SPONTANEOUSLY BROKEN CHIRAL
SYMMETRY AND HARD QCD PHENOMENA

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ABSTRACT

These are the mini-proceedings of the workshop “Spontaneously Broken Chiral Symmetry and Hard QCD Phenomena” held at the Physikzentrum Bad Honnef from July 15 to 19, 2002. Every author presents a summary of his talk. The transparencies of all speakers and further information on the workshop can be found on the website:

http://www.tp2.ruhr-uni-bochum.de/hardreactions.html
Quantum chromodynamics (QCD), being a non-abelian gauge theory, is considered now as the fundamental theory of strong interactions. Experiments at high energy accelerators: SLAC (Stanford), CERN (Geneva), DESY (Hamburg), FNAL (Chicago) found elementary building blocks — i.e. quarks and gluons — and checked that the interaction between them is well described by the equations of QCD. Numerous experiments confirmed that the interaction between elementary particles is decreasing with increase of resolution. This feature corresponds to a decrease of the space-time interval probed in the process and requires a high momentum transfer to the elementary particles (hard process). Thus the Lagrangean of QCD seems to be established both theoretically and experimentally. Challenging problems now are in search for novel QCD phenomena in the case of large hadron (quark-gluon) densities, where the smallness of the coupling constant is insufficient to support applicability of perturbative approaches, and in the case of low energy phenomena in hadronic and nuclear physics where the coupling constant is not small.

Thus one challenge is to build theoretical methods of solving equations of QCD in the regime where effective interaction is not small any more. These problems are becoming more acute with time because various developments suggest the possible existence of plenty of new QCD phenomena, as there are recent observed astrophysical phenomena in neutron stars, strong indications from high energy accelerators like the fast increase of gluon densities with energy, or new theoretical ideas on the possibility of variety of phase transitions in hadronic matter.

The phenomenon of spontaneously broken chiral symmetry (SBCS) together with confinement of color is usually considered as the most important QCD properties and the cornerstones for the understanding of the physics of strong interactions. It is generally believed that the existence of nuclear physics phenomena (and therefore of life!) is closely related to the spontaneous chiral symmetry breaking. So a lot of researchers suggested a variety of ideas how to describe this phenomenon. These approaches are all based on chiral dynamics of the QCD Lagrangean. Many of the predictions were checked experimentally at various accelerators. Appropriate phenomena are investigated now e.g. at SIN (Switzerland), MAMI (Mainz) and ELSA (Bonn). In spite of the evident success in the explanation of a variety of existing data such an approach has the problem to explain the mass of the $\eta'$ meson directly from the QCD Lagrangian. Interesting ideas how to solve this puzzle are known for a long time but only now they become of practical interest because of the possibility to study this problem experimentally. COMPASS (CERN) investigates now phenomena related to the corresponding QCD anomaly. The low energy community accumulated so far a vast amount of interesting phenomenological data and interesting ideas how to explain them. Still a success of low energy approaches has limitations because of important roles of virtual high energy phenomena. At the same time
subtraction constants introduced to account for them can be investigated directly in the high energy phenomena. This physics is natural for intermediate energy machines at JLab or DESY (HERMES). Thus overlap between interests of researchers working on low energy and high energy phenomena in the field of spontaneously broken chiral symmetry is evident.

For many years the theoretical methods used by high- and low-energy communities were essentially different. In particular, the traces of chiral QCD phenomena were not very pronounced. However, the situation changed few years ago when it was noticed that a combination of QCD factorization theorems with chiral algebra can lead to important consequences that can be tested experimentally. Indeed, quite often the quantities measured in high energy processes can be factorized into a ”hard” part, describable mainly in terms of perturbative QCD-methods, and a nonperturbative ”soft” part. It is the soft part that can be analyzed in terms of spontaneously broken chiral symmetry. This conference is an attempt to give the possibility for low energy and high energy communities to exchange information, ideas and to overcome the gap between them.

The basic object of spontaneously broken chiral symmetry — namely the wave function of the pion being a pseudogoldstone mode — is now investigated in the electromagnetic pion form factor at JLab, in production of pions and η in two photon processes at LEP, or in diffractive production of dijets at FNAL. All experiments produce consistent results. Hard exclusive electroproduction of vector and pseudoscalar mesons and deeply virtual Compton scattering, owing to the QCD factorization theorems, allow us to access the structure of hadrons in a new theoretically well controlled way. These processes attracted great interest in both communities and, as a consequence, the communication between them has intensified.

The objective of the present workshop was to invite experts from both groups, who expressed their interest in combining chiral symmetry with hard processes. We choose basically two domains of applications of chiral QCD dynamics:

1. Chiral symmetry at low energies.
2. Chiral symmetry at high energies.

It was agreed not to publish printed proceedings of the workshop but rather to ask the participants to present a one-page summary of their contributions with references to the original papers. These contributions are presented below. The transparencies of the talks presented at the workshop can be found on the website

http://www.tp2.ruhr-uni-bochum.de/hardreactions.html

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New Results on DVCS and Exclusive Meson Production at Hermes

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We present experimental results on beam-spin asymmetry (BSA) in Deeply Virtual Compton Scattering (DVCS) using new set of data taken in year 2000 on hydrogen target. Extracted value of the asymmetry is consistent with published results [1] based on 1996/97 data taking period. In addition we present preliminary results on first measurement of lepton-charge asymmetry (LCA) in DVCS on hydrogen target using electron and positron beams of HERA [2]. While the BSA asymmetry gives an access to imaginary part of DVCS amplitude, the LCA gives an access to real part of DVCS amplitude. Comparison of the sign and the magnitude of LCA with existing models gives a constrain on the so called D-term of polynomial condition of Generalized Parton Distribution [3].

Second subject is devoted to single target-spin asymmetry in electroproduction of pseudoscalar mesons. Here we present new experimental results based on polarized deuteron data. Extracted value of single-spin asymmetry of semi-inclusive positive pions is diluted compared to the published hydrogen target data [4]. When plotted versus $z$ (the ratio of the energy of produced pion over virtual photon energy) for both exclusive $\pi^+$ and $\pi^-$ asymmetry rizes dramatically and has the same sign, being consistent with published data on hydrogen target for $\pi^+$ [5]. The sign of asymmetry for neutral pions at high $z$ is opposite to the charged ones. In addition we present for the first time experimental results on single-spin asymmetry for identified kaons.

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Coherent dijet production in QCD

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Coherent production of hard dijets by incident pions and/or linearly polarized real photons can provide direct measurement for the pion distribution amplitude, clear evidence for chirality violation in hard processes, the first measurement of the magnetic susceptibility of the quark condensate and the photon distribution amplitude. It can also serve as a sensitive probe of the generalized gluon parton distribution.

We consider the possibility to calculate the coherent dijet production cross section using QCD collinear factorization. For the pion, we find that the collinear factorization is valid in the double logarithmic approximation but does not hold beyond because of soft gluon exchanges in the so-called Glauber region. For the real photon the collinear factorization is valid in perturbation theory, but is violated in the chirality-breaking contribution corresponding to the non-perturbative photon wave function. Detailed calculations are presented for the FERMILAB and HERA kinematic regions.

