Summary of the Heavy Flavour Session *

B.A. KNIEHL
II. Institut für Theoretische Physik, Universität Hamburg,
Luruper Chaussee 149, 22761 Hamburg, Germany

F. SEFKOW
DESY,
Notkestr. 85, 22607 Hamburg, Germany

The contributions to the parallel session on heavy flavour production are summarized. In more than 30 presentations new theoretical developments and new experimental results from the Tevatron, HERA, LEP, the B factories and νN scattering were reported.

1 Introduction

Although traditionally centered around deep-inelastic scattering (DIS) and structure functions, this conference series has become one of the prominent places to discuss strong interaction physics in a wider sense. In the heavy flavour case in particular, the focus is on understanding in a common QCD framework the charm, beauty and top cross sections in various production environments.

The experimental results reported in this session were obtained in pp, pN, νN, ep, γp, $\gamma\gamma$ and e^+e^- collisions. Only a personal and biased selection from them can be mentioned in this summary. Since the status of heavy flavour physics at HERA has been well covered in the introductory talk [1], the emphasis is here on new results and on other machines.

The theoretical results presented in this session capture various recent developments in the area of inclusive charmonium, open-charm, and open-bottom production, as well as the heavy-flavour contributions to the structure functions [2, 3].

2 Charmonium (Theory)

Since the discovery of the J/ψ meson in 1974, heavy quarkonium has provided a useful laboratory for quantitative tests of QCD and, in particular, of the

*To appear in the proceedings of the XI International Workshop on Deep Inelastic Scattering (DIS'03), St. Petersburg, April 2003 interplay of perturbative and nonperturbative phenomena. The factorization formalism of nonrelativistic QCD (NRQCD) [4] provides a rigorous theoretical framework for the description of heavy-quarkonium production and decay. This formalism implies a separation of short-distance coefficients, which can be calculated perturbatively as expansions in the strong-coupling constant α_s, from long-distance matrix elements (MEs), which must be extracted from experiment. The relative importance of the latter can be estimated by means of velocity scaling rules; i.e., the MEs are predicted to scale with a definite power of the heavy-quark (Q) velocity v in the limit $v \ll 1$. In this way, the theoretical predictions are organized as double expansions in α_s and v. A crucial feature of this formalism is that it takes into account the complete structure of the $Q\overline{Q}$ Fock space, which is spanned by the states $n = {}^{2S+1}L_J^{(a)}$ with definite spin S, orbital angular momentum L, total angular momentum J, and color multiplicity $a = 1, 8$. In particular, this formalism predicts the existence of color-octet (CO) processes in nature. This means that $Q\overline{Q}$ pairs are produced at short distances in CO states and subsequently evolve into physical, color-singlet (CS) quarkonia by the nonperturbative emission of soft gluons. In the limit $v \to 0$, the traditional CS model (CSM) [5] is recovered. The greatest triumph of this formalism was that it was able to correctly describe [6] the cross section of $p\overline{p} \to J/\psi + X$ at the Tevatron [7], which had turned out to be more than one order of magnitude in excess of the theoretical prediction based on the CSM.

Apart from this phenomenological drawback, the CSM also suffers from severe conceptual problems indicating that it is incomplete. These include the presence of logarithmic infrared divergences in the $\mathcal{O}(\alpha_s)$ corrections to P-wave decays to light hadrons and in the relativistic corrections to S-wave annihilation [8], and the lack of a general argument for its validity in higher orders of perturbation theory. In the case of $\gamma p \to J/\psi + X$ in photoproduction, where next-to-leading (NLO) corrections in the CSM happen to be well defined [9], the NLO prediction encompasses the rather precise HERA data [10] within the theoretical uncertainties.

In order to convincingly establish the phenomenological significance of the CO processes, it is indispensable to identify them in other kinds of high-energy experiments as well, using the very MEs extracted from the Tevatron data [7]. Attempts to do so range from very successful to inconclusive for the time being. Successful examples include the comparison of theoretical predictions of $\gamma\gamma \to J/\psi + X$ [11] and $pp \to J/\psi + X$ [12] with data taken by DELPHI [13] at LEP2 and by PHENIX [14] at RHIC, respectively. Comparison of HERA [15] data of $ep \to J/\psi + X$ in DIS with NRQCD predictions [16] are generally favourable with respect to both normalization and shape, except for the distribution in inelasticity z, where a shape problem familiar from photoproduction [17] is recovered. As for the J/ψ polarization in $p\overline{p} \to J/\psi + X$, measurements at the Tevatron [18] tend to undershoot the theoretical predictions for direct [19] and prompt [20] production in the bins of highest transverse momentum (p_T).

While the k_T-factorization [21, 22] and hard-comover-scattering [23] approaches manage to bring the CSM prediction of $p\overline{p} \to J/\psi + X$ much closer to the Tevatron data [7], they do not cure the conceptual defects of the CSM; NRQCD is still needed for that. However, they reduce the relative importance of the CO contributions at leading order (LO). Since NLO corrections allow for an incoming parton to gain a k_T kick by emitting another parton before entering the hard scattering, one expects k_T-factorization effects to become much less important at NLO. While the evaluation of NLO corrections is well understood in NRQCD, the extension of the k_T-factorization formalism beyond LO is an open problem. The list of open problems in connection with the k_T-factorization formalism also includes the determination of the proper evolution equation (BFKL, CCFM, DGLAP, or mixtures thereof), the establishment of a rigorous operator definition of the unintegrated parton density functions, the restoration of gauge independence for off-shell external partons, the avoidance of ad-hoc regularization to keep propagators away from poles, which are sometimes used in the literature [22], and the recovery of the collinear-parton-model results for asymptotically large values of p_T in practical applications [22].

