Submitted to the International Europhysics Conference on High Energy Physics,
HEP97, Jerusalem, Israel, August 1997

Production of J/ψ Mesons with large $|t|$ at HERA

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Abstract

A measurement of the cross-section for the production of J/ψ mesons with proton dissociation and with large four-momentum transfer squared at the proton vertex, t, has been made. The data were collected by the H1 experiment at the HERA collider in 1994 and 1995, and correspond to a total integrated luminosity of about $8.2\,\mathrm{pb}^{-1}$. The J/ψ meson is identified by the decay to $\mu^+\mu^-$. The cross-section results for $|t| > 1\,\mathrm{GeV}^2$ are compared to a pQCD model which uses BFKL formalism.

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Introduction

This paper is concerned with the process

$$e(k) + p(P) \rightarrow e(k') + V(v) + Y(P') \tag{1}$$

where V is a vector meson and Y is the final state of the proton. The reaction can be either elastic, where Y remains a proton and the elasticity $z \approx 1$ (where $z = E_V/E_\gamma$ in the proton rest frame), or proton dissociative where the proton breaks up into a low mass state and z is close to 1. This production mechanism has been studied in both photo-production and electro-production at HERA when V is a ρ, ω, ϕ or J/ψ [1–10]. If V is a J/ψ then the mass of the charm quark introduces a hard scale and hence it is possible to perform perturbative QCD (pQCD) calculations [11, 12].

All of the above HERA measurements are restricted to the region of low four-momentum transfer squared between the photon and the vector meson, t. If $|t|$ is allowed to become large, *i.e.* $|t| > 1\,\mathrm{GeV}^2$, then an additional hard scale is introduced and therefore improved pQCD calculations can be made [13, 14]. These calculations can also be applied to the lighter vector mesons.

The calculations of [13, 14] use the exchange of a gluon ladder in BFKL formalism [15, 16] and can predict the cross-section and both the t and $W_{\gamma p}$ dependence of vector meson production when $|t|$ is large. The only free parameter in this model is the value of the QCD coupling constant, α_s. Strictly speaking, this α_s should be treated as a parameter which has to be fitted to the data because there is no precise prediction for the corresponding scale. Only at next-to-leading order does it become possible to make statements about the scale of the measured value of α_s and hence make comparisons to other measurements. Therefore the α_s used in this model will be referred to as $\overline{\alpha}_s$. However, it should at least be consistent with the value of α_s at the scale of the mass of the vector meson, m_V, or of $\sqrt{-t}$ if this is larger. However, the scale could be as small as $m_V/4$ or as large as $4m_V$ [17]. Both the magnitude of the cross-section and its dependence on $W_{\gamma p}$ are sensitive to the size of $\overline{\alpha}_s$. The shape of the t distribution is not sensitive to the value of $\overline{\alpha}_s$.

This paper presents results for J/ψ production with proton dissociation and where $|t|$ is large. The measured ep cross-section and the shapes of the t and $W_{\gamma p}$ distributions are compared to the pQCD model for J/ψ production with large $|t|$. A preferred value of $\overline{\alpha}_s$ used by this pQCD model is also determined.

Kinematics

The kinematic variables relevant to reaction (1) are the negative four-momentum squared of the photon $Q^2 = -q^2 = (k - k')^2$, the four-momentum transfer squared between the photon and the vector meson $t = (q - v)^2 = (P - P')^2$, the photon-proton invariant mass $W_{\gamma p}$ (where $W^2_{\gamma p} = (P + q)^2$) and the elasticity of the event $z = P \cdot v / P \cdot q$.

If neither the scattered electron nor the proton final state are observed then it is not possible to measure t directly. However, in the photon-proton centre of mass frame t can be expressed as

$$t = -\frac{1}{z} p_t^{*2} - (1 - z)Q^2 + \left(1 - \frac{1}{z}\right) m_V^2 \tag{2}$$

where p_t^* and m_V are the transverse momentum and mass of the vector meson respectively. Provided z is close to unity and Q^2 is small then to a good approximation $p_t^2 = p_t^{*2} = -t$ where p_t is measured in the electron-proton centre of mass frame, *i.e.* the HERA lab frame.

