*Search for QCD-instanton-induced effects in deep inelastic electron proton scattering at HERA**

Gerd W. Buschhorn
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
80805 München, Germany

1 Introduction

QCD, in contrast to QED, is not exhausted by perturbation theory. While QCD perturbation theory appears to be very successful at higher momentum transfers where the strong coupling constant becomes small, some of the most fundamental properties of hadronic physics like color confinement and hadronization of quarks and gluons, characteristic for the low momentum transfer region, are not accessible to perturbative methods.

QCD is a nonabelian gauge theory. In 1975, Polyakov et al. [1] made the important discovery that such theories in their pure gauge form, i.e. without the involvement of spontaneous symmetry breaking, have localized classical solutions in Euclidean space-time. Since the objects described by these solutions are localized in 3+1 dimensions, they describe "events" rather than normal particles which are localized in 3 dimensions. Accordingly, they were named pseudoparticles by Polyakov [1] and instantons by 't Hooft [2]. The replacement of time t by ix_4 (real x_4) by going into Euclidean space corresponds to the method of calculating tunneling amplitudes in the nonperturbative WKB approximation, where the characteristic exponential suppression factor $\exp(-8\pi^2/g^2)$ is obtained from solving the classical equations for imaginary time. Instantons are, therefore, interpreted as tunneling events. The tunneling, of course, takes place in real (Minkowskian) space, although it is actually computed in Euclidean space. As was first realized by Ringwald and Espinosa [3], the exponential suppression of tunneling processes may be overcome at high energies by multiple emission of gauge bosons accompanying fermion production.

The tunneling events violate a conservation law that is obeyed by perturbative solutions: For the classical (BPST) solutions there exists a charge like quantity

$$\int d^4x F_{\mu\nu}\tilde{F}_{\mu\nu} = \pm\frac{32\pi^2}{g^2} \tag{1}$$

where $F_{\mu\nu}$ is the gauge field strength tensor and $\tilde{F}_{\mu\nu}$ its dual tensor. Since from the Adler-Bell-Jackiw axial triangle anomaly [4] $(g^2/16\pi^2)F_{\mu\nu}\tilde{F}_{\mu\nu}$ equals the anomalous divergence of the axial-vector divergence, tunneling events i.e. instantons connect states of different axial charge $Q_5(t) = \int d^3x J_0^A(x,t)$ and one obtains

$$\Delta Q_5 = Q_5(\infty) - Q_5(-\infty) = \int_{-\infty}^{+\infty} dt \int d^3x \partial_0 J_0^A(x) = \pm 2. \tag{2}$$

This relation holds separately for each flavour and for N_f flavours one has

$$\Delta Q_5 = \pm 2N_f. \tag{3}$$

Due to their topolocical nature (1) and (2) hold in Euclidean as well as in Minkowskian space-time. The violation of the conservation of axial charge i.e. helicity is a most significant property of instanton events.

The relevance of instantons for different aspects of hadronic physics has been reviewed recently [5]. In the following, we discuss recent work on the role of QCD-instantons in deep inelastic electron proton scattering.

2 Instantons in Deep Inelastic Electron Proton Scattering

Balitsky and Braun [6] first showed that the contribution of instanton (I)-induced processes to deep inelastic electron proton scattering from a real gluon calculated in Euclidean space and continued to Minkowski space, rises very rapidly with decreasing Bjorken-x. Their calculations were restricted, however, to $x > 0.3 - 0.35$. A detailed theoretical [7, 8, 9] and phenomenological [10, 11] investigation of deep inelastic scattering at HERA has been pursued by Ringwald, Schrempp and collaborators.

The leading I-induced process contibuting to deep-inelastic ep-scattering, given by a hard quark originating from the virtual photon and reacting in the presence of an instanton with a gluon from the proton, is shown in fig. 1.

