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QUARKONIA PRODUCTION WITH LEPTONS AND HADRONS

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ABSTRACT

We discuss current issues and present the latest measurements on quarkonia production from experiments monitoring hadron-hadron and lepton-hadron collisions. These measurements include cross section and polarization results for charmonium and bottomonium states.

1 Introduction

The study of quarkonia has yielded valuable insight into the nature of strong interactions since the discovery of the J/ψ in 1974. Heavy quarkonia states, $c\bar{c}$ and $b\bar{b}$, provide very useful systems for the study of both perturbative and non perturbative QCD. As far as the strong interactions are concerned, heavy quarkonia are the next simplest particles (probes) after leptons and electroweak gauge bosons. In addition, the charmonium and bottomonium systems exhibit a rich spectrum of orbital and angular excitations and therefore they can potentially provide more information than leptons and electroweak gauge bosons.

The experimental results reported in this review come from $p\bar{p}$ collisions at $\sqrt{s} = 1.96(1.8)$ TeV (CDF and D0 experiments at Fermilab), from collisions of 800 GeV protons with a fixed target (E866 experiment at Fermilab), from $e^{\pm}p$ collisions at $\sqrt{s} = 319(301)$ GeV (H1 and Zeus experiments at DESY) and from collisions of 920 GeV protons with a fixed target (HERA-B experiment at DESY).

This paper is organized as follows. In sections 2 and 3 we describe results from the CDF, D0, E866 Fermilab experiments and from the H1, Zeus, HERA-B DESY experiments respectively and we compare them to current theoretical expectations. In section 4 we discuss conclusions and prospects.

2 Results from the Fermilab Tevatron

The Fermilab Tevatron has operated in the past several years either in a collider mode or in a fixed target mode. In the collider mode 900(980) GeV/c protons collide with antiprotons of the same energy while in the fixed target mode, 800 GeV protons hit a fixed target.

From August 1992 to February 1996 (Run I) the CDF and D0 detectors collected data samples of approximately 110 pb^{-1} each of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. In Run I the crossing time was 3.5 μs for 6 bunches and the typical luminosity of order 10^{31} cm^{-2}sec^{-1}. Run II physics quality data started in March 2002. By September 2003, the CDF and D0 upgraded detectors collected data samples of approximately 240 pb^{-1} each of collisions at $\sqrt{s} = 1.96$ TeV. In Run II the crossing time is 396 ns for 36 bunches and the typical luminosity so far of order 4 x 10^{31} cm^{-2}sec^{-1}.

The E866/NuSea experiment ran for a period of approximately six months during 1996-1997 in the Fermilab Meson-East area at an energy of $\sqrt{s} = 38.8$ GeV.

2.1 Results from the CDF and D0 experiments

2.1.1 Cross sections

The CDF collaboration has previously reported results on the production of J/ψ and $\psi(2S)$ mesons[1, 2]. The measured cross sections for direct production were of the order of 50 times larger than predicted by the Color Singlet Model (CSM)[3]. However calculations based on the NRQCD factorization formalism[4, 5] are able to account for the observed cross sections for $p_T > 5$ GeV/c by including color octet production mechanisms.

Using Run I data CDF has also reported[6] production cross section results of inclusive $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states in the region $0 < p_T < 20$ GeV/c. In addition, it has reported[7] on the fraction of $\Upsilon(1S)$ mesons originating from $\chi_b(1P)$, $\chi_b(2P)$, $\chi_b(3P)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and from direct production for $p_T^{\Upsilon} > 8$ GeV/c. The rate of inclusive Υ production for all three states was found to be higher than color-singlet QCD calculations by a factor of about 5 for $p_T > 4$ GeV/c. Inclusion of color-octet production mechanisms within the NRQCD framework can account for the observed cross section for $p_T >$8 GeV/c. The theoretical prediction for the cross sections diverges at low p_T while the data turn over and approach zero[5, 8].

