DESY 98-115
hep-ph/9808482

hep-ph/9808482 31 Aug 1998

Instanton Searches at HERA*

A. Ringwald and F. Schrempp

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

The present status of our ongoing systematic study of the discovery potential of QCD-instanton induced events in deep-inelastic scattering at HERA is briefly reviewed. We emphasize our recent progress in predicting the cross-sections of instanton-induced processes. Our finalized predictions include a dramatic improvement of the residual renormalization-scale dependencies and the specification of a "fiducial" kinematical region in the relevant Bjorken variables extracted from recent lattice simulations. Published upper limits on instanton-induced cross-sections based on single observables in the final state such as the flow of strange particles and the multiplicity distribution of charged particles are already of the order of our estimate. Thus, a decisive search for instanton-induced events in deep-inelastic scattering at HERA, based on a multi-observable analysis, seems feasible.

*Talk presented at Quarks '98, 10th International Seminar on High Energy Physics, Suzdal, Russia, May 1998; to be published in the Proceedings.

1 Introduction

In this contribution, we briefly review the present status of our ongoing systematic study [1–6] of the discovery potential of QCD-instanton induced events in deep-inelastic scattering (DIS) at HERA.

Hard scattering processes in elementary particle physics are successfully described by the Standard Model of strong (QCD) and electro-weak (QFD) interactions in its perturbative formulation. However, perturbation theory does not exhaust all possible hard scattering processes.

Instantons [7], fluctuations of (non-abelian) gauge fields representing topology changing tunnelling transitions, induce interactions which are absent in conventional perturbation theory. In accord [8] with the general chiral anomaly relation, instantons give rise to (hard) processes in which certain fermionic quantum numbers are violated, notably, chirality (Q_5) in (massless) QCD and baryon plus lepton number ($B + L$) in QFD.

Implications of QCD-instantons for long-distance phenomena have been intensively studied in the past, mainly in the context of the phenomenological instanton liquid model [9] and of lattice simulations [10]. Yet, a direct experimental verification of their existence is lacking up to now. An experimental discovery of such a novel, non-perturbative manifestation of non-abelian gauge theories would clearly be of basic significance.

The deep-inelastic regime is distinguished by the fact that here hard QCD-instanton induced processes may both be *calculated* [11,2,1] within instanton-perturbation theory and possibly *detected experimentally* [3–6]. As a key feature it has recently been shown [2], that in DIS the generic hard scale $\mathcal{Q}$ cuts off instantons with *large size* $\rho \gg \mathcal{Q}^{-1}$, over which one has no control within perturbation theory in the instanton background.

2 Cross-Sections

The leading instanton (I)-induced process in the DIS regime of $e^{\pm}P$ scattering is displayed in Fig. 1. The dashed box emphasizes the so-called instanton-*subprocess* with its own Bjorken variables,

$$Q'^2 = -q'^2 \geq 0; \qquad x' = \frac{Q'^2}{2p \cdot q'} \leq 1. \tag{1}$$

The I-induced cross-section in unpolarized deep-inelastic $e^{\pm}P$ scattering,

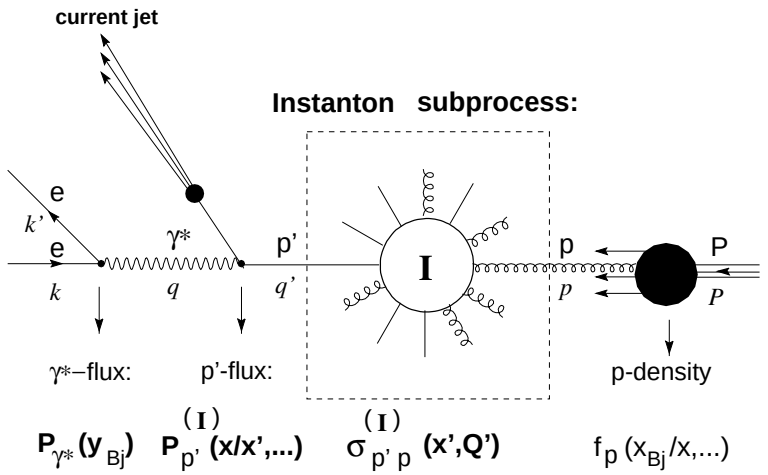

Figure 1: The leading instanton-induced process in the DIS regime of $e^{\pm}P$ scattering, violating chirality by $\triangle Q_5 = 2\,n_f$.

