Vol. 37 (2006) ACTA PHYSICA POLONICA B No 3

HEAVY QUARK PRODUCTION OVERVIEW*

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(Received December 20, 2005)

An overview of the physics of heavy quark production at collider experiments is presented. Recent measurements of open charm and beauty production and of charmonium at HERA, LEP and the Tevatron are reported. The data are compared with each other and with predictions from perturbative QCD calculations. The main results from charmonium measurements at the B-factories are discussed and some of the recently discovered new resonance states are presented.

PACS numbers: 13.60.–r

1. Introduction

The measurement of heavy quark production processes is a powerful means to exploring the dynamics of the strong interactions described by perturbative QCD (pQCD). The largeness of the heavy quark mass provides a "hard" energy scale, making the value of the running coupling constant α_S small enough for perturbative calculations. In the massive scheme [1] the parton densities of the proton and/or the photon consist of only light partons and the heavy quarks are produced dynamically. The dominant LO diagrams are $2 \to 2$ processes with a $c\bar{c}$ or $b\bar{b}$ pair in the final state. In the regime of large transverse momenta of the final state, the heavy quarks may be treated as massless [2]. In variable flavour number schemes (VFNS) attempts are made to provide reliable pQCD predictions over the whole kinematic range [3].

Quantitative predictions of cross sections for the production of heavy hadrons assume factorisation of a number of ingredients: Depending on the initial state (ep, γp, $p\bar{p}$ or $\gamma\gamma$) the parton distributions of the proton and/or the photon, and their evolution, are input to the hard partonic matrix element. For the final state, hadronisation and fragmentation effects are included. Comparisons between measurements and theoretical predictions are key to testing the validity and universality of all these ingredients.

* Presented at the PHOTON2005 Conference, 31 August–4 September 2005, Warsaw, Poland.

2. Open charm production

Differential cross sections of $D^{*\pm}$ mesons have been measured at HERA, at the Tevatron and at LEP (Figs. 1) [4–6]. The predictions from pQCD are in good general agreement with the charm data. However, the theoretical uncertainties are large. The various predictions are somewhat different in different regions of phase space. The comparison of the data with predictions in the massless scheme and in the massive scheme (Fig. 1(c)) illustrates the differences between the two approaches. Detailed studies of charm production have been performed at all experiments, providing insights into the details of the production process as well as the fragmentation properties of charm quarks [7] and the heavy quark structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ of the proton [8].

