On the determination of double diffraction
dissociation cross section at HERA

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Abstract

The excitation of the proton into undetected multiparticle states (double diffraction dissociation) is an important background to single diffractive deep-inelastic processes $ep \rightarrow e'p'\rho^0$, $e'p'J/\Psi$, $e'p'X$ at HERA. We present estimates of the admixture of the double diffraction dissociation events in all diffractive events. We find that in the $J/\Psi$ photoproduction, electroproduction of the $\rho^0$ at large $Q^2$ and diffraction dissociation of real and virtual photons into high mass states $X$ the contamination of the double diffraction dissociation can be as large as $\sim 30\%$, thus affecting substantially the experimental tests of the pomeron exchange in deep inelastic scattering at HERA. We discuss a possibility of tagging the double diffraction dissociation by neutrons observed in the forward neutron calorimeter. We present evaluations of the spectra of neutrons and efficiency of neutron tagging based on the experimental data for diffractive processes in the proton-proton collisions.
1 Introduction

Important information on the pomeron exchange in deep inelastic scattering (DIS) comes from diffractive (large rapidity gap) DIS of Fig.1a,

\[ \gamma^* + p \rightarrow X + p', \]

at small \( x = \frac{Q^2}{(Q^2+W^2)} \ll 1 \), which is being actively studied at HERA [1, 2]. \( X \) here can be either vector mesons \( \rho^0, \phi, J/\Psi, \Upsilon, ... \), or the low-mass (LM), \( M_X^2 \sim Q^2 \), and high-mass (HM), \( M_X^2 \gg Q^2 \), continuum excitations of the photon. In the single diffraction (SD) reaction (1), the final-state proton \( p' \) is separated from the hadronic debris \( X \) of the photon by a large (pseudo)rapidity gap \( \Delta \eta \approx -\ln x_{IP} \), where \( x_{IP} = (M_X^2 + Q^2)/(W^2 + Q^2) \ll 1 \) is the fraction of the proton’s momentum taken away by the pomeron. At the present stage of the H1 and ZEUS detectors, the recoil proton \( p' \) with very small energy loss cannot be registered and the SD events of Fig. 1a could not be experimentally distinguished from the double diffraction dissociation (DD) events of Fig. 1b, \( \gamma^* + p \rightarrow X + Y \), in which proton resonances and/or multiparticle states \( Y \) escape undetected into the beam pipe. The experimental separation of DD at HERA is very important for several reasons. A clean signal of single diffraction of real and virtual photons is important for understanding the \( Q^2 \)-evolution of the pomeron exchange in diffractive reactions and for testing models of the pomeron structure function [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. A comparison of double and single diffraction will provide an unique information on the \( Q^2 \)-dependence of the factorization properties of the pomeron and sheds light on the much disputed issue of whether the soft pomeron exchange at small \( Q^2 \) will be superceded by hard pomeron exchange at larger \( Q^2 \). There are interesting predictions for the cross section and the diffraction slope of pomeron exchange reactions \( \gamma(\gamma^*) + p \rightarrow \rho^0(J/\Psi) + p \), at HERA [13, 14, 15, 16, 17, 18]. The tests of these predicitions require a separation of the background from DD reaction \( \gamma(\gamma^*) + p \rightarrow \rho^0(J/\Psi) + Y \), which can significantly affect the diffraction slope measurements.

The purpose of this paper is twofold. Firstly, following microscopic models, in which the properties of the pomeron do not change significantly from diffraction of hadrons and real photons to diffractive DIS (see for instance: [3, 4, 11]), we present estimates of the DD
background to large rapidity gap and exclusive vector meson production in DIS and real photoproduction, based on the factorization approximation and huge body of experimental information on diffractive hadron-hadron interactions. We find that in the $J/\Psi$ production and diffraction dissociation of photons into high mass states $X$, the ratio of the DD background to the SD production is very large, $\gtrsim 30\%$. This is of particular importance in the interpretation of the $t$-dependence of the $J/\Psi$ production (or the $\rho^0$, $\omega$, $\phi$ production at large $Q^2$). Secondly, we explore in some detail the possibility of tagging DD events by neutrons contained in the proton excitations $Y$. These neutrons can easily be detected in the forward neutron calorimeter (FNC) [20]. We find that an approximately $\kappa_n \sim 25\%$ fraction of double diffraction dissociation events contains a neutron which satisfies a typical neutron energy cut of $z = E_n/E_p > z_{\text{min}} \sim 0.5$. We conclude that the neutron tagging of DD is feasible, and the observed fraction $f_{\text{DD}}^{(n)}$ of neutron tagged diffractive DIS will allow a direct experimental determination of the overall fraction $f_{\text{DD}}$ of diffractive DIS which proceeds via double diffraction dissociation: $f_{\text{DD}} = f_{\text{DD}}^{(n)}/\kappa_n$. The experimental implementation of the neutron tagging of DD shall shed a light on many facets of double diffraction dissociation and the pomeron exchange in DIS.

