Search for QCD Instanton Induced Processes at HERA*

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A search is presented for QCD instanton-induced events in deep-inelastic scattering (DIS) at the electron-proton collider HERA in a kinematic region defined by the Bjorken-scaling variables $x > 10^{-3}$, $0.1 < y < 0.6$ and photon virtualities $10 \lesssim Q^2 < 100\,\mathrm{GeV}$. Several observables characterising hadronic final state properties of QCD instanton-induced events are exploited to identify a potentially instanton-enriched domain. While an excess of events with instanton-like topology over the expectation of the standard DIS background is observed it cannot be claimed to be significant given the uncertainty in the predictions for the background. Upper limits on the cross-section for instanton-induced processes are set and compared to non-perturbative lattice simulations of the QCD vacuum.

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1. Introduction

Instantons [1, 2] are tunnelling phenomena between topologically different vacuum states present in non-abelian gauge theories, which cannot be described by perturbation theory. In the case of QCD, instantons (I) induce hard processes violating chirality. Deep-inelastic scattering (DIS) offers a unique opportunity [3] to discover processes induced by QCD instantons because a sizeable rate is predicted within "instanton-perturbation theory" [4], and instanton events exhibit a characteristic final state signature.

At HERA, the predicted cross section is large enough to make an experimental observation possible, although the expected signal is still small compared to the standard DIS background. Therefore, in this first dedicated search, discriminating observables based on the expected "fire-ball" like topology of I-induced events are combined to a powerful discriminant to identify a possibly I-enriched region in phase space.

This paper concentrates on the results of this new discriminant search and a comparison of the derived cross-section limits with lattice calculations

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which has become available recently. Details of the experimental strategy can be found in [5].

2. QCD Instanton-Induced Processes in DIS

The theory and phenomenology of I-induced processes at HERA has been worked out by Ringwald and Schrempp. These processes dominantly occur in photon-gluon fusion

$$\gamma^* + g \to \sum_{n_f}(q_R + \bar{q}_R) + n_g g, \qquad (I \to \bar{I}, R \to L) \quad ,$$

where q_R ($\bar{q}_R$) denote right handed quarks (anti-quarks) and g gluons. In every I-induced event, one quark anti-quark pair of all n_f kinematically accessible flavours is produced. Charm and bottom quarks can in principle be produced, but their cross section is strongly suppressed. Chirality is violated by these events with $\Delta\chi = 2n_f$. Anti-Instantons contribute to the cross section in the same manner, but here only left handed quarks are in the final state. The quarks are emitted isotropically together with gluons and fragment into a densely populated band of hadrons, homogeneously distributed in azimuth. This band together with the relatively hard jet originating from the current quark form the characteristic final state of I-induced events. The QCDINS [6] Monte Carlo (MC) generator is used to simulate the complete final state of I-induced events in DIS.

The total I-production cross-section at HERA, $\sigma^{(I)}_{\mathrm{HERA}}$, is essentially determined by the cross-section of the I-subprocess $q' + g \to X$ (the quark with 4-momentum q' is produced by the photon splitting in two quarks), denoted by $\sigma^{(I)}_{q'g}$. The latter can be calculated by integrating over all collective I-coordinates, that is over the I ($\bar{I}$)-size ρ ($\bar{\rho}$) and the $I\overline{I}$ distance 4-vector R_μ:

$$\sigma^{(I)}_{q'g}(x', Q'^2) \sim \int d^4R\, e^{i(g+q')\cdot R} \int_0^\infty d\rho \int_0^\infty d\bar{\rho}\, e^{-(\rho+\bar{\rho})Q'} D(\rho) D(\bar{\rho}) \;\ldots\; e^{-\frac{4\pi}{\alpha_s}\Omega}$$

