Anomalous $t$-dependence in diffractive electroproduction of $2S$ radially excited light vector mesons at HERA

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Abstract

Within the color dipole gBFKL dynamics applied to the diffraction slope, we predict an anomalous $t$ dependence of the differential cross section as a function of energy and $Q^2$ for production of radially excited $V'(2S)$ light vector mesons in contradiction with a well known standard monotonous $t$-behaviour for $V(1S)$ mesons. The origin of this phenomenon is based on the interplay of the nodal structure of $V'(2S)$ radial wave function with the energy and dipole size dependence of the color dipole cross section and of the diffraction slope. We present how a different position of the node in $V'(2S)$ wave function leads to a different form of anomalous $t$-behaviour of the differential cross section and discuss a possibility how to determine this position from the low energy and HERA data.
The main goal of this paper is a demonstration of further salient features of the node effect [1, 2, 3, 4, 5] coming from the nodal structure of radial wave function for \( V'(2S) \) vector mesons in conjunction with the gBFKL phenomenology of the diffraction slope [3, 4, 5] leading to anomalous \( t \) dependence of the differential cross section for \( V'(2S) \) production in contrast with the standard monotonous \( t \) behaviour of \( d\sigma(\gamma^* \to V)/dt \) for \( V(1S) \) production.

Diffractive photo- and electroproduction of ground state \( V(1S) \) and radially excited \( V'(2S) \) vector mesons,

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

at high c.m.s. energy \( W = \sqrt{s} \) intensively studied by the recent experiments at HERA represents one of a main source for a further development of the pomeron physics. The pomeron exchange in diffractive leptoproduction of vector mesons at high energies has been intensively studied [8, 1, 9, 2, 10, 11, 12, 13, 14] within the framework of perturbative QCD (pQCD).

The standard approach to the pQCD is based on the BFKL equation [15, 16, 17], which represents the integral equation for the leading-log \( (LLs) \) evolution of the gluon distribution, formulated in the scaling approximation of the infinite gluon correlation radius, \( R_c \to \infty \), (massless gluons) and of the fixed running coupling, \( \alpha_S = \text{const} \). Later, however, a novel \( s \)-channel approach to the LLs BFKL equation (running gBFKL approach) has been developed [18, 19] in terms of the color dipole cross section \( \sigma(\xi, r) \) (hereafter \( r \) is the transverse size of the color dipole, \( \xi = \log(W^2+Q^2/m_V^2+Q^2) \) is the rapidity variable) and incorporates consistently the asymptotic freedom (AF) (i.e. the running QCD coupling \( \alpha_S(r) \)) and the finite propagation radius \( R_c \) of perturbative gluons. The freezing of \( \alpha_S(r), \alpha_S(r) \leq \alpha_S^{fr} \), and the gluon correlation radius \( R_c \) represents the nonperturbative parameters, which describe the transition from the soft (nonperturbative, infrared) to the hard (perturbative) region.

The details of the gBFKL phenomenology of diffractive electroproduction of light vector mesons are presented in the paper [4]. The color dipole phenomenology of the diffraction slope for photo- and electroproduction of heavy vector mesons has been developed in the paper [5]. The analysis of the diffractive production of light [11, 4] and heavy [5] vector mesons at \( t = 0 \) within the gBFKL phenomenology shows that the 1\( S \) vector meson production amplitude probes the color dipole cross section at the dipole size \( r \sim r_S \) (scanning phenomenon [20, 2, 10, 11]), where the scanning radius can be expressed through the scale parameter \( A \)

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

where \( Q^2 \) is the photon virtuality, \( m_V \) is the vector meson mass and \( A \approx 6 \). Thus, 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 \( B(\xi, r) \), and measure so the effective intercept \( \Delta_{eff}(\xi, r) = \partial \log \sigma(\xi, r)/\partial \xi \) and the local Regge slope \( \alpha'_{eff}(\xi, r) = \frac{1}{2} \partial B(\xi, r)/\partial \xi \) in a very broad range of the dipole sizes, \( r \). This fact allows also to study the transition between the perturbative (hard) and nonperturbative (soft) regimes.

