QCD-Instantons at HERA

– An Introduction –

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in collaboration with

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1. **Instantons**
2. **Cross-Sections in DIS**
3. **Signature and Searches**
4. **Conclusions**

Copy available via WWW:

http://www.desy.de/~t00fri/talks.html

– 3rd UK Phenomenology Workshop on HERA Physics, Durham, Sept 1998 –

1. Instantons

♣ Rich vacuum structure of non-abelian gauge theories (QCD) $\Leftarrow$ TOPOLOGY!

- Gauge fields $A_\mu(x)$ carry an integer topological charge Q

- Widely believed that topological fluctuations of gauge fields with $\boldsymbol{Q \neq 0}$ are important in QCD:
  - $U_A(1)$ problem ($m_{\eta'} \gg m_\eta$) ; Veneziano-Witten relation; ['t Hooft '76, Veneziano '79, Witten '79]
  - Breaking of chiral symmetry [Diakonov '96 (Review)]
  - Hadron and glueball spectrum [Schaefer, Shuryak '96 (Review)]

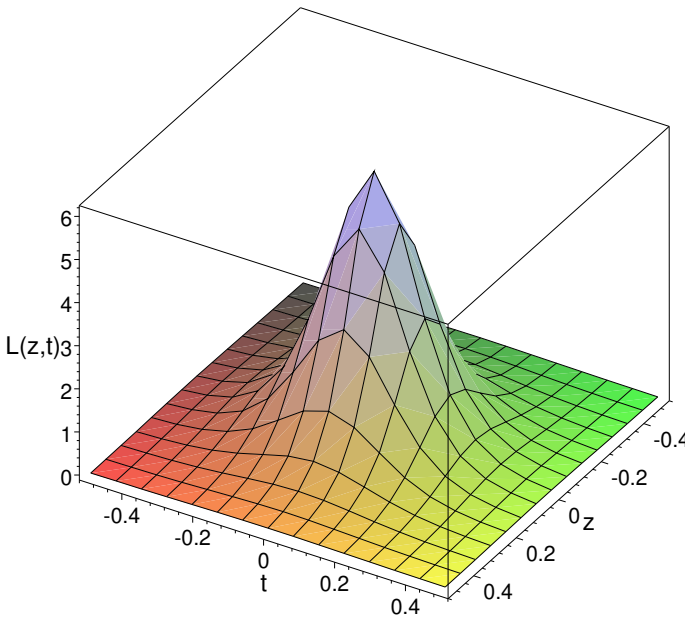
♣ (Anti-)Instantons: [Belavin *et al.* '75, 't Hooft '76]

Simplest non-trivial "building blocks" of topological structure of the vacuum.

♢ Explicit solutions of classical Euclidean field equations $\Leftrightarrow$ Minimize the classical Euclidean action for $Q = +1(-1)$ and (I-size ρ)

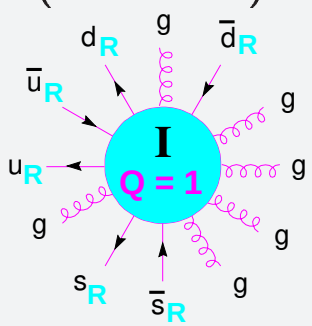
$$\mathcal{L}\left(A_\mu^{(I)}(x;\rho)\right) = \frac{12}{\pi\alpha}\cdot\frac{\rho^4}{(x^2+\rho^2)^4}$$

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

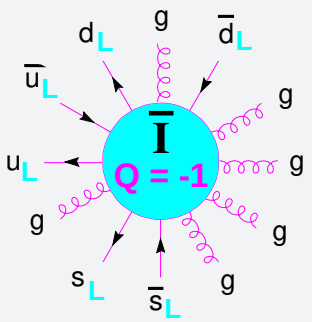


- Non-perturbative fluctuations of gauge-fields, localized ("instantaneous") in time and space.
- Tunnelling transitions between adjacent, topologically inequivalent vacua

Induce processes violating "chirality" $= \#(q_{\rm R}) - \#(q_{\rm L})$ in (massless) QCD



$$\Delta Q_5 = 2n_{\rm f}\cdot Q$$



- in accord with general Adler-Bell-Jackiw ANOMALY
- forbidden in ordinary perturbation theory ($Q = 0$!)