The color evaporation model [24] provides an operative procedure to estimate the production cross sections of heavy quarkonia on the basis of the ones of open heavy-quark pairs. It is intuitive and useful for qualitative studies, and it also significantly improves the description of the Tevatron data as compared to the CSM [25]. However, it does not account for the process-specific weights of the CS and CO contributions, but rather assumes a fixed ratio of 1 : 7.

3 New Charmonium measurements

The analysis of inelastic J/ψ production with HERA I data is essentially completed. At this meeting, ZEUS presented preliminary cross section results for charmonium production in DIS [26] which confirm last year's H1 findings, namely that NRQCD with sizeable CO contributions reproduces the data reasonably well, in particular at higher p_T. However, the dependence on the inelasticity variable z remains at variance with the calculations also in the new ZEUS data.

New experimental testing grounds may provide further clues to clarify the validity of the NRQCD factorization approach. In addition to the $\gamma\gamma$ collision results [13] (Sec. 2), data on charmonium production measured by HERA-B, at the B factories in the e^+e^- continuum, or at the Tevatron in the low p_T regime are entering the stage.

The HERA-B collaboration has published a first measurement of R_{χ_c}, the fraction of J/ψ mesons produced via intermediate χ_c states, which lies considerably below CSM expectations, but matches the NRQCD predictions well [27]. The total statistics of about 3000000 J/ψ and 20000 χ_c mesons produced on different nuclear targets allows them, for example, to measure the cross section dependence on isotope number A. In NRQCD this is not the same for J/ψ and χ_c, since CS and CO pre-resonant states contribute with different strength and interact differently with nuclear matter [28]. A measurement of the A dependence of the χ_c cross section also forms an important ingredient for the interpretation of heavy ion collision data.

A rather new testing field is charmonium production in the e^+e^- annihilation continuum below the $\Upsilon(4S)$ resonance [29]. The cross section was found to be more than an order of magnitude higher than expected, but the momentum spectrum does not exhibit an enhancement at large momenta, which would signal strong CO contributions. According to the preliminary Belle results, $(82 \pm 20)\%$ of the J/ψ mesons are accompanied by another pair of charm quarks. The J/ψ recoil mass spectrum, measured now in a sample corresponding to 101 pb^{-1} and shown in Fig. 1, exhibits several clear $c\bar{c}$ resonances. From these data, rates for many exclusive (double) charmonium modes were be measured, or earlier measurements confirmed with better precision; in addition all exclusive open charm ground states have been observed recoiling against J/ψ mesons.

New possibilities also open up in familiar environments. The Tevatron experiments are vigorously entering back on stage with new data from run II. By the time of the DIS conference, CDF, for example, wrote 150 pb^{-1} to tape and presented analyses making use of about 70 pb^{-1}, to be compared to the run I data set corresponding to 110 pb^{-1}. With their upgraded detector, trigger and data acquisition systems kinematic ranges and channels can be probed which have been inaccessible so far in highest energy $\bar{p}p$ collisions [30]. One example are lowered dimuon trigger thresholds which allow to trigger on J/Ψ mesons decaying at rest and thus to measure their production cross section over the entire momentum range down to $p_T = 0$. The existing measurements of run I start at $p_T > 5$ GeV and cover less than 10% of the total cross section. This allows one to test the NRQCD description over a wider range; it provides increased sensitivity to those CO MEs ($^1S_0$ and ^3P_J) which also govern J/ψ production at HERA and should enable more stringent tests of their universality. However, a complete picture and a meaningful statement on the validity of the NRQCD factorization approach will only emerge once the NLO

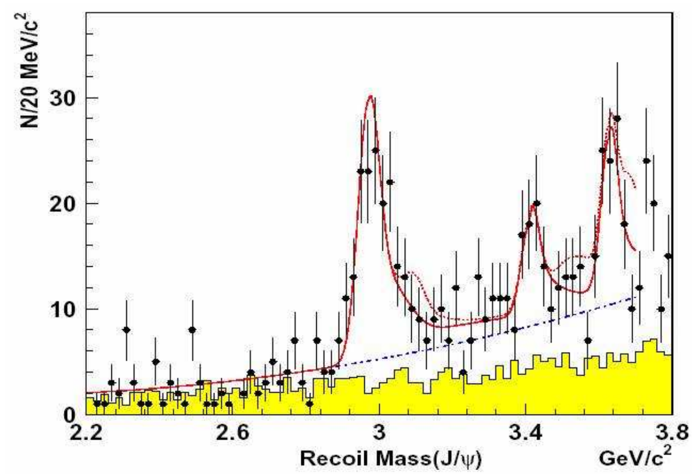

Figure 1: Invariant mass of the system recoiling against J/ψ mesons produced in e^+e^- annihilation below the Upsilon resonance, measured by Belle.

corrections, which are shown to be important in the HERA photoproduction case, become available for hadroproduction as well. This requires a huge effort on the theoretical side, which should bear fruit in the not so far future.

