Jet production at HERA

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New results on the measurements of jet cross sections and the hadronic final state in $e^{\pm}p$ collisions by the H1 and ZEUS experiments at HERA are presented. These are measurements of inclusive jet, dijet and trijet production as well as the production of $D^{*\pm}$ mesons in deep-inelastic scattering (DIS). Furthermore new measurements of the production of exclusive dijet cross sections as well as inclusive dijet cross sections in diffractive DIS and in diffractive photoproduction are presented.

1 Introduction

At the HERA collider in Hamburg, Germany, electrons were collided with protons at a centre-of-mass energy of 319 GeV. The two multi-purpose experiments H1 and ZEUS collected data until 2007 with an integrated luminosity of about $0.5\,\mathrm{fb}^{-1}$ per experiment. 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 measurement of the jet energy scale of 1 %.

2 Recent results of jet production measurements at HERA

2.1 Measurement of multijet production in neutral current DIS

In the neutral current DIS (NC DIS) kinematic region of $150 < Q^2 < 15000\,\mathrm{GeV}^2$ and $0.2 < y < 0.7$, where Q^2 denotes the exchanged photon virtuality and y being the inelasticity, a simultaneous measurement of inclusive jet, dijet and trijet production, so-called multijet production, has been performed by H1 [1]. Furthermore, multijets normalised to the respective NC DIS cross section have been measured, which benefit from cancellation of the normalisation uncertainties and a significant reduction of many other systematic uncertainties. 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 $P_T^{\mathrm{jet}} > 7\,\mathrm{GeV}$. The invariant mass of the two leading jets must further exceed $M_{12} > 16\,\mathrm{GeV}$ for dijet and trijet production.

The measurement features an updated calibration of the measurement of the jet energy, which is based on calibration constants for jets derived using neural networks, as well as a multi-dimensional regularised unfolding method for the correction of detector effects. The latter is composed of a simultaneous unfolding of the three jet measurements together with the NC DIS cross sections where the statistical correlations are considered, thus also enabling to measure the normalised multijet production. The data are compared to predictions in next-to-leading order QCD (NLO) including corrections for hadronisation effects, and studying different parametrisations of the proton. The ratio of normalised k_T-jet cross sections to their NLO predictions is displayed in figure 1 as function of P_T in different Q^2 bins, 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 in general found to be well described by the theoretical predictions and the precision of

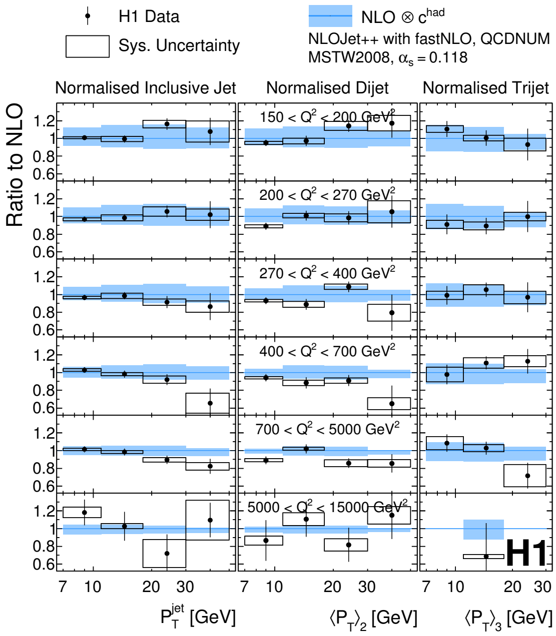

Figure 1 – Ratio of normalised jet cross sections to NLO QCD predictions as a function of Q^2 and transverse momenta observables.

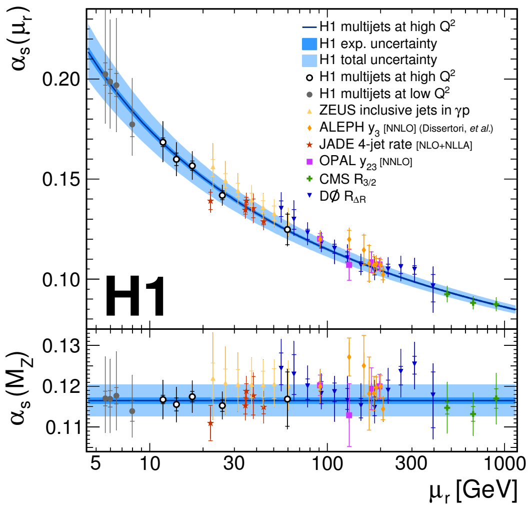

Figure 2 – Values of $\alpha_s(M_Z)$ (and corresponding values of $\alpha_s(\mu_r)$) extracted from the normalised multijet cross sections at different values of μ_r compared to values extracted from other jet data. The prediction for the running using the value of $\alpha_s(M_Z) = 0.1165\,(8)_{\rm exp}\,(38)_{\rm pdf,theo}$ is also shown.

the data is considerably better than that of the NLO calculations, in particular for normalised jet cross sections.

