Search Strategies for Instanton-Induced Processes at HERA

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Abstract: We study the discovery potential for QCD-instanton induced events at HERA. A significant enhancement of the signal compared to the perturbative QCD background may be achieved by merging searches for an excess in strangeness production and multiplicity with information on the expected event shape. While first (preliminary) estimates of the production rates for instanton-induced events are surprisingly large, an upgrade in luminosity appears to be most important, in view of the inherent theoretical uncertainties in the estimates.

1 Introduction

Instantons [1] are known to represent tunnelling transitions in non-abelian gauge theories between degenerate vacua of different topology. These transitions induce processes which are *forbidden* in perturbation theory, but have to exist in general [2] due to Adler-Bell-Jackiw anomalies. The experimental discovery of such a novel, non-perturbative manifestation of non-abelian gauge theories would clearly be of basic significance.

Searches for instanton-induced processes have received new impulses during recent years: It was shown [3] that the natural exponential suppression of these tunnelling rates, $\propto \exp(-4\pi/\alpha)$, may be overcome at *high energies*. Furthermore, deep inelastic scattering (DIS) at HERA offers a unique window [4, 5, 6, 7] to experimentally detect processes induced by *QCD-instantons*. Here, a theoretical estimate of the corresponding production rates also appears feasible [4, 7, 8], since a well defined instanton contribution in the regime of small QCD gauge coupling may be isolated on account of the photon virtuality Q^2.

In this brief report we concentrate on improved search strategies for instanton-induced events at HERA. The main idea is to merge searches for an excess in strangeness production and multiplicity with information on the expected event *shape* (Sect. 3). Our results are based on the instanton Monte-Carlo generator [6, 9] QCDINS 1.3.

While first (preliminary) estimates of the production rates for instanton-induced events at HERA [7, 8] are surprisingly large (Sect. 2), an upgrade in luminosity appears to be most important, in view of the inherent theoretical uncertainties in the estimates.

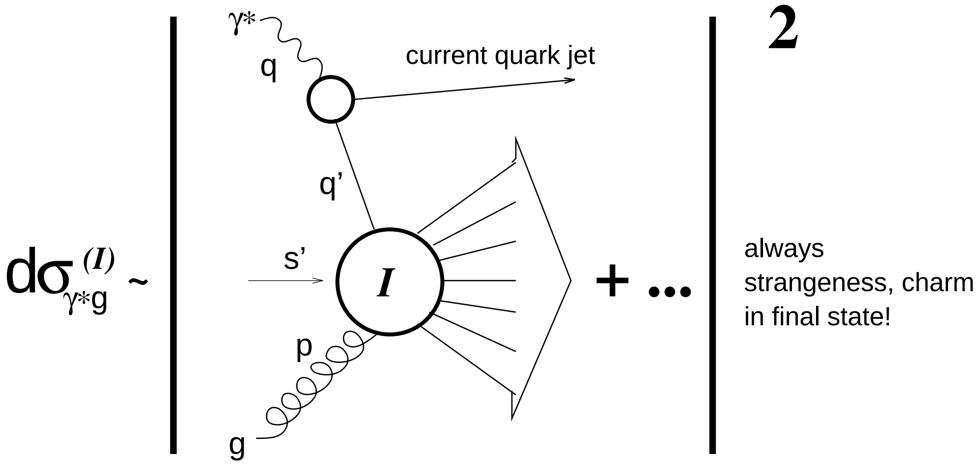

Figure 1: *Instanton-induced contribution to the cross-section of $\gamma^* g$ scattering exhibiting the structure of an I-induced subprocess, denoted by "I".*

2 Instanton-Induced Cross-Sections

The instanton (I) contribution to hadronic observables (e.g. cross-sections) is described in terms of a standard convolution of corresponding partonic observables with parton densities [5, 7, 8]. Therefore, let us confine our theoretical discussion to the partonic level. The generic structure of the I-contribution to the (dominating) $\gamma^* g$ cross-section $d\sigma^{(I)}_{\gamma^* g}(x, Q^2, \ldots)$ is displayed in Fig. 1. The apparent structure of an I-subprocess with cross-section $d\sigma^{(I)}_{q^* g}$ is due to the fact that the virtual photon only couples to instantons via their quark content.

