Introduction to multi-jet final states and energy flows

Craig Buttar[1], *Jon Butterworth*[2], *Valery Khoze*[3], *Leif Lönnblad*[4] *and Niels Tuning*[5]
[1]Department of Physics and Astronomy, University of Glasgow, UK; [2]Department of Physics and Astronomy, University College London, UK; [3]IPPP, University of Durham, UK; [4] Department of Theoretical Physics, Lund University, Sweden; [5]NIKHEF, Amsterdam, The Netherlands.

Abstract

We summarize the activities of Working Group 2 of the HERA/LHC Workshop dealing with multi-jet final states and energy flows. Among the more specific topics considered were underlying event and minimum bias, rapidity gaps and survival probabilities, multi-jet topologies and multi-scale QCD, and parton shower–matrix element matching.

1 Introduction

In many ways, the LHC will become the best QCD machine ever built. It will allow us to study the production of hadrons and jets at unprecedented collision energies and will surely increase our understanding of QCD tremendously. Of course, some may argue that QCD already is a well understood and an integral part of the Standard Model, and the reason for building the LHC is to discover new phenomena, hopefully beyond the Standard Model.

However, the fact is that QCD is still not a completely understood theory. The qualitative aspects of asymptotic freedom and confinement may be under control, but the quantitative predictive power of the theory is still not at a satisfactory level. This is particularly true for the non-perturbative region, but also for the high-energy limit, where the hard scale of a process is much smaller than the total collision energy. The latter situation will be dominant in the bulk of events produced at the LHC. The triggers at the main LHC detectors will discard the majority of such events, but what is left will be processes with hard scales of around 100 GeV, which is still more than a hundred times smaller than the collision energy. And there will be significant amounts of minimum-bias data taken as well.

Except for a handful of gold-plated signals for new physics, any such search will be plagued by huge backgrounds stemming from pure QCD or other Standard Model processes involving jets. Hence, even if the study of QCD may seem to be a mundane preoccupation, it is of the utmost importance if we are to find and understand the few needles of new physics hopefully present in the immense LHC haystack.

Although the Tevatron may seem to be the obvious place to learn about QCD processes relevant for the LHC, the triggers there are typically tuned to high-scale processes, not far from the total collision energy. This means that HERA can give important additional insight, since there the situation is in some senses closer to that of the LHC, with the ratio of the typical hard scale and the total energy in DIS being $\sqrt{\langle Q^2\rangle/S} \sim 0.01$. In addition, HERA allows us to study such processes in a more controlled environment, where one side of the collision is well constrained by our relatively precise understanding of electroweak physics.

In our Working Group we have studied in some detail which lessons about multi-jet final states and general hadronic energy flows can be learned from HERA when preparing for the analysis of LHC data. And in this brief summary we will in a few pages try to distill the progress made by almost a hundred physicists as reported in more than fifty talks in this workshop and also in almost twenty separate contributions to these proceedings. The work was broadly divided into four categories: underlying events and minimum bias; rapidity gaps and survival probabilities; multi-jet topologies and multi-scale QCD; and matrix element–parton shower matching.

The first category may not represent the most striking feature of HERA physics, but it will surely be of great importance for the LHC. And it turns out that there are many possibilities to gain further understanding of underlying events in both photoproduction and DIS at HERA.

The study of rapidity gaps and, in particular, hard diffractive scattering gained momenta when it was observed at HERA, and the suggestion to use such processes to obtain clean signals of new physics at the LHC presents exciting prospects where the experience from HERA will be very important.

Multi-scale processes have already been presented as an important connection between HERA and the LHC. This is not least true for the LHCb experiment, where the understanding of the forward region is vital, a region which has been intensely studied at HERA. Also the recent theoretical development in QCD resummation techniques, which so far have mainly been applied to e^+e^- annihilation, may provide important tools for understanding event shapes at the LHC, and the corresponding application to HERA data will be essential for this understanding.

Finally, the more technical issue of matching fixed-order tree-level matrix elements with parton shower generators as well as other theoretical improvements of such simulation programs will surely be vital for the successful understanding of data from the LHC and also here the comparison to HERA data will be essential for the tuning and validation.