2 Regge factorization and single and double diffraction dissociation

Our analysis of DD is based on the well established similarity of the mass spectrum of hadronic states $Y$ in the double diffraction dissociation process $p + p \to X + Y$ of Fig. 1d and in the single diffraction dissociation process $p + p \to p + Y$ of Fig. 1c, in conformity with the Regge theory factorization for single pomeron exchange:

$$\left. \frac{d\sigma(pp \to XY)}{dM_X^2dM_Y^2dt} \right|_{t=0} = G(p \to X) \cdot G(p \to Y).$$

(2)

In proton-proton interactions, this factorization law has been shown to hold to an accuracy $\lesssim 20\%$ (for a detailed discussion see [21, 22, 23, 24]). Evaluation of the admixture of DD to
large rapidity gap events,
\[
f_{DD}^{ap} = \frac{\sigma_{DD}(ap \rightarrow XY)}{\sigma_{SD}(ap \rightarrow Xp') + \sigma_{DD}(ap \rightarrow XY)}
\]
using the factorization (2) involves integration of the DD cross section over \( t \) and \( M_Y^2 \) and requires a knowledge of the diffraction slope \( b_{DD}(XY) \). For reactions with hadrons and real photons \( (a = p, \pi, K, \gamma; \text{the target is always assumed to be a proton}) \) the gross features of \( b_{ap\rightarrow DD}(XY) \) are consistent with the Regge theory relationship
\[
b_{DD}(ap \rightarrow XY) \approx b_{SD}(ap \rightarrow Xb) + b_{SD}(ap \rightarrow aY) - b_{el}(ap) \tag{3}
\]
and can be described as follows (see also [21, 22, 23, 24]). In the single diffraction excitation of the beam hadron \( a \) or the target proton or in double diffraction dissociation of both the beam and target hadrons into low-mass (LM) states \( X_{LM} \) and \( Y_{LM} \)
\[
b_{DD}(ap \rightarrow X_{LM} + Y_{LM}) \sim b_{SD}(ap \rightarrow X_{LM} + p) \sim b_{SD}(ap \rightarrow a + Y_{LM}) \sim b_{el}(ap). \tag{4}
\]
In single diffraction dissociation when the beam hadron (or target proton) is excited into the high-mass (HM) continuum states, the diffraction slope, as a function of the mass \( M_X \) and \( M_Y \), levels off at a value \( B_{SD} \):
\[
b_{SD}(ap \rightarrow X_{HM} + p) \sim b_{SD}(ap \rightarrow a + Y_{HM}) \equiv B_{SD} \sim \frac{1}{2} b_{el}(pp). \tag{5}
\]
In double diffraction dissociation when both the beam hadron and the target proton are excited into HM states \( X \) and \( Y \), the diffraction slope is also approximately constant, but considerably smaller than \( B_{SD} \):
\[
b_{DD}(pp \rightarrow X_{HM} + Y_{HM}) \equiv B_{DD} \approx 2 \text{GeV}^{-2}, \tag{6}
\]
in agreement with (3)-(5). The well known consequence of the factorization (2) for the fixed masses \( X \) and \( Y \) in the exponential approximation of the \( t \)-dependence is [21, 22, 23]
\[
\sigma_{DD}(ap \rightarrow XY) \approx \frac{\sigma_{SD}(ap \rightarrow aY) \cdot \sigma_{SD}(ap \rightarrow Xp)}{\sigma_{el}(ap)} \cdot \frac{b_{SD}(ap \rightarrow aY) \cdot b_{SD}(ap \rightarrow Xp)}{b_{DD}(ap \rightarrow XY) \cdot b_{el}(ap)}. \tag{7}
\]
For an approximate estimation of the SD and DD cross sections, we integrate over the excitations \( X \) and \( Y \) splitting the mass spectra into the low-mass and high-mass regions and
making use of (3)-(7). In hadronic reactions the boundary between the low-mass (resonances, ...)
and high-mass (the continuum) regions is \( M_{X,Y} \sim 2 \text{GeV} \) [21, 22, 23, 24].

