Emilian Dudas

CPhT-Ecole Polytechnique

String Theory

and

Particle Physics

Outline

- Fundamental interactions : why gravity is different
- String Theory : from strong interactions to gravity
- Brane Universes

- constraints : strong gravity versus string effects

- virtual graviton exchange

- Accelerated unification
- Superstrings and field theories in strong coupling
- Strings and their role in the LHC era

1. Fundamental interactions: why gravity is different

There are four fundamental interactions in nature :

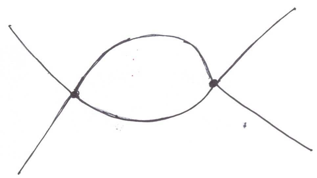
Interaction	Description	distances
$Gravitation$	$Rel.\ gen.$	$Infinity$
$Electromagn.$	$Maxwell$	$Infinity$
$Strong$	$Yang - Mills\ (QCD)$	$10^{-15}m$
$Weak$	$Weinberg - Salam$	$10^{-17}m$

With the exception of gravity, all the other interactions are described by QFT of the renormalizable type.

Physical observables $\longrightarrow$ perturbation theory.

The point-like interactions in Feynman diagrams generate ultraviolet (UV) divergences

Fig. 1 UV divergences in Feynman diagrams



Renormalizable theory $\longrightarrow$ the UV divergences reabsorbed in a finite number of parameters $\longrightarrow$ variation with energy of couplings, confirmed at LEP.

Einstein general relativity is a classical theory . Mass (energy) $\longrightarrow$ spacetime geometry $g_{\mu\nu}$

Its quantization

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_P} h_{\mu\nu}$$

leads to a non-renormalizable theory. The coupling of the grav. interaction is

$$\frac{E}{M_P} \tag{1}$$

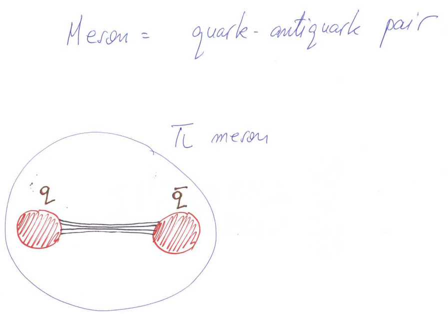
$\longrightarrow$ negligeable quantum corrections at low energies. At high energies $E \sim M_P$ (important quantum corrections) or in strong gravitational fields $\longrightarrow$ theory of quantum gravity is necessary.

2. String Theory : from strong interactions to gravity

1964 : M. Gell-Mann propose the quarks as constituents of hadrons.

Ex : meson

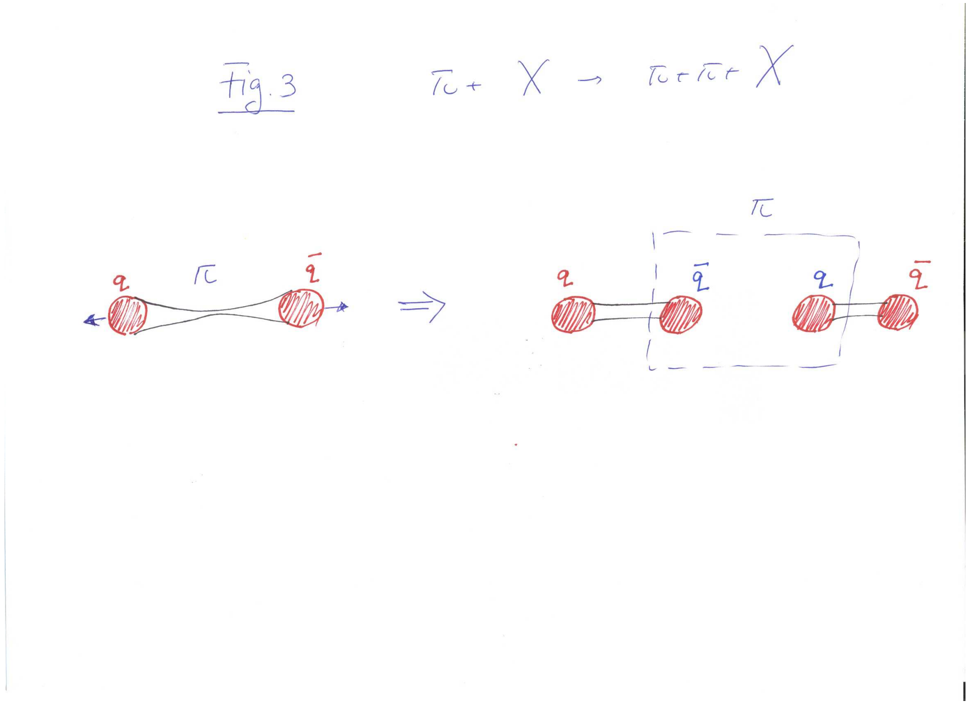
Fig. 2



Quarks are confined in hadrons through interactions which increase with the distance

$\longrightarrow$ the mesons are strings "of color" with quarks at their ends.

