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On mass hierarchies in Orientifolds

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Introduction

• The most obvious puzzle in the Standard model is associated with the masses and mixings of fermions.

• The masses span 15 orders of magnitude (from the lightest neutrino to the top quark).

• The mixings tend to decrease with rising masses.

• Their origin (and overall scale) is linked to the Higgs (or whatever breaks the electroweak symmetry) except maybe neutrinos.

• The ratios are unexplained so far.

• Their specific pattern is crucially linked to the richness of the physics as we observe it.

The Goal

- To investigate which mechanisms can provide a mass hierarchy in orientifolds

- To establish, what type of SM embedding can accommodate such mechanisms

Mechanisms for mass hierarchies

• Several mechanisms have been proposed to explain (parts of) the mass hierarchy of the SM.

• Radiative mechanisms

Weinberg 1972, Zee 1980

• Texture zeros

Fritsch 1977, Weiberg 1977, Wilczek+Zee 1978,Ramond+Roberts+Ross 1993

• Family symmetries

Harari+Haut+Wengers 1978, Froggat+Nielsen 1979, Ibanez+Ross 1994

• Seesaw mechanism

GellMann+Ramond+Slansky 1979, Yanagida 1979

♠ Mechanisms are not easy always to separate: for example texture zeros↔ family symmetries

Can the mechanisms work in string theory?

Little is known, as rarely the issue of the determination of masses is taken up.

• They include making a generation heavier by using high order couplings in the potential for the rest.
Antoniadis+Leontaris+Rizos 1990, Farangi 1992, Antoniadis+Rizos+Tamvakis 1992

• The use of anomalous U(1)'s was advocated at the field theory context
Irges+Lavignac+Ramond 1998

• A form of Froggat-Nielsen mechanism was implemented recently in F-theory
Heckman+Vafa 2008

• The see-saw mechanism was implemented in the heterotic case
Antoniadis+Rizos+Tamvakis 1992, Giedt+Kane+Langacker+Nelson 2005

• New mechanisms have been advocated using (world-sheet) instantons to influence masses
Cremades+Ibanez+Marchesano 2003

• and small neutrino masses by mixing with large-dimension KK states
Antoniadis+Kiritsis+Rizos+Tomaras 2002

Bottom-up SM model building and orientifolds

• Orientifolds have been an ideal arena for the implementation of bottom-up approaches to model building

Anroniadis+Kiritsis+Tomaras 2000, Aldazabal+Ibanez+Quevedo+Uranga 2000

• They allow a modular and algorithmic search/construction procedure that is well tuned to obtain desired features of spectra.

• They contain relatively large numbers of U(1) gauge symmetries that are superficially anomalous, providing quasi-global symmetries that may produce hierarchical interactions.

• This is a blessing when it comes to forbidding unwanted couplings like baryon and lepton number violating interactions or μ terms.

• It can be a curse when they forbid Yukawa couplings for heavy quarks and leptons.

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• An anomalous U(1) is one that becomes massive by mixing with an axion. It may or may not have anomalies

Ibanez+Marchesano+Rabadan 2002, Antoniadis+Kiritsis+Rizos 2002

• It is always broken by non-perturbative effects: defects that couple to the axion that mixes with the gauge boson. (In tune with absence of global symmetries)

• Non-perturbative effects may leave a discrete symmetry behind (as it happens in standard gauge theories).

• In the present context, such a discrete symmetry can play the role of R-symmetry

Which hierarchy mechanisms do not work

• Orientifolds provide important constraints in implementing standard mechanisms for the hierarchy of masses

• The basic reason is that charge assignments must follow the open string algorithm.

• This makes family symmetry implementation radically different from what has been studied so far (because Q cannot be charged)

• The same applies to texture zeros as all approaches consider hermitian setup (not compatible with similarity of Qs).

• The Frogatt-Nielsen mechanism is at odds with the restricted charge assignments in orientifolds

Which hierarchy mechanisms can work

- Absence of tree level Yukawa's because of (anomalous) U(1) symmetries

- Generation of such couplings from instanton effects: possibility of exponential suppression

- Generation of forbidden couplings at higher order in the superpotential via vevs of appropriate scalar fields

- Use of (slightly broken) discrete symmetries of the compactification manifold

The algorithm

• For a given bottom up configuration of the form $U(3)_a \times U(2)_b \times U(1)_c \times U(1)d$, we study the allowed Yukawa couplings

• We choose D-brane configurations that allow only one U quark and one D quark to get a mass (out of all six). We name these the top and bottom quark.

