Instantons/Sphalerons:

Searching for New Physics within the Standard Model

Andreas Ringwald

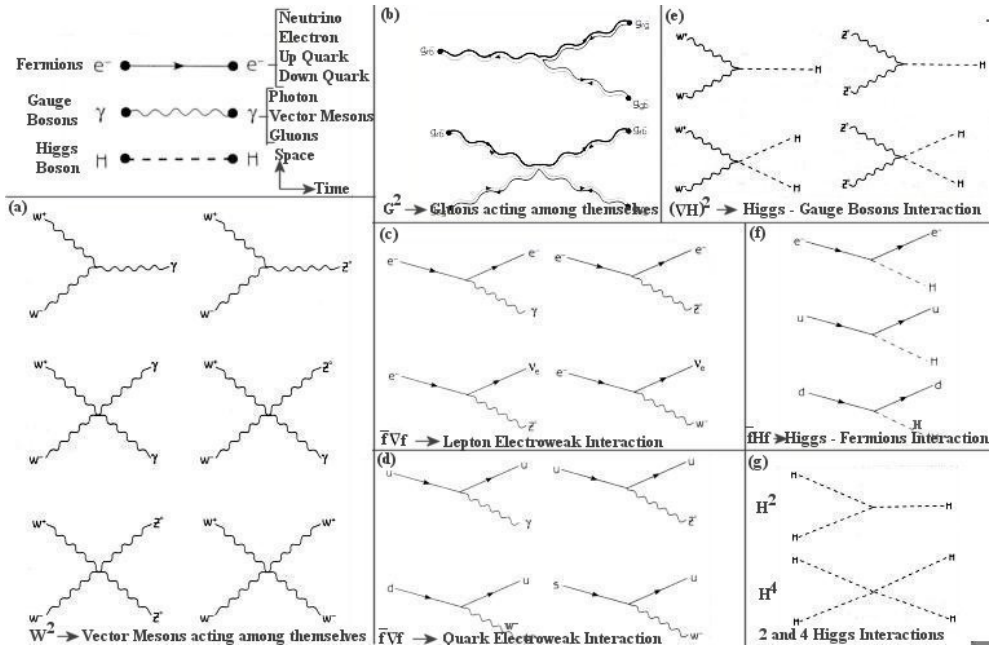
Festkolloquium Fridger Schrempp, February 19th, 2008, DESY

1. Introduction

- Standard Model of electroweak (QFD) and strong (QCD) interactions extremely successful

$\Leftarrow$ Ordinary perturbation theory

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4}\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu} - \frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu} \\
& + \overline{L}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g\tau\mathbf{W}_{\mu} - \frac{1}{2}g'Y\,B_{\mu})L \\
& + \overline{R}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g'Y\,B\mu)R \\
& + |(i\partial_{\mu} - \frac{1}{2}g\tau\mathbf{W}_{\mu} - \frac{1}{2}g'Y\,B_{\mu})\phi|^2 - V(\phi) \\
& - (g_1\overline{L}\phi R + g_2\overline{L}\tilde{\phi}R + herm.conj.) \\
& + \frac{1}{2}g_s(\overline{\Psi_q^j}\gamma^{\mu}\lambda_{jk}^a\Psi_q^k)G_{\mu}^a
\end{aligned}
$$



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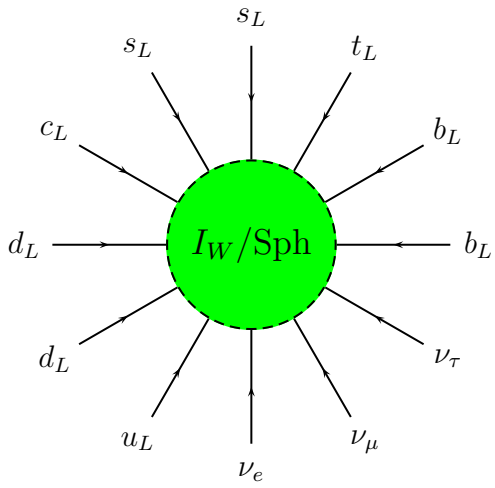
[Adler '69; Bell,Jackiw '69; Bardeen '69]

$B+L$/Chirality-violating processes in QFD/QCD

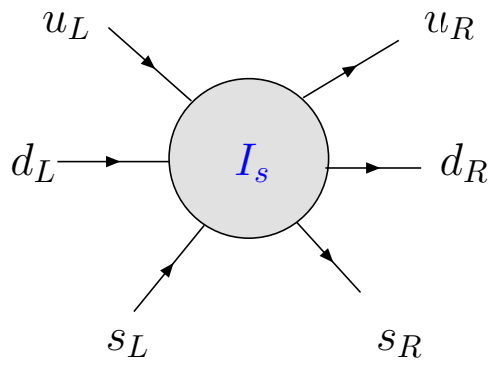
- Induced by topological fluctuations of non-Abelian gauge fields, in particular instantons

[Belavin *et al.* '75; 't Hooft '76]

$\triangle(B+L) = -6$:



$\triangle Q_5 = 6$:



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- $B + L/Q_5$ are anomalous,

$$\begin{aligned} \Delta(B+L) &= -2\,n_g\,\Delta N_{\rm CS}[W] \\ \Delta Q_5 &= 2\,n_f\,\Delta N_{\rm CS}[G] \end{aligned}$$

- Topological fluctuations of the gauge fields W/G, i.e. fluctuations with integer $\triangle N_{\rm CS} \neq 0$, induce anomalous processes
- Instanton: lowest Euclidean action configuration with $\Delta N_{\rm CS} = 1 \Rightarrow$ tunneling
- Sphaleron: lowest static energy configuration with $N_{\rm CS} = 1/2 \Rightarrow$ barrier

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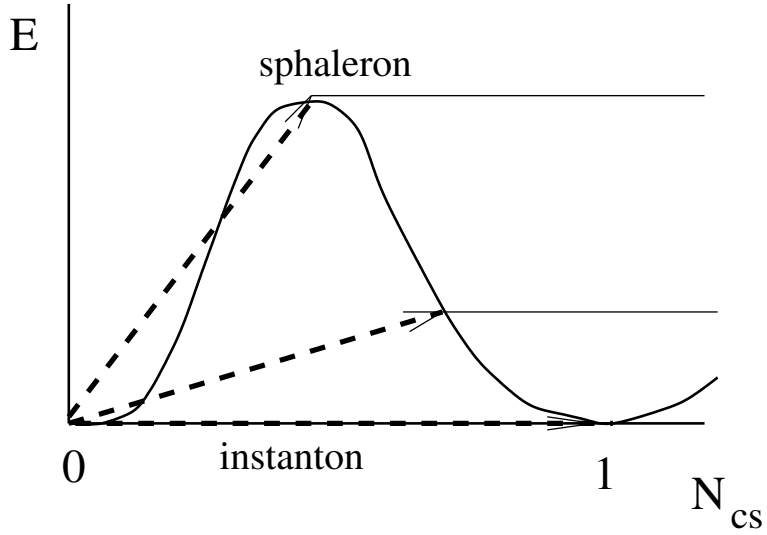


- **Theory:** Topological gauge field fluctuations and associated anomalous processes are predicted to play very important role in
  - QCD in various long-distance aspects: [...; Shuryak; ...]
    - $U(1)_A$ problem ($m_{\eta'} \gg m_\eta$) ['t Hooft '76; ...]
  - QFD at high temperatures: [Kuzmin,Rubakov,Shaposhnikov '85; ...]
    - Crucial impact on baryon and lepton asymmetries of the universe
- **Experiment:** Are they directly observable in high energy reactions?
  - QFD: Intense studies in early 1990s; inconclusive [AR '90; Espinosa '90; ...]
  - QCD: Hard instanton induced processes in deep-inelastic lepton-hadron scattering or in virtual $\gamma/W/Z$ production at hadron colliders
    - reliably calculable and sizeable rate [...; Moch,AR,F.Schrempp '97; F.Schrempp '05; Brandenburg,AR,Utermann '06; F.Schrempp,M.Petermann '08]
    - characteristic final state "fireball" signature [AR,F.Schrempp '94–'01]
    - first encouraging search results from HERA I data [H1 '02; ZEUS '04]
    - looking forward to search in HERA II data and at LHC