It should be noted that all of these categories, presented in more detail below, have a fairly large overlap with other working groups in this workshop. The most obvious overlaps are the working groups for Diffraction and Monte Carlo simulations, but there is also overlap with the heavy flavour and parton distributions working groups.

2 Underlying events and minimum bias

An understanding of the underlying event is an interesting physics topic in its own right but is also crucial in developing robust analyses for LHC physics. The underlying event can enhance central jet production, reducing the effectiveness of the central jet veto in analyses such as the vector boson fusion Higgs channel, or reduce the isolation of leptons resulting in reduced efficiency for identifying isolated leptons. In particular for LHCb and ALICE, where the triggers typically do not mandate high-scale processes, a good understanding of underlying events and minimum-bias events is crucial.

In this workshop there were several contributions dealing with underlying events and multiple interactions. They are all described in a joint contribution to these proceedings [1]. There the event generator models in PYTHIA [2–5], HERWIG/JIMMY [6–8] and SHERPA [9] are presented together with results from tuning these and other models to available data. The contribution also includes a summary of the plenary talk by Gösta Gustafson on the theory and phenomenology underlying events and multiple scattering.

Of the models presented and studied in Ref. [1], the one implemented in PYTHIA is probably the most advanced. This model has recently been developed further, introducing a scheme for *interleaving* the multiple interaction with a transverse-momentum ordered parton shower [3]. In contrast, the default underlying event model in HERWIG is a simple parametrization of UA5 data [10]. However, HERWIG is easily interfaced to the multiple-interaction model in the JIMMY program, which is similar to the PYTHIA model in spirit, although many of the details differ. The JIMMY program has recently been improved, making the generation of events more efficient where the signal process is different from the additional multiple scattering processes. Also the SHERPA event generator is now equipped with multiple interactions. Again, this model is similar in spirit to that in PYTHIA. One interesting aspect which differs is the attempt to incorporate the multiple scatterings in the general CKKW (see Section 5 below) framework of SHERPA.

The CDF Collaboration has carried out studies of the underlying event in jet processes [11–13] and this was used to provide a tuning for PYTHIA. In Ref. [1] a new analysis is presented which has extended these studies by increasing the energy range of the leading jet from around 50 GeV to 450 GeV using E_T from the calorimeter as well as particle $p_\perp$ measured in the tracker, and defining two-jet topologies as a subset of the leading jet to investigate the beam–beam and radiation components of the underlying event. Both PYTHIA tune-A and HERWIG/JIMMY were found to be in good agreement with the data, although both underestimate the transverse energy. The extension to higher energy scale shows that the underlying event activity increases with leading jet $p_\perp$ i.e., the hardness of the primary scatter, but by studying the maximum and minimum activity it is seen that this rise is largely due to bremsstrahlung from the primary scattering rather than secondary interactions between the beam remnants.

The CDF analysis was carried out primarily at 1.8 TeV although some of the early 546 GeV data has also been analysed. This has meant that there is only limited information on the energy dependence of the underlying event. To cover a wider range of energy, ATLAS have used minimum-bias data from the SppS and Tevatron covering 200 GeV to 1.8 TeV in addition to the CDF underlying event data to tune PYTHIA and HERWIG/JIMMY. Comparing the predictions of minimum-bias and underlying event distributions at the LHC using the tuned PYTHIA, the tuned HERWIG/JIMMY and PHOJET [14] shows large variations, emphasizing the need to understand the energy dependence of these processes better. The energy dependence was investigated further by LHCb, again using minimum-bias data to fit the parameters required for the model of energy dependence in PYTHIA.

Both the ATLAS and LHCb analyses have the implicit assumption that minimum bias and the underlying event have the same physics origin. While CDF data supports this, it would be helpful to probe the underlying event directly over a larger range of energy scales. HERA is in a prime position to make such a contribution by studying jets from photoproduction in an energy range corresponding to centre-of-mass energies in the region of 200 GeV, fitting well with the low-energy minimum-bias data. In photoproduction, resolved photons behave like hadrons so that HERA is effectively a hadron–hadron collider. Photoproduction data shows that particle flow and multi-jet measurements require models with multiple interactions to best describe the data but detailed studies of multiple interactions have not been made. However, studies of particle and energy flow in the transverse region similar to that carried out by CDF could be made at HERA.

