ARIADNE at HERA and at the LHC

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Abstract
I describe briefly the status of the ARIADNE program implementing the Dipole Cascade Model and comment both on its performance at HERA, and the uncertainties relating to the extrapolation to LHC energies.

1 Introduction

ARIADNE [1] is a Fortran subroutine library to be used with the PYTHIA event generator [2]. By simply adding a few lines to a PYTHIA steering routine, the PYTHIA parton shower is replaced by the dipole cascade in ARIADNE. For lepton–hadron DIS it can also be used together with the LEPTO [3] generator in a similar fashion. However, even if it thus simple to use ARIADNE also for the LHC, there are a few caveats of which the user should be aware. In this brief presentation of the program, I will first go through the main points of the final-state dipole shower relevant for $\mathrm{e^+e^-}$-annihilation, then I will present the extention of the model to lepton–hadron DIS, and finally describe how the model works for hadron–hadron collisions.

2 The Basic Dipole Model

In the Dipole Cascade Model (DCM) [4, 5], the bremsstrahlung of gluons is described in terms of radiation from colour dipoles between gluons and quarks. Thus, in an $\mathrm{e^+e^-} \to q\bar{q}$ event, a gluon, g_1 may be emitted from the colour-dipole between the q and $\bar{q}$. In this emission the initial dipole is replaced by two new ones, one between q and g_1 and one between g_1 and $\bar{q}$. These may then continue radiating independently in a cascade where each step is a $2 \to 3$ partonic splitting or, equivalently, a splitting of a dipole into two. The splittings are ordered in a transverse momentum variable, $\mathrm{p}_\perp$, defined in a Lorentz-invariant fashion, which also defines the scale in α_S.

There are several advantages of this model. One is that the coherence effects approximated by angular ordering [6] in eg. the HERWIG [7] parton cascade, are automatically included. Another is that the first order $\mathrm{e^+e^-} \to qg\bar{q}$ matrix element correction is in some sense built-in. A major *dis*advantage is that the $g \to q\bar{q}$ splitting does not enter naturally in this formalism. Final-state $g \to q\bar{q}$ splittings are, however, easy to add [8] and for final-state cascades in $\mathrm{e^+e^-}$-annihilation the description is complete. Ariadne is generally considered to be the program which best reproduces event shapes and other hadronic final-state observables at LEP (see eg. [9]).

3 ARIADNE at HERA

While for $\mathrm{e^+e^-}$-annihilation, the DCM is formally equivalent to conventional angular ordered parton showers to modified leading logarithmic accuracy, the situation for collisions with incoming hadrons is quite different. In a conventional shower the struck quark in eg. lepton–hadron DIS is evolved backwards with an initial-state cascade according to DGLAP [10–13] evolution. In contrast, the DCM model for DIS [14] describes all gluon emissions in terms of final-state radiation from colour-dipoles, in a similar way as in $\mathrm{e^+e^-}$-annihilation, with the initial dipole now being between the struck quark and the hadron remnant. Contrary to $\mathrm{e^+e^-}$-annihilation, the remnant must now be treated as an extended object and, since radiation of small wavelengths from an extended antenna is suppressed, the emission of high-$p_\perp$ gluons in the DCM is suppressed in the remnant direction.

Despite this suppression, which is modeled semi-classically, the net result is that gluon emissions are allowed in a much larger phase space region than in a conventional parton shower, especially for limited Q^2 values. Although the emissions are ordered in $p_\perp$, they are not ordered in rapidity (or x). Hence, if tracing the emissions in rapidity, they will be unordered in $p_\perp$, and there are therefore qualitative similarities between the DCM and BFKL evolution [15–17]. This is in contrast to conventional showers which are purely DGLAP-based and where the emissions are ordered both in scale and in x. One of the striking phenomenological consequences of this is that ARIADNE is one of the few programs which are able to describe the high rate of forward (in the proton direction) jets measured in small-x DIS at HERA [18–20], an observable which conventional parton showers completely fail to reproduce. In fact, ARIADNE is in general considered to be the program which best describe hadronic final-state observables at HERA [21].

