

String theory and particle physics

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Plan of the talk

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Why do we talk about string theory?

- ▶ Except for the **neutrino mass and the dark matter** of the universe the Standard Model of particle physics describes all experiments up to an energy (LEP) $\sim 100 \text{ GeV} \iff 10^{-16} \text{ cm} = \frac{1}{1000} \text{ proton}$.
- ▶ It is a gauge field theory with the gauge group:

$$SU(3)_{\text{Colour}} \times SU(2)_L \times U(1)_Y$$

$g_3 \qquad g_2 \qquad g_1$

- ▶ Besides the gauge bosons, quarks and leptons the SM contains also a **scalar (Higgs) field** that breaks the electro-weak symmetry from $SU(2)_L \times U(1)_Y$ to $U(1)_{em}$ and **gives mass to the particles**.
- ▶ LHC will shed some light on this **not yet directly observed particle**.
- ▶ If observed consistency with experiments requires $420 - 182 \text{ GeV} > m_H > 115 \text{ GeV}$.
- ▶ The SM contains three dimensional constants:

$$\Lambda_{QCD} \sim 250 \text{ MeV} ; \langle H \rangle = 246 \text{ GeV} ; M_H$$

- ▶ **The Fermi scale $\implies \sim 246 \text{ GeV}$** .

- ▶ What do we expect at slighter higher energy ?
Supersymmetry, Technicolor...
- ▶ At much higher energies we may expect a grand unification scale: $M_{GUT} \sim 10^{16} GeV$ where the coupling constants associated to the three gauge groups converge to a common value.
- ▶ Planck scale: $M_P = \sqrt{\frac{\hbar c}{G_N}} = 1.2 \cdot 10^{19} GeV$, that is the scale where gravity becomes strong and must be quantized.
- ▶ From the Newton law: $\vec{F} = -G_N M^2 \frac{\vec{r}}{r^3}$ gravity becomes strong at the Planck mass $\frac{G_N M_P^2}{\hbar c} \sim 1$.
- ▶ But gauge field theories coupled with gravity are not renormalizable, due to **the point-like structure of the constituents**.
- ▶ Short distance divergences occur already in classical electrodynamics, where, in order to avoid them, one introduces the classical electron radius to regularize the Coulomb potential:

$$\frac{e^2}{r_0} = mc^2 \Rightarrow r_0 = \frac{e^2}{\hbar c} \cdot \frac{\hbar}{mc} = \frac{1}{137} \cdot \frac{\hbar}{mc} \ll \frac{\hbar}{mc}$$

At this value of r_0 we are already in the quantum theory.

- ▶ In the case of a gauge theory, the theory can be renormalized obtaining a well defined quantum theory.
- ▶ In the case of gravity, that is coupled to **energy** rather than to **charge**, we need to introduce an infinite number of counterterms that destroy **the renormalizability (predictivity) of the theory**.
- ▶ A way to obtain a consistent quantum theory unifying gauge theories with gravity is to go from **point-like objects to small one-dimensional strings**: **1st reason for ST**.
- ▶ It is **an extension of Field Theory** where gauge theories and gravity **are not put by hand**, **but emerge** as an unavoidable part of the theory: **2nd reason for ST**.
- ▶ **3rd reason for ST**: ST has been a laboratory where new mechanisms have been found that then have been used in model building: **Supersymmetry, extra-dimensions....**
- ▶ Through the AdS/CFT correspondence ST has provided important tools for studying gauge theories at strong coupling and more in general also strongly coupled systems: **4th reason for ST**.

Other reasons for ST are

- ▶ Calculations of amplitudes **with many external particles (gluons for instance)** are easier than in field theory.
- ▶ Then it may be difficult to perform **the field theory limit**.
- ▶ Multiloops are known explicitly in the bosonic string, but not in superstring.
- ▶ Black hole physics: **computation of the entropy of a black hole in terms of microstates**.
- ▶ Positive interaction with various branches of mathematics.

But

- ▶ Starting from ST, one would like **to predict in a more or less unique way what we observe in the high energy experiments**.
- ▶ A lot of progress has been made in this direction, **but we are still very far away**.

