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# Photo-production of $\psi(2S)$ Mesons at HERA

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**Abstract**

Diffractive photo-production of $\psi(2S)$ mesons has been observed at HERA at photon-proton centre-of-mass energies in the range 40 to 160 GeV. The $\psi(2S)$ mesons were identified through their decays to $l^+l^-$ and to $J/\psi\pi^+\pi^-$, where the $J/\psi$ subsequently decays to $l^+l^-$, the lepton $l$ being either $\mu$ or $e$. The cross-section for quasi-elastic photoproduction was measured to be $(18 \pm 4(\mathrm{stat}) \pm 4(\mathrm{syst}))$ nb at a photon-proton centre-of-mass energy of 80 GeV. The ratio of the $\psi(2S)/J/\psi$ quasi-elastic cross-sections is $(0.15 \pm 0.05(\mathrm{stat} \oplus \mathrm{syst}))$.

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# 1 Introduction.

At HERA the production of vector mesons is studied at photon-proton centre-of-mass energies ($W_{\gamma p}$) extending well beyond those reached in fixed target experiments. In particular, the production of $J/\psi$ mesons has been reported upon by H1 [1–3] and ZEUS [4]. In this letter a study of the quasi-elastic photo-production of $\psi(2S)$ ($\psi(3685)$) mesons in the photon-proton centre-of-mass energy range $40 < W_{\gamma p} < 160$ GeV is reported. The $\psi(2S)$ mesons are identified via the decays $\psi(2S) \to J/\psi(\to l^+l^-)\pi^+\pi^-$ or $\psi(2S) \to l^+l^-$, where $l$ denotes $\mu$ or $e$.

At HERA energies the process $\gamma p \to Vp$ ($V = J/\psi$ or $\psi(2S)$) can be considered in three parts: the formation of a $c\bar{c}$ quark pair from the photon, the interaction of the quark pair with the proton, and subsequently the formation of the charmonium state, since the production length for a $c\bar{c}$ quark pair from the photon and the formation length for a charmonium state are both considerably greater than the proton radius. The interaction of the $c\bar{c}$ pair with the proton proceeds via the exchange of a colourless object.

The charm quark mass provides a hard scale for a perturbative QCD calculation in which the colourless object is a gluon ladder [5, 6], which leads to a cross-section proportional to the square of the gluon density in the proton. In the framework of Regge theory the exchange of a soft pomeron [7, 8] provides a good description of the photo-production of light vector mesons at HERA [9] but fails for elastic photo-production of $J/\psi$ mesons [3, 4]. An alternative prescription is provided by a model in which the $c\bar{c}$ quark pair from the photon is considered as a colour dipole [10, 11], which interacts with the proton with a cross-section approximately proportional to the square of its transverse size. Consequently the $\gamma p \to Vp$ cross-section is sensitive to the radial wave function of the vector meson, $V$, at a radius characterised by the scale $2/\sqrt{m_c^2 + Q^2/4}$.

# 2 Kinematics.

The variables used for describing $\psi(2S)$ production at HERA are:

$$Q^2 = -q^2 = -(k - k')^2, \quad t = (P - P')^2, \quad s = (P + k)^2, \quad y = \frac{P \cdot q}{P \cdot k},$$

with $k(k')$ being the four-momentum of the incident (outgoing) positron, $P$ that of the incoming proton, $P'$ that of the outgoing proton or the hadronic system $Y$ into which it has dissociated, and $q = k - k'$. Measurements presented here are concerned with the photo-production limit, $Q^2 = 0$ GeV$^2$. The centre of mass energy of the photon-proton system, $W_{\gamma p}$ is given by:

$$W_{\gamma p}^2 = ys - Q^2 + m_p^2 \approx ys.$$

The fraction of the photon four-momentum carried by the $\psi(2S)$ projected on the proton four-momentum

$$z = \frac{P \cdot P_{\psi(2S)}}{P \cdot q}$$

is a convenient measure of the elasticity of the $\psi(2S)$ photo-production reaction. In this letter $\psi(2S)$ meson production is studied in the region $z > 0.95$, referred to here as "quasi-elastic".