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Light-Front Wavefunctions and Hard Exclusive Processes in QCD

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Hard hadronic exclusive processes are now at forefront of QCD studies, particularly because of their role in illuminating hadron structure at the amplitude level and in interpreting the physics of exclusive heavy hadron decays. In the accompanying transparencies, I discuss some of the theoretical issues and empirical challenges to the application of perturbative QCD and factorization theorems, such as the role of soft and higher twist QCD mechanisms, the role of relative orbital angular momentum, single-spin asymmetries in deeply virtual Compton scattering, the behavior of the ratio of Pauli and Dirac nucleon form factors, the apparent breaking of color transparency in quasi-elastic proton-proton scattering, and the measurements of hadron and photon wavefunctions in diffractive dijet production. For recent reviews, see ref. [1, 2]

Electromagnetic, electroweak, and gravitational form factors [3, 4, 5] and the deeply virtual Compton amplitude [6, 7] have an exact representation as overlap integrals of light-front wavefunctions. The Pauli Form factor and the E-generalized parton distribution require overlaps of wavefunctions differing by one unit of relative orbital angular momentum projection \( L_z \). The gravitational spin-flip amplitude \( B(q^2) \) vanishes at \( q^2 = 0 \) in agreement with the equivalence principle [5]. In the case of timelike form factors such as \( B \to M \ell \nu \), and DVCS [6, 7], off-diagonal \( \Delta n = 2 \) contributions are required. [4] These exact light-front representations provide the starting point for the PQCD treatment of form factors and other hard scattering amplitudes. It should be emphasized that the leading-twist contributions to exclusive hard processes are by definition devoid of any integration region where the parton is close to the mass shell. I also note that any model of a soft wavefunction which has Gaussian fall-off in the transverse directions, must also have Gaussian fall-off at the \( x = 0 \) and \( x \to 1 \) endpoints. It is thus inconsistent to fit the \( x \) distributions of such models to the empirical power-law \( (1 - x)^n \) forms, since the power law behavior is accounted for by perturbative QCD.

Perturbative QCD and its factorization properties at high momentum transfer provide a critical guide to the phenomenology of exclusive amplitudes. [1] The leading-twist PQCD predictions have many empirical successes. The reduced amplitude formalism allows the application of perturbative QCD to hard nuclear amplitudes. [10] The fact that the hadron enters through its distribution amplitude—its valence wavefunction evaluated at impact parameter separation

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$b \sim 1/Q$—leads to the color transparency of quasi-elastic hard-scattering in nuclei and diminished initial and final state hadron interactions. 

The chiral structure of hard scattering amplitudes, and the fact that the distribution amplitudes are $L_z = 0$ projections of the hadron light-front wavefunctions lead to hadron-helicity conservation at leading twist. Hiller, Hwang, and I find that a PQCD-motivated form for the ratio of Pauli and Dirac nucleon form factors $\frac{F_2(Q^2)}{F_1(Q^2)} \sim \frac{\log Q^2}{Q^2}$ is consistent with recent data from Jefferson Laboratory. The normalization discrepancy between measurements of the spacelike pion form factor and PQCD predictions may be due to a systematic error in extrapolating electroproduction to the pion pole at $t \to m^2_\pi$.

The effective $(q\bar{q})_\pi(t)\to\pi$ form factor measured in electroproduction $F(t,Q^2)$ is normalized to $f_\pi$ not $f_\pi^2$.

I also discuss the unexpected role of final state interactions in deep inelastic scattering, and their role in shadowing theory, single-spin asymmetries, and diffraction. Similar corrections to the quark propagator can modify DVCS predictions, even in light-cone gauge. I also review features of the model for leading-twist DVCS amplitudes and Bethe-Heitler interference contributions developed by Close and Gunion and myself which incorporates analyticity, crossing behavior, Regge exchange, fixed Regge poles, and leading-twist scaling.

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Factorization for hard exclusive processes

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A review was given of the rationale for factorization in processes such as exclusive deep-inelastic production of mesons.

In high-energy collisions, large ranges of virtualities and rapidities can be accessed, and a factorization theorem separates the different scales and rapidities. The asymptotic freedom of QCD enables perturbative predictions to be made for short-distance coefficient functions and evolution kernels. Connections with non-perturbative physics are made with the aid of operator definitions of (generalized) parton densities and light-front distribution amplitudes.

First, leading regions in momentum space are identified, and they lead to operator definitions of parton densities etc. They also lead to a coordinate-space interpretation that suggests that the results should be valid beyond perturbation theory. A systematic method of successive approximation leads to a perturbative construction of hard scattering coefficients and evolution kernels with subtractions to avoid double counting.

There are a number of complications to overcome: (a) In the parton densities, etc., there are divergences at large transverse momentum and at large gluon rapidity; these must be suitably cutoff, renormalized, or cancelled to obtain correct results. (b) Gluon interactions must be correctly treated so that gauge-invariant results are obtained. (c) Soft final-state interactions must be shown to cancel (or in other situations to factorize); the arguments involve the application of contour deformation in momentum space and the use of the QCD Ward identities, with substantial components of the argument going beyond perturbation theory.

Generalizations of the arguments apply to other processes. The main ideas in the form used here can be found in [1, 2] and the references quoted there.

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Generalized Parton Distributions
in Transverse Space

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The impact parameter formulation allows for a simple physical interpretation of quantities like parton distributions and form factors in terms of quarks and gluons. I investigate the specifics of this representation for generalized parton distributions at nonzero skewness $\xi$ and their relation with Lorentz symmetry on the light cone. An explicit realization of this representation is obtained when the parton distributions are expressed in terms of hadronic light-cone wave functions.

The primary aim of this representation is to provide a framework to investigate exactly how generalized parton distributions simultaneously describe longitudinal and transverse structure of a fast moving hadron, and to compare this information with the one in elastic form factors, in ordinary and in $k_T$ dependent parton distributions.

Details on the material presented in this talk can be found in [1]. This study builds on work by Burkardt for the case of zero skewness $\xi = 0$ [2], and is closely related with ideas recently formulated in [3].

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Recent developments
in chiral perturbation theory

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After a short introduction to chiral perturbation theory, the effective field theory of the standard model at low energies, the present status of the field is briefly reviewed.

Recent advances in the chiral analysis of pion pion scattering [1] are discussed in some detail. Combining the chiral amplitude of next-to-next-to-leading order in the low-energy expansion with experimental input at higher energies via dispersion relations (Roy equations), threshold parameters and phase shifts up to cms energies of 800 MeV have been determined with unprecedented precision. Comparison with recent \( K_{e4} \) data from the BNL-E865 experiment corroborates the status of the quark condensate as dominant order parameter of spontaneous chiral symmetry breaking. As a consequence, we have now direct experimental evidence that more than 94\% of the pion mass is due to the leading term in the chiral expansion.

In general, matching between the chiral low-energy structure and the high-energy behaviour of amplitudes requires nonperturbative methods to bridge the gap between the two regions. The chiral resonance Lagrangian is a phenomenologically successful example where the matching produces the correct low-energy constants of next-to-leading order.

