Summary of activities in Working Group 10: QCD Cascades

Nick Brook[a], Leif Lönnblad[b]

[a] Dept. of Physics & Astronomy, University of Glasgow, Glasgow, UK.
[b] Department of Theoretical Physics, Lund University, Lund, Sweden

Abstract: We summarize the activities in working group 10 concerned with QCD cascades, and find that although much work still needs to be done, much progress was made during this workshop in understanding the merits and deficiencies of different programs.

1 Introduction

The importance of theoretically well founded event generators which describe experimental data to a satisfactory degree can in general not be overstated. But since the whole of this workshop is dedicated to Monte Carlo event generators, we feel it is unnecessary to dwell on this here.

Event generators based on perturbative QCD cascade models have been immensely successful in reproducing the bulk of the data recorded at LEP [1]. Some of us were hoping for a similar development at HERA, but it soon became clear that this was not possible.

Before this workshop there was not one QCD cascade based generator which even came close to the agreement with data achieved at LEP. This was especially true for deep inelastic scattering (DIS) at small x: none of the conventional generators with DGLAP-based [3] initial state cascades was able to even qualitatively describe the measured final state in the proton direction [2]. It was the hope that generators based on BFKL [4] or CCFM [5] evolution could be developed and would be able to describe this region, but the only two such generators available before the workshop, SMALLX [21] and LDCMC [6], did not live up to these expectations.

The only generators which gave a fair description of small-x final states were generally not considered to be on firm theoretical grounds: RAPGAP modeling a resolved virtual photon contribution [7], and ARIADNE [8] based on the colour dipole cascade model [9].

One could hope that the generators at least would give a good description of data at high Q^2 and high x, where DGLAP evolution should be a good approximation of the underlying parton dynamics. But most of the generators were not even able to reproduce data in this region [10].

With this in mind the work of our group was quickly divided into two directions. One was concerned with developing new generators implementing CCFM evolution to better understand the small x region. The other direction was to look at existing generators and try to understand

why some of them failed to describe the high Q^2 region and, if these discrepancies could be fixed, try to tune the parameters in the programs to get as good description as possible of available data.

2 Confronting the Generators

High Q^2 and the Current Breit Hemisphere

Over the course of the workshop much understanding and development of the event generators and the data in the high Q^2 region and the current fragmentation region of the Breit frame has been achieved.

One of the puzzles before the workshop was why the ARIADNE program, which gives a good overall description of the HERA DIS data, had problems describing the high Q^2 region. In this region one naïvely expected our understanding of the underlying physics to be on a firmer theoretical base than at low x and Q^2. Even in the current fragmentation region of the Breit frame, where it is expected that DIS events should resemble one hemisphere of e^+e^- annihilation events, ARIADNE had difficulties in describing the data. This is despite the fact that ARIADNE gives a very good description of e^+e^- data.

The main difference between the treatment of colour dipoles in ARIADNE between e^+e^- and DIS is due to the fact that in DIS the initial parton configuration is not point like; the proton remnant is treated as an extended object. It was observed [11] at high Q^2 the phase space available for radiation was restricted even in the current fragmentation region due to this treatment of the extended proton remnant. This deficiency in the model has been understood and overcome [11] and modifications introduced within ARIADNE. These modifications went a long way towards removing the discrepancies between ARIADNE and the data, though problems still persist in describing the data and are under investigation [12].

Edén questioned the assumptions behind the equivalence of the current fragmentation region of the Breit frame and a single hemisphere in e^+e^- experiments [13]. It was shown that in DIS QCD radiation can give rise to high p_T emissions which have no correspondence in an e^+e^- event; these emissions lead to a de-population of the current fragmentation region. In order to limit the effect of these high p_T emissions, a jet algorithm was applied and DIS events with a jet $p_T > Q/2$ were removed from the comparison. This had a sizeable reduction in the discrepancy between the predictions of the mean charged multiplicity of e^+e^- and DIS Monte Carlo generators at low Q^2. This cut on jet p_T though suppresses the contribution to the DIS sample from boson-gluon fusion. In so doing, charm production is reduced by approximately a factor of 2. Further improvement between the e^+e^- and DIS generators could then be achieved by artificially removing heavy quark contributions from the e^+e^- generator by generating events with just light quarks. It was proposed that the experiments perform further studies of the current fragmentation region, applying this jet selection criteria, to compare with light quark enriched samples from the LEP1 experiments.

