Diffractive Heavy Flavour Production at HERA

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(April 23, 1998)

Diffractive heavy flavour production has been studied at HERA via the observation of either D^*, J/ψ or $\psi(2S)$ mesons for charm production and the observation of Υ mesons for beauty production. Measurements have been made in both photo-production and electro-production and when the proton remains intact or breaks up. These results are then used to test models which describe diffractive heavy flavour production in perturbative QCD.

I. INTRODUCTION

Charm and beauty are produced in positron-proton collisions at HERA predominantly as a $c\bar{c}$ or $b\bar{b}$ pair in the current system. The relevant process for this paper is

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

where X is either a small mass system or a vector meson and Y is the final state of the proton. In diffractive interactions there is no colour transfer between system X and system Y. The kinematics are described by the variables $Q^2 = -q^2 = -(k-k')^2$, $t = (q-x)^2 = (P-P')^2$, $W_{\gamma p}^2 = (q+P)^2$ and $z = P \cdot x / P \cdot q$. The reaction can be either elastic, where Y remains a proton and the elasticity $z \approx 1$, or proton dissociative where the proton breaks up into a low mass state and z is close to 1. Measurements are made for both photo-production and electro-production where $Q^2 \sim 0$ and $Q > 1\,\mathrm{GeV}^2$ respectively.

The results presented are based upon data recorded by the H1 [1] and ZEUS [2] detectors between 1994 and 1997 when positrons with energy 27.5 GeV and protons of energy 820 GeV were collided head-on in HERA. These results are then used to test a Regge based model of Donnachie-Landshoff [3,4] and a number of models which describe diffractive heavy flavour production in perturbative QCD [5–11].

II. ELECTRO-PRODUCTION OF D^*

D^* mesons are identified via the decay $D^{*\pm} \rightarrow D^0\pi^{\pm}_{slow} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$ by both H1 [12] and ZEUS [13]. The transverse momentum, p_t, of the D^* is required to be larger than 1.0 GeV and to restrict the events to electro-production $Q^2 > 10\,\mathrm{GeV}^2$. A diffractive signal from the H1 (ZEUS) data is observed by requiring $|\eta_{D^*}| < 1.25$ (1.5), $M_Y < 1.6$ (4.0) GeV and $x_{I\!P} < 0.05$ ($\eta_{max} < 2.0$) where $x_{I\!P} = (Q^2 + M_X^2)/(Q^2 + W_{\gamma p}^2)$, η_{D^*} is the pseudorapidity of the D^* and η_{max} is the pseudorapidity of the forward most energy cluster in the calorimeter. Figures 1(a) and 1(b) show the ΔM distribution, where $\Delta M = M(K^-\pi^+\pi^+_{slow}) - M(K^-\pi^+)$, from the H1 1994 data and the ZEUS 1995 data respectively. Using fits to these distributions 12 ± 4 events are observed by H1 and 19 ± 5 events are observed by ZEUS which correspond to cross-sections of $380 \pm ^{150}_{120} \pm ^{140}_{110}$ pb and $875 \pm 248 \pm ^{395}_{199}$ pb respectively. The two cross-sections cannot be directly compared because the kinematic ranges of the measurements are different. If the η_{max} cut is removed from the ZEUS analysis $20 \pm 10\%$ of the observed signal is found to be diffractive.

A prediction of the diffractive D^* production cross-section is done using the RAPGAP Monte Carlo [14] program which uses, for the pomeron structure function, a QCD analysis of $F_2^{D(3)}$ [15]. The prediction, for the H1 kinematic range, is found to be approximately 200 pb, which is consistent with the H1 measurement.

III. PHOTO-PRODUCTION OF ELASTIC J/ψ

Elastic J/ψ photo-production has been studied by both H1 [16,17] and ZEUS [18] using the decay channel $J/\psi \rightarrow l^+l^-$ where l is either an electron or muon. Measurements of the photon-proton cross-section have been made by H1 (ZEUS) over the range $30(40) < W_{\gamma p} < 260(140)$ GeV.