4 Open heavy flavours (Theory)

The QCD-improved parton model implemented in the $\overline{\mathrm{MS}}$ renormalization and factorization scheme and endowed with nonperturbative fragmentation functions (FFs), which proved itself so convincingly for light-meson inclusive production [31], also provides an ideal theoretical framework for a coherent global analysis of D- [32] and B-meson data [33], provided that $\mu \gg m_Q$, where μ is the energy scale characteristic for the respective production process and $Q = c, b$. Then, at LO (NLO), the dominant logarithmic terms, of the form $\alpha_s^{n,n+1} \ln^n \left(\mu^2/m_Q^2\right)$ with $n = 1, 2, \ldots$, are properly resummed to all orders by the DGLAP evolution, while power terms of the form $\left(m_Q^2/\mu^2\right)^n$ are negligibly small and can be safely neglected. In this *massless-quark scheme* or *zero-mass variable-flavour-number scheme* (ZMVFNS), which is sometimes quite wrongly referred to as *NLL approximation*,[1] the Q quark is treated as massless and appears as an active parton in the incoming hadron or photon, having a nonperturbative parton density function. The criterion $\mu \gg m_Q$ is certainly satisfied for e^+e^- annihilation on the Z-boson resonance, and for the photo-, lepto-, and hadroproduction of D and B mesons with $p_T \gg m_Q$. Furthermore, the universality of the FFs is guaranteed by the factorization theorem [34], which entitles us to transfer information on how c and b quarks hadronize to D and B mesons, respectively, in a well-defined quantitative way from e^+e^- annihilation, where the measurements are usually most precise, to other kinds of experiments, such as photo-, lepto-, and hadroproduction. In Refs. [32, 33], the distributions in the scaled D- and B-meson energy $x = 2E/\sqrt{s}$ measured at LEP1 were fitted at LO and NLO using, among others, the ansatz by Peterson et al. [35] for the $c \to D$ and $b \to B$ FF at the starting scale $\mu_0 = 2m_Q$. In the $D^{\star\pm}$ (B^+/B^0) case, the ε parameter was found to be $\varepsilon_c = 0.0851$ and 0.116 [32] ($\varepsilon_b = 0.0126$ and 0.0198 [33]) at LO and NLO, respectively. We emphasize that the value of ε carries no meaning by itself, but it depends on the underlying theory for the description of the fragmentation process, in particular, on the choice of the starting scale μ_0, on whether the analysis is performed in LO or NLO, and on how the final-state collinear singularities are factorized in NLO.

In the traditional *massive-quark scheme* or *fixed-flavour-number scheme* (FFNS), the Q quark is treated in the on-mass-shell renormalization scheme, as if it were a massive lepton in triplicate, and it only appears in the final state, but not as an active parton inside the incoming hadron or photon. There are no collinear singularities associated with the outgoing Q-quark lines that need to be subtracted and absorbed into FFs. In fact, in this scheme, there is no conceptual necessity for FFs at all, but they are nevertheless introduced in an ad-hoc fashion in an attempt to match the D- and B-meson data. However, in the absence of a subtraction procedure, there is also no factorization theorem in operation to guarantee the universality of the FFs [34]. By the same token, such FFs are not subject to DGLAP evolution. Thus, there is no theoretical justification to expect, e.g., that a single value of the Peterson ε parameter should be appropriate for different types of experiment or at different energy scales in the same type of experiment. In other words, the feasibility of global data analyses is questionable in this scheme. Moreover, this scheme breaks down for $p_T \gg m_Q$ because of would-be collinear singularities of the form $\alpha_s \ln\left(p_T^2/m_Q^2\right)$, which are not resummed. However, it allows one to calculate a total cross section, which is infeasible in the ZMVFNS.

[1] The nonlogarithmic corrections of relative order α_s are fully included, except for terms that are suppressed by powers of $\left(m_Q^2/\mu^2\right)^n$.

The attempt to split the D- and B-meson FFs into so-called perturbative FFs (PFFs) and nonperturbative remainders is interesting in its own right. However, detailed analysis for $D^{*\pm}$-meson FFs [36] revealed that such a procedure leads to deficient results in practical applications. On the one hand, at NLO, the cross section $d\sigma/dx$ of e^+e^- annihilation becomes negative in the upper x range, at $x \gtrsim 0.9$, where the data is very precise, so that a low-quality fit is obtained unless this x range is excluded by hand [36, 37]. On the other hand, the LO and NLO predictions for other types of processes, such as photoproduction in ep scattering, significantly differ [36], which implies that the perturbative stability might be insufficient.

The idea [33] of performing a coherent analysis of LEP1 and Tevatron data of inclusive B-meson production was recently revived using an unconventional scheme named *fixed-order next-to-leading-logarithm* (FONLL) scheme, in which the traditional result in the FFNS and a suitably subtracted result in a ZMVFNS with PFFs are linearly combined [38]. However, some degree of arbitrariness is inherent to this procedure, as may be understood by noticing that the ZMVFNS term is weighted with an ad-hoc coefficient function of the form $p_T^2/\left(p_T^2+25m_b^2\right)$ so as to effectuate its suppression in the low-p_T range and that this term is evaluated at $p_T^\prime = \sqrt{p_T^2+m_Q^2}$ while the FFNS term is evaluated at p_T. Since the FONLL scheme interpolates between the FFNS and the ZMVFNS with PFFs, it also inherits some weaknesses of both schemes detailed above. In particular, the negativity of the NLO cross section of $e^+e^- \to D/B + X$ in the upper x range forces one to exclude the data points located there from the fit. In Ref. [38], this is achieved by resorting to what is called there the *moments method*, i.e., the large-x region is manually faded out by selecting one particular low moment of the FF, namely the one corresponding to the average x value, thereby leaving the residual information encoded in the data unused.

A rigorous theoretical framework that retains the full finite-m_Q effects while preserving the indispensible virtues of the factorization theorem, namely the universality and the DGLAP scaling violation of the FFs, is provided by the *general-mass variable-flavour-number scheme* (GMVFNS) [34, 39]. In a nut shell, this procedure consists in explicitly performing the $m_Q \to 0$ limit of the FFNS result, comparing the outcome, term by term, with the ZMVFNS result in the $\overline{\mathrm{MS}}$ scheme, and subtracting the difference terms from the FFNS result. Owing to the factorization theorem [34], the hard-scattering cross sections thus obtained can then be convoluted with nonperturbative D- and B-meson FFs extracted from LEP1 data using the $\overline{\mathrm{MS}}$ scheme [32, 33]. This is consistent because the finite-m_Q terms omitted in Refs. [32, 33] are negligibly small, of order m_Q^2/m_Z^2. In fact, a reanalysis of the LEP1 data in the GMVFNS should yield FFs that agree with the FFs of Refs. [32, 33] within the errors. The GMVFNS was recently implemented for direct [40] and single-resolved [41] $\gamma\gamma$ collisions. In the case of $\gamma\gamma \to D^{\star\pm} + X$ at LEP2, the inclusion of finite-m_c effects was found to reduce the cross section by approximately 20% (10%) at $p_T = 2m_c$ ($3m_c$) [40], i.e., their magnitude is roughly m_c^2/p_T^2, as naïvely expected. By analogy, one expects the finite-m_b terms neglected in Ref. [33] to have a moderate size, of order 20% (10%) at $p_T = 10$ GeV (15 GeV). This is considerably smaller than the scale uncertainty and appears insignificant compared to the excess of the CDF data [42] over the traditional NLO analysis in the FFNS [43].