Polar angles in the H1 detector are defined with respect to the direction of the incoming protons.

## 3 Experimental Conditions.

The data presented here were collected in 1994 and 1995 with the H1 detector at HERA, where 27.5 GeV positrons were in collision with 820 GeV protons. They correspond to an integrated luminosity of 2.7 $\mathrm{pb}^{-1}$ in 1994 and 3.6 $\mathrm{pb}^{-1}$ in 1995.

The H1 detector is described in detail elsewhere [12] and only components relevant to the present analysis will be described. The Central Tracker (CT) is centred on the nominal interaction point and covers the polar angular range $20°$ to $165°$. Multiwire proportional chambers (CIP and COP) provide additional information for triggering in this region. Forward of the CT is the Forward Tracker (FT) covering the polar angular range $7°$ to $25°$. Surrounding the trackers is a highly segmented liquid argon (LAr) sampling calorimeter [13] consisting of an inner electromagnetic section and an outer hadronic section. Polar angle coverage is from $4°$ to $153°$. During the 1994 data taking a lead scintillator electromagnetic calorimeter (BEMC) covered the angular range $155°$ to $176°$ and was able to detect scattered positrons down to a $Q^2$ of 4 $\mathrm{GeV}^2$ [14]. This calorimeter was replaced for 1995 data taking by a scintillating fibre and lead calorimeter (SpaCal) with coverage of the angular range $153°$ to $177.5°$, thus extending the acceptance down to a $Q^2$ of 1.2 $\mathrm{GeV}^2$ [15]. The tracking chambers are immersed in a very uniform magnetic field of peak value 1.15T provided by a superconducting magnet that surrounds the LAr calorimeter. Outside this lies the iron return yoke of the magnet which is instrumented to detect muons in the range $4°$ to $171°$. Luminosity is determined by measuring the rate of the reaction $ep \to ep\gamma$.

A first level trigger accepts events in which a $\psi(2S)$ meson is produced if a track of 600 MeV momentum pointing towards an energy cluster in the LAr calorimeter is identified, or two tracks back-to-back in azimuth in the multiwire proportional chambers (CIP and COP) are found, or if there exists a muon signature in the instrumented iron of the return yoke.

## 4 Identification of the $\psi(2S)$.

The $\psi(2S)$ meson is identified using its decays to $J/\psi(\to e^+\ e^-)\pi^+\ \pi^-$, $J/\psi(\to \mu^+\ \mu^-)\pi^+\ \pi^-$, $e^+\ e^-$ and $\mu^+\ \mu^-$ which have branching ratios 1.95$\pm$0.17%, 1.95$\pm$0.17%, 0.88$\pm$0.13% and 0.77$\pm$0.17% respectively [16].

The decay products of the $\psi(2S)$ are measured in the CT to have $p_t > 120$ MeV, and $20° < \theta < 165°$. Particle identification is provided for the leptons by the LAr calorimeter, in which energy deposits typical for muons or electrons are observed, and for muons by tracks found in the instrumented iron return yoke. Lepton must have transverse momentum greater than 800 MeV. No particle identification is required for the pions in the four-track decays of the $\psi(2S)$. It is required that no charged particles other than the decay products of the $\psi(2S)$ are observed. The photon-proton centre of mass energy ($W_{\gamma p}$) is restricted to $40-160$ ($40-120$) GeV for the dimuon (dielectron) samples (see section 5).

Events in which the scattered positron is observed in the backward electromagnetic calorimeter (BEMC in 1994, SpaCal in 1995) or in the LAr calorimeter are rejected, which restricts the acceptance to the kinematic range $Q^2 < 4$ (1.2) $\mathrm{GeV}^2$ for the 1994 (1995) data sample.