A standard evaluation [10] of the I-contribution to the total $q^* g$ cross-section leads to the result [8]

$$\sigma^{(I)}_{q^* g}(x', Q'^2) \simeq \frac{\Sigma(x')}{Q'^2} \left(\frac{4\pi}{\alpha_s(\mu(Q'))}\right)^{21/2} \exp\left[-\frac{4\pi}{\alpha_s(\mu(Q'))} F(x')\right] , \tag{1}$$

where primed variables such as $Q'^2 = -q'^2$ and $x' = Q'^2/(s' + Q'^2) \geq x \geq x_{\rm Bj}$ always refer to the I-subprocess. The running scale $\mu(Q')$ in α_s, satisfying $\mu(Q') = \kappa\, Q' \alpha_s(Q')/(4\pi)$ with $\kappa = \mathcal{O}(1)$, plays the rôle of an effective renormalization scale. The x' dependence resides in the functions $\Sigma(x')$ and the so-called "holy-grail" function $F(x') \leq 1$, which are both known as low-energy expansions in $s'/Q'^2 = (1-x')/x' \ll 1$ within conventional I-perturbation theory. Their form implies a rapid growth of $\sigma^{(I)}_{q^* g}$ for decreasing x'. Unfortunately, in the phenomenologically most relevant region of small x', the perturbative expressions are of little help and we have to resort to some extrapolation based on a suitable resummation technique.

An appropriate approach to resumming instanton perturbation theory is the $I\bar{I}$-valley approximation [11, 10] which we have adopted. It amounts to the identification of the holy-grail function with the known $I\bar{I}$-valley action. It appears reasonable to trust this method down to $x' = 0.2$, where $F(0.2) \equiv S_{I\bar{I}-\rm valley}(0.2) \simeq 1/2$, a value sometimes advocated [12] as the lower bound for the holy-grail function. An important phenomenological/experimental task will be to make sure (e.g. via kinematical cuts on the final state) that x' does not become too small.

Note the following important feature of $\sigma^{(I)}_{q^* g}$ as a function of Q'^2: The Q'^2 dependences from the high inverse power of α_s and the exponential in Eq. (1) compete to produce a strong peak