The experimental investigation of the electroproduction of the radially excited \( (2S) \) vector mesons can extend an additional information on the dipole cross section and on the
dipole diffraction slope. The presence of the node in the 2S radial wave function leads to 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 1, 20, 3, 4. For this reason, the amplitudes of the electroproduction of the 1S and 2S vector mesons probe \( \sigma(\xi, r) \) and \( B(\xi, r) \) in a different way. The onset of strong node effect has been demonstrated in Ref. 4 in electroproduction of radially excited light vector mesons leading to an anomalous \( Q^2 \) and energy dependence of the production cross section. The node effect is much weaker for the electroproduction of 2S heavy vector mesons but still leads to a slightly different \( Q^2 \) and energy dependence of the production cross section for \( \Psi' \) vs. \( J/\Psi \) and to a nonmonotonic \( Q^2 \) dependence of the diffraction slope at small \( Q^2 \lesssim 5 \text{GeV}^2 \) for \( \Psi' \) production 3. Only 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 3. 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.

There are two main reasons which 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 \( B(\xi, r) \) 3, 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, \( B(t = 0) \) 3. 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. This nonmonotonous energy and \( Q^2 \) dependence of the diffraction slope for production of light vector mesons will be detaily studied elsewhere 21.

The effects mentioned above are sensitive to the form of the dipole cross section. In Ref. 22 we presented the first direct determination of the color dipole cross section from the data on the photo- and electroproduction of \( V(1S) \) vector mesons. So extracted dipole cross section is in a good agreement with the dipole cross section obtained from gBFKL analysis 23, 11. This fact confirms a very reasonable choice of the nonperturbative component of the dipole cross section corresponding to a soft nonperturbative mechanism contribution to the scattering amplitude.

In the present paper we concentrate on the production of 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 \( t \) dependence of the differential cross section at different energies and \( Q^2 \) for the production of \( V'(2S) \) vs. \( V(1S) \) vector mesons. As was mentioned above, 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 especially for light vector mesons. 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, \( r \lesssim R_c \).
Thus, in this paper we present the $Q^2$ and energy dependence of the $t$-behaviour of the differential cross section for electroproduction of the ground state and radially excited (2S) light vector meson. and study how the position of the node in the radial wave function for (2S) vector mesons can be extracted from the data. We present an exact prescription how the experimental measurement of the $t$ dependent differential cross section for $V'(2S)$ production could distinguish between the undercompensation and overcompensation scenarios of the $2S$ production amplitude (see below). The explicit form of that $t$-behaviour is connected with the position of the node in radial wave function for $V'(2S)$ vector mesons.

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 $q\bar{g}g...$ 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 \[18, 19\] for the energy evolution. This reflects the fact that in the leading-log $\frac{1}{\nu}$ 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. The detailed discussion about the space-time pattern of diffractive electroproduction of vector mesons is presented in \[5, 4\].

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

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

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 \[24, 18\]. $\sigma(\xi,r,z,q)$ is the scattering matrix for $q\bar{q} - N$ interaction and represents the above mentioned color dipole cross section for $q = 0$. The color dipole cross section $\sigma(\xi,r)$ depends only on the dipole size $r$. For 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 \[24\] 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-
will write the energy dependence of the dipole cross section in both variables, either in vector mesons with the small momentum transfer, \( q_0 \) in the integrands of (5) and (6) 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 [1].

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 [4].

The terms \( \propto \epsilon K_1(\epsilon r) \partial_z \phi(r, z) \) for \( T \) polarization and \( \propto K_0(\epsilon r) \partial^2_z \Phi(r, z) \) for \( L \) polarization in the integrands of (5) and (6) 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 [1].

For small dipole size and \( q_0 = 0 \), in the leading-log \( \frac{1}{z} \) approximation, the dipole cross section can be related to the gluon structure function \( G(x, q^2) \) of the target nucleon through

\[
\sigma(x, r) = \frac{\pi^2}{3} r^2 \alpha_s(r) G(x, q^2),
\]

where the gluon structure function enters at the factorization scale, \( q^2 \sim \frac{B^2}{r^2} \) [25] with the parameter \( B \approx 10 \) [26].
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 $r \approx A_{T,L}/\sqrt{Q^2 + m_T^2}$. 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 $Q^2$. For production of light vector mesons the relativistic corrections play an important role especially at large $Q^2 \gg m_T^2$, and lead to $Q^2$ dependence of $A_{L,T}$ coming from the large-size asymmetric $q\bar{q}$ configurations: $A_L(\rho^0; Q^2 = 0) \approx 6.5$, $A_L(\rho^0; Q^2 = 100 \text{GeV}^2) \approx 10$, $A_T(\rho^0; Q^2 = 0) \approx 7$, $A_T(\rho^0; Q^2 = 100 \text{GeV}^2) \approx 12$ (4). Due to an extra factor $z(1-z)$ in the integrand of (3) in comparison with (4), the contribution from asymmetric $q\bar{q}$ configurations to the longitudinal meson production is considerably smaller.

