Tracking QCD-Instantons in Deep-Inelastic Scattering

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in collaboration with

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– DESY, Hamburg, July 1998 –

1. Introduction

♣ Very rich vacuum structure of non-abelian gauge theories like QCD
⇐ **TOPOLOGY!**

- Gauge fields (in 4d Euclidean space) carry integer topological charge Q: Action $S[A^{Q}{}_{\mu}] \geq \frac{2\pi}{\alpha} \mid Q \mid$.

- Ordinary perturbation theory resides in the sector: $Q = 0$. Expansion about trivial field configuration $A^{a}_{\mu}(x) \equiv 0, S = 0$.

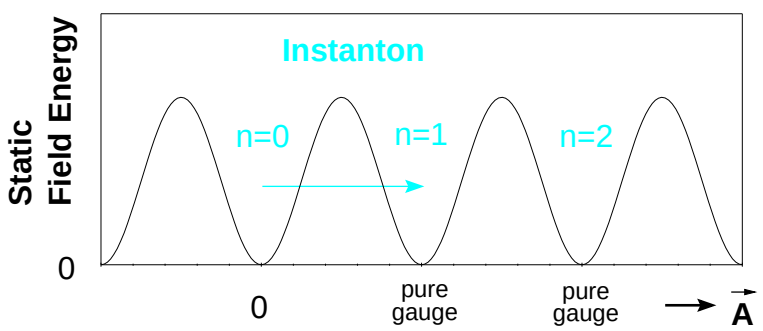
- Number of arguments that topological fluctuations of the gauge fields with $Q \neq 0$ are important in QCD:
  - $U_A(1)$ problem ($m_{\eta'} \gg m_{\eta}$) ['t Hooft '76]; Veneziano-Witten relation;
  - Chiral symmetry breaking [Diakonov '96 (Review)]
  - Hadron and glueball spectrum [Schaefer, Shuryak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

- **Topology:** ∞ many classical ground states characterized by:

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

- 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 $U_n(\vec{x})$, $\Rightarrow$ vacua separated by finite energy barrier

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

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

- non-perturbative topological fluctuations of the gauge-fields, localized ("instantaneous") in time and space.
- Tunnelling transitions between adjacent vacua ($n \Rightarrow n+1$);
- (selfdual) solutions of classical 4d Euclidean field equations,

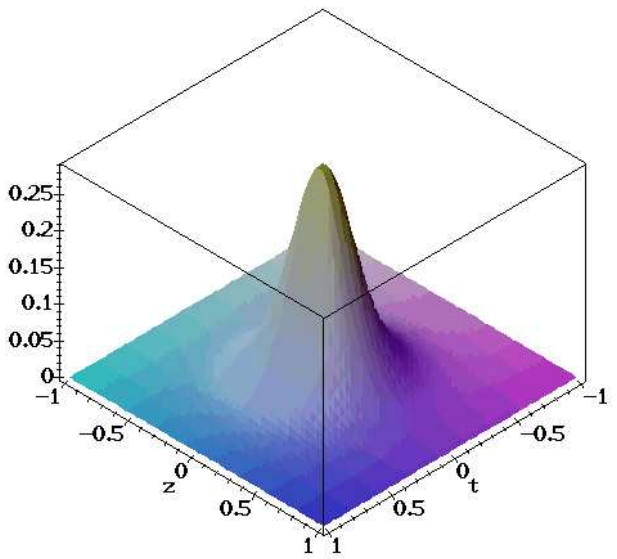
$$A_\mu^{a\,(I)}(x;\rho) = \frac{1}{\sqrt{\pi\alpha}} \cdot \frac{\eta a \mu\nu\, x\nu}{x^2+\rho^2},$$

I-**size** parameter $\rho > 0$ and t'Hooft coefficients $\eta_{a\mu\nu}$;

- carry conserved topological charge $Q = n - (n-1) = 1$;
- Minimize the Euclidean action for $Q = 1$,

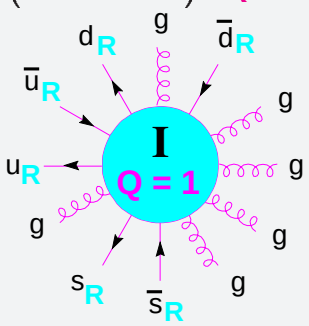
$$\mathcal{L}\left(A_\mu^{(I)}(x;\rho)\right) = \frac{12}{\pi\alpha} \cdot \frac{\rho^4}{(x^2+\rho^2)^4}$$

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

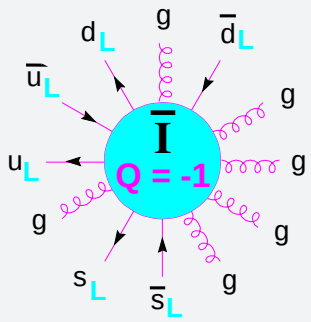


Induce processes violating "chirality": $Q_5 = \#(q_{\rm L}) - \#(q_{\rm R})$

in (massless) QCD



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



* in accord with general Adler-Bell-Jackiw ANOMALY relation,
* 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.

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. '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 theoretical control!
[Moch, Ringwald & F. Sch. '97]

2.1 Illustration: Exclusive DIS Amplitudes

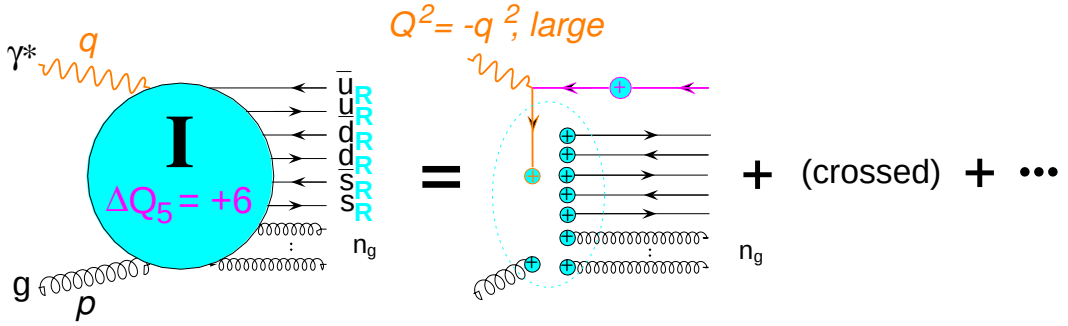
[Moch, Ringwald & F. Sch., Nucl.Phys. **B**507 (1997) 134]

- 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:

- $\boldsymbol{I}$-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 $\boldsymbol{I}$-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 $\boldsymbol{I}$-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:

