Forward π° Production in DIS at HERA

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Production of neutral pions in deep-inelastic positron-proton scattering at small Bjorken-x measured in the H1 detector at HERA is studied. High energy and transverse momentum π° are selected in the region of small polar angles w.r.t the incident proton direction, called forward region. The π° differential cross sections are measured as a funtcion of the kinematical variables Q^2 and Bjorken-x and as a function of the transverse momentum $p^\star_{T,\pi}$ and pseudorapidity η_π of π°-mesons. QCD based Monte Carlo predictions and modified LO BFKL analytical calculations are compared to the data.

1. Introduction

The positron-proton collider HERA has extended the available kinematic space for Deep-Inelastic Scattering(DIS) to regions of large values of the four-momentum transfer $Q^2\,(\leq 10^5)$ and small Bjorken-$x(x \approx 10^{-5})$. Variety of measured processes has allowed for detailed tests on the physics of perturbative Quantum Chromodynamics(QCD). In particular studies at low x could reveal novel features of parton dynamics. In Fig.1 a diagram visualizing the parton evolution in QCD of a DIS event is shown. An initial parton from the proton before it interacts with a virtual photon develops a QCD cascade. Subsequent partons are emitted along the ladder with the fraction of the proton momentum x_i and the transverse momentum k_{Ti}. In distinct regions of Q^2 and x space we have two different modes of QCD parton evolution. At high Q^2 the initial state radiation is described by conventional DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)[1] evolution equations, where at the lowest order the leading $\alpha_s \ln(Q^2/Q_\circ^2)$ contributions are resummed. In this scheme a space-like chain of subsequent gluon emissions is characterized by a strong ordering in transverse momenta $k^2_{T,i} \ll k^2_{T,i+1} \ll \cdots \ll Q^2$. However, at low x but still moderate Q^2 the DGLAP approximation ceases to be valid and in the limit of large positron-proton center of mass energy a second large variable $1/x$ should become important. Resummation of the leading $\alpha_s \ln(1/x)$ terms leads to BFKL(Balitsky-Fadin-Kuraev-Lipatov) [2] evolution equation that takes into account diagrams with strongly ordered fractional momenta $x_i \gg x_{i+1} \gg \cdots \gg x$. No ordering on transverse momenta k_T of emitted gluons is imposed.

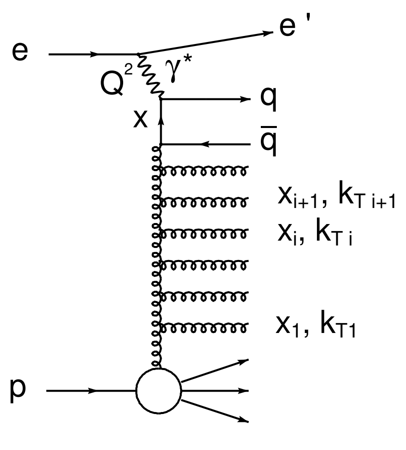

Figure 1. The parton evolution in QCD in the ladder approximation.

Different measurements of DIS at low x have been performed to study the QCD parton dynamics in this region. ZEUS [3] and H1 [4] have measured the proton structure function F_2 in a wide range of x and Q^2. Standard DGLAP QCD evolution

