Tracking QCD–Instantons in Deep-Inelastic Scattering

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in collaboration with

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1. **Instantons**
2. **Instanton-Perturbation Theory in DIS**
   - Exclusive Amplitudes
   - Inclusive Cross-Sections
   - "Fiducial" Region from Lattice Simulations
3. **Cross Sections, Signatures and Searches at HERA**
4. **Beyond Instanton-Perturbation Theory?**
5. **Conclusions**

Copy available via WWW:

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

– Ringberg Conf. on Trends in Theor. Particle Physics, Rottach-Egern, Oct 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]

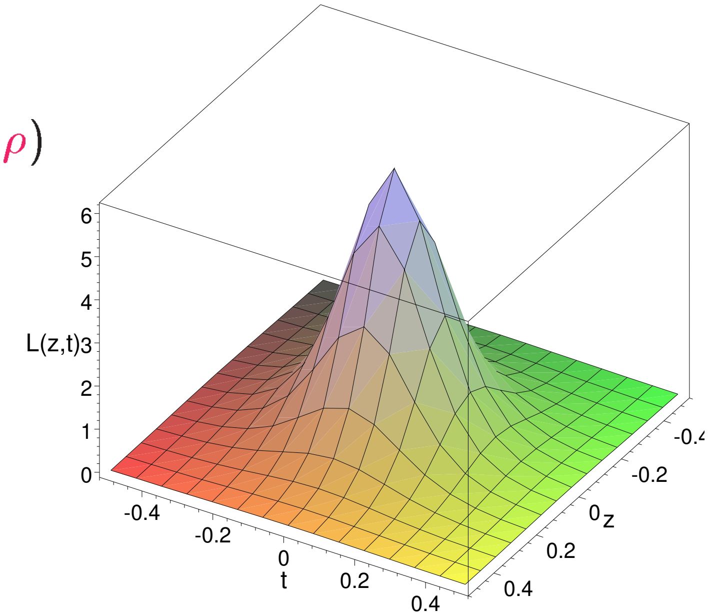
Simplest non-trivial "building blocks" of topological structure of the vacuum.

◇ Explicit solutions of classical Euclidean field equations $\Leftrightarrow$ Local minimum of classical Euclidean action in sector $Q = +1(-1)$:

$$\mathcal{L}\left(A_\mu^{(I)}(x;\rho)\right) \quad ; (I\text{-size } \rho)$$

$$= \frac{12}{\pi\alpha} \cdot \frac{\rho^4}{(x^2+\rho^2)^4}$$

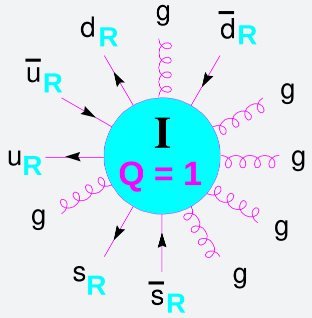
$$\Rightarrow \boxed{S\left[A_\mu^{(I)}\right] = \frac{2\pi}{\alpha}}$$



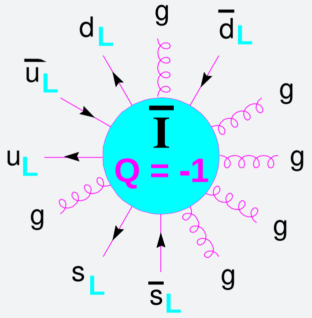
◇ Non-perturbative fluctuations of gauge-fields, localized ("instantaneous") in time and space.

◇ Tunnelling transitions between adjacent, topologically inequivalent vacua

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



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



$*$ 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. Instanton-Perturbation Theory in DIS

[Ringwald & F. Sch., Phys. Lett **B438** (1998) 217,
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 Q cuts off instantons with large size $\boldsymbol{\rho \gtrsim Q^{-1}}$, over which we have no control!

  [Moch, Ringwald & F. Sch. '97]

2.1 Exclusive Amplitudes

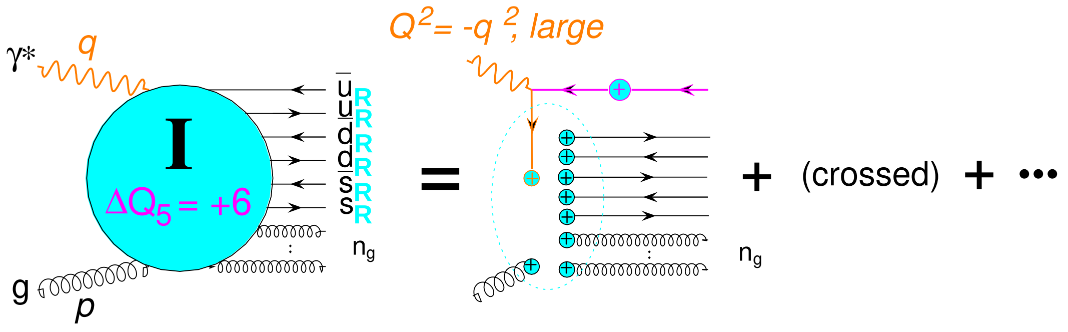
[Moch, Ringwald & F. Sch., Nucl.Phys. **B**507 (1997) 134]

- Consider Instanton ($\boldsymbol{I}$)-induced amplitude for exclusive DIS processes,

$$\triangle Q_5 = 2\, n_f : \qquad \gamma^* + \mathrm{g} \Rightarrow \sum_{\text{flavours}}^{n_f} [\overline{q}_R + q_R] + n_g\, g$$

vanishing to any order of conventional P.T in (massless) QCD:

- *I*-Perturbation Theory: Expand (Euclidean) path integral for relevant Green's functions about classical instanton solution:



- Fourier-transform (F. T.) with respect to external lines.

- LSZ amputate external legs.

- Analytically continue to Minkowski space.

- Basic building blocks: (singular gauge) in (modified) Feynman rules of *I*-perturbation theory:

  - Classical instanton gauge field $A_\mu^{(I)}(x;\rho,U)$ [Belavin *et al.* '75];
  - Quark zero mode fields $\kappa^{(I)}(x;\rho,U)$, $\overline{\phi}^{(I)}(x;\rho,U)$ (Weyl basis);
  - (Non-zero mode) quark propagators $S^{(I)}(x,y;\rho,U)$, $\overline{S}^{(I)}(x,y;\rho,U)$ in the *I*-background [Brown *et al.* '78]

- Collective coordinates: $\boldsymbol{\rho}$ = I-size, $(U)^k_\alpha$ = I-color orientation (color: $k = 1,2,3$ and spinor: $\alpha = 1,2$ indices).

