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Measurement of proton-dissociative diffractive photoproduction of J/ψ mesons at HERA

ZEUS Collaboration

Abstract

The proton-dissociative diffractive photoproduction of J/ψ mesons has been studied in ep collisions with the ZEUS detector at HERA using an integrated luminosity of 36 pb^{-1}. The differential cross-section $d\sigma/dt$ has been measured at $W \simeq 200$ GeV, where W is the centre-of-mass energy of the photon-proton system, for $|t|$ values up to 7 GeV^2, where t is the squared four-momentum transfer at the proton vertex. The results are compared to predictions based on the BFKL and DGLAP low-x QCD evolution equations.

1 Introduction

Many aspects of proton-dissociative photoproduction of vector mesons at large squared four-momentum transfer t have been successfully described by the pQCD-based models in which a nearly-real photon fluctuates into a vector meson which then interacts with a single parton in the proton via color singlet exchange. Such an exchange can be either two gluons [1] (Figure 1, left) or a gluon ladder, "BFKL exchange" [2–4] (Figure 1, right).

In pQCD models t, or the meson mass in the case of the J/ψ, provides the hard scale required for the perturbative treatment of QCD processes. In particular, these models predict t distributions that are relatively hard compared to elastic vector meson photoproduction. With a reasonable choice of two parameters, the model using BFKL exchange can describe the shapes and magnitude of the differential cross section as a function of t for ρ, ϕ and J/ψ mesons [5].

The two classes of models differ, however, in the predicted energy dependence of $d\sigma/dt$: two-gluon exchange yields energy independent cross sections [1] whereas BFKL exchange leads to cross sections that rise with increasing energy [3, 4]. The latter rise has been recently observed in J/ψ photoproduction at large $|t|$ [6]. It is investigated also in this paper in which the differential cross section $d\sigma/dt$ is presented for the diffractive photoproduction process, $\gamma p \to J/\psi\ Y$, where Y is the proton dissociative system. The data were taken at a photon-proton centre-of-mass (CMS) energy $W \simeq 200$ GeV and extend up to $|t| = 7$ GeV^2. These results are compared with the previous ZEUS measurement at $W \simeq 100$ GeV [5] as well as to a prediction of the BFKL model [4] and DGLAP calculations in leading logarithmic approximation [7].

2 Experimental conditions

The data used in this analysis were collected in 1996 and 1997 from ep interactions with the ZEUS detector [8] at HERA, which operated with a proton beam energy of 820 GeV and a positron beam energy of 27.5 GeV, and correspond to an integrated luminosity of 36 pb^{-1}. The main components used for this analysis are the central tracking detector (CTD) [9], uranium-scintillator calorimeter (CAL) [10], muon chambers [11], proton remnant tagger (PRT) [12] and photoproduction tagger at 35m (PT35m) [13].

3 Kinematics and analysis method

The process in question is the proton-dissociative J/ψ production in ep interactions:

$$e(k)p(P) \to e(k')J/\psi(v)Y(P'),$$

where k, k', P, P' and v are the four-momenta of the incident positron, scattered positron, incident proton, diffractive nucleonic system Y and J/ψ, respectively (Figure 2). The kinematic variables used to describe this process are:

- $Q^2 = -q^2 = -(k-k')^2$, the negative squared four-momentum of the exchanged photon;
- $W^2 = (q+P)^2$, the squared CMS energy of the photon-proton system;
- $-t = (P'-P)^2 = (v-q)^2$, the squared four-momentum transfer at the proton vertex.

The events were selected by the ZEUS trigger system and offline cuts in the two J/ψ decay modes. The di-electron sample was triggered by demanding the scattered positron was tagged in the PT35m. It was required offline that at least one particle crosses the CTD and deposits an energy in the CAL. The energy deposit was required to be consistent with an electron. The di-muon sample was triggered by requiring at least one track in CTD matched to an energy deposit in CAL. The energy deposit was required to be consistent with a minimum ionizing particle and associated to a signal in the muon chambers.

Further selection made offline required two energy deposits in the barrel or rear part of CAL associated with the two candidate leptons from the J/ψ decay. To select events with dissociation of the proton, a signal in the PRT or an energy deposit in the forward part of CAL was required. Events with additional energy deposits in the barrel or rear part of CAL, above the noise level, were rejected. These cuts ensure the presence of a rapidity gap of at least three units between the J/ψ and the nucleonic system Y and restrict the mass of dissociated proton system M_Y to be less than 30 GeV.

