HERA Results on
Elastic Hadronic and Sub-Hadronic Diffraction

G. KNIES
(on behalf of H1 and ZEUS collaborations)
Deutsches Elektronen Synchrotron DESY, Hamburg,
D-22607 Hamburg, Germany
E-mail: gerhard.knies@desy.de

Diffractive production of vector mesons in ep collisions at HERA has been measured by the Zeus and the H1 collaborations. Results on production cross sections are presented, and their dependences on collision energy W, momentum transfer t, photon virtuality Q^2, vector meson masses M_V and decay angle correlations are investigated. In particular, the slope b of the t distribution allows diffractive processes at a hadron size scale to be distinguished from those at a sub-hadronic scale. The virtuality of the incoming photon, the mass of the outgoing vector-meson, and the configuration of the outgoing proton as being intact or disintegrated, are employed to select between soft or hard diffractive processes.

1 Introduction

The Optical Theorem implies that any absorptive reactions between two colliding particles generate diffraction in forward direction, irrespective of the nature of the underlying interaction. The p_t distribution of the related elastic process is a transformation of the transverse extension of the absorptive process into momentum space, thus indicating size and nature of the interaction.

In hadron hadron collisions, as e.g. $pp \rightarrow pp$, diffraction at asymptotic energies is well described by

$$d\sigma(W,\ t)/dt \ = \sigma_0'\ e^{bt}\ (W/W_0)^{4(\alpha_0-1)}$$

with $\sigma_0' = d\sigma(W,\ t=0)/dt$ and $\alpha_0 = 1.0808$ as a universal signature [1] for soft hadronic interactions. In pp and $\bar{p}p$ elastic scattering the slope b has been found to be $\sim 10\ GeV^{-2}$ at a collision energy of $W \sim 9\ GeV$, and to grow with energy (shrinkage of the diffraction peak) as $b = b_0 + 4\,\alpha'\,ln(W/W_0)$, with $\alpha' = 0.25\ GeV^{-2}$. The soft pomeron trajectory is $\alpha(t) = \alpha_0 + \alpha' t$. The slope b is connected to the transverse size of the two hadrons (1 and 2) in elastic collisions by $b = R_1^2 + R_2^2$, yielding $R_h^2 \simeq 5\ GeV^{-2}$ as a distance measure for a typical *hadron size* interaction. Values of $R_i^2 \ll 5\ GeV^{-2}$ would indicate the involvement of *sub-hadron size* distances. Thus the value of b is a handle to distinguish short distance from large distance diffractive reactions.

The ep interactons at HERA, in colliding beams of 27.5 GeV electrons and 820 GeV protons, are interpreted for small and moderate $Q^2 \ll M_Z^2$, as absorption of virtual photons in their collision with protons. The related diffractive process is the production of vector mesons, of the type

$$\gamma^{(*)}p \rightarrow VY, \;\text{ with } V = \rho^{\circ},\ \omega,\ \phi,\ J/\Psi,\ \Upsilon, \;\text{ and }\; Y = P, N$$

The proton may remain intact ($Y = P$, elastic diffraction) or break up ($Y = N$, diffractive dissociation). Experimentally, a reaction is accepted as exclusive vector meson channel if V is produced with the kinematically largest possible momentum in the photon direction, and with no other particles in the central detector. Then $t = (\gamma^{(*)} - V)^2 = (p - Y)^2$ can be measured as $\Delta p_{\perp}^2$ of the vector meson, relative to the initial photon-proton collision direction.

2 The HERA switchboard for hadronic - subhadronic scales

The special variables available at HERA for controlling scales in diffractive reactions are, at the photon vertex, the photon virtuality Q^2 and the mass M_V of vector mesons. The exclusive production of a vector meson is an efficient means to select diffractive reactions in ep collisions. Further, the size of the interaction at the proton vertex can - as in pp interactions - be influenced by the switch P/N. The differential cross section for diffractive production of vector mesons can be written as:

$$d\sigma(W,\ t,\ Q^2, M_V, P/N)/dt\ [\gamma^{(*)}\ p \rightarrow V\ Y]\ = \sigma_0'\ e^{bt}\ (W/W_0)^{\epsilon}$$

with $\epsilon = 4(\alpha_0 - 1)$.

