A brief review of the modern QCD theory of diffractive DIS is given. The recent progress has been remarkably rapid, all the principal predictions from the color dipole approach to diffraction - the $(Q^2 + m_V^2)$ scaling, the pattern of SCHNC, shrinkage of the diffraction cone in hard diffractive DIS, the strong impact of longitudinal gluons in inclusive $J/\Psi$ production at Tevatron - have been confirmed experimentally.

1 Introduction: why diffractive DIS is so fundamental

Let us dream of $e$-Uranium DIS at THERA at $Q^2 \sim 10$ GeV$^2$ and $x \sim 10^{-5}$. Violent DIS is usually associated with complete destruction of the target. As well known, deposition of a mere dozen MeV energy would break the uranium nucleus entirely, but a paradoxical yet rigorous prediction from unitarity is that 

$diffractive DIS \ eU \rightarrow e'XU$ with the target nucleus emerging intact in the ground state will make $\approx 50\%$ of total DIS. 

By the celebrated Glauber-Gribov theory of interactions with nuclei, the abundance of diffraction is closely related to nuclear shadowing (NS) in DIS. To this end we recall that in 1974 Nikolaev and V.I. Zakharov reinterpreted NS in terms of the saturation of nuclear parton densities, caused by the spatial overlap of partons from different nucleons of the Lorentz-contracted nuclei. More recently, the NZ picture of saturation has been addressed.

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\[\text{Invited talk at the International Conference on New Trends in High Energy Physics, (experiment, phenomenology, theory), Yalta, Crimea, Ukraine, 22-29 September, 2001,}\]
to within QCD by McLerran and his collaborators \[3\]. If correct, this QCD approach must inevitably lead to 50% diffractive DIS - whether that would be the case or not would serve as a crucial cross-check of the whole approach.

To summarize, diffractive DIS is a key to nuclear parton densities and QCD predictions for the initial state in ultrarelativistic nuclear collisions. Because at HERA the rate of diffractive DIS is mere 10% \[4\], saturation effects are all but marginal, see \[5\].

In this talk I focus on the color dipole approach to diffraction, a more phenomenological approach based on the Regge theory ideas was discussed at the Conference by Kaidalov \[6\].

2 Color dipole link between inclusive and diffractive DIS

Structure functions (SF’s) of DIS are related by optical theorem to the imaginary part of an amplitude of diagonal, \(Q^2_f = Q^2_{in} = Q^2\), forward virtual Compton scattering (CS) \(\gamma_\nu^*(Q^2_{in})p \rightarrow \gamma_\nu^*(Q^2_f)p'\), which for the reason of vanishing \(\gamma^*, \gamma^*\) momentum transfer happens to be diagonal in the photon helicities, \(\nu = \mu\). In the color dipole (CD) factorization \[7\] the CS amplitude takes the form \(A_{CS} = \Psi_f^* \otimes A_{q\bar{q}} \otimes \Psi_{in}\) where \(\Psi_{f, in}\) is the wave function (WF) of the \(q\bar{q}\) Fock state of the photon and the \(q\bar{q}\)-proton scattering kernel \(A_{q\bar{q}}\) is proportional to the color dipole cross section, which for small dipoles is related to the gluon SF of the target,

\[
\sigma(x, r) \approx \frac{\pi^2}{3} r^2 \alpha_s \left( \frac{A}{r^2} \right) G(x, \frac{A}{r^2}).
\]

where \(A \approx 10\) by properties of the Bessel functions \[8\]. Taking for \(\Psi_f^*\) the WF of the vector meson (VM) or the \(X = q\bar{q}\) plane waves gives the diffraction excitation of VM \[8\] or hadronic continuum, \(\gamma^*p \rightarrow Xp'\). The complete set of \(q\bar{q}\) dipoles can be substituted for by a dual complete set of vector meson states, for the discussion of this relationship see Schildknecht’s talk at this Conference \[9\].

Alternatively, diffractive VM production can be obtained from CS keeping the virtuality of the initial photon, \(Q^2 = Q^2_{in}\), fixed, while continuing analytically in the second photon’s virtuality to \(Q^2_f = -m_V^2, \ \gamma_\nu^*(Q^2)p \rightarrow \)
$V_v(\Delta)p'(-\Delta)$. Diffractive VM production is accessible experimentally also at finite ($\gamma^*V$) momentum transfer $\Delta$.

