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SUMMARY OF THE HEAVY FLAVOURS WORKING GROUP

U. KARSHON*, I. SCHIENBEIN** AND P. THOMPSON***
Weizmann Institute of Science, Israel
**Southern Methodist University, Dallas, USA*
***University of Birmingham, UK*

This is a summary of the contributions presented in the Heavy Flavours Working Group of the DIS2006 Workshop.

1. Introduction and Overview

Heavy flavour physics is an ongoing active field of experimental and theoretical research. As in all previous DIS Workshops, the emphasize in this Working Group was on the production of the heavy quarks charm (c) and beauty (b) and on issues related to QCD. We held five pure Heavy Flavours sessions, two joint sessions with the Hadronic Final States Working Group and one joint session with the Structure Functions and Low-x Working Group. In total, there were 23 experimental talks and 12 theoretical ones in all the above sessions.

The many presentations from the two collider HERA experiments H1 and ZEUS were complemented by significant contributions from the Tevatron at Fermilab, the B-factories Babar and Belle and the RHIC heavy ion collider at Brookhaven. The main topics discussed in the Heavy Flavours Working Group were: heavy flavour schemes and fragmentation, heavy quark production at RHIC, open charm and beauty production at HERA, quarkonium production, beauty production at the Tevatron, charm spectroscopy, charm decays and new states at the B-factories. The joint session with the Structure Functions Working Group concentrated in heavy quark structure functions and parton density functions. The joint sessions with the Hadronic Final States Working Group dealt with common theory issues, such as k_T factorization schemes and jet definitions and with searches for exotic baryonic states (pentaquarks).

Following the presentation of the summary talks at the Workshop, the remainder of this document is divided into two parts, a theory and an experimental summary.

2. Theory summary

In this section, we summarize the main theoretical issues that were presented in the Heavy Flavours Working Group of DIS 2006. Several theoretical talks have been related to the treatment of heavy quarks in perturbation theory ('heavy flavour schemes'). In particular, we had discussions on heavy flavour schemes for the fully inclusive case used in global analyses of parton distribution functions (α_s treatment, NNLO, S-ACOT(χ), intrinsic charm). Moreover, we had talks related to heavy flavour schemes in one-particle inclusive processes relevant for global analyses of fragmentation functions and a proper description of kinematic distributions in the momentum of the observed heavy-flavoured hadron (GM-VFNS, evolution with heavy quark thresholds). Other major topics have been a new analysis of heavy quark fragmentation functions, heavy quark production at RHIC, progress on heavy quark production in the k_T-factorization approach and a comparison of charmonium production in the colour evaporation model (CEM) and non-relativistic QCD (NRQCD).

2.1. *Heavy Flavour Schemes*

Heavy flavour schemes have been studied intensively in the past three decades. At the heart of these investigations is the question of how to deal with heavy quarks in perturbative QCD. In the fixed flavour number scheme (FFNS), the heavy quark is treated in fixed order (FO) perturbation theory, i.e., collinear logarithms of the heavy quark mass are computed order by order in perturbation theory. On the other hand, in a variable flavour number scheme (VFNS) these collinear logarithms are absorbed into heavy quark parton distribution functions (PDFs) and fragmentation functions (FFs) at (or close to) the heavy quark mass scale m_h. The logarithms are resummed to all orders in perturbation theory by evolving from m_h to the hard scale Q of the process with the help of the well-known DGLAP renormalization group equations. The number of active flavours, n_f, is 'variable' because at the scale m_h, where the heavy quark PDF is introduced, n_f is increased by one unit. There are several realizations of variable flavour number schemes discussed in the literature due to the fact that the treatment of finite m_h/Q terms is not prescribed by the factorization and renormalization schemes. In the Zero-Mass VFNS (ZM-VFNS) the finite heavy quark mass terms are neglected. On the other hand, General-Mass VFNS (GM-VFNS) have prescriptions how to take into account the m_h/Q pieces which is essential for applications which include regions of phase space where $Q \sim m_h$, such as global fits to determine PDFs.

