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Successful description of exclusive vector meson electroproduction

A Donnachie
Department of Theoretical Physics
University of Manchester
sandy@hep.man.ac.uk

P V Landshoff
Department of Applied Mathematics and Theoretical Physics
University of Cambridge
pvl@damtp.cam.ac.uk

Abstract

Data for the differential cross sections for $\gamma^* p \to \rho^0 p$, $\gamma^* p \to \phi p$ and $\gamma^* p \to J/\psi p$, at all available values of Q^2, fit very well to a combination of soft pomeron, hard pomeron and f_2 exchange.

In a previous paper[1], we presented a zero-parameter fit to data for the differential cross section $d\sigma/dt$ for exclusive ρ^0 photoproduction (that is, from real photons) and pointed out that its success was a triumph for Regge theory. In order to achieve this zero-parameter fit, we made two simple assumptions: that it is valid to use ρ^0 dominance, and that the differential cross section for $\rho^0 p$ scattering is identical to that for $\pi^0 p$ scattering. While it was surprisingly successful to make these assumptions, there is no reason to suppose that they are valid exactly, and so the appearance of new and more accurate data from the H1 collaboration[2], albeit preliminary, call for a reassessment.

The Regge approach to inelastic lepton scattering is steadily gaining support[3]. In this paper, we successfully apply it to differential-cross-section data for exclusive ρ production for $2.8 \leq W \leq 71.7$ GeV and to the ZEUS data[4] for exclusive ρ electroproduction which go up to Q^2 values of more than 40 GeV^2. We then go on to consider the ZEUS data[5] for the differential cross section for exclusive ϕ electroproduction, and the H1 and ZEUS data[6][7] for exclusive J/ψ production.

Real-photon exclusive ρ production

The H1 data start at values of W greater than 20 GeV and, at small t, show $d\sigma/dt$ rising steadily with increasing W, as is characteristic of pomeron exchange. However, as is seen in figure 1, the old fixed-target data[8] at lower values of W show that $d\sigma/dt$ at each fixed value of t initially decreases with increasing W, indicating the presence of a significant contribution from f_2, a_2 exchange. It is therefore necessary to include these fixed-target data in any fit. This we will do, along with the data from ZEUS.

For hadronic elastic scattering $AB \to AB$, the high-energy data fit very well to[9] an amplitude whose $C = +$ form is

$$T(s,t) = i \sum_i X_i \; F_A(t) F_B(t) \; e^{-\frac{1}{2} i\pi\alpha_i(t)} \; (\nu/\nu_i^0)^{\alpha_i(t)-1} \qquad \nu = \tfrac{1}{2}(s-u) \qquad (1)$$

Here, the sum ranges over the exchanges of the soft pomeron and the f_2 and a_2. The contribution from the $C = -$ exchanges ρ, ω is similar, except that the phase is different[9]. The functions $\alpha(t)$ are

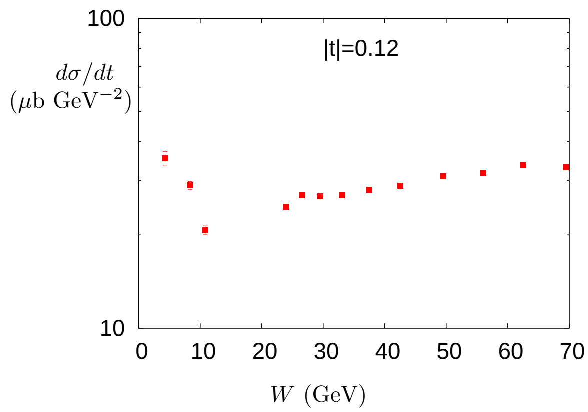


Figure 1: Energy dependence of data for exclusive ρ photoproduction at a fixed value of t.

