Charmonium and Beauty Production in 920 GeV Proton-Nucleus Collisions

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HERA-B is a fixed-target multi-particle spectrometer experiment at the 920 GeV HERA proton beam at DESY. Approximately 150 million events were recorded with a dilepton trigger during the 2002/2003 HERA run. About 300,000 leptonic $J/\psi \to l^+l^-$ decays (170,000 in the $\mu^+\mu^-$ channel and 130,000 in the e^+e^- channel) have been reconstructed in this data sample. In addition, a huge sample of 220 milion minimum biased triggered events were recorded, allowing an independent measurement of the J/ψ production cross section.

The dilepton triggered samples allow for the first time the study of charmonium production in the negative Feynman-x (x_F) region, and will provide an important input for testing the charmonium production mechanism. Results will be presented on the nuclear dependence of charmonium production, on J/ψ, χ_c and ψ' production and on their differential distributions. Furthermore, the first measurement of the nuclear suppression of charmonium production in the negative x_F region will be presented.

In the field of b-quark physics, the available statistics allows a precise measurement of the inclusive $b\bar{b}$ and of the Υ production cross sections. The $b\bar{b}$ production has been tagged via inclusive b-quark decays into a J/ψ, by exploiting the longitudinal separation of $J/\psi \to l^+l^-$ decay vertices from the primary proton-nucleus interaction. The Υ production cross sections, as measured directly in dimuon and dielectron decay channels, will also be presented.

All results presented in this proceedings are preliminary.

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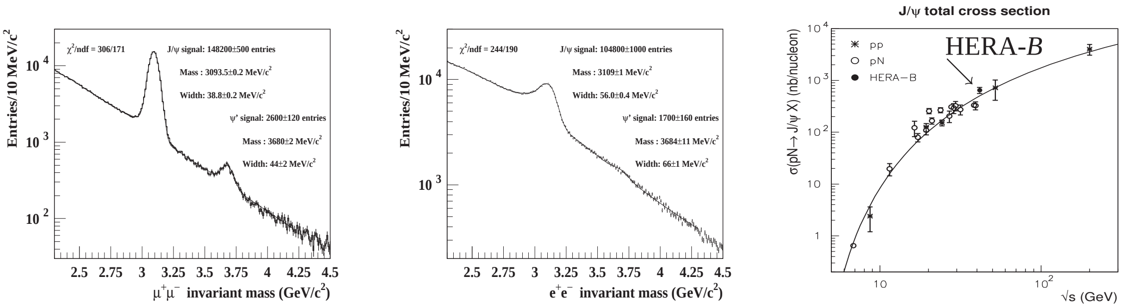

Figure 1: *J/ψ production signal in the invariant mass spectra for both decay channels of triggered data and the determination of the J/ψ reference cross section using minimum biased data from HERA-B and result from other experiments.*

1. Introduction

In the data taking period of 2002/2003 HERA-*B* was routinely running and collected $164 \cdot 10^6$ events applying a dilepton J/ψ–trigger. HERA-*B* is able to reconstruct the decays of J/ψ, ψ', χ_c or Υ either in the $\mu^+\mu^-$ or in the e^+e^- decay channel. In Fig. 1 the J/ψ and ψ' peaks in the invariant mass spectra of the whole data sample are shown, corresponding to a total statistics of $N(J/\psi) \approx 300'000$ and $N(\psi') \approx 5'000$ for both decay channels. The availability of both channels is, besides the increase of statistics, crucial to cross check the results.

The target wires, close to the 920 GeV proton beam of HERA, are made of different materials (Carbon, Tungsten or Titanium) which can be used simultaneously to perform measurements of the dependence on the atomic mass number A and to control systematic effects. This enables a measurement of the nuclear dependence of the J/ψ-production by using two wires of different materials in parallel. In order to minimize the sensitivity to systematic effects from luminosity and Monte Carlo (MC) efficiency determination, all cross section measurements are performed relative to the J/ψ production cross section. In the ratio of cross sections, the luminosity dependence and common systematic effects in the efficiency cancel out. To determine the reference value of $\sigma_{pN}(J/\psi)$ at the HERA-*B* energy, a global analysis has been performed on all published J/ψ cross section measurements including the measurement of HERA-*B* using a sample of $2.3 \cdot 10^8$ minimum bias triggered events, which are independent from the J/ψ triggered data [1] (Fig. 1, right). The best value, obtained from a fit on $\sigma_{J/\psi}(\sqrt{s})$ with the help of a non relativistic QCD model including color octet (NRQCD), is

$$\sigma_{J/\psi}(\sqrt{s} = 41.6\,\text{GeV}) = (501 \pm 44)\,\text{nb/nucleon} \tag{1.1}$$

at the energy of HERA–*B* of $\sqrt{s} = 41.6\,\text{GeV}$. This value will be used for all further analyses as reference cross section.