These measurements can be used to test the Regge based model of Donnachie-Landshoff [3,4] which predicts shrinkage (*i.e.* the slope of the exponential dependence increases with increasing $W_{\gamma p}$), s-channel helicity conservation and the energy dependence of the cross-section to be $\sigma_{\gamma p} \propto W_{\gamma p}^{\delta}$ where $\delta = 0.22$.

For small values of $|t|$, the cross-section is found to have an exponential t dependence and a fit to $\sigma \propto \exp -b|t|$ gives a value of $b = 4.6 \pm 0.4 \pm^{0.4}_{0.6}\,\mathrm{GeV}^{-2}$ from the ZEUS data and in the range $30 < W_{\gamma p} < 150\,\mathrm{GeV}$, $b = 4.1 \pm 0.2 \pm 0.2\,\mathrm{GeV}^{-2}$ from the H1 data. To look for evidence of shrinkage, the slope of the exponential dependence is measured at different values of $W_{\gamma p}$. This can be seen from figure 3(a) where the average p_t^2 is plotted (for $p_t^2 < 1\,\mathrm{GeV}^2$) instead of b such that results [19] for lower $W_{\gamma p}$ can also be compared. The data is consistent with both the prediction of the Donnachie-Landshoff model with shrinkage and a flat $W_{\gamma p}$ dependence. Hence the HERA measurements alone cannot yet make a strong statement on the evidence of shrinkage.

The J/ψ decay angular distributions measured by both H1 and ZEUS are found to be consistent with s-channel helicity conservation (not shown).

The energy dependence of the photon-proton cross-section is shown in figure 2(a) and when fitted to $\sigma_{\gamma p} \propto W_{\gamma p}^{\delta}$ gives a value of $\delta = 0.77 \pm 0.13 (0.92 \pm 0.14 \pm 0.10)$ from the H1 (ZEUS) measurements. The prediction of the Donnachie-Landshoff model fails to describe the steep energy dependence which is observed in the data.

Attempts to describe elastic J/ψ production in perturbative QCD (pQCD) use the exchange of a gluon ladder in the leading log approximation [5,6]. The cross-section in this model (in leading order) is proportional to the square of the gluon density of the proton. Hence, in figure 3(b) the cross-section is expressed in terms of $\bar{x} \cdot g(\bar{x})$ and plotted as a function of $\bar{x} = (Q^2 + m_{J/\psi}^2 - t)/W_{\gamma p}^2$. However, only the shape of the predictions are reliable as the higher order corrections and non-perturbative effects have not been taken into account when calculating the curves. The pQCD model gives good agreement with the data when the gluon density parameterisations of MRS(A′), CTEQ and GRV, which have a strong rise of the gluon density with decreasing values of $\bar{x}$, are used.

IV. ELECTRO-PRODUCTION OF ELASTIC J/ψ

Elastic production of J/ψ in electro-production has been measured by both H1 [20,21] and ZEUS [22]. The $W_{\gamma p}$ dependence of the photon-proton cross-section is measured for $Q^2 = 3.7$ and $16\,\mathrm{GeV}^2$ and can be seen in figure 2(a). The measured δ for these two Q^2 values are found to be consistent with that measured in photo-production.

The dependence of the cross-section on Q^2 has also been measured and can be seen in figure 2(b). A fit of the form $(Q^2 + m_{J/\psi}^2)^{-n}$ to the HERA data gives a value of $n = 2.1 \pm 0.3$ which is consistent with previous measurements for other vector mesons [20,22]. A pQCD model [7], which is an extension of the pQCD model of [5,6], is found to give good agreement with the data.

V. PHOTO-PRODUCTION OF J/ψ WITH PROTON DISSOCIATION

J/ψ production has been studied in photo-production when the proton dissociates [16,17] in the kinematic range of $30 < W_{\gamma p} < 150\,\mathrm{GeV}$. For small $|t|$, an exponential t dependence with $b = 1.6 \pm 0.3 \pm 0.1\,\mathrm{GeV}^{-2}$ and a steep energy dependence, similar to elastic production, is observed.