Four-pion production in \( e^+e^- \) annihilation and in \( \tau \) decays is a case where the leading resonance couplings are not sufficient to extend the low-energy amplitudes into the resonance region. Surprisingly, the amplitudes in the chiral limit available in the literature were found to have the wrong normalization. The next-to-leading-order calculation allows for a straightforward continuation into the resonance region. Unlike for the pion form factor, for instance, additional ingredients are necessary for such an extrapolation like \( \omega \) and \( a_1 \) exchange that only show up in higher orders of the low-energy expansion. With the present form of the amplitudes [2], the \( e^+e^- \) cross sections are well described over a range of several orders of magnitude up to about 1 GeV cms energy. Additional information about the high-energy structure of the amplitudes must be implemented before the full phase space available in \( \tau \) decays can be covered.

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Spin azimuthal asymmetries in pion electro-production in deep inelastic scattering off longitudinally polarized protons, measured by HERMES, are well reproduced theoretically with no adjustable parameters using the chiral quark soliton model for transversity distribution and DELPHI result for averaged over $z$ Collins analysing power $|\langle H_+^1 \rangle / \langle D_1 \rangle | = 12.5 \pm 1.4\%$.

Predictions for azimuthal asymmetries for a longitudinally polarized deuteron target are given. From $z$-dependence of the asymmetry and chiral quark soliton model for transversity the $z$-dependence of the Collins fragmentation function is extracted (see Fig.1).

Using Collins analysing power the first information on $e(x)$ is extracted (see Fig.2) from $A_{LU}^{sin \phi}$ asymmetry of CLAS collaboration. For more details and references see hep-ph/0206267.
Properties of $\eta$ and $\eta'$ mesons can be studied in various hard exclusive reactions: The overall normalization of leading-twist light-cone distribution amplitudes (DAs) that enter perturbative QCD calculations in the factorization approach [1] is provided by weak decay constants. In general these are parametrized in terms of two mixing angles that can be determined from theoretical and phenomenological considerations [2]. In the quark-flavor basis the two mixing angles nearly coincide with a value of about 39°, indicating that OZI-rule violating contributions to the decay constants are small. The shape of the DAs can be constrained by considering the $\eta\gamma$ and $\eta'\gamma$ transition form factors at large momentum transfer [3]. We found that pions, $\eta$ and $\eta'$ mesons have leading-twist DAs that are consistent with the asymptotic form already at low factorization scales. Furthermore, experimental data excludes large “intrinsic” (constituent) charm in $\eta$ and $\eta'$ mesons, in accordance with Refs. [4]. As a consequence, neglecting all OZI-rule violating effects, simple “Brodsky-Lepage” [5] interpolation formulas for $\eta(\eta')\gamma$ form factors can be obtained, that are in approximate agreement with experiment for large and small momentum transfer [6]. Two-body decays of heavy charmonia into $\eta/\eta'$ mesons are sensitive to $\eta-\eta'$ mixing parameters, too [7]. Particularly interesting are the decays of $J/\psi$ or $\psi'$ into $\eta(\eta')\omega$ which are related to the “$\rho-\pi$-puzzle” (see e.g. [8] and references therein). A good knowledge of $\eta$ and $\eta'$ DAs and mixing parameters is also required to understand non-leptonic $B$ decays, in particular the rather large $B \to \eta'K$ branching ratio (see [9] and references therein.)

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Hard diffractive processes and light cone pion wave function.

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In the leading order over $\alpha_s$ the cross section of diffractive production of two high $\kappa_t$ jets unambiguously follows from QCD factorization theorem ref.[1, 2]: as $\sigma(\pi + A \to 2jet + A) = c\alpha_s xG_A\Delta\psi_\pi(z, \kappa_t)^21/R_A^2$. Here $\kappa_t$ is transverse momentum of jet, $\Delta$ is Laplace operator in 2 dimensional $\kappa$ space, $G_A$ is the gluon distribution in a nuclear target, $x = \frac{4k_t^2}{s}$, $R_A$ is the radius of the nuclear target, $c$ is the constant calculated in QCD. (For the review of the history of this process see ref.[2].) For the small $x$ processes the major difference between skewed and usual gluon distributions is accounted for by QCD evolution equation for the skewed parton distributions. At extremely small $x$ perturbative interaction becomes strong leading to significant absorption.

$A$ dependence observed in FNAL ref.[3] is faster than the prediction of ref.[1] for the process where final nucleus is in the ground state. However experimental signature of the process is the strong forward peak $\propto F_A(t)^2$ so final nucleus may appear in excited state. Summing over nuclear excitations leads to the additional $A$ dependence of cross section which agrees well with FNAL data. (ref.[2] and this talk.)

HERA data on hard diffractive processes $\gamma^* + p \to V + p$ where $V = \gamma, \rho, \omega, \phi, \psi$. demonstrated that vector mesons are squeezed by external hard probe.(H.Abramowicz talk at this conference). But just this property is relevant for the applicability of QCD factorization theorem.

To summarize: FNAL,HERA data confirmed predicted by QCD unusual properties of hard diffractive processes and it is worth to use these processes to investigate wave functions of hadrons. This talk is restricted by the discussion of the process: $\pi + A \to 2jet + A$.

Shortest calculation is for the amplitude of high $\kappa_t$ di-jet production by pion projectile off the nucleus Coulomb field. This process gives negligible contribution at FNAL but not at LHC energy range. The conservation of e.m. current is used to express leading term in $s$ in terms of the amplitude of transverse photon field -generalization of the Weizecker-Williams approximation. Main result is that the dominant contribution is given by the amplitude where transverse photon interacts with external lines only. This is the the leading order over $\alpha_s$ generalization of the theorems of F.Low and V.Gribov. Thus we proved that high momentum tail of pion wave function of pion is measurable in this process. High momentum tail of photon wave function is measurable in the similar process: $\gamma + e \to 2jet + e$ which should be measurable at electron colliders(S.Brodsky-comment at this conference).

We introduce concept of post selection to stress the fact that selection of $q\bar{q}$ component in the final state requires squizing of pion wave function in the initial state because in the average configuration around 50% of pion momentum
is carried by gluons. Screening of color in the squized meson wf +asymptotic freedom is the only known effective mechanism of killing of infinite number of degrees of freedom characterizing hadron in the average configuration. Sudakov form factors is well known pQCD analogue of this phenomenon which is also important but for the squized initial state pion wave function only.

We calculate imaginary part of amplitude and restore its real part by virtue of dispersion relations. In the leading order over $\alpha_s$ and all orders over $\alpha_s \ln \frac{k^2}{\mu^2}$ Ward identities have the same form as in QED. Except impulse approximation other diagrams correspond to skewed gluon distribution where the fraction of nucleon momentum carried by gluon in the final state is negative. To avoid strong suppression this gluon should be wee parton. One should also to account for the cancellation between radiative correction to the wf of final state and gluon bremsstrahlung in the jet direction. All in all lead to large virtuality of quarks(similar to that in $e\bar{e} \rightarrow$ hadrons) and to the suppression of all diagrams except those where color in initial hadron is concentrated in the transverse region $\propto 1/k^2_t$. In the evaluation of impulse approximation infrared divergence are cancelled out after proper account of renormalization invariance-renormalization of quark,gluon propagators and vertexes. In ref. it has been suggested to use special l.c. gauge as the effective method to remove infrared divergencies. Thus it was shown that high momentum tail of pion wf is measurable in the considered process. Observed $\kappa_t,z$ dependencies of cross section are in a reasonable agreement with one gluon exchange tail of pion wave function. Relationship between pion distribution function and pion wave function made it possible to calculate distribution function at large virtuality.

