The Strong Force and String Theory

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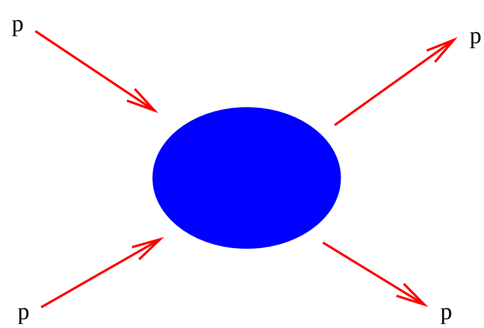
The Hadronic world, 1960-1970

The status of elementary particles and strong interactions in the sixties was very confusing: every "day" a new particle was discovered. In addition to the proton and the neutron a couple of dozens of other particles were known to exist. The list of 'elementary particles' included

$p, n, \pi, K, \Sigma, \Delta, \Omega, \eta, ...$

What is the underlying structure ?

How do these hadrons interact ? What happens when two hadrons collide ?



The S(cattering)-matrix approach was to postulate the various probability amplitudes, according to some axioms and physical assumptions.

The Birth of String theory

In 1968, G. Veneziano proposed an expression for the scattering amplitude of the process $\pi\pi \to \pi\omega$.

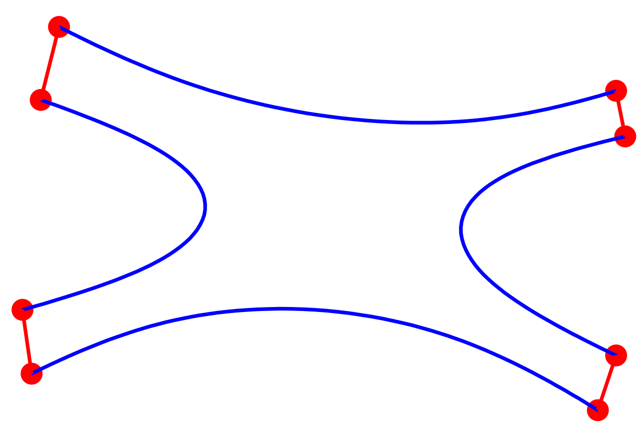
The Veneziano amplitude (s and t are 'moduli' that parametrize the kinematics of the collision)

$$A = \frac{\Gamma(1-\alpha(s))\Gamma(1-\alpha(t))}{\Gamma(2-\alpha(s)-\alpha(t))}$$

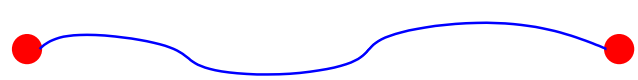
describes *successfully* the probability amplitude at low energies for the above process. Immediately afterwards it was generalized to many other processes.

'Old' String theory - The dual resonance model

In between 1968 and 1973 a lot of effort was made to understand the physics behind the Veneziano amplitude. The emerging picture was that the amplitude describes the interaction of *open strings*



Thus the 'elementary' particles are described by a vibrating open string



The success of open String theory

The mass (energy) of an open string is proportional to its length $E = \sigma L$.

As we shall see, this simple observation will be of great importance later on.

Another important feature is that a rotating open string exhibits $J = McL = \frac{M^2}{\sigma}$.

The relation $M^2 = \sigma J$ between the mass M and the angular momentum J, called 'a linear Regge trajectory' was observed in the sixties in the experiment.

'Old' String theory - Problems

For some technical reasons, namely for the self-consistency of the model, it requires 26 dimensions !

It wasn't clear how to relate the 26d (25 spatial dimensions + time) to our 4d world (x,y,z and t).

Moreover, the model contains a tachyon in its spectrum, a particle with negative mass square $m^2 = -2\sigma$.

In addition, there were spin-two massless particles in the spectrum of the model. Such hadrons were never observed in the laboratory.

Finally, the Veneziano amplitude and its generalizations did not describe accurately collisions at high energies.

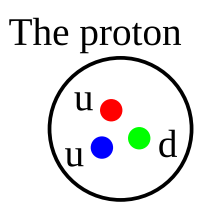
For the above reasons, and mainly due to the discovery of Quantum Chromodynamics (QCD), string theory was almost abandoned ...

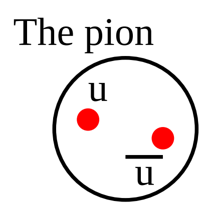
Quantum Chromodynamics (QCD)

In a parallel development, QCD emerged as the correct theory of strong interactions. The work of Gell-man, Zweig, ’t Hooft and finally Politzer, Gross and Wilczek resulted with the following picture:

Hadrons are not really fundamental particles. They are composed of *quarks*: particles with a fractional charge of $\frac{1}{3}$ and $\frac{2}{3}$.