In most of the events, especially at large W, only one lepton from the J/ψ decay is inside the geometric acceptance of the CTD so that its momentum could be measured from the track. The momentum of the other decay lepton was estimated using the measurement of its position in the CAL, the energy of the scattered positron in the PT35m and energy-momentum conservation.

In both samples, the photon-proton CMS energy W was calculated using the energies of the incoming positron (E_e), of the positron scattered and tagged in PT35m ($E_{e'}$) and of the incoming proton (E_p) as $W^2 = 4E_p(E_e - E_{e'})$ and its range was limited to $185 < W < 245$ GeV due to the PT35m acceptance.

In tagged photoproduction events, Q^2 ranges from the kinematic minimum, $Q^2_{min} \approx 10^{-9}\,\mathrm{GeV}^2$, to a maximum value limited by the angular acceptance of the PT35m, $Q^2_{max} \approx$

$0.02\,\text{GeV}^2$. Since the typical Q^2 is small, it can be neglected in the reconstruction of the other kinematic variables. In particular, the squared four-momentum transfer $|t|$ was assumed to be equal to the squared transverse-momentum of the di-lepton system resulting from the J/ψ decay.

4 Monte Carlo simulation

The acceptance and the effects of the detector response were determined using a Monte Carlo simulation. The process $ep \to eJ/\psi Y$ was modelled using the EPSOFT Monte Carlo generator [14, 15]. It was modified to improve the description of the data. In particular, the mass of the system Y was generated according to the expression: $d\sigma/dM_Y^2 \sim (M_Y^2)^{-\beta}$, $\beta = 1.3$ [16] and the t distribution was reweighted to obtain the dependence $d\sigma/d|t| \sim |t|^{-1.7}$, as measured in the data. A non-resonant background due to the $\gamma\gamma$ fusion process, $ep \to el^+l^-Y$, was simulated using the GRAPE generator [17].

5 Results

After all cuts, 114 di-electron and 102 di-muon events were left in the mass range $1.5 < M_{l^+l^-} < 5.0$ GeV . The mass distributions for both samples together with signal and background Monte Carlo are presented in Figure 3. A non-resonant background from $\gamma\gamma \to l^+l^-$ events was subtracted using the GRAPE MC, normalised to the luminosity of the data.

In Figure 4, the differential cross section $d\sigma(\gamma p \to J/\psi\, Y)/dt$ at $W = 206\,\text{GeV}$ is compared with a previous ZEUS measurement at $W = 100\,\text{GeV}$ [5]: the cross section is larger at higher W, which favours BFKL over two-gluon exchange. Fitting the distributions to a $|t|^{-n}$ expression for $1 < |t| < 7$ GeV^2 gives $n = 1.7 \pm 0.2$ $(stat.) \pm 0.3$ $(syst.)$ at 100 GeV and $n = 1.7 \pm 0.2$ $(stat.) \pm 0.3$ $(syst.)$ at 200 GeV.

To investigate the energy dependence of the cross section in more detail, the data were divided into two $|t|$ bins: $1.2 < |t| < 2$ GeV^2 and $2 < |t| < 6.5$ GeV^2. The cross section was determined in these $|t|$ bins at $W = 100\,\text{GeV}$ and $W = 212\,\text{GeV}$. This enabled the calculation of the power δ, used in the parametrisation of the cross section energy dependence: $\sigma \sim W^\delta$. The obtained values of δ are 0.5 ± 0.4 and 0.8 ± 0.5 in the lower and higher $|t|$ bin, respectively. The latter value of the power δ is consistent with that measured by the H1 collaboration [6] in the similar range of |t|.

In Figure 5, the data are compared with a pQCD model [4] which assumes that the photon fluctates into a vector meson which then interacts with a single parton in the proton via gluon ladder exchange. The model provides calculations with leading logarithmic (LL) approximation as well as non-leading corrections (NL). This model has two parameters: $\alpha_s = 0.21$ and s_0 (governing the dynamics of the gluon ladder) which is taken [5] to be 0.5 GeV^2 to fit the ZEUS data on ρ, ϕ and J/ψ photoproduction at $W = 100$ GeV, using the LL approximation. These parameters were used to calculate the cross section at 200 GeV in the LL approximation of the BFKL kernel and also to estimate the NL corrections . As can be seen in the figure, the LL calculations reproduce well the shape of the t distribution at the two energies but rather overestimate the magnitude of its rise with increasing energy W. On the other hand, the LL+NL calculations (using the same values of parameters) predict too steep t distributions but reproduce better the relative rise of the cross section with increasing energy.