The photon vertex is expected to be of hadronic size when the photon is at low enough $Q^2(\lesssim 1\ GeV^2)$, and the outgoing vector meson is light (ρ, ω). Here we expect $R^2_{\gamma\rightarrow\rho,\omega} \sim 5\ GeV^{-2}$. For sufficiently large values of M_V and of Q^2 we expect a sub-hadronic size to prevail, e.g. $R^2_{\gamma^*\rightarrow\rho},\ R^2_{\gamma\rightarrow J/\psi} \ll 5\ GeV^{-2}$. If at the proton side the momentum was transferred to a (constituent) part of the proton only, the interaction was at sub-hadron size, and the proton will break up ($R^2_{p\rightarrow N} \ll 5\ GeV^{-2}$). If the proton remained intact, then the momentum was transferred to the proton as a whole. Hence, at HERA it is possible to select - with the help of Q^2, M_V and P/N - reactions were the number of hadron size vertices [2] is expected to be $n_h = 2,\ 1$ or 0 (and sub-hadronic or short distance vertices $n_s = 0, 1, 2$, correspondingly) and to verify this assessment by measuring b. Since HERA offers also access to a large range of $W(\gamma^{(*)}p)$, from 20 up to 300 GeV, the W dependence can be exploited for signatures of soft or for deviations from soft dynamics, by measuring ϵ.

The measurement of vector meson decays allows to disentangle the independent cross sections for transverse and longitudinal photons at $Q^2 > 0$, and to investigate further expectations for diffraction, like s-channel helicity conservation (SCHC).

3 The t-dependence as indicator for hadronic and sub-hadronic scales

In Figure 1 $d\sigma/dt$ for elastic photoproduction of ρ (a) and of J/ψ (b), and of J/ψ with proton break-up (c) are shown. The slopes b vary considerably, from