The mass distributions obtained are shown in figure 1, where the data from 1994 and 1995 and for both di-lepton types are combined. Figure 1(c) shows a clear signal of 27 events at $\Delta M \equiv M_{(l^+l^-\pi^+\pi^-)} - M_{(l^+l^-)} = M_{\psi(2S)} - M_{J/\psi}$ with negligible background. The experimental resolution of $\Delta M$ is such that a possible contribution from $\psi(3770)$ can be excluded. The number of events in the $\psi(2S) \to l^+l^-$ signal is estimated by fitting the mass distribution to a Gaussian with linear background (figure1(e)). A signal of $40 \pm 8$ events is obtained. The contribution of $\psi(3770)$ to this signal is approximately four orders of magnitude smaller than the $\psi(2S)$ contribution.

## 5 Monte Carlo Model and Acceptances.

Simulation studies were made to obtain the acceptances and efficiencies of triggering, track reconstruction, selection and lepton identification for the $\psi(2S)$ production processes. These studies used event samples generated with the DIFFVM Monte Carlo generator [17], and a computer simulation of the H1 detector response based on the GEANT program [18]. DIFFVM generates events according to the cross-section dependence $\mathrm{d}\sigma/\mathrm{d}t \propto W_{\gamma p}^{4\varepsilon} e^{bt}$ for elastic $\psi(2S)$ production, and $\mathrm{d}^2\sigma/\mathrm{d}t\,\mathrm{d}M_Y^2 \propto W_{\gamma p}^{4\varepsilon} e^{b't} M_Y^{\beta}$ for production with proton dissociation, where $M_Y$ is the effective mass of the hadrons from the proton dissociation. Previously the parameters of the DIFFVM generator are adjusted to reproduce the features of $J/\psi$ elastic and proton dissociation photo-production processes [2,3]. Equal cross-sections for elastic and proton dissociative photo-production of $\psi(2S)$ were assumed, consistent with the results of the $J/\psi$ analysis. The values of the parameters used here were: $\varepsilon = 0.225$, $b = 4.0$ GeV$^{-2}$, $b' = 1.6$ GeV$^{-2}$, $\beta = -2.16$. The decay angular distribution for $\psi(2S)$ decaying directly into two leptons is simulated according to $s$-channel helicity conservation. The Monte Carlo program is found to model all features of the data very well.

Measurements are restricted to the range $40 < W_{\gamma p} < 120(160)$ GeV for the electron(muon) decay channels, where the acceptance is found to be quite independent of $W_{\gamma p}$. The requirement that there be no charged particle observed in the detector, other than the decay products of the $\psi(2S)$ meson, restricts the acceptance approximately to the region $z > 0.95$. Within this kinematic region the combined geometric acceptance, triggering efficiency and selection efficiency is about 6% for the four track decays and 15% for the two track decays .

Uncertainties in the acceptance calculations contribute to systematic uncertainties in the cross-section measurements. The uncertainty due to the use of the Monte Carlo model is estimated to be 5% by varying all parameters used within reasonable limits. Significant systematic uncertainties associated to the detector simulation arise from the track reconstruction efficiency (12%), lepton identification efficiency (6%) and trigger efficiency (6%).

## 6 $\psi(2S)$ Cross-sections.

The combined cross-section from the four track decays using 1994 and 1995 data is

$$\sigma(e^+p \rightarrow e^+\psi(2S)Y) = 2.1 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})\ \mathrm{nb}, \qquad \text{(H1 preliminary)}$$

for the kinematic range $40 < W_{\gamma p} < 160$ GeV, $Q^2 < 4$ GeV$^2$, $z > 0.95$.

The photo-production cross-section at $W_{\gamma p} = 80$ GeV is related to the electro-production cross-section by

$$\sigma_{\mathrm{ep}} = \sigma_{\gamma p}(W_{\gamma p} = 80\mathrm{GeV}) \int \mathrm{d}y \int \mathrm{d}Q^2 f_{\gamma/e}(y, Q^2) \left(\frac{W_{\gamma p}}{80\mathrm{GeV}}\right)^{4\cdot 0.225} \left(1 + \frac{Q^2}{M_{\psi(2S)}^2}\right)^{-2}$$

where the limits of integration are determined by the kinematic range of the electro-production cross-section, and using a spectral flux of transverse photons from the electron [19]

$$f_{\gamma/e}(y, Q^2) = \frac{\alpha}{2\ \pi\ Q^2} \cdot (1 + (1-y)^2 - \frac{2m_e^2 y^2}{Q^2}).$$

Varying the assumed $W_{\gamma p}$ and $Q^2$ dependence of the virtual photon-proton cross-section, implicit in the above relation, within reasonable limits results in a systematic uncertainty in the photo-production cross-section of 3%.

