A kind of prediction from superstring model building

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A PHOTOGRAPH EXPLAINING WHAT IS STRING PHENOMENOLOGY WILL BE READY SOON HERE

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

Introduction

In the late eighties, the compactification of the $E_8 \times E_8$ heterotic string on six-dimensional orbifolds proved to be an interesting method to carry out this task

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

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

  ...

- ...

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

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

- It was not possible to obtain correct Yukawa couplings in these models

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

$$Y_i \sim e^{-T_i} , \qquad T_i \sim R_i^2$$

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

$$\Downarrow$$

  one can span six orders of magnitude the Yukawa couplings, and

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

  Unfortunately, it is extremely difficult to implement this mechanism in a particular model.

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

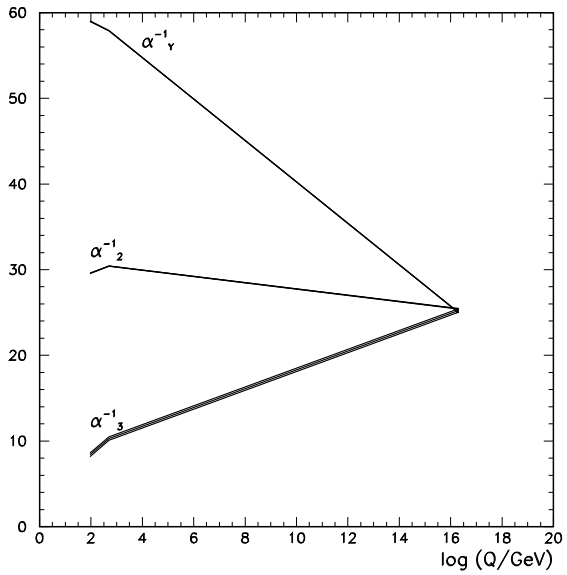
  The experimental confirmation of neutrino masses in the future will make this task even more involved.

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

i) the correct structure for Yukawas

i) 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

  $$D^{(a)} \sim \sum_i Q_i^{(a)} \eta_i \eta_i^* + \frac{g_{GUT}^2 \, tr Q^{(a)}}{192\pi^2} M_P^2$$

  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

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

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

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

- Other thresholds might appear because of the possible presence of higher order operators

$$W \sim \frac{1}{M_P^{m-1}} \eta_1 \cdots \eta_m \xi \xi$$

which would produce masses of the order of $(M_{FI}/M_P)^{m-1} M_{FI}$

Therefore, depending on m, intermediate scale masses might be generated

The presence of particles with these masses is very model-dependent and introduces a high degree of uncertainty in the computation

However, the presence of non-renormalizable couplings is not always allowed in string constructions:

- ♣ They must be gauge-invariant, something that is not easy, because of the large number of $U(1)$ charges associated to the particles in these models
- ♣ This is not sufficient. They must still fulfil the 'stringy' selection rules

  E.g. in model I only a small number of non-renormalizable couplings are allowed by gauge invariance, and all of them are forbidden by the selection rules

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

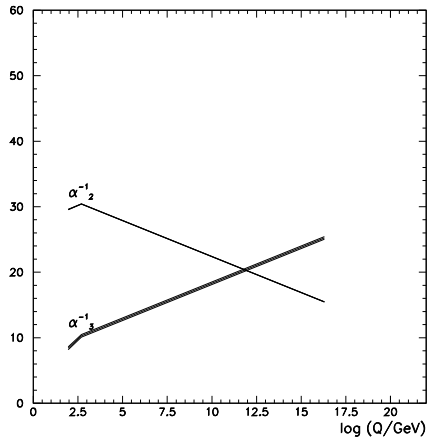
The massive one has a mass of the order of M_{FI}

The massless one must acquire mass through the electroweak symmetry breaking

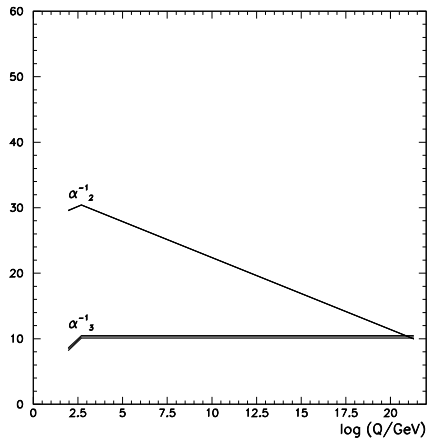
Since e.g. no new quarks have been observed in colliders, their masses must be basically heavier than 200 GeV. We will consider that the masses of these extra particles are of the order of M_S.