$d\sigma_{eP}$, can be shown to factorize [1] (in the Bjorken limit, $Q^2 = -q^2$ large) into a sum of differential parton-parton luminosities, $d\mathcal{L}^{(I)}_{p'p}$, and I-subprocess cross-sections, $\sigma^{(I)}_{p'p}$,

$$\frac{d\sigma^{(I)}_{eP}}{dx'\,dQ'^2} \simeq \sum_{p',p} \frac{d\mathcal{L}^{(I)}_{p'p}}{dx'\,dQ'^2}\,\sigma^{(I)}_{p'p}(x',Q'^2). \tag{2}$$

Here $p' = q', \overline{q}'$ denotes the virtual quarks entering the I-subprocess from the photon side and $p = q, \overline{q}, g$ denotes the target partons. The differential luminosity $d\mathcal{L}^{(I)}_{p'p}$, accounting for the number of $p'p$ collisions per eP collision, has a convolution-like structure [3], involving integrations over the target-parton density, f_p, the γ^*-flux, P_{γ^*}, and the *known* [5] flux $P^{(I)}_{p'}$ of the parton p' in the I-background.

In Eq. (2), the I-subprocess total cross-section $\sigma^{(I)}_{p'p}$ contains the essential instanton dynamics. We have evaluated the latter [1] by means of the optical theorem and the so-called $I\overline{I}$-valley approximation [12] for the relevant $q'g \Rightarrow q'g$ forward elastic scattering amplitude in the $I\overline{I}$ background. This method resums the exponentiating final state gluons in form of the known valley action $S^{(I\overline{I})}$ and reproduces standard I-perturbation theory at larger $I\overline{I}$ separation $\sqrt{R^2}$. While a semi-quantitative evaluation of $\sigma^{(I)}_{p'p}$ may also

be performed by means of standard I-perturbation theory, the use of the $I\overline{I}$-valley method allows to extend our calculations to a somewhat larger range in x'.

Corresponding to the symmetries of the theory, the instanton calculus introduces at the classical level certain (undetermined) "collective coordinates" like the $I\,(\overline{I})$-size parameters $\rho\,(\overline{\rho})$ and the $I\overline{I}$ distance $\sqrt{R^2/\rho\overline{\rho}}$ (in units of the size). Observables like $\sigma^{(I)}_{p'p}$ must be independent thereof and thus involve integrations over all collective coordinates. Hence, we have generically,

$$\begin{aligned}\sigma^{(I)}_{p'p} &= \int_0^\infty \mathrm{d}\rho\, D(\rho) \int_0^\infty \mathrm{d}\overline{\rho}\, D(\overline{\rho}) \int \mathrm{d}^4R \;\ldots \\ &\quad \times \mathrm{e}^{-(\rho+\overline{\rho})Q'} \mathrm{e}^{i(p+q')\cdot R} \mathrm{e}^{-\frac{4\pi}{\alpha_s}(S^{(I\overline{I})}(\xi)-1)}.\end{aligned} \tag{3}$$

The first important quantity of interest, entering Eq. (3), is the I-density, $D(\rho)$ (tunnelling amplitude). It has been worked out a long time ago [8,13] in the framework of I-perturbation theory: (renormalization scale μ_r)

$$D(\rho) = d\left(\frac{2\pi}{\alpha_s(\mu_r)}\right)^6 \exp\left(-\frac{2\pi}{\alpha_s(\mu_r)}\right)\frac{(\rho\,\mu_r)^b}{\rho^5}, \tag{4}$$

$$b = \beta_0 + \frac{\alpha_s(\mu_r)}{4\pi}(\beta_1 - 12\beta_0), \tag{5}$$

in terms of the QCD β-function coefficients, $\beta_0 = 11 - \frac{2}{3}n_f$, $\beta_1 = 102 - \frac{38}{3}n_f$. In this form it satisfies renormalization-group invariance at the two-loop level [13]. Note that the large, positive power b of ρ in the I-density (4) would make the integrations over the $I(\overline{I})$-sizes in Eq. (3) infrared divergent without the crucial exponential cut-off [2] $e^{-(\rho+\overline{\rho})\,Q'}$ arising from the virtual quark entering the I-subprocess from the photon side.