Outline:

2. **Evidence for QCD-Instantons in the Vacuum**

3. **Searches for QCD-Instantons at HERA**

4. **Conclusions and Outlook**

2. Evidence for QCD-Instantons in the Vacuum

- Euclidean functional integral formulation of QCD,

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int [dA][d\psi][d\overline{\psi}]\, \mathcal{O}[A,\psi,\overline{\psi}]\, \mathrm{e}^{-S[A,\psi,\overline{\psi}]}\,,$$

$$Z = \int [dA][d\psi][d\overline{\psi}]\, \mathrm{e}^{-S[A,\psi,\overline{\psi}]}\,.$$

- Perturbation theory:
  - perturbative QCD: expansion about trivial vacuum solution, i.e. vanishing gluon field and vanishing quark fields and thus vanishing Euclidean action, $S = 0$.
  - instanton perturbation theory: generalized saddle-point expansion of the Euclidean functional integral about non-trivial minima of the Euclidean action, $S \neq 0$.

- Non-trivial minima ($\Leftrightarrow$ solutions) have integer Pontryagin index (topological charge)

$$Q \equiv \frac{\alpha_s}{2\pi} \int d^4x \, \frac{1}{2} \mathrm{tr}(G_{\mu\nu} \tilde{G}_{\mu\nu}) \equiv \triangle N_{\mathrm{CS}} = \pm 1, \pm 2, \ldots,$$

and their action is a multiple of $2\pi/\alpha_s$,

$$S \equiv \int d^4x \, \frac{1}{2} \mathrm{tr}(G_{\mu\nu} G_{\mu\nu}) = \frac{2\,\pi}{\alpha_s} \, |Q| = \frac{2\,\pi}{\alpha_s} \cdot (1, 2, \ldots).$$

$\Rightarrow$ Dominant saddle-point for $\alpha_s \ll 1$: $\mid Q \mid = 1$

$\Rightarrow$ Instanton $(Q = 1)$:

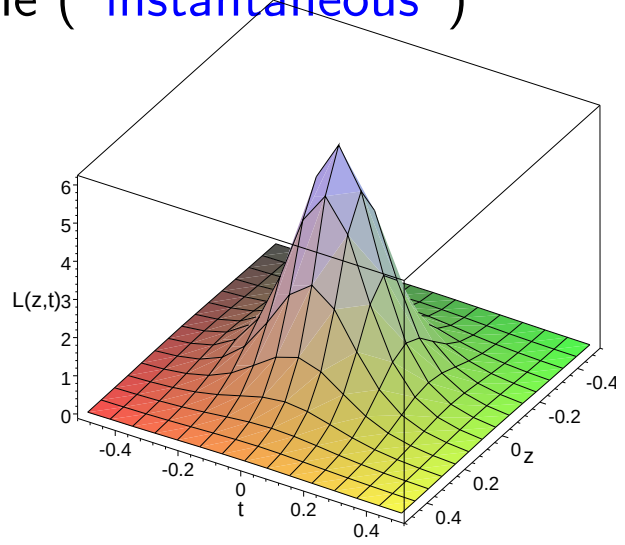
[Belavin *et al.* '75; 't Hooft '76; Callan,Dashen,Gross '76; Jackiw,Rebbi '76]

$$A_\mu^{(I)}(x;\rho,U,x_0) = -\frac{\mathrm{i}}{g}\,\frac{\rho^2}{(x-x_0)^2}\,U\,\frac{\sigma_\mu\,(\overline{x}-\overline{x_0})-(x_\mu-x_{0\mu})}{(x-x_0)^2+\rho^2}\,U^\dagger$$

- size ρ, color orientation U, position x_0
- localized in Euclidean space and time ("instantaneous")

$$\mathcal{L}\left(A_\mu^{(I)}(x;\rho,U,0)\right) = \frac{12}{\pi\alpha_s}\cdot\frac{\rho^4}{(x^2+\rho^2)^4}$$

$$\Rightarrow\quad S\left[A_\mu^{(I)}\right] = \frac{2\,\pi}{\alpha_s}$$



- tunneling between topologically inequivalent $(\triangle N_{\mathrm{CS}} = 1)$ vacua

- Instanton-contribution to vacuum-to-vacuum amplitude, $Z^{(I)} = \langle 0|0\rangle^{(I)}$:

$$\frac{1}{Z^{(0)}}\frac{dZ^{(I)}}{d^4x} = \int_0^\infty d\rho\, D_m(\rho) \int dU$$

- Size distribution $D_m(\rho)$ known in instanton perturbation theory

['t Hooft '76; Bernard '79]

$$\alpha_s(\mu_r)\ln(\rho\,\mu_r) \ll 1, \qquad \rho\, m_i(\mu_r) \ll 1,$$

in 2-loop renormalization-group invariant form, [Morris *et al.* '85]

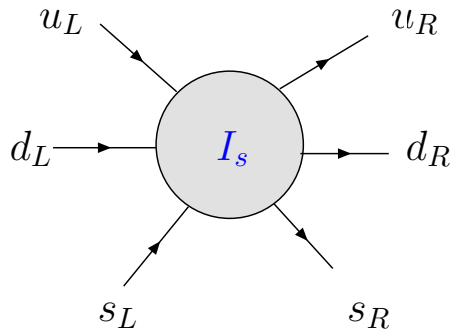
$$\frac{dn_I}{d^4x\, d\rho} = D_m(\rho) = D(\rho) \prod_{i=1}^{n_f} (\rho\, m_i(\mu_r))\, (\rho\,\mu_r)^{n_f\, \gamma_0 \frac{\alpha_s(\mu_r)}{4\pi}}$$

- Suppression of instanton contribution to the vacuum-to-vacuum amplitude for small quark masses $\rho m_i \ll 1$:

$\Leftarrow$ Axial anomaly: [Adler '69; Bell, Jackiw '69]
Any gauge field fluctuation with topological charge Q must be accompanied by a corresponding change in axial charge, $\triangle Q_5 = 2\, n_f\, Q$

$\Rightarrow$ pure vacuum-to-vacuum transitions vanish in massless limit

$\Rightarrow$ Green's functions corresponding to anomalous Q_5 violation: ['t Hooft '76]



$*$ main contribution due to instantons (fermionic zero modes)

$*$ do not suffer from any mass suppression

- Reduced size distribution $D(\rho)$:

$$D(\rho) = \frac{d}{\rho^5} \left(\frac{2\pi}{\alpha_s(\mu_r)} \right)^{2\,N_c} \mathrm{e}^{-\frac{2\pi}{\alpha_s(\mu_r)}} \, (\rho\,\mu_r)^{\beta_0 + (\beta_1 - 4\,N_c \beta_0)\frac{\alpha_s(\mu_r)}{4\pi}}$$

- Clearly non-perturbative: $\propto \mathrm{e}^{-\frac{2\pi}{\alpha_s(\mu_r)}}$
- Power-law behaviour of (reduced) size distribution,

$$D(\rho) \sim \rho^{\beta_0 - 5 + \mathcal{O}(\alpha_s)}; \qquad \beta_0 = \frac{11}{3}\,N_c - \frac{2}{3}\,n_f$$

