Printed ISSN 1330–0016
Online ISSN 1333–9133
CD ISSN 1333–8390
CODEN FIZBE7

FRAGMENTATION AND PARTICLE PRODUCTION IN DEEP INELASTIC SCATTERING AND PHOTOPRODUCTION

TERESA TYMIENIECKA
on behalf of the H1 and ZEUS Collaborations

University of Warsaw, Warsaw, Poland; E-mail address: teresa@fuw.edu.pl

Received 23 October 2007; Accepted 20 February 2008
Online 20 June 2008

Charged particle production has been studied in deep inelastic scattering with the H1 and ZEUS detectors at HERA. The evolution of scaled momentum distribution with respect to Q^2 is shown in the current fragmentation region of the Breit frame in the range from 10 to 40000 GeV^2. Characteristics of the produced particle are presented for (anti)deuteron, (anti)protons, kaon pair production as well as (anti)lambda and K^0.

PACS numbers: 13.87Fh UDC 539.125
Keywords: HERA, fragmentation functions, strange particle production

1. Introduction

This short review of some recent measurements done by the H1 and ZEUS experiments is dedicated to fragmentation [1, 2] and hadron production [3, 4, 5] in *ep* scattering at a centre-of-mass energy of about 300 GeV. Both detectors are situated at the HERA collider in Hamburg, DESY. The main aim of these experiments is investigation of the proton structure, however some specific hadrons are also measured. These measurements allow the mechanism of parton conversion into hadrons as well as hadron characteristics to be studied.

Two quantities describe the kinematics of hadron production: the invariant mass of the hadron system W and the virtuality Q^2 of the exchanged boson, defined as the transverse four-momentum between the incoming electron and proton. If the virtuality $Q^2 \approx 0$, the exchanged boson is nearly real photon and the process is called the photoproduction. If $Q^2 > 1$ GeV^2 the process is called the deep inelastic scattering (DIS). If the exchanged boson is neutral (γ, Z^0) the process is governed by the neutral current (NC). All data presented in this paper are due to the NC exchange.

The best way to describe particle production is to look from the point of view of the exchanged boson colliding with the incoming proton. In their centre of mass, half of the energy $(W/2)$ is carried out by the particles which absorb the boson and the other half is carried by the proton remnant. To the first approximation, one would expect the particle production in the proton remnant to be similar to particle production in pp collisions. Some fraction of particles which have absorbed the exchanged boson are expected to have similar features to those observed in one hemisphere of e^+e^- annihilation. To select them, the simplest way is to use the Breit frame [6]. In the Breit frame, the exchanged boson of $Q/2$ energy is absorbed by the scattered quark which converts into particles in the region called the current region of the Breit frame. The region in between the current region and the proton remnant is called the central region. Thus, depending on the rapidity of the emitted hadron, its features can be similar either to those produced in e^+e^- or pp or unique for ep scattering.

The current region of the Breit frame is populated mainly by hadrons coming from the zero-order of α_s simple quark scattering $\gamma q \to q$ and the first-order α_s QCD Comptons $\gamma q \to gq$. The other first-order α_s process is the boson-gluon fusion (BGF) $\gamma g \to q\bar{q}$, with hadrons populating the edge of the current and central region with the rate depending on Q^2. This process, as well as QCD Comptons from the initial state, do not contribute to the hadron production in e^+e^- and are the main source of differences between the hadron features in e^+e^- and ep scattering.

Fragmentation features are presented here in the form of the scaled momentum distributions measured in the current region of the Breit frame [1, 2]. Then the size of the hadron emitting source is discussed deduced from Bose-Einstein correlations and from the production yields of (anti)deuterons measured in DIS [3, 4] and in photoproduction [7]. For strange particle production [5], only the baryon-to-meson ratios for resolved photons are shown with the significant discrepancies from predictions. The predictions of ARIADNE 4.12 [8] and LEPTO-MEPS 6.5.1 [9] are used to describe the DIS process. The photoproduction data are compared with PYTHIA 6 [10]. For these event generators, hadronisation is performed by the Lund string model [11].