In Figure 6, the data are compared with DGLAP calculations in the LL approximation [7] in the range $Q_0^2 < |t| < M_{J/\psi}^2$, where the parameter Q_0^2 was taken to be 0.5 GeV^2. The other parameter of the model t_0, where the proton dissociative and elastic cross sections are matched, was taken to be 0.6 GeV^2. The values of the parameters were choosen to reproduce the H1 [6] and ZEUS [5] data at W $\approx$ 100 GeV. The DGLAP LL calculations clearly underestimate the observed rise of the cross section with the W energy.

To summarise, the cross section for proton-dissociative J/ψ photoproduction at $W \simeq 200$ GeV and in the $|t|$ range $1 < |t| < 7$ GeV^2 is larger than at $W \simeq 100$ GeV, which favours qualitatively the gluon ladder exchange over the two-gluon exchange. The pQCD BFKL calculations using LL approximation and also non-leading corrections [4] reproduce semi-quantitatively the general behaviour of the data. On the other hand the DGLAP LL model does not describe the rise of the cross section with energy.

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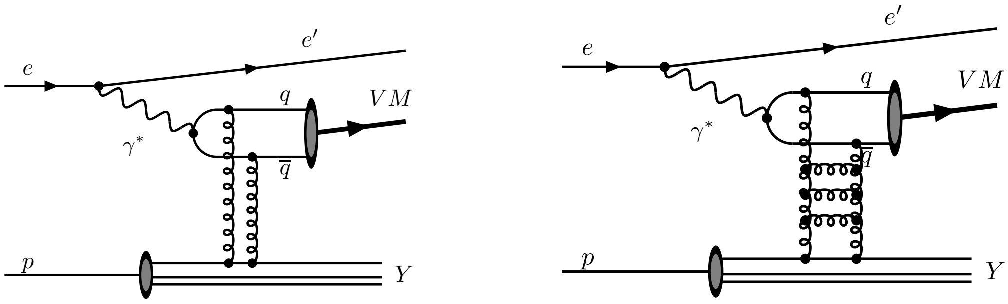

Figure 1: *Left: the pQCD diagram for proton-dissociative vector-meson electroproduction via two-gluon exchange. Right: the pQCD diagram with gluon ladder exchange.*

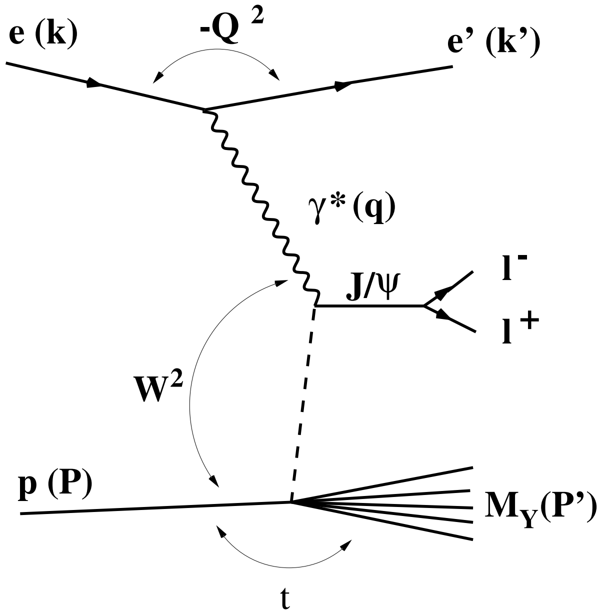

Figure 2: *Schematic diagram of proton-dissociative J/ψ production in ep interactions, $ep \to eJ/\psi\ Y$.*

