INCLUSIVE DIFFRACTION AND LEADING BARYON PRODUCTION AT HERA

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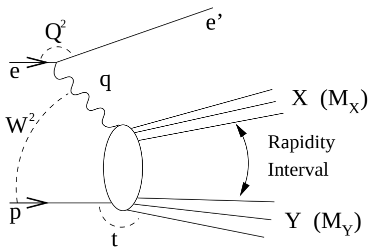
A review of ZEUS and H1 data on diffractive deep inelastic scattering and leading baryon production is presented.

1 Introduction

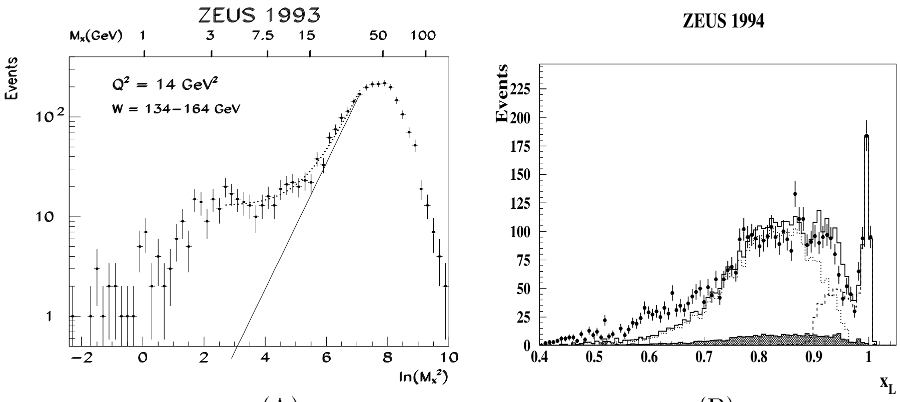
Diffractive processes have been studied for more than thirty years in hadronic interactions [1].

At HERA, diffractive interactions can be thought as a beam of almost-real or virtual photons fluctuating into a hadronic or partonic configuration ($\gamma \to$ vector meson, $q\bar{q}, q\bar{q}g, \ldots$), which diffracts off the proton [2].

The final state (see figure) is characterised subsequently by a hadronic system X of mass M_X originating from the diffractive dissociation of the photon, while the proton either remains intact or is excited to a low mass baryonic state Y. Because of the nature of the colourless exchange, hereafter referred to as *pomeron* ($I\!P$) exchange, the two systems are separated in rapidity.



In addition to the virtual photon-pomeron interaction one also expects meson exchanges to contribute to the total deep inelastic scattering cross section and to the production of nucleons carrying a large fraction of the incoming proton momentum (leading baryons). Assuming a simple Regge expansion, the contribution of a colour singlet exchange to the production of a leading baryon with a fraction of proton beam momentum x_L is of the form $\sim (1-x_L)^{1-2\alpha(t)}$. Thus $I\!P$ exchange is expected to dominate the production cross section for protons with energy close to the proton beam energy, whereas reggeon and pion exchange are of increasing importance at lower values of x_L. Neutron production can only occur through the exchange of an isovector particle, notably the π^+ [3].



(A) (B)

Figure 1: (**A**): *Distribution of ln M_X^2 for W and Q^2 as denoted in the figure. The solid line shows the exponential fall-off of the non-diffractive contribution.* (**B**): *Observed spectrum of the fraction x_L of the proton beam momentum carried by the scattered proton. The full line is the result of fitting this distribution with a sum of contributions from Monte Carlo generators for double dissociation (shaded area), for pion exchange (dotted line) and for photon diffractive dissociation (dashed line).*

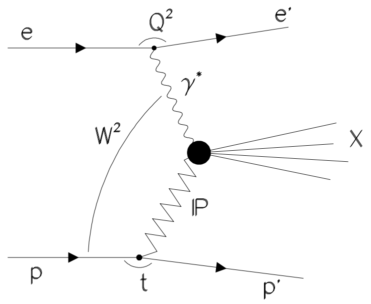
2 Inclusive Diffractive Photon Dissociation