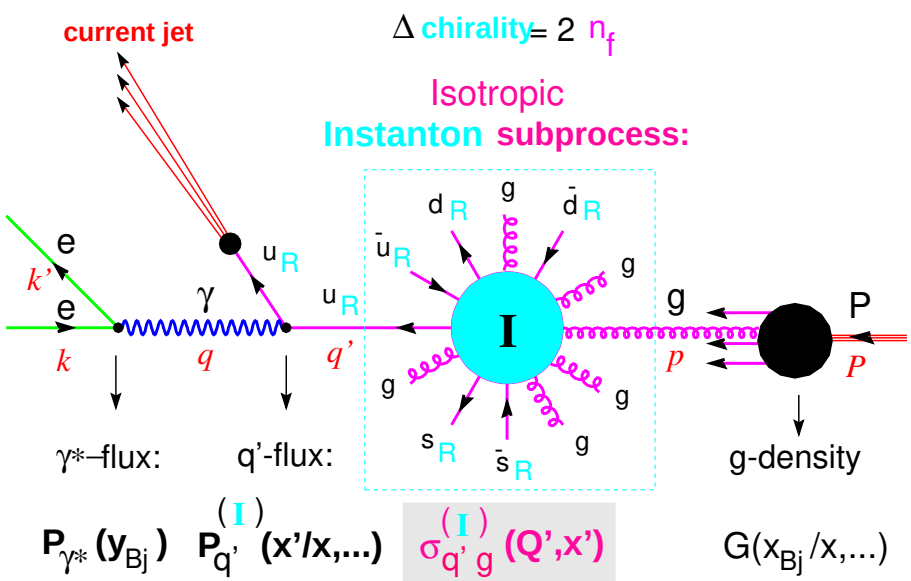
An experimental discovery of **Instantons** as a novel, non-perturbative manifestation of QCD would be of basic significance $\Leftarrow$ **HERA !**.

2. Cross-Sections in DIS

[Ringwald & F. Sch., Phys. Lett **B**, in print,
Moch, Ringwald & F. Sch.,
Nucl. Phys. **B507** (1997) 134]

- **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. '97]
  - ♣ can possibly be also detected experimentally⇐ **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 control!
    [Moch, Ringwald & F. Sch. '97]

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



- Instanton-subprocess with own **Bjorken**-variables, (x', Q'^2):

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

- show within $\boldsymbol{I}$-perturbation theory (Bjorken limit):

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

- Differential luminosity, $\mathrm{d}\mathcal{L}^{(I)}_{q'g}$, accounting for number of $q'g$ collisions per eP collision, has a convolution-like structure. Involves integrations over gluon density, γ^*-flux P_{γ^*} and known q'-flux $\mathrm{P}_{q'}{}^{(I)}$ in $\boldsymbol{I}$-background.

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

- Being an observable, $\sigma^{(I)}_{q'g}(Q', x')$ involves **integrations** over all $\boldsymbol{I}(\overline{\boldsymbol{I}})$-"collective coordinates", including

  $\rho\ (\overline{\rho})$=$I\ (\overline{I})$-sizes and $I\overline{I}$-distance 4-vector R_μ.

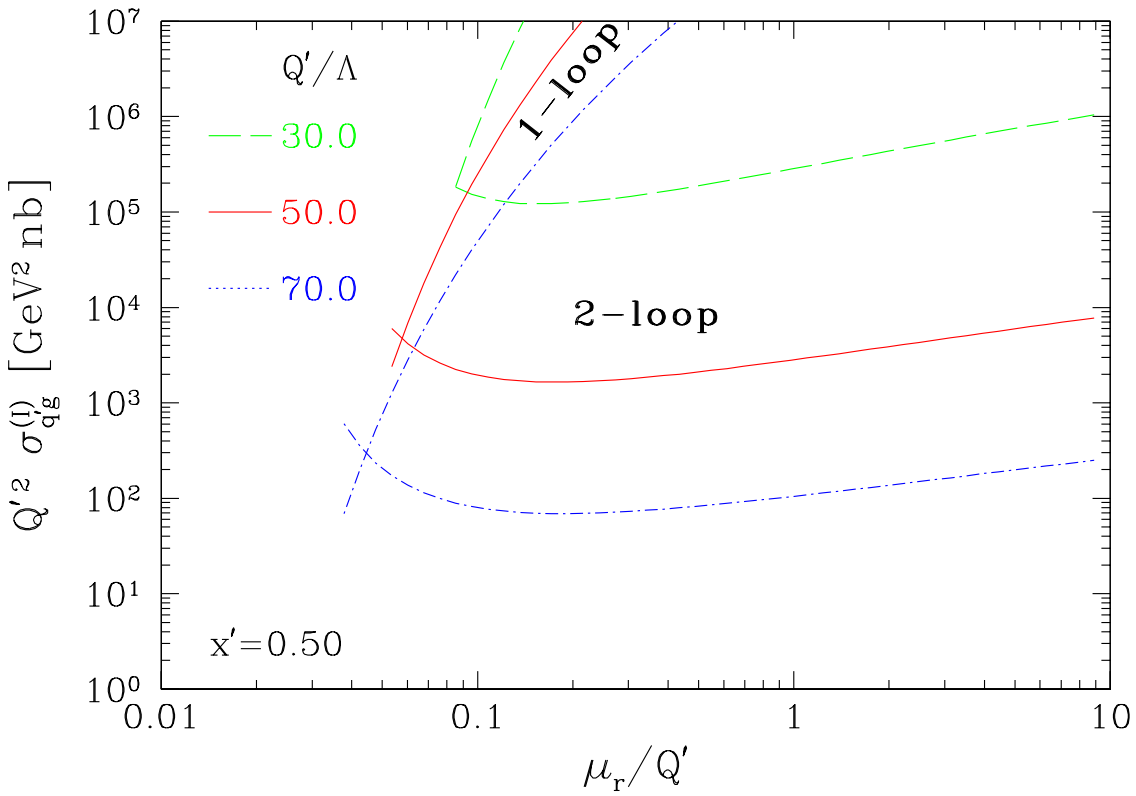
- Finite (!) on account of DIS-virtuality $\boldsymbol{Q' \neq 0}$, "filtering out" only small-size instantons

