Studying QCD in the Final State of High Energy Collisions

J. M. Butterworth
Department of Physics and Astronomy, University College London,
and Hamburg University, Alexander von Humboldt Fellow
E-mail: J.Butterworth@ucl.ac.uk

I give an outline and some discussion of the results presented during the hadronic final states parallel sessions of the meeting, and some opinions about the current state of play and future directions in this area.

1 Event shapes and energy flows: Deep Inelastic Scattering *vs* $\mathbf{e^+e^-}$

To go straight to the main result, the level of precision and understanding achieved can be expressed in terms of measurements of the strong coupling constant α_s, the fundamental parameter of QCD. A selection of such measurements [1, 2] is shown in Fig. 1. The majority of the measurements shown are made using jet cross sections and event shapes properties in the final state of deep inelastic scattering (DIS) at events at HERA or e^+e^- annihilation at LEP, though extractions from parton distributions, as well as those from jet cross sections in $p\bar{p}$ and photoproduction are also shown. More will be said of these in Section 2.

To make these measurements, many technical advances in the QCD calculation of final states have been exploited. In particular, to produce combined LEP results involved lots of dialogue between the experiments and with theorists to obtain agreement on such issues as choice of jet algorithm, treatment of correlations, power corrections and treatment of hadronisation. Convergence on such issues is necessary in order to gain reasonable confidence in the estimated uncertainties on α_s. The HERA measurements are of similar precision to the LEP results but have not yet been combined. Such a combination of results certainly makes sense and is a challenge mainly for the experimentalists. However, in common with the LEP results, it is clear that theoretical uncertainties are at least as large, and often larger than, the experimental errors. Understanding the correlations between the theoretical uncertainties of different measurements (for instance from jet rates, jet shapes, subjets and fits to

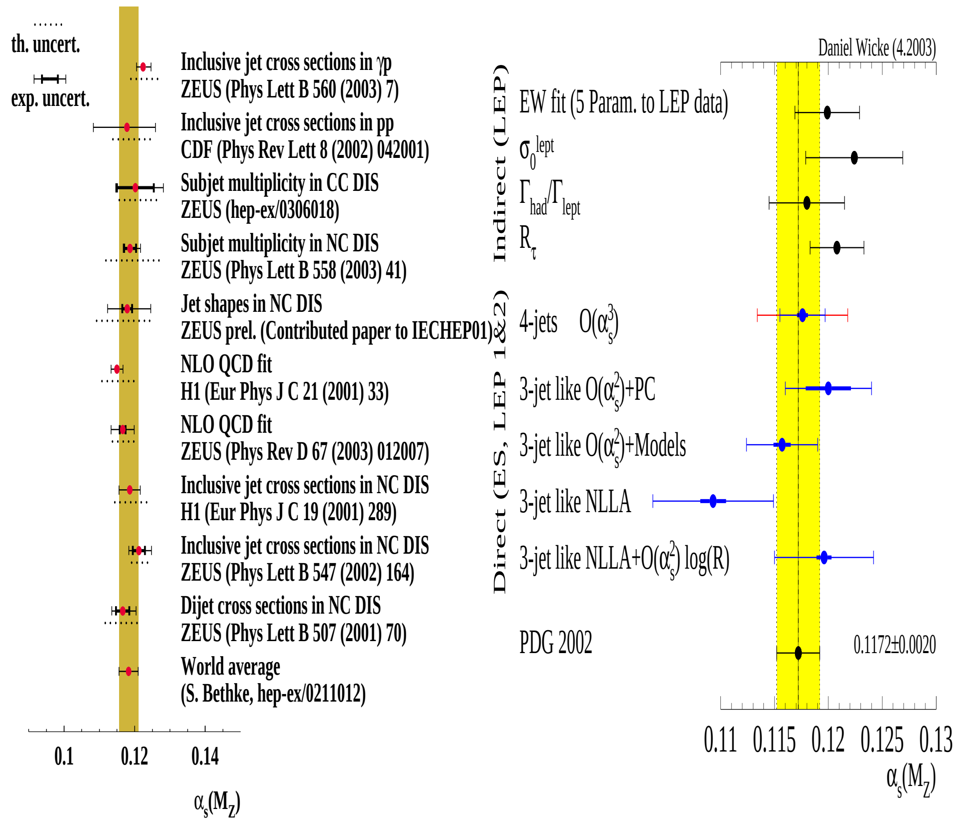

Figure 1: α_s measurements from hadron colliders and LEP.

structure functions) is a challenge for phenomenologists as well as experimentalists, and seems a necessary next step if such measurements are to be fully exploited.

