Particules Élémentaires, Gravitation et Cosmologie

Année 2009-'10

Théorie des Cordes: une Introduction

Cours VIII: 5 mars 2010

La fin d'un rêve, le début d'un autre?

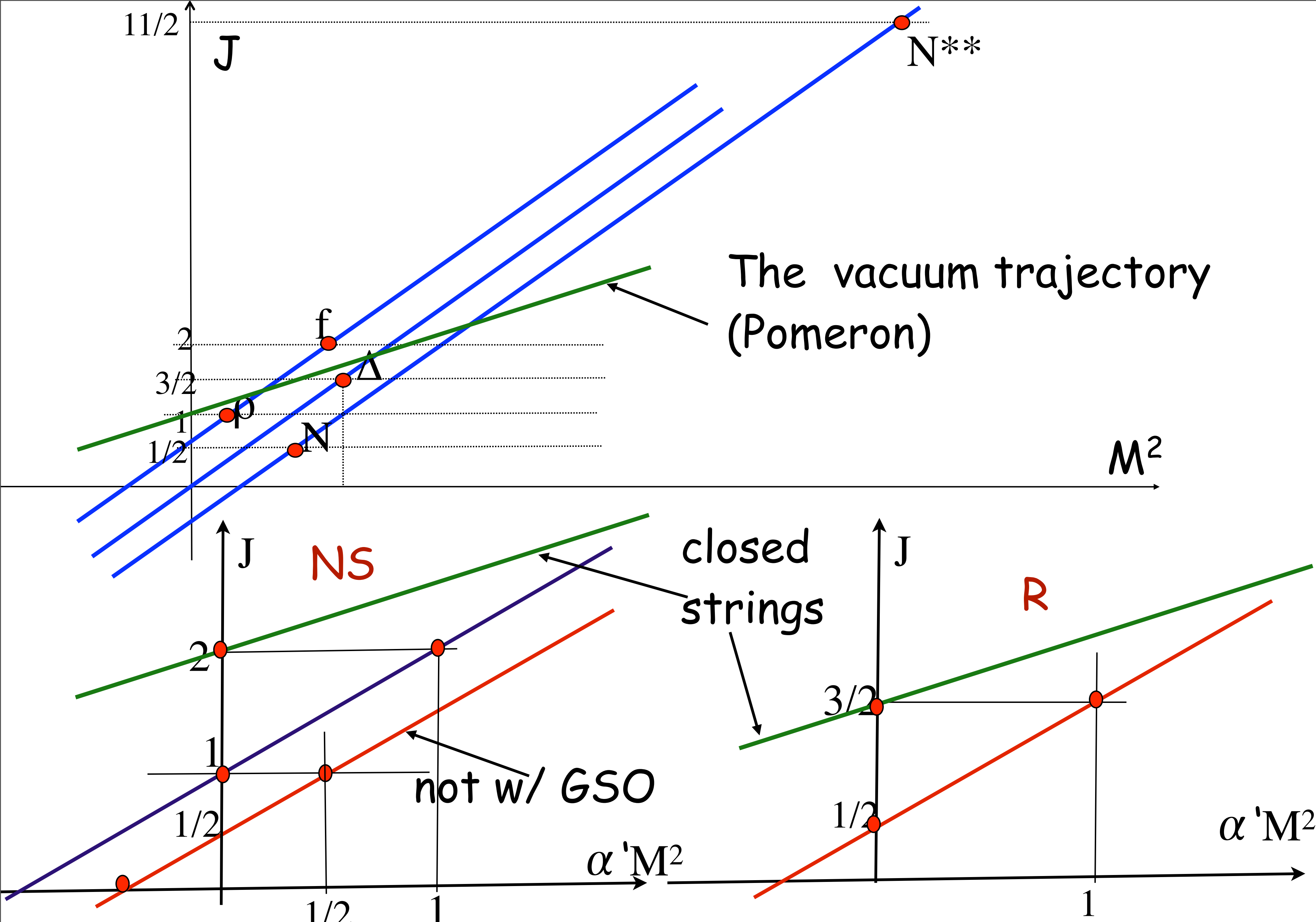
- Experimental shortcomings
- QCD takes over
- The zero-slope limit
- The Scherk-Schwarz proposal

A beautiful theory with too many experimental shortcomings

With its string reinterpretation the DRM had become, around 1972-73, a respectable theory. (For earlier attitudes towards DRM, it's interesting to read a story by Louis Clavelli: http://bama.ua.edu/~lclavell/Weston/).

The absence of ghosts had been a remarkable achievement, like that of adding consistently fermions.