Inclusive photon diffractive dissociation includes all pomeron mediated reactions of the kind $\gamma p \rightarrow XY$, where Y is either the proton (single diffractive dissociation) or an excited state (double diffractive dissociation).
Diffractive dissociation events are characterised by a gap in rapidity between the systems X and Y which is not exponentially suppressed as a function of the gap width, as opposed to non-diffractive interactions, where the colour string connecting the struck parton and the proton remnant fills the rapidity interval during the hadronisation process. Also, single diffractive dissociation events are characterised by a proton emerging from the interaction with small transverse momentum and carrying a large fraction (x_L or z) of the beam momentum ($x_L \gtrsim 0.95$).
Based on these simple features, both ZEUS and H1 have developed selection methods exploiting the main features of their own detectors.
The event selection used by H1 is based on the presence of a gap in rapidity and relies on the ability to measure hadronic activity in the central detector up to $\eta \sim 3.4$ [a] and to veto any activity in the region $3.4 < \eta < 7.5$ [4]. The contribution of events in which the proton has also dissociated is estimated to

[a] The pseudo-rapidity η is defined as $-\ln(\tan(\theta/2))$, where θ is the polar angle measured with respect to the proton direction.

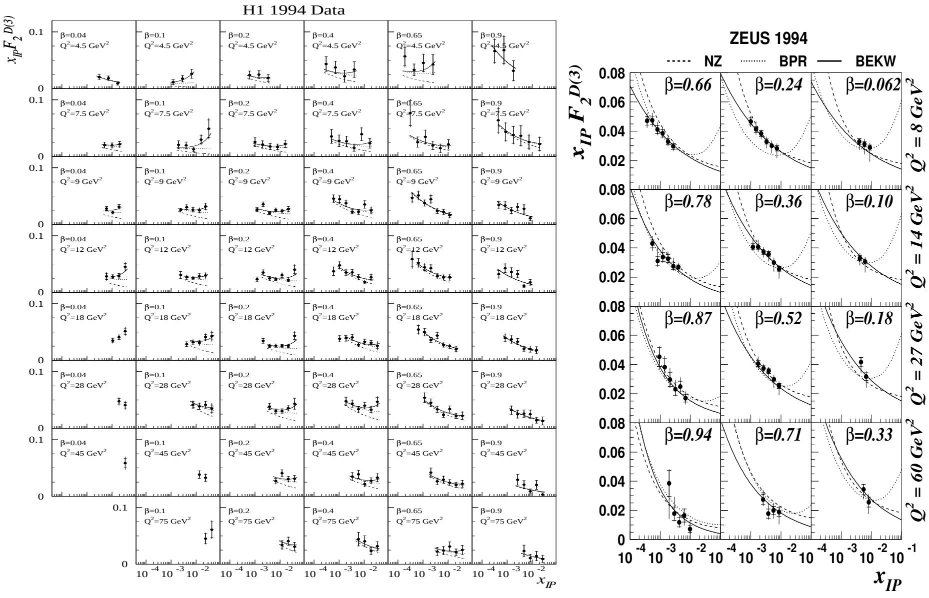
be $\lesssim$ 10% and is restricted to events where the proton dissociates into a mass $M_Y \lesssim$ 1.6 GeV and escapes the forward tagging devices.
The selection method developed by ZEUS (called the M_X *method* in the following) is based on the observation that the invariant mass M_X measured in the calorimeter consists of two components with very different behaviours [5]; the diffractive contribution is identified as the excess of events at small M_X above the exponential fall-off of the non-diffractive contribution with decreasing $\ln M_X^2$ (see fig. 1(A)). Given the size of the non-diffractive subtraction, this method limits the measurements to small masses ($M_X \lesssim 15$ GeV). The contribution of double dissociation is $\sim$ 30% and is restricted to $M_Y \lesssim 5.5$ GeV.
An alternative method developed at ZEUS consists of tagging the scattered proton in the final state using a proton spectrometer (LPS). The spectrum of the scattered proton fractional momentum x_L for a DIS sample is shown in fig. 1(B). A clean selection of diffractive events is obtained by requiring $x_L > 0.97$, where the background contamination from processes such as π trajectory exchange or proton dissociation remains below 3%. The use of this method is limited by statistics due to the low spectrometer acceptance ($\sim$ 6%) [6].

