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Abstract

I give the main ideas and an overview of the literature published in connection with my lectures presented at the Ecole International Joliot Curie 1998 about "Matiere Hadronique".

1 The Theory of the Stochastic Vacuum

Color forces are spin dependent and are a function of the color representations. From meson spectroscopy we know that quark antiquark forces in a color singlet state are more attractive in the $S = 0$ state than in the $S = 1$ state, the pion is much lighter than the ρ meson. Similarily the gluon-gluon interaction is very attractive in the $S = 0$ channel, the lowest glueball state is calculated to be a $J = 0$ glueball. Due to these strong gluon-gluon forces it is possible that the vacuum is a gluon condensed state. Starting from the idea of the gluon condensate Dosch and Simonov [1] developed the concept of a nonlocal gluon field strength correlator. Since the total vacuum is color neutral, the color orientation of the gluons must be random, globally. Only in small domains it is possible to have color aligned gluon configurations. The size of these domains is related to the size of the lowest glueball state and is much smaller than the size of light hadrons. One estimates the correlation length to be about 0.3 fm. The correlators contain two different tensor structures, one can be called a genuine nonabelian correlator, whereas the other one could also arise in abelian field theories. This can be easily seen, if one looks at the electric field- electric field correlation functions for different directions of the electric field. The abelian correlator vanishes when one takes the divergence of the electric field in accordance with abelian field equations in the absence of charges in vacuum. The nonabelian correlator exhibits gluon charges in the vacuum.

A review about this so called Stochastic Vacuum Model can be found in [2], e.g. there it is also explained how it leads to confinement. For the derivation of confinement based on the assumed form of the correlation functions it is very important to have the cumulant expansion of the Wilson loop operator. I recall the Wilson loop associate with a heavy quark system is the exponential phase acquired by a massive quark antiquark propagating along the imaginary time axis in the external gluon fields. At final and initial time the opposite color charges are also connected by these phase factors making altogether a closed loop. The color traces of these exponentials i.e.these Wilson loop operators play an important role in QCD since they are gauge invariant operators. They are directly related to physical quantities like the quark antiquark potential energy. Stochastic vacuum means that the correlators with many gluon fields factor like for a Gaussian distribution. This is an important assumption of the model, which still has to tested in numerical simulations.

Lattice studies identifying the correlation length have been made by the Pisa group [3, 5]. Recent work on a "derivation " of the stochastic vacuum correlators from renormalization group flow equations has been made by Ellwanger [6]. He introduces in the ultraviolett, i.e. at short distances auxiliary fields, for which he assumes a form of the effective low energy action. By analytical calculation he then computes the evolution of the coupling constants of this effective action to the infrared. The effective action for the long distances looks a free dual QCD, i.e the effective coupling is small (!) and the correlation length of the stochastic vacuum is a result of the evolution.

In ref. [4] a derivation of the near light cone Hamiltonian in QCD has been made, which contains zero mode fields, not obtained from a simple transcription of the Euclidean correlators to Minkowski space. These zero mode live in (2+1) dimensions. I think they play an important role in high energy reactions where the colliding hadrons have shrunk to thin pancakes and all the nonperturbative dynamics is in transverse space. Research along these lines is in progress.

2 High Energy Electromagnetic Interactions

The Model of the Stochastic Vacuum allows to connect confinement with high energy diffractive scattering. Its application to high energy hadronic reactions has been first made by Dosch, Ferreira and Krämer in [7]. The first application to electromagnetic reactions is done in ref. [8] with G. Kulzinger and T. Gousset, where the photo- and electroproduction of vector mesons is calculated. The proton structure function in the sea quark region, more exactly the singlet sea quark structure function F_2 is calculated in ref. [9]. The underlying idea of all these high energy reactions is to approximate the projectile and target by two color dipoles. Obviously they are color neutral, assuming a simple valence quark substructure a dipole is the simplest. So also for the nucleon we take a dipole of diquark and a quark. Since the interaction energy of a dipole with an external field is proportional to the size of the dipole, we get cross sections which depend on the sizes of the scattering partners. It presented a real break through in nonperturbative high energy scattering to understand the ratio of πN to NN cross section from the ratio of the size of the pion to the nucleon. In electromagnetic interactions one has the additional advantage that the photon represents a quark antiquark dipole of varying size. By changing the virtuality (the fourvector squared) of the photon one roughly adjusts the size of the dipole in the photon to the inverse virtualty. This physics is the phenomenon of color transparency. The derivation of the photon quark antiquark wave function is done in light cone perturbation theory, where the energy denominators are formed from differences of light cone energies (energy - momentum in z-direction). A problem with this picture is that the high virtualty electroproduction cannot be connected to real photoproduction. With decreasing virtualty the quark antiquark dipole becomes more and more wider until confinement and chiral symmetry limits its size. Perturbation theory breaks down.