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

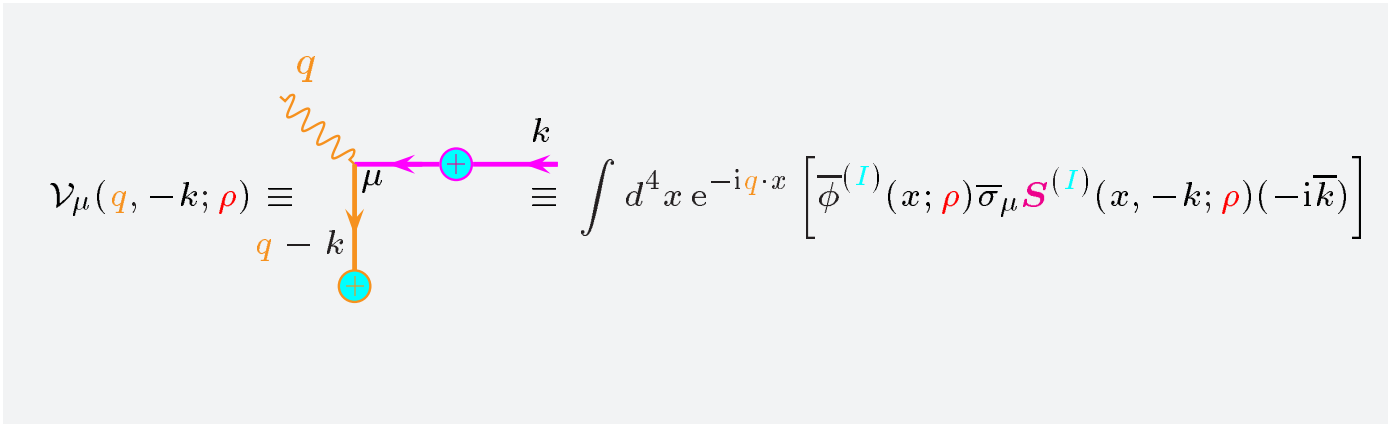
- I-density (renormalization scale μ_r) as generic measure:

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

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

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

- LSZ-amputation of current quark in F.T'ed $\gamma^* q\overline{q}$-vertices ,



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

quite non-trivial and has important physical consequences.

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

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

where,

$$\overline{V}(q,k;\rho) = \frac{\overline{k}}{2q\cdot k}\rho\sqrt{q^2}\; K_1\left(\rho\sqrt{q^2}\right)$$

$$+\left[\frac{\overline{(q-k)}}{(q-k)^2} - \frac{\overline{k}}{2q\cdot k}\right]\rho\sqrt{(q-k)^2}\; K_1\left(\rho\sqrt{(q-k)^2}\right) .$$

- Due to the exponential decrease of the form factors (Bessel K_1 functions)

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

- with virtualities

$$\mathcal{Q} \in \left\{\sqrt{-q^2}\,,\ \sqrt{-(q-k_1)^2}\,,\ \ldots,\ \sqrt{-(q-k_{2n_f})^2}\right\} \geq 0\,,$$

the integration over the instanton size ρ in (leading-order) amplitudes $\mathcal{T}_\mu^{(I)}(q,p,\ldots)$ is finite in DIS $(-q^2 \equiv Q^2 > 0,\ \text{large})$, as long as

$$-(q-k_1)^2, \ldots, -(q-k_{2n_f})^2 \not\Rightarrow 0$$

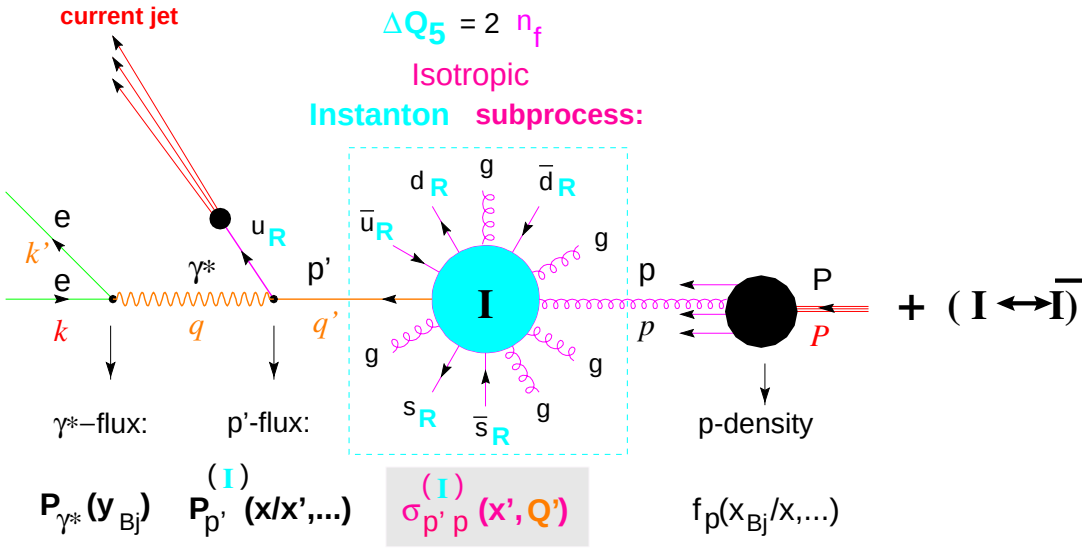
i.e. as long as the internal quarks are not moving collinear to the incoming gluon (just like in pQCD!).

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

2.2 Inclusive DIS Cross Sections

[Ringwald & F. Sch., hep-ph/9805492, hep-ph/9806528; Moch, Ringwald & F. Sch., to appear]

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



- Instanton-subprocess with own Bjorken-variables:

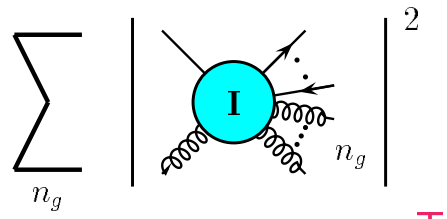
$$Q'^2 = -q'^2 \geq 0; \quad x' = \frac{Q'^2}{2p\cdot q'} \leq 1$$

- Show within I-perturbation theory for large Q^2, Q'^2:

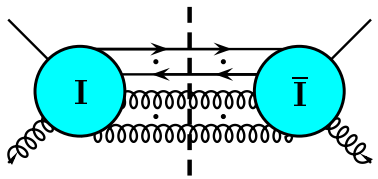
$$\frac{\mathrm{d}\sigma^{(I)}_{eP}}{\mathrm{d}x'\mathrm{d}Q'^2} \simeq \sum_{p',p} \frac{\mathrm{d}\mathcal{L}^{(I)}_{p'p}}{\mathrm{d}x'\mathrm{d}Q'^2} \cdot \sigma^{(I)}_{p'p}(x', Q')$$