- Crucial saddle-point correspondence:

$$\rho^* = \overline{\rho}^* \sim 1/Q' \ , \ R^{*2} \sim 1/(p+q')^2 \Rightarrow \frac{R^*}{\rho^*} \sim \sqrt{\frac{x'}{1-x'}}$$

- Recent recalculation in terms of known, 2-loop RG invariant form of instanton density, $D(\rho)$
  [Ringwald & F. Sch., Phys. Lett **B** in print].⇒

- Great progress in stability: Residual dependence on renormalization scale μ_r strongly reduced!



- Expect μ_r in regime:

$$\mu_r \sim \frac{1}{\langle\rho\rangle} \simeq \frac{1}{\beta_0} Q' = \mathcal{O}(0.1) Q'$$

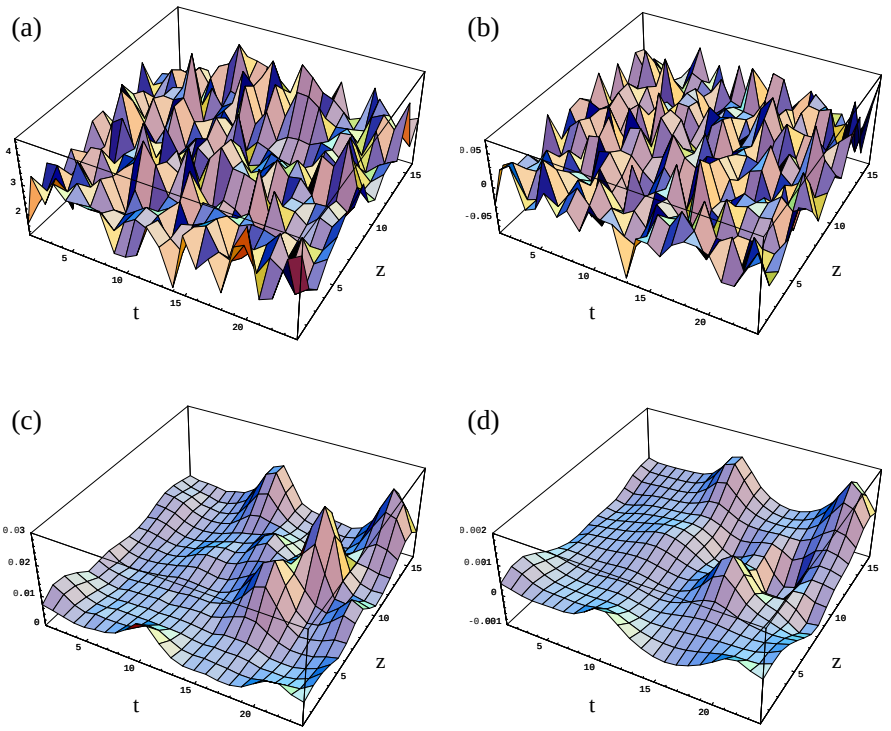
- Use as "best scheme": $\mu_r = 0.15\ Q'$, for which $\partial\sigma^{(I)}_{q'g}/\partial\mu_r \simeq 0$.

