

DIFFRACTIVE VECTOR MESONS IN DIS: MESON STRUCTURE AND QCD * **

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(Received July 10, 2000)

We review the modern status of QCD theory of diffractive vector meson production with the focus on shrinkage of photons with Q^2 and $(Q^2 + m_V^2)$ scaling, j -plane properties of the QCD pomeron and Regge shrinkage of diffraction cone, s -channel helicity non-conservation and sensitivity to spin-orbital properties of vector mesons.

PACS numbers: 12.38.–t

1. Introduction

There are good reasons for special interest in diffractive vector meson production. Recall the fundamental relationship between the inclusive DIS structure function and the forward amplitude of a diagonal $Q_f^2 = Q_{\text{in}}^2 = Q^2$ virtual Compton Scattering (CS)

$$\gamma_\mu^*(Q_{\text{in}}^2)p \rightarrow \gamma_\nu^*(Q_f^2)p', \quad (1)$$

which for purely kinematical reasons of vanishing (γ^*, γ^*) momentum transfer is diagonal in the photon helicities $\nu = \mu$. By analytic continuation to $Q_f^2 = 0$ one obtains DVCS, the still further continuation to $Q_f^2 = -m_V^2$ one obtains from CS the diffractive Vector Meson (VM) production

$$\gamma_\mu^*(Q^2)p \rightarrow \gamma^* V_\nu(\Delta)p'(-\Delta), \quad (2)$$

* Presented at the Meson 2000, Sixth International Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 19–23, 2000.

** This work was partly supported by INTAS grant 97-30494

which is accessible experimentally at finite $(\gamma^*.V)$ momentum transfer Δ . Furthermore, the decays of VM's are self-analyzing and azimuthal correlations of (e, e') , (p, p') and decay planes and polar decay angle distributions allow to reconstruct the full set of helicity amplitudes $A_{\nu\mu}$, which allows to probe the mechanism of generalized CS in full complexity. The new numerical results reported here were obtained in collaboration with Ivanov [1].

2. Color dipole factorization, shrinking photons and $(Q^2 + m_V^2)$ scaling

The small- x CS is best described in Color Dipole (CD) factorization, in which $A_{\nu\mu} = \Psi_{\nu, \lambda\bar{\lambda}}^* \otimes A_{q\bar{q}} \otimes \Psi_{\mu, \lambda\bar{\lambda}}$ where $\lambda, \bar{\lambda}$ stands for q, \bar{q} helicities, $\Psi_{\mu, \lambda\bar{\lambda}}$ is the Wave Function (WF) of the $q\bar{q}$ Fock state of the photon. The QCD pomeron exchange $q\bar{q}$ -proton scattering kernel $A_{q\bar{q}}$, proportional to color dipole cross section, does not depend on, and conserves exactly, the q, \bar{q} helicities. For small dipoles, the CD cross section can be related to the gluon SF of the target,

$$\sigma(x, \mathbf{r}) \approx \frac{\pi^2}{3} r^2 \alpha_S \left(\frac{A}{r^2} \right) G \left(x, \frac{A}{r^2} \right), \quad (3)$$

where $A \approx 10$ follows from properties of of Bessel functions [2].

The diagonal CS, *i.e.*, inclusive DIS, probes CD cross section in broad range of $1/AQ^2 \lesssim r^2 \lesssim 1 \text{ fm}^2$ [3]. The far reaching change from diagonal CS to exclusive VM production is that in the final state one swaps the pointlike photon the $q\bar{q}$ WF of which is singular at $r \rightarrow 0$ [4] for the finite-size VM with WF which is smooth at $r \rightarrow 0$. The crucial change [5, 6] is that diffractive VM production probes the CD cross section and the VM WF at a scanning radius

$$r \sim r_S = \frac{6}{\sqrt{Q^2 + m_V^2}}, \quad (4)$$

which is a manifestation of a shrinkage of the photon with Q^2 .