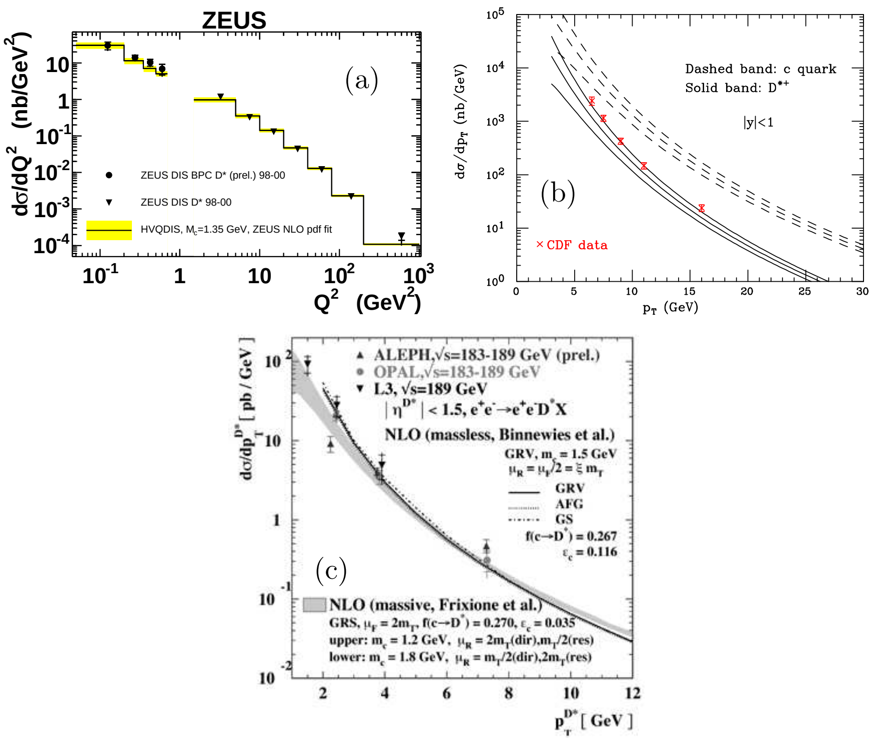

Fig. 1. Differential D^* cross sections measured (a) at HERA, (b) at the Tevatron and (c) in $\gamma\gamma$ collisions at LEP.

3. Open beauty production

Earlier measurements of beauty production in $p\bar{p}$ [9], in $\gamma\gamma$ [10] and in γp collisions [11] indicated excesses of the data over pQCD predictions. Recent measurements and calculations have changed the picture to a certain extent

(Figs. 2): The HERA data [12] data show a trend that the QCD predictions in the massive scheme [13] underestimate the b-production rate, in particular at low Q^2. Depending on the chosen set of structure functions and parameters, the VFNS prediction gives a better description of the data [14]. Comparisons of the new theory developments MC@NLO [15] and FONLL [16] with the Run-II data at CDF [17] show good agreement. Beauty production in $\gamma\gamma$ collisions at LEP, however, still poses a problem as the theory predictions are not able to describe the data [10].

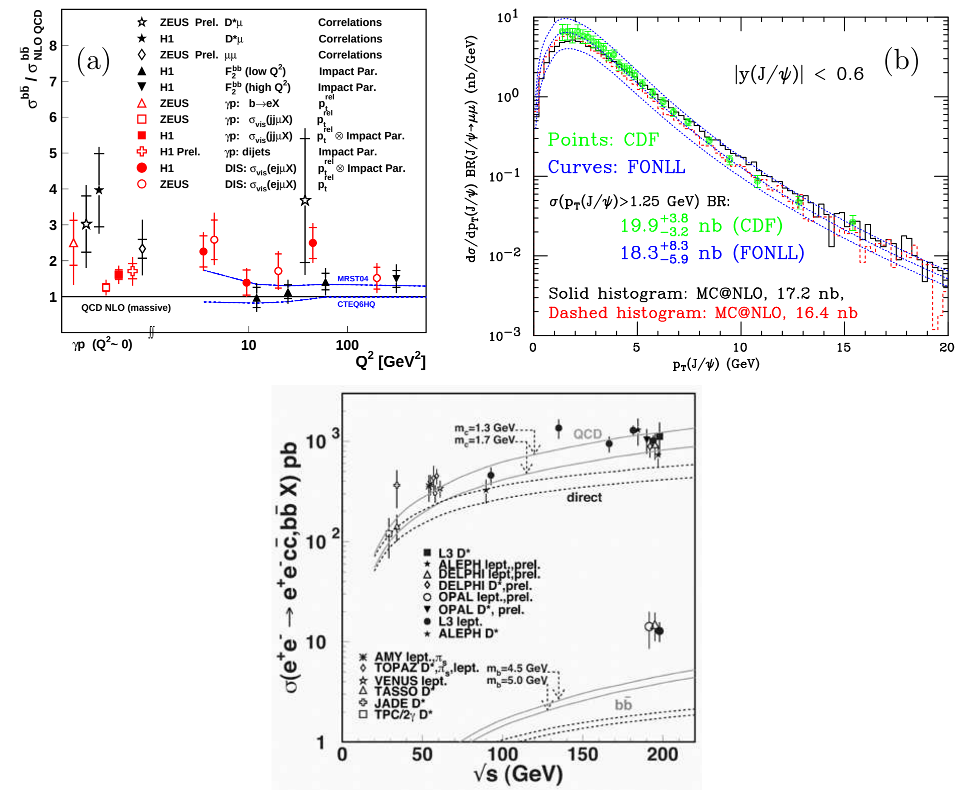

Fig. 2. Beauty cross section measurements (a) at HERA, (b) at the Tevatron and (c) in $\gamma\gamma$ collisions at LEP.