"Fiducial" Region from Lattice Simulations

[Ringwald & F. Sch., hep-ph/9805492, hep-ph/9806528, Phys. Lett. **B**, in print]

Lagrange Density $\mathcal{L}(z,t)$ Topol. Charge Density $q(z,t)$

Before



"Cooling"

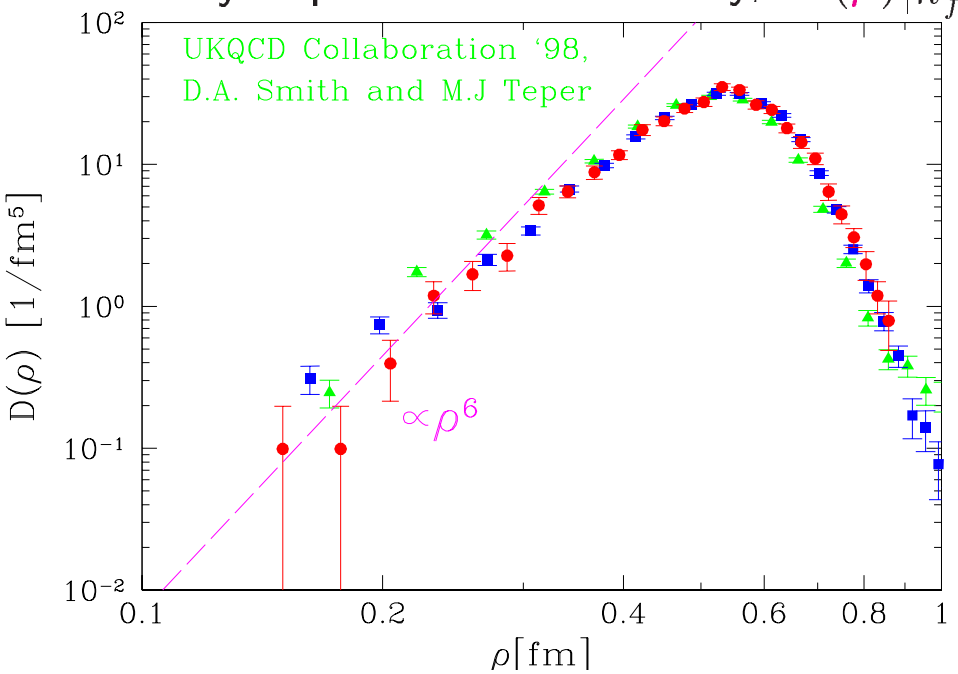
After

"Cooling"

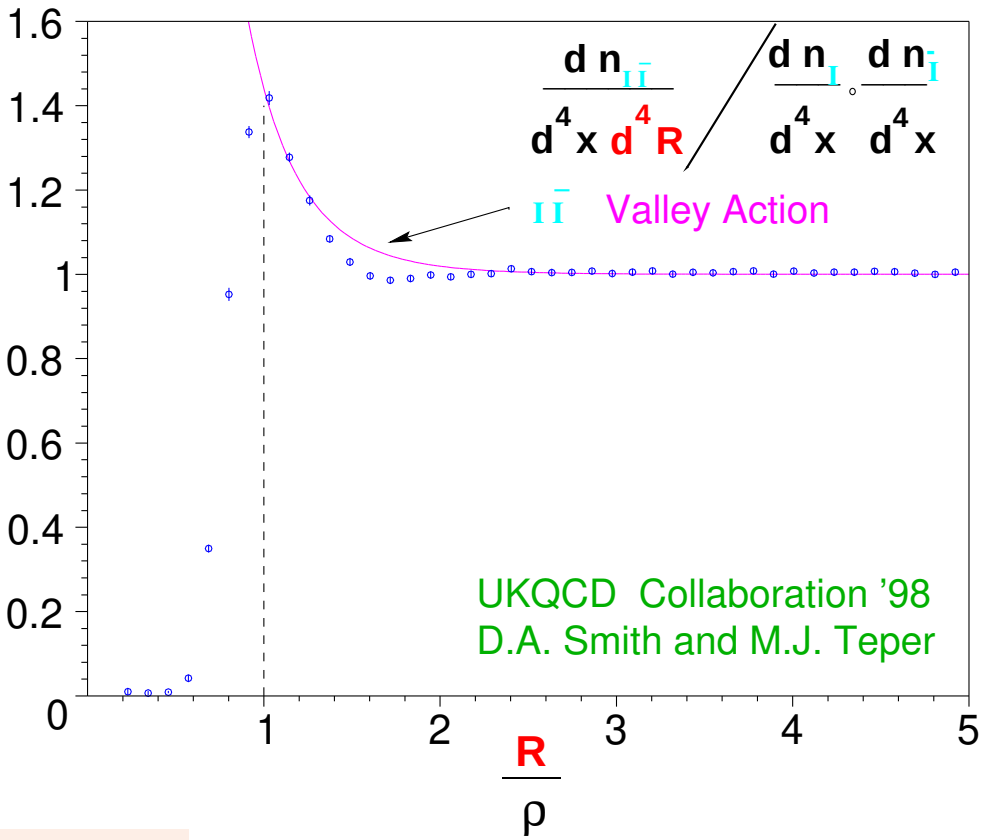
[Chu *et. al* '94]

- I-density: for small-size instantons, $\rho \lesssim \rho_{\max} \simeq 0.3$ fm,

well described by I-perturbation theory, $D(\rho)_{|n_f=0} \propto \rho^6$:



- $I\bar{I}$-interaction: Good description in terms of $I\bar{I}$-valley action for $R/\rho \gtrsim 1$! Semi-classical attraction for large $I\bar{I}$ separation $R/\rho \Rightarrow$ non-perturbative repulsion at $R/\rho \sim 1$.



