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QCD–Instanton Induced Final States in Deep Inelastic Scattering*

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Abstract

We report briefly on a broad and systematic study of possible manifestations of QCD-instantons at HERA. We concentrate on the high multiplicity final state structure, reminiscent of an isotropically decaying "fireball". First results of a Monte Carlo simulation are presented, with emphasis on the typical event-structure and the transverse energy, muon and K^0 flows.

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1 Introduction

The Standard Model of electro-weak (QFD) and strong (QCD) interactions is remarkably successfull. Its perturbative formulation ("Feynman diagrammatics") appears to be theoretically consistent and agrees with present experiments. Nevertheless, even for small couplings, there exist processes that cannot be described by conventional perturbation theory and, notably, violate the classical conservation laws of certain fermionic quantum numbers [1] (see fig. 1).

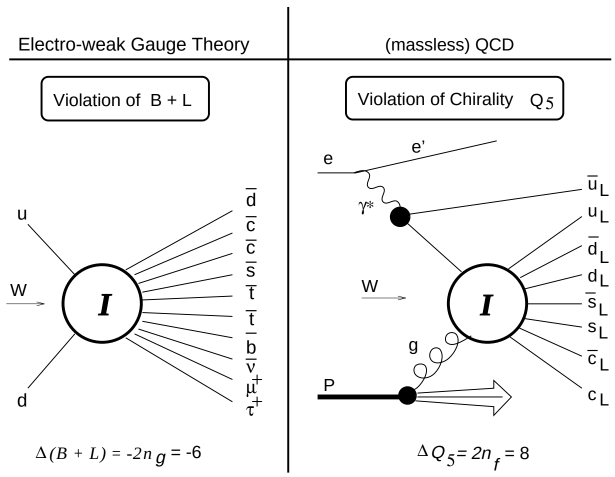

Figure 1: The basic anomalous processes induced by instantons in QFD and QCD, respectively

Such anomalous processes are induced by *instantons* [2] which represent tunnelling processes in Yang-Mills gauge theories, associated with the highly degenerate vacuum structure.

For many years, such tunnelling transitions have been considered largely of academic interest, due to their exponential suppression $\propto \exp(-4\pi/\alpha)$ at low energies. A few years ago, however, much activity in this field was generated by the observation [3] that instanton-induced processes may well become unsuppressed, i.e. observable, *at high energies.*

The basic significance and possible importance of QCD-instanton effects in deep inelastic scattering (DIS) for decreasing Bjorken variable $x_{\rm Bj}$ and high photon virtuality Q^2 has recently been emphasized [4]:

- First of all, QCD-instanton effects for decreasing $x_{\rm Bj}$ are largely analogous [5] to the manifestation of electro-weak instantons at increasing energies. The anomalous $B+L$ violation due to electro-weak instantons is paralleled by a chirality violation induced by QCD-instantons [1] (c.f. fig. 1).

- Secondly, discovery of QCD-instanton induced DIS-events would itself be of basic significance, since they correspond to a novel, non-perturbative manifestation of QCD.

Whereas a promising search for anomalous electro-weak events is only possible in the far future, presumably at a post-LHC collider [6] or at cosmic ray facilities [7], the search for anomalous events induced by QCD-instantons can start right now, in deep inelastic $e^{\pm}p$ scattering at HERA.

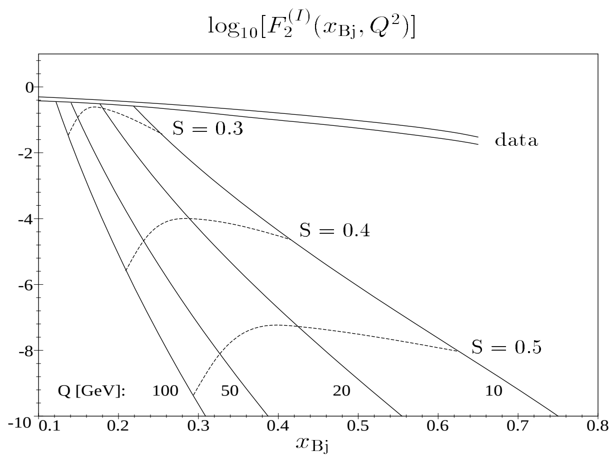

Figure 2: The logarithm of the instanton-induced contribution to the structure function F_2 of the proton. The curves denoted by "data" roughly represent the trend of the experimental data for F_2.