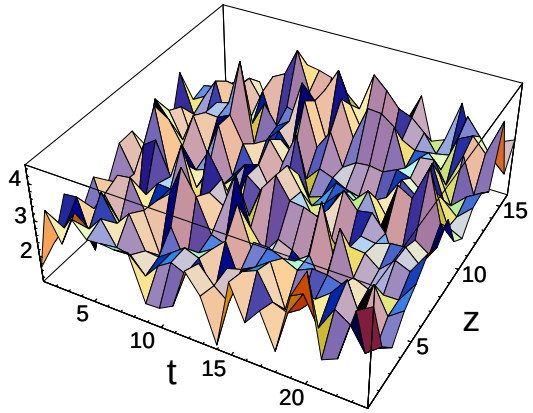
  - dominant contribution to ρ integral generically originates from large ρ
  - spoils the applicability of instanton perturbation theory, $\alpha_s(1/\rho) \ll 1$

- Size distribution basic building block of instanton perturbation theory:
  - ◦ appears in generic instanton contributions to Green's functions

  $\Rightarrow$ important to know the region of validity of the perturbative result

- Crucial information from lattice investigations on the topological structure of the QCD vacuum
  - – Evidence for topological charge fluctuations: e.g. [Chu *et. al* '94]

    Lagrange density (raw data)



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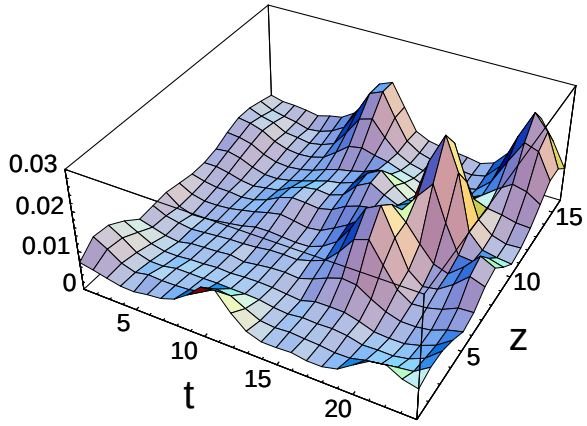
    Lagrange density (smoothed)



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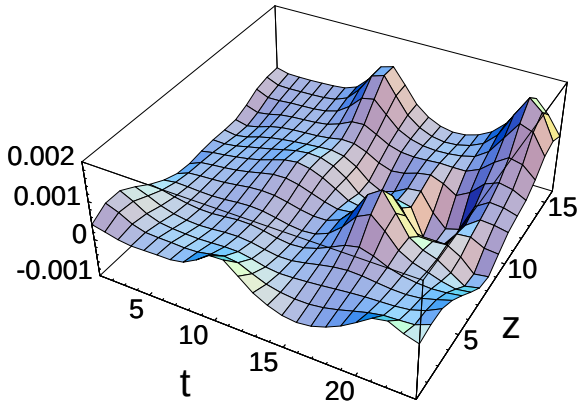
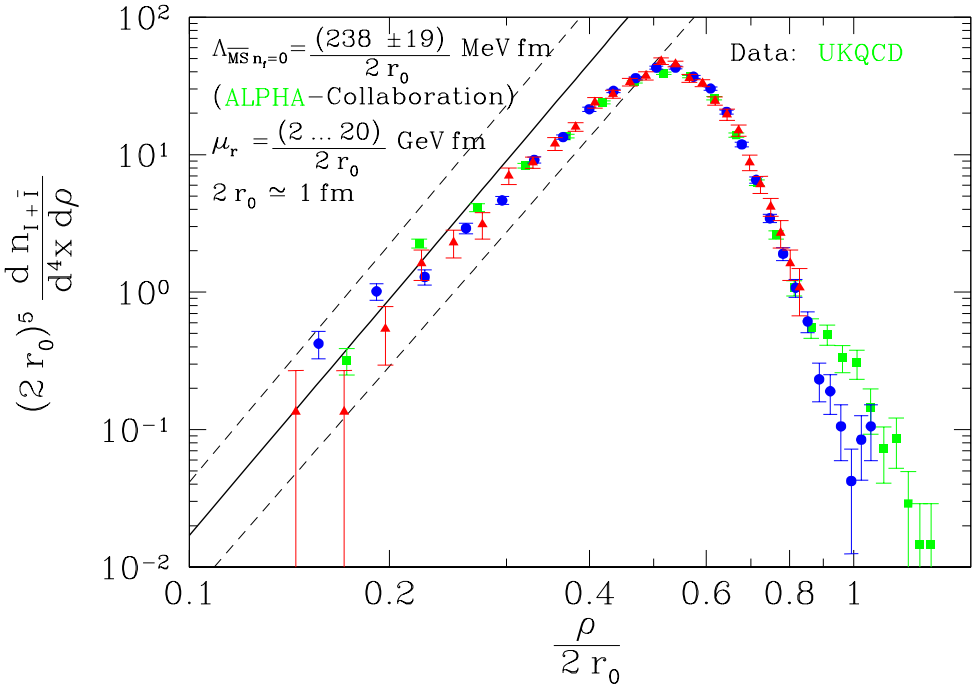
    Topological charge density (smoothed)



– Small size topological charge fluctuations ≡ QCD-instantons:

[AR,F. Schrempp '99]



$\Rightarrow$ Instanton perturbation theory reliable for $\rho\, \Lambda_{\overline{\rm MS}} \lesssim 0.4$

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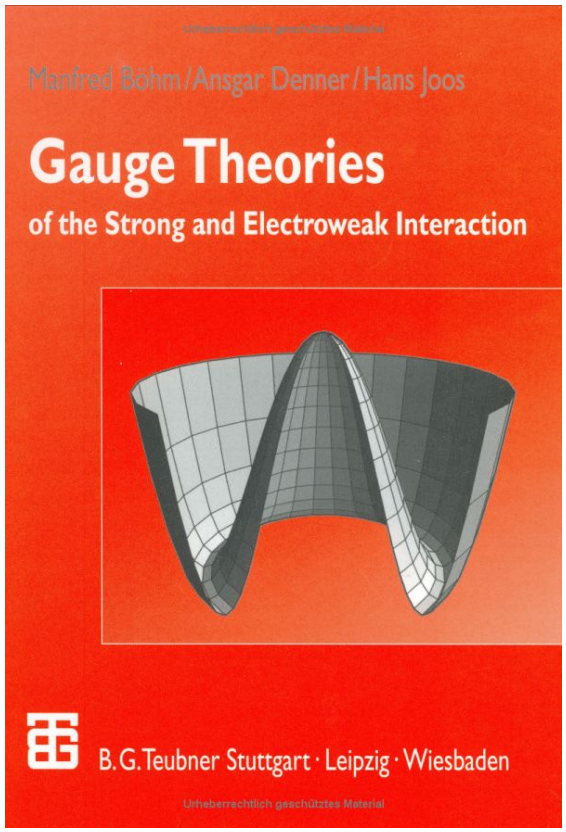


Urheberrechtlich geschütztes Material

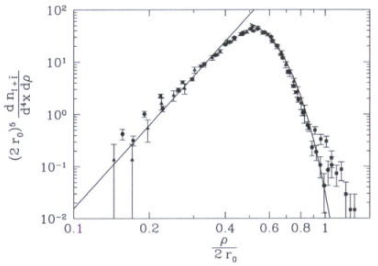


Fig. 3.18 Instanton distribution: the points represent lattice results, the straight line to the left gives the result of perturbative semi-classical approximation, and the line to the right gives a fit to dual gauge theory (from Ref. [Ri99]).

3.7.4.2 Lattice results for instantons

Topological configurations seem to play an important rôle in the understanding of non-perturbative aspects of gauge theories. Figure 3.18 illustrates, how instantons fit in this picture [Ri99]. It shows the density distribution of instantons $D_1(\rho, \alpha(\mu_0))$ (2.9.121) of the size ρ (called λ in Sect. 2.9.3) measured by a cooled lattice approximation [Sm98].

