Hard QCD and Hadronic Final State at HERA

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Abstract. The production of inclusive jets, dijets and trijets was investigated with the high statistics HERA II DIS data. The H1 experiment has determined the corresponding cross sections with improved experimental precision and sophisticated method of unfolding, compared to previous measurements. The results were compared with NLO QCD and NNLO QCD calculations for the first time. Signals of QCD instanton-induced processes were searched for in neutral current deep-inelastic scattering with high momentum transfer Q^2 by H1 collaboration. Compared to earlier publications, the limits were improved by an order of magnitude. A search for a narrow baryonic state in the pK_S^0 and $\bar{p}K_S^0$ system has been performed with the ZEUS detector. Measurements with the ZEUS data in DIS of isolated photons were reported, including studies of kinematic variables sensitive to the event dynamics. The measurements were compared to MC models and to theoretical calculations based on k_t factorisation QCD approach.

INTRODUCTION

The HERA collider was an ep collider with centre-of-mass energy of 319 GeV with two multipurpose experiments, H1 and ZEUS. Both experiments recorded in the years 1992-2007 data with an integrated luminosity of about 0.5 pb^{-1}. The HERA experiments provide important precision measurements of QCD, due to their unique initial state with only one hadron involved. Several years after data taking, both experiments have successively refined their analysis techniques and now have achieved the final precision of their data.

MULTIJETS

Jet production in neutral current (NC) ep Deep-Inelastic Scattering (DIS) is an important process to study the strong interaction and its theoretical description by Quantum Chromodynamics (QCD). In contrast to inclusive DIS process jet production allows for a direct measurement of strong coupling α_s in the Breit frame of reference, where the virtual boson collides head on with a parton from the proton and the Born level contribution to DIS can not generate transverse momentum. Significant transverse momentum P_T in this frame is produced at leading order (LO) in the strong coupling α_s by the boson-gluon fusion and the QCD Compton processes. A new predictions at next-to-next-to-leading order in the strong α_s coupling are now available for inclusive jet and dijet production [2]. These new theoretical developments together with more precise measurements will enable to use DIS jet cross sections for precise studies of QCD.

New double-differential measurements of inclusive jet, dijet and trijet cross sections were provided by H1 collaboration [1] together with these jet cross sections normalised to the inclusive NC DIS cross section of the respective Q^2 -range (normalised jet cross sections). Inclusive jets were measured in the range $4.5 < P_T^{jet} < 50$ GeV. Dijet cross sections were measured as a function of the average transverse momentum of the two jets with the highest P_T^{jet} in an event and trijet cross sections as an average of three jets with the highest P_T^{jet} in an event. Normalised jets cross sections are determined in the identical phase space. The results were compared to NLO QCD and NNLO QCD calculations corrected for hadronisation effects. The ratio of the normalised data double-differential dijet cross sections as functions of Q^2 and $< P_T >_2$ to NLO predictions is presented in Figure 1 together with the predictions in NNLO.

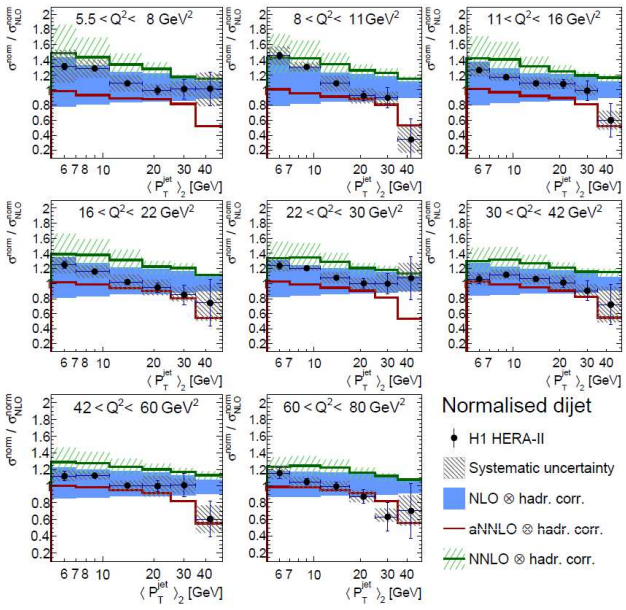

FIGURE 1. Ratio of normalised dijet cross sections to NLO predictions and ratio of the NNLO to the NLO predictions as a function of Q^2 and $< P_T >_2$ [1].