Some qualitative features of the model were in striking agreement with experiments, in particular the linearity of the Regge trajectories, their universal slope, and the degeneracy of even and odd-signature trajectories implied by DHS duality.



11/2
J
N**
The vacuum trajectory
(Pomeron)
f
2
Δ
3/2
ρ
1
N
1/2
M²
J
NS
closed
strings
2
1
1/2
not w/ GSO
α 'M²
1/2
1
J
R
3/2
1/2
α 'M²
1

Other features, however, were in striking disagreement with the data:

1. $D \neq 4$;

2. Presence of massless particles (and of tachyons before GSO). More generally, the low-lying states were not what one wanted for hadrons (no systematic generalization of the $\pi\pi \to \pi\pi$ and $\pi\pi \to \pi\omega$ amplitudes had been found).

However, until then, one could nourish some hope that, by working harder, those problems could be overcome:

1. One had already been able to reduce D from 26 to 10.

Why not to 4? (adding more SUSY on the WS brings down to D=2!);

2. We knew how to deal with tachyons in QFT and how to give mass to massless gauge bosons via the HEB mechanism. Why not try to do the same in string theory?

The real killer was softness!

String theory is "soft" i.e. does not allow "hard" processes in which two colliding strings exchange a large momentum. Such processes are exponentially damped at high E.

We already saw this in the 4-point function (see lecture 4). It had been generalized to multiparticle processes (e.g. to the transverse momentum distribution of one-particle inclusive x-section).

Experimentally, there was mounting evidence that "hard" processes are not so rare in hadronic physics:

1. $R = \sigma(e^+ e^- \to \text{hadrons})/\sigma(e^+ e^- \to \mu^+ \mu^-) \to$ constant.
2. Bj scaling in $e^- p \to e^- + X$ (SLAC) => partons?
3. Large p_t events in pp scattering at the ISR (CERN).
4. Form factors at large q^2.

All evidence for point-like structure in the hadrons.

Even worse was "competition"

~ 1973 QCD came about with its

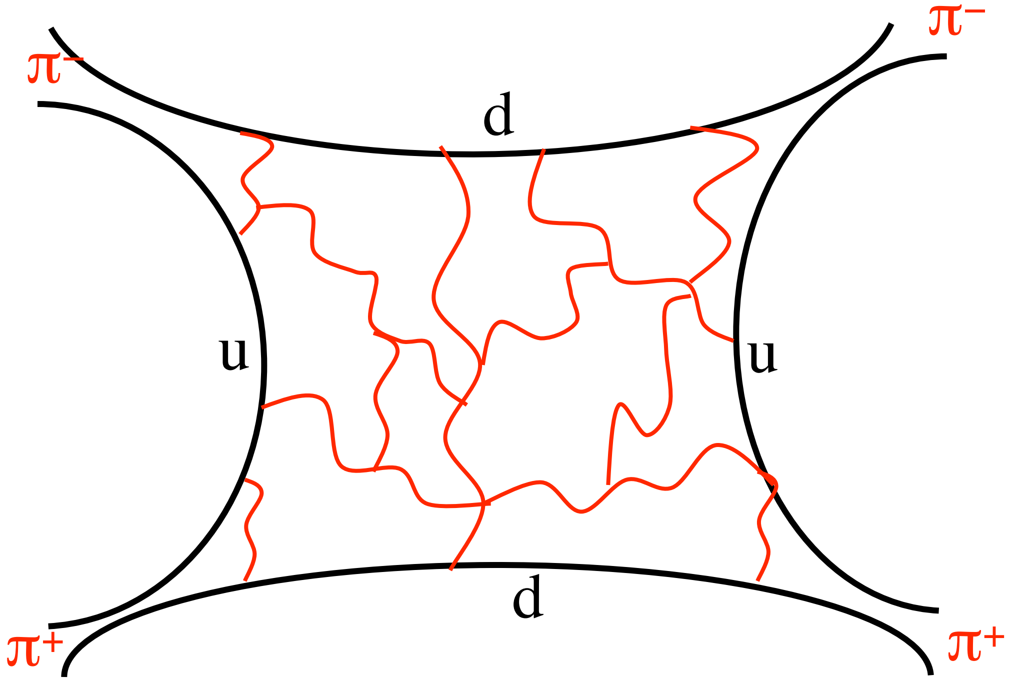
1. Ultraviolet (asymptotic) freedom that could explain those hard processes (2005 course) from the existence of point-like sources inside the hadrons.
2. Conjectured infrared slavery (confinement) explaining why we do not see free quarks and gluons.
3. Furthermore, quark confinement would be realized through the formation of a narrow chromo-electric flux tube (dual Meissner effect, 2006 course) simulating a string stretched between a quark and an antiquark...