where several parts of the integrand have been omitted. $D(\rho)$ ($D(\bar{\rho})$) is the I-size ($\bar{I}$-size) distribution that is calculable within I-perturbation theory [2] for $\alpha_s(\mu_r)\ln(\rho\,\mu_r) \ll 1$ with $\alpha_s(\mu_r)$ being the strong coupling and $N_C = 3$ for QCD. The I-size distribution follows a power law $D(\rho) \sim \rho^{6-2/3n_f+\mathcal{O}(\alpha_s)}$ and the integral over ρ ($\bar{\rho}$) generally diverges for large ρ ($\bar{\rho}$). However, in the DIS regime the exponential factor $e^{-(\rho+\bar{\rho})Q'}$ ensures the convergence of the integral. For large enough Q'^2 effectively only small size instantons contribute to the cross-section. Therefore the I-cross-section is calculable perturbatively in DIS.

I-perturbation theory is only valid for small enough instantons and a dilute instanton gas, i.e. for small ρ and large R/ρ. To find this region of validity, comparisons of the I-density as calculated in I-perturbation theory are done with quenched ($n_f = 0$) lattice simulations of the QCD vacuum. The derived limits $\rho \lesssim 0.35\,\mathrm{fm}$, $R/\rho \gtrsim 1.05$ then translate into $x' \gtrsim 0.35$ and $Q'/\Lambda^{n_f}_{\overline{MS}} \gtrsim 30.8$ where $\Lambda^{n_f}_{\overline{MS}}$ is the QCD scale in the $\overline{MS}$ scheme for n_f flavours. In the resulting kinematical region defined by $x' > 0.35$, $Q'^2 > 113\,\mathrm{GeV}^2$ and with the additional experimentally motivated cuts $x > 10^{-3}$, $0.1 < y < 0.9$, $Q^2 < 100\,\mathrm{GeV}^2$ and the angle of the scattered electron $\theta_e > 156°$, the cross-section calculated by QCDINS[1] is $\sigma^{(I)}_{\mathrm{HERA}} = 43\,\mathrm{pb}$.

3. Event Selection and Search Strategy

For this analysis data taken with the H1 detector in the years 1996 and 1997 was used, when HERA operated with 27.5 GeV electrons and 820 GeV protons. The accumulated data sample amounted to an integrated luminosity of $21.1\,\mathrm{pb}^{-1}$ and in the kinematic region defined above, 375000 DIS events were found. Details of the event selection may be found in [5].

To separate possible I-induced events from the standard DIS background events a discriminant based on range-searching [7] is employed which combines the information about the sphericity of the event, the reconstructed $Q'^2_{\mathrm{rec}} = -q'^2_{\mathrm{rec}}$ and the number of charged particles in the region of the reconstructed I-band. The standard DIS background is modelled by the RAPGAP MC generator, which implements LO matrix elements matched with parton showers and will be referred to as MEPS, and the ARIADNE generator which implements the colour dipole model (CDM). I-induced events are modelled by QCDINS. The discriminant is optimized for a maximum ratio of selected I-events to background events while demanding an I-efficiency of at least 10% by studying only MC generated events.

4. Results

The resulting discriminant D is shown in figure 1a normalized to the shape of the distributions. QCDINS events are concentrated in the region of high likelihood of being I-induced at $D \approx 1$, while data and background MCs peak at $D = 0$. Figure 1b shows the absolute normalized distributions on a double logarithmic scale, illustrating that the background events are suppressed towards $D \approx 1$ to about the same number of events as expected for the signal. The ratio of the difference of the data and the background

[1] To further reduce remaining theoretical uncertainties connected with non-planar diagrams, an additional cut $Q^2 > Q'^2_{\mathrm{min}}$ was advocated [4], this has been neglected here. It was shown however, that the observables used in this analysis are not affected.