♣ Key feature: One-to-one (saddle-point) relation between "conjugate" I-variables in momentum- and (ρ, R) space:

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

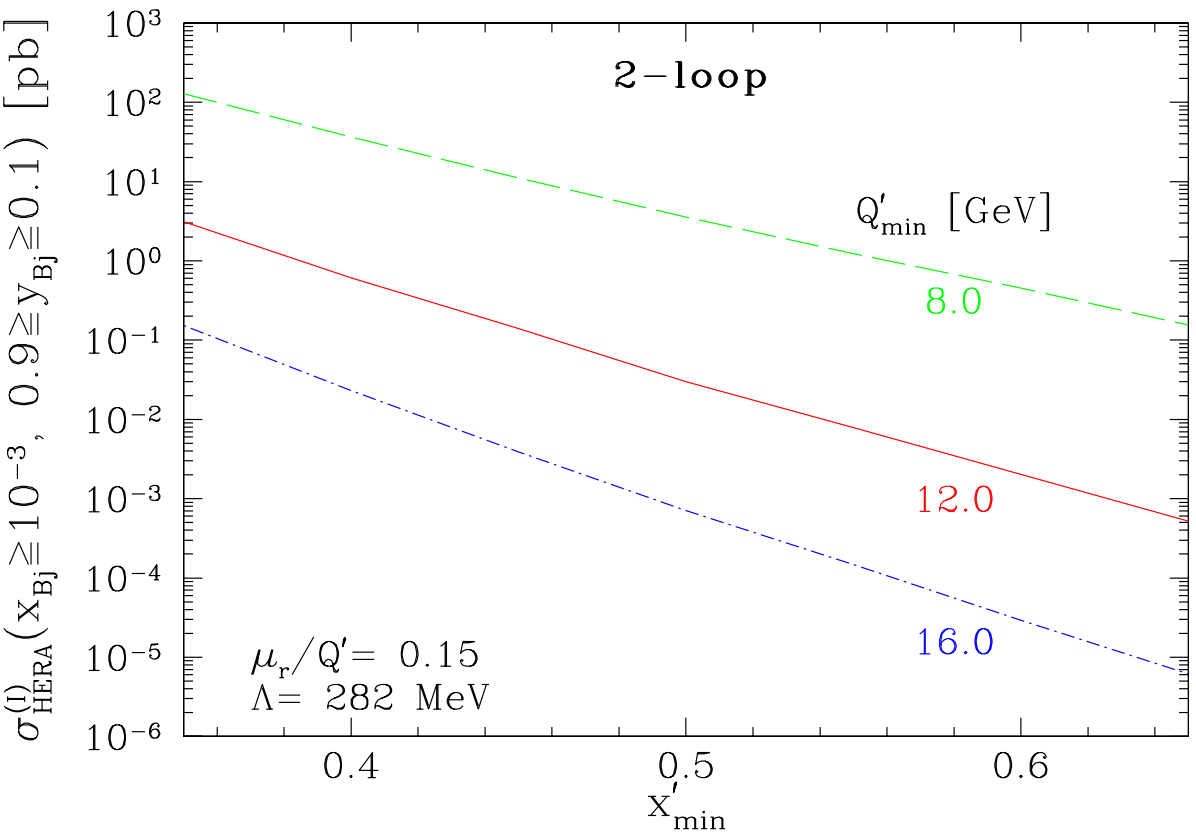
$\Rightarrow$ "Fiducial" kinematical region from lattice constraints:

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

HERA Cross-Section

- "Standard" cuts (lattice!):
  $\mathcal{C}_{\rm std} \equiv x' \geq 0.35, Q' \geq 8\ {\rm GeV}$, $x_{\rm Bj} \geq 10^{-3}, 0.1 \leq y_{\rm Bj} \leq 0.9$.

- I-induced cross-section at HERA, versus (Q', x') cuts:



- Uncertainties:
  - Where to place exactly the (Q', x') cuts?
  - $\Lambda = (282 \pm 65)\ {\rm MeV} \ \Rightarrow \sigma^{(I)}{}_{\rm HERA}(\mathcal{C}_{\rm std}) \simeq \mathbf{126}^{+300}_{-100}$ pb
  - μ_f and μ_r dependencies comparatively small.