- Must be integrated over in Amplitudes:

$$\mathcal{T}_\mu^{(I)}(q, p, \ldots) = \int dU \int_0^\infty d\rho\, D(\rho)\, \mathcal{A}_\mu^{(I)}(q, p, \ldots; U, \rho)$$

- $\boldsymbol{I}$-density (renormalization scale μ_r) as generic measure:

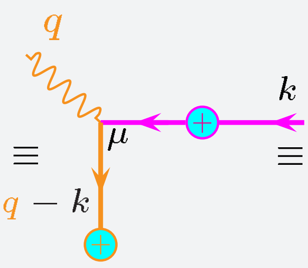
$$D(\rho, \mu_r) = d\left(\frac{2\pi}{\alpha_s(\mu_r)}\right)^6 \exp\left(-\frac{2\pi}{\alpha_s(\mu_r)}\right)\frac{(\boldsymbol{\rho}\,\mu_r)^{\boldsymbol{b}}}{\boldsymbol{\rho}^5}$$

b	$\frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}\mu_r}$	Ref.
β_0	$\mathcal{O}(\alpha_s)$	't Hooft '76
$\beta_0 + \frac{\alpha_s(\mu_r)}{4\pi}(\beta_1 - 12\beta_0)$	$\mathcal{O}(\alpha_s{}^{\mathbf{2}})$	Morris, Ross, & Sachrajda '85

QCD β-function coefficients: $\beta_0 = 11 - \frac{2}{3}\mathrm{n_f}$; $\beta_1 = 102 - \frac{38}{3}\mathrm{n_f}$

- Q^2 only enters in F.T'ed $\gamma^* q\overline{q}$-vertices,

$\mathcal{V}_\mu(q, -k; \rho) \equiv$



$$\equiv \int d^4x\, \mathrm{e}^{-\mathrm{i}q\cdot x}\left[\overline{\phi}^{(I)}(x;\rho)\overline{\sigma}_\mu \boldsymbol{S}^{(I)}(x, -k; \rho)(-\mathrm{i}\overline{k})\right]$$

- After a long and tedious calculation ($v = v_\mu\sigma_\mu$, $\overline{v} = v_\mu\overline{\sigma}_\mu$),

$$\lim_{k^2\to 0}\mathcal{V}_\mu(q, -k; \rho) = 2\pi\mathrm{i}\rho^{3/2}\left[\epsilon\sigma_\mu\overline{V}(q, q'; \rho)\, U^\dagger\right],$$

with $q' = q - k$, $Q' = \sqrt{-q'^{\,2}} \equiv \sqrt{-t} > 0$, $Q = \sqrt{-q^2} \geq 0$,

$$\overline{V}(q, q'; \rho) = \left[\frac{\overline{(q')}}{Q'^{\,2}} + \frac{\overline{q - q'}}{Q'^{\,2} - Q^2}\right] \rho Q' \, K_1\,(\rho Q') - \frac{\overline{q - q'}}{Q'^{\,2} - Q^2} \rho Q \, K_1\,(\rho Q)$$

- Various terms strongly constrained by manifest gauge invariance

$$q^{\mu} \mathcal{T}_{\mu}^{(I)}(q, p, \ldots) = 0$$

- 2^{nd} term ("contact" term) in $\overline{V}(q, q'; \rho)$ necessary to cancel an unphysical pole in physical region at $Q'^{\,2} = Q^2$!

- In DIS: Exponential decrease of all form factors (Bessel K_1 functions)

$$K_1(\rho Q) \overset{\rho Q \Rightarrow \infty}{\sim} \exp\left[-\rho Q\right].$$

$\Rightarrow$ Integration over the instanton size ρ in amplitudes $\mathcal{T}_{\mu}^{(I)}(q, p, \ldots)$ is finite for large $Q > 0$

[as long as the internal quarks are not moving collinear to the incoming gluon (like in pQCD!)].

- ♣ **Hard**, partonic scattering processes (fixed-angle) in **DIS** are reliably calculable in $\boldsymbol{I}$-perturbation theory.
- ♣ Only small size instantons, $\boldsymbol{\rho} < 1/\mathcal{Q}$, are probed in **DIS**.
- ♣ Amplitudes manifestly gauge invariant.

♣ Important Question: Is the hard photoproduction limit $(Q^2 \Rightarrow 0)$ with a high E_t of the current quark jet within the reach of $\boldsymbol{I}$-perturbation theory?

- **True** in ordinary QCD perturbation theory...

♣ Motivation: "Monster" fireball events (ZEUS) (⇒ Sect. 3.2) & lots of further interesting data. . .

- For $\boldsymbol{Q^2 \Rightarrow 0}$: $\rho Q K_1(\rho Q) \overset{Q \Rightarrow 0}{\Rightarrow} 1,$,
- $\Rightarrow$ 2^{nd} term in $\overline{V}(q, q'; \rho)$ $\boldsymbol{\rho}$-independent and $\boldsymbol{\rho}$-integration IR-divergent within $\boldsymbol{I}$-perturbation theory, since there $D(\rho) \sim \rho^6$.
- This divergence is independent of current-quark E_t:

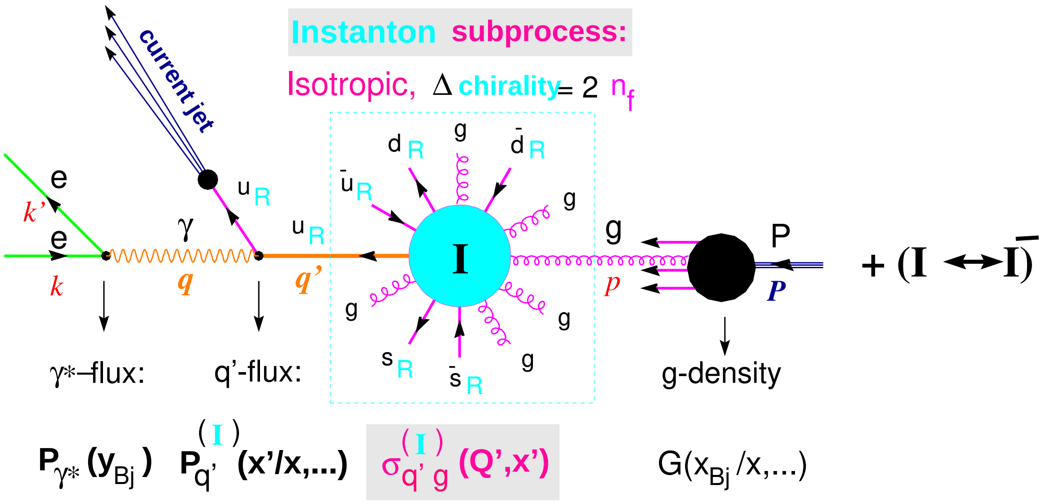
$$Q'^{\,2} = Q^2 + \frac{E_t}{\sqrt{s}} \left(s \exp(-\eta) - Q^2 \exp(\eta)\right) \overset{Q \Rightarrow 0}{\Rightarrow} E_t \sqrt{s} \exp(-\eta)$$

♣ Possible attractive solution: See Sect. 4.

