Vector Meson Production at HERA

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Selected recent results from the HERA experiments ZEUS and H1 on vector meson production in ep collisions are reviewed. The topics covered are elastic photo– and electroproduction of ρ and J/ψ mesons as well as inelastic J/ψ photoproduction. Cross sections as a function of the hadronic centre of mass energy $W_{\gamma p}$ and of the four-momentum transfer to the proton, t, are compared to the expectations from theory. The helicity structure is studied through decay angular distributions.
For inelastic J/ψ production, the results are compared to next-to-leading order QCD expectations in the Colour Singlet Model. It is shown that with the current accuracy of the data there is no need for other production mechanisms.

1. Introduction

Since the first results obtained at the HERA ep collider became available, there is a renewed interest in elastic vector meson production (fig. 1a), especially at large Q^2 (Q^2 is minus the square of the exchanged photon 4-momentum) — more than a few GeV^2 — and large mass of the produced meson, e.g. J/ψ. This is reflected in a number of publications presenting new phenomenological models or refining existing ones (e.g. [1]), and in an effort from the experiments H1 and ZEUS to improve on the quality and kinematic reach of their data.

In fixed target experiments, the elastic reaction $\gamma p \to Vp$ ($V = \rho, \omega, \phi, \ldots$) has been successfully described by Regge theory together with the vector meson dominance model (VDM), exhibiting features typical for soft, hadron-like interactions. These are a small angle peak in the distribution of the vector meson scattering angle with respect to the photon beam direction ("elastic peak"), a steepening of this distribution with increasing energy ("shrinkage"), for $W_{\gamma p} \gtrsim 10\,\mathrm{GeV}$ a slow increase with energy of the cross section $\propto W_{\gamma p}^{4\epsilon} \simeq W_{\gamma p}^{4\cdot 0.0808}$, and s-channel helicity conservation (SCHC).

However, the traditional VDM approach does not give a satisfactory description of J/ψ photoproduction: the cross section is smaller than the VDM prediction, and it increases significantly faster with energy than expected from soft pomeron exchange. This fast rise is predicted in models based on perturbative QCD, where the interaction is described as an exchange of two or more gluons in the t-channel (fig. 1b) between a virtual quark-antiquark pair and the constituents of the proton. In these models, the fast rise of the cross section with energy is driven by the rise of the gluon density in the proton towards smaller x. Calculations have also been performed for other processes where pQCD is thought to be applicable, i.e. elastic ρ production at high Q^2 and high

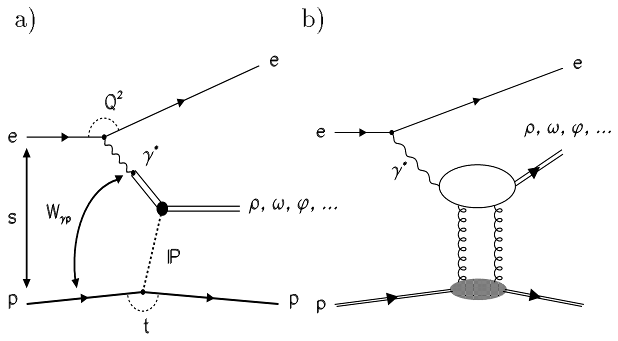

Figure 1. Vector meson production at HERA a) Regge-VDM model (including the definition of kinematic variables) b) pQCD models.

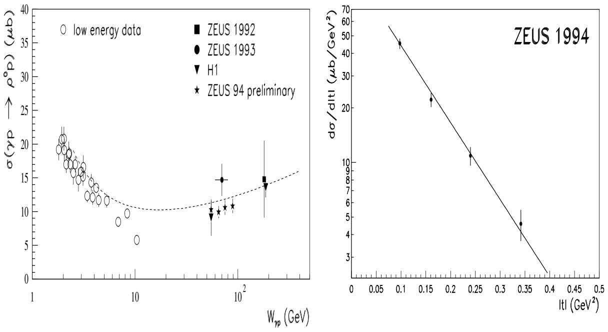

Figure 2. Left: Elastic ρ photoproduction cross section as a function of $W_{\gamma p}$. Right: $d\sigma/d\mid t\mid$, the line being a fit of the form e^{bt}.

$\mid t \mid$ (more than a few GeV^2).

