

Quarkonia production with the HERA – B experiment

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Abstract. Measurements of the dependence of the J/ψ production cross section on its kinematic variables as well as on the target atomic numbers for 920 GeV/c protons incident on different targets have been made with the HERA – B detector. The large collected di-lepton sample allows to study the production ratio of $\psi(2S)$ to J/ψ and of χ_c to J/ψ . We also report on measurements of the $b\bar{b}$ and Υ production cross section.

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1. Introduction

HERA – B is a fixed-target experiment which studies collisions of protons with the nuclei of atoms in target wires positioned in the halo of HERA’s 920 GeV proton beam. The large acceptance of the HERA – B spectrometer coupled with high-granularity particle-identification devices and a precision vertex detector allow for detailed studies of complex multi-particle final states. HERA – B’s sophisticated di-lepton trigger is capable of finding rare interactions containing two leptons coming, for example, from the decay of a J/ψ amidst an overwhelming background of more ordinary proton-nucleus interactions. By using target wires made from a variety of materials (carbon, aluminum, titanium and tungsten) HERA – B is able to study the dependence of various properties of proton-nucleus interactions as a function of atomic number.

Analysis of modest data samples which had been taken in the commissioning run of year 2000 was completed by early 2003 and led to publications on the $b\bar{b}$ cross section [1], the ratio of χ_c to J/ψ production cross sections [2] and on the production cross sections of Λ^0 and K_s^0 [3].

During the HERA run which began in Summer 2002 and ended in March 2003, HERA – B accumulated 150 million events with its di-lepton trigger. The di-lepton sample includes 300,000 events with a J/ψ in the final state, roughly equally divided between di-muon and di-electron decays. This sample is more than 50 times larger than the sample accumulated in the 2000 run, but thanks to the large number of improvements in detector and trigger systems could be recorded in a similar amount of beam time. Thanks to improvements in the data acquisition system, recording rates of a 1000 events

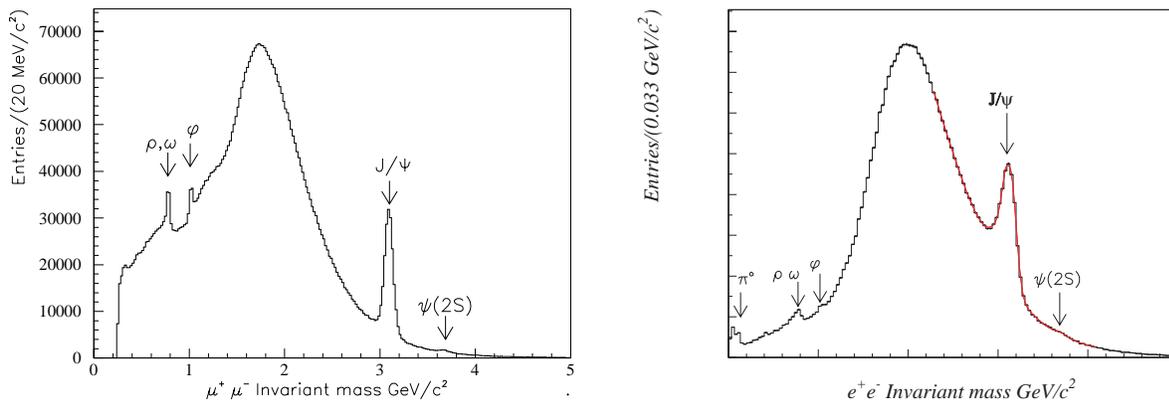


Figure 1. The $\mu^+\mu^-$ (left) and e^+e^- (right) invariant mass spectrum.

per second (more than 1 Terabyte per day) for minimum bias data were achieved which allowed collection of a 200 million events minimum bias sample in just one week of calendar time. This represents an increase in sample size by more than a factor of 100 with respect to the 2000 run. Having successfully accumulated these interesting data samples, the HERA – B Collaboration decided in early 2003 to definitively finish data-taking activities at the end of running period and to concentrate on analyzing the accumulated data. Several studies are in progress on both the di-lepton and the minimum bias samples.

