Corfu, 10 September 2009

On mass hierarchies in orientifolds

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In collaboration with: E. Kiritsis & A. Lionetto

Plan of the talk

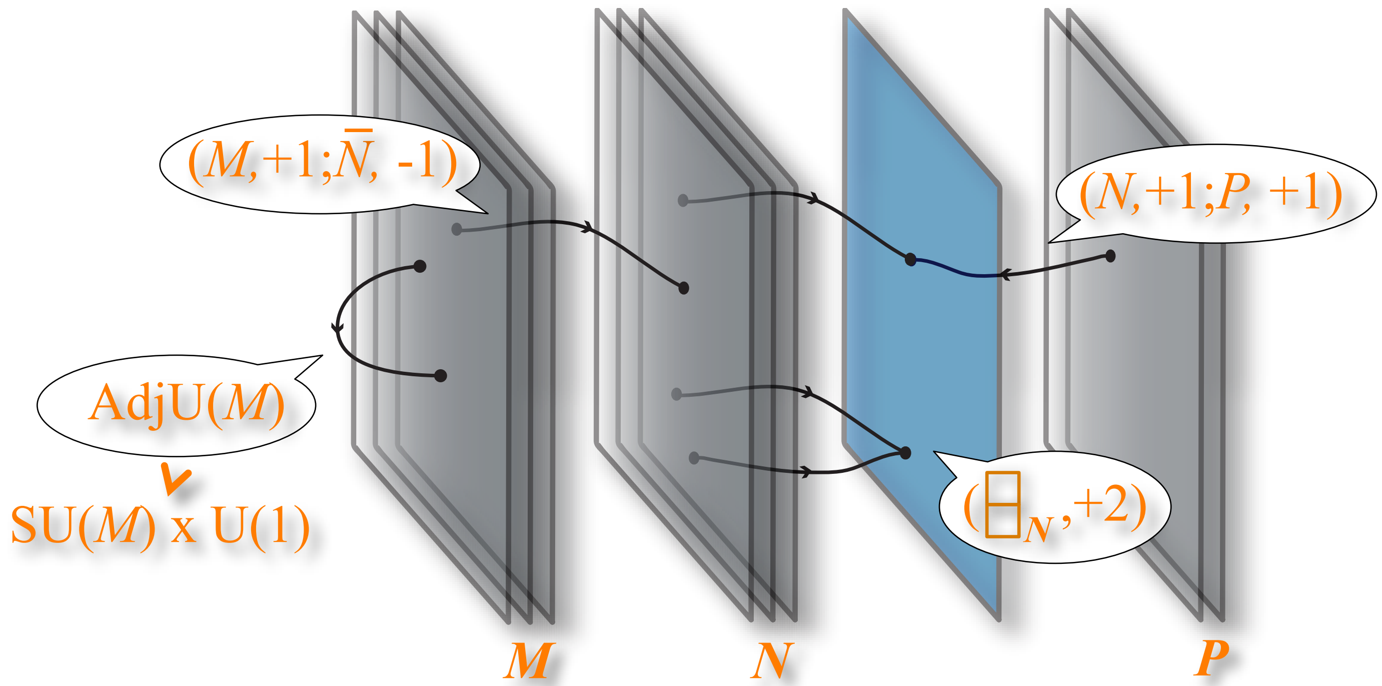
- Introduction and motivation
- D-brane realizations of the Standard Model
- Mass matrix general forms
- An interesting example
- Hierarchies
- Conclusions

Introduction and Motivation

- One of the biggest puzzles of the Standard Model is the origin and hierarchy of masses and mixings.
- The range of masses between the t-quark and the lightest neutrino spans 15 orders of magnitude!
- Several mechanism have been proposed to explain (parts of) the mass hierarchy in SM.
- In this talk we want to:
  - investigate the mechanism for the mass hierarchy in open string models (aka orientifolds).
  - To establish the kind of the SM embeddings that can accommodate such mechanism.

