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# Diffractive Charmonium Production in Deep-Inelastic Scattering at HERA

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**Abstract**

We present results for the exclusive production of $J/\psi$ and $\psi(2S)$ mesons in deep-inelastic $ep$ scattering at HERA in the kinematic region of the photon virtuality $2 < Q^2 < 80$ GeV$^2$ and the photon-proton centre-of-mass energy $40 < W < 160$ GeV. $J/\psi$ mesons are detected via their leptonic decays into two muons or electrons. The cross section for the reaction $\gamma^* p \to J/\psi\, p$ is evaluated as a function of $Q^2$, $W$ and $t$, and the results are compared to phenomenological models. Decay angular distributions are shown. The first observation of $\psi(2S)$ mesons in deep-inelastic scattering at HERA is reported, using the decay mode $\psi(2S) \to J/\psi\, \pi^+\pi^-$. The ratio of the quasi-elastic production cross sections for $\psi(2S)$ and $J/\psi$ is extracted as a function of $Q^2$.

**Abstract: 572**
**Parallel sessions: 7,5**
**Plenary sessions: 9,7**

# 1 Introduction

In this paper, results on the exclusive production of the $J/\psi$ meson in deep-inelastic $ep$ scattering (DIS) are presented. Data from the years 1995 to 1997 are used. Cross sections for the process $\gamma^* p \to J/\psi\, p$ are extracted as a function of $W$ (the $\gamma^* p$ invariant mass) and $Q^2$ (the $\gamma^*$ virtuality) using a data sample one order of magnitude larger than that in a previous publication using 1994 data [1], and the kinematic range is extended with respect to H1 preliminary results from 1995 data [2]. The results are compared to the predictions of a model based on perturbative QCD. An updated measurement of the elastic slope parameter and a first analysis of the helicity structure of $J/\psi$ production in DIS at HERA are also presented.

Also shown is the first measurement of quasi-elastic production of the $\psi(2S)$ meson in DIS at HERA. The ratio of the cross sections for quasi-elastic $\psi(2S)$ and $J/\psi$ production is extracted for two values of $Q^2$.

# 2 Data and Event Selection

The data used in these analyses were collected during the years 1995 to 1997 using the H1 detector [3] at the HERA collider, which was operated with positrons at an energy of 27.5 GeV and protons at 820 GeV. The data used correspond to an integrated luminosity of $21\,\mathrm{p}b^{-1}$ for the $J/\psi$ analysis and $23\,\mathrm{p}b^{-1}$ for the $\psi(2S)$ analysis.

The scattered positron in DIS events is identified as a localized energy deposit of at least 12 GeV in the SpaCal [4], an electromagnetic calorimeter covering the range $155^\circ < \theta < 177^\circ$, where $\theta$ is the polar angle with respect to the proton direction.

## 2.1 Exclusive $J/\psi$ Production

Exclusive $J/\psi$ events are selected as described in [1], using the decay modes $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$. In addition to the scattered positron, there must be exactly two tracks fitted to the event vertex in the central tracking detector (CTD). The tracks are required to lie in the angular range $20^\circ < \theta < 160^\circ$. For the $\mu^+\mu^-$ channel, at least one of the tracks must be identified as a muon. For the $e^+e^-$ channel, both must be identified as electrons. Detectors in the forward region, close to the outgoing proton beam, are used to tag events in which the scattered proton dissociates.

## 2.2 Quasi-Elastic $\psi(2S)$ Production

The $\psi(2S)$ meson is identified here using its decay mode $\psi(2S) \to J/\psi\, \pi^+\pi^-$, where the $J/\psi$ decays to $\mu^+\mu^-$ or $e^+e^-$. Exactly four vertex-fitted tracks are required in the CTD. The criteria for identification of the leptons are stricter than those in the exclusive $J/\psi$ analysis; both muons must be identified in the $\mu^+\mu^-$ channel, and the electrons in the $e^+e^-$ case must pass tighter cuts than in the exclusive $J/\psi$ selection. The leptons and pions must all lie in the angular range $20^\circ < \theta < 160^\circ$. In this analysis exclusive events are not separated from proton dissociation due to the small number of events available.