2.2 Inclusive Cross Sections

[Ringwald & F. Sch., hep-ph/9805492, Phys. Lett **B438** (1998) 217; Moch, Ringwald & F. Sch., to appear]

- Leading instanton-induced, chirality violating process in DIS regime of $e^{\pm}P$ scattering for large $Q^2 = -q^2$, $Q'^2 = -q'^2$:

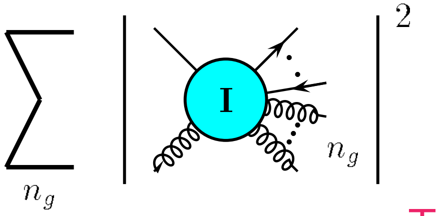


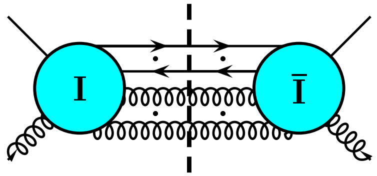
- Instanton-subprocess with own **Bjorken**-variables, $(\boldsymbol{x'}, \boldsymbol{Q'^2})$
- show within I-perturbation theory in Bjorken limit:

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

- Calculable differential $q'g$ luminosities $d\mathcal{L}^{(I)}_{q'g}$:
  - Involve integrations over γ^*-flux $P_{\gamma*}$, q'-flux $P^{(I)}_{q'}$ and g-density G.
  - Account for number of $q'g$ collisions per eP collision.
- Crucial instanton-dynamics in $\boxed{\sigma^{(I)}_{q'g}(Q', x')}$!
- Two alternative ways to obtain the latter:

Summation of Exclusive Cross-Sections	Optical Theorem and $I\overline{I}$-Valley Method





Total cross-section obtained in the form

$$\sigma^{(I)}_{p'p} = \int_0^\infty d\rho\, D(\rho) \int_0^\infty d\overline{\rho}\, D(\overline{\rho}) \int d^4 R\, \{\ldots\} \mathrm{e}^{-Q'(\rho+\overline{\rho})}\, \mathrm{e}^{\mathrm{i}\,(p+q')\cdot R}\, \mathrm{e}^{-\frac{4\pi}{\alpha_s}\Omega\left(\frac{R^2}{\rho\overline{\rho}},\frac{\overline{\rho}}{\rho}\right)}$$

R_μ corresponds to

energy-momentum conservation,	separation between I and $\overline{I}$

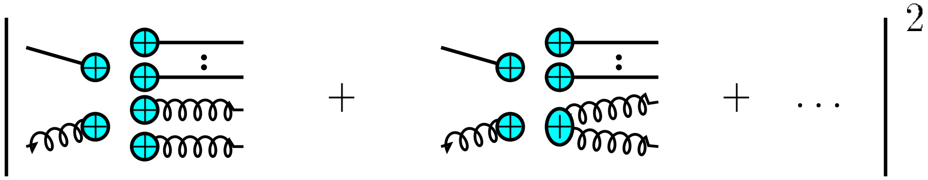
$$(2\pi)^4 \delta^{(4)}(p + q' - \textstyle\sum_i k_i) = \int d^4 R\, \mathrm{e}^{\mathrm{i}(p+q'-\sum_i k_i)\cdot R}$$

$$\int \frac{d^4 k_i}{(2\,\pi)^3}\, \delta^{(+)}(k_i^2)\ \exp\left[-\mathrm{i}\, k_i \cdot R\right] = \frac{1}{(2\pi)^2}\, \frac{1}{-R^2 + \mathrm{i}\epsilon R_0}\ ,$$

$\Omega\left(\frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$ corresponds to

summation and exponentiation of final-state gluons,	interaction between I and $\overline{I}$,

$$\Omega = -6 \left(\frac{\rho\overline{\rho}}{-R^2+\mathrm{i}\epsilon R_0}\right)^2 + 12 \left(\frac{\rho\overline{\rho}}{-R^2+\mathrm{i}\epsilon R_0}\right)^3 \left(\frac{\rho}{\overline{\rho}} + \frac{\overline{\rho}}{\rho}\right) + \ldots$$

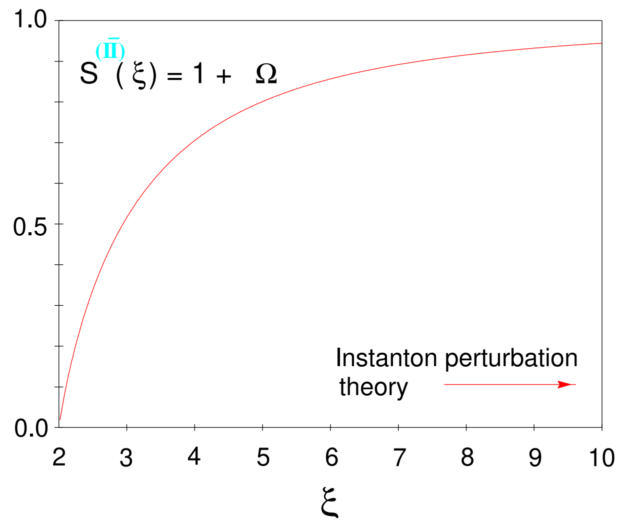


$$\Omega \equiv S^{(I\overline{I})} - 1,$$

with $I\overline{I}$ valley action

$$S^{(I\overline{I})} \equiv \frac{\alpha_s}{4\pi}\, S\left[A_\mu^{(I\overline{I})}\right].$$

Summation of Exclusive Cross-Sections	Optical Theorem and $I\overline{I}$-Valley Method
I-perturbation theory $\Leftrightarrow$	Semi-classical $I\overline{I}$-interaction Ω known for
Ω perturbatively known for large $\frac{R^2}{\rho\overline{\rho}}$.	all conformal separations $\xi \equiv \frac{-R^2+\mathrm{i}\epsilon R_0}{\rho\overline{\rho}} + \frac{\rho}{\overline{\rho}} + \frac{\overline{\rho}}{\rho}$



[V.V. Khoze, Ringwald '91; Verbaarschot '91]

$$\Omega^{\rm valley} \overset{\xi\Rightarrow\infty}{=} -\frac{6}{\xi^2} + \ldots \Leftrightarrow \Omega^{I-\rm P.T.}!$$