Toolkit for Model Building

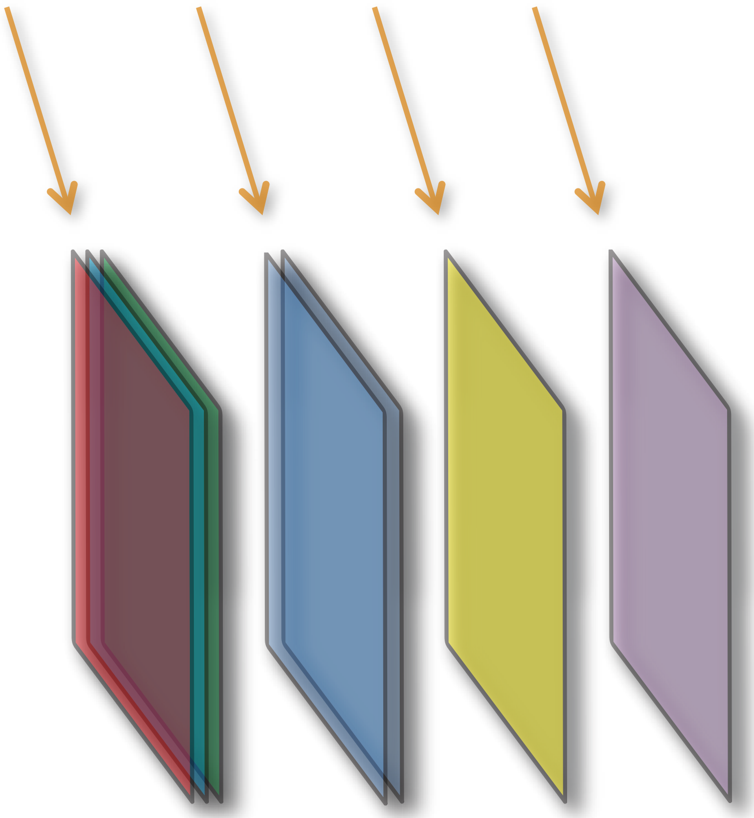
- Gauge Groups and Representations in Orientifold vacua:



- By these simple rules we can proceed and try to embed the SM in open string vacua.

D-brane Standard Models

- In open string vacua the Standard Model is located on some stacks of branes (intersecting or not):



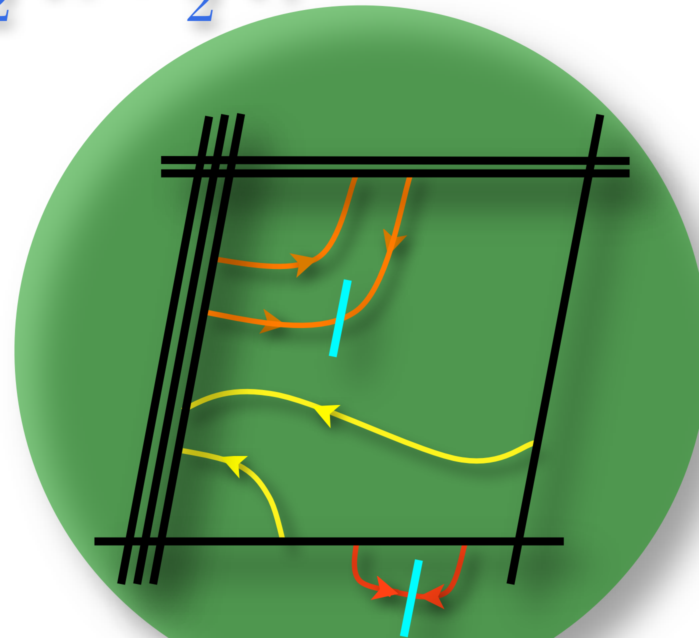
$$SU(3)\times SU(2)\times U(1)_Y$$

$$SU(3)\times SU(2)\times \overbrace{U(1)_3\times U(1)_2\times U(1)\times U(1)'}$$

Antoniadis Kiritsis Tomaras Rizos,
Aldazabal Ibanez Marchesano Quevedo Rabadan Uranga,
Cvetic Shiu Blumenhagen Honecker Kors Lust Ott,
Anastasopoulos Schellekens Dijkstra Huiszoon et al..

