QCD AND HADRONIC STRINGS

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ABSTRACT

This series of lectures is devoted to a review of the connections between QCD and string theories. One reviews the phenomenological models leading to string pictures in non perturbative QCD and the string effects, related to soft gluon coherence, which arise in perturbative QCD. One tries to build a string theory which goes to QCD at the zero slope limit. A specific model, based on superstring theories is shown to agree with QCD four point amplitudes at the Born approximation and with one loop corrections. One shows how this approach can provide a theoretical framework to account for the phenomenological property of "parton-hadron duality".

I. INTRODUCTION

I.1 Historical Survey

I.1.1 Hadronic strings.

It is well known that historically, string theories emerged from strong interaction phenomenology based on Regge pole models and on current algebra inspired "finite energy sum rules". The so called duality property accounts for the fact that finite energy sum rules can be satisfied by means of a high energy component dominated by t-channel Regge pole exchanges and a low energy component dominated by s-channel resonances. In other words, this property expresses the equivalence of two descriptions of a given scattering amplitude, one in terms of t-channel exchanges (i.e. a space-like description) and one in terms of s-channel exchanges (i.e. a time-like description).

The Veneziano's ansatz[1)] is an explicit example of a two body scattering amplitude satisfying crossing symmetry, Regge pole behavior at high energy, resonance dominance at low energy and duality:

$$V(s,t)=\frac{\Gamma(-\alpha(s))\,\Gamma(-\alpha(t))}{\Gamma(-\alpha(s)-\alpha(t))} \qquad \alpha(z)=\alpha_0+\alpha' z \qquad (1)$$

The function $\alpha(z)$, $z=s,t$ is the linear Regge trajectory; α_0 is called the intercept, and α' the slope. It is easy to verify that $V(s,t)$ is Regge behaved at high energy and has resonance poles whenever $\alpha(s)$ is an integer, the residue of which are polynomials in t.

When the implications of duality were systematically studied in all possible two body reactions, it was realized that they fit very well with the quark model. Quark dual diagrams, independently proposed by Harari and Rosner[2)], exhibit precisely this correspondence between the quark model and duality. A quark dual diagram exhibits together the quark content of the interacting particles and the duality properties of the Veneziano's amplitude.

The most important property of such a diagram is that it can be interpreted as a Feynman diagram occurring in a **string** theory: it pictures the world sheet spanned by the string like interacting particles in their time evolution. A topology preserving distortion of such a diagram allows to exhibit t-channel poles, another one shows s-channel poles. This strongly suggests that duality is the reflection of a fundamental symmetry property of string theories, that is **reparametrization** invariance.

The Veneziano's ansatz was the starting point of a very wide theoretical development, including the extension to multiparticle production, the operatorial formulation and the general proof of factorization, the discovery of an exponential spectrum of states at high energy. In all recent review articles about string theories one can find extensive lists of references about these developments; I, however strongly recommend the review article which was the first published on this topics and which contains all the necessary explanations to start studying this field[3)].

I.1.2.QCD

Duality and the string model of hadrons provided a hint for the development of what became the standard model of strong interaction, namely Quantum Chromo Dynamics (QCD), the non abelian gauge theory describing the interactions of quarks and gluons. In effect the string model is the first model in which hadrons are extended structures consisting on confined quarks (the quarks are confined as the end points of open strings). However, despite many efforts, it was impossible to build a consistent string theory of hadrons (it appeared that the only consistent theories would imply the existence of tachyons or ghosts -i.e. negative norm states- or massless particles, all features prohibited in any decent theory of strong interaction). This is mainly the reason why string theories were abandoned for the description of hadrons and strong interactions. Other reasons, going in the same direction, were the discovery of QCD which rapidly appeared as an appealing unifying theory of strong interaction, and the discovery that string theories may be much more useful for other theoretical purposes related to the unification of fundamental interactions.

However, the leadership of QCD as the theory of strong interaction did not invalidate all the string inspired models of hadrons. On the contrary, although none of them is conclusive, all the non perturbative approaches about QCD naturally lead to string like hadrons. We shall rapidly review these approaches: the color dielectric constant model, the topological (or 1/N) expansion and lattice quantization.

More recently string effects were discovered in perturbative QCD, related to soft gluon coherence. We shall spend some time to discuss this very important issue.

I.1.3. The super string explosion

The shift from hadronic physics to gravity physics with strings occurred when it was realized that the lowest energy state of closed string is necessarily a massless spin 2 particle. If one takes for the slope of the Regge trajectory the inverse of the square of the Planck mass, one may hope to obtain this way a candidate for a theory of quantum gravity. And it turned out that the symmetry properties of string theories, in particular the conformal or Weyl invariance, provide actually the best theoretical framework to study quantum geometry and thus quantum gravity. On the other hand, when trying to implement fermions in the framework of string theory one discovered supersymmetry which also points towards a renormalizable theory of quantum gravity. The so called new superstring formalism[4)] which fully exploits the symmetry properties in space-time and on the world sheet of the strings allows to formulate coherent string theories candidate to unify all fundamental interactions including gravity. There was an explosion of enthusiasm when one thought that self consistency constraints (such as the constraint of absence of anomalies) would be (almost) sufficient to uniquely determine the superstring "theory of everything". These constraints not only fix the string action but they also restrict the allowed internal symmetry groups to be a few large dimensional exceptional groups containing as sub groups the symmetry groups of the current standard model, and they even determine the only possible value of space-time dimensionality to be equal to 10.

The compactification scheme of Kaluzza and Klein was revisited and, in the early eighties several people indeed believed that a unifying theory of all fundamental interactions was at hand. A comprehensive review of superstring theory is given in the beautiful book of Green, Schwartz and Witten[5] in which one can find an exhaustive list of references.

I.1.4. Current situation

Currently the enthusiasm of the beginning of superstrings has started to go down, because of the discovery that non perturbative effects in string quantization can very easily invalidate the uniqueness statements of the pioneering time. Actually, it is now believed that very large numbers of string theories can be defined in arbitrary space-time dimensionality (and thus at four dimensions) in a way which satisfies all the usual symmetry requirements[6].

Since, even in the period of enthusiasm one was already lacking very badly reliable phenomenological implications of superstring theories, the situation is becoming worse if one is also loosing the uniqueness argument. This is the reason why I think that it may be interesting to reconsider the whole approach, by starting not from the super unification challenge, but rather from concrete physical problems, lying at the frontiers of the standard model, and looking for hints to solve these problems in the framework of string theories.

I.2. The Frontiers of the Standard Model

I.2.1. Assets

The current standard model of elementary particles and fundamental interactions consists on QCD for the strong interaction and the electroweak unification for the electromagnetic and weak interactions. These theories are local gauge theories, with the groups $SU(3)_{COLOR}$ for QCD and $SU(2)_L XU(1)$ for the electroweak interaction.