For the $J/\psi$ reference sample used in the ratio of cross sections, the cuts used are the same as those used to reconstruct the $J/\psi$ from the $\psi(2S)$ decay.

# 3 Results

## 3.1 Exclusive $J/\psi$ Production

The cross section for exclusive $J/\psi$ production is calculated in a similar manner to that described in [1, 2]. The number of events in the signal region is corrected for non-resonant background using a fit to the mass distribution. A Monte Carlo simulation is used to correct the results for contamination from proton-dissociation background and for acceptance and efficiency effects. The Weizsäcker-Williams approximation is used to convert the measured $ep$ interaction cross section to a $\gamma^* p$ cross section.

The cross section obtained as a function of $W$ is shown in figure 1, together with other results for DIS and photoproduction ($Q^2 = 0$). The $W$ dependence at fixed positive $Q^2$ is found to be similar to that at $Q^2 = 0$, the cross section being approximately proportional to $W$. The data are compared to a model by Frankfurt et al. [5] based on perturbative QCD. In this model the cross section is proportional to the square of the gluon density $xg(x)$. Using gluon densities increasing towards low $x$, as required by other HERA data, a good description of the present data is obtained in this model.

The $Q^2$ dependence, shown in figure 2, is well described by a fitted function proportional to $(Q^2 + m_\psi^2)^{-n}$ with $n = 2.24 \pm 0.19$. The model by Frankfurt et al. also gives a reasonably good description of the $Q^2$ dependence. The vector dominance model (VDM) predicts a less steep dependence.

The elastic slope parameter is determined from the sample of exclusive $J/\psi$ candidates by fitting the measured $t$ distribution, shown in figure 3, with a function of the form $\exp(b_{el}|t|)$ to model the exclusive signal, with additional contributions to allow for the effect of background. The proton-dissociation background falls less steeply with $|t|$ than the exclusive signal, while dilepton production from photon-photon interactions results in a sharp rise with decreasing $|t|$ below $|t| \approx 0.1\,\mathrm{GeV}^2$. The elastic slope parameter thus determined is

$$b_{el} = -3.9 \pm 0.4\ \text{(stat)} \pm 0.4\ \text{(syst)}\ \text{GeV}^{-2}$$

at a mean $W$ of 96 GeV and a mean $Q^2$ of $8\,\mathrm{GeV}^2$. This value of $b_{el}$ is compatible with those obtained by H1 [6] and ZEUS [7] for photoproduction of $J/\psi$ mesons at similar values of $W$: $b_{el} = -4.4 \pm 0.3$ GeV$^{-2}$ (H1) and $b_{el} = -4.6 \pm 0.6$ GeV$^{-2}$ (ZEUS).

In order to investigate the helicity structure of the process, the decay of the $J/\psi$ is used. A number of angles are defined as follows. $\theta^*$ and $\phi$ are respectively the polar and azimuthal angles of the direction of flight of the positive decay lepton in the helicity frame, i.e. in the $J/\psi$ rest frame, with the $z$-axis defined as the direction of the $J/\psi$ in the $\gamma^* p$ centre-of-mass frame, and the $y$-axis perpendicular to the $J/\psi$ production plane. $\Phi$ is the angle between the $J/\psi$ production plane and the electron scattering plane in the $\gamma^* p$ centre-of-mass frame. The polarization angle $\Psi$ is defined as $\phi - \Phi$.

If the helicity of the virtual photon is retained by the $J/\psi$ meson, i.e. the $s$-channel helicity conservation (SCHC) hypothesis is correct, the angular distribution is only a function of $\theta^*$ and $\Psi$:

$$\begin{aligned} \frac{\mathrm{d}^2 N}{\mathrm{d}\cos\theta^*\,\mathrm{d}\Psi} \quad \propto \quad & 1 + \cos^2\theta^* + 2\epsilon R \sin^2\theta^* - \epsilon \sin^2\theta^* \cos 2\Psi \\ & + \sqrt{2\epsilon R(1+\epsilon)} \cos\delta \cos\Psi \sin 2\theta^* \end{aligned}$$

where $R$ is the ratio $\sigma_L/\sigma_T$ of the contributions to the cross section from longitudinally and transversely polarized photons, $\delta$ is the phase difference between the longitudinal and transverse contributions, and $\epsilon$ is the polarization parameter, with a mean value of 0.99 in the kinematic range of this analysis. The acceptance-corrected $\cos\theta^*$ and $\Psi$ distributions are shown in figure 4. Fits with $R$ as a free parameter have been performed and yield for the $\cos\theta^*$ distribution

$$R = 0.34^{+0.27}_{-0.19}.$$

The result obtained from the $\Psi$ distribution is less well constrained, but is compatible within the experimental uncertainty, indicating compatibility with SCHC.