These results have been extended to larger values of $|t|$ [23] for the same kinematic region of $W_{\gamma p}$. For $|t| > 1\,\mathrm{GeV}^2$ the cross-section for J/ψ photo-production with proton dissociation has been measured to be $4.1 \pm 0.3 \pm 0.6\,\mathrm{nb}$ using the H1 1994 and 1995 data. The differential cross-sections $\mathrm{d}\sigma_{ep}/\mathrm{d}p_t^2$ and $\mathrm{d}\sigma_{ep}/\mathrm{d}W_{\gamma p}$ have also been determined and are shown in figures 4(a) and 4(b) respectively. At larger values of $|t|$ (which to a good approximation is p_t^2), the data is seen to deviate from the exponential dependence at low $|t|$ (dashed line of figure 4(a)) and become flatter.

For large $|t|$, predictions from a perturbative QCD model [8,9] using the BFKL evolution equations [24,25] are compared to the data. This model can predict the cross-section and the $W_{\gamma p}$ and t dependence. The only uncertainty in this model is what value should be used for the strong coupling constant, α_s. This is assumed to be a constant and hence is denoted as $\overline{\alpha}_s$. Using the measured cross-section, the preferred value of $\overline{\alpha}_s$ for the pQCD model is found to be $\overline{\alpha}_s = 0.207 \pm 0.007$ and using this value the pQCD model is found to give good agreement with the data in both the t and $W_{\gamma p}$ dependences.

VI. PHOTO-PRODUCTION OF QUASI-ELASTIC $\psi(2S)$

The photo-production of $\psi(2S)$ has been observed using the 1994 and 1995 H1 data [26] via the decays $\psi(2S) \to l^+l^-\pi^+\pi^-$ and $\psi(2S) \to l^+l^-$ where l is either an electron or a muon. Mass distributions of the signals can be seen in figures 5(a) to 5(d). The quasi-elastic cross-section, defined as $z > 0.95$, for an average $W_{\gamma p}$ of 80 GeV has been determined to be $\sigma(\gamma p \to \psi(2S)Y) = 17.9 \pm 2.8 \pm 2.7 \pm 1.4$ nb where the last error is due to the uncertainty in the branching ratios of the $\psi(2S)$ decays.

The quasi-elastic $\psi(2S)$ cross-section is compared to the quasi-elastic J/ψ cross-section to give a ratio of $\sigma(\gamma p \to \psi(2S)Y)/\sigma(\gamma p \to J/\psi Y) = 0.150 \pm 0.027 \pm 0.018 \pm 0.011$ where again the last error is due to the uncertainty in the branching ratios. In figure 5(e) the H1 ratio result, and results from previous fixed target experiments [27–31] are plotted as a function of $W_{\gamma p}$ and are found to be consistent with each other. A prediction of this cross-section ratio has been determined using pQCD [10,11] to be 0.17 at $W_{\gamma p} = 80$ GeV which is consistent with the H1 measurement.

VII. PHOTO-PRODUCTION OF QUASI-ELASTIC Υ

First evidence for Υ in photo-production has been observed in the ZEUS 1995 to 1997 data. Figure 6 shows the signal of 20 events from the decay $\Upsilon \to \mu^+\mu^-$ in the kinematic range $80 < W_{\gamma p} < 280$ GeV. The quasi-elastic cross-section, defined as $M_Y < 4$ GeV, is determined to be $\sigma(\gamma p \to \Upsilon Y) = 0.9 \pm 0.3 \pm 0.3$ nb where the branching ratio of $Br(\Upsilon \to \mu^+\mu^-) = 2.48\%$ has been used.

VIII. CONCLUSIONS

Diffractive heavy flavour production has been observed via the production of D^*, J/ψ, $\psi(2S)$ and Υ at HERA. Measurements have been made for both photo-production and electro-production and for when the proton remains intact or breaks up. Predictions from models of diffractive exchange using pQCD are found to give good agreement with the HERA measurements.