For small instantons, i.e. $\rho \leq 0.3\,\text{fm}$, 't Hooft's semi-classical approximation (Sect. 2.9.3.2) works well. The straight line gives the result of the two-loop approximation of (2.9.121). It is an absolute prediction of $D_1(\rho, \alpha(\mu_0))$ without any fitting parameters. The $\Lambda_{\overline{\text{MS}}}$ parameter is determined by the non-perturbative evolution of Sect. 3.6.3.4: $\Lambda_{\overline{\text{MS}}} = (238 \pm 19)\,\text{MeV}$. The parameter $r_0 \approx 0.5\,\text{fm}$ was introduced in this context.

We speculate that the large instantons are screened with a penetration length of the dual Meissner effect. An extension of 't Hooft's calculation

Urheberrechtlich geschütztes Material

- First principle calculations of instanton contributions only possible for quantities to which large size instantons do not contribute:
  - Short-distance coefficient functions in the operator product expansion of two-point functions [Andrei,Gross '78;...;Novikov *et al.* '80;...; Balitsky,Braun '93]
    Problem:
    - No physics-wise relevant two-point function known which receives contribution solely from instantons

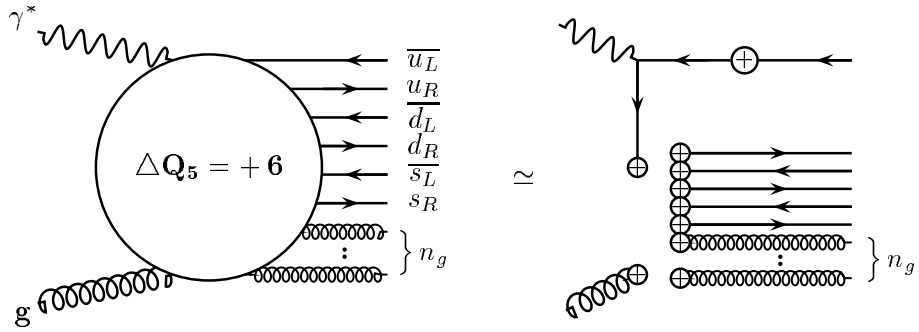
    $\longrightarrow$ Instanton contribution typically hidden beyond large perturbative background
  - Unique possibilities: Anomalous $\triangle Q_5 = \pm 2\, n_f$ hard scattering processes, in particular deep-inelastic lepton-hadron scattering and virtual $\gamma/W/Z$ production in hadron scattering

    [Moch,AR,F.Schrempp '97; F.Schrempp '05; Brandenburg,AR,Utermann '06; F.Schrempp,Petermann '08]

  $\longrightarrow$ In $m_q = 0$ limit, receive contributions only from instantons

  $\longrightarrow$ Large size instantons exponentially suppressed by form factors $\propto \mathrm{e}^{-\mathcal{Q}\rho}$, where $\mathcal{Q}$ is the hard scale (virtuality) of the process

- Deep-inelastic scattering: [Moch,AR,F.Schrempp '97]



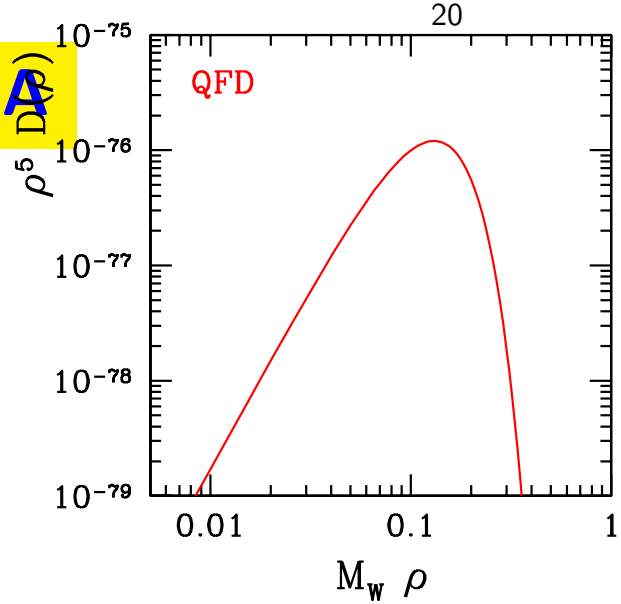
- Virtual $\gamma/W/Z$ production: [F.Schrempp '05; Brandenburg *et al.* '06; F.Schrempp,Petermann '08]

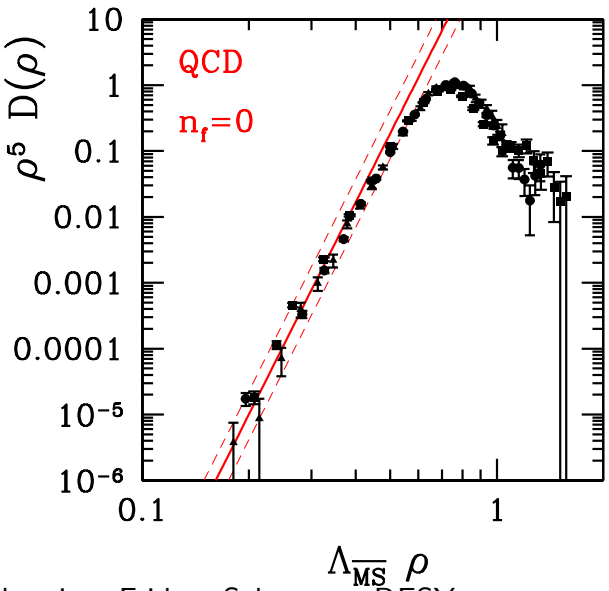
3. Searches for QCD-Instantons at HERA

- Natural scale: sphaleron energy

$$M_{\rm sp} \sim \frac{\pi}{\alpha_g\,\rho} \sim \begin{cases} 10\ \text{TeV} & \text{in QFD} \\ 10\ \text{GeV} & \text{in QCD} \end{cases}$$

[Klinkhamer,Manton '84;..;AR,F.Schrempp '94-'01;..]





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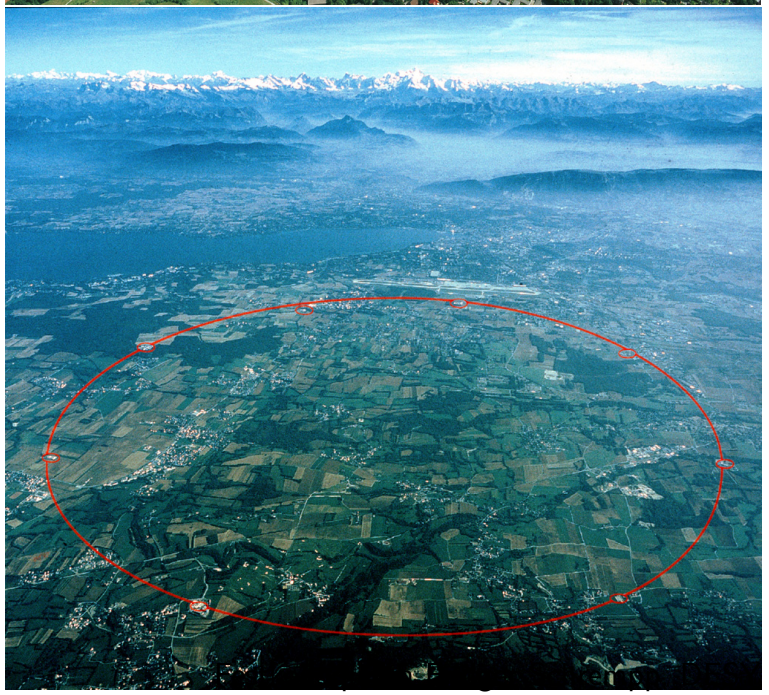
[Klinkhamer,Manton '84;..;AR,F.Schrempp '94-'01;..]