In diffractive DIS and in photoproduction of heavy quarkonia the situation is somewhat
more complicated. Let us consider first the case of real photoproduction. Following the
established tradition, we will refer to the single diffractive photoproduction \( \gamma p \rightarrow V p \) \((V = \rho^0, \omega, \Phi, J/\Psi)\) as "elastic" production and to the double diffraction \( \gamma p \rightarrow V Y \) as "inelastic"
production. It is known experimentally [25] that for elastic production \( b_{el}(\gamma p \rightarrow \rho^0 p) \approx b_{el}(\pi p) \)
(for \( \omega \) production see also [26]). It is natural to expect that:

\[
\begin{align*}
  b_{in}(\gamma p \rightarrow \rho^0 Y_{LM}) &\approx b_{el}(\gamma p \rightarrow \rho^0 p) \approx b_{el}(\pi N), \\
  b_{in}(\gamma p \rightarrow \rho^0 Y_{HM}) &\approx B_{SD}.
\end{align*}
\]

In elastic production of heavy quarkonia \( \gamma p \rightarrow J/\Psi p \), as well as for deeply virtual (large \( Q^2 \gtrsim m_{J/\Psi}^2 \)) photoproduction of light vector mesons, the contribution from the vertices \( \gamma \rightarrow J/\Psi \)
and \( \gamma \rightarrow \rho^0 \) to the diffraction slope becomes small [19]

\[
\Delta b(Q^2) \approx \frac{9}{2(m_V^2 + Q^2)} \ll b_{el}(pp).
\]

For these reasons we expect:

\[
\begin{align*}
  b_{el}(\gamma p \rightarrow J/\Psi p) &\approx b_{in}(\gamma p \rightarrow J/\Psi Y_{LM}) \approx B_{SD}, \\
  b_{in}(\gamma p \rightarrow J/\Psi Y_{HM}) &\approx B_{DD}.
\end{align*}
\]

For the photoproduction of \( \rho^0 \) at intermediate \( Q^2 \gtrsim 2 \text{GeV}^2 \) we expect a smooth interpolation

\[
\begin{align*}
  b_{in}(\gamma p \rightarrow \rho^0 Y_{LM}) &\sim B_{SD} + \Delta b(Q^2), \\
  b_{in}(\gamma p \rightarrow \rho^0 Y_{HM}) &\sim B_{DD} + \Delta b(Q^2).
\end{align*}
\]

Let us consider now diffractive DIS. Let \( \beta \) be the Bjorken variable for DIS on the pomeron:
\( \beta = x/x_P = Q^2/(Q^2 + M_X^2) \). It has been argued [4] that the LM region corresponds to the
interaction of \( \gamma^* \) with the quark-antiquark valence component of the pomeron \((\beta \gtrsim 0.2, \text{i.e.} M_X^2 \lesssim 5Q^2)\). In this case the educated guess is

\[
\begin{align*}
  b_{SD}(\gamma^* p \rightarrow X_{LM} p) &\approx b_{DD}(\gamma^* p \rightarrow X_{LM} Y_{LM}) \approx b_{el}(\pi N), \\
  b_{DD}(\gamma^* p \rightarrow X_{LM} Y_{HM}) &\approx B_{SD}.
\end{align*}
\]
The HM region corresponds to the values of $\beta \lesssim 0.2$, when $\gamma^*$ probes the sea of the pomeron generated by the valence gluon-gluon component of the pomeron [4]. Here one expects the diffractive slopes

$$b_{SD}(\gamma^* p \rightarrow X_{HM} p) \approx b_{DD}(\gamma^* p \rightarrow X_{HM} Y_{LM}) \approx B_{SD},$$

$$b_{DD}(\gamma^* p \rightarrow X_{HM} Y_{HM}) \approx B_{DD}. \tag{17}$$

The prescriptions (8-18) for the diffraction slope in SD and DD, for real and virtual photo-production are educated guesses based on the assumption that the pomeron properties do not depend strongly on flavour and/or $Q^2$ and should be a subject of experimental tests. First of all, even in the best studied proton-proton interactions the value of $B_{DD}$ (Eq.(8)) comes from studying only some exclusive channels. Secondly, it is not excluded that $B_{DD}$ in DIS is slightly different from what is known from hadronic reactions.

### 3 Double diffraction dissociation at HERA

In the case of the ZEUS or H1 collaboration main calorimeters, the hole for the beam pipe determines the minimal polar scattering angle $\theta_m$, and the corresponding maximal pseudo-rapidity $\eta_F = \log \frac{2}{\theta_m}$, of the detected secondary particles. The range of masses $M_Y$ of the undetected excitations $Y$ of the proton can be evaluated as follows: If the proton excites into a state of mass $M_Y \gg m_p$, then the held back pions with the transverse momentum $k_\perp$, transverse mass $\mu_\perp = \sqrt{\mu_\pi^2 + k_\perp^2}$, longitudinal momentum $k_z \approx -\frac{1}{2} M_Y$ and rapidity in the co-moving frame $y \approx -\log(2|k_z|/\mu_\perp) \approx -\log(M_Y/\mu_\perp)$, have the smallest (pseudo)rapidity $\eta$ in the HERA reference frame

$$\eta = \log \frac{2E_p}{M_Y} + y \approx \log \frac{2E_p\mu_\perp^2}{M_Y^2} \approx \log \frac{2E_p k_\perp^2}{M_\perp^2}. \tag{19}$$