4. Charmonium production

In heavy quarkonium production a charm or beauty quark pair hadronises to form a $q\bar{q}$ state. In the color singlet model (CSM) [18] only $c\bar{c}$ quark states with the same quantum numbers as the meson contribute significantly to charmonium production. In the NRQCD factorisation ansatz [19,20], also colour octet quark–anti-quark states, carrying different angular momenta and color charges than the quarkonium, can contribute to the charmonium production cross section. In NRQCD it is expected that at large transverse momenta charmonium production is dominated by gluon fragmentation, leading to a transverse polarisation of the charmonium.

Charmonium production cross sections and polarisations have been measured at the Tevatron [21], in $\gamma\gamma$ collisions at LEP [22], and in γp and ep collisions at HERA [23]. In Fig. 3(a) the HERA data are compared to the colour singlet model prediction which, for photoproduction, is available at next-to-leading order [24]. Good agreement is found between the NLO predictions and the data while the LO prediction is lower in normalisation and wrong in shape. Fig. 3(b) shows a recent measurement of the J/ψ polarisation at the CDF experiment as a function of the transverse momentum [21]. The data contradict the expectation in the NRQCD approach, that the polarisation should rise towards large $p_{\mathrm{t},\psi}$ [20]. NRQCD, as presently available in leading order, does not give a satisfactory description of the data. In contrast, the color singlet model shows a reasonable description of the HERA data, when implemented in calculations to next-to-leading order perturbation theory.

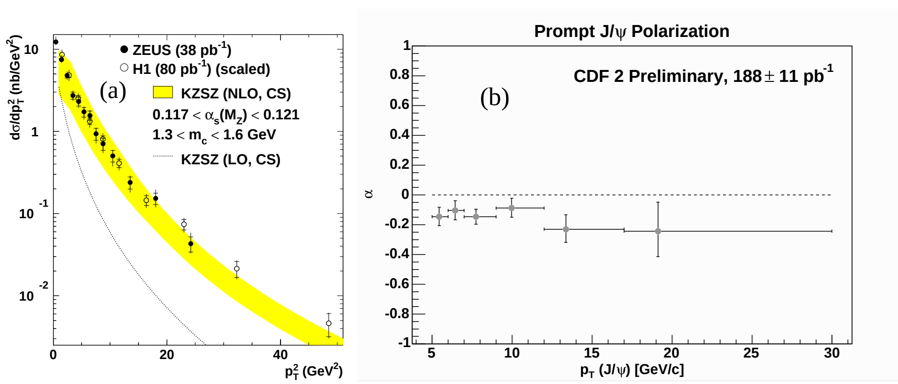

Fig. 3. Measurements of charmonium production (a) of the photoproduction cross section at HERA and (b) of the polarisation at the Tevatron.

Charmonium production has also been measured at the B-factories [25]. Also here, the available theories fail to describe the data in shape and/or normalisation. In particular, in measurements of double $c\bar{c}$ production with associated J/ψ, a production rate about a factor six higher than expected from theory is found. The Belle measurements [26] have recently been confirmed by the BaBar experiment [27]. Fig. 4 shows the recoil spectrum for the system X in inclusive J/ψ production events $e^+e^- \to J/\psi X$. The presence of signals from η_c, η_c', χ_{c0} and absence of J/ψ, $\psi(2S)$, χ_{c1} indicates features of the production process which are yet to be understood.

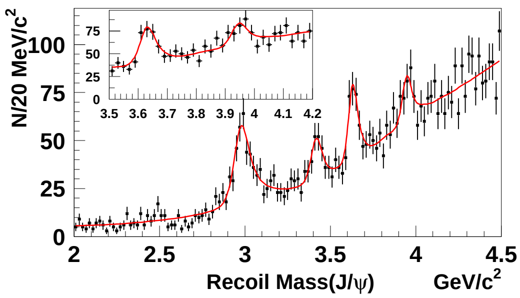

Fig. 4. The mass of the system recoiling against the reconstructed J/ψ.