2. *Fragmentation*

A spectrum of produced hadrons can be calculated from a convolution of three functions: parton density functions (PDFs), hard partonic cross sections and fragmentation functions (FFs). Whereas the partonic cross sections are provided by theorists, now in NLO, PDF and FF are deduced from experimental data according to the orders of the partonic cross sections. Using the PDF from elsewhere and the calculated partonic cross sections, the measured spectra of hadrons can be used to test quark and gluon fragmentation universality.

The fragmentation function represents the probability for a parton to fragment into a particular hadron carrying a fraction of the parton energy. In such a way, fragmentation functions incorporate the long distance, non-perturbative physics of the hadronisation process. Like structure functions, the FF cannot be calculated in perturbative QCD, but can be evolved from a starting distribution at a defined energy scale using the DGLAP evolution [12] equations. The fragmentation functions are expected to be universal and are nearly the same in ep scattering and e^+e^- annihilation.

The fragmentation features are exhibited in the scaled momentum distribution, x_p, where $x_p = 2p^{\mathrm{Breit}}/Q$ is the momentum of a charged particle measured in the current region of the Breit frame, p^{Breit}, scaled by the maximum possible momentum ($Q/2$ for ep and E^*_{beam} for e^+e^-). The spectra, softer with increasing Q^2, are presented in Fig. 1 as functions of $\ln(1/x_p)$ in Q^2 intervals. The main features of

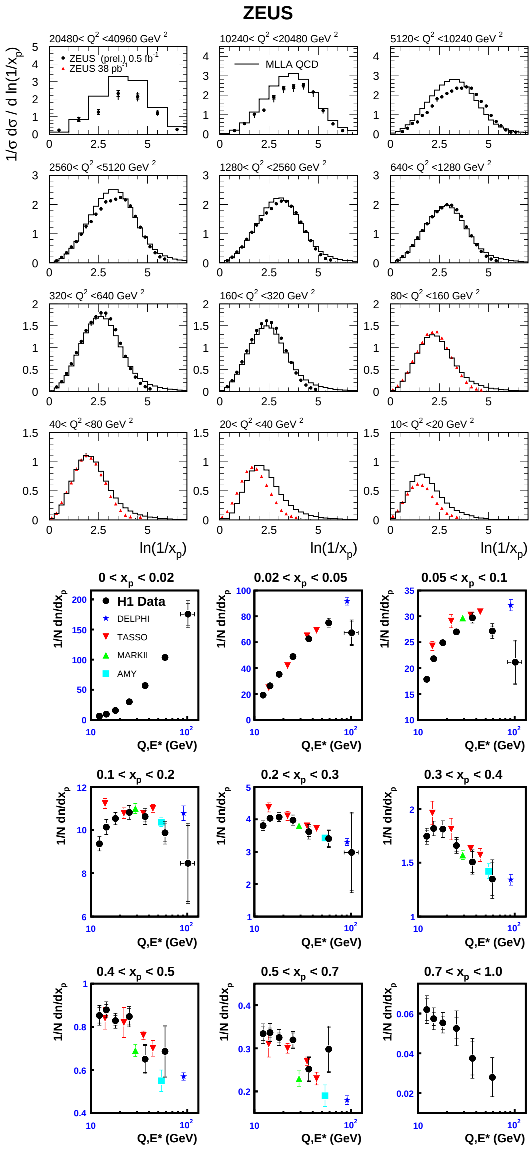

Fig. 1. (top) The charged particle distributions shown as the black dots, as a function of $\ln(1/x_p)$ for different (x, Q^2) bins; the full line represents the MLLA+LPHD predictions; and (bottom) as a function of Q^2 in x_p bins; results from similar measurements from e^+e^- are overlaid.

the data are reproduced by the predictions of ARIADNE and LEPTO (if the soft colour interaction model is switched off), however, failing in the normalisation at the highest Q^2 values (see Refs. [1, 2]). Modified leading log approximation (MLLA) describes basic properties of particle production by multi-gluon emission at leading order, including colour coherence and gluon interference phenomena. The MLLA calculations based on the hypothesis of local parton hadron duality (LPHD) [13], and with parameters fitted to reproduce the e^+e^- data, are compared to the x_p spectra in Fig. 1. The analytical MLLA+LPHD predictions describe the data at the medium Q^2, but not at the low and the highest Q^2. This can be partially explained by a significant migration of particles from (or to) the current region of the Breit frame due to the relative contribution of BGF processes. As Q^2 increases, the peaks are shifted more than expected towards the higher values of $\ln(1/x_p)$. As the energy scale Q increases, the coupling constant α_s decreases and amount of the soft gluon radiation increases. This leads to a fast increase of particles with small fractional momentum x_p. This scaling violation is illustrated in Fig. 1 as a function of Q^2 in the x_p intervals.

