A kind of prediction from superstring model building

Carlos Muñoz
CERN & Madrid Autónoma University

Based on the work:
JHEP 12 (2001) 015

Thursday Seminar, Theory Division, CERN
November 29, 2001

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

  ...

- ...

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

This talk is out of fashion

No D-branes will be involved !

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

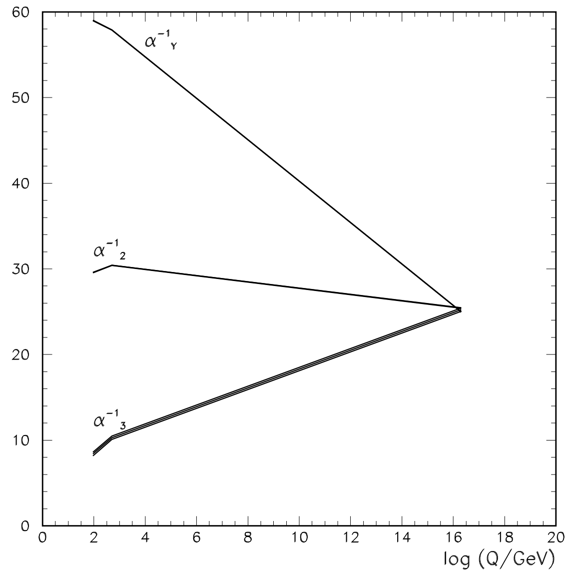
  The experimental confirmation of neutrino masses in the future will make this task even more involved.

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

  A crucial ingredient in our solution is the normalization constant C of the $U(1)_Y$, which is not fixed as in the case of grand unified theories

  Casas, CM, 88

- As a by-product, a strategy to search the Superstring Standard Model will arise.

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

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

  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

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

  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.

RGEs for gauge couplings

$$\frac{1}{\alpha_i(Q)} = \frac{1}{\alpha_i(M_Z)} + \frac{b_i^{NS}}{2\pi} \ln \frac{M_S}{M_Z} + \frac{b_i^{S}}{2\pi} \ln \frac{M_{FI}}{M_S} + \frac{b_i^{FI}}{2\pi} \ln \frac{Q}{M_{FI}}$$

Considering three susy generations of standard particles, two Higgs doublets and an arbitrary number of extra particles with masses close to M_S:

$$b_3^S = 3 - \tfrac{1}{2} n_3$$

$$b_2^S = -1 - \tfrac{1}{2} n_2$$

$$b_Y^S = -C^2 \times (11 + q)$$

$$q = \textstyle\sum_{i=1}^{n_1} Y_i^2 + 2 \sum_{j=1}^{n_2} Y_j^2 + 3 \sum_{k=1}^{n_3} Y_k^2$$

Considering an arbitrary number of extra particles with masses close to M_{FI}:

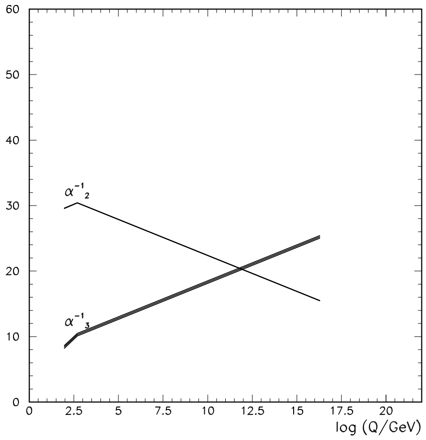
$$b_3^{FI} = b_3^S - \tfrac{1}{2} n_3^{FI}$$

$$b_2^{FI} = b_2^S - \tfrac{1}{2} n_2^{FI}$$

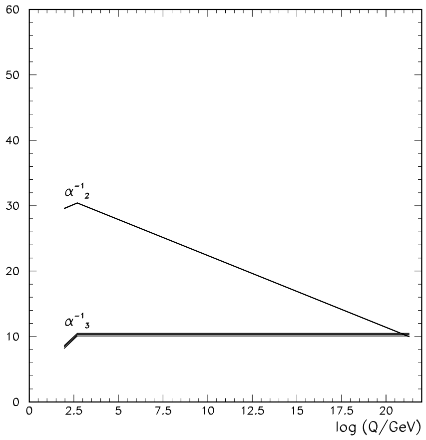
$$b_Y^{FI} = b_Y^S - C^2 \times (q^{FI})$$

