QCD -Instantons – Deep Inelastic Scattering and Lattice Results

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– Theory Seminar, MPI München, November 8th, 1999 –

1. Introduction

♣ Rich vacuum structure of non-abelian gauge theories like QCD ⇐ TOPOLOGY!

- Gauge fields $A_\mu(x)$ with finite action carry an integer topological charge

$$Q = \frac{\alpha}{2\pi} \int d^4x \, \frac{1}{2} \mathrm{tr}(F_{\mu\nu} \tilde{F}_{\mu\nu}) = 0, \pm 1, \pm 2, \ldots$$

- Simplest building blocks of topological structure

Instantons (Q=+1) and **anti-instantons (Q=-1)**:

♢ Explicitly known solutions of classical 4d Euclidean field equations ⇔ minimize classical action for $|Q| = 1$: [Belavin *et al.* '75]

$$A_\mu^{(I)}(x) = \frac{-\mathrm{i}}{\sqrt{4\pi\alpha}} \frac{\rho^2}{y^2} U \frac{\sigma_\mu \overline{y} - y_\mu}{y^2 + \rho^2} U^\dagger, \quad \text{with}$$

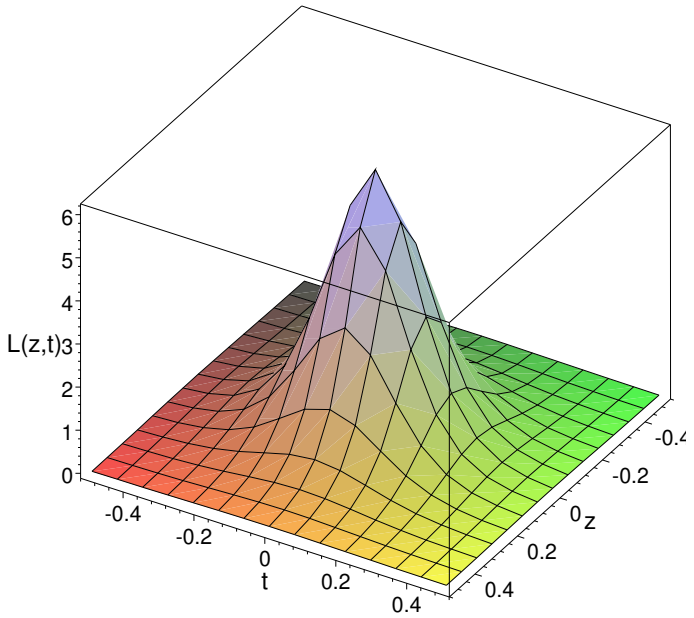
$$y = x - x_0 \quad \text{and} \quad \overline{y} = y_\nu \overline{\sigma}_\nu.$$

I-collective coordinates: size ρ, color orientation U, position x_0; action independent thereof:

(I-position $x_0 = 0$:

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

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



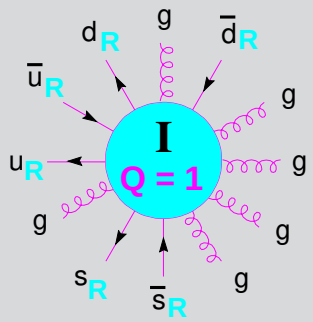
- ◇ Non-perturbative fluctuations of gauge-fields, localized ("instantaneous") in Euclidean time and space.
- ◇ In Minkowski space: Tunnelling transitions between adjacent, topologically inequivalent vacua,

amplitude: $\sim \exp\left(-\frac{2\pi}{\alpha}\right)$.

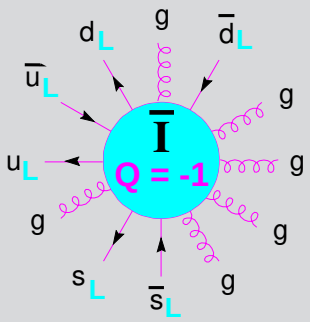
- Instantons widely believed to play an important rôle in various long-distance aspects of QCD :
  - ◦ axial "U(1) problem" (why $m_{\eta'} \gg m_\eta$?) ['t Hooft '76]
    - – Witten - Veneziano formula [Witten '79, Veneziano '79]
    - – different mixing angles for $J^{PC} = 0^{-+}$ and 1^{--} mesons ['t Hooft '99]
  - ◦ breaking of chiral symmetry [Schaefer, Shuryak '98 (review)]

- Also very important short-distance implications of instantons:

induce processes violating "chirality" $Q_5 = \#(q_R) - \#(q_L)$ in QCD with $\approx$ massless quarks ['t Hooft '76]



$$\Delta Q_5 = 2n_f \cdot Q$$



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

♣ An experimental discovery of **instantons** through these anomalous processes would be of basic significance!

♣ **DIS** regime at **HERA** offers unique discovery window for events induced by QCD -instantons, through

♢ their characteristic final-state signature
[Ringwald & F. Sch. '94 - '99,
Carli, Gerigk, Ringwald & F. Sch., hep-ph/9906441 & in prep]

♢ a sizable rate, calculable within I-perturbation theory
[Ringwald & F. Sch., Phys. Lett **B438** (1998) 217,
Moch, Ringwald & F. Sch., Nucl. Phys. **B507** (1997) 134 & in prep]

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!

♣ Lattice simulations: Much recent activity to measure topological fluctuations in the (quenched) QCD vacuum

$\Rightarrow$ important support for basic prerequisites of our calculations in **DIS**, "fiducial" kinematical region. . .
[Ringwald & F. Sch., Phys. Lett. **B 438** (1998) 217, **B 459** (1999) 249]