If we try to separate the mesons into quarks, we produce other mesons



1967-1968 : Veneziano, Nambu, Nielsen,Susskind

• The properties of the hadronic interactions are well described by string-string interactions. The hadrons are the vibrational modes of the quantum strings.

classical string $\longrightarrow$ vibrational modes $\omega_n^2 \sim n M_s^2$

quantum string $\longrightarrow$ particles $M_n^2 \sim n M_s^2$, with $M_s \sim GeV$

Consistency conditions $\longrightarrow$ 26 spacetime dims

$\longrightarrow$ 22 extra space dimensions !

Some problemes of the hadronic strings :

- instability : tachyonic scalar ($M^2 < 0$) in the spectrum
- all string excitations are bosons (bosonic strings)
- spectrum : in addition to the gauge bosons (spin 1), one particle of spin 2 and zero mass.

• Solution of the first two problems : enlarge the symmetry of the theory : Supersymmetry $\rightarrow$ equal number of bosons and fermions (superstrings), six additional space dimensions.

• 1974 (Scherk-Schwarz) : the interactions of the spin 2 particle is that of $h_{\mu\nu}$ in general relativity ! The spectrum of zero mass of the superstrings contain matter particles (fermions,scalars) and the mediators (bosons of spin 1 and spin 2) of all the four fundamental interactions !

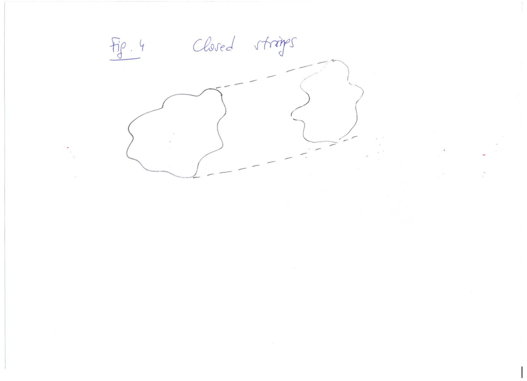
1984-1986 (Green-Schwarz ; Witten, Gross and coll.) : consistency conditions, compactification and chirality in 4d $\leftrightarrow$ topology of the compact six-dim. space.

1997-1998 (Maldacena ; Gubser,Klebanov,Polyakov ; Witten) :

Holographic duality

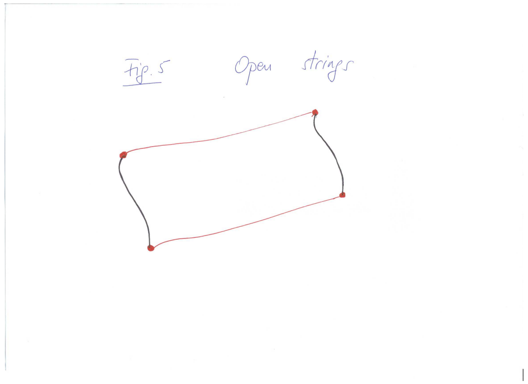
field theory		string theory
in 4d	$\leftrightarrow$	in 10 dims
(strong coupling)		weak coupling .

Closed strings



excitations : gravitons, moduli fields,etc

Open strings



excitations : photon, electrons,etc

Strings do not have point-like interactions $\longrightarrow$ no UV divergences !

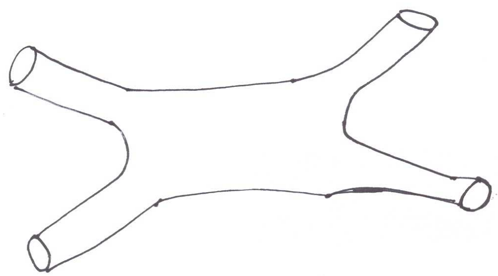


Fig. 6 String interactions

6. Brane Universes

String Theory has hyper-surfaces of p space dims. called D-branes, which contain gauge fields (coupling g) and matter fields

• Unlike the case of the heterotic strings, if SM lives on D-branes, the fundamental string scale is much smaller than the Planck scale, if the internal volume is large.

Brane Universe = the three SM gauge interactions and matter (open strings) are localized on a Dp (ex. D3) brane

Gravity (closed strings) is everywhere ("in the bulk").

