The wave function of 2S radially excited vector mesons from data for diffraction slope

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Abstract

In the color dipole gBFKL dynamics, we predict a strikingly different $Q^2$ and energy dependence of the diffraction slope for the elastic production of ground state $V(1S)$ and radially excited $V'(2S)$ light vector mesons. The color dipole model predictions for the diffraction slope for $\rho^0$ and $\phi^0$ production are in a good agreement with the data from the fixed target and collider HERA experiments. We present how a different form of anomalous energy- and $Q^2$ dependence of the diffraction slope for $V'(2S)$ production leads to a different position of the node in radial wave function and discuss a possibility how to determine this position from the fixed target and HERA data.
1 Introduction

Diffractive photo- and electrodproduction of vector mesons

\[ \gamma^* p \to V p, \quad (V = \rho^0, \Phi^0, \omega^0, J/\Psi, \Upsilon...) \]

is presently intensively studied at HERA and represent a good cross check to test the ideas implemented into various theoretical models \[1, 2, 3, 4, 5, 6, 7, 8, 9\] within the framework of the perturbative QCD (pQCD). Moreover, the high statistics data at HERA during a several last years also to study diffractive electroproduction of radially excited \( V'(2S) \) vector mesons, which are known to have a node (the node effect \[2, 4, 10, 11\]) in the radial wave function leading to peculiarities in investigation of various aspects of their diffractive production. In this paper we demonstrate further salient features of the node effect in conjunction with the gBFKL phenomenology of the diffraction slope \[13, 14, 12\] leading to an anomalous energy and \( Q^2 \) dependence of the diffraction cone.

The details of the gBFKL phenomenology of diffractive electroproduction of vector mesons has been presented in the paper \[11\] and will not be repeated here. The same concerns to the color dipole phenomenology of the diffraction slope for photo- and electro-production of heavy vector mesons developed in the paper \[12\]. We start with the principal result coming from the analysis of the diffractive production of light \[6, 11\] and heavy \[12\] vector mesons at \( t = 0 \) within the gBFKL phenomenology and leading to the conclusion that the 1S vector meson production amplitude probes the color dipole cross section (and the dipole diffraction slope as well) at the dipole size \( r \sim r_S \) (scanning phenomenon \[13, 1, 2, 3\]), where the scanning radius can be expressed through the scale parameter \( A \), photon virtuality \( Q^2 \) and vector meson mass \( m_V \):

\[ r_S \approx \frac{A}{\sqrt{m_V^2 + Q^2}}. \]

Scanning phenomenon allows to study the transition between the perturbative (hard) and nonperturbative (soft) regimes. Changing \( Q^2 \) and the mass of the produced vector meson, one can probe the dipole cross section \( \sigma(\xi, r) \), and the dipole diffraction slope \( B(\xi, r) \) in a very broad range of the dipole sizes, \( r \).

Radially excited \( V'(2S) \) vector mesons can extend an additional information on the dipole cross section and dipole diffraction slope. The presence of the node in the 2S radial wave function leads to the node effect (a strong cancellation of the dipole size contributions to the production amplitude from the region above and below the node position, \( r_n \), in the 2S radial wave function \[3, 15, 12, 11\]). For this reason, the amplitudes for the electroproduction of the 1S and 2S vector mesons probe \( \sigma(\xi, r) \) and \( B(\xi, r) \) in a different way. The onset of the node effect depends on vector meson mass. The node effect has been found to be a strong in electroproduction of radially excited light vector mesons (\( \rho^0, \Phi^0, \omega^0 \)) \[11\] leading to an anomalous \( Q^2 \) and energy dependence of the production cross section. However, node effect is much weaker for the electroproduction of 2S heavy vector mesons (\( J/\Psi, \Upsilon, ... \)) For production of charmonia it leads to a slightly different \( Q^2 \) and energy dependence of the production cross section for \( \Psi' \) vs. \( J/\Psi \) and to a counterintuitive inequality \( B(\Psi') < B(J/\Psi) \) \[12\].
For \( \Upsilon' \) production, the node effect is negligible small and gives approximately the same \( Q^2 \) and energy behaviour of the production cross section and practically the same diffraction slope at \( t = 0 \) for \( \Upsilon \) and \( \Upsilon' \) production [12]. Therefore, it is very important to explore farther the salient features of the node effect with conjunction with the emerging gBFKL phenomenology of the diffraction slope especially in production of \( V'(2S) \) light vector mesons where the node effect is expected to be very strong.

Two main reasons affect the cancellation pattern in the diffraction slope for \( 2S \) state. The first reason is connected with the \( Q^2 \) behaviour of the scanning radius \( r_S \) (see (2)); for the electroproduction of \( V'(2S) \) light vector mesons at moderate \( Q^2 \) when the scanning radius \( r_S \) is close to \( r_n \), due to \( \sim r^2 \) behaviour of \( B(\xi, r) \) [13] even a slight variation of \( r_S \) with \( Q^2 \) strongly changes the cancellation pattern and leads to an anomalous \( Q^2 \) dependence of the forward diffraction slope, \( B(t = 0) \) [12]. The second reason is due to different energy dependence of \( \sigma(\xi, r) \) at different dipole sizes \( r \) coming from the gBFKL dynamics leading also to an anomalous energy dependence of \( B(t = 0) \) for the \( V'(2S) \) production.

The effects mentioned above are sensitive to the form of the dipole cross section and the dipole diffraction slope. In Ref. [16] ([17]) we presented the first direct determination of the color dipole cross section (color dipole diffraction slope) from the data on the photo- and electroproduction of \( V(1S) \) vector mesons. So extracted dipole cross section (dipole diffraction slope) is in a good agreement with the dipole cross section (dipole diffraction slope) obtained from gBFKL analysis [18, 6] ([13, 14, 12]). This fact confirms a very reasonable choice of the nonperturbative component of the dipole cross section (dipole diffraction slope) corresponding to a soft nonperturbative mechanism contribution to the scattering amplitude.

Due to a large value of the scale parameter in (2), the large-distance contributions to the production amplitude from the semiperturbative and nonperturbative region of color dipoles \( r \gtrsim R_c \) becomes substantial (\( R_c \sim 0.27 fm \) is gluon correlation radius introduced in [19, 20]). Only the virtual \( \rho^0 \) and \( \phi^0 \) photoproduction at \( Q^2 \gtrsim 100 \text{ GeV}^2 \) can be treated as a purely perturbative process, when the production amplitude is dominantly contributed from the perturbative region, \( r \lesssim R_c \).

In the present paper we concentrate on the production of \( V'(2S) \) radially excited light vector mesons, where the node in the radial wave function in conjunction with the subasymptotic energy dependence of \( B(\xi, r) \) leads to a strikingly different \( Q^2 \) and energy dependence of the diffraction slope for the production of \( V'(2S) \) vs. \( V(1S) \) vector mesons. We also study how the position of the node in the radial wave function for \( V'(2S) \) vector mesons can be extracted from the data. We present an exact prescription how the experimental measurement of the \( Q^2 \) and energy dependence of the diffraction slope for \( V'(2S) \) production could distinguish between the undercompensation and overcompensation scenarios of the \( 2S \) production amplitude (see Section 4). The explicit form of that \( Q^2 \)- and energy behaviour of the diffraction slope is connected with the position of the node in radial wave function for \( V'(2S) \) vector mesons. This paper is organized as follows. In section 2 we present a very short review of the the color dipole phenomenology of the diffractive photo- and electroproduction of vector mesons including some needful results from the gBFKL phenomenology of the diffraction slope. Section 3 contains the model predictions for \( Q^2 \) and energy depen-
dence of the forward diffraction slope for the $\rho^0$ and $\phi^0$ real and virtual electroproduction. We predict a substantial growth of the diffraction slope with energy in a good agreement with the low energy data and the data from the HERA collider experiments. The subject of section 4 concerns to the anomalous $Q^2$ and energy dependence of diffraction slope for electroproduction of $2S$ radially excited light vector mesons. The summary and conclusions are presented in section 5.