A photoproduction cross-section for $z > 0.95$ at $W_{\gamma p} = 80$ GeV,

$$\sigma(\gamma p \to \psi(2S)Y) = 18 \pm 4(\mathrm{stat}) \pm 4(\mathrm{syst})\ \mathrm{nb} \qquad \text{(H1 preliminary)}$$

is obtained.

The $\psi(2S)$ signal of $40 \pm 8$ events from the analysis of the two track sample yields a statistically independent measurement of the cross-sections for $\psi(2S)$ production:

$$\sigma(e^+p \to \psi(2S)Y) = 2.5 \pm 0.4(\mathrm{stat}) \pm 0.7(\mathrm{syst})\ \mathrm{nb}, \qquad \text{(H1 preliminary)}$$

$$\sigma(\gamma p \to \psi(2S)Y) = 21 \pm 3(\mathrm{stat}) \pm 6(\mathrm{syst})\ \mathrm{nb}, \qquad \text{(H1 preliminary)}$$

for the kinematic intervals above. Here the estimate of the level of background under the $\psi(2S)$ signal contributes a 20% systematic uncertainty. The two and four track results are seen to be consistent.

# 7 The $\psi(2S)/J/\psi$ Cross-section Ratio.

The $J/\psi$ quasi-elastic ($z > 0.95$) photo-production cross-section at $W_{\gamma p} = 80$ GeV is $(119.5 \pm 11.2 \pm 12.0)$ nb [3], yielding a ratio:

$$\frac{\sigma(\gamma p \to \psi(2S)Y)}{\sigma(\gamma p \to J/\psi Y)} = 0.15 \pm 0.05(\mathrm{stat} \oplus \mathrm{syst}) \qquad \text{(H1 preliminary)}.$$

Figure 2 contains a compilation of measurements from fixed target experiments of the ratio of $\psi(2S)$ to $J/\psi$ cross-sections: three photo-production experiments at $Q^2 = 0$ (deuterium target [20] SLAC, lithium target [21] NA14, and deuterium target [22] E401) plus muo-production experiments on an iron target [23](EMC) and more recently on tin and carbon [24](NMC). Of these, the deuterium target data samples were restricted to events in which the decay products of the vector mesons were the only tracks detected; in the lithium target data some inelastic contribution was included and the iron target data included both diffractive and DIS contributions. However, it is apparent that in going to HERA energies there is no significant change in the $\psi(2S)$ to $J/\psi$ cross section ratio.

A prediction of the ratio of elastic cross-sections can be made within the framework of Regge theory. Under the assumptions that the Pomeron coupling strengths to the two vector mesons are identical, and that the proton radius is much greater than those of either the $J/\psi$ or $\psi(2S)$, the ratio of cross-sections is:

$$\frac{\sigma(\gamma p \to \psi(2S)p)}{\sigma(\gamma p \to J/\psi p)} = \frac{\Gamma(\psi(2S) \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \frac{M_{J/\psi}}{M_{\psi(2S)}};$$

which yields a value $0.34 \pm 0.04$. The measured value is seen to be about a factor of 2 smaller.

The colour dipole model results in a prediction for the ratio for elastic photo-production of 0.17 [11], which agrees well with the ratio of quasi-elastic cross-sections reported here. This lower prediction reflects the difference in the radial wave function of the 1S and 2S charmonium states away from the origin.