The GMVFNS scheme can be further improved by implementing the proper kinematic constraints on the threshold behaviour. In the case of the structure function F_2^c, this was done in Ref. [2] by appropriately introducing the variable $\chi = x\left(1 + 4m_c^2/Q^2\right)$ (ACOT(χ) prescription). This was shown to enforce the proper threshold behaviour, to simplify the implementation, and to yield robust predictions.

5 Heavy quark heavy hadron transition

In a number of talks the current understanding of heavy quark fragmentation (or hadronization) was reviewed. This enters into every comparison of production cross sections with theory, to be discussed in the subsequent section.

Above all, fragmentation is very well constrained by experiment. The most precise data are nowadays those on B meson production in e^+e^- annihilation at the Z resonance [44, 45]. The compilation of LEP and SLD measurements in Fig. 2 shows impressive agreement between the different analyses, which are based on exclusive (D^* lepton), semileptonic or inclusive vertex methods to tag the b hadron and infer its momentum from the partially reconstructed final state. The figure displays the unfolded spectrum of the momentum fraction of the weakly decaying hadron, normalized to the beam energy. It reflects both the effects of the hard QCD radiation processes and of the soft transition from the quark to the bound hadronic state. The experiments have also studied how well the data can be described when different parameterizations are used to model the soft phase, and arrive at the same ranking [46], namely that the Lund and the Bowler shapes are preferred with respect to, e.g. the Peterson parameterization. Of course this conclusion is relevant only when a leading order (LO) parton shower approach as it is implemented in the JETSET Monte Carlo program, is used to model the perturbative phase.

At HERA, the charm fragmentation function has been probed [47]. Since

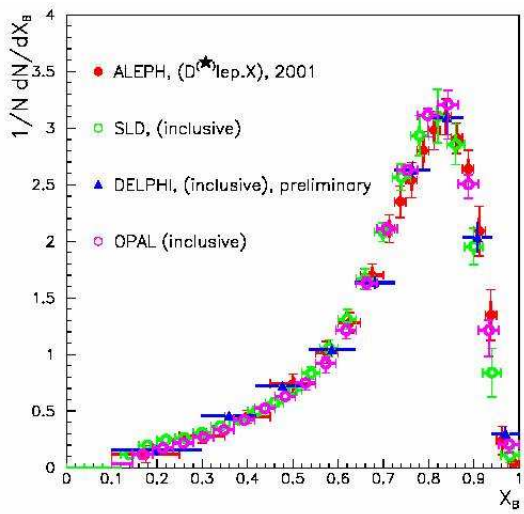

Figure 2: Fractional momentum distribution of the weakly decaying b hadron, measured in e^+e^- annihilation at the Z resonance.

the initial state does not constrain the primordial quark momentum, the beam energy has been replaced by the jet energy to normalize the charm hadron's momentum fraction x. Hard gluon radiation thus affects the observable x spectrum less than in the e^+e^- case. The measured distributions obtained by ZEUS, ARGUS and OPAL, which are of course not expected to agree in detail, exhibit nevertheless the same gross features, and fitting a parton shower Monte Carlo prediction to the ZEUS data yields a Peterson parameter consistent with e^+e^- findings.

An enhancement at low x, attributed to gluon splitting, is observed only in the OPAL data, in the ARGUS and ZEUS case the energies are too low. Gluon splitting to $c\bar{c}$ and $b\bar{b}$ pairs has been explicitly constrained by studying special (3 and 4 jet) event topologies at LEP [45, 48]. For charm, a new and quite precise ALEPH measurement and a new world average of $g_{cc} = (3.01 \pm 0.33)\%$ has been presented at this conference [48]. This is somewhat above theoretical expectation, but consistent within errors. The situation is similar for the ten times smaller g_{bb} value [45]; altogether this shows that also higher order corrections are well under control.

Another way to test the universality of the non-perturbative quark-hadron transition is to compare the fragmentation fractions [47], i.e. the relative rates with which the different weakly decaying heavy hadron states are being produced. ZEUS measured now, in addition to D^*, D^0 and D_s^+, also the production of D^+ and λ_c (to represent the charmed baryons) and have thus determined the complete set, so that the rates can now be normalized to the sum and no recurrence to MC for the total charm cross section has to be made anymore. Table 3 compares the ZEUS results with H1 measurements, showing consistency of the HERA data among each other, and with e^+e^- results, which confirms the universality of characteristics like the occurrence of strange mesons, baryons or vector mesons. These results further validate the practice to use the clean

