Inclusive Jets and α_s at HERA

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A survey is given of recent HERA results in jet production and prompt photon production, together with the evaluation of the QCD coupling constant α_s by a variety of techniques.

1. INTRODUCTION

The presence of quarks and gluons in the proton, together with the varied behaviour of the photon, mean that *ep* collisions at the HERA collider generate a wide-ranging variety of processes in which QCD can be studied and tested. Since 1996, HERA has accumulated well over 100 pb^{-1} of data in each of the major collider experiments, running with 27.5 GeV electrons and positrons, and protons at 820-900 GeV. In this review, a number of recent results connected with jet production are discussed. The primary concern is with the hard QCD scatter that generates the jets, but the properties of a final-state jet itself are also able to provide interesting perspectives on QCD. In both cases, it is now found to be necessary to employ a next-to-leading order (NLO) treatment in perturbative calculations. An important objective is to obtain consistent and accurate measurements of the QCD coupling constant α_s.

2. INCLUSIVE JETS IN PHOTOPRODUCTION AND DIS

Photoproduction at HERA implies low values of the virtuality Q^2 of the virtual photon exchanged in the *ep* collision. The lowest-order diagrams in α_s here correspond to 2→2 processes involving the incident photon itself (direct processes) or a quark or gluon within the photon (resolved processes). The scatter off a quark or gluon in the proton then gives outgoing high-E_T jets. Such processes depend on α_s, and a well-defined measurement of the cross section can enable α_s to be determined.

It is different with the most elementary process in deep inelastic scattering (DIS), where the incident virtual photon is simply absorbed by a quark in the proton, ejecting it to generate a single ob-

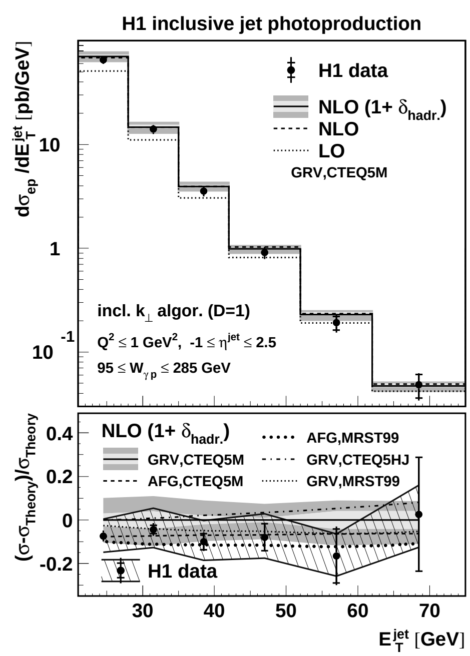

Figure 1. Transverse energy in inclusive jet photoproduction in H1. Data are compared with NLO predictions (Frixione and Ridolfi) using various photon and proton PDFs, with uncertainty bands as indicated.

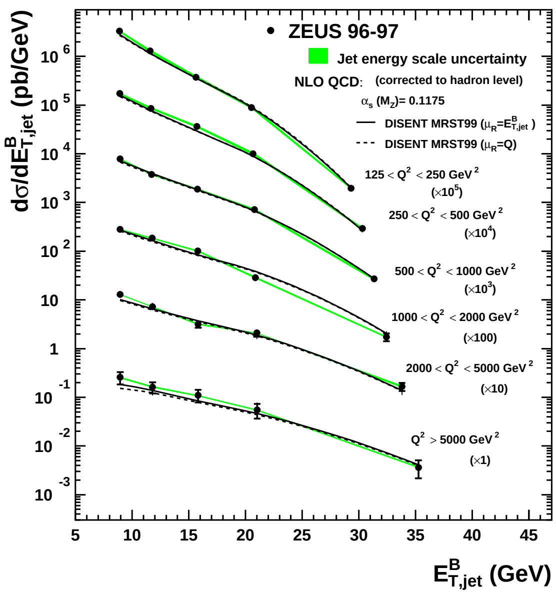

Figure 2. Inclusive jet cross sections in the Breit frame in ZEUS, for different ranges of Q^2. Scaling violations are evident. Comparison is made to NLO calculations using DISENT.