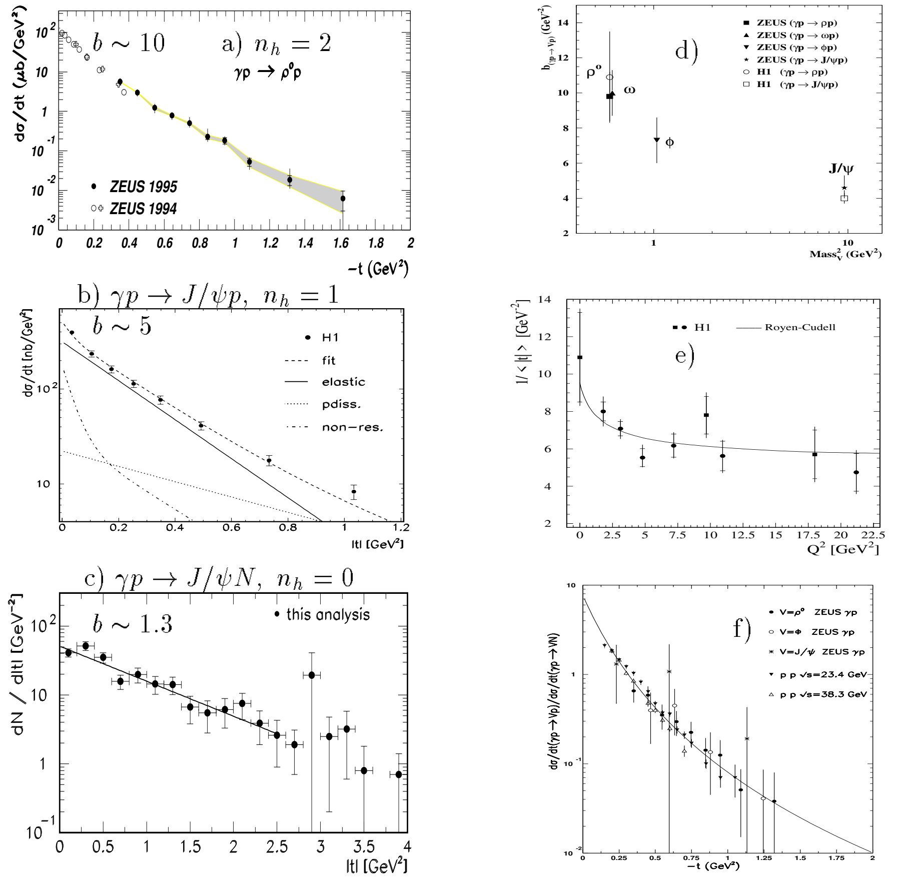


Figure 1: t-dependences in diffractive channels with different numbers of hadron size vertices n_h: $d\sigma/dt$ for a) $\gamma p \to \rho p$ [3], b) for $\gamma p \to J/\psi p$ [4], and c) dN/dt for $\gamma p \to J/\psi N$ from H1 [5]. d) Slope b for $Q^2 = 0$ as a function of vector meson mass M_V^2 [5], e) slope b for $\gamma p \to \rho p$ [6] and a QCD inspired prediction [7] for $1/<-t>$ as a function of Q^2, and f) a compilation [3] of the ratio of the differential cross section of elastic to inelastic diffractive reactions as a function of t, with proton electromagnetic form factor curve.

$\sim 10 \rightarrow \ \sim 5 \rightarrow \ \sim 1\ GeV^{-2}$. Figures 2d and e show how b gets smaller with growing M_V in photoproduction, and with growing photon virtuality Q^2 in light vector meson production, respectively. Interestingly it turns out, that in J/ψ production when $M_V^2 = 9.6\ GeV^2$ is already large, a change from $Q^2 = 0$ to $\langle Q^2 \rangle = 8\ GeV^2$ does not change the slope b any further (see Table 1).

A survey on the effect of proton break-up is shown in Figure 2f, as the ratio of the differential cross sections for proton intact to proton break-up for several reactions. The ratios can be well described by $e^{\Delta b \cdot t}$, with $\Delta b \simeq 4\ GeV^{-2}$ for pp and for γp reactions, implying $R^2_{p \to N} \sim 1\ GeV^{-2}$ instead of $\sim 5\ GeV^{-2}$ as for $R^2_{p \to P}$. It is interesting to note that the ratio of proton coherent to break-up differential cross section extrapolates to $t = 0$ by $e^{\Delta b \cdot t}$ (instead of form factor) to ~ 3, the number of proton constituent quarks [a].

In summary we note, that the slope b is reduced from $\sim$ 10 as in the $n_h = 2$ reaction $\gamma p \ \rightarrow \rho p$ to 4-6 GeV^{-2} in all $n_h = 1$ reactions measured, i.e. when M_V^2 or Q^2 or both go from $\sim 0 \rightarrow \sim 10\ GeV^2$ or further up, or when proton break-up is requested. When both, photon and proton vertices are switched to sub-hadron size (Figure 2c, $n_h = 0$), $b = 1.3\ GeV^{-2}$ is observed. More precise measurements of b in $n_s = 2$ channels, like $\gamma^* p \rightarrow \rho N$, $\gamma^{(*)} p \rightarrow J/\psi N$ should reveal the transverse size of the sub-hadronic constituents off which the deeply inelastic partonic reactions occur in the proton.

4 The W-dependence as analyser for soft vs. hard dynamics

With a handle to select sub-hadronic diffraction channels in hands, we may now analyse the W dependence of $n_h = 1$ reactions for deviations from the known soft behaviour. Here, the quantity measured with the best precision is the t integrated cross section $\sigma_{tot}(\gamma^{(\star)} p \rightarrow Vp) \propto W^{\delta}$, where δ is related to ϵ via $\delta \simeq \epsilon - 4\alpha'/b$. The $n_h = 2$ reactions $\gamma\ p \rightarrow (\rho, \omega, \phi)\ p$ in Fig. 2a yield $\delta = 0.22$, in agreement with $\alpha_0 = 1.08$. For a precision measurement of ϵ, also α' has to be determined.