Here the importance of a running quark mass and its derivation from quark hadron duality has been introduced by the above authors. Quark hadron duality is based on the equivalence of the quark language and the hadronic language to understand strong interaction phenomena. These two languages are dual to each other. (This duality is different from the notion used before.) E.g. the measured electron positron cross section into hadrons can be explained either in terms of hadronic resonances like the ρ, ρ' etc. or in terms of quarks. Above a certain threshold the two descriptions become identical. Also in the low energy domain the quark description captures the average features of the data quite well. We constructed a quark mass operator which is a function of virtualty, such that a free quark description is in optimal agreement with the data in the Euclidean region (i.e. for electron +positron momentum squared negativ). In a very natural way we obtain a constituent quark mass at low resolution. The ρ meson is a good bound state of two constituent quarks. At high resolution our mass approaches the current quark mass. ALl effects of chiral symmetry breaking are stripped from the quark, it becomes more and more naked, the stronger the microscope becomes with which we look at it. Data at fixed W and varying photon virtualty may make it possible to see such an effect. Note there is some ressemblance of this physics at high resolution with the physics at high baryon density and/or high temperature searched for in high energy heavy ion collisions, a subject which has been extensively discussed in other contributions to this school. The electromagnetic probe has the advantage that it prepares a well defined state, the quark antiquark dipole the size of which at low virtualty depends on the running quark mass.

The photo- and electroproduction of excited ρ' states has been calculated in ref. [11], where the two ρ' and ρ'' states are identified as a mixture of $\bar{q}q$ and hybrid $\bar{q}qg$ states. In this work the long range part of the color dipole proton cross section is tested best, because of the large size of the excited vector mesons. The stochastic vacuum model makes predictions for large color dipoles which significantly differ from the two gluon exchange mechanism which is adequate for small color dipoles but its validity for larger dipoles is doubtful. Due to the inherent nonabelian nature in the gluon fluctuations, the cross section between the dipoles has contribution not only from the quarks surrounded by their fields scattering with other, but also from the color string connecting the quarks, which scatters on the string from the other hadron. Clearly at large distances this mechanism becomes more important and it is challenging to identify the resulting rising cross section in the experimental data. The above mentioned work on ρ' and ρ'' production has tried to do this.

3 The Proton Structure Function F_2

The work on F_2 has been reviewed in the light of the new HERA data in collaboration with Metz and D'Alesio in [10]. Here the hard Pomeron is added as an additional mechanism independent from the stochastic vacuum gluon fluctuations. For the hard Pomeron perturbation theory is a guide to model the dependence on x and virtualty. The above authors have computed the structure function F_2 of the proton (for

$0 < Q^2 \leq 6.5\,\text{GeV}^2$, $x \leq 0.01$, $W \geq 10\,\text{GeV}$) and the total cross section of real photoabsorption (for $W \geq 6\,\text{GeV}$) in the framework of a two-component model consisting of a soft and a hard Pomeron. In a fit to 233 data points we obtain a $\chi^2/\text{d.o.f.} = 1.13$ with five free parameters. The result for F_2 vs Q^2 at different values of x is shown in the figure. (Experimental points at (a), from left to right, $x = 0.42 \cdot 10^{-5}$, $x = 0.44 \cdot 10^{-5}$, $x = 0.46 \cdot 10^{-5}$ ($\times$ 8); (b), from left to right, $x = 0.85 \cdot 10^{-5}$, $x = 0.84 \cdot 10^{-5}$, $x = 0.83 \cdot 10^{-5}$ and $x = 0.86 \cdot 10^{-5}$ ($\times$ 6); (c), from left to right, $x = 0.13 \cdot 10^{-4}$ and three points at $x = 0.14 \cdot 10^{-4}$ ($\times$ 5); (d) $x = 0.5 \cdot 10^{-4}$ ($\times$ 4); (e) $x = 0.8 \cdot 10^{-4}$ ($\times$ 3); (f) $x = 0.2 \cdot 10^{-3}$ ($\times$ 2); (g) $x = 0.5 \cdot 10^{-3}$ ($\times$ 1). The data points and curves are rescaled by the numbers in brackets.)

