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Hadronic Final States in Deeply Inelastic Scattering *

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Abstract

Results on hadronic final states in deeply inelastic scattering are reviewed. They comprise jet production and its interpretation in perturbative QCD, signatures to distinguish conventional QCD dynamics from possible new features of QCD at small x, and measurements of inclusive charged particle production. Theoretical developments such as color dipole emission and instanton induced final states are reported on.

1. Introduction

The basic measurement in deeply inelastic scattering (DIS) is a measurement of the cross section $ep \rightarrow eH$ in terms of the structure function F_2, where H stands for any hadronic system. A wealth of information upon the partonic structure of the proton and its dynamics have been obtained from structure function measurements. Measurements of the properties of the hadronic final state H provide complementary information which cannot be obtained from inclusive structure functions.

In the simple quark parton model (QPM) of DIS, a quark is scattered out of the proton by the virtual boson emitted from the scattering lepton. QCD modifies this picture. Partons may be radiated before and after the boson-quark vertex, and the boson may also fuse with a gluon inside the proton by producing a quark-antiquark pair (figure 1). In fact, the parton which is probed by the boson may be the end point in a whole cascade of parton branchings. This parton shower materializes in the hadronic final state, allowing experimental access to the dynamics governing the cascade.

HERA has opened a new kinematic domain to study QCD in DIS, and most contributions in this working group were concerned with HERA physics. In HERA electrons of $E_e \approx 27$ GeV collide with protons of $E_p = 820$ GeV, resulting in a centre of mass energy of $\sqrt{s} \approx 300$ GeV. The kinematic region covered with the present data is roughly $10^{-4} < x < 10^{-1}$, 7 GeV^2 $<$

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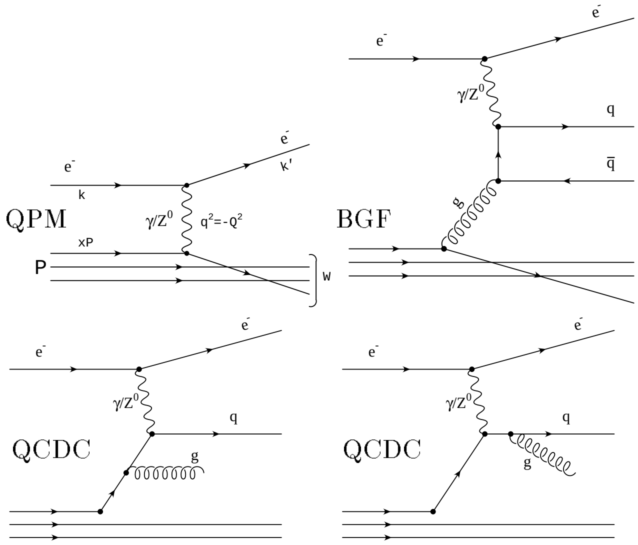


Figure 1. *Diagrams for DIS in $O(\alpha_s{}^0)$ (quark parton model - QPM) and in $O(\alpha_s{}^1)$: boson-gluon fusion (BGF) and QCD Compton (QCDC) processes.*

$Q^2 < 5000\,\mathrm{GeV}^2$ and $40\,\mathrm{GeV} < W < 300\,\mathrm{GeV}$, where W is the invariant mass of the hadronic system, Q^2 the negative 4-momentum transfer squared, and x the Bjorken scaling variable, to be identified with the proton momentum fraction carried by the scattering parton. HERA offers the opportunity to study the evolution of physics quantities over a large kinematic range. The large phase space available for hard QCD radiation, which can be treated in perturbative QCD, leads to prominent jets observable in the final state. Another area of recent interest is the kinematic regime at small x ($x \lesssim 10^{-3}$) but sizeable Q^2 , not accessible at pre-HERA DIS experiments, where novel QCD dynamics are expected to play a rôle (e.g. [1]).

The two HERA detectors ZEUS and H1 [2] are large multipurpose, "almost 4π" detectors built around the beam line. Inner tracking detectors for charged particle detection are surrounded by a magnet and calorimetry. Both the scattered electron serving as a tag for DIS events and the hadronic final state are measured. Note that a substantial part of the hadronic final state, the proton remnant, leaves the detectors unobserved in the beam pipe. The region close to the proton beam direction is often referred to as the forward region.

