TESTS OF QCD: SUMMARY OF DIS 2000

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This summary of the working group 2 of DIS 2000 encompasses experimental and theoretical results of jet physics, open and bound state heavy flavour production, prompt photon production, next-to-leading order QCD calculations and beyond, instantons, fragmentation, event shapes, and power corrections, primarily from deep-inelastic scattering and photoproduction at HERA, but also from the LEP and Tevatron colliders.

1 Jets in deep-inelastic scattering

Schörner, Pöschl, Chapin, and Caron reported on measurements of inclusive jet (1+1) [1], dijet (2+1) [2,3], and three jet (3+1) [4] production by H1 and ZEUS, scanning an enormous region of the kinematic plane and of the jet phase space at HERA. They provide therefore an important and demanding test of the adequacy of the current QCD calculations in next-to-leading order (NLO) of the strong coupling parameter in these regions.

In the photon virtuality Q^2 the measurements cover the range from 5 GeV^2 to 10^4 GeV^2 , in Bjorken-x from 10^{-4} to 0.3, and in $\xi = x(1 + M_{jj}^2/Q^2)$ from $5{\times}10^{-3}$ to 0.1, where ξ in leading order (LO) of the strong coupling parameter is the momentum fraction of the gluon or quark emitted by the proton. Jets are defined using the inclusive k_T-algorithm in the Breit frame. [2] In this frame the transverse energy of a jet is dominated by QCD processes. In the jet phase space the measurements span the range in the transverse energy of the jets in the Breit frame from $5 < E_T < 100$ GeV, in E_T^2/Q^2 from 0.5 to 100, in rapidity from forward to central and backward jets in the HERA frame, and in the three jet invariant mass M_{3j} up to 100 GeV.

The comparison of these jet measurements to QCD calculations in NLO allows to draw the following conclusions: 1) Calculations using Q^2 as renormalization scale can describe almost all of the data at the prize of large uncertainties at low Q^2, when varying the scale by a factor of 1/4 to 4. 2) When using E_T^2 as the relevant scale, good agreement with the data is achieved for large jet E_T ($E_T > 20$ GeV) [1] and for large Q^2 ($Q^2 > 50$ GeV^2) [2,3]. For intermediate values of the ratio E_T^2/Q^2, between 1 and 50, the calculations are below the data [1,3]. The forward jet cross section shown by H1 [1], requiring $x_{jet} > 0.035$ and $1.5 < \eta_{lab} < 2.8$, but without demanding that $E_T^2 \approx Q^2$ as done in previous such analyses by H1 and ZEUS [5], rises more strongly than the NLO prediction for decreasing x down to 10^{-4}. With E_T^2 as the renormalization scale the uncertainties in the predicted cross sections are however much smaller than for the scale Q^2. 3) Typically the discrepancies between data and NLO calculations are large, where the corrections from LO to NLO, the hadronisation corrections, and the renormalization scale uncertainties are large. 4) In a large part of the phase space the theoretical uncertainty due to the renormalization scale are much larger than the experimental errors. The latter are dominated by the uncertainty of the hadronic energy scale of the calorimeters of both H1 and ZEUS.

The NLO QCD scale uncertainty estimates for the DIS dijet cross section as a function of Q^2 and $< E_T >^2 /Q^2$ are exemplified in Figs. 1 and 2 respectively. In Fig. 1 the scale uncertainty can be seen to grow rapidly for decreasing Q^2. In the lower Q^2 region it is much larger than the experimental error. In Fig. 2, in the region where $E_T^2 > Q^2$ the difference between the NLO predictions using $\mu_r^2 = Q^2$ and $\mu_r^2 = E_T^2/4$ is larger than the respective estimated scale uncertainties. Clearly next-to-next-to leading order (NNLO) and also resummed calculations are needed to make further progress.

Forward jet cross sections at very small x are supposed to be a clean test of BFKL or CCFM dynamics. The latter should be *the way* to describe low-x final states to leading double-log accuracy. Lönnblad discussed the implementation of the CCFM equation in different Monte Carlo generators. [6] Two of the programs implementing CCFM, SMALLX [7] and the new complete final state Monte Carlo generator CASCADE [7] are able to describe the forward jet cross sections. However they do so only, if the so-called consistency constraint $k_{ti}^2 > z_i q_{ti}^2$, which has been found to be necessary in BFKL dynamics to account for kinematic effects, is not applied. In addition, the results are found to be sensitive to the treatment of non-singular terms in the gluon splitting function. However, no complete calculation including these terms has been done, and therefore no firm conclusions can be drawn.

