QCD in the Forward Region

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Abstract: We illustrate how improved detection in the forward region can give further knowledge on important unsolved problems of QCD dynamics at small-x and confinement. The physics issues considered are QCD multiparton emission (GLAP, BFKL), proton remnant hadronization and diffractive interactions. The possibility to investigate the transition from diffractive to non-diffractive events and obtain a 'continuous' description of the interaction dynamics is emphasized.

QCD at small-x. The current strong interest in QCD at small-x is likely to remain for some years, given the complexity and importance of the problems involved. The observables considered first, e.g. the rise of F_2 and the large forward transverse energy flow, are presently too inclusive to give decisive results. The measured forward transverse energy flow [1] is consistent with BFKL [2] dynamics, but can also be understood in terms of GLAP evolution [3] combined with non-perturbative hadronization effects [4]. Therefore, one needs to consider other observables and extended coverage of the forward phase space region.

The following results are obtained from Monte Carlo (MC) event simulations in neutral current deep inelastic scattering (DIS) at HERA (27.5 GeV e on 820 GeV p) in the kinematic region $Q^2 > 7\ \mathrm{GeV}^2$, $x > 10^{-4}$, $0.05 < y < 0.7$ (unless otherwise stated).

Fig. 1a shows the mean transverse energy ($E_\perp$) flow in pseudorapidity from the conventional GLAP-based LEPTO 6.5 [5] MC together with the ARIADNE 4.08 [6] MC based on the colour dipole model (CDM). Although CDM is not based on BFKL, it has a similar non-ordering of

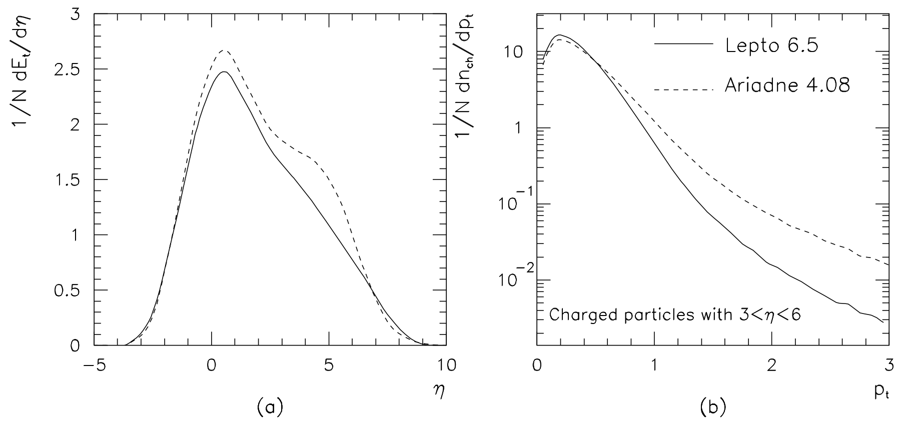

Figure 1: (a) Transverse energy flow in the laboratory system and (b) $p_\perp$ spectrum of charged particles with $3 < \eta < 6$ from LEPTO (solid) and ARIADNE (dashed).

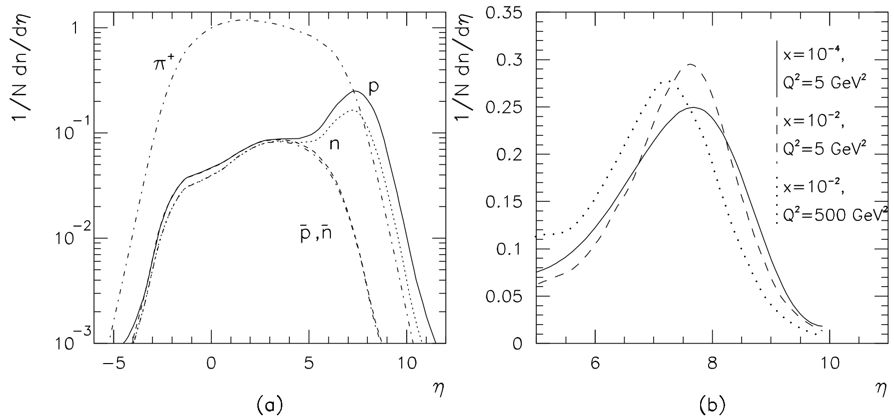

Figure 2: Pseudorapidity distributions in the laboratory frame from LEPTO for (a) various particle species and (b) protons at different fixed x and Q^2.