♠ This is not strictly necessary: For the third generation we can generate the all masses at the right scale via tree level Yukawas

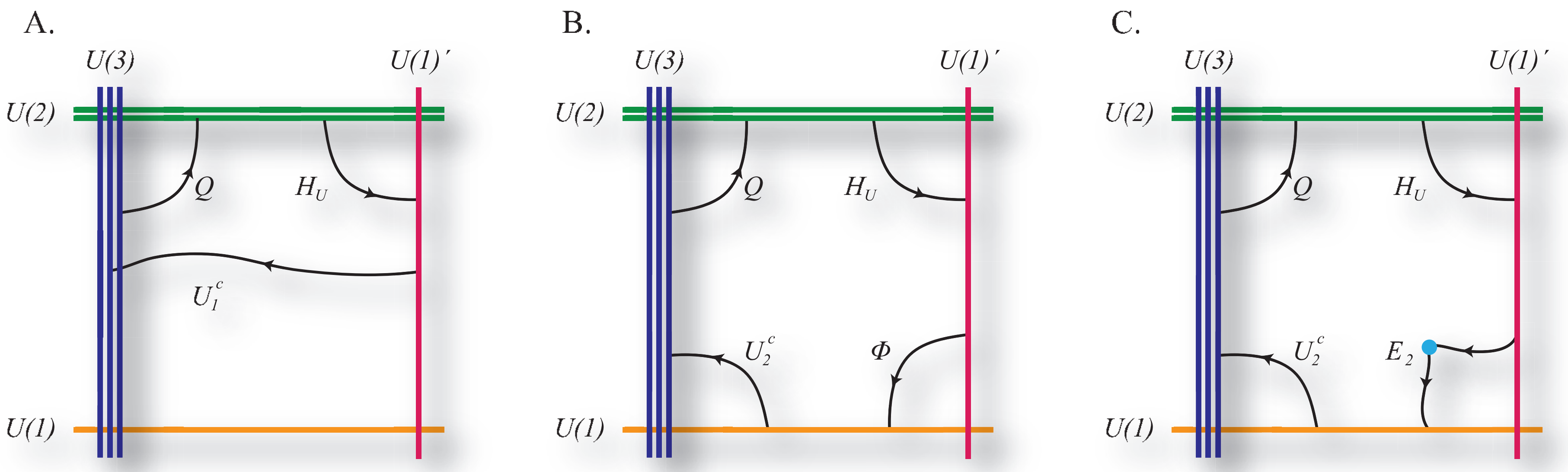
Antoniadis+Kiritsis+Rizos+Tomaras 2002

• We add a scalar Φ between the U(1) branes, give it a vev $\langle\Phi\rangle$ to generate further mass terms.

• All other mass terms are generated by instantons with Yukawa couplings $h_i e^{-S}$. Instantons with the same charge structure are assumed to have the same exponential factors (restrictive).

• The overall mass scales are $\langle H_u \rangle$, $\langle H_d \rangle$, $\langle \Phi \rangle$, $M_s\ e^{-S_i}$. Typically, one instanton factor is relevant. They are fit at will, as there is no serious constraint on their values.

• The coefficients are assumed to be dimensionless numbers in the range [0.1-0.5] (adhoc, perturbativity constraint).



The three types of mass generating terms: The configuration A allows for a Yukawa term. However, in the B and C cases no Yukawa terms can be generated. In the B case there is a higher order term due to the presence of a field Φ, while in the C case there is a contribution from an instanton term E_2.

Quark Mass matrices

$$M_1 = \begin{pmatrix} \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \end{pmatrix} \quad , \quad M_2 = \left(\begin{array}{c|cc} \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Y} \end{array}\right) \sim \left(\begin{array}{ccc} \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \hline \mathcal{Y} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{Y} & \mathcal{Y} & \mathcal{Y} \end{array}\right)$$

$$M_3 = \left(\begin{array}{c|cc} \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \hline \mathcal{Z} & \mathcal{U} & \mathcal{U} \\ \mathcal{Z} & \mathcal{U} & \mathcal{U} \end{array}\right) \quad , \quad M_4 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \end{array}\right) \quad , \quad M_5 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \hline \mathcal{U} & \mathcal{V} & \mathcal{W} \\ \mathcal{U} & \mathcal{V} & \mathcal{W} \end{array}\right)$$

$\mathcal{X}, \mathcal{Y}, \mathcal{Z}, \mathcal{U}, \mathcal{V}, \mathcal{W}$ denotes terms of the same type, either Yukawa, higher-dimension or instantonic terms.