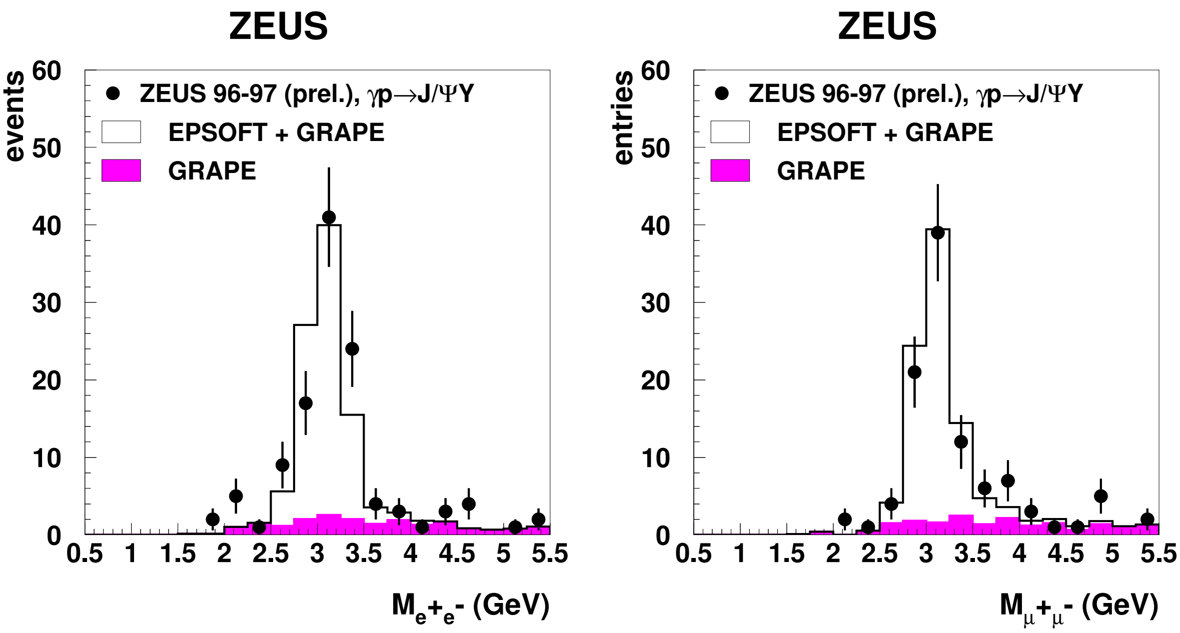

Figure 3: *Mass spectra for e^+e^- (left) and $\mu^+\mu^-$ pairs (right). The data (full circles) are compared to the Monte Carlo distributions. The shaded histograms represent the $ep \to el^+l^-Y$ background as simulated by GRAPE MC generator. The solid line histograms represent the EPSOFT Monte Carlo distribution for the signal added to the background.*

