A Kind of Prediction from String Phenomenology: Extra Matter at Low Energy

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What is String Phenomenology ?

The Search of the Standard Model in String Theory

The compactification of the $E_8 \times E_8$ heterotic superstring on six-dimensional spaces was the starting point for this race

Candelas, Horowitz, Strominger, Witten, 85

For example, in the late eighties, orbifolds spaces proved to be an interesting method to construct four-dimensional standard-like models,

Dixon, Harvey, Vafa, Witten, 85

Ibáñez, Kim, Mas, Nilles, Quevedo, 87

Bailin, Love, Thomas, 87

Casas, Katehou, CM, 87

Font, Ibáñez, Nilles, Quevedo, 88

Kim, 88

Casas, CM, 88

Dixon, Kaplunovsky, Louis, 89

Font, Ibáñez, Quevedo, Sierra, 89

Casas, Mondragon, CM, 89

Katsuki, Kawamura, Kobayashi, Ohtsubo, 90

Kim, Kim, 93

Aldazabal, Font, Ibáñez, Uranga, 96

...

There was also interesting model building using

- Calabi–Yau spaces

  Candelas, Horowitz, Strominger, Witten, 85

  Greene, Kirklin, Miron, Ross, 86

  ...

- Fermionic constructions

  Antoniadis, Bachas, Kounnas, 86

  Kawai, Lewellen, Tye, 86

  Antoniadis, Ellis, Hagelin, Nanopoulos, 88

  Faraggi, Nanopoulos, Yuan, 90

  Chaudhuri, Chung, Hockney, Lykken, 95

  Cleaver, Faraggi, Nanopoulos, 99

  Cleaver, Faraggi, Nanopoulos, Walker, 01

  ...

- ...

This was very interesting:

At least we knew that something close to the real world could arise from strings

But,...

the Standard Model was not found !

A PHOTOGRAPH EXPLAINING WHAT IS GOING ON, CONCERNING THE SEARCH OF THE STANDARD MODEL FROM STRINGS, IN 1988, WILL BE READY SOON HERE

A SECOND PHOTOGRAPH EXPLAINING WHAT IS GOING ON, CONCERNING THE SEARCH OF THE STANDARD MODEL FROM STRINGS, IN 1988, WILL BE READY SOON HERE

In the late nineties it has been discovered that interesting model building can also be made using type I string vacua

Nowadays these are the new superstars

A PHOTOGRAPH EXPLAINING WHAT IS GOING ON, CONCERNING THE SEARCH OF THE STANDARD MODEL FROM STRINGS, IN 2003, WILL BE READY SOON HERE

A SECOND PHOTOGRAPH EXPLAINING WHAT IS GOING ON, CONCERNING THE SEARCH OF THE STANDARD MODEL FROM STRINGS, IN 2003, WILL BE READY SOON HERE

almost 20 years have gone by
since Strings became a realistic theory,
and the Standard Model has not been found yet!

In any case, this talk is out of fashion

No D-branes will be involved !

Introduction

It was shown that the Z_3 orbifold can give rise to four-dimensional models with gauge group

$$SU(3) \times SU(2) \times U(1)^5 \times G_{hidden}$$

and three generations of particles with the correct $SU(3) \times SU(2)$ representations (plus extra particles)

Ibañez, Kim, Nilles, Quevedo, 87

And with the following properties:

Casas, Katehou, CM, 87

- One of the $U(1)$'s is usually anomalous

- Combinations of the non-anomalous $U(1)$'s give the physical hypercharge

- The Fayet–Iliopoulos D-term can give rise to the breaking of the extra $U(1)$'s $D^{(a)} \sim c - \sum_i Q_i^{(a)} C_i C_i^*$

  This is because, in order to preserve supersymmetry at high energies, some scalars with $U(1)$'s quantum numbers acquire large VEVs.