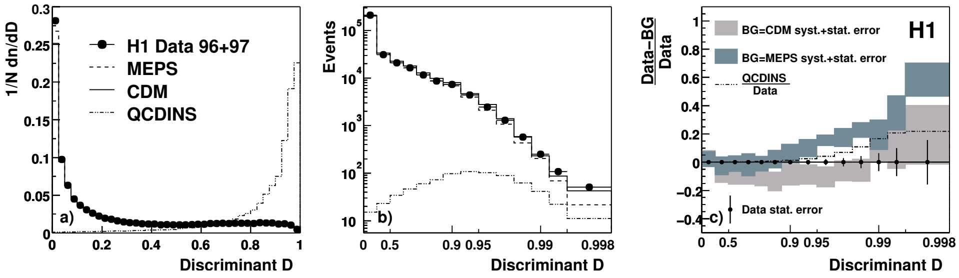

Fig. 1. Distributions of Discriminant

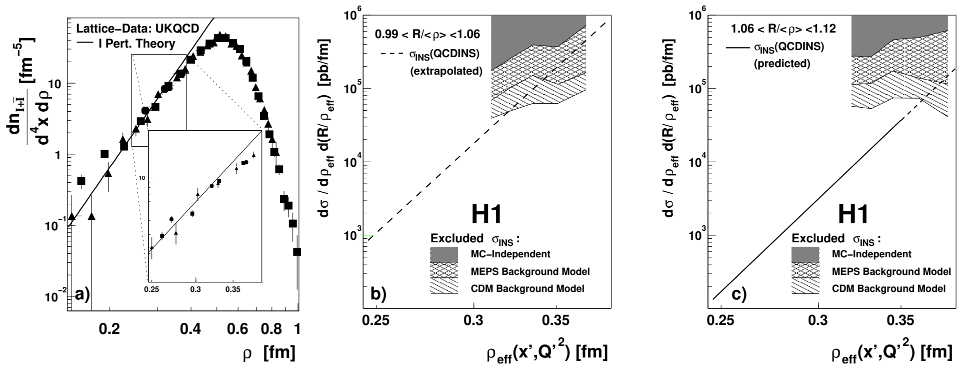

Fig. 2. Confrontation of limits with lattice calculations.

MC prediction to the data is finally shown in figure 1c along with the ratio of the QCDINS prediction to the data. While both background models describe the data in the leftmost bin where the bulk of events is located, the CDM model overshoots the data for medium values of the discriminant, while MEPS describes the data up to $D \approx 0.95$. For large likelihoods of the events to be I-induced the data exceeds the MEPS prediction. This excess, however, cannot be claimed to be significant given the large discrepancy with the CDM model which describes the data within errors. Cutting at $D > 0.988$, 410 events are found in the data while CDM predicts 354^{+40}_{-26} and MEPS 299^{+25}_{-38} (full statistical and experimental errors are included).

No excess of I-induced events can be claimed due to the large uncertainty of the standard DIS background. Therefore we derive limits on the I-cross-section. A background independent limit is obtained by assuming that all seen events are I-induced. This limit depends only on the expected number of I-events. In addition, the dependence of the I-prediction on the distribution of x' and Q'^2 can be reduced by using small bins in x' and

Q'^2 for which limits on the *I*-cross-section are derived. These bins translate into bins in ρ and R/ρ allowing for a comparison with lattice simulations as shown in fig. 2. In fig. 2a the *I*-density in the vacuum as a function of the *I*-size ρ is shown for the UKQCD lattice simulations [8] (data points) as well as the prediction of perturbative theory. A zoom shows the region where a growing discrepancy is expected. The same region is shown in figs. 2b,c, where the cross-section limits are shown for two bins in $R/\langle\rho\rangle$, one being slightly outside ($0.99 < R/\langle\rho\rangle < 1.06$, (b)) and inside ($1.06 < R/\langle\rho\rangle < 1.12$, (c)) the fiducial region of *I*-theory. In the fiducial region H1 data cannot exclude the predicted *I*-cross-section, a "naive" extrapolation towards large ρ is however ruled out.

5. Conclusions

H1 has conducted the first dedicated search for *I*-induced events. Although some excess of events with *I*-like signature is seen in the data, this excess cannot be claimed to be significant due to the large uncertainty of standard DIS background. Background model independent limits however can rule out the strong rise of *I*-induced events predicted by extrapolating *I*-perturbation theory towards large *I*-sizes in accordance with lattice simulations.

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