Up to now there is not a single experimental fact which contradicts the standard model. We shall distinguish three major assets in this standard model.

i) *A unifying principle*: local gauge symmetry

All fundamental interactions obey local gauge invariance, the electromagnetic interaction has an abelian local gauge symmetry and the weak and strong interaction non abelian (or Yang-Mills) symmetries. Even gravity, which one does not know yet how to quantize, obeys a sort of local gauge symmetry, since in the framework of general relativity, it is defined on a Rieman space-time, the metric of which varies from point to point.

ii) *A practical criterion*: renormalizability.

All gauge theories (abelian or non abelian) are renormalizable: this means that all infinities in perturbative expansion can be removed, by means of a re-definition of a finite number of experimentally accessible parameters. This criterion is till now of a practical nature; it allows us to choose, among candidate theories the ones which have some chances to be calculable. For the moment, we do not know a renormalizable theory of quantum gravity, but this has no practical consequence since quantum effects appear in gravitation only at extremely high energies.

iii) *A symmetry breaking mechanism*: the Higgs mechanism, which allows to break the electroweak symmetry with no Goldstone massless boson and without loosing the renormalizability of the theory.

I.2.2.Shortcomings

Despite all its successes the standard model suffers some shortcomings among which we distinguish three major problems.

i) *Quark confinement*. One must recognize that the fact that the only basic fermions which participate to all fundamental interactions, namely the quarks, cannot be isolated as free particles is a very severe difficulty. It is certainly a difficulty on a practical point of view (for imagine how difficult it would have been to build QED if electrons would not have been available as free particles). It is also a theoretical difficulty: the only consistent framework to describe relativistic quantum dynamics is known to be the S matrix theoretical framework. Now this framework involves the so called *asymptotic fields* to describe free incoming and outgoing particles. Quantum field theory can be used in order to perform calculations in terms of the so called *interpolating fields* which are supposed to give asymptotically in time the asymptotic fields. The theoretical problem with quark confinement is that, in strong interaction, the interpolating fields are quark and gluon fields whereas the asymptotic fields are the hadronic fields. In other words, one does not know yet how to build a strong interaction S matrix out of QCD. In fact strong interaction, beyond perturbative QCD is very poorly understood.

Related to quark confinement, is another puzzling question: whereas non abelian gauge symmetry appears as a powerful unifying principle, one is faced with the problem that this type of symmetry is never manifest: color is confined and the electroweak symmetry is broken.

ii) *Quantum gravity*.

Even if one admits that this question has almost no practical consequences, it is quite clear that , on a conceptual basis, it puts very severe problems. What is the theoretical status of the renormalizability criterion if this criterion is not satisfied by the theory of one of the four fundamental interactions? How does quantization of gravity affect the evolution of the very primordial universe? How can one understand the mechanisms which generate the masses which distinguish the families of basic fermions? Are these mechanisms related to quantum gravity? The lack of observation of proton decay implies that the minimal Grand Unified model is not sufficient, is it not due to quantum gravity effects?

iii) *Symmetry breaking*.

The minimal Higgs mechanism, which implies the existence of a massive scalar Higgs boson, has not yet been tested experimentally. Moreover it appears that the currently available experimental data do not allow to strongly constrain the characteristics of this hypothetical particle. On a theoretical ground, the coherence of the minimal Higgs model begins to be questioned on the basis of the so called "triviality" problem[7)].

Also, in the grand unification framework one has to imagine a hierarchy of Higgs mechanisms to break the symmetries at very different scales. One does not understand how such a fine tuning can remain stable when quantum effects are taken into account.

According to a wide consensus among theorists, the way out of these problems (more specifically the ones related to quantum gravity and symmetry breaking) is to be found in either one of the two following approaches: **supersymmetry** and/or **compositeness**.

I.3. A String Based Strategy to Go Beyond the Standard Model.

I.3.1. Strings and the shortcomings of the standard model.

It is quite remarkable that string theories seem relevant in all the problems raised by the shortcomings of the standard model. Quark confinement which is a major difficulty of standard model is almost natural in the framework of string theories; all non perturbative approaches are expected to lead to confinement of quarks as the end points of open strings. Even in perturbative QCD, one discovers now string effects.

It is now widely admitted that string theory is likely to be the shortest way towards a renormalizable (possibly finite) theory of quantum gravity. Supersymmetry and supergravity which are essential in any theory of quantum gravitation fit very well in the framework of superstring theories. The absence of ultra-violet divergences which is specific of string theories is precisely the property one was looking for in order to solve the problems of quantizing general relativity.

Finally, the role of conformal invariance, the basic symmetry of string theories, in the theory of phase transitions also suggests that string quantization can be useful for the understanding of the symmetry breaking mechanisms.

It is also remarkable that superstrings put together the two properties which are expected to lead beyond the standard model, supersymmetry and compositeness.

I.3.2. A string theory of strong interaction.

In this series of lecture, I want to discuss some attempts, in the framework of the above mentioned strategy, to build a string theory of strong interaction. My deep feeling is that such theories have been abandoned too rapidly, and that, revisiting them is now possible and necessary.

I think that strong interaction is the good domain where to try such a program, because, on the phenomenological ground, strong interaction is the weakest point of the standard model. I do not mean by this statement that QCD is not a wonderful and elegant theory, but that perturbative QCD accounts for only a very small part of the strong interaction phenomenology (in contradistinction with the electroweak interaction where the standard model completely describes the available phenomenology).

On the other hand, there already exist phenomenological evidences for string effects in strong interaction physics: duality in soft interaction[illegible] fects in perturbative QCD, parton-hadron duality[8]. The exponential spectrum of states expected in string theories is closely related to the expected deconfinement transition, and one may thus hope that the string theoretical framework is well suited to study the far reaching consequences of the existence of a phase transition in strong interaction physics.

Finally, let us note that the objections against a string theory in strong interaction are no more unremovable objections. Is it argued that string theories imply the existence of massless particles (forbidden by the finite range of strong interaction)? But this objection has not prevented to try QCD which implies massless gluons! String theories imply ghosts? So does QCD (the Fadeev Popov ghosts)! Are there tachyons? Not in superstrings! What about a space-time dimensionality of 10 or 26? Some string theorists assert that there exist thousands of decent string theories in arbitrary space-time dimensions!

So let us try! At least we shall not lack phenomenological implications.[9].

II. STRINGS IN QCD

II.1. The Color Dielectric Constant.