### 3.2 Quasi-Elastic $\psi(2S)$ Production

The invariant mass distributions of the $\psi(2S)$ candidates and of the $J/\psi$ candidates in these events are shown in figure 5. Also shown is the distribution of the mass difference $\Delta m$, which is better resolved than the individual masses involved. The mass distribution for the $J/\psi$ reference sample is also shown.

The quasi-elastic $\psi(2S)$ events and the $J/\psi$ reference sample are divided into two bins in $Q^2$: $1 < Q^2 < 5$ GeV$^2$ and $5 < Q^2 < 80$ GeV$^2$. The ratio of cross sections is shown as a function of $Q^2$ in figure 6. The measurement at low $Q^2$ agrees well with the H1 photoproduction measurement [8]. An indication of a rise with $Q^2$ of the ratio $\sigma_{\psi(2S)}/\sigma_\psi$ is observed at the level of two standard deviations; a rise with $Q^2$ is predicted in models by Frankfurt et al. [9] and Kopeliovich et al. [10].

## 4 Conclusions

Updated, more precise measurements of exclusive $J/\psi$ production in DIS have been presented, covering a larger kinematic range than previous analyses. The dependence of the cross section $\sigma(\gamma^* p \to J/\psi\, p)$ on $W$ and $Q^2$ is described well by a model based on perturbative QCD. The elastic slope parameter is compatible with the value found in photoproduction. The helicity structure of exclusive $J/\psi$ production in DIS has been investigated for the first time at HERA, and no evidence is found for a violation of $s$-channel helicity conservation.

The first evidence from HERA for quasi-elastic production of $\psi(2S)$ mesons in DIS has been presented. The ratio of cross sections for quasi-elastic $\psi(2S)$ and $J/\psi$ production is found to increase with $Q^2$, in agreement with predictions.