- Calculable differential $p'p$ luminosities $\mathrm{d}\mathcal{L}^{(I)}_{p'p}$ in I-background:
  - Account for number of $p'p$ collisions per eP collision.
  - Involve integrations over γ^*-flux P_{γ^*}, p'-flux $P^{(I)}_{p'}$ and p-density f_p,.
- Crucial instanton-dynamics in I-subprocess cross-sections $\sigma^{(I)}_{p'p}(x', Q')$.
- 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

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

R_μ corresponds to

energy-momentum conservation,

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

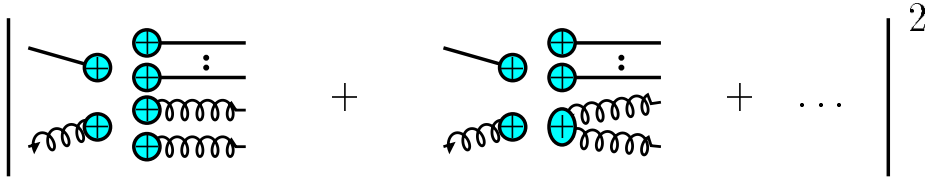
$$\int \frac{d^4k_i}{(2\,\pi)^3}\,\delta^{(+)}(k_i^2)\;\exp\left[-\mathrm{i}\,k_i\cdot R\right] = \frac{1}{(2\pi)^2}\,\frac{1}{-R^2+\mathrm{i}\epsilon R_0}\;,$$

separation between I and $\overline{I}$

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

summation and exponentiation of final-state gluons,

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



interaction between I and $\overline{I}$,

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

with $I\overline{I}$ valley action

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

Summation of Exclusive Cross-Sections

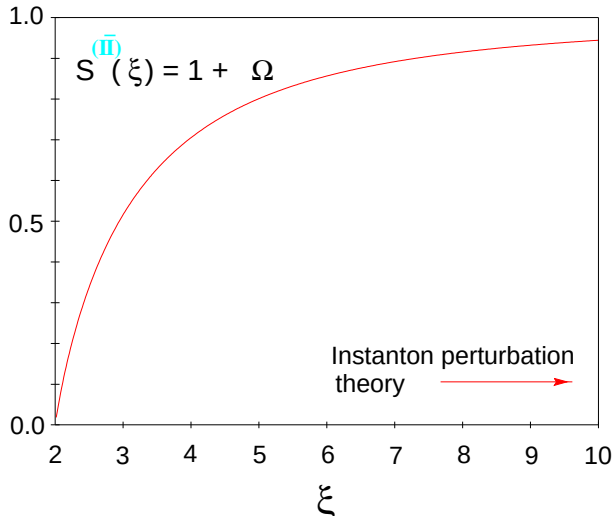
I-perturbation theory $\Leftrightarrow$

Ω perturbatively known for large $\frac{R^2}{\rho\overline{\rho}}$.

Optical Theorem and $I\overline{I}$-Valley Method

Semi-classical $I\overline{I}$-interaction Ω known for

all conformal separations $\xi \equiv \frac{-R^2+i\epsilon R_0}{\rho\overline{\rho}} + \frac{\rho}{\overline{\rho}} + \frac{\overline{\rho}}{\rho}$



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

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

Saddle-point evaluation of collective coordinate integrations,

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

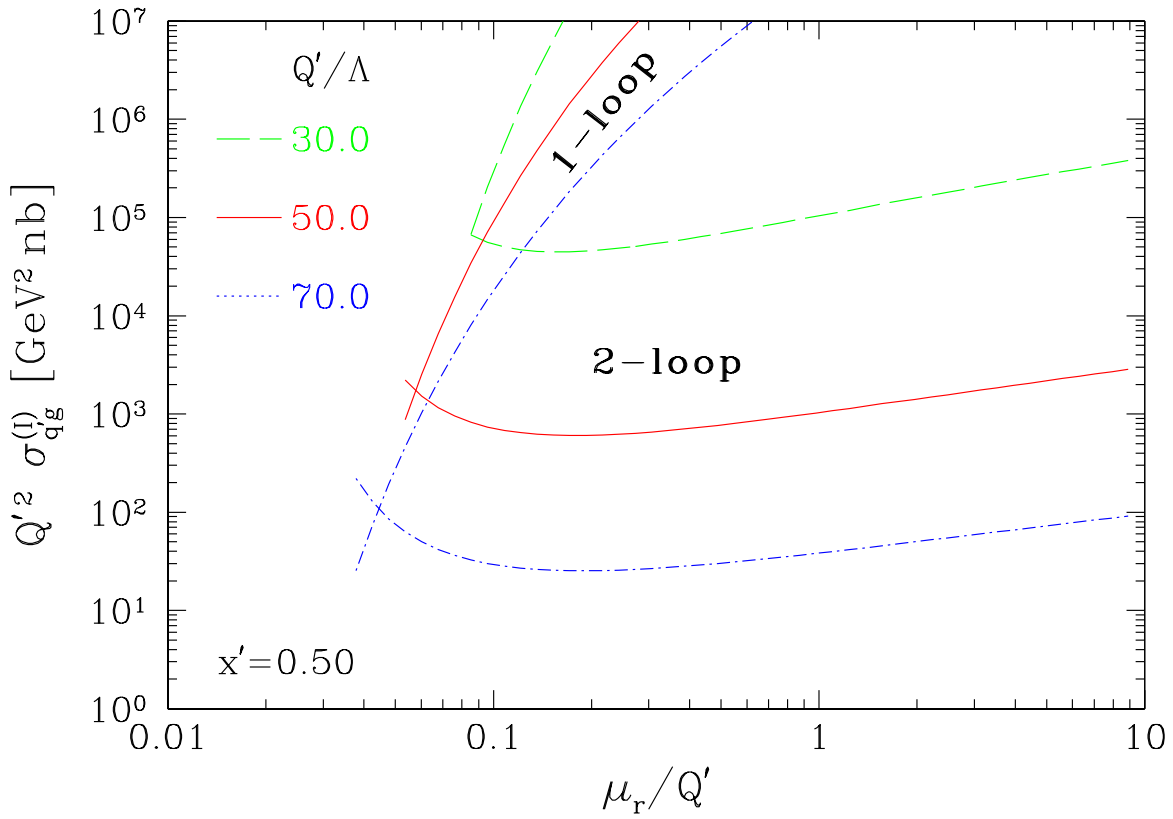
I-perturbation theory $\Leftrightarrow$ large Q' and $x' \sim 1$