Apart from the laboratory frame, the hadronic centre of mass system (CMS) and the Breit frame are used in the analyses. The Breit frame is defined by the condition that the virtual photon does not transfer energy, only momentum. In the QPM picture the scattering quark would thus just reverse its momentum of magnitude $Q/2$. The CMS is defined as the centre of mass system of the incoming proton and the virtual boson, i.e. the CMS of the hadronic final state with invariant mass W. In both systems the hemisphere defined by the virtual photon direction is referred to as the current region, the other (containing the proton remnant) as the target region. The CMS current and target systems are back to back with momentum $W/2$ each. Longitudinal and transverse quantities are calculated w.r.t. the boson direction. With a longitudinal boost from the Breit frame into the CMS, particles formerly assigned to the target hemisphere may now end up in the current hemisphere.

Monte Carlo (MC) models based upon QCD phenomenology are used to simulate the DIS process. The MEPS model (Matrix Element plus Parton Shower), an option of the LEPTO generator [3], incorporates the QCD matrix elements up to first order, with additional soft emissions generated by adding leading log parton showers. In the colour dipole model (CDM) [4, 5] radiation stems from a chain of independently radiating dipoles formed by the colour charges. Both programs use the Lund string model [6] for hadronizing the partonic final state. Deficiencies of the Herwig parton shower model [7] have now been fixed by adding matrix element corrections [8, 9]. This model implements an alternative (cluster) fragmentation scheme [10], allowing for valuable cross checks in the future.

2. Jet physics

The processes contributing to DIS up to first order in α_s are shown in figure 1. The QPM process results in a so-called "1+1" jet topology, while the QCDC and BGF processes give "2+1" jet events, where the "+1" refers to the unobserved remnant jet. From a measurement of the 2+1 jet rate at large x and Q^2 , where the parton densities are well known, α_s can be measured. At small x and Q^2 , one can determine the largely unknown gluon density from the rate of 2+1 jet events, which is then dominated by the BGF graph (assuming α_s to be known). Complications arise from the fact that the initial state contains strongly interacting particles, leading to the evolution of parton showers. Such effects need to be taken into account with the help of MC simulations.

2.1. The strong coupling constant α_s

Both H1 and ZEUS use the modified JADE algorithm [11] with resolution parameter $y_{\mathrm{cut}} = 0.02$ to define jets in the α_s analysis. A pseudoparticle is introduced to account for the unobserved remnant, and then all particles i, j satisfying $m_{ij}^2 < y_{\mathrm{cut}} \cdot W^2$ are merged into jets. The chosen y_{cut} value is a compromise between statistical precision (small y_{cut}), and controllable higher order corrections (large y_{cut}) [12]. In the H1 analysis

[13] an angular cut $\theta_{\rm jet} > 10°$ (w.r.t. the proton direction) protects against parton showers close to the remnant. The obtained jet rates are corrected for detector effects, remaining parton shower contributions and hadronization with the MEPS model. In order to extract α_s from the measured jet rates, it is important to take next to leading order (NLO) corrections into account to reduce dependencies upon $y_{\rm cut}$ and the chosen renormalization and factorization scales [12]. Using PROJET [14] as NLO calculation, the measured jet rate then yields measurements of $\alpha_s\,(Q^2)$ in the range $10\ {\rm GeV}^2 < Q^2 < 3000\ {\rm GeV}^2$, which can be seen to run according to the QCD expectation [13]. However, below $Q^2 = 100\ {\rm GeV}^2$, the corrections are very model dependent (MEPS vs. CDM). Therefore only data at $Q^2 > 100\ {\rm GeV}^2$ are used to extract $\alpha_s\,({m_Z}^2) = 0.123 \pm 0.018$ [13].

For 2+1 jet events with $Q^2 > 160\ {\rm GeV}^2$ and $x > 0.01$, ZEUS has measured the jet distribution in the Lorentz invariant z_p variable [15], which in the centre of mass frame of the virtual photon and the incoming parton is an angular variable $z_p = \frac{1}{2} \cdot (1 - \cos\hat{\theta}_{\rm jet})$. Here $\hat{\theta}_{\rm jet}$ is the angle of the jet w.r.t. the direction of the incoming parton. Perturbation theory in next to leading order (NLO) [14] is able to describe the jet angular distribution down to $z_p \approx 0.1$. For $z_p < 0.1$ an excess of jets is observed. Both, the MEPS (LO matrix element + parton showers) and ME (pure LO matrix element) simulations are similar to the NLO calculation [15]. The excess of jets at $z_p < 0.1$ is therefore unlikely to be cured by next to NLO calculations.

For the α_s extraction, a cut $z_p > 0.1$ restricts the data to a region well described by NLO perturbation theory and QCD models [16]. The preliminary α_s measurements [16] for $100\ {\rm GeV}^2 \lesssim Q^2 \lesssim 3600\ {\rm GeV}^2$ demonstrate the potential of HERA to study the dependence of α_s upon the renormalization scale, and agree well with the QCD expectation (see figure 2). It is expected that already the analysis of the 1994 HERA data, once finalized, will yield a very competitive measurement of $\alpha_s\,({m_Z}^2)$.