The amplitude for each $c\bar{c}$ or $b\bar{b}$ state with definite colour and angular momentum factorizes into a short distance term which can be calculated in NRQCD and a long distance matrix element (LDME) describing the transition to a bound quarkonium state. The LDMEs are not calculable and have been determined from Tevatron data where the Color Octet contributions were found to be sizable. These matrix elements are expected to be universal and can in principle be used in the theoretical predictions for HERA and LEP results.

At large transverse momenta, fragmentation type production is expected to dominate and color-octet matrix elements dominate the color-siglet matrix element contribution. At low transverse momenta, soft gluon effects and non-fragmentation effects from other octet matrix elements that are difficult to calculate theoretically become important and cause theory predictions and data to diverge (see discussion above on the CDF Υ data). The Run-II CDF detector has an improved dimuon trigger with a lower p_T threshold of > 1.4 GeV/c. This has extended the low transverse momentum range of triggered $J/\psi, \psi(2S) \to \mu\mu$ events down to $p_T(\mu\mu) \geq$ 0 GeV/c.

Using a 39.7 pb^{-1} data sample of Run II, CDF measured the inclusive J/ψ cross section for $J/\psi \to \mu^+\mu^-$ decays[9]. A p_T dependent differential cross section (figure 1, left) has been calculated for events with rapidity $|y| < 0.6$ for p_T as low as 0.0 GeV/c. The total integrated cross section for inclusive J/ψ production in $p\bar{p}$ interactions at $\sqrt{s}$ = 1.96 GeV/c^2 is measured to be $240 \pm 1(stat)^{+35}_{-28}(syst)$ nb. These measurements await comparison with updated theoretical calculations in the low p_T region.

Using a sample of 4.7 pb^{-1} of Run II data the D0 collaboration has verified that the J/ψ cross section is independent of the rapidity of the J/ψ for a rapidity range between $0 < |y| < 2$. This check has been performed for $p_T > 5$ GeV/c and $p_T > 8$ GeV/c[10].

Using 37 pb^{-1} of the Run II data CDF performed as well a measurement[9] of the p_T dependent differential (figure 1, right) and integrated inclusive b-hadron production cross section in the decay channel $H_b \rightarrow J/\psi X$, where H_b denotes all b hadrons that decay into J/ψ. The first measurement of the total b-hadron cross section at a hadronic machine has been extracted and was found to be

$$\sigma(p\bar{p} \rightarrow H_b X, |y| < 0.6) Br(H_b \rightarrow J/\psi X) Br(J/\psi \rightarrow \mu\mu) = 24.5 \pm 0.5(stat) \pm 4.7(syst) nb \quad (1)$$

The total single b-quark cross section integrated over one unit of rapidity was found to be

$$\sigma(p\bar{p} \rightarrow \bar{b}X, |y| < 1.0) = 29.4 \pm 0.6(stat) \pm 6.2(syst) \mu b \quad (2)$$