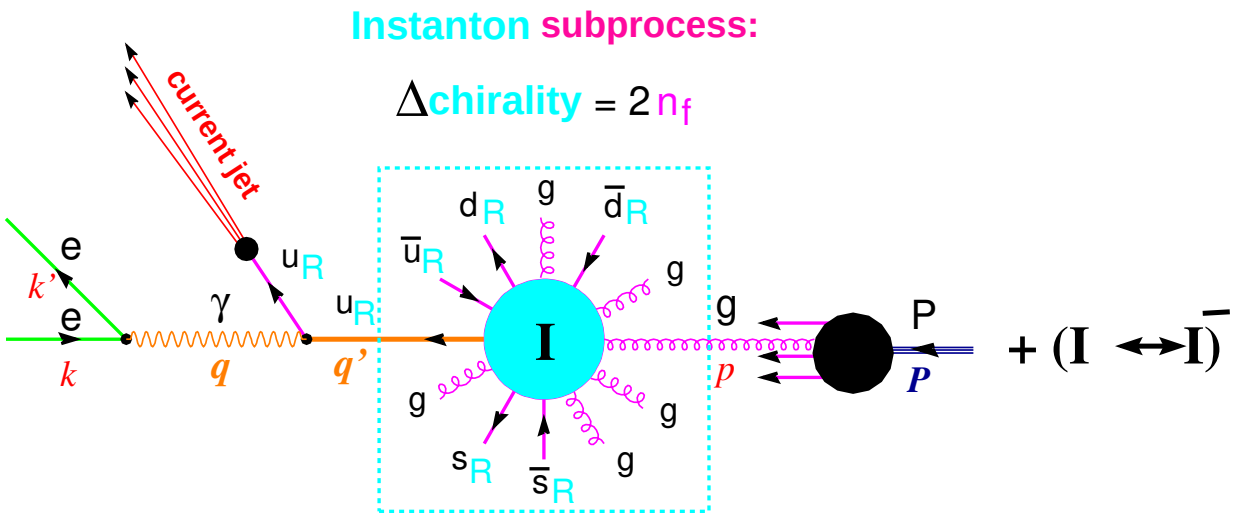
2. Instanton Perturbation Theory in DIS

[Ringwald & F. Sch., Phys. Lett **B438** (1998) 217,
Moch, Ringwald & F. Sch., Nucl. Phys. **B507** (1997) 134 & in prep]

- I-perturbation theory for dilute gas of I's and $\overline{I}$'s light quarks with $\mathrm{m}_q \cdot \rho_{\mathrm{eff}} < 1$

  – Expand Euclidean path integral for generating functional of Green's functions about known, classical I-solution $A_\mu(x) = A_\mu^{(I)}(x) + \cdots$ for small α
  – derive (modified) Feynman rules in momentum space
  – LSZ-amputation along with (careful!) analytic continuation to **DIS**-kinematics

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



- I-subprocess with own **Bjorken**-variables, $(\boldsymbol{x'}, \boldsymbol{Q'^2})$:

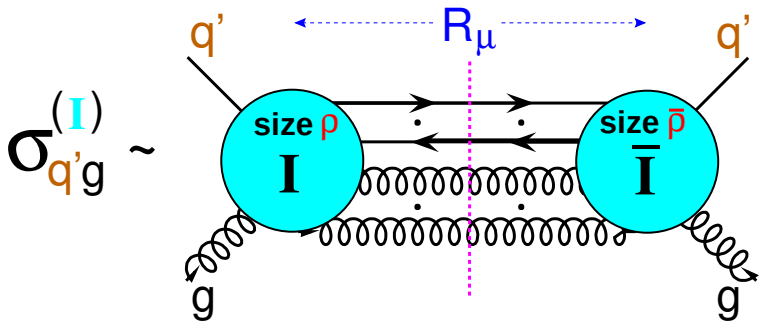
$$\text{large} \quad Q'^2 = -q'^2 > 0; \quad x' = \frac{Q'^2}{2p\cdot q'} \leq 1 \quad \text{fixed}$$

- 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, $\mathrm{d}\mathcal{L}^{(I)}_{q'g}$: number of $q'g$ collisions per eP collision; integrations over gluon density, γ^*-flux P_{γ^*} and known q'-flux $\mathrm{P}_{q'}{}^{(I)}$ in $\boldsymbol{I}$-background.

- Crucial I-dynamics in total cross-section $\sigma^{(I)}_{q'g}(Q', x')$ of $\boldsymbol{I}$-subprocess $q'g \overset{I}{\Rightarrow} X$!



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

I-size ρ, $\overline{I}$-size $\overline{\rho}$, $I\overline{I}$-distance 4-vector R_μ,
and $U{=}I\overline{I}$ relative color orientation

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

Two crucial quantities of I-calculus:

$$D(\rho) = \begin{matrix}\text{(reduced)} \\ I\text{-size distribution}\end{matrix}\,, \quad \Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right) = I\overline{I}\text{-interaction}$$

♢ $D(\rho)$ known in I-pert. theory, for $\alpha(\mu_r)\ln(\mu_r\rho) \ll 1$
(μ_r = renormalization scale)

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

$d =$ known, scheme dependent constant

b	$\frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}\mu_r}$	Ref.
β_0	$\mathcal{O}(\alpha)$	't Hooft '76, Bernard '79
$\beta_0 + \frac{\alpha(\mu_r)}{4\pi}(\beta_1 - 12\beta_0)$	$\mathcal{O}(\alpha^2)$	Morris, Ross & Sachrajda '85

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

Note:

- For $n_f = 0$ (lattice), $D(\rho)$ equals the proper size distribution (in dilute gas approx.), i. e. $D(\rho) \simeq d\, n_I / d^4x\, d\rho$
- Power-law behaviour $D(\rho) \propto \rho^{6-2/3n_f+\mathcal{O}(\alpha)}$ generically spoils applicability of I-perturbation theory, since I-size integrals diverge for large ρ (infrared)
- Exception in **DIS**, where "form factor" $\exp(-Q'(\rho+\overline{\rho}))$ insures $\rho, \overline{\rho} \lesssim 1/Q'$

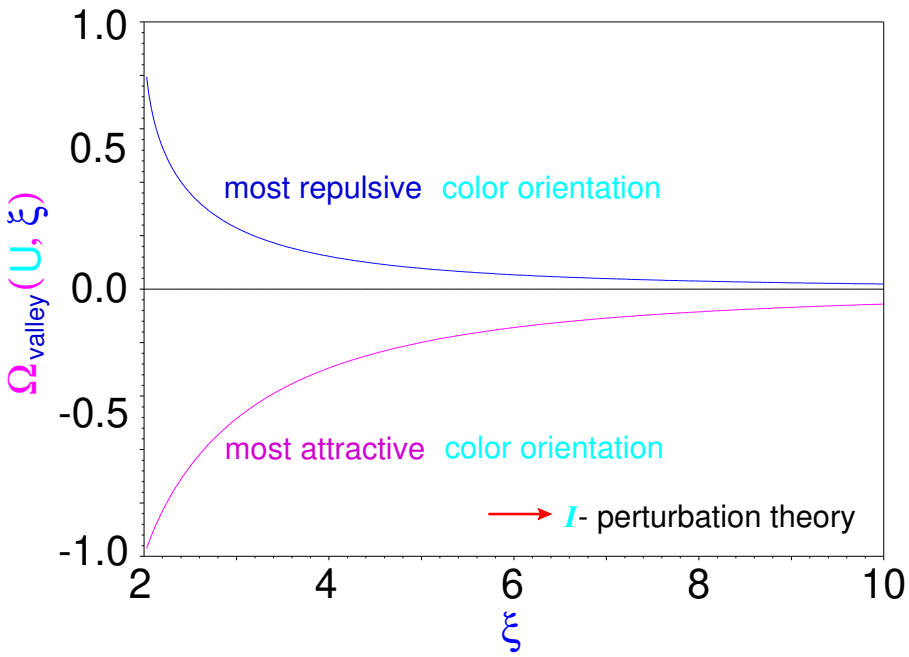
♢ $\Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$

