Moduli Stabilisation in Heterotic String Compactifications

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Introduction

The Standard Model of Particle Physics $\rightarrow$ gauge group $SU(3) \times SU(2) \times U(1)$ – works well at energies of oorder 100 GeV.

It is just an effective theory – at higher energies needs to be modified

Possibilities: Supersymmetry $\rightarrow$ **M**inimal **S**upersymmetric **S**tandard **M**odel (MSSM)

GUT/susy GUT

Supersymmetry = fermionic symmetry: $\leftrightarrow$ fermion

(Super)Multiplets $\rightarrow$ combinations of fields with different spin

Matter $\rightarrow$ chiral supermultiplets $\Phi = (\phi, \psi)$

Lagrangean for these fields is given by three functions

- Kähler potential$K(\Phi, \bar{\Phi})$
- superpotential $W(\Phi)$
- gauge coupling function $f_{ab}(\Phi)$

$$
\begin{aligned}
\mathcal{L} &\sim -g_{i\bar{\jmath}}\partial_\mu \phi^i \partial^\mu \bar{\phi}^{\bar{\jmath}} - \frac{1}{4} Im f_{ab} F^a_{\mu\nu} F^{b\ \mu\nu} + \frac{i}{4} Re f_{ab} F^a_{\mu\nu} \tilde{F}^{b\ \mu\nu} - V\ , \\
g_{i\bar{\jmath}} &= \partial_{\Phi^i}\partial_{\bar{\Phi}^{\bar{\jmath}}} K(\Phi, \bar{\Phi})\ , \\
V &= e^K \left(D_i W \overline{D_j W} g^{i\bar{\jmath}} - 3|W|^2 \right) + \frac{1}{2} Im f^{-1}_{ab} D^a D^b \\
D_i W &= \partial_{\Phi^i} W + (\partial_{\Phi^i} K) W\ .
\end{aligned}
$$

Supersymmetric solutions: $D_i W = 0$.

String theory

String theory is supposed to be valid at energies of order $M_{Pl} = 10^{19} GeV$.

In the low energy limit $\longrightarrow$ supergravity in 10 space-time dimensions

Compactifications on 6-dimensional manifolds $\longrightarrow$ supergravity in 4d: K, W and f can be computed in string theory

There exist 5 consistent superstring theories: type IIA/B, type I, heterotic $SO(32)/E_8 \times E_8$.

4d requirements

N=1 supersymmetry

Standard Model/GUT

- gauge grup $G \supset SU(3) \times SU(2) \times U(1)$

- chiral matter

Type II $\rightarrow$ need additional constructions: intersecting branes, singularities etc.

$SO(32)$ gauge group: does not have the right representations for matter fields in 4d

We are left with $E_8 \rightarrow$ works pretty well

Heterotic models

Bosonic spectrum in 10d: graviton g_{MN}; antisymmetric tensor field B_{MN}; dilaton (scalar) ϕ; gauge fields $E_8 \times E_8$.

Constraints: Bianchi identity

$$dH = trF \wedge F - trR \wedge R \,, \qquad H = dB \quad \text{field strength of} B$$

4d theory

$N = 1$ supersymmetry $\rightarrow$ compactifications on Calabi–Yau manifolds (SU(3) holonomy).

$[trR \wedge R] \neq 0 \rightarrow$ need $trF \wedge F \neq 0 \rightarrow$ breaks E_8 gauge symmetry

We can always set $F \equiv R$ - $SU(3)$ - structure

$E_6 \times SU(3) =$ maximal subgrup of $E_8 \rightarrow$ surviving gauge symmetry in 4d is E_6.