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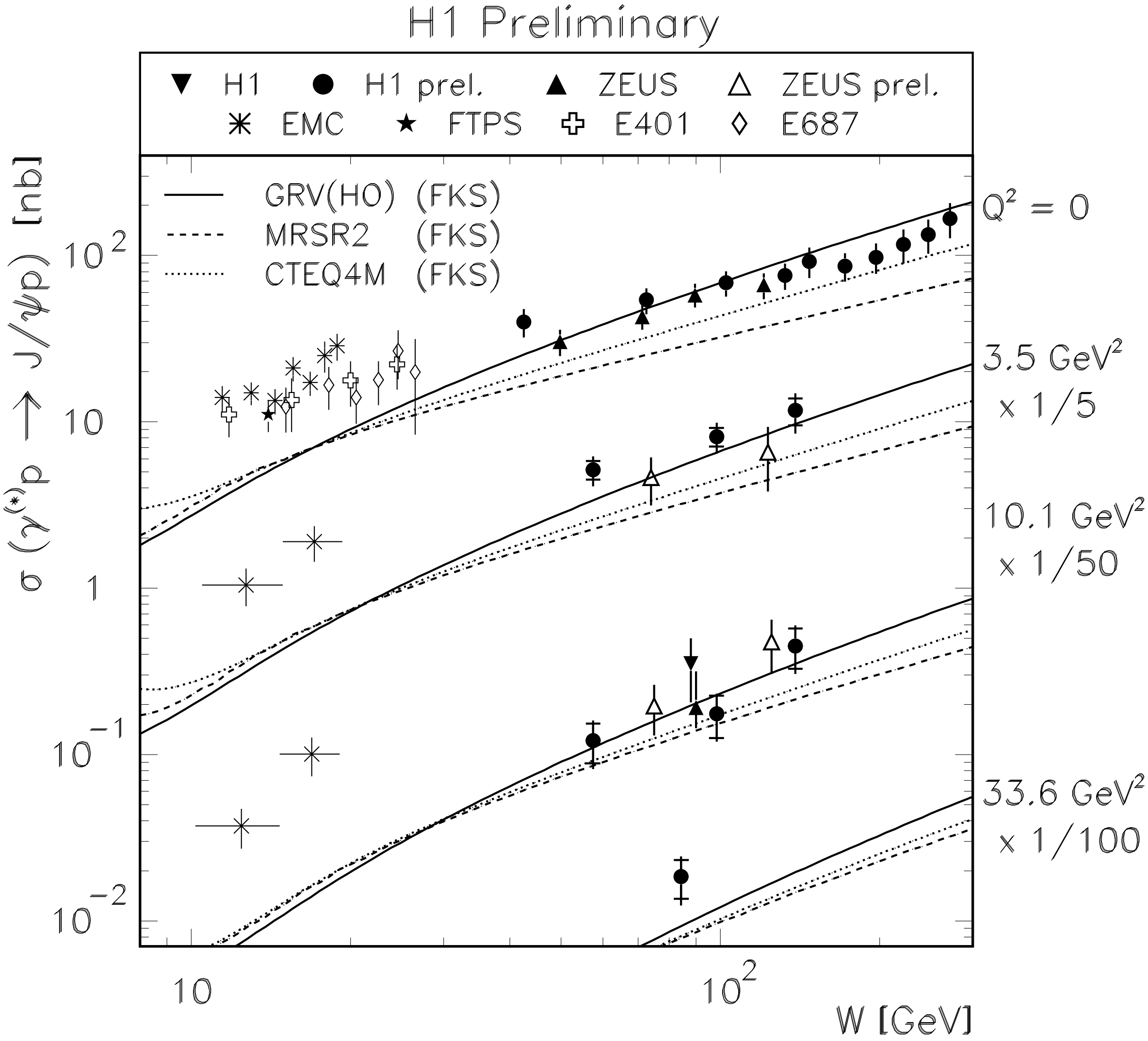


Figure 1: Cross sections for exclusive $J/\psi$ production as a function of $W$ at different values of $Q^2$, measured at HERA in this and other analyses [1, 2, 7, 11] and in the fixed target experiments FTPS (E516) [12], E401 [13], E687 [14] and EMC [15]. Data for $Q^2 > 0\,\mathrm{GeV}^2$ have been scaled by 5, 50, and 100 as indicated. The inner vertical bars on the H1 preliminary points from this analysis indicate the statistical errors, while the outer bars show the statistical and systematic errors added in quadrature. The lines are results of calculations from Frankfurt, Koepf and Strikman [5] using several recent parameterizations of the proton structure function.