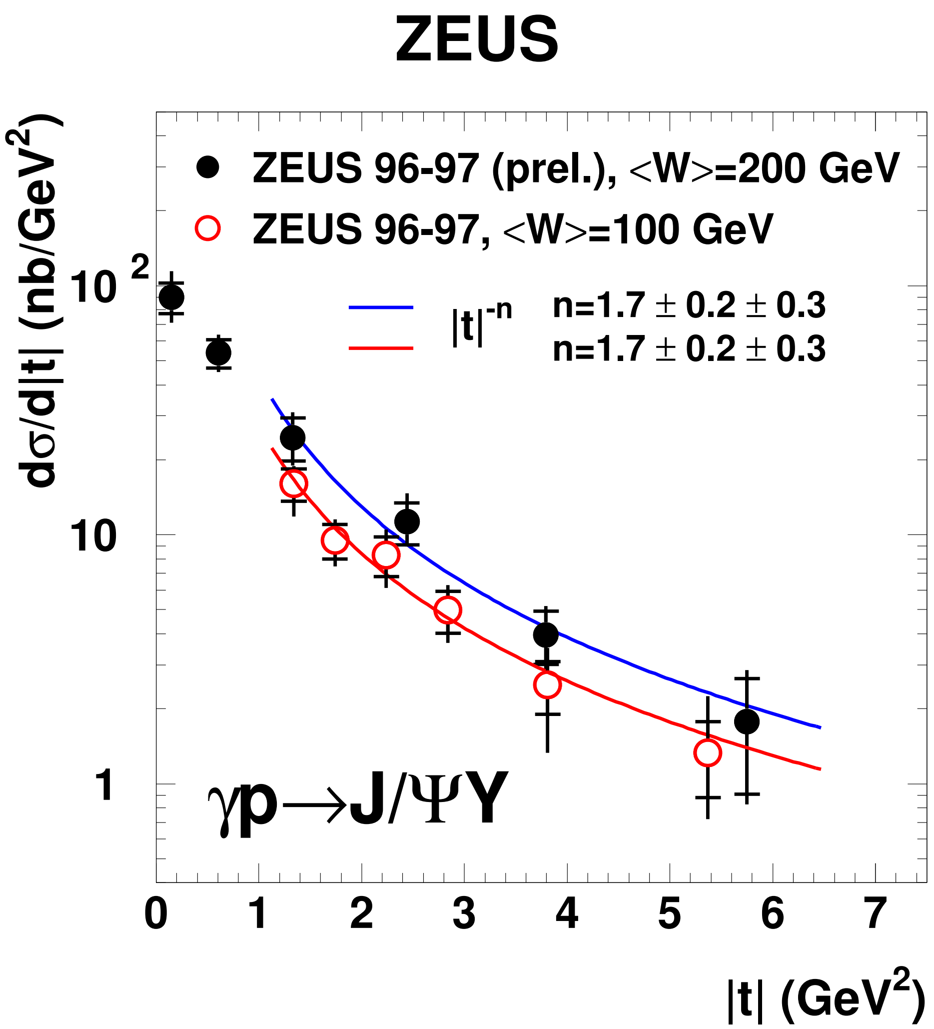

Figure 4: *The differential cross section $d\sigma/d|t|$ for the process $\gamma p \to J/\psi\ Y$ at $W \simeq 200$ GeV (full circles), and at $W \simeq 100$ GeV [5] (open circles). The inner bars represent the statistical uncertainty and the outer represent the statistical and systematic uncertainty added in quadrature. The solid lines represent fits to the expression $|t|^{-n}$.*