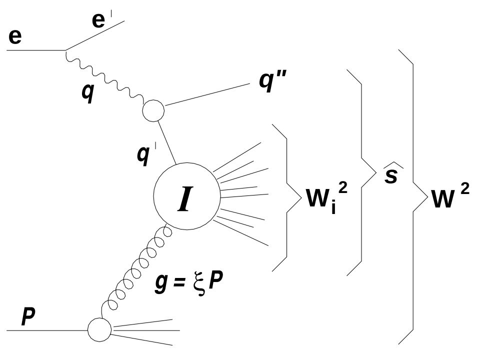

Figure 1: Leading graph for instanton-induced contribution to deep inelastic electron proton scattering. It denotes the instanton subprocess with the observables $Q'^2 = -q'^2 = -(q-q')^2$, $x' = Q'^2/2(g \cdot q')$, $W_i^2 = (q'+g)^2 = Q'^2(1-x')/x'$.

The corresponding contribution with a quark originating from the proton is suppressed by α_s^2 and can be neglected in the kinematical region of interest (see below), where the gluon density is high.

The inclusive deep-inelastic ep cross section in I-perturbation theory in the Bjorken limit can be approximated as

$$\frac{d\sigma_{ep}}{dx'dQ'^2} = \frac{d\mathcal{L}_{qg}}{dx'dQ'^2}\sigma^I_{gg}(x', Q'^2) \tag{4}$$

where $d\mathcal{L}_{qg}/dx'dQ'^2$ is a differential luminosity corresponding to a convolution-like integral over photon flux, quark flux and gluon density and σ^I_{qg} is the total cross section of the I-induced quark-gluon subprocess.

The critical part of (4) is the calculation of σ^I_{qg} which contains all I-dynamics. Outlining the essential dependencies, it can be written as [8, 9]

$$\sigma^I_{qg} = \int_0^\infty d\rho D(\rho) \int_0^\infty d\bar{\rho} D(\bar{\rho}) \int d^4 R e^{-Q'(\rho+\bar{\rho})} e^{i(p+q')\cdot R} \int dU e^{-\frac{4\pi}{\alpha_s}\Omega\left(\frac{R^2}{\rho\bar{\rho}}, \frac{\bar{\rho}}{\rho}, U\right)} \{...\} \tag{5}$$

where the integration is performed over the "collective coordinates" of the instanton i.e. the size ρ weighted with the density distribution function $D(\rho)$, the $I - \bar{I}$-distance vector R and the I- $\bar{I}$-relative colour orientation U. I as well as $\bar{I}$ enter here since the cross section results from the modulus squared of the amplitude for processes induced by single I resp. $\bar{I}$. The function Ω with the large factor $-4\pi/\alpha_s$ contains multiple emission of gluons. $D(\rho)$

is known in I-perturbation theory for $\alpha(\mu_r)\ln(\rho\mu_r) \ll 1$ where μ_r is the renormalization scale. $D(\rho)$ has a powerlaw behaviour.

$$D(\rho) \sim \rho^{6-\frac{2}{3}n_f+0(\alpha)} \tag{6}$$

which in general results in a breakdown of I-perturbation theory for large values of ρ. In deep inelastic scattering, however, the exponential term [7] containing Q' supresses the contribution form large size instantons and is the key for the applicability of I-perturbation theory.

For calculating the cross section for deep inelastic scattering DIS at HERA, the range of collective coordinates has to be known in which I-perturbation theory can be relied on. This range of collective coordinates then has to be translated into the relevant DIS-variables.

For estimating the range of validity of I-perturbation theory QCD lattice results from the UKQCD collaboration [12] have been extremely useful. Fig. 2a shows a comparison of I-perturbation theory with lattice-QCD in the continuum limit [9] for the I-size distribution. The normalization is practically independent on the renormalization scale μ_r, but strongly dependent on the value of $\Lambda_{\overline{MS}}$, for which the recent accurate result from the ALPHA collaboration [13] $\Lambda_{\overline{MS}(n_f=0)} = (238 \pm 19)$MeV has been taken. It has to be noted that the pertubative result is essentially parameter free. Fig. 2b shows the corresponding comparison for the $I-\bar{I}$-distance contribution. Very good agreement down to $I-\bar{I}$-distances $R/<\rho^{-}>\simeq 1$ is observed.