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

$$SU(5) \times SU(2) \times U(1)^3 \ , \quad SO(10) \times U(1)^3,$$
$$SU(4) \times SU(2)^2 \times U(1)^3 \ , \quad SU(2)^2 \times U(1)^6$$
$$SU(3) \times SU(2)^2 \times U(1)^4,$$

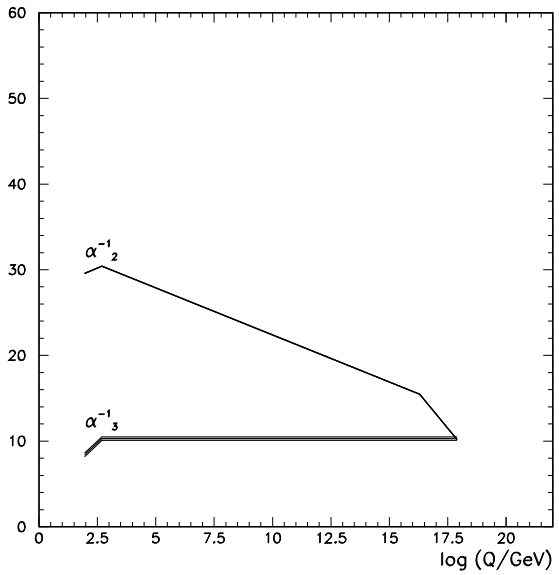
- The patterns of matter are

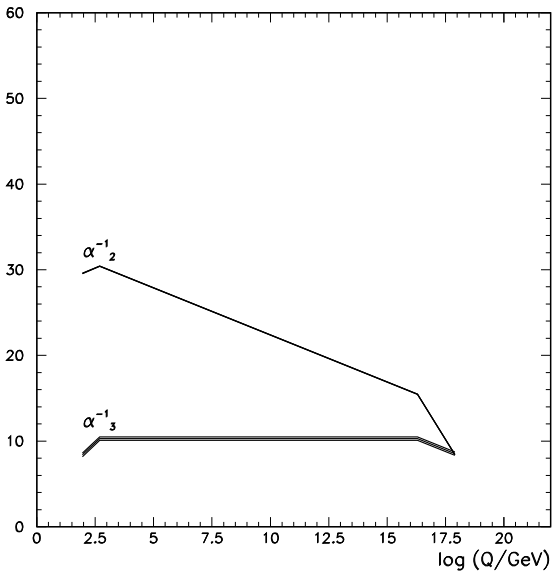
$a)\ n_3^{FI} = 0\ , n_2^{FI} = 12 \rightarrow 3 \times \{4(1,2)\}$

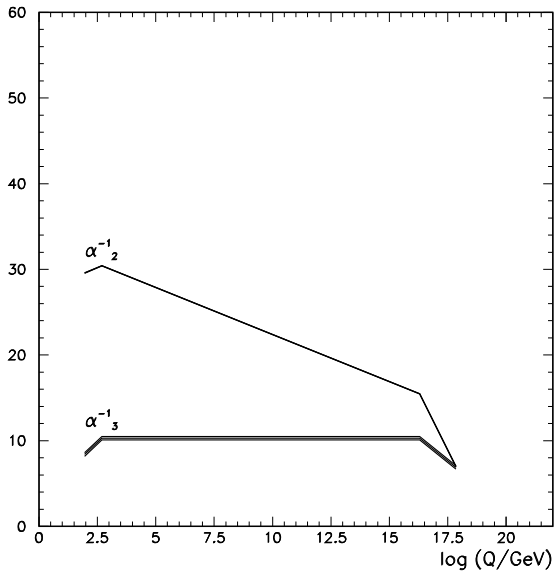
$b)\ n_3^{FI} = 6\ ,\ n_2^{FI} = 18 \rightarrow 3 \times \{(3,1) + (\bar{3},1) + 6(1,2)\}$

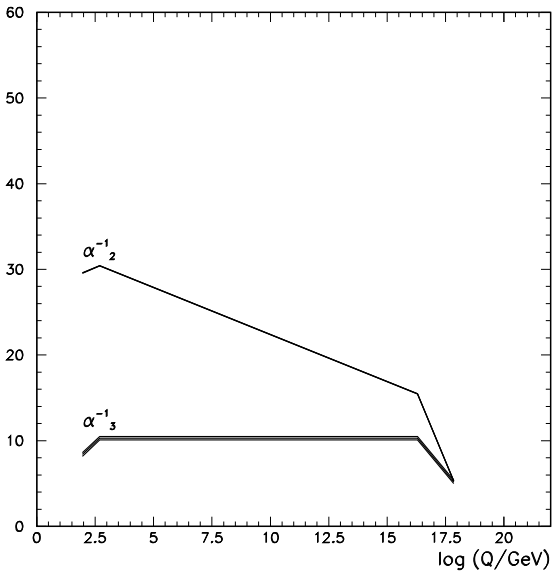
$c)\ n_3^{FI} = 12\ ,\ n_2^{FI} = 24 \rightarrow 3 \times \{2[(3,1) + (\bar{3},1)] + 8(1,2)\}$