The three fundamental consequences of (3) and (4) are:

- (i) the VM production probes [6] the gluon SF of the target at the hard scale $\bar{Q}^2 \approx (0.1-0.25) (Q^2 + m_V^2)$, with slight variations from light to heavy VM's, and $x = 0.5(Q^2 + m_V^2)/(Q^2 + W^2)$,
- (ii) after factoring out the charge-isospin factors all VM production cross section follow a universal function of \bar{Q}^2 , *i.e.* there is $(Q^2 + m_V^2)$ scaling [6], see Fig. 1, the same scaling holds also for the effective intercept $\alpha_{\mathbb{P}}(0) - 1$ of the energy dependence of production amplitude, see Fig. 2,

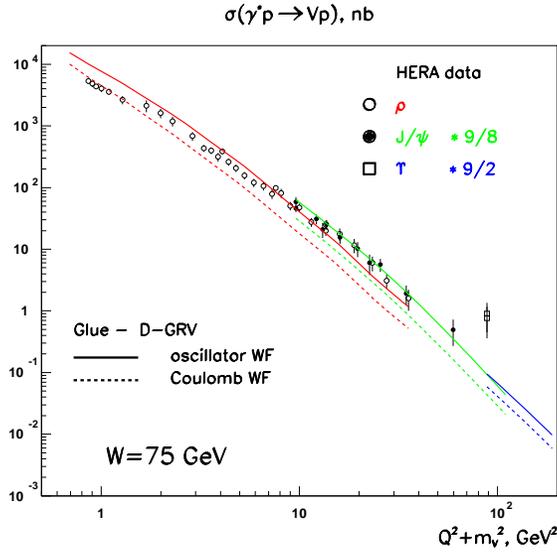


Fig. 1. The test of the $(Q^2 + m_V^2)$ scaling. The divergence of the solid and dashed curves indicates the sensitivity to the WF of the VM. The experimental data are from HERA [8,9].

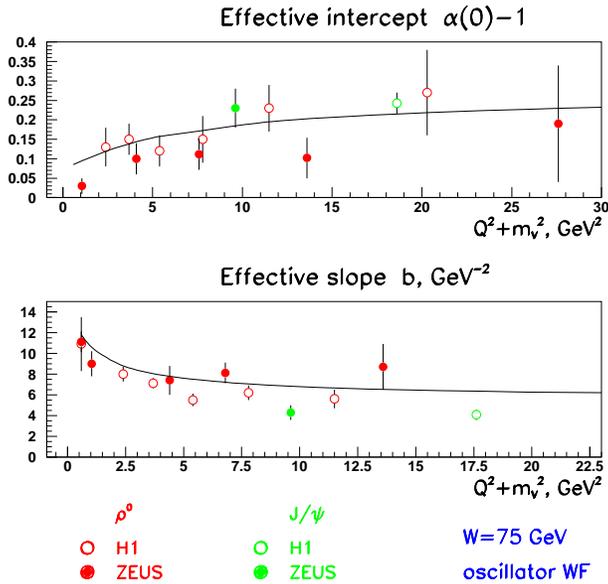


Fig. 2. The $(Q^2 + m_V^2)$ scaling of the effective intercept and diffraction slope.

(iii) the contribution to the diffraction slope B from the $\gamma^* \rightarrow V$ transition vertex decreases $\propto r_S^2$ exhibiting again the $(Q^2 + m_V^2)$ scaling [7], see Fig. 2.

The agreement between theory and experiment [8, 9] is good, although there remains certain sensitivity to not so well known WF of VM's which can not be eliminated at the moment, see also below.