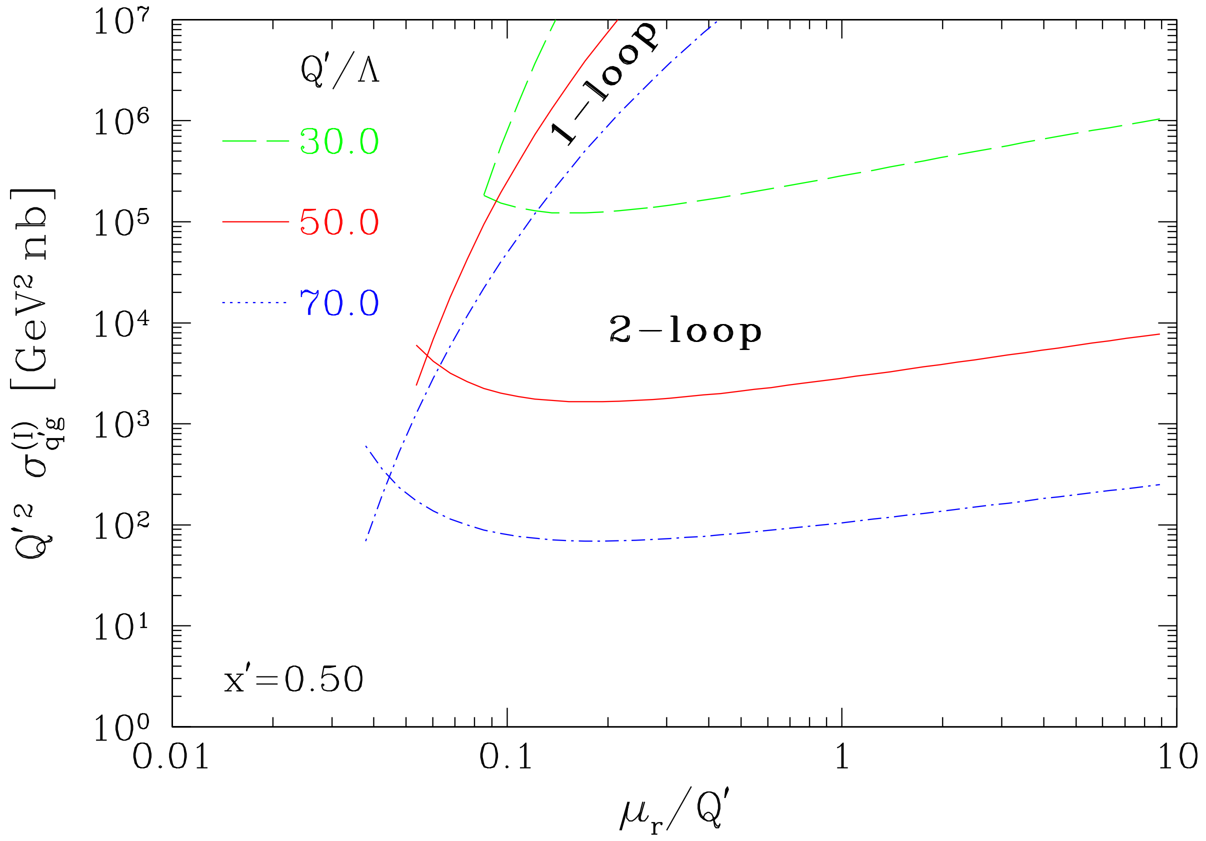
Saddle-point evaluation of collective coordinate integrations,

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

I-perturbation theory $\Leftrightarrow$ large Q' and $x' \sim 1$	Smooth extrapolation towards smaller x'

- Recent recalculation in terms of known, 2-loop RG invariant form of instanton density, $\boldsymbol{D(\rho)}$
[Ringwald & F. Sch., Phys. Lett **B438** (1998) 217].$\Rightarrow$

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



- Expect $\boldsymbol{\mu_r}$ in regime:

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

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

2.3 “Fiducial” Region from Lattice Simulations

[Ringwald & F. Sch., hep-ph/9805492, Phys. Lett **B438** (1998) 217 and in prep.]

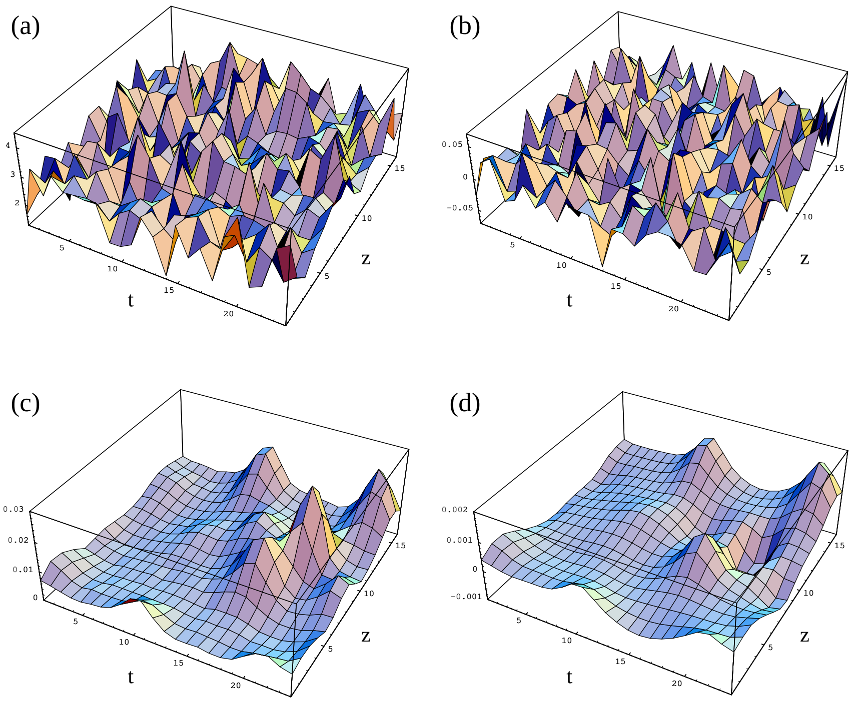
♣ Crucial: Knowledge of “fiducial” (Q', x') region, where I-perturbation theory may be trusted!