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Light-Cone Wavefunction Representations of GPD and SSA

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We give a complete representation of virtual Compton scattering $\gamma^* p \to \gamma p$ at large initial photon virtuality $Q^2$ and small momentum transfer squared $t$ in terms of the light-cone wavefunctions of the target proton. We verify the identities between the skewed parton distributions $H(x, \zeta, t)$ and $E(x, \zeta, t)$ which appear in deeply virtual Compton scattering and the corresponding integrands of the Dirac and Pauli form factors $F_1(t)$ and $F_2(t)$ and the gravitational form factors $A_q(t)$ and $B_q(t)$ for each quark and anti-quark constituent. We illustrate the general formalism for the case of deeply virtual Compton scattering on the quantum fluctuations of a fermion in quantum electrodynamics at one loop [1, 2].

Recent measurements from the HERMES and SMC collaborations show a remarkably large azimuthal single-spin asymmetries $A_{UL}$ and $A_{UT}$ of the proton in semi-inclusive pion leptoproduction $\gamma^*(q)p \to \pi X$. We show that final-state interactions from gluon exchange between the outgoing quark and the target spectator system lead to single-spin asymmetries in deep inelastic lepton-proton scattering at leading twist in perturbative QCD; i.e., the rescattering corrections are not power-law suppressed at large photon virtuality $Q^2$ at fixed $x_{bj}$. The existence of such single-spin asymmetries requires a phase difference between two amplitudes coupling the proton target with $J^z_P = \pm \frac{1}{2}$ to the same final-state, the same amplitudes which are necessary to produce a nonzero proton anomalous magnetic moment. We show that the complex phase from the final-state interaction depends on the angular momentum $L^z$ of the proton’s constituents and is thus distinct for different proton spin amplitudes [3, 4].

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Quantum power correction to the Newton law

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The one-loop relative quantum correction of first order in $\hbar$ to the Newton law should look by dimensional reasons as $l_p^2/r^2$, where $l_p = \hbar c^3$ is the Planck length. Then, the absolute correction to the potential is:

$$U_{qu} = a_{qu} k^2 \hbar m_1 m_2 / c^3 r^3.$$ (1)

The problem is to find the numerical constant $a_{qu}$. In spite of extreme smallness of the quantum correction, its investigation certainly has a methodological interest: this is a closed calculation of a higher order effect in the nonrenormalizable quantum gravity.

The reason why this problem allows for a closed solution is as follows. The Fourier-transform of $1/r^3$ is

$$\int dr \frac{\exp(-iqr)}{r^3} = -2\pi \ln q^2.$$ (2)

This singularity in the momentum transfer $q$ means that the correction discussed can be generated only by diagrams with two massless particles in the $t$-channel. The number of such diagrams of second order in $k$ is finite, and their logarithmic part in $q^2$ can be calculated unambiguously.

We have found the graviton contribution (which is dominant numerically) to the discussed correction. The result for the thus modified Newton potential is

$$U(r) = - \frac{k m_1 m_2}{r} \left(1 + \frac{121}{10\pi} \frac{k\hbar}{c^3 r^2}\right).$$ (3)

The previous calculations of this contribution to the discussed effect are demonstrated to be incorrect.

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Factorization of hard amplitudes in QCD

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Were QCD a linear or at least weak coupling theory, our life would have been much easier. When classical system described by linear physics is disturbed by an external probe, it responds with excitation of those degrees of freedom which carry the same frequencies as the probe itself. Strictly speaking in quantum mechanics it is only true in the Born approximation as higher orders of perturbation theory involve communication between degrees of freedom of various frequencies (summation over the intermediate states) but this does not lead to any real difficulty as long as weak coupling expansion is justified. In those two cases one can indeed speak degrees of freedom, or physics, which plays the leading role a given process.

In QCD the situation is different. The nonlinearity is strong and in a typical situation, even when the probe carry only high frequencies, after a few hard interactions the frequency spectrum spreads out into the low scale, non-perturbative range. The resulting situation is similar to that of Navier-Stokes equation in the turbulent regime - the spectrum of relevant degrees of freedom spreads out over the whole kinematically allowed range, which makes the problem untractable by any known computational scheme. It is remarkable one can still define a class of QCD processes which obey the factorization. Splitting the amplitude into hard, perturbatively computable, and soft, long-distance parts allows for set of non-trivial predictions which can be tested experimentally. More about that can be found in other contributions to these proceedings. Here we mention only that factorization is born deeply into the general structure of relativistic field theory - the requirement of causality in hard kinematics severely restricts the possibility of interaction between quanta of different frequencies.

As the world around us is built mainly of hadrons one will never achieve a deeper understanding of the “standard model” physics below 1 TeV scale without understanding the strong interactions. A good example is the ongoing discussion of the CP violating effects in B-meson decays where the (mis)understanding of the QCD “factorization” makes testing of the electroweak theory in this system to a precision required by cosmological implications (baryon asymmetry) difficult, if not impossible.
Chiral Symmetry and Light Front Wave Functions of Nuclei: From $A = \infty$ to $A = 1$.

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The motivation for light front dynamics[1] and the salient features of the technique[1] formed the introduction. The applications concerned heavy nuclei vs the EMC effect[2], the deuteron[3], and nucleon form factors[4]. Chiral symmetry does not play a big role in heavy nuclei, hence the need to include the deuteron. Computations of deuteron form factors at high momentum transfer depend on nucleon form factors[3], so these are also discussed[3].

Mean field models of nuclei can not explain the EMC effect. Including correlations does not help. This is because the Hugenholtz-van Hove theorem restricts the total plus momentum carried by nucleons[2]. Including mesons can lead to a reproduction of the EMC effect, but then one over-predicts the content of the nuclear sea, in disagreement with experiment.

Chiral symmetry is needed to obtain a deuteron bound state[3], if one uses a relativistic pion-only model. Rotational invariance is respected, even when not manifest in the formalism[3]. Using the different models of nucleon form factors leads to a wide spread in calculated deuteron form factors[3].

Thus there is a need to use the light front to obtain nucleon form factors. Our model, in which the nucleon is treated as a relativistic system of three bound constituent quarks surrounded by a cloud of pions, achieves a very good description of existing data for the four electromagnetic elastic form factors[4].

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The soft physics responsible for single spin asymmetries in hard reactions

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In deep inelastic scattering (DIS) the structure functions can be expressed in terms of quark distribution functions (DF), which have a natural interpretation as quark densities in the lightcone (plus) momentum fraction \( x = \frac{p^+}{P^+} \) (with \( p \) being the quark momentum and \( P \) the target hadron momentum). The DF can be written down as lightcone correlation functions of quark fields with the nonlocality being just in a lightlike (minus) direction. Three DF exist for a spin \( \frac{1}{2} \) hadron, \( f_1^q(x) = q(x), g_1^q(x) = \Delta q(x) \) and \( f_2^q(x) = \delta q(x) \), the latter not accessible in deep-inelastic scattering. Matrix elements including longitudinal \((A^+)\) gluons are absorbed into the definition of the DF providing the gauge link.