the Regge trajectories corresponding to the exchanges; for the soft pomeron we have taken[9]

$$\alpha_1(t) = 1.08 + \alpha'_1 t \qquad \alpha'_1 = 0.25 \text{ GeV}^{-2} \tag{2}$$

and for ρ, ω, f_2, a_2

$$\alpha_2(t) = 0.45 + \alpha'_2 t \qquad \alpha'_2 = 0.93 \text{ GeV}^{-2} \tag{2b}$$

and we have suggested that it is correct to choose $\nu_i^0 = \frac{1}{2}\alpha_i'^{-1}$ $(i = 1, 2, 3)$ as in the Veneziano model. The X_i are real constants, and $F_A(t)$ and $F_B(t)$ are the elastic form factors of the hadrons A and B, in the case of the proton its Dirac form factor

$$F_1(t) = \frac{4m_p^2 - 2.79t}{4m_p^2 - t} \frac{1}{(1 - t/0.71)^2} \tag{3a}$$

We use a form similar to (1) for the process $\gamma p \to \rho p$, but of course ρ and ω exchange do not contribute, and also we include an additional term, corresponding to hard-pomeron exchange. Such a term is clearly seen in data for deep inelastic electron scattering[10] and it may even be present in hadron-hadron scattering[11]. That will surely be the case if it turns out that the correct Tevatron total cross section is that quoted by CDF[12] rather than E710[13]. We believe that the hard pomeron couples to the short-distance structure of the initial hadrons. The short-distance component of the photon is more prominent than that of the proton and we have already noted[1] that the ZEUS data for $\gamma p \to \rho p$ suggest a need for a hard-pomeron contribution.

For the elastic form factor $F_A(t)$ in (1) we again use the Dirac form factor of the proton. In place of $F_B(t)$ we need the $\gamma \to \rho$ transition form factor. Previously[1] we took the pion form factor for this:

$$G(t) = \frac{1}{1 - t/M^2} \tag{3b}$$

with $M^2 = 0.5$ GeV^2. In our new fit, we allow M to be a free parameter. The other free parameters in our fit are the couplings X_0, X_1, X_2 respectively of hard-pomeron, soft-pomeron and f_2, a_2 exchange. We take[10] the intercept $1+\epsilon_0$ of the hard-pomeron trajectory to be 1.44. We do not take the slope α'_0 of the hard-pomeron trajectory to be a free parameter, as it turns out that the quality of the fit is not very sensitive to it. We have previously concluded[1] that preliminary data for $\gamma p \to J/\psi\, p$ require a rather small value, and the fit we describe below reaffirms this, so we choose $\alpha'_0 = 0.01$ GeV^{-2}.

The fit then results in

$$X_0 = 0.069 \qquad X_1 = 5.33 \qquad X_2 = 21.1 \qquad M = 0.91 \text{ GeV} \tag{4}$$