2 Basic formulas from the color dipole phenomenology of vector meson production and the diffraction slope

In the mixed $(r, z)$ representation, the high energy meson is considered as a system of color dipole described by the distribution of the transverse separation $r$ of the quark and antiquark given by the $q\bar{q}$ wave function, $\Psi(r, z)$, where $z$ is the fraction of meson’s lightcone momentum carried by a quark. The Fock state expansion for the relativistic meson starts with the $q\bar{q}$ state and the higher Fock states $q\bar{q}g...$ become very important at high energy $\nu$. The interaction of the relativistic color dipole of the dipole moment, $r$, with the target nucleon is quantified by the energy dependent color dipole cross section, $\sigma(\xi, r)$, satisfying the gBFKL equation [19, 20] for the energy evolution. This reflects the fact that in the leading-log $1/x$ approximation the effect of higher Fock states can be reabsorbed into the energy dependence of $\sigma(\xi, r)$. The dipole cross section is flavor independent and represents the universal function of $r$ which describes various diffractive processes in unified form. At high energy, when the transverse separation, $r$, of the quark and antiquark is frozen during the interaction process, the scattering matrix describing the $q\bar{q}$-nucleon interaction becomes diagonal in the mixed $(r, z)$-representation ($z$ is known also as the Sudakov light cone variable). This diagonalization property is held even when the dipole size, $r$, is large, i.e. beyond the perturbative region of short distances.

Following an advantage of the $(r, z)$-diagonalization of the $q\bar{q} - N$ scattering matrix, the imaginary part of the production amplitude for the real (virtual) photoproduction of vector mesons with the momentum transfer $q$ can be represented in the factorized form

$$\text{Im}\mathcal{M}(\gamma^* \rightarrow V, \xi, Q^2, q) = \langle V|\sigma(\xi, r, z, q)|\gamma^*\rangle = \int_0^1 dz \int d^2r \sigma(\xi, r, z, q)\Psi^*_V(r, z)\Psi_{\gamma^*}(r, z)$$

(3)

whose normalization is $d\sigma/dt|_{t=0} = |\mathcal{M}|^2/16\pi$. In Eq. (3), $\Psi_{\gamma^*}(r, z)$ and $\Psi_V(r, z)$ represent the probability amplitudes to find the color dipole of size, $r$, in the photon and quarkonium (vector meson), respectively. The color dipole distribution in (virtual) photons was derived in [21, 19]. $\sigma(\xi, r, z, q)$ is the dipole scattering matrix for $q\bar{q} - N$ interaction and represents the above mentioned color dipole cross section for $q = 0$. At small $q$ considered in this paper, one can safely neglect the $z$-dependence of $\sigma(\xi, r, z, q)$ for light and heavy vector meson production and set $z = \frac{1}{2}$. This follows partially from the analysis within double gluon exchange approximation [21] leading to a slow $z$ dependence of the dipole cross section.

The energy dependence of the dipole cross section is quantified in terms of the dimen-
sionless rapidity, $\xi = \log \frac{1}{x_{\text{eff}}}$, where $x_{\text{eff}}$ is the effective value of the Bjorken variable

$$x_{\text{eff}} = \frac{Q^2 + m_V^2}{Q^2 + W^2} \approx \frac{m_V^2 + Q^2}{2\nu m_p},$$

(4)

where $m_p$ is the proton mass. Hereafter, we will write the energy dependence of the dipole cross section in both variables, either in $\xi$ or in $x_{\text{eff}}$.

The production amplitudes for the transversely (T) and the longitudinally (L) polarized vector mesons with the momentum transfer, $q$, can be written in more explicit form

$$\text{Im}\mathcal{M}_T(x_{\text{eff}}, Q^2, q) = \frac{N_c C_V \sqrt{4\pi\alpha_{\text{em}}}}{(2\pi)^2} \cdot \int d^2r \sigma(x_{\text{eff}}, r, q) \int_0^1 \frac{dz}{z(1-z)} \left\{ m_q^2 K_0(\varepsilon r) \phi(r, z) - [z^2 + (1-z)^2]\varepsilon K_1(\varepsilon r) \partial_r \phi(r, z) \right\}$$

$$= \frac{1}{(m_V^2 + Q^2)^2} \int \frac{dr^2 \sigma(x_{\text{eff}}, r, q)}{r^2} W_T(Q^2, r^2)$$

(5)

$$\text{Im}\mathcal{M}_L(x_{\text{eff}}, Q^2, q) = \frac{N_c C_V \sqrt{4\pi\alpha_{\text{em}}}}{(2\pi)^2} \frac{2\sqrt{Q^2}}{m_V} \cdot \int d^2r \sigma(x_{\text{eff}}, r, q) \int_0^1 dz \left\{ [m_q^2 + z(1-z)m_V^2] K_0(\varepsilon r) \phi(r, z) - \varepsilon K_1(\varepsilon r) \partial_r \phi(r, z) \right\}$$

$$= \frac{1}{(m_V^2 + Q^2)^2} \frac{2\sqrt{Q^2}}{m_V} \int \frac{dr^2 \sigma(x_{\text{eff}}, r, q)}{r^2} W_L(Q^2, r^2)$$

(6)

where

$$\varepsilon^2 = m_q^2 + z(1-z)Q^2,$$

(7)

$\alpha_{\text{em}}$ is the fine structure constant, $N_c = 3$ is the number of colors, $C_V = \frac{1}{\sqrt{2}}, \frac{1}{3\sqrt{2}}, \frac{1}{2}, \frac{2}{3}, \frac{1}{3}$ for $\rho^0, \omega^0, \phi^0, J/\Psi, \Upsilon$ production, respectively and $K_{0,1}(x)$ are the modified Bessel functions. The detailed discussion and parameterization of the lightcone radial wave function $\phi(r, z)$ of the $q\bar{q}$ Fock state of the vector meson is given in [11].

The terms $\propto \varepsilon K_1(\varepsilon r) \partial_r \phi(r, z)$ for $T$ polarization and $\propto K_0(\varepsilon r) \partial_r^2 \Phi(r, z)$ for $L$ polarization in the integrands of (3) and (4) represent the relativistic corrections which become important at large $Q^2$ and for the production of light vector mesons. For the production of heavy quarkonia, the nonrelativistic approximation can be used with a rather high accuracy [2].

The weight functions, $W_T(Q^2, r^2)$ and $W_L(Q^2, r^2)$, introduced in (3) and (4) have a smooth $Q^2$ behaviour and are very convenient for the analysis of the scanning phenomenon. They are sharply peaked at $r \approx A_{T,L}/\sqrt{Q^2 + m_V^2}$. At small $Q^2$ the values of the scale parameter $A_{T,L}$ are close to $A \sim 6$, which follows from $r_S = 3/\varepsilon$ with the nonrelativistic choice $z = \frac{1}{2}$. In general, $A_{T,L} \geq 6$ and increases slowly with $Q^2$ [3]. For heavy vector meson production, the scale parameters $A_{T,L} \sim 6$ for $\Upsilon$ at $Q^2 \leq 100$ GeV$^2$ and $A_{T,L} \sim 6$ at $Q^2 = 0$ and $A_{T,L} \sim 7$ at $Q^2 = 100$ GeV$^2$ for $J/\Psi$. For this reason, the heavy vector mesons can be treated nonrelativistically, except for small relativistic corrections for the electroproduction of charmonia at very large $Q^2 \sim 100$ GeV$^2$. Not so for the light vector mesons where the
relativistic corrections play an important role especially at large $Q^2 \gg m_V^2$, and lead to $Q^2$ dependence of $A_{L,T}$ coming from the large-size asymmetric $q\bar{q}$ configurations: $A_L(\rho^0; Q^2 = 0) \approx 6.5$, $A_L(\rho^0; Q^2 = 100 \text{ GeV}^2) \approx 10$, $A_T(\rho^0; Q^2 = 0) \approx 7$, $A_T(\rho^0; Q^2 = 100 \text{ GeV}^2) \approx 12$ [9]. Due to an extra factor $z(1-z)$ in the integrand of (6) in comparison with (5), the contribution from asymmetric $q\bar{q}$ configurations to the longitudinal meson production is considerably smaller.