Figure 1 presents also a comparison of the ep data with the e^+e^- data. The main features are the same, providing a rough demonstration of the fragmentation universality, except for the highest Q^2 values at the lower x_p ($0.02 < x_p < 0.1$) with the DELPHI measurements above the ep data and the lower Q^2 value at the medium x_p ($0.1 < x_p < 0.2$) with the TASSO point also above the ep data. It might be explained by processes existing in the ep scattering but not in the e^+e^- annihilation. Comparison between the data and the recent parametrisations of the FF [14] fitted to reproduce the e^+e^- data is discussed elsewhere [15]. None of the FFs describes the strong scaling violations as seen in the data.

3. *Particle production*

The recent measurements provide information on K_s^0, Λ, $\bar{\Lambda}$, d, $\bar{d}$, p, $\bar{p}$ and KK pairs [3, 5, 7, 4]. All measurements are done using HERA data from 1996-2000 with relatively small amount of inactive material in the detectors. Background reduction is done by using the distance of closest approach criterium and identification of hadrons through a combination of their ionisation energy loss per unit length with their momenta. The hadrons are taken with the transverse momentum $p_T^{\mathrm{LAB}} >$ 0.15 MeV and pseudorapidity $|\eta^{\mathrm{LAB}}| < 1.75$, which for DIS events is equivalent to the particle emission in the current and central regions of the Breit frame. For photoproduction, the interactions with high transverse energy are considered.

A (anti)deuteron is a loosely bound state of two (anti)nucleons. According to the coalescence model [16], the cross section, σ_A, for the formation of an object with A nucleons with total energy E_A and momentum P_A, is the product of single-nucleon cross sections in the same reaction, σ_N, with energy E_N and momentum, $p_N = P_A/A$,

$$\frac{E_A}{\sigma_{\mathrm{tot}}}\,\frac{\mathrm{d}^3\sigma_A}{\mathrm{d}^3P_A} = B_A \left(\frac{E_N}{\sigma_{tot}}\,\frac{\mathrm{d}^3\sigma_N}{\mathrm{d}^3p_N}\right)^A$$

where $\sigma_{\rm tot}$ is the total interaction cross section of the colliding particles and the coefficient B_A is inversely proportional to the volume of the region emitting the object A.

For $Q^2 > 1$ GeV^2, the number of $p(\bar{p})$ is found to be 1.52×10^5 (1.62×10^5), whereas the number of $d(\bar{d})$ is 177 ± 17 (53 ± 7) in the same kinematic region. The different detection efficiencies of negative and positive particles explains the difference between p and $\bar{p}$, but not the difference in the observed numbers of d and $\bar{d}$. None of the d or $\bar{d}$ is detected in the current region of the Breit frame, and only 2.5% of the $p(\bar{p})$ events are observed there, in agreement with the e^+e^- measurements.

The coalescence parameter B_2 is shown as a function of the d and $\bar{d}$ transverse momenta per nucleon p_t/M in Fig. 2. For DIS and photoproduction, the size of the emitting source is similar for $\bar{d}$ and does not depend on their transverse momenta. For d, the measured B_2 is significantly larger than for $\bar{d}$ and larger than observed in heavy-ion collisions or e^+e^- annihilation (Fig. 2).