Data in Figures 2a and 2b show what happens when the photon vertex is switched step wise to sub-hadron size by increasing the values of M_V or Q^2, respectively: the W-dependence becomes clearly steeper for growing vector meson masses ($\delta = 0.83 \pm 0.07$, for J/ψ [4]), and similarly by size but with lesser measurement precision for growing photon virtuality. As in case of the b slope, there is no evidence for a further increase of δ when in J/ψ production the virtuality of the incoming photon is raised from 0 to 10 GeV^2 (Figure 2c).

[a] If there are N_D subhadronic diffraction centers with equal amplitudes A_D inside the proton, then this ratio should be $(N_D \cdot A_D)^2/(N_D \cdot A_D^2) = N_D$

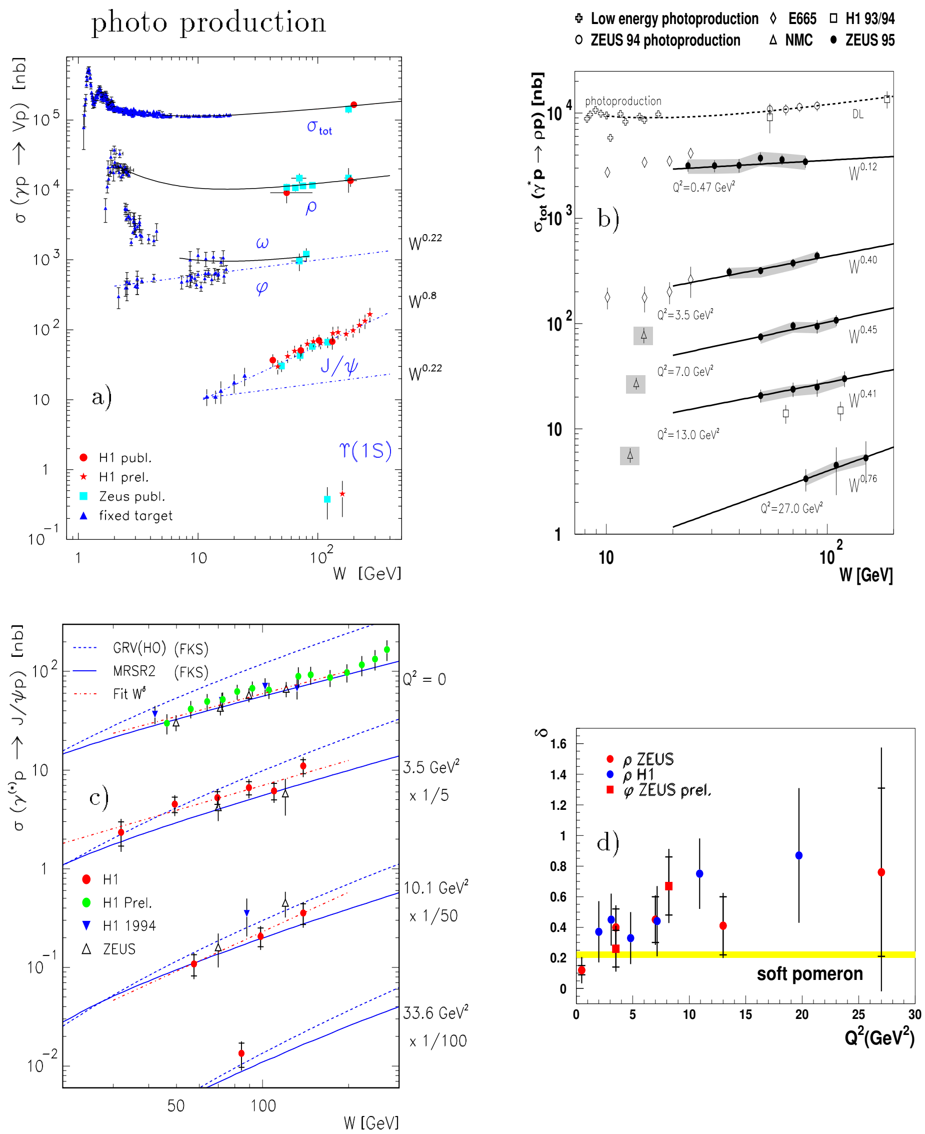


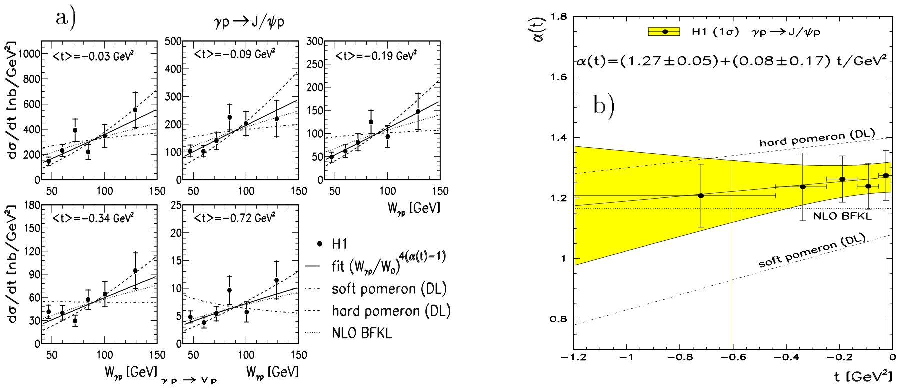
Figure 2: The W-dependence. In various diffractive channels $\sigma(\gamma p \to Vp)$: a) at $Q^2 = 0$ for all V, b) for $V = \rho$ at a set of Q^2 values [8], and c) for $V = J/\psi$ at a set of Q^2 values [8,9], with $\delta = 0.83$ from $Q^2 = 0$ shown as dotted line. d) Summary for exponent δ as a function of Q^2 for $V = \rho$ and ϕ.

Hence, here is no evidence that M_V^2 and Q^2 act additively.

For diffractive J/ψ photoproduction the hard nature of the photon vertex is evident by the t and W dependences. In this case, the W dependence can be predicted quantitatively by a pQCD calculation of a 2-gluon exchange to the photon ($q\bar{q}$) vertex, if a x distribution of the gluon density in the proton, $g(x)$ is introduced. Such predictions - the different curves differ mainly by different