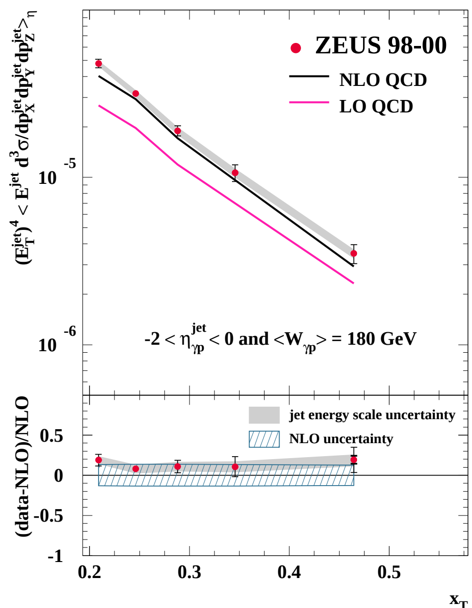

Figure 3. Photoproduced scaled jet cross sections in ZEUS, as a function of the scaling variable $x_T = 2E_T^{\rm jet}/W_{\gamma p}$, compared with LO and NLO QCD calculations.

served jet in the laboratory. This process has no $\alpha_{\rm s}$ dependence, and is sensitive merely to the parton density functions (PDFs) in the proton and to the electromagnetic coupling of the quarks.

To maximise sensitivity to $\alpha_{\rm s}$ in DIS, a good procedure is to measure jets in the Breit frame. Here, the lowest-order jet is found at low E_T. A selection on high-E_T jets thus requires at least two jets to be produced, and so suppresses the ${\alpha_{\rm s}}^0$ contribution to the inclusive jet cross section. By a suitable choice of angular cuts, the effects of the proton remnant can also be suppressed, and sensitivity to $\alpha_{\rm s}$ can be attained.

In all cases, it is necessary to be convinced that a good description of the process is being obtained within QCD. Next-to-leading-order (NLO) calculations are now widely available, and the parton-level cross sections can be corrected to hadron-level cross sections by means of a program such as ARIADNE which contains a well-tried description of the fragmentation within an adequate approximation to NLO QCD. Figs. 1 and 2 illustrate inclusive jet production cross sections from H1 and ZEUS, in photoproduction and DIS (Breit frame) respectively. A lowest-order (LO) calculation is inadequate. Within the present experimental and theoretical uncertainties, it is concluded that the use of NLO QCD is both necessary and sufficient to account for the data. There is little sensitivity to the proton and photon PDFs provided that recent models are used.

Fig. 3 illustrates a recent analysis of inclusive jet cross sections in photoproduction from ZEUS in terms of a scaling variable. Again, the importance of an NLO approach is clearly seen, the LO calculation being far too low. By showing that the scaled jet invariant cross sections vary with the γp centre-of-mass energy, scaling violations in photoproduction were for the first time demonstrated in this study.

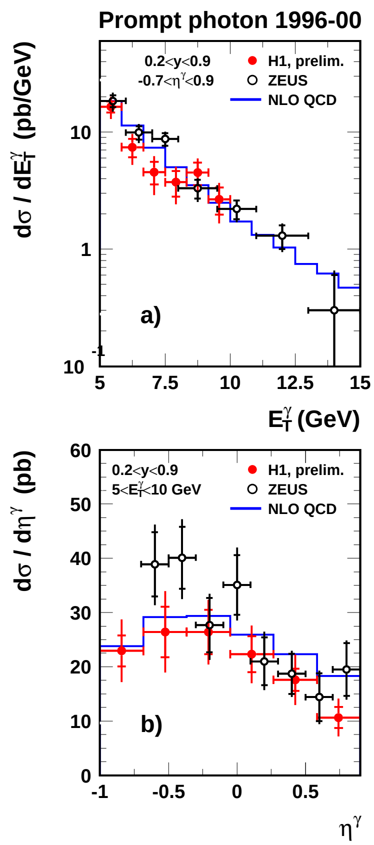

Figure 4. Inclusive prompt photon cross sections from H1 and ZEUS, compared with NLO prediction, as a function of (a) transverse photon energy (b) pseudorapidity.