The n perpendicular extra dimensions can be of macroscopic size

$$R_\perp \ \leq \ 10^{-1} \ mm,$$

constraint coming from search of deviations from Newton's law . The relations

$$M_P^2 \ = \ \frac{1}{g_s} \, V_\perp \ M_s^{2+n}$$
$$g^2 \ = \ g_s V_{||} \ M_s^{6-n}$$

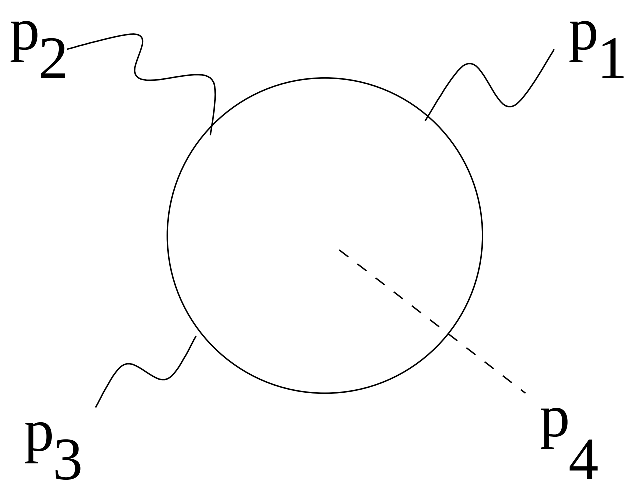
with 2 dims. of extreme size $R_\perp \sim 10^{-1} \ mm$ give a fundamental string scale

$$M_s \sim 3 - 10 \quad TeV$$

Gravity becomes strong at energies

$$M_* = V_\perp^{1/(2+n)} M_s \ > \ M_s$$

$\longrightarrow$ string effects are observable in colliders (LHC), if TeV strong gravity. Ex :The graviton emission in the bulk : three open and one closed string particles



The inclusive cross-section

$$\sigma_{FT} \sim \frac{1}{M_P^2} \sum_{m_i=0}^{RE} \sim \frac{E^n}{M_*^{2+n}}$$

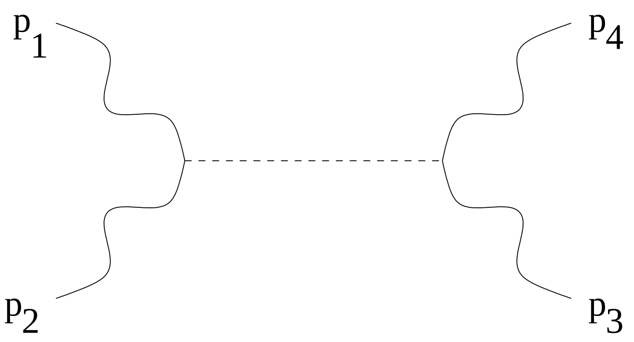
is considered to be reliable at the field-theory level.

However, string effects appear at $M_s < M_*$. By an explicit computation

$$\frac{\sigma - \sigma_{FT}}{\sigma_{FT}} \sim \frac{E^4}{M_s^4}$$

Virtual graviton exchange

Another important process for the large Xtra dim. scenario: virtual graviton exchange



For $n \geq 2$ perpendicular dimensions, summation over virtual gravitons is UV divergent

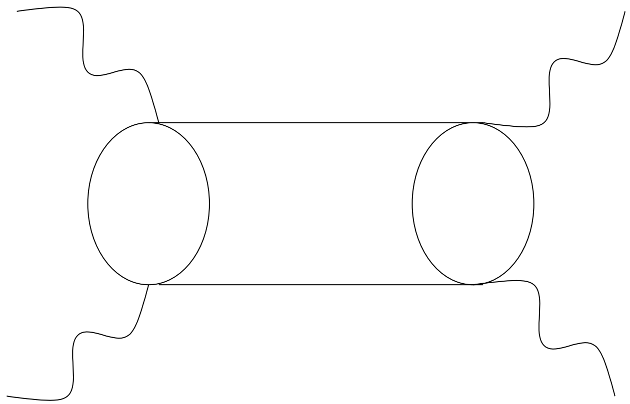
$$A \sim \frac{1}{M_P^2} \sum \frac{1}{s - (m_1^2 + \cdots m_n^2)/R_\perp^2} \sim \frac{1}{M_P^2} R_\perp^2 (R_\perp \Lambda)^{n-2}$$

where the summation was cut for KK masses heavier than Λ. The result can be written

$$A \sim \frac{\Lambda^{n-2}}{M_*^{2+n}} \sim \frac{c^{n-2}}{M_*^4}$$

Generically it is believed that string theory regulates the divergence, so $\Lambda = c\ M_*$.