The forward calorimeter of the ZEUS collaboration misses secondary particles with $\eta \geq \eta_F = 4.3$ [4]. Then, for the proton energy $E_p = 820 GeV$ and typical $k_\perp \sim 0.5 GeV/c$ all the secondary hadrons coming from excitations of the proton with

$$M_Y < M_{max} \approx \sqrt{2E_p k_\perp} \exp(-\frac{1}{2} \eta_F) \sim 4 GeV \tag{20}$$
will escape into the beam pipe. Monte Carlo studies for the ZEUS detector suggest $M_{\text{max}} \approx 5 \text{GeV}$ \cite{27}, which we use in the further analysis. The H1 detector has a similar angular acceptance \cite{2}.

In the following we will use the factorization relation (7) to estimate the double diffraction dissociation background to single diffraction dissociation in DIS (Fig. 1a) in terms of SD cross sections in proton-proton collisions. We start with a brief reminder of salient features of the single diffraction in $p + p \to p' + Y$. The key quantity here is $d\sigma_{\text{SD}} / dt dM_Y^2$, integration of which gives:

$$\sigma_{\text{SD}}(M_Y \leq M_{\text{max}}) = \int_{M_{\text{max}}^2} dM_Y^2 \int dt \frac{d\sigma_{\text{SD}}}{dt dM_Y^2}. \quad (21)$$

Although the diffraction slope $b_{\text{SD}}(M_Y^2)$ exhibits a nontrivial mass dependence, the quantity

$$\Sigma_{\text{SD}} = M_Y^2 \int dt \frac{d^2\sigma_{\text{SD}}}{dt dM_Y^2} \quad (22)$$

is practically flat, $\Sigma_{\text{SD}} = 0.68 \pm 0.05 \text{mb}$, in a broad range of excited masses, $1.7 \lesssim M_Y^2 \lesssim 30 \text{GeV}^2$, and decreases towards smaller $M_Y$ \cite{28, 23}. Compared to Eq.(45) in \cite{23} we neglect the finite-energy corrections. This leads to the simple parametrization

$$\sigma_{\text{SD}}(pp \to pY; M_Y^2 < M_{\text{max}}^2) \approx 2\Sigma_{\text{SD}} \log \left( \frac{M_{\text{max}}}{1.25(\text{GeV})} \right), \quad (23)$$

which gives $1.9 \text{ mb} (2.1 \text{ mb})$ for $M_{\text{max}} = 5 \text{ GeV}$ ($M_{\text{max}} = 6 \text{ GeV}$). The corresponding LM/HM partition is $\sigma_{\text{SD}}(LM) \approx 0.64 \text{ mb}$ and $\sigma_{\text{SD}}(HM) \approx 1.25 \text{ mb} (1.5 \text{ mb})$, with an uncertainty of $\lesssim 20\%$. Consequently, for the LM excitations of the beam proton $X_{LM}$, summing over all the excitations of the target proton $Y$, we obtain by virtue of Eq.(7)

$$f_{\text{DD}}^{pp}(X_{LM}) \equiv \frac{\sigma(pp \to X_{LM}Y)}{\sigma(pp \to X_{LM}, p) + \sigma(pp \to X_{LM}, Y)} \approx \frac{\sigma_{\text{SD}}(pp \to pY)}{\sigma_{\text{el}}(pp) + \sigma_{\text{SD}}(pp \to pY)} \approx 0.21. \quad (24)$$

For the HM excitations of the beam proton $X_{HM}$, care must be taken of the difference between $B_{SD}$ and $B_{DD}$ when integrating over masses of the target proton debris $Y$:

$$f_{\text{DD}}^{pp}(X_{HM}) \equiv \frac{\sigma(pp \to X_{HM}Y)}{\sigma(pp \to X_{HM}, p) + \sigma(pp \to X_{HM}, Y)} \approx \frac{\sigma_{\text{SD}}(LM) + \chi_{DD}\sigma_{\text{SD}}(HM)}{\sigma_{\text{el}}(pp) + \sigma_{\text{SD}}(LM) + \chi_{DD}\sigma_{\text{SD}}(HM)} \approx 0.26, \quad (25)$$