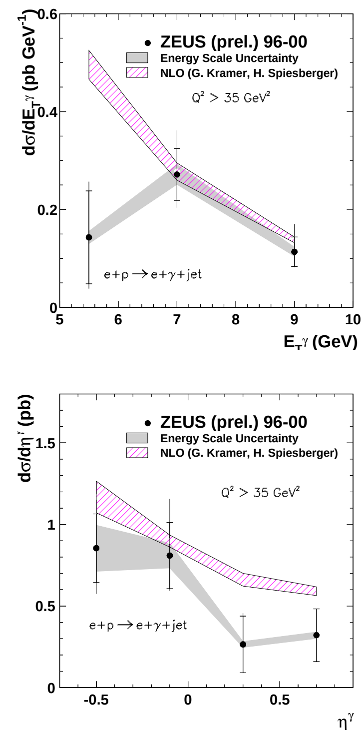

Figure 5. Prompt photon cross sections in DIS from ZEUS, accompanied by a jet, compared with NLO predictions.

3. PROMPT PHOTONS AT HERA.

In a different type of QCD process, a photon may be produced in partonic scatters instead of a quark or gluon. Measurements of these photons provide a further perspective on QCD of interest because the photon emerges directly from the QCD scatter without the fragmentation which effects the conversion of a quark or gluon into an observable jet. H1 have presented new measurements of inclusive prompt photons in photoproduction, which they have compared with earlier ZEUS measurements and with an NLO theoretical prediction from Fontannaz, Guillet and Heinrich (using AFG and MRST2 PDFs for the photon and proton respectively). The results are illustrated in Fig. 4. Bearing in mind the different calorimetric techniques used by the two experiments to identify the photons, the results are in reasonable agreement with each other and with the theory. However more statistics are needed to test the theory in more depth.

ZEUS have given the first measurements of prompt photon production in DIS. The results, show a fair agreement with PYTHIA and HERWIG and (Fig. 5) with a new NLO calculation by Kramer and Spiesberger. The systematic errors are large, however, and an increase in statistics would be highly desirable.

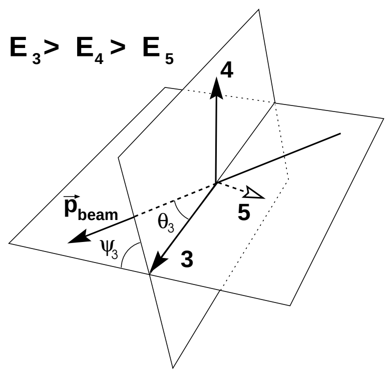

Figure 6. Definitions of geometric angles in three-jet final states (of energy E_3, E_4, E_5) in HERA processes.

4. MULTIJET FINAL STATES

A further means of testing QCD at HERA comes from the study of final states containing more than two jets. Such states can arise in several ways in photoproduction. Since the photon fluctuates into a meson-like intermediate state, there is a possibility for multiparton interactions (MPI), i.e. more than one parton-parton scatter occurs within the context of a given photon-proton interaction. Alternatively expressed, there may be a soft underlying event (SUE) in addition to a given harder scatter. Hard initial or final state gluon radiation may take place, which is modelled in certain basically LO calculations such as PYTHIA and HERWIG. More generally, the processes should be calculable in a suitably higher order of QCD.

In an *ep* process that gives rise to three final-state partons or jets, $1 + 2 \to 3 + 4 + 5$, the geometry of the final state is usefully described by means of angles as shown in Fig. 6. ZEUS have made a preliminary study of four-jet final states, merging together the two jets with smallest combined invariant mass so as to be able to use this geometrical description. Jets of $E_T^{\rm jet} > 5$ GeV are used. The θ_3 distribution is found (fig. 7) to be poorly described by HERWIG without or with its standard SUE option, but satisfactorily when an

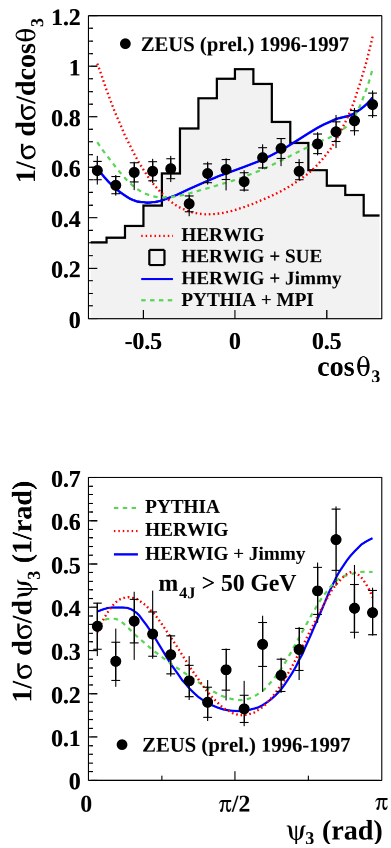

Figure 7. Normalised distribution in the angle θ_3 measured by ZEUS, compared with models including multiparton effects, and with a mass requirement on the four-jet final state.

eikonal model ('Jimmy') is employed to generate a second parton scatter. PYTHIA with its MPI option gives a satisfactory result.