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:

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

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

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

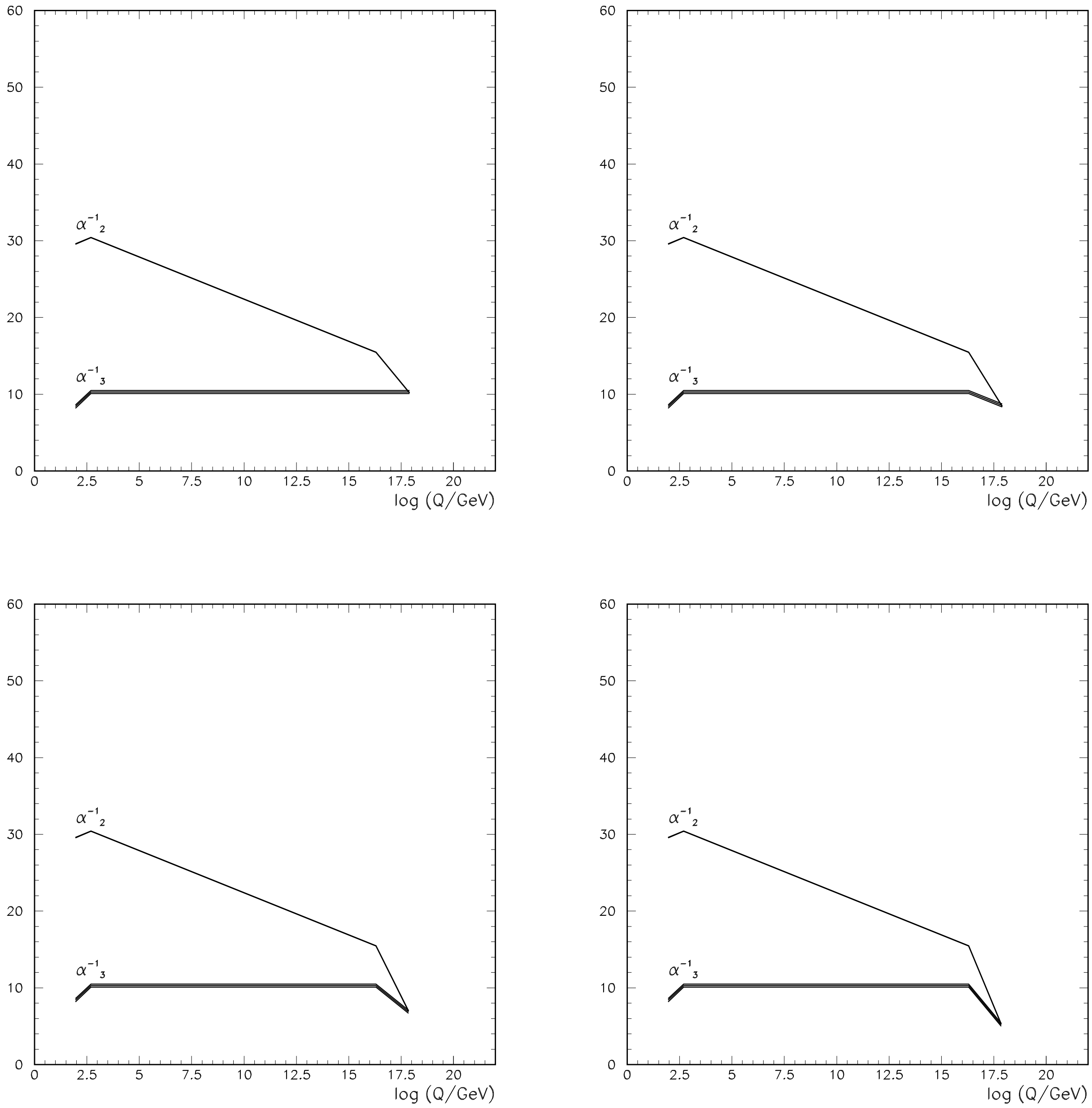
- The patterns of matter are

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

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

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

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



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

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

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

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

$$b_Y^S = -C^2 \times (11 + q) \ , \ \ b_Y^{FI} = b_Y^S - C^2 \times (q^{FI})$$

$$q = \sum_{i=1}^{n_1} Y_i^2 + 2 \sum_{j=1}^{n_2} Y_j^2 + 3 \sum_{k=1}^{n_3} Y_k^2$$

We need to know the hypercharges of the extra doublets and triplets

The 4 extra Higgses have $Y = \pm 1/2 \rightarrow q_H = 2$

The six extra triplets may have e.g.