A big remaining issue is the fact that uncertainty from higher orders can only be estimated from the scale dependence of NLO calculations. Even if experiments agree on a common approach, it remains arbitrary. In addition, perturbative calculations alone do not provide a particularly good fit to the data at LEP [2], and discrepancies are also seen in the H1 data [3] on jet production at low Q^2. There is still an active debate on how the effects of higher orders and non-perturbative physics are best estimated [2]. In particular, treating the scale as a free parameter leads to a good description of the LEP data with fixed-order perturbative calculations alone. However, the physical meaning of such a procedure and the uncertainties it involves remain unclear. An obvious though arduous improvement would be NNLO calculations of some key processes. Other possibilities for improved accuracy are the inclusion of power corrections, and the established technique of resumming key contributions to the cross section to all orders in α_s.

In the latter area, progress following the recent theoretical discovery of non-global logarithms [4] was reported. Significant large logarithms can occur for observables made in a limited region of phase space. Since detector acceptance usually limits measurement to sub-regions of phase space, this is a rather common type of variable! Amongst those expected to be affected are single jet profiles, jet substructure, cuts involving rapidity gaps or just rapidity cuts driven by acceptance, prompt photon isolation cuts based on energy within a cone, interjet energy flows and more. The discovery of these logarithms opens a new phenomenlogical avenue in QCD which is now being actively studied. The question as to whether the improved understanding embodied in this work will lead to more accurate predictions remains open.

To gain the full benefit of new advances in our understanding of QCD without prohibitive cost in theoretical working hours, technical improvements and automation become important. Furthermore, in my opinion, the process of generalizing a technique to the extent that it can be automated is one of the more convincing demonstrations that a real understanding has indeed been achieved. An example of such was given with the CAESAR resummation program, and some first results were reported [5]. This program also applies to event shapes in hadron-hadron collisions. Resummation of large logarithms in event shape variables is needed to make accurate predictions and to describe the data. However, though the theory is 'known', each variable requires a new calculation (on average one paper per variable). The systematic algorithmic approach adopted in CAESAR means a computer can take over. The user provides a routine which calculates the variable, CAESAR makes sure it can be resummed with current theoretical understanding. The result is the equivalent of an analytic calculation, with which one can study scale dependence, apply hadronisation corrections and so on. In addition the result is free of subleading logs and can be matched to NLO matrix elements in principle.

Other technical improvements reported include a master formula for NNLO soft and virtual QCD corrections, calculations of two-loop and n-loop eikonal vertex corrections [6], and resummation in DIS and Drell-Yan [7]. There was also a discussion of rescattering effects on DIS parton distributions [8] and universality-breaking effects in diffractive DIS and Drell-Yan production [9].

2 Jets and energy flows: $p\bar{p}$ *vs* γp *vs* $\gamma\gamma$

Lepton beams provide a spectrum of low-virtuality photons. These photons can fluctuate into virtual $q\bar{q}$ pairs and acquire a hadron-like structure, allowing lepton-lepton and lepton-hadron colliders to mimic hadron-hadron colliders. There is much to be learned from comparisons between jet or energy flow measurements (as well as heavy flavour production, see [10]) in $p\bar{p}$ (Tevatron), γp (HERA) and $\gamma\gamma$ (LEP).

As some compensation for their lower centre-of-mass energy, LEP and HERA can also make cleaner measurements with a pointlike photon. Going to high photon virtuality (in Deep Inelastic Scattering) or to high x_γ (direct photoproduction) allows the photon's hadron-like structure to be effectively "turned off". In such cases effects of, for example, the underlying event (see below) can be greatly altered or removed.

