Tracking QCD-Instantons at HERA

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in collaboration with

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1. **Instantons**

2. **Instanton-Pertubation Theory in DIS**

3. **Rates and Events**

4. **Conclusions**

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– Low x Physics at HERA, Zeuthen, June 1998 –

1. Instantons

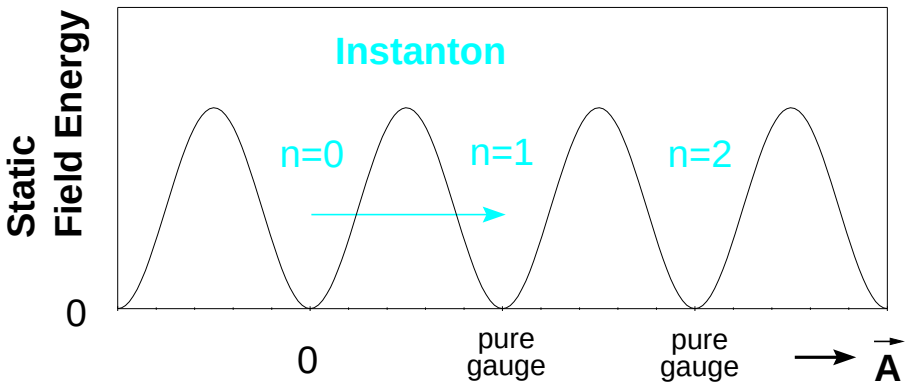
♣ Very rich vacuum structure of non-abelian gauge theories like QCD
$\Leftarrow$ TOPOLOGY!

- ∞ many classical ground states of zero energy ($\mathcal{E} = \vec{E}^2 + \vec{B}^2$)

$$G_{\mu\nu}(x) = 0 \;\Rightarrow\; \vec{A}^{(n)}(x) = -\underbrace{U_n{}^{-1}(\vec{x})\nabla U_n(\vec{x})}_{\text{“pure gauge”}};\; A_0(x) = 0$$

- distinguished by integer topological winding number n, classifying all possible mappings

$$\text{configuration space} : \{\vec{x}\} \Rightarrow \text{group space} : \{U_n(\vec{x})\}$$



- Vacua not transformable into each other by continuous deformation of $U_n(\vec{x})$, separated by finite energy barrier

♣ **Instantons** [Belavin et al. ‘75, ’t Hooft ‘76]

- non-perturbative fluctuations of gauge-fields, localized (“instantaneous”) in time and space.
- Tunnelling transitions between adjacent vacua ($n \Rightarrow n+1$)

– Explicitly known solutions of classical (Euclidean) field equations in 4d with finite action.

– carry conserved topological charge $Q = n - (n-1) = 1$

♣ Induce processes violating "chirality" $= \#(q_{\rm L}) - \#(q_{\rm R})$ in (massless) QCD [and (B+L) in QFD]

$$\Delta \,\text{chirality} = 2n_{\rm flavour} \cdot Q,$$

  * in accord with general Adler-Bell-Jackiw ANOMALY relation,
  * forbidden in ordinary perturbation theory ($Q = 0$!) (Expansion about trivial vacuum field configuration $A_\mu(x) = 0$)

♣ An experimental discovery of **Instantons** as a novel, non-perturbative manifestation of QCD would be of basic significance $\Leftarrow$ **HERA** !.