2. Preliminary results

2.1. The Di-lepton sample

The $\mu^+\mu^-$ invariant mass plot from 80% of the full sample is shown in Fig. 1. A prominent peak containing 150,000 di-muon pairs at the mass of the J/ψ is seen. Other features of the plot include peaks at the masses of the $\psi(2S)$, the $\phi(1020)$, the $\omega(782)$ and the $\rho(770)$. The same features, although at lower resolution due to the bremsstrahlung emitted by the electrons, can be seen in the e^+e^- mass plot shown in Fig. 1. The $J/\psi \rightarrow e^+e^-$ peak contains 100,000 events.

2.2. Differential distributions of J/ψ

The large data sample in connection with the large acceptance of the HERA – B spectrometer allows for a precise determination of the kinematical distributions of J/ψ . The p_T -distribution is plotted Fig. 2 for 80% of the e^+e^- sample. Note the wide range of up to 4.8 GeV/c in transverse momentum.

The average p_T is determined by fitting the following expression to the data

$$\frac{d\sigma}{dp_T^2} = \beta \cdot \left[1 + \left(\frac{35 \cdot \pi \cdot p_T}{256 \cdot \langle p_T \rangle} \right)^2 \right]^{-6}.$$

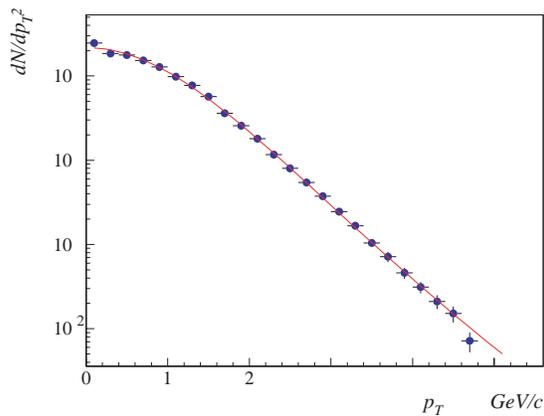


Figure 2. The p_T distribution of $J/\psi \rightarrow e^+e^-$.

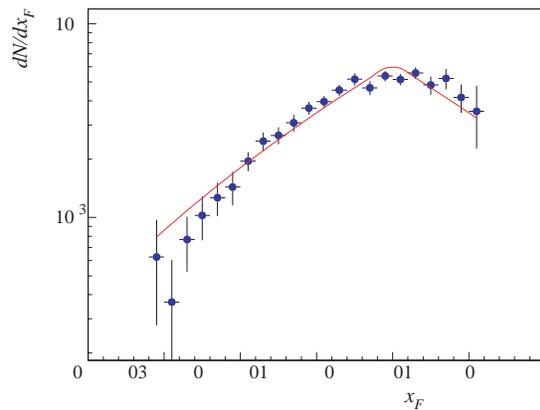


Figure 3. The x_F distribution of $J/\psi \rightarrow e^+e^-$.

The outcome of this analysis can be found in Table 1. The HERA – B data confirm the well known trend of p_T -broadening with increasing atomic number as it was reported during this conference for example by Phenix [4].

Table 1. Average transverse momentum of J/ψ . For the HERA – B results only statistical errors are given.

| Target | Exp. | Range in p_T | $\langle p_T \rangle (e^\pm)$ | $\langle p_T \rangle (\mu^\pm)$ | error |
|--------|----------|----------------|-------------------------------|---------------------------------|-------|
| C 920 | Hera-B | ≤ 4.8 | 1.22 | 1.22 | 0.01 |
| W 920 | Hera-B | ≤ 4.8 | 1.29 | 1.29 | 0.01 |
| Si 800 | E771 [5] | ≤ 3.5 | | 1.20 | 0.01 |
| Au 800 | E789 [6] | ≤ 2.6 | | 1.29 | 0.009 |

The range in x_F of J/ψ which is accessible with the HERA – B detector can be seen from Fig. 3. It is for the first time that J/ψ -production can be measured in the backward region. However, due to still ongoing acceptance calculations, only a small fraction of about 10% of the e^+e^- sample is shown in this plot. In order to compare this distribution with other results, the expression

$$\frac{d\sigma}{dx_F} = \beta \cdot (1 - |x_F|)^c$$

was fitted to our data. For the time being, only a range for the slope c can be quoted (see Table 2).