Charged fields:

$$\mathbf{248} = (\mathbf{78}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{8}) \oplus (\mathbf{27}, \mathbf{3}) \oplus (\overline{\mathbf{27}}, \bar{\mathbf{3}})$$

Decompositionn of Dirac operator

$$\not{\nabla}_{10} = \not{\nabla}_4 + \not{\nabla}_6 \qquad \rightarrow \; \not{\nabla}_6 - \text{mass operator in 4d} \; ;$$

Massless fields in 4d $\Leftrightarrow$ $\not{\nabla}_6 \psi = 0$

For Calabi–Yau manifolds with $F = R$

$$\not{\nabla}_6 \psi_{\mathbf{3}} \;\; = \;\; 0 \quad \leftrightarrow \quad H^{0,1}(T^{1,0}X) \equiv H^{2,1}(X) \; ;$$

$$\not{\nabla}_6 \psi_{\bar{\mathbf{3}}} \;\; = \;\; 0 \quad \leftrightarrow \quad H^{0,1}(T^{0,1}X) \equiv H^{1,1}(X) \; ;$$

Number of generations $= |h^{1,1} - h^{2,1}| = |\chi|/2$

Neutral fields (moduli)

- $\delta g_{ab} =$ complex structure deformations – $h^{2,1}$ - complex
- $\delta g_{a\bar{b}}$ Kähler class deformations– $h^{1,1}$ - real
- $B_{a\bar{b}}$ – $h^{1,1}$ real
- dilaton ϕ and axion $B_{\mu\nu}$: $S = a + ie^{\phi}$

In total $h^{1,1} + h^{2,1} + 1$ neutral chiral fields.

Results

- superpotential: cubic in the charged fields; does not depend on the moduli (for CY manifolds).

- can obtain a dependence on the moduli from fluxes and/or manifolds with $SU(3)$ structure.

- Kähler potential for moduli fields: specific to string compactifications

- Kähler potential for matter fields: $gC\bar{C}$

- $f_{ab} = S\delta_{ab}$

Specific model

Heterotic string compactifications on manifolds with SU(3) structure.

Effective theory: Supergravity + super Yang-Mills theory E_6 gauge group + one chiral superfield in $\overline{\mathbf{27}}$ C^A + one chiral singlet superfield T $(h^{1,1} = 1,\ h^{2,1} = 0)$

$$K = -3\ln(T+\bar{T}) + \frac{3}{T+\bar{T}} C^A \bar{C}_A$$

$$W = ieT + \frac{1}{3} j_{ABC} C^A C^B C^C \ .$$

Supersymmetric solutions

I. $C = 0$**:** $D_T W = ie - 3/(T + \bar{T})(ieT) = 0 \Rightarrow e = 0$ not good.

II. $C \neq 0$ what changes?

a. $E_6 \supset SO(10) \times U(1)$ $\overline{\mathbf{27}} = \mathbf{10}^{-2} \oplus \overline{\mathbf{16}}^{1} \oplus \mathbf{1}^{4}$

b. $E_6 \supset SU(3) \times SU(3) \times SU(3)$ $\overline{\mathbf{27}} = (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}) \oplus (\bar{\mathbf{3}}, \mathbf{1}, \bar{\mathbf{3}}) \oplus (\mathbf{1}, \mathbf{3}, \mathbf{3})$

a

$< \mathbf{1} > \neq 0, \quad < \mathbf{10} > = < \mathbf{16} > = 0 \;\longrightarrow\; E_6 \to SO(10)$

No $\mathbf{1}^3$ coupling in W

$$D_1 W \quad = \quad 0 + \frac{3\bar{C}_1}{T+\bar{T}} W = 0 \qquad \Longrightarrow W = 0 \; ,$$

$$D_T W = e = 0 \quad \text{not} \quad \text{good}$$

b

$< (\mathbf{1},\mathbf{3},\mathbf{3}) > \neq 0 \;\longrightarrow\; E_6 \to SU(3) \times SU(2) \times SU(2)$

There exist $(\mathbf{1},\mathbf{3},\mathbf{3})^3 \equiv B^3$ coupling in W

$$D_B W = B \cdot B + \bar{B} \cdot W = 0$$

B – small fluctuations $\Rightarrow B \ll 1 \;\Rightarrow\; W = eT \sim B \ll 1$

but e is cuantised and $T + \bar{T} \gg 1$ for the supergravity approximation

Conclusions

- The system under scrutiny $(h^{1,1} = 1,\ h^{2,1} = 0)$ does not have satisfying supersimetric solutions
- have to consider more complicated models $(h^{2,1} \neq 0)$
- more complicated superpotential and there may exist viable solutions