THE POMERON IN EXCLUSIVE J/ψ VECTOR MESON PRODUCTION

R. Fiore\textsuperscript{a} *, L.L. Jenkovszky\textsuperscript{b} †, F. Paccanoni\textsuperscript{c} ‡ and A. Prokudin\textsuperscript{d} § ¶

\textsuperscript{a}Dipartimento di Fisica, Università della Calabria
Instituto Nazionale di Fisica Nucleare, Gruppo collegato di Cosenza
I-87036 Arcavata di Rende, Cosenza, Italy

\textsuperscript{b}Bogolyubov Institute for Theoretical Physics
Academy of Science of Ukraine
UA-03143 Kiev, Ukraine

\textsuperscript{c}Dipartimento di Fisica, Università di Padova
Instituto Nazionale di Fisica Nucleare, Sezione di Padova
Via F. Marzolo 8, I-35131 Padova, Italy

\textsuperscript{d}Dipartimento di Fisica Teorica, Università Degli Studi di Torino
Instituto Nazionale di Fisica Nucleare, Sezione di Torino
Via P. Giuria 1, I-10125 Torino, Italy
Institute For High Energy Physics, 142284 Protvino, Russia

An earlier developed model for vector meson photoproduction, based on a dipole Pomeron exchange, is extended to electroproduction. Universality of the non linear Pomeron trajectory is tested by fitting the model to ZEUS and H1 data as well as to CDF data on \( \bar{p}p \) elastic scattering.

1. Introduction

Elastic production of vector mesons in electron-proton interaction has provided a deeper understanding of the diffraction phenomenon and finds a sensible description in a variety of models. The first attempts to describe diffractive photoproduction were based on vector dominance model \[1\] and Regge theory \[2\]. Since various aspects of the deep inelastic scattering and of elastic processes are both present in photoproduction it is quite natural that perturbative QCD can help to understand many features of the HERA experimental results. Examples where perturbative QCD has been applied to this process can be found in Ref. \[3\].

In these perturbative calculations regarding diffractive processes, that in this case have characteristic features of the elastic ones, non perturbative contributions are present and their description becomes an important ingredient of the theoretical model while lying outside perturbation theory. Hence, models based on Regge pole phenomenology maintain their important task in helping to construct a representation of non perturbative aspects of the scattering amplitude. For the processes under consideration many papers based on Regge poles exchange successfully reproduced \[10\] new experimental HERA data.

The aim of this paper is to expound the properties of the most important and intricate Regge exchange: the vacuum, or Pomeron exchange. J/ψ photoproduction and, apart from small sublead-
ing contributions, \(\phi(1020)\) photoproduction are genuine Pomeron filters that, together with very high energies reactions, permit a careful study of the non perturbative features of diffraction.

2. The model

A convenient way to obtain rising cross sections with the Pomeron intercept equal to one assumes that the Pomeron is a double Regge pole. This means that the \(t\)-channel partial wave, corresponding to the Pomeron exchange, has a double pole for \(t = \alpha(t)\). In this choice we are comforted by the numerous successes of this model in its applications to hadronic reactions [4,5,6,7].

We choose the invariant scattering amplitude in the form

\[
A(s,t) = i f(t) \left( -i \frac{s}{s_0} \right)^{\alpha_P(t)} \left[ \ln \left( -i \frac{s}{s_0} \right) + g(t) \right],
\]

where \(g(t)\) and \(f(t)\) are functions, for the moment undetermined, of the momentum transfer. \(\alpha_P(t)\) is the Pomeron trajectory with \(\alpha_P(0) = 1\).

The choice of the function \(f(t)\), that represents the product of the vertices \(\gamma\)-Pomeron-meson and proton-Pomeron-proton, will be made by imposing the condition that the Pomeron exchange is pure spin \(\alpha_P\) exchange. It has been shown in [8] that this constraint leads to a vertex of the form \(\left[ (\alpha_P(t) - 1) f_1(t) + (\alpha_P(t) + 1) f_2(t) \right] \) and, in the neighborhood of \(t = 0\), to a term vanishing with \(t\) whatever the form of the trajectory could be.