gives a good description of the data over many orders of magnitude in both variables. The strong rise of F_2 with decreasing x can be satisfactory described by NLO DGLAP approach as well as BFKL effects. The observable F_2 is too inclusive to distinguish between different alternatives. The study of DIS events accompanied by an energetic jet of high transverse momentum close to the proton remnant [5] and associate process of DIS with a single forward particle [6] have been advocated as especially sensitive to the QCD dynamics at low x. For these processes soft non-perturbative hadronization effects are expected to be minimized. New results from H1 [7] and ZEUS [8] experiments on forward jet production have recently been published. However, this measurement has ambiguity derived from jet finding algorithm and in addition the detection of a jet in the very forward region is difficult experimentally as here we cope with high particle and energy densities. Production of DIS events with a single forward particle is a more refined version of the forward jet production. In this case a forward jet is identified by its single energetic decay product. In analogy to forward jet analysis selection of a single particle with high transverse momentum suppresses the DGLAP evolution and the choice of the fractional momentum greater than Bjorken-x enhances the phase space for BFKL effects. In addition the advantage of single particle detection is the possibility to reach smaller angles than for jets. However, the rate of the process is suppressed in comparison to forward jet production and fragmentation effects are expected to be more significant. The neutral pion is the most suitable particle to be measured at high transverse momentum in the forward region in the H1 detector.
The first analysis of single particle spectra in Bjorken-x for charged particles and π°-mesons produced in the forward region was made [7]. In this paper we present new results from the H1 experiment [9] on high transverse momentum forward π° production in DIS with higher statisticsand in the extended phase space region.

2. Experimental setup and data selection

The data used for this analysis were collected in 1996 with the H1 detector at HERA, which collides beams of 27.5 GeV positrons and 820 GeV protons, and correspond to an integrated luminosity of 5.8 pb^{-1}. A detailed description of the H1 detector can be found in [10]. DIS events are selected by identification of scattered positrons in the H1 backward lead/scintillating fiber calorimeter(SPACAL). Its energy resolution for electrons is $\sigma_E/E \approx 0.075/\sqrt{E}$. Measurement of the energy and the polar angle of the scattered positron allows for the determination of the DIS kinematic variables Q^2 and y. The analysis is restricted to the range $0.1 < y < 0.6$ and $2.0 < Q^2 < 70.0$ GeV^2, and Bjorken-x extends over two orders of magnitude down to $x \approx 10^{-5}$. The photoproduction background is reduced to a negligible level.
The π°-mesons are measured in the finely segmented liquid argon(LAr) sampling calorimeter covering the polar angle range $4^\circ < \Theta < 154^\circ$ with full azimuthal coverage, where Θ is obtained with respect to the proton beam direction. The LAr calorimeter consists of an electromagnetic section with lead absorbers, that provides an energy resolution of $\sigma_E/E \approx 0.12/\sqrt{E}$, and a hadronic section with steel absorbers. Test beam measurements show an energy resolution of $\sigma_E/E \approx 0.50/\sqrt{E}$ for charged pions. The total depth of both calorimeters varies between 4.5 and 8 interaction length. Especially in the forward region the LAr calorimeter has very fine granularity; the electromagnetic section has four longitudinal segments and a cell size is small (3.5 x 3.5 cm^2). The absolute energy scales are known to 3% and 4% for electromagnetic and hadronic section respectively.
The signals from tracking detectors inside the calorimeter system are used for reconstructing the position of the interaction vertex. The trigger used in the collection of the data is based on the signal from the SPACAL calorimeter validated by a well defined primary event vertex and the track activity in the central tracker.

3. Identification of forward π° -mesons

The π° -mesons are measured via the dominant decay channel $\pi^\circ \to 2\gamma$ using calorimetric information only. The π° candidates are selected in the region $5^\circ < \Theta_\pi < 25^\circ$, where Θ_π is the polar angle of the produced π° w.r.t the incoming proton direction. Candidates are required to have an energy $x_\pi = E_\pi/E_p > 0.01$, where E_p is the proton beam energy. The cut on the minimum transverse momentum of π° -meson, $p^\star_{T,\pi}$, defined in the center of mass system of the virtual photon and the proton in order to separate from the effects of the event kinematics, is set to 2.5 GeV. At high π° energies requested here, the two photons from the decay cannot be separated in the LAr calorimeter and their energy deposits are reconstructed as one calorimetric cluster. Photon induced showers are selected by a very detailed analysis of longitudinal and transverse shower development in the LAr calorimeter. The selection criteria resulting from the simulation of calorimetric response are based on the compact nature of electromagnetic showers. Following conditions have been applied to search for π° cluster candidates [9]:

- more than 90% of the cluster energy deposited in the electromagnetic part of the LAr calorimeter.
- the fraction of the cluster energy in the shower core consisting of the most energetic group of adjacent cells, including the hottest cell, must exceed 50%.
- the lateral spread of the shower quantified in terms of lateral shower moments calculated relative to the shower's principal axis is required to be less than 4.0 cm.
- longitudinal extension of the shower defined as the difference of the fraction of the energy deposited in the fourth longitudinal layer from that in the second layer as seen from the interaction point is greater than 0.4.

