# Confronting QCD Instantons with HERA Data

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**Abstract.** The sensitivity of existing HERA data on the hadronic final state in deep-inelastic scattering (DIS) to processes induced by QCD instantons is systematically investigated. The maximally allowed fraction of such processes in DIS is found to be on the percent level in the kinematic domain $10^{-4} \lesssim x \lesssim 10^{-2}$ and $5 \lesssim Q^2 \lesssim 100$ GeV$^2$. The best limits are obtained from the multiplicity distribution.

## I INTRODUCTION

The standard model contains hard processes which cannot be described by perturbation theory, and which violate classical conservation laws like baryon and lepton number $B + L$ in the case of the electroweak sector and chirality in the case of strong interactions [1]. Such anomalous processes are induced by instantons [2].

Observable instanton effects in electroweak processes are only expected to be sizable in the multi-TeV region and are therefore out of the present experimental reach. QCD instantons, however, could be observed in in deep-inelastic scattering (DIS) at HERA colliding 27.5 GeV positrons on 820 GeV proton [3–6].

The theoretical background of the cross-section calculation and aspects of instanton phenomenology based on a Monte Carlo simulation [7] for the QCD instanton have been discussed by F. Schrempp and A. Ringwald [8,9] at this conference. In this contribution limits on instanton production are derived from the most sensitive data on the hadronic final state of DIS events, namely the multiplicity distributions [10], the transverse energy flows [11] and hard particle production [12].

## II INSTANTON PRODUCTION AT HERA

At HERA, events induced by QCD instantons predominantly invoke a quark-gluon fusion process. The total cross-section is given by a convolution of the probability to find a gluon in the proton $P_{g/p}$, the cross-section $\sigma_{q^*g}(x', Q'^2)$ of the instanton induced sub-process and the probability that a photon splits in a quark-antiquark pair in the instanton background $P^{(I)}_{q^*/\gamma}$

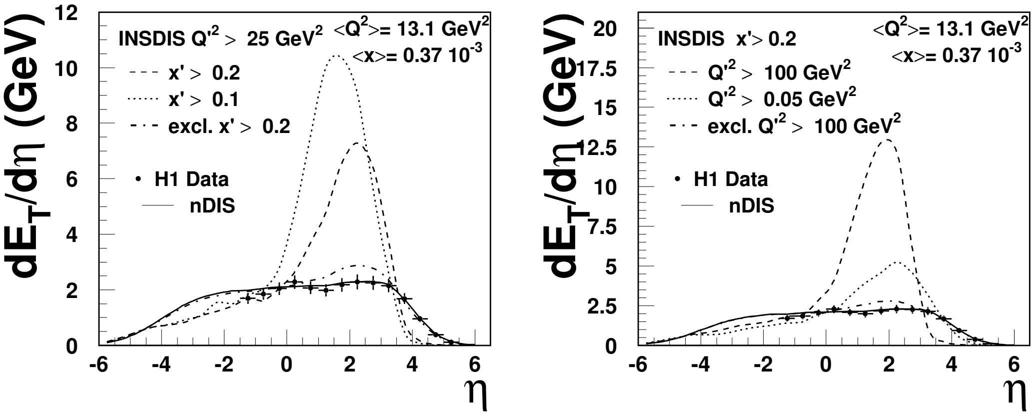


**FIGURE 1.** *Mean transverse energy as function of the pseudo-rapidity in the hadronic center of mass frame. The proton moves to the left. Shown are H1 data [11], a standard DIS prediction based on ARIADNE (solid line,nDIS) and the instanton expectation in various phase space regions in the ($x'$ ,$Q'$ ) plane (broken lines,INSDIS).*

[5,6]. Besides the squared transverse momentum transfer $Q^2$ and the Bjorken-$x$ scaling variable, this scattering process is characterized by $Q'^2$, the virtuality of the quark ($q^*$), and $x'$, the Bjorken scaling variable associated with the $q^*g$ sub-process. $\sigma_{q^*g}(x', Q'^2)$ decreases with increasing $Q'^2$ and exponentially grows with decreasing $x'$. Due to inherent ambiguities - in particular the exponential behaviour at low $x'$ - the calculation is only reliable for $x' \gtrsim 0.2$ and $Q'^2 \gtrsim 25$ GeV$^2$.

Since the highest event rate is expected in the low-$x$ regime, DIS data down to $x \approx 10^{-4}$ are analyzed in this study. When comparing to theory predictions, the phase space is restricted to the theoretically controllable regime by imposing limits on ($x'$, $Q'^2$). The characteristics of the hadronic final state of instanton induced events are considered to be more robust than predictions of the absolute event rate [5]. To investigate the sensitivity of the event topology to $x'$ and $Q'^2$, different instanton scenarios with varying cut-off parameters are examined.

## III EXPERIMENTAL SIGNATURE

In its own rest frame the instanton isotropically decays into a multi-parton state, consisting of gluons and all quark flavours which are kinematically allowed. After fragmentation of the semi-hard partons, a densely and uniformly populated band of particles with characteristic flavours is expected in a certain pseudo-rapidity ($\eta$) region.