It has been shown in Ref. [9] that the simple form for the elastic differential cross section of vector meson photoproduction

\[
\frac{d\sigma}{dt} = 4\pi \left[ a e^{bt} + c t e^{dt} \right]^2 \left( \frac{s}{s_0} \right)^{2\alpha(t) - 2} \left[ \left( \ln \frac{s}{s_0} + g \right)^2 + \pi^2 4 \right],
\]

where \(g\) is a constant, gives a good quality fit to the experimental data [9,10]. We notice that the form [2] satisfies also the aforesaid conditions and will be adopted in this paper.

Since the amplitude, in the Regge form, should have no essential singularity at infinity in the cut plane, \(\Re \alpha(s)\) is bounded by a constant, for \(s \to \infty\), and this leads to the bound \(|\alpha(s)| < Ms^\theta\) for \(s \to \infty\) with \(q < 1\) and \(M\) an arbitrary constant. The choice [11]

\[
\alpha_P(t) = 1 + \gamma \left( \sqrt{t_0} - \sqrt{t_0 - t} \right),
\]

where \(t_0 = 4m_p^2\) and \(\gamma = m_{\pi}/1 GeV^2\), satisfies the above conditions and reproduces the standard Pomeron slope at \(t = 0\), \(\alpha'_P(0) \simeq 0.25 GeV^{-2}\). Eq. (3) for the trajectory defines uniquely the model for photoproduction.

Consider now electroproduction of a vector meson. As noticed in Refs. [12,13] a commonly adopted form for the \(Q^2\) dependence of the \(J/\psi\) cross section is

\[
\sigma_{\gamma^* p \to J/\psi p} \propto \frac{1}{(1 + Q^2/M_{J/\psi}^2)^n},
\]

where \(n \simeq 1.75\), according to the ZEUS Collaboration [12], and \(n \simeq 2.38\) according to the H1 Collaboration [10].

For large \(Q^2\) all the amplitudes but the double flip one, for diffractive vector meson electroproduction, can be evaluated in perturbative QCD [14]. In the longitudinal photon amplitudes, a factor \(Q/M_{J/\psi}\) is a consequence of gauge invariance irrespective of the detailed production dynamics. If we consider only the dominant twist \(s\)-channel helicity conserving amplitudes, the factor in Eq. 4 thus finds a natural explanation. The \(Q^2\) dependence, however, will appear also in the strong coupling and in the gluon structure function through the hard scale of perturbative QCD [14].

In our approach, based on Regge pole theory, the factor [11] will be certainly present in electroproduction, multiplying the differential cross section [2], but this will not complete all the possible corrections. Since, in the dipole Pomeron formalism, the product of the vertices can affect the parameter \(g\), all the parameters can acquire a weak \(Q^2\) dependence. We neglect this dependence in \(a, b, c, d\) and assume that \(g\) varies as \(g \times [1 + Q^2/(Q^2 + M_{\pi}^2)]^{\gamma}\) where \(\gamma\), if this assumption is correct, is small. One can interpret this functional dependence of \(g\) as coming from a \(Q^2\) dependence of \(s_0\) in \(\ln(s/s_0)\).
The final form of the differential cross section is:

$$\frac{d\sigma}{dt} = 4\pi \left(1 + \frac{Q^2}{M^2_{J/\psi}}\right)^{-\beta} \left[ae^{bt} + ct e^{dt}\right]^2 ,$$

$$\left(\frac{s}{s_0}\right)^{2\alpha \rho(t)-2} \left(\ln \left(\frac{s}{s_0}\right) + g(Q^2)\right)^2 + \frac{\pi^2}{4}, \quad (5)$$

where, for $Q^2 = 0$, all the parameters have the same value as for photoproduction. We notice that the value of $\beta$ includes a factor $(1 + Q^2/M^2_{J/\psi})$ that comes from the contribution of the longitudinal amplitude, relevant at $Q^2 \neq 0$, which leads to $|A|^2 = |A_T|^2 + |A_L|^2$. The approximate relation $A_L \sim Q A_T/M_{J/\psi}$ can be applied in this phenomenological approach.

In the following Section the parameterizations $\mathbb{2}$ and $\mathbb{3}$ will be applied to $J/\psi$ photoproduction and electroproduction.