- within I-perturbation theory:
  known as series for $R^2/\rho\overline{\rho} \gg 1$;
- within "$I\overline{I}$-valley" approximation:
  [Yung '88, Khoze & Ringwald '91, Verbaarschot '91]
  analytically known $\Rightarrow$

conformally invariant

$I\overline{I}$-distance

$\xi = \frac{R^2}{\rho\overline{\rho}} + \frac{\rho}{\overline{\rho}} + \frac{\overline{\rho}}{\rho}$



♣ For (large) $Q' \neq 0$, all collective coordinate integrations in $\sigma^{(I)}_{q'g}$ in terms of unique saddle point:

$U^* \Leftrightarrow$ most attractive color orientation

$$\rho^* = \overline{\rho}^* \sim \frac{4\pi}{\alpha(\frac{1}{\rho^*})}\frac{1}{Q'}; \qquad \xi^* - 2 \equiv \frac{R^{*\,2}}{\rho^{*\,2}} \overset{Q' \text{ large}}{\sim} 4\frac{x'}{1-x'}$$

$$\sigma^{(I)}_{q'g}(Q',x') \simeq \underbrace{D(\rho^*)^2 \cdot \mathrm{e}^{-\frac{4\pi}{\alpha(\frac{1}{\rho^*})}\Omega_{\mathrm{valley}}(U^*,\xi^*)}}_{\sim\left(\frac{\Lambda_{\overline{\mathrm{MS}}}}{Q'}\right)^{2\beta_0\,(1+\Omega_{\mathrm{valley}}(U^*,\xi^*))}} \underbrace{H(\xi^*,\rho^*)}_{\frac{1}{\sqrt{\det(\mathrm{Hessian})}},\ldots}$$

♢ $\Rightarrow$ formally, for large Q' and small $(1-x')$:
dilute gas ($R/\rho \gg 1$) of small I's and $\overline{I}$'s ($\rho \sim 1/Q'$)!

- Very sensitive to $\Lambda_{\overline{\mathrm{MS}}}$

$D(\rho)$ and $\Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$: Link between **DIS** and **lattice** observables!

♢ **Lattice** $\Rightarrow$ Independent, non-perturbative information on range of validity of their predicted form in (ρ, R)

♢ Due to crucial one-to-one saddle-point correspondence of effective I-coordinates

$\Rightarrow$ "fiducial" (Q',x') region for our predictions in **DIS**!

3. Implications of Lattice Results

[Ringwald & F. Sch., Phys. Lett. **B 438** (1998) 217, hep-lat/9903039 and Phys. Lett. **B 459** (1999) 249]

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

- Recent high-quality lattice simulation of quenched QCD ($n_f = 0$) [UKQCD, Smith & Teper, '98,. . .]

$\beta \equiv 6/g_0^2(a)$:	$=$	6.4	6.2	6.0	
i. e. lattice spacing a :	$\simeq$	0.055	0.072	0.10	fm
volume $V = (n_s^3\, n_t)\, a^4$:	$=$	$32^3\, 64$	$24^3\, 48$	$16^3\, 48$	a^4
	$\simeq$	18.6	18.0	18.2	fm^4

- **Throughout**: use Sommer scale r_0: $2\, r_0 \simeq 1$ fm rather than string tension σ to convert to physical units ($r_0 \Leftrightarrow$ force $F_{\overline{q}q}$ between static quarks: $r_0^2 F_{\overline{q}q}(r_0) = 1.65$) .

♣ Topological structure over fairly wide range of sizes $a \ll \rho \ll V^{1/4}$ accessible.

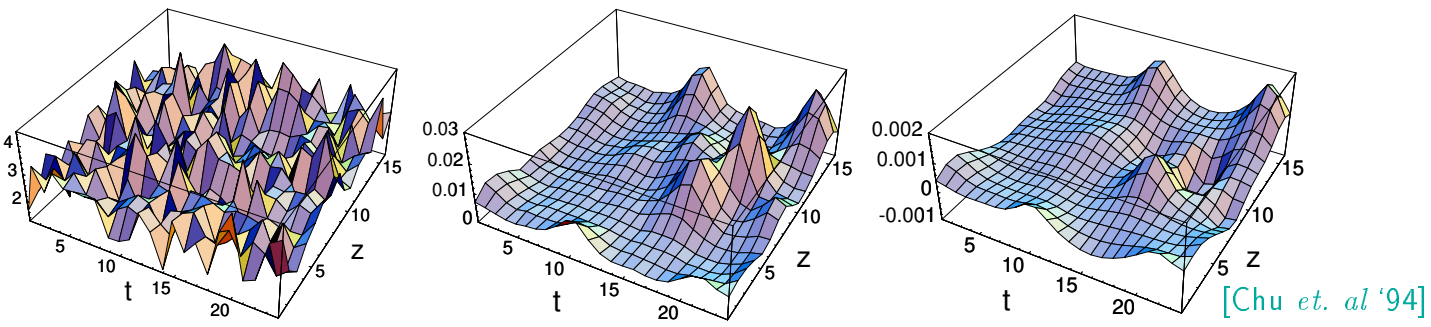
♣ Range of validity of I-perturbation theory?

  - Crucial: $\Rightarrow$ "fiducial" $(Q',\ x')$ region for **DIS** predictions!
  - Interesting question by itself. . .

Cooling

- Designed to filter out (dominating) fluctuations of short wavelength $\mathcal{O}(a)$, while affecting topological fluctuations of size $\rho \gg a$ comparatively little.

Lagrange Density **Topological Charge Density**



[Chu *et. al* '94]

Before Cooling **After** Cooling

- **In practice**: $n_{\rm cool}$ sweeps trough the lattice links replacing existing link matrices $\Rightarrow$ new ones, locally minimizing (or reducing) the action

- $\Rightarrow$ Sequence of increasingly smooth or 'cold' lattice fields. May then study local topological structures (I, $\overline{I}$) via pattern recognition algorithms (c. f. Fig.)

- Cooling also removes I's and $\overline{I}$'s, e.g. via $I\overline{I}$ annihilation $\Rightarrow$ **UKQCD**: "under-relaxed" (i. e. slow) cooling

- No objective criterium available yet, on quantitative amount of "vacuum damage" introduced by cooling. . .