$p_\perp$ in the emissions, which combined with a low $p_\perp$-cutoff in the emissions gives a larger $E_\perp$ flow at large rapidities.

The present data only extend to $\eta \simeq 3$ and cannot demonstrate BFKL behaviour due to the uncertainties from hadronization effects. An extension of the detectable range would be helpful, but a decisive test may still be impossible using the transverse energy flow. The hadronization effects should not be so important for other less inclusive observables like the rate of forward jets or the tail of the $p_\perp$-distribution [7] of charged particles in a forward rapidity bin. This is illustrated in Fig. 1b, where emissions at high $p_\perp$ are suppressed for the GLAP-based model. Here, one should be more sensitive to few hard emissions in perturbative QCD rather than a cumulative effect from many soft particle emissions in the hadronization.

Proton remnant. Confinement and non-perturbative QCD are still major unsolved problems in particle physics. Related to this is the hadronization of the proton remnant. In MC models the remnant can be defined on the parton level as the proton 'minus' the parton that enters the hard scattering. Since the partons are not observable, the experimental definition of the remnant is not clear and cannot be made unambigously event-by-event, except in the case of large rapidity gaps (see below).

Fig. 2a shows pseudorapidity distributions of different particle species as obtained with LEPTO. This illustrates that a natural statistical definition of the remnant region is where $p - \bar{p} > 0$, i.e. at $\eta \gtrsim 5$. This is, however, model dependent given the uncertainties in how the remnant should be treated. This concerns, in particular, the case when the remnant is not a simple diquark, but a more complex parton system remaining when a sea quark or gluon interacted. The remnant can then have effects down to much more central rapidities [4]. These issues could be investigated by measuring very forward (anti)baryon spectra (see also Fig. 3d). The background of very forward charged pions (Fig. 2a) is quite large in the angular η-variable, but much less in terms of energy or momentum since the pions in general are much softer than the baryons (cf. Fig. 3d).

The variation of the proton spectrum with x and Q^2 shown in Fig. 2b is rather limited. This is expected as long as the remnant is considered a spectator relative to the hard scattering system. The leading proton spectrum is, therefore, not directly affected by the perturbative QCD radiation, which otherwise has substantial effects in the forward region as discussed above.

However, since the spectator system takes the remaining energy-momentum it is affected by the fraction going into the hard system and thereby indirectly by the QCD emissions. For the same x (dashed and the dotted lines in Fig. 2b) the proton spectrum is somewhat softer for larger Q^2. This allows more QCD radiation and thereby a larger momentum fraction for the parton from the proton and hence a softer proton spectrum.

Transition to diffraction. Although the observed rapidity gap events can be phenomenologically described in terms of Regge-based models of pomeron exchange, there are still theoretical problems in understanding the pomeron concept and its interaction mechanism. Moreover, the gap events are then described by one kind of model with no clear direct connection, or 'continuous' transition, to the models for normal DIS. The theoretical description should preferably contain both event types, and a smooth transition, within a common framework.

Recently introduced models [8,4] attempts to describe the rapidity gap events without using Regge or pomeron concepts. In the soft colour interaction (SCI) model [4], the main assumption is that the partons produced in the perturbative phase may exchange colour, through soft non-perturbative gluon exchange, with the colour field of the proton remnant. The hard scattering system may then become a colour singlet which is well separated from the colour singlet proton remnant system, i.e. a rapidity gap appears between them.