⇒ Anomalous processes in
QFD: VLHC ($> 20??$)
QCD: HERA ($\leq$ '07), LHC ($\geq$ '08)

⇒ Search for QCD-instantons in hadronic final state at HERA and LHC



Event generator QCDINS

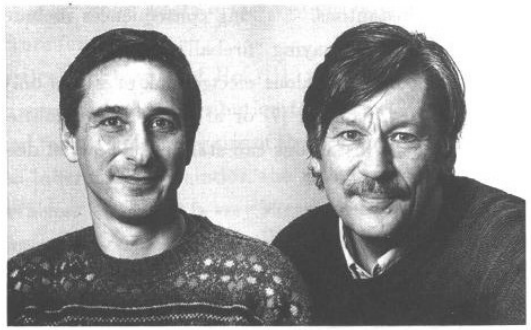
[AR,F.Schrempp '94-'01; Gibbs,AR,F.Schrempp '95]

- **Hard subprocess:**
  - isotropic in $q'g$ CM
  - flavour democratic
  - large parton multiplicity

$$\langle n_q + n_g \rangle = 2\,n_f - 1 + \mathcal{O}(1)/\alpha_s \gtrsim 8$$

QCD-INSTANTON INDUCED EFFECTS
TOWARDS SMALL x_{Bj}

A. Ringwald and F. Schrempp
Deutsches Elektronen-Synchrotron DESY
D-22603 Hamburg , GERMANY



Abstract

We report briefly on a broad and systematic study of possible manifestations of QCD-instantons at HERA. Considerable motivation comes from the close analogy between instanton-induced $B+L$ violation in electroweak processes and effects of QCD-instantons in deep inelastic scattering. We concentrate on the high multiplicity final state structure, reminiscent of an isotropically decaying "fireball".

[AR,F.Schrempp '94]

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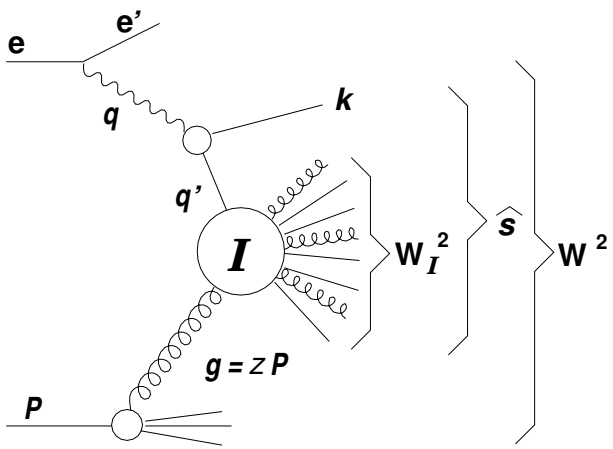

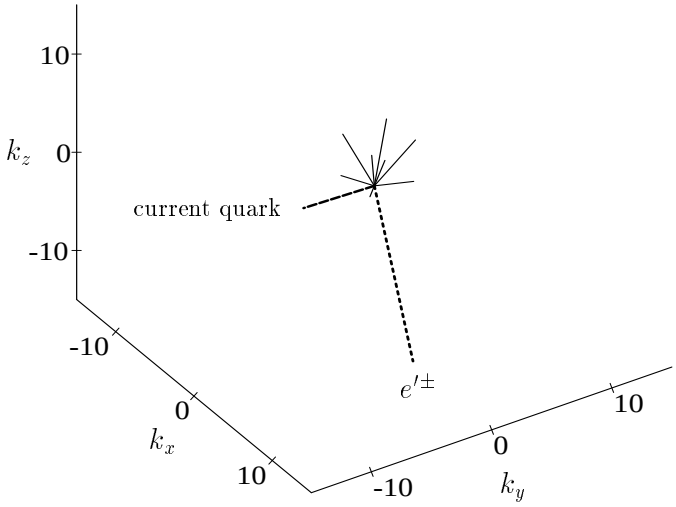

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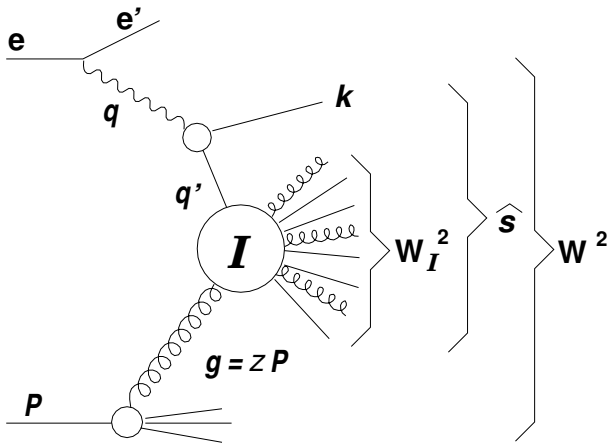

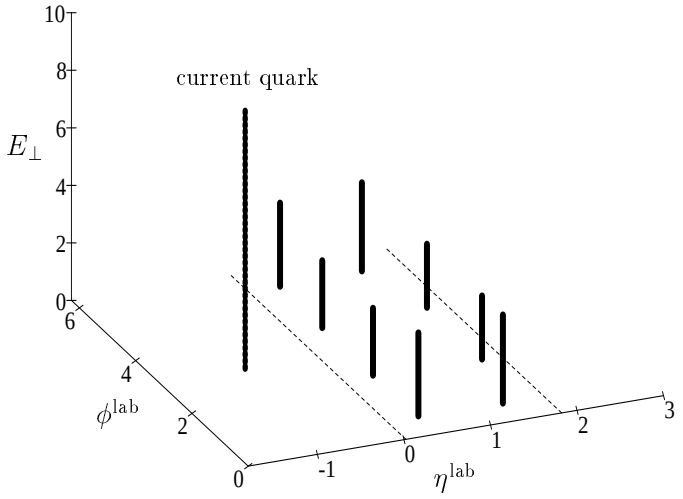

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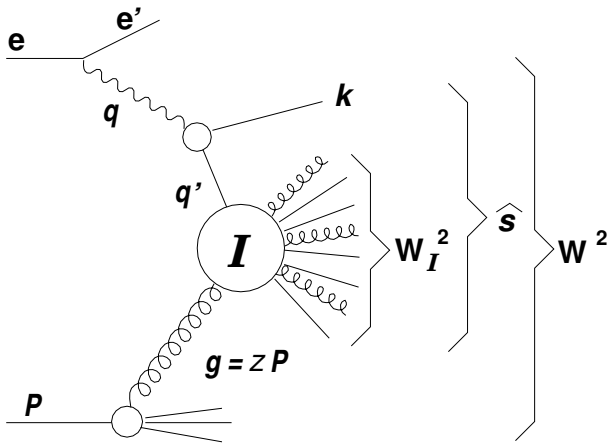
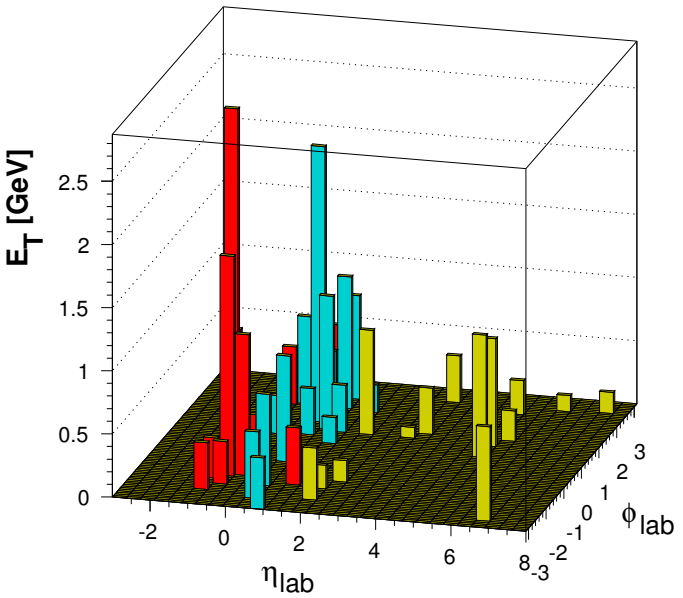
$$\langle n_q + n_g \rangle = 2\,n_f - 1 + \mathcal{O}(1)/\alpha_s \gtrsim 8$$