Semi-inclusive DIS involves two hadrons. Including also the hard scale \( q \), one has three momenta, hence besides the lightcone plus and minus directions, transverse momenta are relevant. One needs to consider DF and fragmentation functions (FF) depending on transverse momenta of partons. The functions appear in azimuthal asymmetries involving the azimuthal angle of the production plane with respect to the lepton scattering plane in leptoproduction.

Single spin asymmetries in hard cross sections can be traced to T-odd DF and FF [1]. While T-odd FF, such as the Collins function describing the fragmentation of transversely polarized quarks into pions, appear naturally [2], T-odd DF are less natural. All T-odd effects at leading order involving hadrons with spin \( S < 1 \), require transverse momentum dependent DF and FF. The operator structure of the corresponding soft parts requires operators beyond leading twist, which under specific conditions also allow T-odd effects for DF [3]. The latter is connected to the fact that the gauge link has to bridge transverse separations in the quark-quark correlation functions, requiring not only longitudinal but also leading transverse gluon contributions.

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Instanton vacuum QCD effective action beyond chiral limit

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Instantons represent a very important component of the QCD vacuum. Their properties are described by the average instanton size \( \rho \sim 1/3 \text{ fm} \) and inter-instanton distance \( R \sim 1 \text{ fm} \) \[1\]. The Lee&Bardeen’s fermionic determinant \( \det N \) (in the field of \( N_+ \) instantons and \( N_- \) antiinstantons) is \[2\]:

\[
\det N = \det B, \quad B_{ij} = i m \delta_{ij} + a_{ji}, \quad a_{++} = -< \Phi_{-0} | i \tilde{\theta} | \Phi_{+0} >. \quad (4)
\]

\( \Phi_{\pm,0} \) are quark zero-modes generated by instantons(antiinstantons). \( \det N \) averaged over instanton/anti-instanton positions, orientations and sizes is a partition function of light quarks \( Z_N \). Small packing parameter \( \pi^2 \left( \frac{\rho R}{4} \right)^4 \sim 0.1 \) provide independent averaging over instanton collective coordinates. We calculate \( Z_N \) by the fermionisation of it \[3\], which is the natural way to introduce the constituent quarks. But it is a non-unique procedure beyond chiral limit. Natural way of resolving this problem is an application of the axial-anomaly low-energy theorems \[4\]. Then the partition function satisfying the theorems is as follows:

\[
Z_N = \int D\psi D\bar{\psi} \exp(\int d^4x (\bar{\psi} (i \tilde{\Theta} + i m) \psi + \sum_{\pm} \left( \frac{2V}{N} \right)^{N_f-1} (iM)^{N_f} \int d^4kd^4l \frac{1}{(2\pi)^8} \times \det \exp(-i(k-l)x) F(k^2) F(l^2) \psi_f^\dagger(k) \frac{1}{2} (1 \pm \gamma_5) \psi_g(l)). \quad (5)
\]

This effective action, being derived from Lee&Bardeen fermionic determinant, certainly coincide in the chiral limit with Diakonov&Petrov effective action \[5\]. As a first application of this effective action it were calculated the terms of order \( O(m) \) and \( O(m^2) \) of Gasser and Leutwyler phenomenological chiral lagrangian \[6\] and found that

\[
\bar{l}_3^\text{theor} = 1.39, \quad \bar{l}_3^\text{phenom} = 2.9 \pm 2.4, \quad \bar{l}_4^\text{theor} = 3.57, \quad \bar{l}_4^\text{phenom} = 4.3 \pm 0.9. \quad (6)
\]

We see the good correspondence of the theory with phenomenology at least for these quantities. The calculations of other couplings are in the progress.

I am very grateful to the organizers of the workshop for the invitation and friendly atmosphere.

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Hadron Structure and Chiral Physics on the Lattice

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Lattice field theory is the only known way to solve nonperturbative QCD, and hence plays a crucial role in our understanding of the structure of hadrons and of the QCD vacuum. Given the focus of this conference, this talk emphasizes two ways in which spontaneously broken chiral symmetry is a central issue in contemporary lattice QCD.

Lattice Evidence for the Role of Instantons

Lattice calculations provide strong evidence for the presence of instantons in the QCD vacuum, and for their role in producing spontaneous chiral symmetry breaking and in the physics of light quarks. Two point correlations of meson currents in the QCD vacuum show the detailed behavior specified by the instanton-induced 't Hooft interaction [1]. By minimizing the action locally in a process known as cooling, the instanton content of the quenched and full QCD vacuum was extracted [2, 3, 4]. Comparison of hadronic observables calculated with all gluons and those obtained using only the instantons remaining after cooling yielded qualitative agreement for hadron masses, quark distributions, and vacuum correlation functions of hadron currents [2]. Calculation of the lowest quark eigenmodes revealed zero modes correlated spatially with the instantons and truncation of the quark propagators to the zero mode zone produced the full strength of the $\rho$ and $\pi$ contributions to vacuum correlation functions [5]. The topological susceptibility calculated on the lattice produces the result $(180\,\text{MeV})^4$ required by the Veneziano-Witten formula to produce the observed $\eta'$ mass. And finally, using the Banks Casher relation, the zero modes associated with instantons have been shown to provide the full value of the chiral condensate $\langle \bar{\psi}\psi \rangle$. Taken together, this whole body of evidence shows that instantons and their associated quark zero modes play a central role in light quark physics.

Moments of Structure Functions

Ground state matrix elements specifying moments of quark density and spin distributions in the nucleon have been calculated in full QCD [6, 7]. It has been shown that physical extrapolation of these observables to the chiral limit by including the physics of the pion cloud resolves previous apparent conflicts with experiment [8] and that computational resources of the order of 8 Teraflops years are required for a definitive calculation of the quark structure of the nucleon.

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Saturation Signals in Hard Diffractive QCD

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The interpretation of nuclear opacity in terms of a fusion and saturation of nuclear partons has been introduced in 1975 way before the QCD parton model. The pQCD discussion of the fusion has been initiated by by Mueller and McLerran and Venugopalan.

Based on the consistent treatment of intranuclear distortions, we derive the two-plateau spectrum of FS quarks in the opacity/saturation regime. We find a substantial nuclear broadening of inclusive FS spectra, which is especially strong for truly inelastic DIS with color excitation of the target nucleus, and demonstrate that despite this broadening the FS sea parton density exactly equals the IS sea parton density calculated in terms of the WW glue of the nucleus as defined according to. We pay a special attention to an important point that coherent diffractive DIS makes precisely 50 per cent of total DIS. We point out that the saturated diffractive plateau measures precisely the momentum distribution in the $q\bar{q}$ Fock state of the photon. There emerges quite a nontrivial pattern of nuclear effects: The density of WW glue of an ultrarelativistic Lorentz-contracted nucleus per unit area in the impact parameter plane exhibits strong nuclear dilution, but because of the anti-collinear splitting of WW gluons into sea quarks the density of nuclear sea saturates. The results presented in this talk have partly been published elsewhere.