In this way it was possible to construct supersymmetric vacuum states (I,II) where

Casas, CM, 87

Font, Ibañez, Nilles, Quevedo, 87

- $SU(3) \times SU(2) \times U(1)^8 \times SO(10)$
  $\rightarrow SU(3) \times SU(2) \times U(1)_Y \times SO(10)_{hidden}$
  FI

- with three generations of particles.

- baryon and lepton number violating operators absent.

Recently, another model (III) has been analyzed

$SU(3) \times SU(2) \times U(1)^8 \times SU(5) \times SU(2)$

Giedt, 01

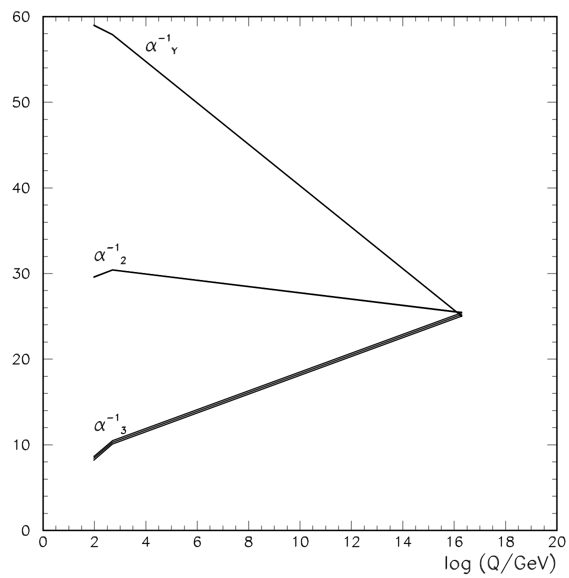
Unfortunately, we cannot claim that one of these models is the Superstring Standard Model, e.g.

- $3\times\{(3,2)+2(\bar{3},1)+(1,2)+1\}+3\times\left\{(16)'+4[(3,1)+(\bar{3},1)]+12(1,2)+56\cdot 1\right\}$
  $\rightarrow 3\times\{(3,2)+2(\bar{3},1)+(1,2)+1\}+3\times\left\{4(1,2)+4\cdot 1+(16)'+11\cdot 1'\right\}$
  FI

However, we are optimistic people, and therefore we argue that if the Standard Model arises from this type of constructions, there must exist one model with

no extra matter

- But then a third problem arises: the unification scale, $M_{GUT} \approx 2 \cdot 10^{16}$ GeV, deduced from LEP experiments (assuming $C^2 = 3/5$)



cannot be obtained because in the heterotic string, $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV, with g_{GUT} the unified gauge coupling

Kaplunovsky, 88

Since the running of the gauge couplings and the amount matter are related, may be it is not a good strategy to eliminate the whole extra matter

Antoniadis, Ellis, Kelley, Nanopoulos, 91

Antoniadis, Leontaris, Tracas, 92

Bailin, Love, 92

Gaillard, Xiu, 92

Faraggi, 93

- Imposing the unification of the couplings at $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV we will be able "to predict" the existence of *three generations of supersymmetric Higgses and vector-like colour triplets* at low energy

Scales

To analyse the gauge couplings, we need to first clarify which are the relevant scales for the running between M_Z and M_{GUT}

- The supersymmetric scale M_S.
- The Fayet–Iliopoulos scale M_{FI}:

  $SU(3) \times SU(2)$ singlets develop VEVs in order to cancel the Fayet–Iliopoulos D-term

  $$D^{(a)} \sim \sum_i Q_i^{(a)} C_i C_i^* + \frac{g_{GUT}^2 \; trQ^{(a)}}{192\pi^2} M_P^2$$

  Remarkably enough, in all constructed models there is a large subset of singlets with $Y = 0$

  An estimate can be done with the average result

  $$\langle C_j \rangle \sim 10^{16-17} \text{ GeV}$$

  After the breaking, many particles acquire a high mass through $\langle C_j \rangle \xi \xi$

  In this way vector-like triplets and doublets and also singlets become very heavy $\Rightarrow$ $M_{FI} \approx 10^{16-17}$ GeV.