The integrands in Eqs. (3) and (4) 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

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

with the parameterization of both components at small $q$

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

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 corresponding diffraction slopes.

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

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

and can be easily included in the production amplitudes (3), (4) using substitution

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

The formalism for calculation of $\sigma_{pt}(\xi, r)$ in the leading-log $s$ approximation was developed in Refs. [24, 18, 19]. The nonperturbative contribution, $\sigma_{npt}(\xi, r)$, to the dipole cross section was used in Refs. [23 11 4 3 5] 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 [23] the proton structure function at very small $Q^2$, the

\footnote{additive property of a such decomposition of the dipole cross section has been detaily discussed in [4 5]}

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real photoabsorption and diffractive real and virtual photoproduction of light and heavy vector mesons. A larger contribution of the nonperturbative pomeron exchange to \( \sigma_{\text{tot}}(\gamma p) \) vs. \( \sigma_{\text{tot}}(\gamma^* p) \) can, for example, explain a much slower rise with energy of the real photoabsorption cross section, \( \sigma_{\text{tot}}(\gamma p) \), in comparison with \( F_2(x, Q^2) \propto \sigma_{\text{tot}}(\gamma^* p) \) observed at HERA. Besides, the reasonable form of this soft cross section, \( \sigma_{\text{soft}}(\gamma p) \), was confirmed in the process of the first determination of the dipole cross section from the data on vector meson electroproduction. The so extracted dipole cross section is in a good agreement with the dipole cross section obtained from the gBFKL dynamics. 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, \( R_S \), 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.

If one starts with the familiar impact-parameter representation for amplitude of elastic scattering of the color dipole

\[
\text{Im} \mathcal{M}(\xi, r, \vec{q}) = 2 \int d^2 \vec{b} \exp(-i\vec{q}\vec{b}) \Gamma(\xi, \vec{r}, \vec{b}),
\]

then the diffraction slope \( B = -2d \log \text{Im}\mathcal{M}/dq^2|_{q=0} \) equals

\[
B(\xi, r) = \frac{1}{2} \langle \vec{b}^2 \rangle = \frac{\lambda(\xi, r)}{\sigma(\xi, r)},
\]

where

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

The generalization of the color dipole factorization formula to the diffraction slope of the reaction \( \gamma^* p \to V p \) reads:

\[
B(\gamma^* \to V, \xi, Q^2) \text{Im} \mathcal{M}(\gamma^* \to V, \xi, Q^2, \vec{q} = 0) = \int_0^1 dz \int d^2 \vec{r} \lambda(\xi, r) \Psi_V^*(r, z) \Psi_{\gamma^*}(r, z).
\]

The diffraction cone in the color dipole gBFKL approach for production of vector mesons has been detaily studied in [5]. 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 - \( R_N^2/3 \):

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

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 \( Q^2 \lesssim 50 \text{GeV}^2 \) 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 \( 2\alpha'_{\text{IP}}(\xi - \xi_0) \) 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, \( 1/3 \frac{R_N^2}{N} \), 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 detailedly studied in the paper [3]. Here we assume the conventional Regge rise of the diffraction slope for the soft pomeron [5]:

$$B_{npt}(\xi, r) = \Delta B_d(r) + \Delta B_N + 2\alpha'_{npt}(\xi - \xi_0),$$  (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 [30], which suggest $\alpha'_{npt} = 0$. In (18) the proton size contribution is

$$\Delta B_N = \frac{1}{3}R_N^2,$$  (19)

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

$$B_d(r) = \frac{r^2}{8} + \frac{r^2}{3r^2 + aR_N^2},$$  (20)

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 $\alpha'_{npt} = 0.15\text{GeV}^{-2}$ [5].