In the case of inelastic J/ψ production, a hard gluon from the proton interacts with the photon to form a $c\bar{c}$ pair. Traditionally, this process is described in the Colour Singlet Model [2], where another gluon is subsequently radiated in order to restore the J/ψ colour quantum numbers. At HERA, inelastic J/ψ production is separated from diffractively produced J/ψ mesons by use of the elasticity variable z, $z = (E - p_z)_{J/\psi}/(E - p_z)_{\rm all}$. For diffractive production, $z \gtrsim 0.95$, while for inelastic production $0 < z < 1$. So-called *resolved* photon contributions and J/ψ mesons from the decay of b hadrons cluster at small values of z.

In the following sections, only a small selection of the many results will be discussed. First, results on elastic production of ρ mesons are presented, both in photoproduction and at higher Q^2, followed by elastic J/ψ production and finally inelastic J/ψ photoproduction.

2. Elastic photo- and electroproduction of ρ mesons

The results of the ρ measurements in photoproduction [3] show all the typical features of the VDM-photon and Regge model. The cross section continues its slow rise with energy typical for the pomeron trajectory, after extrapolating by more than one order of magnitude from the low energy measurements to HERA (fig. 2). The exponential fall-off of the cross section $\propto e^{bt}$ has been measured e.g. by the ZEUS collaboration [4] to be $b = 9.8 \pm 0.8 \pm 1.1\,\mathrm{GeV}^{-2}$ (fig. 2). As expected by SCHC, decay angular distributions show predomenantly transverse polarized ρ mesons, reflecting a smooth transition to a real photon beam with no longitudinal degree of freedom for the photon helicity. Similar results, albeit with less significance due to limited statistics, have also been obtained for photoproduction of ω and ϕ mesons.

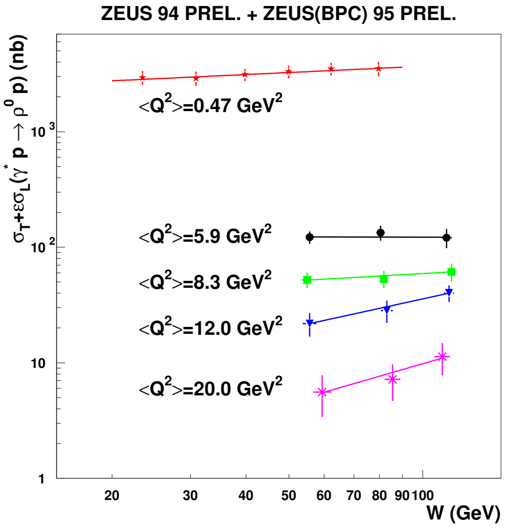

Figure 3. ρ production cross section as a function of $W_{\gamma p}$. The lines are the results of fits of the form $W_{\gamma p}^{\delta}$.

With increasing Q^2, one of the key questions is how the cross section behaves as a function of $W_{\gamma p}$. First analyses [5,6] from H1 and ZEUS depend in this respect strongly on the comparison with results from fixed target experiments. However recent results from the E665 collaboration [7] appear at variance with the previous fixed target data. Hence a precise measurement from the HERA experiments alone is desirable. Current measurements are still limited by statistics, as shown [8] in fig. 3, but there is an indication for a stronger rise of the cross section at higher Q^2, for example $\sigma_{\gamma p} \propto W^{\delta}$ with $\delta = 0.18 \pm 0.05 \pm 0.13$ at $Q^2 = 0.47\,\mathrm{GeV}^2$ and $\delta = 0.86 \pm 0.46 \pm 0.40$ at $Q^2 = 12\,\mathrm{GeV}^2$.

At higher Q^2, longitudinally polarized ρ mesons contribute. The fraction of longitudinally polarized ρ mesons r^{04}_{00} increases from values close to 0 in photoproduction [3] to 0.36 ± 0.04 for $0.45 < Q^2 < 0.85\,\mathrm{GeV}^2$ [8]. For $8 < Q^2 < 50\,\mathrm{GeV}^2$, ρ mesons are predominantly longitudinally polarized with $r^{04}_{00} = 0.73 \pm 0.05 \pm 0.02$ [6]. Experimentally r^{04}_{00} is determined from the angular distribution of the decay pions in the ρ rest frame, between the direction of the positively charged decay pion and the ρ direction in the $\gamma^* p$ centre of mass system [9]. Besides this angle θ, also the angle ψ between the ρ decay plane and the lepton scattering plane has been measured and found to support the hypothesis of SCHC. Decay angular distributions for intermediate Q^2 regions are shown in fig. 4.