Detector and Event Selection

The integrated luminosity used for this analysis was $8.2\,\mathrm{pb}^{-1}$ which was collected by the H1 detector in 1994 and 1995 ($3.1\,\mathrm{pb}^{-1}$ in 1994 and $5.1\,\mathrm{pb}^{-1}$ in 1995). During this period HERA collided 27.5 GeV positrons on 820 GeV protons. A detailed description of the H1 detector can be found in [18].

The J/ψ mesons are identified using their decays to unlike sign muon pairs. The triggers used in this analysis, which are described in detail in [2], use a combination of tracking and muon information. The muons from the decay of the J/ψ are measured in the central tracker and are required to have $p_t > 120$ MeV and $20^\circ < \theta < 160^\circ$. The polar angle, θ, is measured with respect to the outgoing proton, or forward, direction. The muons are identified by either the LAr calorimeter, in which energy deposits typical for muons are required, or by demanding tracks found in the instrumented iron return yoke.

A p_t cut of 1 GeV is applied to the J/ψ to enrich the sample of events with $|t| > 1\,\mathrm{GeV}^2$. By only requiring one of the two muons to be identified, the number of events in the sample is doubled. The background is still small due to the cut applied to the p_t of the J/ψ and this can be seen from the invariant mass distribution of the event sample, after all analysis cuts, in figure 1.

The relation $t = -p_t^2$ is only a good approximation when Q^2 is small and when z is close to unity. To restrict the analysis to small values of Q^2, events with a scattered positron in the backward electromagnetic calorimeter (BEMC in 1994, SpaCal in 1995) are rejected. This restricts the acceptance to the kinematic range $Q^2 < 4$ (1.2) GeV^2 for the 1994 (1995) data sample. The acceptance is restricted to the region of $z > 0.95$ by the requirement that no particles other than the decay products of the J/ψ are observed in the angular range $15^\circ < \theta < 178^\circ$.

Elastic events are removed by requiring activity either in the proton remnant tagger or forward muon detector, where the activity is due to secondary scattering, or in the forward part of the LAr calorimeter ($4^\circ < \theta < 15^\circ$).

Finally the photon-proton centre of mass energy is restricted to $30 < W_{\gamma p} < 150\,\mathrm{GeV}$.

Monte Carlo Model

Monte Carlo studies were made to obtain the acceptances and efficiencies of triggering, track reconstruction, selection and muon identification for the J/ψ production processes. Each Monte Carlo event that was produced went through a computer simulation of the H1 detector response.

To simulate J/ψ production at large $|t|$, when the proton dissociates, the event generator HITVM [19] was used. This generator incorporates the pQCD calculations of [14]. As mentioned earlier, the magnitude of the cross-section is very sensitive to the input value of $\overline{\alpha}_s$ such that the cross-section can change by a factor of 20 when changing the value of $\overline{\alpha}_s$ from 0.2 to 0.3. The shape of the $W_{\gamma p}$ distribution is also sensitive to the value of $\overline{\alpha}_s$. However, the shape of the t distribution is not sensitive to the value of $\overline{\alpha}_s$. The Monte Carlo sample used to determine the acceptance and efficiency for $|t| > 1\,\mathrm{GeV}^2$ had a value of $\overline{\alpha}_s = 0.2$ and it describes well the data at large $|t|$ and the $W_{\gamma p}$ dependence for this kinematic region.

Due to the smearing in the approximation $t = -p_t^2$ and the small contribution from events with small $|t|$ but non-zero Q^2, it is necessary to consider J/ψ production with proton dissociation when $|t| < 1\,\mathrm{GeV}^2$ when calculating the acceptance for events with $|t| > 1\,\mathrm{GeV}^2$. Therefore

	1994	1995
Trigger	9.0%	9.0%
Single track reconstruction	3.0%	3.0%
Single muon identification	6.0%	6.0%
Monte Carlo Acceptance	6.0%	8.0%
DIFFVM normalisation	8.0%	8.0%
Ratio of $\sigma_{elastic}/\sigma_{p-diss}$	28.0%	28.0%
Branching ratio	3.0%	3.0%
Luminosity	1.5%	1.2%

Table 1: Systematic errors.