Using the expressions (5) and (6) for the $T$ and $L$ production amplitudes in conjunction with Eqs. (9) and (10), we can calculate the differential cross section of vector meson electroproduction as a function of $t$.

Following the simple geometrical properties of the gBFKL diffraction slope, $B(\xi, r)$, (see Eq. (17) and [1]), one can express its energy dependence through the energy dependent effective Regge slope, $\alpha'_{eff}(\xi, r)$

$$B_{pt}(\xi, r) \approx \frac{1}{3} < R_N^2 > + \frac{1}{8}r^2 + 2\alpha'_{eff}(\xi, r)(\xi - \xi_0).$$  (21)

The effective Regge slope, $\alpha'_{eff}(\xi, r)$, varies with energy differently at different size of the color dipole [3]; at fixed scanning radius and/or $Q^2 + m_V^2$, it decreases with energy. At fixed rapidity $\xi$ and/or $x_{eff}$ [1], $\alpha'_{eff}(\xi, r)$ 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 (18).

Now we will concentrate on the production of radially excited $2S$ light vector mesons and will study the differential cross section $d\sigma/dt$ as a function of $t$. The most important feature of the production of $V'(2S)$ vector mesons is the node effect - 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 [1] when the scanning radius $r_S$ for some value of $Q^2$ is close to $r_n \sim R_V$ ($R_V$ is the vector
meson radius). The energy dependence of the node effect is due to 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 was demonstrated in Ref. [3]. 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.

There are several reasons to expect that, for the production of \(2S\) light vector mesons, the node effect depends on the polarization of the virtual photon and of the produced vector meson \([4]\). First, the wave functions of \(T\) and \(L\) polarized (virtual) photon are different. Second, different regions of \(z\) contribute to the \(M_T\) and \(M_L\). Third, 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 the nonrelativistic limit of heavy quarkonia where the node effect is very weak and is approximately polarization independent. There is a weak polarization dependence of the node effect which is the most marginal for \(\Psi'\) production \([4]\) 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 which can occur in the \(2S\) production amplitude; the undercompensation and the overcompensation scenario \([4]\). 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 come from the expression \((16)\) and will be presented elsewhere \([22]\). The matrix element on l.h.s of \((16)\) represents the well known production amplitude \(\langle V(V')|\sigma(\xi, r)|\gamma^*\rangle\). As was mentioned, the \(1S\) production amplitude is dominated by contribution from dipole size corresponding to the scanning radius \(r_S \sim 3/\epsilon\) \([2]\) with the scale parameter \(A \sim 6\) at \(Q^2 = 0\) slightly dependent on \(Q^2\) \([11]\). However, due to \(\propto r^2\) behaviour of the slope parameter (see \((17)\) and \((18)\)), the integrand of the matrix element on the r.h.s of Eq. \((16)\), \(\langle V(1S)|\sigma(\xi, r)B(\xi, r)|\gamma^*\rangle\), is \(\sim r^5 \exp(-\epsilon r)\) and is peaked by \(r \sim r_B = 5/\epsilon = 5/3r_S\).

The node of the radial wave function of the \(2S\) states leads to peculiarities in \(t\) dependence of the differential cross section. Following the simple geometrical properties of the diffraction slope \((17)\), \((18)\), because of \(\propto r^2\) behaviour, the large size negative contribution to the production amplitude from the region above the node position corresponds to larger value of the diffraction slope than small size contribution from the region below the node position. It means, that the negative contribution to the \(V'(2S)\) production amplitude coming from the region above the node position, \(r \gtrsim r_n\), has a steeper \(t\) dependence than the positive

\footnote{Manifestations of the node effect in electroproduction on nuclei were discussed earlier, see \([3]\) and \([31]\).}
contribution coming from the small size dipoles, \( r \gtrsim r_n \). It can be expressed in a somewhat demonstrative form as a \( t \)-dependent production amplitude:

\[
\mathcal{M}(t) = \alpha \exp\left(-\frac{1}{2}B_1 t\right) - \beta \exp\left(-\frac{1}{2}B_2 t\right),
\]

