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Jet production and measurements of α_s at HERA

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Abstract. Results on the measurements of the hadronic final state in $e^{\pm}p$ collisions by the H1 and ZEUS experiments at HERA are presented. These are measurements on the production of prompt photons in photoproduction, inclusive jet, dijet and trijet production in deep-inelatic scattering and on the search for QCD instantons. The jet production data is employed for the extraction of the strong coupling constant $\alpha_s(M_Z)$.

1 Introduction

The HERA collider was an $e^{\pm}p$ collider with centre-of-mass energy of 319 GeV with two multi-purpose experiments, H1 and ZEUS. Both experiments recorded in the years 1992–2007 data with an integrated luminosity of about 0.5 pb^{-1}. Several years after data taking, both experiments have successively refined their analysis techniques and now have achieved the final precision of their data with, for instance, a precision of the jet energy scale of 1 %. In the current era of hadron-hadron colliders, the HERA experiments provide important precision measurements of QCD, due to their unique initial state with only one hadron involved.

2 Prompt photons in photoproduction

The production of isolated photons in an hadronic environment, so-called prompt photons, is an important process to test the understanding of underlying QCD processes since prompt photons are unaffected by hadronisation and thus are a direct probe of the partonic hard process. Contrary, non-prompt photons, i.e. photons originating from decays of secondary particles such as π^0, are described using fragmentation functions.

New measurements on the production of isolated photons in photoproduction [1, 2] are presented, where photoproduction processes are defined by a the negative four-momentum transfer squared of the scattered electron of $Q^2 < 1\,\mathrm{GeV}^2$. The measurement is based on data collected with the ZEUS detector corresponding to an integrated luminosity of 374 pb^{-1}. Prompt photons have been measured inclusively and with an accompanying jet as function of the photon and jet kinematic variables in the phase space of the photon of $-0.7 < \eta^{\gamma} < 0.9$ and with a transverse energy of $6 < E_T^{\gamma} < 15$ GeV. The number of prompt photon events was determined by a fit to the energy-weighted width of the energy-cluster comprising the photon candidate which allows for a clear separation of isolated photons from background of photons originating from the decay of neutral mesons. The data are compared to NLO

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predictions including fragmentation terms [3] which give a good description of the data. The data are further compared to predictions using the k_T-factorization method (LMZ) [4] which describe the photon distributions well, but give a less good description at low η^{jet} and for the resolved enhanced region. The uncertainties on the theory predictions obtained by scale variations are typically larger than the uncertainties of the data. Figure 1 shows the production of an isolated photon as function of E_T and the production of an isolated photon accompanied by a jet as function of η_{jet}.

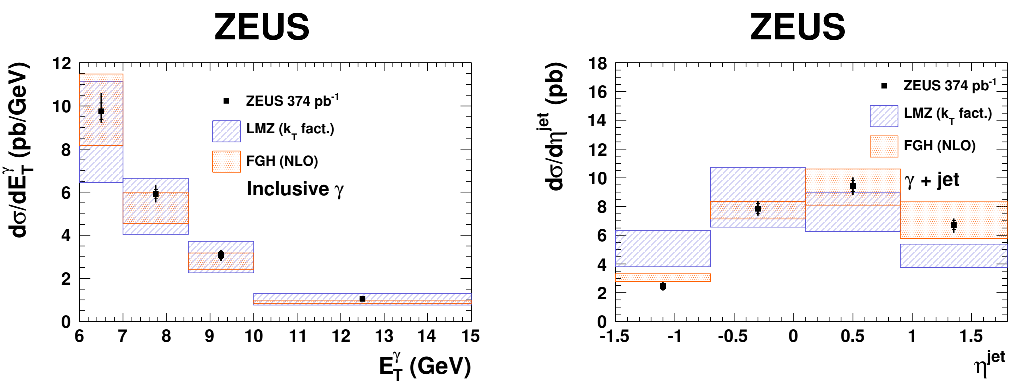

Figure 1. Cross sections of photoproduction of isolated photons as function of E_T (left) and of an isolated photon accompanied by a jet as function of η_{jet} (right). The data are compared to predictions of next-to-leading order pQCD and of the k_T-factorisation method.