II.1.1. Vacuum polarization

It is well known, in QED, that quantum effects are equivalent to what is called "vacuum polarization": the virtual photon exchanged between two electrons say, can materialize into electron-positron pairs which screen the interacting charges. At lowest order in perturbative QED, the photon propagator is modified by the fermion loop diagram, the effect of which is to renormalize the charge. The vacuum is a sort of a polarizable medium withe a dielectric constant which accounts for quantum screening effects: at zero distance the charge is infinite (this is the "bare" charge) and at a finite distance, the renormalized charge is finite:

$$\alpha(r)=\frac{\alpha}{1+2\alpha/3\pi Ln(rm)} \qquad (2)$$

In QED the quantum vacuum polarization is thus a screening effect which turns out to be extremely small, whereas $\alpha(h/m_ec)=1/137$, one has $\alpha(h/Mc)=1/128$ for $Mc^2=10^{15}$ Gev.

In QCD, due to gluon self coupling, quantum vacuum polarization amounts to an **anti-screening** effect: gluon loops contribute with the opposite sign with respect to quark loops, and their contributions change the sign of the effect. The anti-screening effect can be represented in terms of a vacuum color dielectric constant smaller than 1. Let κ_L the color dielectric constant of the vacuum, considered as a quantum mechanically polarized medium, contained in a box of volume L^3. If $g=g_l$ is the color charge for L=l, of order of a proton radius, and if we put $\kappa_l=1$, then the renormalized charge is defined as $g^2{}_L=g^2/\kappa_L$. Anti-screening means that $g_L>g_l$ for L>l i.e. $\kappa_L<\kappa_l$ for L>l. Calculations at order of one loop lead to:

$$\kappa_L/\kappa_l=\{1+g^2/8\pi^2(11-2N_f/N_c)Ln(L/l)+O(g^4)\}^{-1} \qquad (3)$$

where N_f is the number of flavors and N_c the number of colors. One sees that anti-screening occurs provided that $11N_c>2N_f$, i.e. that $N_f<17$, for $N_c=3$.

II.1.2. Bag and string models

A non perturbative assumption leading to permanent quark confinement consists on supposing that κ_L goes to zero when L goes to infinity, not only at leading order of perturbation but at all orders. In fact if such is the case the QCD vacuum would be a "perfect color dia-electric"[10] which would repel the color electric field in the same way as a supra-conductor, which is a perfect QED dia-magnet repels the magnetic field.

Because of this repulsion effect, color singlet systems like ($Q\bar{Q}$) mesons or (QQQ) baryons will be confined in "bags", i.e. bubbles of ordinary vacuum inside the dielectric.

Since all the color flux lines going out of a quark arrive at the anti-quark, the latter feels the whole potential proportional to the distance r, with no $1/r^2$ solid angle suppression like in ordinary electrodynamics. The bag model is compatible with string confinement: if one excites a bag by trying to separate the quark and the anti-quark one obtains a cigar shaped fireball.

The string model of hadrons has a good phenomenological support[11]. Let λ be the string tension, i.e. the coefficient of proportionality of the potential in terms of the distance. Knowing λ, we can evaluate the Regge trajectory slope, by calculating the angular momentum of a rotating string in terms of its mass: $J/m^2=\alpha'=1/2\pi\lambda\approx0.95$ Gev^{-2}. It is one of the most remarkable properties of strong interaction phenomenology that all known hadrons (mesons as well as baryons) lie on essentially linear Regge trajectories with a universal slope $\alpha'\approx0.95$ Gev^{-2} which appears as the fundamental constant of strong interaction.

The most striking example is the ρ-f_0 exchange degenerate Regge trajectory on which six materializations are known and which governs in the negative t region the high energy behavior of the π-nucleon charge exchange reaction $\pi^- p \to \pi^0 n$

II.2. Lattice Quantization.

II.2.1. General method.

The general method which has been proposed to study non perturbative QCD consists on replacing a quantum field theoretic problem by a statistical problem about a system near a critical point. The formal operation allowing to perform this replacement is the so called Wick rotation, which changes the Minkowski space-time into a euclidian four dimensional space-time, i.e. which uses a pure imaginary time. In this rotation, the exponential of i times the integral of action becomes the exponential of minus the hamiltonian, and thus the path integral functional of the field theoretic problem becomes the partition function of the statistical problem. A D dimensional field theory becomes the statistical mechanics of D+1 dimensional objects in euclidian space.

Lattice quantization consists in treating the statistical equivalent problem on a lattice with a finite lattice spacing. This discretization of space is essentially a regularization of the quantum field theory, by an ultra violet cut off Λ of the order of the inverse of the lattice spacing a. Locality of the field theory is insured by considering interactions only between near neighbors on the lattice.

The equivalent of renormalization , i.e. the removing of the ultra violet cut off, consists in considering the lattice near a critical point, that is near a second order phase transition. One knows in effect, that near a critical point, the statistical system is affected by fluctuations ranging at very different scales, from microscopic scales (of the order of a, the lattice spacing) to macroscopic scales, much larger than a. At a critical phase transition, the correlation length ξ goes to infinity as compared to a. But this feature is precisely equivalent to renormalization: a typical mass of the order of the inverse of ξ, goes to zero with respect of Λ the inverse of a.

The renormalization group approach of Wilson[12)] which consists in averaging the fluctuations of the critical system, scale after scale is completely equivalent to the Callan-Symanzik equations in the renormalized field theory. Moreover, since near a critical point renormalization group equations imply some universality properties, one may hope that some symmetric broken by lattice regularization (like Lorentz invariance) may be approximately restored.

On the whole a critical lattice may be a good model for renormalized QCD. Such a model can allow to perform some analytical calculations (in the strong coupling region, with the mean field approximation say), or to perform numerically (with Monte-Carlo programs) the average over all configurations.

II.2.2.The Wilson loop and quark confinement.

A lattice model for QCD with zero flavor can be designed by considering a SU(3) transformation U on a link between two neighboring sites. The action is written in terms of the elementary string or Wilson loop: four links bordering an elementary "plaquette". In the strong coupling region one finds that the action for a pair of a heavy quark and its anti-quark is proportional to the number of plaquettes contained in the domain bordered by the quark and anti-quark world lines. This is the "area law" according to which the potential between the two color charges is proportional to their distance, an indication of string like confinement.

The string tension λ, i.e. the coefficient of proportionality between the potential and the distance, can be evaluated by means of Monte-Carlo calculations. One finds:

$$\lambda=(220\pm60)\ \Lambda_L,$$

where Λ_L, the lattice QCD scale parameter is related to the usual QCD scale parameter Λ_{QCD} by the scaling condition near the critical point, by $\Lambda_L=\Lambda_{QCD}/83.5$. Now, λ is determined by the universal Regge slope $\alpha'=0.95\ \mathrm{Gev}^{-2}$ to be 420 Mev; which gives

Λ_{QCD}=130 + 170 Mev, in excellent agreement with the world average value for this parameter. This result is one of the most important result of non perturbative QCD: in the strong coupling region, there is confinement of quarks as the end points of strings, and the calculated string tension agrees with the value extracted from strong interaction phenomenology.

II.3. Topological (1/N) Expansion.

II.3.1. Gluon fishnet diagrams.