(22)

where \( \alpha \) and \( \beta \) represent the contribution to the matrix element from the region below and above the node position, respectively. In (22) \( B_1 \) and \( B_2 \) are the effective diffraction slopes, which correspond to integration over dipole size \( r \) from 0 to the position of the node \( r_n \) and above the node position. Thus, the inequality \( \alpha > \beta \) corresponds to the undercompensation whereas \( \alpha < \beta \) to the overcompensation regime. The destructive interference of these two amplitudes results in a decrease of the effective diffraction slope for the \( V'(2S) \) meson production for small \( t \) in contrary with the familiar increase for the \( V(1S) \) meson production. Such a situation is shown in Fig. 1, where we present the model predictions for the differential cross section as a function of \( t \) for production of \( V(1S) \) and \( V'(2S) \) mesons at different c.m.s. energies \( W \) and at \( Q^2 = 0 \). Real photoproduction measures the purely transverse cross section. As was mentioned in the paper [4], using our wave functions, at \( W \lesssim 150 \text{GeV} \) for \( \rho'(2S) \) production and at \( W \lesssim 20 \text{GeV} \) for \( \phi'(2S) \) production, the forward production amplitude (3) is in undercompensation regime whereas the matrix element \( < V'(2S)|\sigma(\xi, r)B(\xi, r)|\gamma > \) on r.h.s. of Eq. (14) is in the overcompensation regime. As the result we predict the negative valued diffraction slope at \( t = 0 \) and \( Q^2 = 0 \). For this reason and due to destructive interference of two contributions to the production amplitude (22) with different \( t \) dependencies, the differential cross section firstly rises with \( t \), flattens at \( t \sim (0.1 - 0.2) \text{GeV}^2 \) having a maximum. At large \( t \), the node effect is weak in \( t \)-dependent production amplitude because of a steeper \( t \) dependence from the large size dipoles and the differential cross section falls down following the differential cross section for \( V(1S) \) production. The position of the maximum can be roughly evaluated from (22) as follows:

\[
t_{\text{max}} \sim \frac{1}{B - A} \log \left[ \frac{\beta^2 B^2}{\alpha^2 A^2} \right],
\]

(23)

with the supplementary condition

\[
\frac{\beta}{\alpha} > \frac{A}{B}
\]

(24)

where \( A = 2B_1 \) and \( B = 2B_2 \), \( A < B \). If the condition (24) is not fulfilled the differential cross section \( d\sigma/dt \) for production of \( V'(2S) \) vector mesons has no maximum and has a standard monotonous \( t \)-behaviour like for production of \( V(1S) \) mesons.

The nonmonotonous \( t \)-behaviour of the differential cross section for \( \rho'(2S) \) and \( \phi'(2S) \) production in the photoproduction limit is strikingly different from the familiar decrease with \( t \) of the differential cross section for the \( \rho(1S) \) and \( \phi(1S) \) real photoproduction. Here we can not insist on the precise form of the \( t \) dependence of the differential cross section, the main emphasis is on the likely pattern of the \( t \) dependence coming from the node effect.

At larger energies, \( W \gtrsim 150 \text{GeV} \) for the \( \rho'(2S) \) photoproduction and \( W \gtrsim 30 \text{GeV} \) for \( \phi'(2S) \) photoproduction, the node effect becomes weaker and we predict the positive valued diffraction slope at \( t = 0 \) because of positive valued matrix elements \( < V'(2S)|\sigma(\xi, r)|\gamma > \) (3) and \( < V'(2S)|\sigma(\xi, r)B(\xi, r)|\gamma > \) on the r.h.s. of Eq. (14). For this reason, the nonmonotonous \( t \) dependence of the differential cross section is changed for the monotonous
one, but still the effective diffraction slope decreases towards small $t$ in contrary to the familiar increase for the $\rho^0(1S)$ and $\rho^0(1S)$ photoproduction (see Fig. 1).