## 8 Summary.

Measurements of the quasi-elastic photo-production cross-section for $\psi(2S)$ at a $W_{\gamma p}$ value of 80 GeV at HERA have been reported. The ratio between the quasi-elastic $\psi(2S)$ and $J/\psi$ photo-production cross-sections is compatible with those measured at lower energies, and is a factor of two smaller than that predicted by a simple calculation assuming factorisation in the framework of Regge theory. However the measured ratio does agree well with the predictions from a model in which the photon fluctuates into a $c\bar{c}$ quark pair which then behaves as a colour dipole in its interaction with the proton.

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## References

[1] T. Ahmed *et al.*, H1 Collaboration *Phys. Lett.* B338 (1994) 507.

[2] S. Aid *et al.*, H1 Collaboration *Nucl. Phys.* B468 (1996) 3.

[3] S. Aid *et al.*, H1 Collaboration *Nucl. Phys.* B472 (1996) 3.

[4] M. Derrick *et al.*, Zeus Collaboration *Phys. Lett.* B350 (1995) 120.

[5] M.G. Ryskin, *Z. Phys.* C57 (1993) 89.

[6] M.G. Ryskin, R.G. Roberts, A.D. Martin and E.M. Levin, preprint DTP/95/96 CBPF-NF-079-95, RAL-TR-95-065, hep-ph/9511228 (1995), revised February 1996.

[7] A. Donnachie and P.V. Landshoff, *Phys. Lett.* B296 (1992) 227.

[8] A. Donnachie and P.V. Landshoff, *Phys. Lett.* B348 (1995) 213.

[9] S. Aid *et al.*, H1 Collab., *Nucl. Phys.* B463 (1996) 3; M. Derrick *et al.*, Zeus Collab., *Z. Phys.* C63 (1994) 391; M. Derrick *et al.*, Zeus Collab., *Z. Phys.* C69 (1995) 39; M. Derrick *et al.*, Zeus Collab., *Z. Phys.* C73 (1996) 73; M. Derrick *et al.*, Zeus Collab., *Phys. Lett.* B377 (1996) 259.

[10] B.Z. Kopeliovich and B.G. Zakharov, *Phys. Rev.* 44 (1991) 3466.

[11] B.Z. Kopeliovich, J. Nemchik, N.N. Nikolaev and G.G. Zakharov, *Phys. Lett.* B309 (1993) 179.

[12] *The H1 Detector at HERA*, I. Abt *et al.*, H1 Collaboration, *Nucl. Inst. Meth.* A386 (1997) 310, 348.

[13] B. Andrieu *et al.*, H1 Calorimeter Group, *Nucl. Inst. Meth.* A336 (1993) 460.

[14] J. Ban *et al.*, H1 BEMC Group *Nucl. Inst. Meth.* A372 (1996) 399.

[15] T.Nicholls *et al.*, *Nucl. Inst. Meth.* A374 (1996) 149; R.D. Appuhn *et al.*, *Nucl. Inst. Meth.* A386 (1997) 397.

[16] R. Barnett *et al.*, Particle Data Group, *Phys. Rev.* D54 (1996) 1.

[17] B. List *Diploma Thesis* Techn. Univ. Berlin (1993) unpublished.

[18] R. Brun *et al.*, CERN-DD/EE-84-1 (1987)

[19] V. M. Budnev *et al.*, *Phys. Rep.* C 15 (1975) 181;
C.F.Weizsäcker,*Z. Phys.* 88 (1934) 612;
E.J.Williams,*Phys. Rev.* 45 (1934) 729.

[20] U. Camerini *et al.*, *Phys. Rev. Lett.* 35 (1975) 483.

[21] R. Barate *et al.*, NA14 Collab., *Z. Phys.* C33 (1987) 505.

[22] M. Binkley *et al.*, E401 Collab., *Phys. Rev. Lett.* 50 (1983) 302.

[23] J.J. Aubert *et al.*, EMC Collab., *Nucl.Phys.* B213 (1983) 1.

[24] P. Amaudraz *et al.*, NMC Collab., *Nucl. Phys.* B371 (1992) 553.