Due to the simultaneously recorded data sets with carbon and tungsten target, HERA – B is well suited to study the A-dependence of J/ψ -production, which is usually parametrized as

$$\sigma_{pA} = \sigma_{pN} \cdot A^\alpha; \quad \alpha = \frac{1}{\log(A_W/A_C)} \cdot \log \left(\frac{N_W \mathcal{L}_C \epsilon_C}{N_C \mathcal{L}_W \epsilon_W} \right).$$

Table 2. Exponent c of x_F distribution of J/ψ . For the HERA – B results only statistical errors are given.

| Target | Exp. | Range in x_F | $c(e^\pm)$ | $c(\mu^\pm)$ | error |
|----------|----------|----------------------------|------------|--------------|-------|
| C, W 920 | Hera-B | $-0.35 \leq x_F \leq 0.15$ | 5 - 6.5 | | 0.3 |
| Si 800 | E771 [5] | $-0.05 \leq x_F \leq 0.25$ | | 6.54 | 0.23 |
| Au 800 | E789 [6] | $-0.03 \leq x_F \leq 0.13$ | | 4.91 | 0.18 |
| Cu 800 | E789 [7] | $0.30 \leq x_F \leq 0.95$ | | 5.21 | 0.04 |

Thus the measurement of α requires the ratio of the number of observed J/ψ 's, the ratio of luminosities ($\mathcal{L}_{C,W}$) and the ratio of the reconstruction efficiencies ($\epsilon_{C,W}$) for the two different target materials. Up to now, the absolute ratio of luminosities is still under evaluation. Therefore our data points, determined from 25% of the e^+e^- sample (see Fig. 4), were normalized to the E866 result [8] in the overlap region of the x_F distribution.

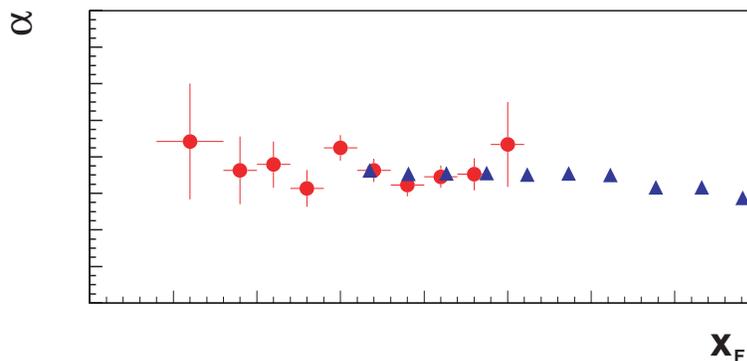


Figure 4. α versus x_F for J/ψ . The HERA – B points were normalized to the E866 data in the region of overlap.

2.3. Production ratio of $\psi(2S)$ to J/ψ

A precise measurement of the $\psi(2S)$ cross section allows to test the importance of color octet production channels [9]. Analyzing 30% of the e^+e^- data sample (Carbon target), a clear $\psi(2S)$ peak can be seen in Fig. 5. In order to minimize systematic uncertainties, the following ratio

$$R_{\psi(2S)} = \frac{\sigma(\psi(2S))}{\sigma(J/\psi)} = \frac{n(\psi(2S))}{n(J/\psi)} \cdot \frac{Br(J/\psi \rightarrow e^+e^-)}{Br(\psi(2S) \rightarrow e^+e^-)} \cdot \frac{\epsilon(J/\psi)}{\epsilon(\psi(2S))}$$

is determined. We obtain a result of $R_{\psi(2S)} = 0.13 \pm 0.02$ which is in good agreement with the result of the Muon channel. For the time being, no systematic error can be quoted because studies are ongoing. Based on results of E771 [10] and E789 [11], we use $R_{\psi(2S)} = (357 \pm 8 \pm 27)$ nb/nucleon [1] to determine the $\psi(2S)$ production cross

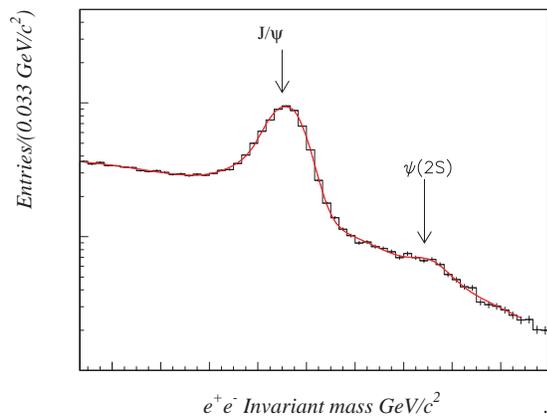


Figure 5. The e^+e^- invariant mass spectrum.