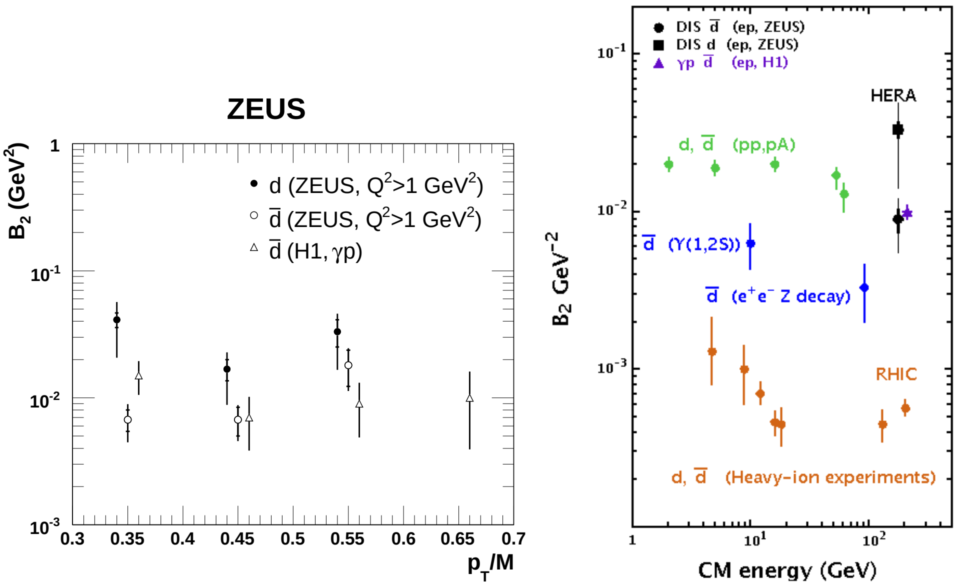

Fig. 2. (Left) The B_2 parameter as a function of transverse momentum per nucleon p_T/M for (anti)deuteron emitted in DIS and photoproduction. For clarity, the points are horizontally shifted. (Right) Comparison of the B_2 values from the existing data on (anti)deuteron production.

The second method which permits determination of the size of the source from which particles originate is based on the Bose-Einstein correlation (BEC) [3]. Bose-Einstein correlations originate from the symmetrization of the two-particle wave function for identical bosons and cause an enhancement of the probability for the boson pair emission with small relative momenta Q_{12}, as shown in Fig. 3. The enhancement depends on the size of the emitting source r. The new data are for pairs of charged $K^{\pm}K^{\pm}$ or neutral $K_s^0 K_s^0$. The values of the parameter r for kaons are presented in Fig. 3 and compared with the values obtained from e^+e^- annihilation at LEP. They agree with values obtained for unidentified charged particles in DIS. Most of kaons originate from this central region.

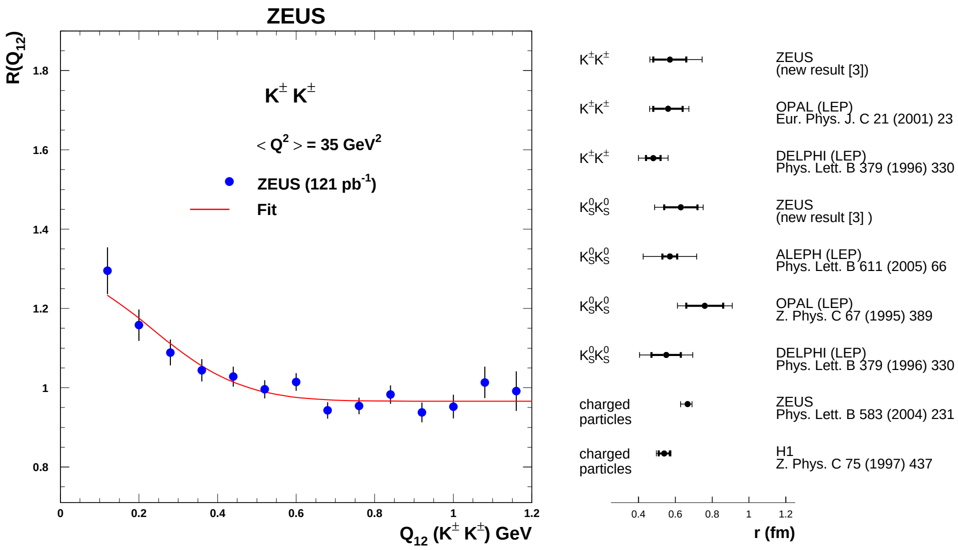

Fig. 3. (Left) The two particle correlation function $R(Q_{12})$ as a function of the relative kaon four-momenta Q_{12} with a fit to Goldhaber's parametrisation giving the size r of the emitting source. (Right) Comparison of DIS and LEP results for r.

