QCD and Hadronic Final States at the LHC \(^a\)

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Hadronic final states at the LHC will be an interesting testing ground for QCD. A good understanding of QCD radiation will also be important for the discovery of new physics at the LHC. I discuss some aspects of this subject and give a few examples.

1 Introduction

The Large Hadron Collider will offer the chance of discovering the Higgs boson, supersymmetry, extra dimensions, or even more surprising new physics\(^b\).

The discovery of any new particle and even more so the precise determination of its properties will require a good understanding of the relevant background processes. The background processes as well as basically all production cross sections at the LHC involve strong interaction physics — at least via the non-perturbative parton distribution functions (pdfs) for the initial state hadrons. A good knowledge of QCD will thus be mandatory for any discovery at the LHC. At the same time the LHC will allow us to test QCD in a new kinematical region. This will make it possible to learn more about the complicated dynamics of QCD.

Along with the high luminosity the accessible kinematical range is one of the most important features of the LHC. In parton collisions at the LHC Bjorken-\(x\) will range from 1 down to values as small as \(10^{-6}\). This range of \(x\) is comparable to the one studied at HERA but the corresponding values of \(Q^2\) will be significantly higher. Due to this there are for example excellent prospects for obtaining improved parton distribution functions and for testing DGLAP evolution. In particular it will be possible to constrain the gluon distribution function from jet and photon production data. The kinematical range of the

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\(^b\)Many of the remarks in this talk also apply to the upgraded Tevatron.
LHC will also allow one to study the interesting dynamics of small-\(x\) QCD at larger momentum scales \(Q^2\) at which a perturbative treatment becomes possible.

A variety of aspects of QCD can be studied by measuring different properties of the hadronic final states emerging from proton–proton collisions. These final state properties include jet shapes, angular distributions, multiplicities, heavy quark fractions, fragmentation etc. These observables will be especially useful in investigating the challenging problems related to the hadronisation process and the transition region from hard (perturbative) to soft (non–perturbative) interactions in QCD.

In the following I will briefly discuss three examples that highlight some of the aspects mentioned above.\(^\text{1}\) For a much more detailed overview of issues related to studying QCD at the LHC and a complete list of references the reader is referred to.\(^\text{2}\)

## 2 Small-\(x\) Dynamics in Forward Dijets and their Azimuthal Decorrelation

The dynamics of QCD in the high–energy limit (or correspondingly at small Bjorken-\(x\)) is expected to exhibit very interesting properties. Processes in which the squared energy \(s\) is much larger than the momentum transfer \(t\), \(s \gg t \gg \Lambda^2_{\text{QCD}}\), are typically enhanced due to the existence of large \(\ln(s/t)\) logarithms. These logarithms can be resummed to all orders in perturbation theory, resulting in the celebrated BFKL equation.\(^\text{2, 3}\) The corresponding cross sections grow like powers of the energy, \(\sigma \sim s^\lambda\), with \(\lambda = \frac{\alpha_S}{12} \ln 2/\pi \simeq 0.5\). However, in many processes it has turned out to be difficult to disentangle BFKL physics from DGLAP evolution.

The production of jet pairs with large rapidity separation \(\Delta y\) in hadron collisions has been suggested as a particularly well–suited process for isolating small-\(x\) effects. On the parton–level the corresponding cross section is predicted to rise as \(\hat{\sigma}_{jj} \sim \exp(\Delta y)\). In order to compare with the experimentally measured cross section, however, this subprocess has to be convoluted with the pdfs of the colliding hadrons. Unfortunately, the pdfs decrease faster with \(\Delta y\) than \(\hat{\sigma}_{jj}\) increases, and the small-\(x\) effects are again very difficult to observe. It has been pointed out that the decorrelation in the relative azimuthal angle \(\Delta \phi\) of the two jets is relatively insensitive to the pdfs and in fact should lead to a clearly visible effect of BFKL dynamics. Here \(\Delta \phi\) is defined as \(|\phi_1 - \phi_2| - \pi\). In lowest order the two jets originate from the scattering of two partons via one–gluon exchange and are thus produced back–to–back,

\(^{\text{1}}\)The choice is of course biased by my own interests and prejudices.
i.e. $\Delta \phi = 0$. The BFKL calculation of this quantity predicts a much larger decorrelation than is expected at fixed order due to the emission of additional gluons between the jets. This effect is illustrated in Fig. 1. The results in this figure have been obtained using a Monte Carlo method to evaluate the leading order BFKL equation. This approach leads to a more realistic prediction than the analytic solution because it allows one to overcome some deficiencies inherent in the latter by implementing for example a running coupling and correct kinematical constraints for the produced gluons. The curves are obtained for different lower cuts on the transverse momenta of the jets, $p_T > 20 \text{ GeV}$, $p_T > 50 \text{ GeV}$, and $p_T > 20 \text{ GeV}$, and for LHC as well as for the Tevatron. The characteristic BFKL decorrelation is clearly visible. It increases with increasing $\Delta y$ before flattening off and finally decreasing again at the kinematical limit. Recent data obtained by the D0 collaboration are in reasonable agreement with the predictions. The effect should be even more pronounced at the LHC due to the larger energy that also makes a larger range in $\Delta y$ available.

