Leading Baryons at ZEUS

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A large fraction of events in ep collisions at HERA has a leading baryon (proton or neutron) in the final state that carries a sizeable fraction of the longitudinal momentum of the incoming proton. These events are a powerful tool to study the transition from hard to soft physics. I will review recent ZEUS results on the production of leading protons and neutrons and compare them to phenomenological models.

1 Introduction

At HERA the semi-inclusive process:

$$e + p \rightarrow e + LB + X,$$

where LB is a leading baryon (LN = leading neutron, LP = leading proton) that carries a sizeable fraction of the longitudinal momentum of the incoming proton, x_L, and X a unresolved hadronic system can be studied in Deep Inelastic Scattering (DIS, $Q^2 > 1-3$ GeV^2) and photoproduction, γp, ($Q^2 \sim 0$ GeV^2) [1]. In the former case the scale for particle production decreases from Q^2 in the current region to a soft hadronic scale in the proton fragmentation region. In the γp regime everything is soft, but a hard scale can be introduced, e.g. by the requirement of high-p_T jets in the final state.

A general approach to the semi-inclusive processes is provided by the *fracture function* formalism [2]. The fracture functions are non-perturbative universal functions (that absorb collinear singularities) with the Q^2 evolution governed by known evolution equations. Dynamical exchange models allow to link them to concepts like the structure function of exchanged objects, for exampsle Reggeon trajectories. In the framework of object-exchange models leading proton production proceeds through isoscalar contributions (like the Pomeron, dominant in the diffractive region, and Reggeons like the f_0) and isovevector contributions (like the π^0). Leading neutrons can be produced only via isovector exchanges (like π^+ and ρ^+). Predictions are also provided by Monte Carlo (MC) fragmentation models, for example HERWIG [3], ARIADNE - based on the Color Dipole Model [4] and matrix elements and parton shower (MEPS) with the Soft Color Interation (SCI) model [5]. The sketch of the process and its possible interpretations are shown in Figure 1, taking the leading neutron production as an example.

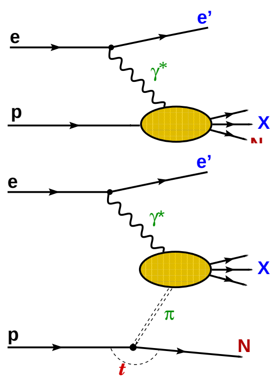

Figure 1: Leading baryon production at HERA. Fragmentation (top) and particle-exchange (bottom) models are shown.

In the hypotesis of limiting fragmentation, in the high-energy limit the production of particles in the target fragmentation region is independent of the nature of the incident particle. In ep collisions the incident particle is the exchanged virtual photon ($\gamma^\star$): the dependence of the cross section on the lepton variables (x, Q^2) is independent of the baryon variables (x_L, p_T^2). In the One Pion Exchange model (OPE) of LN production, the cross section is given by the product $f_\pi(x_L, p_T^2) \times \sigma_{\gamma^\star\pi}(s_{\gamma^\star\pi}, Q^2)$ of the exchanged pion flux-factor times the $\gamma^\star\pi$ cross-section. $s_{\gamma^\star\pi}$ represents the squared center-of-mass energy of the photon-pion system. Such a dependence links the lepton and baryon variables, therefore exact factorization is broken in such a model. In the exchange model the phenomenon of rescattering and absorption is predicted to occur. In LN production the absorption is due to the rescattering of the neutron on the exchanged-photon hadronic component. The effect is enhanced when the transverse size of the photon is large compared to the size $r_{\pi n}$ of the pion-neutron system. More absorption is expected in photoproduction than in DIS, because in DIS the size of the photon is smaller. As $r_{\pi n} \propto 1/p_T$, a depletion at high-p_T is expected in photoproduction relative to DIS. As the pion flux-factor is such that the average $< r_{\pi n} >$ increases with x_L, more absorption is expected to be observed at low x_L. All these effects imply a violation of the factorization. Additional corrections were also considered, among which enhanced absorptive corrections, the calculation of the migrations in x_L and p_T^2 and the inclusion of the additional exchanges ρ and a_2 [6].

2 Experimental tools

At ZEUS the leading neutrons were catched by a Forward Neutron Calorimeter (FNC) and Tracker (FNT) [9]. The FNC, located in the outgoing proton beamline at Z=107 m (Z=0 is the nominal interaction point) was a 10 $\lambda_{\rm int}$ lead-scintillator sampling calorimeter. The neutron energy resolution was $\sigma_E/E = 0.65/\sqrt{E}$ (E in GeV), and the energy scale was known to 2%. The FNT was a scintillator hodoscope at 1 $\lambda_{\rm int}$ with angular resolutions on the transverse coordinates $\sigma_{\rm x,y} = 0.23$ cm and on the polar angle $\sigma_\theta = 22$ μrad.