Further detailed studies have been performed [2] for photon plus jet cross sections for the direct-enhanced and the resolved-enhanced photoproduction regions separately, defined by $x_\gamma^{\text{meas}} > 0.8$ and $x_\gamma^{\text{meas}} < 0.8$, respectively, where x_γ^{meas} is the fraction of the virtual photon's momentum participating in the production of γ + jet system. The LMZ-predictions have problems describing the rapidity distribution of the jet for the resolved-enhanced region. In order to study regions which are particular sensitive to higher order radiation also new observables like the rapidity separation of the jet and the photon have been investigated. The measured double differential cross sections are potentially valuable input to future photon PDF fits.

3 Trijet production in DIS (ZEUS)

The production of trijet events in neutral current deep-inelastic scattering (NC DIS) in the kinematic region of $125 < Q^2 < 20000\,\text{GeV}^2$ and an inelasticity of $0.2 < y < 0.6$ has be investigated by the ZEUS experiment [5]. The measuement is based on data corresponding to an integrated luminosity of $295\,\text{pb}^{-1}$. Jets are found using the k_T jet algorithm in the Breit frame of reference and are required to have a transverse momentum exceeding $E_{T,B}^{\text{jet}} > 8\,\text{GeV}$ and to lie well in the detector acceptance in pseudorapditiy of $-1.0 < \eta_{\text{lab}}^{\text{jet}} < 2.5$. The invariant mass of the two leading jets must fulfill $M_{12} > 20\,\text{GeV}$. The major source of experimental uncertainty are the jet energy scale of 1 % (3 %) for jets with transverse energies in the laboratory frame above (below) 10 GeV, as well as model systematics when correcting for detector effects. The data are compared to predictions in next-to-leading order QCD (NLO), using the nlojet++ [6] program together with the HERAPDF1.5 [7] parameterisation of the parton densities in the proton. The NLO predictions are corrected for hadronisation effects using correction factors obtained from the ARIADNE and LEPTO event generators. For a large variety of single and double-differential measurements investigated, the NLO predictions give a good description of the data. The uncertainty on NLO predictions, obtained from a variation of the renormalisation and the factorisation scales by factors of two, as well as a variation of the strong coupling constant $\alpha_s(M_Z)$ by 0.002, is typically of a similar size as the experimental uncertainties for single differential measurements.

4 Multijet production in DIS (H1)

Inclusive jet, dijet and trijet production in NC DIS in the kinematic region of $150 < Q^2 < 15000\,\mathrm{GeV}^2$ and $0.2 < y < 0.7$ has been measured by the H1 experiment. The data were taken during the HERA-II period and correspond to an integrated luminsity of $351\,\mathrm{pb}^{-1}$. Jets are found using the k_T or the anti-k_T jet algorithm in the Breit frame and are required to have a transverse momentum exceeding $P_T^{\mathrm{jet}} > 7\,\mathrm{GeV}$ and to lie well in the detector acceptance in pseudorapditiy of $-1.0 < \eta_{\mathrm{lab}}^{\mathrm{jet}} < 2.5$. In case of dijet and trijet production the invariant mass of the two leading jets must exceed $M_{12} > 16\,\mathrm{GeV}$.

The data are corrected for detector effects using a multi-dimensional regularised unfolding method as implemented in the TUnfold package [8]. The inclusive jet, dijet and trijet data as well as NC DIS cross sections are unfolded simultaneously taking the statistical correlations between these measurements into account. The procedure also enabled to measure jet cross sections normalised to the inclusive NC DIS cross sections in respective Q^2 bins, so-called normalised jet cross sections. The normalised jet cross sections benefit from cancellation of the normalisation uncertainties and a significant reduction of many other systematic uncertainties. Jet cross sections, as well as normalised jet cross sections are measured as function of Q^2 and the transverse mometum of the jet P_T, where P_T represents the transverse momentum of the jet, P_T^{jet}, in case of inclusive jets or the average transverse momentum, $< P_T^{\mathrm{jet}} >_2$ ($< P_T^{\mathrm{jet}} >_3$), of the two (three) leading jets in case of dijet (trijet) production. The data are compared to NLO predictions obtained from the nlojet++ program [6] together with different parametrisations of the proton. The renormalisation scale is chosen to be $\mu_r^2 = (P_T^2 + Q^2)/2$ and the factorisation scale is chosen to be $\mu_f^2 = Q^2$. The NLO predictions are corrected for hadronisation effects with correction factors obtained from the Djangoh [9] and Rapgap event generators [10]. The normalised cross sections using the k_T algorithm are displayed in figure 2 as function of P_T in different Q^2 bins together with NLO calculations obtained using the MSTW2008 PDF set [11]. The ratio of data to predictions displayed in the right panel provides a detailed comparison. The data are in general well described by the theoretical predictions, while the precision of the data is considerably better than that of the NLO calculations.