2.1.1. *Fully Inclusive Case*[1,2]

R. Thorne, in his contribution, has emphasized the importance of using a GM-VFNS for performing a fully-global analysis of PDFs. Here, the term 'fully-global analysis' is opposed to semi-global fits which only include a part of the available experimental information. Nevertheless, there are several applications which require the knowledge of PDFs in a FFNS. The MRST group now provides such parton distributions[3] by evolving from the MRST04 partons at $Q_0 = 1$ GeV but keeping $n_f = 3$ fixed in the splitting functions *and* α_s.

Another subject of his talk has been the construction of a GM-VFNS at NNLO which is used in a global analysis of PDFs at NNLO[4]. So far, this is the only existing detailed proposal for a GM-VFNS at NNLO and it should be stressed again that the development of such a scheme is mandatory for global parton analyses at this order.

W.-K. Tung has reported on a new implementation of a heavy flavour scheme based on the GM-VFNS of Collins[5] in the CTEQ `Fortran` package. This scheme, the S-ACOT(χ) scheme, combines the kinematic constraints of the ACOT(χ) rescaling procedure[6] with the simplifications of the S-ACOT scheme[7] which states that it is a convenient *scheme choice* to neglect the heavy quark mass terms in all processes with a heavy quark in the initial state. It should be noted that heavy quark initiated contributions including the full heavy quark mass dependence have been computed in next-to-leading order (NLO) for deep inelastic scattering in Ref. [8]. However, similar calculations for other processes have not been performed. This new implementation has been utilized in a new global analysis of parton distributions, incorporating the complete HERA I data sets as described in the Structure Functions session summary.

Conventional global fits assume that heavy quark PDFs are *radiatively generated* by QCD evolution, fully relying on perturbatively computed boundary conditions[9]. Although the assumption of a purely perturbative charm or bottom PDF does not contradict any experimental data it is important to test it in a quantitative way. While the possible amount of intrinsic charm has been analysed before in the literature, see e.g. Ref. [10], it has never been done in the context of a global analysis which is the appropriate approach since the various quark and gluon PDFs are intimately linked. Within the framework of the new implemented S-ACOT(χ) scheme, the CTEQ collaboration has included a non-perturbative charm distribution at the input scale $Q = m_c$ and has performed a global analysis[2]. Their results show that the best fit favours a small non-perturbative charm component at the input scale, although the difference between this and a conventional fit with no intrinsic charm falls well within the uncertainty range of the global fit. Furthermore, the magnitude of the intrinsic charm component is limited to carry at most 1.8% of the proton's momentum at $Q = m_c$.

2.1.2. *One-Particle Inclusive Case*[11,12]

For the same reasons as in the fully inclusive case it is important to work out the details of a GM-VFNS for one-particle inclusive production of heavy quarks/hadrons. B. Kniehl reported on progress in the development of such a scheme[13,14]. Employing universal fragmentation functions for D^0, D^+, D_s^+, and $D^{\star+}$ mesons (and complex conjugates)[15] extracted from a fit to LEP1 data from the OPAL collaboration, a good description of CDF run II data could be achieved[16]. More results in this GM-VFNS are expected in the future for B-meson production at the Tevatron and heavy-flavoured hadron production in deep inelastic scattering at HERA.

Another topic was the evolution of FFs across heavy quark thresholds[12]. While the proper perturbative relations ('matching conditions') between the parton distributions below and above the heavy quark thresholds are known and used in NLO QCD since 20 years[17] this problem has been ignored so far in fits to light hadron fragmentation functions. In his talk, M. Cacciari discussed the relevant NLO matching conditions for fragmentation functions which should be used in the evolution across heavy flavour thresholds[18] in cases where the heavy flavour FFs are radiatively generated. As an interesting application, it will be possible to perform fits to light hadron fragmentation data parametrizing only the three light quarks and the gluon FFs while the charm and bottom FFs are purely perturbative.