where $\chi_{DD}$ here is a new parameter defined as

$$\chi_{DD} = \frac{B_{SD}}{B_{DD}} \cdot \frac{B_{SD}}{b_{el}}. \quad (26)$$
In the evaluation above we have used \( \sigma_{el}(pp) \approx 7.3 \text{ mb} \) and \( \chi_{DD} \approx 1.5 \). If \( M_{max} = 6 \text{ GeV} \), we find a somewhat larger \( f_{DD}^{pp}(X_{LM}) \approx 0.23 \) and \( f_{DD}^{pp}(X_{HM}) \approx 0.28 \). The very small value of the slope in DD processes (see Eq. (3)) leads to an enhanced effect of excitation of the target proton in high mass states \( Y_{HM} \) and to a large admixture \( f_{DD}^{pp}(X_{HM}) \). Please note that \( f_{DD}(X_{HM}) \) depends crucially on the poorly known \( B_{DD} \), of which direct measurement is yet lacking, and still larger values of \( \chi_{DD} \) and as a consequence larger values of \( f_{DD}(X_{HM}) \) are possible.

The structure function of the pomeron is operationally defined through the cross section for single diffraction dissociation of virtual photons \([3, 4, 5]\). In the present HERA experiments the cross section for double diffraction dissociation constitutes an unwanted background. Therefore the extraction of the SD cross section from large rapidity gap data requires a correction for the DD background. Extrapolation of the above considerations for hadronic reactions to diffractive DIS requires the assumption that properties of the pomeron exchange do not change from hadronic scattering to diffractive DIS. Under this assumption we find that \( f_{DD}(\gamma^* \rightarrow X_{LM}) \) and \( f_{DD}(\gamma^* \rightarrow X_{HM}) \) will be approximately independent of \( x_{IP} \) and \( Q^2 \):

\[
\begin{align*}
  f_{DD}(\gamma^* \rightarrow X_{LM}) & \approx f_{in}(\gamma \rightarrow \rho^0) \approx f_{DD}^{pp}(X_{LM}) \approx 0.21 - 0.23 , \quad (27) \\
  f_{DD}(\gamma^* \rightarrow X_{HM}) & \approx f_{in}(\gamma \rightarrow J/\Psi) \approx f_{DD}(\gamma^* \rightarrow \rho^0, Q^2 \gtrsim M_{J/\Psi}^2) \approx f_{DD}^{pp}(X_{HM}) \approx 0.26 - 0.28 . \quad (28)
\end{align*}
\]

Notice that the contribution from the DD background in the HM (small-\( \beta \)) region is larger than in the LM (large-\( \beta \)) region. A correct interpretation of the experimentally observed \( \beta \) distributions in terms of the pomeron structure function will require a careful correction for the \( \beta \)-dependence of the background. Experimental determination of the \( (x_{IP}, Q^2) \)-dependence of \( f_{DD} \) would be an extremely interesting test of the current ideas on the pomeron.

Similarly, in the photo- and electroproduction of the \( J/\Psi \) (and heavier quarkonia) the expected ”inelastic” background \( f_{in}(\gamma \rightarrow J/\Psi) \sim f_{DD}^{pp}(X_{HM}) \approx 0.26 - 0.28 \) is larger than in real photoproduction of \( \rho^0 \), which is consistent with the H1 data \([4]\). Such a large admixture of inelastic events with a very small diffraction slope \( B_{in}(J/\Psi) \sim B_{DD} \) can substantially affect measurements of the energy dependence of the slope \( B_{el}(J/\Psi) \), which is very important for testing the BFKL pomeron. In the photoproduction of \( \rho^0 \), the background from ”inelastic” production is weaker and the slopes of the ”elastic” and ”inelastic” components differ less:
\( B_{el}(\rho^0) \approx b_{el}(\pi N) \) \( [25] \) vs. the expected \( B_{in}(\rho^0) \approx B_{SD} \). According to Eq.(10) the decrease of \( \Delta b(Q^2) \) with \( Q^2 \) leads to an increase of the admixture of inelastic \( \rho^0 \) production with \( Q^2 \), which can be described by the \( Q^2 \)-dependence of the parameter \( \chi_{DD} \) in the counterpart of Eq.(25)

\[
\chi_{DD}(Q^2) \approx \frac{(B_{SD} + \Delta b(Q^2))^2}{(B_{DD} + \Delta b(Q^2))b_{el}}. \tag{29}
\]

We expect that the \( f_{in}(\gamma^* \rightarrow \rho^0) \) rises with \( Q^2 \) from \( f_{in}(\gamma \rightarrow \rho^0) \) for real photoproduction up to 0.28 at large \( Q^2 \). This prediction could be easily tested at HERA.

\section{4 Neutron tagging of double diffraction dissociation at HERA}

The strong admixture (Eqn.(26,27)) of DD processes in diffractive DIS makes its direct determination very important issue. A direct detection of charged particles from double diffraction dissociation is hardly possible. On the other hand, observation of very forward neutrons is easier \([20]\). Therefore in the following we wish to discuss the feasibility of neutron tagging in more detail.