ZEUS prel. (γp) $P_T(D,\Lambda_c) > 3.8\,\mathrm{GeV}$, $\lvert\eta(D,\Lambda_c)\rvert < 1.6$	**Combined** e^+e^- **data**	**H1 prel. (DIS)**
$f(c \to D^+) = 0.249 \pm 0.014^{+0.004}_{-0.008}$	0.232 ± 0.010	$0.202 \pm 0.020^{+0.045\ +0.029}_{-0.033\ -0.021}$
$f(c \to D^0) = 0.557 \pm 0.019^{+0.005}_{-0.013}$	0.549 ± 0.023	$0.658 \pm 0.054^{+0.117\ +0.086}_{-0.142\ -0.048}$
$f(c \to D_s^+) = 0.107 \pm 0.009 \pm 0.005$	0.101 ± 0.009	$0.156 \pm 0.043^{+0.036\ +0.050}_{-0.035\ -0.046}$
$f(c \to \Lambda_c^+) = 0.076 \pm 0.020^{+0.017}_{-0.001}$	0.076 ± 0.007	
$f(c \to D^{*+}) = 0.223 \pm 0.009^{+0.003}_{-0.005}$	0.235 ± 0.007	$0.263 \pm 0.019^{+0.056\ +0.031}_{-0.042\ -0.022}$

Figure 3: Fragmentation fractions for charm hadrons.

and precise measurements from e^+e^- annihilation to model and interpret ep data. They give experimental support to a rigorous scheme to relate the QCD theory of quarks to observable single hadrons, which was sketched above and which provides a powerful means to probe parton dynamics.

6 Open c, b and t production

From an industrious community at HERA and other machines, cross section data on open heavy flavour production keep coming in and providing new challenges to the common QCD framework.

The two-photon analyses at LEP2 are being finalized. $b\bar{b}$ production, after the L3 and OPAL observations, is now also seen by DELPHI [49] to be in excess of the massive NLO QCD prediction by more than a factor of 2. Direct and resolved photon processes contribute here with similar strength. The result appears to be in contrast to the two-photon data on charm production which are reproduced by theory, within errors. An inspection of the p_T spectrum (Fig. 4) reveals that data lie rather at the upper side of the error range of the theoretical prediction, in particular for small transverse momenta. One should

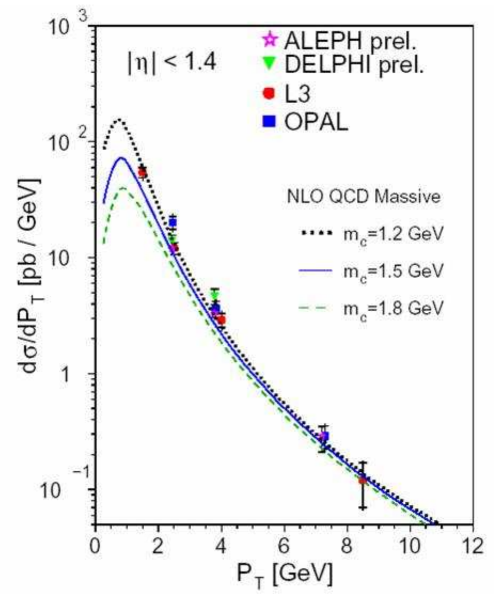

Figure 4: D^* cross section in two photon interactions at LEP2, compared with fixed order (massive) QCD calculations.

bear in mind that the $b\bar{b}$ data are dominated by final states with $p_T \sim m_b$, populating a region where the factorization ansatz may be at the limit of its validity.

Thanks to their upgraded trigger capabilities, CDF was able to present the first open charm cross section data from the Tevatron to this conference [30]. The results, presently extracted from a rather small amount of luminosity, are shown in Fig. 5 in comparison with resummed QCD calculations in the FONLL scheme.. The data tend to be above the central prediction, but come closer as p_T increases and thus follow the behaviour of the theoretical scale uncertainty.

Several new results were reported from HERA. H1 charm photoproduction cross sections have been updated using the full pre-upgrade luminosity [50]. They rely on events with a tagged final state positron and have therefore smaller statistics than the ZEUS measurements. They are found to be above

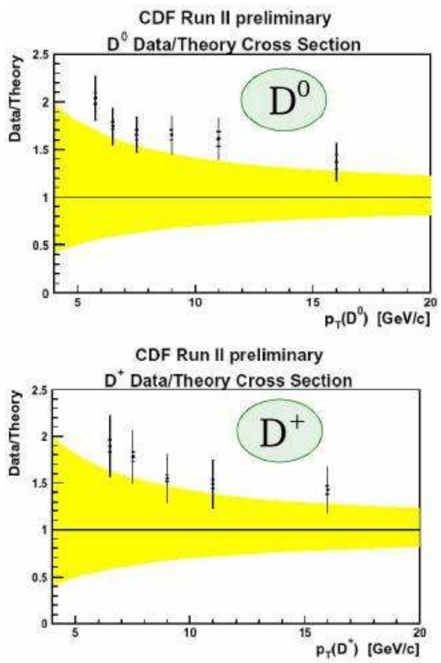

Figure 5: Charm meson production rate at the Tevatron, normalized to resummed QCD predictions in the FONLL scheme.

the massive fixed order QCD predictions, again particularly at low transverse momenta, see Fig. 6. The ZEUS data [51], also shown, have meanwhile a "terrible precision", as it may be seen from the theoretical point of view. They are in principle sensitive to the charm density in the photon, in the massless picture, however the calculations using different parton density parameterizations differ most at low p_T where the theoretical uncertainties are much larger than these differences.

In DIS, a number of new results from their ongoing heavy quark production analyses were reported by CHORUS [52]. For example, their data on charm meson production in charged current neutrino nucleon scattering improve the experimental constraints on the strange content of the nucleon. – H1 measured first differential jet cross sections [53], for dijet events produced in association with D^* mesons. Comparing with Monte Carlo predictions using different schemes for the evolution of the parton cascade, agreement is observed within expectation.

