String theory and particle physics

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Plan of the talk

1. Why do we talk about string theory?
2. String Theory
3. Dp branes
4. Standard Model from magnetized D branes
5. AdS/CFT
6. Conclusions and Outlook

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) $\sim 100\ GeV \Longleftrightarrow 10^{-16} cm = \frac{1}{1000}$ proton.
- It is a gauge field theory with the gauge group:

$$\begin{array}{ccccc} SU(3)_{Colour} & \times & SU(2)_L & \times & U(1)_Y \\ g_3 & & g_2 & & g_1 \end{array}$$

- 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 $420 - 182 GeV > m_H > 115 GeV$.
- The SM contains three dimensional constants:

$$\Lambda_{QCD} \sim 250 MeV \ ; \ < H >= 246 GeV \ ; \ M_H$$

- The Fermi scale $\Longrightarrow \sim 246 GeV$.

- 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:

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

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

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

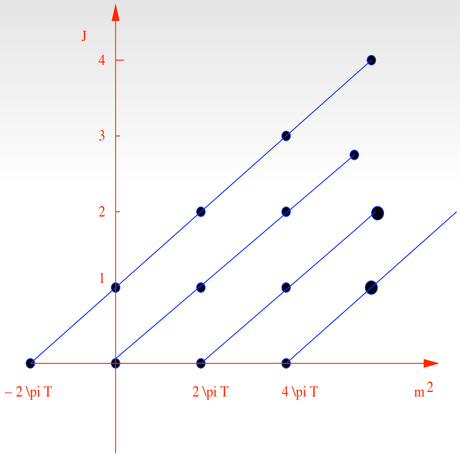
- The string tension $T = \frac{Energy}{unit\ length}$ is equal to $T = \frac{1}{2\pi\alpha'}$.
- String theory is an extension of field theory !
  - Quantum Mechanics $\underset{h \to 0}{\Longrightarrow}$ Classical Mechanics

    Special Relativity $\underset{c \to \infty}{\Longrightarrow}$ Galilean Mechanics

    String Theory $\underset{\alpha' \to 0}{\Longrightarrow}$ Field Theory

- In the limit $\alpha' \to 0$ one recovers the UV divergences of quantum gravity unified with gauge theories $\Longrightarrow$ point-like structure.
- Can we see stringy effects in experiments?
- If $\alpha' E^2 << 1$, 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 have 5 ten-dimensional consistent string theories: IIA, IIB, I, Het. $E_8 \times E_8$ and Het. $SO(32) \Longrightarrow$ 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,

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

- 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

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

  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

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

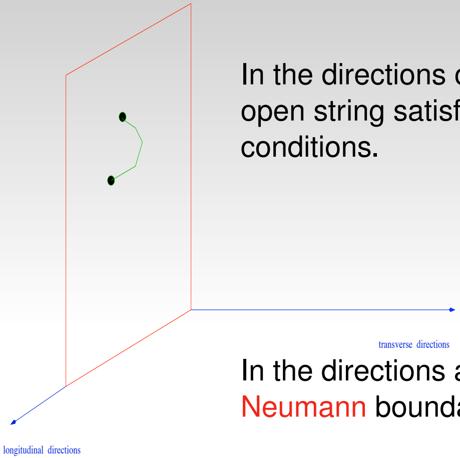
  They are additional non-perturbative states of string theory with tension and RR charge given by:

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

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

$$\partial_\sigma X^\mu(\sigma=0,\pi;\tau)=0 \quad \mu=0\dots p \qquad \textit{Neumann b.c.}$$
$$\partial_\tau X^i(\sigma=0,\pi;\tau)=0 \quad i=p+1\dots 10 \qquad \textit{Dirichlet b.c.}$$

- An open string is described by the string coordinate $X^\mu(\sigma,\tau)$ and $\sigma=0,\pi$ correspond to the two end-points.

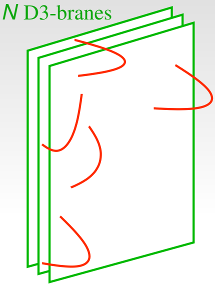


In the directions orthogonal to the brane the open string satisfies Dirichlet boundary conditions.