2.2. *Heavy Quark Fragmentation*[19]

C. Oleari gave a theoretical introduction to heavy quark fragmentation functions. Moreover, he reported on results of a recent QCD analysis of D and B meson FFs[20] using Belle and CLEO data at $\sqrt{S} = 10.6$ GeV and LEP1 data at $\sqrt{S} = m_Z$. This study is interesting for at least two reasons. First, the D-meson data from the B-factories are very precise and, secondly, the two different energy scales allow to test the universality of the fragmentation functions. The analysis was performed in NLO QCD (NLO initial conditions, evolution, and coefficient functions) including soft gluon resummation effects at the next-to-leading-log (NLL) level, evolution with proper matching at the bottom threshold (as discussed in the previous section) and correcting the data for QED initial state radiation. As a result, the description of CLEO and Belle data for D mesons was very good in the whole x-range. However, evolving the fit of CLEO and Belle data to the Z-pole resulted in a bad description of ALEPH data in the large-x (large-N) region questioning the universality of the fragmentation functions. Note that the analogue in the space-like sector would be PDFs determined from data of the structure function $F_2(x, Q^2)$ at low-Q^2 which, after DGLAP evolution to large Q^2, result in a bad description of the structure function data at the high scale. In this case one would probably think of target mass corrections or higher twist effects as possible explanations of the discrepancy. For the fragmentation functions, a possible explanation[20] of this worrisome result could be non-perturbative corrections to the coefficient function of type $1 + C(N-1)/Q^2$ or $1 + C(N-1)/Q$. Clearly, more work is needed here in the future.

2.3. *Heavy Quark Production at RHIC*[21]

M. Cacciari has presented QCD benchmark predictions for open charm and bottom production at RHIC[22] based on the FONLL framework[23] supplemented with suitable spectra for the decay of the heavy flavoured hadron H_Q into the observed electron. The corresponding theoretical uncertainties are discussed in detail which should be an important part of any reliable theoretical study. As a result, within errors the theoretical predictions are in fair agreement with the RHIC data for pp and dAu collisions at $\sqrt{S_{NN}} = 200$ GeV. However, the central curves undershoot the data by a factor 2–3. All in all, it is presently too early to draw definite conclusions on the applicability of standard QCD heavy quark calculations at RHIC.

Single inclusive electron spectra are also of great interest in relativistic nucleus–nucleus collisions since they test ideas about energy loss of particles in media. Generally, at transverse momenta of a few GeV, the energy loss of the heavier bottom quarks is expected to be smaller than that of the lighter charm quarks. Accordingly, the electrons from b-decays are much less suppressed. A calculation of the suppression of single inclusive electrons in *Au–Au* collisions compared to *pp* collisions (quenching ratio) shows that the result depends critically on the relative contribution of charm and bottom production, which is affected by large perturbative uncertainties[24]. Therefore, it would be very helpful to disentangle experimentally the *b*- and *c*-decay contributions.

2.4. *Heavy Quarks and k_T-Factorization*[25,26]

We had two talks dealing with heavy quark production in the k_T-factorization approach which involve a resummation of small-x logarithms which become large at high energies. N. Zotov, reported on a study of HERA beauty photoproduction data and found reasonable agreement with the data[27]. A similar study of beauty electroproduction can be found in Ref. [28]. In general, it is important to note that much progress has been made towards a global understanding of k_T-factorization by working out this picture for several processes. This allows to study all relevant data sets with one unintegrated gluon distribution along with a systematic study of theoretical uncertainties including a variation of scales. The kinematic region of very small x is also a regime where the gluon density is growing so large that gluon recombination effects are becoming relevant. Such effects can be taken into account with the help of the Balitsky-Kovchegov equation which adds a non-linear term to the linear BFKL evolution equation of the gluon. As has been discussed by K. Peters at this meeting, the results for bottom production at the Tevatron and the LHC with and without the non-linear correction to the evolution are very similar such that linear gluon evolution can be safely applied in the k_T-factorization approach[26].