The power of jet measurements is impressively demonstrated by the ZEUS

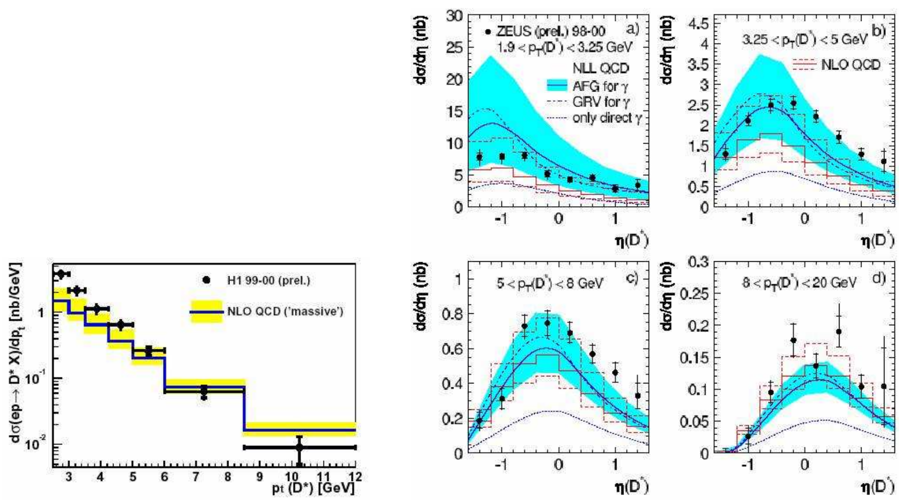

Figure 6: Charm meson cross section, measured by H1 and ZEUS at HERA, compared to massive (labeled "NLO") and massless (labeled "NLL") NLO QCD calculations.

analysis of charm dijet angular distributions in photoproduction, which has recently been finalized [47]. The cross sections (Fig. 7) are measured as a function of $\cos\theta^* = \tanh(\eta_{jet\,1} - \eta_{jet\,2})$ which can be reconstructed from the two jet rapidities and corresponds to the polar angle of the outgoing parton in the partonic rest frame in a $2 \rightarrow 2$ process. This is done separately for events with reconstructed x_γ above or below 0.75, i.e. in regions where either direct or resolved photon contributions dominate. First, the dependence on the absolute value of $\cos\theta^*$ reflects the shape of the hard QCD matrix element; for low x_γ the steep behaviour indicates the predominance of gluon exchange in resolved processes, as also observed in inclusive jet data. Associating the D^* meson with one of the jet tags a final state charm quark. The data show that for low x_γ the latter is found predominantly in the photon direction (negative $\cos\theta^*$). This would not be expected in gluon gluon fusion (and is not seen in the direct, high x_γ case dominated by photon gluon fusion), but matches well the predictions based on diagrams with a c quark originating from the hadronic photon structure in the initial state. Such processes are included in the fixed order massive QCD calculation, but only as HO correction to direct photoproduction. In the massless picture, this is a leading order process, and large NLO corrections are indeed found in the single inclusive case. One should also note the rather large uncertainty of the prediction in the massive scheme in

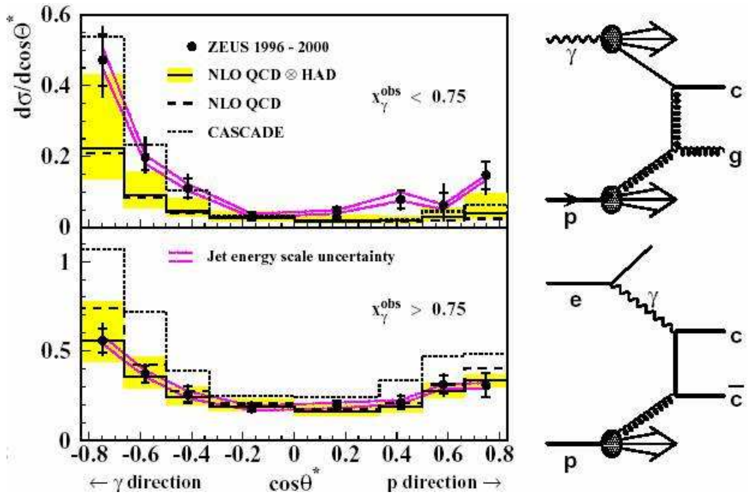

Figure 7: Angular distributions of charm tagged dijet events at HERA; diagrams for charm excitation and boson gluon fusion.

this region. This example shows how constraints in HERA kinematics and the quark hadron correlation in heavy meson production can be used to identify corners of phase space where improvements in the calculations are needed.

b production at HERA is omitted in this write-up. Interesting discussions on the different cross section definitions of H1 and ZEUS and on their respective shortcomings took place [54, 55, 56], but the overall picture changed with new H1 photoproduction results appearing at the 2003 summer conferences [57], with better precision and presented in a way allowing direct comparison to ZEUS. They show consistency between old and new data, and between experiments in the observable range; altogether they tend to be above expectations based on NLO QCD in the massive scheme.

In hadroproduction, HERA B has appeared on the scene with a b cross section measurement [58], which is in agreement with QCD predictions. 30 times more statistics has been collected, so one awaits the measurement of differential cross sections.

Tagged b jet cross sections are in principle less affected by theoretical uncertainties arising from collinear radiation than B meson or b quark cross sections. The latest D0 data from run 2 [59] are consistent with run 1 results and are compared with MC predictions in Fig. 8.