Since the SUE/MPI processes interfere with QCD studies, it is desirable to eliminate them by suitable requirements on the event. If it is insisted that the combined mass of the four jets exceeds 50 GeV, both HERWIG and PYTHIA give good descriptions of the distribution, and the SUE/MPI effects are much reduced. This condition applies to the kinematics of the events used in the inclusive jet measurements discussed above.

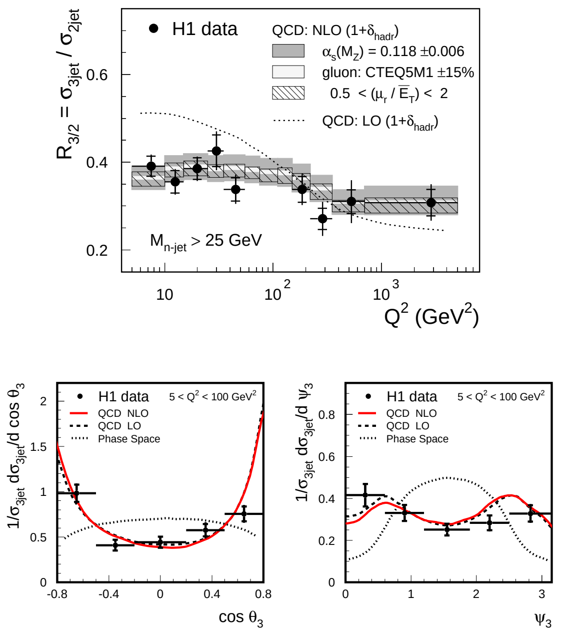

Figure 8. (Upper) 3-jet/2-jet ratio, (lower) θ_3 and ψ_3 distributions in DIS measured by H1, compared with LO and NLO predictions and with phase space.

In DIS, the SUE/MPI effects should be absent or largely suppressed. H1 have compared three-jet distributions with the NLOJET calculation (Nagy and Trócsányi) evaluated at LO and NLO. Results are illustrated in Fig. 8. While both versions describe well the shape of the angular distributions, and phase space does not, only the NLO calculation correctly predicts the cross section as a function of Q^2.

5. DETERMINATION OF α_s

The analyses presented above have shown in a variety of ways that NLO calculations are able to give a good description of QCD-governed processes at HERA involving outgoing jets. It is therefore possible to use these processes with assurance to evaluate the QCD coupling constant α_s, even though the experimental situation is intrinsically less clean than in e^+e^- colliders. A number of accurate α_s measurements have been published by H1 and ZEUS in recent years. One technique, in which no explicit jet measurement is required, is to carry out global QCD-based fits to the structure functions measured in DIS, in the course of which, α_s is determined. The results of these determinations are tabulated below.

ZEUS have used the specific measurement of inclusive jets in both DIS and photoproduction to measure α_s. In the Breit Frame measurements described above, an accurate determination of α_s requires that an explicit dependence of the proton PDFs on α_s in an NLO context be taken into account, which can be done in the MRST99 parameterisation. In their analysis of photoproduced jets, ZEUS fit the measured jet cross sections to the NLO calculation of Klasen, Klainwort and Kramer. Figs. 3 and 9 illustrate the effects of the theoretical and experimental uncertainties on this measurement.

In the upper plot of Fig. 9, values of α_s obtained by several techniques at HERA are plotted as a function of the QCD scale of the relevant hard interaction, as indicated in the figure. The running of α_s is clearly exhibited, and the different methods are consistent. These conclusions are confirmed in the lower plot of Fig. 9, which illustrates the consistency of the photoproduced jet behaviour in the ZEUS data.

