - complex CG coefficients when spinorial representations are involved

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>

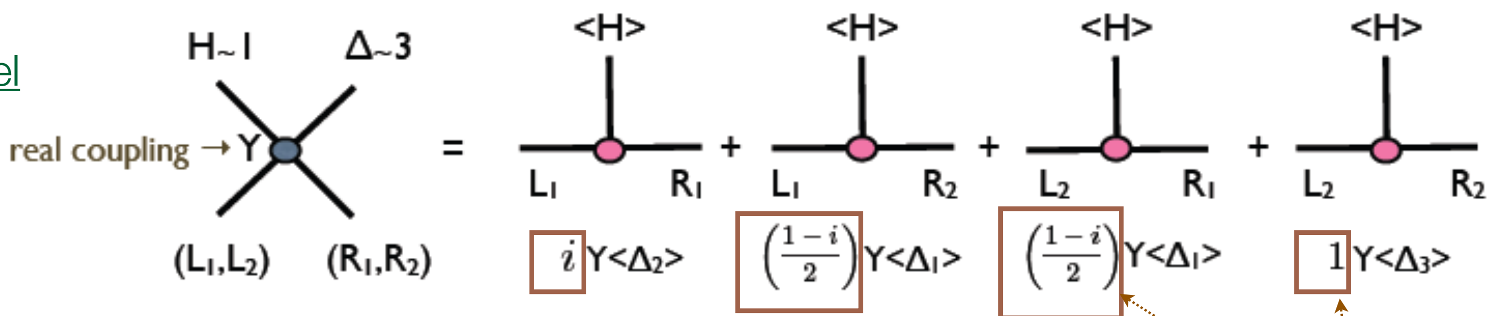


A Novel Origin of CP Violation

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 ⇒ extrememly 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′

$$\begin{array}{cc} & \begin{array}{cc} L_1 & L_2 \end{array} \\ M = & \begin{pmatrix} i & \frac{1-i}{2} \\ \frac{1-i}{2} & 1 \end{pmatrix} Y\langle\Delta\rangle \end{array} \begin{array}{c} R_1 \\ R_2 \end{array}$$

Model Predictions

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

- SU(5) x T´:

	SU(5)		T´
	$10(Q,\, u^c,\, e^c)_L$	:	$(T_1, T_2) \sim 2$, $T_3 \sim 1$
	$\overline{5}(d^c, \ell)_L$	:	$(F_1, F_2, F_3) \sim 3$

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

- effective neutrino mass matrix (2 parameters):

$$M_\nu = \frac{\lambda v^2}{M_x}\begin{pmatrix} 2\xi_0 + u & -\xi_0 & -\xi_0 \\ -\xi_0 & 2\xi_0 & u - \xi_0 \\ -\xi_0 & u - \xi_0 & 2\xi_0 \end{pmatrix}$$

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

Form diagonalizable:

- no adjustable parameters
- neutrino mixing from CG coefficients!

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

- mass sum rule: $m_1 - m_3 = 2m_2$

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

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

normal hierarchy predicted!!

Model Predictions

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

- Charged Fermion Sector (7 parameters)

$$M_u = \begin{pmatrix} ig & \frac{1-i}{2}g & 0 \\ \frac{1-i}{2}g & g+(1-\frac{i}{2})h & k \\ 0 & k & 1 \end{pmatrix} y_t v_u \qquad M_d,\ M_e^T = \begin{pmatrix} 0 & (1+i)b & 0 \\ -(1-i)b & (1,-3)c & 0 \\ b & b & 1 \end{pmatrix} y_d v_d \phi_0 \eta_0$$

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)

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

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

CGs of SU(5) & T´

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

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

neutrino mixing angle

1/2

quark mixing angle

CG: leptonic Dirac CPV

prediction for Majorana phases: 0, π

prediction for Dirac CP phase: δ = 227 degrees

⇒ connection between leptogenesis & CPV in neutrino oscillation

Sum Rules: Quark-Lepton Complementarity

Quark Mixing

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

Lepton Mixing

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

- QLC-I (BM)

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

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

- 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

  improved $\delta\theta_{12}$ from SuperK possible

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

Form Dominance

M.-C.C., S.F. King, JHEP0906, 072 (2009)

- Form diagonalizability:
  - masses and mixing angles decouple
  - effective neutrino mass matrix depends on only ≤ 3 parameters
- general type-I seesaw, without CPV:
  - effective neutrino mass matrix (symmetric, real) ⇒ 6 parameters
- Seesaw mechanism in RH Majorana diagonal basis:

$$M_{RR} = \mathrm{diag}(M_A, M_B, M_C) \qquad M_D = (A, B, C)$$

$$M^{\nu}_{eff} = M_D M_{RR}^{-1} M_D^T \qquad M^{\nu}_{eff} = \frac{AA^T}{M_A} + \frac{BB^T}{M_B} + \frac{CC^T}{M_C}$$

- form diagonalizability if: $A_i = aU_{i1}, \quad B_i = bU_{i2}, \quad C_i = cU_{i3}$

light neutrino masses: $a^2/M_A, \; b^2/M_B, \; c^2/M_C$ U: MNS matrix

e.g. A_4, T´ models:
2 flavons suffice for $U = U_{TBM}$
alignment due to symmetry

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} :

