Cattedra Enrico Fermi 2015-2016

La teoria delle stringhe: l'ultima rivoluzione in fisica?

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Lezione # 6.2: 17.12.2015

Fermioni, GSO, supersymmetria
QCD e fine della stringa adronica

Piano della lezione

- Condizione di Virasoro e vincolo sul D
- Indicazioni a favore di una stringa sottostante
- La stringa classica di Nambu-Goto

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- Fermioni, GSO, supersimmetria
- Problemi fenomenologici e sopravvento di QCD

Shortcomings of the bosonic string

1. Presence of a tachyon
2. Presence of massless particles
3. Absence of fermions
4. $D \neq 4$

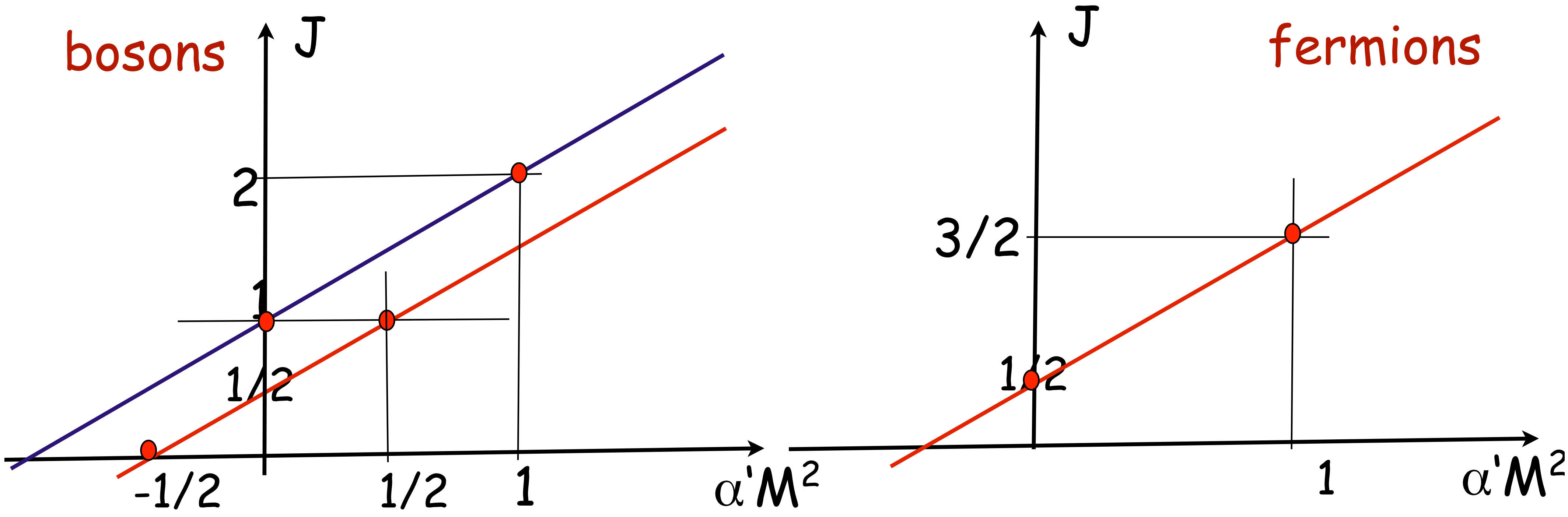
Adding fermions

Even before the string reinterpretation of the DRM, Neveu & Schwarz and Ramond managed to generalize the operator formalism by adding to the bosonic field $Q(z)$ a Grassmann (i.e. anticommuting) field $\psi(z)$.

Unfortunately this this did not help much with the other problems:

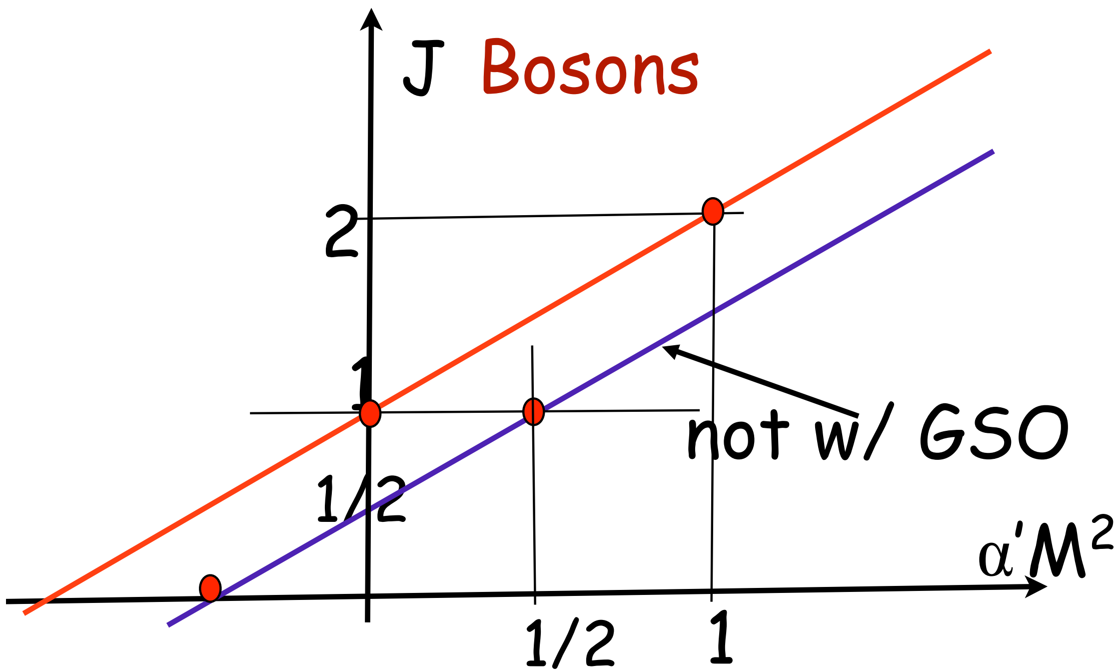
1. In the original NSR formulation a tachyon was still present
2. There were still massless particles in the spectrum
3. D could be reduced from 26 to 10, still far from 4!

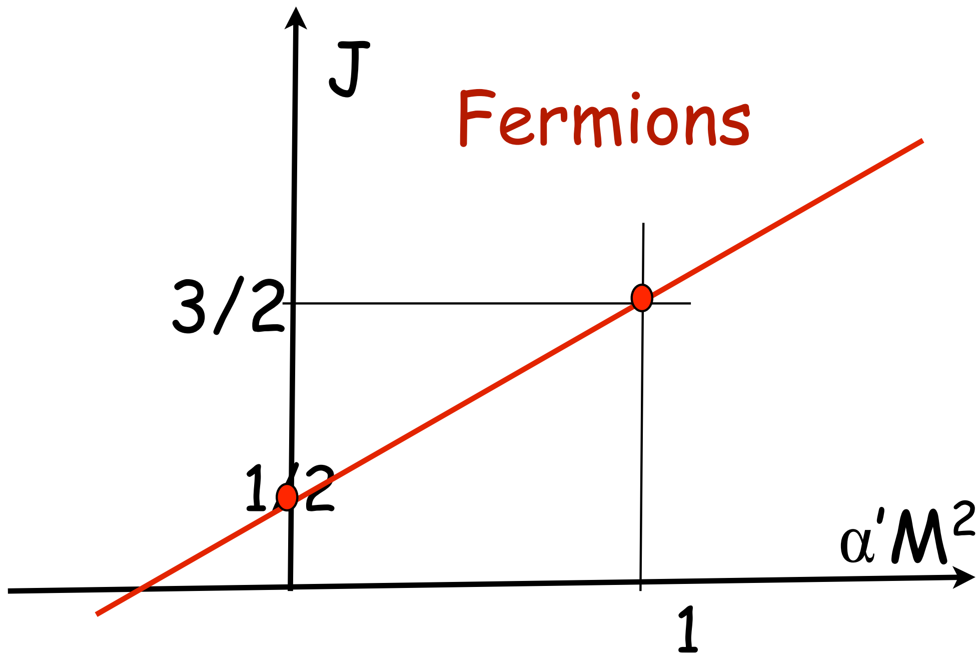
With respect to the bosonic string the NSR model is much richer: it has also fermions (with no tachyon) and a bosonic trajectory with intercept 1/2 (with a tachyon on it). It also has an amusing (though only partial) degeneracy between the bosonic and fermionic spectra.