There are two kinds of hadrons: mesons and baryons. Mesons consists of a quark and an antiquark and baryons consists of 3 quarks.





Similarly to the electromagnetic force which is mediated by the photon, the strong force (the color force) is mediated by 8 gluons.

Quantum Chromodynamics (QCD)

QCD is a *gauge field theory*, based on the gauge group $SU(3)$. The QCD Lagrangian

$$L = -\frac{1}{4g^2} F^{a\mu\nu} F^{a}_{\mu\nu} + \bar{q}^i \not{D} q^i$$

describes the kinetic motion of gluons and quarks, and their interaction.

(For the mathematicians: there are 8 gluons, since the gluon field transforms in the adjoint representation of the $SU(3)$ group. Similarly there are 3 colors of quarks since the quark field transforms in the fundamental representation of the $SU(3)$ group.)

QCD leads to an highly non-trivial and unexpected phenomenon:

Asymptotic freedom ! (Nobel prize 2004)

David J. Gross   H. David Politzer   Frank Wilczek

1973 - Asymptotic Freedom

Gross, Politzer and Wilczek showed that the QCD Lagrangian leads to a force that becomes weaker as the quarks become closer.

The charge of the strong interaction vanishes asymptotically as the distance between the quarks approaches zero

$g^2(r) = -\frac{1}{\log r}$

Similarly, as the distance between quarks increases the interaction becomes stronger.

This behavior is different (and hence counter-intuitive) than the way gravity, or electromagnetism operate: in those cases the force decreases as the distance between masses (or charges) is increased.

Confinement

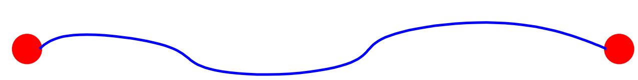
The result of Gross, Politzer and Wilczek lead to a conjecture, which is called *confinement*:

“At large distances the potential energy between a quark and an antiquark is $V = \sigma r$, hence it is impossible to separate a quark from an antiquark.”

Quarks are always confined. This is why it is impossible to isolate a quark.

Although QCD is confirmed by many experiments (and the Nobel prize committee), the confinement hypothesis was not proved yet.

It is, however, very easy to obtain a confining behavior if one assume a model where the quarks are connected by an open string ...



1973-1983

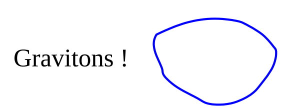
The great success of QCD as the fundamental theory of strong interactions shifted the focus from the 'dual resonance model'.

For a decade string theory was almost completely abandoned. There were few people who kept studying its properties (among them, David Olive).

In this period, however, there were two important developments:

i. The discovery of Superstrings: string models with supersymmetry, no tachyons and a critical dimension $D = 10$.

ii. Scherk and Schwarz suggested that string theory is the theory of quantum gravity: they suggested that gravitons are massless closed strings modes with spin two !



1984 - The (S-)matrix reloaded

In 1984, Green and Schwarz proved that superstring theories are a consistent framework of quantum gravity.

Suddenly $\sim 10^3$ theoretical physicists stopped whatever they were doing and started working on string theory.

Since then, string theory is considered as a candidate for a theory of quantum gravity and even as the theory of everything !!!

1998 - Maldacena's conjecture

In 1998 J. Maldacena made the following bold conjecture:

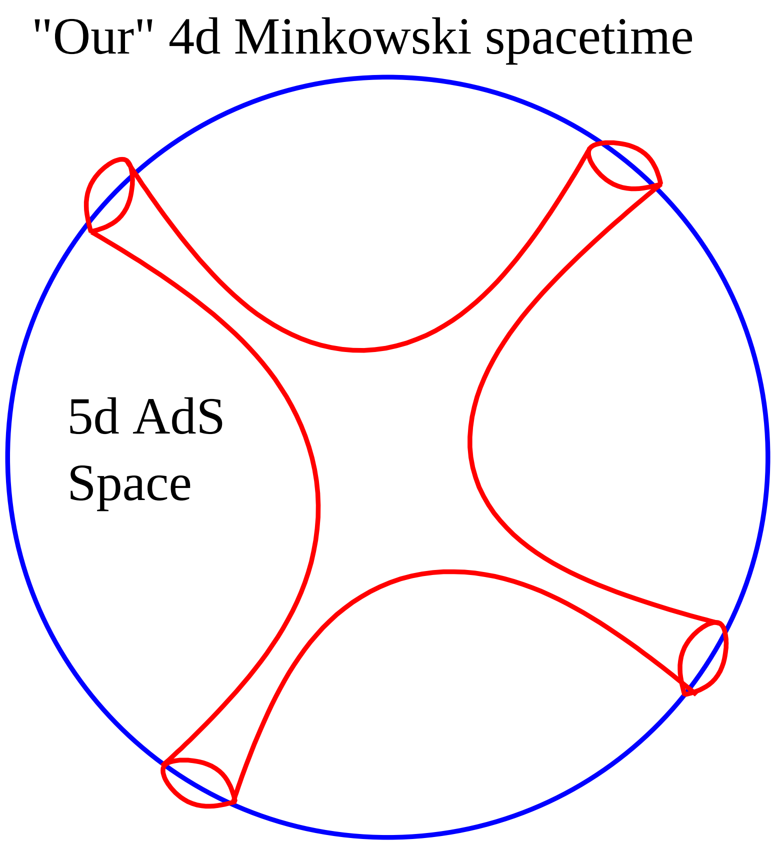
"Type IIB string theory on $AdS_5 \times S^5$, is equivalent to $3+1$d Superconformal gauge theory"

Maldacena suggested that string theories can describe gauge theories, as suggested 30 years before by Venezinao, but the description of our 4d world involves strings that propagate in a 10 dimensional curved spacetime.

How does it work ?

The answer was provided by E. Witten.

Maldacena's conjecture - The Anti de Sitter / Conformal Field theory Correspondence

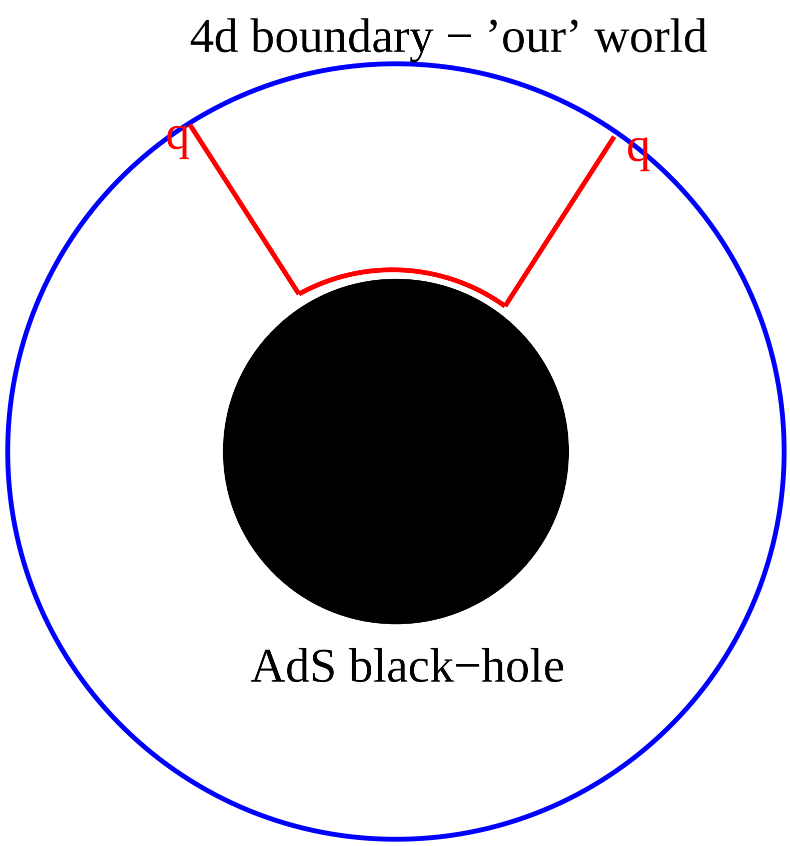


According to Witten, in order to calculate the scattering amplitude of 4 hadrons in 4d, one should consider the scattering amplitude of 4 closed strings in the bulk 5d Anti de-Sitter space.

Confinement and String Theory

Witten argued that in order to describe more realistic models of strong interactions, we need to use an 'AdS black hole' geometry.

Let's see how confinement manifests itself in this modern description



The QCD string 'enters' the fifth dimension and rests on the horizon of the black hole.

For large separation $E = \sigma L$

Summary

String theory exists for over 35 years.

It started its life as a theory of strong interactions and revived in 1984 as the 'theory of everything'.

In 1998 string theory was suggested, again, as the dual of gauge theories.

In the past 7 years we witness an amazing development in this direction.

Will we ever find the string dual of QCD ?