Example: The Madrid Model

- All SM particles for $Y = \frac{1}{6}Q_3 + \frac{1}{2}Q_1 + \frac{1}{2}Q_1'$:



Q : (1,-1, 0, 0) or (1,+1, 0, 0)

U : (-1, 0,-1, 0) or (-1, 0, 0,-1)

D : (-1, 0,+1, 0) or (-1, 0, 0,+1)

L : (0,-1,-1, 0) or (0,-1, 0,-1)
(0,+1,-1, 0) or (0,+1, 0,-1)

E : (0, 0, 1, 1) or (0, 0, 2, 0) or (0, 0, 0, 2)

N^c : (0, 2, 0, 0) or (0, 0, 1,-1) or (0, 0,-1, 1)

H_u : (0,-1,+1, 0) or (0,-1, 0,+1)
(0,+1,+1, 0) or (0,+1, 0,+1)

H_d : (0,-1,-1, 0) or (0,-1, 0,-1)
(0,+1,-1, 0) or (0,+1, 0,-1)

Anastasopoulos Dijkstra
Kiritsis Schellekens

- Particles of different families can have different charges.

Model building

- In the last years, there are several approaches towards the search for the Standard Model in String theory.
- However, non of them successfully describes all features of the SM or MSSM... We are working on this...
- Today, several new techniques have been established and can be applied in this task.
- Instead of a blind search, a better technique would be to focus in string vacua with some acceptable phenomenological criteria.
- In this talk, we will focus on the mass-terms and hierarchy in such models.

Masses in D-brane models

- How do fermions get masses in D-brane models?
- The usual $SU(3)\times SU(2)\times U(1)_Y$ is embedded in (for example):

$$SU(3)\times SU(2)\times U(1)_3\times U(1)_2\times U(1)\times U(1)'$$

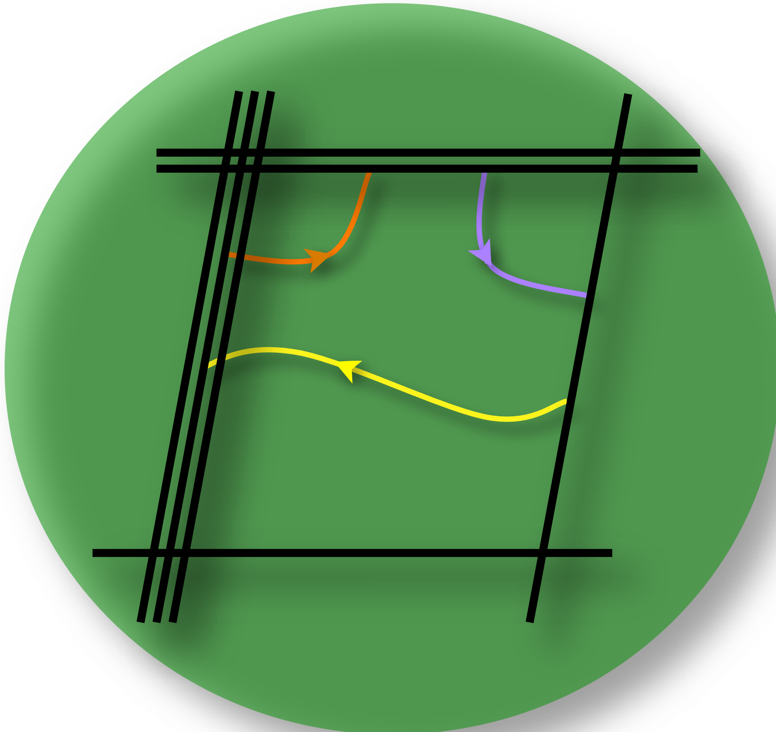
- The "mass-terms" in this case should respect more conditions.
- This forbids several Yukawa terms.
- Could these different terms give an answer to hierarchy?