- 1,2,4 are relevant when Q have same charges. This is the case when $U(2)_b \to SP(2)_b$

- The pattern says that two quark masses out of the three are zero (small).

Lepton Mass matrices

• In the lepton sector, in addition to the previous mass matrices we can also have vacua where all the entries in the mass matrix are different:

$$M_6 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \hline \mathcal{U} & \mathcal{V} & \mathcal{W} \\ \hline \mathcal{R} & \mathcal{S} & \mathcal{T} \end{array}\right)$$

• This is because there are less constraints on the charge of the lepton sector.

Three stack models

There are two possible hypercharge embeddings

Antoniadis+Dimopoulos

For the "SU(5)-like hypercharge embedding $Y = -\frac{1}{3}Q_{\mathbf{a}} - \frac{1}{2}Q_{\mathbf{b}}$, the only possible form for both quark mass matrices M_U and M_D is

$$M_1 = \begin{pmatrix} \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \end{pmatrix}$$

For "SU(5)-like hypercharge embedding $Y = \frac{1}{6}Q_{\mathbf{a}} + \frac{1}{2}Q_{\mathbf{c}}$, there are two different possible charge assignments for the d-quarks allowing the corresponding mass matrix to be of the form

$$M_1 = \begin{pmatrix} \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \end{pmatrix} \quad , \quad M_2 = \left(\begin{array}{c|cc} \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Y} \end{array}\right)$$

Four-stack models

- For AKT embeddings $Y = -\frac{1}{3}Q_{\mathbf{a}} - \frac{1}{2}Q_{\mathbf{b}} + Q_{\mathbf{d}}$ or $Y = \frac{2}{3}Q_{\mathbf{a}} + \frac{1}{2}Q_{\mathbf{b}} + Q_{\mathbf{c}}$, both M_U, M_D can be of the form M_1 or M_2

Antoniadis+Kiritsis+Tomaras 2000

- The same is true for $Y = \frac{1}{6}Q_{\mathbf{a}} + \frac{1}{2}Q_{\mathbf{c}} - \frac{3}{2}Q_{\mathbf{d}}$, or $Y = -\frac{1}{3}Q_{\mathbf{a}} - \frac{1}{2}Q_{\mathbf{b}}$

- For the Madrid embedding $Y = \frac{1}{6}Q_{\mathbf{a}} + \frac{1}{2}Q_{\mathbf{c}} - \frac{1}{2}Q_{\mathbf{d}}$

Ibanez+Marchesano+Rabadan, 2001

quark mass matrices can be $M_U \sim (M_1, M_2, M_3)$ and $M_D \sim (M_1 \cdots M_5)$

$$M_1 = \begin{pmatrix} \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \mathcal{X} & \mathcal{X} & \mathcal{X} \end{pmatrix} \quad , \quad M_2 = \left(\begin{array}{c|cc} \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Y} \end{array}\right) \sim \left(\begin{array}{ccc} \mathcal{X} & \mathcal{X} & \mathcal{X} \\ \hline \mathcal{Y} & \mathcal{Y} & \mathcal{Y} \\ \mathcal{Y} & \mathcal{Y} & \mathcal{Y} \end{array}\right)$$

$$M_3 = \left(\begin{array}{c|cc} \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \hline \mathcal{Z} & \mathcal{U} & \mathcal{U} \\ \mathcal{Z} & \mathcal{U} & \mathcal{U} \end{array}\right) \quad , \quad M_4 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \end{array}\right) \quad , \quad M_5 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \hline \mathcal{U} & \mathcal{V} & \mathcal{W} \\ \mathcal{U} & \mathcal{V} & \mathcal{W} \end{array}\right)$$

Example I

There are 8 bottom up configurations (including the CP Charges) that have maximal freedom.