In a different approach, ZEUS have measured α_s using the structure of jets in DIS measured in the laboratory frame. These are predominantly quark jets. Here, as in the two other determinations ust discussed, a k_T-clustering jet finder was employed. In such a jet finder, there is a parameter $y_{\rm cut}$ which designates the degree of 'closeness' of particles or particle clusters which are to be aggregated within a jet. Normally this parameter is set to unity, but if it is decreased, more jet-like objects become distinguished, referred to as 'subjets'. The increase of the average total number of subjets $<n_{\rm sbj}>$ with decreasing $y_{\rm cut}$ is sensitive to α_s, since the first feature of the jet substructure to be encountered is the possible final-state radiation of a hard gluon within the overall jet. Eventually a sensitivity to details of the fragmentation emerges at small $y_{\rm cut}$ values.

By careful study it was found that the NLO

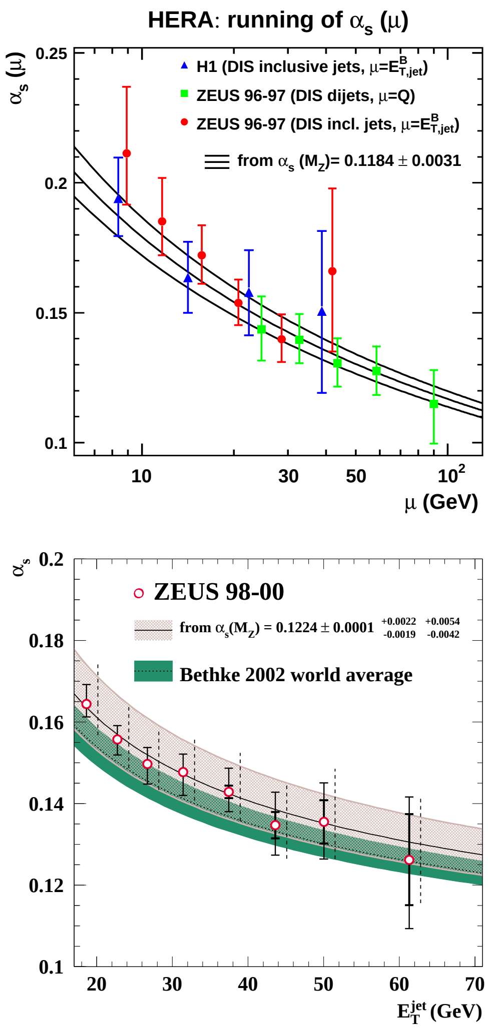

Figure 9. Fitted values of α_s obtained in various HERA analyses, plotted as a function of the QCD scale variable. Upper plot: scale variable (μ) taken as the dominant momentum transfer in the process, namely the unsquared photon virtuality or the transverse jet energy. Lower plot: taken as the transverse energy of jets in photoproduction. In both cases comparison is made with a recent world average value of α_s shown with its uncertainty.

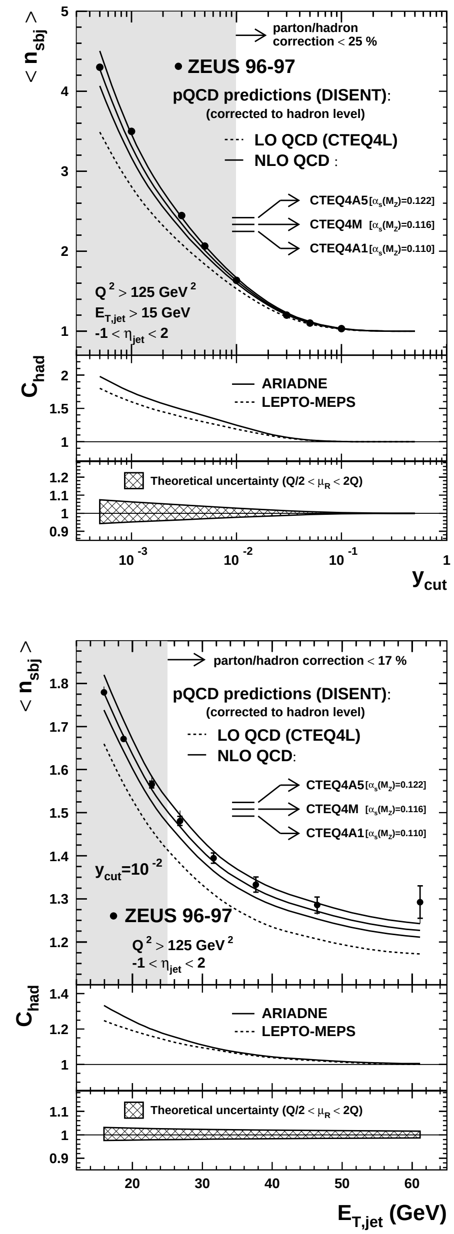

Figure 10. Subjet multiplicity measured by ZEUS as a function of $y_{\rm cut}$, corrected to hadron level by means of ARIADNE. There is good agreement with NLO QCD, but not LO. Variations of α_s and proton PDF are indicated.

