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VECTOR MESONS ρ, ρ' AND ρ'' DIFFRACTIVELY PHOTO- AND LEPTOPRODUCED

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In the framework of non-perturbative QCD, we calculate high-energy diffractive production of vector mesons ρ, ρ' and ρ'' by real and virtual photons on a nucleon. The initial photon dissociates into a $q\bar{q}$-dipole and transforms into a vector meson by scattering off the nucleon which, for simplicity, is represented as quark-diquark. The relevant dipole-dipole scattering amplitude is provided by the non-perturbative model of the stochastic QCD vacuum. The wave functions result from considerations in the frame of light-front dynamics; the physical ρ'- and ρ''-mesons are assumed to be mixed states of an active 2S-excitation and some residual rest (2D- and/or hybrid state). We obtain good agreement with the experimental data and get an understanding of the markedly different $\pi^+\pi^-$-mass spectra for photoproduction and e^+e^--annihilation.

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1. Introduction

Diffractive scattering processes are characterized by small momentum transfer, $-t \lesssim 1$ GeV^2, and thus governed by non-perturbative QCD. To get better insight in the physics at work, we investigate exclusive vector meson production by real and virtual photons. In this note, we summarize recent results from Ref. 1 on ρ-, ρ'- and ρ''-production (see also Ref. 2). In Refs. 1 and 3, we have developed a framework which we can here only flash through.

We consider high-energy diffractive collision of a photon, which dissociates into a $q\bar{q}$-dipole and transforms into a vector meson, with a proton in the quark-diquark picture, which remains intact. The scattering amplitude T can be written as an integral of the dipole-dipole amplitude and the corresponding wave functions. In-

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tegrating out the proton side, we have

$$T_V^\lambda(s,t) = \mathrm{i}s \int \frac{\mathrm{d}z\mathrm{d}^2\mathbf{r}}{4\pi}\, \psi^\dagger_{V(\lambda)}\psi_{\gamma(Q^2,\lambda)}(z,\mathbf{r})\; J_p(z,\mathbf{r},\Delta_T)\;, \tag{1}$$

where $V(\lambda)$ stands for the final vector meson and $\gamma(Q^2,\lambda)$ for the initial photon with definite helicities λ (and virtuality Q^2); z is the light-cone momentum fraction of the quark, $\mathbf{r}$ the transverse extension of the $q\bar{q}$-dipole. The function $J_p(z,\mathbf{r},\Delta_T)$ is the interaction amplitude for a dipole $\{z,\mathbf{r}\}$ scattering on a proton with a fixed momentum transfer $t=-\Delta_T^2$; for $\Delta_T=0$, due to the optical theorem, it is the corresponding total cross section (see below Eq. (4)). It is calculated within the non-perturbative QCD. In the high-energy limit, Nachtmann [4] derived a non-perturbative formula for the dipole-dipole scattering whose basic entity is the vacuum expectation value of two lightlike Wilson loops. This gets evaluated [5] in the model of the stochastic QCD vacuum.

2. The model of the stochastic QCD vacuum

Coming from the functional integral approach, the model of the stochastic QCD vacuum [6] assumes that the non-perturbative part of the gauge field measure, i.e., long-range gluon fluctuations that are associated with a non-trivial vac-

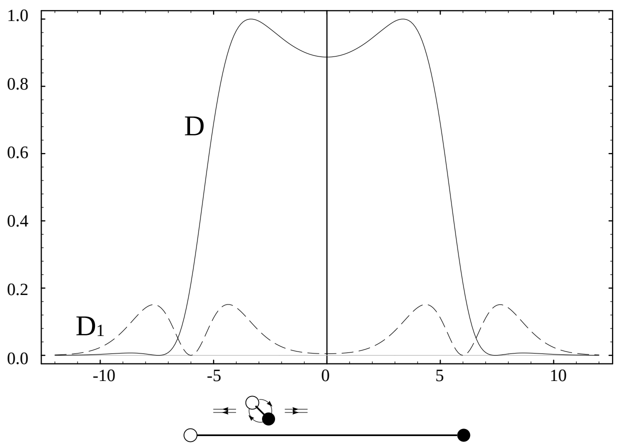

Fig. 1. Interaction amplitude (arbitrary units) of two colour dipoles as function of their impact (units of correlation lengths a). One large $q\bar{q}$-dipole of extension $12a$ is fixed, the second, small one of extension $1a$, is averaged over all its orientations, shifted along on top of the first one. For the D_1-tensor structure of the correlator, there are only contributions when the endpoints are close to each other, whereas for the D-structure, large contributions show up also from between the endpoints. This is to be interpreted as interaction with the gluonic string between the quark and antiquark.