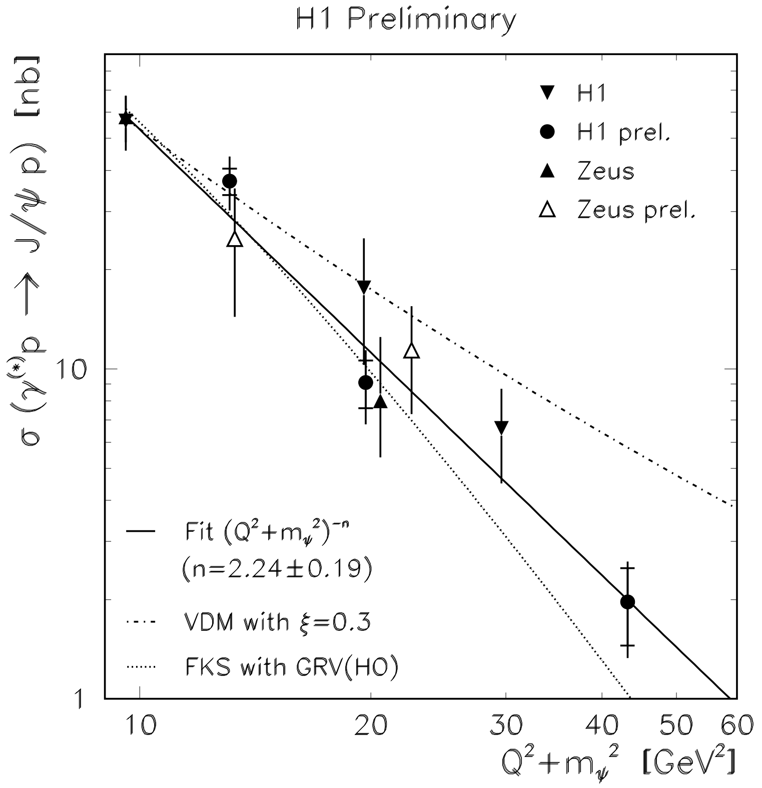


Figure 2: Cross section for exclusive $J/\psi$ production at $W = 90$ GeV as a function of $Q^2 + m_\psi^2$. The inner vertical bars on the H1 preliminary points from this analysis indicate the statistical errors, while the outer bars show the statistical and systematic errors added in quadrature. The full line is a fit of the form $(Q^2 + m_\psi^2)^{-n}$, yielding the result $n = 2.24 \pm 0.19$. The dotted line is the prediction of Frankfurt, Koepf and Strikman [5] using the gluon density GRV(HO); the dash-dotted line is a VDM parameterization.

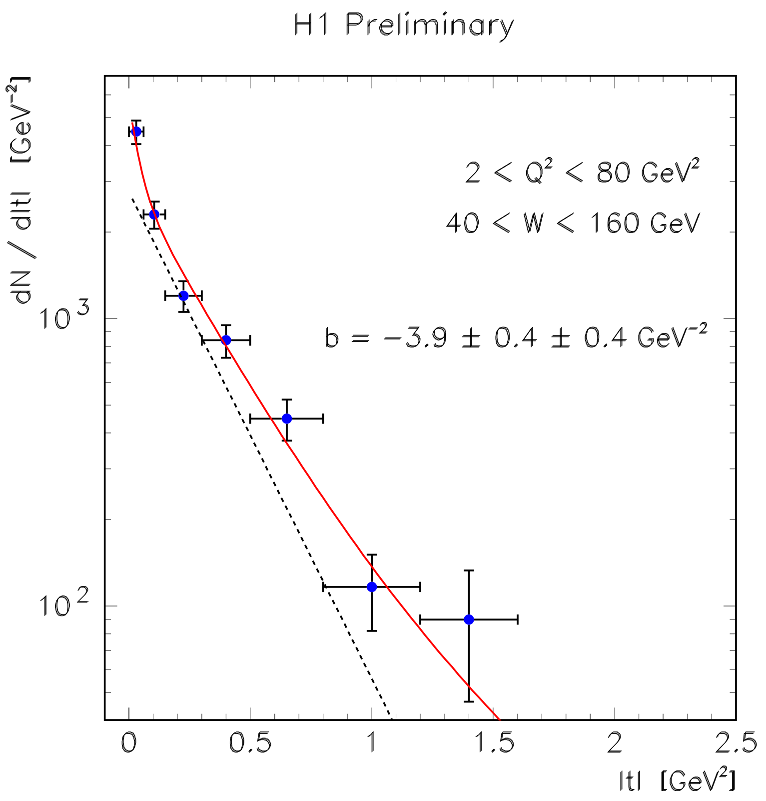


Figure 3: Distribution of $|t|$ for exclusive $J/\psi$ candidates. The vertical bars indicate the statistical error. The full line is a fit to the data, including background contributions. The dashed line is the contribution $\exp(b_{el}|t|)$ from exclusive $J/\psi$ production.