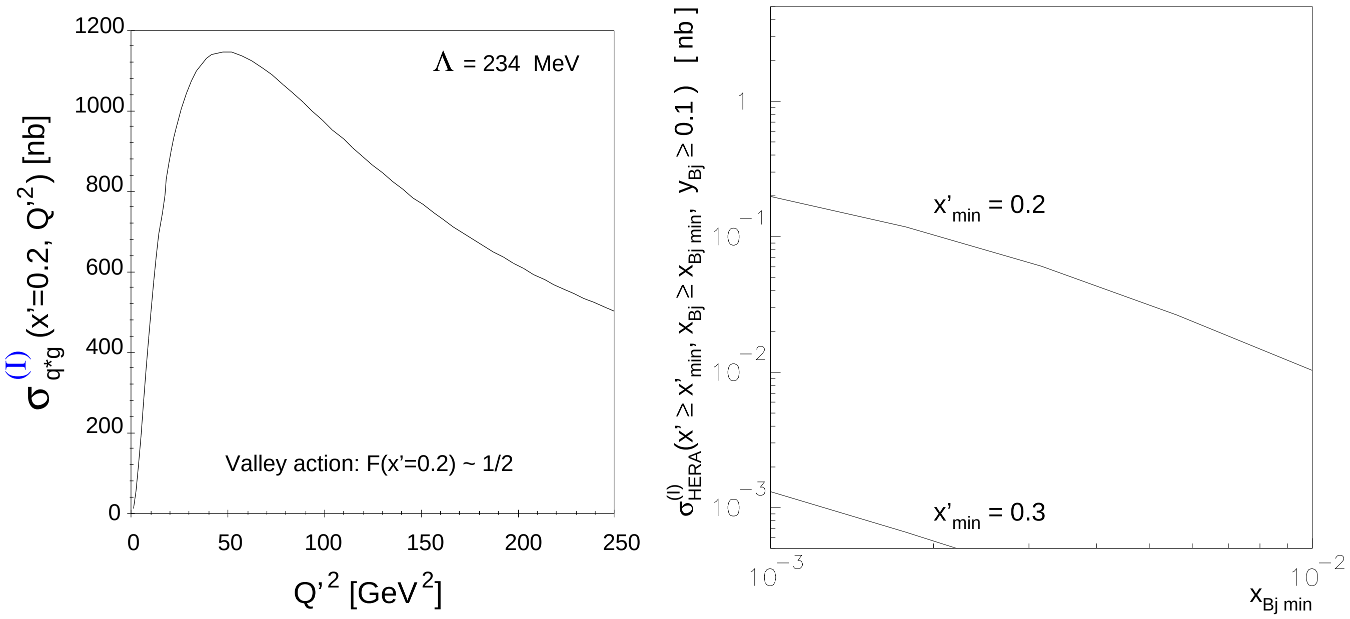

Figure 2: *Left:* Q'^2 *dependence of the total cross-section,* $\sigma^{(I)}_{q^*g}(x', Q'^2)$*, for fixed* $x' = 0.2$*. Right:* I*-induced total cross-section for HERA (preliminary) with various cuts.*

far away from the IR region, e.g. $Q'_{\rm peak}(x' = 0.2) \approx 31\,\Lambda$. This implies that in the Bjorken limit $\sigma^{(I)}_{\gamma^* g}(x, Q^2)$ is dominated by this peak, since it involves an integration over Q'^2. This strongly peaked structure also feeds through into the invariant-mass distribution ($\sqrt{s'}$) of the I-subprocess, via $s' \simeq Q'^2(1/x'_{\rm min} - 1)$, an important feature for the search strategies to be discussed below.

In Fig. 2 (right) we present the resulting I-induced total cross section for HERA for two values (0.2, 0.3) of the lower x' cut (c.f. discussion above), as a function of the minimal Bjorken x considered. It is surprisingly large. So far, only the (dominating) gluon contribution has been taken into account. The inherent uncertainties associated with the renormalization/factorization scale dependences may be considerable and are presently being investigated. Therefore, the results in Fig. 2 are still to be considered preliminary.

3 Search Strategy

The typical I-induced event (Fig. 3) from the Monte-Carlo generator [9] QCDINS 1.3, illustrates most of the important features characteristic for the underlying instanton mechanism: A current-quark jet along with a densely populated hadronic "band" of width $\triangle\eta = \pm 0.9$ in the $(\eta_{\rm lab}, \phi_{\rm lab})$-plane [5]. The band reflects the *isotropy* in the I-rest system. The total $E_T = \mathcal{O}(20)$ GeV is large as well as the multiplicity, $N_{\rm band} = \mathcal{O}(25)$. Finally, there is a characteristic flavour flow: All (light) flavours are democratically represented [2] in the final state. Therefore, strongly enhanced rates of K^0's and μ's (from strange and charm decays) represent crucial signatures for I-induced events.

The search strategy proposed here relies upon two characteristics of the hadronic final state in I-induced DIS, namely:

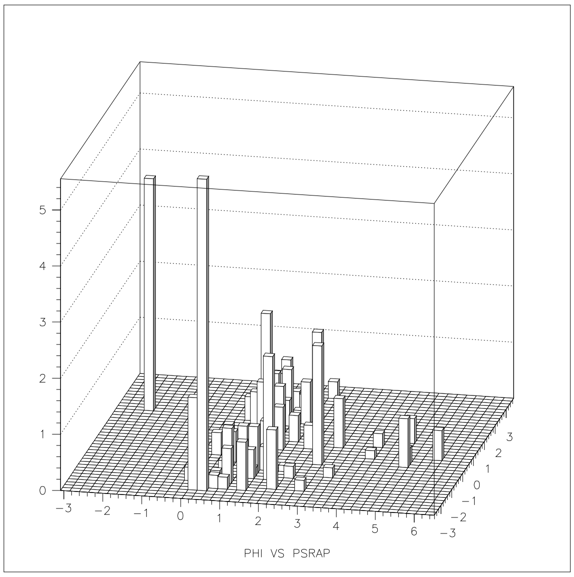

Figure 3: *Lego plot* $(\eta_{\rm lab}, \phi_{\rm lab}, E_T[{\rm GeV}])$ *of a typical I-induced event in the HERA-lab system at* $x_{\rm Bj} = 10^{-3}$.