From the very beginning of dual models, it was expected that, if there is a local underlying field theory, one should recover dual amplitudes by summing infinite series of Feynman diagrams. With QCD, one expects to obtain quark dual diagrams by summing planar diagrams, the so called gluon fishnet diagrams. 't Hooft[13] has proposed to rearrange the perturbative expansion of QCD into a topological expansion, in which Feynman amplitudes are grouped in families characterized by the topology of the two dimensional manyfold on which the Feynman diagrams can be drawn. This expansion is indeed well suited for connecting local field theories and string theories: the two dimensional manyfold defining the topology in the local field theory is just the world sheet of the string theory. For this purpose, 't Hooft has introduced, as shown in fig; a notation which exhibits the color and flavor quantum numbers of the quanta of QCD by means of two lines for each propagator. This notation which allows to follow the quantum number flows in a given diagram plays the same role as the Chan Paton[14] factors which allow to implement internal symmetries in string theories.

The basic property of the 1/N expansion is the dominance of planar diagrams at the large N limit. Let us consider two diagrams which contain both three loops. They contribute to the same order in the QCD perturbative expansion, they have the same dependance in the momenta of the external particles. But the planar one which contains three closed color loops has a N^3 color factor, whereas the non planar one (it has the one handle topology) involves only one closed color loop, and, thus, a color factor equal to N. At the large N limit, the non planar diagram is suppressed by a factor $1/N^2$ with respect to the planar diagram.

One thus expects that, at the limit where N goes to infinity, only amplitudes corresponding to planar diagram should survive. Now the sum of these amplitudes corresponding to planar diagrams in, say, the scattering amplitudes of four mesonic sources, is precisely the so called gluon fishnet contribution. All the cuttings of a planar sum of diagrams show color singlet states, which can be interpreted as strings with flavor at the end points. The basic conjecture of the 1/N expansion approach is thus *that string confinement occurs in QCD at the limit where N goes to infinity.*

II.3.2.Topological expansion.

The topological expansion of QCD is a rearrangement of the perturbative expansion in terms of topological components, characterized by the topology of the two dimensional manyfold on which the Feynman diagrams can be drawn.The argument described above indicates that the topological expansion is also an expansion in powers of 1/N. The scattering amplitude for n external mesonic sources is written as:

$$A_n(\{p_i\})=\beta^n \Sigma_{b,h,l,w}(g^2)^{b-1}(g^2)^{2h}(g^2N_c)^{l}(g^2N_f)^{w} * \\ *B^n_{b,h,l,w}(\{p_i\}) \qquad (3)$$

where n is the number of external mesonic sources,with four momenta denoted as p_i, Nc is the number of colors, N_f the number of flavors and b, h, l, and w the topological indices defined as follows:

b is the number of **boundaries**, i.e. flavor loops to which external sources are attached.

h is the number of **handles**; h is also called the **genus**;

l is the number of closed **color loops**;

w is the number of "**wormholes**", i.e. internal flavor loops or holes in the manyfold. Such a topology is generated by an internal quark loop.

The reduced amplitude B depends on the external momenta and on the topological indices.

There are essentially two types of conjectures about the topological expansion of QCD, leading to a connection with string theories, they have been proposed by 't Hooft and by Veneziano.

i) The 't Hooft limit.

This is the large N_c limit. One assumes that N_c goes to infinity whereas g^2N_c and N_f are kept fixed.The non perturbative assumption is that the summation over l, the number of closed color loops leads to confinement of quarks as the end points of open strings. Since g^2N_c is not necessarily small, the summation over l is indeed non perturbative. The summations over b, h, and w are instead perturbative (in powers of $1/N_c$). They would correspond to the perturbative unitarization of an open string theory.

A comment is in order, at this point, about the summation over b, the number of boundaries. Since the number of boundaries can never exceed n, the number of external particles, the summation over b is always finite (for a fixed number of external particles, of course). So, the only infinite summations are the ones over h, the number of handles and w, the number of "wormholes".

ii) The Veneziano limit.

In this limit, the summation over w is also assumed to be non perturbative. Not only N_c but also N_f are assumed to go to infinity. N_c/N_f, g^2N_c, and g^2N_f are now kept fixed. In terms of string theories, in this limit, a part of the unitarization is assumed to be non perturbative: *all* internal quark loops, preserving the planar topology, are supposed to be resummed. One is thus left with only one perturbative summation, the one over h, the number of handles. Since a handle is topologically equivalent to the emission and re-absorbtion of a virtual **closed string**, one may say that only the contribution of virtual closed strings to the unitarization is treated perturbatively.

The Veneziano's limit allows to connect QCD with the Dual Topological Unitarization (DTU) scheme[15)] which was phenomenologically successful in the implementation of unitarity in the dual framework. This scheme involves three basic items.

* It is an **iterative** unitarization procedure. The discontinuity of the N^{th} iteration is computed as the shadow scattering of the $(N-1)^{th}$ one.

* Duality is implemented by using for the zeroth iteration a narrow resonance dual model à la Veneziano (which can be taken as the infinite N_c limit of QCD, if one wants to connect DTU with the topological expansion of QCD).

* At all steps of the iteration procedure, one **neglects interferences**. The first two items lead to a topological expansion. The topologies which are neglected when one neglects interferences have been shown to be recovered in higher iterations

The basic feature of DTU is that *all non linear aspects of unitarity are concentrated in the planar topology*. Higher topologies (h>0) can be calculated (once the planar topology is fixed) through *linear* equations

II.3.3.DTU at the first iteration

On a phenomenological ground, the major interest of DTU is that it leads to a qualitatively good description of high energy soft hadronic interactions already at the first iteration, and that higher iterations fit well in the framework of the eikonal approximation[16)].

Suppose one wants to compute the total cross section by means of DTU, at the first iteration. According to the fact that one considers no twist at all or the sum over all possible twists in the tree diagrams of the narrow resonance dual model of the zeroth iteration, one obtains two components in the total cross section, at the first iteration

The planar topology with b=1 involves the exchange of a non singlet Regge pole

$$\gamma_R(\alpha' s)^{\alpha_R-1}=\Sigma_n\sigma^{I}_{n};\quad \sigma^{I}_{n}=\frac{(g^2 N Ln\alpha' s)^n}{n!}(\alpha' s)^{2\alpha_0-2}\frac{1}{N} \qquad (4)$$

The cylindrical topology with b=2 involves the exchange of a singlet Pomeron

$$\gamma_P(\alpha' s)^{\alpha_P-1}=\Sigma_n\sigma^{II}_{n};\quad \sigma^{II}_{n}=\frac{(g^2 N Ln\alpha' s)^n}{n!}(\alpha' s)^{2\alpha_0-2}\frac{2^{n-1}-N}{N^2} \qquad (5)$$