3. Shrinkage of the diffraction cone

If the pomeron is the Regge pole with the trajectory $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t$, then the diffraction slope would rise with energy, $B(W^2) = B_0 + 2\alpha'_{\mathbb{P}} \log(W^2/W_0^2)$. The common prejudice based on scaling $\alpha_S = \text{const}$ approximation is that the BFKL pomeron is a fixed branching point, *i.e.*, $\alpha'_{\mathbb{P}} = 0$, with no shrinkage of the diffraction cone. Which is almost tautological because in this approximation one is short of any length scale. This toy model is nice because it is exactly solvable but it is not QCD, in which the Asymptotic Freedom (AF), *i.e.*, running coupling α_S , and the fact that perturbative gluons have finite propagation radius, introduce the perhaps related length scale. The consistent implementation of AF into color dipole BFKL equation has been done by Zakharov, Zoller and myself in 1994 [10]. The corresponding QCD pomeron has been proven to be a series of moving Regge poles [11]. As a matter of fact, already in 1975 Fadin, Kuraev and Lipatov noticed that AF brings about the fundamental transformation of the QCD pomeron from a fixed branching point to a series of moving poles [12]. With the specific infrared regularization used in [3, 10, 11] we found $\alpha'_{\mathbb{P}} \approx 0.07 \text{ GeV}^{-2}$ for the rightmost hard BFKL pole and a somewhat smaller slope for trajectories of subleading poles. Under plausible boundary condition, the interference of the rightmost and subleading pomerons was shown to produce a shrinkage with $\alpha'_{\text{eff}} \sim 0.15 \text{ GeV}^{-2}$ [7]. Such a sensitivity of shrinkage of the diffraction cone to subleading Regge components in pp and $p\bar{p}$ scattering is old news.

Our fundamental prediction of shrinkage of the diffraction cone for hard diffractive DIS has been confirmed recently by the ZEUS collaboration [13], which measured the energy dependence of diffraction slope for the J/Ψ photoproduction with the result $\alpha'_{\mathbb{P}} = 0.098 \pm 0.035(\text{stat}) \pm 0.050(\text{syst})$, which is consistent with our numerical results [7].

4. Pomeron helicity-flip and breaking of SCHC

As emphasized above, the helicity of quarks in $q\bar{q}$ -target scattering is conserved exactly, which for long has been believed to entail the S -Channel Helicity Conservation (SCHC). The fundamental point is that the sum of