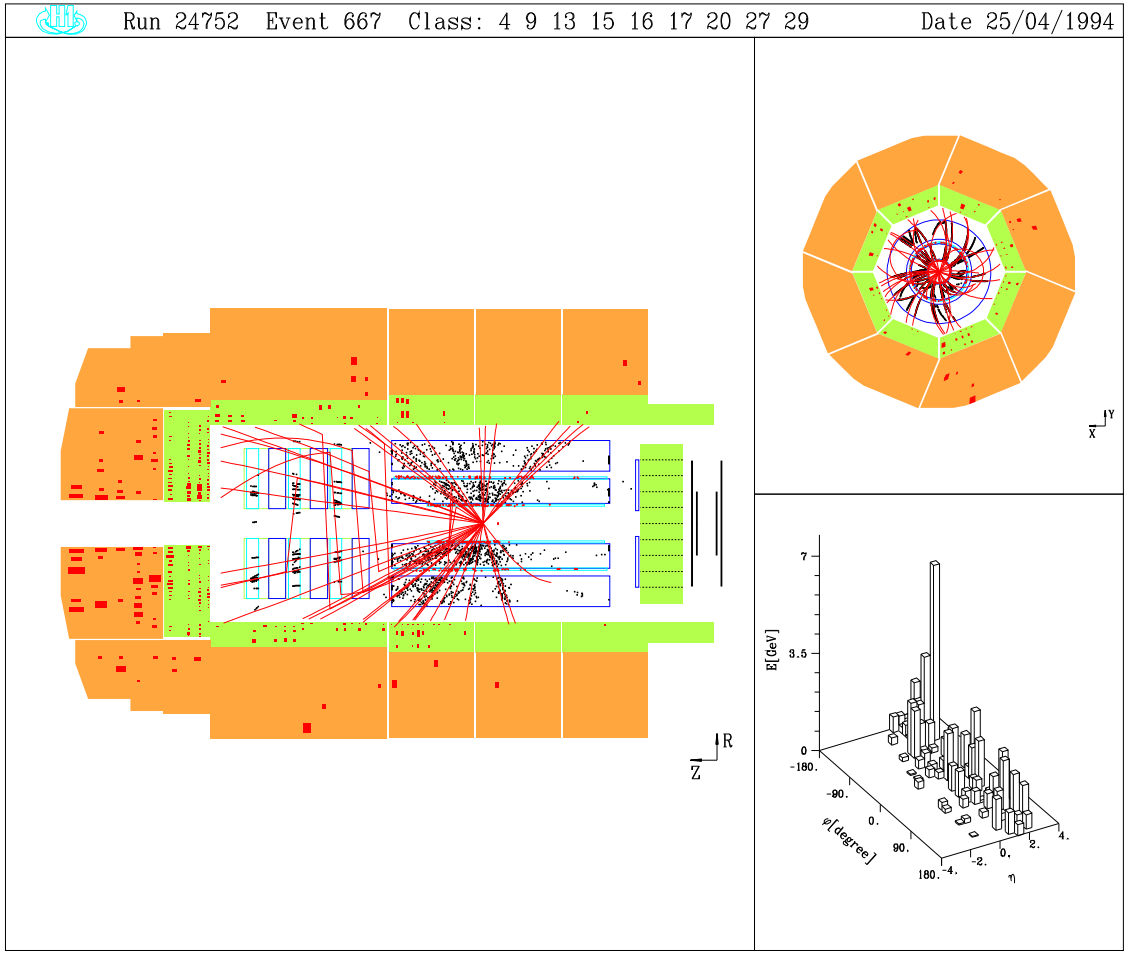
- **Parton shower:**
  HERWIG

- **Hadronization:**
  HERWIG/JETSET





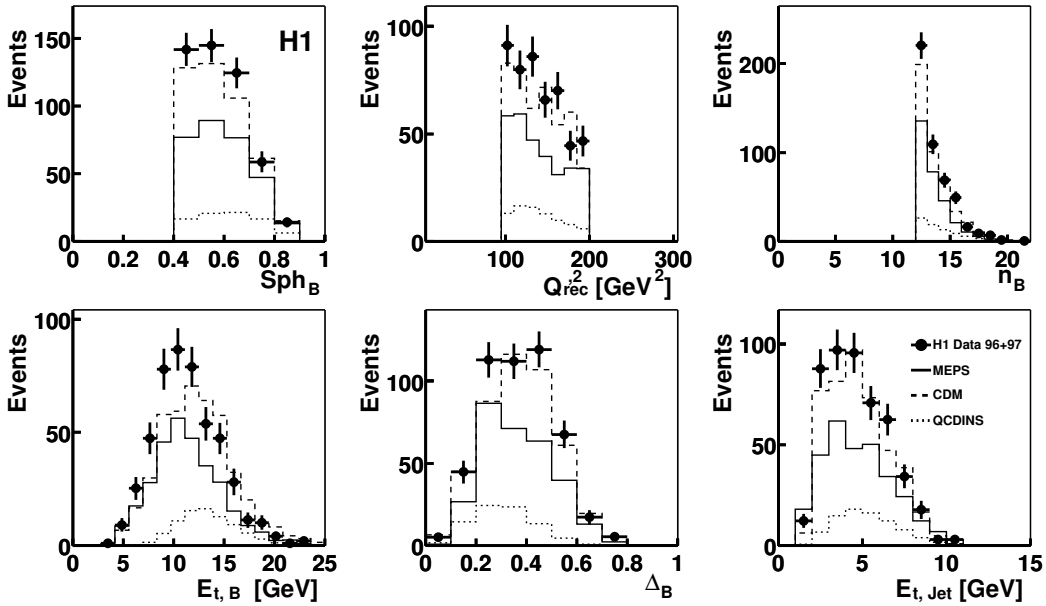
Such "fireballs" have been observed at HERA ...