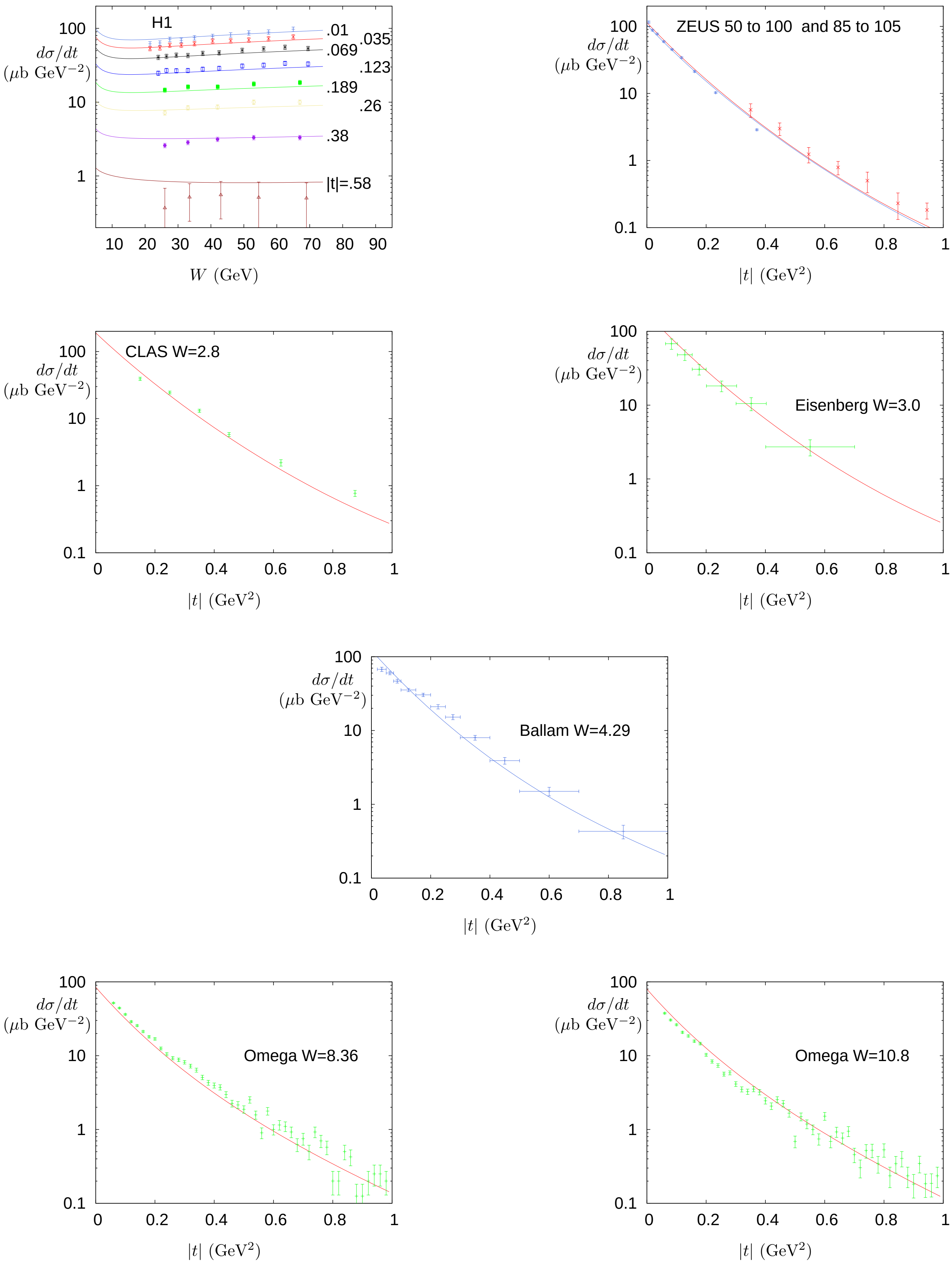
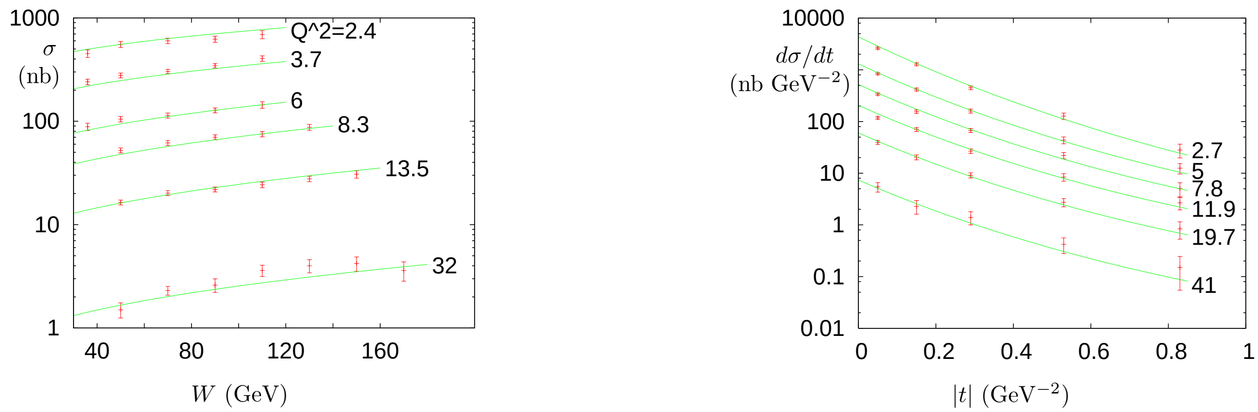


Figure 2: Fits to data for exclusive ρ photoproduction



(a) (b)