Leading protons were detected using the Leading Proton Spectrometer (LPS) [10]. It consisted of 54 planes of microstrip silicon detectors (hit resolution 30 μm) grouped into six stations, S1 to S6, located along the outgoing proton beamline between Z=20 m and Z=90 m. The stations S1 to S3 and S4 to S6 are two independent spectrometers due to their different phase-space coverage. Charged particles inside the beampipe were deflected by the HERA beamline magnets and measured with a resolution better than 1% on the longitudinal momentum. This is the first time that the LPS stations S1 to S3 are used.

Both the FNC/FNT and the LPS measured the transverse momentum with a resolution better than the proton beam spread ($\simeq$ 40 MeV in the horizontal plane and $\simeq$ 90 MeV in the vertical plane).

3 Results

The data presented [1] were obtained with the ZEUS detector at HERA. The production of LP in DIS used an integrated luminosity L_{int}=12.8 pb^{-1} (see [11] for details about the analysis) while LN in DIS and γp used L_{int}=40 pb^{-1} [12].

3.1 x_L and p_T^2 depedence

The LP yield is flat in x_L below the diffractive peak while the LN yield goes to zero at the kinematic limit $x_L \to 1$.

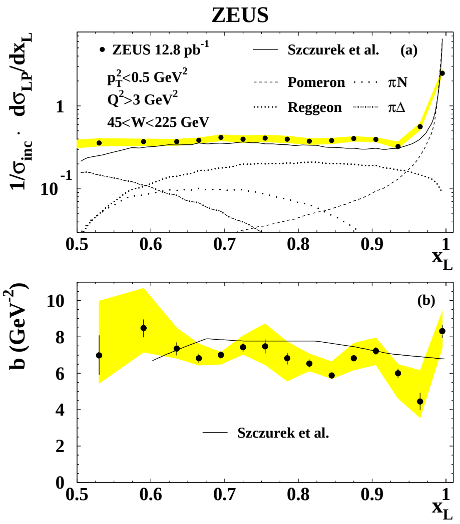

Figure 2: LP x_L yield in DIS (top) and p_T^2 b-slopes as a function of x_L (bottom).

The squared transverse-momentum distribution for both LP and LN decreases exponentially with p_T^2 at fixed x_L. The double-differential yield $\frac{1}{\sigma_{\rm inc}}\frac{d^2\sigma_{\rm LP}}{dx_L dp_T^2}$ can be fit with the form $a(x_L)e^{-b(x_L)p_T^2}$. In Figure 2 the x_L spectrum of LP production in DIS ($Q^2 > 3\,{\rm GeV}^2$) and the b-slope as a function of x_L are shown.

While Monte Carlo models generally fail to reproduce the characteristics of these distributions, the model of [13] based on reggeon exchanges reproduces well the experimental trend. At intermediate-low x_L the model includes the exchange of isoscalars, notably the f_0 trajectory, that are needed explain the observed rate.

This is confirmed by comparing the x_L yield for LP and LN (Figure 3, for $p_T^2 < 0.04\,{\rm GeV}^2$). In a particle exchange model the only exchange of isovectors would result in half as many protons as neutrons, while the data show the opposite.

The LP b-slope is almost flat with x_L, while the LN b-slope rises with x_L, the crossing point being at $x_L \simeq 0.7$.

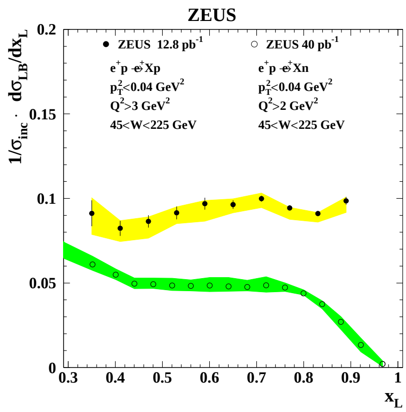

Figure 3: x_L yields for LP (full symbols) and LN (open circles) in DIS in the same p_T^2 range.

3.2 Q^2 dependence

About 24% of DIS events have a LP with $0.32 < x_L < 0.92$ almost independently of x_L and Q^2. The average LP yield as a function of Q^2, for two different x_L bins is show in Figure 4. In the figure there is also the γp result from a previous ZEUS measurement [14]. The data do not exclude a slow decrease of the yield with Q^2, consistent with a small factorization-breaking effect.

The LN yield decreases with Q^2, and this is a large effect when going from DIS to γp. In Figure 5 it is shown the measurement of the ratio of the γp and DIS x_L distributions. The measurement is compared to predictions. The models [6] are based on the OPE approximation and include absorption corrections. They show a good agreement with the data once the predictions are rescaled by the factor $(1-x_L)^{-0.13}$ that takes into account the different center-of-mass energy dependence of the real and virtual photon-pion cross section.