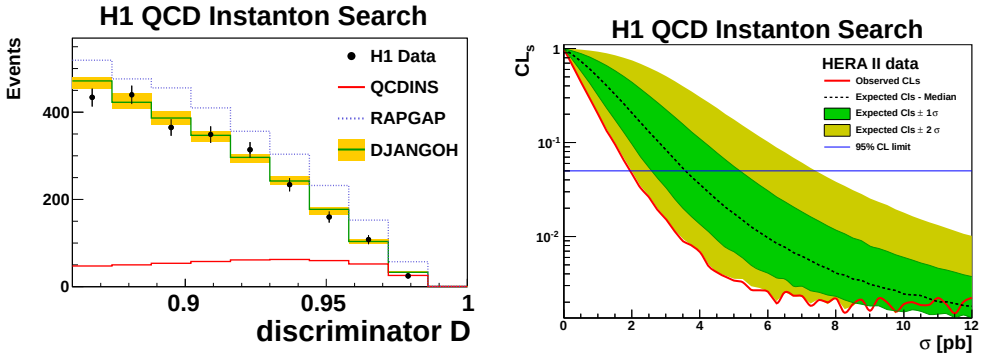

FIGURE 2. a) Distribution of the discriminator D in the signal region $D > 0.86$. Data, the RAPGAP and DJANGOH DIS background predictions and the QCDINS signal prediction are shown. The error band, shown only for DJANGOH, represents the MC statistical and systematic uncertainties added in quadrature. b) Observed CLs as a function of the instanton cross section. The 95% CL limit is indicated by a horizontal line.

Both aNNLO [3] and NNLO theoretical predictions improve significantly the description of the data. The strong coupling $\alpha_s(M_Z) = 0.1175(5)_{exp}(^{+54}_{-47})_{th}$ determined from a fit of NLO predictions to the normalised jet cross sections is consistent with other world measurements and demonstrates the high experimental precision of the data.

INSTANTONS

In QCD instantons are non-perturbative fluctuations of the gluon field. They can be interpreted as tunnelling transitions between topologically different vacua. Deep-inelastic scattering in ep interactions offers a unique opportunity to discover a class of hard processes induced by QCD instantons. The instanton cross sections is calculable within instanton-perturbation theory and was expected to be in HERA kinematics, sizable – 10 pb.

The new analysis was performed using the full ep collision data set taken in the years 2003-2007 by the H1

experiment with the total integrated luminosity of 351 pb^{-1} [4]. Two Monte Carlo models, RAPGAP and DJANGOH, were used to estimate the background from the standard NC DIS processes. The instanton- induced processes were modelled by the program QCDINS. The events were selected to cover the phase space region defined by $0.2 < y < 0.7$, $x > 10^{-3}$ and $150 < Q^2 < 15000$ GeV^2. Observables used to discriminate the instanton induced contribution from the standard DIS processes are based on the hadronic final state (HFS). In order to extract the expected instanton signal a multivariate data analysis technique was used. The observables have been chosen which provide the best signal to background separation. The distribution of the discriminator D is shown in Figure 2a). The simulated background events are mainly concentrated at low discriminator values while the simulated instanton signal events are peaked at the large values. It is seen from Figure 2a) that no evidence for QCD instanton-induced processes was observed, the region of large discrimintor values is very well described by RAPGAP. The data were also used to set the exclusion limit, as shown in Figure 2b). In the kinematic region defined by the theory cut-off parameters an upper limit of 2 pb on the instanton cross section at 95% CL was determined which is in contradiction with theoretically predicted value.

PENTAQUARKS

The ZEUS experiment reported in 2004 evidence for a peak structure in the pK_S^0 (and $\bar{p}K_S^0$) mass system in deep inelastic scattering (DIS) data, consistent with a Θ^+ resonance corresponding to five-quarks configuration ($uudd\bar{s}$) [5]. The H1 collaboration presented mass distributions in a similar kinematic region [6], but did not find any structure and presented an upper limit. To clarify the production of strange pentaquarks in DIS, a search for the Θ^+ resonance in the HERA II data with an integrated luminosity of 358 pb^{-1} has been performed [7].