A comparison between MLLA predictions and the ARIADNE Monte Carlo at the parton level were made during the workshop [14]. It was shown for the e^+e^- scenario there was a good agreement between the MLLA truncated parton spectra and that generated from ARIADNE. The MLLA predictions for the current region of the Breit frame in DIS are identical to the

e^+e^- predictions, so the study was extended to DIS. It was shown that a reasonable agreement only became possible with the introduction of the previously discussed modifications of the proton remnant in ARIADNE. At lower Q^2 discrepancies between the MLLA predictions and ARIADNE were observed. These discrepancies could well be due to the problems discussed by *Edén* [13].

Comparisons with Data

During the workshop a forum was established between the H1 and ZEUS collaborations for a joint coordinated investigation of the generators, working closely with the programs' authors. The HzTool package [15] was substantially updated to include the majority of H1 and ZEUS hadronic final state data both for DIS and photoproduction. A concerted effort was also made to include preliminary data from the collaborations in this program.

During the course of the workshop there were two investigations of the Monte Carlo predictions compared to the HERA DIS data [12, 16]. One attempted to 'tune' the program's in the higher (x, Q^2) region [12]. In this study the ARIADNE [8], HERWIG [17] and LEPTO [18] Monte Carlo generators for DIS data were investigated [12]. Other programs such as RAPGAP [19] and those developed over the duration of the workshop are planned to be examined as part of a continuing program of work by the authors. The other study [16] concentrated on a comparison with new energy flow [20] data and particle spectra data and, in addition, included a comparison of the data with the RAPGAP program.

Both studies found that modifications to the generators (e.g. new soft colour interaction implementation in LEPTO and the high Q^2 changes in ARIADNE) helped tremendously in trying to describe the data. Unfortunately, it proved difficult to find sets of parameters within the generators studied that would describe the whole range of distributions at both low and high Q^2. As a compromise various setting have been given, optimised for particular regions of phase space.

The momentum generated by the workshop in trying to 'tune' the generators will allow more detailed investigations, including generators not so far studied. The ultimate aim of the forum, set up as a consequence of the workshop, is to have event generators that are able to describe the HERA data as impressively as they do the LEP data !

3 Developing New Generators for small x

The fact that DGLAP-based generators have not been able to reproduce small-x DIS final states measured at HERA has often been taken as an indication that effects of BFKL or CCFM evolution is visible in the data. This view has been strengthened since the ARIADNE generator, which has the feature of $k_\perp$-non-ordering in common with BFKL, qualitatively describes the data.

To really verify that BFKL evolution is responsible for e.g. the high rate of forward jets, or the large forward transverse energy flow, it is necessary to have an event generator with BFKL dynamics properly implemented. One such generator, SMALLX [21], has been available for quite some time. It implements CCFM evolution, which in the small-x limit is equivalent to BFKL, but it could only generate events at the parton level.

Not long before the workshop, the LDCMC generator was released which implements the Linked Dipole Chain model, a reformulation of the CCFM evolution. Although this generator describes the small-x region slightly better than DGLAP-based ones, it was clearly not able to explain the data in the forward region to a satisfactory level [6].

Before the workshop it was already clear that small-x DIS final states could be described by adding to a normal DGLAP-based generator, a contribution corresponding to a resolved virtual photon. This model was treated in detail in Working Group 30, while our group concentrated on developing CCFM-based models. So, although resolved virtual photons may be a reasonable way to describe small-x final states we will not discuss them further here.

During this workshop, a lot of effort was put into developing old and new generators based on CCFM evolution. *Goerlich and Turnau* have developed the SMALLX generator so that it is now interfaced to the Lund string fragmentation model implemented in JETSET [22]. Using a simple parameterization of the input gluon density they can evolve F_2, but fail to find a good description of the HERA data. Regardless of this poor agreement, they use this gluon parameterisation to generate the hadronic final state. They find that they cannot describe the transverse energy flow, but contrary to LDCMC they overshoot the data rather than undershoot it [23].

Much effort has also been put into trying to understand the discrepancies between the LDCMC and data. The LDC model should, to leading order, be equivalent to CCFM, but the program also includes estimates of non-leading effects and has e.g. included the evolution of quark chains and the correction of splitting functions to reproduce $2 \to 2$ matrix elements for local hard sub-collisions in the ladder. However, no significant progress was made during this workshop, and LDCMC still does not reproduce data at small x.