Naturally, the first observables where manifestations of QCD-instantons may be looked for are the nucleon structure functions.

Within the theoretical framework of Ref. [4], we have performed [8] a state of the art evaluation of the instanton-induced contribution to $F_2(x_{\rm Bj},Q^2)$ (see fig. 2). It rises strongly with decreasing $x_{\rm Bj}$ and tends to reach the size of the experimental data around $x_{\rm Bj} \approx 0.1 \div 0.25$. Unfortunately, due to inherent uncertainties, the calculation cannot be trusted anymore for $x_{\rm Bj} \lesssim 0.35$, say. Nevertheless, the trend is very suggestive!

There are a number of reasons [8] that favour experimental searches for instanton-induced "footprints" in the multi-particle final state over searches via the structure functions, the latter being the most inclusive observables in deep inelastic scattering. It is the purpose of this contribution to present a brief status report on our phenomenological analysis of the instanton induced final state.

2 The Instanton Induced Final State

2.1 Characteristic Features

The instanton-induced contribution to the multi-particle final state in DIS arises in form of an instanton-induced subprocess (denoted by "I" in fig. 3) along with a current-quark jet. The relevant kinematical variables are summarized in table 1.

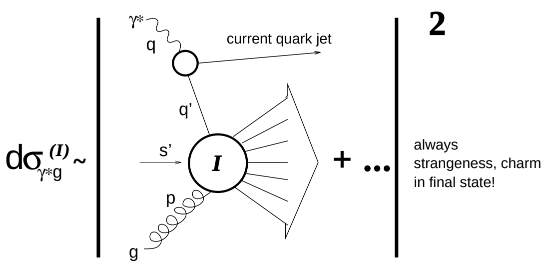

Figure 3: Structure and kinematics of the instanton-induced contribution to the $\gamma^* g$ cross section

Our phenomenological analysis is based on the following set of characteristic features which have emerged from various theoretical investigations:

- *Isotropic* emission of many semi-hard partons in the I-rest system, $\vec{q'} + \vec{p} = 0$, reminiscent of a "decaying fireball".
- *High multiplicity*: $\langle n^{(I)}_{q+g} \rangle_{n_f=4} \simeq 10$ (!) at HERA [8].
- Characteristic flavour flow (strangeness, charm) [1].

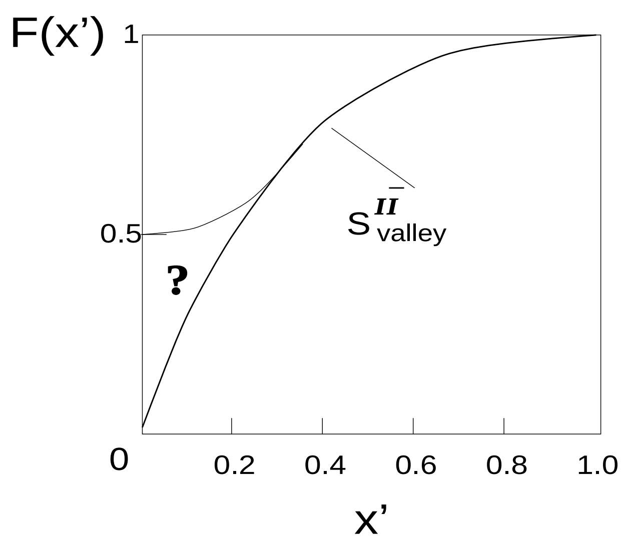

Figure 4: "Holy grail" function $F(x')$. The lower curve corresponds to the prediction from the $I\bar{I}$ valley method, with $S^{I\bar{I}}_{\text{valley}}$ denoting the valley action.