An interesting question is whether there is also an underlying event present in DIS at HERA. As explained in Refs. [15, 16] it is possible to relate diffraction and saturation to multiple-interaction processes also for DIS using a QCD reformulation of the so-called AGK cutting rules [17]. And since diffractive processes have been clearly seen at high Q^2 at HERA, it is reasonable to expect that multiple interactions may also be present. A good place to search for such effects is in forward-jet production at HERA. In [18] preliminary results are presented indicating that multiple-interaction effects may indeed give a noticeable increase in the measured forward-jet cross-section in resolved virtual photon processes at small x and moderate Q^2.

The connection between multiple interactions, saturation and diffraction was also discussed in the plenary talk by Gösta Gustafson. He pointed out a possible problem with the qualitative AGK predictions for the hadronic multiplicity in multiple-interaction events. Taking the tuning of PYTHIA to CDF data at face value, there is an indication that the colour flows of secondary interactions are not independent from the primary scattering. Rather, the different colour flows seem to combine in a way where the total string length is minimized, resulting in a multiplicity which does not grow proportionally to the number of scatterings. Currently there is no theoretical understanding of this phenomenon. Gustafson also pointed out the problem that all multiple-interaction models discussed here rely on collinear factorization of the individual scatterings in a region where we expect $k_\perp$ factorization to be the relevant formalism. In fact, using $k_\perp$ factorization, the soft divergencies in the partonic cross section present in the conventional models may be removed, which could make the extrapolation of the model predictions to high energy more constrained.

3 Rapidity gaps and survival probabilities

A characteristic signature of diffractive processes is the existence of a large rapidity gap (LRG) in the final state, defined as a region of (pseudo-) rapidity devoid of hadronic activity. A rapidity gap may be adjacent to a leading proton or may arise between the decay products of final hadronic systems. The appearance of the rapidity gaps is intimately related to the exchange in the t-channel of objects with vacuum quantum numbers (Pomeron in the Regge theory, di-gluon Pomeron in pQCD, photon or W -mediator). The diffractive rapidity gap events have been studied in great detail at the ISR, SPS, HERA and the Tevatron. The LHC is the first collider which will have enough energy to allow the events with several (n = 2–4) LRGs.

The activity of our Working Group was focused mainly on the LRGs in the hard diffractive processes. For specifics of the photon and W-mediated reactions see, for example, Refs. [19–22].

An intensive discussion concerned the breakdown of factorization in hard hadronic diffractive processes. It is the consequence of unitarization effects, that both hard and Regge factorization are broken. This breakdown of factorization is experimentally seen [23] as the suppression of the single diffractive dijet cross section at the Tevatron as compared to the prediction based on HERA results. The observed suppression is in a quantitative agreement with the calculations [24] where the unitarization effects are described by multi-Pomeron exchange diagrams. The analysis of the current CDF diffractive dijet data with one or two rapidity gaps shows a good agreement with this approach. The situation with the factorization breaking in dijet photoproduction is not completely clear and further experimental and theoretical efforts are needed. A possible way to study this effect is to measure the ratio of diffractive and inclusive dijet photoproduction, see Ref. [25].

It is important to emphasize that the rapidity gap signal is very powerful but, at the same time, quite a fragile tool. We have to pay a price for ensuring such a clean environment. The gaps may easily fade away (filled by hadronic secondaries) on account of various sources of QCD 'radiation damage':

(i) soft or hard rescattering between the interacting hadrons (classic screening/unitarization effects or underlying event);

(ii) bremsstrahlung induced by the 'active' partons in the hard subprocesses;

(iii) radiation originating from the small transverse distances in two-gluon Pomeron dipoles.

An essential issue in the calculation of the rate of events with LRG concerns the size of the factor W which determines the probability for the gaps to survive in the (hostile) QCD environment. As discussed in the contributions of Brian Cox [26] and Jeff Forshaw [27], this factor is a crucial ingredient for evaluation of the discovery potential of the LHC in the exclusive processes with double proton tagging.