The main experimental challenge of the identification of π° -mesons in this analysis is the large particle density and thus big energy overlaps in the forward region at HERA. From studies based on Monte Carlo events using a detailed simulation of the H1 detector, the efficiency for finding π° -mesons after all selection cuts, in the kinematic range $5^\circ < \Theta_\pi < 25^\circ$, $x_\pi = E_\pi/E_p > 0.01$ and $p^\star_{T,\pi} > 2.5$ GeV, is above 45%. The overlap of a π° induced cluster with another hadron shower is mainly responsible for losses of π° detection efficiency. The purity of the selected π° -meson sample is at the level of 70%, with impurities from misidentified hadrons and from secondary interaction of charged hadrons with passive material in the detector.
The verification of the π° detection method has been done by applying the same cuts to select electromagnetic clusters in the case of lowered π° energy, when two decay photons can be separated. A clear π° mass peak can be reconstructed that is well described by the H1 detector simulation. In the previous H1 analysis [7] the π° cross section and the equivalent from izospin symmetry cross section of $(\pi^+ + \pi^-)/2$, resulting from charged particle measurements in the same phase space, were compared. Both cross sections were found to agree well.

4. Results

Inclusive forward π° cross-sections have been determined as a function of Q^2 , and as a function of x ,η_π and $p^\star_{T,\pi}$ in three regions of Q^2 for $p^\star_{T,\pi} > 2.5$ GeV.
All cross sections are corrected for detector effects, π° detection efficiencies and for influence of QED radiation by a bin-by-bin unfolding procedure. The typical systematic uncertainty is 15-25 %, while a statistical error is of about 10 %.
Experimental results are compared to Monte Carlo models based on the DGLAP parton evolution. LEPTO6.5 [11] incorporates first order QCD matrix elements complemented by LO DGLAP parton showers. The Monte Carlo RAPGAP2.06 [12] is also based on the DGLAP formalism but in addition to the standard direct process includes contributions from the resolved photon component. We also compare the data with recent theoretical predictions provided by modified LO BFKL calculations [13] convoluted with π°

fragmentation functions. In this approach "consistency constraints" are applied to restrict the phase space of emitted gluons to the kinematically allowed region. This formalism allows to implement into BFKL equation the dominant part of higher order effects and to resum them to all orders.

The cross sections as a function of x in three regions of Q^2 are shown in Fig. 2. A strong rise toward small x is satisfactory described by modified LO BFKL calculations, only at the lowest value of Q^2 the predictions are slightly below the data. The DGLAP predictions as implemented in LEPTO6.5 are below the data, however as expected the deviations are smaller for higher x and Q^2. An improved description of the data is obtained by including additional resolved photon contributions as in RAPGAP2.06.