Figure 3: Fits to exclusive ρ electroproduction data[4]: (a) the total cross section and (b) the differential cross section at $\langle W \rangle = 90$ GeV, each at various values of Q^2.

where the units for the X_i are such that $|T(s,t)|^2$ is the differential cross section in μb GeV^{-2}. The comparison with the high-energy data is shown in the upper plots of figure 2. The ZEUS data were taken over two energy ranges and the figures suggest that there may be a problem with the higher-energy data. The fits to the low-energy data are shown in the lower plots of figure 2. The Omega data have been normalised from their fit to the un-normalised differential cross section and their quoted total cross section.

Because of the small value of X_0, the contribution from the hard pomeron to the fit is small and, except at the largest values of W and t, the hard-pomeron contribution is not really required.

Exclusive ρ electroproduction

For non-zero Q^2, the differential cross section receives contributions from both transverse and longitudinal photons and its form is not well constrained by our understanding of QCD. So our fit is largely informed by trial and error.

An obvious guess is to make the replacement

$$M^2 \to M^2 + Q^2 \qquad (5a)$$

in (3b). Because the f_2, a_2 exchange contribution is small at the energies for which there are data, we omit it. Initially the coefficients of the soft and hard pomerons were fitted to the data at each Q^2 to give an indication of their Q^2 dependence. A good description of the Q^2 dependence of X_0 and X_1 is obtained if we multiply them by

$$H(Q^2; Q_{1i}^2, Q_{2i}^2, Q_{3i}^2) = \frac{1}{(1 + Q^2/Q_{1i}^2)^2} + \frac{Q^2/Q_{2i}^2}{(1 + Q^2/Q_{3i}^2)^3} \qquad i = 0, 1 \qquad (5b)$$

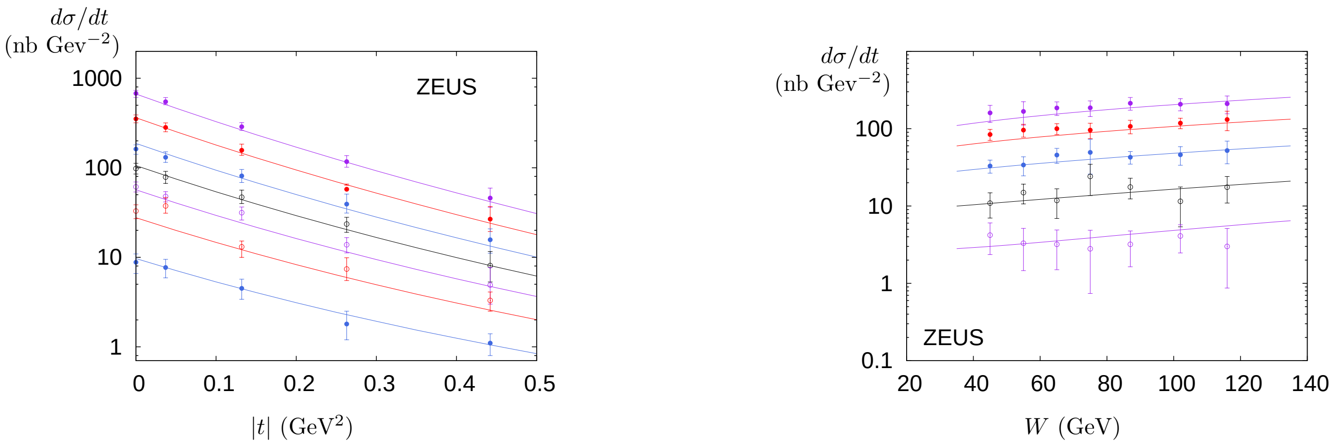
So, keeping X_0, X_1 and M fixed, we make our fit varying the 6 parameters in (5b). This results in the values

$$Q_{10}^2 = 8.2 \quad Q_{20}^2 = 3.9 \quad Q_{30}^2 = 0.16$$
$$Q_{11}^2 = 1.8 \quad Q_{21}^2 = 63.6 \quad Q_{31}^2 = 10.7 \qquad (5c)$$

all in GeV^2 units. The fit is shown in figure 3.