Symbolically, the survival probability W can be written as

$$W = S^2 T^2. \tag{1}$$

S^2 is the probability that the gaps are not filled by secondary particles generated by soft rescattering, i.e., that no other interactions occur except the hard production process. Following Bjorken [28, 29], who first introduced such a factor in the context of rescattering, such a factor is often called the survival probability of LRG. The second factor, T^2, is the price to pay for not having gluon radiation in the hard production subprocess. It is related to Sudakov-suppression phenomena and is incorporated in the pQCD calculation via the skewed unintegrated parton densities. The physics of Sudakov suppression is discussed in more detail in the contribution of Jeff Forshaw to these Proceedings [27].

In some sense the soft survival factor S^2 is the 'Achilles heel' of the calculations of the rates of diffractive processes, since, in principle, S^2 could strongly depend on the phenomenological models for soft diffraction. This factor is not universal, but depends on the particular hard subprocess, as well as on the distribution of partons inside the proton in impact parameter space. It has a specific dependence on the characteristic momentum fractions carried by the active partons in the colliding hadrons [24].

However, the good news is that, as discussed in these Proceedings by Uri Maor et al. [30], the existing estimates of S^2 calculated by different groups for the same processes appear to be in a reasonably good agreement with each other. This is related to the fact that these approaches reproduce the existing data on high-energy soft interactions, and, thus, result in the similar profile of the optical density in the impact parameter space. Another reason results from the comparatively small role of the high-mass diffractive dissociation.

Note that it is possible to check the value of S^2 by observing double-diffractive dijet production [31]. The gap survival in the Higgs production via the WW-fusion process can be probed in Z production which is driven by the same dynamics, and has a higher cross-section, see Refs. [32, 33]. Let us emphasize that it is the presence of this factor which makes the calculation infrared stable, and pQCD applicable. Neglecting the Sudakov suppression would lead to a considerable overshooting of the cross section of the hard central exclusive processes at large momentum transfer.

4 Multi-jet topologies and multi-scale QCD

In this workshop work on a wide range of topics regarding jet production and multi-scale processes has been presented [34]. It is of great interest to know what the LHC will teach us in the area of QCD, but at the same time uncertainties on the theoretical predictions for processes at the LHC should be limited as far as possible beforehand. By using the knowledge attained at HERA, our models can be sharpened and our theories can be tested.

Predictions of the event topology of $gg \to H$ at the LHC have been investigated for various parton shower models — such as PYTHIA, HERWIG and ARIADNE, that have proven their validity at HERA — and uncertainties in the event selection have been estimated [35, 36]. In the parton cascade as implemented in some of these programs, the parton emissions are calculated using the DGLAP approach, with the partons ordered in virtuality. DGLAP accurately describes high-energy collisions of particles at moderate values of the Bjorken-x by resummation of the leading log terms of transverse momenta ($\alpha_s \ln Q^2$). However, to fixed order, the QCD scale used in the ladder is not uniquely defined. There are many examples were more than one hard scale plays a role in the hard scatter, such as the virtuality Q, the transverse momentum E_T of the jet, or the mass of a produced object. Also, at low values of Bjorken-x large logarithms appear ($\alpha_s \ln 1/x$), leading to large corrections.

The CCFM formalism takes this into account, describing the evolution in an angular ordered region of phase space, while reproducing DGLAP and BFKL in the appropriate asymptotic limits. The CASCADE program has implemented the CCFM formalism, describing the low-x F_2 data and forward jet data at HERA. The predictions for the jet production at the LHC have been studied, both in the context of a $gg \to H$, as well as in the context of the forward event topology at LHCb [37].

In order to get reliable predictions for exclusive final-state processes, unintegrated parton density functions $f(x, Q^2, k_\perp)$ (uPDFs) become indispensable. For example, in the small-x regime, when the transverse momenta of the partons are of the same order as their longitudinal momenta, the collinear approximation is no longer appropriate and $k_\perp$ factorization has to be applied, with the appropriate CCFM evolution equations. In this workshop various parametrizations for unintegrated gluon densities matched to HERA F_2 data were compared to each other [38]. It is, however, still questionable if these densities are constrained enough for reliable predictions for Higgs production cross-section. Final-state measurements like photoproduction of D^*+jet events could however constrain these uPDFs further. It is argued that it is important to reformulate perturbative QCD in terms of fully unintegrated parton densities, since neglecting parton transverse momentum leads to wrong results. The HERA F_2 data has also been fitted using non-linear BFKL evolution, expressed with a universal dipole cross section, which in turn can be related to the unintegrated gluon distribution.