The integrands in Eqs. (5) and (6) contain the dipole cross section, $\sigma(\xi, r, q)$. As was mentioned, due to a very slow onset of the pure perturbative region (see Eq. (2)), one can easily anticipate a contribution to the production amplitude coming from the semiperturbative and nonperturbative $r \gtrsim R_c$. Following the simplest assumption about an additive property of the perturbative and nonperturbative mechanism of interaction, we can represent the contribution of the bare pomeron exchange to $\sigma(\xi, r, q)$ as a sum of the perturbative and nonperturbative component [11, 12]

$$
\sigma(\xi, r, q) = \sigma_{pt}(\xi, r, q) + \sigma_{npt}(\xi, r, q), \quad (8)
$$

with the parameterization of both components at small $q$

$$
\sigma_{pt,npt}(\xi, r, q) = \sigma_{pt,npt}(\xi, r, q = 0) \exp\left(-\frac{1}{2}B_{pt,npt}(\xi, r)q^2\right). \quad (9)
$$

Here $\sigma_{pt,npt}(\xi, r, q = 0) = \sigma_{pt,npt}(\xi, r)$ represent the contribution of the perturbative and nonperturbative mechanisms to the $q\bar{q}$-nucleon interaction cross section, respectively, $B_{pt,npt}(\xi, r)$ are the corresponding diffraction slopes.

A small real part of production amplitudes can be taken in the form [22]

$$
\text{Re} M(\xi, r) = \frac{\pi}{2} \cdot \frac{\partial}{\partial \xi} \text{Im} M(\xi, r). \quad (10)
$$

and can be easily included in the production amplitudes (5), (6) using substitution

$$
\sigma(x_{eff}, r, q) \rightarrow \left(1 - i\frac{\pi}{2} \frac{\partial}{\partial \log x_{eff}}\right)\sigma(x_{eff}, r) = \left[1 - i\alpha_V(x_{eff}, r)\right]\sigma(x_{eff}, r, q) \quad (11)
$$

The formalism for calculation of $\sigma_{pt}(\xi, r)$ in the leading-log $s$ approximation was developed in [21, 19, 20]. The nonperturbative contribution, $\sigma_{npt}(\xi, r)$, to the dipole cross section was used in Refs. [18, 9, 11, 12] where we assume that this soft nonperturbative component of the pomeron is a simple Regge pole with the intercept, $\Delta_{npt} = 0$. The particular form together with assumption of the energy independent $\sigma_{npt}(\xi = \xi_0, r) = \sigma_{npt}(r)$ ($\xi_0$ corresponds to boundary condition for the gBFKL evolution, $\xi_0 = \log 1/x_0$, $x_0 = 0.03$) allows one to successfully describe [18] the proton structure function at very small $Q^2$, the real photoabsorption [4] and diffractive real and virtual photoproduction of light [11] and heavy [12] vector mesons. A larger contribution of the nonperturbative pomeron exchange to $\sigma_{tot}(\gamma p)$ vs. $\sigma_{tot}(\gamma^* p)$ can, for example, explain a much slower rise with energy of the real photoabsorption cross section, $\sigma_{tot}(\gamma p)$, in comparison with $F_2(x, Q^2) \propto \sigma_{tot}(\gamma^* p)$ observed at HERA [23, 24]. Besides, the reasonable form of this soft cross section, $\sigma_{npt}(r)$, was confirmed in the process of the first determination of the dipole cross section from the experimental data on vector meson electroproduction [16]. The so extracted dipole cross section
is in a good agreement with the dipole cross section obtained from the gBFKL dynamics \[6, 18\]. Thus, this nonperturbative component of the pomeron exchange plays a dominant role at low NMC energies in the production of the light vector mesons, where the scanning radius, \(r_S\) \(2\), is large. However, the perturbative component of the pomeron become more important with the rise of energy also in the nonperturbative region of the dipole sizes.

Now we present the basic aspects of the diffraction slope coming from the gBFKL phenomenology \[13, 12\]. As the result of the generalization of the factorization formula (3) to the diffraction slope of the reaction \(\gamma^* p \rightarrow V p\) one can write

\[
B(\gamma^* \rightarrow V, \xi, Q^2) \Im M(\gamma^* \rightarrow V, \xi, Q^2, q = 0) = \frac{1}{i} \int_0^1 dz \int d^2 r \lambda(\xi, r) \Psi_V^*(r, z) \Psi_{\gamma^*}(r, z). \tag{12}
\]

where

\[
\lambda(\xi, r) = \int d^2 b \overline{b} \overline{b} \Gamma(\xi, r, \overline{b}). \tag{13}
\]

Then the diffraction slope expressed through the amplitude of elastic scattering of the color dipole \(\Im M\)

\[
B(\xi, r) = -2d \log \Im M(\xi, r, q)/dq^2 \bigg|_{q=0} \tag{14}
\]

equals

\[
B(\xi, r) = \frac{1}{2} \langle \overline{b}^2 \rangle = \lambda(\xi, r)/\sigma(\xi, r). \tag{15}
\]

The amplitude \(\Im M(\xi, r, q)\) in (14) within the impact-parameter representation reads

\[
\Im M(\xi, r, q) = 2 \int d^2 b \exp(-iq\overline{b})\Gamma(\xi, r, \overline{b}), \tag{16}
\]

where \(\Gamma(\xi, r, b)\) is the profile function and \(b\) is the impact parameter defined with the respect to the center of the \(q\overline{q}\) dipole.

The diffraction cone in the color dipole gBFKL approach for production of vector mesons has been detaily studied in \[12\]. Here we only present the salient feature of the color diffraction slope reflecting the presence of the geometrical contribution from beam dipole - \(r^2/8\) and the contribution from the target proton size - \(R_N^2/3\):

\[
B(\xi, r) = \frac{1}{8} r^2 + \frac{1}{3} R_N^2 + 2\alpha'_{IP}(\xi - \xi_0) + O(R_c^2), \tag{17}
\]

where \(R_N\) is the radius of the proton. For electroproduction of light vector mesons the scanning radius is larger than the correlation one \(r \gtrsim R_c\) even for \(Q^2 \lesssim 50 GeV^2\) and one recovers a sort of additive quark model, in which the uncorrelated gluonic clouds build up around the beam and target quarks and antiquarks and the term \(2\alpha'_{IP}(\xi - \xi_0)\) describe the familiar Regge growth of diffraction slope for the quark-quark scattering. The geometrical contribution to the diffraction slope from the target proton size, \(\frac{1}{3} R_N^2\), persists for all the dipole sizes, \(r \gtrsim R_c\) and \(r \lesssim R_c\). The last term in (17) is also associated with the proton size and is negligibly small.

The soft pomeron and diffractive scattering of large color dipole has been also detaily studied in the paper \[12\]. Here we assume the conventional Regge rise of the diffraction slope for the soft pomeron,

\[
B_{npt}(\xi, r) = \Delta B_d(r) + \Delta B_N + 2\alpha'_{npt}(\xi - \xi_0), \tag{18}
\]
where $\Delta B_d(r)$ and $\Delta B_N$ stand for the contribution from the beam dipole and target nucleon size. As a guidance we take the experimental data on the pion-nucleon scattering \cite{25}, which suggest $\alpha'_{npt} = 0.15 \text{GeV}^{-2}$. In (18) the proton size contribution is

$$\Delta B_N = \frac{1}{3} R_N^2,$$

and the beam dipole contribution has been proposed to have a form

$$B_d(r) = \frac{r^2}{8} \frac{r^2 + aR_N^2}{3r^2 + aR_N^2},$$

where $a$ is a phenomenological parameter, $a \sim 1$. We take $\Delta B_N = 4.8 \text{GeV}^{-2}$. Then the pion-nucleon diffraction slope is reproduced with reasonable values of the parameter $a$ in the formula (20): $a = 0.9$ for $\alpha'_{npt} = 0.15 \text{GeV}^{-2}$ \cite{14}.