uum structure of QCD, can be approximated by a stochastic process in the gluon field strengths with convergent cumulant expansion. Further, assuming this process to be Gaussian, one arrives at a description through the second cumulant $\langle g^2 F^A_{\mu\nu}(x;x_0) F^{A'}_{\rho\sigma}(x';x_0)\rangle$, which has two Lorentz tensor structures multiplied by the correlation functions D and D_1, respectively. D is non-zero only in the non-abelian theory, or in the abelian theory with magnetic monopoles and yields linear confinement, whereas the D_1-structure is not confining.

The underlying mechanism of (interacting) gluonic strings also shows up in the scattering of two colour dipoles, cf. Fig. 1, and essentially determines the T-amplitude if large dipole sizes are not suppressed by the wave functions. To confront with experiment this specific large-distance prediction, we intend to study the broad ρ-states and, especially, their production by broad small-Q^2 photons. Before we start the discussion of our results, we have to specify these states and fix their wave functions as well as that of the photon.

3. *Physical states ρ, ρ' and ρ''*

Analyzing the $\pi^+\pi^-$ invariant-mass spectra for photoproduction and e$^+$e$^-$-annihilation, Donnachie and Mirzaie [7] concluded evidence for two resonances in the 1.6 GeV region whose masses are compatible with the 1^{--} states $\rho(1450)$ and $\rho(1700)$. We make as simplest ansatz

$$\begin{aligned} |\rho(770)\rangle &= |1\mathrm{S}\rangle\ , \\ |\rho(1450)\rangle &= \cos\theta\ |2\mathrm{S}\rangle + \sin\theta\ |\mathrm{rest}\rangle\ , \\ |\rho(1700)\rangle &= -\sin\theta\ |2\mathrm{S}\rangle + \cos\theta\ |\mathrm{rest}\rangle\ , \end{aligned} \tag{2}$$

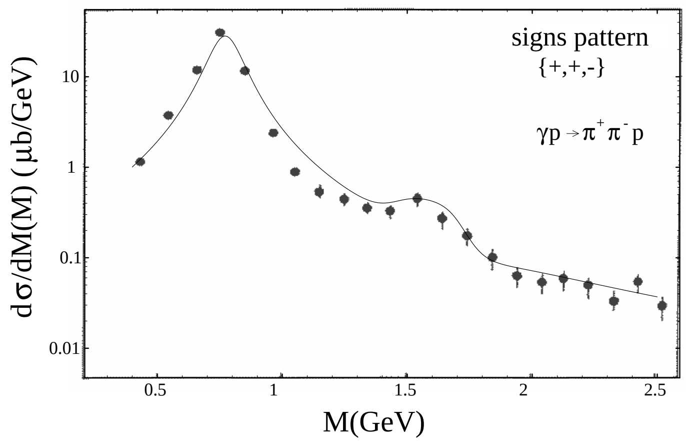

Fig. 2. Mass spectrum of $\pi^+\pi^-$-photoproduction on the proton: The interference in the 1.6 GeV *region is constructive, in contrary to the case of* e$^+$e$^-$*-annihilation into $\pi^+\pi^-$. We display our calculation together with the experimental data [7].*

where $|\text{rest}\rangle$ is considered to have $|2\text{D}\rangle$- and/or hybrid components whose couplings to the photon both are suppressed, see Refs. 8, 9 and 10, respectively. With our convention of the wave functions, the relative signs $\{+,-,+\}$ of the production amplitudes of the ρ-, ρ'- and ρ''-states in e^+e^--annihilation determine the mixing angle to be in the first quadrant; from Ref. 7 then follows $\theta \cong 41°$. With this value and the branching ratios of the ρ'- and ρ''-mesons into $\pi^+\pi^-$ extracted in Ref. 7, we calculate the photoproduction spectrum as shown in Fig. 2 with the observed signs pattern $\{+,+,-\}$; for details see Ref. 1. We will understand below from Fig. 3 the signs change of the 2S-production as due to the dominance of large dipole sizes in photoproduction, in contrary to the coupling to the electromagnetic current $f_{2\text{S}}$ being determined by small dipole sizes.