	$\gamma^* g$	I-subprocess
Bj.-Variables	$Q^2 = -q^2$ $x = \frac{Q^2}{2pq}$	$Q'^2 = -q'^2$ $x' = \frac{Q'^2}{2pq'}$

Table 1: Relevant kinematical variables, with the primed quantities referring to the I-subprocess in fig. 3. Note that $x_{\rm Bj} < x < x' < 1$.

- Strong peaking of the I-subprocess total cross section [4, 5] for decreasing Bjorken variables x', Q'^2:

$$s'\sigma_{\rm tot}^{(I)}(x', Q'^2) \sim \exp\left\{-\frac{4\pi}{\alpha_s^{\rm eff}(Q'^2)} F(x')\right\}$$

  The importance of instanton-induced events at small x' crucially relies on the precise functional dependence of the "holy grail" function $F(x')$ (c.f. fig. 4). Unfortunately, it is reliably known only at large $x' \sim 1$ within instanton-perturbation theory. By means of the $I\bar{I}$ valley method [5] $F(x')$ is obtained beyond perturbation theory for *all* x', however with intrinsic ambiguities as typically depicted in fig. 4.

From the above properties, the qualitative event structure is expected to consist of a current-quark jet along with a densely populated hadronic "band" in the $(\eta_{\rm lab}, \phi_{\rm lab})$-plane [8]. The hadronic band directly reflects the isotropy in the I-rest system along with a large multiplicity of semi-hard quarks and gluons.

2.2 Monte Carlo Simulation

A Monte Carlo simulation for instanton-induced events at HERA (QCD INSTANTON MC 1.0), based on HERWIG 5.8, has been essentially completed [9]. It includes full hadronization. While it should already account for the composition of the final state quite well, we do not yet quote absolute production rates, since a *reliable* theoretical estimate of the cross sections, in particular at smaller values of x' and Q'^2, is quite difficult and still in progress [10, 11].

The main questions addressed so far, concern the typical event-structure, and transverse energy as well as muon and K^0 flows and some characteristic event distributions.

Let us present the results for a sample of instanton-induced events, corresponding to an intermediate small x' behaviour of the "holy grail" function $F(x')$ (c.f. fig. 4):

$$F(x') = \begin{cases} S_{\rm valley}^{I\overline{I}}(x'), & \text{for } x' \geq 0.12, \\ \text{const.}, & \text{for } x' < 0.12 \end{cases}$$

Throughout, we take $x_{\rm Bj} \geq 10^{-3}, y_{\rm Bj} \geq 0.1$. Furthermore, we impose a cut on the total invariant mass in the I-subprocess, $\sqrt{s'} \geq 10$ GeV, in order to guarantee a minimum virtuality $Q'^2 \geq 1$ GeV^2.

In fig. 5 a typical instanton-induced event is displayed. The current-quark jet (around $\eta_{\rm lab} \simeq -0.5$) along with the expected, densely populated hadronic "band", centered around $\eta_{\rm lab} \simeq 2.5$, are apparent. The electron is shown here as well.

In fig. 6, the transverse energy flow versus $\eta_{\rm lab}$ is displayed. It exhibits a strong enhancement across the hadronic "band", since each of the many hadrons from the I-subprocess contributes a comparable energy into a single $\eta_{\rm lab}$ bin of width ≈ 1.8.

A related important quantity is the distribution of the transverse energy for hadrons within the "band" (fig. 7). It peaks around $E_t \simeq \sqrt{s'}_{\rm min} = 10$ GeV, i. e. at a value much larger than the one from present experimental data.