Following the simple geometrical properties of the gBFKL diffraction slope, $B(\xi, r)$, (see Eq. (17) and [13]), one can express its energy dependence through the energy dependent effective Regge slope, $\alpha'_{eff}(\xi, r)$

$$B_{pt}(\xi, r) \approx \frac{1}{3} < R_N^2 > + \frac{1}{8} r^2 + 2 \alpha'_{eff}(\xi, r)(\xi - \xi_0).$$

The effective Regge slope, $\alpha'_{eff}(\xi, r)$, varies with energy differently at different size of the color dipole [13]; at fixed scanning radius and/or $Q^2 + m_V^2$, it decreases with energy. At fixed rapidity $\xi$ and/or $x_{eff}$ [11], $\alpha'_{eff}(\xi, r)$ rises with $r \lesssim 1.5 \text{fm}$. At fixed energy, it is a flat function of the scanning radius. At the asymptotically large $\xi$ ($W$), $\alpha'_{eff}(\xi, r) \rightarrow \alpha'_{IP} = 0.072 \text{GeV}^{-2}$. At the lower and HERA energies, the subasymptotic $\alpha'_{eff}(\xi, r) \sim (0.15 - 0.20) \text{GeV}^{-2}$ and is very close to $\alpha'_{soft}$ known from the Regge phenomenology of soft scattering. It means, that the gBKFL dynamics predicts a substantial rise with the energy and dipole size, $r$, of the diffraction slope, $B(\xi, r)$, in accordance with the energy and dipole size dependence of the effective Regge slope, $\alpha'_{eff}(\xi, r)$ and due to a presence of the geometrical component, $\propto r^2$, in [17] and [13].

Generalized factorization formula (12) for the forward diffraction slope can be re-written for somewhat better understanding of anomalous properties of the forward diffraction slope for production of $V'(2S)$ vector mesons

$$B(\gamma^* \rightarrow V, \xi, Q^2, q = 0) = \frac{\langle V|\sigma(\xi, r)B(\xi, r)|\gamma^* \rangle}{\langle V|\sigma(\xi, r)|\gamma^* \rangle} = \frac{\int_0^1 dz \int d^2 r \sigma(\xi, r)B(\xi, r)\Psi_V^*(r, z)\Psi_{\gamma^*}(r, z)}{\int_0^1 dz \int d^2 r \sigma(\xi, r)\Psi_V^*(r, z)\Psi_{\gamma^*}(r, z)}$$

(22)

3 Diffraction slope for $\rho^0$ and $\phi^0$ electroproduction: model predictions vs. experiment

Firstly the model predictions for the diffraction slope will be tested taking the fixed target and HERA data of $V(1S)$ vector meson production. The color dipole gBFKL dynamics
predicts a substantial growth with energy of the diffraction slope coming from Eqs. (18) and (21). According to simple geometrical behaviour, $\propto$ predicts a substantial growth with energy of the diffraction slope coming from Eqs. (18) and (21), we expect a shrinkage of the diffraction slope with $Q^2$ in accordance with the scanning property in vector meson production (see Eq. (4)). In Fig.1 we compare the model predictions for $Q^2$ dependence of the diffraction slope for $\rho^0$ production with the low energy data of the CHIO [29] NMC [27] and E665 [25] collaborations and the data from H1 [30, 31, 32] and ZEUS [32, 33, 34, 35, 36] experiments. Although the experimental data have still large error bars, they show a trend to smaller values of the diffraction slope as $Q^2$ increases. We predict a steep shrinkage of $B(\rho^0)$ with $Q^2$ on the scale $Q^2 \in (0, 5)$ GeV$^2$: it falls down, by $\sim 4$ GeV$^{-2}$ from $\sim 8.7$ GeV$^{-2}$ at $Q^2 = 0$ down to $5.0$ GeV$^{-2}$ at $Q^2 = 5$ GeV$^2$ and to 4.6 GeV$^{-2}$ at $Q^2 = 10$ GeV$^2$ in accordance with the low energy CHIO, NMC and E665 data. At HERA energy, we predict a higher shrinkage from $\sim 10.7$ GeV$^{-2}$ at $Q^2 = 0$ down to $\sim 6.0$ GeV$^{-2}$ at $Q^2 = 10$ GeV$^2$ not in disagreement with the data of H1 and ZEUS collaborations. Concerning the shrinkage of the diffraction slope with energy $W$, in the photoproduction limit $Q^2 = 0$ the data show a possible presence of the considerably large rise from the fixed target to HERA energy range. However, the large error bars of the data affect the large errors on $\alpha'$-fit [34] and preclude any definitive statement. In Fig.2 we predict this substantial growth, by $\sim 2.3 - 2.4$ GeV$^{-2}$ from $\sim 8.3 - 8.4$ GeV$^{-2}$ at $W = 10$ GeV up to $\sim 10.7$ GeV$^{-2}$ at $W = 100$ GeV in accordance with the data from the fixed target experiments [37] and the data from HERA experiments [29, 30, 32, 33]. This rise corresponds to effective Regge slope, $\alpha' \sim 0.25 - 0.26$ GeV$^{-2}$.

We would like to emphasize, that the overall effective Regge slope, $\alpha'$, contains the energy dependent contribution of the perturbative component, $\alpha'_{\text{eff}}(\rho, r)$, characterizing the energy rise of the gBFKL slope, $B_{\text{pt}}(\xi, r)$ (see Eq. (17)), and the constant nonperturbative (soft) Regge slope, $\alpha'_{\text{npt}} = 0.15$ GeV$^{-2}$, corresponding to the soft component of the slope, $B_{\text{npt}}(\xi, r)$ (see Eq. (18)). As was mentioned in Ref. [13], in the energy range, $W \in (50 - 200)$ GeV, the effective Regge slope, $\alpha'_{\text{eff}}(\xi, r)$, varies slowly within the interval $\sim (0.15 - 0.20)$ GeV$^{-2}$ at different scanning radii $\lesssim 1$ fm and is approximately a flat function of the scanning radius at fixed energy corresponding to HERA experiments; for instance, at $W = 100$ GeV, $\alpha'_{\text{eff}} \sim 0.15$ GeV$^{-2}$ at $r_S \sim 0.1$ fm, $\alpha'_{\text{eff}} \sim 0.16 - 0.17$ GeV$^{-2}$ at $r_S \sim 0.2 - 0.5$ fm, $\alpha'_{\text{eff}} \sim 0.19 - 0.20$ GeV$^{-2}$ at $r_S \sim 0.6 - 0.9$ fm, $\alpha'_{\text{eff}} \gtrsim 0.20$ GeV$^{-2}$ at $r_S \gtrsim 1.0$ fm. $\alpha'_{\text{npt}}$ only slightly modifies the overall effective Regge slope $\alpha'$. In Fig.2 we show also the energy dependence of the slope parameter for $\rho^0$ virtual photoproduction at $Q^2 \sim 10$ GeV$^2$ vs. NMC [27] and H1 [30, 31] data. The growth with energy $W$ is much smaller than at $Q^2 = 0$: $B(\rho^0)$ rises from $\sim 4.4$ GeV$^{-2}$ at $W = 10$ GeV up to $\sim 6.0$ GeV$^{-2}$ at $W = 100$ GeV. It correspond to effective Regge slope $\sim 0.17$ GeV$^{-2}$. At $Q^2 \sim 20 - 30$ GeV$^2$, we predict $\alpha' \sim 0.15$ GeV$^{-2}$, which is in accordance with value of the effective shrinkage rate of the diffraction slope for $J/\Psi$ elastic photoproduction ($Q^2 = 0$) presented in the paper [12]. It confirms an approximate flavor independence of the effective Regge slope in the scaling variable $Q^2 + m_T^2$.