2.5. *Charmonium Production: CEM vs. NRQCD*[29]

J. Lee reported on a detailed comparison of charmonium production cross sections in the colour evaporation model (CEM) and the framework of non-relativistic QCD (NRQCD)[30]. The CEM is a simple model describing the transition from a $c\bar{c}$ pair into charmonium which has been invented about 30 years ago. On the other hand, NRQCD is quite a general framework derived from QCD. Therefore it is possible to derive relationships between the NRQCD non-perturbative matrix elements that follow from the model assumptions of the CEM. Such relations do not respect the velocity-scaling rules of NRQCD and lead to a rather different picture of the transition of a quark anti-quark pair into a quarkonium. Phenomenologically, these relationships are also in disagreement with values of the matrix elements that have been extracted from the Tevatron data for charmonium production at large transverse momenta[30]. Finally, also a direct comparison of the CEM and NRQCD predictions with charmonium production data from CDF show that the CEM fits are not satisfactory both in normalization and slope, even if multiple gluon emission effects are included in form of k_T smearing. On the other hand, NRQCD factorization which has more free parameters than the CEM gives a satisfactory fit to the data. For more details see[29,30].

3. Experimental summary

The study of heavy flavour production in ep and hadron-hadron collisions provides important information on the gluon density of the proton and a test of the understanding of many aspects of QCD. The measurement of heavy flavours at the e^+e^- B-factories and at the Tevatron allows to constrain the parameters describing CP violation and provide a wealth of information on heavy flavour hadron spectroscopy. In heavy ion collisions at RHIC heavy flavour production is a vital tool for the understanding of QCD at high densities. At this workshop new results from the HERA-II data taking period were shown. The experiments H1 and ZEUS have upgraded many aspects of their detectors including those relevant for heavy flavour production. For example, results using the newly installed ZEUS micro-vertex detector were presented. The large luminosity delivered by the HERA upgrade combined with the detector enhancements will continue to see improved precision of heavy flavour measurements. The HERA experiments also continue to finalise their remaining HERA-I measurements with many results shown as preliminary last year presented in their final form at this workshop. These included the measurements of charm fragmentation in photoproduction by ZEUS, charm and beauty jets in photoproduction by H1 and the inclusive production of charm and beauty in DIS by H1.

3.1. B_s *Mixing*

The first measurements of the B_s-$\bar{B}_s$ mixing oscillation frequency made at the Tevatron by the D0[31] and CDF[32] collaborations were presented by T. Kuhl. Mixing in the B_s sector is only measured indirectly at the B-factories due to a low centre of mass energy. A determination of the oscillation frequency Δm_s between the mass eigenstates allows the extraction of the V_{td} matrix element which improves the understanding of CP violation in the standard model. The measurement was made possible by the 1fb^{-1} of data collected by each experiment. The D0 collaboration fully reconstructed the decay of a B_s meson and tagged the opposite meson via its semi-leptonic decay. The mixing asymmetry is measured as a function of the decay length allowing the most likely value of Δm_s to be extracted in a fit. A value in the range $17 < \Delta m_s < 21\text{ps}^{-1}$ at 90% confidence level was found by D0 (figure 1). The measurement has also been performed by CDF which makes use of an impact parameter trigger and the explicit reconstruction of many hadronic and semi-leptonic decay channels in the tracking detectors. A more accurate value of $17.33^{+0.42}_{-0.21}(stat.) \pm 0.07(sys.t)\text{ps}^{-1}$ is measured (figure 1). These results on Δm_s improve considerably the constraints on the CKM unitarity triangle. Further indication that the Tevatron experiments are becoming B-factories themselves was provided by the talk on B resonances and B hadron decays at D0 by D. Gele.

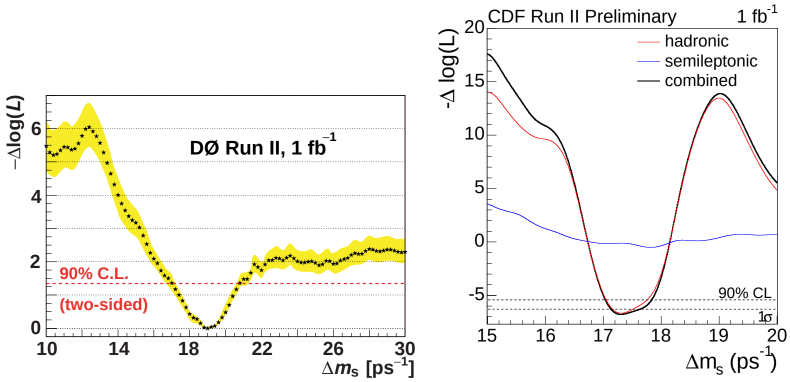

Figure 1. The likelihood for different values of the oscillation frequency Δm_s shown for D0 (left) and CDF (right).