- Various proposals to approach physics of uncooled vacuum:

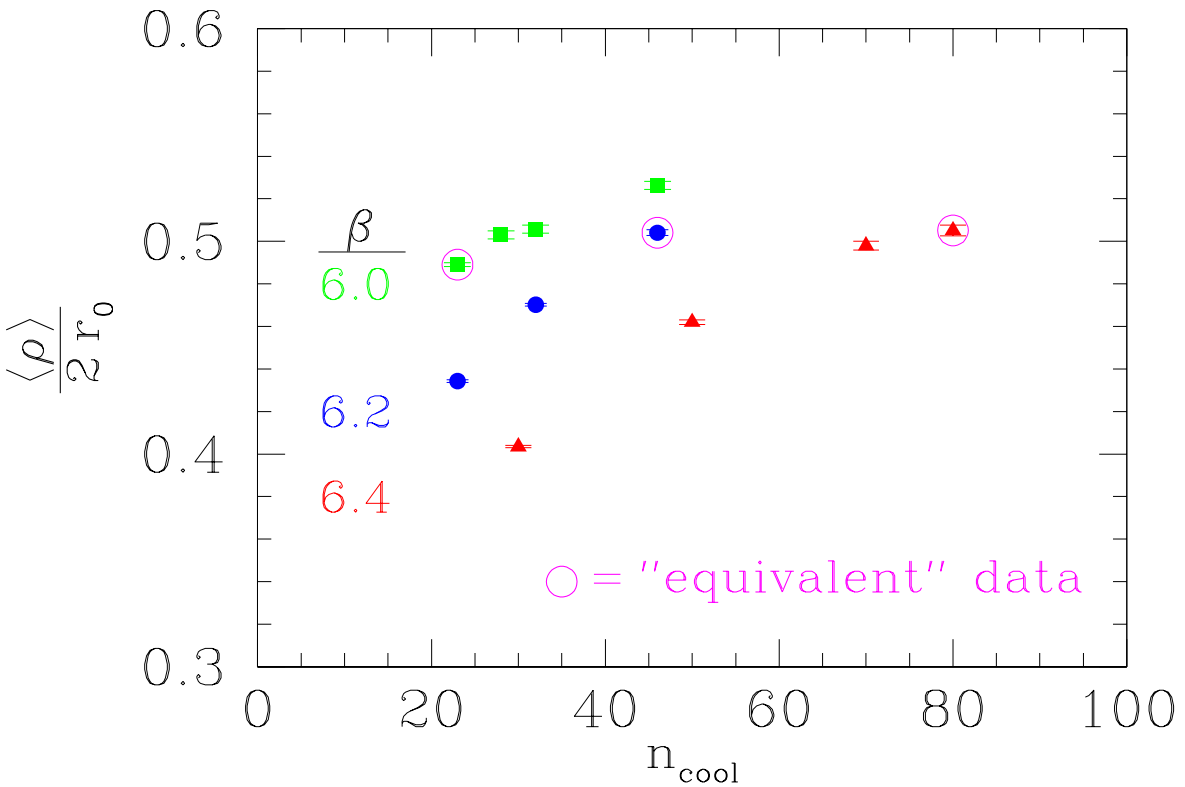
  $\Rightarrow$ **UKQCD:** Starting from smallest reliable $n_{\rm cool} \simeq 23$ at $\beta = 6.0$, say, find further "equivalent" pairs $(\beta, n_{\rm cool})$ giving $\sim$ same shape & normalization of distributions.

♢ **Result:** pairs $(\beta, n_{\rm cool}) = (6.0, 23),\ (6.2, 46),\ (6.4, 80)$ used for continuum limit, $a \to 0$!

? Crucial question remains: Why $(\beta, n_{\rm cool}) = (6.0, 23)$ as "starting pair" distinguished? (c. f. below!)

- **Illustration**: average I-size $\langle \rho \rangle$

- Fixed β: strong dependence on $n_{\rm cool}$, unlike "equivalent" data.



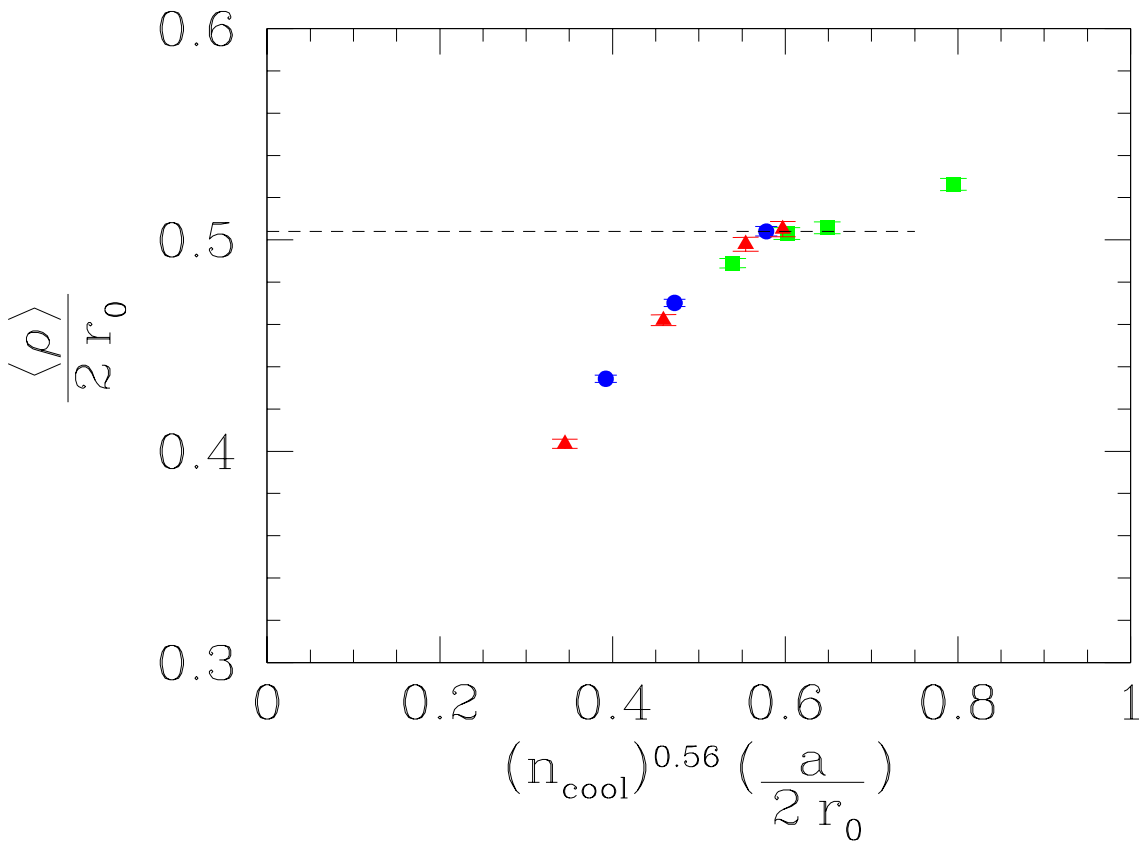
- Striking observation: [Ringwald & F. Sch., Phys. Lett. **B 459** '99]

  Cooling is kind of "diffusion process": length scale up to which it smoothes configurations grows with $n_{\rm cool}$.