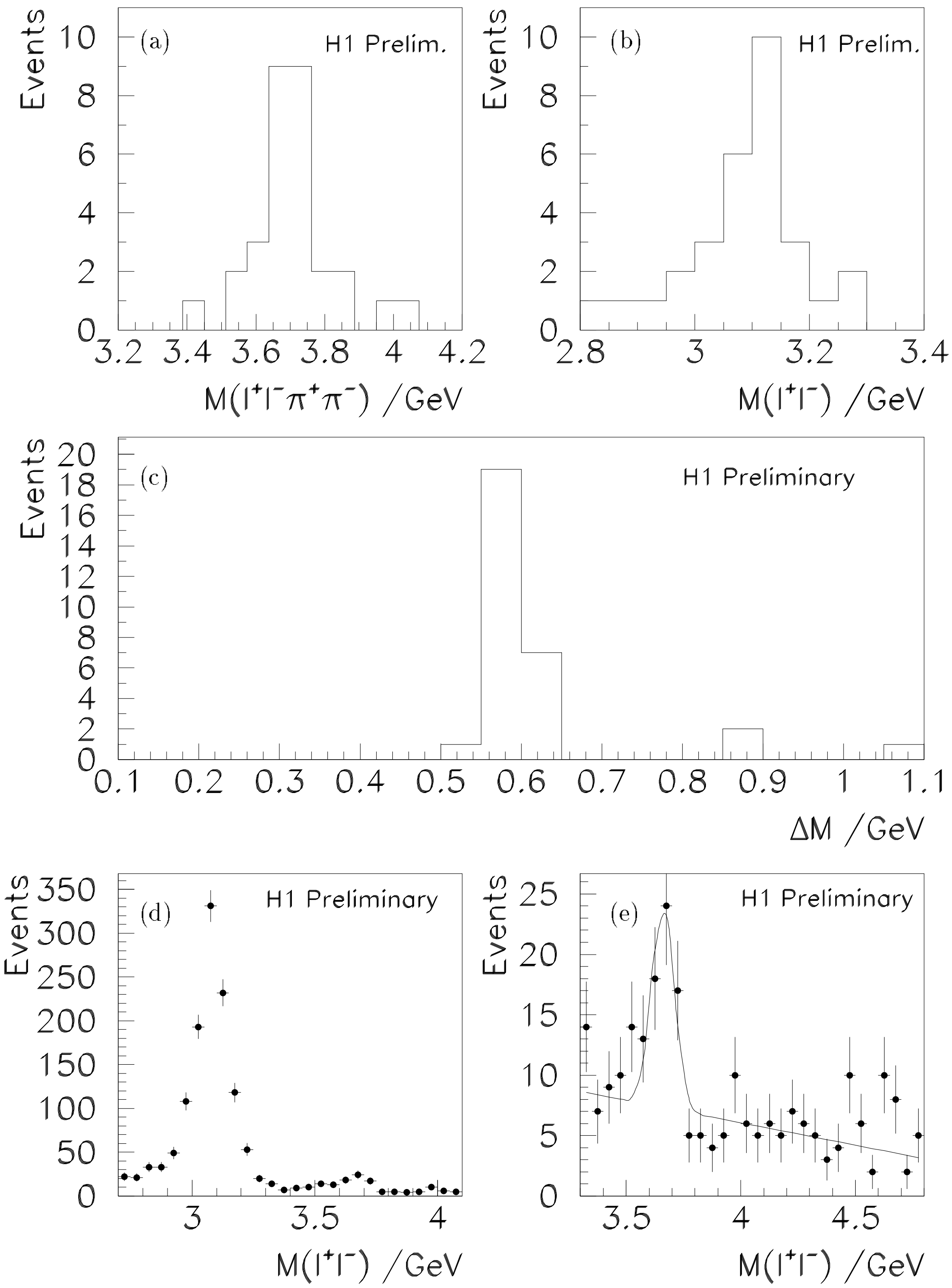


Figure 1: The effective mass plots for the four track sample: a) the four track effective mass, b) the di-lepton effective mass, and c) the $\Delta M$ distribution where $\Delta M = M_{(l^+l^-\pi^+\pi^-)} - M_{(l^+l^-)}$. Effective mass distributions for the two track sample: d) the di-lepton effective mass in the $J/\psi$ and $\psi(2S)$ mass region, e) the di-lepton effective mass in the $\psi(2S)$ mass region. The solid curve is a Gaussian plus exponential fit to the data.