- Here is an example with $V_u, V_d, M_s, v_{\Phi_1} = \frac{\langle\Phi_1\rangle}{M_s}, v_{\Phi_2}\frac{\langle\Phi_2\rangle}{M_s}, E_1, E_2, E_3, E_4, E_5$

$$M_U = V_u \begin{pmatrix} 1 & v_{\Phi_1} & v_{\Phi_1} \\ E_1 & E_2 & E_2 \\ E_1 & E_2 & E_2 \end{pmatrix}, \quad M_D = V_d \begin{pmatrix} 1 & v_{\Phi_2} & v_{\Phi_2} \\ E_1 & E_3 & E_3 \\ E_1 & E_3 & E_3 \end{pmatrix}, \quad M_L = V_d \begin{pmatrix} E_4 & v_{\Phi_1} & 1 \\ E_4 & v_{\Phi_1} & 1 \\ E_4 & v_{\Phi_1} & 1 \end{pmatrix}$$

$$M_N = \begin{pmatrix} 0 & 0 & 0 & V_uE_1 & V_uE_1 & V_uE_1 \\ 0 & 0 & 0 & V_uE_1 & V_uE_1 & V_uE_1 \\ 0 & 0 & 0 & V_uE_1 & V_uE_1 & V_uE_1 \\ V_uE_1 & V_uE_1 & V_uE_2 & M_sE_5 & M_sE_5 & M_sE_5 \\ V_uE_1 & V_uE_1 & V_uE_2 & M_sE_5 & M_sE_5 & M_sE_5 \\ V_uE_1 & V_uE_1 & V_uE_2 & M_sE_5 & M_sE_5 & M_sE_5 \end{pmatrix}$$

Correct eigenvalues are obtained with

$$V_u \sim m_t, \quad , \quad V_d \sim m_b \quad , \quad E_1 \sim E_2 \sim m_c/m_t \quad , \quad E_3 \sim E_4 \sim m_s/m_b$$

$$v_{\phi_1} \sim m_u/m_t \quad , \quad v_{\phi_2} \sim m_d/m_b$$

and $E_5 \sim 0.6 - 0.7$ for $M_s \leq 10^{12}$ GeV, or $E_5 \sim 10^{-7}$ if $M_s \sim M_{GUT}$.

- The mixing turns out to have the right magnitude

$$\mathrm{CKM(1TeV)} = \begin{pmatrix} 0.970 & 0.240 & 0.007 \\ 0.240 & 0.970 & 0.013 \\ 0.010 & 0.011 & 0.999 \end{pmatrix}$$

$$\mathrm{U}_\nu = \begin{pmatrix} -0.42 - 0.23i & -0.53 + 0.38i & -0.19 - 0.54i \\ 0.69 - 0.21i & -0.34 + 0.10i & -0.55 + 0.17i \\ 0.20 - 0.44i & 0.65 & -0.16 - 0.55i \end{pmatrix}$$

- Similar results apply for large values of the string scale

Branes at a Z_3 singularity

• Z_3 acts on the doublet-triplets but not on the antiquarks that correspond to strings ending on other branes.

• The matrix of up and down quarks has the form $M_4 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \end{array}\right)$

• We must break the Z_3 by moving-off the orbifold point

• We use a basis $v_0 = \frac{1}{\sqrt{3}}\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$, $v_+ = \frac{1}{\sqrt{6}}\begin{pmatrix} 2 \\ -1 \\ -1 \end{pmatrix}$, $v_- = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}$

• v_+ has eigenvalue $+1$ under the action of reflection while v_- has eigenvalue -1. We may now parameterize a general mass matrix as

$$\sum_{ij} A_{ij}\; v_i \otimes v_j \quad , \quad i,j = 0, \pm \quad , \quad M_{ij} = \epsilon^{i-1} A_{ij}$$

so there is hierarchical breaking of the symmetries (Z_3 and reflection)

$$MM^\dagger = B_{ij}\ \epsilon^{(i+j-2)} \quad , \quad B = AA^T$$

with eigenvalues ($\epsilon \ll 1$)

$$m_0^2 = B_{00} + \mathcal{O}(\epsilon^2) \quad , \quad m_1^2 = \frac{(B_{00}B_{++} - B_{0+}^2)^2}{B_{00}}\epsilon^2 + \mathcal{O}(\epsilon^4)$$

$$m_2^2 = \frac{(det\ B)}{(B_{00}B_{++} - B_{0+}^2)^2}\epsilon^4 + \mathcal{O}(\epsilon^6)$$

• We generate a natural hierarchy of the masses if for up quarks $\epsilon_u = \lambda^4$ while for the down-type quarks $\epsilon_d = \lambda^2$ with $\lambda \simeq 0.22$.