The measurements are used to extract values of the strong coupling constant $\alpha_s(M_Z)$. Using the normalised inclusive jet, dijet and trijet measurements simultaneously, the best experimental precision of 0.7 % is obtained and the value extracted yields

$$\alpha_s(M_Z)|_{k_t} = 0.1165\ (8)_{\mathrm{exp}}\ (5)_{\mathrm{PDF}}\ (7)_{\mathrm{PDFset}}\ (3)_{\mathrm{PDF}(\alpha_s)}\ (8)_{\mathrm{had}}\ (36)_{\mu_r}\ (5)_{\mu_f}\ ,$$

where 'exp' denotes the total experimental uncertainty, 'PDF' the uncertainty from the MSTW2008 PDF eigenvectors, 'PDFset' the variation of the input PDF when using a parametrisation different than the MSTW2008 set, 'PDF(α_s)' a variation of ± 0.002 of $\alpha_s(M_Z)$ as the input to the PDF fit, 'had' the hadronisation uncertainty and 'μ_r' ('μ_f') the uncertainty on the variation of the renormalisation (factorisation) scale. The latter one represents an estimate of the uncertainty on the trunctation of the perturbative series since coefficients beyond NLO are not yet calculated. Values of $\alpha_s(M_Z)$ extracted at different values of the renormalisation scale μ_r are further extracted and compared to values from other jet measurements in figure 3. A good agreement of the running with the expectation from the renormalisation group equation is found as well as consistency with extractions from other jet data.

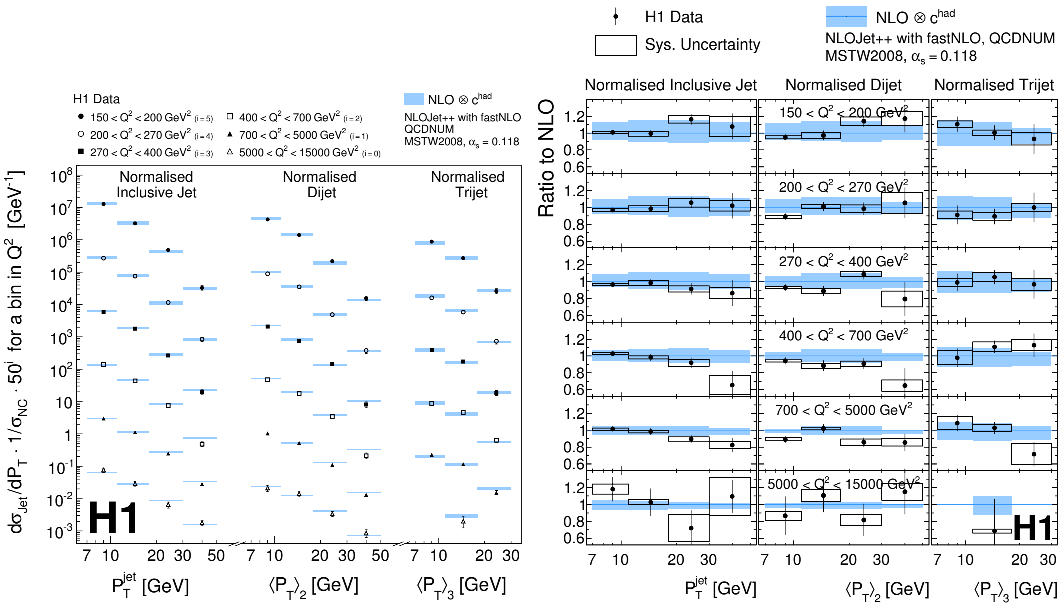

Figure 2. Normalised double-differential cross sections for jet production in DIS as a function of Q^2 and P_T (left). The inner and outer error bars indicate the statistical uncertainties and the statistical and systematic uncertainties added in quadrature. The NLO QCD predictions, corrected for hadronisation and electroweak effects, together with their uncertainties are shown by the shaded band. The right panel shows the ratio of data to predictions.