In the deep inelastic regime the integrals over collective coordinates are dominated by a unique saddle point [8] which relates the collective coordinates to the Bjorken variables Q', x' of the I-subprocess as

$$\rho^*, \bar{\rho}^* \sim 1/Q', \quad R^{*2} \sim 1/(p+q')^2 \rightarrow R^{*2}/\rho^*\bar{\rho}^* \sim Q'^2/(p+q')^2 = x'/1-x'. \tag{7}$$

The limits on the collective observables then transform into limits of the DIS variables in the following way:

$$\begin{array}{lcl} \rho^* \leq 0.30 - 0.35 fm & & Q'/\Lambda_{\overline{MS}} \geq 30.8 \\ & \rightarrow & \\ R^*/\rho^* \geq 1 & & x' \geq 0.35 \end{array} \tag{8}$$

With these cuts, additional general cuts of $x > 10^{-3}$ and $0.1 < y < 0.9$ and a "technical cut" of $Q'^2_{min} = Q^2_{min}$, in order to suppress contributions

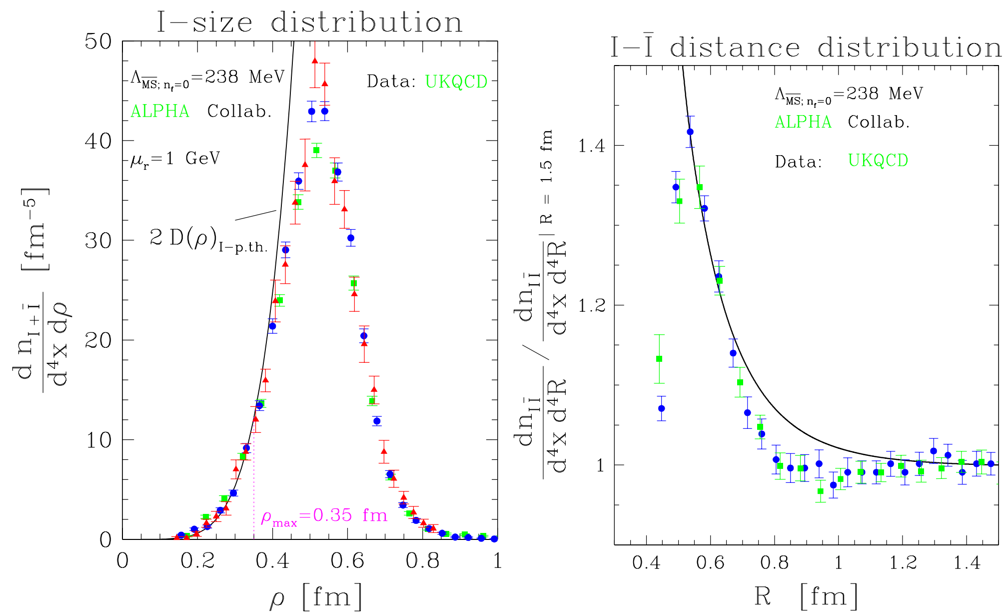

Figure 2: Comparison of "collective coordinates" obtained from instanton-perturbation theory (curve) with the continuum limit of equivalent lattice QCD data (points): a) $I(\bar{I})$-size distribution; b) $I-\bar{I}$-distance distribution, normalized to the value at $R = 1.5 fm$. From Refs. [9, 19]

from nonplanar graphs which are hard to calculate, a total cross section for I-induced events of 29 ± 10 pb is obtained, where the errors refer to the uncertainty in $\Lambda_{\overline{MS}}$ only. For a total integrated luminosity of about 100 pb^{-1}, which will be reached for each of the HERA experiments H1 and ZEUS by fall 2000, this corresponds to about 3.000 I-events. Since the total cross section for standard DIS events is several orders of magnitude higher it is evident, however, that a search of I-induced effects has to make use of specific event characteristics.