2. Instanton-Perturbation Theory in DIS

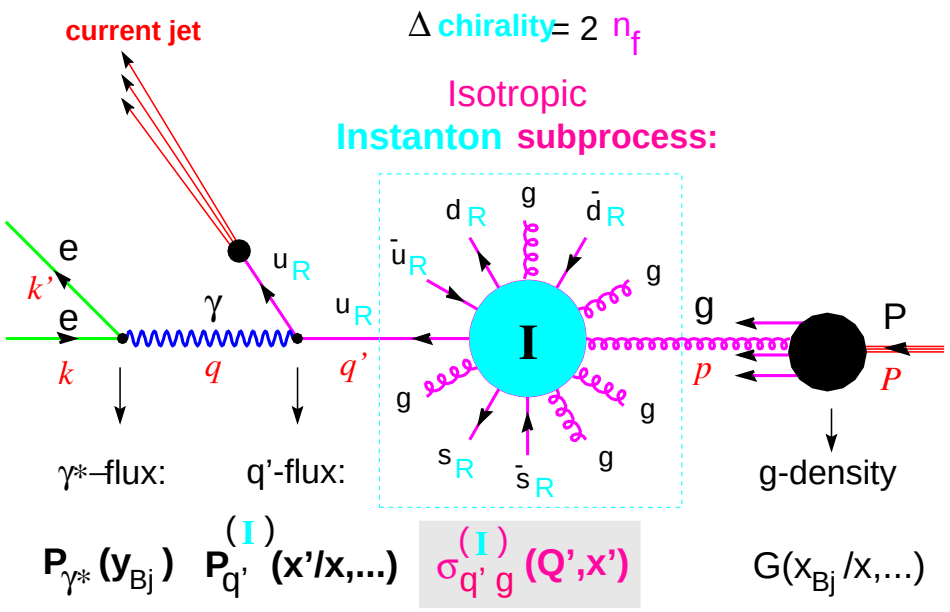
- **DIS** distinguished, since hard instanton-induced processes

♣ are calculable within instanton-perturbation theory
[Balitsky & Braun '93; Ringwald & F. Sch. '94 - '98;
Moch, Ringwald & F. Sch., Nucl.Phys. **B507** (1998) 134]

♣ can possibly be also detected experimentally $\Leftarrow$ **HERA** .
[Ringwald & F. Sch. '94 - '98]

♣ Key feature: hard generic DIS scale $\mathcal{Q}$ cuts off instantons with large size $\rho \gtrsim \mathcal{Q}^{-1}$, over which we have no theoretical control!
[Moch, Ringwald & F. Sch., Nucl.Phys. **B507** (1998) 134]

- Leading instanton-induced, chirality violating process in DIS regime of $e^{\pm}P$ scattering:



- Instanton-subprocess with own **Bjorken**-variables:

$$Q'^2 = -q'^2 > 0; \quad 0 \leq x' = \frac{Q'^2}{2p\cdot q'} \leq 1$$

- show within $\boldsymbol{I}$-perturbation theory:

$$\frac{\mathrm{d}\sigma_{\mathrm{HERA}}{}^{(I)}}{\mathrm{d}x'\mathrm{d}Q'^2} \simeq \frac{\mathrm{d}\mathcal{L}^{(I)}_{q'g}}{\mathrm{d}x'\mathrm{d}Q'^2} \cdot \sigma^{(I)}_{q'g}(Q', x')$$

- calculable differential $q'g$ luminosity $\mathrm{d}\mathcal{L}^{(I)}_{q'g}$ in $\boldsymbol{I}$-background:
  $\Leftrightarrow$ number of $q'g$ collisions per eP collision in intervals $(x', x' + \mathrm{d}x')$, $(Q'^2, Q'^2 + \mathrm{d}Q'^2)$,

- involves $\{x_{\mathrm{Bj}}, y_{\mathrm{Bj}}, x\}$-integrations over gluon density $\mathrm{G}(x_{\mathrm{Bj}}/x, \ldots)$, γ^*-flux $\mathrm{P}_{\gamma^*}(y_{\mathrm{Bj}})$ and known q'-flux $\mathrm{P}_{q'}{}^{(I)}(x'/x, \ldots)$.

- crucial instanton-dynamics in $\boldsymbol{I}$-subprocess cross-section $\sigma^{(I)}_{q'g}(Q', x')$!

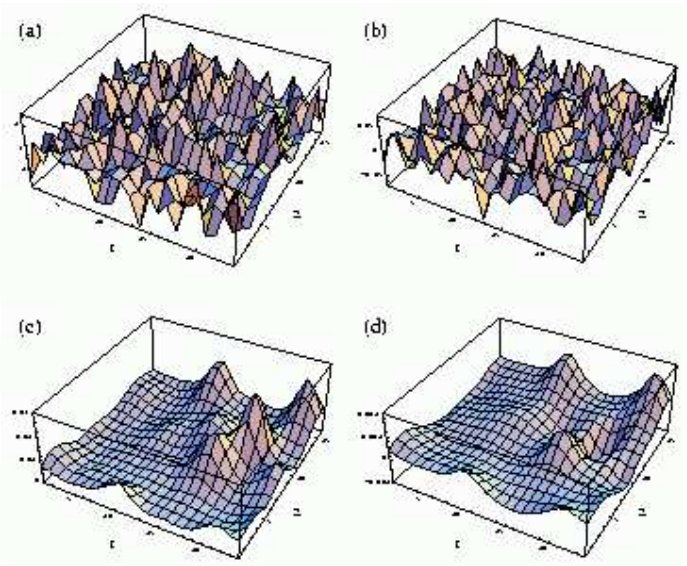
♣ Experimentally: Reconstruction of (Q'^2, x') from event topology!
⇐ (F. Schr. in Final State Discussion Session)