Monte Carlo event samples were produced using the Monte Carlo generator DIFFVM [20] which uses non-perturbative models for diffractive vector meson production with and without proton dissociation. The latter case, *i.e.* elastic J/ψ production, must also be included because some elastic events survive the analysis cuts. The non-perturbative models use

$$\mathrm{d}\sigma_{\gamma p}/\mathrm{d}t \quad \propto \quad W_{\gamma p}^{4\varepsilon} e^{bt} \tag{3}$$

$$\mathrm{d}\sigma_{\gamma p}/\mathrm{d}t\,\mathrm{d}M_Y^2 \quad \propto \quad W_{\gamma p}^{4\varepsilon} e^{b't} M_Y^{\beta} \tag{4}$$

for elastic production and production with proton dissociation respectively. M_Y is the effective mass of the hadrons from the proton dissociation. The values of the parameters used for this analysis are $\varepsilon = 0.225$, $b = 4.0$ GeV^{-2}, $b' = 1.6$ GeV^{-2} and $\beta = -2.16$ and they were determined from fits to the observed J/ψ elastic and proton dissociation photo-production processes when the p_t of the J/ψ is less than 1 GeV [2]. For small $|t|$, the resulting agreement between data and the non-perturbative models is very good for both the t and $W_{\gamma p}$ dependence.

The decay angular distribution for J/ψ decaying directly into two leptons is taken according to s-channel helicity conservation in both the HITVM and DIFFVM Monte Carlo generators. This is consistent with what has been observed in the data at small $|t|$ [2].

The number of proton dissociation DIFFVM Monte Carlo events, relative to the number of HITVM Monte Carlo events, is determined using the generated t distribution. In figure 2, the generated t distributions are shown for both the HITVM and DIFFVM Monte Carlo samples. The normalisation of the DIFFVM sample has been determined such that the transition from the DIFFVM sample to the HITVM sample, at $|t| = 1\,\mathrm{GeV}^2$, is smooth for the kinematic range $30 < W_{\gamma p} < 150\,\mathrm{GeV}$. The resulting combination of proton dissociation DIFFVM events with $|t| < 1\,\mathrm{GeV}^2$ and HITVM events with $|t| > 1\,\mathrm{GeV}^2$ provides a good description of the full kinematic range in t and can therefore be used to determine the smearing due to the approximation $t = -p_t^2$. The $W_{\gamma p}$ dependence is also found to be well described.

The number of elastic DIFFVM Monte Carlo events, relative to the total number of proton dissociation Monte Carlo events, is determined using the experimentally determined ep cross-sections of [2] for elastic and proton dissociative J/ψ production.

Systematic Uncertainties

Uncertainties in the detector acceptance and efficiency calculations contribute to systematic uncertainties in the cross-section measurements. A breakdown of these uncertainties is given in table 1. Significant systematic uncertainties associated with the detector simulation arise from the track reconstruction efficiency, lepton identification efficiency and trigger efficiency.

	1994	1995
N^{corr}_{data}	103.7 ± 11.0	83.2 ± 9.7
$\mathcal{L}$ (nb^{-1})	3088 ± 46	5091 ± 61
Br $(J/\psi \to \mu^+\mu^-)$	0.06 ± 0.002	0.06 ± 0.002
$\mathcal{E}$	0.109 ± 0.006	0.058 ± 0.004
$\mathcal{F}$	0.79 ± 0.06	0.88 ± 0.09
$\mathcal{E}/\mathcal{F}$	0.138 ± 0.008	0.066 ± 0.005

Table 2: Variables used in the cross-section calculation.

The large error on the ratio of elastic to proton dissociation ep cross-sections ($\sigma_{elastic}/\sigma_{p-diss}$) has only a small influence on the overall efficiency calculation because of the low number of elastic events passing the cuts.

J/ψ Cross-sections

The cross-section for $e\ p \to e\ J/\psi\ Y$ when $|t| > 1\,\mathrm{GeV}^2$ is calculated from

$$\sigma(e\ p \to e\ J/\psi\ Y)|_{|t|>1\,\mathrm{GeV}^2} \quad = \quad \frac{N^{corr}_{data} \times \mathcal{F}}{\mathcal{L} \times \mathcal{E} \times \mathrm{Br}\,(J/\psi \to \mu^+\mu^-)} \tag{5}$$

where N^{corr}_{data} is the number of data events in the peak after subtracting the non-J/ψ background, $\mathcal{L}$ is the integrated luminosity, $\mathcal{F}$ is the fraction of events with $|t| > 1\,\mathrm{GeV}^2$ and $\mathcal{E}$ is the selection efficiency for events with $|t| > 1\,\mathrm{GeV}^2$. Similarly the differential cross-section is calculated using