3 Search Strategies for I-induced Events at HERA

The Monte Carlo generator QCDINS [14], developed on the basis of the perturbative model discussed above for the detailed simulation of I-induced events, yields the following event characteristics [10]:

- a jet ("current jet") from the outgoing quark in the primary photon interaction (compare fig. 1)
- after removal of the current jet a uniformly populated band of hadrons in $\eta - \phi$-space (with the pseudorapidity η and the azimuthal angle ϕ) resulting nearly in isotropic decay in the hadronic CMS (defined by $\mathbf{q} + \mathbf{P} = 0$)
- high parton multiplicity (for 3 flavours: 3 $(q\bar{q})$-pairs; at α_s a mean value of $O(1/\alpha_s) \simeq 3$ gluons) resulting in a mean charged hadron multiplicity of about 20
- "flavour democracy" resulting in a significantly higher fraction of strange hadrons in I-induced than in standard DIS-events
- a higher total transverse momentum of $\simeq$5 GeV/η-unit as compared to $\simeq$ 2 GeV/η-unit for DIS-events [15]

A typical MC-event is shown in fig. 3.

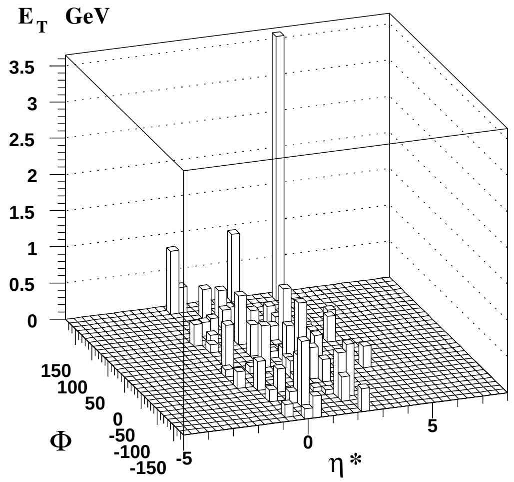

Figure 3: Distribution of the transverse energy E_T in pseudorapidity (η)-azimuthal (ϕ)-plane in the hadronic CMS for a typical instanton-induced HERA-event generated by QCDINS ($x = 0.0012, Q^2 = 66$ GeV$^2, p_T$(Jet) $=$ 3.6 GeV) after typical detector cuts. Clearly recognizable are the current jet at $\phi = 160^{\rm o}, \eta \simeq 3$ and the instanton band at $0 \lesssim \eta \lesssim 2$. From Ref. [11]

Search strategies for I-induced events in a background of normal DIS events based on Monte Carlo data have been discussed by Carli, Gerigk, Ringwald and Schrempp [11]. The aim is to enrich I-induced events in a data sample by cutting on selected observables while optimizing the separation power, defined as the ratio of the detection efficiencies for I-induced and DIS-events; in addition, a lower limit of 10% for the I-detection efficiency is required. Fig. 4 shows the optimization for the number of charged hadrons contained in the I-band after removal of the current jet.

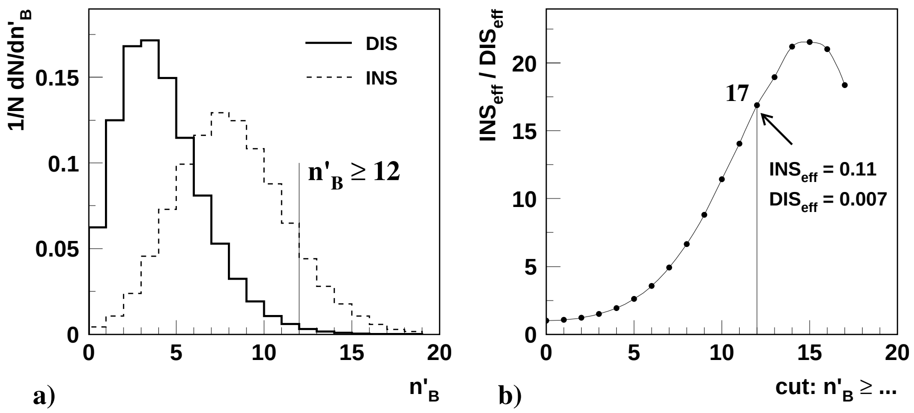

Figure 4: a) Normalized MC-generated distributions of the number of hadrons n'_B in the instanton band for instanton induced (INS) and normal events (DIS) after removal of the current jet hadrons. b) Maximum separation power INS_{eff}/DIS_{eff} as function of cuts on n'_B (see (a)) keeping the instanton efficiency INS_{eff} at $\geq 10\%$. From Ref. [11]

Cuts on single observables typically result in a separation power of $\lesssim 20$ and, therefore, cuts on several observables have to be combined in order to achieve a higher background reduction. Correlations among the different variables, however, tend to weaken the effect of combinations. For a set of 6 selected observables, which are shown in fig. 5, a separation power of about 130 was obtained.