- $\Rightarrow$ random walk argument:

  "cooling radius": $\frac{r_{\rm cool}}{2\,r_0} = {\rm const.}(\sqrt{n_{\rm cool}})^{1+\delta}\frac{a}{2\,r_0}$; δ small

- **Fig.:** $\frac{\langle\rho\rangle}{2r_0}$ vs. $\frac{r_{\rm cool}}{2\,r_0}$ for all $(\beta, n_{\rm cool})$ on a single smooth curve, exhibiting a clear plateau $\Leftrightarrow$ "equivalent" data!



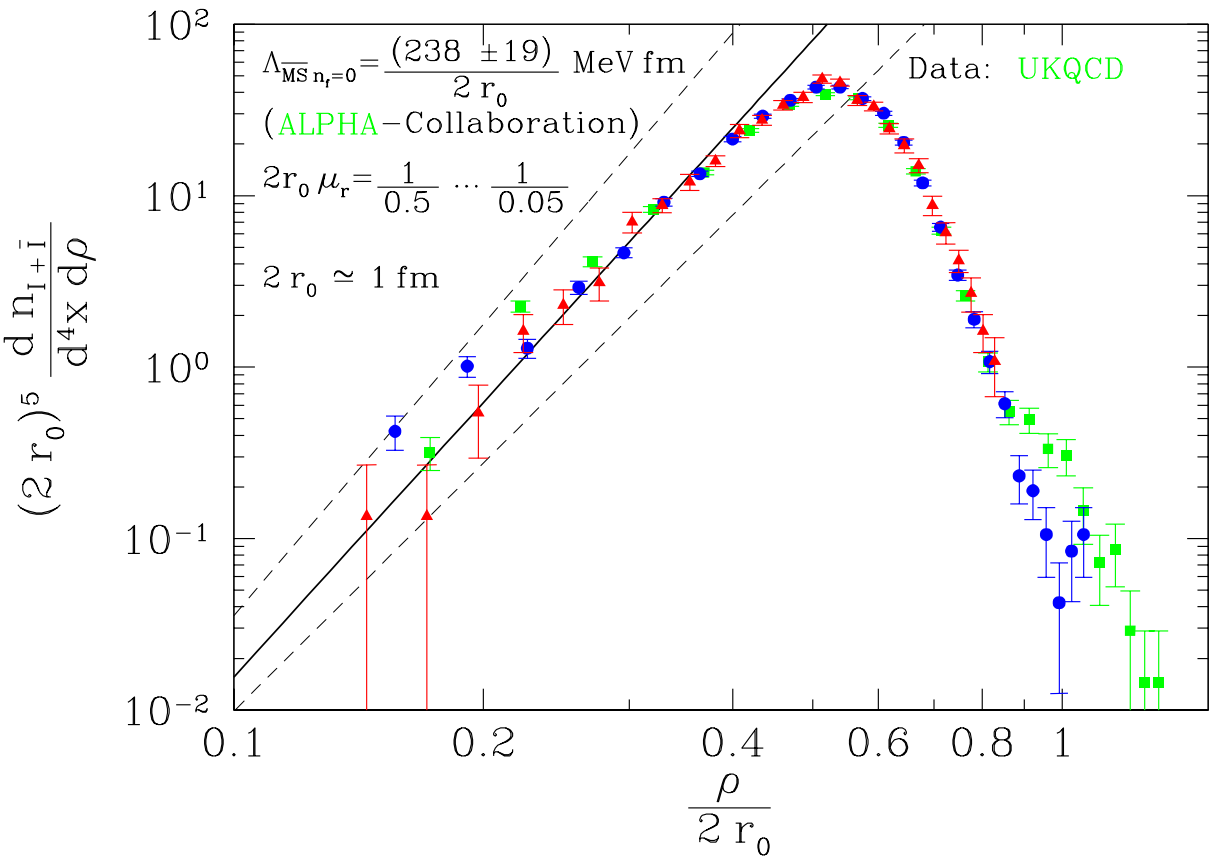
- In summary: plateau region = correct regime for extracting physical information about instantons!

I-Size Distribution $\frac{d\,n_{I+\bar{I}}}{d^4x\;d\rho}$

- Perform continuum limit of "equivalent" data via ansatz

$$(2r_0)^5 \frac{d\,n_{I+\overline{I}}}{d^4x\,d\rho} = \mathrm{f}\left(\frac{\rho}{\langle\rho(a)\rangle}\right) \qquad \left\{ \begin{array}{lcl} \langle\rho(a)\rangle & \approx & \langle\rho(0)\rangle + \mathcal{O}(a^2) \\ \rho & \Rightarrow & \frac{\langle\rho(0)\rangle}{\langle\rho(a)\rangle} \cdot \rho \end{array} \right.$$

$$(2r_0)^5 \frac{d\,n_{I+\overline{I}}}{d^4x\,d\rho}\Big|_{\mathbf{UKQCD}} \stackrel{?}{\simeq} 2\,D(\rho)\Big|_{I-\text{perturbation theory}}$$



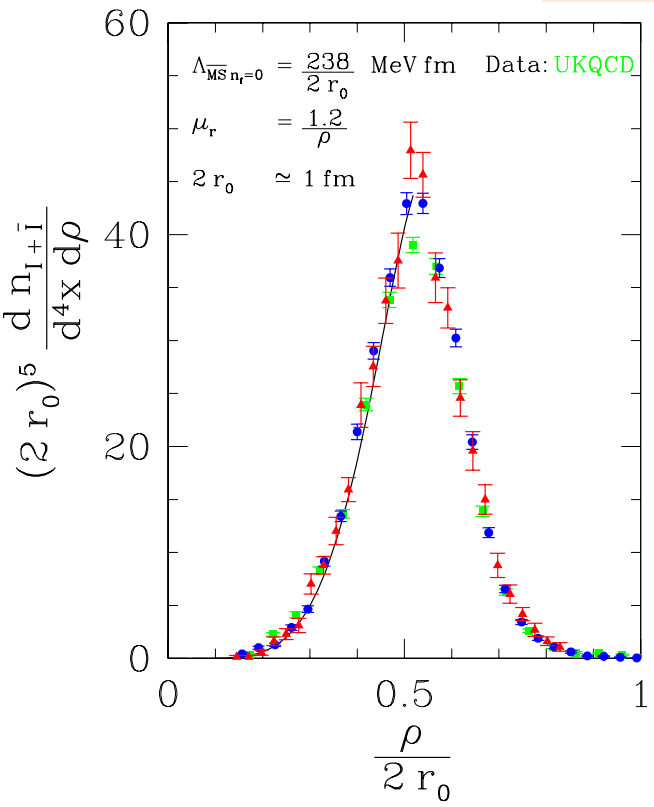
- Parameter-free **agreement** in shape and normalization,

  for $\rho/2r_0 \lesssim 0.35$ i. e. $\rho \cdot \Lambda_{\overline{\mathrm{MS}}}^{(n_f=0)} \lesssim 0.42$