Fig.3 shows the analogical $W$ dependence of the slope for real $\phi^0$ photoproduction together with the data from fixed target [38, 39] and collider HERA experiments [40]. Unfortunately, the error bars are quite a large to see a clear evidence of the shrinkage of
$B(\phi^0)$ with energy. The model predictions do not show a deviation from the data and it is not in disagreement with the conclusion about a shrinkage of the diffraction peak with energy expected from the gBFKL dynamics. The energy growth of $B(\phi^0)$ on the interval of $W \in (10 - 100) \text{GeV}$, is expected to correspond to overall effective Regge slope $\alpha' \sim 0.20 - 0.21 \text{GeV}^{-2}$.

Regarding a comparison with the data, the most straightforward theoretical predictions are for the forward production and we calculate $da/dt|_{t=0}$ and $B(t = 0)$. The data on the vector meson production correspond to a slope extracted over quite a broad range of $t$ using an extrapolation to $t = 0$, and the minimal value of $t$, corresponding to the fist experimental point in $t$-distribution, is relatively far from $t = 0$. Also the range of $t$ is different in different experiments. This fact explains quite a large dispersion of the low-energy data which is the most striking for $\phi^0$ production depicted on Fig.3 (see also Fig.2). Moreover, the above extrapolation is not always possible and one often reports the $t$-integrated production cross sections. Because of the model calculations are at $t = 0$ and because of a well known rapid rise of the diffraction slope towards $t = 0$, the experimental data may underestimate $B(V)$ at $t = 0$. For average $\langle t \rangle \sim 0.1-0.2 \text{GeV}^2$ which dominate the integrated total cross section, the diffraction slope is smaller than at $t = 0$ by $\sim 1 \text{GeV}^{-2}$ \cite{25}. We take these $\pi N$ scattering data for the guidance, and for more direct comparison with the presently available experimental data instead of the directly calculated $B(t = 0)$ we report in Figs.1-3 the value

$$B = B(t = 0) - 1 \text{GeV}^{-2}$$

The uncertainties in the value of $B$ and with this evaluation \cite{25} presumably do not exceed 10% and can be reduced when more accurate data will become available. However, hereafter we will present the model predictions for the diffraction slope at $t = 0$.

More detailed predictions for the energy and $Q^2$ dependence of the forward diffraction slope $B(V, t = 0)$ for the $\rho^0$ and $\phi^0$ production (for $T$, $L$ and mixed $T + \epsilon L$ polarizations, with $\epsilon = 1$) are presented in Fig.4. They show a substantial shrinkage of the elastic peak with energy at different $Q^2$. The energy rise of the diffraction slope is more evident than for the production of heavy vector mesons \cite{12}.

The rate of rise with energy of the diffraction slope decreases slowly with $Q^2$: on the interval of the c.m.s. energy $W \in (10 - 100) \text{GeV}$ the corresponding $\alpha' \sim 0.25 \text{GeV}^{-2}$ at $Q^2 = 0$, $\alpha' \sim 0.21 \text{GeV}^{-2}$ at $Q^2 \sim 0.5 \text{GeV}^2$, $\alpha' \sim 0.19 \text{GeV}^{-2}$ at $Q^2 \sim 1.0 \text{GeV}^2$, $\alpha' \sim 0.17 \text{GeV}^{-2}$ at $Q^2 \sim 5.0 \text{GeV}^2$ and $\alpha' \sim 0.16 \text{GeV}^{-2}$ at $Q^2 \sim 20 \text{GeV}^2$. The effective Regge slope becomes still smaller at very large $Q^2$ and $W$ when the scanning radius $r_S \lesssim R_c$ and a contribution of $\alpha'_{npt} = 0.15 \text{GeV}^{-2}$ to overall $\alpha'$ becomes practically insignificant. At $Q^2 \gtrsim 100 \text{GeV}^2$ when the scanning radius $r_S \lesssim R_c$, and one can observe a standard picture of a decreasing rate of energy growth of $B(V)$ expected from gBFKL dynamics (see Fig. 4).

The above results for the energy growth of the slope parameter can be tested in higher statistics data from HERA experiments measuring the exclusive electroproduction of vector mesons. The measurement of energy rise of the slope parameter at different $Q^2$ can give an information about a contribution of the nonperturbative component of the diffraction slope, $B_{\text{npt}}(\xi, r)$, and the effective Regge slope, $\alpha'_{\text{eff}}(\xi, r)$. The more precise data could also test the universal properties of diffraction slope and effective Regge slope for production of different
vector mesons, i.e. a similarity between the production of different vector mesons when compared at the same value of the scanning radius $r_S$ and/or the same value of $Q^2 + m_V^2$ (see Eq. (3)). Such a comparison must be performed at the same energy and/or rapidity $\xi$, which also means the equality of $x_{eff}$ at equal $Q^2 + m_V^2$ (see [11, 13]). The value of $Q^2$ must be large enough so that the scanning radius $r_S$ is smaller than the radii of vector mesons, $r_S \lesssim R_V$. It means, that for all reactions $\gamma^* p \rightarrow V p$ with the same $r_S$ and $\xi$, we predict approximately the same $B(V)$ and $\alpha'_{eff}$ [12].

Although a new data on the diffraction slope were obtained from collider HERA experiments measuring the real (virtual) photoproduction of vector mesons, the present experimental information on the energy and $Q^2$ dependence of the diffraction slope for vector meson production is not still very conclusive. Especially, it concerns to $J/\Psi$ photoproduction. There are no data yet on the diffraction slope for the real (virtual) photoproduction of $\Upsilon$ and the radially excited $(2S)$ heavy vector mesons. The data on the diffraction slope measuring the photo- and electroproduction of light vector mesons presented on Figs. 1-3 have still large error bars. The ZEUS and H1 data on virtual photoproduction give $B(\rho^0, W \sim 80\, \text{GeV}, Q^2 < 25\, \text{GeV}^2) = 5.1 + 1.2 - 0.9(stat) \pm 1.0(syst)\, \text{GeV}^{-2}$ [35], $B(\rho^0, W \sim 100\, \text{GeV}, Q^2 = 28\, \text{GeV}^2) = 4.4 + 3.5 - 2.8(stat) + 3.7 - 1.2(syst)\, \text{GeV}^{-2}$ [36], and $B(\rho^0, W \sim 75\, \text{GeV}, Q^2 = 21.2\, \text{GeV}^2) = 4.7 \pm 1.0(stat) \pm 0.7(syst)\, \text{GeV}^{-2}$ [31] which is close to $B(J/\Psi, W = 90\, \text{GeV}, Q^2 = 0) = 4.7 \pm 1.9\, \text{GeV}^{-2}$, $B(J/\Psi, W = 90\, \text{GeV}, Q^2 = 0) = 4.0 \pm 0.3\, \text{GeV}^{-2}$ from H1 data [31, 12] and to $B(J/\Psi, W = 90\, \text{GeV}, Q^2 = 0) = 4.5 \pm 1.4\, \text{GeV}^{-2}$ $B(J/\Psi, W = 90\, \text{GeV}, Q^2 = 0) = 4.6 \pm 0.4(stat) + 0.4 - 0.6(syst)\, \text{GeV}^{-2}$ from ZEUS data [43, 44] in accordance with $(Q^2 + m_V^2)$- scaling of the diffraction slope. High statistics data are needed from the both fixed target and the collider HERA experiments for both the exploratory study of very interesting $Q^2$ and energy dependence of $B(V)$ and the precise test of the $(Q^2 + m_V^2)$- scaling of the diffraction slope.