4 Recent H1 Results

Based on this experience, the technique for enhancing I-induced events has recently been applied by the H1 collaboration to real data [16]: Out of a set of 6 observables a subset of 3 observables has been selected on which cuts are applied (called in the following "primary observables") while the effect

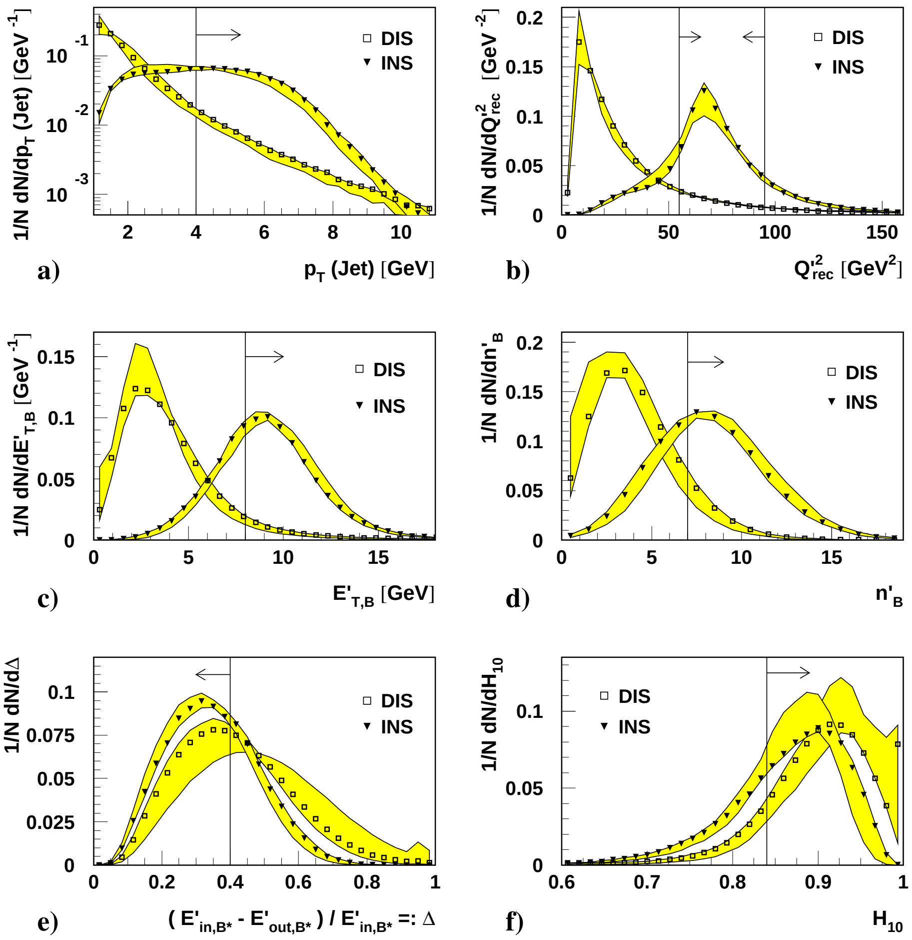

Figure 5: Normalized distributions of characteristics observables for normal DIS events (ARIADNE) and I-induced events (QCDINS + HERWIG). Shaded bands indicate model uncertainties, arrows show optimized cuts with the allowed region left of the cut. Variables: p_T and Q'^2 refer to the current jet (compare fig. 1), $E'_{T,B}$ and n'_B are the total transverse energy and number of hadrons, resp. in the I-band after removal of the current jet, Δ is a measure of the isotropy of events (see text). H_{10} are the Fox-Wolfram-moments. From Ref. [11]

of these cuts on the distributions of the other observables not subjected to cuts (called "secondary observables") is studied. The preliminary results are based on a total integrated luminosity of 15.8 pb^{-1} collected by H1 in 1997 and corresponding to about 260 k DIS-events within fixed cuts of $x >$

$10^{-3}, 0.1 < y < 0.6$ and $\Theta_e > 156^o$.