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The leading-twist two gluon distribution amplitude in exclusive processes involving $\eta$ and $\eta'$ mesons

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The brief review of work in progress [1] has been presented. The formalism for treating the leading-twist two-gluon Fock components appearing in hard processes that involve $\eta$ and $\eta'$ mesons has been reexamined permitting a critical appraisal of the relevant literature [2]. A consistent set of conventions for the definition of the gluon distribution amplitude, the anomalous dimensions as well as the projector of a two-gluon state onto an $\eta$ or $\eta'$ state has been established. The $\eta, \eta'$–photon transition form factor has been calculated to order $\alpha_s$ and as a crucial test of the consistency of this set of conventions the cancellation of the collinear and UV singularities has been explicitly shown. An estimate of the lowest Gegenbauer coefficients of the gluon and quark distribution amplitudes has been obtained from a fit to the $\eta, \eta'$–photon transition form factor data [3]. The results were applied to $\chi \to \eta\eta/\eta'\eta'$ decays, deeply virtual electroproduction of $\eta$ and $\eta'$ mesons (DVEM) and $g^*g^*\eta'$ vertex. While for DVEM the two-gluon contributions are suppressed for small momentum transfer $t$, for the $g^*g^*\eta'$ vertex a significant dependence on $gg$ contributions has been observed.

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Review of confinement scenario.

V. Petrov

The phenomenon of the quark confinement in the Yang-Mills theories is investigated already for 25 years but up to now no self-consistent approach which would be able to explain all known experimental facts was proposed. It is widely accepted that the explanation of the quark confinement in the QCD (which implies in turn the absence of the states with non-integer baryon charge) requires that the potential between static sources in pure glue theory should linearly grow with distance. However the way from pure glue theory to the quark confinement in QCD was never completely traced and there are some confinement scenario on the market which do not imply linear potential in the pure glue theory (we mean, first of all, V.N. Gribov's scenario).

We collect all known theoretical facts about confinement. These facts lead to the rather contradictory picture of this phenomenon. From one side confinement is hard and based on the string-like picture (most convincing facts are linear Regge trajectories and Hagedorn type of all QCD thermodynamics). From the other side it is rather soft and almost invisible, as it follows from the success of perturbation theory (in describing hadron collisions at high energies), QCD sum rules, different models of the QCD vacuum (for example, instanton liquid model).

We classify all possible sources of the linear potential in the Yang-Mills theory. The successful scenario should solve the puzzle which can be formulated as follows. Linear potential implies long range correlations in some correlators. From the other side in the gauge invariant sector all states should be massive and all correlators should decay exponentially. It is almost impossible to provide both features simultaneously and, indeed, we demonstrate that all known scenario of "electrical" confinement lead to massless particles in the spectrum or even to tachyons.

More promising are scenarios based on the so-called "magnetic" confinement. We explain, in details, why (opposite to electrical case) it is possible to have linear potential and massive spectrum in the same theory. We follow all known theoretical examples (dual superconductor, Polyakov's 2+1 Georgi-Glashow model, SUSY Witten-Seiberg model) and demonstrate that from the general point of view they all are based on the same phenomenon in the dual formulation of the theory.

The main feature of this phenomenon is spontaneous breakdown of the color group down to $U(1)$ as it was mentioned by t'Hooft many years ago. In the presented examples this breakdown is introduced in the theory "by hands" but we argue that, in fact, spontaneous breakdown of color is an inherent property of such a confinement mechanism.

We itemize all possible magnetic objects which can lead to the confinement in the electrical sector of the theory. First of all one needs the objects with long ranged interaction: monopoles, vortices and the object with $1/r^2$ tail are the only candidates. However these objects are stable only in the presence of
charged condensate ("elementary" or "composite" Higgs effect) and magnetic charge is quantized also only for this reason. Moreover we demonstrate that objects with long-range interaction (e.g. monopoles) cannot survive in the full $SU(N)$ environment: if the color in the theory is not broken these objects induce the dynamical Higgs effect theirselves. The notion of "non-Abelian" monopoles is contradictory — these objects cannot exist. All this can be said also about vortices and, in addition, in the theory with non-broken symmetry they are unstable under decay into chain of monopole-like objects. Color can remain unbroken for the dual objects which has $1/r^2$ tail — their interaction is weaker but still they are long-ranged enough in order to provide a linear potential. We discuss this case in some details and prove that most probably this possibility leaves massless particles in the spectrum.

Thus if one would accept that color group in QCD remains unbroken (we discuss some possible contradictions with experimental data), one has not too many possibilities to have linear potential in the pure glue theory. We do not mention yet another class of scenario which are based on so-called "stochastic confinement" but, as we show, they are all relies on the lattice-type mechanism ("compactness" of the gauge group) which, surely, cannot be reproduced in the continuum limit.

In other words, at present there is no single satisfactory scenario of confinement. It is clear only that the explanation of this phenomenon should come from some unknown dynamics in the gauge-invariant dual representation of the Yang-Mills theory.
Positivity bounds on GPDs

P.V. Pobylitsa

Generalized parton distributions (GPDs) appear in the QCD description of various hard processes e.g. deeply virtual Compton scattering and hard exclusive meson production. GPDs are defined in terms of matrix elements of parton fields $\phi_{\alpha}(x)$ over hadron states $|P, i\rangle$ (with $x$ being parton momentum fraction)

$$G^{\alpha_1 \alpha_2}_{P_1 i_1, P_2 i_2}(x_1, x_2) = \langle P_2, i_2|\phi_{\alpha_2}^\dagger(x_2) \phi_{\alpha_1}(x_1)|P_1, i_1\rangle$$ (7)

The positivity of the norm in the Hilbert space of states

$$\left\| \sum_{i\alpha} \int \frac{dP^+ d^2 P_{\perp} dx}{2P^+(2\pi)^3} \theta(x) f_{i\alpha}(x, P) \phi_{\alpha}(x)|P, i\rangle \right\|^2 \geq 0$$ (8)

allows to derive rather nontrivial inequalities for GPDs. Various positivity bounds for GPDs corresponding to specific choices of the function $f_{i\alpha}(x, P)$ have been already discussed in literature [1]. In ref. [2] inequality (8) is analyzed for arbitrary functions $f_{i\alpha}(x, P)$. As a result new positivity bounds are derived for generalized parton distributions using the impact parameter representation. These inequalities are stable under the evolution to higher normalization points. The full set of inequalities is infinite.