However, despite appearencies, this is a one-loop diagram in string theory,



which has a dual interpretation (the open-closed duality) :

i) Tree-level gravitational exchange.

ii) One-loop diagram with charged states running in the loop.

Main corrections to four-point functions : tree-level exchanges of string oscillators.

Experimental constraints:

- parallel dimensions : $R_{||} \leq 10^{-17}$ cm
- perpendicular dimensions : $R_{\perp} \leq 10^{-1}$ mm

- If SUSY breaking on the branes, $M_{SUSY} \sim M_s$

$$m_{\text{bulk moduli}} \sim \frac{M^2_{SUSY}}{M_P} \sim 10^{-3} eV$$

The cosmology is completely different in the early univers

$\rightarrow$ observable signatures in the CMB ?

5. Accelerated Unification

• Gauge coupling unification seems to predict a very high unification scale M_s, inaccessible to colliders.

Is there's a way to get unification at low energies ?

- Yes. The elementary particles: electron, quarks, etc propagate in the extra dimensions . Their Kaluza-Klein states produce an accelerated evolution of the couplings.

$\longrightarrow$ accelerated unification .

The one-loop evolution of gauge couplings in 4d between energy scales μ_0 and μ is

$$\frac{1}{\alpha_a(\mu)} = \frac{1}{\alpha_a(\mu_0)} + \frac{1}{2\pi}\sum_r \mathrm{Str} \int_{1/\mu^2}^{1/\mu_0^2} \frac{dt}{t} Q_{a,r}^2 \left(\frac{1}{12} - \chi_r^2\right) e^{-tm_r^2} \ .$$

- Start with MSSM in 4d and extend it to $R^4 \times S^1$, a circle of radius $R_{||}$. In this case the running generalizes to

$$\frac{1}{\alpha_a(\mu)} = \frac{1}{\alpha_a(\mu_0)} + \frac{1}{2\pi}\sum_r \mathrm{Str} \int_{1/\mu^2}^{1/\mu_0^2} \frac{dt}{t} \times$$
$$Q_{a,r}^2 \left(\frac{1}{12} - \chi_r^2\right) \left(\sum_n e^{-tm_{n,r}^2(R_{||})} + e^{-tm_r^2}\right) \ ,$$

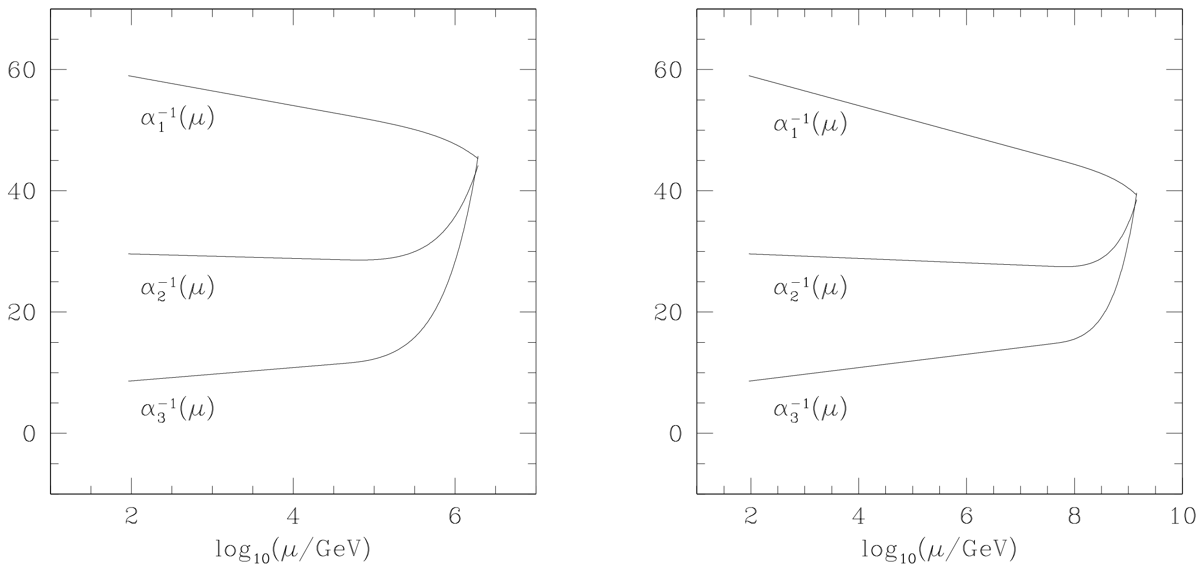
Take $\mu_0 = M_Z$, one finds

$$\frac{1}{\alpha_a(\mu)} = \frac{1}{\alpha_a(M_Z)} - \frac{b_a}{2\pi} \ln \frac{\mu}{M_Z} - \frac{\tilde{b}_a}{2\pi} \int_{1/\mu^2}^{1/M_Z^2} \frac{dt}{t} \theta_3^\delta \left(\frac{it}{\pi R_{||}^2}\right)$$