4 Anomalous diffraction slope in electroproduction of 2S radially excited vector mesons

Now we concentrate on the production of radially excited $V(2S)$ light vector mesons, where the node effect is known to be presented - the $Q^2$ and energy dependent cancellations from the soft (large size) and hard (small size) contributions, i.e. from the region above and below the node position, $r_n$, to the $V(2S)$ production amplitude. The strong $Q^2$ dependence of these cancellations comes from the scanning phenomenon (2) when the scanning radius $r_S$ for some value of $Q^2$ is close to $r_n \sim R_V$. The energy dependence of the node effect comes from the different energy dependence of the dipole cross section at small ($r < R_V$) and large ($r > R_V$) dipole sizes. The strong node effect in production of radially excited light vector mesons leading to an anomalous $Q^2$ and energy dependence of the production cross section has been demonstrated in Ref. [14].

More detailed discussion of the data on the slope parameter for heavy vector meson production is presented in Ref. [12].

Manifestations of the node effect in electroproduction on nuclei were discussed earlier, see [10] and [15].
Note, that the predictive power is weak and is strongly model dependent in the region of \( Q^2 \) and energy where the node effect becomes exact.

For the production of \( V'(2S) \) light vector mesons, the node effect depends on the polarization of the virtual photon and of the produced vector meson [11]. The wave functions of \( T \) and \( L \) polarized (virtual) photon are different. Different regions of \( z \) contribute to the \( \mathcal{M}_T \) and \( \mathcal{M}_L \). Different scanning radii for production of \( T \) and \( L \) polarized vector mesons and different energy dependence of \( \sigma(\xi, r) \) at these scanning radii lead to a different \( Q^2 \) and energy dependence of the node effect in production of \( T \) and \( L \) polarized \( V'(2S) \) vector mesons. Not so for production of heavy quarkonia, where the node effect is very weak and is approximately polarization independent. However, there is a weak polarization dependence of the node effect for \( \Psi' \) photoproduction [12] and this weak node effect still leads to a nonmonotonic \( Q^2 \) dependence of the diffraction slope. For \( \Upsilon' \) production the node effect is negligibly small and is polarization independent with very high accuracy.

There are two possible scenarios for the node effect: the undercompensation and the overcompensation regime [11]. In the undercompensation case, the \( 2S \) production amplitude \( \langle V'(2S)|\sigma(\xi, r)|\gamma^* \rangle \) is dominated by the positive contribution coming from small dipole sizes, \( r \lesssim r_n \) (\( r_n \) is the node position), and the \( V(1S) \) and \( V'(2S) \) photoproduction amplitudes have the same sign. This scenario corresponds namely to the production of \( 2S \) heavy vector mesons, \( \Psi'(2S) \) and \( \Upsilon'(2S) \). In the overcompensation case, the \( 2S \) production amplitude \( \langle V'(2S)|\sigma(\xi, r)|\gamma^* \rangle \) is dominated by the negative contribution coming from large dipole sizes, \( r \gtrsim r_n \), and the \( V(1S) \) and \( V'(2S) \) photoproduction amplitudes have the opposite sign.

The anomalous properties of the diffraction slope can be understood from the expression (22). The denominator represents the well known production amplitude \( \langle V(V^*)|\sigma(\xi, r)|\gamma^* \rangle \). As it was mentioned, the \( 1S \) production amplitude is dominated by contribution from dipole size \( r \sim r_S \) (2). However, due to \( \propto r^2 \) behaviour of the slope parameter (see [18] and (21)), the integrand of the matrix element in the numerator, \( \langle V(1S)|\sigma(\xi, r)B(\xi, r)|\gamma^* \rangle \), is \( \sim r^2 \exp(-er) \) and is peaked by \( r \sim r_B = 5/3r_S \).

Let us start from \( T \) polarized \( \rho'(2S) \) In Ref. [11] using our model wave functions for vector mesons, we found the undercompensation scenario at \( Q^2 = 0 \) for the production amplitude \( \langle V'_T(2S)|\sigma(\xi, r)|\gamma^* \rangle \), which is positive valued. However, because of the large numerical factor \( \sim 10 \) for \( r_B \sim 10/\sqrt{Q^2 + m_V^2} > r_S \), the matrix element \( \langle V'_T(2S)|\sigma(\xi, r)B(\xi, r)|\gamma^* \rangle \) in the numerator of Eq. (22) corresponds to the overcompensation scenario at \( Q^2 = 0 \) and at energy range \( \lesssim 15 - 20 \) GeV and is negative valued. As the result, the numerator and denominator have the opposite signs resulting in a negative value for the diffraction slope, \( B(V'_T(2S)) \) at \( Q^2 = 0 \). However the node effect for production of \( \phi'(2S) \) is weaker resulting in positive valued numerator of Eq. (22). Both the numerator and denominator have the same sign and we start with positive valued diffraction slope. Such a situation is depicted in Fig. 5 (bottom boxes) for both the \( \rho'(2S) \) and \( \phi'(2S) \) production, where we present the model predictions for the forward diffraction slope \( (t = 0) \) as a function of \( Q^2 \) at different values of the c.m.s. energy \( W \).

A decrease of the scanning radius with \( Q^2 \) leads to a very rapid decrease of the negative contribution to the diffraction slope coming from \( r \gtrsim r_n \) and consequently, leads to a steep rise of the negative valued \( B(V'_T(2S)) \) with \( Q^2 \) for \( \rho'(2S) \) production (positive valued
$B(\mathcal{V}'(2S))$ with $Q^2$ for $\phi'(2S)$ production). For $\rho'(2S)$ production at some value of $Q^2 \sim Q^2_T \sim 0.01 \text{GeV}^2$, one encounters the exact cancellation of the large and small distance contributions, i.e. the exact node effect for the numerator of Eq. (23), and $B(\mathcal{V}'(2S)) = 0$. Not so for $\phi'(2S)$ production, where the numerator of Eq. (22) is in the undercompensation regime already at very small energies $\sim 5 \text{ GeV}$.

We would like to emphasize that the position of $Q^2_T$ is model dependent and can be shifted towards to smaller or to larger values.

At larger $Q^2$ and smaller scanning radius, one enters the undercompensation scenario also for numerator $(\mathcal{V}'(2S)|\sigma(\xi, r)B(\xi, r)|\gamma^*)$. Thus, the diffraction slope will be positive valued and continues to rise strongly with $Q^2$ due to a more rapid decrease with $Q^2$ of the negative contribution to the slope parameter coming from $r \gtrsim r_n$ in numerator than in denominator (the numerator has much stronger node effect than the denominator). At still larger $Q^2$, i.e. smaller scanning radii $r_S$, the node effect also for the numerator becomes to be weaker and as the result, the slope parameter at fixed energy $W$ and some value of $Q^2 \sim (0.5 - 2.0) \text{GeV}^2$, has a maximum of $B(\mathcal{V}'(2S))$. At very large $Q^2 \gg m_T^2$, when the node effect becomes negligible, $B(\mathcal{V}'(2S))$ has the standard $Q^2$- behaviour and decreases monotonously with $Q^2$ following the behaviour of the diffraction slope $B(\mathcal{V}_{L,T}(1S))$ for $V(1S)$ mesons (see Fig. 4).