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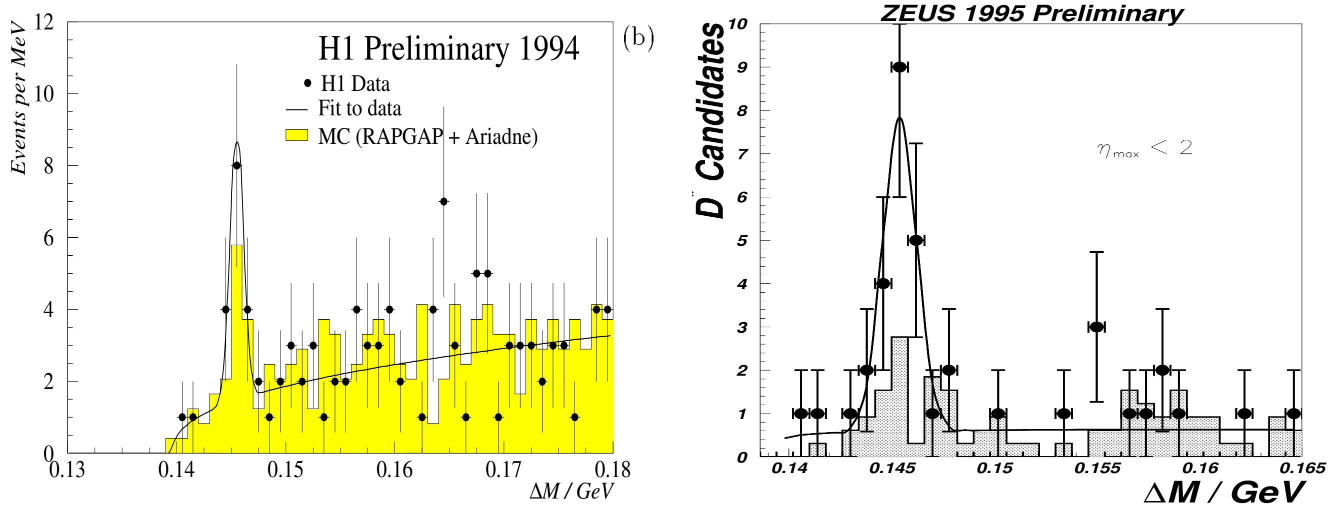

FIG. 1. Signals for D^* production in electro-production in the distribution of $\Delta M = M(K^-\pi^+\pi^+_{slow}) - M(K^-\pi^+)$ from (a) the H1 1994 data and (b) the ZEUS 1995 data. Both plots show fitted curves using the form $a(\Delta M - M_{\pi^+})^b + Gaussian$.