Leontaris
Anastasopoulos Kiritsis Lionetto
Cvetic Halverson Richter

Yukawa-like terms

- Consider some SM particles to be:

```
Q  : ( 1,-1, 0, 0)
D1 : (-1, 0,+1, 0)    D2,3 : (-1, 0, 0,+1)
Hd : ( 0, 1,-1, 0)

φ1 : ( 0, 0, 1,-1)
φ2 : ( 0, 0,-1, 1)

E1 : ( 0, 0, 1,-1)
```

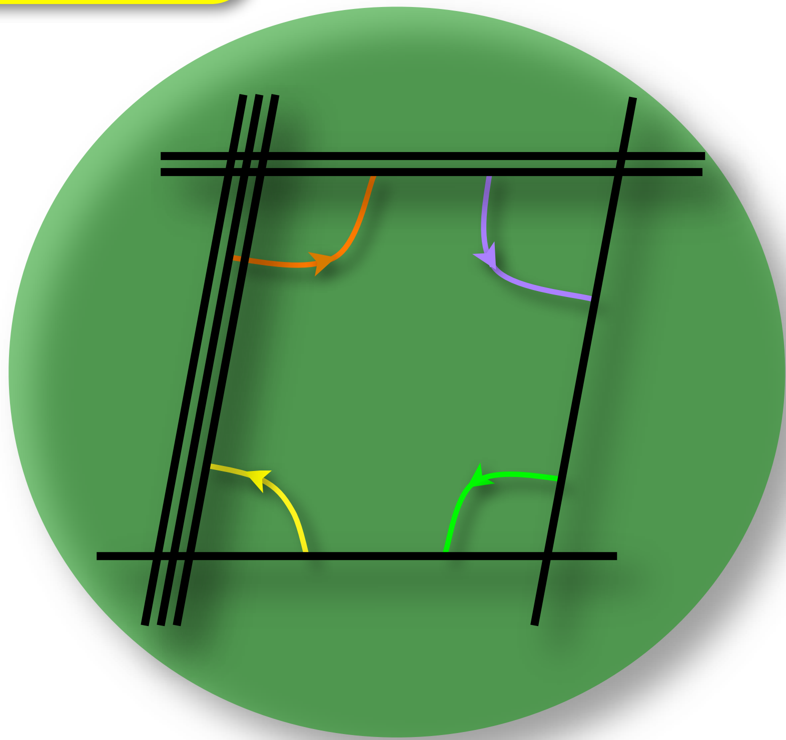


- Yukawa terms: $g_i Q D H_d$

Yukawa-like terms

- Consider some SM particles to be:

```
Q    : ( 1,-1, 0, 0)
D_1  : (-1, 0,+1, 0)    D_2,3 : (-1, 0, 0,+1)
H_d  : ( 0, 1,-1, 0)

φ_1  : ( 0, 0, 1,-1)
φ_2  : ( 0, 0,-1, 1)

E_1  : ( 0, 0, 1,-1)
```