1. The event shape, which is determined by the isotropic production [5] of large numbers of partons and hence hadrons, in the I-subprocess rest frame.

2. The democratic production of all kinematically allowed quark flavours.

The former allows an experimental estimate of $\sqrt{s'}$ to be made. In a frame in which the virtual photon (γ^*) and the proton (P) are collinear, such as the $\gamma^* P$ centre-of-mass frame, it is easy to show that $\sqrt{s'}/2 = E_{out} = \sum_n^N |\vec{p}_n \cdot \hat{\imath}|$, where the E_n are the energies of the N final state hadrons (assumed massless) and $\hat{\imath}$ is a unit vector normal to the $\gamma^* P$ direction, $\hat{k}$, chosen such that the sum is minimised. Large values of E_{out} occur in I-induced events, whereas in (1+1) or (2+1) jet DIS events (where the +1 refers to the proton remnant) E_{out} only receives contributions due to the k_T spread of the jets. In addition, in $(1+1)$ jet events E_{in} is small, where $E_{in} = \sum_n^N |\vec{p}_n \cdot \hat{\jmath}|$ with $\hat{\imath} = \hat{\jmath} \times \hat{k}$. Events with $(2+1)$ jets have $E_{out} << E_{in}$, whereas $E_{out} \lesssim E_{in}$ for I-induced events (isotropy). The separation obtainable using E_{out} and E_{in} between events arising from higher order QCD processes, leading to the production of three or more jets, and I-induced events can be enhanced by calculating E'_{out} and E'_{in} using only hadrons in a limited range of pseudorapidity, close to the pseudorapidity at which the transverse energy is maximal. This modification is effective as the isotropic distribution of energy in the I-subprocess centre-of-mass leads to a peaked E_{out} distribution in the $\gamma^* P$ frame, with a full-width half-maximum $\sim$ 1.5 units of pseudorapidity, whereas the jets produced in higher-order QCD processes may be spread over a large pseudorapidity range. The power of an I-induced event selection based upon event shape is illustrated in Fig. 4 as is the correlation between the I-subprocess centre-of-mass energy and $2E_{out}$. The values of E_{out} and E_{in} were calculated using hadrons within 1.5 units of pseudorapidity of the mean E_T weighted pseudorapidity. The QCDINS 1.3 Monte Carlo was used to simulate the I-induced events and standard DIS was simulated using HERWIG [13]. Nominal HERA detector acceptance cuts were applied, but no allowance was made for finite detector resolution. The separation illustrated in the figure is thus better than that obtainable using the HERA detectors.

