Aspects of String Compactifications and Moduli Stabilisation

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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 order 100 GeV (includes Higgs boson)

It is just an effective theory – need "Beyond SM" at higher energies.

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

GUT/susy GUT

Supersymmetry $=$ fermionic symmetry: boson $\leftrightarrow$ 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 $f_{ab}(\Phi)$

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

Supersymmetric solutions: $D_iW = 0$.

String theory

Replaces point particles by 1d extended objects – strings.

Supposed to be valid at energies of order $M_{Pl} = 10^{19} GeV$.

Contains gravity – good candidate for a theory of quantum gravity.

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.

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

$E_8 \rightarrow$ works pretty well

Compactification

Simple example 5d $\longrightarrow$ 4d on S^1

5d scalar field $\phi \longrightarrow$ 4d scalar field

$$\text{5d vector field} \longrightarrow \begin{cases} A_\mu & - \quad \text{4d vector field} \\ A_5 & - \quad \text{4d scalar} \end{cases}$$

$$\text{5d metric} \longrightarrow \begin{cases} g_{\mu\nu} & - \quad \text{4d metric} \\ g_{\mu 5} & - \quad \text{4d vector field} \quad (U(1) \text{ gauge field}) \\ g_{55} & - \quad \text{4d scalar} \end{cases}$$

Structure of the 4d theory depends on the internal (6d) manifold.

$N = 1$ susy in 4d requires a globally defined (covariantly constant) spinor in 6d

Need $SU(3)$ holonomy $\Rightarrow$ Calabi–Yau manifolds (complex, Kähler, Ricci-flat manifolds)

$$\mathbf{4} = \mathbf{1} \oplus \mathbf{3}$$

Solve Einstein equations for 4d Minkowski space

Heterotic E_8 string $\rightarrow$ relistic 4d models e.g. gauge group E_6 and chiral matter

Problems: moduli

Deformations of the internal geometry which preserve the background

δg_{mn} such that $\delta R_{mn}(\delta g) = 0$.

Kähler class deformations $\delta g_{a\bar{b}}$

Complex structure deformations δg_{ab}.

All couplings and masses in 4d depend on the vev's of he moduli.

Large vacuum degeneracy

Need to fix moduli!

Turning on fluxes

10d tensor fields of various degree – usually set to zero in KK compactifications

Flux $=$ vev for the field strengths of these fields

$$\int_{\gamma_p} F_p = n$$

Generate suerpotentials for the moduli

$$W = \int_{CY} \sum_{p-\mathrm{even}} F_p \wedge e^J + F_3 \wedge \Omega$$

J - two form, Ω- three form specific to CY manifolds – depend on moduli.

Moduli stabilsation

Not all moduli enter the flux superpotential

Need generalisations to manifolds with $SU(3)$ structure – geometric fluxes

Very few cases where all moduli appear in W

Almost always need to rely on non-perturbative effects (gaugino condensation, world-sheet or brane instantons)

$$W = W_{\text{flux}} + e^{-S}$$

Fluxes are quantised $\rightarrow W_{\text{flux}} \sim \mathcal{O}(1)$

Usually $S \gg 1 \rightarrow e^{-S} \ll 1$