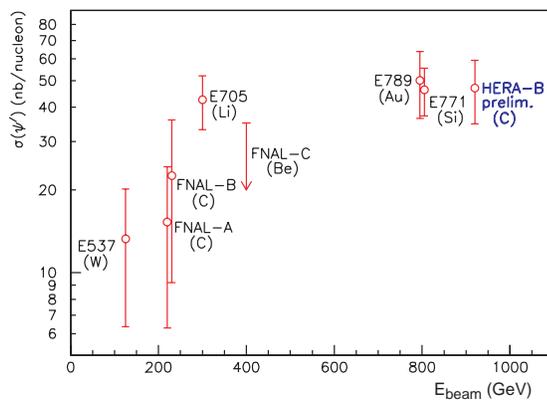


Figure 6. The $\psi(2S)$ cross section as function of the proton beam energy.

section $\sigma(\psi(2S)) = (46 \pm 12)$ nb/nucleon. This preliminary value is shown in Fig. 6 together with results of other experiments.

2.4. Production ratio of χ_c to J/ψ

A measurement of the production ratio of χ_c to J/ψ will help to choose between models [12, 13, 14, 15] attempting to describe the production of quarkonium states. Using the year-2000 data set, HERA – B measured the fraction of J/ψ coming from χ_c decays

$$R_{\chi_c} = \frac{\sum_{i=1}^2 \sigma(\chi_{ci}) \cdot Br(\chi_{ci} \rightarrow J/\psi \gamma)}{\sigma(J/\psi)} = \frac{n(\chi_c)}{n(J/\psi)} \cdot \frac{\epsilon(J/\psi)}{\epsilon(\chi_c) \cdot \epsilon(\gamma)}$$

based on 380 ± 74 reconstructed χ_c mesons to be $R_{\chi_c} = 0.32 \pm 0.06 \pm 0.04$ [2] which is in good agreement with the NRQCD calculations [14]. The state χ_{c0} was neglected due to its small branching ratio. Fig. 7 shows the mass difference $\Delta m = m(1^+1^- \gamma) - m(1^+1^-)$ for 15% of the $\mu^+\mu^-$ data sample recorded during the 2002/03 period. For the full sample over 10,000 reconstructed χ_c mesons are expected in both final states which will lead to a much more precise measurement.

2.5. $b\bar{b}$ Cross Section

A precise measurement of the b cross section in hadronic interactions at fixed target energies would be welcome in part as a test of calculations, in part to give guidance for setting the parameters of the theory [16, 17].

The principle of the HERA – B B cross section determination is to measure the rate of J/ψ 's which originate typically 1 cm downstream of the target and compare it to the rate of directly produced J/ψ 's. Using this technique and the data collected during the

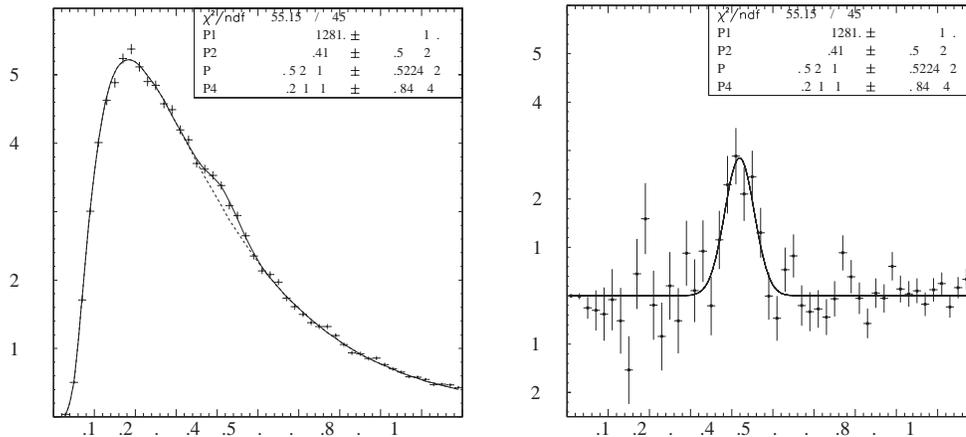


Figure 7. Spectrum of the mass difference $\Delta m = m(l^+l^-\gamma) - m(l^+l^-)$ before (left) and after subtraction (right) of the combinatorial background.