$$\simeq \frac{1}{\alpha_a(M_Z)} - \frac{b_a}{2\pi} \ln \frac{\mu}{M_Z} + \frac{\tilde{b}_a}{2\pi} \ln(\mu R_{||})$$

$$- \frac{\tilde{b}_a}{2\pi} [(\mu R_{||})^\delta - 1] \ .$$

- The power-like term $(\mu R_{||})^\delta >> 1$ overtakes the logarithmic terms in the higher-dimensional regime and governs the eventual unification pattern.



Unification of gauge couplings in the presence of extra spacetime dimensions. We consider two representative cases: $R^{-1} = 10^5$ GeV (left), $R^{-1} = 10^8$ GeV (right). In both cases we have taken $\delta = 1$ and $\eta = 0$.

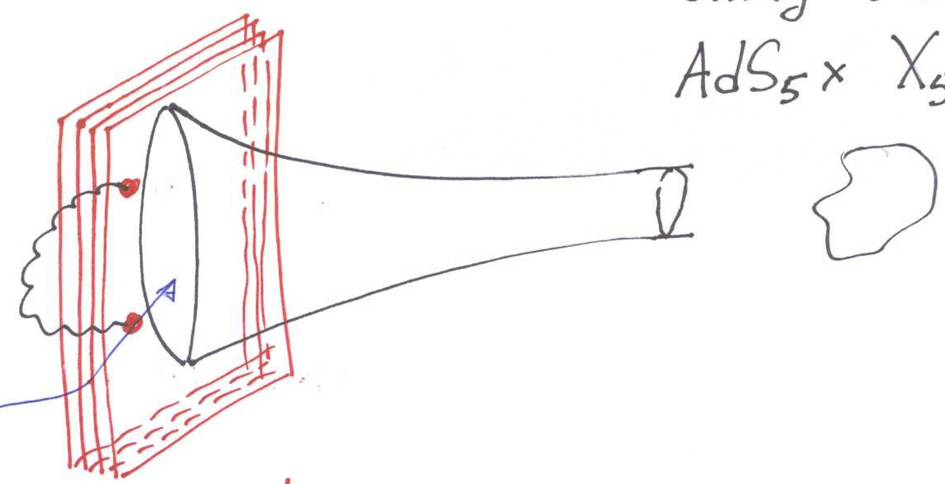
7. Superstrings and field theories in strong coupling

field theories		string theory
in 4d	$\leftrightarrow$	weak coupling
(strong coupling)		in 10 dims, comp.
SUSY, conformal		sur $AdS_5 \times X_5$

Fig. 9

AdS / CFT correspondence

(field theory ⟺ string theory correspondence)



$\longrightarrow$ Nonperturbative methods in field theory

Ex.(1) : Holographic QCD : 5d computation of hadrons properties (Sakai-Sugimoto, 2004)

- (large) N_c D4 branes $\rightarrow SU(N_c)$ gauge group (QCD)
- N_f $D8 - \overline{D}8$ pairs $\rightarrow SU(N_f) \times SU(N_f)$ chiral symmetry
- Geometry of chiral symmetry breaking
- Meson observables via tree-level 5d KK techniques

Ex. (2) : RHIC physics : quark-gluon plasma viscosity in strong coupling regime

- Some agreement between experimental value and computation via (AdS/CFT) correspondence at finite T

Strings : their futur role in particle physics ?

The LHC (Large Hadron Collider) era started, with energies (2009) of 14 TeV, in searching for physics Beyond the Standard Model. Possibilities :

- Discovery of the Higgs scalar, nothing else $\longrightarrow$ problem for all high energy community

- No discovery $\rightarrow$ perturbative consistency (unitarity) of the SM broken around 1 TeV

• new nonperturbative physics (ex. technicolor) $\longrightarrow$ holographic studies ?

• Discovery low-energy SUSY :

$\longrightarrow$ if transmission SUSY breaking is gravitational $\longrightarrow$ Supergravity $\longrightarrow$ Superstrings

$\longrightarrow$ try to discover signatures of moduli fields

• Large extra spacetime dimensions $\leftrightarrow$ string theory at a low scale M_s $\longrightarrow$ spectacular effects of strings : Regge states, unification at low energy, etc