2.1 The diffractive structure function



In the Ingelman-Schlein model [7], diffractive DIS is depicted as a two step process: first a pomeron, modeled as a colorless object made of partons, is emitted by the proton, then the photon interacts with a pomeron constituent (see figure). This approach, where the virtual photon probes directly the partonic structure of the pomeron, led to the concept of diffractive structure function F_2^D.
In addition to the variables used to describe inclusive DIS such as Q^2, W, x and y, new variables need to be introduced to account for the additional vertex in the diagram. These are: $x_{I\!P} = \frac{q\cdot(p-p')}{q\cdot p} \simeq \frac{M_X^2+Q^2}{W^2+Q^2}$ and $t = (p-p')^2 \simeq -p_T^2/x_L$, where M_X is the mass of the photon dissociated system, p_T and x_L are the transverse momentum and fractional momentum, respectively, of the scattered proton. With the above picture in mind, $x_{I\!P}$ can be interpreted as the fraction of the proton momentum carried by the pomeron and a scaling variable equivalent to Bjorken-x but relative to the pomeron momentum is defined as $\beta = \frac{Q^2}{2q\cdot(p-p')} = \frac{x}{x_{I\!P}} \simeq \frac{Q^2}{Q^2+M_X^2}$.

The diffractive structure function F_2^D is related to the four-fold differential



(A) (B)

Figure 2: **(A)**: *the diffractive structure function* $F_2^{D(3)}$ *multiplied by* $x_{I\!P}$ *as a function of* $x_{I\!P}$ *for fixed values of* β *and* Q^2 *as measured using H1 data. The solid line represents a fit in which the pomeron and the reggeon exchange contribute with maximum interference. The pomeron contribution alone is shown as a dashed line, the interference term is shown as a dotted line.* **(B)**: *the diffractive structure function* $F_2^{D(3)}$ *multiplied by* $x_{I\!P}$*, as a function of* $x_{I\!P}$ *for fixed values of* β *and* Q^2*, measured using the ZEUS data. The data are compared with the predictions of some of pQCD inspired models*[9]*.*

cross section

$$\frac{d^4\sigma^D_{(ep\to e'Xp')}}{d\beta dQ^2 dx_{I\!P} dt} = \frac{4\pi\alpha^2}{\beta Q^2}(1-y+\frac{y^2}{2})F_2^{D(4)}(\beta,Q^2,x_{I\!P},t) \quad ,$$

where contributions from the longitudinal structure function and from Z° exchange have been neglected. In the Ingelman-Schlein approach, the diffractive structure function is expressed as the product of two terms $F_2^{D(4)} = f_{I\!P/p}(x_{I\!P},t)F_2^{I\!P}(\beta,Q^2)$, where the first term depends on $x_{I\!P}$ and t and is called the *pomeron flux factor*. In the simple Regge model, the flux factor takes the same form as in hadron-hadron interactions and is usually expressed as

$f_{I\!P/p}(x_{I\!P}, t) = N\beta^2_{I\!P/p}(t){x_{I\!P}}^{1-2\alpha_{I\!P}(t)}$, where $\beta(t)$ is the function describing the coupling of the pomeron trajectory to the proton. We refer to this assumption as *Regge factorisation* at the proton vertex. The second term ($F_2^{I\!P}$) represents the *structure function of the pomeron.*

In most of the analyses the proton is not detected and t is not measured, so the t-integrated diffractive structure function $F_2^{D(3)} \propto \frac{1}{{x_{I\!P}}^a} F_2^{I\!P}(\beta, Q^2)$ is used. The exponent a is related to the the pomeron trajectory *averaged over t* through the relation $\overline{\alpha_{I\!P}} = 1 + a/2$. If Regge factorisation holds, a single exponent a independent of β and Q^2 should be able to describe the $x_{I\!P}$ dependence of the diffractive structure function.

The measurements of H1 [4], based on the data collected in 1994 (integrated luminosity of 1.96 pb^{-1}), cover the kinematic region $4.5 < Q^2 < 75$ GeV^2, $0.0002 < x_{I\!P} < 0.04$ and $0.04 < \beta < 0.9$ and are shown in fig. 2 (A) as $x_{I\!P} \cdot F_2^{D(3)}$, as a function of $x_{I\!P}$, for different values of β and Q^2. As shown in the figure, in the low β, high $x_{I\!P}$ region a breaking of factorisation is observed. The factorisation breaking is predicted by various models based on pQCD [9]. However, the data are well described by including the exchange of a reggeon in addition to the pomeron. A fit to the data yields $\alpha_{I\!P}(0) = 1.203 \pm 0.02(\mathrm{stat.}) \pm 0.013(\mathrm{syst.})^{+0.03}_{-0.035}(\mathrm{mod.})$ and for the intercept of the secondary trajectory $\alpha_{I\!R}(0) = 0.50 \pm 0.11(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})^{+0.09}_{-0.010}(\mathrm{mod.})$.