Figure 1: The decorrelation in azimuthal angle in dijet production at the Tevatron ($\sqrt{s} = 1.8 \text{ TeV}$) and LHC ($\sqrt{s} = 14 \text{ TeV}$) as a function of dijet rapidity difference $\Delta y$. The upper curves are: (i) Tevatron, $p_T > 20 \text{ GeV}$ (dotted curve), (ii) LHC, $p_T > 20 \text{ GeV}$ (solid curve), and (iii) LHC, $p_T > 50 \text{ GeV}$ (dashed curve). For comparison, the lower curves are for dijet production in the process $qq \rightarrow qqH$. (Figure from [7].)
3 Minijet Multiplicities in Higgs Production

The discovery of the Higgs boson at the LHC will obviously require a good prediction for background processes leading to the same final state as a decaying Higgs boson. But its identification could also be affected by a very large number of mini–jets produced in the same hard scattering process. The number of mini–jets in a hard collision is therefore an important aspect of the hadronic final state. At the same time it is an interesting observable for studying the dynamics of QCD radiation in a hard scattering process.

A mini–jet is a jet with a transverse momentum above some resolution scale $\mu_R$ which is much smaller than the hard scattering scale $Q$. The mini–jet rate at small $x$ involves not only large logarithms of $1/x$ but also additional large logarithms of the form $T = \ln(Q^2/\mu_R^2)$ that need to be resummed. The mean number of mini–jets in a hard small–$x$ process has been computed based on the BFKL formalism. The results are expected to hold also in the framework of CCFM evolution based on angular ordering of gluon emissions. The results include all terms of the form $(\alpha_s \ln x)^m T^m$ with $1 \leq m \leq n$. The terms involving $m = n$ are called double–logarithmic (DL), whereas the terms with $m < n$ correspond to single–logarithmic (SL) corrections.

The central production of a Higgs boson is a typical example for the application of the formalism developed in \cite{4,5}. The dominant production mechanism is expected to be gluon–gluon fusion, and the momentum fractions of the gluons $x = M_H/\sqrt{s}$ are of order $\sim 10^{-3}$. Fig. 2 shows the mean number $N$ of mini–jets and its dispersion $\sigma_N$ as a function of the Higgs mass. In these numbers we do not include the jets originating from the proton remnants. The DL terms approximate the result very well and the SL terms are less significant in this case. In total the mini–jet multiplicity does not vary much with the Higgs mass. Even for low resolution scales $\mu_R$ the number of mini–jets is fairly low, and the identification of the Higgs boson should not be seriously affected.

4 Jet Shapes in Hadron Collisions

Very interesting properties of the hadronic final states are encoded in the jet shape variables like thrust, $C$-parameter, etc. A variety of these infrared and collinear safe observables has been studied in $e^+e^-$ collisions and in DIS. It has been found that they exhibit significant non–perturbative power corrections. Jet shapes are therefore optimal observables for studying the interplay between perturbative and non–perturbative effects. The mean value of a given event shape variable $F$ has the form $\langle F \rangle = \langle F_{\text{pert}} \rangle + \langle F_{\text{NP}} \rangle$. The non–perturbative correction to the perturbative result $\langle F_{\text{pert}} \rangle$ is power–suppressed, $\langle F_{\text{NP}} \rangle =$
$C_F \mu/Q^p$, where the exponent $p$ can be obtained via a renormalon analysis\cite{11}. Remarkably, the power corrections to different observables have been found to be (approximately) universal, i.e. the scale $\mu$ is the same for certain classes of event shapes, and $C_F$ is a perturbatively calculable coefficient depending on the variable under consideration. This universality holds to within $\sim 15\%$ which is quite surprising for a quantity that \textit{a priori} does not need to be universal at all. The dispersive approach to power corrections\cite{12} goes a step further and assumes that the notion of an (effective) strong coupling constant $\alpha_{\text{eff}}$ can be extended to very low momenta in the sense that its integral moments have a universal meaning. Then the magnitude of the non–perturbative power correction (i.e. $\mu$) can be related to low–momentum averages of the coupling, for example to

$$\alpha_0(2\text{ GeV}) = \frac{1}{2\text{ GeV}} \int_{0}^{2\text{ GeV}} \alpha_{\text{eff}}(q) \, dq.$$  \hspace{1cm} (1)

The value for this quantity as extracted from $e^+e^-$ and in DIS data is around 0.5. For a recent review of the phenomenology of power corrections see\cite{13}.

Power corrections are known to originate from non–perturbative effects in the hadronisation process. It would certainly be very interesting to confirm the universality of power corrections also in the environment of hadronic collisions at the LHC, or alternatively to identify characteristic differences to $e^+e^-$ collisions and DIS. The theoretical description of power corrections in hadronic collisions is more complicated than in those cases, and so far there
have been only very few theoretical studies\cite{1}. Additional difficulty originates from gluon radiation from the initial state particles before a hard interaction takes place. This gluon radiation can change the geometry and thus affect the event shape variables. Another potential difficulty is related to the definition of the hard scale $Q$ to which the power suppression refers. In hadronic collisions there is no hard (perturbative) scale in the initial state (like the center–of–mass energy in $e^+e^-$ collisions or the photon virtuality in DIS). Thus the hard scale and the hemispheres relevant for the theoretical analysis need to be defined using the hard final state particles which in turn can only be observed as jets. This probably requires a very careful treatment of the details of the jet definition in use. Despite these theoretical obstacles I expect the investigation of power corrections to event shape variables to become a very interesting and important class of measurements at the LHC.

5 Conclusions

The LHC will offer ample opportunity to test and to extend our understanding of many aspects of QCD. At the same time a good knowledge of QCD will be essential for fully exploiting the discovery potential of the LHC.

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