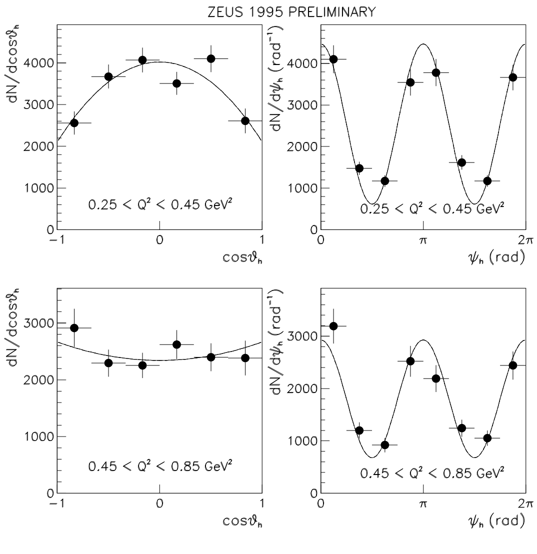

Figure 4. Acceptance corrected decay angular distributions for events from the $M_{\pi\pi}$ region between 0.6 and 1.0 GeV.

Assuming SCHC, as suggested by the present data, r^{04}_{00} is related to R, the cross section ratio for ρ production by longitudinal and transverse virtual photons:

$$R = \sigma_L/\sigma_T \propto \frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

In fig. 5, results on the measurement of R as a function of Q^2 from the ZEUS and H1 experiments are shown together with fixed target measurements [6] at lower energy. A rise of R with increasing Q^2 is observed even from the HERA data alone, as predicted by most models for ρ meson electroproduction.

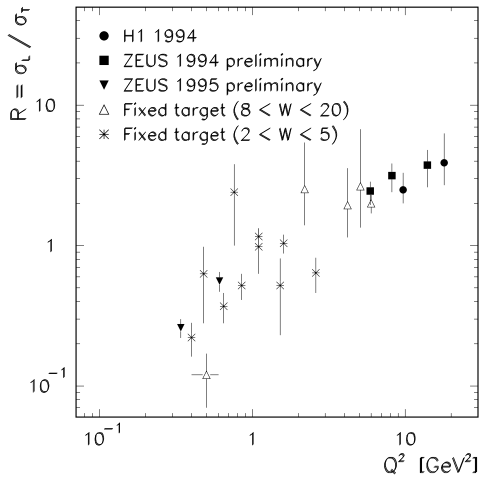

Figure 5. $R = \sigma_L/\sigma_T$ for elastic ρ production as a function of Q^2.

3. Elastic photo- and electroproduction of J/ψ mesons

J/ψ production is analysed in the decay channels $J/\psi \to \mu^+\mu^-, e^+e^-$, and results are available both for photoproduction and at higher Q^2 [10–12].

The strong rise of the photoproduction cross section $\propto W^{0.9}_{\gamma p}$ as compared to fixed target results already reported in the first HERA measurements has been confirmed in the meantime using HERA data alone. In the model of Ryskin et al. [13] the cross section can directly be translated into a gluon density. The sensitivity to different gluon parameterizations is high, since the cross section is directly proportional to the *square* of the gluon density, but on the other hand there are significant normalization uncertainties in the calculation.

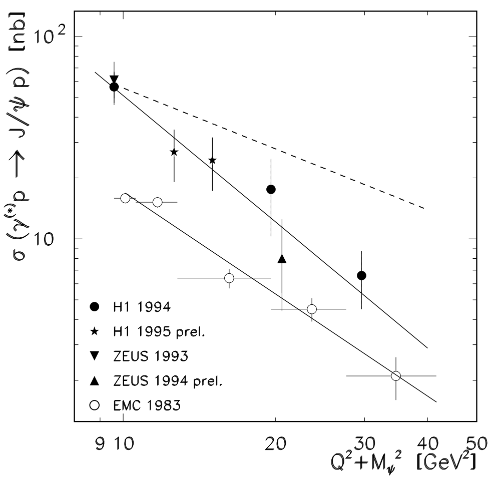

Figure 6. Virtual photon proton cross section for elastic J/ψ production as a function of $Q^2 + m_\psi^2$. The lines are fits to the data of the form $(Q^2 + m_\psi^2)^{-n}$, the dashed curve is $\propto 1/(Q^2 + m_\psi^2)$.