The primary observables chosen for the analysis were the number of hadrons n_b in the I-band, the sphericity Sph of the event in the hadronic CMS (both after removal of the current jet) and the squared momentum transfer Q'^2 of the I-subprocess (c.f. fig. 1). The normalized distribution of these observables are compared in fig. 6 with two quite different models for DIS processes, i.e. the colour dipole model CDM [17] and the matrix element-parton shower-model MEPS [18] as implemented in the Monte Carlo ARIADNE resp. RAPGAP. Agreement on the level of 5-20% is observed. The signal expected for I-induced events from QCDINS is $10^2 - 10^3$ below the DIS background.

A systematic investigation of the effect of cutting primary observables has been carried out. The following combinations of cuts have been studied: $n_b > 5, 6, 7, 8, 9$; $Sph > 0.4, 0.5, 0.55, 0.6, 0.65$; $Q'^2(\mathrm{GeV}^2)$: $95, 100, 105, 110, 115 < Q'^2 < 200$. The results have been classified in 3 scenarios: "A" for the highest instanton efficiency ϵ_{INS}, "B" for high instanton efficiency at good separation power $\epsilon_{INS}/\epsilon_{DIS}$ and "C" for the highest separation power at an instanton efficiency $\geq 10\%$ (see table 1).

Table 1:

Scen ario	Cuts			ϵ_{ins}	$\frac{\epsilon_{ins}}{\epsilon_{DIS}}$	
	$Q'^2(\mathrm{GeV}^2)$	Sph	n_b		CDM	MEPS
A	95.0-200.0	0.40	5	32%	35	34
B	105.0-200.0	0.40	7	21%	56	52
C	105.0-200.0	0.50	8	11%	86	71

As example, the effect of cut C on primary observables is shown in fig. 7. A background reduction by a factor of 600-800 is achieved. The remaining 549 events are to be compared with 362 ± 25 events expected from CDM and 435 ± 30 events from MEPS. For the resulting distributions the shape of the excess with respect to the DIS models is compatible with the QCDINS expectation. It has to be noted, however, that the excess is of the same magnitude as the difference between the two DIS models and that also the QCDINS prediction is subject to systematic uncertainties [19].

As secondary observables were chosen the total transverse energy E_{tb} of hadrons contained in the I-band, the transverse energy E_{tjet} of the current

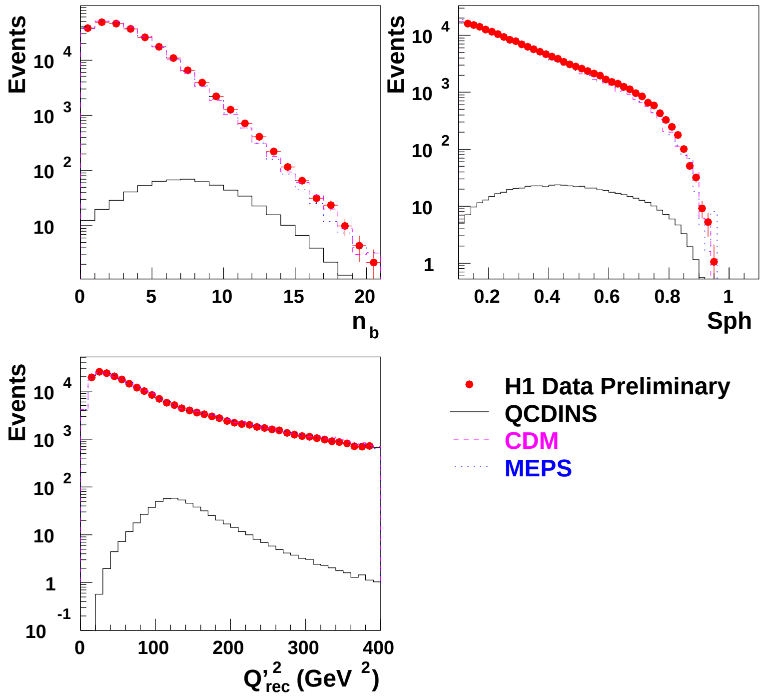

Figure 6: Observables used to cut ("primary observables"): Comparison of data with Monte Carlo (see text). From Ref. [16]