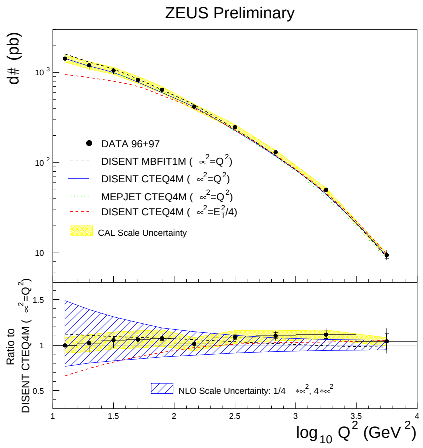

Figure 1: Dijet cross section as a function of Q^2 compared to NLO QCD calculations for the renormalization scales Q^2 and $E_T^2/4$ using DISENT and MEPJET [7]. For the ratio of data to NLO an uncertainty estimate for the scale Q^2 is given by the shaded band. [3]

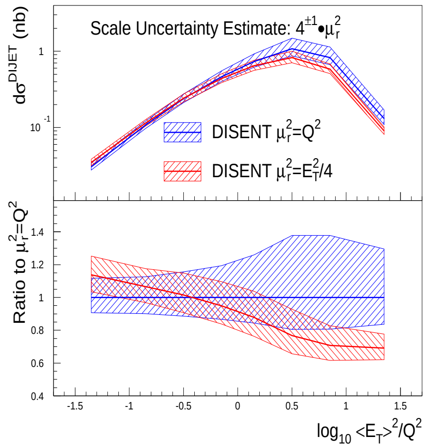

Figure 2: NLO QCD scale uncertainty estimates for the DIS dijet cross section as obtained with the DISENT [7] program. [3]

2 Jets in γp, γ^*p, and $\gamma\gamma$

A photon is not just a photon and not just a hadron. In LO QCD it has two components, a direct one, which couples electromagnetically to one of the partons of the other beam, and a resolved one. In the latter it fluctuates into a $q\bar{q}$ or even more complicated partonic state. In jet production the probing scale is given by the E_T^2 of the jets and the 'size' of the photon by Q^2. Therefore, when $E_T^2 \gg Q^2$ the structure of the photon may be resolved.

Maxfield discussed the assumptions and problems encountered in the measurement of cross sections for low E_T jet production by real and virtual photons and the extraction of the effective photon parton densities by H1. [8] Measurements at low x_γ, the fractional momentum of the parton in the photon, require measuring low-E_T jets. This demands a good experimental understanding and simulation of the pedestal transverse energy due to multiple interactions of the remnant partons of the photon and the proton in addition to the E_T of the jets from the hard subprocess.

The photoproduction of dijets as a function of E_T has been measured by H1 at high E_T up to about 90 GeV and is in good agreement with NLO QCD calculations. [9] A ZEUS measurement of the dijet cross section for lower E_T as a function of x_γ, also presented by Wing, shows the data overshooting the NLO prediction by about 50% for $x_\gamma < 0.8$, see Fig 3, which is considered to be due to inadequacies of the current parameterizations of the photon parton densities at scales of about $E_T^2 \approx 200$ GeV^2. [9] Improved photon parton densities should be expected from fits including this new HERA data.