After summation over n one obtains the following consistency relations:

$$\alpha_R=2\alpha_0-1+g^2N$$
$$\alpha_P=2\alpha_0-1+2g^2N \qquad (6)$$
$$\gamma_P/\gamma_R=1/2N$$

The most basic property of DTU is the so called **planar bootstrap** according to which the planar topology is stable in the iterative unitarization. This planar bootstrap implies that the output intercept α_R of the first iteration is equal to the input intercept α_0. From this condition the system of equations (6) leads to the determination of the coupling constant:

$$g^2=(1-\alpha_0)/N$$

which justifies a posteriori the topological (1/N) expansion, and also to the determination of the Pomeron intercept

$$\alpha_P=1,$$

independent of the value of the coupling constant. This last result is the major result of DTU; at the first iteration this scheme is able to provide a good model for high energy total cross sections since it implies a Pomeron with intercept equal to one. Moreover, the last equation of system (6) implies, since the residue of the Pomeron is much smaller than that of the planar Regge pole, a weakly coupled Pomeron, in good agreement with phenomenological observation.

II.3.4.Higher topologies

The contribution of higher topologies can be computed in DTU by means of a perturbative expansion (it is an expansion in powers of $1/N^2$). Since each handle corresponds to a virtual Pomeron, this expansion corresponds to absorptive corrections through multiple Pomeron exchanges.

The techniques of cutting rules[17)] and eikonal approximation[18)] can be used to evaluate the higher topology contributions, leading to efficient phenomenological models[19)].

As far as string theories are concerned, we note that whereas planar bootstrap is related to non perturbative unitarization of open strings, higher topologies correspond to a perturbative unitarization of closed strings.

II.4. String Effects in Perturbative QCD.

II.4.1.The Lundt string effect

The Lundt group which uses string fragmentation as a model for hadronization, was the first to remark a string effect in the framework of hard multiple particle rections[11)] .The three jet events in e^+e^- annihilation into hadrons are interpreted, in the framework of perturbative QCD, as due to the hadronization of a quark, anti-quark gluon system. The string model suggests that hadrons are produced in the fragmentation of two strings, one connecting the quark and the gluon and one connecting the anti-quark and the gluon. This model suggests that there should exist a relative de-population of hadrons between the quark and the anti-quark.

An analysis of the Jade[20)] data allows to compare the predictions of the Lundt Monte Carlo simulation (which involves a string effect) with those of the independent hadronization model which implies no such effects. The agreement with data is much better for the Lundt model than for independent hadronization model.

II.4.2.Soft gluon interferences.

Afterwards a very important connection was found between string effects and soft gluon interferences discovered by A. Mueller[21)], in 1983.

This author found a mistake in the use of the leading logarithm approximation (LLA) in perturbative QCD. In a time like gluon cascade, there is a kinematical region in which soft gluon emission amplitudes *may interfere destructively*. This effect has a QED analogue. Consider the emission of a photon by an electron-positron pair. If the angle of emission of the photon is larger than the opening angle of the fermion pair, there are destructive interferences between the amplitudes of emission of the photon by the electron and by the positron. At large angle, the photon is actually emitted coherently by the pair.

In QCD, one can take this effect into account by *ordering the angles* of emission of the gluons. This leads to the so called modified leading logarithm approximation (MLLA). This modification has a strong effect on the spectra of produced particles. In fact it affects the x domain. In the ordinary LLA, the x domain is limited by kinematics to be larger than Q_0^2/Q^2, where Q_0 is the infrared cut off. In the MLLA, x is now limited to be larger than Q_0/Q. Since it is the small x region which provides the highest multiplicity of produced particles, the effect of soft gluon coherence is to **reduce the multiplicity**. More specifically, its effect is to change the predicted multiplicity from $\exp(\sqrt{(A Ln(Q^2/Q_0^2))})$ to $\exp(\sqrt{(A 1/2 Ln(Q^2/Q_0^2))})$, where A is a well known QCD constant.

The effect of soft gluon coherence is also to modify the spectrum of the produced gluons, which is expected now to show a dip at small rapidity. When this effect was discovered, it was thought that it was rather academic, because it concerns in principle only gluons and not hadrons. It was expected that hadronization was likely to obscure the effect: each parton should, through hadronization, lead to softer hadrons which will fill the expected dip in the rapidity distribution. Surprisingly, dips in the rapidity distribution of hadrons produced in e^+e^- annihilation, have been observed. Moreover, it has been shown that if the MLLA is used with an infrared cut off Q_0 as small as Λ_{QCD}, the predicted **parton** distribution agrees with the observed **hadron** distribution. The authors of this observation have called *local parton-hadron duality* this intriguing property according to which hadrons and partons have essentially the same distributions[8)].

II.4.3.Soft gluon interference and string effect.

In fact, the Leningrad group has discovered a deep connection between soft gluon coherence, parton-hadron duality and string effects.[22)]. Indeed, at the parton level, soft gluon coherence provides a perturbative QCD explanation of the Lundt string effect. As shown in details in ref[23)], interferences occur between the amplitudes of emission of gluons by the same color flux line; interfering soft gluons can be considered as resulting from a string fragmentation. If parton-hadron duality holds, then the string effect will show up at the hadron level, as a consequence of soft gluon coherence. The authors of ref[26)] have systematically studied the connection between soft gluon coherence and string effects. They have first generalized the angle ordering technique to space like cascades. Some how, the cascade has to be studied backward in time and the angles have to decrease from the hard vertex to the partons which are almost colinear with the incoming partons.

Marchesini and Weber have then shown that there are string effects in hard parton-

parton collisions (which should show up at the hadron level if parton-hadron duality holds).

In my opinion, the observation of the dominance of planar structures in perturbative QCD shows that there is a deep connection between QCD and string theories. Actually, this connection is well exhibited if one takes seriously the 't Hooft notation to represent quark and gluon propagators with two lines, and if one considers these propagators as *string* propagators. For instance, a duality transformation can change a space-like cascade into a time-like cascade. The backward angle ordering in the space-like case is then transformed into the ordinary ordering of the time-like case. One can also hope indeed that parton-hadron duality can receive an explanation in the framework of string theories.

III. SUPERSTRING REGULARIZATION OF QCD

III.1. String Quantization vs Lattice Quantization.

According to the strategy which was explained in the introduction, we need not only to find string effects in QCD, but also recover QCD in the framework of string theories. From the very beginning of duality and string theories, it was realized that the α' going to zero limit of a string theory is a point like field theory[24]. According to the way how this limit is taken, and according to the specific string theory one starts with, one can obtain various point like field theories: ϕ^3 and ϕ^4 field theories, Yang Mills and spontaneously broken Yang Mills theories, say. If one wants to build a string theory, the α' going to zero limit of which is QCD, we know already that this string theory has to involve fermionic strings as well as bosonic strings. This feature at once is a hint to look for such a string model in the framework of superstring theory.