The associated unitary matrix that diagonalizes the mass matrix is

$$U = \begin{pmatrix} 1 - \frac{a^2}{2}\epsilon^2 & a\epsilon & b\epsilon^2 \\ -a\epsilon & 1 - \frac{a^2+c^2}{2}\epsilon^2 & c\epsilon \\ (ac-b)\epsilon^2 & -c\epsilon & 1 - \frac{c^2}{2}\epsilon^2 \end{pmatrix}$$

both for up and down quarks.

- The CKM matrix is:

$$V_{CKM} = U_U^\dagger U_D = \begin{pmatrix} 1 + a_d a_u \epsilon_d \epsilon_u & a_d \epsilon_d - a_u \epsilon_u & -a_u c_d \epsilon_d \epsilon_u \\ a_u \epsilon_u - a_d \epsilon_d & 1 + (a_d a_u + c_d c_u)\, \epsilon_d \epsilon_u & c_d \epsilon_d - c_u \epsilon_u \\ -a_d c_u \epsilon_d \epsilon_u & c_u \epsilon_u - c_d \epsilon_d & 1 + c_d c_u \epsilon_d \epsilon_u \end{pmatrix}$$

$$= \begin{pmatrix} 1 - \frac{1}{2}\lambda^4 a_d^2 & \lambda^2 a_d - \lambda^4 a_u & \lambda^4 b_d \\ \lambda^4 a_u - \lambda^2 a_d & 1 - \frac{1}{2}\lambda^4 \left(a_d^2 + c_d^2\right) & \lambda^2 c_d - \lambda^4 c_u \\ \lambda^4 (a_d c_d - b_d) & \lambda^4 c_u - \lambda^2 c_d & 1 - \frac{1}{2}\lambda^4 c_d^2 \end{pmatrix}$$

- If now we assume $a_u << 1$, $c_d << 1$ and in addition $a_d \sim 5$, $b_d \sim 1$, $c_u \sim 10$, the CKM becomes:

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^4 a_d^2 & \lambda^2 a_d & \lambda^4 b_d \\ -\lambda^2 a_d & 1 - \frac{1}{2}\lambda^4 a_d^2 & -\lambda^4 c_u \\ \lambda^4 (a_d c_d - b_d) & \lambda^4 c_u & 1 \end{pmatrix} = \begin{pmatrix} 0.970 & 0.242 & 0.0023 \\ -0.242 & 0.970 & -0.023 \\ -0.0023 & 0.023 & 1 \end{pmatrix}$$

- This is in absolute value close to the data.

Outlook and Open problems

• Traditional mechanism for mass hierarchies do not apply in orientifolds.

• A hybrid of anomalous U(1) symmetries, appropriate charges, higher order Yukawa couplings, and the see-saw mechanism can generate the full hierarchy of the SM model (under optimal conditions)

• A similar goal can be achieved by taking advantage of Z_3 discrete symmetries present near Z_3 singularities in the compactification manifold.

• A search for SM embedding with the optimal spectra in interesting (and under way).

Five stack models

- There are 23 distinct hypercharge embeddings

- 12 of them have either M_U or M_D or both on them of the form M_1.

- 8 of them have either M_U or M_D or both on them of the form M_1 or M_2.

The remaining three are the most interesting ones where the mass matrices M_U and M_D can have at least three scales:

- For $Y = \frac{1}{6}Q_{\mathbf{a}} + \frac{1}{2}Q_{\mathbf{c}} - \frac{1}{2}Q_{\mathbf{d}} - \frac{3}{2}Q_{\mathbf{e}}$ and $Y = \frac{1}{6}Q_{\mathbf{a}} + \frac{1}{2}Q_{\mathbf{c}} - \frac{1}{2}Q_{\mathbf{d}}$, M_U can be of the form $(M_1 \cdots M_3)$ while M_D can be of the form $(M_1 \cdots M_5)$.

- For the "Madrid-like" 5 stacks extension: $Y = \frac{1}{6}Q_{\mathbf{a}} + \frac{1}{2}Q_{\mathbf{c}} + \frac{1}{2}Q_{\mathbf{d}} + \frac{1}{2}Q_{\mathbf{e}}$, both M_U and M_D can be of the form $(M_1 \cdots M_5)$.