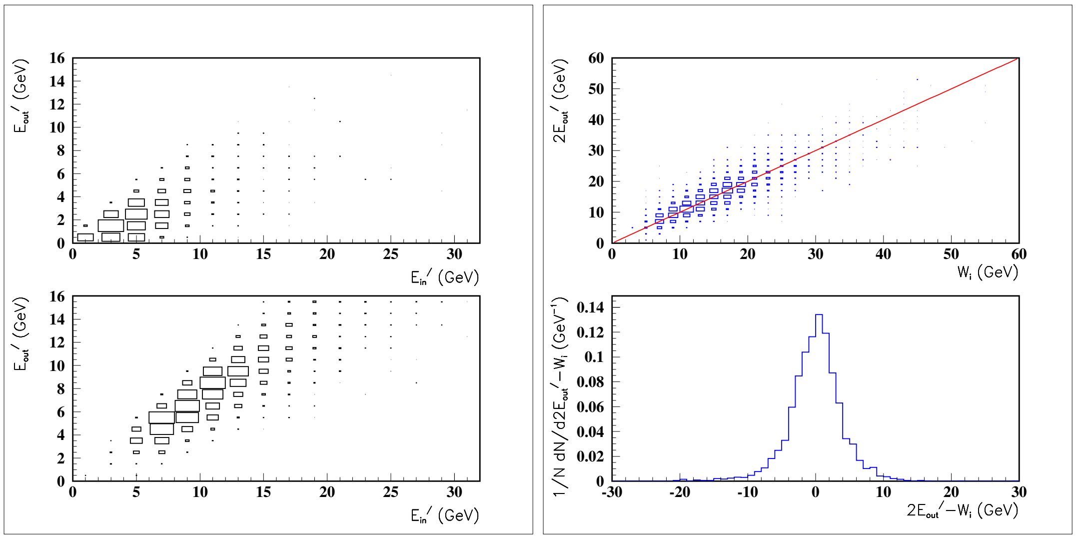

Figure 4: *Left: Distribution of I-induced (lower plot) and standard DIS events in the* (E'_{in}, E'_{out}) *plane with logarithmic z scale for the kinematic region* $0.001 < x < 0.01$, $0.1 < y < 0.6$ *and* $20 < Q^2 < 70\ GeV^2$. *Right: Correlation between* $2E_{out}$ *and the I-subprocess centre-of-mass energy,* $W' = \sqrt{s'}$.

The production of large numbers of partons in the I-subprocess also leads to large charged particle multiplicities in the hadronic final state (c.f. Fig. 3). This is of particular interest for an instanton search if the HERA detectors can extend their multiplicity measurements to include the region covered by the forward trackers.

The second characteristic of I-induced DIS events, their flavour democracy, has been used by the H1 collaboration in a recent study of strange particle production in DIS [14]. Instanton-induced events contain more strange particles than standard DIS events. The H1 measurements showed no evidence for anomalous K^0 production and hence it was possible to place an upper limit of 0.9 nb on the cross-section for I-induced DIS.

A second feature associated with the flavour democracy of I-induced events is the large number of muons they contain. These result largely from the decay of charmed particles. Unfortunately their energies are rather low, the transverse momenta of the muons in the laboratory frame is typically less than 1.5 GeV, and hence their detection is a challenging task for the experimenters.

4 Conclusions

The cross-section for instanton-induced processes in DIS at HERA is surprisingly large. Current cross-section estimates do, however, contain large uncertainties. The isotropy of the hadron production in the instanton subprocess rest frame and the democratic flavour production make a search for instanton-induced events using event shape, multiplicity and particle identification a feasible proposition. Given the uncertainties in the cross-section estimates, of highest priority for this search is the total luminosity available. Upgrades to the tracking in the forward region of the HERA detectors could improve their sensitivity to instanton-induced events, but little is gained by upgrades to the calorimetry in the forward direction.

References

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

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

[3] A. Ringwald, *Nucl. Phys.* B **330** (1990) 1;
O. Espinosa, *Nucl. Phys.* B **343** (1990) 310.

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

[5] A. Ringwald and F. Schrempp, DESY 94-197, hep-ph/9411217, in: "Quarks '94", Proc. Eighth Int. Seminar, Vladimir, Russia, May 11-18, 1994, eds. D. Gigoriev et al., pp. 170-193.

[6] M. Gibbs, A. Ringwald and F. Schrempp, DESY 95-119, hep-ph/9506392, in: Proc. Workshop on Deep Inelastic Scattering and QCD, Paris, France, April 24-28, 1995, eds. J.-F. Laporte and Y. Sirois, pp. 341-344.

[7] A. Ringwald and F. Schrempp, DESY 96-125, hep-ph/9607238, to appear in: Proc. Workshop DIS96 on Deep Inelastic Scattering and Related Phenomena, Rome, Italy, April 15-19, 1996.

[8] S. Moch, A. Ringwald and F. Schrempp, to be published.

[9] M. Gibbs, A. Ringwald and F. Schrempp, to be published.

[10] V.V. Khoze and A. Ringwald, *Phys. Lett.* B **259** (1991) 106;
I. Balitsky and V. Braun, *Phys. Rev.* D **47** (1993) 1879.

[11] A. Yung, *Nucl. Phys.* B **297** (1988) 47.

[12] V. Zakharov, *Nucl. Phys.* B **353** (1991) 683;
M. Maggiore and M. Shifman, *Nucl. Phys.* B **365** (1991) 161; *Nucl. Phys.* B **371** (1991) 177;

[13] M. Seymour, Comp. Phys. Comm. **67** (1993) 465.

[14] H1 Collaboration, S. Aid et al., DESY 96-122 (1996).