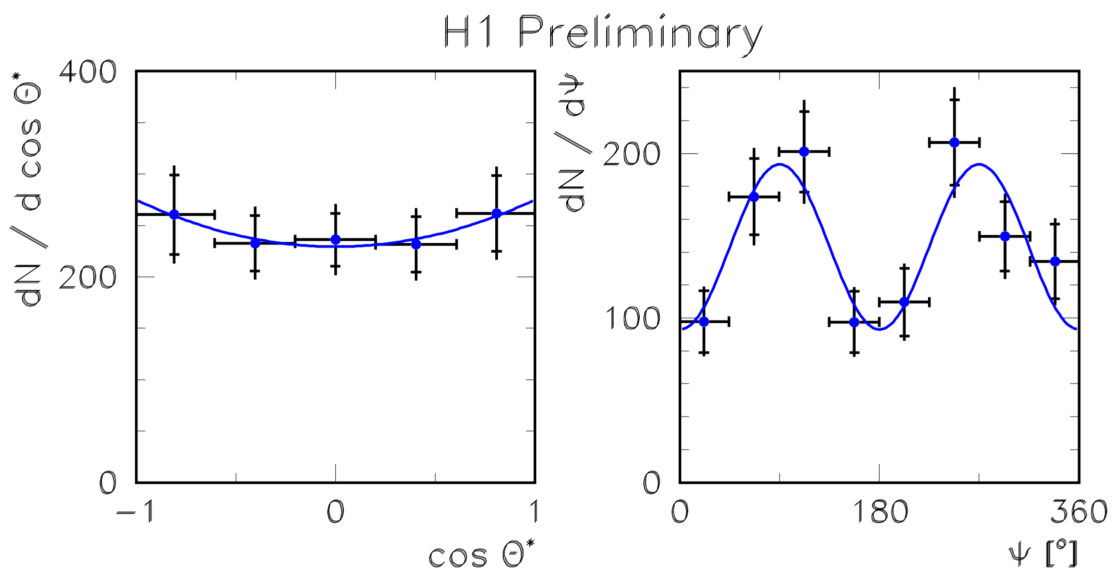


Figure 4: Angular distributions for exclusively produced $J/\psi$ mesons in the kinematic range $40 < W < 160$ GeV and $2 < Q^2 < 80$ GeV$^2$: (a) $\cos\theta^*$, the $J/\psi$ decay angle in the helicity frame; (b) $\Psi$, the polarization angle in the $\gamma^* p$ centre-of-mass frame. The inner vertical bars indicate the statistical errors, while the outer bars show the statistical and systematic errors added in quadrature. The lines are fits to the data with $R$ as a free parameter, as described in the text.