We adopt the following point of view: all the extra matter is massless or very heavy

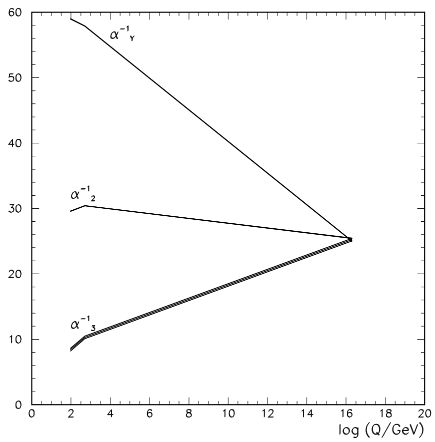
The massive one has a mass of the order of M_{FI}

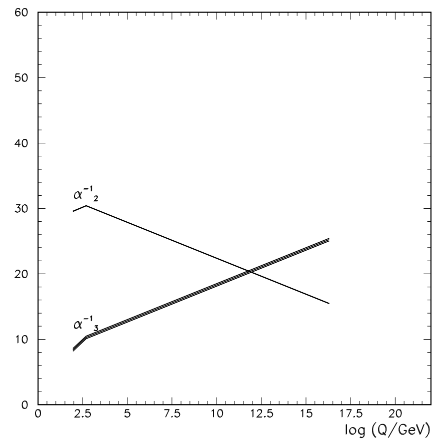
The massless one must acquire mass through the electroweak symmetry breaking

Since e.g. no new quarks have been observed in colliders, their masses must be basically heavier than 200 GeV. We will consider that the masses of these extra particles are of the order of M_S.

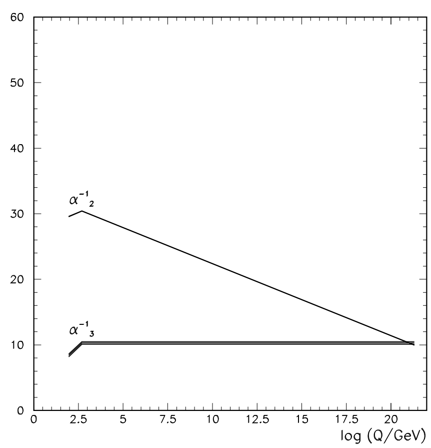
Let us concentrate on $\alpha_{3,2}$ neglecting the scale M_{FI}

The most natural possibility is $3 \times \{(1,2)+(1,2)\}$ light susy Higgses, i.e. $n_2 = 4$:





We could try to improve this situation by assuming also $3 \times \{(3,1)+(\bar{3},1)\}$, i.e. $n_3 = 6$:



The next simplest possibility, $n_2 = 7$ and $n_3 = 6$, produces the crossing at the scale $\approx 10^{15}$ GeV. More extra triplets would imply at least $n_3 = 12$ and therefore α_3^{-1} becomes negative at the scale $\approx 10^{13}$ GeV

Summarizing, α_3 never crosses α_2 at $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV

Thus let us include the scale M_{FI} in the analysis of the interesting case $n_2 = 4, n_3 = 6$

To study the RGEs we need to know n_2^{FI} and n_3^{FI}

Model building implies

Casas, Mondragón, CM, 89

Giedt, 01

- There exist only 192 three-generation models with $SU(3) \times SU(2) \times U(1)^5$ gauge group associated to the first E_8

- They have only five possible gauge groups associated to the second E_8:

  $SU(5) \times SU(2) \times U(1)^3 \ , \quad SO(10) \times U(1)^3$,

  $SU(4) \times SU(2)^2 \times U(1)^3 \ , \quad SU(2)^2 \times U(1)^6$

  $SU(3) \times SU(2)^2 \times U(1)^4$,

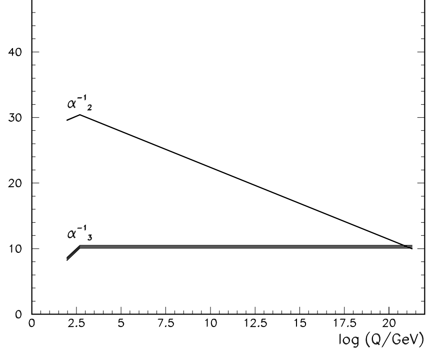
- The patterns of matter are

  $a)\ n_3^{FI} = 0 \ , n_2^{FI} = 12 \rightarrow 3 \times \{4(1,2)\}$

  $b)\ n_3^{FI} = 6 \ , \ n_2^{FI} = 18 \rightarrow 3 \times \{(3,1) + (\bar{3},1) + 6(1,2)\}$

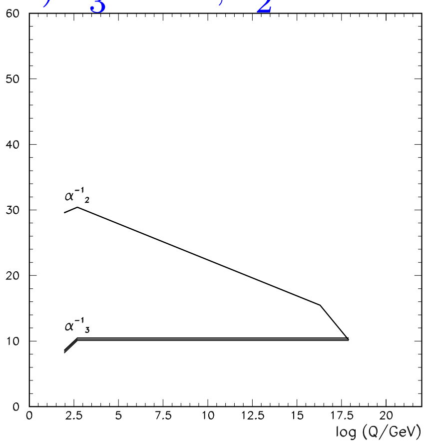
  $c)\ n_3^{FI} = 12 \ , \ n_2^{FI} = 24 \rightarrow 3 \times \{2[(3,1) + (\bar{3},1)] + 8(1,2)\}$

  $d)\ n_3^{FI} = 18 \ , \ n_2^{FI} = 30 \rightarrow 3 \times \{3[(3,1) + (\bar{3},1)] + 10(1,2)\}$