The second important quantity of interest, entering Eq. (3), is the $I\overline{I}$-interaction, $S^{(I\overline{I})} - 1$. In the valley approximation, the $I\overline{I}$-valley action, $S^{(I\overline{I})} \equiv \frac{\alpha_s}{4\pi}\,S[A^{(I\overline{I})}_\mu]$, is restricted by conformal invariance to depend only on the "conformal separation", $\xi = R^2/\rho\overline{\rho} + \rho/\overline{\rho} + \overline{\rho}/\rho$, and its functional form is explicitly known [12]. It is important to note that the interaction between I and $\overline{I}$ remains *attractive* for all separations ξ; specifically, the $I\overline{I}$-valley action decreases monotonically from 1 at infinite conformal separation to 0 at $\xi = 2$, which corresponds to $R^2 = 0$ and $\rho = \overline{\rho}$.

The collective coordinate integration in the cross-section (3) can be performed via *saddle-point techniques*. One finds $R^*_\mu = (\rho^*\sqrt{\xi^* - 2}, \vec{0})$ and

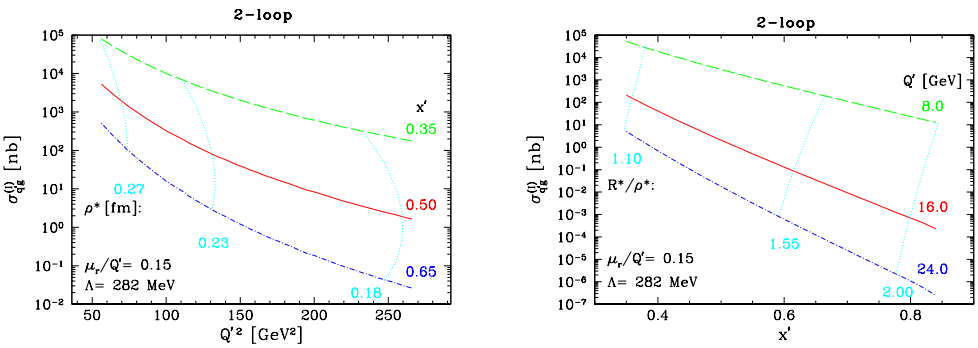

Figure 2: I-subprocess cross-section [1].

$\rho^* = \overline{\rho}^*$, where the saddle-point solutions ρ^* and ξ^* behave qualitatively as

$$\rho^* \sim \frac{4\pi}{\alpha_s Q'}; \qquad \sqrt{\xi^* - 2} = \frac{R^*}{\rho^*} \sim 2\sqrt{\frac{x'}{1-x'}}. \tag{6}$$

Thus, the virtuality Q' controls the $I(\overline{I})$-size: As one might have expected intuitively, highly virtual partons probe only small instantons. The Bjorken-variable x', on the other hand, controls the conformal separation between I and $\overline{I}$: for decreasing x', the conformal separation decreases.

Our quantitative results [1] on the *dominating* cross-section for a target gluon, $\sigma^{(I)}_{q'g}$, are shown in detail in Fig. 2, both as functions of Q'^2 (left) and of x' (right). The dotted curves in Fig. 2, indicating lines of constant ρ^* (left) and of constant R^*/ρ^* (right), nicely illustrate the qualitative relations (6) and their consequences: the Q' dependence essentially maps the I-density, whereas the x' dependence mainly maps the $I\overline{I}$-interaction.

Compared to our earlier estimates based on the one-loop renormalization-group invariant form [8] of the I-density $D(\rho)$, the residual dependence on the renormalization scale has now dramatically weakened (c.f. Fig. 3 (left)). This important stabilization of our predictions originates from the use of the *two-loop* renormalization-group invariant improvement (4, 5) of $D(\rho)$ from Ref. [13].