Exclusive ϕ electroproduction

As for ρ electroproduction, for the fit to ϕ electroproduction we consider only the hard and soft pomeron contributions and restrict the fit to the high-energy data[5]. The data comprise differential



(a) (b)

Figure 4: Fit to exclusive ϕ electroproduction: (a) at $\langle W\rangle = 75$ GeV and $Q^2 = 2.4, 3.6, 5.2, 6.9, 9.2,$ 12.6 and 19.7 GeV^2 and (b) at $\langle Q^2\rangle = 5$ GeV^2 and $|t| = 0.025, 0.12, 0.25, 0.45$ and 0.73 GeV^2.

cross sections at $\langle W\rangle = 75$ GeV at seven different values of Q^2, and the energy dependence at $\langle Q^2\rangle = 5$ GeV^2 at three different values of t. The data were fitted independently at each value of Q^2 to determine X_0 and X_1 as functions of Q^2. We found that they could be well represented by

$$X_0 = \frac{1.28}{(1+Q^2/Q_0^2)} \qquad X_1 = \frac{28.19}{(1+Q^2/Q_1^2)^2} \tag{6a}$$

with

$$Q_0^2 = 7.5 \text{ GeV}^2 \qquad Q_1^2 = 5.0 \text{ GeV}^2, \tag{6b}$$

except at $Q^2 = 5$ and 5.2 GeV^2. At 5(5.2) GeV^2 X_0 lies below(above) the curve and X_1 lies above(below). In (6a) the units are such that $|T(s,t)|^2$ is the differential cross section in nb GeV^{-2}. The data do not put a significant constraint on the mass M of the form factor $G(t)$ of (3b) or on whether separate form factors are required for the soft and hard pomeron, provided only that M is large for the hard pomeron. For simplicity a large value was taken for both so that $G(t)$ is effectively constant and the t dependence is given entirely by the Regge behaviour and the proton form factor. The fit is shown in figure 4.

Exclusive J/ψ photoproduction

For exclusive J/ψ production from real photons, we use a fit exactly similar to that for exclusive ρ production. This results in

$$X_0 = 1.78 \qquad X_1 = 6.75 \qquad X_2 = 0.21 \qquad M = 64.3 \text{ GeV} \tag{7}$$

where again the units are such that $|T(s,t)|^2$ is the differential cross section in nb GeV^{-2}. This gives the fits shown in figure 5.

We have remarked previously that, while the soft pomeron seems not to couple to c quarks, it does couple to the J/ψ, and that there is old evidence[14] that the J/ψ consists of a significant $q\bar{q}$ component, not just $c\bar{c}$. The fit is not good at low energy and large t; we cannot explain why the differential cross section is so large there.

Exclusive J/ψ electroproduction

For exclusive J/ψ electroproduction we again repeat the procedure used for ρ electroproduction, first fitting the data at each Q^2 and then determining an appropriate Q^2 dependence. A feature of the J/ψ electroproduction is that the energy dependence does not vary much with Q^2 or t and is very