Going from photoproduction to high Q^2 introduces another scale into the consideration besides the vector meson mass. The virtual photon proton cross section falls steeply as a function of Q^2 (fig. 6), and can be parameterized following a $(Q^2 + m_\psi^2)^{-n}$ ansatz. A fit to the data [11] yields $n = 2.1 \pm 0.3$, comparable to results for ρ electroproduction [6]. The striking difference however is that in the case of ρ production at high Q^2 the vector meson mass can be neglected, while this is not the case for the J/ψ. This leads to a dramatic increase of the ratio of the cross sections for ρ and J/ψ production: while J/ψ photoproduction is suppressed by factors of 100 to 1000 with respect to ρ, the ratio approaches unity at Q^2 of the order of 10 to $20\,\mathrm{GeV}^2$.

The virtual photon proton cross section has also been evaluated as a function of $W_{\gamma p}$ (fig. 7) for different Q^2 regimes. Although the precision of the data is only moderate, it seems as if the

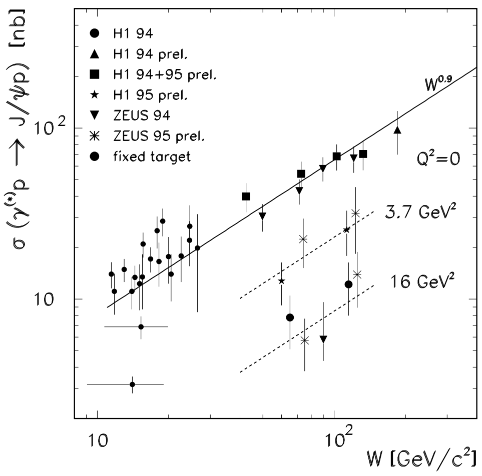

Figure 7. Elastic J/ψ production cross sections as a function of $W_{\gamma p}$. Lines $\propto W_{\gamma p}^{0.9}$ are drawn to guide the eye.

rise of the cross section in photoproduction and at higher Q^2 is of comparable size. Again, in the model of Ryskin et al. these results can be transformed into a gluon density, and offer a complementary way of extracting the gluon density at HERA.

4. Inelastic photoproduction of J/ψ mesons

Cross section measurements done by H1 and ZEUS [14] as a function of $W_{\gamma p}$ and differentially in p_t^2 of the J/ψ show a good agreement with next-to-leading order QCD calculations in the Colour Singlet Model by Krämer et al. [15], if the measurements are restricted to a range where the model is thought to be reliable, i.e. $z < 0.8$ and $p_t^2 > 1\,\mathrm{GeV}^2$.

In fig. 8 the differential cross section $d\sigma/dz$ is shown. The z dependence is particularly sensitive to possible colour octet contributions to J/ψ production as proposed to explain the high quarkonium production rates observed at the Tevatron. Calculations in the Colour Octet Model have been performed by Cacciari et al. [16], where the colour octet matrix elements used had been

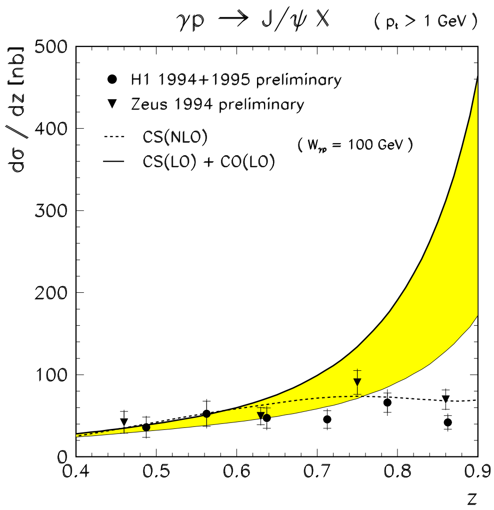

Figure 8. Differential cross section $d\sigma/dz$ as a function of z. The curves are predictions in the Colour Singlet Model in NLO and the sum of colour octet and colour singlet contributions in leading order QCD. The band indicates the uncertainty in the colour octet prediction due to initial state radiation.

extracted from fits to prompt J/ψ production data from the Tevatron. The measured distribution disfavors large colour octet contributions, but note the large uncertainties of the theoretical prediction.

5. Conclusions

H1 and ZEUS have measured the elastic production of light and heavy vector mesons both in photoproduction and at high Q^2. Photoproduction of light vector mesons is well described by VDM plus pomeron exchange. This description fails in the case of the J/ψ and, though experimentally not yet settled, also in the case of high Q^2 ρ production, where a hard scale is present. The ρ meson polarization is purely transverse in photoproduction and mainly longitudinal at high Q^2. Inelastic J/ψ production is found to be in agreement with next-to-leading order QCD calculations in the Colour Singlet Model.

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