Vector Meson production in $ep \to epV$

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Abstract: The diffractive production of vector mesons in ep interactions at low x is a subject of heated debates. This chapter consists of four contributions written by the original authors and expresses the possible scenarios which are to be investigated experimentally.

1 Hard diffractive vector meson production

contributed by **L. Frankfurt, W. Koepf and M. Strikman**

The derivation of our QCD formulas [1] consists of three essential steps:
(i) The process factorizes into three stages: the creation of a quark-gluon wave packet, the interaction of this packet with the target, and the formation of the vector meson. The wave packet's large coherence length, $\frac{1}{2m_N x}$, justifies using completeness over the intermediate states.
(ii) For longitudinal polarization, the end point contribution is suppressed by $1/Q^2$, which supports applying the factorization theorem. This important result follows from the well known light-cone wave function of a photon and conformal symmetry of PQCD, which dictates the dependence of the vector meson's asymptotic wave function on the momentum fraction carried by the quarks. For transverse polarizations, the onset of the hard regime is expected at much larger Q^2 since large distance effects are suppressed only by the square of a Sudakov type form factor, $exp(-\frac{4\alpha_s}{3\pi}\ln^2\frac{Q^2}{k_t^2})$.
(iii) As a result of the QCD factorization theorem, the hard amplitude factorizes from the softer blob [2]. Thus, within the leading $\alpha_s \ln Q^2$ approximation, the cross section of hard diffractive processes can be written in terms of the distribution of bare quarks within the vector meson and the gluon distribution in the target.

The respective cross section can thus be expressed through the light-cone wave function of the vector meson, $\psi_V(z, b = 0)$, a well defined and intensively researched object in QCD. In addition, there is not much freedom in the choice of this wave function since the absolute normalization of the cross section is related to the vector meson's leptonic decay width, $\Gamma_{V\to e^+e^-}$. Our numerical analysis has found a number of distinctive features of these hard diffractive processes (see Ref.[3] and references therein):

1. A significant probability of small transverse size ($b_{q\bar{q}} \approx 3/Q$) minimal Fock $q\bar{q}$ configurations within the vector meson's light-cone wave function.
2. A fast increase of the cross section at small x and a relatively slow Q^2 dependence, both resulting from the Q^2 evolution of the parton distributions.
3. To avoid contradiction with b-space unitarity, the increase of the cross section with decreasing x should slow down. For $Q^2 \sim 5$ GeV^2, this is expected at $x \sim 10^{-3}$ [3].
4. For longitudinal polarization, an almost flavor and energy independent t-slope, while for transverse polarizations, soft QCD may reveal itself in a larger value as well as an energy dependence of the latter.
5. At large Q^2, the diffractive electroproduction ratio of ρ and ϕ mesons follows from the form of the e.m. current in the standard model, i.e. restoration of $SU(3)$ symmetry. Some enhancement of the relative yield of the ϕ meson is expected due to its smaller size.
6. The diffractive photoproduction of J/ψ meson is dominated by relativistic $c\bar{c}$ configurations. Significant diffractive photoproduction of Υ mesons.
7. Large cross sections for the production of excited states, $ep \to epV'$, with a ratio proportional to $M_{V'}\Gamma_{V' \to e^+e^-}$, in qualitative difference from photoproduction processes.
8. Model estimates found large $1/Q^2$ corrections to the basic formulas resulting from quark Fermi motion within the vector meson and from shadowing effects evaluated within the eikonal approximation. However, the reliability of these estimates is still unclear since similar corrections follow from the admixture of $q\bar{q}g$ components to the vector meson's wave function and because the elastic eikonal approximation is inappropriate. Note that, in an exact calculation, the contribution of more than two rescatterings by the $q\bar{q}$ pair should be zero due to energy-momentum conservation.

2 γ^* p $\to$ V p at small t

contributed by **P. V. Landshoff**

All models [4, 5, 6, 7, 8, 9] couple the γ^* to the vector meson V through a simple quark loop, to which is attached a pair of gluons which interact with the proton. The models differ in two essentials: what they assume about the wave function that couples V to the $q\bar{q}$, and what they assume about how the gluons interact with the proton.