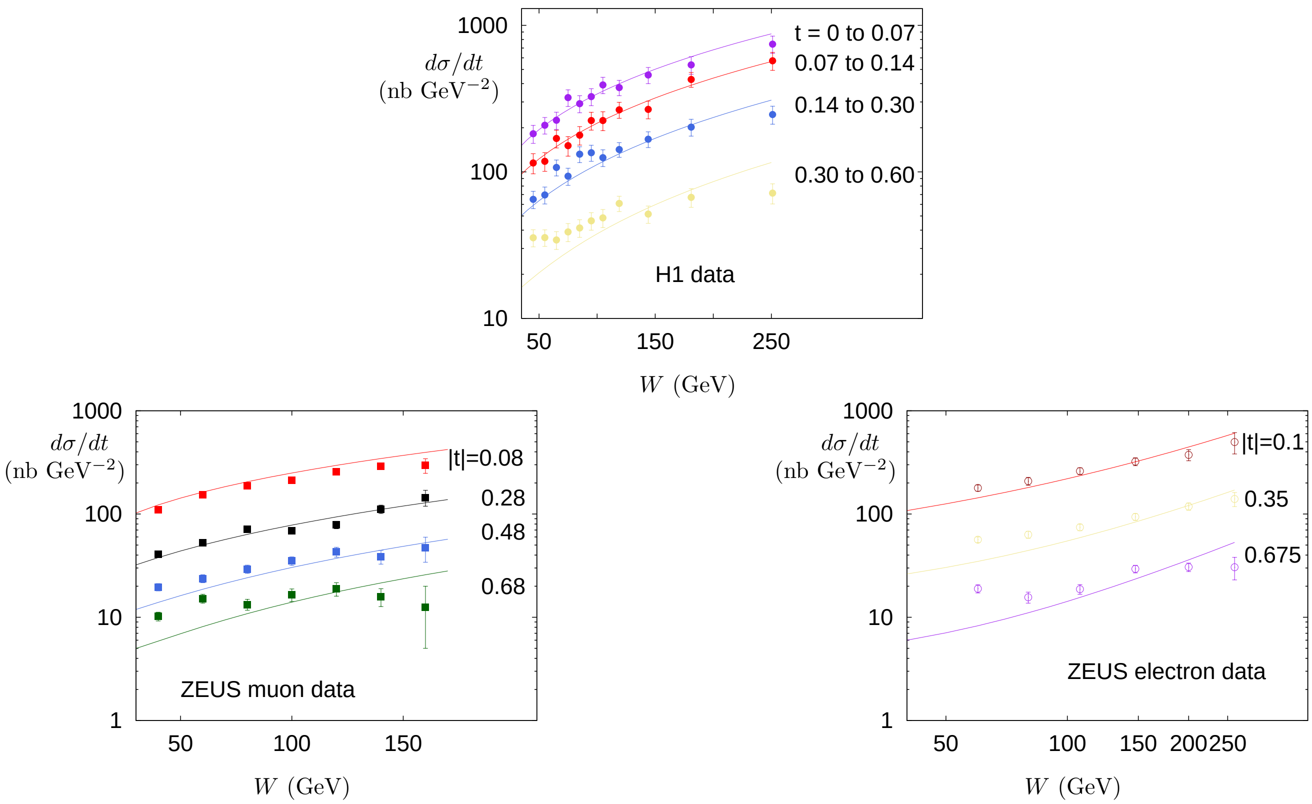


Figure 5: Fits to data for exclusive J/ψ photoproduction

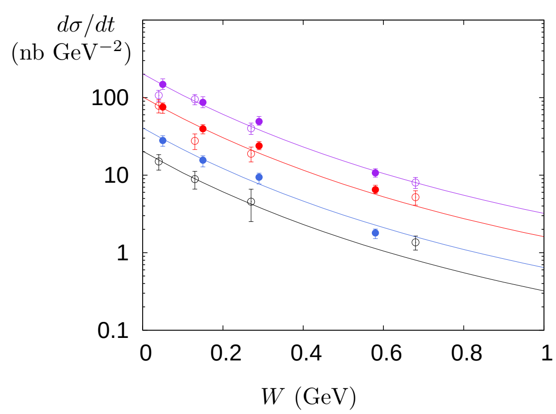


Figure 6: Fit to exclusive J/ψ electroproduction differential cross section at $\langle W \rangle = 90$ GeV, at $Q^2 =$ 3.2, 7.0, 16 and 22.4 GeV^2.

close to that of small-t J/ψ photoproduction. It is found adequate to give both X_0 and X_1 the same Q^2 dependence, multiplying X_0 and X_1 of (7) by

$$H(Q^2, Q_1^2) = \frac{1}{(1 + Q^2/Q_1^2)} \tag{8a}$$

with

$$Q_1^2 = 5.23 \text{ GeV}^2 \tag{8b}$$

The fit is shown in figure 6.

In conclusion, we have shown that Regge theory, with the inclusion of the hard pomeron, gives a good fit to data for the exclusive photo and electroproduction of vector mesons. Thus we disagree with a view recently expressed[15] that the understanding of elastic vector meson photoproduction is still a challenge.

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