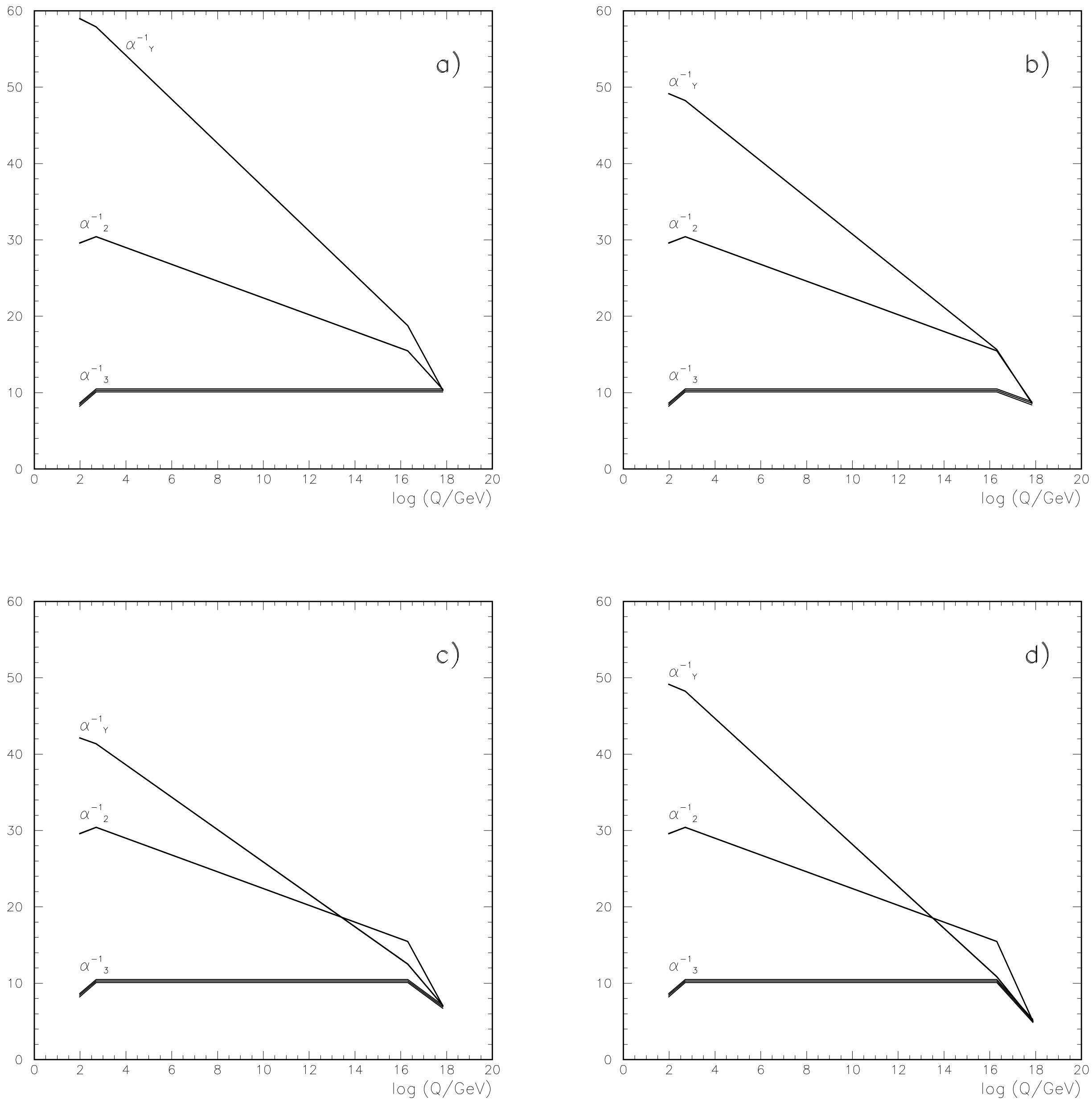
$$Y = \pm 1/3, \pm 1/6, \pm 1/15 \rightarrow q = 4, 2.5, 2.08$$

$$q^{FI} = \ ?$$

But also we need to know the Y's of the extra singlets. They are present in large numbers $\sim 3\times$(25–60). Thus the analysis has to be carried out on a model-by-model basis