- ⇐ Recent lattice simulations of QCD [UKQCD, Smith & Teper, ‘98,. . .]: “Snapshots” of QCD-vacuum in (Euclidean) space-time, including all non-perturbative, topological features like instantons:

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

Before “Cooling”

After “Cooling”

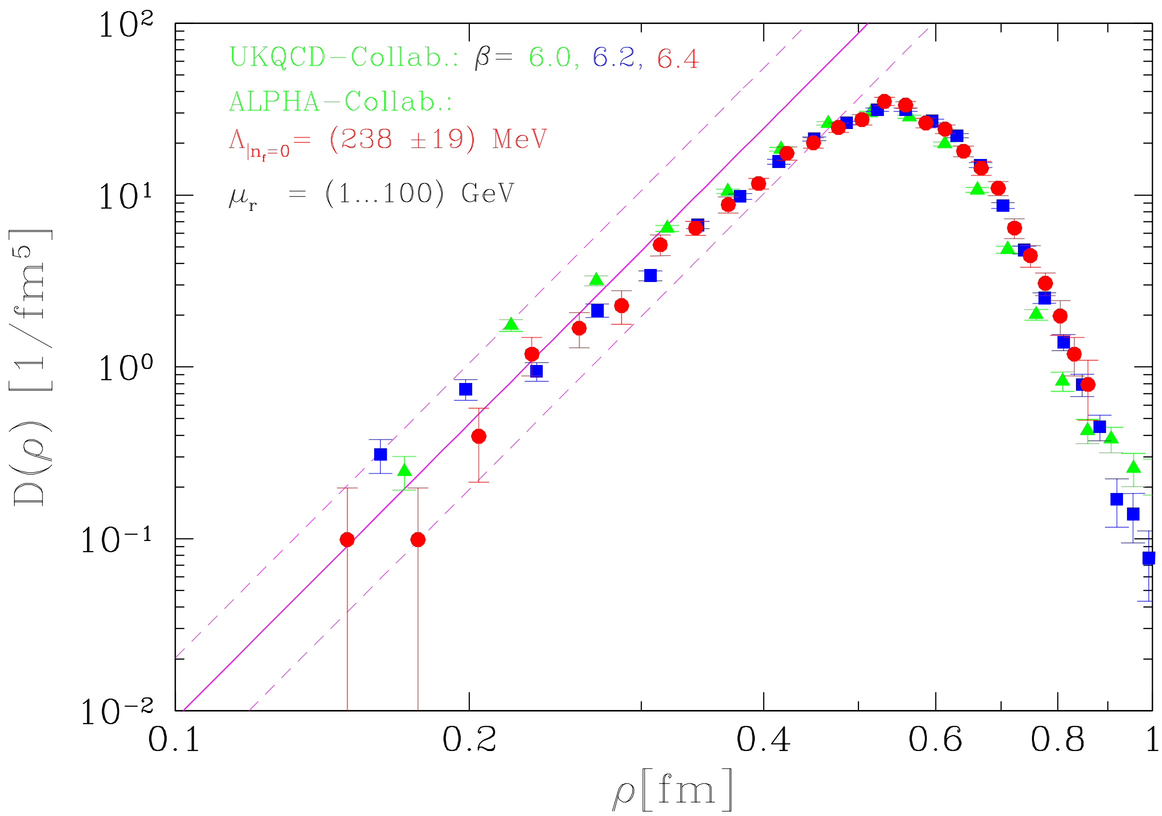


[Chu *et. al* ‘94]

- See 3 instantons $(q(x) > 0)$ and 1 anti-instanton $(q(x) < 0)$!
- **Cooling:** Designed to filter out (dominating) fluctuations of short wavelength $\mathcal{O}(a)$, while affecting topological fluctuations of size $\rho \gg a$ comparatively little.

- **Caveats:** Lattice artefacts $\Leftrightarrow$ continuum limit; dependence on "cooling"...

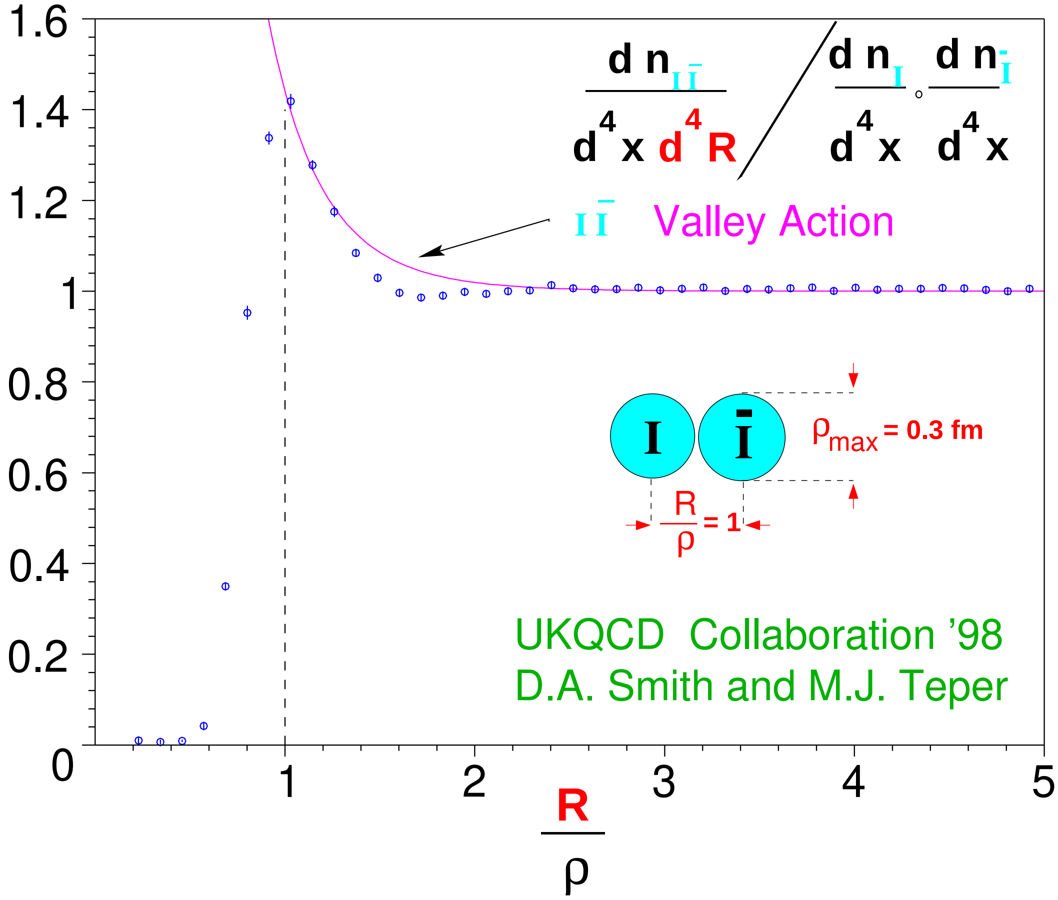
- **I-density:** for small-size instantons, $\rho \lesssim \rho_{\rm max} \simeq 0.3$ fm, well described by I-perturbation theory, $D(\rho)_{|n_f=0} \propto \boldsymbol{\rho^6}$:



♣ Surprisingly, inclusive absolute normalization!

- Very sensitive to $\Lambda_{|n_f=0}$, very in-sensitive to ren. scale μ_r.

- **$I\bar{I}$-interaction:** UKQCD-Collaboration: Number-density of $I\bar{I}$-pairs as function of their distance R. $\Rightarrow$ Good description in terms of $I\bar{I}$-valley action for $R/\rho \gtrsim 1$!