Example I: addedum

$$\mathrm{CKM}(10^{12}\mathrm{GeV}) = \begin{pmatrix} 0.974 & 0.221 & 0.020 \\ 0.221 & 0.975 & 0.003 \\ 0.019 & 0.007 & 0.999 \end{pmatrix}$$

$$\mathrm{U}_\nu(10^{12}\mathrm{GeV}) = \begin{pmatrix} 0.56 - 0.47i & 0.05 - 0.01i & 0.66 + 0.06i \\ -0.47 + 0.36i & 0.42 - 0.25i & 0.61 + 0.09i \\ 0.29 - 0.01i & 0.86 & -0.31 - 0.24i \end{pmatrix}$$

$$\mathrm{CKM}(\Lambda_{GUT}) = \begin{pmatrix} 0.971 & 0.235 & 0.017 \\ 0.235 & 0.971 & 0.002 \\ 0.017 & 0.001 & 0.999 \end{pmatrix}$$

$$\mathrm{U}_\nu(\Lambda_{GUT}) = \begin{pmatrix} 0.82 & 0.11 - 0.44i & 0.20 + 0.24i \\ -0.38 - 0.32i & 0.56 - 0.12i & 0.33 + 0.54i \\ 0.19 + 0.14i & -0.05 + 0.67i & 0.69 \end{pmatrix}$$

RETURN

Example II

$$M_L = V_d \begin{pmatrix} v_{\Phi_2} & 1 & 1 \\ 1 & v_{\Phi_1} & v_{\Phi_1} \\ 1 & v_{\Phi_1} & v_{\Phi_1} \end{pmatrix}$$

$$M_N \sim \begin{pmatrix} 0 & 0 & 0 & V_uE_1 & V_uE_1 & V_uE_1 \\ 0 & 0 & 0 & V_uE_2 & V_uE_2 & V_uE_2 \\ 0 & 0 & 0 & V_uE_2 & V_uE_2 & V_uE_2 \\ V_uE_1 & V_uE_2 & V_uE_2 & M_sE_4 & M_sE_4 & M_sE_4 \\ V_uE_1 & V_uE_2 & V_uE_2 & M_sE_4 & M_sE_4 & M_sE_4 \\ V_uE_1 & V_uE_2 & V_uE_2 & M_sE_4 & M_sE_4 & M_sE_4 \end{pmatrix}$$

M_s	V_u	V_d	v_{Φ_1}	v_{Φ_2}	E_1	E_2	E_3	E_4
1 TeV	644000	8920	0.62	0.34	1.66×10^{-6}	0.0008	0.003	0.35
10^{12} GeV	452960	3160	0.53	0.52	1.54×10^{-6}	0.0006	0.004	3×10^{-9}
Λ_{GUT}	378800	2440	0.56	0.55	1.32×10^{-6}	0.0006	0.004	5×10^{-14}

$$\mathrm{CKM(1TeV)} = \begin{pmatrix} 0.973 & 0.229 & 0.003 \\ 0.229 & 0.972 & 0.042 \\ 0.006 & 0.041 & 0.999 \end{pmatrix}$$

in agreement with data and

$$\mathrm{U}_{\mathrm{Neutrino\ Mixing}} = \begin{pmatrix} 0.484 + 0.118i & 0.166 - 0.687i & -0.486 - 0.117i \\ 0.294 + 0.643i & 0.001 & 0.295 + 0.642i \\ -0.5i & 0.707 & 0.5i \end{pmatrix}$$

$$\mathrm{CKM}(\Lambda_{GUT}) = \begin{pmatrix} 0.973 & 0.228 & 0.003 \\ 0.228 & 0.972 & 0.042 \\ 0.006 & 0.041 & 0.999 \end{pmatrix}$$

$$\mathrm{U}_{\mathrm{Neutrino\ Mixing}}(\Lambda_{GUT}) = \begin{pmatrix} -0.43 - 0.11i & 0.76 - 0.06i & 0.05 - 0.46i \\ -0.07 - 0.34i & -0.18 - 0.59i & 0.70 \\ 0.82 & 0.13 - 0.11i & 0.02 - 0.54i \end{pmatrix}$$