Smooth extrapolation towards smaller x'

♣ Resulting $q'g$ cross-sections: [Ringwald & F. Sch., hep-ph/9805492, hep-ph/9806528]

- Great progress in stability, i.e. predictivity by using 2-loop RG invariant form of I-density $D(\rho)$ in calculation of I-subprocess cross sections:

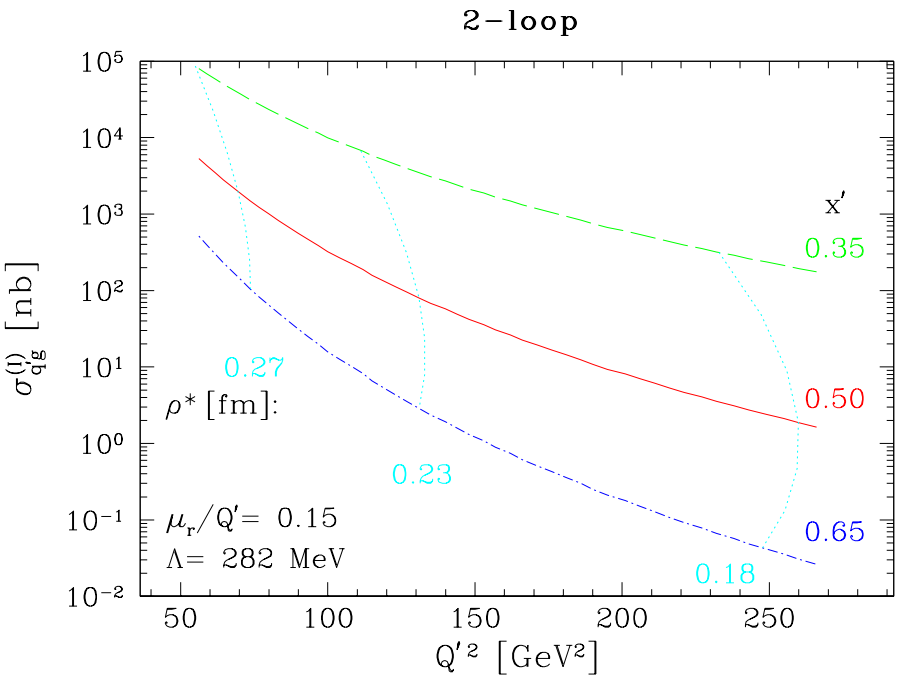
Residual dependence on renormalization scale μ_r strongly reduced!



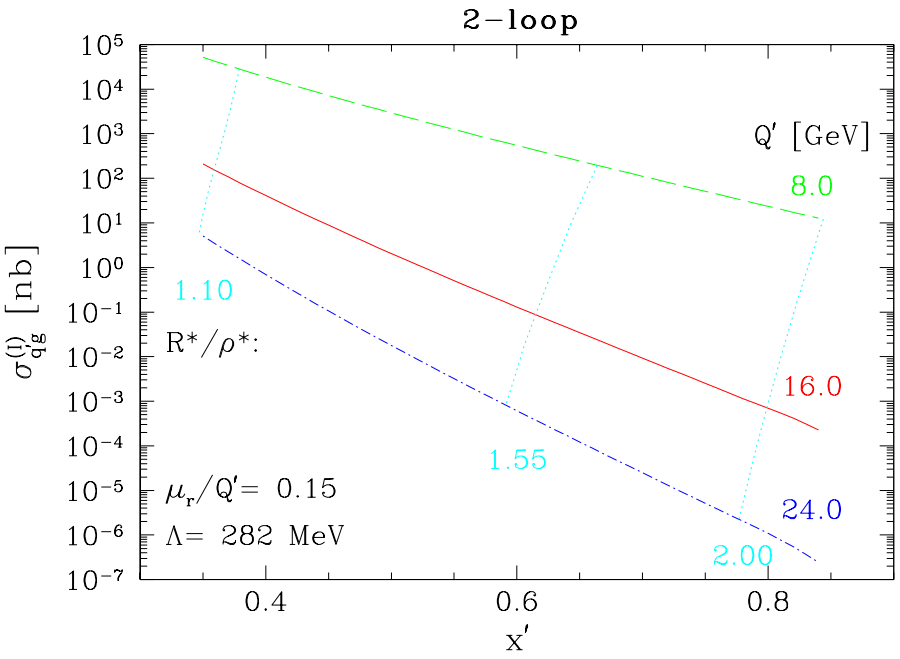
- Expect μ_r in regime:

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

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



Q'^2 probes I-density: $\sigma^{(I)}_{q'g} \sim D(\rho^*)^2 \sim (\rho^{*\,(\boldsymbol{b}-5)})^2 \sim (1/Q'^2)^{\boldsymbol{b}-5}$



x' probes $I\bar{I}$-interaction: $\sigma^{(I)}_{q'g} \sim \exp\left(-\frac{4\pi}{\alpha_s}\,\Omega\left(\frac{R^{*\,2}}{\rho^{*\,2}}\right)\right)_{|\frac{R^*}{\rho^*} \sim \sqrt{\frac{x'}{1-x'}}}$

2.3 "Fiducial" Region from Lattice Simulations

[Ringwald & F. Sch., hep-ph/9805492, hep-ph/9806528; Moch, Ringwald & F. Sch., to appear]

- Prediction of I-induced rates at **HERA** requires knowledge of "fiducial" (Q', x') region, where I-perturbation theory may be trusted!

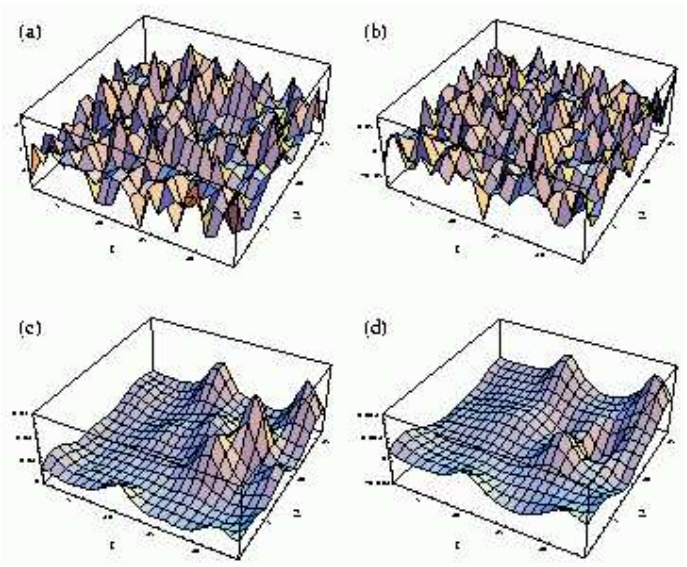
♣ **Experimentally:** Reconstruction of (Q'^2, x') from event topology!