- Below $R/\rho \sim 1$, rapid breakdown of semi-classical picture ($I\bar{I}$-attraction) in form of non-perturbative $I\bar{I}$-repulsion.

♣ 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:

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

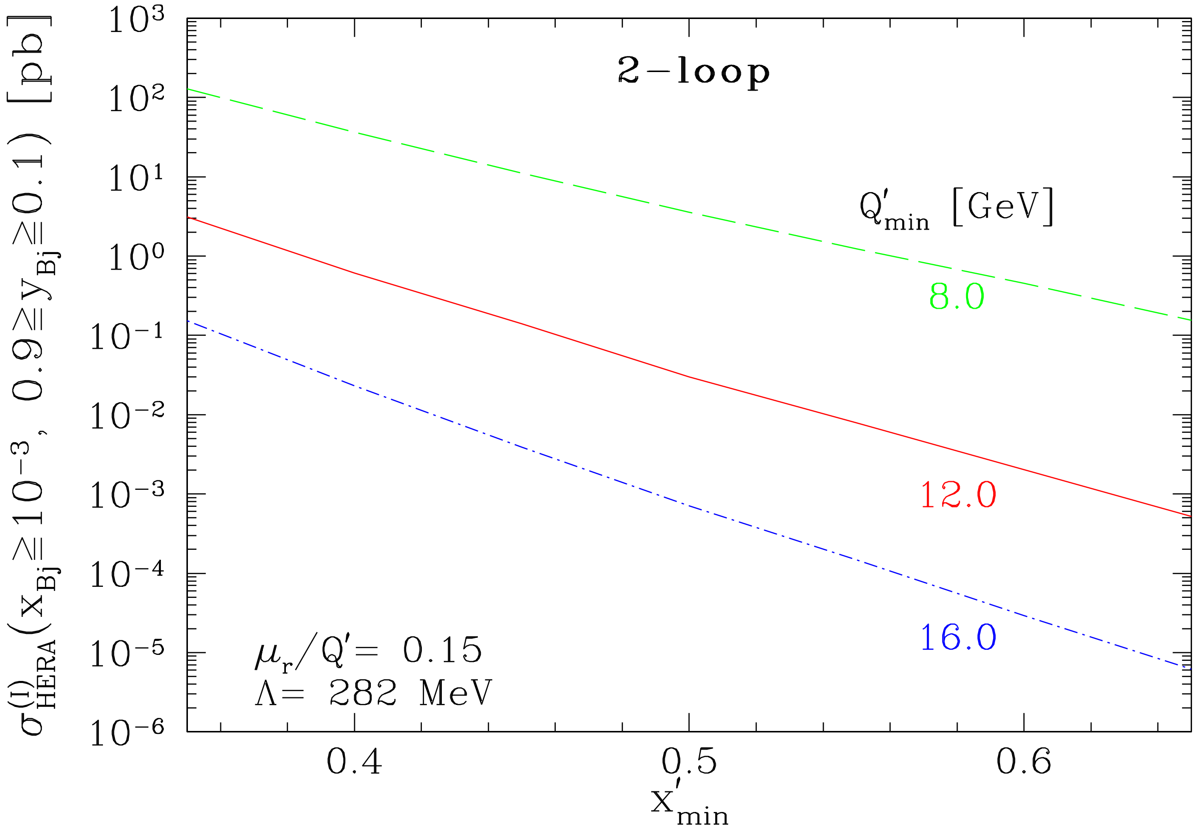
3. Cross-Sections, Signatures and Searches at HERA

3.1 HERA Cross Section

- "Standard" cuts (lattice!):

$\mathcal{C}_{\rm std} \equiv x' \geq 0.35, Q' \geq 8$ 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?
  - $\Lambda = (282 \pm 65)$ 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.

3.2 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]

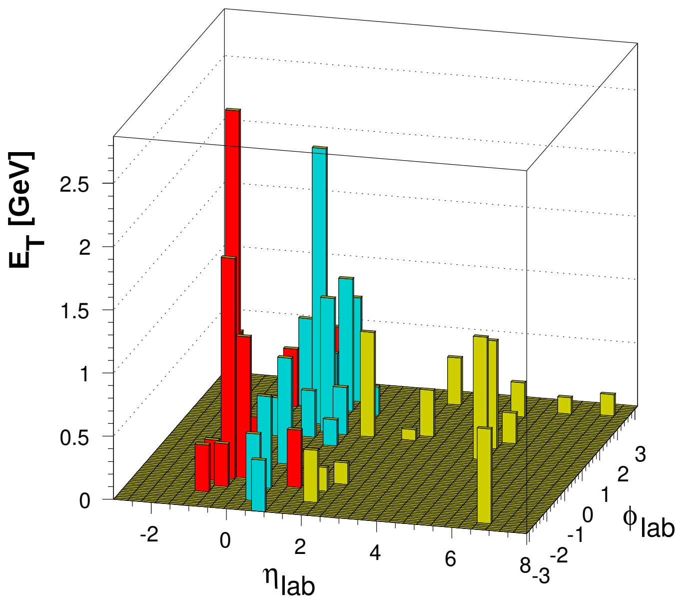
  ◇ Instanton-induced hard subprocess

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

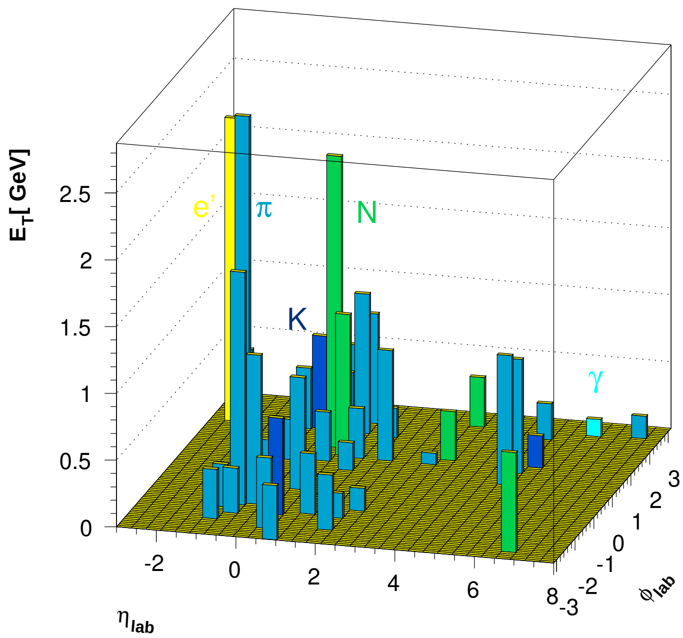
  ◇ "HZTOOLS" package fully integrated⇒ all published H1/ZEUS data, jet analysis . . .