3. $J/\psi$ photoproduction and electroproduction

Following the analysis of Ref. $\mathbb{5}$ we apply Eq. $\mathbb{2}$ to the new dataset of $J/\psi$ photoproduction $\mathbb{9}$

$$\gamma + p \rightarrow J/\psi + p \quad (6)$$

In the experiment, the $J/\psi$ is identified from its leptonic decay modes, electron $J/\psi \rightarrow e^+e^-$ or muon $J/\psi \rightarrow \mu^+\mu^-$ pair, with different systematic errors specific to the electron or muon decay channel. For this reason the dataset $\mathbb{9}$ presents two separate measurements of the process Eq. $\mathbb{2}$, according to the way of the $J/\psi$ detection. Hence, as a first attempt, we limit our fit to the region $W \leq 160$ GeV, where data from both decay channels are given, and check the predictions of the model for the differential cross section and the total integrated cross section.

As noticed in the previous paper $\mathbb{6}$, the parameter $d$ varies little in the fit, so that we keep the same value $d = 0.851$ GeV$^{-2}$ fixed, thus leaving only four parameters free. As in previous paper $\mathbb{5}$ we set $s_0 = 1$ GeV$^2$. In order to avoid the region of inelastic background we limit the $t$ region to $|t| < 1$ GeV$^2$. In the fit we use differential cross sections only. For the electron channel we have obtained the results shown in Column 2 of Table $\mathbb{1}$ with $\chi^2$/d.o.f. = 1.5. For the muon channel the results are presented in Column 3 of Table $\mathbb{1}$ with $\chi^2$/d.o.f. = 1.0.

If we use all the two channel data altogether we obtain a very high $\chi^2$/d.o.f. = 1.9. To implement a better analysis one needs a more complete set of data on differential cross sections in both channels.

In order to proceed with the fitting procedure we must choose one of these channels. As soon as our model is valid for high energies and the data on $J/\psi$ exclusive photoproduction in $e^+e^-$ channel cover a region of higher energies ($30 < W < 300$ GeV) and has a better statistic than $\mu^+\mu^-$ channel ($30 < W < 160$ GeV), we choose the $e^+e^-$ channel data. The result is presented in Column 4 of Table $\mathbb{1}$ with $\chi^2$/d.o.f. = 1.2.

Without any fitting we achieve a good agreement with the data on integrated elastic cross section, $\chi^2$/point = 0.95. The high error of $c$ is due to the scarcity of the data on the differential cross section in the region $0 < |t| < 1$ GeV$^2$. A more complete set of high accurate data will allow us to arrive at a definite conclusion about the values of parameters.

Now we use Eq. $\mathbb{5}$ in order to describe electroproduction of $J/\psi$. We fix all the parameters obtained by fitting the photoproduction data (see Column 4 of Table $\mathbb{1}$) and fit two parameters $\beta$ and $\gamma$ to the dataset $\mathbb{7}$. The values of the parameters are the following: $\beta = 1.94 \pm 0.42$, $\gamma = 0.69 \pm 0.24$ and $\chi^2$/d.o.f. = 0.81.

The factor $[1 + Q^2/(Q^2 + M^2_{J/\psi})]^7$ grows up to 1.5 in the available region of photon virtuality $0 < Q^2 < 50$ GeV$^2$.

In the case of $\gamma = 0$ we obtain $\beta = 2.86 \pm 0.09$ and $\chi^2$/d.o.f. = 1.07. We proved that the fit is rather insensitive to the value of $0 < \gamma < 1$.

4. Pomeron universality

The model we consider is consistent with $s$-channel unitarity and asymptotic factorizability. Universality, in this context, refers to the choice

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6The data are available from $\mathbb{15}$.