Because of a possible overcompensation scenario for the longitudinally polarized $\rho'(2S)$ and $\phi'(2S)$ mesons in the forward direction and at small $Q^2$ (see Ref. [4]), we present in Fig. 2 the model predictions for the differential cross sections as a function of $t$ at different energies $W$ and at fixed $Q^2 = 0.5\,\text{GeV}^2$ for the production of $T$, $L$ polarized and polarization unseparated $\rho'(2S)$ and $\phi'(2S)$ mesons. As it was mentioned above, at $Q^2 = 0.5\,\text{GeV}^2$, the node effect becomes weaker, the amplitude for $\rho_T'(2S)$ and $\phi_T'(2S)$ production at $t = 0$ is in undercompensation regime and the corresponding slope parameter $B(\gamma_T'(2S))$ is positive valued because of the positive valued matrix element $< V'(2S)|\sigma(r,z)B(r,z)|\gamma^* >$ on the r.s.h. of Eq. (16). For this reason, we predict the standard decrease of $d\sigma(\gamma^* \rightarrow V_T'(2S))/dt$ with $t$ (see bottom boxes in Fig. 2). The above mentioned maximum of $d\sigma/dt$ for the undercompensation regime is absent due to a weaker node effect and because the condition (24) is not fulfilled.

However, for $Q^2 \ll 0.5\,\text{GeV}^2$, the amplitude for $\rho'_L(2S)$ and $\phi'_L(2S)$ production in forward direction, $(t = 0)$ (and the matrix element $< V'_L(2S)|\sigma(r,z)B(r,z)|\gamma^* >$ as well), is still in overcompensation regime with the positive valued diffraction slope $B(V'_L(2S))$ at small energies $W \ll 20\,\text{GeV}$. It follows in anomalous $t$ dependence of $d\sigma(\gamma^* \rightarrow V'_L(2S))/dt$ shown if Fig. 2 (middle boxes). With the increase of $t$, because of the above mentioned interference of two different contributions to the production amplitude with different $t$ dependencies, one encounters the exact cancellation of the large and small distance contributions. This fact corresponds to the exact node effect at some $t \sim t_{\text{min}}$. Thus, the differential cross section firstly falls down rapidly with $t$, have a minimum at $t \sim t_{\text{min}}$, following by a rise when the overcompensation scenario of $t$- dependent production amplitude is changed for the undercompensation one and the slope parameter becomes to be negative. At larger $t$, further pattern of $t$- behaviour is practically the same as the nonmonotonous $t$ dependence of $d\sigma(\gamma^* \rightarrow V'_L(2S))/dt$ at $Q^2 = 0$ (see Fig. 1).

The position of the minimum, $t_{\text{min}}$, in differential cross section is model dependent and can be roughly estimated from (22)

$$t_{\text{min}} \sim \frac{1}{B - A} \log \left[ \frac{\beta^2}{\alpha^2} \right].$$ (25)

With our wave functions we find $t_{\text{min}} \sim 0.03\,\text{GeV}^2$ for $\rho'_L(2S)$ production and $t_{\text{min}} \sim 0.05\,\text{GeV}^2$ for $\phi'_L(2S)$ production at $Q^2 = 0.5\,\text{GeV}^2$ and at $W = 5\,\text{GeV}$. However, we can not exclude a possibility that this minimum will take a place at larger $t$. At $Q^2 < 0.5\,\text{GeV}^2$, $t_{\text{min}}$ will be also located at larger values of $t$. At higher energy, the position of $t_{\text{min}}$ is shifted to a smaller value of $t$ unless the exact node effect is reached at $t = 0$. At still larger energy, when longitudinally polarized $2S$ production amplitude is in undercompensation regime, this minimum disappears and we predict the pattern of $t$- behaviour of $L$ differential cross section very similar to one like nonmonotonous $t$ dependence of $d\sigma(\gamma \rightarrow V'_L(2S))/dt$ in the photoproduction limit described in Fig. 1. These predicted anomalies can be tested at HERA measuring the diffractive electroproduction of $2S$ radially excited light vector mesons.
in the separate polarizations, \( T \) and \( L \).

Conclusions

We study the diffractive photo- and electroproduction of ground state \( V(1S) \) and radially excited \( V' (2S) \) vector mesons within the color dipole gBFKL dynamics with the main emphasis related to the differential cross section \( d\sigma / dt \), which is connected with 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 color dipole gBFKL phenomenology of the slope parameter.