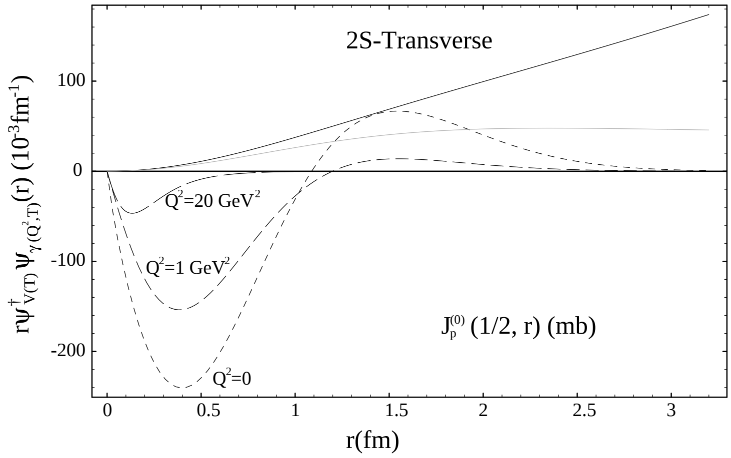

Fig. 3. Dipole-proton total cross section $J_p^{(0)}$ and effective overlap $r\psi^\dagger_{V(T)}\psi_{\gamma(Q^2,T)}$ as function of the transverse dipole size r. The black line shows the total cross section of a $q\bar{q}$-dipole $\{z = 1/2, \mathbf{r}\}$, averaged over all orientations, for scattering on a proton, i.e. the function $J_p^{(0)}(1/2, r)$; the full line shows the cross section for a completely abelian, non-confining theory. The T-amplitude is obtained by integration over the product of J_p and the overlap function, which essentially is the effective overlap shown for $Q^2 = 0$, 1 and 20 GeV^2 as short, medium and long dashed curves, respectively.

4. Light-cone wave functions

In the high-energy limit, the photon can be identified as its lowest Fock, i.e. $q\bar{q}$-state. The vector-meson wave function distributes this $q\bar{q}$-dipole $\{z, \mathbf{r}\}$, accordingly.

Photon: Using the light-cone perturbation theory (LCPT), we get explicit expressions for both longitudinal and transverse photons. The photon transverse size, which we will see to determine the T-amplitude, is governed by the product εr, $\varepsilon = \sqrt{z\bar{z}Q^2 + m^2}$ and $r = |\mathbf{r}|$. For high Q^2, longitudinal photons dominate by a power of Q^2; their z-endpoints being explicitly suppressed, LCPT is thus applicable. For moderate Q^2, also transverse photons contribute, which have large extensions because endpoints are not suppressed. For Q^2 smaller than 1 GeV^2, LCPT definitively breaks down. However, it was shown [11] that a quark mass phenomenologically interpolating between a zero valence and a 220 MeV constituent mass astonishingly well mimics chiral symmetry breaking and confinement. Our wave function is thus given by LCPT with such a quark mass $m(Q^2)$ (for details cf. Refs 1 and 3).

Vector mesons: The vector-meson wave functions of the 1S- and 2S-states are modelled according to the photon. We only replace the photon energy denominator $(\varepsilon^2 + \mathbf{k}^2)^{-1}$ by a function of z and $|\mathbf{k}|$ for which ansätze, according to Wirbel and Stech [12] are made; for the "radial" excitation, we account by using both a polynomial in $z\bar{z}$ and the 2S-polynomial in $\mathbf{k}^2$ of the transverse harmonic oscillator. The parameters are fixed by the demands that the 1S-state reproduces M_ρ and f_ρ, and the 2S-state is both normalized and orthogonal to the 1S-state. For details cf. Ref. 1.

5. *Results*

Before presenting some of our results [1], we stress that all calculated quantities are absolute predictions. Due to the applied eikonal approximation, the cross sections are constant with total energy s and refer to $\sqrt{s} = 20$ GeV, where the proton radius is fixed. (The two parameters of the model of the stochastic QCD vacuum, the gluon condensate $\langle g^2 FF \rangle$ and the correlation length a, are determined by matching low-energy and lattice results, cf. Ref. 5.)