The K^0 and muon flows, displayed in figs. 8 and 9, again peak at the center of the band of hadrons emerging from the I-subprocess. This is presumably a distinctive signature for instanton induced events. It directly reflects the basic fact that in *each* such event a pair of strange and of charmed quarks is produced (c.f. fig. 1). We find $\langle N_{K^0_S} \rangle \simeq 1.8$ and $\langle N_\mu \rangle \simeq 0.2$.

3 Conclusion

A systematic phenomeological and theoretical investigation of the discovery potential for QCD-instanton induced events is under way. Clearly, HERA offers a unique window in DIS! A discovery of such events would be of basic importance: first of all, as a novel, non-perturbative manifestation of QCD and secondly, because of the close analogy to anomalous $B + L$ violation in electro-weak processes in the multi-TeV regime.

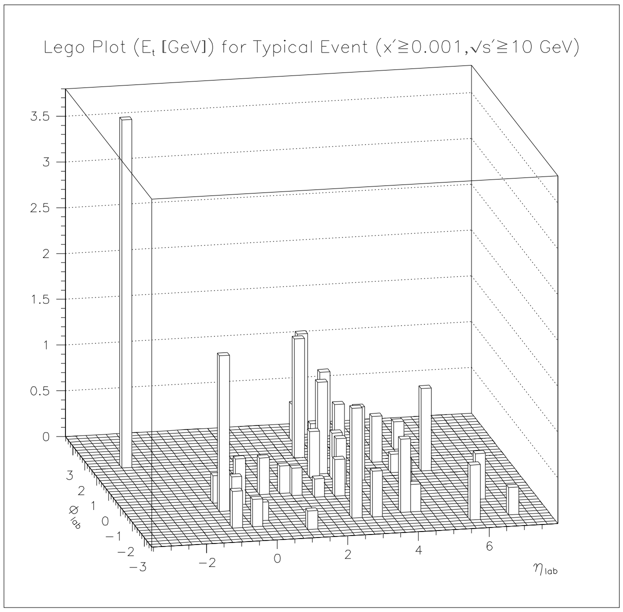

Figure 5: A typical instanton-induced event in the lab. system

Acknowledgements

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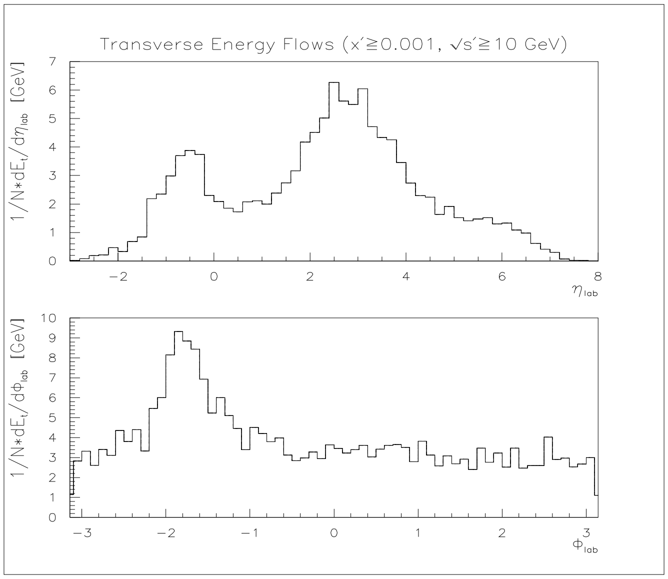

Figure 6: Hadronic transverse energy flows versus $\eta_{\rm lab}$ and $\phi_{\rm lab}$, respectively