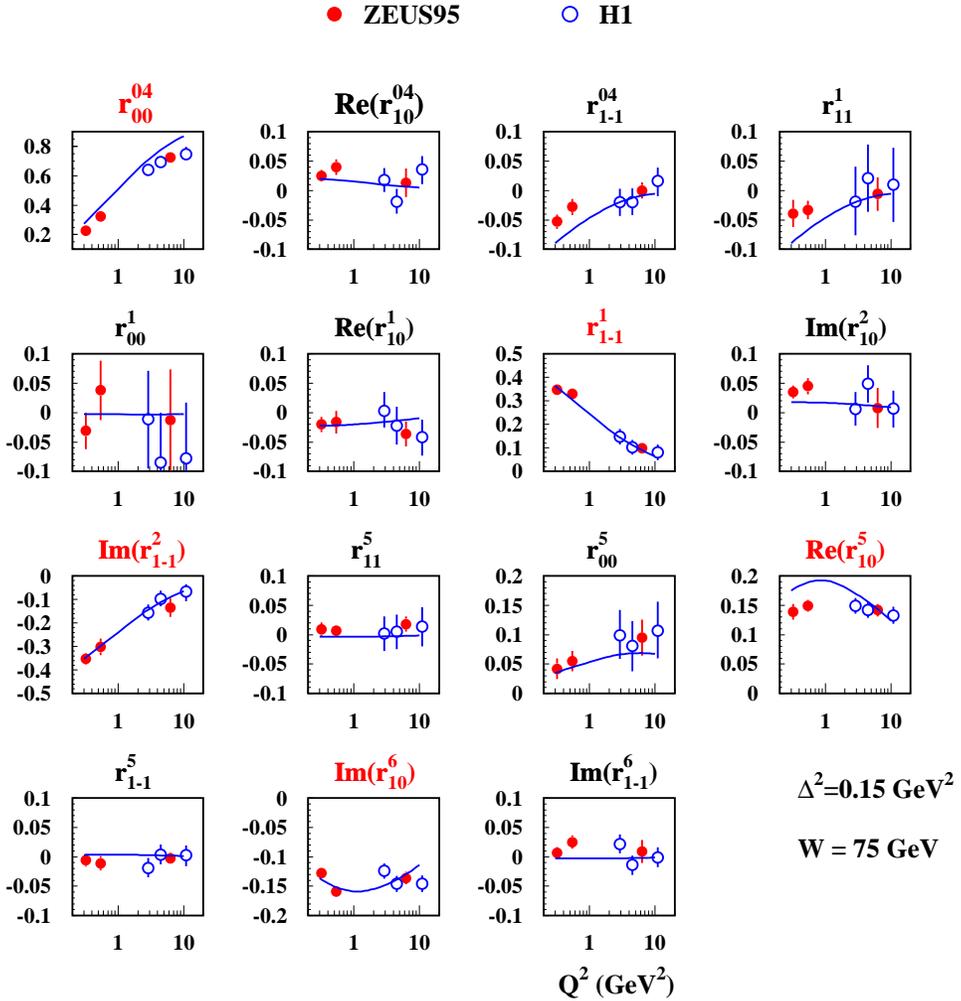


Fig. 3. Predictions for the spin density matrix in the ρ^0 production *vs* the experimental data from HERA.

quark and antiquark helicities equals helicity of neither photon nor vector meson. Only for the nonrelativistic massive quarks, $m_f^2 \gg Q^2$ the only allowed transition is $\gamma_\mu^* \rightarrow q_\lambda + \bar{q}_{\bar{\lambda}}$ with $\lambda + \bar{\lambda} = \mu$. In the relativistic case transitions of transverse photons γ_\pm^* into the $q\bar{q}$ state with $\lambda + \bar{\lambda} = 0$, in which the helicity of the photon is transferred to the $q\bar{q}$ orbital momentum, are equally allowed. Consequently, the QCD pomeron exchange SCHNC transitions $\gamma_\pm^* \rightarrow (q\bar{q})_{\lambda+\bar{\lambda}=0} \rightarrow \gamma_L^*$ and $\gamma_\pm^* \rightarrow (q\bar{q})_{\lambda+\bar{\lambda}=0} \rightarrow \gamma_\mp^*$ are allowed [14, 15] and SCHNC persists at small x . We emphasize that the above

argument for SCHNC does not require the applicability of p QCD. Furthermore, the leading contribution to the proton structure function comes entirely from transitions of transverse photons — the fact never mentioned in textbooks.

The first ever direct QCD evaluation [14] of SCHNC effect — the LT-interference of transitions $\gamma_L^* p \rightarrow p' X$ and $\gamma_{\pm}^* p \rightarrow p' X$ into the same continuum diffractive states X — has been reported by Pronyaev, Zakharov and myself in 1997. Experimentally, it can be measured at HERA by both H1 and ZEUS via azimuthal correlation between the (e, e') and (p, p') scattering planes and can be used the determination of the otherwise elusive $R = \sigma_L/\sigma_T$ for diffractive DIS is found in [15]. The principal issue is that this asymmetry persists, and even rises slowly, at small x_P .

SCHNC helicity flip only is possible due to the transverse and/or longitudinal Fermi motion of quarks and is extremely sensitive to spin-orbit coupling in the vector meson, I refer for details to [16, 17]. The consistent analysis of production of S -wave and D -wave vector mesons is presented only in [17]. One would readily argue based on the results [14, 15] that by exclusive–inclusive duality [18] between diffractive DIS into continuum and vector mesons the dominant SCHNC effect in vector meson production is the interference of SCHC $\gamma_L^* \rightarrow V_L$ and SCHNC $\gamma_T^* \rightarrow V_L$ production, *i.e.*, the element r_{00}^5 of the vector meson spin density matrix. The overall agreement between our theoretical estimates [1] of the spin density matrix r_{ik}^n for diffractive ρ^0 assuming pure S -wave in the ρ^0 -meson and the ZEUS [19] and H1 [20] experimental data is very good. There is a clear evidence for $r_{00}^5 \neq 0$, see Fig. 3.