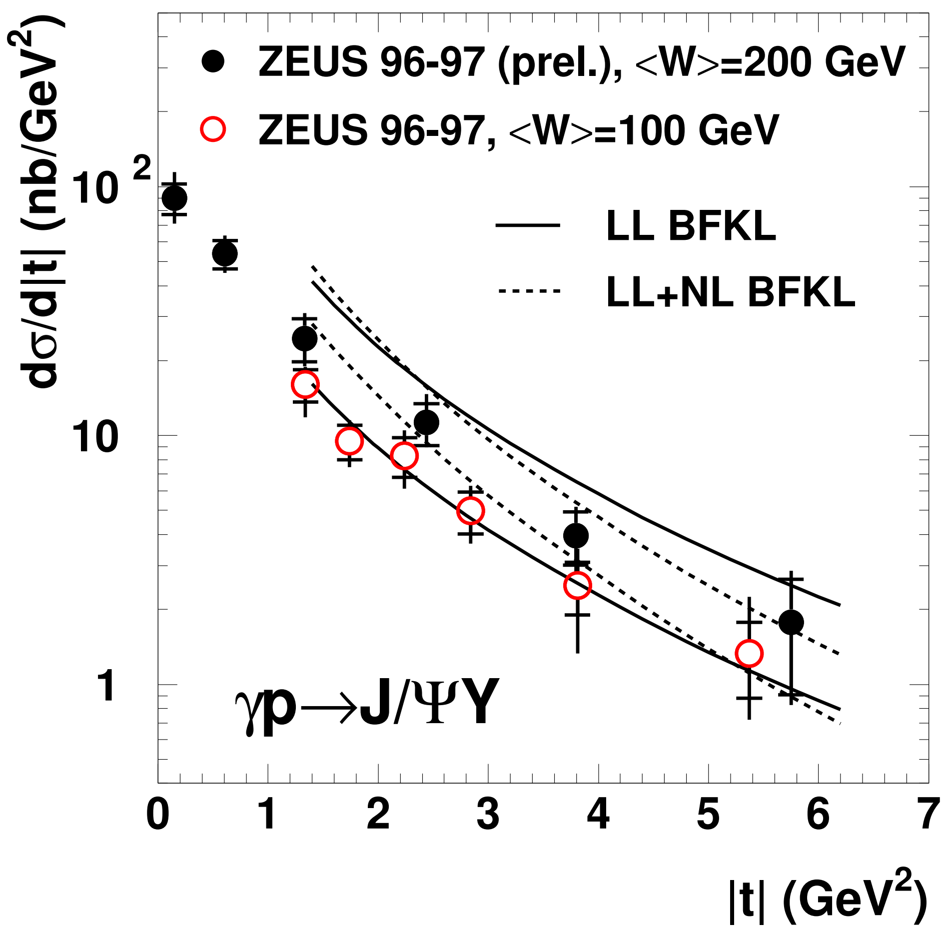

Figure 5: *The differential cross-section $d\sigma/d|t|$ for the process $\gamma p \rightarrow J/\psi\ Y$ at $W \simeq 200$ GeV (full circles) and at $W \simeq 100$ GeV [5] (open circles). The lines represent the results of BFKL calculations* [4] *at the two energies: the solid ones – in the leading logarithms approximation (LL) and the dashed ones – including non-leading corrections (NLL).*

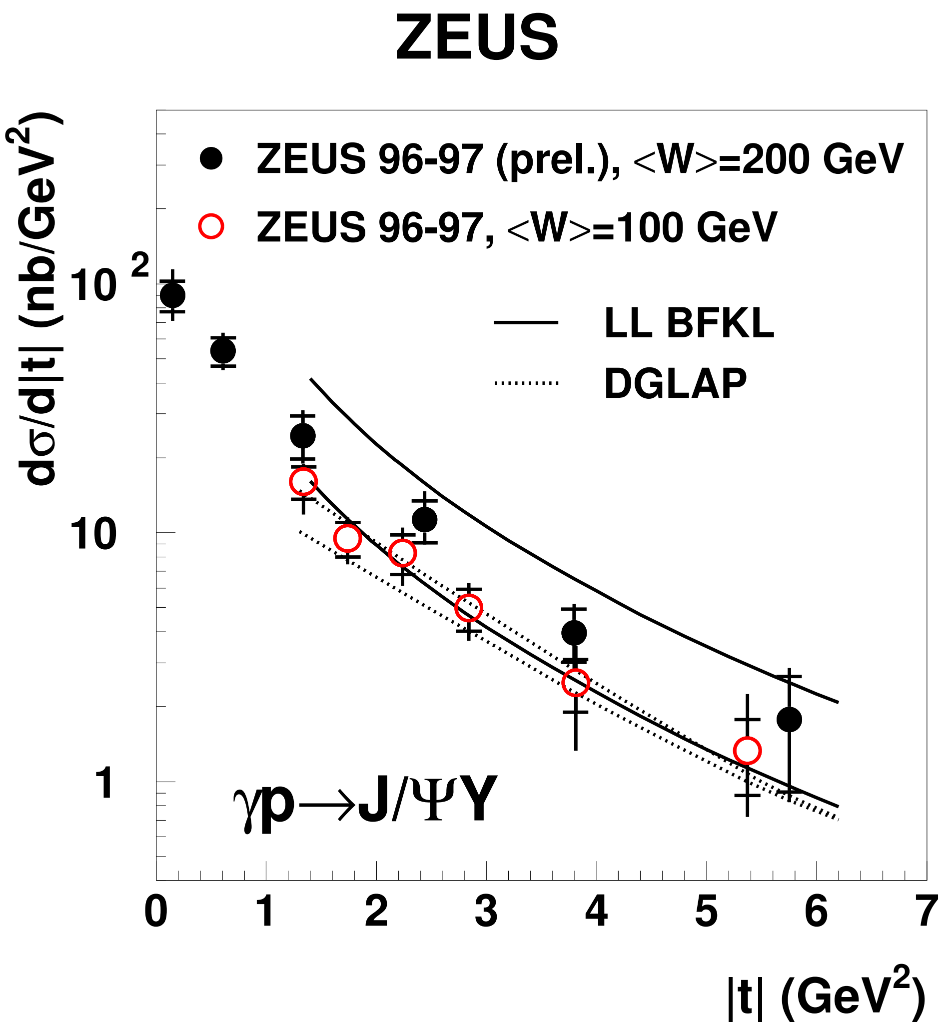

Figure 6: *The differential cross-section $d\sigma/d|t|$ for the process $\gamma p \to J/\psi\ Y$ at $W \simeq 200$ GeV (full circles) and at $W \simeq 100$ GeV [5] (open circles). The solid lines represent the results of BFKL calculations [4] and the dashed ones the result of DGLAP calculations [8] at two energies.*