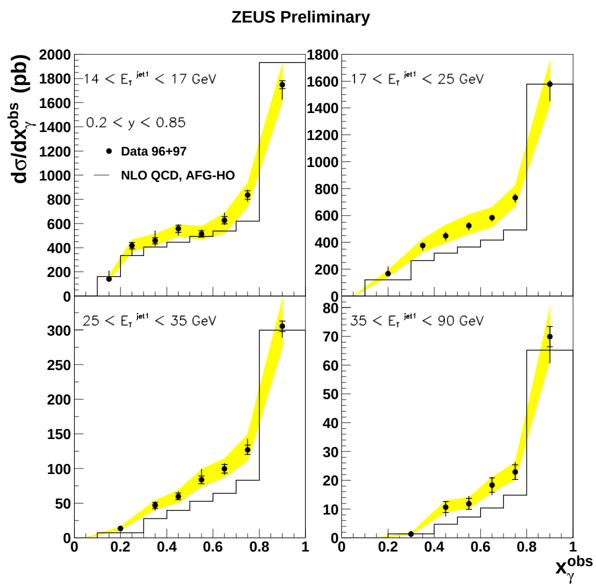

Figure 3: Dijet photoproduction cross section measurement in $x_\gamma^{\rm obs}$ in slices of $E_T^{\rm jet1}$ compared to the NLO QCD prediction. The band around the points displays the error due to the uncertainty associated with the calorimeter energy scale. [9]

Surrow showed results from OPAL at LEP on dijet production for the case of quasi-real photons from both colliding beams, i.e. both photon virtualities are almost zero. [10] They are well described by NLO QCD calculations.

3 Measuring α_s using jets in deep-inelastic scattering

The extraction of the strong coupling parameter α_s with increasing precision is an important task of the HERA experiments. A new result from ZEUS, using measurements of the dijet cross section and of the dijet rate in bins of the photon virtuality Q^2 was presented by Hadig. [11] In their analysis the parton density functions (pdfs) are taken from global fits of other measurements. For the first time, the error on α_s due to the uncertainty in the pdfs is estimated including their correlations [12]. From the dijet cross section they obtain

$$\alpha_s(M_Z) = 0.1186 \pm 0.0019\,(\mathrm{stat.})\,^{+0.0020}_{-0.0007}\,(\mathrm{exp.})\,^{+0.0035}_{-0.0033}\,(\mathrm{E-scale})$$
$$^{+0.0048}_{-0.0038}\,(\mathrm{ren.scale}) \pm \mathbf{0.0031}\,(\mathrm{pdf}) \pm 0.0005\,(\mathrm{hadr.})$$

and from the dijet rate

$$\alpha_s(M_Z) = 0.1166 \pm 0.0019\,(\mathrm{stat.})\,^{+0.0023}_{-0.0005}\,(\mathrm{exp.})\,^{+0.0036}_{-0.0034}\,(\mathrm{E-scale})$$
$$^{+0.0050}_{-0.0042}\,(\mathrm{ren.scale}) \pm \mathbf{0.0012}\,(\mathrm{pdf}) \pm 0.0005\,(\mathrm{hadr.})\,.$$

It can be seen that the uncertainties due to the pdfs partially cancel when using the dijet rate. The extracted values have an experimental precision which allows to have an impact on the world average of α_s. The major errors which need to be reduced in the future are the theory error due to the renormalization scale followed by the experimental error due to the hadronic energy scale of the calorimeter.

4 Azimuthal asymmetries in deep-inelastic scattering

A basic prediction of perturbative QCD, which is however difficult to verify experimentally, is the distribution of the azimuthal angle Φ between the lepton scattering plane and the hadron production plane, defined by the exchanged virtual photon and an outgoing hadron. For parton production this azimuthal dependence has the form

$$d\sigma/d\Phi = A + B\cos\Phi + C\cos 2\Phi, \tag{1}$$

resulting from the polarisation of the exchanged photon. Brook reported on such a measurement by ZEUS using single hard particles. [13] The measured value for $< \cos\Phi >$ is found to be negative, and the value for $< \cos 2\Phi >$, measured for the first time, is positive and increases with the transverse momentum of the particles. Both results agree, within large statistical errors, with QCD calculations.