Intuitivelely one may expect [2,11] $\mu_r \sim 1/\langle\rho\rangle \sim Q'/\beta_0 = \mathcal{O}(0.1)\,Q'$. Indeed, this guess turns out to match quite well our actual choice of the "best" scale, $\mu_r = 0.15\ Q'$, determined by $\partial\sigma^{(I)}_{q'g}/\partial\mu_r \simeq 0$ (c.f. Fig. 3 (left)).

Important information about the range of validity of I-perturbation for

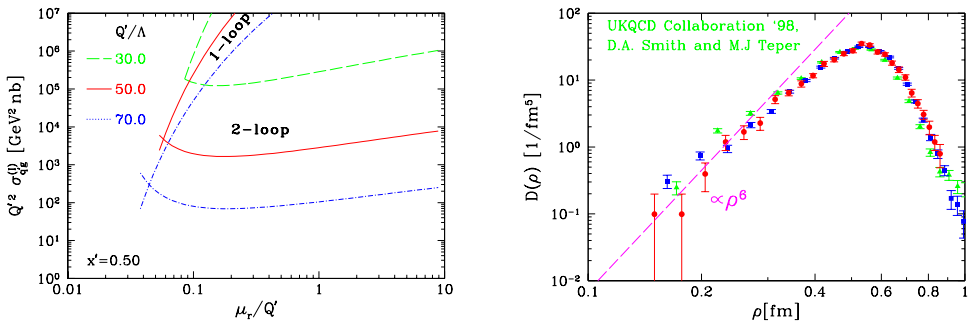

Figure 3: *Left:* Renormalization-scale dependence of the I-subprocess cross-section for a target gluon [1]. *Right:* Support for the validity of I-perturbation theory for the I-density $D(\rho)$ from recent lattice data [1,14].

the I-density and the $I\overline{I}$-interaction, in terms of the instanton collective coordinates ($\rho \leq \rho_{\rm max}, R/\rho \geq (R/\rho)_{\rm min}$), can be obtained from recent (non-perturbative) lattice simulations of QCD and translated via the saddle-point relations (6) into a "fiducial" kinematical region ($Q' \geq Q'_{\rm min}, x' \geq x'_{\rm min}$) [1]. In fact, from a comparison of the (one-loop) perturbative expression of the I-density (4) with recent lattice "data" [14] one infers [1] semi-classical I-perturbation theory to be valid for $\rho \lesssim \rho_{\rm max} \simeq 0.3$ fm (c.f. Fig. 3 (right)). Similarly, it can be argued [1] that the attractive, semi-classical valley result for the $I\overline{I}$-interaction is supported by lattice simulations down to a minimum conformal separation $\xi_{\rm min} \simeq 3$, i.e. $(R^*/\rho^*)_{\rm min} \simeq 1$. The corresponding "fiducial" kinematical region for our cross-section predictions in DIS is then obtained as [1]

$$\left.\begin{array}{lcl} \rho^* & \lesssim & 0.3 \text{ fm}; \\ \frac{R^*}{\rho^*} & \gtrsim & 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} Q' & \geq & Q'_{\rm min} \simeq 8 \text{ GeV}; \\ x' & \geq & x'_{\rm min} \simeq 0.35. \end{array}\right. \tag{7}$$

Fig. 4 displays the finalized I-induced cross-section at HERA, as function of the cuts $x'_{\rm min}$ and $Q'_{\rm min}$, as obtained with the new release "QCDINS 1.6.0" [6] of our I-event generator. For the following "standard cuts",

$$\mathcal{C}_{\rm std} = x' \geq 0.35, Q' \geq 8\,{\rm GeV}, x_{\rm Bj} \geq 10^{-3}, 0.1 \leq y_{\rm Bj} \leq 0.9, \tag{8}$$

including the minimal cuts (7) extracted from lattice simulations, we specifically obtain

$$\sigma^{(I)}_{\rm HERA}(\mathcal{C}_{\rm std}) \;=\; 126^{+300}_{-100}\ {\rm pb}, \tag{9}$$