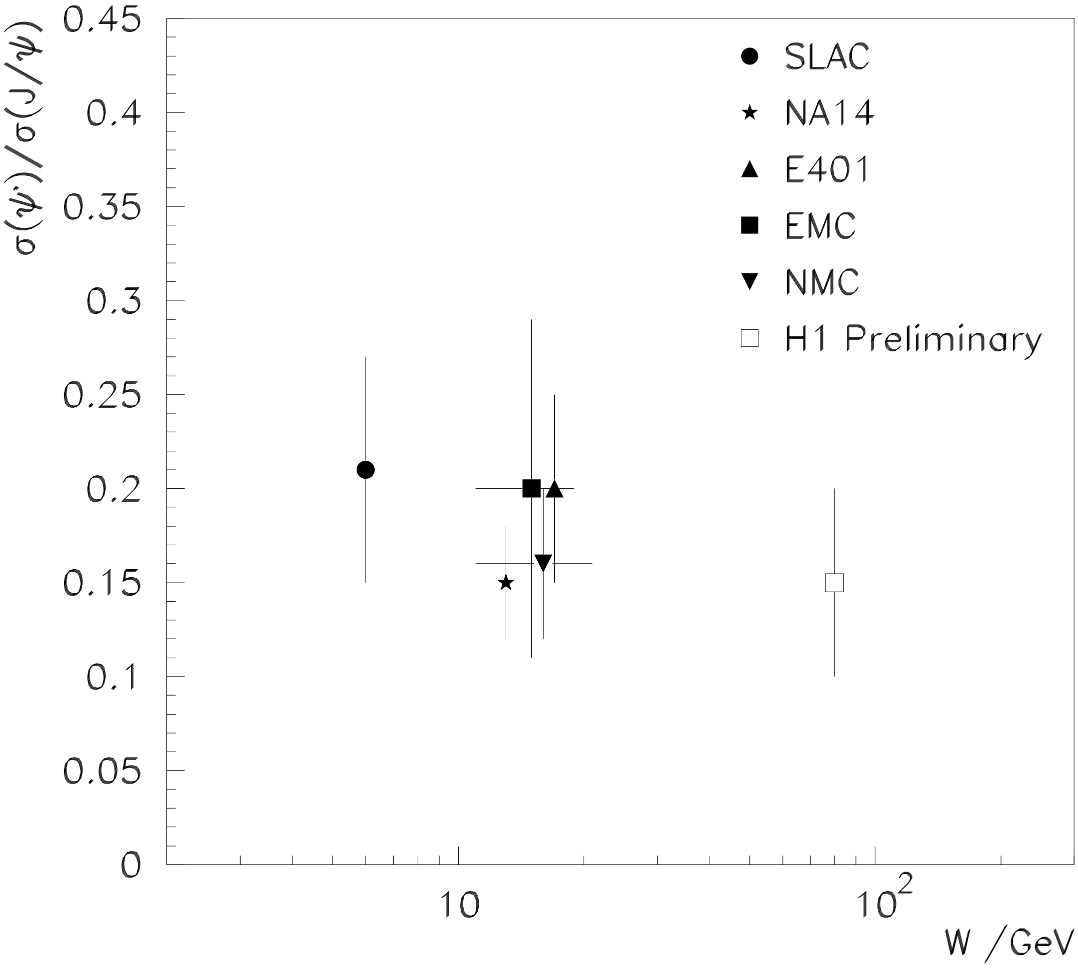


Figure 2: The ratio of the cross-sections for $\psi(2S)$ and $J/\psi$ photo-production as a function of photon-proton centre-of-mass energy, $W_{\gamma p}$. The results from the present analysis are shown together with those from earlier fixed target experiments [20–24]. The ratios from the fixed target experiments have been corrected using the latest decay branching ratios. The error bars shown on the low energy measurements are statistical only.