The more interesting situation is for production of $L$ polarized $\mathcal{V}'(2S)$ mesons resulting in a very spectacular pattern of $Q^2$ dependence of the slope parameter shown in Fig. 5 (middle boxes). Using our model wave functions, we predicted overcompensation for the production amplitude $(\mathcal{V}'(2S)|\sigma(\xi, r)|\gamma^*)$ [11]. Because of $r_B > r_S$, the matrix element $(\mathcal{V}'(2S)|\sigma(\xi, r)B(\xi, r)|\gamma^*)$, will be also in the overcompensation regime. For this reason, the both matrix elements have the same sign and according to (22) the slope parameter $B(\mathcal{V}'(2S))$ will be positive valued at $Q^2 = 0$ (see Fig. 5). Consequently, with the decrease of the scanning radius with $Q^2$, there is a rapid decrease of the negative contributions to the numerator and denominator of Eq. (22) coming from $r \gtrsim r_n$. For some $Q^2 \sim Q^2_T \sim 0.5 - 1.0 \text{GeV}^2$ one encounters the exact node effect firstly for the denominator due to $r_B > r_S$. This fact corresponds to a presence of the peak for $B(\mathcal{V}'(2S))$ for both the $\rho'_L(2S)$ and $\phi'_L(2S)$ production. The value of $B(\mathcal{V}'(2S))$ corresponding to this exact node effect will be finite due to a different node effect for the real and imaginary part of the production amplitude. This fact also reflects the continuous transition of $B(\mathcal{V}'(2S))$ from positive to negative values when the matrix element in denominator passes from the overcompensation to undercompensation regime. Thus, for $Q^2 \gtrsim Q^2_L \sim 0.5 - 1.0 \text{GeV}^2$, the denominator will be in the undercompensation regime and $B(\mathcal{V}'(2S))$ starts to rise from its minimal negative value. Note, that the numerator is still in the overcompensation. The further pattern of the $Q^2$ behaviour of $B(\mathcal{V}'(2S))$ is analogical to that for $Q^2$ dependence of $B(\mathcal{V}'(2S))$. However, the exact node effect for the numerator in Eq. (22), resulting in $B(\mathcal{V}'(2S)) = 0$, will be at $Q^2 \sim Q^2_L > Q^2_T$. For $\phi'(2S)$ production because of different node effect for the real and imaginary part of production amplitude, at HERA energy range $W \sim 50 - 200 \text{ GeV} B(\mathcal{V}'(2S))$ never reaches the zero value corresponding to the exact node effect for the numerator of Eq. (22).

For the production of polarization unseparated $\mathcal{V}'(2S)$, the anomalous properties of $B(\mathcal{V}'(2S))$ are essentially invisible and the corresponding slope parameter $B(\mathcal{V}'(2S))$ is
shown in Fig. 5 (bottom boxes). Although the above value of $Q^2_0$ is too small to be measured experimentally (we can not exclude that $Q^2$ dependence of $B(V_T'(2S))$ will start from positive valued $B(V_T(2S))$ at small energies also for $\rho'(2S)$ production), we predict nonmonotonic $Q^2$ dependence of the diffraction slope for production of $T$ polarized and polarization unseparated $\rho'(2S)$ and $\phi'(2S)$, strikingly different from monotonic $Q^2$ behaviour of the slope parameter for $V(1S)$ production (see Fig. 4). For production of $\rho_L'(2S)$ and $\phi_L'(2S)$, we predict anomalous $Q^2$ behaviour of $B(V_L'(2S))$. Here we can not insist on the precise values of $Q^2_1$, $Q^2_L$ and $Q^2_F$ which is subject of the soft-hard cancellations. We would like to only emphasize that the exact node effect for $B(V_L'(2S))$ at $Q^2 = 0$. Fig. 6 demonstrates (top boxes) steeper rise with energy of the diffraction slope at lower $Q^2$. There are several reasons for such a behaviour. First, the gBFKL dynamics predicts a steeper rise with energy of the positive contribution to the $2S$ amplitudes $V'(2S)\sigma(\xi,r)|\gamma^*\rangle$ and $\langle V'(2S)|\sigma(\xi,r)B(\xi,r)|\gamma^*\rangle$ coming from small size dipoles $r \lesssim r_n$ than the negative contribution coming from large size dipoles $r \gtrsim r_n$. Thus, the destructive interference of these two contributions is weaker at higher energy. Second, at $Q^2 = 0$, the denominator of Eq. (23) is in the undercompensation, whereas the numerator is in the overcompensation regime (numerator is in the overcompensation regime for $\phi'(2S)$ production) and the corresponding scanning radii for the numerator and denominator are different, $r_B > r_S$. Third, the energy dependence of the slope parameter is given by the effective Regge slope $\alpha'$. Thus, the above destructive interference in numerator decreases drastically with $W$ the negative contribution from $r \gtrsim r_n$ until the exact node effect is reached, i.e. $B(V_T'(2S)) = 0$, and the undercompensation scenario also for the numerator of Eq. (23) starts to be realized at $W \sim 20\text{GeV}$. However, closeness of the node position in the numerator of Eq. (23) leads to a small negative value of $B(V_T'(2S))$ at $W \sim 5\text{GeV}$ and as a result it leads in a little bit steeper growth with energy of $B(V_T'(2S))$ than the expected energy rise of the slope coming only from the effective Regge slope. For example, for $\rho'(2S)$ production we predict the rise of $B(V_T'(2S))$, by $\sim 2.8\text{GeV}^{-2}$, from $W = 10$ to $100\text{GeV}$. At $Q^2 \gtrsim 1.0\text{GeV}^2$, when both the numerator and denominator are in the undercompensation regime and the node effect becomes weak, the energy growth of $B(V'(2S))$ is connected mainly with the effective Regge slope and we predict approximately the same quantities and energy growth for $B(V'(2S))$ and $B(V(1S))$ (compare Fig. 4 and Fig. 6).

The successful separation of the longitudinally polarized $V_T'(2S)$ mesons at HERA offers an unique possibility to study an anomalous $Q^2$ and energy dependence of the diffraction slope connected with the overcompensation scenario of the denominator of Eq. (22). At $Q^2 = 0$.
0, we have onset of the overcompensation scenario for both the numerator and denominator of Eq. (22). At moderate energy and $Q^2$ closed but smaller than $Q^2_L \sim 0.5 \text{GeV}^2$, the negative contribution coming from $r > r_n$ still takes over in the denominator (the numerator is safely in the overcompensation regime due to $r_B > r_S$). Due to a steeper rise with energy of the positive contribution to the $2S$ production amplitude coming from small size dipoles $r \sim r_n$ than the negative contribution coming from large size dipoles $r \gg r_n$, we find an exact cancellation of these two contributions to the denominator and a maximum of the diffraction slope $B(V'_L(2S))$ at some intermediate energy followed by a rapid continuous transition from the positive to negative values, when the matrix element in denominator of Eq. (22) passes from the overcompensation to the undercompensation regime. Different node effect for the real and imaginary part of the production amplitude provides such a continuous transition. Then, at larger energies, the production amplitude is in the undercompensation regime, $B(V'_L(2S))$ is negative valued and starts to rise from the minimal negative value. This situation is depicted in Fig. 6 (middle boxes), where we predict with our model wave functions such a nonmonotonic energy behaviour of $B(V'_L(2S))$ for both $\rho(2S)$ and $\phi(2S)$ production at $Q^2 \lesssim 0.7 – 1.0 \text{GeV}^2$. The position $W_t$ of maximum and the transition from the positive to negative values of the longitudinally polarized diffraction slope depends on $Q^2$. For example, at $Q^2 \sim 0.7 \text{GeV}^2$, we find $W_t \sim 70 – 80 \text{GeV}$. Then, the position of $W_t$ is shifted to smaller values of $W$ at larger $Q^2 \gtrsim 0.7 \text{GeV}^2$ at can be measured at HERA.