2.1 Tevatron Data

As well as a review of some Run I data [11, 12], some first results on jets, dijets and shapes where shown from Tevatron Run II [13, 14]. The improvements include the higher beam energy (which gives a significant increase in the cross section at very high transverse energy) and better triggers. The calorimeter energy scale is currently known to around 5%, though this is expected to improve in the near future. Measurements of fully corrected cross sections - i.e. with detector effects removed - were presented and offer the hope of precision jet measurements in the near future. The measurements of inclusive jets now extend up to 550 GeV. There is no sign of any excess with respect to NLO

QCD at high $E_T^{\rm Jet}$, and comparison with Run I data [15] shows good agreement between the data sets. Dijet mass distributions have also been measured using the new data, and compared to NLO QCD for masses up to 1364 GeV, again showing good agreement.

Some early results on jet shapes were shown. The results were not corrected for detector effects, but HERWIG and PYTHIA, both containing leading-logarithmic parton showers, were passed through a detector simulation for comparison, and describe the data quite well. There is a noticeable broadening of jets at high rapidities.

2.2 HERA γp Data

Jets in photoproduction have been measured up to $E_T^{\rm Jet} = 90$ GeV at HERA [3, 16] with dijet pairs up to masses of 140 GeV [17]. The effects of hadronisation and underlying events are important below about around 15 GeV, but not above. The calorimeter energy scale is known to around 1% for these energies, and the measurements are thus rather precise. An example of the precision achieved here is given by measurements of scaling violations in photoproduction [16], made by exploiting the variable-energy photon beam at HERA, which give a rather accurate determination of α_s (see Fig. 1). Inclusive and dijet measurements are sensitive to the PDF of the photon and the proton, particularly the gluon in the proton at high x. They should be included in future global fits of photon and proton PDFs. This is an issue of some importance for understanding QCD backgrounds both at a future linear e^+e^- collider and at the LHC.

Prompt photons have also been measured in photoproduction and DIS at HERA [18] - new results from H1 and ZEUS (respectively) were presented. There is good agreement between the collaborations and with NLO pQCD for photoproduction. The NLO calculation also describes the first DIS measurement reasonably well, at least in normalisation. However, there are differences in some trends, and the LO Monte Carlos completely fail (in different ways!) to describe this process. Since prompt photons give, in principle at least, more direct access to the hard scattering process, they are a good testing ground for QCD and for determination of PDFs, as well as being a calibration tool at hadron colliders. The isolation requirement leads to sensitivity to QCD final state effects which is different from that seen in jet cross sections - underlying events reduce the cross section, rather than increasing it.

2.3 LEP $\gamma\gamma$ Data

Extensive and precise OPAL results on dijet production in $\gamma\gamma$ collisions were shown [19]. Jet shapes and jet cross sections have been measured and events have been separated into regions dominated by collisons between pointlike photons, hadronic photons or one of each. There is in general good agreement with NLO QCD calculations, though some discrepancies are seen at low $E_T^{\rm Jet}$ when both photons are hadronic (see below for some discussion of this). Results on inclusive hadron production and jet cross sections in two-photon events from L3 were also presented [20]. These data are generally consistent with OPAL (where the kinematic regions overlap), and with NLO QCD except at the highest transverse energies, where the inclusive hadron and jet data both lie above the calculation. OPAL do not measure to such high transverse energies. This is the most striking discrepancy between the data and NLO QCD reported during the sessions, and clearly requires an explanation.

In summary of this section - in most cases NLO QCD calculations for the important observables are there, and generally describe the data. However, there is a catch in that in many, even most, cases the data are more accurate than the available predictions. This is a similar situation to that discussed in Section 1. This is not necessarily an indication of a lack of understanding of QCD, since many improvements in the calculations are possible in principle. Hence the importance of practical improvements such as those discussed in Section 1 is worth reiterating.

As well as higher order calculations and resummations, it is also important that non- and semi-perturbative effects can be isolated. In some cases it is beneficial to avoid these effects, but they remain important and interesting in their own right in several areas. Hadron-hadron collisions at the LHC are the near future of high energy physics, and it is becoming clear that quantitative and precise information on hadronic final states from Tevatron, HERA and LEP will be essential to fully exploit the opportunities of this new machine. An example of the kind of studies which are now beginning in several places was given in this session [11].