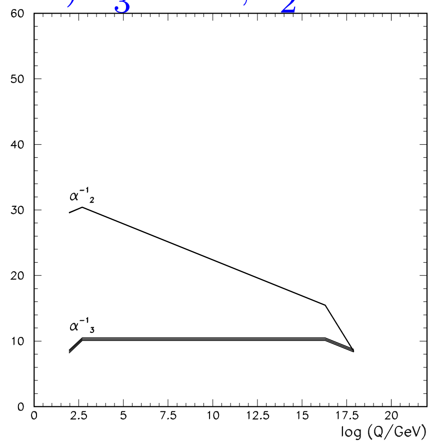


$\downarrow$

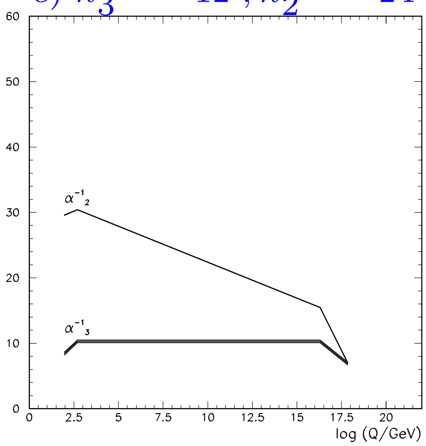
$a)\ n_3^{FI} = 0\ ,\, n_2^{FI} = 12$



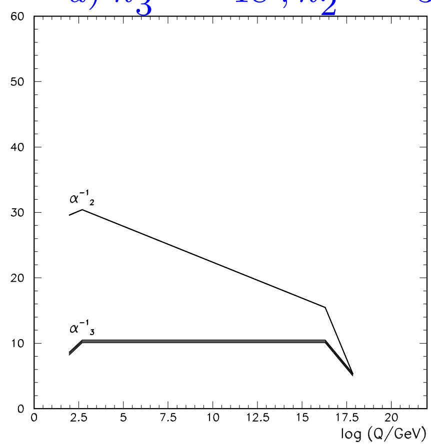
$b)\ n_3^{FI} = 6\ ,\, n_2^{FI} = 18$



$c)\ n_3^{FI} = 12\ ,\, n_2^{FI} = 24$



$d)\ n_3^{FI} = 18\ ,\, n_2^{FI} = 30$



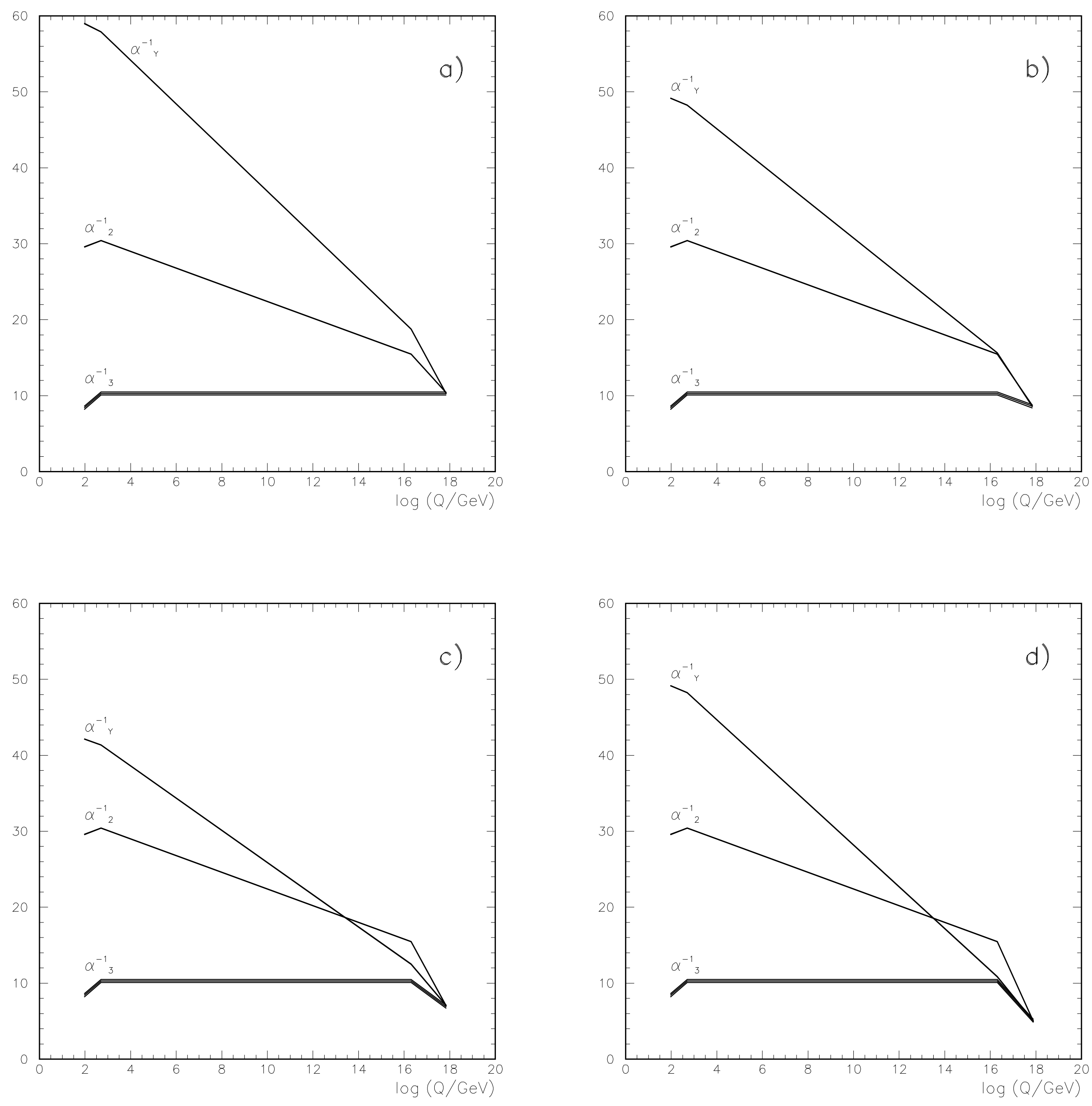
Unification of the gauge couplings at $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV, when $M_{FI} \approx 2 \cdot 10^{16}$ GeV