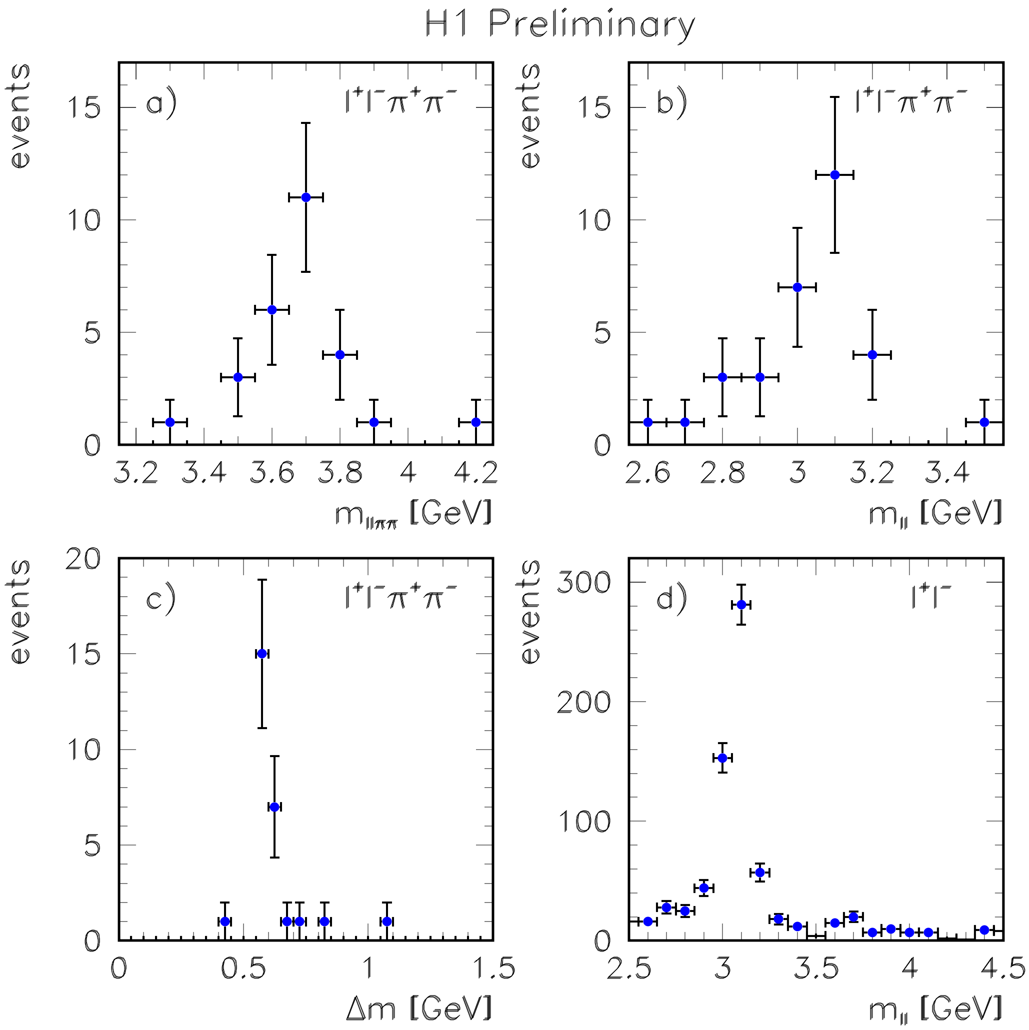


Figure 5: Mass spectra from the analysis of quasi-inelastic $\psi(2S)$ production: (a) mass $m_{ll\pi\pi}$ of the reconstructed $\psi(2S)$; (b) mass $m_{ll}$ of the reconstructed $J/\psi$ from the $\psi(2S)$ decay; (c) mass difference $\Delta m = m_{ll\pi\pi} - m_{ll}$; (d) mass of the reconstructed $J/\psi$ from the reference selection. The vertical bars indicate the statistical error.

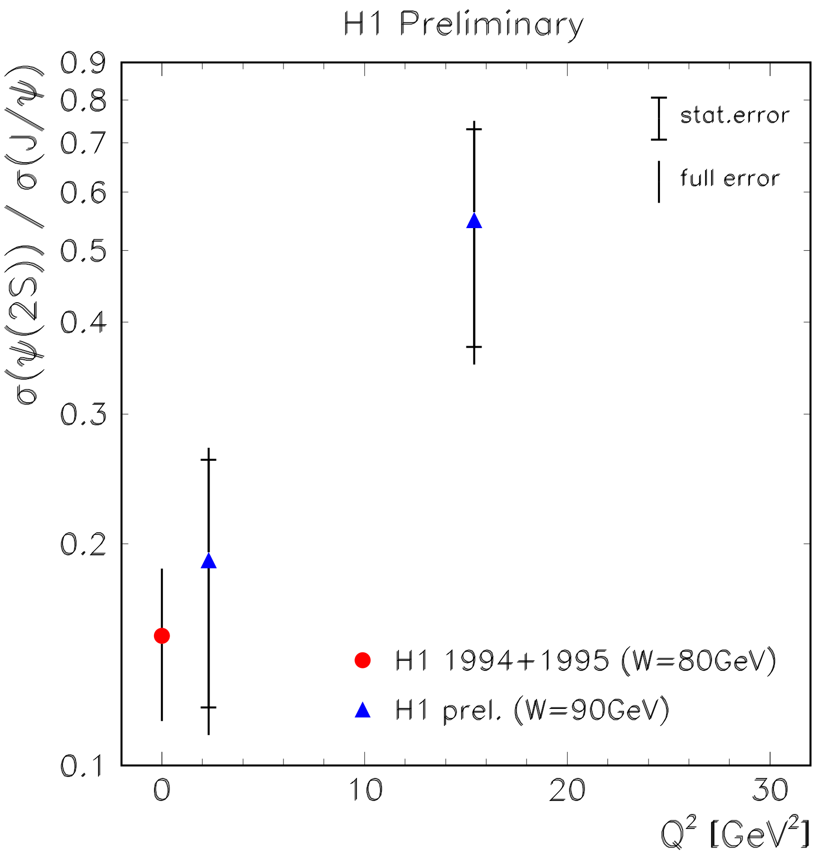


Figure 6: Ratio of cross sections for quasi-elastic $\psi(2S)$ and $J/\psi$ production as a function of $Q^2$. The inner vertical bars on the H1 preliminary points from this analysis indicate the statistical errors, while the outer bars show the statistical and systematic errors added in quadrature.