Generalization to excitation of the $q\bar{q}g$ or higher Fock states of the photon is straightforward [10, 11], within the CD approach inclusive cross section of diffractive DIS is simply a sum of differential cross sections of quasielastic scattering of different Fock states of the virtual photon off the target nucleon or nucleus. To this end, one may say that diffractive DIS probes the partonic structure of the virtual photon [10, 11, 4] in a manner closely related to how the structure of the deuteron is probed in diffraction excitation of the deuteron to the proton-neutron continuum states. With certain reservations CD results can be reinterpreted in terms of the parton structure of the pomeron. For virtual photons, higher Fock states of the photon build up perturbatively starting from the lowest $q\bar{q}$ state, which entails the solid result [10, 11, 4] that gluons and charged partons carry about an equal fraction of the momentum of the pomeron.

The formalism set in [10, 11] and especially in [1, 12, 13, 14] is a basis of modern parameterizations of the diffractive structure function [15]. Unfortunately the use of the discredited Ingelman-Schlein-Regge factorization and DGLAP evolution which is not warranted at large $\beta$ [11, 12, 13, 14]. Also, the intrinsic transverse momentum of gluons [16] has not yet been incorporated correctly into the diffractive jet analysis [17]. For the above reasons, the still simplified form of this analysis makes conclusions [15, 17, 18] on the gluon content of the pomeron highly suspect.

3 The $Q^2 + m_V^2$ scaling

While DIS probes CD $\sigma(x,r)$ in a broad range of $\frac{1}{\lambda Q^2} \lesssim r^2 \lesssim 1 \text{ fm}^2$, the diffractive VM production probes $\sigma(x,r)$ at a scanning radius [19, 5]

$$r \sim r_S = \frac{6}{\sqrt{Q^2 + m_V^2}},$$

and the gluon SF of the target at the hard scale $Q^2 \approx (0.1-0.25)\ast(Q^2 + m_V^2)$ and $x = 0.5(Q^2 + m_V^2)/(Q^2 + W^2)$. After factoring out the charge-isospin factors, that entails the $(Q^2 + m_V^2)$ scaling of the VM production cross section [5], see fig. 1. The same scaling holds also for the effective
Figure 1: The test of the \((Q^2 + m_V^2)\) scaling. The divergence of the solid and dashed curves indicates the sensitivity to the WF of the VM. The experimental data are from HERA [20].

The intercept \(a_H(0) - 1\) of the energy dependence of the production amplitude and contribution to the diffraction slope \(B\) from the \(\gamma^* \rightarrow V\) transition vertex, which is \(\propto r_S^2\) and exhibits the \((Q^2 + m_V^2)\) scaling [21, 22], see fig. 2. This \((Q^2 + m_V^2)\) scaling formulated in 1974, has recently become a popular way of presenting the experimental data [18]. The theoretical calculations [23] are based on the differential glue in the proton found in [24].
Figure 2: The \((Q^2 + m_V^2)\) scaling of the effective intercept and diffraction slope \cite{23}.

4 Shrinkage of the diffraction cone in hard diffraction

Gribov’s shrinkage of the diffraction cone \(B = B_0 + 2\alpha'_I \log W^2\), quantized in terms of the slope \(\alpha'_I\) of the pomeron trajectory, is the salient feature of hadronic scattering. By the unitarity relation, diffractive elastic scattering is driven by multiproduction processes, and in the unitarity context the shrinkage of the diffraction cone is well known to derive from the Gribov-Feinberg-Chernavski diffusion in the impact parameter space.

At this Conference, we heard from Whitmore of the ZEUS finding \cite{18} of the shrinkage of the diffraction cone in \(\gamma p \rightarrow J/\Psi p\) with the result

\[
\alpha'_{eff} = 0.122 \pm 0.033\,(stat) + 0.018 - 0.032\,(syst) \text{ GeV}^{-2}.
\]
Precisely such a shrinkage has been predicted in 1995 by Nikolaev, Zakharov and Zoller [21] to persist within QCD even for hard processes.

First, in the usual approximation $\alpha_S = \text{const}$ the BFKL pomeron is the fixed cut in the complex-$j$ plane [25]. Already in their first, 1975, publication on QCD pomeron, Kuraev, Lipatov and Fadin commented that incorporation of the asymptotic freedom splits the cut into a sequence of moving Regge poles [25], see Lipatov [26] for more details. Within the CD approach, the Regge trajectories of these poles where calculated in [21, 27]. The CD cross section satisfies the CD BFKL equation [28],

$$\frac{\partial \sigma(x,r)}{\partial \log \frac{1}{x}} = K \otimes \sigma(x,r),$$

which has the Regge solutions

$$\sigma_n(x,r) = \sigma_n(r)x^{-\Delta_n}.$$ 

The CD kernel $K$ is related to the flux of Weizsäcker-Williams gluons around the $q\bar{q}$ dipole.