- Error band $\Leftrightarrow$ error of $2r_0\Lambda_{\overline{\mathrm{MS}}}^{(n_f=0)} = (238 \pm 19)$ MeV fm
  [ALPHA-Collaboration, Nucl. Phys **B 544** (1999) 669]

- Almost independent of μ_r for large range $0.5 \lesssim \mu_r \lesssim 5$ GeV.

- Improved choice: $\mu_r \rho = \mathcal{O}(1)$, to minimize $\ln(\mu_r \rho)$-corrections $\Rightarrow$ **agreement** up to the peak, $\rho/2r_0 \lesssim 0.5$!



$I\bar{I}$-Distance Distribution $\frac{d(n_{I\bar{I}})}{d^4x\, d^4R}$ = number of unlike charges in the spherical shell of width δR a distance R away from each charge, normalized by shell volume ($\Leftarrow$ **UKQCD**)

- First direct test of $I\bar{I}$-valley form for $I\bar{I}$-interaction Ω!

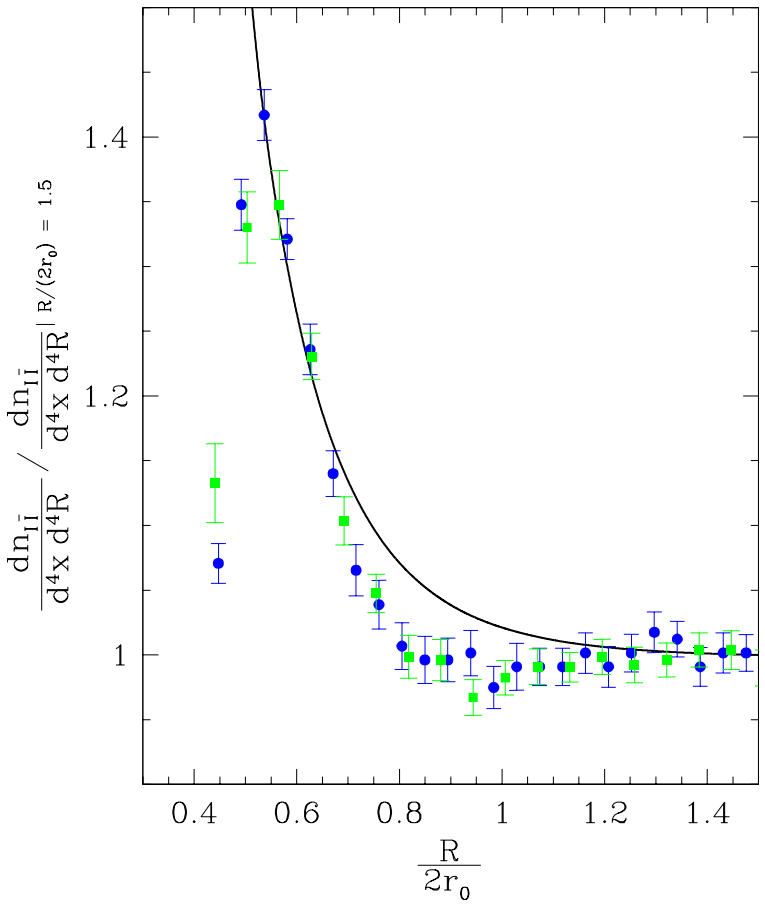
$$\frac{d\, n_{I\bar{I}}}{d^4x\, d^4R}\Big|_{\text{UKQCD}} \overset{?}{\simeq}$$

$$N \int_0^\infty d\rho \int_0^\infty d\overline{\rho}\ \ D(\rho)\, D(\overline{\rho}) \int dU\, \mathrm{e}^{-\frac{4\pi}{\alpha}\ \Omega_{\text{valley}}\left(U,\, \frac{R^2}{\rho\overline{\rho}},\, \frac{\overline{\rho}}{\rho}\right)}$$

- Substitute $D(\rho)$ by lattice results, $\alpha = \alpha_{\overline{\rm MS}}(\frac{s_{I\bar{I}}}{\sqrt{\rho\bar{\rho}}})$, perform 4 integrations numerically. 1 parameter $\mathcal{O}(1)$: $s_{I\bar{I}} \simeq 0.82$

- Continuum limit of "equivalent" data analogously to I-size distribution (too bad, $\beta = 6.4$ data missing!):

$$(2r_0)^8 \frac{d\,n_{I\bar{I}}}{d^4x\,d^4R} = \mathrm{f}\left(\frac{R}{r(a)}\right) \qquad \left\{ \begin{array}{lcl} r(a) & \approx & r(0) + \mathcal{O}(a^2) \\ R & \Rightarrow & \frac{r(0)}{r(a)} \cdot R \end{array} \right.$$



- Continuum distributions from rescaling of the "equivalent" data at $\beta = 6.0$ and $\beta = 6.2$ are nicely consistent.

- Good **agreement** with $\Omega_{\rm valley}$ for $\frac{R}{2r_0} \gtrsim 0.5$, i. e. $\frac{R}{\rho} \gtrsim 1$

♣ In summary:

♢ Good **agreement** of lattice results with I-perturbation theory very interesting by itself.

♢ Lattice constraints translate via saddle point into "fiducial" kinematical region in **DIS**:

$$\left.\begin{array}{lcl} \rho \cdot \Lambda_{\overline{\rm MS}}^{(n_f=0)} & \lesssim & 0.42 \\ R/\rho & \gtrsim & 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} Q'/\Lambda_{\overline{\rm MS}}^{(n_f)} & \gtrsim & 30.8, \\ x' & \gtrsim & 0.35, \end{array}\right.$$

implying $\Omega_{\rm valley}(U^*, \xi^*) \gtrsim -0.5$ which should be reliable

♢ Promising: Try replacing $D(\rho)$ and $I\overline{I}$-interaction Ω by the actual form measured on the lattice! ⇒ **DIS**-cuts may be much relaxed,. . .