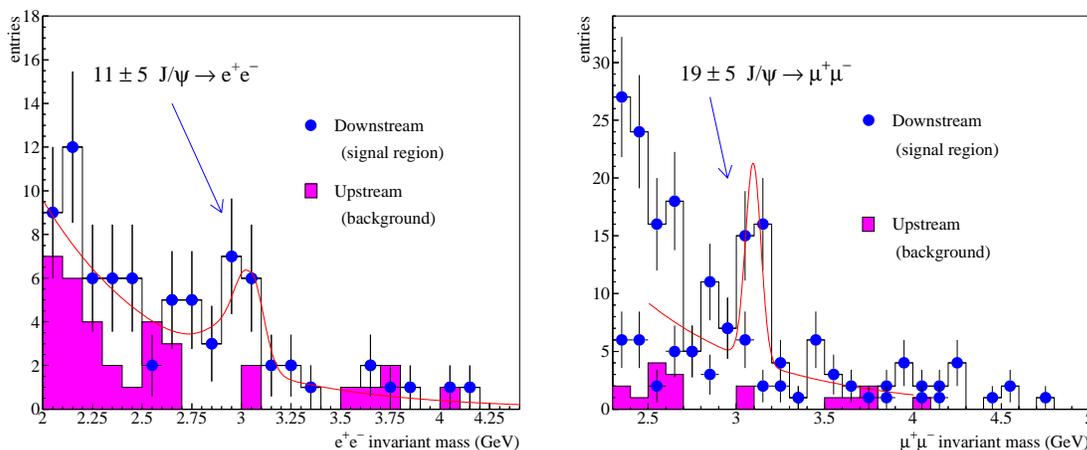


Figure 8. Invariant mass distribution of e^+e^- (left) and $\mu^+\mu^-$ pairs (right) after application of vertex cuts. Points with error bars: lepton pairs downstream of the vertex. Shaded histogram: lepton pairs which, due to finite measurement resolution, appear to originate upstream of the main interaction point.

year-2000 running period, a total $b\bar{b}$ production cross section of $\sigma(b\bar{b}) = (32 \pm 13 \pm 6)$ nb/nucleon was derived. The much larger new sample will allow a considerably more precise measurement. Fig. 8 shows the e^+e^- (left) and $\mu^+\mu^-$ (right) invariant mass spectra from 35% of the data sample after applying vertex cuts to suppress the directly-produced J/ψ 's. The downstream samples clearly show the J/ψ but not the upstream samples. For the full sample we expect approximately 100 J/ψ 's from b decay. Cut optimization and systematic studies are underway. A preliminary estimate of the cross section/nucleon, which is 1.5σ below the 2000 result, is shown in Fig. 9 together with the results of E771 [10] and E789 [11]. The latest QCD calculations [16, 17] are indicated by their central values as well as upper and lower bounds.

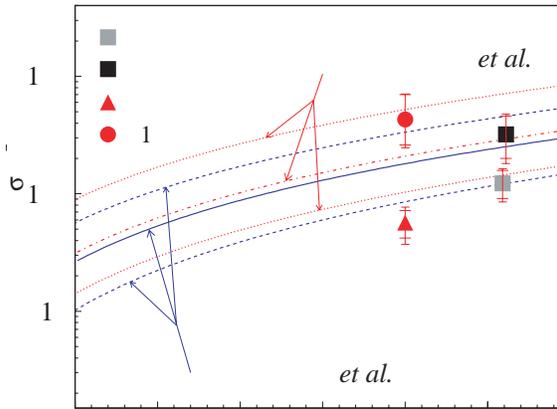


Figure 9. Comparison of the HERA – B results of 2000 and 2004 with other experiments and theoretical predictions.

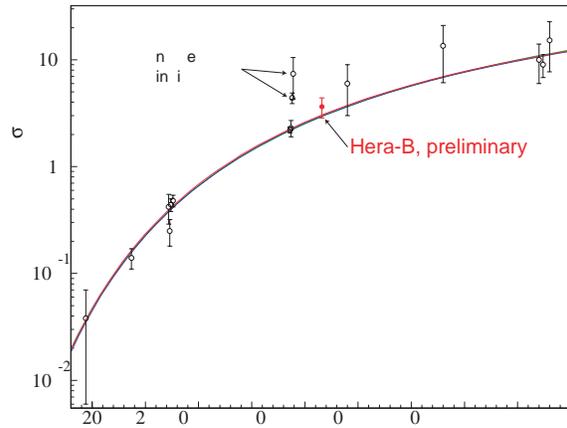


Figure 10. $Br \cdot \frac{d\sigma}{dy}|_{y=0}$ for Υ production as function of the center-of-mass energy. The fit to the data is described in the text.