The NZZ strategy was to evaluate $\alpha'_n$ from the energy dependence of $\lambda(x,r) = B\sigma(x,r)$, which satisfies the inhomogeneous equation

$$\frac{\partial \lambda(x,r)}{\partial \log \frac{1}{x}} - K \otimes \lambda(x,r) = L \otimes r^2 \sigma(x,r),$$

and has solutions

$$\lambda_n(x,r) = 2\sigma_n(x,r) \cdot \alpha'_n \log \frac{1}{x},$$

which correspond to the Regge rise of the diffraction slope with energy. Because $B = \frac{1}{2}\langle b^2 \rangle$ and the impact parameter $b$ receives a contribution from the gluon-$q\bar{q}$ separation $\rho$, the inhomogeneous term $L \otimes r^2 \sigma(x,r)$ is driven by precisely the impact parameter diffusion of WW gluons. Because $\alpha'_n$ is driven by the inhomogeneous term, there is a manifest relationship between $\alpha'_n$ and the Gribov-Feinberg-Chernavski diffusion in the impact parameter space. Evidently, the dimensionfull quantity $\alpha'_n$ depends on the infrared regularization of QCD, within the specific regularization [28, 29] which has lead to an extremely successful description of the proton structure function (see [30] and references therein), for the rightmost hard BFKL pole we found $\alpha'_{IP} \approx 0.07$ GeV$^{-2}$. The contribution from subleading BFKL poles was found to be still substantial at subasymptotic energy of HERA with the result $\alpha'_{eff} \approx 0.15 - 0.17$ GeV$^{-2}$ [21], this prediction from 1995 agrees perfectly with the ZEUS finding.
5 Digression: Longitudinal photons and gluons in DIS

In DIS incident leptons serve as a source of virtual photons and experimentally one studies a virtual photoproduction of various hadronic states. While real photons are transverse ones, i.e., have only circular polarizations, $\mu = \pm 1$, virtual photons radiated by leptons have also the longitudinal polarization, which in the scaling limit equals

$$ \epsilon_L = \frac{2(1 - y)}{2(1 - y) + y^2}, $$

where $y$ is a fraction of the beam lepton energy taken away by the photon, so that the photoabsorption cross section measured in the inclusive DIS equals $\sigma = \sigma_T + \epsilon_L \sigma_L$. The effect of longitudinal photons, quantified by $R_{DIS} = \sigma_L / \sigma_T \sim 0.2$, is marginal, though.

The branching of gluons into gluons is a dominant feature of QCD evolution at small $x$. In the conventional collinear approximation one treats gluons as having only the physical transverse polarizations. However, in close analogy to virtual photons, virtual gluons have also a substantial longitudinal polarization. In striking contrast to inclusive DIS, diffractive excitation of VM and small mass continuum is that they are entirely dominated by $\sigma_L$ [5, 13]. As we shall see below, in inclusive production too interaction of longitudinal virtual photons could be outstanding in defiance of the collinear factorization [31].

6 Spin dependence of vector meson production

Regarding the spin dependence of diffractive VM, the fundamental point is that the sum of quark and antiquark helicities equals helicity of neither the photon nor vector meson. If for the nonrelativistic massive quarks, $m_q^2 \gg Q^2$ the only allowed transition is $\gamma^*_\mu \to q_\lambda + \bar{q}_\bar{\lambda}$ with $\lambda + \bar{\lambda} = \mu$. In the relativistic case transitions of transverse photons $\gamma^*_\perp$ into the $q\bar{q}$ state with $\lambda + \bar{\lambda} = 0$, in which the helicity of the photon is transferred to the $q\bar{q}$ orbital momentum, are equally allowed. Consequently, in QCD the $s$-channel
helicity non-conserving (SCHNC) transitions

\[ \gamma^* \rightarrow (q\bar{q})_{\lambda+\bar{\lambda}=0} \rightarrow \gamma_L^* \]

and

\[ \gamma^* \rightarrow (q\bar{q})_{\lambda+\bar{\lambda}=0} \rightarrow \gamma_T^* \]

are allowed \[32, 33\] and SCHNC persists at small \( x \) despite the exact conservation of the helicity of quarks in \( q\bar{q} \)-target scattering. This argument for SCHNC does not require the applicability of pQCD. Furthermore, the leading contribution to the proton structure function comes entirely from SCHNC transitions of transverse photons \[24\] - the fact never mentioned in textbooks.