♣ **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 configuration- and momentum space:

$$\rho^* \sim 1/Q', \qquad \frac{R^*}{\rho^*} \sim \sqrt{\frac{x'}{1-x'}}$$

- 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"

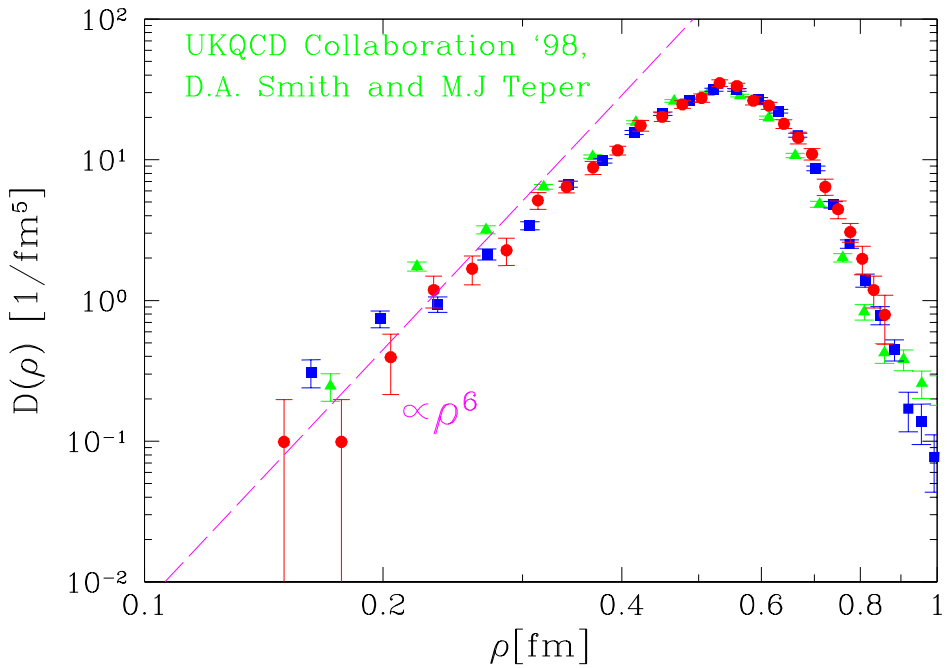
After cooling

[Chu et al. '94]

- See 3 instantons $(q(x) > 0)$ and 1 anti-instanton $(q(x) < 0)$!

- **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" . . .
- [UKQCD, Smith & Teper '98]:
  lattice spacing: a $=$ 0.055 - 0.1 fm
  lattice volume: V $= [16^3 \cdot 48 - 32^3 \cdot 64]a^4$
  $= [0.88^3 \cdot 2.64 - 3.2^3 \cdot 6.4]\mathrm{fm}^4$
- Allowing to study properties of Instanton ensemble with sizes $a \ll \rho \lesssim V^{1/4}$. Up to now: only gluons ($n_f = 0$).

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

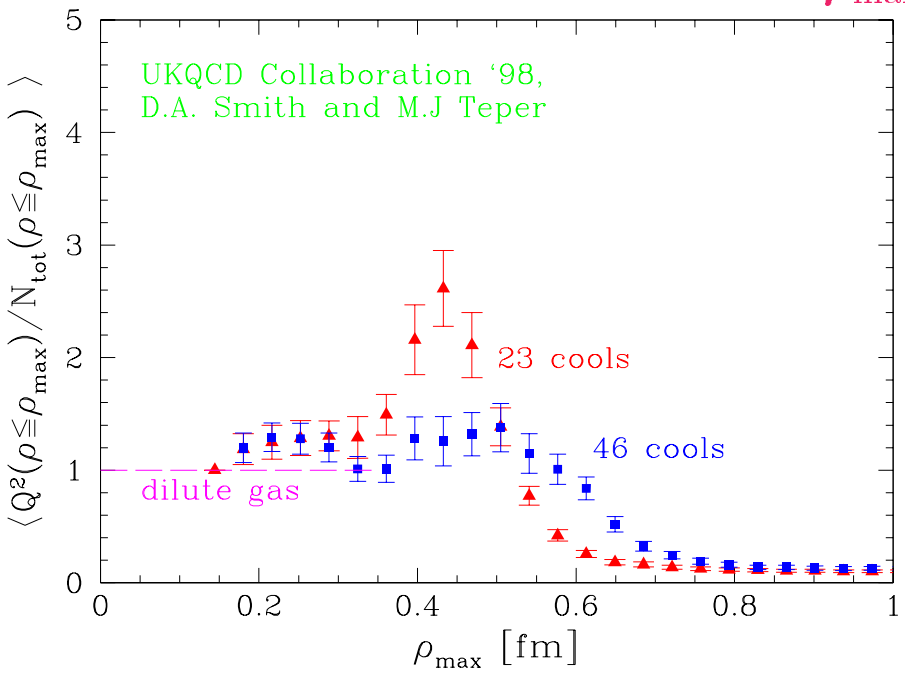


$\Rightarrow$ I-perturbation theory for $\rho \lesssim \rho_{\mathrm{max}} \simeq 0.3$ fm!

♣ **"Dilute" I-gas?** For a dilute gas, number fluctuations are poissonian and correlations among n_I and $n_{\overline{I}}$ distributions absent:

$$\langle Q^2 \rangle = \langle ((+1) n_I + (-1) n_{\overline{I}})^2 \rangle = \langle n_I + n_{\overline{I}} \rangle \text{ or } \langle \frac{Q^2}{N_{\rm tot}} \rangle = 1$$

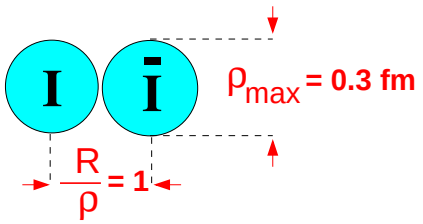
- Check whether this holds for Instantons **smaller than** $\rho_{\rm max}$,



$\Rightarrow$ **Dilute** I-gas for $\rho \lesssim \rho_{\rm max} \simeq 0.3$ fm, independent of "cooling"!