But, before trying to build a specific string model giving QCD at the α' going to zero limit, we have to understand the possible physical significance of such a limit. Our idea is compare such an approach with the standard lattice quantization approach. As we said above, lattice quantization is essentially a regularization/renormalization scheme. Discretizing space-time corresponds to the regularization of the local field theory and considering the lattice in a critical situation in which fluctuations occur at all scales corresponds to the renormalization. Let us stress that this scheme obeys the same philosophy as all other schemes like Pauli Vilars regularization or dimensional regularization, in the sense that regularization breaks some symmetries which are more or less restored by renormalization. The interesting property of lattice regularization is that, whereas it badly violates Lorentz invariance, it preserves gauge invariance.

We propose here to *completely inverse this philosophy*, that is to look for a regularization scheme which would **add symmetries** to the original problem, symmetries which would be **broken by renormalization**. Now string theories have this extremely interesting property that **the more symmetric they are, the more ultra-violet regular they are**. We are thus going to try a "string regularization" of QCD, namely we want to build a string theory satisfying the following requirements:

i) to involve bosonic and fermionic strings,

ii) to have massless vectors and massless spinors as ground states,

iii) to be ultraviolet regular,

iv) to have color as a global symmetry, in such a way that the α' going to zero limit has color as a local symmetry,

v) to give, at the tree approximation, QCD at the limit in which α' goes to zero.

Such a theory exists, it is a superstring theory, at 10 space-time dimensions, with space-time and world sheet supersymmetries, with full reparametrization and conformal invariances. Such a theory has indeed many more symmetries than QCD, and it is much more ultra violet regular. To perform renormalization, we have to send α' to zero, to compactify from 10 to 4 dimensions and to break some of the additional symmetries. When one does all these operations one obtains a four dimensional string theory, with a finite and "running" α' showing all the expected properties of renormalized QCD, including of course the string effects. This is what we are going to describe in the remaining lectures.

III.2. Why Superstrings?

III.2.1. Factorization.

The so called new formalism[25] of superstring allows to derive some properties of superstrings which are very useful for our purpose. The first one is the factorization of the amplitudes in the tree approximation as the product of a kinematical factor involving the wave functions of the external particles by an invariant amplitude involving all the string dynamical properties. For instance, the four point amplitude in the tree approximation is written as

$$A_{Tree}=K(1,2,3,4)\ A_{inv}(\alpha',s,t) \qquad (7)$$

where the kinematical factor K does not depends on the Regge slope α' whereas the invariant amplitude A_{inv} contains all the dependence on α'.

The second crucial property is that the **same kinematical factor** is factorized in the planar one loop amplitude. In the case of the four point amplitude we have:

$$A_{Loop}=K(1,2,3,4)\int Loop\ inv\ amplitude \quad (8)$$

III.2.2.Slope renormalization.

The third property which is of interest for our purpose is that the most divergent part of the one loop planar amplitude can be expressed in terms of the derivative with respect of α' of th tree amplitude. One finds, for the four point amplitude:

$$A_{DIV}=const.g^2/\alpha'^2\partial/\partial\alpha'\ A_{Tree} \quad (9)$$

A few comments are in order about these properties.

i) They all have been proved for four point amplitudes. Calculations to check them in more complicated cases are tedious. We are currently doing the calculations for five point amplitudes. The properties are likely to hold also in this case.

ii) Because of traces identities, two point and three point planar loop amplitudes vanish.

iii) In equation (9), the coefficient of proportionality between A_{DIV} and the derivative with respect to α' of A_{Tree} is equal to g^2/α'^2 only **in ten space-time dimensions**. In such a case, in effect, the dimensionality of the coupling constant g is L^3, the coefficient α'^2 in the denominator allows to recover an L^2 factor in order that A_{Loop} and A_{Tree} have the same dimensionality (we remind that α' has a dimensionality equal to L^2, in all space-time dimensions). After compactification at four space-time dimensions, where g is dimensionless, eq. (9) would become:

$$A_{DIV}= const.g^2\alpha'\partial/\partial\alpha'\ A_{Tree} \quad (10)$$

III.3. The Four Point Amplitudes at the Born Approximation.

III.3.1.The spin wave functions

Thanks to the factorization property, it is possible to break the additional symmetries and to compactify from ten to four space-time dimensions in the kinematical factor. This means that, in order to recover QCD out of our superstring theory we have just to define the gluon polarization vectors, quark spinors and gamma matrices which enter in the kinematical factor, in the usual four dimensional space-time. We have explicitly verified that we obtain by this procedure, the QCD four point amplitudes if in the invariant amplitude we let α' go to zero. All four point amplitudes are written in the following generic form:

$$A(1,2,3,4)=1/2g^2\frac{\Gamma(1-\alpha's)\Gamma(1-\alpha't)}{s\,t\,\Gamma(1-\alpha's-\alpha't)}K(1,2,3,4) \quad (11)$$

where $s=(k_1+k_2)^2$, $t=(k_1-k_3)^2$ and where only the kinematical factor K depends on the external particles'. If ζ_i are the gluons polarization vectors, u_i and v_i the quark and anti-quark spinors and γ the gamma matrices, we obtain,

for the $gg \to gg$ reaction

$$K(\zeta_1,k_1;\zeta_2,k_2;\zeta_3,k_3;\zeta_4,k_4)=(st\zeta_1.\zeta_3\,\zeta_2.\zeta_4+su\zeta_2.\zeta_3\,\zeta_1.\zeta_4+tu\zeta_1.\zeta_2\,\zeta_3.\zeta_4)+$$
$$+2s\{((\zeta_1.k_4\,\zeta_3.k_2\,\zeta_2.\zeta_4+(1\leftrightarrow 2))+(3\leftrightarrow 4)\}+$$
$$+2t\{((\zeta_1.k_3\,\zeta_2.k_4\,\zeta_3.\zeta_4+(1\leftrightarrow 4))+(2\leftrightarrow 3\}+$$
$$+2u\{((\zeta_1.k_4\,\zeta_2.k_3\,\zeta_3.\zeta_4+(1\leftrightarrow 3))+(2\leftrightarrow 4)\} \qquad (12)$$

for the $qg \to gq$ reaction

$$K(u_1,\zeta_2,\zeta_3,u_4)=2t\bar{u}_1\gamma.\zeta_2\,\gamma.(k_3+k_4)\,\gamma.\zeta_3\,u_4-$$
$$-4s(\bar{u}_1\,\gamma.\zeta_3\,u_4\,k_3.\zeta_2-\bar{u}_1\gamma.\zeta_2\,u_4\,k_2.\zeta_3-\bar{u}_1\gamma.k_3\,u_4\,\zeta_2.\zeta_3), \qquad (13)$$

for the $qg \leftrightarrow qg$ reaction

$$K(u_1,\zeta_2,u_3,\zeta_4)=2t\bar{u}_1\gamma.\zeta_2\,\gamma.(k_3+k_4)\,\gamma.\zeta_4u_3+2s\bar{u}_1\gamma.\zeta_4\gamma.(k_2+k_3)\,\gamma.\zeta_2u_3 \qquad (14)$$

and for the $q\bar{q} \leftrightarrow \bar{q}q$ reaction

$$K(u_1,v_2,v_3,u_4)=-2s\bar{v}_2\gamma^{\mu}v_3\,\bar{u}_4\gamma_{\mu}u_1+2t\bar{v}_2\gamma^{\mu}u_1\,\bar{u}_4\gamma_{\mu}v_3. \qquad (15)$$

III.3.2.The Chan-Paton factors.

