Leading Baryons at Low $x_L$ in DIS and Photoproduction at ZEUS

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Abstract. Results obtained by the ZEUS collaboration on leading baryon production in the proton fragmentation region are presented. The reaction $\gamma p \rightarrow NX$, with $N$ a proton or a neutron, is examined both at low and high photon virtuality.

DEFINITIONS AND KINEMATICS

At the HERA collider at DESY (Hamburg, Germany), 820 GeV protons collide with 27.5 GeV electrons or positrons. In Fig. 1(a), a diagram of the reaction $ep \rightarrow NX$ is shown. A photon $\gamma^*$ with virtuality $q^2 = -Q^2$ is emitted at the electron vertex. $W^2 = (q + p)^2$ is used to denote the centre of mass energy of the virtual photon-proton ($\gamma - p$) system and $x, y$ are the standard Bjorken variables. The mass of the proton is denoted by $m_p$.

In addition, leading baryons (LB) are described by two other variables: $t$, the square of the four-momentum transfer at the proton vertex, defined as $t = (p - p')^2 \simeq -\frac{(p_z')^2}{x_L} - m_p^2 \frac{(1-x_L)^2}{x_L}$ and $x_L$, the fraction of the incoming proton momentum carried by the leading baryon, defined as $x_L = p_z'/p_z$.

In the following, deep inelastic scattering (DIS) events are defined as those having photon virtuality $Q^2 > 4$ GeV$^2$ and the energy of the scattered electron $E_e > 8$ GeV, while photoproduction (PHP) events have $Q^2 < 0.02$ GeV$^2$ and $12 < E_e < 18$ GeV.

The ZEUS detector [1], one of the two general purpose detectors at HERA, is instrumented with high resolution calorimeters and tracking chambers. In the far forward direction, it is equipped with a lead scintillator calorimeter [2] (forward neutron calorimeter, FNC), located 106 m downstream of the nominal interaction point, and with a leading proton spectrometer [3] (LPS), consisting of silicon strip

1) LP, LN stand for leading proton and neutron respectively
2) Following the HERA convention, angles are measured with respect to the proton beam direction. Therefore ‘forward direction’ is used to indicate the direction of the proton beam. Angles are often expressed using the pseudorapidity $\eta$ defined as: $\eta = -\ln(\tan(\theta/2))$. The central ZEUS calorimeter measures up to $\eta = 4.2$. 
FIGURE 1. a) Diagram for the reaction ep → NX b) Schematic of the ZEUS far forward detector system. S1,...,6 are the six LPS stations.

detectors operating inside movable roman pots located in six stations between 23 and 90 m downstream of the interaction region, Fig 1 b).

PROPERTIES OF EVENTS WITH A LEADING BARYON

Fig 2 a) shows the fraction of DIS events with a LN with $E_n > 200$GeV as a function of $Q^2$ and W (the ratio is uncorrected for detector acceptance). As can be seen from these plots, and analogous ones for events with a LP, the fraction of DIS events with a LB is independent of $x$, $y$, and $Q^2$.

To estimate the fraction of events with a LP generated by pomeron exchange, the ‘GAPCUT’ selection method was introduced. An event is accepted by GAPCUT if either the pseudorapidity of the most forward energy deposition in the central detector is less than 1.8 or a pseudorapidity gap of at least 1.5 units with its forward edge between $2.5 < \eta < 4$ is present. According to MC studies, GAPCUT has an efficiency of 40-60% for pomeron mediated events, while it rejects non pomeron events with an efficiency > 99%. Fig 2 b) shows the $x_L$ spectrum for all DIS events, for those events that pass GAPCUT and the ratio of the two spectra. It is clear from this picture that only a small fraction of events with $0.6 < x_L < 0.9$ is generated by pomeron exchange.

LB production has been studied both at high and low $Q^2$. Fig 3 a) shows the $x_L$ spectra for LP measured in DIS and PHP events while Fig 3 b) shows the $x_L$ spectra for LN measured in DIS events and in interactions of the proton beam with gas in the beam-pipe. Both a) and b) are not corrected for LPS or FNC acceptance so they cannot be directly compared with each other. In both figures, the relative normalization of the two spectra is arbitrary. The similarity of the two spectra in each figure is remarkable, suggesting a production mechanism that does not depend on the type of interaction.
FIGURE 2. a) Fraction of DIS events with a LN in the final state vs W and $Q^2$ b) $x_L$ spectrum for all DIS events, for GAPCUT events and the ratio of the two spectra.

For LP, the $x_L$ spectrum was divided into ten bins, and in each bin the t distribution was fitted using a simple exponential $(dN/dt \propto e^{bt})$. Three different t ranges have been tried for the fit ($0.08 < -t < 0.5$ GeV$^2$, $-t < 0.5$ GeV$^2$, all available bins) and no systematic effect on the result was observed. Fig 4, on the left, shows the bins available for the fit. On the right, the top figure shows the measured ‘b’ values as a function of $x_L$ while on the bottom the acceptance corrected fraction of DIS events with a leading proton in a given $x_L$ bin is shown. This plot shows that 8-10% of DIS events have a LP in the interval $-t < 0.5$ GeV$^2$ and $0.6 < x_L < 0.9$. For LN [4], in the interval $-t < 0.5$ GeV$^2$ and $x_L > 0.5$, this fraction is $9.1^{+3.6}_{-5.7}$%. These two measurements, even if both have large errors, indicate that events with a LB represent a significant fraction of all DIS events and that the amount of LP and LN is comparable.

The values of b in bins of $x_L$ are compared to different MC models in Fig 5. LEPTO6.5 [5], which generates LB via ‘soft colour interaction’ and is proposed as a model capable to explain all aspects of DIS events, including LB production and diffraction, fails to reproduce the data. LEPTO6.5 also predicts a fraction of GAPCUT events much higher than measured. RAPGAP [6] and EPSOFT [7]3, which both describe diffractive scattering, have been used to simulate both single (SD) and double diffraction (DD)(in DD the proton also breaks up and a leading proton with $x_L < 1$ can be generated in the fragmentation). These models however cannot be compared to the data over the whole $x_L$ range since they simulate only

3) EPSOFT models diffractive processes as soft hadronic collisions
the events produced by pomeron exchange which are, according to Fig 2 a), only a small fraction of the total sample at low $x_L$. For $x_L>0.95$, where pomeron exchange dominates, data and the various MC predictions agree. RAPGAP was also used to generate ‘pion exchange’ events, in which the virtual photon scatters off a pion generated at the proton vertex via the processes $p \rightarrow p\pi^0$ or $p \rightarrow n\pi^+$. According to [8], pion exchange is expected to dominate the cross section for LB production in the interval $0.7 < x_L < 0.9$. Fig 5 d) shows that this model agrees well with the data in this interval.

The value of the slope parameter ‘b’ was also measured in two large $x_L$ intervals, $0.6 < x_L < 0.75$ and $0.75 < x_L < 0.9$, for the subset of events that pass GAPCUT.

**FIGURE 3.** a) LP spectra measured in DIS and PHP events b) LN spectra measured in DIS and beam gas events

**FIGURE 4.** Left side: $x_L$-$t$ bins used in the fits. Right side: (top) measured slope parameter $b$ in bins of $x_L$, (bottom) fraction of DIS events with a LP in a given $\Delta x_L$ bin.
In both intervals, the value $b_{\text{GAPCUT}}$ is consistent with the values of the LP measured in all DIS events as if the fact that the interaction is diffractive did not influence the properties of the LP.

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