♣ **$I\overline{I}$-interaction?** Semi-classical attraction at larger $I\overline{I}$-separation R turns for $R^2/(\rho\overline{\rho}) \sim 1$ into a non-perturbative repulsion! ($\langle R/\rho \rangle \sim 0.83 \ldots 2$). [UKQCD,. . . ,SU(2): DeGrand, Hasenfratz, Kovács '97]

♣ **"Fiducial" kinematical region** from lattice simulations:



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

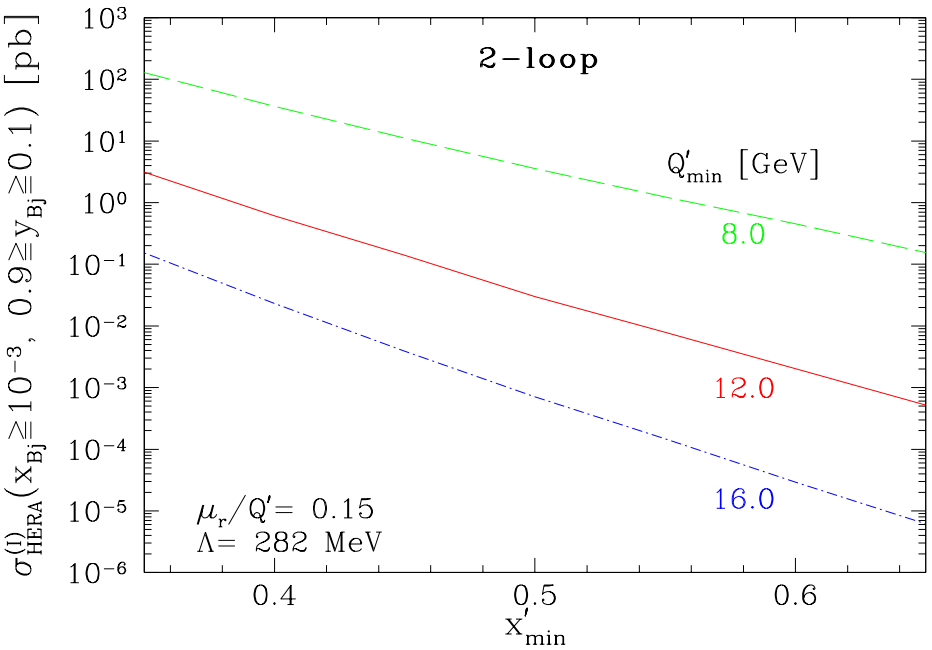
3. HERA Cross-Section

[Ringwald & F. Sch., hep-ph/9805492, hep-ph/9806528; Moch, Ringwald & F. Sch., to appear]

- "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, as function of (Q', x') cuts:



- Uncertainties:
  - Where to place exactly the (Q', x') cuts?
  - $\Lambda_{|n_f=3} = (282 \pm 65)\ {\rm MeV} \ \Rightarrow \sigma^{(I)}{}_{\rm HERA}(\mathcal{C}_{\rm std}) \simeq 126^{+300}_{-100}$ pb
  - μ_f and μ_r dependencies comparatively small. ($\Leftarrow$ $D(\rho)$ at 2 loop!)

- 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 integrated luminosity accumulated by experiments at **HERA**,

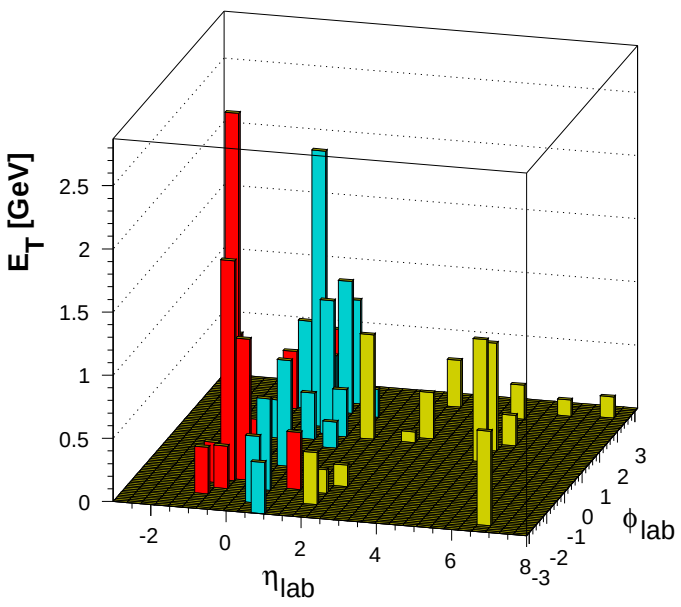
  $\mathcal{L} = \mathcal{O}(80)\ {\rm pb}^{-1} \ \Rightarrow$ $\mathcal{O}(10^4)$ I-induced events on tape.

4. Searches at HERA

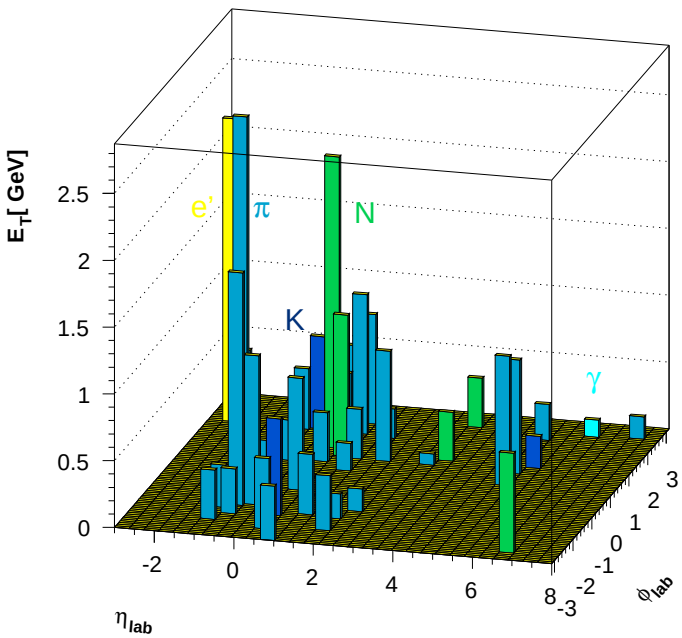
- Important tool: [Gibbs, Ringwald & F. Sch. '95; anonymous ftp: theopc3.desy.de]
  "QCDINS 1.6.0" : Monte-Carlo generator for I-induced DIS-events
  - Instanton-induced hard subprocess
  - Leading-log parton shower and hadronization (HERWIG 5.9)
  - "HZTOOLS" package fully integrated⇒ all published H1/ZEUS data, jet analysis . . .