$$\frac{\mathrm{d}\sigma_{ep}}{\mathrm{d}x} \quad = \quad \frac{N^{corr}_{data-bin} \times \mathcal{F}_{bin}}{\mathcal{L} \times \mathcal{E}_{bin} \times \mathrm{Br}\,(J/\psi \to \mu^+\mu^-)} \cdot \frac{1}{\Delta B} \tag{6}$$

where x is either the p_t^2 of the J/ψ or $W_{\gamma p}$, ΔB is the bin width in x and $N^{corr}_{data-bin}$, $\mathcal{F}_{bin}$ and $\mathcal{E}_{bin}$ are bin dependent versions of the variables defined in equation (5).

Figure 3 shows the differential cross-section $\mathrm{d}\sigma_{ep}/\mathrm{d}p_t^2$ for J/ψ production with proton dissociation. The open points are taken from [2] and the closed points are from this analysis. Both sets of points are determined using the 1994 and 1995 data and are restricted to the kinematic range $30 < W < 150\,\mathrm{GeV}$. The dependence of $\mathrm{d}\sigma_{ep}/\mathrm{d}p_t^2$ is seen to become less steep for $p_t^2 > 2\,\mathrm{GeV}^2$ and therefore deviates from the single exponential t dependence (dashed line) which describes the data at small $|t|$.

Using the numbers given in table 2, the cross-section for J/ψ production with proton dissociation in kinematic range $|t| > 1\,\mathrm{GeV}^2$ and $30 < W < 150\,\mathrm{GeV}$ is determined, using the 1994 and 1995 data, to be

$$\sigma(e\ p \to e\ J/\psi\ Y)|_{|t|>1\,\mathrm{GeV}^2} = 4.1 \pm 0.3|_{\mathrm{stat}} \pm 0.6|_{\mathrm{syst}}\ \mathrm{nb}.$$

Using this cross-section the value of $\overline{\alpha}_s$ preferred by the pQCD model of [14] is

$$\overline{\alpha}_s = 0.207 \pm 0.007$$

where the error represents the combined statistical and systematic uncertainty. Considering the caveats already stated, the measured value of $\overline{\alpha}_s$ is close to $\alpha_s(m_{J/\psi}) \approx 0.24$ [21].

In figure 3 the theoretical prediction shown (solid line) uses a combination of the pQCD model, using the measured value of $\overline{\alpha}_s$, when $|t| > 1\,\mathrm{GeV}^2$ and the non-perturbative model when $|t| < 1\,\mathrm{GeV}^2$. It can be seen that the theoretical prediction agrees well with the data which implies that the pQCD model predicts the correct t dependence.

Figure 4 shows the differential cross-section $\mathrm{d}\sigma_{ep}/\mathrm{d}W_{\gamma p}$ for J/ψ production with proton dissociation and $|t| > 1\,\mathrm{GeV}^2$. The pQCD model is shown using the measured value of $\overline{\alpha}_s$ or this value after either adding or subtracting its error. The theoretical prediction is seen to describe well the shape of the data.

Summary

The cross-section for J/ψ production with proton dissociation has been measured for the kinematic range $|t| > 1\,\mathrm{GeV}^2$ and $30 < W_{\gamma p} < 150\,\mathrm{GeV}$. The dependence of the differential cross-section $\mathrm{d}\sigma_{ep}/\mathrm{d}p_t^2$ on p_t^2 is found to be less steep for p_t^2, and therefore $|t|$, values greater than $2\,\mathrm{GeV}^2$. A pQCD model describes well both the normalisation and its t and $W_{\gamma p}$ dependences.

Acknowledgements

We are grateful to the HERA machine group whose outstanding efforts have made and continue to make this experiment possible. We thank the engineers and technicians for their work in constructing and now maintaining the H1 detector, our funding agencies for financial support, the DESY technical staff for continual assistance, and the DESY directorate for the hospitality which they extend to the non-DESY members of the collaboration.