As we already said, the Chan-Paton[14)] factors allow to take into account quantum numbers in the framework of string theories. These factors consist on traces of product of operators of the adjoint representation of the symmetry group written in the fundamental representation of the group. If, for the group one takes U(N), instead of SU(N), the matrices which represent the operators of the adjoint representation are very simple in the fundamental representation: they have only one non zero matrix element equal to 1. So, in the U(N) case, the Chan-Paton factors reduce to Kronecker delta symbols corresponding to the quantum number flows of a duality diagram. Taking the trace is equivalent to count the number of possible duality diagrams. This is the reason why the 't Hooft notation for gluon propagators exhibits the connection between QCD and string dynamics. If N is assumed to be large, the difference between SU(N) and U(N) is of order $1/N^2$, in the general case, and exactly vanishes in the case of pure gluonic amplitudes.

We have thus used the Chan-Paton factor technique for U(N) QCD. The problem is that this technique is known to work only in the case in which external particles belong to the adjoint representation of the group. So it has to be generalized to QCD with quarks.

We have done such a generalization. Consider the group $U(N_c+N_f)$. The operators of the adjoint representation of this group, can be, in the fundamental representation , written in terms of block matrices, which have obvious definitions. Let us use Greek indices for colors and Latin indices for flavors, lower indices for quantum numbers and upper indices for anti-quantum numbers. We have the following straightforward equations:

$$(G_\alpha{}^\beta)_{\alpha'}{}^{\beta'} = \delta_{\alpha\alpha'}\delta_{\beta\beta'}$$
$$(Q_\alpha{}^b)_{\alpha'}{}^{b'} = \delta_{\alpha\alpha'}\delta_{bb'} \qquad (16)$$

which read in the following way: the matrix element labeled by color α' and anti-color β' of the gluon matrix of color α and anti-color β is equal to $\delta_{\alpha\alpha'}\,\delta_{\beta\beta'}$ and the matrix element labeled by color $\alpha'$and anti-flavor b' of the quark matrix of color α and anti-flavor b is equal to $\delta_{\alpha\alpha'}\,\delta_{bb'}$. In order to have simply oriented quark dual diagrams we call anti-flavor the flavor of a quark and flavor the flavor of an anti-quark.

We have verified that with this method, we obtain exactly all the four point amplitudes of QCD at lowest order, by taking the α' going to zero limit of the string theory with the Chan-Paton factors defined in equation (16). For instance the Chan-Paton factor for the $qg\rightarrow qg$ reaction is

$$Tr(Q_\alpha{}^a G_\beta{}^\alpha G_\gamma{}^\beta Q^\gamma{}_a) \qquad (17)$$

We have verified that the amplitudes vanish if one replaces any of the ζ_i by k_i, which expresses gauge invariance.

III.4. Loop Corrections to the Four Point Amplitudes.

III.4.1.Next order in α'.

One of the major interests of superstring theories is that loop integral can be very easily computed. Provided that one is at the critical dimension, planar loop diagrams vanish for amplitudes with less than four external particles (this is due to trace identities satisfied by fermionic operators), and the most divergent part of the one planar loop amplitude, for four external particles is just the derivative with respect to α' of the tree diagram amplitude (see equation 9). This suggests that when taking the α' going to zero limit , the corrections of order α' are related to one loop corrections to the Born approximation.

Let us consider the four point amplitude, in the superstring formalism, at 10 dimensions, with exact supersymmetry and with α' different from zero, and without the Chan-Paton factors. The tree diagram amplitude is written as

$$A^{10}{}_{Tree} = (g^2)^{(10)} K(1,2,3,4) A^{inv}{}_{tree}(\alpha', s, t) \qquad (18)$$

where we recall that $(g^2)^{(10)}$ has the dimension L^6, and that the whole dependance on α' is concentrated in the invariant amplitude. Let us compute the planar loop amplitude, *before breaking supersymmetry and before going to 4 dimensions*. We know, from equation (9), that the divergent part of the one loop amplitude is proportional to the tree amplitude.

Then we perform *renormalization*.. This means that:

i) we compactify from ten to four dimensions

ii) we break supersymmetry

iii) we implement color symmetry by means of the Chan-Paton factors

iv) we let α' go to zero, more precisely we set $\alpha'=1/Q^2$, where Q is a large energy scale.

As we already said, we obtain, this way, from the tree amplitudes, the QCD four point amplitudes, at the Born approximation, at order $1/Q^2$. It is then very interesting to evaluate the effects of the one loop corrections. Let us first remember that $(g^2)^{(4)}$ is dimensionless, in such a way that the coefficient of proportionality between A_{DIV} and A_{Tree} is $g^2\alpha'$ at four dimensions instead of g^2/α'^2 at ten dimensions. Then we have to take into account the effects of renormalization, at the one loop level on g^2: in superstring theory this is related to the difficult problem of compactification. But, fortunately, we know, from perturbative QCD how to renormalize, at the one loop level, the coupling constant. We thus can write:

$$A^{(4)}_{Loop}=(g^2)^{(4)}_{renor}/Q^2\partial/\partial\alpha'(A_{Tree}^{(4)})\,|_{\alpha'=0} \qquad (19)$$

III.4.2.A color superstring model.

It is extremely interesting that equation (19) is the beginning of a Taylor expansion in (g^2/Q^2), a small parameter, and this is true only at four dimensions , and certainly not at ten dimensions. We can now straightforwardly write a superstring four point tree amplitude, at four dimensions, with a finite α', which coincides, at the leading logarithm approximation with QCD, perturbatively renormalized at the one loop level:

$$A_{SST}^{(4)}=\alpha_S(Q^2)\ CP\ K(1,2,3,4)\ 1/st\ \Gamma(1-\alpha'_{REN}s)\Gamma(1-\alpha'_{REN}t)/\Gamma(1-\alpha'_{REN}(s+t)) \quad (20)$$

where $\alpha_S(Q^2)$ is the usual logarithmically decreasing running QCD coupling constant, and where $\alpha'_{REN}=\alpha_S(Q^2)/Q^2$.Th Chan-Paton factors and the kinematical factor are the ones which occur in the Born approximation.