The diffraction slope for the production of \( 2S \) light vector mesons shows very interesting and anomalous behaviour as function of c.m.s. energy \( W \) and \( Q^2 \) and will be detaily analysed elsewhere \cite{21}. As a consequence of the node in \( 2S \) radial wave function, we predict a strikingly different \( t \) dependence of the differential cross section for production of \( V' (2S) \) vs. \( V(1S) \) mesons. The origin is in destructive interference of the large distance negative contribution to the production amplitude from the region above the node position with a steeper \( t \)-dependence and small distance positive contribution to the production amplitude from the region below the node position with a weaker \( t \)-dependence. As a result, at \( Q^2 = 0 \) (when the \( T \) polarized \( V'_T (2S) \) mesons are only produced) as a consequence of the undercompensation scenario for \( T \) polarized forward production amplitude, we predict a nonmonotonous \( t \)-dependence of \( d\sigma (\gamma \rightarrow V'_T (2S)) / dt \) and a decreasing effective diffraction slope for \( V'_T (2S) \) mesons towards to negative values at small \( t \) in contrary with the familiar increase for the \( V(1S) \) mesons. The differential cross section \( d\sigma (\gamma \rightarrow V'_T (2S)) / dt \) firstly rises with \( t \) having a maximum at \( t \sim t_{\text{max}} \) given by Eq.\((23)\). At large \( t \) when the node effect is weaker \( d\sigma (\gamma \rightarrow V'_T (2S)) / dt \) has the standard monotonous \( t \)-behaviour like for production of \( V(1S) \) vector mesons. The position of the maximum is model dependent and is shifted to smaller values of \( t \) with rising energy and \( Q^2 \) due to a weaker node effect.

For production of \( L \) polarized \( V'_L (2S) \) mesons, there is overcompensation at \( t = 0 \) leading to an exact cancellation of the positive contribution from large size dipoles and the negative contribution from small size dipoles to the production amplitude and to a minimum of the differential cross section at some value of \( t \sim t_{\text{min}} \). The position of \( t_{\text{min}} \) is given by Eq. \((23)\), is energy dependent and leads to a complicated anomalous \( t \)-dependence of \( d\sigma (\gamma^* \rightarrow V'_L (2S)) / dt \) at fixed \( Q^2 \). Thus, \( d\sigma (\gamma^* \rightarrow V'_L (2S)) / dt \) firstly falls down with \( t \) having a minimum at \( t \sim t_{\text{min}} \) when the overcompensation scenario is changed for the undercompensation one. The following pattern of \( t \)-behaviour is then the same like for \( d\sigma (\gamma \rightarrow V'_T (2S)) / dt \) at \( Q^2 = 0 \). These anomalies are also energy and \( Q^2 \)-dependent and
can be studied at HERA.

The experimental investigation of $t$- dependent differential cross section for real photo-production ($Q^2 = 0$) of $V'(2S)$ mesons at fixed target and HERA experiments, offers an unique possibility to make a choice between the undercompensation and overcompensation scenarios. The presence of the minimum in $t$- dependent $d\sigma(\gamma \rightarrow V'(2S))/dt$ in a broad energy region from small to large energies, corresponds to the overcompensation scenario, whereas its absence corresponds to the undercompensation scenario.

The position of the node in the radial $(2S)$ wave function can be tested also by the vector meson data with separate polarizations ($L$) and ($T$) at $Q^2 > 0$. The existence of the minimum in $t$- dependent differential cross section is connected again with the overcompensation scenario in $(2S)$ production amplitude whereas the undercompensation scenario reflects the maximum of $d\sigma/dt$ and/or the standard monotonous $t$- behaviour.

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Figure captions:

Fig. 1 - The color dipole model predictions for the differential cross sections \( d\sigma(\gamma^* \rightarrow V(V'))/dt \) for the real photoproduction \((Q^2 = 0)\) of the \( \rho^0, \rho'(2S), \phi^0 \) and \( \phi'(2S) \) at different values of the c.m.s. energy \( W \).

Fig. 2 - The color dipole model predictions for the differential cross sections \( d\sigma_{L,T}(\gamma^* \rightarrow V'/')/dt \) for transversely (T) (top boxes) and longitudinally (L) (middle boxes) polarized radially excited \( \rho'(2S), \phi'(2S) \) and for the polarization-unseparated \( d\sigma(\gamma^* \rightarrow V')/dt = d\sigma_T(\gamma^* \rightarrow V')/dt + \epsilon d\sigma_L(\gamma^* \rightarrow V')/dt \) for \( \epsilon = 1 \) (bottom boxes) at \( Q^2 = 0.5 \text{ GeV}^2 \) and different values of the c.m.s. energy \( W \).