Of the many features investigated in the strange-particle production [5], only baryon-to-meson ratios differ significantly from expectations provided by the event generators. The baryon-to-meson ratio is given by $(N(\Lambda) + N(\bar{\Lambda}))/N(K_s^0)$ where $N(\Lambda), N(\bar{\Lambda}), N(K_s^0)$ refer to the number of indicated hadrons. The measured ratios (not shown here) are reasonably well reproduced for DIS and for photoproduction corresponding to direct photon processes $\gamma q(\bar{q}) \to gq(\bar{q})$ in which the photon takes part in the hard scattering as a point-like particle $x_\gamma^{\rm OBS} \approx 1$. The variable $x_\gamma^{\rm OBS}$ is a traditional measure of the photon energy fraction transferred to the dijet system of the most energetic jets [5]. For resolved photons processes in which the photon acts as a source of partons $x_\gamma^{\rm OBS} < 1$ no agreement is found. Thus for them the baryon-to-meson ratios is investigated for a sample split into many particle events, i.e. 'fireball-like' and a few particle events using the fraction of the total transverse energy carried by two jets of the highest transverse energy $(E_T^{\rm jet}/E_T^{\rm total})$. The features of the 'fireball-like' sample $(E_T^{\rm jet}/E_T^{\rm total} > 0.3)$ are not reproduced by PYTHIA (Fig. 4).

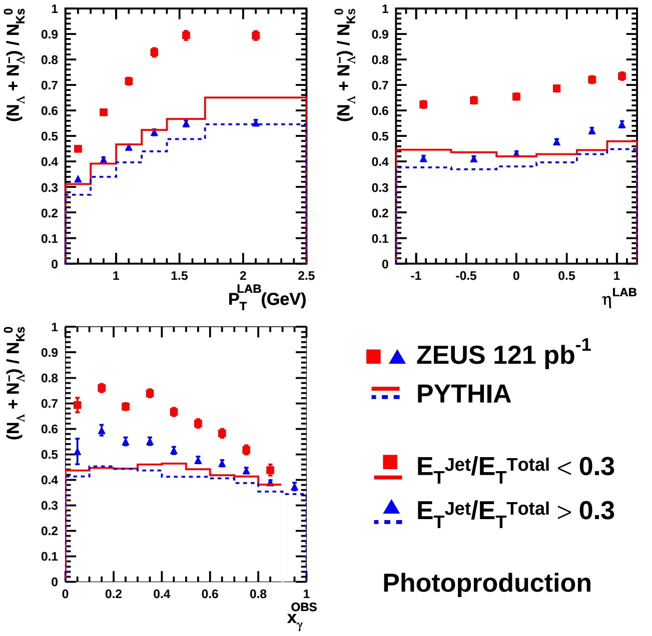

Fig. 4. The baryon-to-meson ratio as a function of the kinematic variables: transverse momentum $P_T^{\rm LAB}$ and pseudorapidity $\eta^{\rm LAB}$ of the strange hadron and $x_\gamma^{\rm OBS}$ (see text) for the fireball-like events $E_T^{\rm jet}/E_T^{\rm total} > 0.3$ (squares) and the others (triangles). The similar predictions from PYTHIA are shown.

4. *Summary and conclusions*

Electron-proton scattering at the HERA energy is a rich source of high precision data for studies of the hadronic final state. The recent measurements of the H1 and ZEUS experiments provide hadron scaled momentum x_p distributions measured in the current region of the Breit frame up to the virtuality Q^2 of 40000 GeV^2, as well as information on the production of $d(\bar{d})$, $p(\bar{p})$, $\Lambda(\bar{\Lambda})$, K_s^0 and kaon pairs. The review is limited to the presentation of some significant discrepancies from predictions.