The most interesting property of this model is that it takes into account the string effects which are equivalent to soft gluon coherence.

IV. PARTON-HADRON DUALITY.

IV.1. Infrared Problems.

The color superstring model which we have derived takes into account the string effects which are present in perturbative QCD. It is indeed very tempting to push this model towards lower values of Q^2 for which non perturbative effects, related to infrared singularities become important.

For the moment, our model amplitude is manifestly infrared singular: eq. (20) shows poles at s=0 and t=0. However this problem is just the one which is encountered in any application of perturbative QCD. Such problems are usually dealt with by means of infrared cutoffs treated as parameters. We can apply the same method with our amplitude, by giving a mass to the gluons and to the quarks. Of course, we can do that **in the amplitude** in such a way that we do not meet the inconsistency problems of string theories with intercept different from 1. In fact, when one gives a mass to the gluons and to the quarks, one has to shift the intercept of the Regge trajectory away from 1, but this can be done in the amplitudes written at four space-time dimensions, for which ultra violet problems have been already solved.

Typical informations on non perturbative QCD which one can obtain from our approach would be some hints about the actual value of the mass to give to the gluons and to the quarks. One can also try and consider the model amplitude of eq. (20) with α'_{REN} of order of the hadronic slope, and apply the techniques of DTU in this domain. But before doing this we want to show that our approach can provide a theoretical framework to account for the phenomenological property of parton-hadron duality.

IV.2. Flavor Superstrings.

The $qq \to qq$ amplitude written in eq.(15) is very easily understandable in terms of QCD: the first term of the right hand side corresponds to the t-channel gluon pole and the second term to the s-channel gluon pole. But we see that the term which has the gluon pole in one channel has not the gluon pole in the crossed channel. With the Chan-Paton factors which we use, when there is the gluon pole in one channel, the crossed channel is colorless and has the quantum numbers of the adjoint representation of $U(N_f)$. So the pole which is dual to the gluon pole in one channel is a "mesonic" state lying on the first daughter trajectory, i.e. with a mass squared equal to $1/\alpha'$. We thought that such a state could be the intermediate vector boson. But such a state has to couple to the quark anti-quark current with the same coupling constant as the gluon. So if such a state is identified to a gauge boson, it is only at the grand unification scale that it can be done. If one then considers regularized QCD as a "bare" string theory, then α'_{bare} is of order of $1/M^2_{GUT}$ i.e. 10^{-30} Gev^{-2}.

It thus appears that if one wants to gauge the color group, one has to send the pole dual to the gluon at large mass. From this remark we see that it could have been possible to gauge instead the flavor group, by using another set of Chan-Paton factors involving the quark matrices and "mesonic" (or flavor changing) matrices:

$$(M^{a}{}_{b})^{a'}{}_{b'}=\delta_{aa'}\delta_{bb'} \qquad (21)$$

We thus see that there is another possible set of superstring amplitudes equivalent to a renormalized gauge theory which one can derive from our approach; we call them "flavor superstring amplitudes" because it is now flavor which is gauged.

The equivalence of color superstrings and flavor superstrings could provide an explanation to parton-hadron duality. Consider e^+e^- annihilation into hadrons in a QCD model taking into account soft gluon coherence. According to the standard calculations one uses a two stage process: firstly a partonic cascade governed by perturbative QCD, involving, because of soft gluon coherence only color planar configurations, and secondly, once the virtualness of the partons has reached the infrared cutoff, a hadronization stage (which may be decomposed into sub processes like the annihilation of gluons into quark-antiquark pairs, the formation of color singlet clusters, and the decay of these clusters). It is very reasonable to keep in all the hadronization subprocesses the planarity of the flavor and color topologies. Actually it is only if one keeps this planarity, that the consequences of soft gluon coherence show up at the hadron level. So, if one arrives to the final hadrons with only planar configurations, one sees that the hadronic distribution can be described in terms of a cascade, completely analogous to the QCD cascade but with flavor replacing color. Flavor superstrings amplitudes describe the cascade of "running hadrons" into which the colored partons can hadronize at any scale. We thus see that our scheme can account for both local (i.e. at all scales) and exclusive[26)] (i.e. in terms of amplitudes) parton-hadron duality.

IV.3. Towards Hadronic Superstrings.

The fact that our approach seems to be compatible with parton-hadron duality suggests a possible scenario to include non perturbative renormalization. Let us recall our main motivation to use superstring techniques in QCD physics: a superstring theory at the critical dimension provides a regularization of QCD, and all the perturbative renormalization of ultra violet divergences is taken into account through coupling constant and slope renormalization. One is left with infrared problems, but these do not invalidate the theory, on the contrary they are an indication that there is an ambiguity in choosing the vacuum, or, in other words that there is a phase transition. Parton-hadron duality is nothing but the coexistence, at all scales which are smaller than a typical hadronic size, of a partonic and a hadronic phases, i.e. the degeneracy of a partonic vacuum and a hadronic vacuum.

When Q^2 goes down to about 1 Gev^2 or below, all the usual non perturbative models based on color screening or on 1/N expansion are expected to work in our approach. Actually, our approach is particularly well suited, since precisely the 1/N expansion had been proposed to connect gauge theories with dual models. We thus expect our approach to provide a scheme like DTU with a more solid theoretical ground.

V. CONCLUSIONS.

We hope to have been able to show that there are real bridges between QCD and string theories. For establishing such bridges the key discovery has been the discovery of string effects in perturbative QCD, in connection with soft gluon coherence. As long as string models were relevant only in the non perturbative domain of QCD, all such models were lacking firm calculational grounds. Now that we have superstring amplitudes coinciding with perturbative QCD at the leading logarithm approximation, and satisfying gauge invariance and soft gluon coherence, we can use these amplitudes as a calculational tool to approach the non perturbative domain.

With respect to the understanding of gauge theories, we want to stress that our approach corresponds to a new way of thinking renormalization. Instead of a regularization which breaks symmetries and a renormalization which hopefully restores them, we propose a regularization which adds symmetries to the initial problem and a renormalization which breaks some of the additional symmetries and may leave some extra unexpected symmetries. Superstrings are well suited for such an approach, since their ultra violet regularness is a consequence of their huge amount of symmetries (conformal invariance, supersymmetry on the world sheet, space-time supersymmetry). Renormalization is, in our scheme equivalent to compactification and to symmetry breaking. But after renormalization, our amplitudes have a new symmetry property, duality, which shows up in soft gluon coherence and maybe in parton-hadron duality.

With respect to superstrings what we propose is a change in attitude. We propose to adopt somehow the same attitude as technology with respect to fundamental research. We think that it is misleading to look for phenomenological **implications** of superstrings; we think possible to find instead phenomenological **spin-offs** from them. We think to have found one.

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