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

This means that the combination for the hypercharge depends on the model and, even for a specific model, there exist many acceptable combinations



a) E.g. for $q = 2.08$ and $q^{FI} = 12$ we need to have $C^2 \approx 3/5$ in order to unify α_1 with $\alpha_{2,3}$

b) $q = 2.08$, $q^{FI} = 12 \rightarrow C^2 \approx 3/6$

c) $q = 2.5$, $\quad q^{FI} = 9 \rightarrow C^2 \approx 3/7$

d) $q = 4$, $\qquad q^{FI} = 5 \rightarrow C^2 \approx 3/6$

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

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

Potential problem

FCNCs may appear when fermions of given charge receive their mass through couplings with several Higgs doublets

Glashow, Weinberg, 77

e.g. the Yukawa Lagrangian for $q = d, s, b$

$$H_1^0\ \bar{q}_j \lambda^1_{jk} q_k + H_2^0\ \bar{q}_j \lambda^2_{jk} q_k + H_3^0\ \bar{q}_j \lambda^3_{jk} q_k$$

$$\langle H_i^0 \rangle = \nu_i \to \bar{q}_j \underbrace{(\nu_1 \lambda^1_{jk} + \nu_2 \lambda^2_{jk} + \nu_3 \lambda^3_{jk})}_{M_{jk}} q_k$$

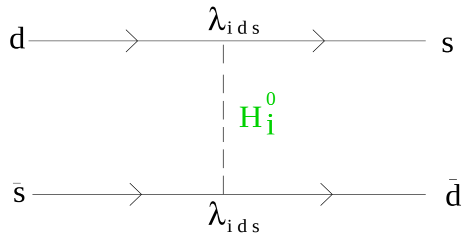
the transformations diagonalizing the mass matrix of d-quarks

$$\underbrace{\bar{q}_L U_L^{-1}}_{\hat{\bar{q}}}\ \underbrace{U_L M U_R^{-1}}_{M_d}\ \underbrace{U_R q_R}_{\hat{q}}$$

do not diagonalize the Yukawa interactions

$$H_1^0\ \hat{\bar{q}} \underbrace{U_L \lambda^1 U_R^{-1}}_{\hat{\lambda}^1} \hat{q} + H_2^0\ \hat{\bar{q}}\ \underbrace{U_L \lambda^2 U_R^{-1}}_{\hat{\lambda}^2} \hat{q} + H_3^0\ \hat{\bar{q}}\ \underbrace{U_L \lambda^3 U_R^{-1}}_{\hat{\lambda}^3} \hat{q}$$

Flavour-changing neutral Higgses can contribute e.g. at the tree level to K^0-$\bar{K}^0$ mixing



There are two approaches in order to solve this potential problem:

♣ The Yukawa couplings have some symmetries eliminating FCNCs completely

If the matrices are proportional, one can always choose a basis in which only one generation of Higgses couples to quarks.

$$H_1^0\ \bar{q}_j\lambda^1_{jk}q_k + H_2^0\ \bar{q}_j\alpha\lambda^1_{jk}q_k + H_3^0\ \bar{q}_j\beta\lambda^1_{jk}q_k \to H'\ \bar{q}_j\lambda^1_{jk}q_k$$

trivial case when $\alpha = \beta = 0$

♣ The extra Higgses are sufficiently massive making $\Delta S = 2$ neutral currents small enough not to contradict the experimental data

The actual lower bound on Higgs masses depends on the particular texture choosen for the Yukawa matrices, in order to reproduce the quark masses and mixing angles, but can be as low as 120-200 GeV