This band of high hadronic activity can be identified in the mean transverse energy flow (d$E_T$/d$\eta$) (see Fig. 1). While the data exhibit a plateau of about 2 GeV per $\eta$ unit, large mean transverse energies of up to $\mathcal{O}$(10 GeV) are predicted for instanton events. The height and the position of the instanton

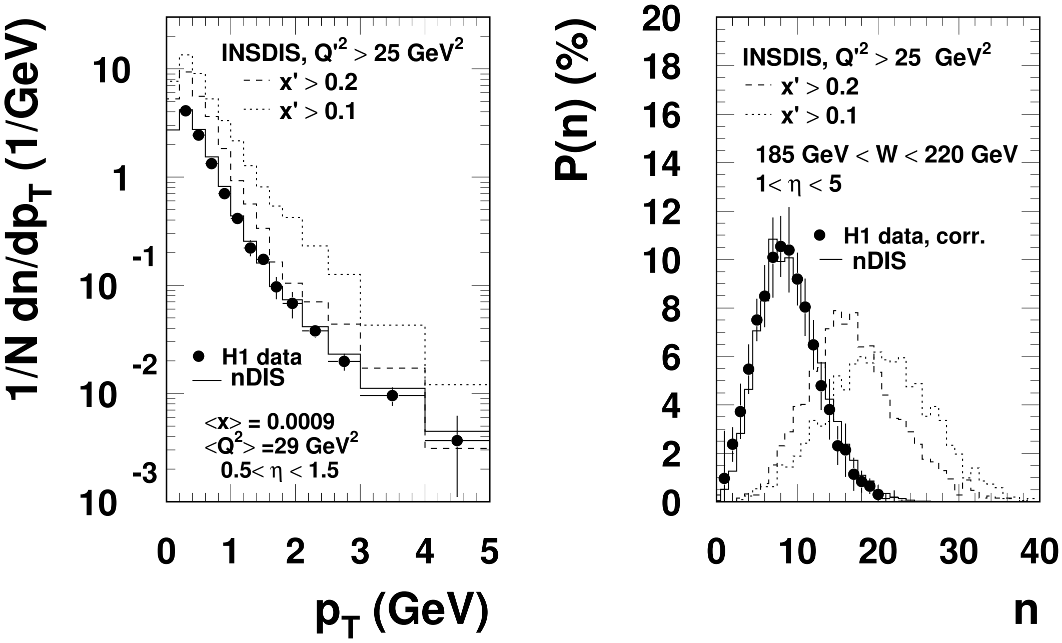


**FIGURE 2.** *Transverse momentum and multiplicity distribution of charged particles in the hadronic center of mass frame. Shown are H1 data [12,10], a standard DIS prediction based on ARIADNE (solid line,nDIS) and the instanton expectation in different phase space region in the ($x'$,$Q'^2$) plane (broken lines,INSDIS).*

band depends on with the instanton mass $M_{\rm ins} \approx \sqrt{Q'^2/x'}$, i.e. for decreasing $x'$ and increasing $Q'^2$ it gets stronger and moves towards the proton remnant. For large $M_{\rm ins}$ also the transverse momentum spectrum of charged particles becomes harder for instanton events than for normal DIS (see Fig. 2).

A distinct signature of instanton events is a large particle multiplicity. In Fig. 2 the distribution of the charged particles multiplicity in $1 < \eta < 5$ for large $W \approx \sqrt{Q^2/x}$ is shown. The mean of this distribution logarithmically depends on $M_{\rm ins}^2$.

## IV BOUNDS FROM HERA DATA

The standard DIS Monte Carlo simulation program ARIADNE [13] provides an excellent description of all available HERA data on the hadronic final state [14]. Upper bounds on the cross-section of instanton induced events ($\sigma_{\rm lim}$) in DIS can be determined from their distinct event topology. Assuming that the data on $\mathrm{d}E_T/\mathrm{d}\eta$ consist of normal DIS together with a certain fraction of instanton events, the maximally allowed fraction of instanton events ($f_{\rm lim}$) can be extracted using a $\chi^2$ procedure. An example of a superposition of normal DIS with the fraction of instanton events which can be excluded at