Yet it was (psychologically?) difficult to give up: What about DHS duality and the topological structure of string theory's perturbation theory, so much unlike that of any "normal" QFT?

I gave up ~1974, when 't Hooft showed that even topology comes out of QCD, provided one considers a 1/N expansion….

In SU(N) QCD, at large N, duality diagrams take up a precise meaning: they are planar Feynman diagrams bounded by quark propagators & filled with gluons (2006 course).

NB: this is not usual perturbation theory and has DHS duality



- They give, at leading order, the zero-width approximation we had been using all the time.
- At next-to-leading order the non-planar diagrams should give new quarkless bound states, the glueballs, and presumably the Pomeron as the Regge trajectory glueballs lie on.
- The Hagedorn temperature is re-interpreted as a deconfining temperature for quarks and gluons.
- It all seemed to fall beautifully into place…
- Was that beautiful theoretical construction completely worthless?
- Hard to believe but, for ~10 years, most people stopped working on strings.

The zero-slope limit

(Scherk '71, Neveu-Scherk '72, Yoneya '72-'73)

We have argued that Quantum String Theory (QST) reduces to Classical String Theory (CST) when the size L of the string is large compared the fundamental length of QST:

$$l_s^2 \equiv 2\alpha'\hbar$$

This looks obvious: the classical limit corresponds to h --> 0. One could think that it also corresponds to the limit α'--> 0

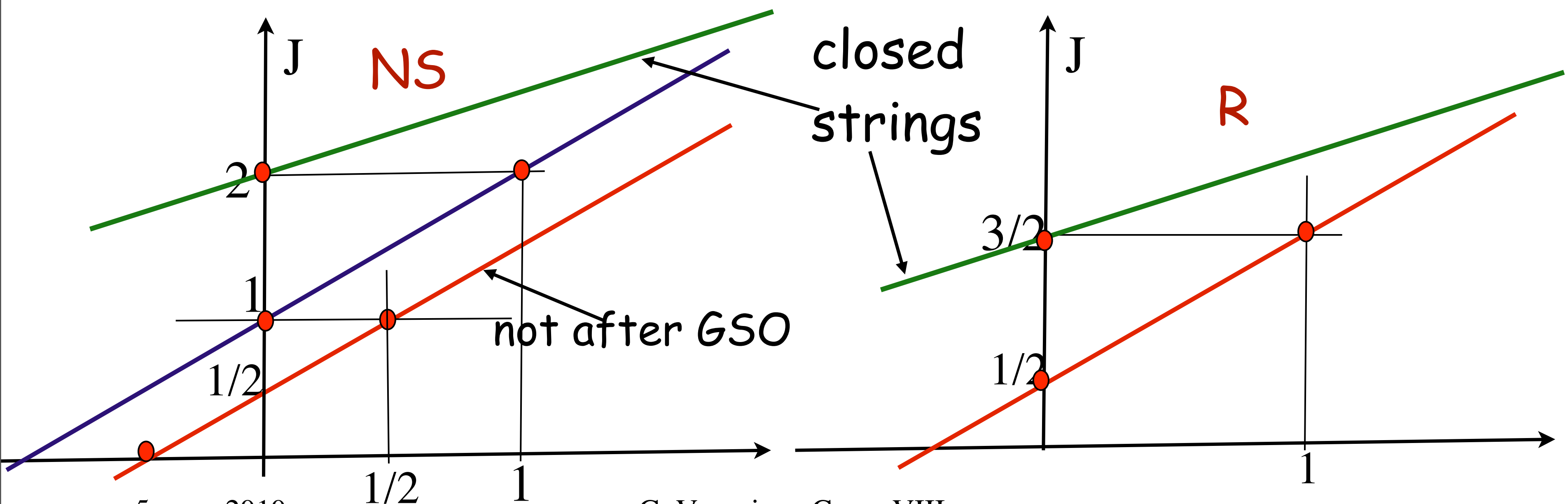
but this latter statement is wrong. Indeed:

$$L = \alpha' M >> l_s = \sqrt{\alpha'\hbar} \Rightarrow M \gg \sqrt{\frac{\hbar}{\alpha'}} \equiv M_s$$

- $M_s = h/l_s$ is the characteristic mass/energy scale of string theory providing its typical excitation energy/level spacing.
- The CST limit is rather α'--> infinity. Surprisingly little is known about this limit of QST...

Q: What is then the α'--> 0 limit? The answer is that QST goes over to conventional QFT ! QST is thus an extension of QFT, very much like Relativity and QM are extensions of classical mechanics and reduce to it in the appropriate limits.