assumptions on $g(x)$ - agree with the measurements (Figure 2c). The dependence of δ in $\sigma_{tot}^{diff}(W)$ on Q^2 (Fig. 2d) can be related to $\lambda(Q^2)$ in the proton structure function $F_2^p(x) \propto x^{-\lambda(Q^2)}$, or to the W dependence of $\sigma_{tot}(\gamma^* p; Q^2, W) \propto W^{2\lambda(Q^2)}$, respectively, as measured in DIS. The Optical Theorem relation implies $\epsilon(Q^2) = \lambda(Q^2)$. This relation is experimentally well fullfilled. Because of the rising parton density inside the proton with falling x, the diffractive cross section for virtual photons grows faster with W than the soft diffractive cross section (see Fig. 2d).

5 Shrinkage as test for soft vs. hard dynamics

Shrinkage of the diffraction peak, i.e. the growth of the effective size of hadrons with growing W is a characteristic feature in soft hadronic diffraction, with a strength of $\alpha' = 0.25\ GeV^{-2}$. For a hard BFKL pomeron exchange [10], no



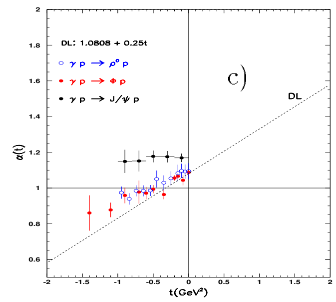


Figure 3: Shrinkage. a) W dependence of $d\sigma/dt$ in different t intervals [4], b) $\alpha(t)$ from the 5 t intervals of a) and the fit [4], c) $\alpha(t)$ results for diffractive production of ρ (open points), ϕ (shaded) and J/ψ (full) including ZEUS, H1, E401 and EMC data [3,11].

shrinkage is expected. With the large range of W covered by HERA experiments, the shrinkage parameter α' can be obtained from the W dependence of $d\sigma/dt \propto (W/W_0)^{4(\alpha_0+\alpha' t-1)}$ at different t values within a single experiment, thus avoiding systematic differences from different measurements.