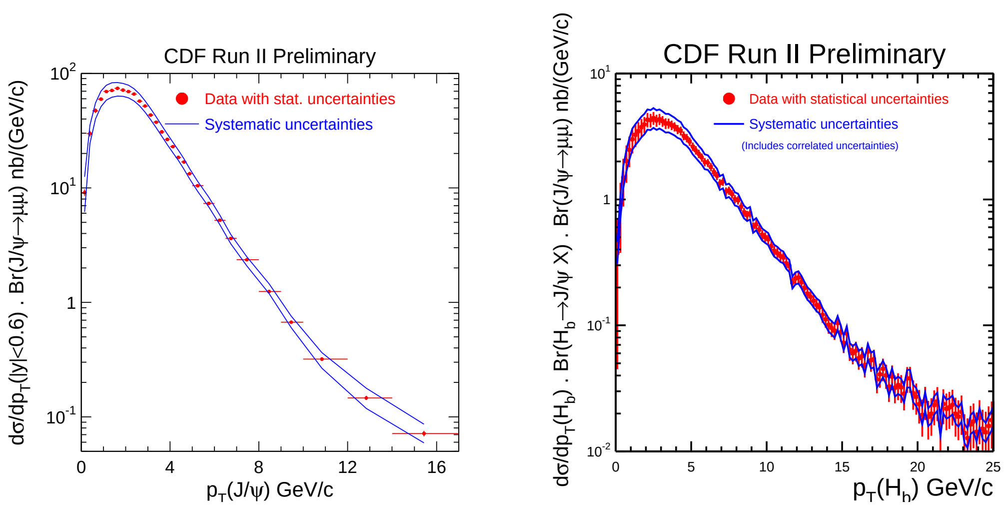

Figure 1: *The differential $p\bar{p} \rightarrow J/\psi X$ cross section as a function of $p_T(J/\psi)$ (left) and the differential $H_b \rightarrow J/\psi X$ cross section as a function of $p_T(H_b)$ (right).*

Using Run I data CDF has measured[2] as well the fraction of J/ψ mesons originating from χ_c meson decays. It has also measured[11] the relative rate of

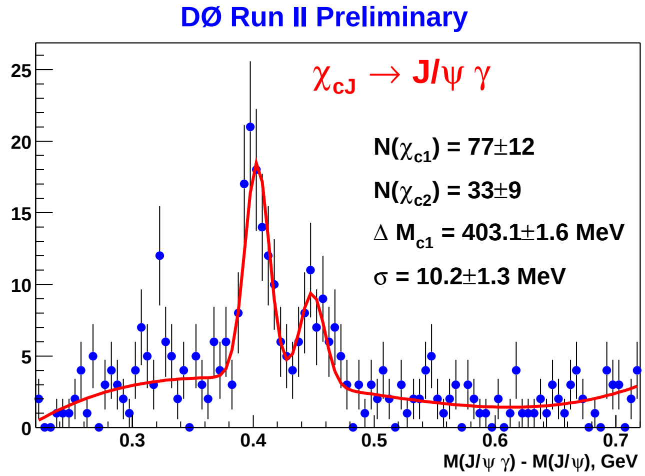

Figure 2: *The $M(J/\psi\gamma) - M(J/\psi)$ distribution from Run II D0 data. The χ_{c1} and χ_{c2} states are observed via their decays into $J/\psi\gamma$ where the photon is reconstructed through conversions into e^+e^- pairs.*

production of the charmonium states χ_{c1} and χ_{c2} through their decay into $J/\psi\gamma$ where the photon from the decay is reconstructed through conversion into e^+e^- pairs. This makes the resolution of the two states possible. The CDF result appears to prefer an approximately equal production of the two χ_{cJ} states, although it is consistent with the expectation that the cross sections are proportional to $(2J+1)$ at high $p_T(\chi_{cJ})$. Both the CDF and D0 colalborations are pursuing these analyses further with Run II data. In figure 2 we show the charmonium states χ_{c1} and χ_{c2} reconstructed from a sample of 114 pb^{-1} of Run II data collected with the D0 detector[10]. These states are observed via their decays into $J/\psi\gamma$ where the photon is reconstructed through conversions.

CDF has also searched for the η_b(1S) state via the $\eta_b \to J/\psi J/\psi$; $J/\psi \to \mu\mu$ decay channel using approximately 100 pb^{-1} of Run I data. A small cluster of 7 events was observed in the search window of 9.36 to 9.46 GeV/c^2 while 1.8 background events were expected. The probability that the background could mimic the data was assessed to be 1.5%. A simple fit to the mass of the cluster gave 9455±6(stat) MeV/c^2. Since the cluster of events was small, a 95% C.L. upper limit on $\sigma_{\eta_b}(|y| < 0.4)Br(\eta_b \to J/\psi J/\psi)[Br(J/\psi \to \mu\mu)]^2$ was calculated, giving 18 pb with an 11% relative systematic uncertainty. Run II data will be used to repeat this search and improve the limit or make an observation.