String Theory

- ▶ String theory provides a UV finite quantum theory of gravity because has a parameter α' of the dimension of a *(length)²* that acts as a **physical ultraviolet cutoff** $\Lambda = \frac{1}{\sqrt{\alpha'}}$ in the loops.
- ▶ From point particle to string

$$S_{particle} = -mc \int \sqrt{-dx^\mu dx_\mu} \implies S_{string} = -cT \int \sqrt{d\sigma^{\mu\nu} d\sigma_{\mu\nu}}$$

- ▶ The string tension $T = \frac{\text{Energy}}{\text{unit length}}$ is equal to $T = \frac{1}{2\pi\alpha'}$.
- ▶ String theory is an **extension** of field theory !

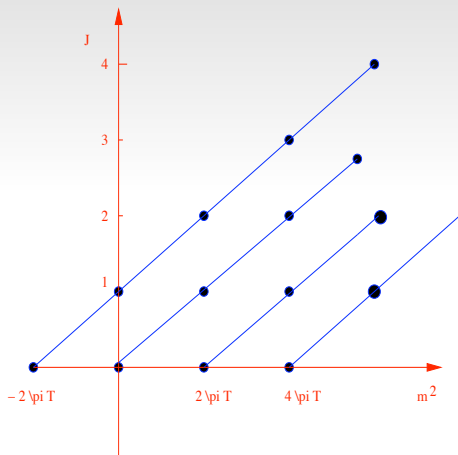
▶ Quantum Mechanics $\xRightarrow{h \rightarrow 0}$ Classical Mechanics

Special Relativity $\xRightarrow{c \rightarrow \infty}$ Galilean Mechanics

String Theory $\xRightarrow{\alpha' \rightarrow 0}$ Field Theory

- ▶ In the limit $\alpha' \rightarrow 0$ one recovers the UV divergences of quantum gravity unified with gauge theories \implies **point-like structure**.
- ▶ Can we see stringy effects in experiments?
- ▶ If $\alpha' E^2 \ll 1$, then one will see only the limiting field theory.
- ▶ Only if $E \sim \frac{1}{\sqrt{\alpha'}}$, then we can **start to see stringy effects**.
- ▶ But α' can only be determined from experiments.

The spectrum of the bosonic open string



Remember that $T = \frac{1}{2\pi\alpha'}$ and $m^2 = \frac{1}{\alpha'} (\sum_{n=1}^{\infty} n a_n^\dagger \cdot a_n - 1)$

- ▶ Around 1985 it was clear that we had 5 **ten-dimensional** consistent string theories: **IIA, IIB, I, Het. $E_8 \times E_8$ and Het. $SO(32)$** \implies unified in **M theory**.
- ▶ They are **inequivalent** in string perturbation theory ($g_s < 1$), **supersymmetric** and **unify**, in a consistent quantum theory, gauge theories with gravity.
- ▶ We observe only 4 and not 10 non-compact dimensions!
- ▶ We need to compactify six of them:

$$R^{1,9} \rightarrow R^{1,3} \times M_6$$

M_6 is a compact six-dimensional manifold.

- ▶ If we want to preserve at least $\mathcal{N} = 1$ supersymmetry, M_6 must be a **Calabi-Yau manifold**.
- ▶ But then the four-dimensional physics will depend not only on α' , but also on the **shape and the size of M_6** .

- ▶ The parameters, characterizing a particular compactification, and also g_s correspond to **v.e.v of some scalar fields, called moduli.**
- ▶ They are fixed by the minima of their potential: **Moduli Stabilization.**
- ▶ Too many consistent compactifications: **Landscape Problem.**
- ▶ Originally the most promising string theory for phenomenology was considered the **Heterotic $E_8 \times E_8$** that was studied intensively.
- ▶ But in this theory both the fundamental string length $\sqrt{\alpha'}$ and the size of the extra dimensions are very small, of the order of the Planck length,

$$\frac{1}{\sqrt{\alpha'}} \equiv M_s = \frac{M_{Pl.} \sqrt{\alpha_{GUT}}}{2} \sim \frac{M_{Pl.}}{10} ; \quad \frac{R}{\sqrt{\alpha'}} \sim 1$$

- ▶ Too small to be observed in present and even future experiments!
- ▶ One needs a very good control of the theory to be able to extrapolate to low energy.