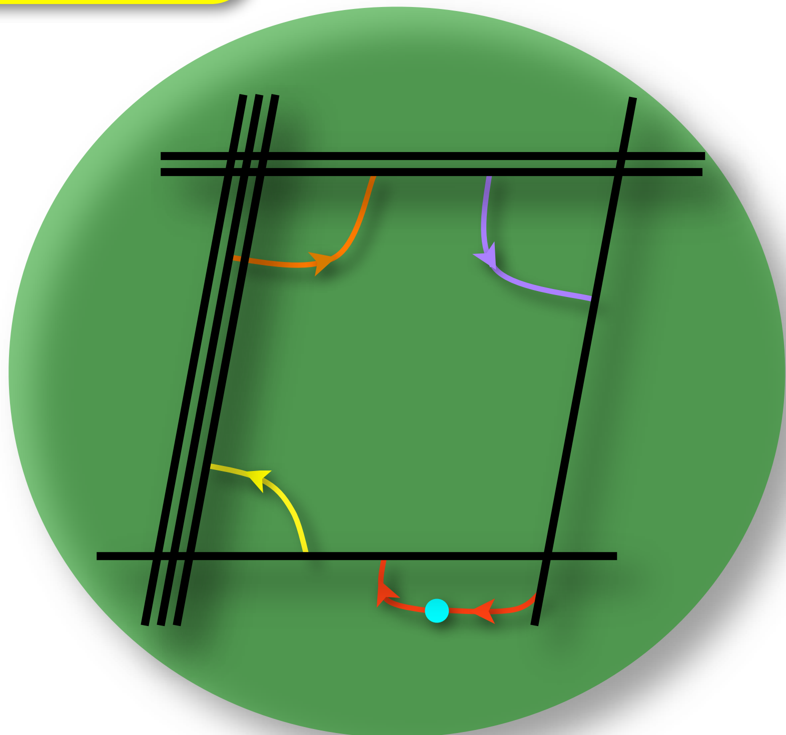


- Yukawa terms: $g_i Q D H_d$
- Higher order terms: $g_i Q D H_d \frac{\phi}{M_s}$

Yukawa-like terms

- Consider some SM particles to be:

```
Q   : ( 1,-1, 0, 0)

D_1 : (-1, 0,+1, 0)      D_2,3 : (-1, 0, 0,+1)

H_d : ( 0, 1,-1, 0)

φ_1 : ( 0, 0, 1,-1)

φ_2 : ( 0, 0,-1, 1)

E_1 : ( 0, 0, 1,-1)
```



- Yukawa terms: $g_i Q D H_d$
- Higher order terms: $g_i Q D H_d \frac{\phi}{M_s}$
- Instantonic contributions: $g_i Q D H_d \times e^{-Vol_I I}$

Yukawa-like terms $\Leftrightarrow$ Textures

- The mass terms can *a priori* be generated by:
  - Yukawa terms: $g_i Q U H_u \qquad \sim \langle H_u \rangle$
  - Higher order terms: $g_i Q U H_u \dfrac{\phi}{M_s} \qquad \sim \langle H_u \rangle \dfrac{\langle \phi \rangle}{M_s}$
  - Instantons: $g_i Q U H_u \times e^{-Vol_I I} \qquad \sim \langle H_u \rangle e^{-Vol_I}$
- Such terms depend on selection rules based on the U(1) charges.
- All terms with the same charges under the U(1)'s will have the same mass generating terms.
- Therefore, we can make a list of all possible "orientifold textures".

Quark Textures

- All D-brane realizations of the SM have either:
  - $Q_1 = Q_2 = Q_3$ or $Q_1 \neq Q_2 = Q_3$
  - $U_1 = U_2 = U_3$ or $U_1 \neq U_2 = U_3$
  - $D_1 = D_2 = D_3$ or $D_1 \neq D_2 = D_3$ or $D_1 \neq D_2 \neq D_3$
- The form of the mass matrix will be:

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

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Quark Textures

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  - $U_1 = U_2 = U_3$ or $U_1 \neq U_2 = U_3$
  - $D_1 = D_2 = D_3$ or $D_1 \neq D_2 = D_3$ or $D_1 \neq D_2 \neq D_3$
- The form of the mass matrix will be:

$$M_2 = \left(\begin{array}{c|cc} x & y & y \\ x & y & y \\ x & y & y \end{array}\right) \sim \left(\begin{array}{ccc} x & x & x \\ \hline y & y & y \\ y & y & y \end{array}\right)$$

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Quark Textures

- All D-brane realizations of the SM have either:
  - $Q_1 = Q_2 = Q_3$ or $Q_1 \neq Q_2 = Q_3$
  - $U_1 = U_2 = U_3$ or $U_1 \neq U_2 = U_3$
  - $D_1 = D_2 = D_3$ or $D_1 \neq D_2 = D_3$ or $D_1 \neq D_2 \neq D_3$
- The form of the mass matrix will be:

$$M_3 = \left(\begin{array}{c|cc} \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \hline \mathcal{Z} & \mathcal{U} & \mathcal{U} \\ \mathcal{Z} & \mathcal{U} & \mathcal{U} \end{array}\right)$$