Finally, a theoretical description of hard diffractive processes at HERA can provide information on the so-called generalized, or skewed, gluon distribution (depending on the x of the emitted and absorbed gluon), providing for a theoretical description for diffractive Higgs production at the LHC.

The role of HERA is also emphasized in the area of resummed calculations, obtaining accurate QCD parameters such as the strong coupling, quark masses and parton distribution functions, which are vital inputs for predictions at the LHC. For example, event-shape distributions at HERA led to the finding of non-global logarithms, influencing observables at the LHC such as energy flows away from jets. Additionally, HERA data seem to confirm $1/Q$ power corrections (arising from gluon emission with transverse momentum $\sim \Lambda_{QCD}$), demonstrating that these corrections are not affected by the presence of the initial-state proton. HERA data is also used to study dijet E_T and angular spectra, in order to test NLL perturbative predictions. Finally, we have discussed whether additional small-x terms are needed to accommodate HERA DIS data, which at LHC energies would result in a broadening of the vector boson p_T spectrum.

5 Parton shower/matrix element matching

The LHC is, of course, mainly a machine for discovering new physics. But irrespective of what new phenomena may exist, we know for sure that LHC events will contain huge numbers of hadrons, and that a large fraction of these events will have many hard jets produced by standard QCD processes. Such events are interesting in their own right, but they are also important backgrounds for almost any signal of new physics. Unfortunately the standard Parton Shower (PS)-based event generators of today are not well suited to describe events with more than a couple of hard jets. The alternative is to use matrix element (ME) generator programs; this typically can generate up to six hard partons according to the exact fixed-order tree-level matrix elements. But these generators are not well suited for describing the conversion of these hard partons into jets of hadrons.

To get properly generated events it is therefore important to interface the ME generators to realistic hadronization models; this requires that also soft and collinear partons are generated according to PS models to get reliable predictions for the intra- and inter-jet structure. When adding a PS to an event from a ME generator, it is important to avoid double-counting. Hence the PS must be *vetoed* to avoid generating parton emissions above the cutoff needed to avoid divergences in the ME generator. In addition the PS assumes that the emissions are ordered in some evolution variable (scale) and uses Sudakov form factors to ensure that there was no additional emission with a scale between two generated emissions. This also generates the virtual corrections to the splittings. The ME generators, of course, have no such ordering since all diagrams are added coherently. However, there is still a need for a cutoff in some scale to regulate soft and collinear divergencies, and to naively add a PS to events from a ME generator will therefore give a strong dependence on this cutoff.

A solution to this problem was presented by Catani et al. [39]. This so-called CKKW procedure is based on using a jet reconstruction algorithm on the ME-generated event to define an ordering of the emissions and then reweight the event according to Sudakov form factors obtained from the reconstructed scales. In this way it was shown that the dependence on the ME cutoff cancels to NLL accuracy. The procedure was originally developed for e^+e^- annihilation where it was further developed in Ref. [40], but lately it has also been applied to hadron–hadron collisions [41–45] using several different parton shower models. In addition, an alternative procedure, called MLM, was developed by Mangano [46, 47] which is similar in spirit to CKKW, but which has a simpler interface between the ME and PS program.

There was some hope that during this workshop an implementation of CKKW for DIS would also be developed. This would be interesting, not least because the procedure would then be tested in a small-x environment, and comparing with such HERA data as well as with high-scale Tevatron data should then give a more reliable understanding about the uncertainties when extrapolating to the LHC. Although some progress has been made on the application to DIS [48] there was not enough time to make a proper implementation. Instead the activities were focused on comparing the predictions of some of the programs (SHERPA [9] and MADGRAPH/MADEVENT [49]+ARIADNE [50] using CKKW, and ALPGEN [51]+PYTHIA [4] using MLM) for the case of W+jets production at the Tevatron and the LHC. This process is very interesting in its own right, but is also an important background for almost any signal of new physics at the LHC. The results are presented in these proceedings [52] and it was found that the models give fairly similar predictions for jet rates, but some differences were found, for example, for the rapidity correlation between jets and the W. The latter may be related to the fact that W production, especially at the LHC, can be considered to be a small-x process ($m_W/\sqrt{S} \sim x \sim 0.005$) and we know that there are large differences between parton shower models in this region. This emphasizes again the importance of confronting the ME+PS matching procedures with HERA DIS data also.