5 Search for instantons

Instantons are a fundamental theoretical prediction of QCD. They exist in QCD and weak interactions and are associated with tunneling transitions between topologically non-degenerate vacua. Instanton-induced processes in QCD become calculable and perhaps observable in DIS due to the presence of a hard scale. Cross sections and characteristic event signatures can be calculated using the Monte Carlo generator QCDINS [7] and were discussed by

Schrempp, together with theoretical uncertainties on the event topology and the rates.[14]

Mikocki from the H1 collaboration presented first results on a dedicated search for instanton-induced processes in DIS.[15] They are based on some of the expected characteristics of the hadronic final state of such processes. Choosing simple cuts on three observables, requiring highest background reduction ($\approx$ 0.1%) while keeping an efficiency of $\approx$ 10% for instanton-induced processes, 549 events are observed in the data. For the background, i.e. standard DIS, 435^{+36}_{-22} events are estimated using the leading order matrix elements and a parton shower model, which is part of RAPGAP[7], and 363^{+22}_{-26} using the colour dipole model, as implemented in ARIADNE[7]. The errors on the standard DIS background include only the experimental systematic errors and no model uncertainties. An excess in data over standard DIS events is seen which is qualitatively compatible with the expected instanton signal. However, the size and shape of this excess is at the level of the discrepancy between the standard QCD models themselves.

6 Status of higher-order calculations

QCD predictions in leading order (LO) of perturbation theory suffer generally from large higher-order corrections and scale uncertainties. They depend on the renormalization scale in the strong coupling constant α_s and on the factorization scales in the parton densities and fragmentation functions. At next-to-leading order (NLO), the renormalization and factorization scales appear also explicitly in the hard cross section, thus reducing the scale dependence considerably and making the theoretical predictions more reliable.

NLO QCD calculations for HERA physics have been performed for jet production in DIS, real and virtual photoproduction, heavy flavour production in DIS and photoproduction, prompt photon production in DIS and photoproduction, and inclusive hadron photoproduction (for references see e.g. [7,16]).

The improved performance of HERA, the upcoming luminosity upgrade, and the better understanding of the H1 and ZEUS detectors contribute to reduced statistical and systematic errors on experimental measurements, with the exception of the still substantial energy scale uncertainty. Consequently, comparisons between experimental data and NLO QCD predictions are more and more dominated by theoretical scale uncertainties, limiting the discriminating power of the data for α_s and parton density determinations. For many observables it appears thus mandatory to improve the theoretical predictions beyond NLO. The first option consists in calculations in next-to-next-to-leading order (NNLO) of QCD.

Glover reported that the last three years have seen significant progress in this technically difficult field: Double unresolved tree amplitudes and single unresolved one-loop amplitudes have been calculated in the infrared limit, and many massless two-loop integrals have been evaluated, the most difficult ones being the double-box diagrams. [17]

The remaining challenges are to integrate out the infrared behavior of the unresolved cross sections and to analytically evaluate the two-loop matrix elements. It might still take several years before the first NNLO Monte Carlo program becomes available.

7 New results from resummation

An alternate route is to resum QCD corrections from gluon radiation in the soft (small transverse momentum q_T) and threshold (large $x_T = 2q_T/\sqrt{s}$) regions of phase space. Resummation techniques rely on the observation that the perturbative series exponentiates. They have been applied to e^+e^- annihilation, Drell-Yan production, and very recently also to DIS, where more work is needed. For photoproduction resummed calculations are not available.

Data for q_T distributions in semi-inclusive DIS do not exist. However, the rapidity distribution of the transverse energy flow has been measured by H1 [18], and the rapidity η can be related to q_T in the Breit frame if the photon virtuality Q is fixed ($q_T = Qe^\eta$). Nadolsky showed that the data compare favourably to the resummed predictions. [19]

Resummed predictions for DIS event shape variables like thrust have been calculated by Dasgupta, but have not yet been confronted with data. [20] When compared to NLO thrust distributions, they show a constant difference with respect to DISASTER++ [7] as expected, but a thrust-dependent difference with respect to DISENT [7].

8 Prompt photon production

A physical process where resummation plays a very important role is prompt photon production. Prompt photons could help to constrain the gluon density in the proton and the photon, since initial gluons generally dominate the production cross sections by 80% or more. Unfortunately, this possibility has been put on hold since the transverse momentum distributions of prompt photons in fixed target (e.g. E706 [21]) and collider (e.g. UA2 [22] and CDF [23]) experiments differ widely from the perturbative NLO expectations. [a]

[a] This is not the case for off-shell photons, which might therefore be better suited to determine the unpolarized and polarized gluon densities in the proton.

While threshold resummation reduces the scale dependence of the theoretical prediction and improves the description of the E706 data at large q_T, it does not increase the cross section at small q_T.