This does not mean that the DCM is perfect in any way. Most notably, the initial-state $g \to q\bar{q}$ and $q \to g^\star q$ (where the q is emitted into the final-state) splittings are not easily included. While the former process has been included as an explicit initial-state splitting step [22], the latter is currently absent in the the ARIADNE program. In addition, the treatment of the initial-state $g \to q\bar{q}$ splitting has been found to be somewhat incomplete, as it by construction imposes ordering in both $p_\perp$ and rapidity, thus excluding certain regions of the allowed phase space. At HERA, the incomplete treatment of the $g \to q\bar{q}$ and $q \to g^\star q$ splittings can be shown to be a small effect. However, this is not always the case at the LHC.

4 ARIADNE at LHC

Given the great success of ARIADNE at LEP and HERA, it is natural to assume that it also would do a good job at the Tevatron and the LHC. In principle, the extention of the DCM to hadron–hadron collisions is trivial, and indeed it is simple to run ARIADNE together with PYTHIA for hadron–hadron collisions. Whichever hard sub-process, PYTHIA generates, the relevant dipoles between hard partons and hadron remnants are constructed and are allowed to radiate. In addition, the initial-state $g \to q\bar{q}$ splittings are included from both sides. However, for many processes there are modifications needed.

The most obvious processes are Drell-Yan and vector boson production, where a quark from one hadron annihilates with an anti-quark from the other. The gluon radiation is then initiated by the dipole between the two remnants, and we have a suppression in both directions. However, it is unphysical to give the remnants a large transverse momentum from the recoil of the gluon emission. In DIS, this is resolved by introducing so-called recoil gluons [14], but here it is clear that the recoil should be taken by the vector boson or the Drell-Yan lepton pair. Such a procedure was introduced in [23], and together with a correction where the first emission is matched to the $qg \to qZ$ and $q\bar{q} \to gZ$ matrix elements, it describes well eg. the Z^0 $p_\perp$ spectrum measured at the Tevatron [24,25]. There are still some differences wrt. conventional parton showers. Eg. the rapidity correlation between the vector boson and the hardest jet is more flat in ARIADNE due to the increased phase space for emissions [26]. Although W and Z^0 production at the Tevatron is not a small-x process, the effect is related to higher rate of forward jets in ARIADNE for DIS. Such correlations have not yet been measured at the Tevatron, but another related effect is the somewhat harder $p_\perp$-spectrum of the Z^0 for low $p_\perp$ in ARIADNE, which is compatible with Tevatron measurements [26]. For a conventional cascade to be able to describe the low-$p_\perp$ spectrum, a quite substantial "non-perturbative" intrinsic transverse momentum must be added to the incoming quarks [27,28].

Going from the Tevatron to the LHC, there is a substantial increase in phase space for QCD radiation, and it can be argued that W and Z^0 production at the LHC is a small-x process with $x \propto m_Z/\sqrt{S} < 0.01$. Indeed ARIADNE predicts a harder $p_\perp$-spectrum for the W at the LHC as compared to conventional showers [29].

Also Higgs production can be argued to be almost a small-x process at the LHC, if the Higgs is found with a mass around the "most likely" value of $\approx$ 120 GeV. However, Higgs production is a gluon-initiated process, and the absence of the $q \to g^\star q$ splitting is a serious deficiency giving a much softer $p_\perp$-spectrum for the Higgs in ARIADNE as compared to conventional showers [30]. Hence the predictions from ARIADNE for this and similar processes can currently not be trusted. Furthermore, the increased phase-space at the LHC means that predictions also for quark-initiated processes may become affected by the deficiencies in the treatment of initial-state $g \to q\bar{q}$ mentioned above.

5 Conclusion

The success of the DCM as implemented in ARIADNE in describing hadronic final-state observables as measured at LEP and HERA makes it tempting to use it also to make predictions for the LHC. The temptation is even more difficult to resist as it is so simple to run ARIADNE together with PYTHIA for any LHC process. Currently, this must be done with great care. As explained above, it is possible to obtain reasonable predictions for vector boson production. Also standard jet-production should be fairly safe. However, for Higgs production, one of the most interesting processes at LHC, ARIADNE in its current state turns out to be quite useless.

ARIADNE is currently being rewritten in `C++` within the framework of THEPEG [31, 32]. The planned features includes a remodeling of initial-state $g \to q\bar{q}$ splittings as well as the introduction of the $q \to g^\star q$ process. In addition the matching to fixed-order tree-level matrix elements à la CKKW [26, 33–35] will be implemented for the most common sub-processes. When this version is released, hopefully during 2006, it should therefore be safe to use ARIADNE to produce LHC predictions.

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