We emphasize that SCHNC helicity flip only is possible due to the transverse and/or longitudinal Fermi motion of quarks and is extremely sensitive to spin-orbit coupling in the vector meson, I refer for details to \[33, 34\]. The consistent analysis of production of \( S \)-wave and \( D \)-wave vector mesons is presented only in \[34\]. The dominant SCHNC effect in vector meson production is the interference of SCHC \( \gamma_L^* \rightarrow V_L \) and SCHNC \( \gamma_T^* \rightarrow V_L \) production, i.e., the element \( r_{00}^5 \) of the vector meson spin density matrix. The overall agreement between our theoretical estimates \[23\] of the spin density matrix \( r_{ik}^n \) for diffractive \( \rho^0 \) assuming pure \( S \)-wave in the \( \rho^0 \)-meson and the ZEUS \[35\] and H1 \[36\] experimental data is very good, there is a clear evidence for \( r_{00}^5 \neq 0 \), see fig. 3.

7 Issues with \( R = \sigma_L/\sigma_T \)

Still another fundamental point about spin properties of diffractive DIS is that the vertex of the SCHC transition \( \gamma_L^* \rightarrow (q\bar{q})_{\lambda+\bar{\lambda}=0} \) is proportional to \( Q \), which entails \[3\]

\[ R = \frac{\sigma_L(\gamma_L^*p \rightarrow V_Lp)}{\sigma_T(\gamma_T^*p \rightarrow V_Tp)} \sim \frac{Q^2}{m_V^2} \gg 1 \]

for diffractive VM’s. As was first noticed in \[3\], a numerical analysis with realistic soft WF gives values of \( R \) substantially smaller than a crude estimate \( R \approx Q^2/m_V^2 \). Still, the theoretical calculations \[23\] seem to overpredict \( R = \sigma_L/\sigma_T \) at large \( Q^2 \), see fig. 4, for the compilation of the experimental data see \[37\].
As it was shown in [34], $R = \sigma_L/\sigma_T$ is very different for the $S$ and $D$-wave states. As a result, an admissible $S - D$ mixing brings the theory to a better agreement with the data, see fig. 4. Furthermore, the recent data from ZEUS [37] do indicate, the experimental value of $R$ tends to rise with the time. Here I would like to raise the issue of sensitivity of $R$ to the short distance properties of vector mesons [38].

Consider $R_{el} = \sigma_L/\sigma_T$ for elastic CS $\gamma^* p \rightarrow \gamma^* p$, which is quadratic in
the ratio of CS amplitudes. By optical theorem one finds

\[ R_{el} = \frac{\sigma_L(\gamma_L^*p \rightarrow \gamma_L^*p)}{\sigma_T(\gamma_T^*p \rightarrow \gamma_T^*p)} = \left| \frac{A(\gamma_L^*p \rightarrow \gamma_L^*p)}{A(\gamma_T^*p \rightarrow \gamma_T^*p)} \right|^2 = \left( \frac{\sigma_L}{\sigma_T} \right)^2_{DIS} \approx 4 \cdot 10^{-2} \]

Here I used the prediction \[23\] for inclusive DIS \( R_{DIS} = \sigma_L/\sigma_T |_{DIS} \approx 0.2, \)
which is consistent with the indirect experimental evaluations of \( R_{DIS} \) at HERA. Such a dramatic change from \( R_{el} \ll 1 \) to \( R \sim Q^2/m_V^2 \ll 1 \) suggests that predictions for \( R \) in diffractive VM production are extremely sensitive to the poorly known admixture of quasi-pointlike \( q\bar{q} \) components in VM.

8 Longitudinal gluons and polarization of a direct \( J/\Psi \) and \( \Psi' \) at Tevatron

There is a long standing mystery of the predominant longitudinal polarization of prompt \( J/\Psi \) and \( \Psi' \) produced at large transverse momentum \( p_\perp \) as observed

Figure 4: The sensitivity of \( R = \sigma_L/\sigma_T \) for the \( \rho \) production to the S-D-mixing \[23\], for the compilation of the experimental data see \[37\].
by the CDF collaboration in inclusive $p\bar{p}$ interactions at Tevatron \[39\], see fig. 5, in which the polarization parameter

$$\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + \sigma_L}$$

is shown (the observed $\Psi'$ are arguably the direct ones, the prompt $J/\Psi$'s include the $J/\Psi$'s both from the direct production and decays of higher charmonium states) . Specifically, the color-octet model \[40\] is able to parameterize the observed reaction cross section (for a criticism of the standard formulation of the color-octet model see \[41\]), but fails badly in its predictions \[42, 43\] for the polarization parameter $\alpha$, see fig. 5.