At higher $Q^2$ and smaller scanning radii, the further pattern of the energy behaviour of $B(V'_L(2S))$ is an analogical to $W$ dependence of $B(V'_T(2S))$. At still larger $Q^2$, after the exact node effect was reached also in the numerator of Eq. (22) at $\sim Q^2_L > Q^2'_L$, both the numerator and denominator are in the undercompensation regime. Consequently, the node effect also in the numerator starts to be weaker with $Q^2$ and the energy growth of $B(V'_L(2S))$ is controlled practically by the effective Regge slope. As the result we predict again almost the same quantities and energy growth for $B(V'_L(2S))$ and $B(V_L(1S))$.

If the leptoproduction of the transversally and longitudinally polarized $V'_T(2S)$ and $V'_L(2S)$ mesons will be separated experimentally, there is a possibility of experimental determination of a concrete scenario in $T$ and $L$ polarized $2S$ production amplitude by a measurement of the corresponding diffraction slopes at $t = 0$ and at $Q^2 = 0$, where the node effect is found to be the strongest. If at the same energy and $Q^2 = 0$ the slope parameter for $V'_T(2S)$ production will be smaller (it can be also negative valued) than the corresponding slope parameter for $V_T(1S)$ production, then the $2S$ production amplitude is in the undercompensation regime. In the opposite case, if $B(V'_L(2S)) > B(V_T(1S))$, then the corresponding $T$ polarized $2S$ amplitude is in the overcompensation. The analogical conclusion concerns to $L$ polarized $2S$ production amplitude, where the values of $Q^2$ should be high enough to have the data with a reasonable statistics, however must not be very large in order to have a strong node effect. We propose the range of $Q^2 \in 0.5 – 2.0 \text{GeV}^2$ for a possible study of the overcompensation scenario at HERA. The further supplementary indication of the overcompensation scenario is assumed to be an existence of the maximum and/or minimum of the diffraction slope and subsequent a sudden rise of $B(V'(2S))$ at some nonzero value of $Q^2$. 

15
5 Conclusions

We study the diffractive photo- and electroproduction of ground state $1S$ and radially excited $2S$ vector mesons within the color dipole gBFKL dynamics with the main emphasis related to the diffraction slope. There are two main consequences of vector meson production coming from the gBFKL dynamics. First, the energy dependence of the $1S$ vector meson production is controlled by the energy dependence of the dipole cross section which is steeper for smaller dipole sizes. The energy dependence of the diffraction slope for $V(1S)$ production is given by the effective Regge slope with a small variation with energy. Second the $Q^2$ dependence of the $1S$ vector meson production is controlled by the shrinkage of the transverse size of the virtual photon and the small dipole size dependence of the color dipole cross section. The $Q^2$ behaviour of the diffraction slope is given by the simple geometrical properties, $\sim r^2$, coming from the gBFKL phenomenology of the slope parameter. In the gBFKL dynamics, we expect a fast subasymptotic shrinkage of the diffraction cone from the CERN/FNAL to HERA energy due to intrusion of large distance effects. We have predicted a reach pattern of $Q^2$ and energy dependence of the diffraction slope for the $\rho^0$ and $\phi^0$ production and find a substantial rise (by $\sim 2.3 - 2.4 \text{GeV}^{-2}$ for $\rho^0$ production and by $\sim 1.9 - 2.0 \text{GeV}^{-2}$ for $\phi^0$ production) from the fixed target, $W \sim 10 - 15 \text{GeV}$, to the collider HERA, $W \sim 100 - 150 \text{GeV}$, range of energy. The model predictions for the diffraction slope for the $\rho^0$ and $\phi^0$ production are in agreement with the data from the fixed target (CHIO, NMC) and collider HERA (H1, ZEUS) experiments. However, the relatively large error bars of the data preclude any definite statement about a shrinkage of the slope parameter with energy. The data show a trend to smaller values of the diffraction slope as $Q^2$ increases.

The second class of predictions is related to the diffraction slope for the production of $2S$ vector mesons. As a consequence of the strong node effect in electroproduction of $2S$ light vector mesons $\rho'(2S)$ and $\phi'(2S)$, we present the strong case for the anomalous $Q^2$ and energy dependence of the diffraction slope at $t = 0$. We find a nonmonotonic $Q^2$ dependence of the slope parameter which can be tested at HERA in the range of $Q^2 \in (0 - 10) \text{GeV}^2$ measuring the virtual photoproduction of $\rho'(2S)$ and $\phi'(2S)$ mesons. For the production of longitudinally polarized $2S$ mesons, the production amplitude is in the overcompensation scenario and we find a very rapid transition of the slope parameter $B(V_L'(2S))$ from positive to negative values at $Q^2 = Q_L'^2 \sim 0.5 - 2.0 \text{GeV}^2$ as a consequence of a reaching of the exact node effect by passing from the overcompensation to undercompensation scenario in $2S$ production amplitude. The position of this rapid transition, $Q_L'^2$, is energy dependent and leads to nonmonotonic energy dependence of $B(V_L'(2S))$ at fixed $Q^2$.

At $Q^2 = 0$, when the node effect is strong, for undercompensation scenario we predict smaller $B(V_L'(2S))$ than $B(V_T(1S))$. However, for overcompensation scenario we predict larger $B(V_L'(2S))$ than $B(V_T(1S))$. This is a very crucial point of a possible experimental determination of a concrete scenario measuring (and the position of the node as well) the diffraction slope at $t = 0$ for the production of $V'(2S)$ mesons in the photoproduction limit.

At larger $Q^2$ and/or shorter scanning radius, the node effect becomes weak and we predict for $V'(2S)$ mesons the standard monotonic $Q^2$ and energy dependence of the slope parameter like for $V(1S)$ mesons. One needs the higher accuracy data from the both fixed...
target and the collider HERA experiments for the exploratory study of $Q^2$ and energy
dependence of the diffraction slope at $t = 0$.

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Figure captions:

Fig. 1 - The color dipole model predictions for the $Q^2$ dependence of the diffraction slope for the production of $\rho^0$ vs. the low-energy fixed target CHIO [26], NMC [27], E665 [28] and high-energy ZEUS [32, 33, 34, 35, 36] and H1 [29, 30, 31] data.

Fig. 2 - The color dipole model predictions for the $W$ dependence of the diffraction slope for the production of $\rho^0$ vs. the low-energy fixed target [37, 27], and high-energy ZEUS [32, 33, 34] and H1 [29, 30, 31] data. The top solid curve is a prediction for the diffraction slope at $Q^2 = 0$. The lower dashed curve represents a prediction at $Q^2 = 10\text{ GeV}^2$.

Fig. 3 - The color dipole model predictions for the $W$ dependence of the diffraction slope for the real photoproduction of $\phi^0$ vs. the low-energy fixed target [38, 39] and high-energy ZEUS data [40].

Fig. 4 - The color dipole model predictions for the $W$ dependence of the diffraction slope $B(t = 0)$ for production of transversely (T) (top boxes), longitudinally (L) (middle boxes) polarized and polarization-unseparated (T) + $\epsilon$(L) (bottom boxes) $\rho^0$ and $\phi^0$ for $\epsilon = 1$ at different values of $Q^2$.

Fig. 5 - The color dipole model predictions for the $Q^2$ dependence of the diffraction slope $B(t = 0)$ for production of transversely (T) (top boxes), longitudinally (L) (middle boxes) polarized and polarization-unseparated (T) + $\epsilon$(L) (bottom boxes) $\rho'(2S)$ and $\phi'(2S)$ for $\epsilon = 1$ at different values of the c.m.s. energy $W$.

Fig. 6 - The color dipole model predictions for the $W$ dependence of the diffraction slope $B(t = 0)$ for production of transversely (T) (top boxes), longitudinally (L) (middle boxes) polarized and polarization-unseparated (T) + $\epsilon$(L) (bottom boxes) $\rho'(2S)$ and $\phi'(2S)$ for $\epsilon = 1$ at different values of $Q^2$. 

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$Q^2 = 0 \text{ GeV}^2$

$B$ (GeV$^{-2}$)

$W$ (GeV)

- ■ ZEUS 1994
- ○ fixed target