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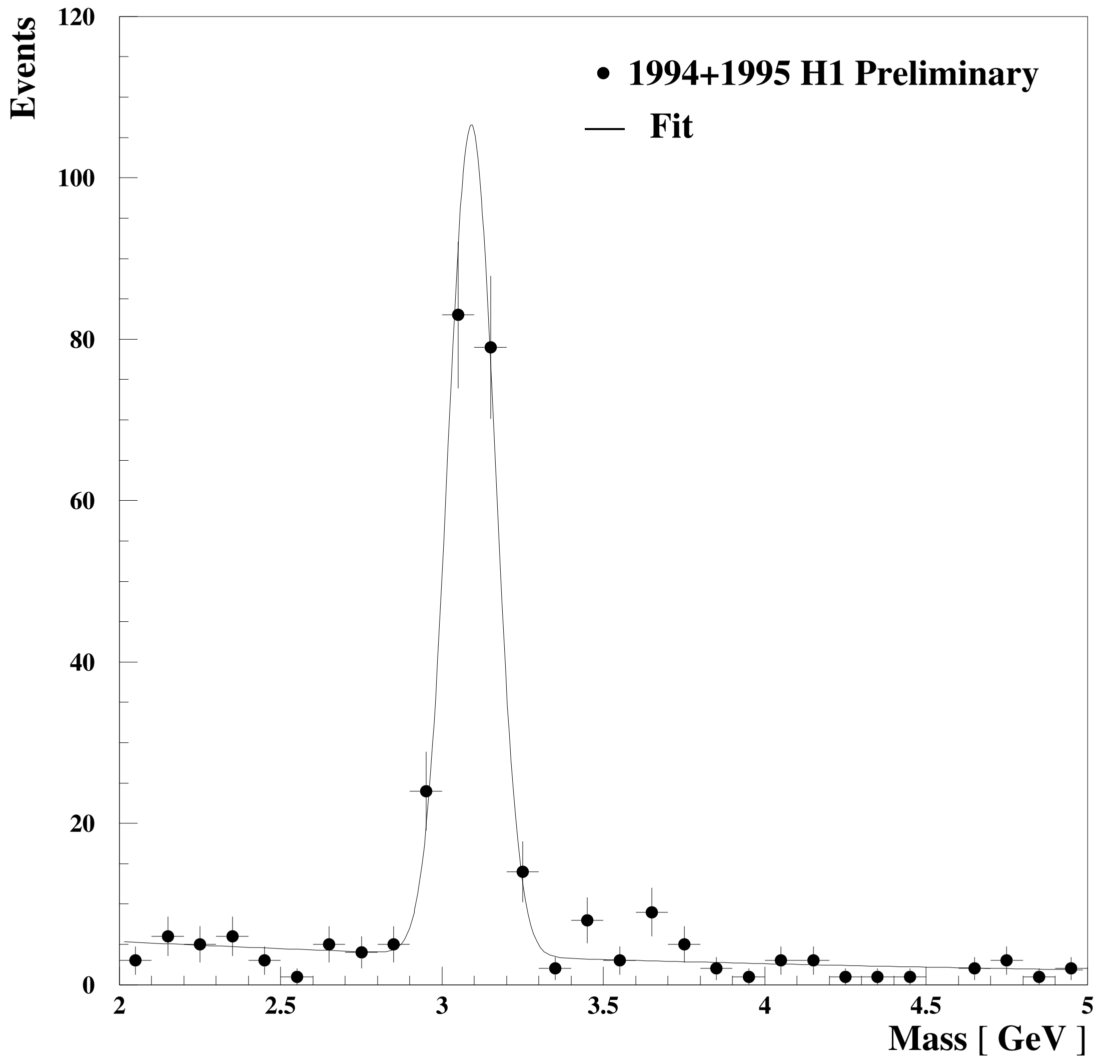

Figure 1: The invariant mass distribution of dimuon events for the combined 1994 and 1995 data sample. The vector sum of the p_t of the two muons is restricted to the range $1 < p_t^2 < 10\,\mathrm{GeV}^2$. The curve is a fit of a Gaussian plus an exponential background to the J/ψ mass region. The mean and width of the Gaussian is $3.091 \pm 0.006\,\mathrm{GeV}$ and $72 \pm 5\,\mathrm{MeV}$ respectively.