In Fig. 3, we display – for the transverse 2S-state, $\lambda = T$ – both functions,

$$J_p^{(0)}(z,r) \quad := \quad \int_0^{2\pi} \frac{\mathrm{d}\varphi_{\mathbf{r}}}{2\pi}\, J_p(z,\mathbf{r},\Delta_T = 0)\,, \tag{3}$$

$$r\psi^\dagger_{V(\lambda)}\psi_{\gamma(Q^2,\lambda)}(r) \quad := \quad \int \frac{\mathrm{d}z}{4\pi} \int_0^{2\pi} \frac{\mathrm{d}\varphi_{\mathbf{r}}}{2\pi}\, |\mathbf{r}|\, \psi^\dagger_{V(\lambda)}\psi_{\gamma(Q^2,\lambda)}(z,\mathbf{r})\,, \tag{4}$$

which together, see Eq. (1), essentially determine the leptoproduction amplitude. It is strikingly to see how for decreasing virtuality Q^2, the outer positive-region of the wave functions effective overlap $r\psi^\dagger_{V(\lambda)}\psi_{\gamma(Q^2,\lambda)}$ wins over the inner negative part due to the strong rise with r of the dipole-proton interaction amplitude $J_p^{(0)}$, which itself is a consequence of the string interaction mechanism discussed above. *In praxi*, dipole sizes up to 2.5 fm contribute significantly to the cross section.

Our results for integrated elastic cross sections as functions of Q^2 are given in Fig. 4. For the ρ-meson, our prediction is about $20-30\%$ below the E665-data [13]. However, we agree with the NMC-experiment [14] which measures some definite superposition of longitudinal and transverse polarization (see Table 3 in Ref. 1). For the 2S-state, due to the nodes of the wave function, we predict a marked structure; the explicit shape, however, strongly depends on the parametrization of the wave functions.

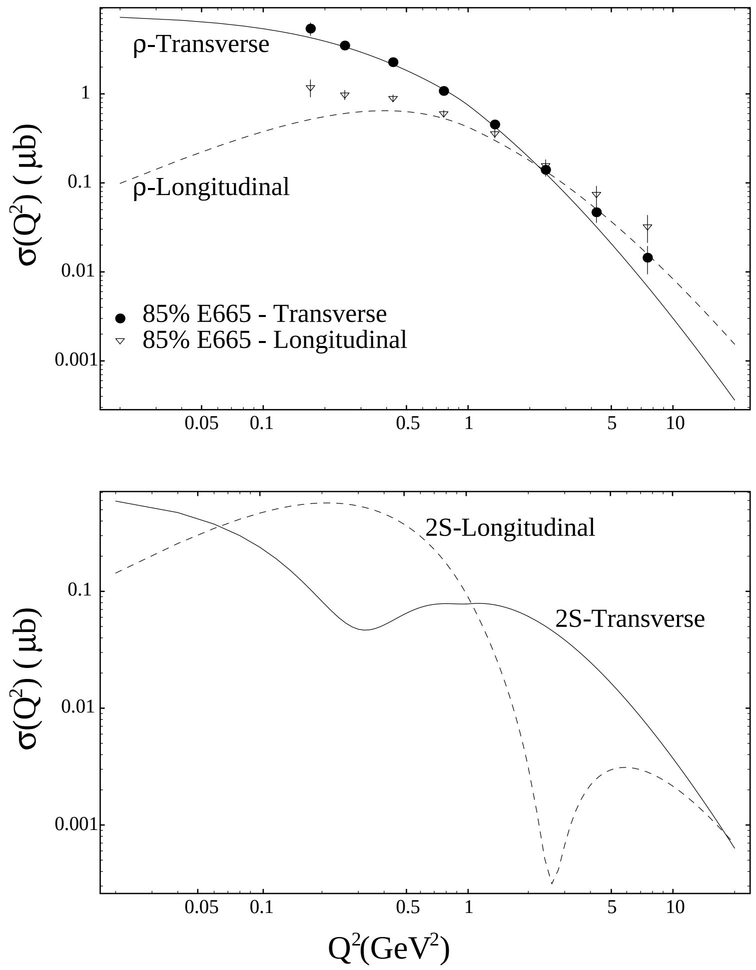

Fig. 4. Integrated cross sections of the ρ-meson and the 2S*-state as a function of Q^2. E665 [13] provides data for the ρ; the pomeron contribution, which corresponds to our calculation, we roughly estimate as 85% of the measured cross section, cf. Ref. 15.*

In Fig. 5, we display the ratio $R_{LT}(Q^2)$ of longitudinal to transverse cross sections and find good agreement with experimental data for the ρ-state. For the 2S-state, we again predict a marked structure which is very sensitive to the node positions in the wave functions.