Our soft Pomeron is calculated from the Stochastic Vacuum Model, which can be considered as approximation of QCD in the infrared region. The SVM describes the complicated structure of the QCD vacuum in terms of a nonlocal gluon condensate, where the variation of the condensate in Minkowski space-time is governed by the correlation length a. In the framework of the SVM, diffractive scattering of two particles is equivalent to the scattering of two Wegner-Wilson-loops, leading automatically to cross sections in the color-dipole picture. To fix the distribution of the loops in the transverse space, valence quark wave functions of the particles have to be introduced.

The wave function of the photon is determined in perturbation theory and accounts for a fluctuation of the γ^* into a $q\bar{q}$ state. This description differs from VMD frequently used in the region of low Q^2. A sufficient simultaneous description of F_2 and $\sigma_{\gamma p}$ for low and high W by means of VMD is difficult, and requires in general further parameters. VMD of the photon enters in our picture only through the determination of the quark masses by quark-hadron duality.

Our soft Pomeron contains only one free parameter which regulates the overall normalization of the Q^2 dependent quark masses in the photon wave function. Compared to previous work on F_2 at fixed $W = 20\,\text{GeV}$, performed only with a soft Pomeron, our fit favors a reduction of the quark masses by 13%. Such a reduction improves also e.g. the cross section for photoproduction of ρ-mesons. The remaining (four) parameters of the soft Pomeron have been taken from other sources and left unchanged.

The cross sections of the SVM are energy-independent, contrary to the $s^{0.08}$ behaviour of the soft Pomeron in hadron-hadron scattering. To describe the data on F_2 obtained in fixed-target experiments and at HERA a hard Pomeron has to be considered in addition. The hard Pomeron exchange in F_2 has been parametrized by the leading order QCD evolution of a power-behaved structure function ($F_2 \propto x^{-\lambda}$). Assuming a singular gluon input, the evolution does not produce a Q^2-dependence in the intercept, and hence the result is not in conflict with Regge theory. The parametrization has been multiplied by a simple phenomenological factor in order to obtain a finite result in the case of real photoproduction. Our fit leads to $\lambda = 0.38$, which is close to a recently proposed value ($\lambda = 0.42$) by Donnachie and Landshoff.

During the last time many people investigated F_2 at low x and especially at low Q^2 with different models. The approaches comprise shadowing effects, Pomerons with a Q^2 dependent intercept, VMD calculations in combination with perturbative evolution. With a soft and a hard Pomeron Donnachie and Landshoff [12] presented for a large kinematical region a very good fit to $\sigma_{\gamma p}$ and F_2 using 10 parameters. In this work not only the intercepts, but also the residues of both Pomerons have been fitted. In contrast to this the residue of our soft Pomeron is fixed by the Stochastic Vacuum Model and related to parameters of nonperturbative QCD. In addition, at higher values of Q^2, the residue of the hard Pomeron follows the (leading order) evolution of QCD.

Our work strongly overlaps with the approach of Adel, Barreiro and Ynduráin [13], since we are using essentially the same expression for the hard Pomeron. However, we differ in the way of performing the limit $Q^2 \to 0$ in the hard part and, in particular, in the ansatz of the soft Pomeron, where in [13] a single VMD pole has been taken. The parametrization of Ref. [13], which is obtained from a fit to F_2, fails in describing the data on $\sigma_{\gamma p}$ at low *cm* energies.

Further extension of the model to $\gamma\gamma$ collisions has been made in ref. [14]. The future presents many challenges : a fundamental understanding of the energy dependence observed at HERA, the role of unitarity for a theory with growing cross sections and in general a synthesis of Regge theory with QCD.

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References

[1] H. G. Dosch and Yu. A. Simonov, Phys. Lett. **B 205**(1988) 339

[2] H. G. Dosch, Prog. Part. Nucl. Phys. **33**,121 (1994)

[3] A. Di Giacomo and H. Panagopoulos, Phys. Lett. **B285**, 133,(1992)

[4] H. W. L. Naus, T. J. Fields and J. P. Vary and H. J. Pirner , Phys. Rev **D56** (1997) 8602

[5] E. Meggiolaro, hep-ph/9807567

[6] U. Ellwanger, hep-ph/ 9807380

[7] H.G. Dosch, E. Ferreira and A. Krämer, Phys. Rev. D **50**, 1992 (1994).

[8] H.G. Dosch, T. Gousset, G. Kulzinger and H.J. Pirner, Phys. Rev. D **55**, 2602 (1997).