Because the models have the same quark loop, there is general agreement that the γ^* and the V should have the same helicity, and that

$$\frac{\sigma_L}{\sigma_T} \propto \frac{Q^2}{m_V^2} \tag{1}$$

so that at large Q^2 longitudinal production dominates. Presumably the detailed dependence of σ_L/σ_T on Q^2 is sensitive to the form of the wave function. The very simple form assumed by DL fits the data reasonably well [10], but more theoretical work is needed to decide just how much can be learnt about the wave function from this. Also, according to (1), for heavier flavours it will need a larger Q^2 to achieve dominance of the longitudinal polarisation; it is likely that most of the J/ψ production at HERA will be transverse.

The way in which the gluons couple to the proton will determine the W-dependence. If they couple through a soft pomeron, then

$$\frac{d\sigma}{dt} = f(t, Q^2)\, e^{4(\epsilon - \alpha'|t|)\log W} \tag{2}$$

with $\epsilon \approx 0.08$ and $\alpha' = 0.25$ GeV^{-2}. If the data find a larger value of ϵ, this may be a sign of the BFKL pomeron (though this is unlikely [11]), or of whatever other mechanism is responsible for the rapid rise seen in νW_2 at small x. Some of the models seek to make a direct connection between the energy dependence of exclusive vector electroproduction and the rise of νW_2 at small x, but there are theoretical problems in this. The soft-pomeron form (2) predicts that the t-slope changes with W in a particular way; if the soft pomeron is not involved the forward-peak shrinkage will surely not ocurr at the same rate and is likely to be significantly slower, though this is not understood. Notice that $f(t, Q^2)$ contains the square of the elastic form factor of the proton and so is not a simple exponential: the t-slope will vary with t. Notice also that its measurement is particularly sensitive to any contamination from nonelastic events, which become increasingly important as $|t|$ increases.

3 Shadowing corrections in diffractive QCD leptoproduction of vector mesons

contributed by **E.Gotsman, E. Levin and U. Maor**

In our paper [12] the formulae for the shadowing corrections (SC) for vector meson diffractive dissociation (DD) in DIS have been obtained within the framework of the DGLAP evolution equation in the region of low x. It is shown that the rescatterings of the quarks is concentrated at small distances ($r^2_{\perp} \propto \frac{1}{Q^2 z(1-z) + m^2_q}$) and can be treated theoretically on the basis of perturbative QCD.

The numerical calculation of the damping factor defined as:

$$D^2 \;=\; \frac{\frac{d\sigma(\gamma^* p \rightarrow V p)}{dt}\,[\,with\;\;SC\,]}{\frac{d\sigma(\gamma^* p \rightarrow V p)}{dt}\,[\,without\;\;SC\,]}\,|_{t=0} \tag{1}$$

shows that the SC (i) should be taken into account even at HERA kinematic region and they generate the damping factor of the order of 0.5 for J/Ψ production at $W = 100 - 200 GeV$ for $Q^2 = 0 - 6 GeV^2$ (see [12] for details); (ii) t he value of the SC is bigger than uncertainties related to the unknown nonperturbative part of our calculations, and (iii) DD in vector meson for DIS can be used as a laboratory for investigation of the SC.

The calculation of the SC for the gluon structure function depends on a wide range of distances including large ones ($r^2_{\perp} > \frac{1}{Q^2 z(1-z) + m^2_q}$). This causes a large uncertainty in the pQCD calculations which, however become smaller at low x. We show that the gluon shadowing generates damping, which is smaller or compatible with the damping found in quark sector.

The cross section of the vector meson DD is shown to be proportional to $(\frac{dF^{exp}_2}{d\ln Q^2})^2$ [12]. This formula takes into account all possible SC and it is derived in the leading log approximation of pQCD (for the GLAP evolution). It means that the experimental data for DD for vector meson production provides information about $dF_2/\ln Q^2$, from which we could extract the gluon structure function in the DGLAP evolution equation in the region of low x.