4. Rate, Signatures and Searches at HERA

HERA Cross Section, $\sigma^{(I)}_{\rm HERA}$

Upgrade of [Ringwald & F. Sch., Phys. Lett **B438** (1998) 217]

• Known Uncertainties?

◦ Where to place exactly the (Q', x')-cuts? ⇐ Lattice!

$$\mathcal{C}_{\rm std} \equiv \frac{(Q', Q)}{\Lambda_{\overline{\rm MS}}^{(n_f)}} \gtrsim 30.8,\ x' \gtrsim 0.35,\ x_{\rm Bj} \geq 10^{-3},\ 0.1 \leq y_{\rm Bj} \leq 0.9$$

- Strong dependence on $\Lambda_{\overline{\rm MS}}^{(n_f=3)}$? $\Leftarrow$ PDG'98 $\Leftarrow$ PDG'96

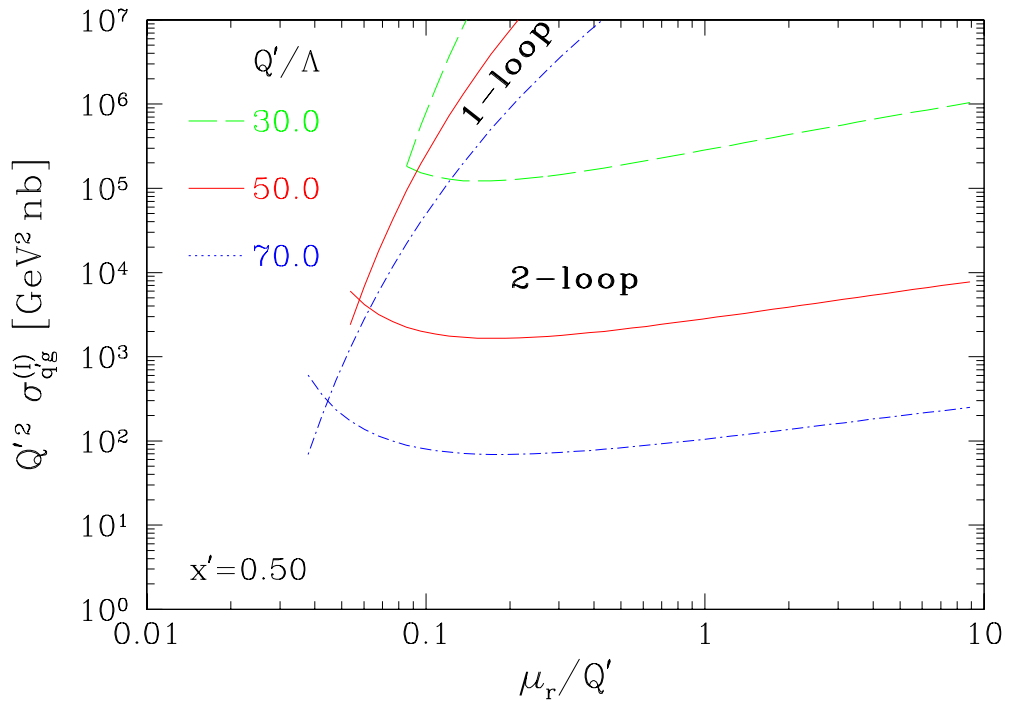
$$\alpha_s(M_Z) = 0.119 \pm 0.002 \quad \overset{3-\text{loop}}{\Leftrightarrow} \quad \Lambda_{\overline{\rm MS}}^{(n_f=5)} = 0.219\,^{+0.025}_{-0.023}\ \text{GeV}$$

with 3-loop flavour-reduction: $\Lambda_{\overline{\rm MS}}^{(n_f=3)} = 0.346\,^{+0.031}_{-0.029}$ GeV,

Much reduced error!

- Mild dependence on renormalization scale μ_r $\Leftarrow$ 2-loop RG-invariance of $D(\rho)$!

Great progess in stability compared to 1-loop (Fig.).



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

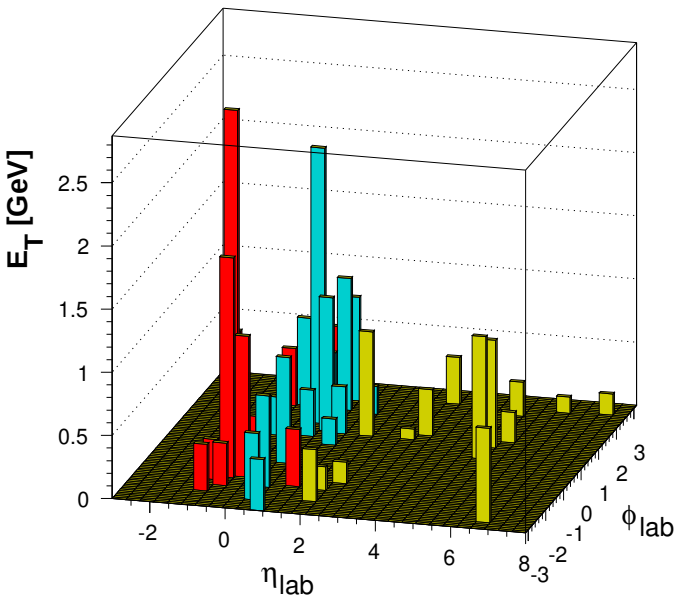
Use as "best scheme": $\mu_r = 0.15\ Q'$: $\partial\sigma^{(I)}_{q'g}/\partial\mu_r \simeq 0.$

- ⇒ Upgraded, I-induced **HERA** cross section:
  $\sigma^{(I)}_{\text{HERA}}(\mathcal{C}_{std}) = 29.2\ ^{+9.9}_{-8.1}$ pb,
  with much reduced known uncertainties!

Characteristic Final-State Signature

Indispensable Tool: QCDINS (2.0)

Monte-Carlo generator for I-induced **DIS**-events:
[Gibbs, Ringwald & F. Sch. '95, Ringwald & F. Sch, '99, to appear, http://www.desy.de/~t00fri/qcdins/qcdins.html]



- current jet
- "band"-region: ⇔
  Isotropic decay of "fireball" ⇒
  $n_f \cdot q + n_f \cdot \overline{q} + \mathcal{O}(\frac{1}{\alpha}) \cdot g =$
  $\mathcal{O}(10)$ partons in I-rest system

  ♢ large total E_t
  ♢ large multiplicity
  ♢ (light) flavour 'democracy':
  ⋆ **strangeness** ⇒ K^0, Λ's
  ♢ No further jets

I-Search Strategies

- Both **H1** and **ZEUS** are currently searching for instanton-induced events!