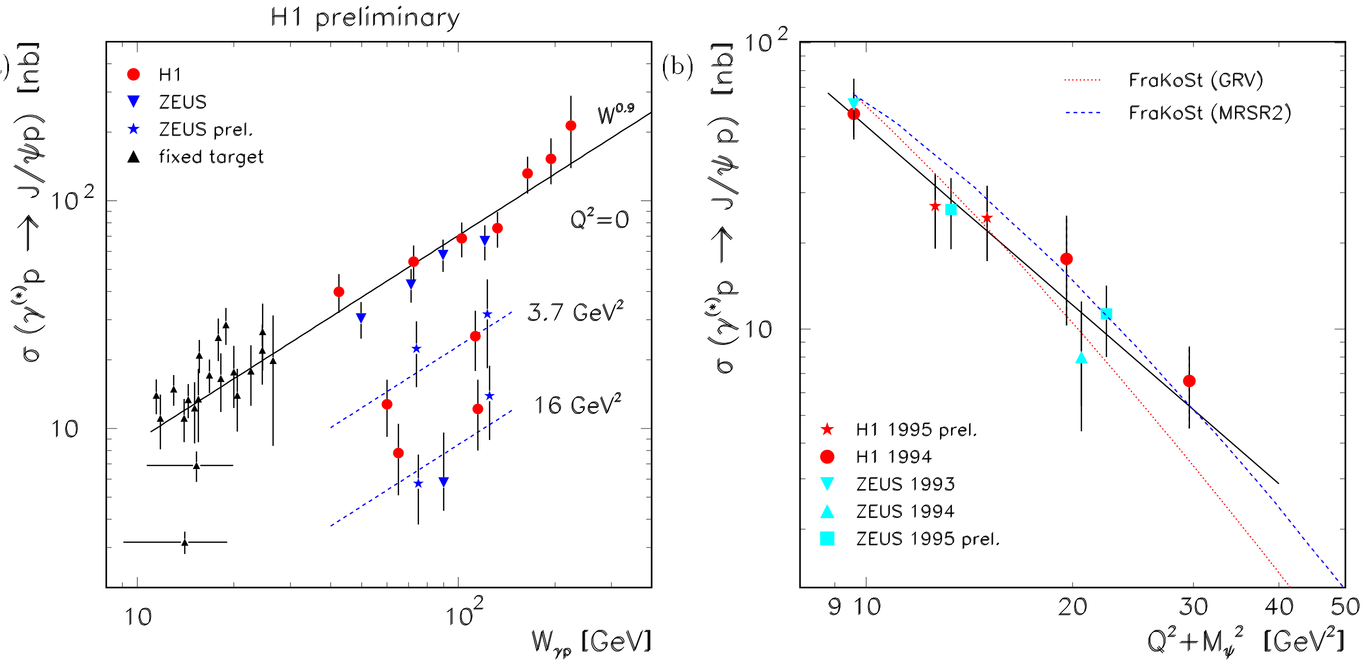

FIG. 2. The photo-proton cross-section measurements for elastic J/ψ production as a function of (a) $W_{\gamma p}$ where curves of the form $\sigma \sim W_{\gamma p}^{0.9}$ are also shown and (b) $Q^2 + M^2_{J/\psi}$ where a fit to the data and the predictions of [7] are also shown.