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: $\star$ **Strangeness** $\Rightarrow K_S^0$'s

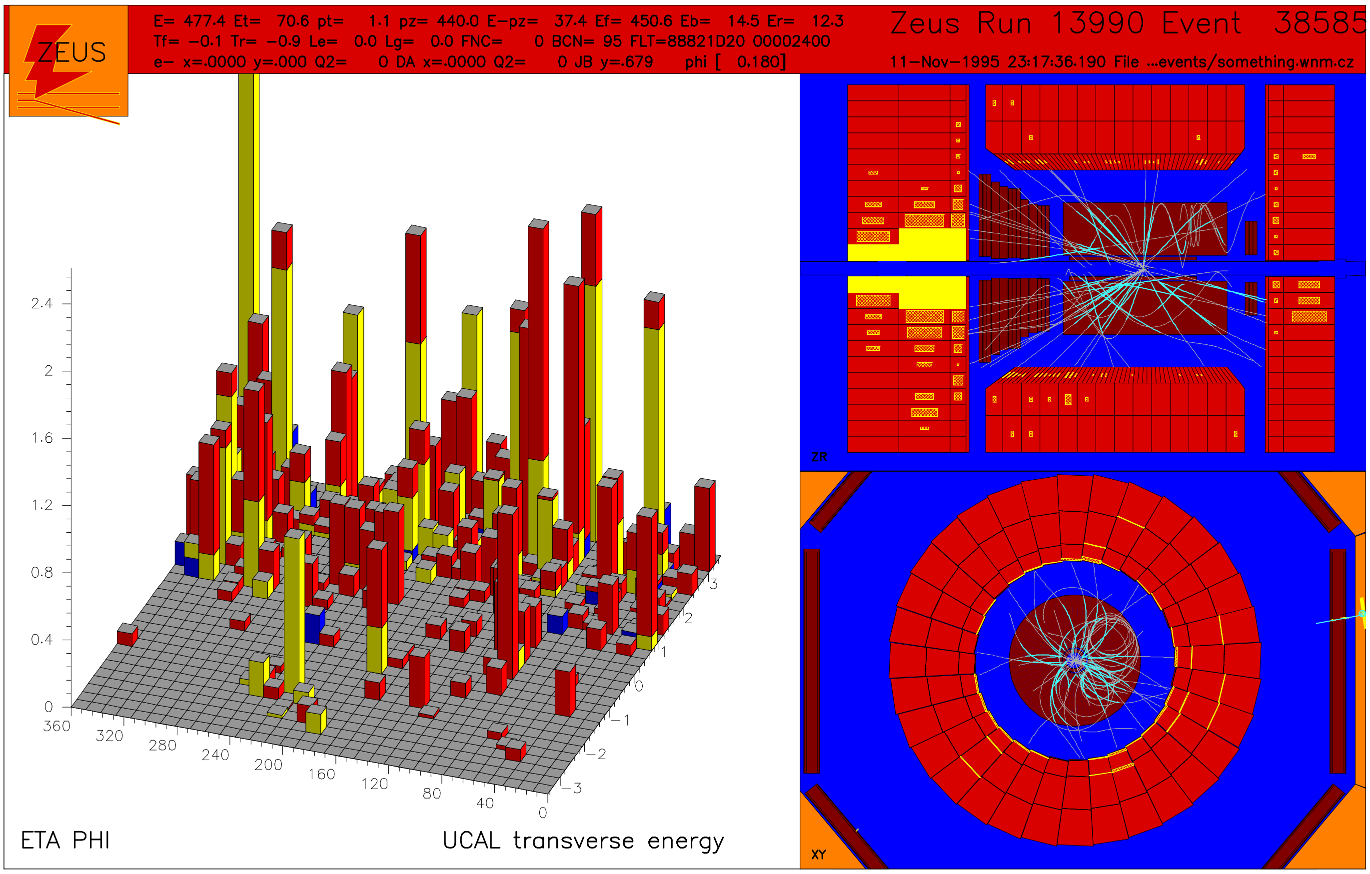
Search Strategies

- 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)?

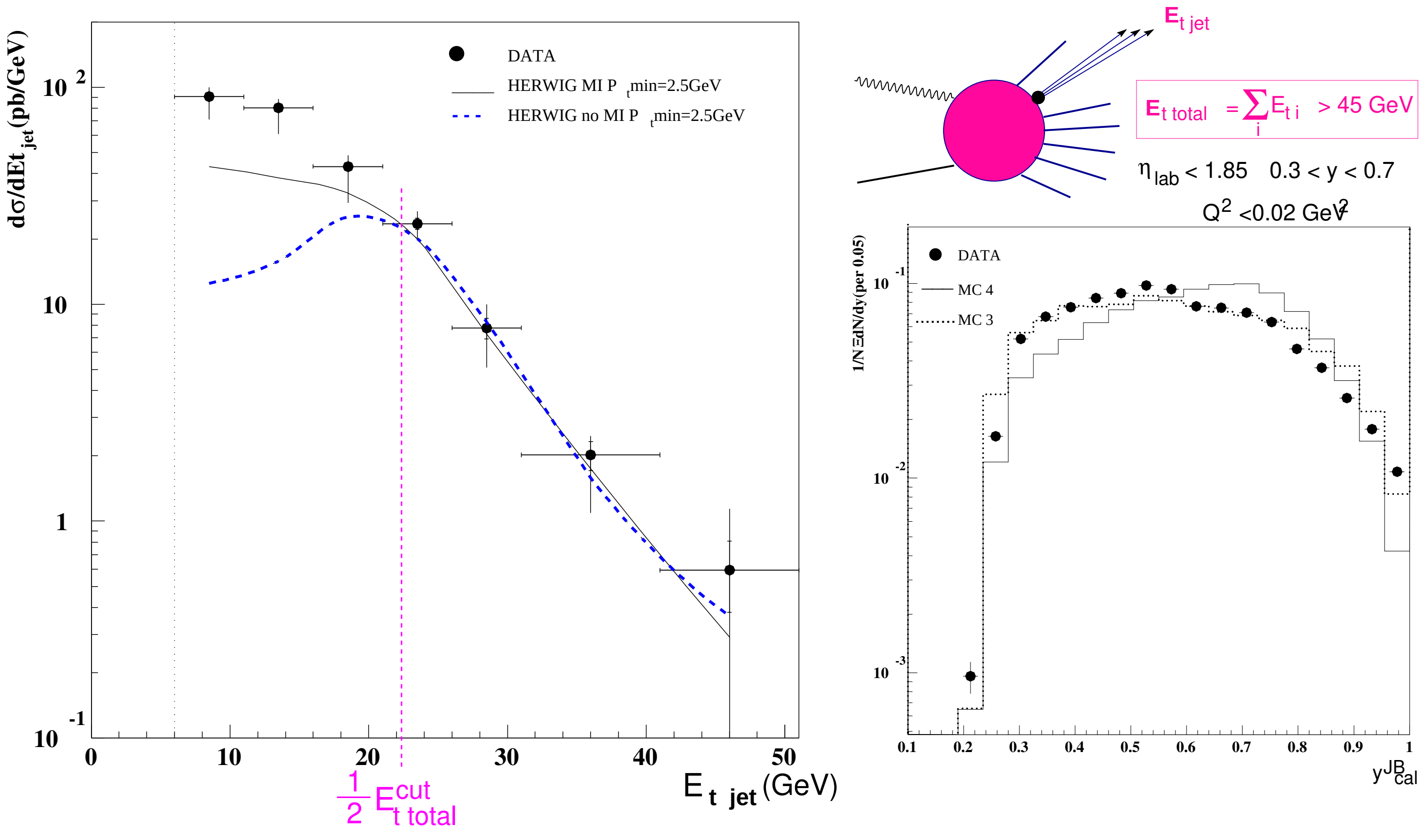
- Substantial number of spectacular fireball events with large $E_{\mathrm{t\,total}}$ observed by ZEUS at small Q^2