Masses in KST vacua

The spectrum is

$$
\begin{array}{lcl lcl}
Q_1,\ Q_2,\ Q_3 & : & (\ \ 1,+1,\ \ 0,\ \ 0) & & & \\
U_1^c & : & (-1,\ \ 0,-1,\ \ 0) & U_2^c\ U_3^c & : & (-1,\ \ 0,\ \ 0,-1) \\
D_1^c & : & (-1,\ \ 0,+1,\ \ 0) & D_2^c\ D_3^c & : & (-1,\ \ 0,\ \ 0,+1) \\
L_1^c & : & (\ \ 0,+1,\ \ 0,-1) & L_2^c\ L_3^c & : & (\ \ 0,+1,-1,\ \ 0) \\
E_1^c,\ E_2^c,\ E_3^c & : & (\ \ 0,\ \ 0,+1,+1) & & & \\
N_1^c & : & (\ \ 0,\ \ 0,-1,+1) & N_2^c,\ N_3^c & : & (\ \ 0,\ \ 0,\ \ 0,\ \ 0)
\end{array}
$$

Kiritsis+Schellekens+Tsulaia 2008

The two MSSM Higgses are described by

$$H_u\ :\ (0,-1,+1,0)\quad ,\quad H_d\ :\ (0,+1,-1,0)\ .$$

The quark mass matrices for this vacuum are:

$$M_U = V_u \begin{pmatrix} 1 & 1 & E_1^* \\ 1 & 1 & E_1^* \\ 1 & 1 & E_1^* \end{pmatrix} \quad , \quad M_D = V_d \begin{pmatrix} 1 & 1 & E_1 \\ 1 & 1 & E_1 \\ 1 & 1 & E_1 \end{pmatrix}$$

- the lepton and neutrino mass matrices are given by:

$$M_L = V_d \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ E_1 & E_1 & E_1 \end{pmatrix}$$

$$M_N = \begin{pmatrix} 0 & 0 & 0 & V_u & V_u E_1^* & V_u E_1^* \\ 0 & 0 & 0 & V_u & V_u E_1^* & V_u E_1^* \\ 0 & 0 & V_u^2/M_s & V_u E_1 & V_u & V_u \\ V_u & V_u & g_{31} V_u E_1 & M_s E_1^2 & M_s E_1 & M_s E_1 \\ V_u E_1^* & V_u E_1^* & V_u & M_s E_1 & M_s & M_s \\ V_u E_1^* & V_u E_1^* & V_u & M_s E_1 & M_s & M_s \end{pmatrix}$$

- We obtain

M_s	V_u	V_d	E_1
1 TeV	644000	2230	2.191
10^{12} GeV	452960	3160	3.429
Λ_{GUT}	378800	2440	3.245

• The corresponding CKM matrices:

$$\mathrm{CKM}(1\mathrm{TeV}) = \begin{pmatrix} 0.727 & 0.444 & 0.522 \\ 0.554 & 0.755 & 0.350 \\ 0.403 & 0.481 & 0.777 \end{pmatrix}$$

$$\mathrm{CKM}(10^{12}\mathrm{GeV}) = \begin{pmatrix} 0.825 & 0.533 & 0.184 \\ 0.496 & 0.841 & 0.214 \\ 0.269 & 0.085 & 0.959 \end{pmatrix}$$

$$\mathrm{CKM}(\Lambda_{GUT}) = \begin{pmatrix} 0.662 & 0.543 & 0.515 \\ 0.554 & 0.675 & 0.486 \\ 0.503 & 0.498 & 0.705 \end{pmatrix}$$

CKM (Data)

$$\mathrm{CKM(Data)} =$$

$$= \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415 \pm 0.001 \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

Detailed plan of the presentation

- Title page 0 minutes
- Collaborators 1 minutes
- Introduction 3 minutes
- The Goal 4 minutes
- Mechanisms for mass hierarchies 6 minutes
- Can the mechanisms work in string theory? 8 minutes
- Bottom-up SM model building and orientifolds 11 minutes
- Which hierachy mechanisms do not work 13 minutes
- Which hierachy mechanisms do work 15 minutes
- The algorithm 18 minutes
- Quark Mass matrices 20 minutes
- Lepton Mass matrices 20 minutes
- Three-stack models 22 minutes
- Four-stack Models 24 minutes
- Example I 28 minutes
- Branes at a Z_3 singularity 32 minutes
- Outlook 33 minutes

- Five-stack Models 35 minutes
- Example I: addedum 37 minutes
- Example II 39 minutes
- Masses in KST vacua 41 minutes
- CKM (Data) 41 minutes