2. Charmonium Production

The nuclear dependence of the J/ψ production can be measured with low systematic uncertainty by using two different targets with different materials (carbon and tungsten) simultaneously:

$$\sigma(pA \to J/\psi X) = A^{\alpha} \cdot \sigma(pN \to J/\psi X) \;\Rightarrow\; \alpha = \frac{1}{\ln(A_\text{W}/A_\text{C})} \cdot \ln\left(\frac{N(J/\psi)_\text{W}}{N(J\psi)_\text{C}} \cdot \frac{\mathscr{L}_\text{C}}{\mathscr{L}_\text{W}} \cdot \frac{\varepsilon_\text{C}}{\varepsilon_\text{W}}\right) \tag{2.1}$$

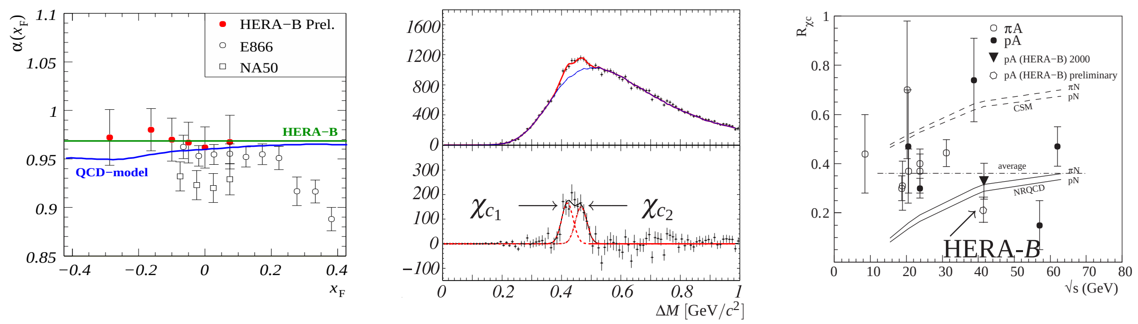

Figure 2: *First measurement of the nuclear dependence α in the negative x_F region, the $\chi_C \to J/\psi\gamma$ reconstruction using the mass difference ΔM and comparison of the production ratio R_{χ_c} to various models.*

A possible suppression of the J/ψ production by nuclear effect leads to $\alpha < 1$. HERA-*B* is the first fixed target experiment covering the region of negative Feynmann-x ($x_F = \frac{p_L^{\text{cms}}}{(p_L^{\text{cms}})_{\max}}$) in the range of $x_F \in [-0.35, 0.15]$. The negative x_F region corresponds to small forward momenta of the produced $c\bar{c}$ pair corresponding to a formation of the J/ψ inside the nucleus. The measurement of HERA-*B* is compatible with a constant small suppression with $\alpha = 0.969 \pm 0.003_{\text{stat}} \pm 0.021_{\text{sys}}$ (Fig. 2, left). This is in good agreement with the theoretical predictions [2].

Beside the J/ψ, a clear peak of the ψ' state is detected at $M \approx 3.7\,\text{GeV}/c^2$ (Fig. 1). The study of the ψ' to J/ψ production ratio in proton nucleus interactions is a good framework to compare the existing models of charmonium production and of charmonium absorption in nuclear matter. The ratio is given by

$$R_{\psi'} = \frac{BR(\psi' \to l^+l^-) \cdot \sigma(\psi')}{BR(J/\psi \to l^+l^-) \cdot \sigma_{J/\psi}} = \frac{N_{\psi'}}{N_{J/\psi}} \cdot \frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi'}} \tag{2.2}$$

First preliminary results from the μ channel give $R_{\psi'} = (1.797 \pm 0.068_{\text{stat}} \pm 0.030_{\text{sys}})\,\%$. The measurements have also been done individually for the various target materials leading to $R(\text{C}) = (1.664 \pm 0.068_{\text{stat}} \pm 0.030_{\text{sys}})\,\%$ (Carbon, $A = 12.01$, 65 % of total statistics), and $R(\text{W}) = (1.584 \pm 0.113_{\text{stat}} \pm 0.029_{\text{sys}})\,\%$ (Tungsten, $A = 183.85$, 31 % of total statistics). These results are in good agreement with previous measurements from other experiments.