In this light, there are some contrasts between the three major colliders discussed in the meeting. The Tevatron has the advantage of higher centre-of-mass energy and actual proton beams. The QCD analyses from Run I were of course limited by the understanding at the time and used methods (such as choice of jet algorithm and underlying event corrections) which make quantitative comparisons with theory difficult. Unfortunately, despite the advances in phenomenological understanding between Run I and Run II, the (infrared-unsafe) cone algorithm still appears to be at least the default choice, and the collaborations are sometimes still correcting for energy outside jet ("underlying event") which is actually part of current QCD calculations. These issues are not important for the present data, but if the hoped-for understanding of the detectors is reached, it will become important to use more robust and model-independent techniques to control uncertainties in the comparison with theory. There is a lot of potential here, and there are people on the experiments battling to realise it. At HERA there are mature analyses now being published. High precision has been achieved (even in photoproduction!) and there has been overall a fairly good take-up of new phenomenological developments. New data from HERA II will extend the precision region up in transverse energy closer to the kinematic limit. The data from LEP2 which are still being published show in general statistically limited but elegant and exciting results. The effort available to analyse the data is inevitably winding down, and the question is, has everything that is needed really been done? At least the discrepancy between L3 data and NLO QCD should be understood, and measurements at the highest transverse energies from other LEP experiments would help.

An area of common concern in these studies is the effect of underlying events and minimum bias data on final state observables such as jet cross sections, jet shapes and energy flows between jets. This is even an issue at lepton colliders - for example, in the subset of OPAL $\gamma\gamma$ data [19], where both photons are hadronic, NLO QCD lies below the data, whereas elsewhere it is in good agreement. This is exactly what one would expect of a significant contribution from secondary scattering between the photon remnants. Similar effects are observed in Tevatron and HERA data, and indeed direct evidence for multiple hard scattering has been published by CDF [21]. QCD based models for this physics exist, and have been implemented in Monte Carlo programs [22], but they need to be fairly complex to describe the correlations, fluctuations and energy dependencies seen in the data. These models are currently being tested and tuned using Tevatron, HERA, LEP and older hadron-hadron data [23], and for example, the latest CDF minimum-bias data [12, 24] have only been successfully described by simulations including such physics. A reasonable understanding of such effects is a necessary input for detector development and precision measurements at current machines, LHC and FLC.

3 Fragmentation, resonances and non-perturbative effects

There were presentations on scalar meson resonance production from HERMES [25], H1 [26] and ZEUS [27]. Scalar mesons can be glueball candidates, and since there is evidence for too many of them to fit into the expected multiplets, studying their production cross sections in different environments is of particular interest. HERMES and H1 observe the $f_0(980)$ in the $\pi\pi$ decay channel. H1 also see the f_2, and ZEUS, looking at $K^0_s K^0_s$ decays see the $f_2(1525)$ and what is probably the $f_0(1710)$. This latter, which is a favoured glueball candidate, is seen in the target region of the Breit frame in DIS. ZEUS have also shown new results on strangeness production in DIS which show signs of an interesting dependence on kinematic region, in particular in the target region of the Breit frame [27].

Moving to particle production from nuclear targets, a model of quenching of hadron momentum spectra in DIS on nuclear targets was presented [28] . In this model it is assumed that all quenching is due to rescattering of partons in nuclei before hadronisation rather than after. This means that such effects can be treated in partonic calculations, and the model makes some definite predictions, one of which is saturation of these effects for large nuclei (since above some radius the rescattering length is determined by the length of time to hadronise, not by nuclear size). Another is that and K^+ and K^- production should be equally suppressed. These variables are proposed as a very sensitive way of distinguishing between this model and others where quenching takes place after hadronisation.

There were also presentations on Nuclear attenuation in semi-inclusive electroproduction of hadrons at HERMES [29] and on searches for QCD instantons at ZEUS [30].