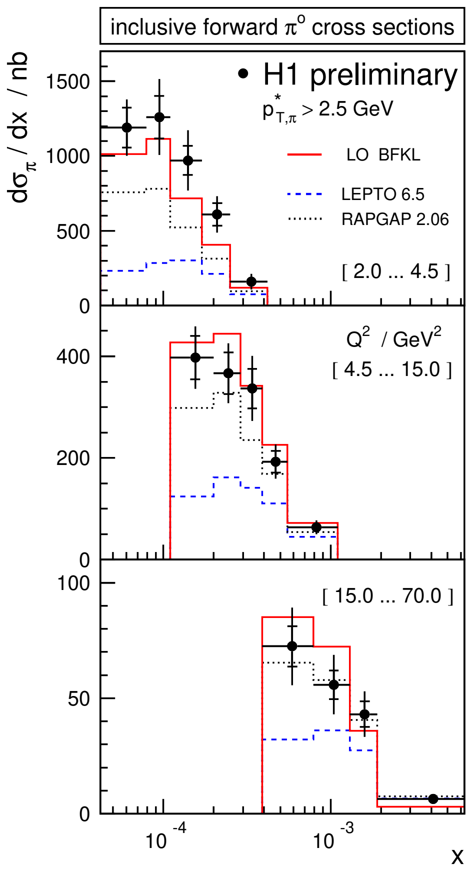

Figure 2. Inclusive π°-meson production cross-section as a function of Bjorken-x in three regions of Q^2.

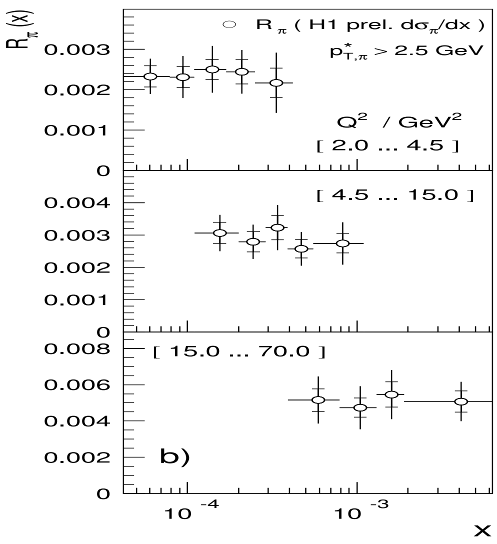

Figure 3. The rate of π°-meson production in DIS as a function of Bjorken-x in three regions of Q^2.

Fig. 3 shows the rate of π°-meson production in DIS as a function of x obtained by dividing the π° measured cross section by the inclusive ep cross section in corresponding bins of x and Q^2. From Fig. 2 and Fig. 3 it is interesting to note that the rise of the π° cross section shows the same rise towards low x as the inclusive ep cross section. F_2 is satisfactory described by NLO QCD DGLAP fit. However, as can be seen from Fig. 2, when one tries the parton distribution functions as extracted with DGLAP and use LO matrix elements and LO DGLAP parton showers, the π° cross section cannot be described.

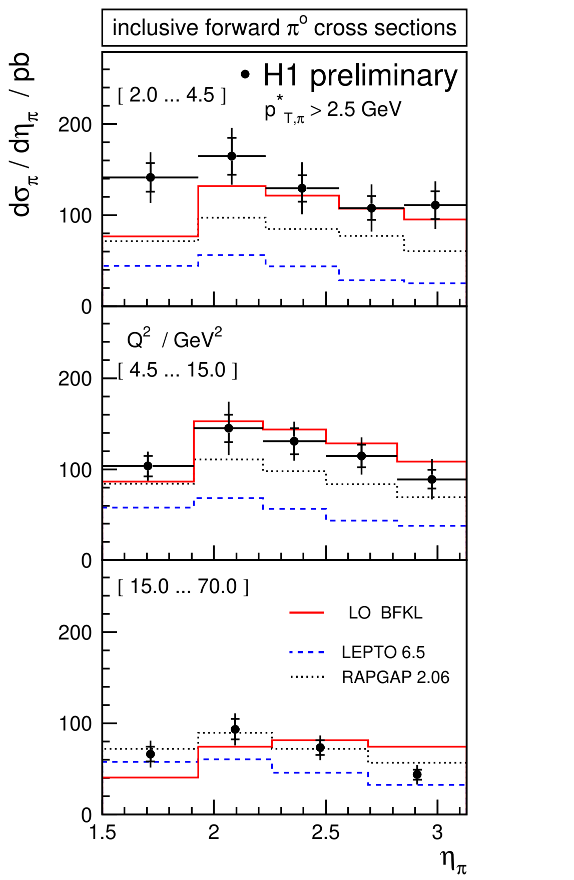

Figure 4. Inclusive π°-meson production cross-sections as a function of η_π in three regions of Q^2.