5. A fly in the pie: the σ_L/σ_T puzzle?

In Fig. 4 we show separately the predictions for σ_L and σ_T . Evidently, the toy models with soft wave functions for VM fail at large Q^2 . The natural interpretation is that these toy models underestimate the admixture of small size color dipoles in vector mesons.

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

$$R_{\text{el}} = \left| \frac{A(\gamma_L^* p \rightarrow \gamma_L^* p)}{A(\gamma_T^* p \rightarrow \gamma_T^* p)} \right|^2 = \left(\frac{\sigma_L}{\sigma_T} \right)_{\text{DIS}}^2 \approx 4 \times 10^{-2} \quad (5)$$

Here I used the prediction [3] for inclusive DIS $R_{\text{DIS}} = \sigma_L/\sigma_T|_{\text{DIS}} \approx 0.2$, which is consistent with the indirect experimental evaluations at HERA. The result $R_{\text{el}} \ll 1$ for diagonal CS with production of the pointlike final state photon must be contrasted to theoretical expectation $R \sim Q^2/m_V^2 \gg 1$ for non-pointlike vector meson production. Such a dramatic change from

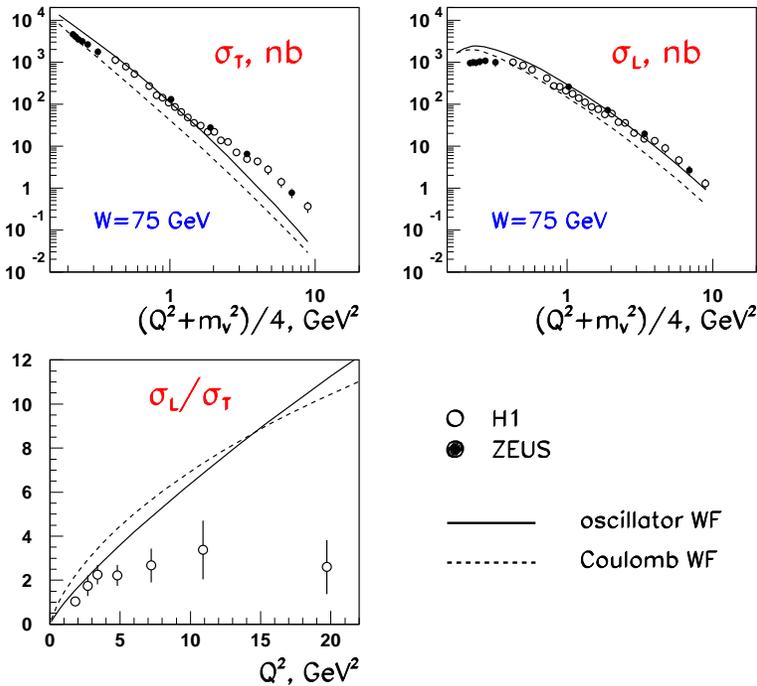


Fig. 4. The demonstration that soft WF of the ρ^0 underestimates σ_T at large Q^2 .

R_{el} to R for VM's suggests that predictions for R are extremely sensitive to admixture of quasi-pointlike $q\bar{q}$ in VM. Evidently, such an admixture would lower the theoretical results for R for the ρ^0 and the possible elimination of the observed disagreement between experiment and theoretical evaluations of R based on too crude a soft WF of VM's is good news! A consistent theoretical analysis of the short distance WF of VM's is as yet lacking.

6. Helicity flip and spin-orbit coupling in VM's

In the D -wave state the total spin of $q\bar{q}$ pair is predominantly opposite to the spin of the D -wave vector meson. As a results, SCHNC in production of D -wave vector mesons is much stronger [17] than for the ground state S -wave mesons, which may facilitate the long disputed D -wave *vs* $2S$ -wave assignment of the $\rho'(1480)$ and $\rho'(1700)$ and of the $\omega'(1420)$ and $\omega'(1600)$. Striking predictions for D -wave vector meson production include [1, 17] abnormally large higher twist corrections [17] and non-monotonous Q^2 dependence of $R^D = \sigma_L/\sigma_T$.