Similarly disappointing results were presented by *Salam* [24], who reported on the work done by the Milan group on CCFM phenomenology. They investigated different possible formulations of the so-called non-Sudakov form factor [5]. Although their modifications were formally sub-leading and only important as $z \to 1$ in the splittings, large effects were noticed. With the modification which led to the largest correction, they were able to reproduce the F_2 measured at HERA, but not the final state properties, such as forward jet rates. It should be noted that they did not try to include the, formally sub-leading, $1/(1-z)$ pole in the splitting function, which also could give rise to large corrections.

Also *Jung* [25] has used a somewhat non-standard form of the non-Sudakov form factor introduced in [26]. Implementing this in the SMALLX program[1] he obtains a good description of F_2. For the final state properties, he finds a large dependency on the so-called *kinematical*, or *consistency constraint*, which was introduced ensure that the standard form of the non-Sudakov form factor is below unity in the allowed phase space. Since the non-Sudakov used by *Jung* does not suffer from this problem, the consistency constraint is not needed, and without it a good description of the data, e.g. forward jet rates, is obtained.

From the SMALLX program it is possible to extract the evolved unintegrated gluon density. This is used by *Jung* in a completely new program, CASCADE, which implements CCFM in a backward evolution framework [25]. Also with this program a reasonable description of small x data is obtained, although the agreement between CASCADE and SMMOD is not perfect due to differences in the normalizations of the unintegrated gluon density between the two programs.

[1] Together with some other modifications, the obtained version of SMALLX is called SMMOD.

Clearly much progress has been made during this workshop, although much work is still needed. The fact that there exist three hadron-level generators which all claim to (in leading order) implement the same CCFM evolution, but giving completely different results, urgently calls for further investigations. In comparing these models among themselves and with data, it is important to have good observables which are sensitive to the characteristics of BFKL/CCFM evolution. Two new such observables was suggested during the workshop. *Goerlich and Turnau* suggested measuring the difference in transverse energy flow with and without a forward high-$k_\perp$ particle. This showed a good separation power between the DGLAP-based LEPTO generator, their own SMALLX generator and ARIADNE [23]. A similarly good separation power was shown for some observables based on transverse momentum transfer proposed by *Van Mechelen and De Wolf*. By summing vectorially all transverse momentum on either side of a given rapidity cut, the $k_\perp$ of the propagator gluon is reconstructed, and correlations can be measured as function of rapidity. In this way it should be possible to test the $k_\perp$-non-ordering property of BFKL evolution [27].

More general advice to event generator authors, was given by *Levin* [28], who discussed the recently calculated next-to-leading corrections to BFKL [29], and their implications for small-x evolution. He also presented indications that so-called screening corrections due to the large gluon density at small x, are becoming visible at HERA, and urged Monte Carlo authors to consider including such corrections in their programs.

4 Conclusions

As far as QCD cascades are concerned, this has been a very productive workshop. During the workshop we have increased our understanding of the high Q^2 region and why the standard generators had problems describing the corresponding hadronic final states. Now, most of these problems have been solved and attempts to tune the parameters of these generators has started. But many difficulties still remains, and it has not been possible to find a single consistent set of parameters for any of the generators which can describe all observables at high Q^2.

At small x the situation is even worse. But also here much work has been invested and much progress has been made during the workshop. There are now three hadron-level generators implementing CCFM evolution. Although only one of them has been shown to be able to reproduce the characteristics of small-x final states, the situation is much better than before the workshop, when only the ARIADNE and RAPGAP (with resolved virtual photons) programs gave a reasonable description. By carefully comparing all these different models we may soon be able to understand better the underlying parton dynamics.

Although the workshop is now over, the work will continue and so will the fruitful collaboration between experimentalists and event generator authors.

References

[1] See eg. I.G. Knowles, T. Sjöstrand, et al., in the proceedings of the Physics at LEP 2 workshop, eds. G. Altarelli, T. Sjöstrand and F. Zwirner, CERN yellow report 96-01, vol. 2, p 103.

[2] See eg. H1 Collaboration, C. Adloff et al., *Nucl. Phys.* **B485** (1997) 3, hep-ex/9610006.