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Quark Textures

- All D-brane realizations of the SM have either:
  - $Q_1 = Q_2 = Q_3$ or $Q_1 \neq Q_2 = Q_3$
  - $U_1 = U_2 = U_3$ or $U_1 \neq U_2 = U_3$
  - $D_1 = D_2 = D_3$ or $D_1 \neq D_2 = D_3$ or $D_1 \neq D_2 \neq D_3$
- The form of the mass matrix will be:

$$M_4 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \end{array} \right)$$

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Friday, September 11, 2009

Quark Textures

- All D-brane realizations of the SM have either:
  - $Q_1 = Q_2 = Q_3$ or $Q_1 \neq Q_2 = Q_3$
  - $U_1 = U_2 = U_3$ or $U_1 \neq U_2 = U_3$
  - $D_1 = D_2 = D_3$ or $D_1 \neq D_2 = D_3$ or $D_1 \neq D_2 \neq D_3$
- The form of the mass matrix will be:

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

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Lepton Textures

- Similar textures also for the Lepton mass matrix:

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

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

$$M_3 = \left(\begin{array}{c|cc} \mathcal{X} & \mathcal{Y} & \mathcal{Y} \\ \hline \mathcal{Z} & \mathcal{U} & \mathcal{U} \\ \mathcal{Z} & \mathcal{U} & \mathcal{U} \end{array}\right)$$

$$M_4 = \left(\begin{array}{c|c|c} \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \\ \mathcal{X} & \mathcal{Y} & \mathcal{Z} \end{array}\right)$$

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

- In this case, there is an extra possibility:

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

for $L_1 \neq L_2 \neq L_3\,, \;\; E_1 \neq E_2 \neq E_3\,.$

8 Madrid type models

- We are interested in bottom-up configurations where in all mass matrices appear Yukawas- and Higher- and Instantonic-terms.

- This pluralism might allow for solutions where the three masses from each matrix will be in 1-1 correspondence with the Yukawas-, Higher- and Instantonic-terms.

- Even if that is not general, it provides however a general first assessment of D-brane vacua as to their ability to generate multiple scales for masses and mixings.

- Within the “Madrid” class of models we have found 8 charge assignments with a single H_u and a single H_d , free of anomalies with the above property.

One from the 8 models

- The MSSM Particles:

Q_1 : (1,-1, 0, 0) $Q_{2,3}$: (1,+1, 0, 0)

U_1 : (-1, 0,-1, 0) $U_{2,3}$: (-1, 0, 0,-1)

D_1 : (-1, 0, 1, 0) $D_{2,3}$: (-1, 0, 0,+1)

$L_{1,2,3}$: (0,-1,-1, 0)

E_1 : (0, 0, 2, 0) E_2 : (0, 0, 1, 1) E_3 : (0, 0, 1, 1)

$N^c_{1,2,3}$: (0, 2, 0, 0)

H_u : (0, 1, 1, 0)

H_d : (0, 1,-1, 0)

ϕ_1 : (0, 0,-1,+1)

ϕ_2 : (0, 0,+1,-1)

E_1 : (0,-2, 0, 0)

- The U-quark mass matrix:

$$M_U = V_u \begin{pmatrix} g_1 & g_2\, v_{\phi_1} & g_3\, v_{\phi_1} \\ g_4\, E_1 & g_5\, E_2 & g_6\, E_2 \\ g_7\, E_1 & g_8\, E_2 & g_9\, E_2 \end{pmatrix}$$

where

$$V_u = \langle H_u \rangle,\ v_{\phi_i} = \langle \phi_i \rangle / M_s\,,\ E_i = e^{-S_i}$$