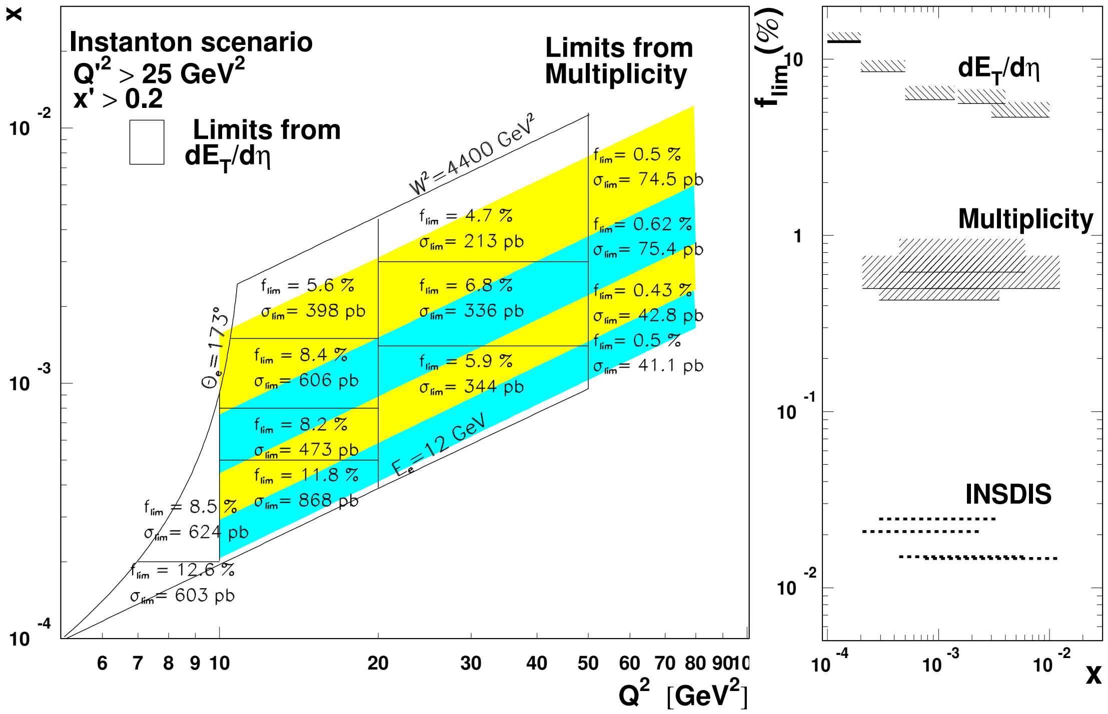


**FIGURE 3.** *Limits on instanton production with $Q'^2 > 25$ GeV$^2$ and $x' > 0.2$ from transverse energy flows and the multiplicity distribution. a) The cross-section limits ($\sigma_{\rm lim}$) together with the maximally allowed instanton fraction $f_{\rm lim}$ in the ($x$,$Q^2$) plane obtained from the d$E_t$/d$\eta$ (open fields) and multiplicity analysis (shaded fields). b) ($f_{\rm lim}$) versus $x$ is compared to the theory prediction in the $W$ bin considered in the multiplicity analysis (dotted line).*

95% confidence level (C.L.) is shown in Fig. 1 (dashed dotted line). In Fig. 3 the results for instantons with $x' > 0.2$ and $Q'^2 > 25$ GeV$^2$ are summarized (open fields). For $10^{-4} \lesssim x \lesssim 10^{-2}$ and $10 < Q^2 < 50$ GeV$^2$, $f_{\rm lim}$ values of about $5-10\%$ can be excluded. This corresponds to cross-section limits of $\approx 200-800$ pb. The best limits are obtained in the domain of higher $x$ and $Q^2$. These results can vary by at most a factor 2 when using different choices in the details of the DIS model[1]. Here, however, we used the most conservative choices.

Any dependence on the DIS model can be avoided by exploiting the fact that no events with a certain charged particles multiplicity have been observed in the data. For such high multiplicity still a reasonable efficiency ($8-20\%$) for instanton events is expected (see Fig. 2). At 95% C.L. $f_{\rm lim}$ is then obtained from $f_{\rm lim} = 3/(\epsilon_i N_{DIS})$ where $\epsilon_i$ is the efficiency to detect instanton events at

[1] proton structure function, hadronisation parameters etc.

large multiplicity and $N_{DIS}$ is the total number of observed DIS events. The obtained limits in different $W$ bins are displayed in Fig. 3 (shaded areas). For $80 < W < 220$ GeV, values $f_{\rm lim} \approx 0.5\%$ and $40 \lesssim \sigma_{\rm lim} \lesssim 80$ pb are obtained.

These bounds are not yet stringent enough to test the theory which predicts an instanton fraction of $\mathcal{O}(0.01\%)$. In the theoretically unsafe region (low $x'$), where the instanton fraction is expected to be large, limits can also be derived to constrain the theory.

## V CONCLUSION

The observation of instanton effects in DIS events at HERA would be a novel, non-perturbative manifestation of QCD and would furthermore provide valuable indirect information about $B + L$ violation in the multi-TeV region induced by electroweak instantons. The distinct event topology of instanton induced events allows to discriminate them from normal DIS events. Using existing HERA data on the hadronic final state corresponding to an integrated luminosity of $\mathcal{O}(1\ \mathrm{pb}^{-1})$, the maximally allowed fraction of instantons in DIS is found to be of $\mathcal{O}(1\%)$ for $80 < W < 220$ GeV and $x' > 0.2$ and $Q'^2 > 25$ GeV$^2$. The predicted instanton fraction is $\approx 0.01 - 0.02\%$, i.e. still below the level excluded by existing HERA data. The higher luminosity of $\mathcal{O}(10\ \mathrm{pb}^{-1})$ already collected by HERA and dedicated instanton searches will allow to test the absolute prediction of the cross-section in the near future.

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