# LEADING NEUTRON PRODUCTION AND $F_2^\pi$ AT HERA*

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*(Received September 16, 2002)*

New results on leading neutron production at HERA are presented for cross sections in photoproduction, in deep inelastic scattering and in an intermediate $Q^2$ range. The data with medium to high photon virtuality are presented in terms of structure functions. Vertex factorization is tested for the semi-inclusive leading neutron data, as well as for events with a dijet system in the final state.

PACS numbers: 13.60.Rj, 14.40.Aq

## 1. Introduction

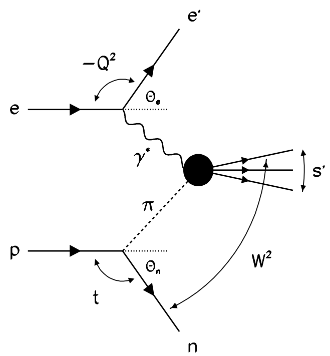
The study of $ep$ scattering events with a leading baryon at HERA has the aim of determining the production mechanisms that lead to the formation of leading protons or neutrons. One possible production mechanism is One-Pion-Exchange (OPE) as depicted in Fig. 1 for the production of neutrons. An important issue is a possible violation of factorization. Vertex factorization can be expressed with two hypotheses (see Fig. 1 for illustration):

(a) the rate of produced neutrons is independent of the type of the particle at the upper vertex;

(b) the cross section dependence on the baryon variables, $x_{\mathrm{L}}$ and $t$ or $p_{\mathrm{T}}$ of the leading neutron, is independent of the particle production and the kinematic variables at the photon vertex.

The experiments H1 and ZEUS have each installed a dedicated calorimeter (FNC) along the beam line in the direction of the outgoing proton to

* Presented at the X International Workshop on Deep Inelastic Scattering (DIS2002) Cracow, Poland, 30 April–4 May, 2002.




Photon vertex
lepton variables:
$Q^2$, $x$, $W$, $y$
$\Uparrow$
$\Downarrow$
Proton vertex
leading baryon variables:
$x_{\mathrm{L}} \equiv z \;=\; E_n/E_p$
$t = (n-p)^2 \;=\; -\frac{p_{\mathrm{T}}^2}{x_{\mathrm{L}}} - \frac{m_n^2(1-x_{\mathrm{L}})^2}{x_{\mathrm{L}}}$

Fig. 1. Kinematic variables in *ep* collisions and illustration of vertex factorization.

measure leading neutrons. The analysis cuts in the baryon variables are: $x_{\mathrm{L}} > 0.2$ (ZEUS semi-inclusive data) or $x_{\mathrm{L}} \gtrsim 0.5$ (H1 dijet data) and for both $p_{\mathrm{T}} < (0.66 x_{\mathrm{L}})$ GeV from the restriction in the scattering angle $\theta_n < 0.8$ mrad. Vertex factorization tests are performed by measurements in three different regions of photon virtuality $Q^2$: photoproduction $\gamma p$ ($Q^2 < 0.02$ GeV$^2$), low $Q^2$ (0.1 GeV$^2 < Q^2 < 0.74$ GeV$^2$) and DIS ($Q^2 > 4$ GeV$^2$).

## 2. Cross section ratios and factorization

The ZEUS Collaboration looked at semi-inclusive cross section ratios

$$r^{\mathrm{LN}(3)}(x_{\mathrm{L}}, x, Q^2) = \frac{N^{\mathrm{LN}}(x_{\mathrm{L}}, x, Q^2)}{N(x, Q^2)}\,\frac{1}{\varepsilon^{\mathrm{LN}}} = \frac{F_2^{\mathrm{LN}(3)}(x_{\mathrm{L}}, x, Q^2)}{F_2(x, Q^2)} \tag{1}$$

by measuring [1] the number of events with a leading neutron, corrected for FNC acceptance ($\varepsilon^{\mathrm{LN}}$), and dividing by the total number of events with no FNC requirement as a function of the variables $x_{\mathrm{L}}$, $x$ and $Q^2$. The results are presented by integrating over the available phase space in $p_{\mathrm{T}}^2$. The advantage of this ratio method is the near complete cancellation of systematic errors such as, for example, the luminosity measurement. In Fig. 2 the ratio is shown as a function of $x_{\mathrm{L}}$ for the three different $Q^2$ ranges of $\gamma p$, low $Q^2$ and DIS on the left side and on the right side for different $Q^2$ ranges in the DIS regime. In 5%–15% of the events a leading neutron appears in the forward direction. The general behavior as a function of $x_{\mathrm{L}}$ is similar for all $Q^2$ values: an increase with rising $x_{\mathrm{L}}$, which is mostly due to the increase of acceptance in $p_{\mathrm{T}}$, and a rapid decrease towards the kinematic limit.