It has been speculated that intrinsic q_T effects could be responsible for the discrepancy meaning that the partons in the colliding hadrons are not exactly collinear. Phenomenologically this can be motivated by re-expressing the delta-function $\delta(q_T)$ as a Gaussian exponential function or using parton densities which are not integrated over q_T. These considerations must be put on firm theoretical ground: Recoil effects have to be taken into account, and the modified parton distributions have to be related to the usual ones which are used in other scattering processes.

A possible solution, reported on by Vogelsang, consists in the form of a q_T-profile function, which also permits to resum the low and high q_T regions simultaneously. [24] Although the numerical result still lies somewhat below the E706 data at low q_T, the discrepancy is significantly reduced, see Fig. 4. A

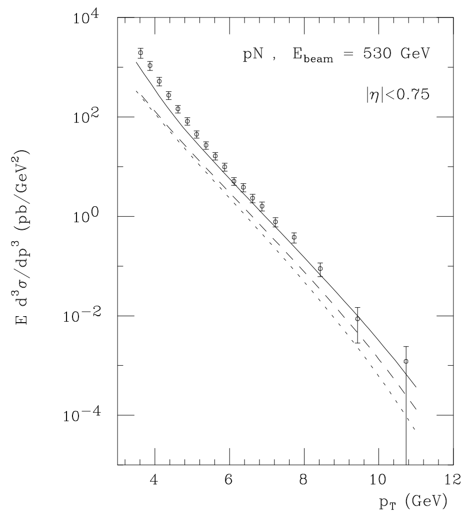

Figure 4: $Ed^3\sigma_{\mathrm{pN}\to\gamma X}/dp^3$. The dotted line represents the full NLO calculation, while the dashed and solid lines respectively incorporate pure threshold resummation and the joint threshold and transverse momentum resummation. [24]

drawback of this (as of any resummed) approach is that it is necessary to match the resummed and perturbative predictions at a fixed value of q_T which is *a priori* undetermined.

Prompt photon production has also been measured by ZEUS at HERA in photon-proton scattering and was reported on by Lee. [25] The measurements cover the range in transverse momentum p_T^γ from 5 to 15 GeV and in pseudo-rapidity η^γ from -0.7 to 0.9. The p_T^γ distribution agrees very well with NLO QCD predictions, shedding doubt on the universality of intrinsic q_T effects. However, the experimental errors are still dominated by statistics. An update of the analysis is in progress. It is also important to keep in mind that the colliding photon at HERA has a much smaller transverse size than a proton (or even a nucleon) in hadron collisions, which leads to smaller intrinsic q_T effects at least on the photon side. The NLO calculations describe the η^γ distribution only well in forward (proton) direction, but are below the data in the backward region. This would seem to indicate an inadequacy of the current photon parton densities.

9 Non-perturbative hadronization corrections

Both NNLO and resummed perturbative calculations are furthermore subject to non-perturbative corrections. These arise, e.g., when partons hadronize into jets, and they can become very important in certain regions of phase space like the backward region of jet photoproduction.

A possible remedy is the combination of perturbative predictions with parton showers and hadronization from existing Monte Carlo models. These models require a well-defined colour flow for the underlying hard scattering matrix element which poses a problem for interference terms. In a first approximation they can be split up and added to the squared matrix elements. Furthermore, beyond LO one has to be careful not to doublecount emission of real partons in the higher order matrix element and in the parton shower. The two can be separated by cutting on the invariant mass of the parton pair.

10 Fragmentation functions

The inclusive cross section for the production of single charged hadrons is expressed in terms of universal fragmentation functions (FF) which incorporate the long-distance, non-perturbative physics of the hadronization process. The scale dependence of the fragmentation functions is governed by an evolution equation, similar to the evolution equation for parton densities. The initial condition for the evolution equation, however, is not calculable in perturbation theory and must at present be taken from experiment.