jet and a third quantity Δ_b, which is a measure for the isotropy of events [20, 21]. It is obtained by finding the two axes with respect to which the projection of all hadronic momenta (after removal of the current jet) is minimal (E_{in}) resp. maximal (E_{out}) and forming $(E_{in} - E_{out})/E_{in} = \Delta_b$. Δ_b measures the E_t-weighted azimuthal isotropy; it takes small values for isotropic events, expected for I-induced reactions, and large values for pencil-like 2-jet-events, expected to constitute a major fraction of the DIS-background.

The effect of cut C on the secondary observables is shown in fig. 8. While an excess of events over both DIS Monte Carlos is observed also here, differences in the shape of the distributions are recognizable; neither the shape of the DIS Monte Carlos nor the shape of the signal expected from QCDINS are well reproduced by the data.

These results do not yet allow any firm conclusion on a possible contribution of I-induced processes to deep inelastic electron proton scattering. Never-

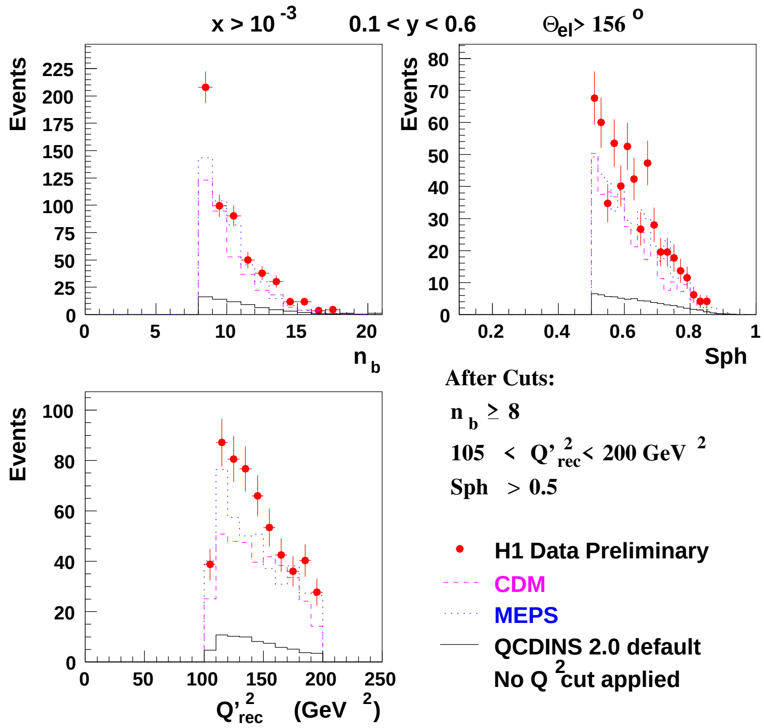

Figure 7: Observables used to cut ("primary observables") after cuts. From Ref. [16]

theless, the observed excess of events and the gross similarity between data and predictions are intriguing and motivate the continuation of these studies with higher statistics and further refined techniques. The ultimate signal of I-induced effects would consist, of course, in demonstrating the violation of helicity-conservation in DIS-events.