5. New heavy particles

The large data sets at the B-factory experiments have led to discoveries of so far unknown states. One prominent example is the X(3872) which was first discovered by Belle in the decay channel $X(3872) \to J/\psi\pi^+\pi^-$ and was subsequently confirmed by CDF, BaBar and D0 (Fig. 5(a)) [28]. The $X(3872)$ has a mass of $3871.9 \pm 0.6\,\text{MeV}$, in comparison to the $D^0\bar{D}^{0*}$ threshold of $3871.3 \pm 1.0\,\text{MeV}$. It is produced in B-decays. No signal was found in continuum production using ISR events [29]. The mass distribution of the $\pi^+\pi^-$ is consistent with coming from ρ^0-decays. Decays of $X \to J/\psi\omega$ and $X \to J/\psi\gamma$ have also been seen. The favoured quantum numbers are $J^{\rm PC} = 1^{++}$. According to [30] the findings are consistent with the $X(3872)$ being a $D^0\bar{D}^{0*}$ molecule.

Belle found a candidate $Y(3940)$ in decays $B \to K(J/\psi\omega)$ with a mass above $D\bar{D}^*$ threshold, but no decays into $D\bar{D}^*$ have been seen [31]. This state is to be distinguished from the $X(3940)$ state (Fig. 4) for which $D\bar{D}^*$

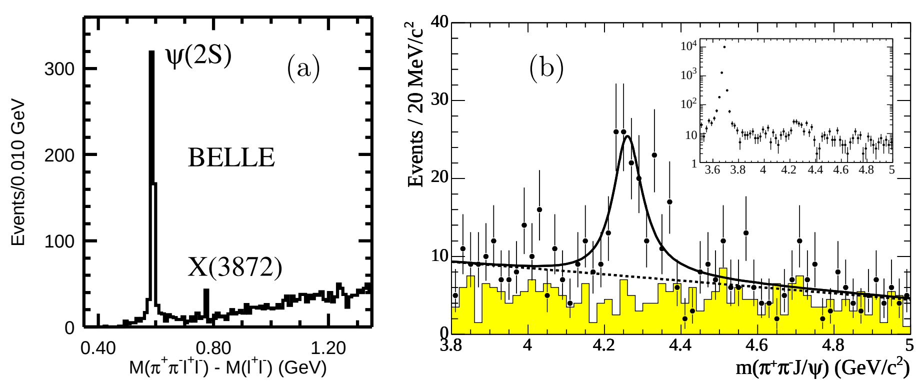

Fig. 5. (a) Distribution of $M(\pi^+\pi^-l^-l^-) - M(l^+ - l^-)$ as observed by Belle for B-decay candidates. (b) The $\pi^+\pi^-J/\psi$ invariant mass spectrum as observed in ISR events at BaBar. The inset shows the same spectrum over a wider range including the $\psi(2S)$ resonance.

decays were found, but no evidence for decays into $J/\psi\omega$ [32]. BaBar found a signal ($Y(4260)$, Fig. 5(b)) of 125 ± 23 events in a continuum scan using ISR events [33]. These states are just a few of the many new particles that have been discovered in recent years and which carry the potential of opening up new fields of QCD.

6. Conclusions

The study of heavy quark production provides crucial insights into the workings of the strong interactions, described by QCD. Open charm production processes are generally well described by perturbation theory. However, the theoretical uncertainties are still large. The beauty production measurements still show a trend to be higher than massive NLO calculations. The measurements from LEP are in excess of the expectation by a factor 3. The production of charmonium states still gives unsolved problems. Precision measurements at HERA and the Tevatron will provide further input to improving the theories. The large data sets of the B-factories have the potential of opening up new fields of QCD spectroscopy.

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