SFB-lectures

Phenomenological Aspects of String Theory

Jan Louis
Universität Hamburg

Outline of the lectures:

1. Overview (January 19)
2. Compactifications (January 26, today)
3. Supersymmetry Breaking (Feburary 2)

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String Theory

basic idea: point-like objects $\longrightarrow$ extended objects (strings)

Strings move in 10-dimensional space-time background

one way to make contact with "our world": Compactification

$\Rightarrow$ space-time background:

$$\mathcal{M}_{10} = R_{1,3} \times Y_6$$

$R_{1,3}$: four-dimensional Minkowski-space

Y_6: compact manifold – determines amount of supersymmetry

alternative: Y_6 is not a manifold (but a conformal field theory).

Different string theories:

Type I, Type II, Heterotic

they differ in spectrum of excitations and their interactions

massless spectrum in $R_{1,9}$:

	Type IIA	Type IIB	Type I	Heterotic
B:	$G_{MN},\ H_3 = dB_2,\ \Phi$			
B:	$F_2 = dC_1,\ F_4 = dC_3$	$l,\ F_3 = dC_2,\ F_5^* = dC_4$	$F_2^a = DA_1^a,\ {\scriptstyle G = SO(32),\, E_8 \times E_8}$	
F	$\Psi^{1,2},\ \lambda^{1,2}$	$\Psi^{1,2},\ \lambda^{1,2}$	$\Psi^1,\ \lambda^1,\ \chi^a$	

$F_p = p$-form field strength

$A, B, C =$ gauge potentials

$\Psi, \lambda, \chi =$ gravitino, dilatino, gaugino

Compactification: determine Y_6

Lorentz group on space-time background $\mathcal{M}_{10} = R_{1,3} \times Y_6$ decomposes

$$SO(1,9) \to SO(1,3) \times SO(6)$$

spinor decompose accordingly:

$$\mathbf{16} \to (\mathbf{2}, \mathbf{4}) \oplus (\bar{\mathbf{2}}, \bar{\mathbf{4}})$$

existence of supercharges Q requires:

$\Rightarrow$ nowwhere vanishing and globally defined spinor η needs to exist

$\Rightarrow$ Y_6 has to be manifold with G-structure

$\Rightarrow$ structure group is reduced $SO(6) \to G$

example:

$$SO(6) \to SU(3): \qquad \mathbf{4} \to \mathbf{3} + \mathbf{1}$$

$\Rightarrow$ Y_6 has $SU(3)$-structure

type II: $N = 2$ in $d = 4$, heterotic, type I: $N = 1$ in $d = 4$

supersymmetry of the background requires: $\langle \delta \text{fermions} \rangle = 0$

$$\begin{aligned}
\delta\Psi_m &= \nabla_m \eta + (\gamma F)_m \cdot \eta + \ldots = 0 \ , \qquad m = 1, \ldots, 6 \\
\delta\lambda &= (\gamma F) \cdot \eta + \ldots = 0 \ , \\
\delta\chi^a &= (\gamma F^a) \cdot \eta + \ldots = 0 \ ,
\end{aligned}$$

$\langle F \rangle \neq 0$ corresponds to background flux

$\Rightarrow$ for $F = 0$: $\quad \nabla_m \eta = 0 \quad \Rightarrow Y_6$ is Calabi-Yau manifold

$\Rightarrow$ for $F \neq 0$: $\quad \nabla_m \eta \neq 0 \quad \Rightarrow Y_6$ is manifold with $SU(3)$ structure

heterotic and type I: additional constraint

$$tr(R \wedge R) = (F^a \wedge F^a) \leftrightarrow R_{[mn|p}{}^{q} R_{rs]q}{}^{p} = F^a_{[mn} F^a_{rs]} \neq 0$$

$\Rightarrow F^a_{mn}$ needs a VEV

$\Rightarrow$ breaking of the gauge group,

$$\text{e.g.: standard embedding} \qquad \begin{aligned} E_8 \times E_8 &\rightarrow E_8 \times E_6 \\ SO(32) &\rightarrow SO(26) \end{aligned}$$

physical interpretation: E_6 is GUT group, E_8 is hidden sector

Kaluza-Klein compactification in space-time background: $R_{1,3} \times Y_6$

- massless scalars

$$\Delta_{10}\phi = (\Delta_4 + \Delta_6)\phi = (\Delta_4 + m^2)\phi = 0$$

  for

$$\phi = \sum_n \phi^n(x) Y^n(y) \qquad \text{and} \qquad \Delta_6 Y^n = m_n^2 Y^n$$