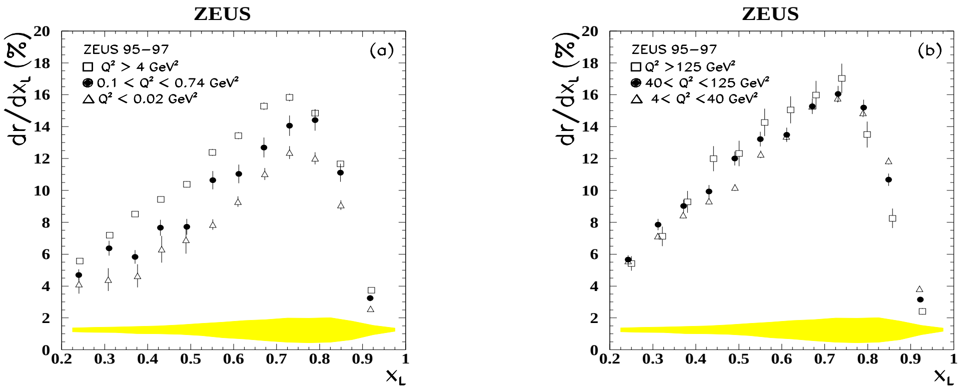



Fig. 2. Ratio of leading neutron events to all events as a function of $x_{\mathrm{L}}$ for different $Q^2$ ranges.

The vertex factorization hypotheses can be tested using these neutron spectra. According to hypothesis (a) the cross section for leading neutron production relative to the total cross section should be the same in $\gamma p$ and in $pp$ interactions. In comparisons both ratios as a function of $x_{\mathrm{L}}$ for $p_{\mathrm{T}}^2 = 0$ show the same shape [1], which is described by an OPE-parameterization being valid for $\pi$ exchanges dominating at larger $x_{\mathrm{L}}$ values. However, in normalization, the $\gamma p$ data lie a factor of approximately two below the $pp$ data [1], which is a strong factorization breaking.

The hypothesis (b) was tested with HERA data alone by looking at the ratio as a function of $x_{\mathrm{L}}$ for different values of $Q^2$, $x$, $W$ and $y$ [1]. In Fig. 2 the rate in the range $0.64 < x_{\mathrm{L}} < 0.82$ for example rises from $\gamma p$ to DIS by approximately 20%, which means a mild violation of vertex factorization. This could be attributed to absorptive effects: in the case of DIS the photon is point-like while in $\gamma p$ the quasi-real photon is more hadron-like and re-scattering processes of the leading neutron are possible. Similar effects are measured in events with leading protons [2, 3].

## 3. Structure functions

In the DIS regime the ratio shows only a very weak dependence on $x$ and $Q^2$ [1]. This flatness of the ratio means according to equation (1) that $F_2^{\mathrm{LN}(3)}$ and $F_2$ have very similar $x$ and $Q^2$ dependences. In fact the unfolded $F_2^{\mathrm{LN}(3)}$ is well described by a scaled $F_2$ parameterization [1]. $F_2^{\mathrm{LN}(3)}$ has been analyzed also in the restricted range $p_{\mathrm{T}} < 0.2$ GeV for the two $x_{\mathrm{L}}$ values 0.3 and 0.7 as published by the H1 Collaboration [4]. While the shapes of the measured curves are similar for both $x_{\mathrm{L}}$ ranges, the normalization only agrees for $x_{\mathrm{L}} = 0.7$.

In order to determine the pion structure function, $F_2^{\mathrm{LN}(3)}$ is separated into a $\pi$-flux and $F_2^{\pi}$. The $\pi$-flux is poorly constrained and several parameterizations are available. To deal with this large uncertainty two extreme possibilities were chosen [1]. They differ by approximately a factor of two and encompass the results of other models. In one normalization an effective flux has been used that is taken from hadron scattering data. It is displayed in Fig. 3 on the left side. The measured $F_2^{\pi}$ is well described by a scaled $F_2$ parameterization, which reveals a clear similarity of the pion structure with the proton structure in the measured kinematic range. Only at larger $Q^2$ the data lie above the parameterization. The parameterization for $F_2^{\pi}$ from Glück *et al.* (GRV) shows a similar shape, but is too high in normalization. Using the second normalization fixed by the Additive Quark Model for the data leads to an agreement in normalization for $F_2^{\pi}$–GRV (Fig. 3, right side). Also here the data are slightly higher than the model at higher $Q^2$ values. Another $F_2^{\pi}$ model from Sutton *et al.* (SMRS) does not describe the data either in shape or in normalization.