The diffractive structure function $F_2^{D(3)}$ has also been measured by ZEUS, with the full 1994 DIS statistics (corresponding to 2.61 pb^{-1}) in the range $7< Q^2 <140$ GeV^2, $60< W <200$ GeV and for small masses ($M_X <15$ GeV) using the M_X method and the results are shown in fig. 2 (B).
In the small $x_{I\!P}$ range covered by the data ($x_{I\!P} \lesssim 0.01$), a good fit of the $x_{I\!P}$ dependence of $F_2^{D(3)}$ was obtained assuming a single power a in each β bin [8], giving support to the Regge factorisation at low $x_{I\!P}$ values corresponding to a t-averaged pomeron trajectory of $\overline{\alpha_{I\!P}} = 1.127 \pm 0.009(\mathrm{stat.})^{+0.039}_{-0.012}(\mathrm{sys.})$.

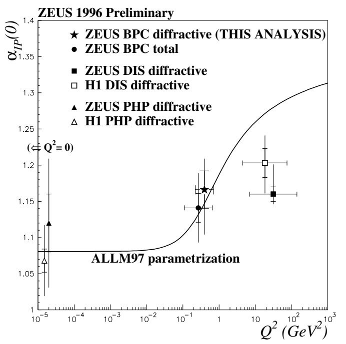


Figure 3: *Pomeron intercept as a function of Q^2 measured by the ZEUS and H1 experiments* [4, 8, 10, 11, 12]*. The curve is obtained from the ALLM97 parametrisation* [13]

Most recently the value $\overline{\alpha_{I\!P}}$ has been measured using ZEUS data in the kinematic region $0.22< Q^2 <0.7$ GeV^2 and $90< W <220$ GeV, yelding $\overline{\alpha_{I\!P}} = 1.133 \pm 0.026(\mathrm{stat.})^{+0.043}_{-0.062}(\mathrm{sys.})$ [10].

The average over the t-distribution gives $\alpha_{I\!P}(0) \sim \overline{\alpha_{I\!P}} + 0.03$. The values of $\alpha_{I\!P}(0)$ as a function of Q^2 measured at HERA [4 8 10 11 12] are shown in fig. 3; for $Q^2 > 0.2$ GeV^2 the value of the pomeron intercept appears larger than the value $\alpha_{I\!P}(0) \sim 1.08$ obtained from soft hadron-hadron interactions [14].

2.2 The partonic structure of the pomeron

The validity of the QCD factorisation theorem [15] was extended to diffractive DIS [16]. As a consequence, the use of the DGLAP evolution equation [17] to describe the scaling violations of $F_2^{D(3)}$ is justified and *diffractive* parton distributions of the proton can be derived in a way similar to the ordinary parton distributions of the proton are derived from the inclusive F_2. If, in addition, Regge factorisation is assumed, the pomeron structure function $F_2^{I\!P}$ can be expressed at LO in terms of parton densities *in the pomeron.* No momentum sum rule should be imposed because of the theoretical uncertainties on the normalisation of the pomeron flux factor and because it is not clear that such a rule is appropriate for parton distributions of a virtual exchange.

H1 has performed a QCD fit to $F_2^{D(3)}$ assuming both pomeron and reggeon flux factors as determined from the data in the $4.5 < Q^2 < 75$ GeV^2 range [4].

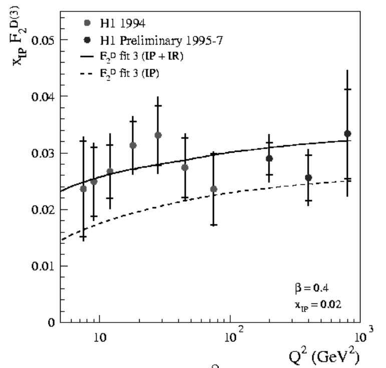


Figure 4: *Q^2 dependence of $x_{I\!P} F_2^{D(3)}$ at $\beta = 0.4$ and $x_{I\!P} = 0.02$. The results of a QCD fit to the data in which both quarks and gluons contribute are also shown.*

The measurement of $x_{I\!P} F_2^{D(3)}$ as a function of Q^2 for fixed $x_{I\!P} = 0.02$ and for fixed $\beta = 0.4$ values, compared with the expectations of the fit, is shown in fig. 4. The low Q^2 fit also describes the high Q^2 data [18].