- similarly for p-forms C_p and the metric $g_{mn} = g^0_{mn} + \delta g_{mn}$

  $\Rightarrow$ massless $d = 4$ spectrum $=$ zero modes of Δ_6 $=$ harmonic forms on Y_6

- harmonic forms $\omega_{(p,q)}$ are elements of cohomolgy groups $H^{(p,q)}(Y)$

  multiplicity is counted by Hodge numbers

  for Calabi-Yau manifold:

$$h^{p,q} = \mathrm{dim} H^{p,q}(Y), \qquad \begin{array}{ccccccc} & & & 1 & & & \\ & & 0 & & 0 & & \\ & 0 & & h^{1,1} & & 0 & \\ 1 & & h^{1,2} & & h^{1,2} & & 1 \\ & 0 & & h^{1,1} & & 0 & \\ & & 0 & & 0 & & \\ & & & 1 & & & \end{array}$$

massless spectrum arranges itself into supermultiplets

- heterotic string (with standard embedding and $G = E_8 \times E_6$)
  - gravitational multiplet
  - vector multiplets in adjoint of $E_8 \times E_6$
  - chiral matter multiplets

$$h^{(1,1)}(\overline{\mathbf{27}} + \mathbf{1}) \;\oplus\; h^{(1,2)}(\mathbf{27} + \mathbf{1})$$

$\Rightarrow$ # of chiral generations $\sim h^{(1,1)} - h^{(1,2)} \sim \chi$ (Euler number)

- type IIA:
  - gravitational multiplet
  - $h^{(1,1)}$ $U(1)$-vector multiplets
  - $h^{(1,2)}$ uncharged hypermultiplets

$\Rightarrow$ type II does not look very promising

$\Rightarrow$ need to insert space-time filling D-branes

$\Rightarrow$ non-Abelian gauge bosons and charged matter as excitations of D-branes which choices went in so far?

- which string theory
- which compactifications manifolds Y_6
- which embedding
- which D-branes

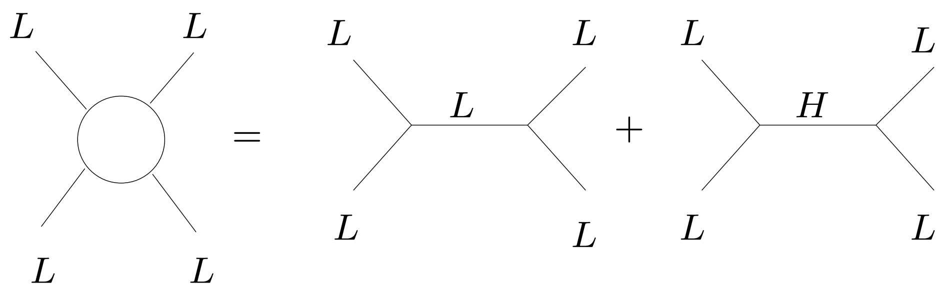
$\Rightarrow$ $\mathcal{O}(10^5)$ choices (far more if non-geometrical backgrounds included)

did not impose:

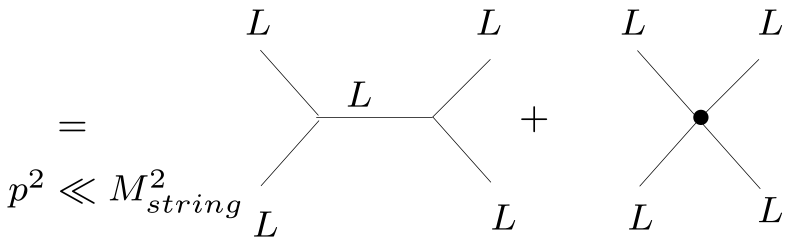
- $n_g = 3$
- constraint on G/spectrum

The low effective action

Integrating out the heavy modes H results in the low energy effective action $\mathcal{L}_{\rm eff}(L)$ of the light modes L



+ t and u channels



+ t and u channels

for $p^2 \ll M^2_{string}$: amplitudes of an effective field theory

$D = 4, N = 1$ effective Lagrangian

[Wess, Bagger]

➪ spectrum:

multiplet	B	F
gravity multiplet	$g_{\mu\nu}$	Ψ_μ
vector multiplets	V_μ	χ
chiral multiplets	M	λ