4.1 Lego Plot of Typical Event

Characteristics



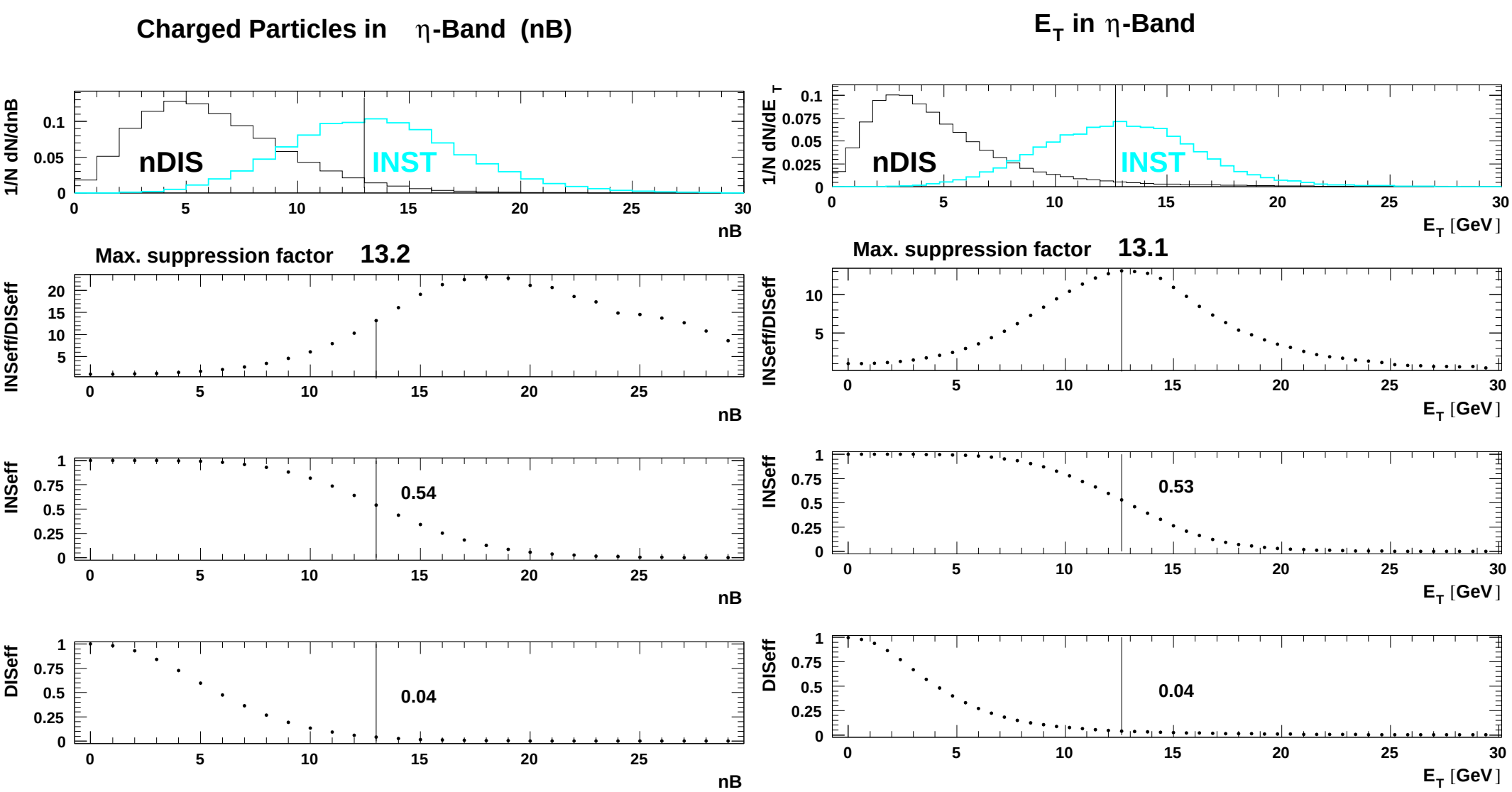
Particle Composition



- Current jet
- Hadronic "band": ⇔ **Isotropy** in I-rest system
  - Large total E_T
  - Large multiplicity
  - No jets in "band" !
  - Characteristic flavor flow:
    ⋆ **Strangeness** ⇒ K_S^0's

4.2 Search Strategies

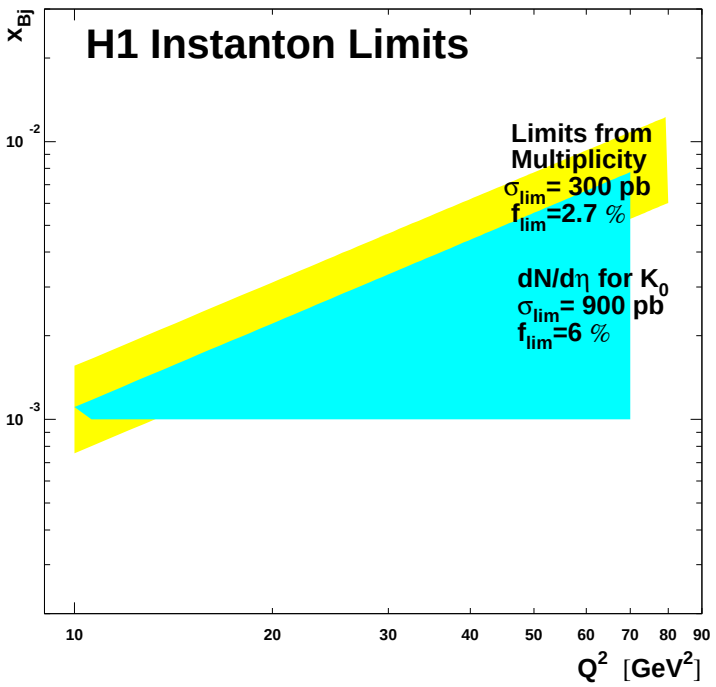
- Despite high rate of instanton-induced events at HERA, no single observable known (yet) with sufficient **nDIS** rejection.
- Hence, dedicated multi-observable analysis required.
- Need to understand pQCD background in tails of distributions!
- Neural network filters are being tried and have very good 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:
- **Example: instanton-enriched data**
  - Instanton-induced events are expected to yield high multiplicity and high E_T, notably in the "band" of width $\Delta\eta = \pm\mathcal{O}(1)$.
  - Place optimal single-variable cuts to produce $\boldsymbol{I}$-enriched data samples, assuming INSefficiency> 0.5. All plots im $\gamma^* P$ c.m.s;
  - $Q^2 > 5$ GeV^2, $0.1 < y_{\rm Bj} < 0.6$, i.e. $x_{\rm Bj} \gtrsim 10^{-4}$; no detector-sim.