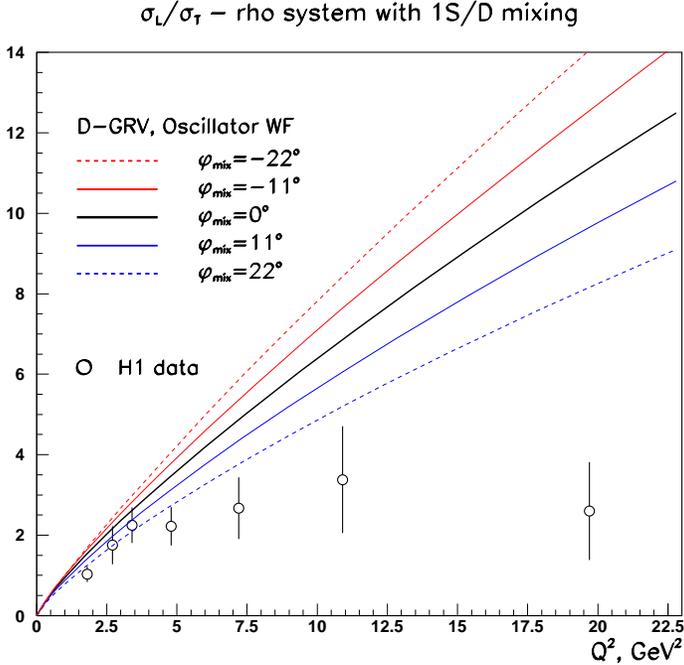


Fig. 5. The sensitivity of $R = \sigma_L/\sigma_T$ for J/Ψ production to the S - D -mixing.

Besides that, for D -wave vector mesons we predict anomalously small σ_L/σ_T which by virtue of S - D mixing could affect R for the ground state vector mesons. As well known, all popular confining potentials give rise to the tensor force. Recall a large S - D mixing angle, $\varphi_{SD} \sim 14^\circ$, in an even such a loosely bound system as a deuteron. The only well established D -wave quarkonium is $\Psi(3770)$, for which the pure D -wave assignment suggests the leptonic decay width $\Gamma(\Psi(D) \rightarrow e^+e^-) = 0.046$ keV to be contrasted to the experimental finding $\Gamma_{\text{exp}}(\Psi(3770) \rightarrow e^+e^-) = 0.26$ keV. Attributing the enhancement of the leptonic decay width to the mixing with the $J/\psi(1S)$, one finds two solutions for the S - D -mixing angle, $\varphi_{SD} \approx 23^\circ$, $\varphi_{SD} \approx -9^\circ$. The results presented in Fig. 5 show that R can be lowered substantially and σ_L/σ_T puzzle can be eliminated to a large extent at the expense of admissible S/D mixing.

7. Conclusions

- Consistent use of the recently determined unique differential gluon structure function of the proton [21] within κ -factorization approach eliminates the sensitivity of vector meson production amplitudes to

the gluon structure function of the proton.

- Consistent incorporation of S and D wave vector meson spinorial structures allows for analysis of either pure S and D states or their mixture.
- Predictions of κ -factorization approach are in agreement with experiments both on ground and excited vector mesons; the only discrepancy — underprediction of σ_T at large Q^2 — signals that presently used soft wave function Ansätze do not exhaust the whole physics at short distances.
- We predict very different behavior of basic $1S/2S/D$ state observables.
- A large part of σ_L/σ_T puzzle can be eliminated at the expense of strong S/D mixing in ρ system; the relatively large e^+e^- decay width of $\psi(3770)$ suggests that mixing indeed can be strong.

Thanks are due to the organizers of Meson 2000 for the most exciting workshop.

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