7The data are available from $\mathbb{15}$, $\mathbb{16}$. 
Photoproduction

| e⁺e⁻ channel | µ⁺µ⁻ channel | e⁺e⁻ channel |
|---------------|---------------|---------------|
| W < 160 GeV   | W < 160 GeV   | W < 300 GeV   |
| a [GeV⁻²]     | (1.8 ± 0.1) · 10⁻³ | (1.83 ± 0.09) · 10⁻³ | (1.97 ± 0.13) · 10⁻³ |
| b [GeV⁻²]     | 1.55 ± 0.49   | 2.25 ± 0.24   | 1.40 ± 0.51   |
| c [GeV⁻⁴]     | (−0.48 ± 0.54) · 10⁻³ | (−0.97 ± 0.19) · 10⁻³ | (−0.35 ± 0.67) · 10⁻³ |
| d [GeV⁻²]     | 0.851         | 0.851         | 0.851         |
| g              | −4.23 ± 0.37  | −4.25 ± 0.22  | −4.58 ± 0.29  |

Table 1
Values of parameters obtained by fitting J/ψ photoproduction data.

Figure 1. Elastic cross section of J/ψ photoproduction. The dashed line corresponds to J/ψ → e⁺e⁻ channel fit (Column 2 of Table 1). The dotted line corresponds to J/ψ → µ⁺µ⁻ channel fit (Column 3 of Table 1). The solid line corresponds to J/ψ → e⁺e⁻ channel fit (Column 4 of Table 1).

Figure 2. Differential cross section of exclusive J/ψ photoproduction for 147.5 ≤ W ≤ 260 GeV. Line aliases and symbols are the same as in Fig. 1.

for the Pomeron trajectory that provides a reliable description of exclusive vector meson production. The conjecture that the trajectory in Eq. (3) is universal is supported by the following example.

We consider the proton-antiproton scattering at sufficiently high energies, where only the Pomeron presumably contributes. Following tradition [17], it is a customary practice to adopt a linear Pomeron trajectory in order to describe hadronic interactions. In a different approach [618] that provides a satisfactory fit to pp and ¯pp data a square root trajectory similar to that of Eq. (3) has been preferred. It is interesting to update this last fit using Eq. (3) and the same parameters adopted for photoproduction: \( t_0 = 4m_π^2 \) and \( \gamma = m_π/1\text{GeV}^2 \).

In order to use the asymptotic formula, we choose the data on the differential cross section at energies \( \sqrt{s} = 546 \text{ GeV} \) and 1.8 TeV [19]. As we take into account neither Pomeron daughters nor possible odderon contributions, we concentrate on the region of low \(|t|\), 0 < |t| < 0.2 GeV². The
result is presented in Table 2 with $\chi^2$/d.o.f. = 1.04.

\[
\begin{align*}
\text{a} &= 0.41 \pm 0.01 \text{ [GeV}^{-2}], \\
\text{b} &= 7.61 \pm 3.36 \text{ [GeV}^{-2}], \\
\text{c} &= -1.12 \pm 1.40 \text{ [GeV}^{-4}], \\
\text{d} &= 7.72 \pm 0.52 \text{ [GeV}^{-2}], \\
\text{g} &= 2.86 \pm 0.41.
\end{align*}
\]

Table 2
Values of parameters obtained by fitting $p\bar{p}$ data.

In Figs. 4 5 we depict respectively the results of the fit for the differential cross section and the predicted total and elastic cross sections of $\bar{p}p$ scattering.

The non linear trajectory of Eq. 3 provides a satisfactory agreement with the data also for this hadronic process. We consider the obtained result as an argument in support of the Pomeron universality.

5. Conclusions

The aim of this paper was to study the Pomeron exchange in reactions where non leading contributions are absent or negligible. We have chosen $J/\psi$ and $\phi(1020)$ photoproduction and electroproduction as Pomeron filters.

Our analysis is based on the dipole Pomeron model assuming a Pomeron trajectory with intercept equal to one and a non linear $t$-dependence. The choice of the vertices is based on covariant Reggeization as explained in Section 2 of Ref. 8.

To reduce the number of free parameters we have used an approximate form of the vertex. As a result, we have obtained a good description of the data on $J/\psi$ and $\phi(1020)$ (see details in Ref. 20) photoproduction and electroproduction.

To demonstrate the universality of the chosen trajectory we applied the model to $\bar{p}p$ scattering at sufficiently high energies where only the Pomeron contributes. The good agreement with the experimental data is an argument in favor of the chosen Pomeron trajectory.

We are convinced to have reached a deeper understanding of the properties of the soft dipole Pomeron.
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