Possible improvements to the QCD PS approach were discussed in three other contributions to these proceedings. All of these are based on experience of Monte Carlo programs for QED resummation. One of these contributions [53] describes a new algorithm for forward evolution of the initial-state parton cascade in which the type and energy of the final parton is predefined/constrained. Contrary to the widely used backward-evolution algorithms [54], this algorithm is similar to the one used in the LDCMC generator [55] and does not need a fully evolved PDF parametrization as input.

Using an operator formalism, another contribution [56] describes what we can learn about QCD parton showers from the popular PHOTOS generator, which combines in a clever way soft photon resummation and hard collinear photon resummation in QED. Finally there is a contribution [57] which describes a more ambitious attempt to combine ME+PS calculations for both QCD and QED, preserving the proper soft gluon limit and the standard factorization of collinear singularities. All of these contributions represents work which is still in a rather early stage. Nevertheless, they signal important efforts which may lead to interesting new Monte Carlo tools for the LHC era.

6 Conclusions and outlook

In this summary we hope to have made it clear that there is a rich flora of interesting topics relating to jets and hadronic energy flows where the understanding of results from HERA will be important for the upcoming analysis of LHC data. It should also be clear that although substantial progress has been made during this workshop, we have only started to botanize among these topics. Hence, as we now thank the participants of our Working Group for all the work they have contributed to the workshop, we would also like to remind them, and also other readers of these proceedings, that there is much work still to be done.

References

[1] C. Buttar *et al.*, *Underlying events*, these proceedings.

[2] T. Sjöstrand and M. van Zijl, Phys. Rev. **D36**, 2019 (1987).

[3] T. Sjöstrand and P. Z. Skands, Eur. Phys. J. **C39**, 129 (2005). hep-ph/0408302.

[4] T. Sjšṫrand, and others, Comput. Phys. Commun. **135**, 238 (2001). arXiv:hep-ph/0010017.

[5] T. Sjöstrand, L. Lönnblad, S. Mrenna, and P. Skands (2003). hep-ph/0308153.

[6] J. Butterworth *et al.*, http://hepforge.cedar.ac.uk/jimmy/.

[7] J. M. Butterworth, J. R. Forshaw, and M. H. Seymour, Z. Phys. **C72**, 637 (1996). hep-ph/9601371.

[8] G. Corcella *et al.*, JHEP **01**, 010 (2001). hep-ph/0011363.

[9] T. Gleisberg *et al.*, JHEP **02**, 056 (2004). hep-ph/0311263.

[10] UA5 Collaboration, G. J. Alner *et al.*, Nucl. Phys. **B291**, 445 (1987).

[11] CDF Collaboration, J. Huston, Int. J. Mod. Phys. **A16S1A**, 219 (2001).

[12] CDF Collaboration, T. Affolder *et al.*, Phys. Rev. **D65**, 092002 (2002).

[13] CDF Collaboration, D. Acosta *et al.*, Phys. Rev. **D70**, 072002 (2004). hep-ex/0404004.

[14] R. Engel, *Phojet program and manual*. http://www-ik.fzk.de/∼engel/phojet.html.

[15] H. Kowalski, *Multiple interactions in DIS*, these proceedings.

[16] J. Bartels, *Multiple scattering at HERA and at LHC - remarks on the AGK rules*, these proceedings.

[17] V. A. Abramovsky, V. N. Gribov, and O. V. Kancheli, Yad. Fiz. **18**, 595 (1973).

[18] J. Turnau and L. Lönnblad, *Forward jets and multiple interactions*, these proceedings.

[19] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. **C23**, 311 (2002). hep-ph/0111078.

[20] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. **C21**, 99 (2001). hep-ph/0104230.

[21] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. **C18**, 167 (2000). hep-ph/0007359.

[22] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. **C24**, 459 (2002). hep-ph/0201301.

[23] CDF Collaboration, T. Affolder *et al.*, Phys. Rev. Lett. **84**, 5043 (2000).