3.2. *Heavy-Quark Jets*

Final results[33] on the measurement of heavy flavour dijets in photoproduction from H1 were shown by L. Finke. The cross sections are obtained by measuring the displacement from the primary vertex of all tracks with precise spatial information from the H1 vertex detector. This allows the fraction of c and b components of an inclusive dijet sample to be determined. The cross section is plotted as a function of p_T of the highest p_T jet in figure 2. Taking into account the theoretical uncertainties, the charm cross sections are consistent with the NLO QCD calculations, while the predicted cross sections for beauty production are somewhat lower than the measurement.

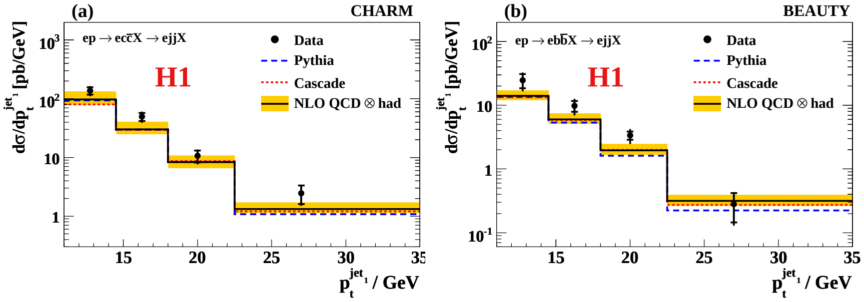

Figure 2. The differential dijet cross section as a function of p_T of the highest p_T jet for charm (left) and beauty (right) flavoured jets.

3.3. *The Inclusive Production of Heavy Flavours*

Final results[34] on the inclusive production of charm and beauty quarks in DIS were presented by P. Laycock. The measurements were made using a method based on the displacement of tracks from the primary vertex. The double differential reduced cross sections in Q^2 and x are measured in the range $Q^2 > 12$ GeV^2 and $0.0002 \leq x \leq 0.005$. The charm results are found to be compatible with those made using measurements of D^* cross sections where the extrapolation to the full phase space is larger. The results are also found to be compatible with the predictions of NLO QCD although the differences in the predictions is as large as a factor of 2 at low x and low Q^2. The HERA-II data may be able to further investigate these theoretical differences.

3.4. *Beauty from $D^* - \mu$ and $\mu - \mu$ Correlations*

It has long been established that the measurement of events in which both heavy quarks are tagged by a signature of their decay provides large enough acceptance to measure the total cross section with small extrapolation uncertainties. A. E. Nuncio Quiroz presented results from ZEUS on the description of $D^* - \mu$ and $\mu - \mu$ photoproduction cross section data by an interface of the NLO QCD program FMNR and the Monte Carlo program

PYTHIA. Comparisons of the data and theory were, as expected, to be the same at the hadron and b-quark level. The ZEUS $D^* - \mu$ data were found to be compatible with previous measurements of H1 when extrapolated to the same phase space using the new interface. The double tag correlation results continue to show the largest difference in the central values to NLO QCD (typically factor 2-3). However, the statistical significance of this discrepancy is still small due to the low tagging probabilities and more data is needed.