Remark that at low energy we have

$$3\times\{(3,2) + 2(\bar{3},1) + (1,2)\} + 3 \times \{(3,1) + (\bar{3},1) + 2(1,2)\}$$

Does α_1 join the other two couplings at M_{GUT} ?

The hypercharge for the physical particles is obtained as a combination of $U(1)$'s, $Y = \sum c_i U_i$, and therefore $C = (\sum c_i^2)^{-1/2}$



A kind of prediction from this superstring scenario

We have at low energy (excluding singlets)

$$\boxed{3 \times \{(3,2) + 2(\bar{3},1) + (1,2)\}}$$

$$+$$

$$\boxed{3 \times \{(3,1) + (\bar{3},1) + 2(1,2)\}}$$

i.e. the matter content of the Supersymmetric Standard Model with three generations of Higgses and vector-like colour triplets

This is a modest prediction compared with the ones that are common nowadays:

- 1 TeV scale
- 10^{11} GeV scale
- 1 mm dimension
- black hole production
- ...
- ...

Phenomenology of several families of susy Higgses

They have a much richer phenomenology than that of the Higgses in the MSSM, where there are "only"

3 neutral Higgses + 1 charged Higgs

♣ $3 \times \{H + \bar{H}\}$

11 neutral Higgses + 5 charged Higgses

multi doublets $\longrightarrow$ Flores, Sher 82
Haber, Nir, 89
four doublets $\longrightarrow$ Drees, 88
Nelson, Randall, 93
Masip, Rasin, 95
six doublets $\longrightarrow$ Griest, Sher, 89
Aranda, Sher, 00

♣ $3 \times \{H + \bar{H} + N\}$

17 neutral Higgses + 5 charged Higgses

Ellis, Nanopoulos, Petcov, Zwirner, 86

Phenomenology of vector-like colour triplets

♣ IMPLICATIONS ON THE SCALAR POTENTIAL

- Since these fields, say D and $\overline{D}$, are light, they must acquire masses above the experimental limit $\sim$ 200 GeV

  This can be carried out through couplings with some of the extra singlets with $Y = 0$, say N_i, which are usually left at low energies, even after the Fayet-Iliopoulos breaking.

  (for example, in model I there are 13 of these singlets)

  Thus couplings $N_i D\overline{D}$ should be present.

- From the electroweak symmetry breaking, the fields N_i a VEV might develop:

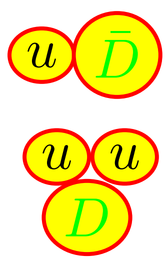
  Given the large number of singlets present in orbifold models, the mechanism for generating a μ term through couplings of the type $N_j H\bar{H}$ seems to be natural

♣ HYPERCHARGES

- Model II with $C^2 = 3/11$ has triplets with hypercharge $\pm 1/6$

  Model III with $C^2 = 15/37$ has triplets with hypercharge $\pm 1/15$

  This non-standard fractional electric charge means that they have necessarily colour-neutral fractionally charged states, since the triplets bind with the ordinary quarks



$$\frac{2}{3} - \frac{1}{6} = \frac{1}{2}$$

$$\frac{2}{3} + \frac{2}{3} + \frac{1}{6} = \frac{3}{2}$$

  Model I with $C^2 = 3/17$ has 'standard' extra triplets, i.e. with electric charges $\mp 1/3$ and $\pm 2/3$

  These will give rise to colour-neutral integrally charged states

  For example, a d-like quark D forms states of the type $u\overline{D}$, uuD, etc.