- Fraction of I-induced events to normal DIS events,

$$f^{(I)} \equiv \frac{\sigma^{(I)}_{\rm HERA}(\mathcal{C}_{\rm std})}{\sigma^{(\rm nDIS)}_{\rm HERA}(\mathcal{C}_{\rm std})} \;=\; \mathcal{O}(1)\ \%\,,$$

- Total luminosity accumulated by experiments at **HERA**,
  $\mathcal{L} = \mathcal{O}(80)\ \mathrm{pb}^{-1} \;\Rightarrow\;$ $\mathcal{O}(10^4)$ I-induced events on tape.

3. Signatures and Searches

- Important tool: "QCDINS 1.6.0" :

  Monte-Carlo generator for I-induced DIS-events
  [Gibbs, Ringwald & F. Sch. '95; anonymous ftp: theopc3.desy.de]

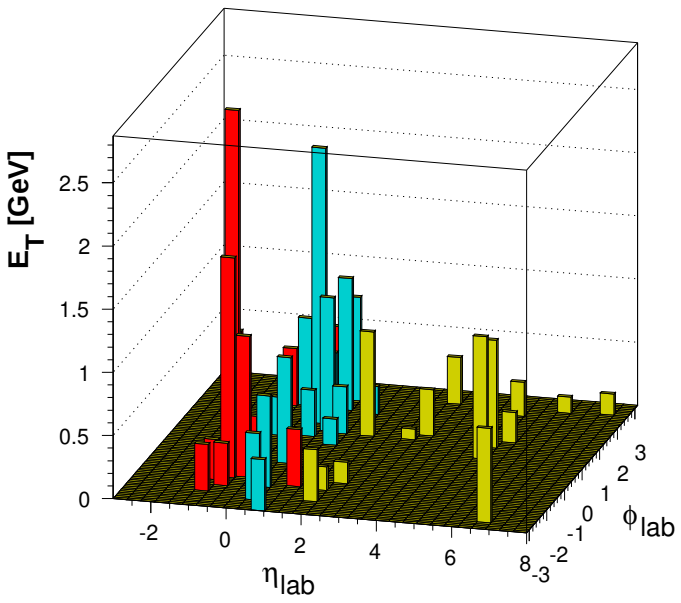
  ♢ Instanton-induced hard subprocess

  ♢ Leading-log parton shower & hadronization (HERWIG 5.9)

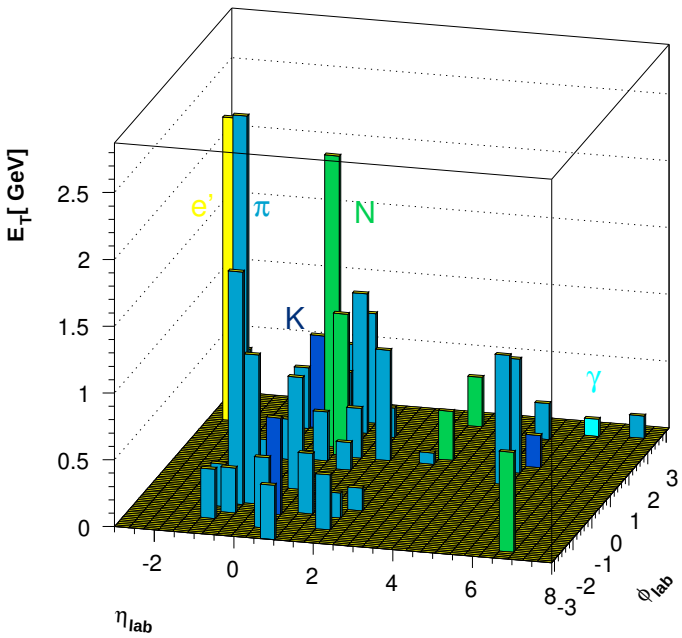
  ♢ "HZTOOLS" package fully integrated⇒ all published H1/ZEUS data, jet analysis . . .

Lego Plot of Typical Event

Characteristics



Particle Composition



- Current jet

- Hadronic "band": $\Leftrightarrow$ **Isotropic** production of **"Fireball"** in I-rest system

  - ♢ Large total E_T
  - ♢ Large multiplicity
  - ♢ No jets in "band" !
  - ♢ Characteristic flavor flow: ⋆ **Strangeness** $\Rightarrow$ K^0_S's