3.5. *Heavy Quark Production at HERA-II*

A number of preliminary measurements from the HERA-II data taking period were presented at the workshop by the ZEUS collaboration. Even though the data samples analysed thus far represent only a small fraction of the HERA-II luminosity accumulated they demonstrate the technical performance of the detector and provide an indication of what is feasible once the full luminosity has been collected and analysed. Results on beauty production in events with a jet and associated muon were presented by O. Kind. In photoproduction the beauty cross section was obtained using a method combining information from the relative transverse momentum of the muon with respect to the jet ($p_T^{\rm rel}$) and the impact parameter of the muon track as measured precisely by the micro-vertex detector. The cross section as a function of the p_T of the muon is shown in figure 3 and is seen to be compatible with the HERA-I measurement and with a massive NLO QCD calculation. The measurement in DIS was obtained using the $p_T^{\rm rel}$ method alone and was also found to be in agreement with previous measurements which tend to be somewhat higher than the QCD predictions.

The use of the ZEUS micro-vertex detector in charm production was shown by F. Karstens. The combinatorial background in the measurement of $D^+ \to K^-\pi^+\pi^+$ (+c.c.) can be reduced by a factor 30 when cutting on the significance of the decay length of the reconstructed D^+ meson. The invariant mass before and after the significance cut can be seen in figure 3.

3.6. *Beauty Production at the Tevatron*

Results on the production of b jets at CDF were presented by D. Jeans. The cross section for beauty jets was presented as a function of p_T of the jet in the range $38 < p_T < 400$ GeV. The beauty component of the data is extracted by fitting the invariant mass spectrum of particles coming from

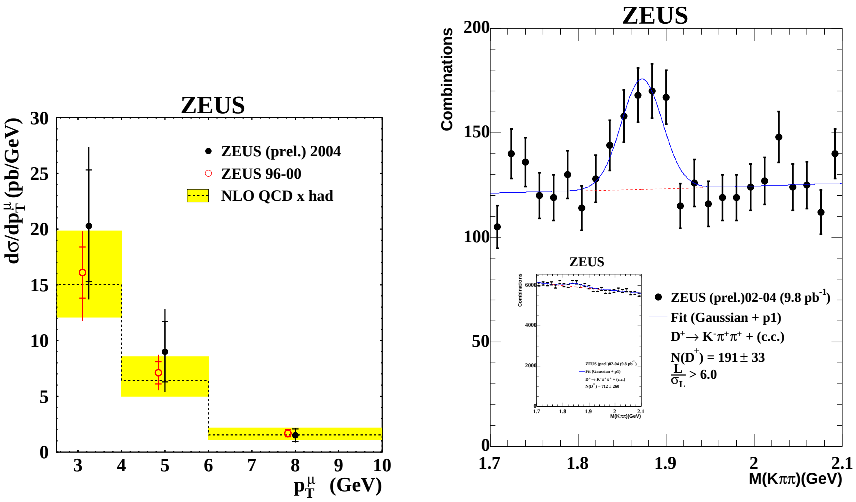

Figure 3. The cross section for muon plus jets in photoproduction as a function of the p_T of the muon (left). The invariant mass spectra for $M(K\pi\pi)$ before and after cutting on the decay length significance of the D^+ candidate.

an explicitly reconstructed secondary vertex associated with the jet. The efficiency for tagging a b-jet is larger than 40% for $p_T < 150$ GeV (figure 4). The resulting jet cross section is found to be in agreement with a fixed order massive calculation in QCD. However, the scale uncertainties of both the data (due to the jet energy scale) and the theoretical prediction are very large. These could possibly be reduced by measuring the b-jet fraction. The measurement of Z^0 production associated with a tagged b-jet was also presented. The production process is sensitive to the proton b-PDF. The CDF result is found to be in agreement with the predictions of a massless NLO QCD calculation.

The status of the level of agreement between experimental data and theoretical predictions of b-production at the Tevatron was investigated by F. Happacher. The ratio of all published measurements to the same MC calculation was presented. It is observed that the ratio varies by an amount larger than expected on statistical grounds. Therefore, a single theory would have difficulty describing all the available data. However, NLO QCD is able to describe the latest preliminary results from CDF and D0 (see above). Hopefully, the final data from Run-II will help to settle the remaining differences between the data sets.