A measurement of the production ratio of χ_c to the J/ψ production is an other important tool to discriminate between different models [2, 3, 4, 5] for quarkonium production. HERA-*B* has access to these states via the radiative decay channel $\chi_c \to J/\psi\gamma \to l^+l^-\gamma$ selecting the χ_c using the mass difference $\Delta M = M(l^+l^-\gamma) - M(l^+l^-)$. The background is determined by event mixing and subtracted from the spectrum, leading to the lower ΔM distribution in the middle of Fig. 2. Using a signal description consisting of two Gaussian the two states χ_{c_1} and χ_{c_2} can be separated in the μ-decay channel. The production ratio R_{χ_c}

$$R_{\chi_c} = \frac{\sum_{i=1}^{2} \sigma(pA \to \chi_{c,i}) \cdot BR(\chi_{c,i} \to J/\psi\gamma)}{\sigma(pA \to J/\psi)} = \frac{N_{\chi_c}}{N_{J/\psi}} \cdot \frac{\varepsilon_{J/\psi}}{\varepsilon_{\chi_c}} \cdot \frac{1}{\varepsilon_\gamma} \tag{2.3}$$

has found to be $R_{\chi_c} = 0.21 \pm 0.05_{\text{stat}}$ using the data from the μ-channel only. This ratio can be used to test various QCD models for charmonium formation. As can been seen in Fig. 2 the Color Singlet Model (CSM) is disfavored with respect to the NRQCD model.

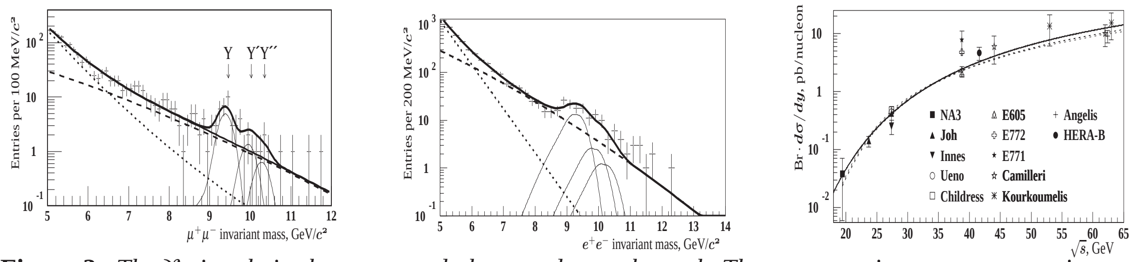

Figure 3: *The Υ signals in the muon and electron decay channel. The cross section measurement is compared to the Craigie parameterization (line, [7]) and to an NLO calculation (dotted line, [10]).*

3. Beauty Production

The Υ production cross section is determined, as in the case of χ_c and the ψ', by comparing the relative yields of Υ and J/ψ production with subsequent normalization to the known J/ψ cross section (Eq. 1.1), again using both leptonic decay channels (Fig. 3):

$$BR(\Upsilon \to l^+l^-) \cdot \frac{d\sigma}{dy}(\Upsilon)\Big|_{y=0} = BR(\Upsilon \to l^+l^-) \cdot \sigma_{J/\psi} \cdot \frac{N_\Upsilon}{N_{J/\psi}} \frac{\varepsilon_{J/\psi}}{\varepsilon_\Upsilon} \frac{1}{\Delta y_{\mathrm{eff}}} \tag{3.1}$$

Here, the efficiencies ε are determined from MC simulations and Δy_{eff} is the coefficient relating the full and the differential Υ production cross section at mid rapidity $y = 0$ via $\sigma = \Delta y_{\mathrm{eff}} d\sigma/dy|_{y=0}$. The signal determination in the invariant mass spectra (Fig. 3) uses a Gaussian shape for signal description and a combination of combinatorial background (dotted lines) and Drell-Yan (dashed lines) for the background shape. The relative production fraction of $\Upsilon(1S) : \Upsilon(2S) : \Upsilon(3S)$ is fixed at the values measured by E605 [6]. The measurements in the electron and muon channel are compatible and lead to a combined result of

$$BR(\Upsilon \to l^+l^-) \cdot \frac{d\sigma}{dy}\Big|_{y=0} = (4.7 \pm 1.1)\,\mathrm{pb/nucleon} \tag{3.2}$$

In Fig. 3 the HERA-B measurement is compared with results of previous experiments and found to be in good agreement. All measurements are fitted using the Craigie parameterization $f(\sqrt{s}) = \sigma_0 \cdot \exp(-m_0/\sqrt{s})$ and yielding $\sigma_0 = (182 \pm 21)\,\mathrm{pb/nucleon}$ and $m_0 = (167 \pm 4)\,\mathrm{GeV}$ [7].