2.2. *The gluon density in the proton*

The 2+1 jet sample (defined with the cone algorithm in the CMS) in the range $10\ {\rm GeV}^2 < Q^2 < 100\ {\rm GeV}^2$ is used to extract the gluon density $g(x_g, Q^2)$, because there the BGF graph (figure 1) dominates (BGF:QCDC $\approx 4:1$ [16, 17]). The momentum fraction x_g which the gluon carries is calculated from the invariant mass^2 $\hat{s}$ of the hard subsystem forming the 2 jets via $x_g = x(1 + \hat{s}/Q^2) \approx \hat{s}/W^2$. Special cuts remove events affected by parton showers [16, 17]. The MEPS model is used to unfold detector effects, the QCDC contribution, QPM background and remaining parton shower contributions.

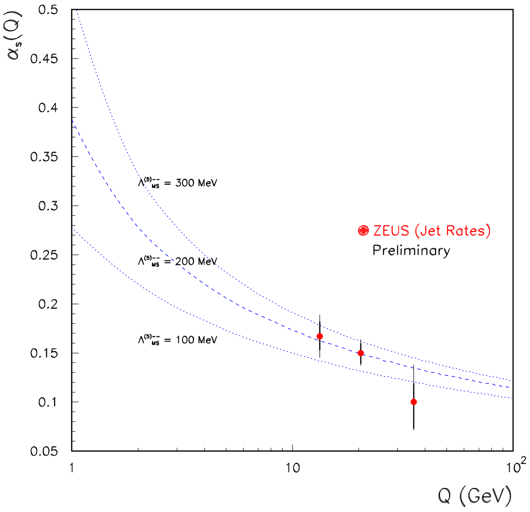


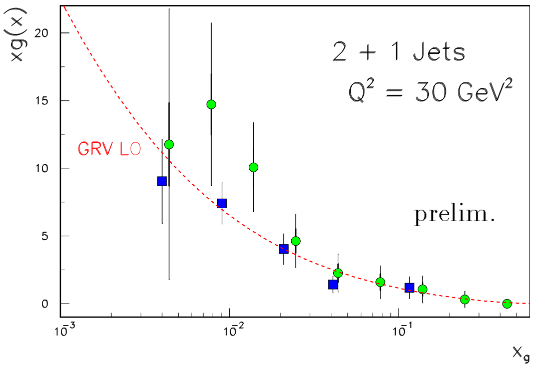
Figure 2. *Preliminary $\alpha_s\,(Q)$ measurements from ZEUS, compared to the QCD predictions corresponding to $\Lambda_{\overline{\rm MS}} = 100$, 200 and 300 GeV.*

The MEPS model employs a cut-off for invariant parton-parton masses $m_{ij}^2 > y_{\rm min} \cdot W^2$ to regulate divergencies of its LO matrix element. In order to access x_g as small as possible, $\hat{s}$ is chosen as small as experimental resolution allows, and as problems with the diverging LO matrix element can be avoided. It has to be ensured that the BGF events to be analyzed are actually generated by the model and do not fall below that cut-off [16, 17].

The H1 analysis [16] uses a fixed cut-off $\hat{s} > 100\ {\rm GeV}^2$ to define BGF events, and they parametrize the MEPS cut-off such as to follow the limit at which the order α_s contribution exceeds the total cross section within a margin of $\Delta\sqrt{\hat{s}} = 2\ {\rm GeV}$. ZEUS uses the standard $y_{\rm min}$ cut-off scheme in the MEPS model and defines BGF events via $\hat{s} > y_{\rm min} \cdot W^2$. The parameter $y_{\rm min}$ is then varied between 0.0025 and 0.01 to study its influence on the result. The H1 and ZEUS results [16] agree well with each other, but yield different size systematic errors (figure 3). The ZEUS errors receive large contributions from the $y_{\rm min}$ variation. The rise of the measured gluon density towards small x can be described by a LO gluon density [18] following the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) [21] equations. The data are also consistent with the indirect determination of $g(x_g, Q^2)$ from the scaling violations of F_2 [19], providing a non-trivial test of QCD.

2.3. *Open Points*

Lack of understanding of parton showers close to the remnant (model dependent corrections, failure of NLO calculations) currently prevents the α_s analysis to make full use of the large statistics data at $Q^2 < 100\ {\rm GeV}^2$.


xg(x)
20
15
10
5
0
2 + 1 Jets
$Q^2 = 30\ GeV^2$
GRV LO
prelim.
10^{-3}
10^{-2}
10^{-1}
x_g