Indeed, in this limit, the excited levels of the string are pushed to infinite mass and one is left with just the lowest states (which, as we have argued, are very quantum!). If we keep α_0 fixed we are left with just the massless states...



The α'--> 0 limit can also be seen as the low-energy limit ($s \ll M_s^2$) for the interaction of massless strings.

What Neveu-Scherk (for open strings) and Yoneya (for closed strings) found is hardly surprising (a posteriori!). At leading order in the momenta, the massless J=1 open string states couple like (abelian or non abelian) *gauge* bosons, while the massless J=2 closed string states couple exactly like a graviton in (semiclassical) *general* relativity.

This is what we should expect. As we have stressed many times, *gauge* invariance is needed for describing a massless J=1 particle, while *general* covariance is needed for describing a massless J=2 particle. But it's important to verify explicitly that this is indeed the case.

Example of a zero-slope limit

Let us consider the 3 and 4-point functions for massless J=1 open strings (including the Chan-Paton factors) and take the low-energy limit. For the 3-point function the leading term is linear in the momenta. Using $\varepsilon_i p_i = 0$ (for each i) we find:

$$
\begin{aligned}
& A(p_1, \epsilon_1, a_1; p_2, \epsilon_2, a_2; p_3, \epsilon_3, a_3) = \\
= \quad & 4g_s(2\alpha')^{\frac{D-4}{4}} Tr(\lambda^{a_1}\lambda^{a_2}\lambda^{a_3}) \left(\epsilon_1 \cdot \epsilon_2 \; (p_1 - p_2) \cdot \epsilon_3 + cyclic\right)
\end{aligned}
$$

where g_s is the so-called string coupling (see below). The sum in the bracket is odd under change from cyclic to anticyclic order: we thus recover a coefficient proportional to the structure constants of the group and also, precisely, the momentum/polarization dependence of a non-abelian gauge (Yang-Mills) theory with action:

$$
S = -\frac{1}{2g_D^2} \int d^D x \; Tr[F_{\mu\nu} F^{\mu\nu}] \quad ; \quad g_D = 2g_s(2\alpha')^{\frac{D-4}{4}}
$$

For the 4-point function we get two contributions: the first comes from the spin one massless pole times two three-point vertices; the second is a genuine, irreducible 4-point interaction and coincides, again, with what would follow from the same Yang-Mills action.

What is the string coupling g_s? It is a free parameter that we have already seen in the 4-point function, the overall factor we called β. In this new notation $\beta \sim g_s^2$.

Indeed all the properties of string theory are preserved if we multiply the N-point function by a factor g_s^{N-2}. Because of factorization we dispose of just one arbitrary parameter normalizing e.g. the 3-point function. Thus g_s is the fundamental (tree-level) coupling of 3 open strings! It turns out that the coupling of 3 closed strings is, instead, g_s^2. We will give an interesting reinterpretation of the string couplings next week.

The Scherk-Schwarz proposal (1974)

- By 1974 nobody believed any more that QST could be the correct theory of strong interactions.
- Instead, the realization that at low-energy QST could reproduce gauge and gravitational interactions prompted Scherk and Schwarz to make a very bold conjecture.
- Could QST be used instead to describe the elementary particles of QCD, i.e. the quarks and the gluons themselves and then, why not, the gauge bosons of the other SM interactions and then, why not, the graviton and gravitational interactions? In short a TOE...
- Of course, a change in $\alpha'(l_s)$, was also necessary.

- It was indeed a very bold proposal but, at least, it had the advantage of turning (at least some) defeats into victories. Why?
- The appearance of massless particles, a big embarrassment for strong interactions, was now a very welcome feature. QST predicted their existence, hence that of gauge and gravitational interactions.
- The softness of QST could solve the long standing problems with quantizing GR. Not only, it could even completely eliminate the UV problems of QFT (even if those could be put "under the rug" through the process of renormalization).
- Also, QST cried for SUSY, a possible solution to the hierarchy problem of the SM if conveniently broken.