4 Vector mesons

contributed by **N. N. Nikolaev and B. G. Zakharov**

The amplitude of exclusive vector meson production [14, 15, 16, 17, 18] reads (we suppress the polarization subscripts T and L) $\mathcal{M} = \int d^2\vec{r}dz\Psi^*_V(z,\vec{r})\sigma(x,r)\Psi_{\gamma^*}(z,\vec{r})$, where Ψ_{V,γ^*} are the color dipole distribution amplitudes and $\sigma(x,r)$ is the color dipole cross section. On top of the gBFKL component which dominates $\sigma(x,r)$ at $r \lesssim R_c = 0.3\,\mathrm{fm}$, at larger r in $\sigma(x,r)$ there is a soft component. The non-negotiable prediction as that at a sufficiently small x the rising gBFKL component takes over at all r. The small but rising gBFKL contribution provides a viable description of the rise of soft cross sections. $\mathcal{M}_{T,L}$ are dominated by $r \approx r_S = 6/\sqrt{Q^2+m_V^2}$. The large value of the scanning radius r_S is non-negotiable and makes vector meson production at best semiperturbative, unless $Q^2 + m_V^2 \gtrsim$20-40 GeV^2, i.e., unless $r_S \lesssim R_c$. Because the scanning radius r_S is so large, the formulas for the production amplitudes in terms of the vector wave function at the origin are of limited applicability at the presently studied Q^2. When $r_S \lesssim R_c$ and the soft contribution is small, one can relate $\mathcal{M}_{T,L}$ to the gluon density in the proton but at a very low factorization scale $q^2_{T,L} = \tau(Q^2 + m_V^2)$ with τ =0.05-0.2 depending on the vector meson. The energy dependence of vector meson production at $r_S \sim 0.15\,\mathrm{fm}$, i.e., $Q^2(\Upsilon) \sim 0$ and $Q^2(J/\Psi) \sim 100\,\mathrm{GeV}^2$ and $Q^2(\rho) \sim 200\,\mathrm{GeV}^2$ probes the asymptotic intercept of the gBFKL pomeron. The major gBKL predictions are:

1. A steady decrease of R_{LT} with Q^2 in $\sigma_L/\sigma_T = R_{LT}Q^2/m_V^2$ with $R_{LT} \sim 1$.

2. When fitted to $W^{4\Delta}$, the effective intercept Δ is predicted to rise with Q^2. It also rises with W and flattens at a Q^2 independent $\Delta \approx 0.4$ at a very large W. The universal energy dependence is predicted for all vector mesons if one compares cross sections at identical $\bar{Q}^2$.

3. Comparing the Q^2 dependence of $\mathcal{M}_{T,L}$ makes no sence, the real parameter is r_S and/or $\bar{Q}^2 = Q^2 + m_V^2$, the ratios like $(J/\Psi)/\rho$ exhibit wild Q^2 dependence but we predict the flavor dependence disappears and these ratios are essentially flat vs.$\bar{Q}^2$. The Q^2 dependence must follow the law $\propto \bar{Q}^{2n}$, where n is about flavor independent, typically $n \sim 2.2$ at HERA. The $\propto \bar{Q}^{2n}$ fits are strongly recommended.

4. Strong suppression of the $2S/1S$ cross section ratios by the node effect is a non-negotiable prediction, these ratios are predicted to rise steeply and then level off on a scale $Q^2 \lesssim m_V^2$. Steady rise of these ratios with energy is predicted. For the D-wave vector mesons the ratio $D/1S$ is pedicted to have a weak Q^2 dependence in contrast to the $2S/1S$ ratio.

5. The gBFKL pomeron is a moving singularity and we predict the conventional Regge shrinkage of the diffraction cone. The rise of diffraction slope by ~ 1.5 GeV^{-2}, which is about universal for all vector mesons and at all Q^2, is predicted to take place from the CERN/FNAL to HERA energies. An inequality of diffraction slopes $B(2S) < B(1S)$ is predited. For the $\rho'(2S)$ and $\phi'(2S)$ the diffraction cone can have a dip and/or flattening at $t = 0$. For the 1S states, the diffraction cone for different vector mesons must be equal if compared at the same $\bar{Q}^2$.

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