➪ effective Lagrangian

$$
\begin{aligned}
L &= -\left(\tfrac{1}{2}R + G_{I\bar{J}} D_\mu M^I D^\mu \bar{M}^{\bar{J}} + \tfrac{1}{4}\mathrm{Re} f_{\kappa\lambda}\, F^\kappa_{\mu\nu} F^{\lambda\mu\nu} + \tfrac{1}{4}\mathrm{Im} f_{\kappa\lambda}\, F^\kappa \tilde{F}^\lambda + V\right) , \\
&\quad + \text{fermions} \\
V &= e^K \left(G^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2\right) + \frac{1}{2} (\mathrm{Re}\ f)^{-1\ \kappa\lambda} D_\kappa D_\lambda \ .
\end{aligned}
$$

L is completely determined in terms of K, W, f:

- Kähler metric: $G_{I\bar{J}} = \partial_I \bar{\partial}_J K(M, \bar{M})$
- holomorphic superpotential: $W(M)$, $\quad D_I W = \partial_I W + (\partial_I K) W$
- holomorphic gauge kinetic function: $f(M) = g^{-2} + i\,\frac{\Theta}{8\pi^2}$

Properties of K, W, f

- Kähler potential K receives quantum corrections at all orders
- Superpotential W has no perturbative quantum corrections

$$W = W^{(0)} + W^{(\text{np})}$$

- gauge kinetic function f has only 1-loop quantum corrections

$$f = f^{(0)} + f^{(1)} + f^{(\text{np})}$$

<u>Next:</u> compute K, W, f for your favorite string background.

Generic features perturbatively:

- effective potential V has flat directions (moduli T)
  $\Rightarrow$ continuous vacuum degeneracy parameterized by $\langle T \rangle$

- $W(T, Q) = Y_{ijk}(T)\, Q^i Q^j Q^k$, $Q =$ charged matter field.
  $\Rightarrow$ Yukawa coupling Y dynamically determined!

- similarly, gauge couplings $g = g(\langle T \rangle)$
  $\Rightarrow$ g is dynamically determined
  If moduli are undetermined couplings are still free parameters.

- need to stabilize moduli and break supersymmetry
  known mechanism:
  1) Fluxes/generalized geometries
  2) Gaugino condensation/non-perturbative effects

Background fluxes [Polchinski,Strominger,...]

$$\text{allow} \qquad \int_{\gamma_p^I \in Y} F_p = e_I \neq 0 \qquad \text{keeping} \qquad dF_p = 0 = d^\dagger F_p$$

$$\Rightarrow F_p \; = \; e_I \, \omega_p^I \, , \qquad \omega_p \in H^p(Y)$$

$$e_I = \text{const.} = \begin{cases} \text{quantized in string theory} \\ \text{continuous in low energy approximation} \end{cases}$$

consistency: tadpole cancellation condition

properties:

- large Y: e_I small perturbation such that light spectrum does not change
- low energy supergravity $\Rightarrow$ gauged/massive supergravity
- potential generated $\Rightarrow$ vacuum degeneracy (partially) lifted
- supersymmetry spontaneously broken

Background fluxes and the landscape

Fluxes are additional discrete parameters which are allowed in a compactification.

- How many fluxes do we have?

  number of cycles: $I = 1, \dots, \mathcal{O}(100)$

  allowed values of e_I (solutions of tadpole condition): $e = 1, \dots, 10.$

  $\Rightarrow$ for a given Calabi-Yau we have $\approx 10^{300}$ different vacua (landscape of vacua)

- what do they determine?

  generate potential for moduli $\Rightarrow \langle T \rangle$

  - value of the moduli $\Rightarrow$ value of Yukawa and gauge couplings
  - spontaneous supersymmetry breaking
  - value of the cosmological constant [Bousso,Polchinski]

$$\Lambda = -\Lambda_0 + \sum_{IJ} e_I e_J N^{IJ}$$

$\Rightarrow$ anthropic/statistical explantion of small Λ:

$$\exists\ e_I : 0 < \Lambda < \epsilon$$

Discussion/Summary

➪ can construct realistic string backgrounds in $d = 4$ via compactifications

➪ can compute the effective action reliably in pertubation theory

➪ background fluxes appear as additional parameters

$\Rightarrow$ landscape of vacua

➪ open question: are they all consistent non-pertubatively?

(are they all vacua of M-theory?)

- if no, which are consistent?
- if yes, what does it mean?

  one option:

$$\begin{array}{ccccc} \text{QM} & \longrightarrow & \text{QFT} & \longrightarrow & \text{ST} \\ \downarrow & & \downarrow & & \downarrow \\ \text{H} & \longrightarrow & \text{SM} & \longrightarrow & \text{string background} \end{array}$$