2.1.2 *Polarization*

Within NRQCD[4, 5] it is predicted that directly produced J/ψ, ψ(2S) or Υ mesons will be increasingly transversely polarized at high p_T.

CDF has measured with Run I data the polarization of the J/ψ, ψ(2S) and Υ(1S) states decaying into two muons. The muons from the decay of the above mesons are assumed to have an angular distribution proportional to $1 + \alpha cos^2(\theta^*)$ where θ^* is the polar angle in the rest frame of the meson. The variable α is defined as $\alpha = (\sigma_T - 2\sigma_L)/(\sigma_T + 2\sigma_L)$ where σ_T and σ_L are the cross sections for transversely and longitudinally polarized states respectively and can vary between ±1. Unpolarized mesons have $\alpha = 0$, while $\alpha = +1$ or -1 correspond to fully transverse or longitudinal polarizations respectively.

CDF has measured the J/ψ and ψ(2S) polarizations using 110 pb^{-1} of Run I data and the Υ(1S) polarization using 77 pb^{-1} of Run I data. In figure 3 (left) we show the measurement[12] of the polarization variable α for prompt J/ψ's and for J/ψ's originating from B decays. These polarization measurements at $\sqrt{s}$ =1.8 TeV indicate that the polarization from B decays is generally consistent with zero, as expected. In both the J/ψ and ψ(2S) cases, CDF does not observe increasing prompt transverse polarization for $p_T \geq 12$ GeV/c. Although the measurements are limited by statistics, especially the ψ(2S), they appear to indicate that no large transverse transverse prompt polarization is present at high p_T, in disagreement with NRQCD factorization predictions.

In figure 3 (right) we show the measurement[6] of the polarization variable α for inclusive Υ(1S). α is predicted to be small for p_T less than 10 GeV/c but is increasing steadily with p_T. The prediction is compatible with the CDF measurement of $\alpha = 0.03 \pm 0.28$ for p_T in the range from 8 GeV/c to 20 GeV/c. The Υ(1S) data are consistent with unpolarized production in the region $0 < p_T < 20$ GeV/c. Although the Run I CDF data did not provide sufficient information for $p_T > 20$ GeV/c this should be possible with Run II data. In Run II it should be also possible to measure the polarizations of the Υ(2S) and Υ(3S) states. This would be particularly interesting in view of the Υ polarization measurements from the fixed target Fermilab experiment E866 discussed in the following section.

2.2 Results from the E866/NuSea experiment

The E866 experiment has studied the production of dimuons in the collision of 800 GeV/c protons with a copper beam dump. Among other interesting results, they derived polarizations from the angular distribution of 2 million dimuons in the range

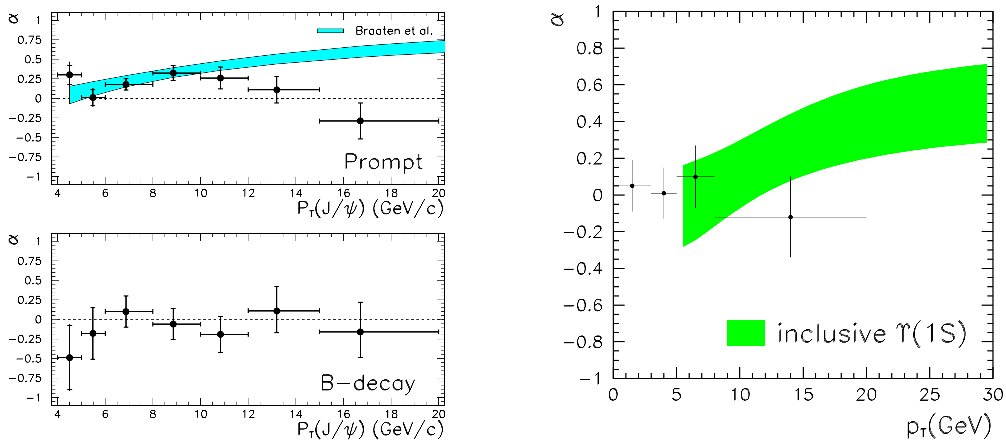

Figure 3: *Polarization variable α for inclusive J/ψ mesons from prompt production and B-hadron decay. The shaded band shows an NRQCD prediction[13] which includes the contribution from χ_c and ψ(2S) decays (left). Polarization variable α for inclusive Υ(1S) states from CDF Run I data as a function of Υ(1S) p_T. The theoretical band represents the NRQCD prediction[14] (right).*