The interpretation of the data on neutron tagged DD requires knowledge of the neutron content for specific final states \( Y \). It is known from hadronic reactions that to a good approximation the spectrum of the final state \( Y \) can be approximated in terms of three distinct components. The first prominent component is \( Y = \pi N \) with the cross section \( \sigma_1 = \sigma_{SD}(pp \rightarrow p + (\pi N)) \approx (0.4 - 0.45) \text{ mb} \). This is the predominantly LM channel, because the observed \( M_Y \) spectrum has a characteristic broad bump which peaks at \( M_Y \approx 1.5 \text{ GeV} \), extends up to \( M_Y \lesssim 1.8 \text{ GeV} \) and is followed by a tail up to \( M_Y \lesssim 2.4 \text{ GeV} \) \([24, 22]\). Since the diffractively excited \( \pi N \) system is in isospin \( \frac{1}{2} \) state, the average multiplicity of neutrons in the \( \pi N \) final state \( \langle n^{(1)}_n \rangle = \frac{2}{3} \). The second prominent, predominantly LM channel, is \( Y = N\pi\pi \). It is dominated by \( \Delta\pi \) production \([30, 31]\). The measured cross section is \( \sigma_{SD}(pp \rightarrow p + (p\pi^+\pi^-)) \approx (0.15-0.2) \text{ mb} \). The observed mass spectrum has a broad peak at
\[ M_Y \sim 1.7\, GeV \text{ and a tail up to } M_Y \lesssim 2.5\, GeV \text{ [21, 22]. A simple isospin analysis leads to} \]

\[ \sigma_2 = \sigma_{SD}(pp \rightarrow p + (N\pi\pi)) \approx \frac{9}{5} \sigma_{SD}(pp \rightarrow p + (p\pi^+\pi^-)) = (0.27 - 0.36)\, mb \quad (30) \]

and a small multiplicity of neutrons \( \langle n_n^{(2)} \rangle = \frac{2}{3} \). Inspection of Eq. (23) shows that \( \sigma_{SD}(N\pi + N\pi\pi) \approx 0.7 - 0.8\, mb \) practically exhausts the contributions from \( M_Y \lesssim 2.3\, GeV \). For the excitation of the continuum of still higher masses \( 5 \lesssim M_V^2 \lesssim 25\, GeV^2 \), Eq. (23) gives an estimate of \( \sigma_3 \approx 1.1 - 1.4\, mb \). There are no direct experimental data on the spectrum of neutrons in the continuum HM excitation. However, because of a well known similarity of secondary particle spectra in the pomeron-proton and hadron-proton collision at a similar center-of-mass energy [21, 22, 23, 24], production of neutrons from HM excitations can be approximated by a meson-exchange model [32, 33, 34], which gives a good description of the hadronic production data. In the specific model [33, 34] we find a mean multiplicity of neutrons \( \langle n_n^{(3)} \rangle = 0.2 \).

Putting together the three components discussed above, we find an average multiplicity of neutrons in double diffraction dissociation

\[ \langle n_n^{DD} \rangle \equiv \frac{\sum \langle n_n^{(i)} \rangle \sigma_i}{\sum \sigma_i} \approx 0.30 - 0.31 \quad (31) \]

Thus the expected fraction of neutron tagged large rapidity gap events equals \( f_{DD}^{(n)} = \langle n_n^{DD} \rangle \cdot f_{DD} \approx 0.08 \).

Experimental cuts on the neutron energy make the evaluation of the \( z \)-distribution of the produced neutrons very important. Let us start the evaluation with the \( n\pi \) system assuming full angular coverage for the outgoing neutrons. Let \( \theta_{GJ} \) be the so-called Gottfried-Jackson angle between the neutron and the \( n\pi \) motion axis. Then

\[ \Phi_1(z) = \int d\cos \theta_{GJ} dM_Y \frac{1}{N_{ev}} \frac{dN_{ev}}{dM_Y d\cos \theta_{GJ}} \delta(z - \frac{E^* + p^* \cos \theta_{GJ}}{M_Y}) \quad (32) \]