In Figure 3a data for the hard diffractive process of J/Ψ photoproduction are shown. A fit yields $\alpha(t) = (1.27\pm0.05)+(0.08\pm0.17)t$, see Figure 3b. These data are compatible with no shrinkage and with the strong shrinkage of soft diffraction, but incompatible with the soft diffraction intercept of $\alpha_0 = 1.08$, however. Statistics and lever arm in W are not yet sufficient to exclude soft shrinkage. Even when data from ZEUS, H1, and fixed target experiments at lower W are included, the difference in α' of ρ and J/ψ is not significant (see Fig. 3c and Table 1). Shrinkage in the $n_h = 1$ reaction seems to be smaller than in the soft reactions, and it is compatible with zero.

6 Q^2 Dependence of transverse and longitudinal photons: light on pointlike and hadronic behavior of the photon

Photons interact with hadrons by their couplings to the electric charges of the pointlike quarks, with modifications from their fluctuations into vector meson states. At $Q^2 \sim 0$ this leads to strong cross section enhancements from the nearby ρ and ω poles. The distance of photons at virtuality Q^2 to the respective meson poles is given by $Q^2 + M_V^2$.

In Figure 4a the total diffractive production cross section of the various vector mesons is plotted versus the same distance to their respective poles. The cross sections are multiplied with the inverse SU(4) factors for the effective couplings of the respective $q\bar{q}$ wave function, i.e. with the relative factors 9/9, 9/1, 9/2, 9/8 and 9/2 for ρ, ω, ϕ, J/ψ and Υ, respectively. With these two "trivial" differences regarding quark masses and effective electromagnetic couplings of resonant states eliminated, the total diffractive production cross sections for ρ, ω, ϕ and J/ψ mesons appear to follow a universal shape. The Υ values seem to be higher.

From the known helicity mix of virtual photons and from the measurement of the vector meson decay angular distributions (not shown), it is possible to separate the independent cross sections for transverse and longitudinal photons, since the decay correlations also show that s-channel helicity is - at least approximately - conserved [12,6]. The ratio $R = \sigma_L/\sigma_T$ is shown in Figure 4b as a function of Q^2, together with predictions from pQCD [7,14] and from a

GVDM ansatz [15]. The rise of this ratio expected for small Q^2 flattens off at $Q^2 > 5\ GeV^2$, reaching $R \sim 3$. The pQCD and the GVDM based models provide sufficient internal flexibility to be adjustable to these data.

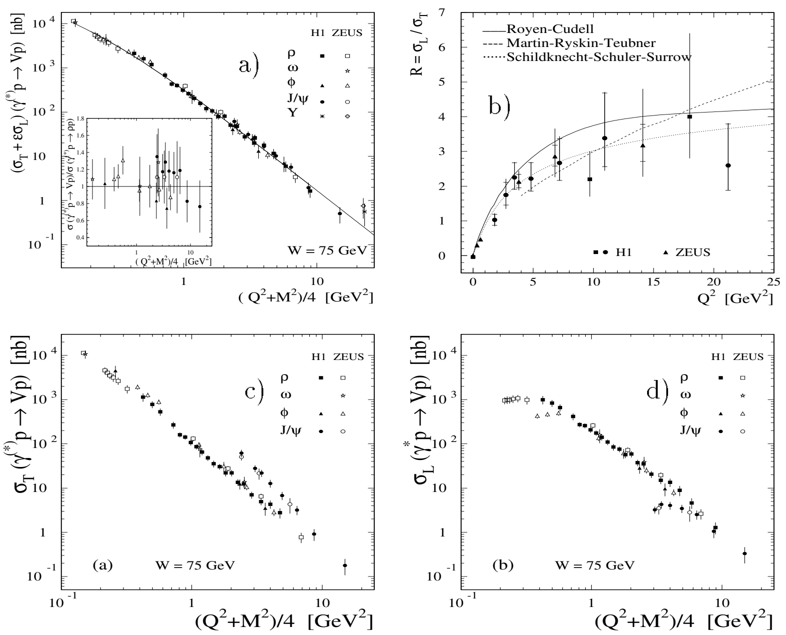


Figure 4: The Q^2-dependence. a) for the total cross section $\sigma(\gamma^{(*)}p \to Vp)$ [13], b) for the ratio σ_L/σ_T in elastic ρ production [6], c) for the transverse cross section σ_T and d) for the longitudinal cross section σ_L [13]. All cross sections are scaled to the $SU4$ coupling of the ρ wave function.