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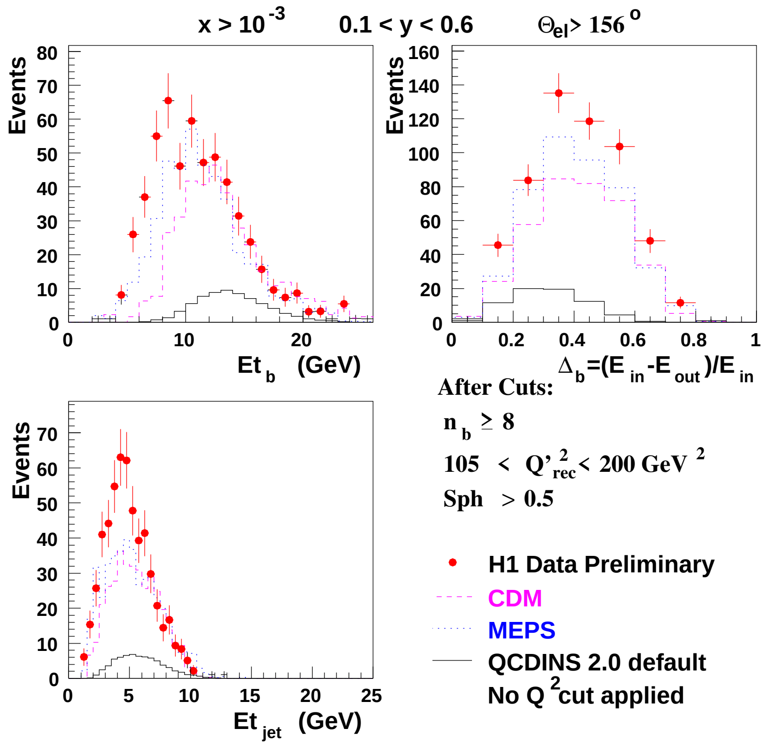

Figure 8: Observables not used to cut ("secondary observables") after cuts on "primary observables". From Ref. [16]

* Talk given at the Crimea Summer School Seminar "New Trends in High Energy Phyics", May 27 - June 4, 2000, Yalta (Mishkor)

References

[1] A. M. Polyakov, Phys. Lett. 59B (1975) 82, A. A. Belavin, A. M. Polyakov, A. S. Schwartz, Yu. S. Tyupkin, Phys. Lett. 59B (1975) 85

[2] G. 't Hooft, Phys. Rev. Lett. 37 (1976) 8, G. 't Hooft, Phys. Rev. D14 (1976) 3432

[3] A. Ringwald, Nucl. Phys. B330 (1990) 1, O. Espinosa, Nucl. Phys. B343 (1990) 310

[4] S. L. Adler, Phys. Rev. 177 (1969) 2426, J. S. Bell, R. Jackiw, Nuov. Cim. 60 (1969) 47

[5] T.V. Schäfer, E.V. Shuryak, Rev. Mod. Phys. 70 (1998) 323

[6] I. Balitsky, V. Braun, Phys. Lett. B438 (1993) 237

[7] S. Moch, A. Ringwald, F. Schrempp, Nucl. Phys. B507 (1997) 134

[8] A. Ringwald, F. Schrempp, Phys. Lett. B438 (1998) 217

[9] A. Ringwald, F. Schrempp, Phys. Lett. B459 (1999) 249

[10] A. Ringwald, F. Schrempp, hep-ph/9411217, in Quarks '94, eds. D. Yu. Grigoriev et al., World Scientific, Singapore 1995

[11] T. Carli, J. Gerigk, A. Ringwald, F. Schrempp, DESY 00-067, MPI-PhE/99-02, hep-ph/9906441, in Monte Carlo Generators for HERA Physics, eds. A. T. Doyle et al.

[12] D. A. Smith, M. J. Teper, Phys. Lett. D58 (1998) 014505

[13] S. Capitani, M. Lüscher, R. Sommer, H. Wittig (ALPHA Coll.), Nucl. Phys. B544 (1999) 669

[14] A. Ringwald, F. Schrempp, hep-ph/9911516, Comput. Phys. Commun. (1999) in print

[15] H1 Collaboration, S. Aid et al., Phys. Lett. B356 (1995) 118

[16] S. Mikocki (H1 Collaboration), 8th International Workshop on Deep Inelastic Scattering (DIS2000) in Liverpool, UK, June 2000, hep-ex/0007008

[17] B. Andersson, G. Gustafson, L. Lönnblad, U. Petterson, Z. Phys. C43 (1989) 625

[18] M. Bengtsson, T. Sjöstrand, Z. Phys. C37 (1998) 465

[19] A. Ringwald, F. Schrempp, 8th International Workshop on Deep Inelastic Scattering (DIS2000) in Liverpool, UK, June 2000, DESY 00-089, hep-ph/0006215

[20] M. Gibbs et al., in Proc. of the Workshop: Future Physics at HERA, eds. G. Ingelman et al., Vol. 1, p. 509, Hamburg 1996

[21] J. Gerigk, Diploma Thesis, MPI-PhE/98-20