We review the status of hard interactions, in particular of jet and heavy flavor production, at HERA and LEP. Emphasis is given to recent theoretical developments. Instantons, event shapes, and prompt photons are also briefly discussed.

1 Introduction

At the DIS 2000 conference in Liverpool, a large variety of perturbative QCD calculations for jet and heavy flavor production was confronted with experimental data from HERA, LEP, and the TEVATRON. In many cases, though not all, reasonable agreement between theory and experiment was found, thus constituting a successful test of QCD as the theory of strong interactions. The further reaching goals of extracting and testing the non-perturbative fundamental parameters of this theory were, however, not reached at the same level. Considerable room for improvement was left for the determination of the strong coupling \( \alpha_s(Q^2) \), the hadron and photon fragmentation functions, and the structure functions of the proton and in particular of the photon. Experimental results for the polarization of the \( J/\Psi \) charmonium shed new doubt on the theory of heavy quark-antiquark bound states, Non-Relativistic QCD (NRQCD), and the precise values of its non-perturbative operator matrix elements remained unclear. In many cases DIS 2000 had to leave as desiderata the reduction of the experimental and theoretical uncertainties, in particular in the hadronic energy scale and in the dependence on the renormalization and factorization scales.

The experimental errors can often be reduced by considering rates instead of absolute cross sections. Theoretical progress is harder to reach and requires tedious next-to-leading order (NLO), next-to-next-to-leading order (NNLO), and resummed calculations and may also necessitate the inclusion of power corrections. Sufficient theoretical interest is thus mandatory for precise determinations of parton densities etc., which also form the basis for reliable estimates of signals and backgrounds of physics beyond the Standard Model. In this paper we review progress along these lines at and prior to the DIS 2001 conference in Bologna. The paper is organized from the general to the
detailed features of the hadronic final state. In Sec. 2, the current status of instantons and event shapes is discussed. Sec. 3 summarizes recent progress for jet production and Sec. 4 for prompt photon production. Open and bound-state heavy flavor production is discussed in Sec. 5, and Sec. 6 contains a brief summary.

2 Instantons and Event Shapes

At DIS 2000 a first dedicated search for instantons was presented by the H1 collaboration. It yielded an excess of 549 observed events over $435^{+36}_{-22}$ and $363^{+22}_{-26}$ events expected from matrix elements plus parton showers (MEPS) and the color dipole model (CDM). Four of the six observables agreed in shape with the expected instanton signal, but the two distributions in the transverse energies of the instanton band ($E_{t_b}$) and of the current jet ($E_{t_{jet}}$) deviated. The discrepancy could now be traced back to the fact that a fiducial cut on $x \geq 0.15$, which depletes the theoretically unreliable low $Q^2$ region, was
As can be seen in Fig. 1 this affects exactly the two transverse energies $E_{T_b}$ and $E_{T_{jet}}$, which should agree better in shape with the data if the cut $x \geq 0.15$ is implemented.

The event shape variables thrust $T$, jet mass $\rho$, jet broadening $B_T$ and $B_W$, and the $C$-parameter provide a means to describe general features of a multi-particle hadronic final state in $e^+e^-$ annihilation. The dominant contributions from low multiplicities can be calculated perturbatively, but...
these calculations become sensitive to hadronization and power corrections at the edges of phase space. A universal description of the event shape variables is possible with the help of the running strong coupling \( \alpha_s(Q^2) \) and its effective value in the infrared regime \( \alpha_0 \). Recently the event shape variables have been shown to depend on the particle masses and thus on their definitions in terms of momenta (\( p \)-scheme) or energies (\( E \)-scheme) and also on the decay level of the particles (resonance or decay). In the \( E \)-scheme mass effects are absent and, as Fig. 2 demonstrates, the uncertainties in the \( \alpha_s(Q^2) \) and \( \alpha_0 \) determinations from different event shape variables are reduced.