[9] H. G. Dosch, T. Gousset and H. J. Pirner Phys. Rev **D57** (1998)

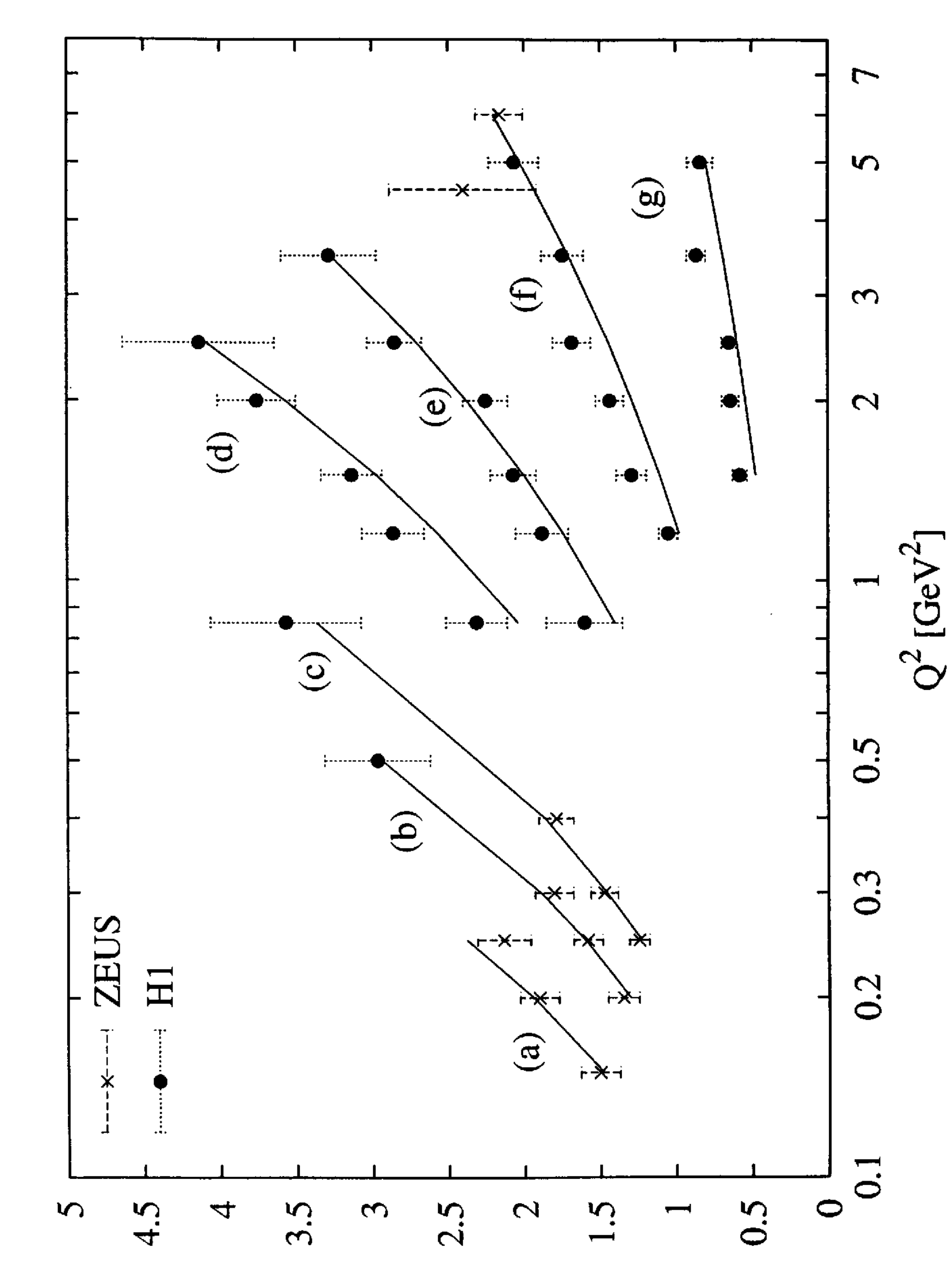
[10] U. D'Alesio, A. Metz and H. J. Pirner to be submitted to Eur. Phys. J C

[11] G. Kulzinger, H. G. Dosch and H. J. Pirner, hep-ph/9807448 to be published in Eur. Phys. J. C

[12] A. Donnachie and P.V. Landshoff, hep-ph/9806344.

[13] K. Adel, F. Barreiro and F.J. Yndurain, Nucl. Phys. **B495**, 221 (1997).

[14] A. Donnachie, H. G. Dosch, M. Rueter, hep-ph/9810206



ZEUS
H1
(a)
(b)
(c)
(d)
(e)
(f)
(g)
F_2
Q^2 [GeV^2]
0.1
0.2
0.3
0.5
1
2
3
5
7
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5