♣ Theoretically: Derive "fiducial" (Q'^2, x') region for validity I-perturbation theory and "dilute I-gas" picture from recent lattice simulations of QCD [UKQCD, Smith & Teper, '98]

♣ Key feature: One-to-one (saddle-point) relation between "conjugate" I-variables in momentum- and $(\vec{x}, t)$-space: e.g.

large Q' ⇔ small I-size $\rho^*(Q', x')$.
increasing x' ⇔ increasing $I - \overline{I}$-distance $R^*_{I\overline{I}}(x', Q')$

- Lattice simulations: "Snapshots" of QCD-vacuum in (Euclidean) space-time, including all non-perturbative, topological features like instantons:



Lagrange density $L(x)$ | topological charge density q(x)

Before "cooling"

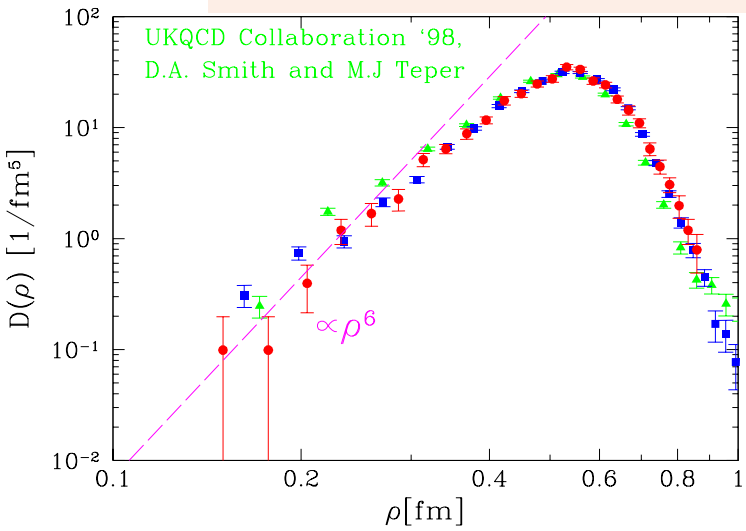
After cooling

[Chu et al. '94]

- See 3 Instantons$(q(x) > 0)$ and 1 Anti-Instanton $(q(x) < 0)$!

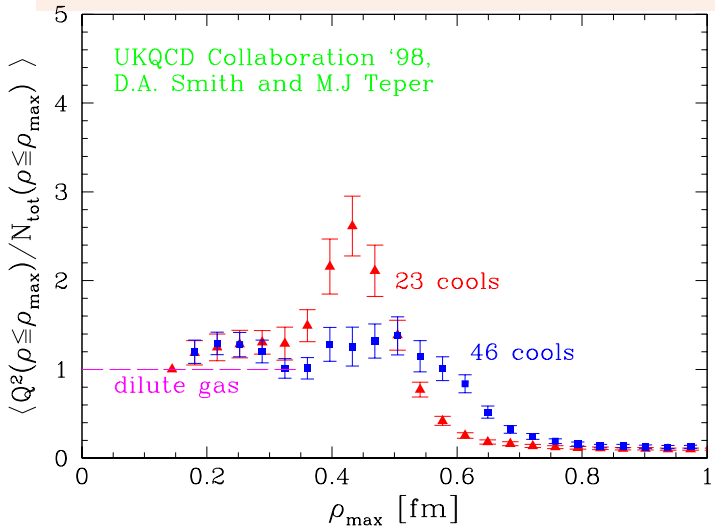
♣ I-perturbation theory:

I-density: $D(\rho) = \frac{\mathrm{d}n_I}{\mathrm{d}x^4\mathrm{d}\rho} \overset{(n_{\mathrm{flavour}}=0)}{\propto} \rho^6$