H1/ZEUS searches at HERA I

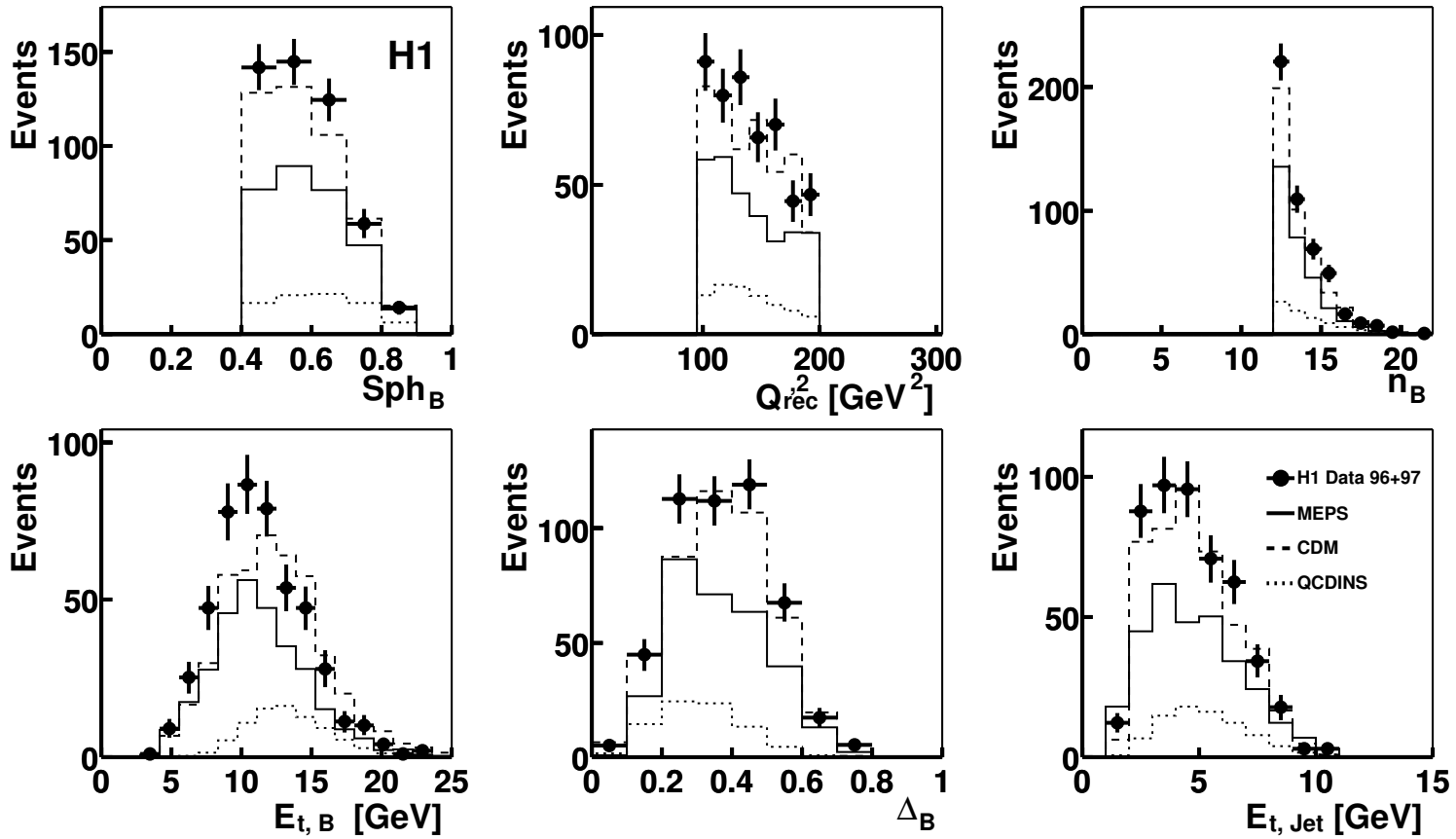
[H1 '02; ZEUS '04]

- Instanton-enriched samples by cuts on discriminating observables



[H1 '02]

The H1 excess:

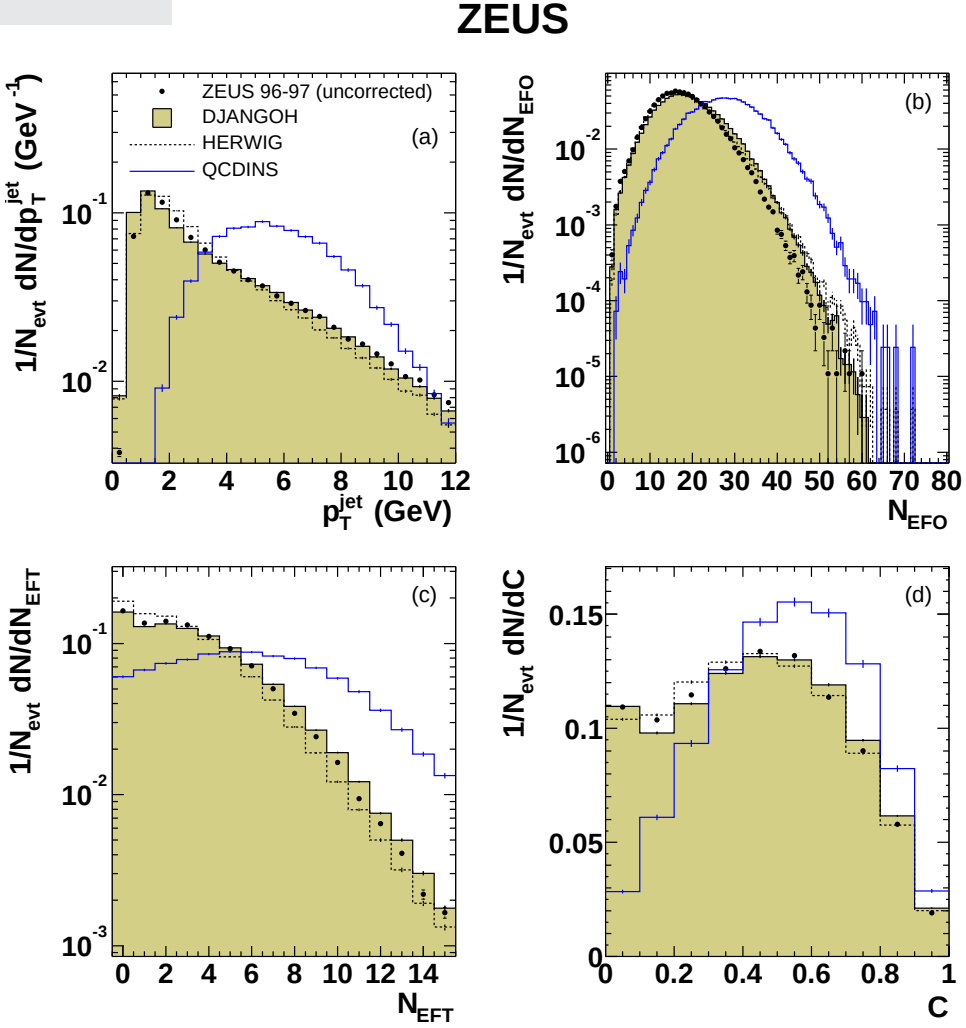


... intriguing, but inconclusive ...

H1/ZEUS searches at HERA I

[H1 '02; ZEUS '04]

- Instanton-enriched samples by cuts on discriminating observables

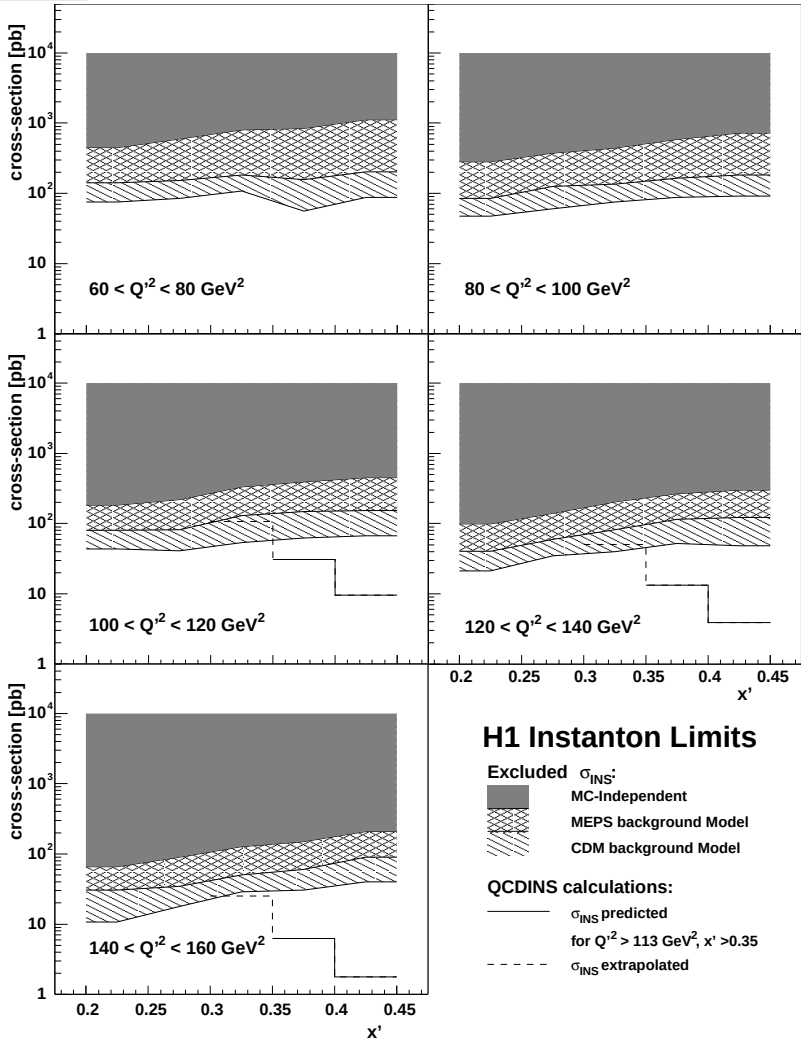


H1/ZEUS searches at HERA I

[H1 '02; ZEUS '04]