- ▶ Later on in 1998 it became clear that in type I and II and in a **brane world** one could allow for much larger values for the string length $\sqrt{\alpha'}$ and for the extra dimensions.
- ▶ What is a Dp brane?

Dp branes

- ▶ Type II string theories are theories of closed strings at the perturbative level.
- ▶ But at the non-perturbative level there are additional states that are in general p -dimensional with $p \neq 1$.
- ▶ They are called Dp branes: generalization in string theory of the **solitons** in field theory.
- ▶ Where do they come from?
- ▶ The spectrum of massless states of the II theories is given in the table

$G_{\mu\nu}$	$B_{\mu\nu}$	ϕ	NS-NS sector
Metric	Kalb-Ramond	Dilaton	
C_0, C_2	C_4, C_6	C_8	RR sector IIB
C_1, C_3	C_5	C_7	RR sector IIA

- ▶ the RR C_i stands for an antisymmetric tensor $C_{\mu_1\mu_2\dots\mu_i}$

- ▶ They are generalizations of the electromagnetic potential A_μ

$$\int A_\mu dx^\mu \implies \int A_{\mu_1 \mu_2 \dots \mu_{p+1}} d\sigma^{\mu_1 \mu_2 \dots \mu_{p+1}}$$

As the electromagnetic field is coupled to **point-like particles** so they are coupled to **p-dimensional objects**.

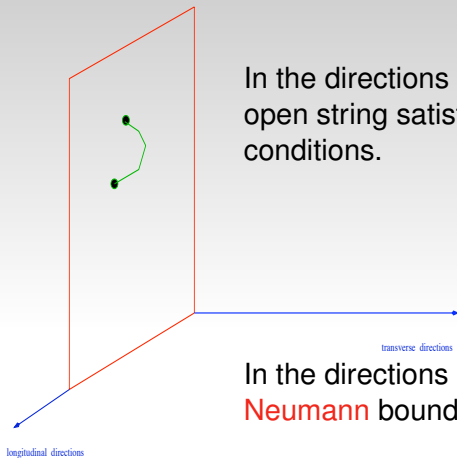
- ▶ There exist classical solutions of the low-energy string effective action that are coupled to the metric, the dilaton and are charged with respect a RR field. For them we get

$$C_{01\dots p} \sim \frac{1}{r^{d-3-p}} \iff C_0 \sim \frac{1}{r} \text{ if } d = 4, p = 0$$

They are additional **non-perturbative** states of string theory with tension and RR charge given by:

$$\tau_p = \frac{\text{Mass}}{p\text{-volume}} = \frac{(2\pi\sqrt{\alpha'})^{1-p}}{2\pi\alpha' g_s} \quad ; \quad \mu_p = \sqrt{2\pi}(2\pi\sqrt{\alpha'})^{3-p}$$

- ▶ They are called **D(irichlet)p branes** because they have open strings attached to their (p+1)-dim. world-volume.

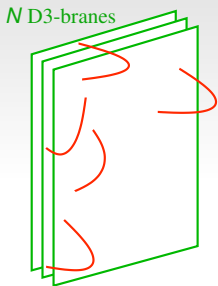


In the directions orthogonal to the brane the open string satisfies **Dirichlet** boundary conditions.

In the directions along the brane they satisfy **Neumann** boundary conditions.

- ▶ The open strings (**gauge theory**) live in the $(p+1)$ -dim. worldvolume of a D_p brane, while closed strings (**gravity**) live in the entire ten dimensional space.

- ▶ If we have a stack of N parallel D branes, then we have N^2 open strings having their endpoints on the D branes:



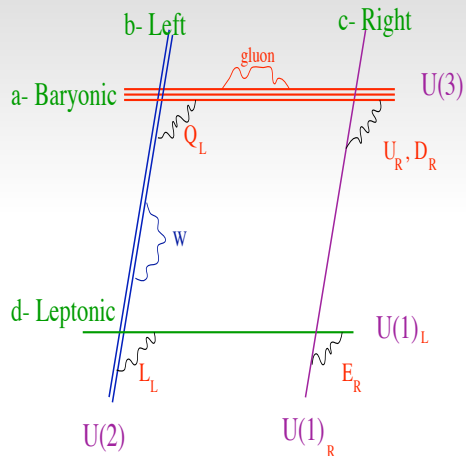
The open strings attached to a stack of parallel D branes transform according to the adjoint representation of $U(N)$

- ▶ The massless spin 1 ($\frac{1}{2}$) bosons (fermions) correspond to **gauge bosons (gauginos)**.
- ▶ Those fermions are non-chiral in four dimensions.