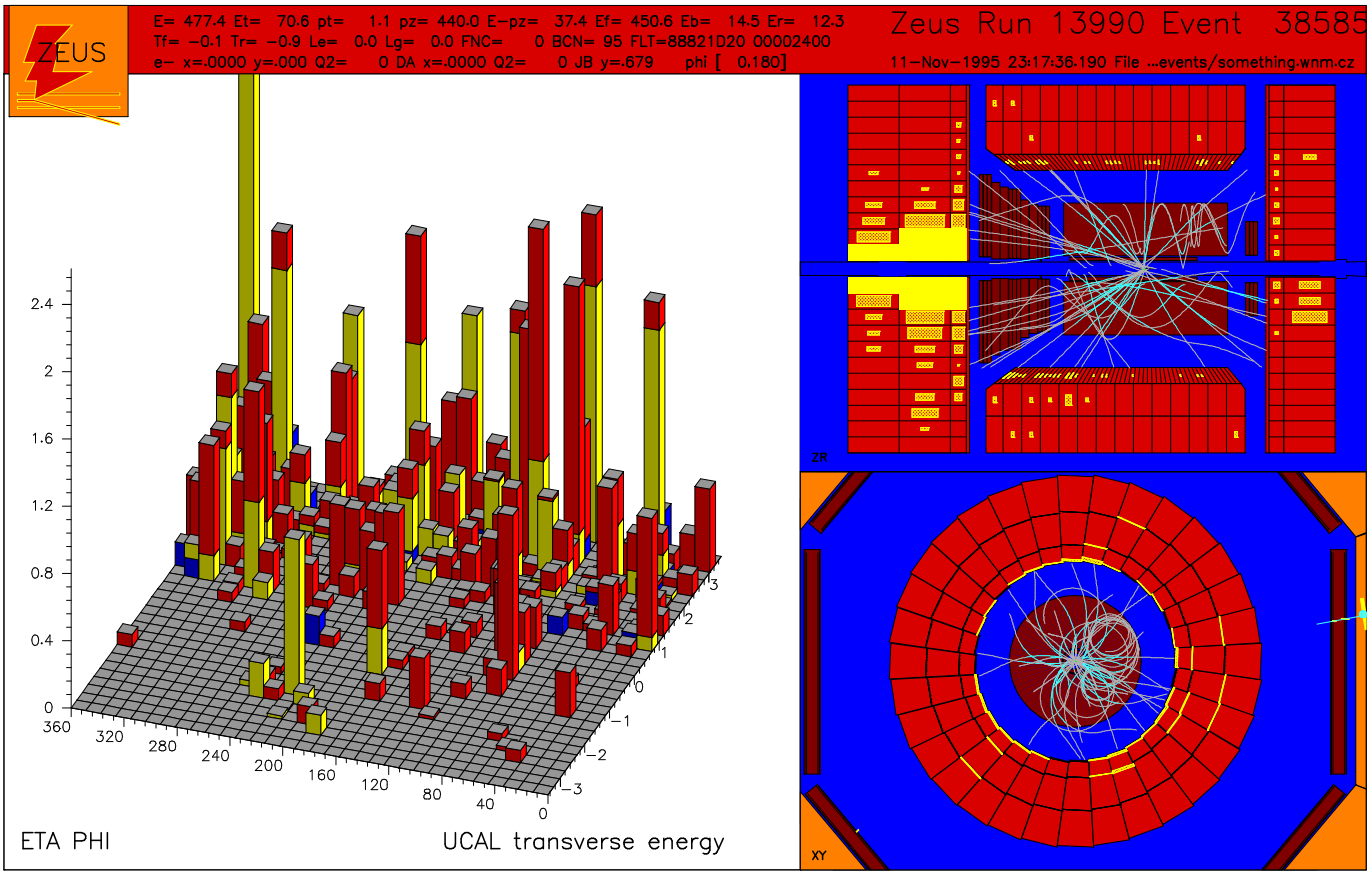
Search Strategies

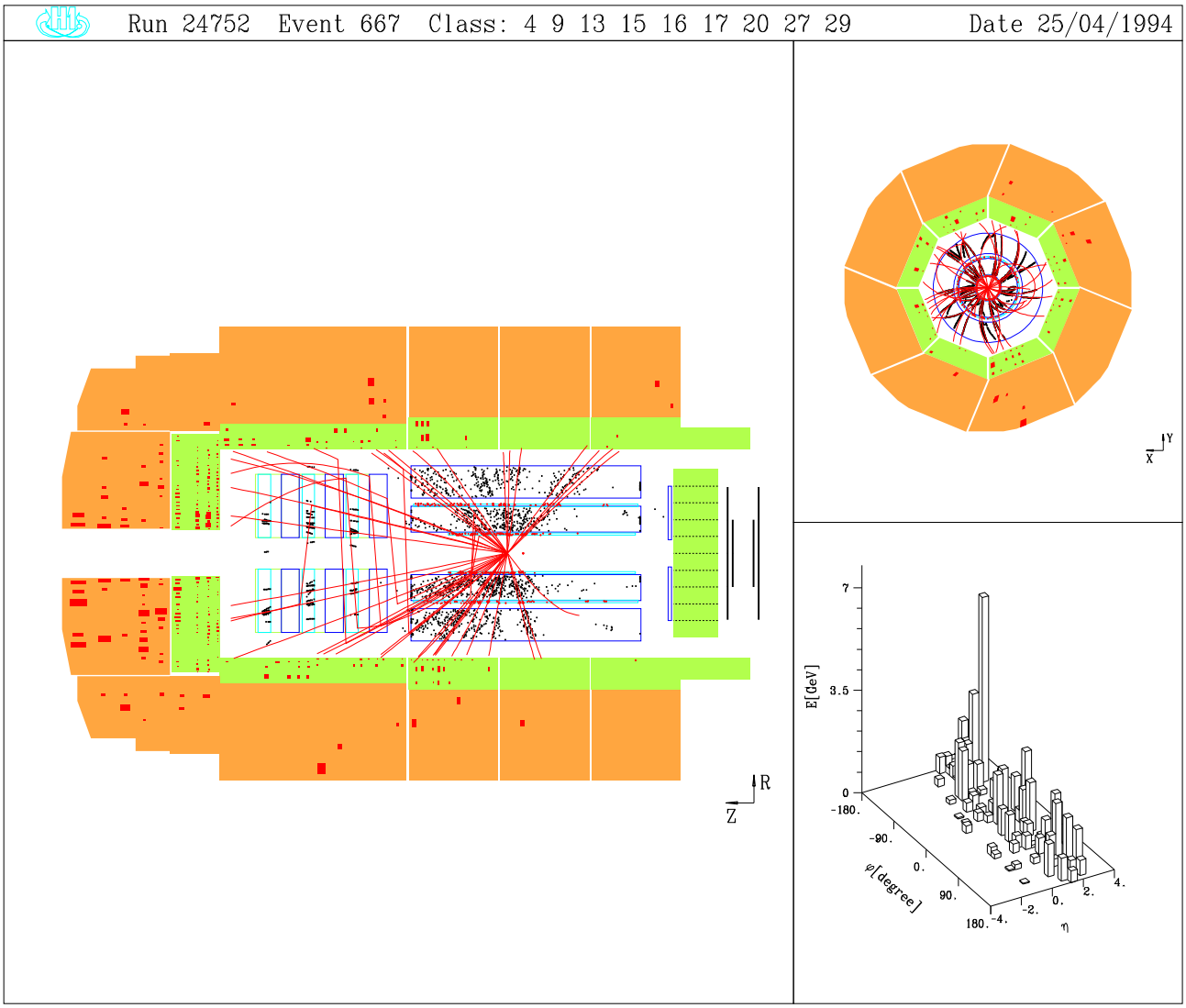
- Despite high rate of instanton-induced events at HERA, no single observable known (yet) with sufficient **nDIS** rejection.

- Hence, dedicated multi-observable analysis required.
- Need to understand pQCD background in tails of distributions!
- Neural network filters are being tried and have very good analysing power if applied to $\gtrsim \mathcal{O}(5)$ observables!
- Strategies to produce instanton-enriched data sample and to reconstruct (Q'^2, x') look quite promising...

I-induced Processes at small Q^2 (Photoproduction)?

- Large E_T fireball events observed at small Q^2





- Seem to exhibit all characteristics of I-induced processes.
- Need to extend theoretical analysis to small Q^2.
  $\Rightarrow$ [My talk in WG2 ...]
- Looking forward to more detailed experimental analysis
  $\Rightarrow$ [Roman Walczak's talk in WG2 ...]

4. Conclusions

- Topological fluctuations: Important aspect of QCD.
- Much improved calculation of $\frac{\mathrm{d}\sigma_{\mathrm{HERA}}{}^{(I)}}{\mathrm{d}x'\mathrm{d}Q'^2}$ within I-perturbation theory/"dilute" I-gas picture.
- Linked 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 multi-particle final-state signature.
- Best present **HERA**-limits on the fraction $f^{(I)}$ of I-induced events in DIS at HERA come from multiplicity distribution and E_T flow,

$$f^{(I)}_{\mathrm{lim}}(\mathcal{C}_{\mathrm{std}}) \simeq \mathcal{O}(1)\ \%\,.$$

[H1 Collaboration, Z. Phys. C72 (1996) 573; Carli, Kuhlen, Nucl. Phys. B511 (1998) 85]

- Already close to our theoretical estimate from "fiducial region",

$$f^{(I)}(\mathcal{C}_{\mathrm{std}}) \simeq \mathcal{O}(1)\ \%\,.$$

- "Monster" Fireball-events in photoproduction look exciting...

Decisive search for instanton-induced events at **HERA** seems feasible!