The value of $\alpha_s(M_Z)$ is the most precise value ever derived at NLO from jet data recorded in a single experiment.

5 Search for QCD instantons

Instantons are an intrinsic part of QCD as realisations of non-perturbative fluctuations of the gluon field and can be interpreted as tunnelling transitions between topologically non-equivalent vacua. An experimental observation of instanton-induced processes would constitute a discovery of a basic non-perturbative QCD. Instanton-induced events are modelled by the QCDINS MC generator [12] and are characterized by a "fire-ball" like topology with large particle multiplicities in a broad η-region.

Signals of QCD instanton-induced processes are searched for in DIS by the H1 experiment [13] in the kinematic region of $150 < Q^2 < 15000\,\mathrm{GeV}^2$ and an inelasticity of $0.2 < y < 0.7$. The expected signal is extracted using a probability density estimator (PDERS), where also other neural networks such as two variants of boosted decision trees and neural network multi-layer perception have been investigated. Standard DIS processes are modelled using the RAPGAP MC and the DJANGO MC is applied to estimate a model uncertainty. Input to the PDERS are topological variables defined in the instanton rest-frame, such as the sphericity, Fox-Wolfram moments and azimuthal isotropy as well as the number of charged particles and the energy of the instanton band. The instanton-band and the instanton rest-frame are found from the hadronic final state after removing the constitutents of the hardest jet. Many further variables are explored to control the separation power of the multivariate analysis and a good description of the discriminator in the background region is found. The data are

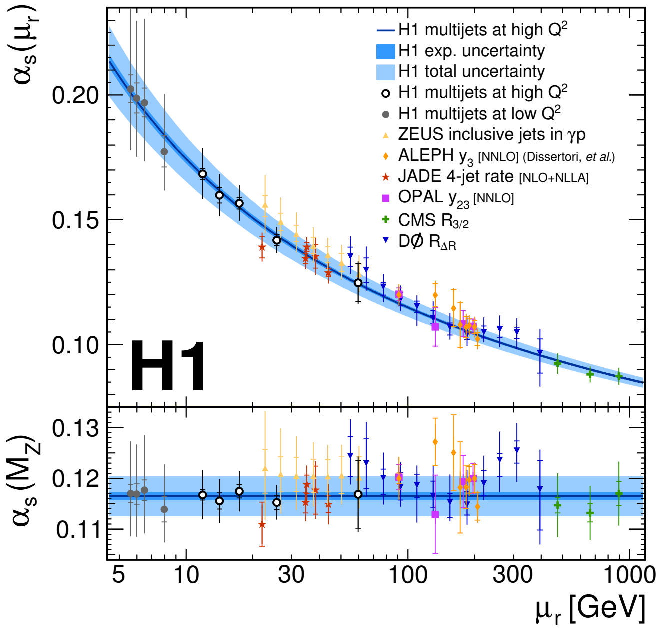

Figure 3. Values of $\alpha_s(M_Z)$ (and corresponding values of $\alpha_s(\mu_r)$) extracted from the normalised multijet cross sections at different values of μ_r compared to values extracted from other jet data. The prediction for the running of $\alpha_s(\mu_r)$ using the extracted value of all measurements of $\alpha_s(M_Z) = 0.1165\,(8)_{\text{exp}}\,(38)_{\text{pdf,theo}}$ is also shown.

found to be consistent with the background also in the instanton enhanced region and no evidence for a QCD instanton is found. An upper limit of 1.6 pb for the instanton cross section is extracted at a confidence limit of 95 % in comparison with a cross section predicted by QCDINS of 10 pb.

6 Summary

New measurements of the hadronic final state in $e^{\pm}p$ physics with the final data precision and high statistical significance are presented from the H1 and ZEUS measurements. The measurements are mostly well described by theoretical predictions while the data precision often overshoots the precision of the predictions. The data was employed for precision extractions of the strong coupling constant $\alpha_s(M_Z)$ and may further be used to improve the presciption of the proton and the photon PDFs.

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