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We show that for the processes \( \gamma^* (q) N(p) \rightarrow \pi(k) N(p') \) near the threshold\(^4\) the two limits \( Q^2 \rightarrow \infty \) \((Q^2 = -q^2)\) and \( m_\pi \rightarrow 0 \) do not commute. For \( Q^2 \ll \Lambda^3/m_\pi \) (\( \Lambda \) is a typical hadronic scale) one can apply classical soft pion theorems by Nambu \( \text{et al.} \)\(^1\) which express the threshold amplitudes of the \( \gamma^* N \rightarrow \pi N' \) reaction in terms of e.m. and axial form factors of the nucleon. In the kinematics where \( Q^2 \gg \Lambda^3/m_\pi \) one can derive new soft pion theorems \(^2\) which also express the threshold amplitudes in terms of the nucleon form factors. The particular expressions depend on the form of the light-cone wave functions (LCWF) of the nucleon, i.e. sensitive to the partonic content of the nucleon wave function. If we assume that the dominant component of the nucleon LCWF is symmetric we obtain, for instance, at \( Q^2 \gg \Lambda^3/m_\pi \) we have \(^2\)

\[
A(\gamma^* p \rightarrow \pi^0 p)|_{\text{th}} = \frac{1}{3f_\pi} \left( \frac{5}{2} G_{M_p}(q^2) - 4 G_{M_n}(q^2) \right) + O \left( \frac{m_\pi}{\Lambda} \right),
\]

which should be contrasted with \(^1\)

\[
A(\gamma^* p \rightarrow \pi^0 p)|_{\text{th}} = \frac{g_A}{2f_\pi} G_{M_p}(q^2) + O \left( \frac{m_\pi}{\Lambda} \right),
\]

for \( \Lambda^2 \ll Q^2 \ll \Lambda^3/m_\pi \). The new soft pion theorems for hard processes are in agreement with measurements of \( \gamma^* N \rightarrow \pi N' \) reaction near threshold by E136 collaboration \(^3\). We also discussed soft pion theorems for other hard exclusive processes, see details in \(^4\).

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Pion properties in the non-local chiral quark model

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In this talk [1], following our previous work [2, 3] and Refs. [4, 5], we present a simple, nonperturbative model in which quarks acquire a momentum dependent dynamical mass. The model is based on the instanton model of the QCD vacuum, however, the form of the nonlocality is simplified in order to perform all calculations directly in the Minkowski space-time.

Using this model we calculate pion light cone wave functions and distribution amplitudes, two pion distribution amplitudes and skewed parton distributions which allow us to calculate pion structure function and the electromagnetic form factor. The aim of this study is twofold. Firstly, we calculate in the unique framework different characteristics of the pion and secondly, we perform various tests in order to gain confidence in the model as well as to find its limitations. We argue that the model, given its simplicity both conceptual and technical, works much better than one might have initially expected.

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Power-Law Wave Functions and Generalized Parton Distributions for Pion

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In Ref. [1], we study a model based on a power-law ansatz \( \psi(x, k_\perp) \sim 1/\sqrt{x(1-x)(a + bk_\perp^2)}^2 \) for the pion light cone wave function, where \( a = 1 + s^2(x - 1/2)^2/x(1-x) \), \( b = 1/4\lambda^2x(1-x) \); with \( s = m/\lambda \) being the ratio of the effective quark mass \( m \) and the pion size parameter \( \lambda \). We derive a parametric expression for the pion form factor and show that \( m \) and \( \lambda \) can be easily adjusted to provide a curve close to existing experimental data.

Our parametric representation for the form factor has the form of a reduction relation connecting the pion form factor and the double distribution (DD) \( F(x, y; t) \). This model DD has the correct spectral and symmetry properties and it also has the factorized structure used in phenomenological models: it looks like a distribution amplitude with respect to the \( y \) variable and like a parton density with respect to the \( x \) variable. Furthermore, it provides a nontrivial example of the interplay between \( x, y \) and \( t \) dependence of DDs. With an explicit model for DDs at hand, one can calculate the relevant skewed distributions.

The simple toy model is not very realistic: the valence parton density obtained in this model differs rather strongly from the phenomenologically established form. We fix this deficiency by adopting a model with a more realistic \( x \)-profile at \( t = 0 \), but preserving the analytic structure of the interplay between \( x, y \) and \( t \) dependence generated by the power-law ansatz. We show that by slightly changing \( m \) and \( \lambda \) it is still possible to get a good description of the pion form factor data. We present skewed parton distributions (SPDs) obtained from the “realistic” DD. These SPDs satisfy such important constraints as reduction relations to usual parton densities and form factors, they also have correct spectral and polynomiality properties, thus providing a model for the pion GPDs that can be used in phenomenological applications.

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How quantum mechanics of the glue can help us understand RHIC puzzles

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I was given two talks, on a request of the organizers. The first summarized recent data from the Relativistic Heavy Ion Collider at Brookhaven have displayed a number of striking features, some predicted some not. The existence of strong collective flow suggests Bang-like (hydrodynamical) behavior, with very rapid equilibration and short mean free paths. The equation of state is close to that predicted by lattice QCD, suggesting that the experiments really are producing Quark-Gluon Plasma for the first time since the Big Bang. Strong jet quenching, the large azimuthal asymmetry for hadrons with large transverse momentum, and the apparent absence of backward jets, all point directly to very strong absorption in the system. Dynamical models based on perturbative QCD extrapolated down to 1-2 GeV momenta fail miserably to explain these data quantitatively. At the moment no non-perturbative explanations of the dynamics are yet available. The week after Bad Honnef workshop, at Quark Matte 2002 in Nantes, many of these statements got much stronger support from second RHIC run.

The second talk was about new development in semi-classical theory of high energy collisions, hadronic or heavy ions. Sudden deposition of energy makes virtual gluon fields real, without significant change in any of the coordinates. The same is true for the topological coordinate, the Chern-Simons number $N_{CS}$. It implies that virtual fields under the barrier in QCD vacuum (instantons) can be excited to states at the barrier. Those are, gluomagnetic clusters of particular structure, the “turning states” related to electroweak sphalerons and have the mass peaked in the range of 2.5-3 GeV. These clusters immediately explode into a thin shell of coherent transverse field which then becomes several outgoing gluons and quarks. New classical solutions for YM and Dirac eqns are found describing both processes. We argue that such clusters should be multiply produced in heavy ion collisions, and give some estimates of their effect at the RHIC energies.

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Baryon Form Factors and GPD’s
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An important part of the Jefferson Lab (JLab) current and long range programme is to measure form factors and exclusive reactions out to as high momentum transfer as possible. In parallel, during the past several years there has been important progress in the characterization of these reactions at experimentally accessible momentum transfers, in terms of generalized parton distributions (GPDs). A variety of exclusive form factor like reactions provide different moments $< x^m >$ of these GPD’s. For example the elastic form factors give us the $m = 0$ moments, while Compton scattering and high-$t$ meson production provide the $m = -1$ moments of the $H$ and $E$ GPD’s. The $N \rightarrow \Delta$ resonance transition magnetic form factor $G_M^{\Delta}$ selects the isovector components. As a function of $t$ these reactions provide important constraints on models of the transverse and longitudinal structure of the nucleon and it’s excitations, which were accessible to inclusive deep inelastic scattering (DIS).