The measurements are used to extract values of the strong coupling constant $\alpha_s(M_Z)$, where the simultaneous extraction from the normalised multijet measurement yields the best experimental precision of 0.7 % with a value of $\alpha_s(M_Z)|_{k_t} = 0.1165\ (8)_{\rm exp}\ (38)_{\rm PDF,theo}$, where 'exp' denotes the total experimental uncertainty, 'PDF,theo' the uncertainty from the PDFs and orders beyond NLO. Values of $\alpha_s(M_Z)$ are further determined at different values of the renormalisation scale μ_r and are compared in figure 2 to values from other jet measurements. The values are found to be consistent with the other values and also to be in good agreement with the expectations for the running from the renormalisation group equation. The value of $\alpha_s(M_Z)$ is the most precise value ever derived at NLO from jet data recorded in a single experiment.

2.2 Trijet production in DIS

The ZEUS experiment has measured [2] the production of inclusive trijets in the NC DIS kinematic region of $125 < Q^2 < 120000\,{\rm GeV}^2$ and $0.2 < y < 0.6$, where jets are found using the k_T cluster algorithm and are required to exceed a transverse momentum in the Breit frame of $E_{\rm T,B}^{\rm jet} > 8\,{\rm GeV}$. The double-differential measurement based on an integrated luminosity of $295\,{\rm pb}^{-1}$ exhibits good agreement with predictions in NLO QCD.

2.3 Exclusive dijets in diffractive DIS

The ZEUS experiment has measured [3] the production of exclusive dijets in diffractive DIS for $Q^2 > 25\,{\rm GeV}$ and for $\gamma^* p$ centre-of-mass energies in the range $90 < W < 250\,{\rm GeV}$. The exclusive dijet events, with jet transverse momenta greater than 2 GeV, have been reconstructed in the centre-of-mass system frame using the exclusive k_T algorithm. The normalised cross section is given as a function of the angle ϕ, and is shown in figure 3, where ϕ is defined by the γ^*-dijet plane and the γ^*-$e^\pm$ plane in the rest frame of the diffractive final state. The comparison of

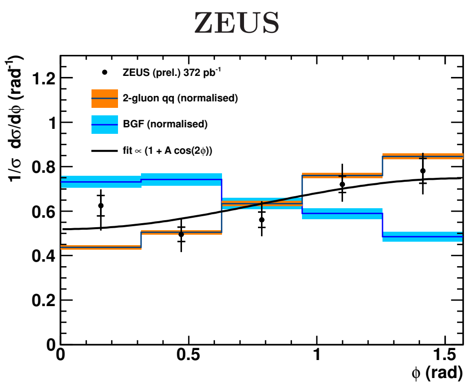

Figure 3 – The normalised differential cross section for the production of exclusive dijets as function of ϕ. The cross section is parameterised with a simple function and compared to two different theoretical models.

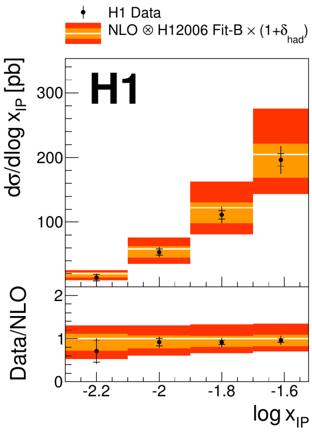

Figure 4 – Diffractive dijet differential cross section as a function of the fractional proton longitudinal momentum loss, $\log x_{I\!P}$, compared to NLO predictions.

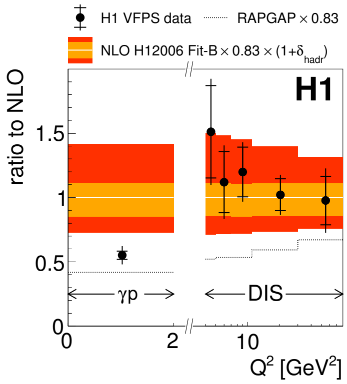

Figure 5 – Diffractive dijet cross sections in the PHP and DIS regime normalised to the NLO calculation as a function of Q^2.

the shape to theoretical predictions based on the Two-Gluon-Exchange model or the Resolved-Pomeron model exhibits a preference for the former, which is further supported by the study of a parameterised function as motivated by theory.