Similar event shape variables can be defined in deep-inelastic scattering, where non-global observables require special care in resummed calculations due to soft emission between hemispheres. A discrepancy in the thrust distribution \( d\sigma/dt_2 \) between the perturbative DISENT prediction on the one

\[ k_{\perp} \text{ algorithm} \]

\[ \mu_R^2 = \mu_F^2 = \mu^2 \]
\[ \mu_R^2 = \mu_2^2 \quad \text{&} \quad \mu_F^2 = Q_{\text{H.S.}}^2 \]
\[ \mu_F^2 = \mu_1^2 \quad \text{&} \quad \mu_R^2 = Q_{\text{H.S.}}^2 \]

Figure 3. Scale dependence of the NLO three-jet cross section in DIS.

\( \sigma_{3+1}(f_{\text{cut}} = 0.2) \, [\text{nb}] \)

\( \mu^2/Q_{\text{H.S.}}^2 \)

\( 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \quad 1.6 \quad 1.8 \quad 2.0 \)

\( z \)

\( 6 \)
Figure 4. The NLO dijet photoproduction cross section as a function of the observed momentum fraction of the partons in the photon compared to ZEUS and OPAL data.

3 Jet production in DIS, $\gamma p$, and $\gamma\gamma$

The strong coupling $\alpha_s(M_Z)$ can be determined in DIS not only in structure function measurements, but also in jet production. Recent determinations by the H1 and ZEUS collaborations are in good agreement with the world average and have quite competitive error bars. Both the experimental and theoretical errors in these determinations could be reduced, since jet rates were analyzed instead of absolute jet cross sections. Nevertheless, the uncertainty in the H1 three-jet rate from the LO scale variation was still larger than the sensitivity to $\alpha_s(M_Z)$. This could now be changed since a NLO three-jet calculation in DIS has recently become available. The calculation uses helicity amplitudes, crossed from the result $e^+e^- \rightarrow 4$ jets, which have been calculated by several groups, and it has been numerically checked against the NLO dijet result of DISASTER++. How much the NLO corrections reduce the scale dependence can clearly be seen in Fig. 3.

For jet production in photon-proton collisions three different NLO calculations have become available over the last years. Although they use different phase-space slicing and subtraction techniques, they agree well within the numerical accuracy.
come available which uses a phase space slicing technique in transverse energy $E_T$ and jet radius $R$. This calculation has also been found to agree with the calculation by Klasen and Kramer. Furthermore it has confirmed previous observations that dijet cross sections defined with an identical cut on both jet transverse energies are infrared sensitive due to incomplete cancellations of virtual and real corrections. In addition, Aurenche et al. remark that this sensitivity propagates into the variable $x_\gamma^{obs} = \sum_{i=1,2} E_{T,i} e^{-\eta_i} / (2E_\gamma)$ and propose to replace the transverse energy of the second jet by that of the first jet. However, this prescription still does not cure the (integrable) singularity at $x_\gamma^{obs} = 1$ so that it remains necessary to choose a large bin width in $x_\gamma^{obs}$. This is demonstrated in Fig. 4, where recent ZEUS data with a bin width of 0.2 and OPAL data with a bin width of 0.1 are compared to NLO QCD predictions using AFG and GRV photon densities. At small $x_\gamma^{obs}$, both experiments find lower cross sections than suggested by the used photon densities.
At HERA jets can be produced in photoproduction in association with a leading neutron. If the energy transfer between the proton and neutron is small, the cross section is dominated by virtual pion exchange and the dijet cross section can be used to determine the parton densities in the pion. In Fig. 5 the NLO dijet photoproduction cross section with a leading neutron is shown as a function of the observed momentum fraction of the partons in the pion. Unfortunately, equal cuts on $E_T$ have been used in the ZEUS measurement, but the SMRS pion densities seem to agree better with the data than the GRS densities.
4 Prompt photons in photoproduction