The scaling violation observed [4] cannot be described by parametrisations containing only quarks; the best fit is obtained with a gluon distribution peaking at high values of the pomeron fractional momentum. The fraction of the pomeron momentum carried by gluons is found to be $> 80\%$ [4 18].

3 Leading Proton and Neutron Production

The production of leading baryons (LB) has been studied by ZEUS [19 20] and H1 [21] in a wide x_L range ($0.2 < x_L < 1$). These processes allow the study of the proton fragmentation region for low transverse momenta (p_T) carried by the LB ($p_T < 0.9$ GeV). Two different approaches exist. In the Regge models, the LB production is mediated by a colour singlet (pomeron, pion or reggeon) between the virtual photon and the incoming proton. If this mechanism is valid, the structure of the exchanged object may be studied. In the fragmentation approach, the LB simply emerge from the target fragmentation and tests of different fragmentation models can be performed.

The production rate of LB has been measured by ZEUS and is shown in fig. 5 [19].The production of LB in the range $0.2 < x_L < 0.9$ and scattering angle $\theta < 0.8$ mrad contributes to $\sim 12\%$ of the inclusive cross section. In contrast to the expectation of proton fragmentation models, the production of leading neutrons (LN) is significantly lower than that of leading protons (LP). As shown in fig. 5, the standard fragmentation models, like the colour dipole model, as implemented in the ARIADNE program [22], cannot describe the data in both shape and normalisation.

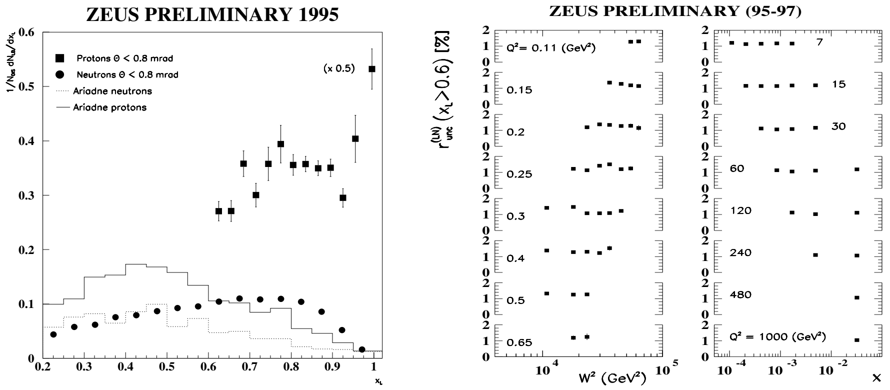


Figure 5: *Left: x_L spectrum for protons and neutrons with scattering angle $\theta < 0.8$ mrad compared to the predictions of the ARIADNE MC. Right: Uncorrected ratio of events with a LN and all inclusive DIS events for $x_L > 0.6$ and $\theta < 0.8$ mrad as a function of x and W^2 at fixed values of Q^2.*

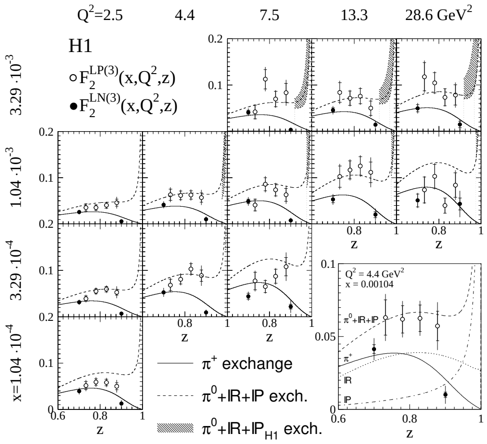
The uncorrected ratio of events with a LN in the range $x_L > 0.6$ and $\theta < 0.8$ mrad and all inclusive DIS events (r_{unc}) as a function of W^2 and x in different Q^2 bins as measured by ZEUS is shown in fig. 5. The ratios are flat, showing that the LN production mechanism exhibits the same x and Q^2 behaviour as the inclusive DIS cross section. Similar conclusions can be obtained from the measurement of LP [20] made by ZEUS and from the measurement of LB structure functions performed by H1 [21].