In Figure 3, the pK_S^0 ($\bar{p}K_S^0$) invariant-mass distribution is shown in the mass range from 1.4 to 1.9 GeV. The distribution contains 3107 pK_S^0 candidates and 2833 $\bar{p}K_S^0$ candidates. The pion contamination in the proton candidates was estimated to be less than 10%. The dashed line represents the Θ^+ signal as would be observed if it had the same strength as reported in the ZEUS HERA I result. It is evident, that HERA I peak at 1.52 GeV was not confirmed in this analysis. Upper limits on the production cross section of such a resonance have been set as a function of the pK^0 mass in [7].

PROMPT PHOTONS

The production of isolated photons in a 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. On the other hand, non- prompt photons, i.e. photons originating from decays of resonances such as are described using fragmentation functions represent a sizable background to the studied process.

Photons which are produced promptly in the collision before quarks and gluons form hadrons are either emitted from a quark as a part of hadron process (QQ–photons in Figure 4) or are radiated from an incoming or outgoing lepton (LL–photons in Figure 4).

The mesurement is based on DIS data sample corresponding to an integrated luminosity of 374 pb^{-1} taken during the years 2004–2007 with the ZEUS detector. This measurement follows earlier analyses of isolated photons in photoproduction by the ZEUS and H1 collaborations, as well as in DIS(see e.g. [8]). To extract signal from background

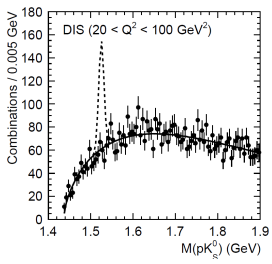

FIGURE 3. The pK_S^0 ($\bar{p}K_S^0$) distribution for the DIS sample, the solid line is the result of a fit using the background function. The dashed line represents the signal corresponding to the ZEUS HERA I result.

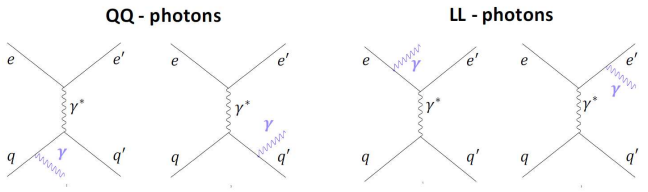

FIGURE 4. a) QQ - photons: emitted from a quark as part of hard process, b) LL - photons: radiated from an incoming or outgoing lepton.

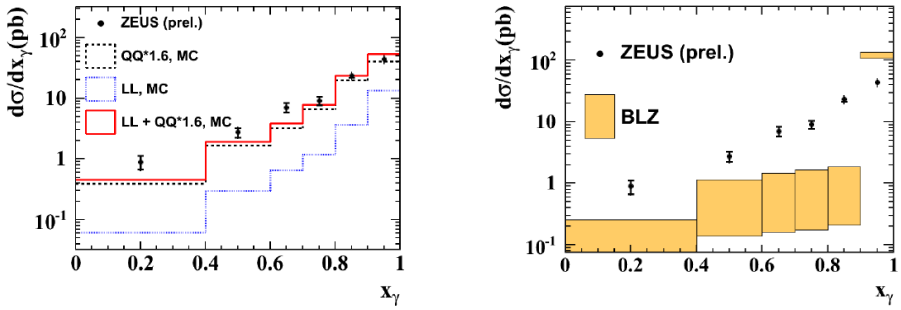

FIGURE 5. Differential cross section in x_γ (fraction of virtual photons momentum in hard subprocess) compared to a) weigthed LO Monte Carlos b) BLZ theoretical calculations. The theoretical uncertainties are indicated by the width of shaded area.

the energy-weighted mean width of the electromagnetic cluster in calorimeter relative to its centroid was used. The number of isolated-photon events in the data was determined by a χ^2 fit in each measured cross-section bin. The differential cross sections in dependence on x_γ (fraction of virtual photons momentum in hard subprocess) are compared to results of two Monte Carlos simulating QQ and LL processes, PYTHIA and DJANGO & HERACLES in Figure 5a). PYTHIA cross sections are reweigthed by a factor 1.6 to describe the normalisation of the data. It is seen that shape of x_γ distribution is decribed satisfactorily. In Figure 5b) the same experimental distribution is compared to a predictions of the model BLZ [9], which uses k_t –factorization QCD approach. In this model the photon radiation from the quarks as from the lepton is taken into account. It is seen that theory is systematically below the data and also a shape of x_γ is not well described.

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