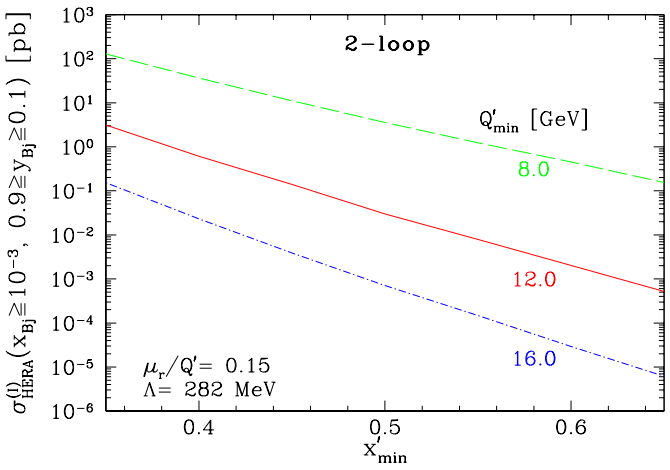

Figure 4: I-induced cross-section at HERA [1].

where the uncertainties result mainly from the experimental uncertainty in the QCD scale Λ. Hence, with the total luminosity accumulated by experiments at HERA, $\mathcal{L} = \mathcal{O}(80)$ pb^{-1}, there should be already $\mathcal{O}(10^4)$ I-induced events from the kinematical region (8) on tape. Note also that the cross-section quoted in Eq. (9) corresponds to a fraction of I-induced to normal DIS (nDIS) events of

$$f^{(I)}(\mathcal{C}_{\rm std}) = \frac{\sigma^{(I)}_{\rm HERA}(\mathcal{C}_{\rm std})}{\sigma^{\rm (nDIS)}_{\rm HERA}(\mathcal{C}_{\rm std})} = \mathcal{O}(1)\,\%. \tag{10}$$

Thus, it appears to be a question of *signature* rather than a question of *rate* to discover I-induced scattering processes at HERA. Hence, we turn next to the *final states* of I-induced events in DIS.

3 Searches at HERA

A Monte-Carlo generator, QCDINS, for instanton-induced events in DIS, interfaced to HERWIG, has been developed [4–6]. The Monte-Carlo simulation essentially proceeds in three steps. First, quasi-free partons are produced by QCDINS with the distributions prescribed by the hard process matrix elements. Next, these primary partons give rise to parton showers, as described

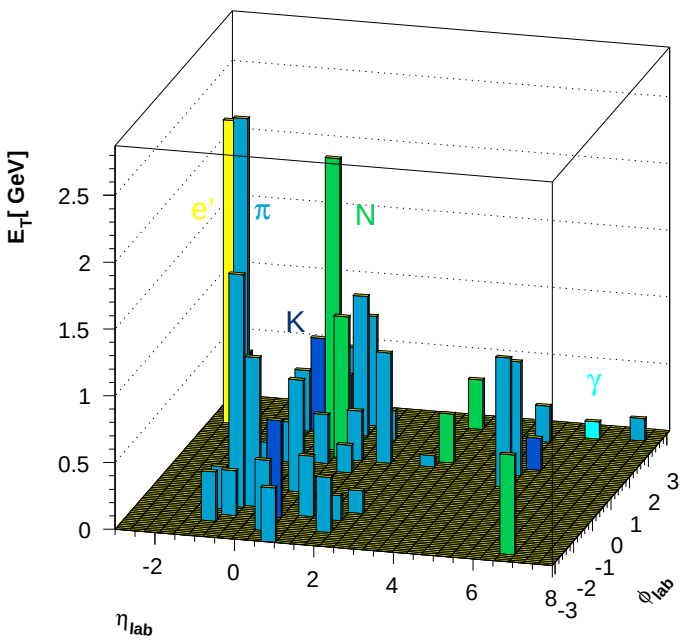

Figure 5: Lego plot of a typical I-induced event in the HERA lab system.

by HERWIG. Finally, the showers are converted into hadrons, again within HERWIG.