$8.1 < m_{\mu^+\mu^-} < 15.0$ GeV. The data cover the kinematic range $0.0 < x_F < 0.6$ and $p_T < 4.0$ GeV/c. In figure 4 we show the polarization variable α as a function of p_T and x_F. The Υ(1S) data show almost no polarization at small x_F and p_T. The data show a finite transverse polarization at either large p_T or large x_F. This observation disagrees with an NRQCD calculation that predicts a polarization in the range of 0.8-0.31 (averaged over x_F and p_T) for these energies[15]. A fit to the Υ(1S) state for a polarization independent of x_F and p_T gives $\alpha = 0.07 \pm 0.04$. The observation that the polarization of the cross-section-weighted average of the Υ(2S+3S) states is much larger than that of the Υ(1S) state at all x_F and p_T contrasts sharply with what is seen in the charmonium system[12].

3 Results from HERA at DESY

At the HERA storage ring at DESY electrons or positrons of 27.6 GeV and protons of 920 GeV (820 GeV before 1998) collide resulting in a center of mass energy $\sqrt{s}$ of 319 GeV (301 GeV). The HERA I running period ended in September 2000 after having delivered to the H1 and Zeus experiments over $100 pb^{-1}$ of data. The HERA-B experiment operated at the same ring as a fixed target experiment. It studied charmonium and other heavy flavor states by inserting wire targets into the halo of the 920 GeV proton beam circulating in the HERA ring.

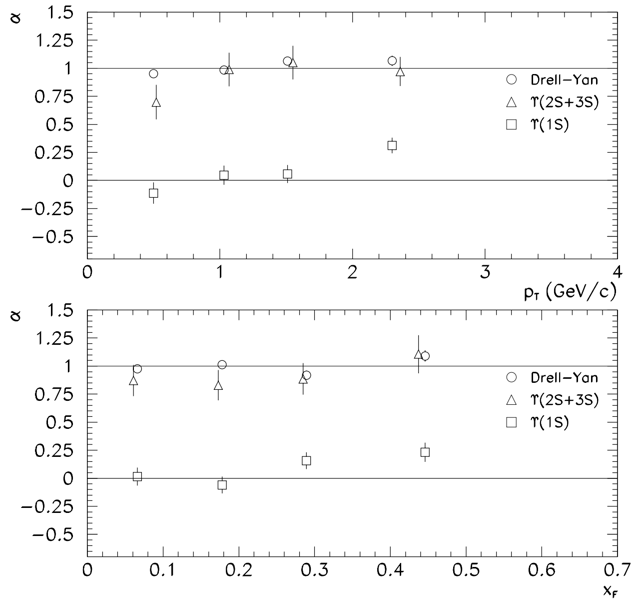

Figure 4: *α vs p_T for the Drell-Yan sidebands and the Υ(1S) and Υ(2S+3S) regions (top). α vs x_F for the same mass regions (bottom). The errors shown are statistical; there is an additional systematic error not shown of 0.02 in α for Drell-Yan polarizations and 0.06 in α for quarkonium polarizations.*

3.1 Results from the H1 and Zeus experiments

The production of J/ψ mesons, $ep \to eJ/\psi X$ has been studied intensively at HERA. In ep collisions quarkonia are predominantly produced via the photon gluon fusion mechanism, where a photon emmited by the incoming electron interacts with a gluon in the proton forming a quark-antiquark pair. The high available energy allows the contributing mechanisms to be studied in a wide kinematic range in both Q^2 and $W_{\gamma p}$ where Q^2 is the negative squared four-momentum of the exchanged photon and $W_{\gamma p}$ is the center of mass energy of the photon-proton system. The major contribution in this production mechanism is due to the exchange of almost real photons corresponding to a photon virtuality $Q^2 \approx 0$ (photoproduction). In deep inelastic scattering (DIS) Q^2 is large, often defined experimantally by $Q^2 > 2$ GeV^2.