[3] V.N. Gribov, L.N. Lipatov, *Sov. J. Nucl. Phys.* **15** (1972) 438 and 675;
G. Altarelli, G. Parisi, *Nucl. Phys.* **B126** (1977) 298;
Yu.L. Dokshitzer, *Sov. Phys. JETP* **46** (1977) 641.

[4] E.A. Kuraev, L.N. Lipatov and V.S. Fadin, *Zh. Eksp. Teor. Fiz.* **72** (1977) 373, *Sov. Phys. JETP* **45** (1977) 199;
Ya.Ya. Balitsky and L.N. Lipatov, *Yad. Fiz.* **28** (1978) 1597, *Sov. J. Nucl. Phys.* **28** (1978) 822.

[5] M. Ciafaloni, *Nucl. Phys.* **B269** (1988) 49;
S. Catani, F. Fiorani, G. Machesini, *Phys. Lett.* **B234** (1990) 339, *Nucl. Phys.* **B336** (1990) 18.

[6] B. Andersson, G. Gustafson, J. Samuelsson, *Nucl. Phys.* **B463** (1996) 217;
H. Kharraziha and L. Lönnblad, *J. High Energy Phys.* **3** (1998) 006

[7] H. Jung, et al., DESY-98-051, hep-ph/9805396.

[8] L. Lönnblad, *Comput. Phys. Comm.* **71** (1992) 15.

[9] B. Andersson et al., *Z. Phys.* **C43** (1989) 621;
L. Lönnblad, *Z. Phys.* **C65** (1995) 285

[10] D. Krücker, in the proccedings of the DIS '98 workshop, Brussels 1998, Eds. G.H. Coremans and R. Rosen, p462;
T. Carli, talk presented at ICHEP 98, Vancouver, Canada, 23-29 Jul 1998, to be published in the proceedings.

[11] L. Lönnblad, 'The Colour-Dipole model and the ARIADNE program at high Q^2', these proceedings.

[12] N. H. Brook et al., 'A Comparison of Monte Carlo Event Generators to HERA Data', these proceedings.

[13] P. Edén, 'Comparing Quark Jets in e^+e^- and DIS', these proceedings

[14] N. H. Brook, 'MLLA Parton Spectra Compared to ARIADNE', these proceedings.

[15] J. Bromley et al., HZTOOL*: A Package for Monte Carlo - Data Comparision at HERA*, `http://dice2.desy.de/~h01rtc/hztool.html`

[16] G. Grindhammer et al., 'A Comparison of Energy Flows and Particle Spectra in Deep Inelastic Scattering at HERA with Monte Carlo Models', these proceedings.

[17] G. Marchesini et al., Computer Phys. Commun. 67 (1992) 465,

[18] G. Ingelman, *in* Proc. HERA workshop, Eds. W. Buchmüller and G. Ingelman, Hamburg (1991) Vol. 3, 1366.
G. Ingelman, A. Edin and J. Rathsman, Computer Phys. Commun. 101 (1997) 108.

[19] H. Jung, Computer. Phys. Commun. 82 (1994) 74, see also
`http://www-h1.desy.de/~jung/rapgap.html`

[20] H1 Collab., C. Adloff et al., DESY-99-091, submitted to Eur. Phys. J. C.

[21] G. Marchesini, B. Webber, *Nucl. Phys.* **B386** (1992) 215.

[22] T. Sjöstrand, *Comput. Phys. Comm.* **82** (1994) 74

[23] L. Goerlich and J. Turnau, 'Some Properties of the CCFM Monte Carlo – SMALLX', these proceedings.

[24] G. Salam, 'Small-x final states and the CCFM equation', these proceedings

[25] H. Jung, 'CCFM prediction on forward jets and F_2: parton level predictions and a new hadron level Monte Carlo generator CASCADE ', these proceedings.

[26] J. Kwiecinski, et al., *Phys. Rev.* **D52** (1995) 1445

[27] E.A. De Wolf and P. Van Mechelen, 'Transverse momentum transfer and low x parton dynamics at HERA', these proceedings.

[28] E. Levin, 'Low x new for Monte Carlo', these proceedings.

[29] V.S. Fadin, N.L. Lipatov, *Phys. Lett.* **B429** (1998) 127,
M. Ciafaloni, *Phys. Lett.* **B429** (1998) 349.