parton generator DISENT, corrected to the hadron level, was able to give a consistently accurate description of the variation of $< n_{\rm sbj} >$ with $y_{\rm cut}$ (Fig. 10. top)). The data are insensitive to details of the proton PDF used. Varying $\alpha_{\rm s}$, a fit was performed to $< n_{\rm sbj} >$ plotted as a function of $E_T^{\rm jet}$, using a value of $y_{\rm cut} = 0.01$ which minimises the theoretical and experimental uncertainties (Fig. 10, bottom). An overall optimal value of $\alpha_{\rm s}$ was extracted.

The $\alpha_{\rm s}$ values obtained by these three methods are as follows, the quoted errors being respectively the statistical, experimental systematical and theoretical uncertainties.

Inclusive jets in DIS Breit Frame:

$$0.1212 \ \pm 0.0017 \,^{+0.0003}_{-0.0001} \,^{+0.0028}_{-0.0027}$$

Inclusive jets in photoproduction:

$$0.1224 \ \pm 0.0001 \,^{+0.0022}_{-0.0019} \,^{+0.0054}_{-0.0042}$$

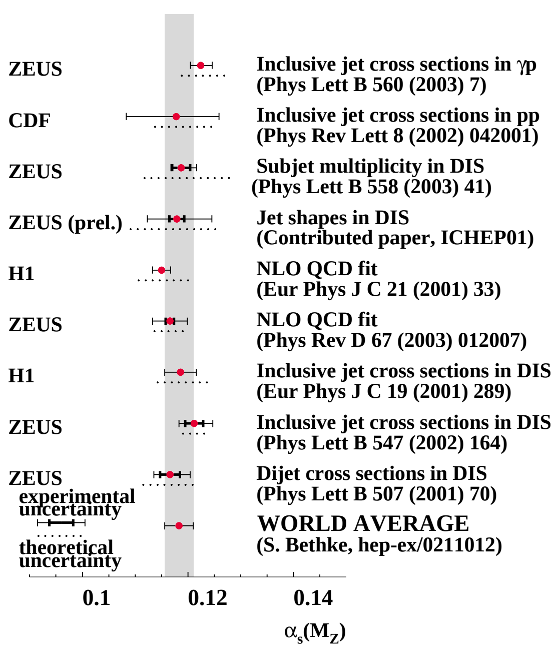

Figure 11. Summary of recent HERA and CDF $\alpha_{\rm s}$ determinations.

DIS subjet multiplicities:

$$0.1187 \ \pm 0.0017 \,^{+0.0024}_{-0.0009} \,^{+0.0093}_{-0.0076}$$

These results are compared with those from the DIS fits and some other recent measurements in Fig. 11.

The statistical accuracy is now reduced below the uncertainties due to the experimental systematics and the NLO theoretical modelling that is needed to extract the results. The current world average value is quoted as 0.1183 ± 0.0027, dominated largely by results from e^+e^- colliders. It may be concluded that the HERA measurements are very competitive with most others, and that a consistent account of QCD is being presented over a wide range of parton phenomena.

6. CONCLUSIONS

The results summarised above show the outstanding success that HERA has achieved in studying QCD-governed processes in ep-initiated reactions. Many of the processes are investigated uniquely at HERA, and include the generation of high-energy jets and photons from interactions that are initiated by photons over a wide range of virtuality. At NLO, QCD is able to give a reliable description of essentially all the processes studied, both in photoproduction and in DIS. To achieve this, recent PDFs for the proton and photon are required, and the QCD coupling $\alpha_{\rm s}$ must be appropriately set by means of fits to the data. Experimental values for $\alpha_{\rm s}$ are obtained in this way whose quality compares very favorably with those obtained by other means.