Previous HERA measurements on quarkonia production show good agreement with the colour singlet model (CSM), but small colour octet contributions could not be ruled out.

Recent results in photoproduction and in a large kinematic region from H1[16] and Zeus[17] are shown in figure 5. Photon-proton cross sections $\sigma_{\gamma p}$, $d\sigma/dz$

and $d\sigma/dp_{t,\psi}^2$ are shown in the range $0.3 < z < 0.9$ where z is the fraction of the photon energy transferred to the J/ψ meson in the proton rest frame. There is good agreement between the two experiments. The data are also well described by the NLO CSM calculations[18]. In contrast, the LO calculation is too steep in $p_{t,\psi}^2$.

In figure 6 we show the differential J/ψ cross section from photoproduction as a function of z. The distribution can be described in the full range of z by LO NRQCD calculations[18].

Inelastic electroproduction of J/ψ mesons[16] is studied in the region $2 < Q^2 < 100$ GeV^2 for $0.3 < z < 0.9$ and for $p_{t,\psi}^{*2} > 1$ GeV^2, where $p_{t,\psi}^{*2}$ is the squared transverse momentum of the J/ψ meson in the photon-proton center of mass system. In figure 7 we show the differential J/ψ electroproduction cross section from H1 as a function of Q^2 and $p_{t,\psi}^{*2}$. Neither the full NRQCD calculation[19] nor the colour singlet part can describe the data in normalization over the full range. A high Q^2 and $p_{t,\psi}^{*2}$ agreement with the full NRQCD calculation is found.

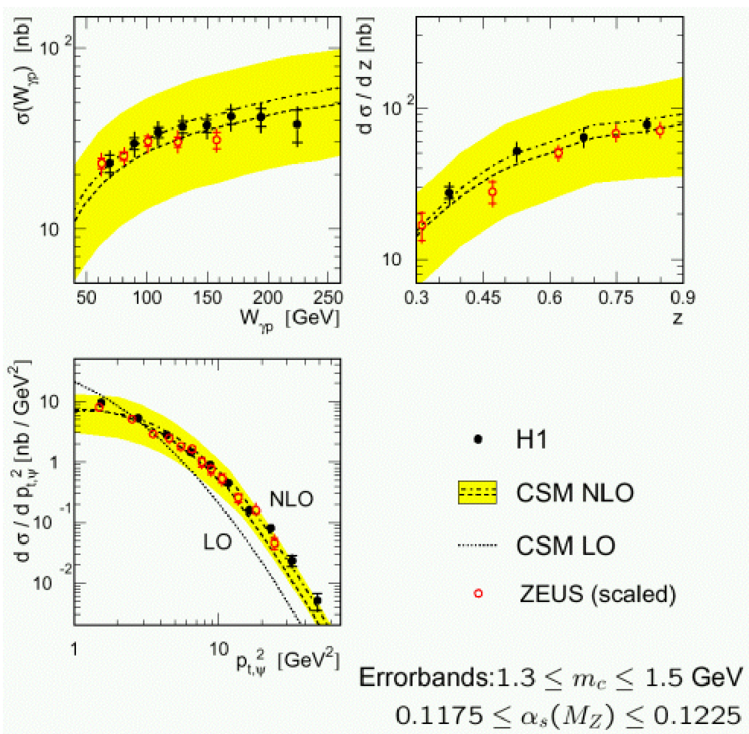

Figure 5: *Total J/ψ photoproduction cross section as a fuction of $W_{\gamma p}$ and differential cross sections as a function of z and $p_{t,\psi}^2$. The Zeus points are shifted by up to 12% to account for differences in the covered kinematic range. The CSM calculation in NLO is also shown and seems to be reporucing the shape of the data. The uncertainty in the theoretical calculations is shown by a band including normalization uncertainties due to the value of α_s and the charm mass.*