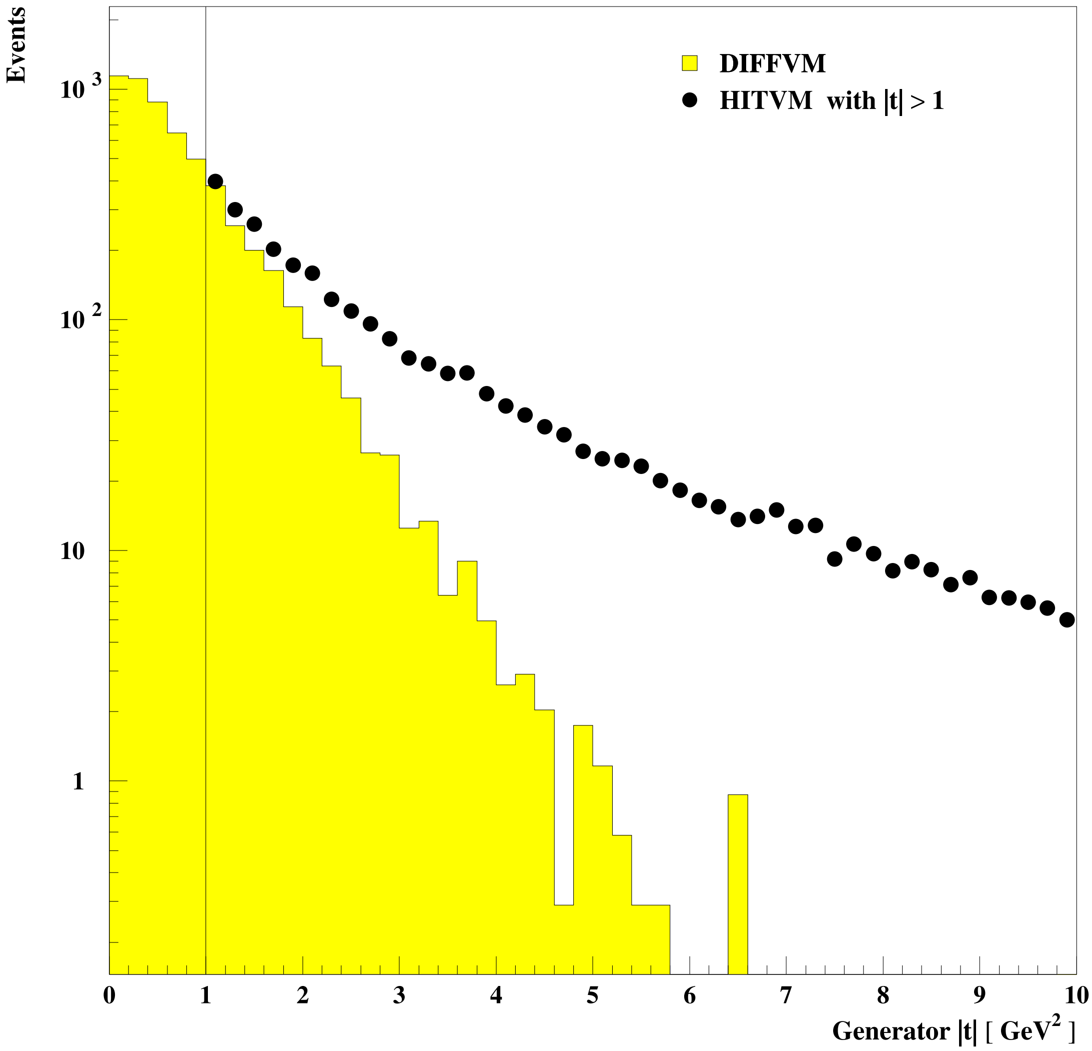

Figure 2: Generated $|t|$ distributions from the DIFFVM and HITVM Monte Carlo generators for J/ψ production with proton dissociation. The analysis uses DIFFVM when $|t| < 1\,\mathrm{GeV}^2$ and HITVM when $|t| > 1\,\mathrm{GeV}^2$. The normalisation of DIFFVM in relation to HITVM is determined at the point $|t| = 1\,\mathrm{GeV}^2$ such that, for the t distribution, there is a smooth transition between the two Monte Carlo spectra.