[T. Carli (H1) & J. Gerigk (H1) '98]

4.3 Experimental Limits in DIS at HERA

- Method:
  - Use Monte-Carlo event generator only for simulation of the event shapes rather than for the prediction of the absolute rates.
  - Determine the maximum allowed fraction of I-induced events, $f_{\rm lim}^{(I)}$, by comparison with the measured event shapes.
  - Can be turned into upper bound on I-induced cross-section, $\sigma_{\rm lim}^{(I)}$.
- H1 Bounds:
  - Search for K^0 excess in "band" region [H1, Nucl. Phys. B480 (1996) 3]
  - Search for excess in charged multiplicity [H1, Z. Phys. C72 (1996) 573]

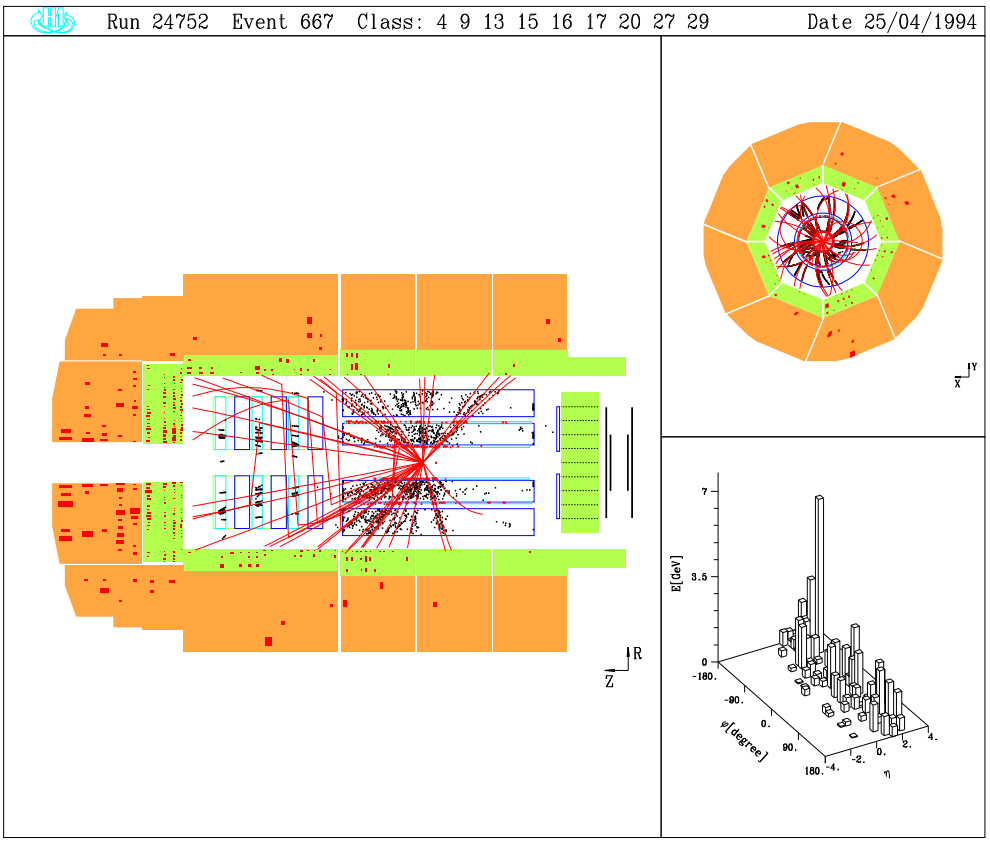


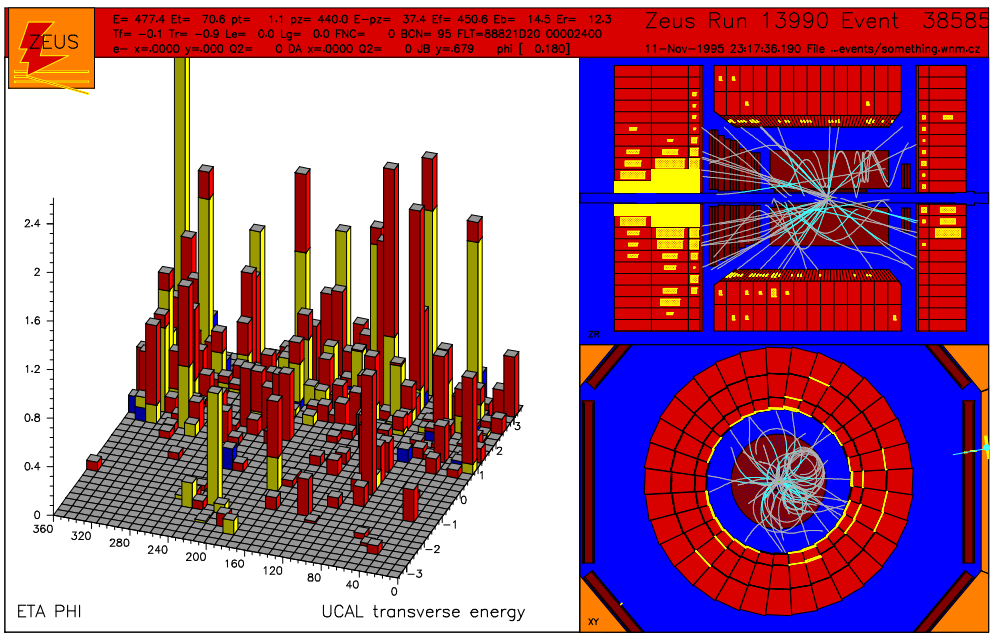
- Extended Analysis: [Carli, Kuhlen, Nucl. Phys. B511 (1998) 85]
  - Most stringent bounds from multiplicity distribution,

$$f_{\rm lim}^{(I)} = \mathcal{O}(1)\ \%.$$

4.4 I-induced Processes at HERA at small Q^2?

- Large E_T fireball events are observed at small Q^2:





- Exhibit all of the characteristics of I-induced processes.

4. Conclusions

- Topological fluctuations: Important aspect of QCD.
- DIS distinguished: Hard I-induced processes are calculable and can possibly also be detected experimentally at **HERA**!
- 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, based on 2-loop RG-invariant I-density.
- Profit from recent activity of the "lattice-community" studying the topological features of the QCD ground state non-perturbatively.
  [UKQCD: Smith, Teper '98; Forcrand *et al.* '97; DeGrand *et al.* '97;
  Michael, Spencer '95; Chu *et al.* '94; . . .]
- Possible to link the 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 isolate "instanton-enriched" data samples in DIS and to reconstruct (Q', x') are promising and in progress.
- 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,

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

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

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

- Decisive search for instanton-induced events at HERA seems feasible.