3.1 The LB structure function

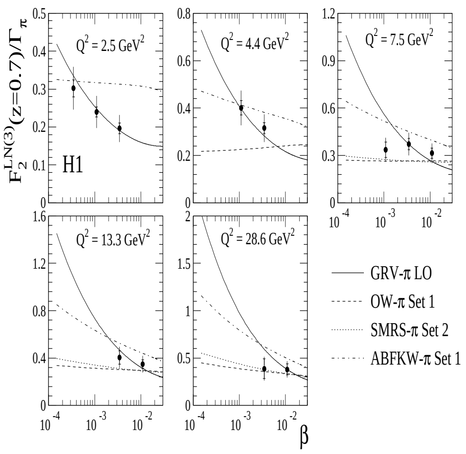
In analogy with the inclusive structure function F_2 the four-fold differential cross section for LB production may be written in terms of the semi-inclusive structure function $F_2^{LB(4)}$ as follows:

$$\frac{d^4\sigma}{dx dQ^2 dz dp_T^2} = 2\pi\alpha^2 x Q^2 (1 - y + \frac{y^2}{2}) F_2^{LB(4)}(x, Q^2, z, p_T^2).$$

where the fraction of the proton beam momentum carried by the LB is indicated as z. The LB structure function has been measured using the H1 data in



(A)



(B)

Figure 6: **(A)**: *LN and LP structure functions as a function of z in different Q^2 bins. The data are compared to a Regge model of which the composition into different contributions are superimposed.* **(B)**: $F_2^{LN(3)}/\Gamma_\pi(z)$ *plotted as a function of β for fixed values of Q^2. The data, which may be interpreted as being equal to the pion structure function F_2^π, are compared to different parametrisations.*

the region $z \geq 0.7$ and $p_T < 0.2$ GeV [21] and compared to the predictions of a Regge model based on $I\!P$, $I\!R$ and π exchange. For LP production π°, $I\!P$ and f_2 exchange have been considered, while for LN only π^+ are assumed [3]. For F_2^π, the GRV-LO [23] parametrisation has been used and it is assumed that [24]

$F_2^{I\!R} = F_2^{\pi}$ and $F_2^{I\!P} = 0.22 F_2^{I\!R}$ at low β. The comparison of the structure function with the different contributions is shown in fig. 6 (A). The LN data can be described by π^+ exchange alone, whereas for the LP data, the $I\!R$ exchange appears to contribute approximately 2/3 of the cross section; $I\!P$ exchange appears to became important only in the diffractive peak.

Since within the Regge model the LN cross section is saturated by π-exchange only, the measurement of F_2^{LN} at $z = 0.7$ and the p_T-integrated π flux factor $\Gamma_\pi(z) = \int dp_T f_{\pi/p}(z, p_T)$ can be used to estimate the π structure function F_2^{π} at low β values: $F_2^{\pi} \sim F_2^{LN(3)}(\beta, Q^2, z = 0.7)/\Gamma_\pi(z)$.

The estimated F_2^{π} within this model is shown in fig. 6 (B) in a previously unexplored low β region. The GRV-LO parametrisation [23] is consistent with the data.

4 Summary

Diffractive interactions have recently attracted a lot of interest, as the soft pomeron no longer describes all the diffractive data measured at HERA. Regge factorisation appears not to hold; this seems to be explained as the effect of additional subleading exchanges. The resulting pomeron intercept is higher than that in soft hadronic interactions starting from $Q^2 > 0.2$ GeV^2.

While pomeron exchange is a well-defined concept in Regge phenomenology, its picture in terms of partons is still an open question. The HERA results show that it is possible to describe inclusive diffraction in DIS with a factorisable model in which a pomeron structure function evolves with Q^2 according to the DGLAP evolution equations. Although the precise shape of the gluon distribution is not well constrained by the present measurements, the data exhibit some preference for a substantial gluon component in the pomeron.

The semi-inclusive structure function of LB shows the same x, Q^2 and W dependence as the inclusive structure function indicating the projectile-target factorisation. Moreover the standard fragmentation Monte Carlo models are not able to describe the data. The LB production in the non-diffractive region seems to be described by Regge-inspired models. Within this framework, the pion structure function may be measured in the low β region from the measured F_2^{LN}.

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