The increased energy of the upgraded Tevatron implies an extra bonus of 30% in the expected top production rate – and the possibility to test its energy

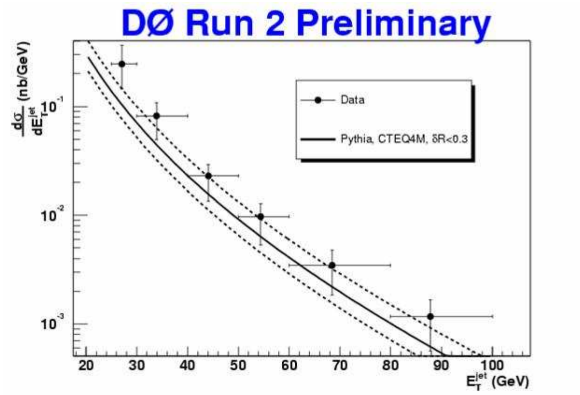

Figure 8: b tagged jet cross section at the Tevatron.

dependence. The first top cross section [60] from run 2 was presented and found to be consistent with such expectations, within large errors still, but marking a first step towards QCD tests with differential top distributions.

7 Conclusion

As for heavy-quarkonium production, the NRQCD factorization approach [4] represents a rigorous theoretical framework that is renormalizable, devoid of infrared singularities, and predictive. It generalizes the CSM curing its defects. However, NRQCD predictions for charmonium suffer from sizeable normalization uncertainties at LO, and it is an important task for the future to evaluate NLO corrections, both in α_s and v^2. At LO, there is room for nonperturbative ingredients, such as k_T factorization, hard-comover enhancement, and shape functions, which tend to reduce the relative importance of the CO processes and ameliorate the well-known shortages of NRQCD to describe the large-z behaviour of inelastic photoproduction at HERA and the charmonium polarization in hadroproduction at large p_T at the Tevatron. The necessity for such nonperturbative effects is expected to be reduced as NLO corrections are included.

As for open heavy-flavour production, the notorious excess of measurements of inclusive D- and B-meson production in various experiments over the respective FFNS analyses implemented with phenomenological FFs not conceptually necessitated by factorization is expected to be reduced to an acceptable level by adopting the GMVFNS, in which the massive quark also appears in the initial state and would-be collinear singularities are subtracted to match the $\overline{\rm MS}$ calculation for $p_T \gg m_Q$. Then, the factorization theorem is at work, guaranteeing the universality and DGLAP evolution of the (nonperturbative) FFs, and a global data analysis is feasible.

From the experimental side, one notes that many new results continue to increase the variety of channels with which the QCD framework of heavy flavour production is confronted. The Tevatron definitely presented itself as an upcoming charm, beauty and top factory. The gross picture for open heavy flavours is that theory undershoots, in particular at low p_T, and that error bands in the predictions should be taken seriously, as they are in general being exhausted once data appear. HERA analyses continue to explore new domains of precision and phase space; they hold the potential to provide further guidance to refine strategies in perturbative QCD, in particular with the enhanced potential of the upgraded collider and detector coming to production mode this year [61].

Acknowledgements

We thank all participants for their contributions to a very lively and interesting session, and the organizers for the invitation to a location so rich of exceptional charm and beauty.

References

[1] B. Naroska, these proceedings.

[2] W.-K. Tung, S. Kretzer, and C. Schmidt, J. Phys. G **28**, 983 (2002); W.-K. Tung, in these proceedings.

[3] F. Olness, in these proceedings.

[4] G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. D **51**, 1125 (1995); **55**, 5853(E) (1997).

[5] V.G. Kartvelishvili, A.K. Likhoded, and S.R. Slabospitskiĭ, Yad. Fiz. **28**, 1315 (1978) [Sov. J. Nucl. Phys. **28**, 678 (1978)]; E.L. Berger and D. Jones, Phys. Rev. D **23**, 1521 (1981); R. Baier and R. Rückl, Phys. Lett. **102B**, 364 (1981); Z. Phys. C **19**, 251 (1983).

[6] E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995); P. Cho and A.K. Leibovich, Phys. Rev. D **53**, 150 (1996); **53**, 6203 (1996).

[7] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 572 (1997); **79**, 578 (1997); D0 Collaboration, B. Abbott *et al.*, *ibid.* **82**, 35 (1999).

[8] R. Barbieri, R. Gatto, and E. Remiddi, Phys. Lett. **61B**, 465 (1976).

[9] M. Krämer, J. Zunft, J. Steegborn, and P.M. Zerwas, Phys. Lett. B **348**, 657 (1995); M. Krämer, Nucl. Phys. **B459**, 3 (1996).

[10] H1 Collaboration, C. Adloff *et al.*, Eur. Phys. J. C **25**, 25 (2002); ZEUS Collaboration, S. Chekanov *et al.*, *ibid.* **27**, 173 (2003).

[11] M. Klasen, B.A. Kniehl, L.N. Mihaila, and M. Steinhauser, Phys. Rev. Lett. **89**, 032001 (2002).

[12] M. Klasen, B.A. Kniehl, L.N. Mihaila, and M. Steinhauser, Phys. Rev. D **68**, 034017 (2003); M. Klasen and B.A. Kniehl, in these proceedings.

[13] DELPHI Collaboration, J. Abdallah *et al.*, Phys. Lett. B **565**, 76 (2003); M. Chapkine, in these proceedings.

[14] PHENIX Collaboration, S.S. Adler *et al.*, hep-ph/0307019.

[15] H1 Collaboration, C. Adloff *et al.*, Eur. Phys. J. C **10**, 373 (1999); **25**, 41 (2002).

[16] B.A. Kniehl and L. Zwirner, Nucl. Phys. **B621**, 337 (2002).

[17] M. Cacciari and M. Krämer, Phys. Rev. Lett. **76**, 4128 (1996); P. Ko, J. Lee, and H.S. Song, Phys. Rev. D **54**, 4312 (1996); **60**, 119902(E) (1999); B.A. Kniehl and G. Kramer, Eur. Phys. J. C **6**, 493 (1999).

[18] CDF Collaboration, T. Affolder *et al.*, Phys. Rev. Lett. **85**, 2886 (2000).

[19] M. Beneke and M. Krämer, Phys. Rev. D **55**, 5269 (1997); A.K. Leibovich, *ibid.* **56**, 4412 (1997).