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 Dp 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 $U(N)$

- A stack of N D branes has a $U(N) = SU(N) \times U(1)$ gauge theory living on their worldvolume and is described by the DBI Lagrangian in $p+1$ dimensions:

$$L = -\tau_p \left(\sqrt{-\det\left(G_{\alpha\beta} + 2\pi\alpha' F_{\alpha\beta}\right)} \right) \sim -\frac{\tau_p (2\pi\alpha')^2}{4} \mathrm{Tr}\left(F^2\right) + \ldots$$

- The mass spectrum of the open strings attached to two parallel D branes a and b at distance y_{ab} is given by:

$$(m^2_{BOS})_{ab} = \frac{1}{\alpha'} \left(\sum_{n=1}^{\infty} n a_n^\dagger \cdot a_n + \sum_{r=1/2}^{\infty} r \psi_r^\dagger \cdot \psi_r - \frac{1}{2} \right) + \frac{y_{ab}^2}{\alpha'(2\pi\sqrt{\alpha'})^2}$$

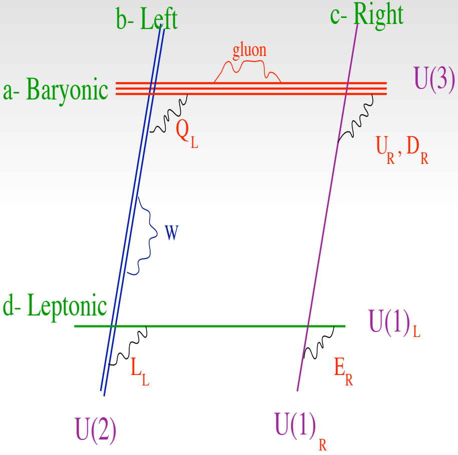
$$(m^2_{FER})_{ab} = \frac{1}{\alpha'} \left(\sum_{n=1}^{\infty} n a_n^\dagger \cdot a_n + \sum_{n=1}^{\infty} n \psi_n^\dagger \cdot \psi_n \right) + \frac{y_{ab}^2}{\alpha'(2\pi\sqrt{\alpha'})^2}$$

y_{ab} is the distance between the two D branes.

- The fermions are non-chiral in four dimensions.
- They describe the supersymmetric partners of the gauge fields, called gauginos, but not the quarks and leptons that are chiral.
- 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

- Find a D brane configuration without tadpoles $\Longrightarrow$ absence of non-abelian anomalies.
- The mixed and $U(1)$ anomalies are eliminated by a generalized Green-Schwarz mechanism $\Longrightarrow$ purely stringy mechanism!
- The gauge bosons corresponding to the $U(1)$ groups get a mass by a generalized Stückelberg mechanism.
- This is purely stringy alternative way (to the Higgs mechanism) to give a mass to the gauge bosons.
- The gauge boson, corresponding to a combination of the four $U(1)$'s, remains massless $\Longrightarrow$ hypercharge $U(1)$.
- The gauge symmetry, corresponding to the $U(1)$'s with a massive gauge boson, becomes a global symmetry as B and L.
- But, unlike the SM, these global $U(1)$ give rise to massive gauge bosons that could be observed at LHC if the string length is around $10\,TeV$.

- These global $U(1)$'s are global symmetries at each order of string perturbation theory.
- However, they can be broken by instantons.
- They may be pure stringy effects that disappear in the field theory limit ($\alpha' \rightarrow 0$).
- Those extra effects are needed to generate Majorana neutrino masses and semi-realistic Yukawa couplings.
- In the case of magnetized D branes the ground state is degerate (Landau levels) and this gives the number of generations of quarks and leptons.
- Those models are very promising, but a lot of work still has to be done to make them more realistic.

AdS/CFT

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

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

  is equivalent to

  Type IIB string theory compactified on $AdS_5 \times S^5$ (g_s, R)
- $\mathcal{N} = 4$ 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:

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

- It opens the possibility to study a gauge theory at strong coupling.
- When the ' t Hooft coupling $N g_{YM}^2 >> 1$, 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^2_{YM} 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.