Further results refering to cross sections differential in $-t$ and the ratio of $2\pi^+2\pi^-$-production via ρ' and ρ'' to $\pi^+\pi^-$-production via ρ are given in Ref. 1.

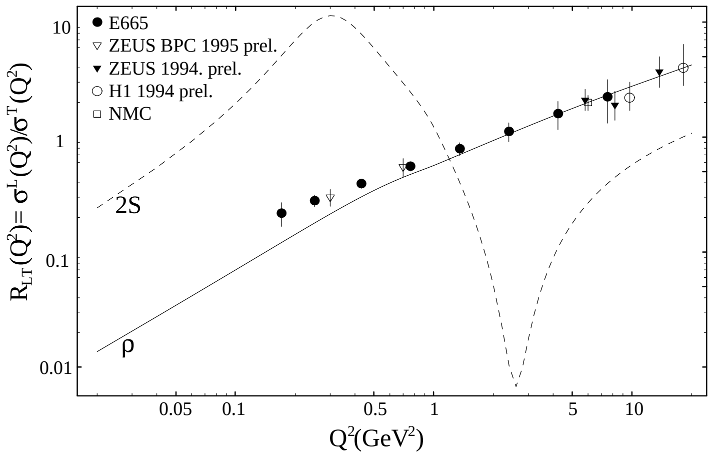

Fig. 5. Ratio of longitudinal to transverse integrated cross sections as function of Q^2, both for the ρ-meson and the 2S-state. There are only data for ρ-production [13].

6. Conclusion

We have presented a realistic calculation of photo- and leptoproduction of the three lowest lying ρ-meson states in which are assumed the ρ' and ρ'' to be mixed quark-antiquark $2S$-states with some inert residual component. The decay characteristics of the ρ' point to a sizeable hybrid admixture which may also exist for the ρ''.

With our ansatz, the interference pattern in e^+e^--annihilation of two charged pions induces a mixing angle which implies that the ρ' and ρ'' are about one half a quark-antiquark $2S$-state and one half hybrid and/or $2D$-excitation, which reproduces the essentially different interference pattern of photoproduction of two charged pions.

Our calculation gives evidence of diffraction as scattering of colour neutral states due to the long-range gluon fluctuations. The large vector-meson excited states test favourably our picture of a dipole-proton cross section increasing with the quark-antiquark transverse distance r due to the string-string interactions which emerge from the model of the stochastic vacuum as an essential consequence of non-perturbative QCD. Especially transverse photoproduction has a matrix element where the elementary dipole-proton cross section is sampled between 1 and 2 fm.

The consequences of this mechanism are confronted with observations and a good agreement was found where experimental data are available.

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DIFRAKTIVNO FOTO- I LEPTONSKI PROIZVEDENI VEKTORSKI MESONI ρ, ρ' I ρ''

U okviru neperturbativne QCD, izračunali smo difraktivnu tvorbu vektorskih mezona ρ, ρ' and ρ'' na nukleonu na visokim energijama s realnim i virtualnim fotonima. Početni se foton razdvaja na $q\bar{q}$-dipol i pretvara u vektorski mezon pri raspršenju na nukleonu, koji se, radi jednostavnosti, predstavlja kao kvark-dikvark. Tražena se dipolno-dipolna amplituda dobije neperturbativnim modelom stohastičkog QCD vakuuma. Valne se funkcije dobiju razmatranjem u sustavu dinamike valne fronte. Pretpostavlja se da su fizički mezoni ρ'- i ρ'' miješana stanja aktivne 2S-uzbude i ostatka (2D i/ili hibridnih stanja). Dobiva se dobro slaganje s eksperimentalnim podacima i postiže razumijevanje izrazito različitih masenih spektara $\pi^+\pi^-$ za fototvorbu i poništenje e^+e^-.