Multi-jet final states and energy flows
Summary of working group activities

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Abstract

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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

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 dominating in the bulk of events produced at the LHC. Even if the triggers at the main LHC detectors will discard most of such events, it is still true that 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.

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 sense closer to 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 electro-weak 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 both in photo-production 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. There 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

$\Longrightarrow$ Initial text by: Craig

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 can reduce the isolation of leptons resulting in reduced efficiency for identifying isolated leptons.

$\Longrightarrow$ Need something about heavy ions and LHCb

The CDF collaboration has carried out studies of the underlying event in jet processes [**?**] and this was used to provide a tuning for PYTHIA. A new analysis [**?**] has extended these studies by increasing the energy range of the leading jet from around 50GeV to 450GeV using Et 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 agreementwith the data, although both underestimate the transverse energy. The extension to higher energy scale shows that the underlying event activity increases with leading jet $p_\perp$ ie. 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.

However, the CDF analysis has been carried out primarily at 1.8TeV and some of the early 546GeV data has been analysed. This has meant that there is only limited information on the energy dependence of the underyling 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 shows large variations, emphasising the need to understand the energy dependence of these processes better. The energy dependence has been 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 200GeV, 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 [?].

There are four simulation programmes that have been studied: PYTHIA [?], HERWIG+JIMMY [?], SHERPA [?] and PHOJET [?].

PYTHIA has a well developed model of minimum bias and the underlying event [?] [?]. It describes pp and ppbar but currently does not have a model for $\gamma^* p$ events at HERA. This is being developed as part of the workshop [?] so that underlying event data can be studies over a larger range of centre of mass energies [?].

HERWIG can be used to describe the describe the hard jets and has a model for soft underlying event based on the UA5 minimum bias model [?].

$\Longrightarrow$ **Summary of Underlying events contribution**

$\Longrightarrow$ **Summary of Underlying events in DIS contribution**

3 Rapidity gaps and survival probabilities

$\Longrightarrow$ **Initial text by: Valery**

$\Longrightarrow$ **Summary of Uris contribution**

$\Longrightarrow$ **Summary of Exclusive diffractive production contribution**

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 many details 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. [**?**, **?**, **?**, **?**].

An intensive discussion concerned the breakdown of factorisation in in hard hadronic diffractive processes. It the consequence of unitarisation effects, that both hard and Regge factorisation are broken. This breakdown of factorisation is experimentally seen [**?**] 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 [**?**] where the unitarisation 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 factorisation 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 [**?**].

It is important to emphasise 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) due to various sources of QCD "radiation damage":

(i) soft rescattering between the interacting hadrons (classic screening or unitarisation effects);

(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 and Jeff Forshaw, 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 [**?**, **?**], 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. In more detail the physics of of Sudakov suppression is discussed in the contribution of Jeff Forshaw to these Proceedings [**?**].

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 [?].

However, the good news is that, as discussed in these Proceedings by Uri Maor et al. [**?**], 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 [**?**]. 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 Ref. [?, ?]. Let us emphasise 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

⟹ Initial text by: Niels

⟹ Summary of jet production contribution

⟹ Summary of Unintegrated PDFs contribution

⟹ Summary of Resummation contribution

5 Parton shower/ME matching

⟹ Initial text by: Leif

LHC is, of course, mainly a machine for discovering new physics. But irrespectively of what new phenomena may exist, we know for sure that the 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, which 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, which requires that also soft and collinear partons are generated according 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 divergencies 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 emissions with a scale between two generated emissions. These also generates the virtual corrections to the splittings. The ME generator, 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. [?]. 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 [**?**], but lately it has also been applied to hadron-hadron collisions in [**?**, **?**, **?**, **?**, **?**] using several different parton shower models. In addition an alternative procedure was developed by Mangano [**?**, **?**] 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 there would also be developed an implementation of CKKW for DIS. 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 LHC. Although some progress has been made on the application to DIS [**?**] 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 [**?**] and MADGRAPH/MADEVENT [**?**]+ARIADNE [**?**] using CKKW, and ALPGEN [**?**]+PYTHIA [**?**] 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 [**?**] and it was found that the models give fairly similar predictions for jet rates, but some differences were found eg. 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 also with HERA DIS data.

⟹ Summary of Future development of Parton Shower contributions

6 Conclusions and outlook

⟹ Initial text by: Leif

⟹ Bragging how well we performed and how important the achievements of our working group are for LHC in general and for the connection between HERA and LHC in particular.

⟹ Ending with a comment about future work and collaboration

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