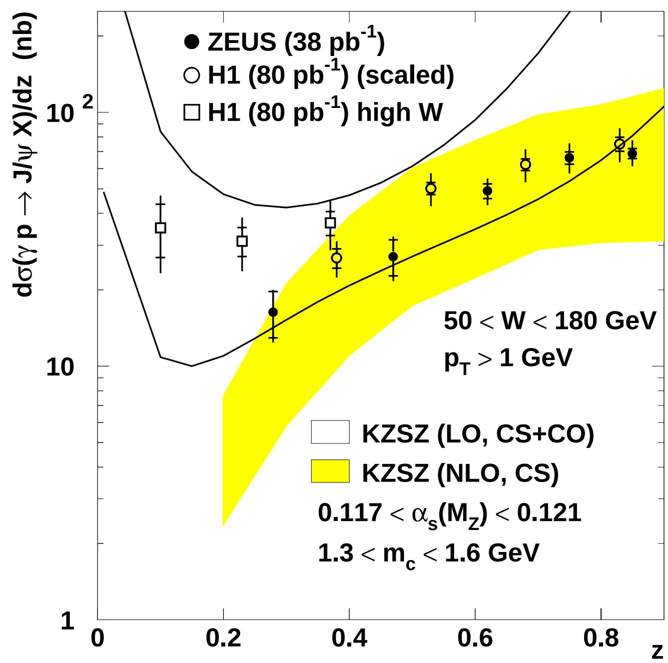

Figure 6: *Differential J/ψ photoproduction cross section as a function of z for H1 and Zeus data and for $p_T > 1$ GeV/c. The data is compared with predictions of the NLO colour singlet model and a prediction including both colour singlet and colour octet contributions in LO.*

3.2 Results from the HERA-B experiment

In the period November 2002- February 2003 HERA-B has collected about 150x10^6 events with a di-lepton trigger. The main goal was to study the charmonium production in pA collisions at $\sqrt{(s)}$ =41.6 GeV with different materials.

One of the interesting measurements they have made is of the fraction of J/ψ's produced via radiative χ_c decays in interactions of 920 GeV protons with carbon and titanium targets. Averaging over all types of collisions they obtain R_{χ_c} =0.32 ± 0.06(stat) ± 0.04 (sys). In Fig. 8 we show the measurement of R_{χ_c} from the HERA-B experiment in comparison with similar measurements from other fixed target experiments. The HERA-B result is compatible with most of the previous data. Due to the relatively large uncertainties a flat energy dependence as predicted by CEM cannot be ruled out. NRQCD predicts relatively well the slope of the energy dependence although its absolute predictions fall below most of the data. Similarly, the CSM predictions fall above most of the data. Although the