2.6. Production cross section of Υ

In order to search for Υ -mesons, both C and W data samples were combined assuming an A-dependence of $\alpha = 1$. As can be seen in Fig. 11, an Υ -signal is visible in both $\mu^+\mu^-$ and e^+e^- final states. The shape of the signals was derived from a Monte Carlo simulation with the relative production rates of the three Υ -states fixed on E605 [18] data. The background is described by a term for the combinatorial background and a Drell-Yan term dominating at high invariant masses.

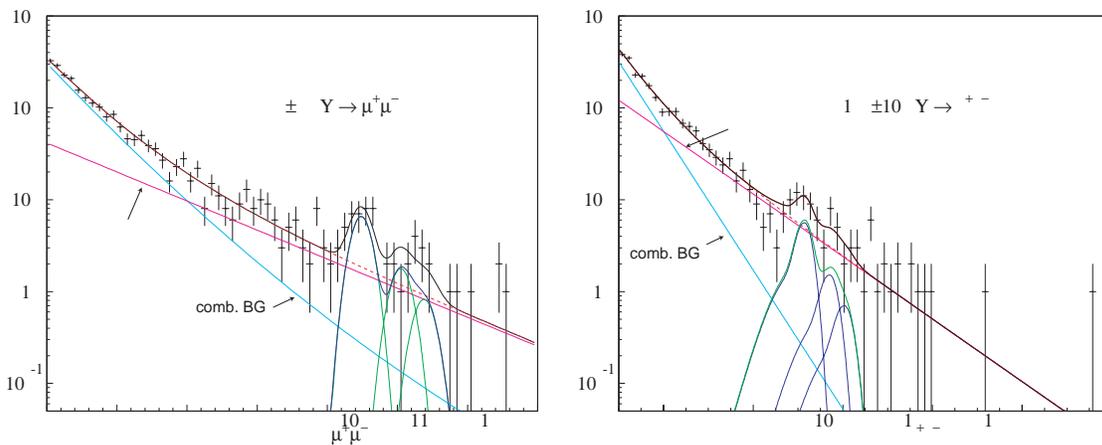


Figure 11. The $\mu^+\mu^-$ (left) and e^+e^- (right) invariant mass spectrum.

As for the previous analyses, the cross section is determined relative to the J/ψ

cross section:

$$\sigma_{\Upsilon} = \sigma(J/\psi) \cdot \frac{n(\Upsilon)}{n(J/\psi)} \cdot \frac{Br(J/\psi \rightarrow \ell^+\ell^-)}{Br(\Upsilon \rightarrow \ell^+\ell^-)} \cdot \frac{\epsilon(J/\psi)}{\epsilon(\Upsilon)}$$

The results of both subsamples are in good agreement. We obtain a combined production cross section times branching ratio at mid-rapidity of $Br \cdot \frac{d\sigma}{dy}|_{y=0} = (3.4 \pm 0.8)$ pb/N. In Fig. 10 the HERA – B measurement is compared to the results of other experiments. The new point from HERA – B will help to clarify the experimental situation which is controversial in the energy regime of $\sqrt{s} \sim 40$ GeV. The energy dependence of the cross section can be described with the parameterization [19] $Br \cdot \frac{d\sigma}{dy}|_{y=0} = \sigma_0 \cdot \exp(-\frac{m_0}{\sqrt{s}})$.

3. Summary

The final data taking period of the HERA – B experiment was used to accumulate 150 million events with its di-lepton trigger. These events were produced in pC and pW interactions of the 920 GeV proton beam of Hera. The di-lepton sample includes 300,000 events with a J/ψ decaying into electron- or muon-pairs. Studies of the dependence of the J/ψ production cross section on its kinematic variables as well as on the target atomic number were shown which turn to advantage the large acceptance in p_T and the backward hemisphere. Preliminary results of the $\psi(2S)$ to J/ψ as well as χ_c to J/ψ production cross section ratios were shown. New results on measurements of the $b\bar{b}$ and Υ production cross section were also discussed.

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