GSO projection and SUSY

- In 1976, Gliozzi, Scherk and Olive found a smart way to eliminate the tachyon. They introduced, in the NSR model, a fermonic "parity" P_F.
- GSO then proved that P_F is conserved so that a projection on states with $P_F=+1$ is consistent ($P_F=-1$ states do not appear as intermediate states). The trajectory with the tachyon is eliminated.
- Half of the fermions are also projected out.
- The fermionic ground state becomes a Majorana-Weyl spinor in D=10. It has 8 ($2^5/4$) components (just like a massless vector which has 10-2 = 8).
- The spectrum exhibits a symmetry between bosons and fermions (Supersymmetry or SUSY) which extends to interactions


J
Bosons
2
1
1/2
not w/ GSO
α'M²
1/2
1

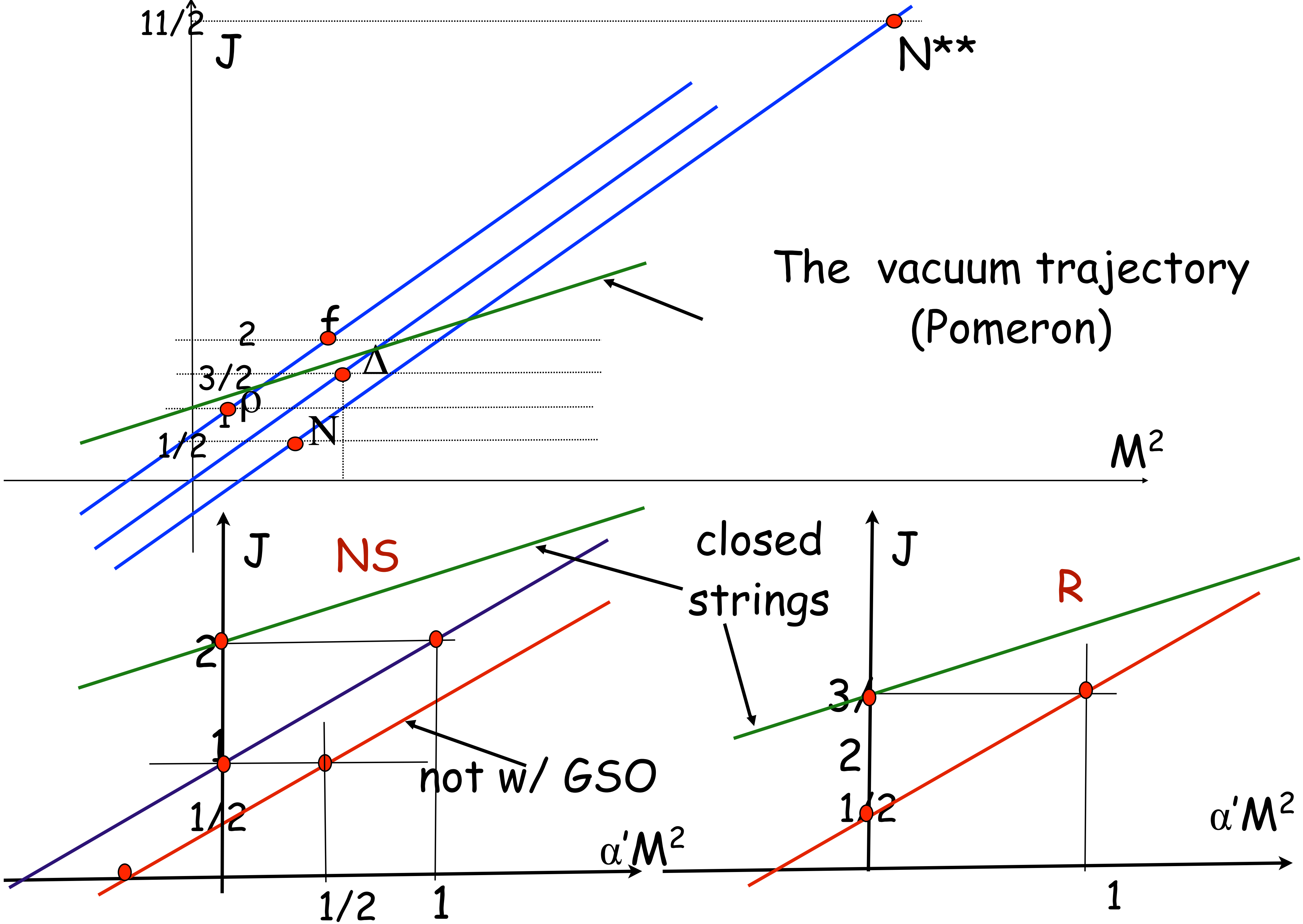

J
Fermions
3/2
1/2
α'M²
1

A beautiful theory with too many experimental shortcomings

With the addition of fermions, the construction of ghost and tachyon-free models, and its string interpretation, the DRM had become, around 1972-'73, a respectable theory.

Some qualitative features of the model were in striking agreement with experiments, in particular the linearity of the Regge trajectories with universal slope.

Yet it did not look like the real world!