Fermion masses and mixing angles

Crucial ingredients in our analysis were

i) Three families of Higgses

ii) The FI breaking

Both ingredients favour to obtain the correct Yukawa couplings in these models with three generations

Abel, CM, 03

The main difficulty in superstring phenomenology resides in how to obtain the weird structure of fermion masses and mixing angles

The correct model must reproduce also the correct mass hierarchy for quarks and leptons.

$$\frac{m_t}{m_u} \sim 10^5, \qquad \frac{m_\tau}{m_e} \sim 10^3$$

Orbifold spaces have a beautiful mechanism to generate a mass hierarchy: Yukawa couplings can be computed and they get suppression factors

Hamidi, Vafa, 86

Dixon, Friedan, Martinec, Shenker, 86

$$\lambda \sim e^{-\sum_i c^i_\lambda T_i}\ , \qquad Re\ T_i \sim R_i^2$$

which depend on the distance between the fixed points to which the relevant fields are attached

$$\Downarrow$$

one can span five orders of magnitude the Yukawa couplings

Ibáñez 86

Casas, CM, 90

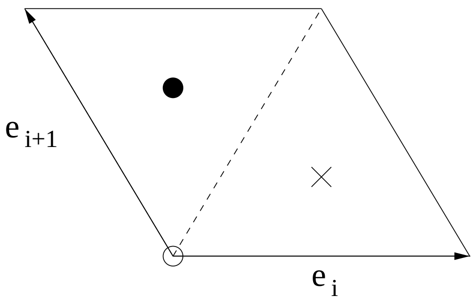
Unfortunately, this is not the end of the story

$$\mathcal{M}_{\mathsf{CKM}} = \begin{pmatrix} 0.9745-0.9760 & 0.217-0.224 & 0.0018-0.0045 \\ 0.217-0.224 & 0.9737-0.9753 & 0.036-0.042 \\ 0.004-0.013 & 0.035-0.042 & 0.9991-0.9994 \end{pmatrix}$$

$$\Downarrow$$

$$H_u^0\ \bar{u}_{L\alpha} {\lambda_u}^{\beta\gamma} u_{R\gamma} + H_d^0\ \bar{d}_{L\alpha} {\lambda_d}^{\beta\gamma} d_{R\gamma}$$

one can get in principle this kind of structure, e.g. in orbifolds



Two dimensional sublattices ($i = 1, 3, 5$) of the Z_3 orbifold, and fixed points

$$\begin{array}{ccccc} & & & \circ & H_u^0 \\ & \circ & \circ & \times & \\ & & & \cdot & \end{array}$$

$$\begin{array}{ccccc} & & & \circ & Q_t \\ Q & \circ & \circ & \times & Q_c \\ & & & \cdot & Q_u \end{array}$$

$$\begin{array}{ccccc} & & & \circ & t_R \\ u_R & \circ & \circ & \times & c_R \\ & & & \cdot & u_R \end{array}$$

This implies, at the renormalizable level,

$$\begin{array}{cccc} H_u^0 & \circ & \circ & \circ \\ Q_t & \circ & \circ & \circ \\ t_R & \circ & \circ & \circ \end{array} \qquad \begin{array}{cccc} H_u^0 & \circ & \circ & \circ \\ Q_c & \circ & \circ & \times \\ u_R & \circ & \circ & \cdot \end{array} \qquad \begin{array}{cccc} H_u^0 & \circ & \circ & \circ \\ Q_u & \circ & \circ & \cdot \\ c_R & \circ & \circ & \times \end{array}$$

i.e. $\lambda_{tt} \sim 1, \quad \lambda_{cu} = \lambda_{uc} \sim e^{-R_5^2} \equiv \epsilon_5$

$$\longrightarrow \mathcal{M}^u = gN \begin{pmatrix} 0 & v^u \epsilon_5 & 0 \\ v^u \epsilon_5 & 0 & 0 \\ 0 & 0 & v^u \end{pmatrix}$$