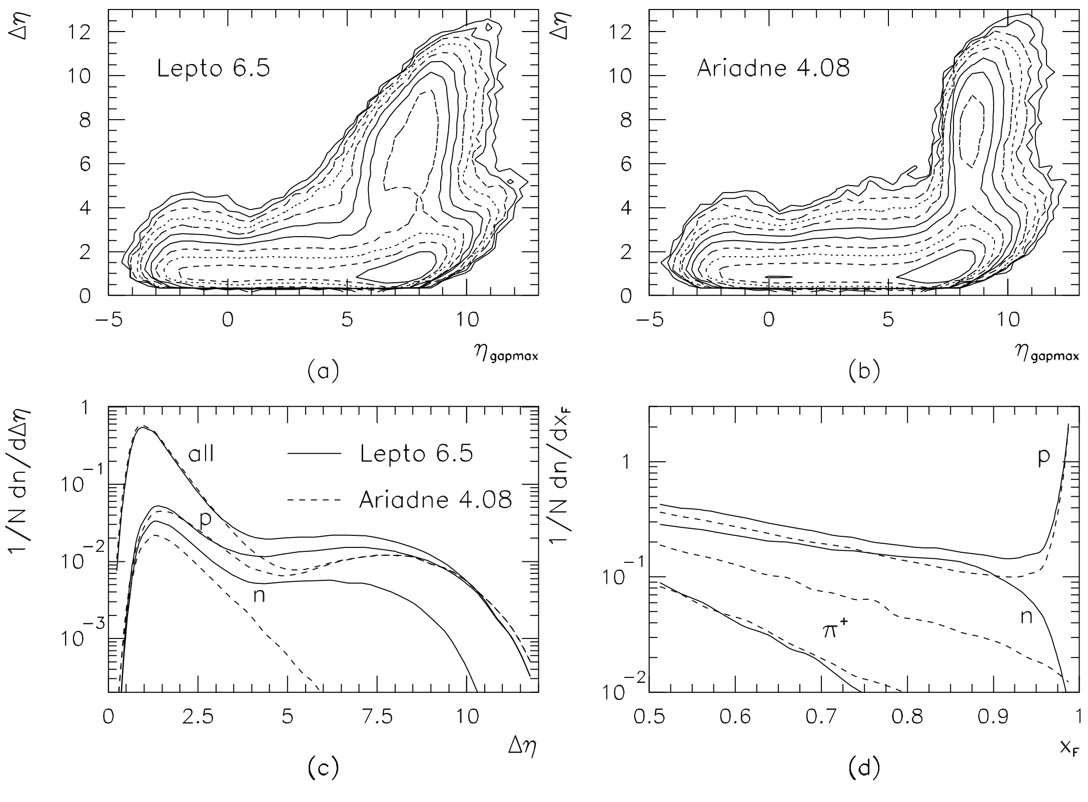

Figure 3: (a,b) Size ($\Delta\eta$) of the largest gap in each event versus the position of its upper edge (η_{gapmax}) with iso-lines showing changes by a factor two in the number of events per bin. (c) Distribution in $\Delta\eta$ for all events and those with a leading proton or neutron. (d) x_F-distribution for leading protons, neutrons and pions. Monte Carlo results from LEPTO (solid) with SCI and ARIADNE (dashed) representing models including pomeron exchange.

The position of the largest gap in the event is different in this model (Fig. 3a) as compared to a pomeron-based model (Fig. 3b). The latter gives a large rapidity gap by construction, as a kinematical consequence of a soft pomeron exchange, which gives a two-component structure in Fig. 3b when added to normal non-gap events. In the SCI model, on the other hand, gaps appear as random fluctuations and can be of arbitrary size, providing the smoother transition in Fig. 3a between smaller gaps at any rapidity and the large gaps ($\Delta\eta \gtrsim 4$) at very forward rapidities. The remainder system forward of the gap has a continuous mass spectrum, but for large gaps it is dominated by a proton (Fig. 3c) giving a characteristic diffractive peak (Fig. 3d). However, the continuum of higher mass states (see [4]) could describe proton dissociation, which in a Regge model must be added separately. Also leading neutrons emerge in the model as shown in Fig. 3cd, but give only a small contribution to the large-rapidity-gap events. This corresponds to pion exchange in Regge, which is not included in ARIADNE resulting in the exponential fall-off in Fig. 3c due to fluctuations in normal hadronization.

The development of a consistent theoretical description of both diffractive and normal DIS would benefit from measurements of these kinds of observables. In particular, dependences on the gap size, the properties of the forward system, leading particles and effective quantum number exchange over the gap etc. should then be considered.

Conclusions. Improved forward detection capabilities, both in coverage and quality (energy/momentum measurements and particle identification) would give new information of interest for several important physics issues:

- Novel perturbative QCD at small-x, e.g. BFKL dynamics may be observable through $E_\perp$ flow, jets or high-$p_\perp$ particles at very forward rapidities.
- Non-perturbative QCD and confinement, e.g. issues in connection with the hadronization of the proton remnant and its correlation with the hard interaction.
- The transition from diffractive to normal DIS events and a 'continuous' theoretical description of the interaction dynamics.

The forward rapidity region can be moved more into the detector by lowering the proton energy. With the lowest realistic beam energy of 300 GeV the forward region essentially moves about 1 unit of rapidity towards the center. Although this certainly helps to some extent, it does not give enough improved coverage for most of these issues. One should also realize that a limitation of the forward coverage, e.g. due to low-β insertions for increased luminosity, would essentially remove the discussed opportunities.

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