[20] E. Braaten, B.A. Kniehl, and J. Lee, Phys. Rev. D **62**, 094005 (2000); B.A. Kniehl and J. Lee, *ibid.* **62**, 114027 (2000); B.A. Kniehl, G. Kramer, and C.P. Palisoc, Report No. DESY 03-096, hep-ph/0307386, Phys. Rev. D (in press).

[21] K. Sridhar, A.D. Martin, and W.J. Stirling, Phys. Lett. B **438**, 211 (1998); Ph. Hägler, R. Kirschner, A. Schäfer, L. Szymanowski, and O.V. Teryaev, Phys. Rev. Lett. **86**, 1446 (2001); Phys. Rev. D **63**, 077501 (2001); F. Yuan and K.-T. Chao, *ibid.* **63**, 034006 (2001); Phys. Rev. Lett. **87**, 022002 (2001); V.A. Saleev, Phys. Rev. D **65**, 054041 (2002); V.A. Saleev and D.V. Vasin, Phys. Lett. B **548**, 161 (2002); A.V. Lipatov and N.P. Zotov, Eur. Phys. J. C **27**, 87 (2003); A.V. Kotikov, in these proceedings; V.A. Saleev, in these proceedings; N.P. Zotov, in these proceedings.

[22] S.P. Baranov, Phys. Rev. D **66**, 114003 (2002).

[23] P. Hoyer and S. Peigné, Phys. Rev. D **59**, 034011 (1999); N. Marchal, S. Peigné, and P. Hoyer, *ibid.* **62**, 114001 (2000); S. Peigné, in these proceedings.

[24] H. Fritzsch, Phys. Lett. **67B**, 217 (1977); F. Halzen, *ibid.* **69B**, 105 (1977); M. Glück, J.F. Owens, and E. Reya, Phys. Rev. D **17**, 2324 (1978).

[25] G.A. Schuler and R. Vogt, Phys. Lett. B **387**, 181 (1996); J.F. Amundson, O.J.P. Eboli, E.M. Gregores, and F. Halzen, *ibid.* B **390**, 323 (1997).

[26] I. Katkov, in these proceedings.

[27] D.Krücker, in these proceedings.

[28] R. Vogt, Nucl. Phys. A **700** (2002) 539 [arXiv:hep-ph/0107045].

[29] P. Pakhlov, in these proceedings.

[30] A. Meyer, in these proceedings.

[31] B.A. Kniehl, G. Kramer, and B. Pötter, Nucl. Phys. **B582**, 514 (2000); **B597**, 337 (2001); S. Kretzer, Phys. Rev. D **62**, 054001 (2000); L. Bourhis, M. Fontannaz, J.P. Guillet, and M. Werlen, Eur. Phys. J. C **19**, 89 (2001).

[32] J. Binnewies, B.A. Kniehl, and G. Kramer, Phys. Rev. D **58**, 014014 (1998).

[33] J. Binnewies, B.A. Kniehl, and G. Kramer, Phys. Rev. D **58**, 034016 (1998); G. Kramer, in these proceedings.

[34] J.C. Collins, Phys. Rev. D **58**, 094002 (1998); private communication.

[35] C. Peterson, D. Schlatter, I. Schmitt, and P.M. Zerwas, Phys. Rev. D **27**, 105 (1983).

[36] J. Binnewies, B.A. Kniehl, and G. Kramer, Z. Phys. C **76**, 677 (1997).

[37] M. Cacciari and M. Greco, Phys. Rev. D **55**, 7134 (1997).

[38] M. Cacciari and P. Nason, Phys. Rev. Lett. **89**, 122003 (2002).

[39] M.A.G. Aivazis, J.C. Collins, F.I. Olness, and W.-K. Tung, Phys. Rev. D **50**, 3102 (1994); F.I. Olness, R.J. Scalise, and W.-K. Tung, *ibid.* **59**, 014506 (1999); A. Chuvakin, J. Smith, and W.L. van Neerven, *ibid.* **61**, 096004 (2000).

[40] G. Kramer and H. Spiesberger, Eur. Phys. J. C **22**, 289 (2001); H. Spiesberger, in these proceedings.

[41] G. Kramer and H. Spiesberger, Eur. Phys. J. C **28**, 495 (2003).

[42] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **75**, 1451 (1995); CDF Collaboration, D. Acosta *et al.*, Phys. Rev. D **65**, 052005 (2002).

[43] P. Nason, S. Dawson, and R.K. Ellis, Nucl. Phys. **B327**, 49 (1989); **B335**, 260(E) (1990); W. Beenakker, H. Kuijf, W.L. van Neerven, and J. Smith, Phys. Rev. D **40**, 54 (1989).

[44] U. Kerzel, in these proceedings.

[45] H. Landsman, in these proceedings.

[46] K. Harder, "B fragmentation and energy correlation in Z $\to$ B anti-B decays (LEP-1, SLD)," *Prepared for 31st International Conference on High Energy Physics (ICHEP 2002), Amsterdam, The Netherlands, 24-31 Jul 2002*

[47] L. Gladilin, in these proceedings.

[48] A. Giammanco, in these proceedings.

[49] P. Achard, in these proceedings.

[50] G. Flucke, in these proceedings.

[51] R. Hall-Wilton, in these proceedings.

[52] G. De Lellis, in these proceedings.

[53] S. Schmidt, in these proceedings.

[54] M. Corradi, in these proceedings.

[55] V. Chiochia, in these proceedings.

[56] C. Gerlich, in these proceedings.

[57] O. Behnke, prepared for EPS conference, Aachen, July 2003.

[58] M. Bräuer, in these proceedings.

[59] A. Khanov, in these proceedings.

[60] Yu. Gotra, in these proceedings.

[61] B. List, in these proceedings.