- Instanton-enriched samples by cuts on discriminating observables
- Large uncertainties in predictions of normal processes from different event generators

$\Rightarrow$ Upper limits on instanton-induced cross section; about a factor three above predictions



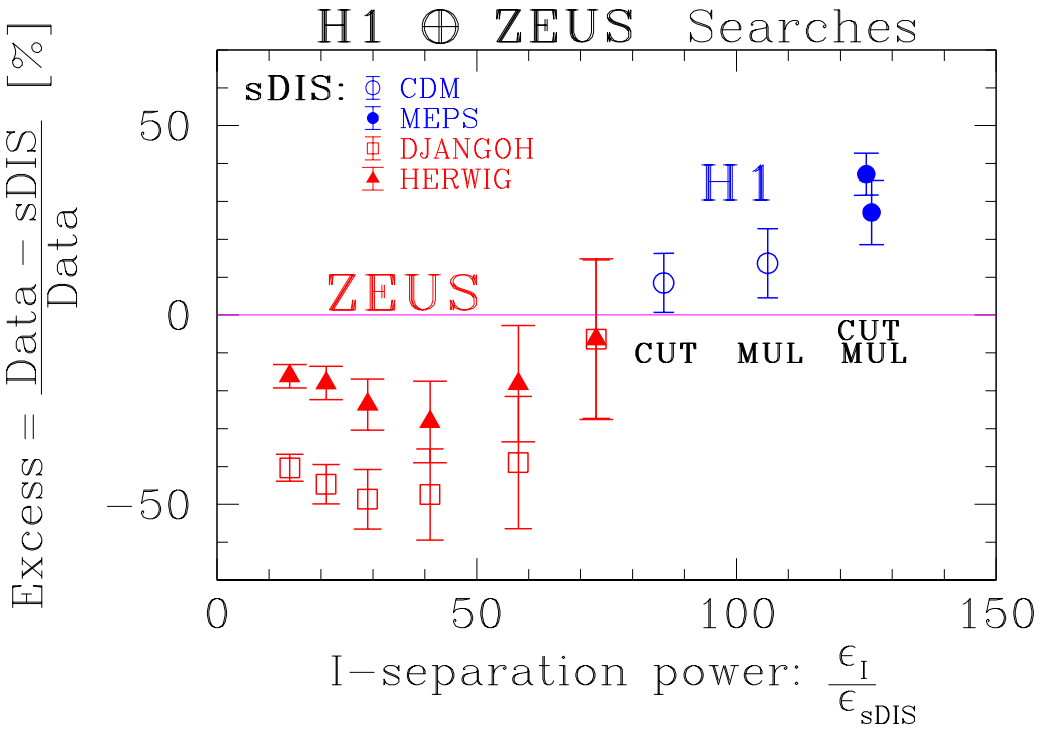
H1/ZEUS searches at HERA I

[H1 '02; ZEUS '04]

- Instanton-enriched samples by cuts on discriminating observables
- Large uncertainties in predictions of normal processes from different event generators

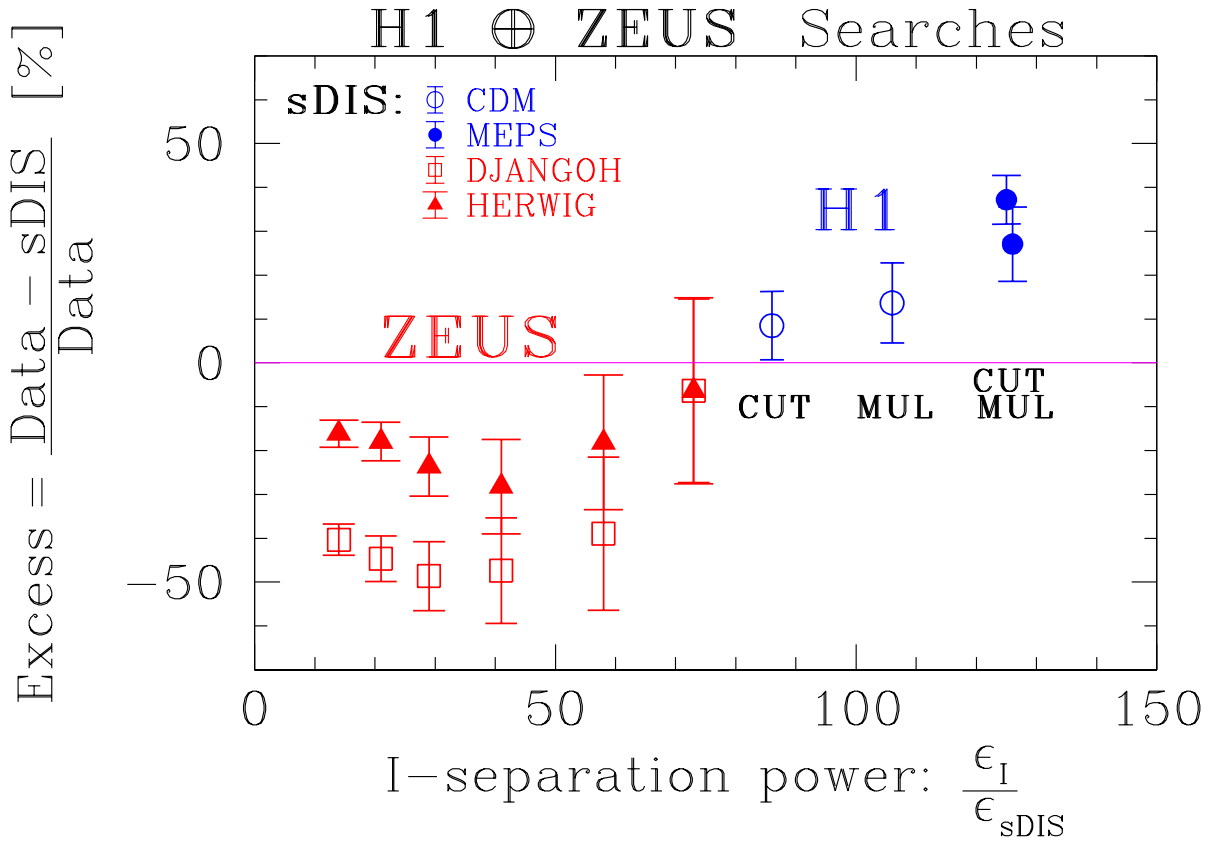
$\Rightarrow$ Upper limits on instanton-induced cross section; about a factor three above predictions

- Larger statistics from HERA II allow harder cuts $\Rightarrow$ may reach higher instanton separation power $\epsilon_{\mathrm{I}}/\epsilon_{\mathrm{sDIS}}$



[F. Schrempp '04]

Fridger's summary on the H1/ZEUS "excess" at HERA I:



⇒ increases with separation power ... encouragement for HERA II!

4. Conclusions and Outlook

- Instantons/sphalerons and the associated anomalous processes are
  - a solid prediction of QCD and QFD
  - of fundamental significance
    - for a solution to the $U(1)_A$ problem
    - for an understanding of the matter–antimatter asymmetry of the universe

$\Rightarrow$ Mandatory to search for them in collider experiments!

- Searches at HERA I: inconclusive, but encouraging results
- Searches at HERA II: H1 and ZEUS should not miss this opportunity!
- Searches at LHC: ground is laid ...