2.4 Inclusive dijet production in diffractive DIS (LRG)

The H1 experiment has presented a measurement [4] of single- and double-differential dijet production cross sections in diffractive DIS ($4 < Q^2 < 100\,\mathrm{GeV}^2$), where diffractive events are identified by requiring a large rapidity gap (LRG), i.e. an empty interval in rapidity between the high-mass hadronic final state and the elastically scattered proton or its low-mass excitation. The fully unfolded measurement investigates the kinematic range of the fractional proton longitudinal momentum loss of $x_{I\!P} < 0.03$, by identifying k_T-jets with a minimum transverse momentum of 5.5 and 4.5 GeV of the leading and subleading jet, respectively. The comparison to NLO QCD predictions, employing diffractive parton distribution functions (DPDF), exhibits a good agreement as shown in figure 4, while theoretical uncertainties from higher orders beyond NLO and from the DPDFs overshoot the experimental precision in a wide kinematical region.

The double-differential data is further used to determine the value of the strong coupling constant for the first time in diffractive DIS processes to $\alpha_s(M_Z) = 0.119\,(4)_{\mathrm{exp}}\,(12)_{\mathrm{theo}}$, thus illustrating the good agreement of theory to data and showing the experimental uncertainties to be significantly smaller than the uncertainties of the theory predictions.

2.5 Measurement of dijet production in diffractive DIS and photoproduction with a leading proton

Diffractive hadron-hadron interactions are found to be suppressed as compared to NLO predictions which are based on DPDFs obtained from HERA. Dijet production in diffractive photoproduction (PHP) allows the process to be studied in a similar environment to that of two interacting hadrons, where in the past discrepancies between the ZEUS and H1 measurements were a subject of debate.

The H1 experiment has presented measurements of unfolded differential dijet production cross sections in diffractive PHP ($Q^2 < 2\,\mathrm{GeV}^2$) as well as in diffractive DIS ($4 < Q^2 < 80\,\mathrm{GeV}^2$) in the kinematic range of $0.01 < x_{I\!P} < 0.024$ [5]. The leading final state proton is tagged in the H1 Very Forward Proton Spectrometer (VFPS) 220 m away from the interaction point, thus providing a complementary experimental method to previous analyses in PHP and DIS, which were based on the LRG method. The DIS dijet data are found to be well described by NLO predictions using DPDFs. In PHP, NLO predictions convoluted with DPDFs and photon PDFs overestimate the measured total cross sections, as shown in figure 5. However, the shapes of the investigated differential cross sections are described within the experimental and theoretical uncertainties. A detailed study of cross section ratios and double-ratios to NLO predictions or parton-shower improved leading-order MC predictions, where one profits from cancellations of uncertainties, confirms the previous H1 measurements based on the LRG method, while now possible contributions from proton-dissociative processes alone are excluded as an explanation for the observed suppression.

2.6 Measurement and combination of D^* cross sections

The H1 and ZEUS collaborations have combined their measurements of the production of $D^{*\pm}$ mesons in NC DIS in the range $5 < Q^2 < 1000\,\mathrm{GeV}^2$ and $0.02 < y < 0.7$ into a common dataset[6]. This effort yields measurements as function of the transverse momentum, $p_T(D^*)$ (see fig. 6), the pseudorapidity and inelasticity of the of the D^* meson, as well as of Q^2 and y, with significantly reduced experimental uncertainties compared to a single dataset, since the measurements benefit from increased statistical precision as well as from the uncorrelated systematic uncertainties of the two experiments. The combination exhibits that the individual datasets are consistent and the data are found to be reasonably well described by predictions in NLO QCD, while the combined data yields a much higher precision than the NLO predictions. The combination is further extended to data taken during the HERA-I period which extends the kinematic range down to $Q^2 > 1.5\mathrm{GeV}^2$ and the double-differential cross sections obtained as function of Q^2 and y are also well described by NLO predictions.

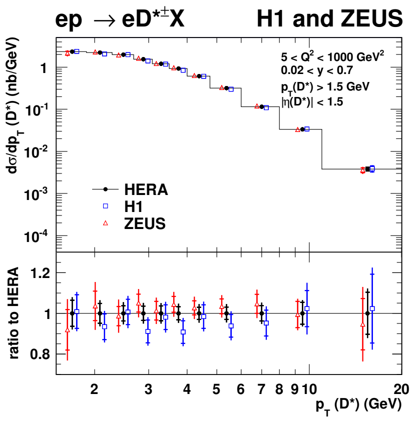

Figure 6 – Differential D^* production cross section as function of the transverse momentum of the D^* meson, $p_T(D^*)$. Data from the H1 and ZEUS experiments are shown together with the combined D^* production cross section.

3 Summary

Several new results on measurements of the hadronic final state in $e^{\pm}p$ collisions from HERA have been presented. In general good agreement between standard model expectations and data is observed, while the experimental uncertainties of the analyses presented here are often smaller than uncertainties on the predictions. Though, dijet production in diffractive photoproduction is not satisfactorily described by NLO predictions. The study of exclusive dijets in diffractive DIS sheds new light on the production principle of diffractive events. The H1 multijet measurements yields the most precise extraction of the strong coupling constant from jet cross sections reported so far.

References

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