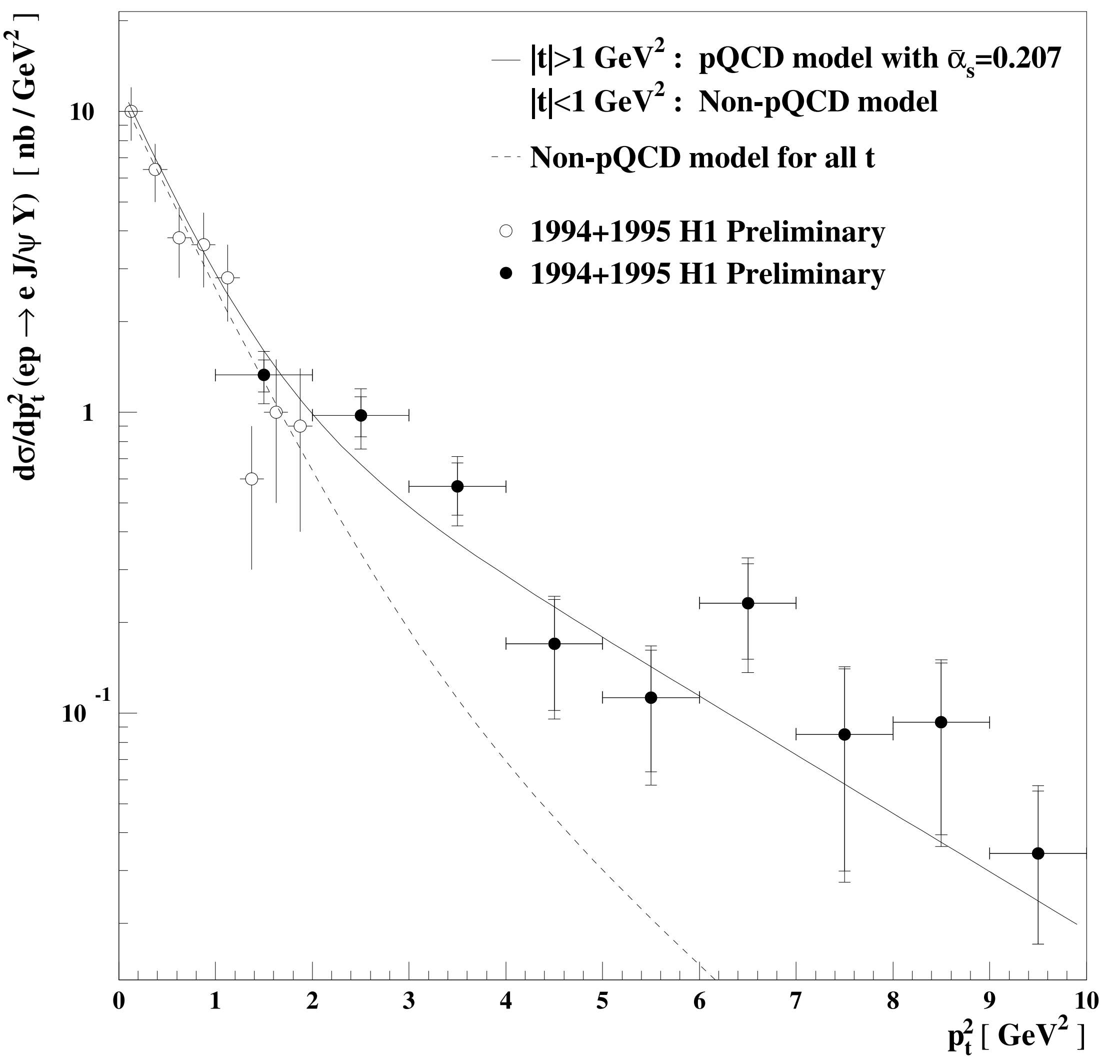

Figure 3: Distribution of the differential cross-section $\mathrm{d}\sigma_{ep}/\mathrm{d}p_t^2$ for J/ψ production with proton dissociation. The open points are taken from [2] where $Q^2 < 4\,\mathrm{GeV}^2$. The closed points are for this analysis, where the measurements have been corrected for the restricted Q^2 range and the full t kinematic range. The solid line represents the combination of the pQCD calculations for $|t| > 1\,\mathrm{GeV}^2$ and the non-perturbative model when $|t| < 1\,\mathrm{GeV}^2$. The normalisation was determined using the measured cross-section for $|t| > 1\,\mathrm{GeV}^2$, corresponding to an input value of $\overline{\alpha}_s = 0.207$. The dashed line represents the prediction from the non-perturbative model when the full t kinematic range is used.