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

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

1. D = 10;

2. Presence of massless particles of J up to 2.

More generally, the low-lying states were not what one wanted for hadrons (no systematic generalization of the $\pi\pi \rightarrow \pi\pi$ and $\pi\pi \rightarrow \pi\omega$ 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 brings down to D=2!);

2. Why not a Higgs-like mechanism to give masses?

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 suppressed at high energy.

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 decreasing like a power.

All evidences for point-like structures in the hadrons.

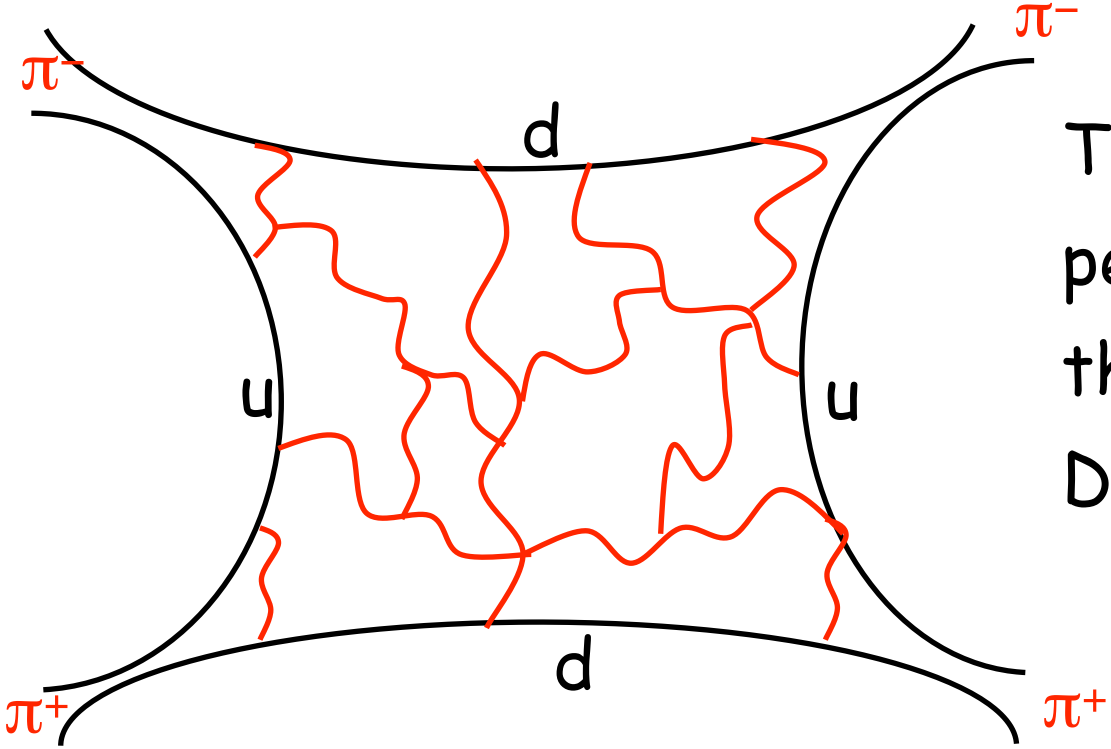
Even worse was "competition"

~ 1973 QCD came about with its

1. Ultraviolet (asymptotic) freedom that could explain those hard processes from the existence of point-like sources (quarks and gluons) 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 (a dual Meissner effect) 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 acquire a precise meaning: they correspond to planar Feynman diagrams bounded by quark propagators & filled with gluons.



This is not usual perturbation theory and has DHS duality!

Overwhelming virtues of large-N QCD

- Even if it has no dimensionful parameter to start with, QCD generates a mass scale via "dimensional transmutation" giving, for instance, the string tension $T \sim \Lambda_{QCD}^2$ (kept fixed as we vary N_c)
- It gives, at leading order in $1/N_c$, the zero-width approximation of the DRM (tree-level string theory).
- The coupling of 3 mesons is $O(N_c^{-1/2})$(i.e. $\Gamma/M=O(1/N_c)$)
- 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 naturally into place…
- Was that beautiful theoretical construction completely worthless?

The Scherk-Schwarz proposal

- 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 huge change in α', was also necessary.
- Until 1984 the proposal did not receive much attention
- People where busy working out the predictions of the newly born SM and testing it.
- Many new ideas were born (lattice gauge theory, instantontons, supersymmetry in QFT)
- Who could care less about quantum gravity?
- Things changed overnight in the summer of 1984 after a paper by M. Green and J. Schwarz…

Buone vacanze
e spero a Marzo!