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







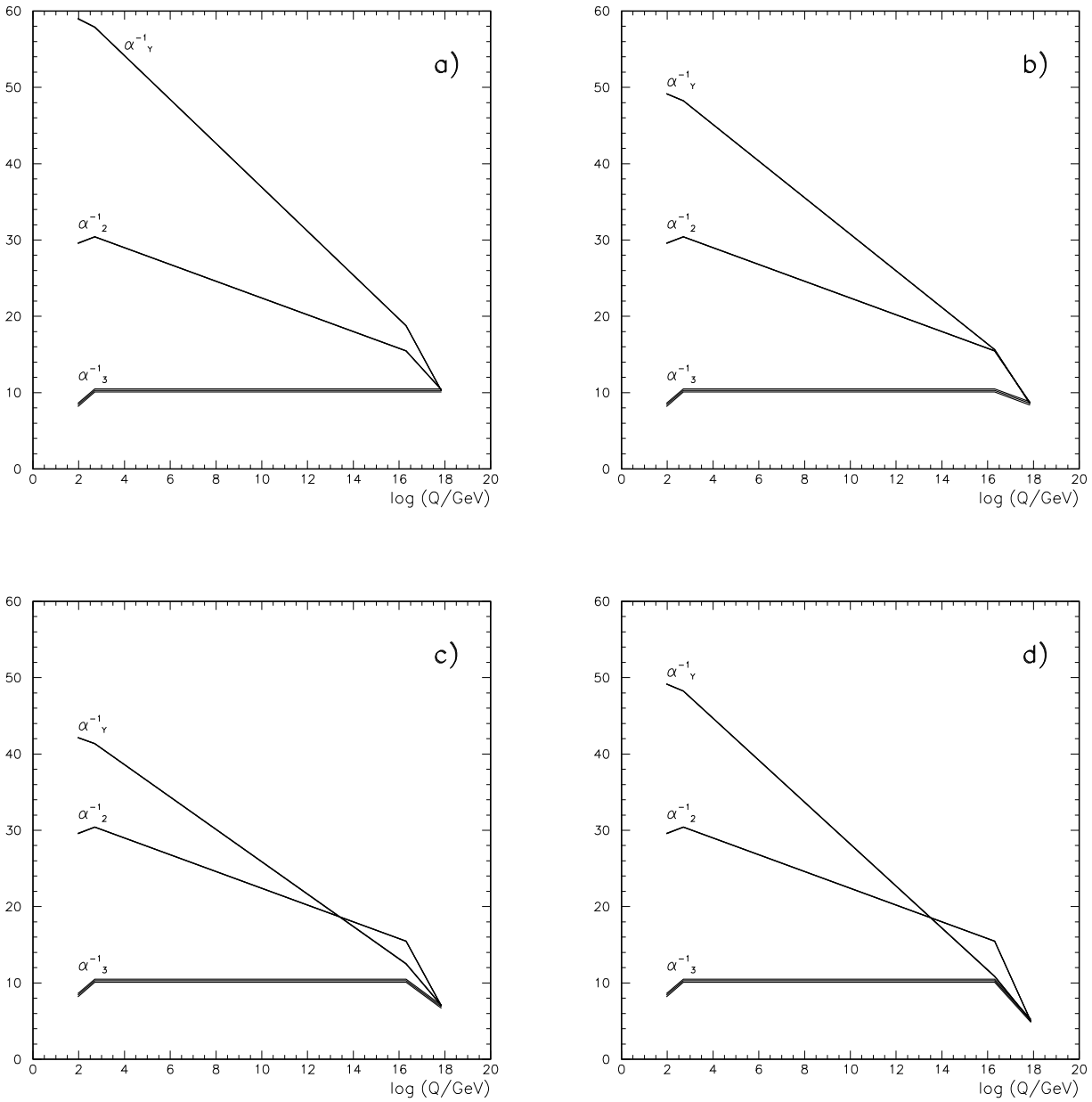


Unification of the gauge couplings at $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV, when $M_{FI} \approx 2 \cdot 10^{16}$ GeV

Remark that at low energy we have

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

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


a)
b)
c)
d)
α^{-1}_Y
α^{-1}_2
α^{-1}_3
log (Q/GeV)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20

A kind of prediction from this superstring scenario

We have at low energy (excluding singlets)

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

$$+$$

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

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 → Flores, Sher 82
Haber, Nir, 89

four doublets → Drees, 88
Nelson, Randall, 93
Masip, Rasin, 95

six doublets → 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:

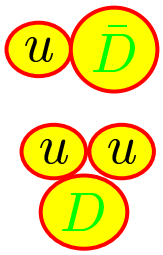
  Given the large number of singlets present in orbifold models, the mechanism for generating a μ term through couplings of the type $N_j H \bar{H}$ seems to be natural

♣ 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.

Conclusions

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

α_3 and α_2 cross 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)

The unification with α_1 is obtained if the model has the appropriate normalization of the hypercharge

The unification of the MSSM using $SU(5)$ is just an accident, without any physical relevance

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

It would be nice to find an explicit model with these properties (and correct Yukawas). At least our analysis gives rise to a possible strategy