♣ "dilute" I-gas:

$$\langle Q^2/N\mathrm{tot}\rangle = 1;$$
$$Q^2 = ((+1)n_I + (-1)n_{\overline{I}})^2;\ N_{\mathrm{tot}} = n_I + n_{\overline{I}}$$



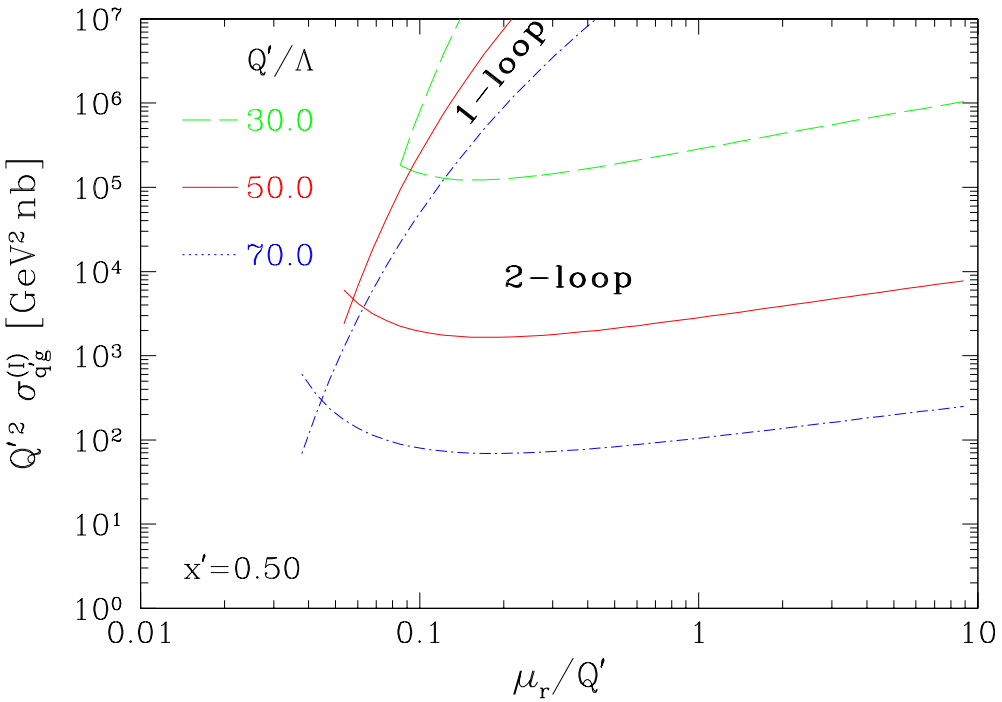
- "Fiducial" kinematical region from lattice constraints:

$$\left.\begin{array}{lll} \rho & \lesssim & 0.3\ \mathrm{fm} \\ \frac{R_{I\overline{I}}}{\rho} & \gtrsim & 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{lllll} Q' & \gtrsim & Q'_{\mathrm{min}} & \simeq & 8\ \mathrm{GeV} \\ x' & \gtrsim & x'(Q'_{\mathrm{min}}) & \simeq & 0.35. \end{array}\right.$$