As an example, following ref. [1] I have obtained GPD’s from two-body model wave functions [2] with a wave function having a Gaussian plus power law dependence on parton $k_\perp$, which is constrained to agree simultaneously with experimental data on $G_M^p$ and $G_E^p/G_M$ over the full range of measured $Q^2$. Reasonable results can then also be obtained for other form factors, such as the $G_M^\Delta$ for the $N \rightarrow \Delta$ transition, for which the relevant GPD is approximated by the isovector part of elastic GPD. This is shown in Figure 1 below. The GPD’s are currently being applied to the neutron form factors using isospin invariance.

Figure 1: Left: Proton magnetic form factor $G_M^p/G_D$, where $G_D = 1/(1 + Q^2/0.71)^2$. The data are from SLAC [3]. The curves are GPD fits as in ref. [2]. The dashed curve uses a Gaussian parton $k_\perp$ wave function, while the solid curve uses a Gaussian plus power $k_\perp$ wave function [4]. Centre: Proton electric form factor $G_E^p/G_M$. The data are from JLab [4], and the curve is the GPD fit. Right: The $P \rightarrow \Delta$ form factor $G_M^\Delta/3G_D$. The data is a world compilation. The curve utilizes the isovector part of the GPD’s obtained in the right and centre elastic form factors, renormalized to account for the measured value at $Q^2 = 0$. 

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In summary, it is expected that the theoretical community will continue to more rigorously progress with the application of GPDs to high $t$ exclusive reactions in parallel with the anticipated progress in experimental measurements.

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Small x phenomena and gluon tomography of nucleon

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It was demonstrated in [1] for the case of small x and in [2] in a general case that in the limit of large $Q^2$ the amplitude of the process $\gamma^*_L + N \rightarrow V + N$ at fixed $x$ is factorized into the convolution of a hard interaction block calculable in perturbative QCD, the short-distance $q\bar{q}$ wave function of the meson, and the generalized/skewed parton distribution (GPD) in the nucleon. The t-dependence of GPD's provides unique information about the impact parameter distribution of the partons in nucleons. The data have confirmed a number of the predictions of [1] including approximate restoration of SU(3) symmetry, convergence of the t-slope of the $\rho^-$ meson production at large $Q^2$ to the slope of the $J/\psi$ production. The extension of the analysis of [1] in [3] to account for the finite transverse size effects for $J/\psi$ production indicates the squeezing starts already from $Q^2 \sim 0$. The difference of the t-dependences of $\rho$ and $J/\psi$ predicted in [3] agrees well with the recent HERA data. This allowed us [4] to use the data on $J/\psi$ photoproduction to extract the two-gluon form factor of nucleon $\Gamma(t)$ from the data. We find that $\Gamma(t) = (1 - t/m^2_{gg})^{-2}$ with $m^2_{gg} \approx 1 \text{GeV}^2$ provides a good description of the t-dependence of the elastic photoproduction of $J/\psi$-mesons between the threshold region of $E_\gamma = 11 \text{GeV}$ (Cornell), $E_\gamma = 19 \text{GeV}$ (SLAC) and $E_\gamma = 100 \text{GeV}$ (FNAL) including the strong energy dependence of the t-slope. It is also well matched with the recent HERA data. We argue that a larger mass scale entering in $\Gamma(x_i \geq 0.05, t)$ than in the e.m. form factor is due to suppression of scattering off the gluons belonging the soft pion fields for $x \geq 0.05$.

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Deeply virtual Compton scattering with soft pion production

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We discuss the extension of the Generalized Parton Distribution (GPD) formalism to hard exclusive processes such as deeply virtual Compton scattering (DVCS) involving the production of a soft pion. The evaluation of this process is relevant for DVCS experiments which do not have the resolution to distinguish the nucleon final state from a nucleon in addition with a soft pion.

In addition, the DVCS processes with an additional soft pion is also of interest by itself. Indeed, by using soft-pion theorems, it is shown to be possible to link the GPDs entering in the ordinary DVCS process and the DVCS process with an associated soft pion produced [1].

We also give first numerical predictions for the DVCS processes on the nucleon with an additional soft $\pi^0$ or $\pi^+$ and compare it with the original DVCS process.

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Experimental Tests of Chiral Dynamics

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The contribution discussed three different aspects of chiral dynamics. In the first part some recent experiments close to the \( \pi N \) threshold were presented showing good agreement for experiments with photons \( (Q^2 = 0) \) \[1\] but rather severe deviations for experiments with electrons \( (Q^2 \leq 0.1 \text{ (GeV/c)}^2) \) \[2\]. On the other hand, the generalized polarizabilities determined in virtual Compton scattering \( p(e, ep)\gamma \) at 0.3 \( \text{(GeV/c)}^2 \) agree well with the calculations of chiral perturbation theory \[3\]. This means that one may have to consider not so much a “convergence radius” of chiral perturbation theory, but some additional dynamics of the \( \pi \) cloud.

The second part took up this idea and showed how the observed narrow excited states of the nucleon below the \( \pi N \) threshold could be explained in the framework of chiral dynamics \[4\].

Thirdly, an attempt was made to put the ideas of effective field theories in the context of general many body physics.

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QCD operators and the chiral Lagrangian

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The low–energy behavior of strong interactions is described by the chiral Lagrangian, formulated as an expansion in derivatives of the pion field. It allows one to compute not only scattering amplitudes of soft pions, but also matrix elements of the vector and axial vector current operators between multipion states, describing electroweak interactions of pions. However, these are by no means the only “interesting” operators one can evaluate between soft–pion states. Certain classes of composite QCD operators arise in the factorized description of hard scattering processes in QCD, such as deeply virtual Compton scattering or hard electroproduction of multipion states, whose matrix elements define generalized parton distributions (GPD’s) or distribution amplitudes of the pions. These operators can be normalized at a low scale $\mu^2 < 1\text{GeV}^2$ (independent of the hard scale $Q^2$ of the scattering process), and the study of their matrix elements between soft–pion states is a legitimate problem of low-energy physics. These matrix elements are interesting in themselves, as well as as input for the calculation of chiral loop corrections to both pion and nucleon matrix elements.

In this talk I review some aspects of the problem of “bosonization” (i.e., translation into pion operators) of QCD operators appearing in the factorized description of hard scattering processes in QCD. While the vector and axial vector current operators of the effective chiral theory could be identified on grounds of their symmetry properties alone, this is generally not possible for the QCD operators appearing in the factorization of hard processes. A non-trivial exception is the energy–momentum tensor (EMT) of QCD, which is the Noether current related to translational invariance. Identifying the traceless part of the QCD EMT with the one derived from the chiral Lagrangian one obtains a sum rule for the second moment of the pion GPD’s [1]. A similar reasoning applied to the trace anomaly allows to determine the long–range interaction of heavy quarkonia from first principles [2].

In general, the translation of QCD composite operators into pion operators requires dynamical information. A very useful model in this respect is the picture of the QCD vacuum as “medium” of instantons [3]. It allows not only to derive the chiral Lagrangian (i.e., the constants $F_{\pi}^2$, etc.) but also provides a script for the bosonization of QCD operators, including such containing gluon fields [4]. This approach preserves subtle structures such as relations following from the QCD equations of motion or the $U(1)$ and trace anomalies. In particular, we review the predictions for higher–twist matrix elements (quark–gluon correlations) determining power corrections to deep–inelastic scattering.

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