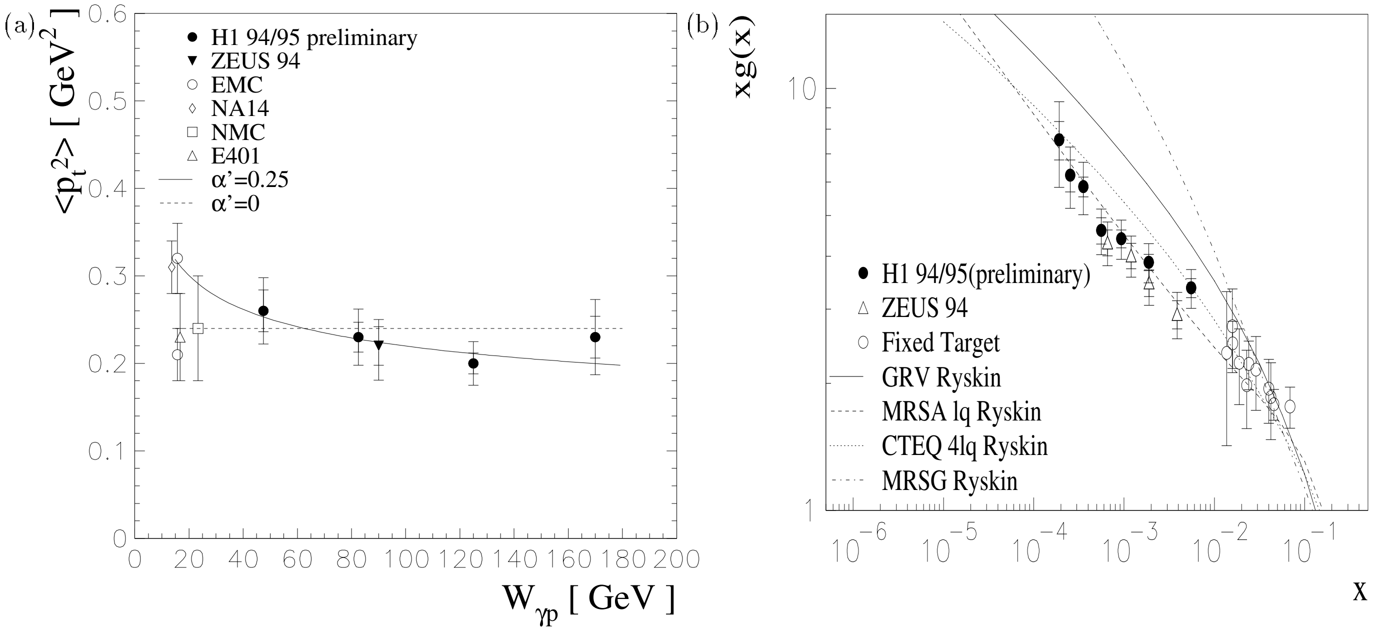

FIG. 3. For photo-production of elastic J/ψ, the plots show (a) the average p_t^2, for $p_t^2 < 1\,\mathrm{GeV}^2$, as a function of $W_{\gamma p}$ compared to prediction of the Donnachie-Landshoff model with shrinkage and a flat $W_{\gamma p}$ dependence and (b) the cross-section measurements of figure 2(a) converted to $\bar{x} \cdot g(\bar{x})$ using the leading-order equation of [6] as a function of $\bar{x}$. Comparisons to different gluon densities are also shown.

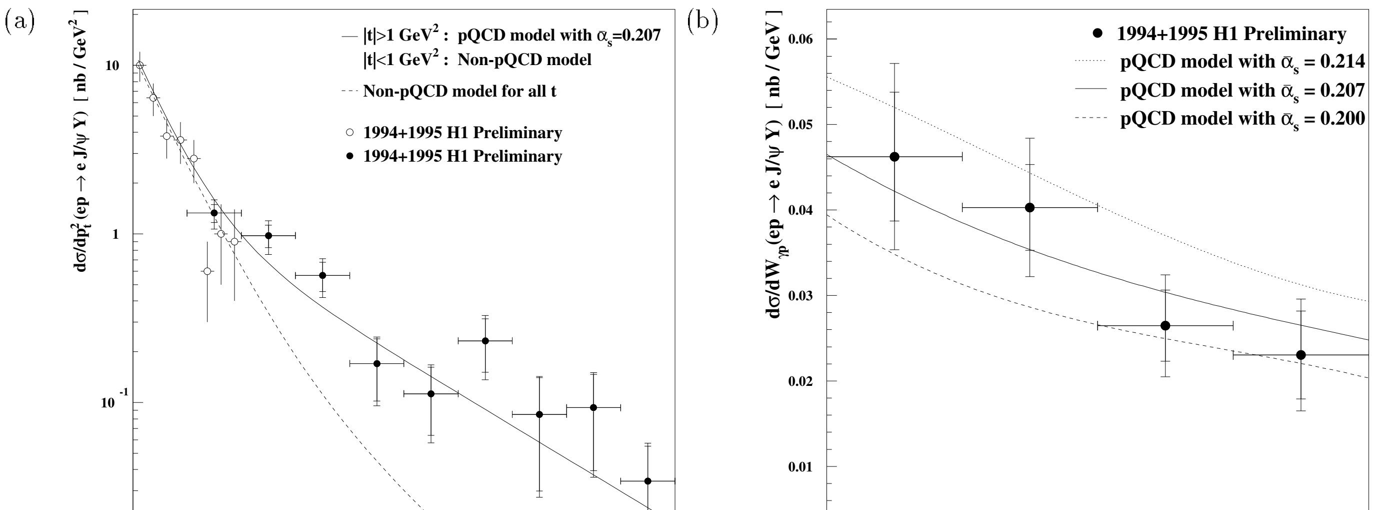

FIG. 4. The differential electron-proton cross-section measurements for J/ψ production with proton-dissociation as a function of (a) p_t^2 where the dashed line is the expectation from a single exponential fitted to the low $|t|$ data and the solid line is the prediction from a pQCD model using BFKL formalism [8,9] and (b) $W_{\gamma p}$ where the measurements are for $|t| > 1\,\mathrm{GeV}^2$ and the curves are predictions from the pQCD model using three different values of $\overline{\alpha}_s$.