Two speakers presented new results on Bose-Einstein Correlations, as well as a compliation of a wide variety of older LEP results [30, 32]. These correlations are fascinating and fundamental quantum-mechnical effect which give a rather direct probe of the hadron production region in high energy collisions. This of course is a poorly understood and important area in QCD, being where confinement takes place. The new OPAL (and older L3) analysis elegantly avoids coulomb effects by using neutral pion pairs. Of particular interest is whether the size and shape of the hadron production region depends strongly on the hard scattering process. The ZEUS [30] data, using inclusive hadrons in DIS, indicate that there is no such dependence, since the effect is shown to be constant over a very wide range of Q^2.

Results on colour reconnection show how non-perturbative QCD may affect the W mass measurement at LEP New studies in $e^+e^- \to W^+W^-$ at $\sqrt{s} = 189 \to 208$ GeV using particle flow were presented [31]. Several models can now be ruled out, and no definite effect seen in Z or WW. The end effect on the W mass is 22 ± 43 MeV.

4 Unintegrated parton distributions and low x

Low-x and diffractive physics were covered in detail in another working group [33]. However, some areas where the hadronic final state can be used to investigate this physics were discussed in this session.

A general motivation is the search for a connection between the behaviour of total cross sections at high energies (high s) and low-x partonic physics. As s/t becomes large, x becomes small and large rapidity intervals are available in the hadronic final state. It is interesting to study whether calculations which include to all orders (resum) terms containing large logarithms of $1/x$, or (equivalently) large rapidities, describe the data better than those which only resum large logarithms in the hard scale Q^2. A feature of the former calculations is that they break strong ordering in the scale, and thus parton distributions should explicitly include significant incoming parton virtuality, or transverse momentum, rather than their integratal. Cross sections at high s have in the past been described using Regge phenomenology, and so studying low-x physics may determine whether or not Regge phenomenology is an emergent property of QCD.

One area where such physics may appear is in high rapidity jets in DIS. New results from H1 [34] and ZEUS [35] were presented. The ZEUS results show an interesting excess in the inclusive jet cross section at high jet rapidities. When further cuts are applied to ensure that Bjorken x is small for the whole event, such that there is indeed a large evolution in x between the photon vertex and the forward jet, the uncertainties in the NLO QCD calculation increase (as indeed might be expected if the series is not converging so well due to large logarithms in x), and though the data still lie above the calculation, they are within these uncertainties.

The status of the CASCADE Monte Carlo, which uses the CCFM equation and unintegrated parton distributions was presented [36]. New fits are now available, including a better treatment of soft regions of the cascade using cut offs, and non-leading contributions. The new fits give better agreement with new H1 [34] forward jet data.

New results on rapidity gaps and energy flows between jets in photoproduction were also shown by ZEUS [37]. These extend previous measurements [38] of this process at HERA and confirm evidence for hard colour singlet exchange in these collisions. This is an exciting process since as with the forward jets in DIS, the momentum exchange across the rapidity interval (a gap, in this case) is much greater than $\Lambda_{\rm QCD}$ and so perturbative QCD should apply; but at the same time, s/t is large, and the process is in some sense diffractive.

New H1 data on dijet production at low Bjorken-x in DIS [39] show an increasing decorrelation of dijet pairs as x decreases, as is qualitatively expected if low-x terms are becoming important. Three-jet LO calculations do not describe the data, though NLO three jet calculations [40] do much better [41]. Nevertheless, there is still a very interesting excess in the data at the lowest x and Q^2.

There was a presentation showing that use of Regge theory to determine the starting parton distributions and DGLAP evolution to describe their Q^2 dependence was shown to describe the latest inclusive DIS data rather well [42]. Finally there was a presentaion on the effect of unintegrated gluon distributions on inclusive particle production in hadronic collisions at SPS [43]. In the latter case it seems that the effects could be significant. Such studies again motivate a broad approach to model comparisons across hadronic final states in different processes and at different energies.

5 Summary

Making quantitative QCD studies in final states is technically challenging for experiment and theory. Lots of excellent new measurements have been presented during the meeting, along with promises of more to come. There have also been some significant advances in theory and phenomenology. Next-to-leading order QCD is in general needed to provide a satisfactory understanding of current data. Where such calculations exist, perturbative QCD is doing well, though within large theoretical uncertainties. Non- or semi- perturbative effects are being studied quantitatively and there are interesting models on the market. Incremental but real progress continues to be made in this critically important area of high energy physics.

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