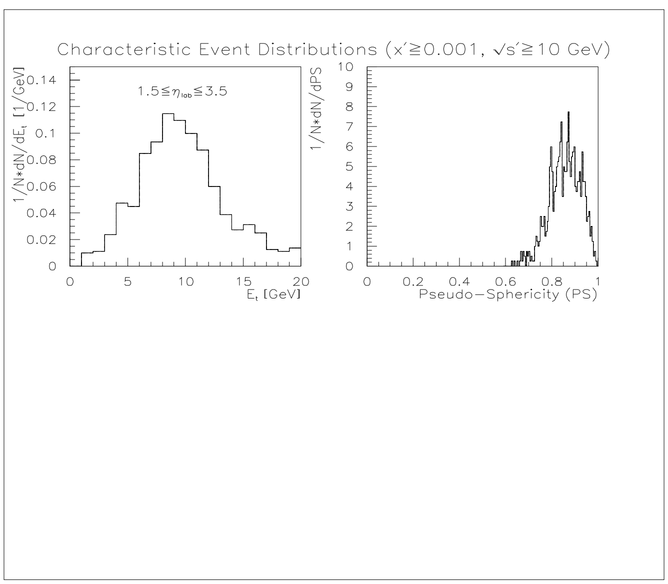

Figure 7: Transverse energy and pseudo-sphericity distributions

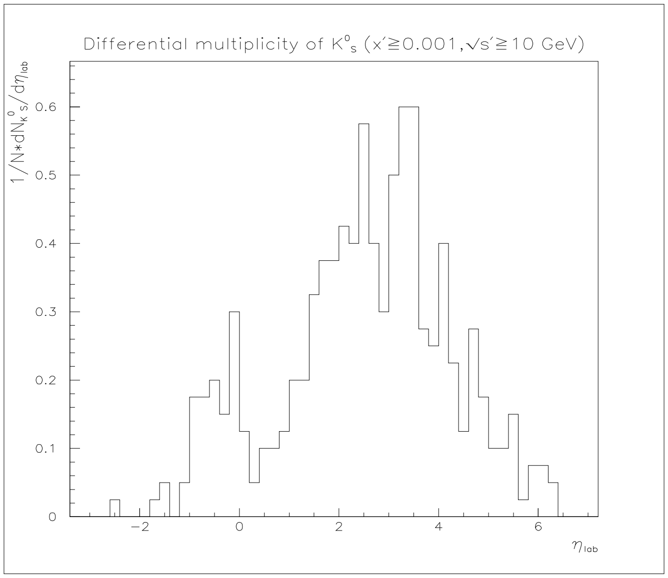

Figure 8: Flow of K_S^0 versus $\eta_{\rm lab}$, peaking around the center of the hadronic "band" from the I-subprocess

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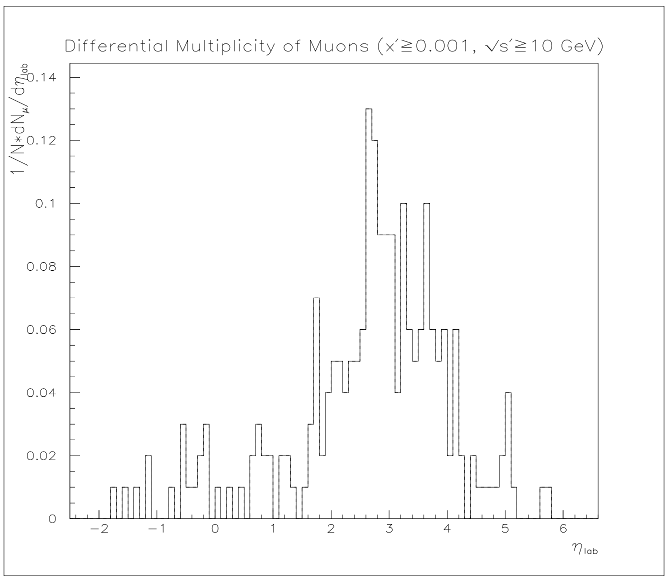

Figure 9: Flow of muons versus $\eta_{\rm lab}$, peaking around the center of the hadronic "band" from the I-subprocess