- H1 see similar events.

♣ Seem to exhibit all characteristics of I-induced processes.

- Quantitative Analysis just startet [PhD Thesis C. Nath (Oxford) '98]:



- Events with few, 'big' jets: $E_{\rm t\,jet} \gtrsim \frac{1}{2} E^{\rm cut}_{\rm t\,total} = 22.5$ GeV well understood (Fig., left).

♣ Excess by $\mathcal{O}(10)$ of events without 'big' jets: $6 \text{ GeV} < E_{\rm t\,jet} \ll \frac{1}{2} E^{\rm cut}_{\rm t\,total}$!

⇒ Large $E_{\rm t\,total} > 45$ GeV arises from many particles with moderate $E_{\rm t}$ (⇒ fireballs!)

- "Multiple scattering" corrections improve rate (Fig., left) but necessarily give disagreement with y-distribution (Fig., right).

♣ Look for strangeness, muons (from charm) in fireball events!

♣ Can we extend our instanton analysis to $Q^2 \Rightarrow 0$, E_t large?

4. Beyond Instanton-Perturbation Theory?

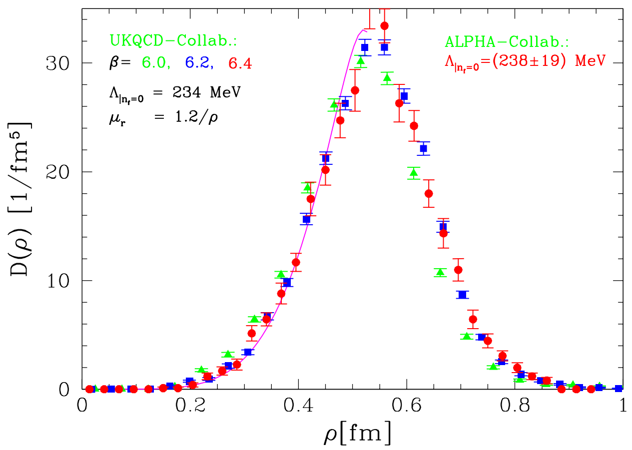
- Consider two most strongly varying entries in I-calculus:

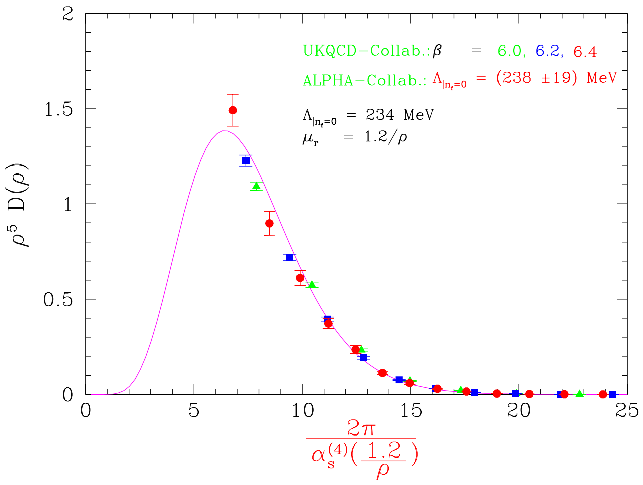
I-density $D(\rho, \mu_r)$ and $I\overline{I}$-interaction $\Omega(R, \rho, \overline{\rho}, U)$

- Sect. 2.3 $\Rightarrow$ Predictions from I-perturbation theory and $I\overline{I}$-valley approach agree surprisingly well with lattice simulations for $\rho \lesssim 0.3$ fm and $R/\rho \lesssim 1$!

- Dramatic, further improvement by more clever choice of ren. scale: $\mu_r \rho = s = \mathcal{O}(1)$, to avoid large $\log(\mu_r \rho)$ corrections

$$\rho^5 D(\rho) = d \left(\frac{2\pi}{\alpha_s(\frac{s}{\rho})}\right)^6 \exp\left(-\frac{2\pi}{\alpha_s(\frac{s}{\rho})}\right) s^{\,\beta_0 + \frac{\alpha_s(\frac{s}{\rho})}{2\pi}(\beta_1/2 - 6\beta_0)}$$





♣ Proposal: Attempt to extend our predictions beyond proper regime of $\boldsymbol{I}$-perturbation theory, by taking $D(\rho, \mu_r)$ and $\Omega(R, \rho, \overline{\rho}, U)$ from lattice simulations:

- $D(\rho) \overset{\rho \text{ large}}{\Rightarrow} 0 \Rightarrow$ Photoproduction limit finite and calculable and kinematical range of predictions in DIS much extended!

- Cuts in (Q', x') for instanton searches at **HERA** may be much relaxed!

- Many quantities of interest may be calculated now. . .

  Determined by physics around peak position of $D(\rho)$: $\langle \rho \rangle \simeq 0.5$ fm.

5. Conclusions

- Topological fluctuations: Important aspect of QCD.

- Much improved calculation of $\frac{d\sigma_{\rm HERA}{}^{(I)}}{dx'dQ'^2}$ within $\boldsymbol{I}$-perturbation theory/ "dilute" $\boldsymbol{I}$-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,
$$f^{(I)}_{\rm lim}(\mathcal{C}_{\rm std}) \;\simeq\; \mathcal{O}(1)\ \%\,.$$
[H1 Collaboration, Z. Phys. C72 (1996) 573; Carli, Kuhlen, Nucl. Phys. B511 (1998) 85]

- Already close to our theoretical estimate from "fiducial region",
$$f^{(I)}(\mathcal{C}_{\rm std}) \simeq \;\mathcal{O}(1)\ \%\,.$$

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

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