The x_p distributions support the concept of quark fragmentation universality in ep scattering and e^+e^- annihilation. Some deviations are observed at low and high Q^2 in ep collisions and are partially explained by BGF and higher order QCD processes which do not occur in e^+e^- annihilation. Thus neither the next-to-leading predictions of fragmentation functions nor the MLLA+LPHD calculations based on the e^+e^- data describe the distributions in the entire range of the measured Q^2.

The first observation of d and $\bar{d}$ production in DIS is presented. For the same kinematic region, the rate of d is three times larger than for $\bar{d}$. The relative $\bar{d}$ cross section (or the B_2 parameter) is the same for DIS and photoproduction. In terms of the coalescence model, $d(\bar{d})$ come from the smaller production volume than $d(\bar{d})$ in AA collisions or e^+e^- annihilation. Contrary to $d(\bar{d})$, the size of the kaon production volume deduced from the Bose-Einstein correlation is similar to the size estimated from e^+e^- data.

Gross features of K_0^s, Λ and $\bar{\Lambda}$ are reasonably well reproduced by the available event generators except for the ratio of baryon-to-meson in the resolved photon region. The ratio is significantly larger than expected.

Acknowledgements

We thank the organizers for hospitality and friendly atmosphere during the conference Hadron′07.

References

[1] H1 Collaboration, F. D. Aaron et al., Phys. Lett. B **654** (2007) 148.

[2] ZEUS Collaboration, http://www-zeus.desy.de/public_results/functiondb.php?id=ZEUS-prel-07-006.

[3] ZEUS Collaboration, S. Chekanov et al., Phys. Lett. B **652** (2007) 1.

[4] ZEUS Collaboration, S. Chekanov et al., Nucl. Phys. B **786** (2007) 181.

[5] ZEUS Collaboration, S. Chekanov et al., Eur. Phys. J. C **51** (2007) 1.

[6] R. P. Feynman, *Photon-Hadron Interactions*, in *Frontiers in Physics*, W. A. Benjamin Inc., Reading, MA, 1972; K. H. Streng, T. F. Walsh and P. M. Zerwas, Z. Phys. C **2** (1979) 237.

[7] H1 Collaboration, A.Aktas et al., Eur. Phys. J. C **36** (2004) 413.

[8] L. Lönnblad, Comp. Phys. Comm. **71** (1992) 15.

[9] G. Ingelman, A. Edin and J. Rathsman, Comp. Phys. Comm. **101** (1997) 108.

[10] T. Sjöstrand et al., Comp. Phys. Comm. **135** (2001) 238.

[11] B. Andersson et al., Phys. Rep. **97** (1983) 31.

[12] V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. **15** (1972) 438; G. Altarelli and G. Parisi, Nucl. Phys. B **126** (1977) 298; Yu. L. Dokshitzer, Sov. Phys. JETP **46** (1977) 641.

[13] Y. I. Azimov, Y. L. Dokshitzer, V. A. Khoze and S. I. Troian, Z. Phys. C **27** (1985) 65.

[14] S.Kretzer, Phys. Rev. D **62** (2000) 054001; B. A. Kniehl, G. Kramer and B. Potter, Phys. Rev. Lett. **85** (2000) 5288; S. Albino, B. A. Kniehl and G.Kramer, Nucl. Phys. B **725** (2005) 181.

[15] C. Sandoval, Fizika B (Zagreb) **17** (2008) 337.

[16] S. T. Butler and C. A. Pearson, Phys. Rev. **129** (1963) 836.

RAZLAMANJE I TVORBA ČESTICA U DUBOKO-NEELASTIČNOM RASPRŠENJU I FOTOTVORBI

Istraživali smo tvorbu nabijenih čestica u duboko-neelastičnom raspršenju s detektorima H1 i ZEUS kod HERA-e. Pokazujemo razvoj sumjerne impulsne raspodjele u ovisnosti o Q^2 u području strujnog razlamanja u Breitovom sustavu u području od 10 do 40000 GeV^2. Predstavljaju se značajke ovih proizvedenih čestica: (anti)deuterona, (anti)protona, parova kaona, (anti)lambda i K^0.