The $b\bar{b}$ production cross section is also measured relative to prompt J/ψ production cross section using the inclusive $b \to J/\psi X$ decay channel to tag the b-flavored events. Within the HERA-B acceptance, the $b\bar{b}$ cross section ratio is:

$$R_{\Delta\sigma} = \frac{\Delta\sigma(b\bar{b})}{\Delta\sigma_{J/\psi}} = \frac{n_{b\bar{b}}}{BR(b\bar{b} \to J/\psi X) \cdot \sum_i n^i_{J/\psi} \cdot \varepsilon^i_R \cdot \varepsilon^i_{\Delta z, b\bar{b}} \cdot A_i^{\alpha_b - \alpha}} \tag{3.3}$$

where $n_{b\bar{b}}$ is the total number of J/ψ events with a detached vertex found in the acceptance, $n^i_{J/\psi}$, ε^i_R, and $\varepsilon^i_{\Delta z, b\bar{b}}$ are, respectively, the number of prompt J/ψ decays, the b to prompt J/ψ selection efficiency ratios and the detached vertex selection efficiencies measured on the subsample i taken with a target of the atomic weight A_i. The $b\bar{b}$ cross section in full phase space is then evaluated as $\sigma(b\bar{b}) = R_{\Delta\sigma} \cdot \Delta\sigma_{J/\psi}/f_{b\bar{b}}$, where $f_{b\bar{b}} = (90.6 \pm 0.5)\,\%$ is the fraction of J/ψ mesons from b decays in the HERA-B acceptance range. The b hadrons decaying into J/ψ are selected from the large background of J/ψ mesons produced directly at the target by exploiting the b lifetime in a detached

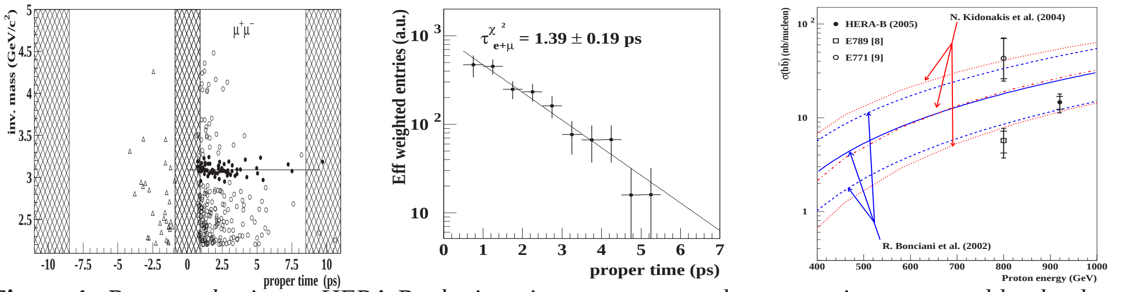

Figure 4: *Beauty selection at HERA-B: the invariant mass versus the proper time measured by the decay length, the life time measurement and the comparison of the inclusive cross section measurement of $\sigma(b\bar{b})$ to theoretical models and other experiments.*

vertex analysis making use of the average decay length of 8000 μm and the vertex resolution of the Silicon Vertex Detector of 450 μm. The life time measurement of the detached candidates is a clear signature for the b flavor origin of the decay. In Fig. 4 the scatter plot of the dilepton mass versus the proper time and the proper-time of the detached J/ψ events are shown. The mean life time of $\tau = (1.39 \pm 0.16)$ ps is in good agreement to the expected value for b hadrons.

The total $b\bar{b}$ production cross section analysis has been done separately for both decay channels and the results are combined by a joint unbinned maximum likelihood fit using $R_{\Delta\sigma}$ as free parameter providing the final value of $R_{\Delta\sigma} = 0.032 \pm 0.005_{\text{stat}} \pm 0.004_{\text{sys}}$ [12]. To compare the result to other experiments and theoretical prediction, the ratio has been extrapolated to the full phase space and the reference $\sigma_{J/\psi}$ cross section (Eq. 1.1) was used:

$$\sigma(b\bar{b}) = (14.9 \pm 2.2_{\text{stat}} \pm 2.4_{\text{sys}})\,\text{nb}/\text{nucleon} \tag{3.4}$$

This result, based on 83 well selected b events, can be compared with the available measurements obtained in pAu (E789) [8] and pSi (E771) [9] at 800 GeV proton momentum (Fig. 4, right). After correction for the different CMS energies [11], the result of HERA-B is consistent within $1.8\,\sigma$.

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