Georgi, Nanopoulos, 79

McWilliams, Li, 81

Shanker, 82

Cheng, Sher, 87

Haber, Nir, 90

Krasnikov, 92

Antaramian, Hall, Rasin, 92

Aranda, Sher, 00

It would be very interesting to analyze which approach arises naturally in these orbifold models thanks to the stringy selection rules

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

For instance, the mechanism generating a μ term through the Kähler potential, $K = \frac{1}{(U+\bar{U})(T+\bar{T})} H \bar{H}$, is not available in prime orbifolds as Z_3

Lopes-Cardoso, Lüst, Mohaupt, 94

Antoniadis, Gava, Narain, Taylor, 94

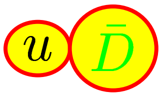
- Some of these singlets N_k might not have the necessary couplings to develop VEVs and then might be candidates for right-handed neutrinos.

♣ HYPERCHARGES

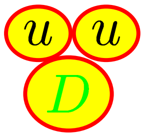
- Model II with $C^2 = 3/11$ has triplets with hypercharge $\pm 1/6$

  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.

These results are consistent with general arguments: level-one string models can be modular invariant and free of colour-neutral fractionally charged states if and only if

$$\frac{7}{12} + \frac{C^{-2}}{4} = 0 \text{ (mod 1)}$$

Schellekens, 90

It is trivial to see that only the model with $C^2 = 3/17$ fulfils this condition.

- ‘Non-standard’ extra triplets

  The lightest colour-neutral fractionally charged state will be stable because of the electric charge conservation

  The estimation of its relic abundance through thermal production, contradicts limits on the existence of fractional charge in matter (less than 10^{-20} per nucleon)

  Athanasiu, Atick, Dine, Fischler, 88

  Inflation is necessary to dilute these particles

  Since particles with $m \sim 10^3 \times T_{RH}$ may be produced during reheating

  Chung, Kolb, Riotto, 99

  we need $T_{RH} \lesssim 1$ GeV not to produce them again.

Another possibility to solve the problem:

Antoniadis, Ellis, Hagelin, Nanopoulos, 89

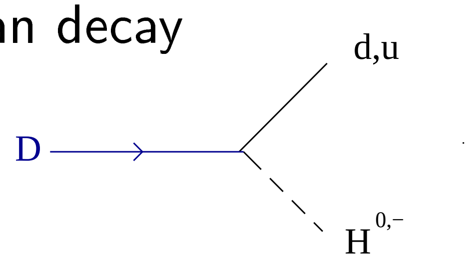
extra triplets transform also under a non-Abelian group in the hidden sector, and then they may be confined into integrally charged states

does not work in these models

- ‘Standard’ extra triplets.

  Colour-neutral integrally charged states may be unstable, since FCNC couplings with ordinary quarks are possible, $HQ\overline{D}$

  As a consequence, the D’s can decay



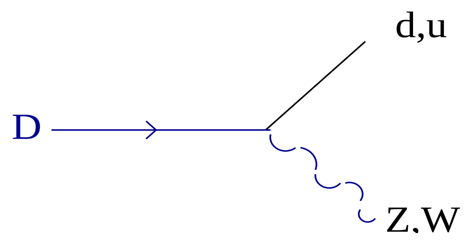
  Other decay channels are also present:

  FCNC couplings may appear if all fermions with the same charge and helicity do not have the same $SU(2)$ quantum numbers, because of their mixing through mass matrices

  Glashow, Weinberg, 77

  Paschos, 77

  Then decays of the D’s through charged and neutral currents are possible



  Thus models where this type of triplets are light ($\sim M_S$) may unify the couplings at M_{GUT} without any cosmological problem, and will only be observed in collider experiments.

Analyses of their production modes and decays will be similar to those of extra fermions in E_6 theories

Of course, there are further dangerous operators involving the D's, like $QL\overline{D}$, $\bar{u}\bar{d}\overline{D}$, etc., which must be forbidden by $U(1)$ gauge invariance or 'stringy' selection rules.

- The colour-neutral integrally charged states are not automatically unstable in all models:

  The appropriate Yukawa couplings, $HQ\overline{D}$, may be forbidden by $U(1)$ gauge invariance or stringy selection rules, and therefore these states would be stable.

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