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

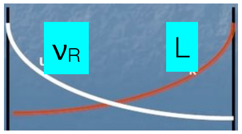
$\theta_{sol} = 30^o + O(\varepsilon)$, $\theta_{13} = O(\varepsilon)$

Curing FCNC Problem: Family Symmetry vs MFV

- low scale new physics severely constrained by flavor violation

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

- Warped Extra Dimension
  - wave function overlap ⇒ naturally small Dirac mass

UV  SM (us)

  - non-universal bulk mass terms (c) ⇒ FCNCs at tree level ⇒ Λ > O(10) TeV
  - fine-tuning required to get large mixing and mild mass hierarchy
  - Minimal Flavor Violation M.-C.C., H.B. Yu (2008); quark sector: A. Fitzpatrick, G. Perez, L. Randall (2007)

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

  - T´ symmetry in the bulk for quarks & leptons: M.-C.C., K.T. Mahanthappa, F. Yu (PLB2009); A4: Csaki, Delaunay, Grojean, Grossmann
    - TBM mixing: common bulk mass term, no tree-level FCNCs
    - TBM mixing and masses decouple: no fine-tuning
    - can accommodate both normal & inverted mass orderings
- Family Symmetry: alternative to MFV to avoid FCNCs in TeV scale new physics
  - many family symmetries violate MFV, possible new FV contributions

TeV Scale Seesaw and Non-anomalous U(1)

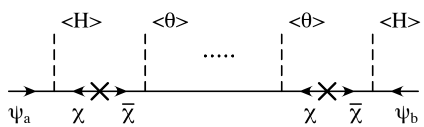
M.-C. C., de Gouvea, Dobrescu (2006)

- SM x $U(1)_{NA}$ + 3 ν_R: charged under $U(1)_{NA}$ symmetry, broken by <ϕ>
- $U(1)_{NA}$ 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

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



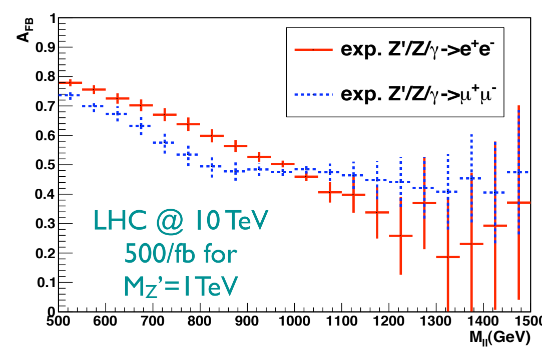
Λ ~ TeV!

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

- anomaly cancellation: relate flavorful fermion charges

  $\Rightarrow$ 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)



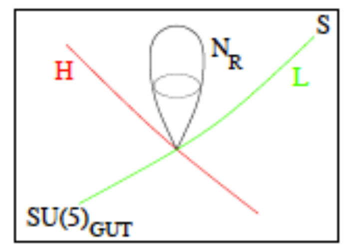
F-theory GUT

Bouchard, Heckman, Seo, Vafa (2009)

- strongly coupled Type-II B string theory (10D) → N=1 SUSY (4D)
- matter fields live on 6D curves
- Yukawa interaction: intersection of three curves
  - strengths determined by gauge coupling $\varepsilon \sim \sqrt{\alpha_{GUT}}$
  - N_R far from SU(5) surface ⇒ suppression of m_ν
  - KK seesaw ⇒ effective neutrino mass matrix

$$M_*^4 = \alpha_{GUT}^{-1} M_{GUT}^4$$

string compactifiction scale



$$\frac{\lambda_{(\nu)}^{\mathrm{Maj}}}{\Lambda_{\mathrm{UV}}} = \overline{y} \cdot \frac{1}{M} \cdot \overline{y}^T \sim \frac{\Sigma}{M_*} \begin{pmatrix} \varepsilon^2 & \varepsilon^{3/2} & \varepsilon \\ \varepsilon^{3/2} & \varepsilon & \varepsilon^{1/2} \\ \varepsilon & \varepsilon^{1/2} & 1 \end{pmatrix}$$

  - prediction for mixing and mass hierarchy

$$U_{PMNS} \sim \begin{pmatrix} 1 & \epsilon^{1/2} & \epsilon \\ \epsilon^{1/2} & 1 & \epsilon^{1/2} \\ \epsilon & \epsilon^{1/2} & 1 \end{pmatrix}$$

$$\theta_{12} \sim \theta_{23} \sim \alpha_{GUT}^{1/4} \sim 30^\circ, \quad \theta_{13} \sim \alpha_{GUT}^{1/2} \sim \theta_C \sim 0.2,$$

$$m_1 : m_2 : m_3 \sim \alpha_{GUT} : \alpha_{GUT}^{1/2} : 1$$

normal hierarchy

- Flipped SU(5) (can come from F-theory): improved light threshold calculation

  $p \to e^+ \pi^0$: $\tau \sim$ (1-30) x 10^{34} yr, within reach of HyperK, DUSEL

Li, Nanopoulos, Walker (2009)

Conclusion

- current data ⇒ TBM mixing
- finite group family symmetry T´ x SU(5):
  - group theoretical origin of mixing
  - CP violation from complex CG ciefficients

    δ = 227 degrees
  - QLC:

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

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

- Family Symmetry curing FCNC problem in low (TeV) scale new physics
- More precise measurements important for pinning down the underlying new physics