(The normalization is such that \( \int_0^1 dz \Phi_1(z) = 1 \). Notice the useful lower bound \( z \gtrsim m_n^2/M_Y^2 \), which shows that all the neutrons from excitations with \( M_Y^2 \lesssim m_n^2/z_{\text{min}} \) pass the \( z_{\text{min}} \) cut \( z \gtrsim z_{\text{min}} \). With \( z_{\text{min}} \approx 0.5 \) [24] one has to worry only about the loss of neutrons from excitations with \( M_Y^2 \gtrsim 2 GeV^2 \). At such \( M_Y \), the \( \cos \theta_{GJ} \) distribution measured [29] exhibits a strong forward peak at \( \cos \theta_{GJ} = 1 \), which results in a peak at \( z \sim 1 \), and a less prominent
backward peak at \( \cos \theta_{GJ} = -1 \), which contributes to \( z \sim m_n^2 / M_Y^2 \). The results of the evaluation of \( \Phi_1(z) \) using the experimental data on the \((M_Y, \cos \theta_{GJ})\) distribution of \( N_{ev} \) from Ref. [29] are presented in Fig. 2a (solid line). The \( \Phi_1(z) \) distribution peaks at \( z \sim 1 \). A comparison with a flat \( \cos \theta_{GJ} \) distribution (dashed line) shows a rather weak dependence of the loss of neutrons on a detailed form of the \( \cos \theta_{GJ} \) distribution. We find that a \( \epsilon^{(1)}_n \approx 0.85 \) fraction of neutrons from \( n\pi^\pm \) excitations of the proton passes the \( z_{min} = 0.5 \) cut.

One can repeat a similar analysis for the \( n\pi\pi \) excitation, modelling it by \( \Delta\pi \) production (see [30, 31]). Again we can use the experimentally measured mass distribution as given for instance in Ref. [22]. The \( z \)-spectra of neutrons are fairly independent of the angular distributions in the Gottfried-Jackson frame. We assume the \( \cos \theta_{GJ} \) distribution for the \( \Delta\pi \) system the same as for the \( N\pi \) component and take isotropic distribution in the \( \Delta \rightarrow n + \pi \) decay. While the \( z \) distribution of primary \( \Delta' \)'s is very similar to \( \Phi_1(z) \), the \( z \) distribution of neutrons after the \( \Delta \rightarrow n\pi \) decay becomes peaked at \( z \sim 0.6 \) (Fig. 2b). Even so, the loss of neutrons from \( n\pi\pi \) excitations of the proton is not strong and we find \( \epsilon^{(2)}_n \approx 0.71 \) for the \( z_{min} = 0.5 \) cut.

For the \( z \)-distribution of fast neutrons from HM excitations we take the spectrum for non-diffractive DIS calculated and tested against hadronic experimental data in Ref. [34]. At \( z \gtrsim 0.5 \) it is dominated by the familiar pion exchange mechanism. The results for \( \Phi_3(z) \) are presented in Fig. 2b. We find \( \epsilon^{(3)}_n \approx 0.64 \) for the \( z_{min} = 0.5 \) cut. Finally, putting together all the three components, we find \( \epsilon^{DD}_n(z_{min} = 0.5) \equiv \sum_i \frac{\epsilon^{(i)}_n(z_{min} = 0.5)(n^{(i)}_n)\sigma_i}{\sum_i (n^{(i)}_n)\sigma_i} \approx 0.75 \).

It is interesting to compare the neutron production in diffractive and non-diffractive DIS. In the latter case the major source of forward neutrons is the pion exchange with deep inelastic scattering on pions (for a detailed formalism see Ref. [32] and for a discussion [34]). For small \( x \) relevant at HERA, we can use the pion structure function from GRV model [35], which gives \( F^\pi_2(x, Q^2) \approx (0.7-0.8)F^p_2(x, Q^2) \). The resulting spectrum of neutrons from non-diffractive DIS \( \Phi^{DIS}(z) \) (neutrons from \( \Delta \) decays included) is shown in Fig. 3a. The average multiplicity of neutrons in non-diffractive DIS at small \( x \) equals \( \langle n^{DIS}_n \rangle = 0.15 \) and a \( \epsilon^{DIS}_n = 0.64 \) fraction of neutrons passes the \( z_{min} = 0.5 \) cut.

Notice, that the spectrum of neutrons from DD events is peaked at larger \( z \) in compari-
son to non-diffractive DIS, which suggests an interesting possibility to enhance the observed fraction of large rapidity gap events by increasing the $z_{\text{min}}$ cut, at the expense of losing a part of statistics. The $z$-cut dependence of $\epsilon_n^{DD}(z_{\text{min}})$ and $\epsilon_n^{DIS}(z_{\text{min}})$ for DD and non-diffractive DIS, respectively, is shown in Fig. 3b, and the gain factor $R_n(z_{\text{min}}) \equiv \epsilon_n^{DD}(z_{\text{min}})/\epsilon_n^{DIS}(z_{\text{min}})$ is shown in Fig. 3c.