- ▶ How do we describe matter fields: quarks and leptons?
- ▶ The simplest way is to have **D branes at angles or magnetized D branes** (with a magnetic field in the extra dimensions).

Standard Model from magnetized D branes

Can one use magnetized D branes to construct string extensions of the Standard Model and of the MSSM?



Four stacks of magnetized branes: *a, b, c, d*.

$$SU(3)_a \times SU(2)_b \times U(1)_a \times U(1)_b \times U(1)_c \times U(1)_d$$

Marchesano, thesis, 2003

AdS/CFT

- ▶ The discovery of D branes in 1995 has also led in 1997 to the formulation of the **Maldacena conjecture**:

$$\mathcal{N} = 4 \text{ super Yang-Mills } (g_{YM}, N)$$

is equivalent to

Type IIB string theory compactified on $AdS_5 \times S^5$ (g_s, R, α')

- ▶ $\mathcal{N} = 4$ super Yang-Mills is a **conformal invariant** and **supersymmetric** gauge theory containing **a gauge boson, 6 real scalars and 4 Majorana fermions**.
- ▶ It lives on the 4-dim. world-volume of a D3 brane.
- ▶ The parameters of the two theories are related as follows:

$$g_{YM}^2 = 4\pi g_s \quad ; \quad \frac{R^4}{(\alpha')^2} = Ng_{YM}^2$$

- ▶ It opens the possibility to study a gauge theory **at strong coupling**.
- ▶ When the 't Hooft coupling $Ng_{YM}^2 \gg 1$, the curvature is small and we can use **classical supergravity** to study the gauge theory.
- ▶ But this gravity lives in 10 dims. and **has nothing to do with 4 dim. gravity**

- ▶ If g_{YM}^2 is large, but the 't Hooft coupling is not large, then we have to use **the tree diagrams of type IIB string theory**.
- ▶ Extension to **less supersymmetric and non-conformal** gauge ths.
- ▶ Construct classical supergravity solutions corresponding to them with the aim of studying the properties of the gauge theories living on their world-volume.
- ▶ Properties as the β -function, the chiral anomaly, the gaugino condensate etc. have been studied in detail.
- ▶ D brane configurations having QCD on the world-volume have also been studied reproducing **the low-energy hadron physics**.
- ▶ See f.i. the model (**with chiral symmetry breaking**) constructed by Sakai and Sugimoto.
- ▶ The mass spectrum is obtained in terms of a dimensional parameter as the temperature.
- ▶ Λ_{QCD} is not properly generated and Kaluza-Klein states cannot be decoupled.

- ▶ The AdS/CFT idea has also been used to study gauge theories **at finite temperature and density**.
- ▶ The most important result has been **the calculation of the viscosity** of the nuclear matter at strong coupling produced in heavy ion experiments, namely

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

that is very small compared with the same quantity at weak coupling:

$$\frac{\eta}{s} \sim \frac{1}{\lambda^2}$$

Conclusions and Outlook

- ▶ This year (2009) is extremely important for high energy physics because **LHC will start to collect data**.
- ▶ Those data will give us information about the structure of our world at distances between $\frac{1}{1000}$ to $\frac{1}{100.000}$ of a proton.
- ▶ Remember that **a proton has a dimension of 10^{-13} cm**.
- ▶ Up to now there is **no evidence** that string theory has anything to do with Nature.
- ▶ **A huge number of vacua** and **no compelling model!**
- ▶ On the other hand, the work on string theory has generated **new ideas and mechanisms**.
- ▶ It has provided us with methods that allow to study gauge theories **at strong coupling** and may be useful to study the properties of **strongly coupled condensed matter systems**.
- ▶ **It is hard to believe that ST will not stay with us also in the future.**