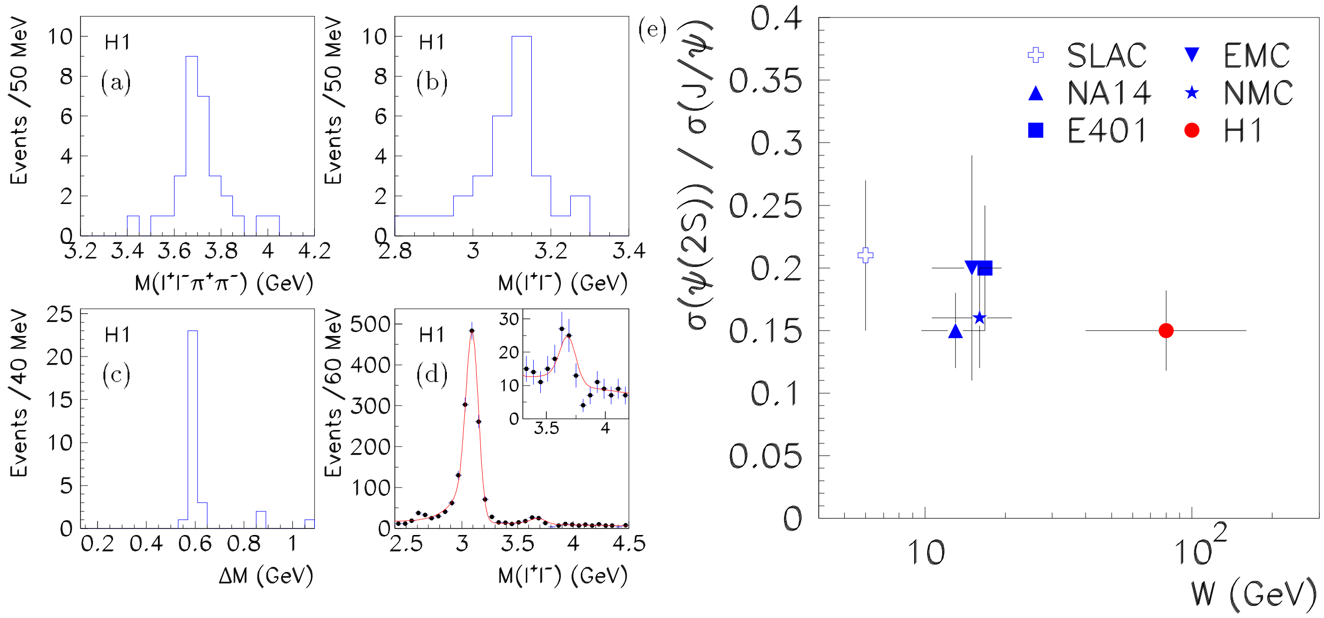

FIG. 5. Mass distributions for $\psi(2S)$ quasi-elastic photo-production using the decay (a,b,c) $\psi(2S) \rightarrow l^+l^-\pi^+\pi^-$ and (d) $\psi(2S) \rightarrow l^+l^-$ here $l = e, \mu$ and $\Delta M = M(l^+l^-\pi^+\pi^-) - M(l^+l^-)$. Also shown is (e) the ratio of the J/ψ and $\psi(2S)$ cross-section measurements as a function of $W_{\gamma p}$ compared with results from earlier fixed target experiments.

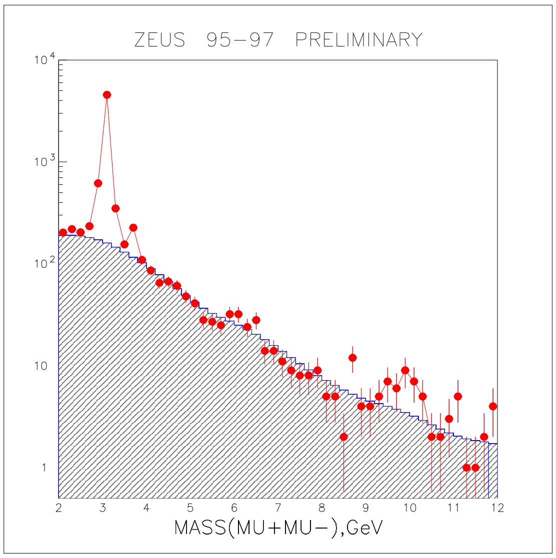

FIG. 6. Mass distribution of di-muon pairs in the 1995-1997 ZEUS data which shows first evidence for Υ production.