[24] A. B. Kaidalov, V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. **C21**, 521 (2001). hep-ph/0105145.

[25] A. B. Kaidalov, V. A. Khoze, A. D. Martin, and M. G. Ryskin, Phys. Lett. **B567**, 61 (2003). hep-ph/0306134.

[26] B. Cox *et al.*, *Diffractive Higgs production: experiment*, these proceedings.

[27] J. Forshaw, *Diffractive Higgs production: theory*, these proceedings.

[28] J. D. Bjorken, Int. J. Mod. Phys. **A7**, 4189 (1992).

[29] J. D. Bjorken, Phys. Rev. **D47**, 101 (1993).

[30] U. Maor *et al.*, *Gap-survival and factorization breaking*, these proceedings.

[31] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. **C14**, 525 (2000). hep-ph/0002072.

[32] H. Chehime and D. Zeppenfeld, Phys. Rev. **D47**, 3898 (1993).

[33] V. A. Khoze, M. G. Ryskin, W. J. Stirling, and P. H. Williams, Eur. Phys. J. **C26**, 429 (2003). hep-ph/0207365.

[34] Z. Czyczula *et al.*, *Multi-jet production and multi-scale QCD*, these proceedings.

[35] Z. Czyczula and E. Richter-Was, *MSSM Higgs production with the Yukawa bbH coupling induced mechanisms*. In [34], these proceedings.

[36] G. Davatz and A. Nikitenko, *$gg \to H$ at the LHC: Uncertainty due to a Jet Veto*. In [34], these proceedings.

[37] E. Rodrigues and N. Tuning, *Forward Studies with CASCADE at LHC Energies*. In [34], these proceedings.

[38] J. Collins *et al.*, *Unintegrated parton density functions*, these proceedings.

[39] S. Catani *et al.*, JHEP **11**, 063 (2001). `hep-ph/0109231`.

[40] L. Lönnblad, JHEP **05**, 046 (2002). `hep-ph/0112284`.

[41] F. Krauss, JHEP **08**, 015 (2002). `hep-ph/0205283`.

[42] S. Mrenna and P. Richardson, JHEP **05**, 040 (2004). `hep-ph/0312274`.

[43] F. Krauss, A. Schalicke, S. Schumann, and G. Soff, Phys. Rev. **D70**, 114009 (2004). `hep-ph/0409106`.

[44] N. Lavesson and L. Lönnblad, JHEP **07**, 054 (2005). `hep-ph/0503293`.

[45] F. Krauss, A. Schaelicke, S. Schumann, and G. Soff (2005). `hep-ph/0503280`.

[46] M. Mangano, *The so-called mlm prescription for me/ps matching*. `http://www-cpd.fnal.gov/personal/mrenna/tuning/nov2002/mlm.pdf`. Talk presented at the Fermilab ME/MC Tuning Workshop, October 4, 2002.

[47] M. L. Mangano, M. Moretti, and R. Pittau, Nucl. Phys. **B632**, 343 (2002). `hep-ph/0108069`.

[48] C. Åberg, *Correcting the colour dipole cascade with fixed order matrix elements in deep inelastic scattering*. Diploma thesis, LU-TP 04-25 (2004).

[49] F. Maltoni and T. Stelzer, JHEP **02**, 027 (2003). `hep-ph/0208156`.

[50] L. Lönnblad, Comput. Phys. Commun. **71**, 15 (1992).

[51] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, JHEP **07**, 001 (2003). `hep-ph/0206293`.

[52] S. Hoeche *et al.*, *Matching parton showers and matrix elements*, these proceedings.

[53] S. Jadach and M. Skrzypek, *Constrained non-Markovian Monte Carlo modeling of the evolution equation in QCD*, these proceedings.

[54] M. Bengtsson and T. Sjöstrand, Z. Phys. **C37**, 465 (1988).

[55] H. Kharraziha and L. Lönnblad, JHEP **03**, 006 (1998). `hep-ph/9709424`.

[56] P. Golonka and Z. Was, *PHOTOS as a pocket parton shower: flexibility tests for the algorithm*, these proceedings.

[57] B. Ward and S. Yost, *QED$\otimes$QCD Exponentiation and Shower/ME Matching at the LHC*, these proceedings.