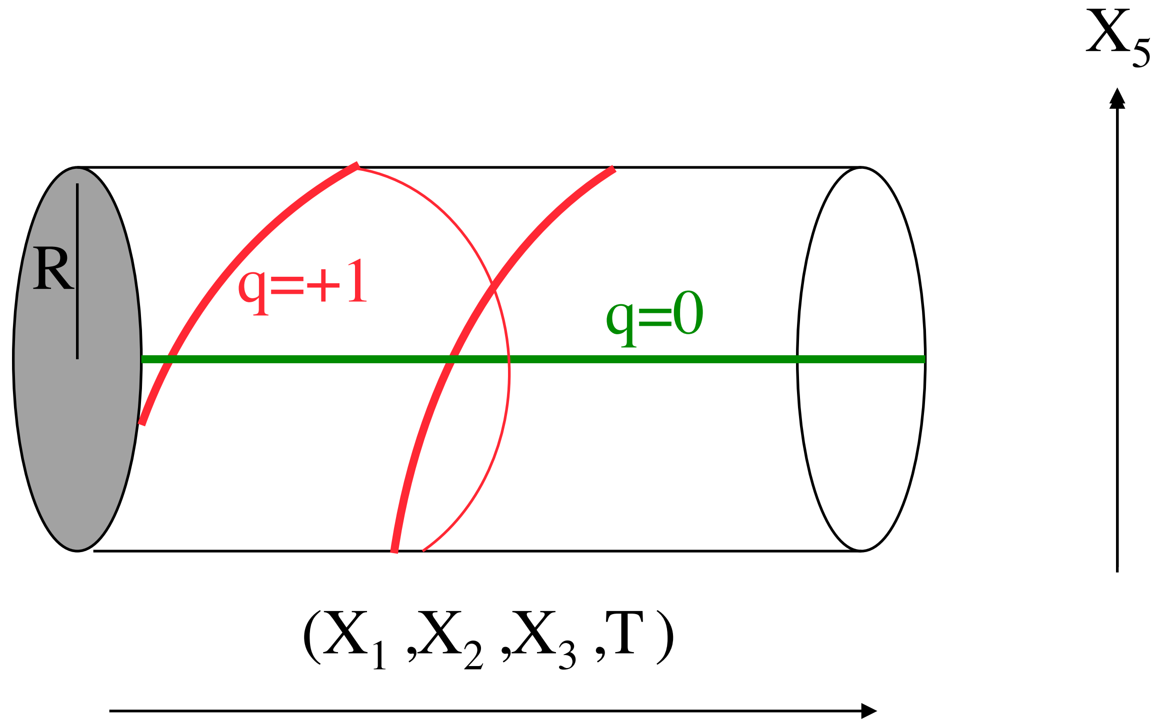
- The problem of D=10 still remained but people knew, since the work of Kaluza and Klein in the 20's, that the extra dimensions (6 in our case) could be made compact, become invisible as such, and provide a new mechanism for generating gauge interactions.
- In fact, with its fundamental length, QST could possibly solve a long-standing problem in KK theory: what fixes the size of the compact dimensions?

A quick reminder of KK theory

Th. Kaluza (1921) and O. Klein (1926) (KK) managed to reformulate electromagnetism + gravity as just GR in a space containing one extra spatial dimension.
In KK theory the extra dimension of space is a circle of radius R. The e.m. potential A_μ becomes,

essentially, the component $g_{\mu 5}$ of the 5-dimensional

metric, while g_{55} plays the role of a scalar field associated with the proper radius of the circle.
After some initial skepticism, Einstein admitted that the KK idea was very appealing.



p_5 is quantized in units of h/R.

$q = p_5/M_P = n\, l_P/R$, $n = 0, \pm 1, \pm 2, ..$

Quantization of electric charge as outcome of KK theory!! KK Unification $F_C = F_N$ at $E \approx hc/R = M_C c^2$.

M_C = mass of typical KK excitations.

QM is central to the KK idea.

The basic unit of electric charge (in natural units) becomes l_P/R, where $l_P \sim 10^{-33}$ cm is Planck's length, the fundamental length that can be constructed out of c, h and G_N. Given $\alpha \sim 10^{-2}$, R should be ~ 10 l_P

But what fixes R itself? Why should it not shrink down to zero?
Another problem with conventional KK theory is that even QED becomes non-renormalizable in D=5!
These questions, left unanswered in KK theory, will have interesting reformulations (and perhaps answers) in QST.

- The start of another, even more ambitious dream? Actually, not many people took the Scherk-Schwarz proposal seriously and this for several reasons:
- The SM had just been completed with its strong and electroweak sectors. There was a lot to do, theoretically and experimentally, in order to work out predictions and to check them against the data. It was a very intense and fruitful period in QFT:
- Already mentioned: large-N expansions, SUSY
- Others: computing hard processes in QCD, lattice gauge theories, instantons, U(1)&CP problems, FCNC, CP violation, GUTs...
- People could not care less about strings and Q-Gravity...
- Last but not least: it did not look easy to get chiral fermions from superstring theory. The start of the new dream had to wait 10 more years...(see seminar)