Two new analyses to extract fragmentation functions for charged hadrons from e^+e^- annihilation data have been presented by Pötter and Kretzer.[26,27] Both analyses have been performed at leading and next-to-leading order in QCD. The fitted fragmentation functions describe all data sets within their respective errors. A comparison between the two independent FF extractions reveals good agreement when the sum over all flavours is taken. However, significant differences are found for the individual flavour fragmentation functions into $\pi^{\pm}$ and $K^{\pm}$, which are not well constrained by the data. [27]

Using experimental measurements of inclusive single hadron production at different energies one can extract the strong coupling α_s from the scaling violations in the fragmentation functions. A new α_s determination with a competitive error and a value consistent with the world average has been presented at this workshop. [26]

11 Inclusive particle production and MLLA

Safonov presented results on jet fragmentation, i.e. inclusive momentum distribution and multiplicities in jets, from CDF. [28] He demonstrated that calculations in the modified-leading approximation (MLLA) and assuming local parton hadron duality can provide a simple and compact description of the data. Milstead reported on inclusive particle production in the Breit frame in DIS as studied by H1 and ZEUS. [29] Here a consistent description of various moments of the fragmentation function by MLLA has not yet been achieved.

12 Event shapes and power corrections

The first new ZEUS measurements of event shapes were reported by Wollmer along with those from H1 by Rabbertz. [30] These measurements allow for an extraction of α_s and another parameter α_0 that characterizes the behavior of the strong coupling in both the high energy and low energy (non-perturbative) regimes. Several event shapes are considered, but there is a rather wide spread in results. Biebel reviewed the measurements from LEP [31] and Dasgupta the theoretical situation [20] of power corrections. The conclusion so far is that there is still a need for deeper understanding of the experimental and theoretical uncertainties associated with these measurements.

13 Photoproduction of charm and beauty

The production of heavy flavours provides new opportunities to study the dynamics of perturbative QCD and to extract information on the proton and photon structure. HERA has provided a wide spectrum of D^* measurements and first results on D_s mesons by ZEUS were reported by Gladilin. [32] It is not guaranteed *a priori* that charm cross sections can be reliably predicted in perturbation theory. The NLO calculations are indeed plagued by large uncertainties and they tend to underestimate the D^* cross section, in particular in the forward direction and at low x_γ where resolved photon processes contribute. Potentially large next-to-next-to-leading order corrections and higher-twist contributions may have to be included to improve the theoretical predictions. Other possible explanations for the discrepancies include non-perturbative string effects between the proton remnant and the charm quark or an enhancement of the low-x gluon component of the photon, which is currently not well constrained experimentally. A similar picture has emerged in $\gamma\gamma$ collisions at LEP. As shown by Andreev, the two-photon D^* cross section is slightly underestimated by NLO theory in the experimentally visible region, in particular at low p_t where resolved photon processes are prominent. [33]

Due to the larger b quark mass, theoretical predictions should be under much better control for the beauty cross section. Still, it is well known that Tevatron data for the b transverse momentum distribution are systematically larger than NLO QCD predictions. This trend is supported by recent HERA and LEP measurements which show that the beauty photoproduction cross section is significantly higher than the NLO theory. [34,33] Kuhr presented the H1 and ZEUS results displayed in Fig. 5. Also the beauty cross section in $\gamma\gamma$

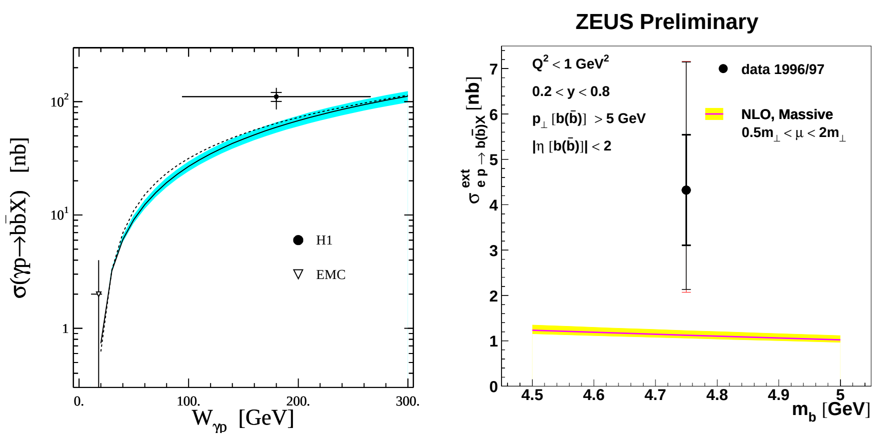

Figure 5: Left: total photoproduction cross section for beauty production measured by H1 compared to the NLO QCD prediction. Right: cross section measured by ZEUS extrapolated to the parton level compared to the NLO QCD prediction. [34]