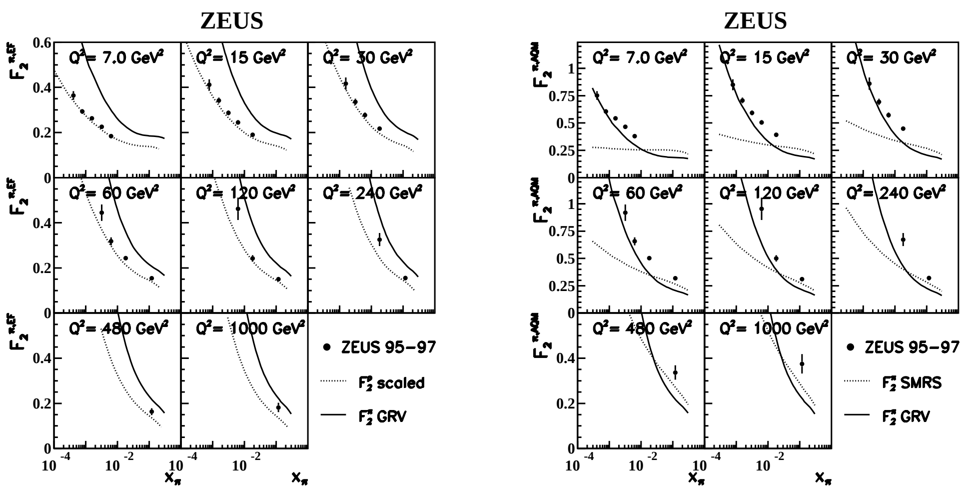



Fig. 3. $F_2^{\pi}$ calculated with an effective OPE-flux (left) and the Additive Quark Model (right) as a function of $x_\pi$ with $x_\pi = x/(1 - x_{\mathrm{L}})$.

## 4. Dijets with leading neutrons

The One-Pion-Exchange picture has been tested with leading neutron data by the H1 Collaboration [5] by studying events containing two jets in the hadronic final state. The energy spectrum of the leading neutrons is compatible with Monte Carlo simulations of pion exchanges for $\gamma p$ (POMPYT) and DIS (RAPGAP) for neutron energies corresponding to $x_{\mathrm{L}} \gtrsim 0.5$. Using the jet information, the momentum fraction of the scattered parton inside the exchanged pion, $x_\pi$, can be calculated. The differential cross section as a function of $x_\pi$ has been measured and compared to simulations with different pion structure functions. Data and simulations agree within the systematic errors. Corresponding results have been published by the ZEUS Collaboration [6].

For these dijet data, the ratio of events with a leading neutron to all events has also been analyzed and is shown in Fig. 4 as a function of $Q^2$. Within the experimental uncertainties there is no evidence for any breaking of factorization.

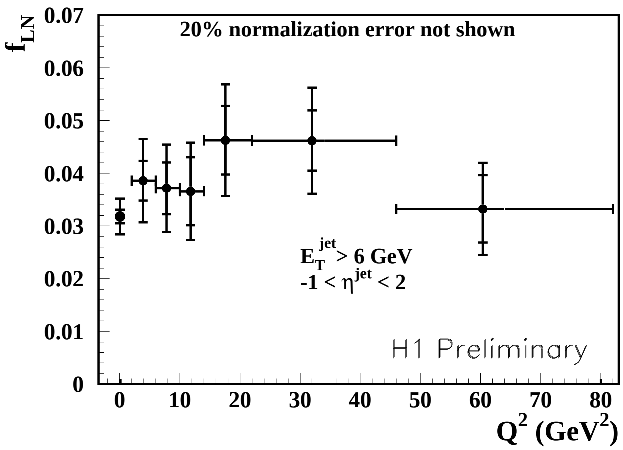



Fig. 4. Ratio of leading neutron dijet events to all dijet events as a function of $Q^2$.

It is my pleasure to thank my ZEUS and H1 colleagues, especially M. Arneodo, A. Buniatian, M. Derrick, G. Iacobucci, G. Levman, P. Newman, W. Schmidke and Y. Yamazaki for helpful discussions and contributing to the results presented here. Many thanks to the organizers for a very interesting conference.

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