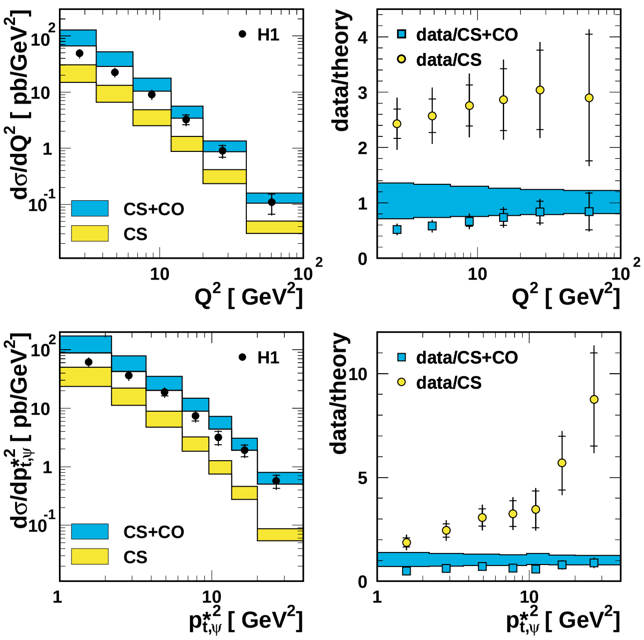

Figure 7: *Differential J/ψ electroproduction cross section as a fuction of Q^2 and $p^{*2}_{t,\psi}$. The data are compared to a full NRQCD calculation[19] (dark band) and to the LO colour singlet contribution alone (light band). Data over theory ratios are also presented.*

corresponding CDF Run I measurement[2] at $\sqrt{s} = 1.8$ TeV is not shown in this plot, interestingly enough, it is consistent with the HERA-B measurement.

4 Conclusions-Prospects

In this paper we have presented results on cross sections and polarization of quarkonia from measurements at hadron-hadron and lepton-hadron collisions. The study of quarkonia has proven so far a very interesting and challenging ground for QCD and QCD inspired models. Several new analyses of Fermilab and DESY have become available during the past year. Although the theory so far has been able to describe several features of quarkonia production, there are discrepancies with theoretical expectations in many of the above mesurements (e.g most experimental cross sections are higher than the theoretical predictions). Some of these measurements are currently limited by statistics.

For the Fermilab Tevatron, Run II is well underway. Approximately 1.4

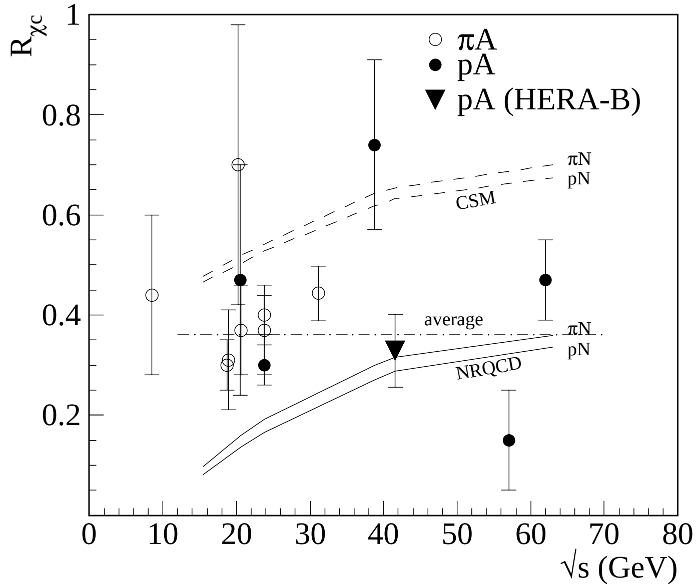

Figure 8: *Comparison of the R_{χ_c} HERA-B measurement with those of other pp, pA, πp and πA experiments. The dot-dashed line is the average of all presented measurements. Also shown are predictions for pN and πN interactions obtained from Monte Carlo based on the CSM and NRQCD calculations.The Color Evaporation model (CEM) predicts a constant value.*

(9)fb^{-1} of data is expected by the end of FY05(FY09). The CDF and D0 experiments will increase their statistics by factors of 14 to 90. With their better muon and silicon coverage and improved trigger capabilities in comparison to Run I they are expected to provide improved as well as additional measurements on quarkonia production which can shed light on the production mechanisms.

After the recent HERA upgrades, the H1 and Zeus experiments are also expected to collect additional data sets of approximately 100 pb^{-1} by the summer of 2004 and further increases in the following years. The upgrades may allow for polarized e$^{\pm}$ beams and the additional data will certainly allow for measurements atlarger Q^2 and p_T.

Hopefully improved and more detailed calculations will become available in parallel and a better understanding of higher order corrections will allow to address current and future problems.

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