3. Rates and Events

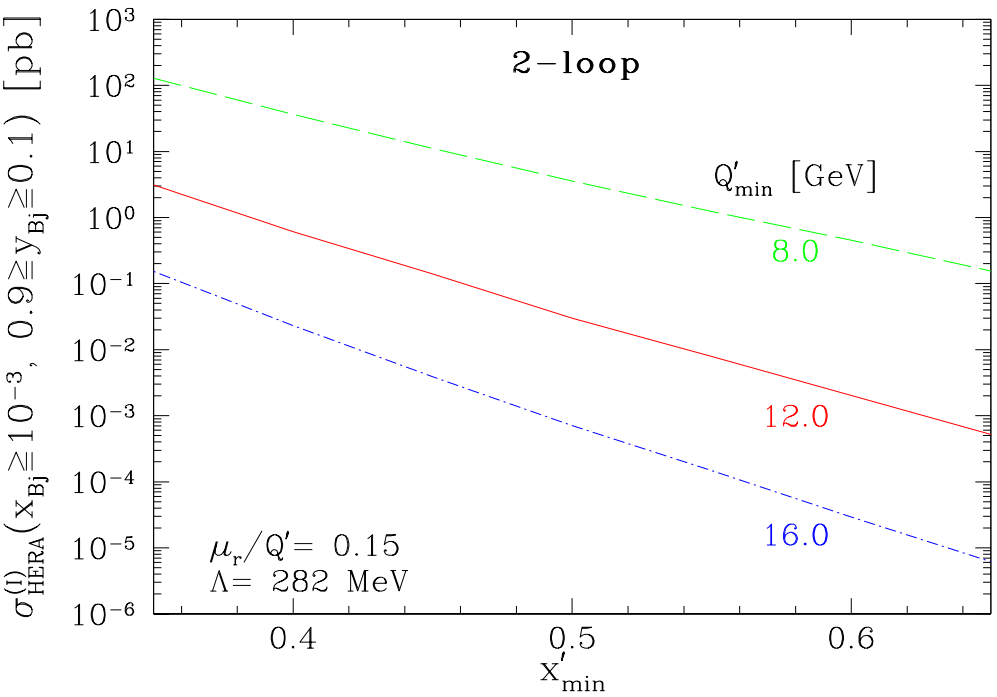
[Moch, Ringwald & F. Sch. to appear]

- "QCDINS 1.6.0" : Upgrade of our MC-generator for I-induced DIS-events [Gibbs, Ringwald & F. Sch. '95; anonymous ftp: theopc3.desy.de]
  - Instanton-induced hard subprocess
  - Leading-log parton shower and hadronization (HERWIG 5.9)
  - "HZTOOLS" package fully integrated⇒ all published HERA data, jet analysis . . .
- Great progress in stability by using 2-loop RG invariant form of I-density $D(\rho)$ in calculation of I-subprocess cross-sections:
  Residual dependence on renormalization scale μ_r strongly reduced!



- Use as "best scheme": $\mu_r = 0.15\ Q'$, for which $\partial\sigma^{(I)}_{q'g}/\partial\mu_r \simeq 0$.

- Finalized I-induced cross-section at **HERA**, versus $x'_{\rm min}$ and $Q'_{\rm min}$ cuts:



  - For minimal cuts, as extracted from UKQCD-lattice simulation,

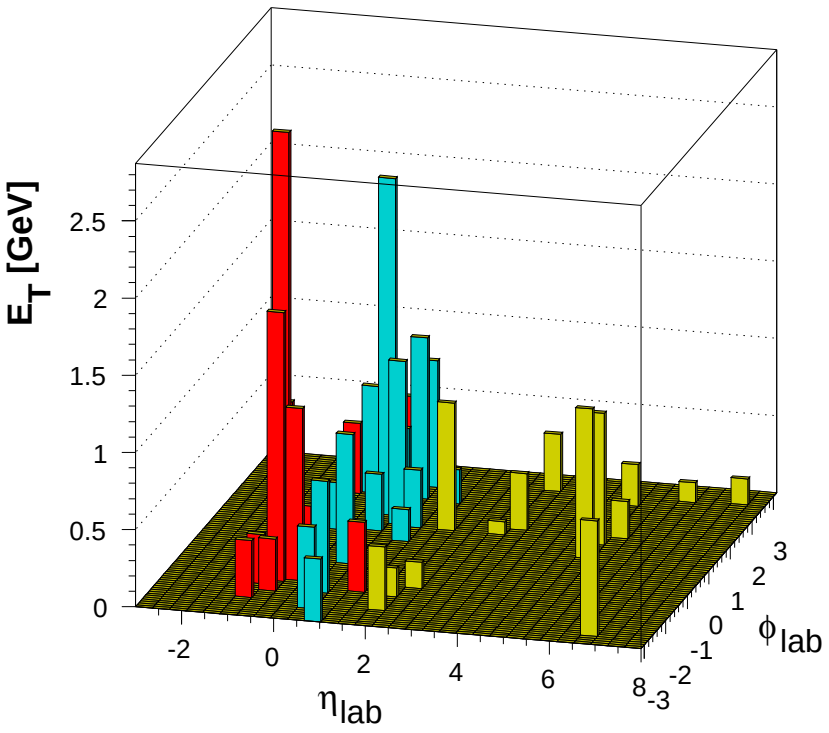
$$\sigma^{(I)}_{\rm HERA}(x' \geq 0.35, Q' \geq 8\ {\rm GeV}) \simeq 126\ {\rm pb}$$