In Fig. 5 we display the lego plot of a typical I-induced event at HERA, as generated by QCDINS. Its characteristics directly reflect the essential features of the underlying I-subprocess and thus may be intuitively understood:

After hadronization, the current quark in Fig. 1 gives rise to a current-quark jet. No further distinct qjets are expected, since the partons from the I-subprocess are emitted spherically symmetric in the $p'p$ c.m. system ("I-c.m. system"). The gluon multiplicities are generated according to a Poisson distribution with mean multiplicity $\langle n_g \rangle^{(I)} \sim 1/\alpha_s \sim 3$. In view of the large required chirality violation $\Delta Q_5 = 2n_f = 6$, the total mean parton multiplicity is large, of the order of ten. After hadronization, we therefore expect from the I-subprocess a final state structure reminiscent of a decaying fireball: $\gtrsim$20 hadrons are produced, always including *strange* ones. They are concentrated in a "band" at fixed pseudorapidity η in the (η, azimuth angle ϕ)-plane. Due to the boost from the I-c.m. system to the HERA-lab system, the center of the band is shifted away from $\eta = 0$. Its width is of order

$\Delta\eta \simeq 1.8$, as typical for a spherically symmetric event. For $x' \simeq 0.35$ and $Q' \simeq 8$ GeV, the total invariant mass of the I-system, $\sqrt{s'} = Q'\sqrt{1/x' - 1}$, is expected to be in the 10 GeV range. All these expectations are clearly reproduced by our Monte-Carlo simulation.

These features have been exploited by experimentalists at HERA to place first upper limits on the fraction of I-induced events to normal DIS events, in a similar kinematical region as our standard cuts (8): From the search of a K^0 excess in the "band" region, the H1 Collaboration could establish a limit of $f_{\rm lim}^{(I)} = 6$ %, while the search of an excess in charged multiplicity yields $f_{\rm lim}^{(I)} = 2.7$ % [15]. The limit from the charged multiplicity distribution has been further improved in Ref. [16] to about 1 %.

Since these experimental upper limits already range close to our estimate (10), it becomes extremely interesting to investigate further possibilities to discriminate I-induced from nDIS final states. A dedicated multi-observable analysis is in progress, with the aim of producing an instanton-enriched data sample. Furthermore, strategies to reconstruct x' and Q'^2 from the final state are being developped.

Altogether, a *decisive* search for I-induced at HERA appears to be feasible.

References

[1] A. Ringwald and F. Schrempp, DESY 98-081, hep-ph/9806528, *Phys. Lett.* B, in press.

[2] S. Moch, A. Ringwald and F. Schrempp, *Nucl. Phys.* B **507**, 134 (1997).

[3] A. Ringwald and F. Schrempp, DESY 94-197, hep-ph/9411217, in: Proc. *Quarks '94*, Vladimir, eds. D. Gigoriev et al., pp. 170-193.

[4] M. Gibbs, A. Ringwald and F. Schrempp, hep-ph/9506392, in: *Proc. DIS 95*, Paris, eds. J.-F. Laporte and Y. Sirois, pp. 341-344.

[5] A. Ringwald and F. Schrempp, DESY 97-115, hep-ph/9706399, in: *Proc. DIS 97*, Chicago, eds. J. Repond and D. Krakauer, pp. 781-786.

[6] T. Carli, A. Ringwald and F. Schrempp, in preparation.

[7] A. Belavin, A. Polyakov, A. Schwarz and Yu. Tyupkin, *Phys. Lett.* B **59**, 85 (1975).

[8] G. 't Hooft, *Phys. Rev. Lett.* **37**, 8 (1976); *Phys. Rev.* D **14**, 3432 (1976); *Phys. Rev.* D **18**, 2199 (1978) (Erratum).

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

[10] P. van Baal, *Nucl. Phys. (Proc. Suppl.)* **63**, 126 (1998).

[11] I. Balitsky and V. Braun, *Phys. Lett.* B **314**, 237 (1993).

[12] A. Yung, *Nucl. Phys.* B **297**, 47 (1988);
V.V. Khoze and A. Ringwald, *Phys. Lett.* B **259**, 106 (1991);
J. Verbaarschot, *Nucl. Phys.* B **362**, 33 (1991).

[13] T. Morris, D. Ross and C. Sachrajda, *Nucl. Phys.* B **255**, 115 (1985).

[14] D. Smith and M. Teper, hep-lat/9801008, *Phys. Rev.* D **58**, (1998).

[15] S. Aid *et al.*, H1 Collaboration, *Nucl. Phys.* B **480**, 3 (1996); *Z. Phys.* C **72**, 573 (1996);

[16] T. Carli and M. Kuhlen, *Nucl. Phys.* B **511**, 85 (1998).