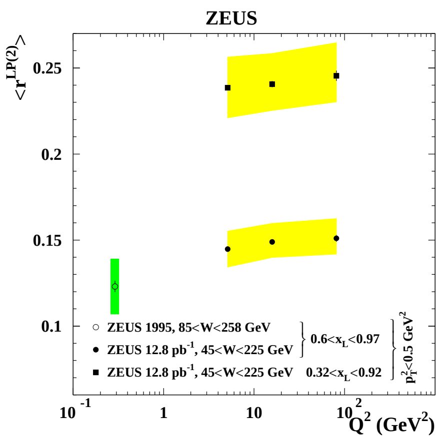

Figure 4: Average LP yield as a function of Q^2 for two different x_L bins.

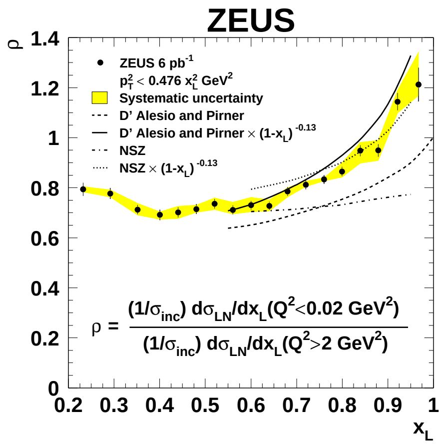

Figure 5: Ratio of photoproduction and DIS x_L distributions in LN production.

Also in the case of LN production, both in DIS and γp, Monte Carlo models generally fail to reproduce all the characteristics of the data, with improvements from models that include one-particle-exchange mechanisms [7]. OPE models [8] do reproduce the shapes but not the rates. It turns out that the π-exchange alone is not enough. A good improvement is obtained when the contribution of additional Reggeons is included, notably the ρ and a_2 [6]. As an example Figure 6 shows the b-slope in DIS as a function of x_L and the difference of the slopes in DIS and γp compared with the model predictions that include these additional contributions. We have seen that absorption effects set on going from a hard to a soft scale, for example from DIS to γp. What happens if we reintroduce a hard scale in γp? This was done through the selection of events with a LN in the final state and two high-E_T jets ($E_T > 6.5$ and 7.5 GeV). The results (see [1] for the details) are that while in the inclusive photoproduction it was observed a suppression of the LN yield at low x_L compared to DIS, consistent with expectations from absorption, in photoproduction plus jets a suppression is observed at high-x_L. Albeit there are not yet firm conclusions, it is known that a possible explanation comes from a kinematic effect linked to the different

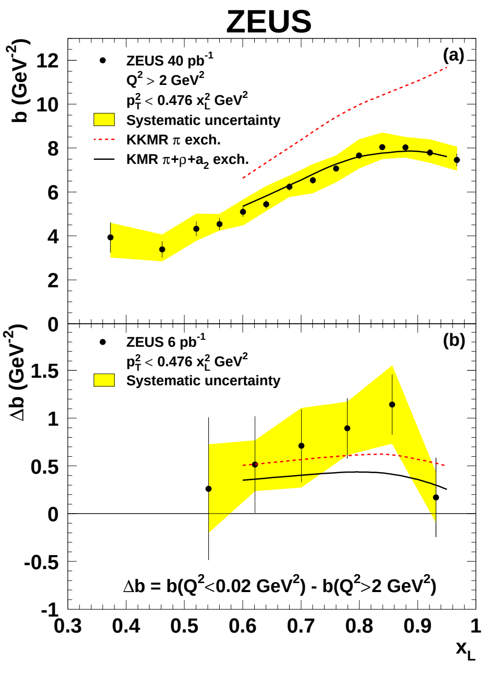

Figure 6: a) LN b-slopes in DIS as a function of x_L, b) b-slope difference γp-DIS.

forward energy flows for the two processes.

4 Conclusions

Recent ZEUS data about leading proton and neutron production in DIS, photoproduction and photoproduction plus dijets allowed to study characteristics of the events that appear passing from hard to soft scale processes. The leading proton production was studied for the first time down to $x_L > 0.32$ through the first use of the stations S1 to S3 of the ZEUS Leading Proton Spectrometer. Clear factorization breaking effects are seen going from hard to soft processes, strong in leading neutron and less pronounced in leading proton production. In general, standard MC models fail to describe the data, with improvements when particle-exchange models are implemented. The measured rate in the intermediate-low x_L region can be explained with isoscalar and isovector contributions. Pure π-exchange is not enough for the description of the leading neutron data, particularly the slope of the exponential dependence on p_T^2. Recent calculations that include absorption and migration effects and additional exchange contributions (ρ, a_2) improved quite a bit the agreement with the data.

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