One from the 8 models

- The MSSM Particles:

Q_1 : (1,-1, 0, 0)　　$Q_{2,3}$: (1,+1, 0, 0)

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$L_{1,2,3}$: (0,-1,-1, 0)

E_1 : (0, 0, 2, 0)　　E_2 : (0, 0, 1, 1)　　E_3 : (0, 0, 1, 1)

$N^c_{1,2,3}$: (0, 2, 0, 0)

H_u : (0, 1, 1, 0)

H_d : (0, 1,-1, 0)

ϕ_1 : (0, 0,-1,+1)

ϕ_2 : (0, 0,+1,-1)

E_1 : (0,-2, 0, 0)

- The U-quark mass matrix:

$$M_U = V_u \begin{pmatrix} g_1 & g_2\, v_{\phi_1} & g_3\, v_{\phi_1} \\ g_4\, E_1 & g_5\, E_2 & g_6\, E_2 \\ g_7\, E_1 & g_8\, E_2 & g_9\, E_2 \end{pmatrix}$$

where

$$V_u = \langle H_u \rangle,\; v_{\phi_i} = \langle \phi_i \rangle / M_s\,,\; E_i = e^{-S_i}$$

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Q_1 : (1,-1, 0, 0) $\quad$ $Q_{2,3}$: (1,+1, 0, 0)

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D_1 : (-1, 0, 1, 0) $\quad$ $D_{2,3}$: (-1, 0, 0,+1)

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E_1 : (0, 0, 2, 0) $\quad$ E_2 : (0, 0, 1, 1) $\quad$ E_3 : (0, 0, 1, 1)

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H_u : (0, 1, 1, 0)

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- The U-quark mass matrix:

$$M_U = V_u \begin{pmatrix} g_1 & g_2\, v_{\phi_1} & g_3\, v_{\phi_1} \\ g_4\, E_1 & g_5\, E_2 & g_6\, E_2 \\ g_7\, E_1 & g_8\, E_2 & g_9\, E_2 \end{pmatrix}$$

where

$$V_u = \langle H_u \rangle,\ v_{\phi_i} = \langle \phi_i \rangle / M_s\,,\ E_i = e^{-S_i}$$

All Mass Matrices

- The U-quark, D-quark, Lepton and Neutrino mass matrices:

$$M_U = V_u \begin{pmatrix} g_1 & g_2\, v_{\phi_1} & g_3\, v_{\phi_1} \\ g_4\, E_1 & g_5\, E_2 & g_6\, E_2 \\ g_7\, E_1 & g_8\, E_2 & g_9\, E_2 \end{pmatrix} \qquad M_D = V_d \begin{pmatrix} q_1 & q_2\, v_{\phi_2} & q_3\, v_{\phi_2} \\ q_4\, E_1 & q_5\, E_3 & q_6\, E_3 \\ q_7\, E_1 & q_8\, E_3 & q_9\, E_3 \end{pmatrix}$$

$$M_L = V_d \begin{pmatrix} l_1\, E_4 & l_2\, v_{\phi_1} & l_3 \\ l_4\, E_4 & l_5\, v_{\phi_1} & l_6 \\ l_7\, E_4 & l_8\, v_{\phi_1} & l_9 \end{pmatrix}$$

$$M_N \sim \begin{pmatrix} 0 & 0 & 0 & V_u E_1 & V_u E_1 & V_u E_1 \\ 0 & 0 & 0 & V_u E_1 & V_u E_1 & V_u E_1 \\ 0 & 0 & 0 & V_u E_1 & V_u E_1 & V_u E_1 \\ V_u E_1 & V_u E_1 & V_u E_1 & M_s E_5 & M_s E_5 & M_s E_5 \\ V_u E_1 & V_u E_1 & V_u E_1 & M_s E_5 & M_s E_5 & M_s E_5 \\ V_u E_1 & V_u E_1 & V_u E_1 & M_s E_5 & M_s E_5 & M_s E_5 \end{pmatrix}$$