collisions at LEP as measured by L3 [33]

$$\sigma_{tot}(ee \to eeb\bar{b}X) = (9.9 \pm 2.9 \pm 3.8) \text{ pb} \qquad \text{[L3]}$$

is higher than the NLO QCD calculation of ≈ 3 pb. The discrepancy between NLO theory predictions and experiment in beauty production should be taken seriously and possible theoretical explanations have been discussed by Ellis in the final plenary session. [35] The HERA luminosity upgrade and alternative experimental techniques using microvertex-detection will provide important additional information in the future. [34]

14 Charm production in deep-inelastic scattering

The charm contribution to the total structure function F_2 at small x at HERA is sizeable, up to 25%. A proper description of the charm contribution to DIS is thus required for a global analysis of structure function data and a precise extraction of the parton densities in the proton.

Considerable theoretical effort has been devoted to including heavy quark effects in DIS. As reviewed by Smith and Tung, different so-called variable flavour number prescriptions have been defined in the literature. [36,37] These prescriptions incorporate the correct heavy quark threshold behavior and sum terms $\propto \alpha_s \log Q^2/M_c^2$ when the hard scale Q of the reaction is significantly larger than the heavy-quark mass M_c. The structure functions calculated using different prescriptions generally differ at finite order in perturbation theory, since the treatment of the matching conditions and the extent to which finite mass effects are retained in the coefficient functions is ambiguous.

Experimentally, charm production in DIS at HERA has not only been studied for inclusive structure functions but differential cross sections for D^* production are available as well. [32] The predictions for differential distributions in variable flavour number prescriptions at $\mathcal{O}(\alpha_s)$ are spoiled by large scale dependences, with the exception of the Q^2 and $p_t(D^*)$ distributions where the agreement with data is good. [37] The scale dependence is significantly reduced when higher-order corrections are included. The comparison of HERA data with $\mathcal{O}(\alpha_s^2)$ calculations [36] shows good overall agreement, with a possible slight excess of data in the forward region. Hadronization effects may well be responsible for the deviation, similar to D^* photoproduction. A first measurement of the charm contribution to the photon structure function has been presented at this workshop and satisfactory agreement, within the still sizeable statistical uncertainty, with theory was found. [33]

15 Quarkonium production

Exciting phenomenological developments in quarkonium physics followed from the application of non-relativistic QCD (NRQCD), an effective field theory that includes the so-called colour-octet mechanisms. Although gluon fragmentation into colour-octet charm quark pairs appears as the most plausible explanation of the large direct ψ production cross section observed at the Tevatron, the applicability of NRQCD factorization to charmonium production is still not established quantitatively.

Inclusive charmonium production at HERA offers unique possibilities to assess the importance of different quarkonium production mechanisms. Krüger showed that no conclusive evidence for colour-octet processes has been observed in J/ψ photoproduction or J/ψ production in DIS so far.[38] The measurements of J/ψ production through resolved photon processes, for which first results have been reported at this workshop[38], could be important to clarify the issue once more statistics has been accumulated.

The single most crucial test of the NRQCD approach is the analysis of direct J/ψ and ψ' polarization at large p_t at the Tevatron. NRQCD predicts a substantial fraction of transverse polarization at p_t above $\sim$ 10 GeV, as discussed in Lee's review.[39] As shown in Fig. 6 this prediction is not supported by recent Tevatron data. The absence of transverse polarization in J/ψ and ψ' hadroproduction at large p_t, if confirmed by the higher statistics data expected at Run II at the Tevatron, would represent a serious problem for the application of NRQCD to charmonium production.