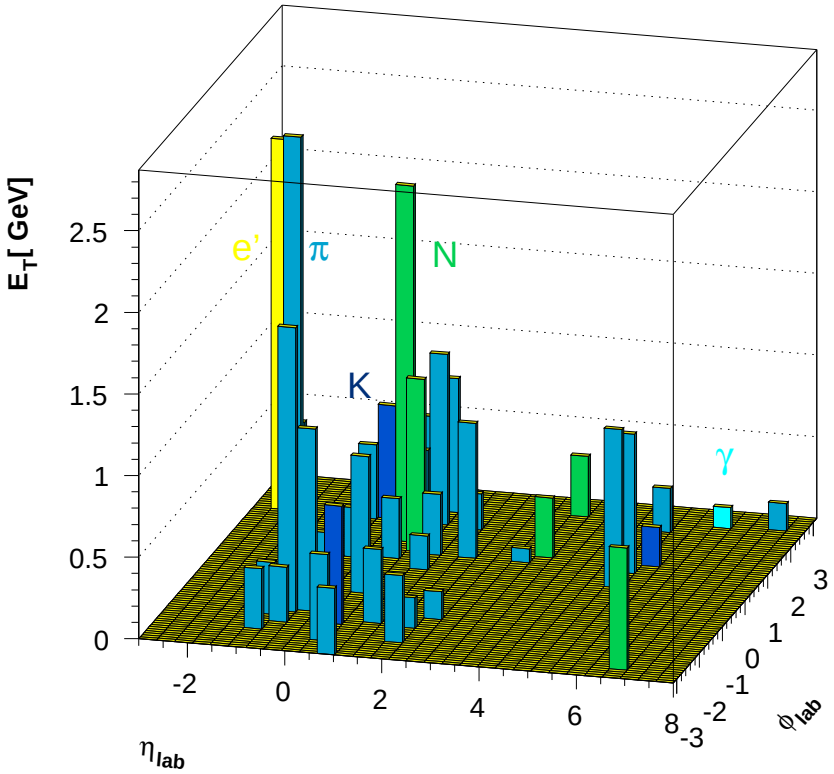
    for $x_{\rm Bj} \geq 10^{-3}, 0.1 \leq y_{\rm Bj} \leq 0.9$.

  - Hence, with total integrated luminosity accumulated by experiments at HERA, $\mathcal{L} = \mathcal{O}(100)\ {\rm pb}^{-1} \Rightarrow$

$\mathcal{O}(10000)$ I-induced events on tape!

Lego-Plots of Typical Event:





- Current jet
- Hadronic "band": $\Leftrightarrow$ **Isotropy** in I-rest system
  - Large total E_T
  - Large multiplicity
  - No jets in "band" !
  - Characteristic flavor flow:
    - **Strangeness** $\Rightarrow$ K^0_S's

same event with particle composition

4. Conclusions

- Topological fluctuations: Important aspect of non-Abelian gauge theories.
- Much improved calculation of $\frac{\mathrm{d}\sigma_{\mathrm{HERA}}{}^{(I)}}{\mathrm{d}x'\mathrm{d}Q'^2}$ within $\boldsymbol{I}$-perturbation theory/"dilute" $\boldsymbol{I}$-gas picture. [Moch, Ringwald & F. Sch. to appear]
- Profit from recent activity of the "lattice-community" studying the topological features of the QCD ground state non-perturbatively.
  [Smith, Teper '98; Forcrand *et al.* '97; DeGrand *et al.* '97; Michael, Spencer '95; Chu *et al.* '94; . . .]
- Tried to link new lattice results with I-induced processes in DIS $\Rightarrow$ "fiducial" (Q', x') region.
- DIS at **HERA** offers unique window to detect I-induced events through their characteristic multi-particle final-state signature.
- studies of experimental strategies to reconstruct (Q', x') are important and in progress.
- Best present experimental limits at **HERA** come from multiplicity distribution and E_T flow, approaching theoretical estimate from "fiducial region"! [H1 Collaboration, Z. Phys. C72 (1996) 573; Carli, Kuhlen, Nucl. Phys. B511 (1998) 85]
- Decisive search for instanton-induced events at **HERA** seems feasable.