Up to now we have considered the ideal case of full angular acceptance for outgoing neutrons. In realistic case of FNC the angular acceptance in the polar angle $\theta$ is finite ($\theta_m$). This means that only neutrons with transverse momentum $k_{\perp} \leq z k_{\perp,m} = z E_p \theta_m$ can reach the FNC. The $k_{\perp}$-acceptance rises with $z$. For a Gaussian $k_{\perp}$-distribution, the effect of the angular cut can be included by the simple substitution

$$
\Phi_i(z) \longrightarrow \Phi_i(z) \left[ 1 - \exp \left( - \frac{z^2 k_{\perp,m}^2}{\langle k_{\perp}^2(z) \rangle} \right) \right].
$$

The mean transverse momentum squared of neutrons $\langle k_{\perp}^2(z) \rangle$ can, in principle, be directly measured by FNC. The experimental information on $\langle k_{\perp}^2(z) \rangle$ is contained in the data from the hadronic experiments, although it is not cited directly in the relevant experimental publications. For a rough estimate, we take $\langle k_{\perp}^2(z) \rangle = 0.25 GeV^2$ and $\theta_m = 7 \cdot 10^{-4}$, which is relevant for the test FNC of the ZEUS collaboration [20]. The effect of such an angular cut on the neutron spectra is is shown in Figs. 4. It somewhat enhances the observed DD signal compared to the signal of non-diffractive DIS.

Neutron tagging is an efficient tool for testing the mechanism of DD. For instance, zooming at neutrons with $z \sim 1$ suppresses the ”inelastic” background in the $J/\Psi$ production and allows a more accurate determination of $B_{el}(J/\Psi)$. On the other hand, zooming at $z \sim 0.5$ would enhance the inelastic background and enable a determination of $B_{in}(J/\Psi)$, which is also a quantity of theoretical interest.

5 Conclusions

Based on the Regge factorization, we find a substantial contribution of double diffraction dissociation to exclusive production of vector mesons and large rapidity gap events at HERA. In diffractive excitations of virtual photons into low mass states the DD background fraction
is $f_{DD}(\gamma^* \to X, M_X^2 \sim Q^2) \approx 0.21 - 0.23$, whereas for high mass excitations of the photon the double diffraction dissociation background is somewhat larger $f_{DD}(\gamma^* \to X, M_X^2 \gg Q^2) \approx 0.26 - 0.28$. Therefore careful corrections for DD background are necessary for the interpretation of the large rapidity gap data in terms of the $\beta$-dependence of the pomeron structure function.

In real photoproduction of light vector mesons we expect an inelastic background $f_{in}(\gamma \to \rho^0) \sim 0.21 - 0.23$. In contrast, in the $J/\Psi$ photoproduction the inelastic background is expected to be stronger: $f_{in}(J/\Psi) \sim 0.26 - 0.28$.

The presented simple estimates confirm the feasibility of tagging the double diffraction events by fast neutrons from products of diffraction excitation of the proton. Including effects of finite angular acceptance, we have estimated the fraction of double diffraction dissociation events in the large rapidity gap sample to be $f_{DD} \approx 0.21 - 0.23$. Approximately 25% of the double diffraction dissociation events contain a neutron with $E_n/E_{\text{beam}} > 0.5$.

We find that the spectrum of neutrons from DD events peaks at $z$ larger than that for non-diffractive DIS, which should facilitate their experimental observation. The experimental determination of the $Q^2$ and $x_{\text{IP}}$ dependence of the spectrum and multiplicity of neutrons in the large rapidity gap events (including real photoproduction), and comparison with the related proton-proton interactions, will be of great importance for testing the factorization properties of the pomeron in an entirely new kinematical domain of deep inelastic scattering.

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Figure captions:

Fig. 1 - - - Single and double diffraction dissociation in DIS and proton-proton scattering.

Fig. 2 - - - a) The normalized spectrum of neutrons for the $N\pi$ component for the experimentally observed forward-backward peaked (solid curve) and flat (dashed curve) $\cos\theta_{GJ}$ distributions.
- - - b) Normalized spectra of neutrons $\Phi_i(z)$ for the $N\pi$ (solid curve), $N\pi\pi$ (dashed curve) and the high mass (dotted curve) components of DD.

Fig. 3 - - - a) Spectrum of neutrons from diffractive (solid) and non-diffractive (dashed) DIS normalized to unity.
- - - b) The fraction of neutrons with $z \gtrsim z_{\text{min}}$ (tagging efficiency) for DD $\epsilon_n^{DD}(z_{\text{min}})$ (solid curve) and non-diffractive DIS $\epsilon_n^{DIS}(z_{\text{min}})$ (dashed curve).
- - - c) The gain factor $R_n(z_{\text{min}})$ with full angular acceptance.

Fig 4 - - - The effect of the finite angular acceptance of FNC on the neutron spectra from diffractive (solid) and non-diffractive (dashed) DIS.