In Figures 4c and d, σ_T and σ_L are shown separately [13] in the same way as their sum in 4a). σ_T exhibits a striking power law behavior, as $(Q^2+M_V^2)^{-n}$. There are differences in the slopes ($n = 2.5\pm0.1(\rho,\omega), 2.8\pm0.1(\phi)$ and $3.2\pm0.2(J/\psi)$) and in the absolute values of σ_T for the respective vector mesons. It appears that the σ_T-lines for the various vector mesons might fall on top of each other when as ordinate $Q^2+aM_V^2$ with a proper value $a < 1$ would be used instead of $a = 1$. The various σ_L distributions are also clearly different by their threshold behavior, but they seem to merge to the same power law line in $(Q^2+M_V^2)$ with growing Q^2. The apparent universality of $\sigma_T + \epsilon\sigma_L$ in Fig. 4a) across the whole $(Q^2+M_V^2)$ range may thus be fortuitous.

7 Summary

Experiments at HERA have, in exclusive vector meson production channels, at their disposal a switchboard by which the photon and the proton vertices can be selected for diffraction at a hadronic or at a sub-hadronic scale, by choosing small or large values for Q^2 and M_V, and by distinguishing intact and broken-up scattered protons (P/N-switch). The t slope b allows to see the actual number of hadron size vertices ($n_h = 2, 1, 0$). $n_h = 2$ reactions show the expected soft hadronic behavior as $b \sim 10\ GeV^{-2}$, $\delta = 0.22$ and shrinkage in $W-t$ correlation. For $n_h = 1$ channels t slopes of $b \sim 5\ GeV^{-2}$, a W exponent of $\delta \simeq 0.8$ and no evidence for shrinkage are observed. For $n_h = 0$ a t slope of $b = 1.3\ GeV^{-2}$ is found. There is no evidence that M_V^2 and Q^2 add up in their impact on b and δ.

The total transverse cross section σ_T however shows a powerlaw behavior in $(Q^2+M_V^2)^{-n}$, which is getting steeper when vector mesons get heavier. The big differences of the production cross sections for the various vector mesons vanish nearly when "trivial" differences like the different electromagnetic couplings of their respective $SU4$ $\bar{q}q$ wave functions and their different constituent quark masses are taken into account.

Future measurements with higher statistics for diffractive production of vector mesons at large Q^2 and with proton break-up ($n_s = 2$ channels) may reveal the size and potentially also the number of subhadronic constituents of the proton in deeply inelastic ep scattering, and thus provide novel tests of QCD.

n_h	channel	b	δ	α'
2	$\gamma p \to (\rho, \omega) p$	$10 - 11$	.22	$.13 \pm .04$
	$\gamma p \to \phi p$	$7.3 \pm 1.0 \pm .8$	.22	$.16 \pm .03$
1	$\gamma^*(Q^2 = 4.5) p \to \phi p$	$5.8 \pm .5 \pm .6$		
1	$\gamma p \to J/\psi p$	$4.73 \pm .25 \pm .35$	$.83 \pm .07$	$.02 \pm .07$
1	$\gamma^*(Q^2 = 8.0) p \to J/\psi p$	$4.1 \pm 0.3 \pm 0.4$		
1	$\gamma^* p \to \rho p$	$\simeq 6$		
1	$\gamma p \to VP/N$	$b_P - b_N \simeq 3.5$		
0	$\gamma p \to J/\psi N$	$1.3 \pm 0.1 \pm 0.2$		

Table 1: Typical values for b, δ and α' reactions with 2, 1 and 0 hadron size vertices. Units are powers of GeV.

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