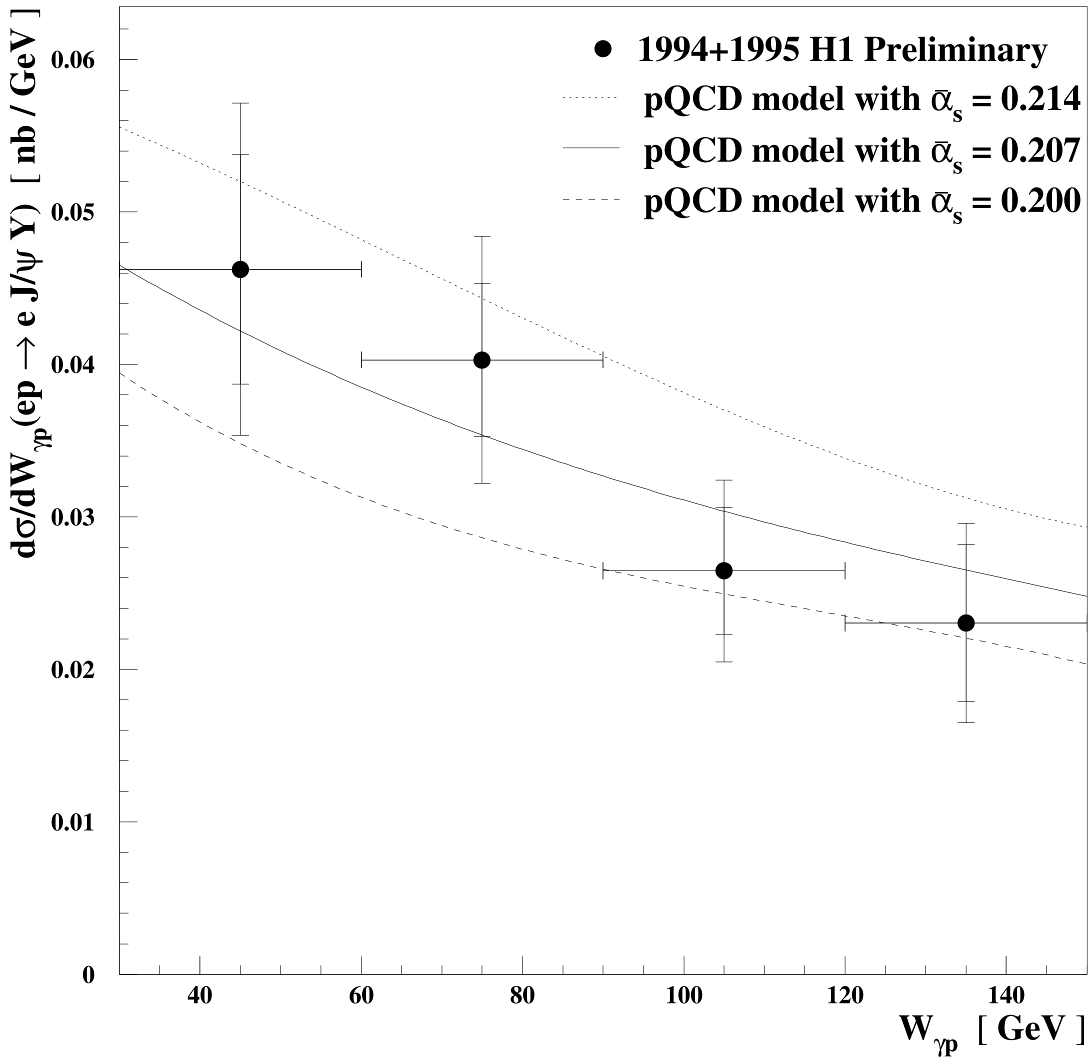

Figure 4: Distribution of the differential cross-section $\mathrm{d}\sigma_{ep}/\mathrm{d}W_{\gamma p}$ for J/ψ production with proton dissociation and with $|t| > 1\,\mathrm{GeV}^2$. The points show the combined 1994 and 1995 data where the inner and outer error bars represent the statistical and combined statistical and systematic errors respectively. The theoretical predictions (curves) are for the pQCD model using three different values of $\overline{\alpha}_s$.