Prompt photon production is known to suffer from uncertainties due to fragmentation contributions, isolation ambiguities, and possibly intrinsic transverse momenta of the scattering initial partons. ZEUS have analyzed prompt photon photoproduction and observed an excess over the LO QCD expectation in the $p_{\perp}$, $p_{\parallel}$, and $\Delta\phi$ distributions. They have then attributed these effects to an effective $\langle k_T \rangle$ of $1.69 \pm 0.18 \pm 0.20$ GeV, which includes effects coming from the initial-state parton showering as modelled within PYTHIA. This value of $\langle k_T \rangle$ seems to be consistent with determinations in hadron collisions at different energies (see Fig. [3]), which are, however, obtained using a variety of methods. The data could not yet be confronted with a complete NLO QCD calculation or resummed QCD results. Such a comparison will be complicated by the fact that equal cuts on the transverse energies of the photon
and recoiling jet have been used ($E_T > 5$ GeV). Nevertheless, the ZEUS data seem to support the trend that the effective $\langle k_T \rangle$ in the proton rises with the available hadronic energy.

5 Heavy flavor production

The production of heavy quark-antiquark bound states is described by the effective field theory of Non-Relativistic QCD (NRQCD). It predicts the production of intermediate color-octet bound states, which transform non-perturbatively into the observed color-singlet quarkonia by soft gluon radiation. The color-octet mechanism is clearly needed to describe the transverse
momentum spectra of $J/\psi$ and $\Psi'$ mesons at the TEVATRON. However, recent ZEUS data confirm that it is not needed in photoproduction, where the NLO color-singlet prediction is fully sufficient to describe the data. To clarify the situation NLO corrections have to be included in other quarkonium processes like photon-photon collisions. In this case direct, single-resolved, and double-resolved processes contribute at large, intermediate, and small $p_T$. The real corrections to the direct channel have recently been calculated and are shown in Fig. 3. At large $p_T$ they increase the direct LO cross section by about an order of magnitude.

Open charm production has been measured in DIS by the ZEUS and H1 collaborations. While ZEUS find good agreement in the $Q^2$ and $x$ distributions, H1 see an excess over NLO QCD predictions using GRV parton densities and the Peterson fragmentation function at small $p_T$ and forward rapidities $\eta$ (see Fig. 3). Unfortunately the data are not sensitive enough to distinguish between different fixed and variable flavor schemes.

A particularly interesting topic is the bottom cross section, which is in excess over massive QCD predictions in hadron-hadron, photon-hadron, and photon-photon collisions (see Fig. 9 for the HERA results). Different explanations can be found for this excess ranging from light bottom squarks and gluinos to resummed calculations in the massless evolution scheme and unintegrated gluon densities.
6 Summary

In summary, perturbative and non-perturbative QCD continues to be a challenge in hard interactions, jet and heavy flavor production. In many cases it is the theoretical error which is now dominating and requires a substantial effort in multi-particle NLO, NNLO, and resummed calculations. The most challenging discrepancies consist in the bottom cross section and in quarkonium production, where the universality of NRQCD and its color-octet mechanism are seriously challenged from the persisting TEVATRON-HERA anomaly.

After the luminosity upgrade HERA II will be the only European collider producing new data on high $Q^2$ and $E_T$ jet production, bottom differential cross sections and decays, and it will have an increased discovery reach for physics beyond the Standard Model. At higher energies, jet and heavy flavor production could be studied at a future THERA collider.

Acknowledgments

The author thanks R. Nania for the kind invitation and financial support, B.A. Kniehl, G. Kramer, L. Mihaila, and M. Steinhauser for their collaboration, and M. Dasgupta, M. Fontannaz, G. Grindhammer, P. Hodgson, J. Meyer, J. Repond, J. Whitmore, M. Wing, and Z. Trocsanyi for helpful discussions. Financial support by the Deutsche Forschungsgemeinschaft through Grant No. KL 1266/1-1, by the Bundesministerium für Bildung und Forschung through Grant No. 05 HT9GUA 3, and by the European Commission through the Research Training Network Quantum Chromodynamics and the Deep Structure of Elementary Particles under Contract No. ERBFMRX-CT98-0194 is gratefully acknowledged.

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