Solving for the Unknowns

- The U-quark mass matrix is:

$$M_U = V_u \begin{pmatrix} g_1 & g_2\, v_{\phi_1} & g_3\, v_{\phi_1} \\ g_4\, E_1 & g_5\, E_2 & g_6\, E_2 \\ g_7\, E_1 & g_8\, E_2 & g_9\, E_2 \end{pmatrix}$$

- We are looking for solutions where:

$$\begin{aligned} \lambda_1^U &\sim V_u v_{\phi_1} &= m_u \\ \lambda_2^U &\sim V_u E_2 &= m_c \\ \lambda_3^U &\sim V_u &= m_t \end{aligned}$$

in the perturbative regime $|g_i| \in [0.1 - 0.5]$.

- This type of solutions could naturally explain the hierarchy in the ***u***, ***c***, ***t*** quark masses.

Solutions for all the Unknowns

- An interesting solution for all scales ($1\ \text{TeV},\ 10^{15}\ \text{MeV},\ \Lambda_{\text{GUT}}$):

$$
\begin{array}{ll}
V_u \sim m_t, & V_d \sim m_b \\
E_1 \sim E_2 \sim m_c/m_t & E_3 \sim E_4 \sim m_s/m_b \\
v_{\phi_1} \sim m_u/m_t & v_{\phi_2} \sim m_d/m_b
\end{array}
$$

- The last instanton related to the Majorana term:

$$
\begin{array}{rcl}
1\ \text{TeV scale} & : & E_5 \sim 0.654 \\
10^{15}\ \text{MeV scale} & : & E_5 \sim 0.754 \\
\Lambda_{\text{GUT}}\ \text{scale} & : & E_5 \sim 2.5 \times 10^{-7}
\end{array}
$$

- The last instanton appears always as $E_5 \times M_s$ and initiates the seesaw mechanism.

$$
\begin{array}{ll}
V_u \sim m_t, & V_d \sim m_b \\
E_1 \sim E_2 \sim m_c/m_t & E_3 \sim E_4 \sim m_s/m_b \\
v_{\phi_1} \sim m_u/m_t & v_{\phi_2} \sim m_d/m_b
\end{array}
$$

$$
\begin{array}{rcl}
1 \text{ TeV scale} & : & E_5 \sim 0.654 \\
10^{15} \text{ MeV scale} & : & E_5 \sim 0.754 \\
\Lambda_{\text{GUT}} \text{ scale} & : & E_5 \sim 2.5 \times 10^{-7}
\end{array}
$$

- The CKM matrix:

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

- The mixing-neutrino matrix:

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

- Comparing with Data:

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

- This model could give a natural explanation of the hierarchy.

More/Less D-brane stacks

- The smaller is the number of different Yukawa-type terms $\Rightarrow$
  the more related are the mass matrices $\Rightarrow$
  the more difficult is to find the previous hierarchical solutions.

- Therefore, it is easy to show that in:

  - 3-stacks models: No such solutions.

  - 4-stacks models: Only few such solutions (Madrid).

  - 5-stacks (or more) models: More solutions are expected/found...

“Bad” terms

- A bonus: undesired terms could be absent due to the extended symmetries.

- So, apart from the mass terms, some extra terms could be present:

$$H_u H_d \,, \quad QDL \,, \quad DDU \,, \quad LEL \,, \quad H_u H_d \nu \,, \quad H_d \cancel{E} H_d \,, \quad \nu\nu\nu$$

- However, now they can be present due to instantonic effect.

- There are non-dangerous and dangerous terms (for small M_s).

- All 8 bottom-up models have no dangerous terms.

Conclusions

- Open string textures are different from the traditional ones.
- Yukawa-, Higher- and Instantonic-terms can generate the full hierarchy of the Standard Model: From the t-quark down to neutrinos.
- Undesired terms can be eliminated without problems due to the extended additional U(1) symmetries.
- Search for optimal embeddings in consistent orientifolds (with cancelled tadpoles) is very interesting (and in progress).