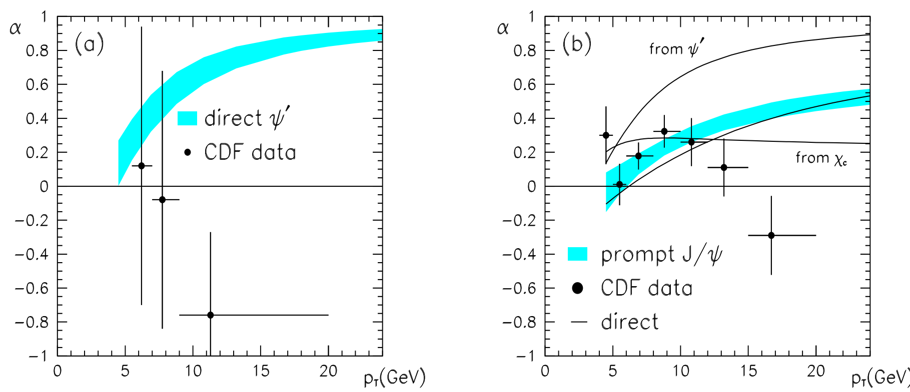

Figure 6: Polarization variable α vs. p_T for (a) direct ψ' and (b) prompt J/ψ compared to CDF data.[39] 100% transverse polarization corresponds to $\alpha = 1$.

16 Discussion session

After 33 experimental and 12 theoretical presentations we ended our working group meetings with a highly attended discussion session on future directions in QCD at HERA. Three 'provocateurs', M. Wing, J. Repond, and K. Ellis started off the discussion.

Wing presented his views on the interesting directions in photoproduction. [40] Ellis expressed his discomfort with the experimental results of too high cross sections for $b\bar{b}$-production compared to current NLO QCD calculations, and he discussed possible theoretical solutions. Repond pointed out that while most of us believe QCD to be *the theory* of strong interactions, we do lack precision, i.e. α_s is only known to about 3%, we want to know where perturbative QCD is good enough, where are higher order or resummation calculations needed and how to do them correctly. To pursue this experimentally, precision data and wide coverage of the available phase space are needed. The luminosity upgrade of HERA will allow to reduce statistical and with much effort by the experimentalists also systematic errors. Also needed are of course precision theory which already now is often trailing the experiments. Repond convincingly pleaded for an increase in the manpower in theory to address, together with the experimentalists, the outstanding QCD-issues at HERA.

We had an interesting discussion and good participation on the issues mentioned above and some others brought up by the audience until we ran out of time. Clearly we did not have enough time, probably we had too many topics and not good enough structuring. The interest in such discussions however could be seen from the lively debate we had and the wishes for more by many people afterwards.

17 Executive conclusions

- For many results, on jet cross sections, the determination of α_s, on charm cross sections, the major uncertainty is theoretical due to the renormalization scale, followed by the experimental error due to the hadronic energy scale of the calorimeter. Both need to be improved in the future.
- Using dijet rates instead of the dijet cross section, the error on α_s due to the uncertainties in the parton density functions could be halved. In addition, this error can now be determined, since parton densities with correlated errors have become available.
- Results on dijet production suggest that the parton densities of the photon should be revised and improved by including HERA and LEP data in a global fit.
- A first dedicated search for instantons in deep-inelastic scattering was reported by H1.
- Several important pieces of next-to-next-to-leading order calculations have been computed. The challenge is now to calculate the remainder

and to assemble the pieces.

- Resummed calculations for semi-inclusive hadron production and thrust distributions at HERA are now available. Predictions for prompt photon and jet production are still missing.

- Next-to-leading order QCD calculations for charm and beauty photoproduction underestimate experimental data from HERA and LEP. The discrepancy is particularly significant in the case of beauty production where perturbative calculations should be on safe grounds.

- In contrast, the comparison of HERA and LEP data on charm production in DIS shows good overall agreement with $\mathcal{O}(\alpha_s^2)$ calculations. A proper description of the charm contribution to DIS is important for a precise extraction of the parton densities in the proton.

- HERA measurements so far show no conclusive evidence for colour-octet contributions to charmonium production in γp and deep-inelastic reactions. The absence of transverse polarization in J/ψ and ψ' hadroproduction at large p_t represents a serious problem for the application of non-relativistic QCD to charmonium production.

- Finally, one important echo from the discussion session of the last day was that given the high experimental precision which has been reached, more theoretical support is clearly needed.

Acknowledgments

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