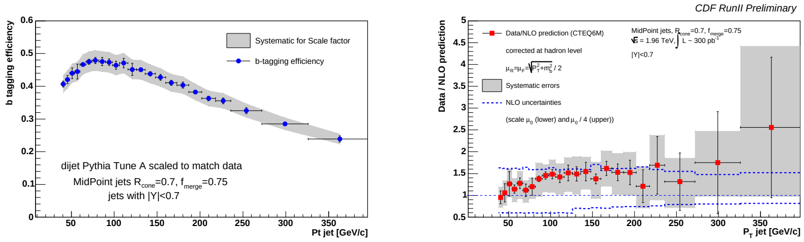

Figure 4. The efficiency of tagging b-jets as a function of the jet p_T (left) and the ratio of the b-jet cross section in data to a NLO QCD calculation (right).

3.7. *Charm Quark Fragmentation and Spectroscopy*

The large charm production cross section at HERA allows the study of the fragmentation of charm quarks into the various charmed hadrons. Final results[35] on charm fragmentation in photoproduction from ZEUS were presented by W. Dunne. The fraction of charm quark hadronizing into D^0, D^+, D_s mesons and the Λ_c baryon were presented. The fractions are measured by explicitly reconstructing the products in the nominal decay modes of the charmed hadrons in the ZEUS central tracking detector. The fractions are found to be compatible with measurements from H1 and ZEUS in DIS and with those from e^+e^- scattering supporting the hypothesis of a universal charm fragmentation. The hypothesis is further tested by measuring related quantities such as the ratio of charged to neutral meson production, the ratio of vector meson to vector plus pseudoscalar meson production and the strangeness suppression factor. Again the range of preferred values are found to be consistent with those from e^+e^- scattering. L. Gladilin presented an overview of experimental results on heavy quark fragmentation. This included results on charm fragmentation fractions from ep and e^+e^- colliding experiments. A summary on the latest results on the measurements of heavy flavour fragmentation functions which is the momentum fraction of the quark carried by the heavy flavour hadron were also presented.

The B-factories continue to provide a wealth of information on charm spectroscopy. The latest results form Babar, Belle and CLEO on charm spectroscopy, charm decays and the production of new states was presented by M. Saleem.

3.8. *Quarkonium Production*

Final results[36] on the elastic production of J/ψ mesons in photoproduction from H1 were shown by Y.C. Zhu. The results are sensitive to different parameterisations of the gluon density of the proton in a region where it is not constrained by measurements of the inclusive proton structure function. The B-factories are a source of a huge amount of quarkonium data. The latest results on quarkonium spectroscopy, new states and charm baryons from Babar and Belle were presented by L. Vitale and H. Kichimi, respectively.

3.9. *Heavy Flavour Production at RHIC and HERA-B*

The mass of charm quarks and the fact that they are mostly produced via gluon fusion in hadron-hadron collisions makes them ideal probes of the dynamics of heavy ion collisions and their description by perturbative QCD. The production of charm at forward and backward rapidities in pp and dAu collisions at the PHENIX experiment was presented by X. Wang. Charm production at forward rapidity is found to be suppressed consistent with predictions in two different models, the colour glass condensate and a model based on power corrections. However, at backward rapidity the results differ from the expectations although more precise data is required. Measurements from STAR for central heavy flavour production in $AuAu$ collisions were also shown by M. Calderon. The suppression of heavy flavours w.r.t. pp collisions at high p_T suggests large energy loss similar to light quarks. However, the results are difficult to interpret without experimentally distinguishing c and b contributions and therefore detector upgrades are being performed. The understanding of heavy flavour suppression in an ordinary nuclear state is also crucial for interpreting the formation of quark-gluon plasma. The results on J/ψ production, and many other processes, at the high-energy fixed target experiment HERA-B were presented by R. Spighi.

3.10. *Towards the LHC*

The first of hopefully many contributions to the heavy flavour sessions from the LHC experiments was made by C. Ciocca who gave a presentation on the study of top pair production at CMS. The heavy flavour session was concluded by a presentation by M. Wing illustrating the relevance of heavy flavour production at HERA to the LHC. The participants of the conference were encouraged to participate in the ongoing HERA-LHC workshop[37].

Acknowledgments

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