Figure 5: Predictions \[42, 43\] from the color-octet model for the polarization parameter $\alpha$ vs. $p_\perp$ for direct $\Psi$ and prompt $J/\Psi$ compared to CDF data \[39\].

Arguably, production of charmonium states at mid-rapidity is controlled by gluon-gluon collisions. Now recall that in the standard collinear factorization the colliding gluons are regarded as on-mass shell, and transversely polarized, ones. Which is the principal reason, why one predicts the predominantly transverse polarization of the produced $J/\Psi$ and $\Psi'$.

The QCD subprocesses for direct production of $C = -1$ vector states of charmonium are shown in fig. 6. In order to emphasize an impact of their virtuality of the colliding gluons, I indicate explicitly the origin of the gluon $g^*$. As I mentioned in section 5, beside the familiar transverse polarization,
Figure 6: The diffractive QCD subprocesses for the production of prompt vector states of charmonium in hadronic reactions.

Highly virtual gluons have also the hitherto ignored longitudinal polarization [31].

In order to illustrate our principal point let me focus on the ”diffractive” mechanism of fig. 6a. It dominates at large invariant masses $\hat{w}$ of the $Vg'$ system, $\hat{w}^2 \gg M_{\Psi}^2$. The virtuality of the gluon $g^*$ is controlled by the transverse momentum $k_\perp$ of the gluon $g^*$, so that $Q^2 \approx k_\perp^2$. The sub-process $g^* + g \rightarrow J/\Psi g'$ proceeds predominantly in the forward direction, which implies that the transverse momentum of the $g^*$ is transferred to the $J/\Psi$, so that $p_\perp \approx k_\perp$. The difference between color octet two-gluon state in the $t$-channel of fig. 6a and color-singlet two gluon state in the diffractive pomeron exchange is completely irrelevant for spin properties of the $J/\Psi$ production, and for the diffractive mechanism of fig. 6a we unequivocally predict $R = \sigma_L/\sigma_T \sim p_\perp^2/m_{\Psi}^2$, i.e., $\alpha \rightarrow -1$ for very large $p_\perp$. After some color algebra, one can readily relate the total cross section of the ”diffractive” mechanism to the cross section of photoproduction of $J/\Psi$ on nucleons. We found that ”diffractive” mechanism is short of strength and could explain only $\sim 10$ per cent of the observed yield of the direct $J/\Psi$.

The diagrams of fig. 6b dominate for $\hat{w} \sim m_{\Psi}$. Arguably, the above estimate for the $p_\perp$ dependence of $R$ applied to this mechanism too. Crude estimates show that the contribution from this mechanism is commensurate to, or larger than, that from the ”diffractive” large-\hat{w} mechanism.

Besides the predominantly ”forward” production when the transverse momentum of the $g^*$ is transferred predominantly to the direct $J/\Psi$, one must also consider the large angle reaction $g^*g \rightarrow J/\Psi + g$, which could affect the polarization parameter $\alpha$. The full numerical analysis has not been com-
pleted yet, still we believe that the so far neglected longitudinal gluons resolve a riddle of the longitudinal polarization of direct $J\Psi$ and $\Psi'$.

9 Conclusions

The QCD theory of diffractive DIS is gradually coming of age. The fundamental $(Q^2 + m_V^2)$ scaling predicted in 1994 has finally been recognized by experimentalists. The shrinkage of the diffraction cone for hard photoproduction $\gamma p \rightarrow J/\Psi p$ discovered by the ZEUS collaboration is the single most important result. It shows that the BFKL pomeron is a (series of) moving pole(s) in the complex-$j$ plane. The slope of the pomeron trajectory and the rate of shrinkage of the diffraction cone for hard photo- and electroproduction predicted in 1995 has been confirmed experimentally. So far neglected longitudinal gluons are predicted to dominate production of direct vector mesons at large transverse momentum in hadronic collisions and resolve the long-standing riddle of the dominant longitudinal polarization of the $J/\Psi$ and $\Psi'$ discovered by CDF.

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