This is not sufficient and one has to use non-renormalizable couplings Casas, CM, 90

Casas, Gómez, CM, 92

- Importantly for our analysis, having three families of Higgses, o o (o x .), introduces more Yukawa couplings

$$\mathcal{M}^u = gN \begin{pmatrix} v_1^u & v_3^u \varepsilon_5 & v_2^u \varepsilon_5 \\ v_3^u \varepsilon_5 & v_2^u & v_1^u \varepsilon_5 \\ v_2^u \varepsilon_5 & v_1^u \varepsilon_5 & v_3^u \end{pmatrix} \quad \mathcal{M}^d = gN\epsilon_1 \begin{pmatrix} v_1^d & v_3^d \varepsilon_5 & v_2^d \varepsilon_5 \\ v_3^d \varepsilon_5 & v_2^d & v_1^d \varepsilon_5 \\ v_2^d \varepsilon_5 & v_1^d \varepsilon_5 & v_3^d \end{pmatrix}$$

But this is not sufficient yet because
$(V_{CKM})_{13} \approx 3.8 \times 10^{-5}$, $(V_{CKM})_{23} \approx 4.8 \times 10^{-6}$

- The FI breaking provides a second crucial ingredient in our analysis which appears at the renormalizable level.

  Namely, after the gauge breaking some physical particles appear combined with other states, and the Yukawa couplings are modified in a well controled way

  e.g. the couplings $\langle C_1 \rangle \xi_1 f$, $\langle C_2 \rangle \xi_1 \xi_2$,

  will give rise to two very massive states ξ_1, $\xi_2' \sim \langle C_1 \rangle f + \langle C_2 \rangle \xi_2$

  and one massless $f' \sim \langle C_2 \rangle f - \langle C_1 \rangle \xi_2$

  The Yukawa couplings and hence mass matrices of the effective low energy theory are modified accordingly: $HQf \sim \langle C_2 \rangle HQf'$.

$$\begin{pmatrix} v_1 \epsilon_5 & v_3 \varepsilon_5 & v_2 \\ v_3 \varepsilon_5^2 & v_2^u & v_1^u \\ v_2 \varepsilon_5^2 & v_1 \varepsilon_5 & v_3/\epsilon_5 \end{pmatrix}$$

The experimental fact that neutrinos are massive makes this task more involved:

$$\frac{m_t}{m_u} \sim 10^5, \quad \frac{m_\tau}{m_e} \sim 10^3, \quad \frac{m_e}{m_\nu} \gtrsim 10^6$$

One can find interesting mechanisms to try to explain these experimental results.

For example, if the Yukawa coupling for the neutrino is of order m_e and the see saw scale is 1 TeV, then the expected neutrino mass is

$$\frac{m_e^2}{1\ TeV} = 0.25 \text{ eV}$$

This suggests that a natural situation is one in which a see-saw mass of order a few TeV is generated by the electroweak symmetry breaking.

Abel, CM, 03

$$W_\nu \sim \lambda_\nu \langle H_2^0 \rangle \bar{\nu}_L \nu_R + \langle N \rangle \nu_R \nu_R + \langle N \rangle H_2^0 H_1^0$$

with $\lambda_\nu \sim e^{-R^2}$ and therefore very small,

and $\langle N \rangle \sim 1$ TeV

Conclusions

We have attacked the problem of the unification of gauge couplings in the heterotic string

They unify at the right scale, when a certain type of extra matter is present. Three families of susy Higgses and vector-like colour triplets might be observed in forthcoming experiments

(since we believe in the Higgs mechanism, in supersymmetry, and in the heterotic string)

Although we have been working with orbifolds, our arguments are quite general and can be used for other schemes, since extra matter and anomalous $U(1)$'s are generically present in compactifications of the heterotic string

Crucial ingredients in our analysis were three families of Higgses and the FI breaking. Both favour to obtain the correct Yukawa couplings in these models