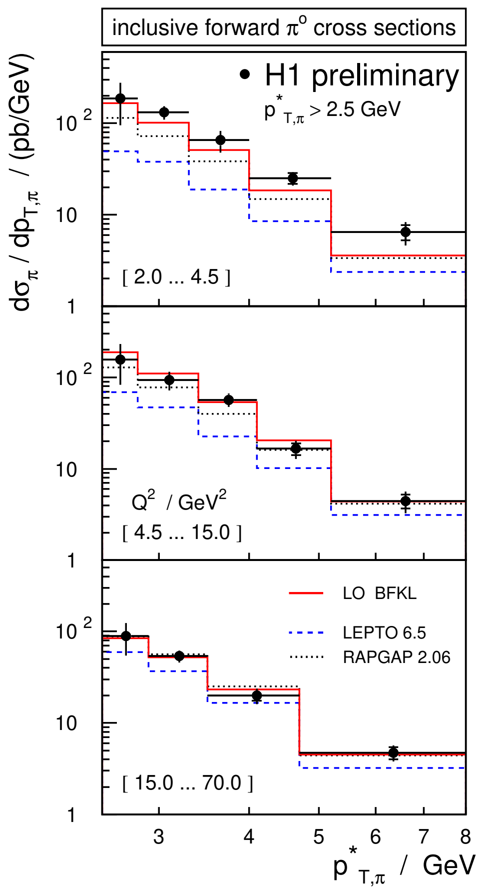

Figure 5. Inclusive π°meson production cross-sections as a function of $p^\star_{T,\pi}$ in three regions of Q^2.

Fig. 4 and Fig. 5 show $d\sigma_\pi/d\eta_\pi$ and $d\sigma_\pi/dp^\star_{T,\pi}$ respectively. The spectra are similar for all Q^2 regions and the best description of the data is again provided by modified LO BFKL calculations. Discrepancies between predictions of different models are smaller at higher Q^2. Fig. 6 shows the inclusive π° cross section as a function of Q^2 that falls steeply with increasing Q^2. Differential cross sections $d\sigma_\pi/dQ^2$ and $d\sigma_\pi/dx$ have also been measured for the higher threshold of the π°-meson transverse momentum, $p^\star_{T,\pi} > 3.5$ GeV. No significant change in the shape of the distributions is observed, but the cross sections are reduced by about a factor of three.

5. Conclusions

Differential cross sections of forward π° production in deep-inelastic positron-proton scattering have been measured as a function of x, Q^2, $p^\star_{T,\pi}$ and η_π. The DIS phase space covers the region $2.0 < Q^2 < 70.0$ GeV^2 and extends over two orders of magnitude in x down to $x \approx 10^{-5}$. The measurement provides test of QCD evolution at

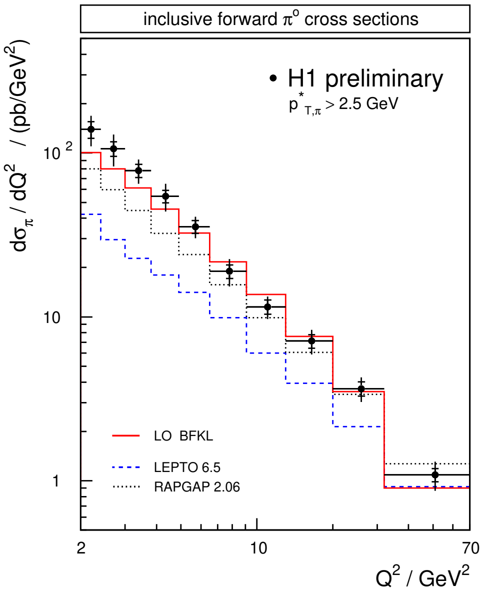

Figure 6. Inclusive π°-meson production cross-section as a function of Q^2.

low x. Modified LO BFKL calculations gives satisfactory description of all measured cross sections. Models based on LO DGLAP formalism are below the data. An improved description is obtained by inclusion of contributions from resolved photon processes.

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