- Essential Problematics?
  - I-signal expected, where normal **DIS** (pQCD) background is often poorly known: large $n >> \langle n \rangle$, $E_t >> \langle E_t \rangle, \ldots$.
  - Not a question of I-rate!

$$\textbf{H1} \bigoplus \textbf{ZEUS}: \int \mathcal{L} dt = 2\,\mathcal{O}(40)\ \mathrm{pb}^{-1} \Rightarrow$$

$\mathcal{O}(2300)$ I-events from "fiducial region" on tape **!?**

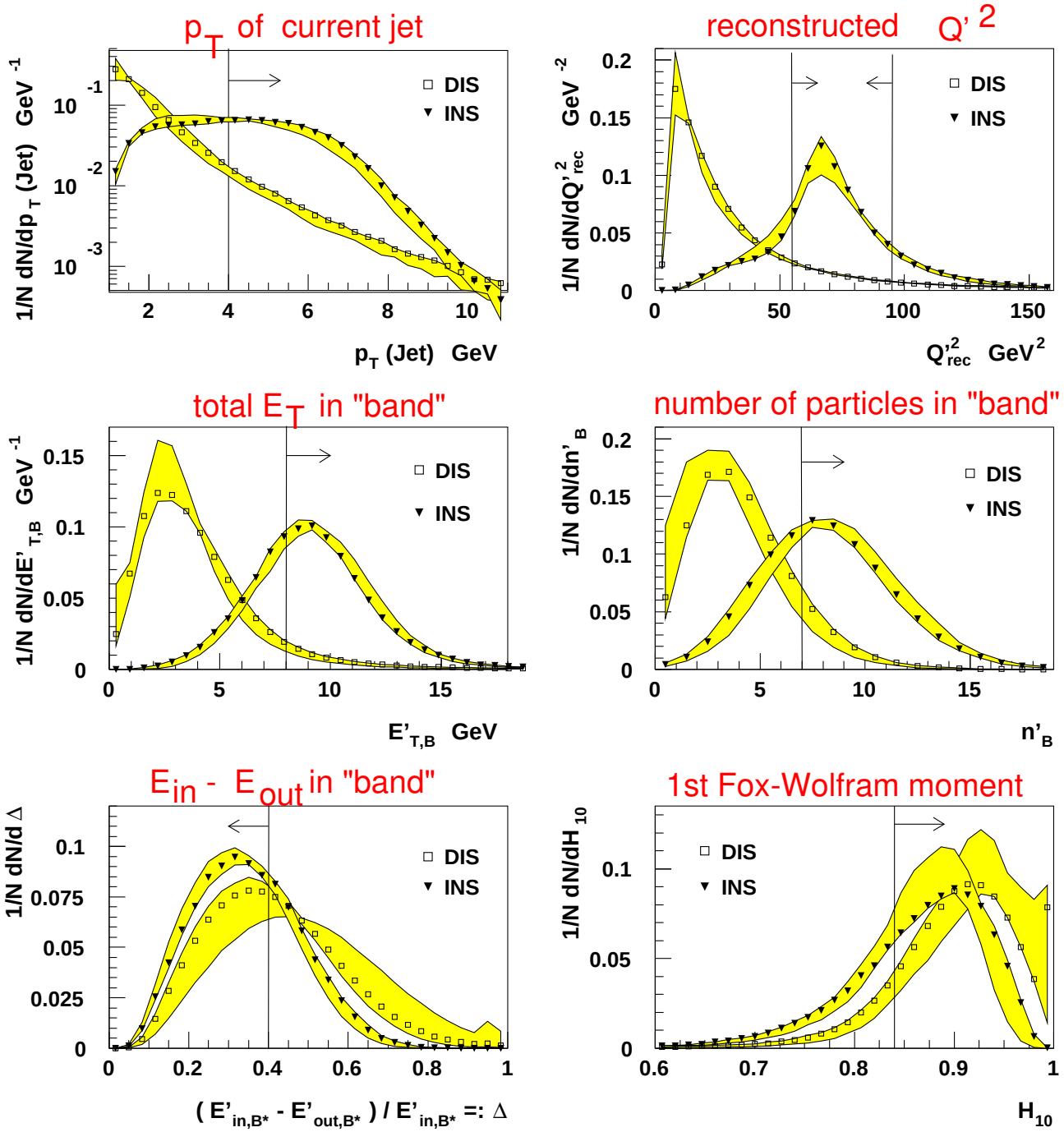
  - No single observable known with sufficient **nDIS** rejection. Hence, dedicated multi-observable analysis required.

- I-Enriched Data Sample

[T. Carli, J. Gerigk, A. Ringwald & F. Sch., hep-ph/9906441
T. Carli, J. Gerigk, B. Koblitz, A. Ringwald & F. Sch., to appear]

  - Goal: Isolate I-enriched data sample by means of optimized cuts to a set of I-sensitive **DIS**-observables.
  - Optimize I-separation power$:=\frac{\mathrm{INS}_{\mathrm{eff}}}{\mathrm{DIS}_{\mathrm{eff}}}$, $\mathrm{INS}_{\mathrm{eff}} \gtrsim 0.1$

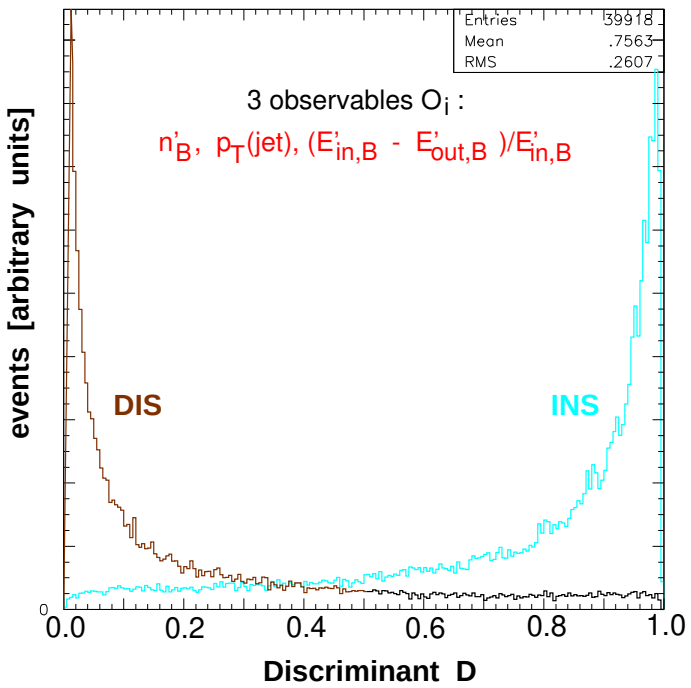
- For **single** observables $\Rightarrow$ separation power $\lesssim \mathcal{O}(20)$
- Set of 6 "best" observables (among ~ 30) enhance I-separation power to $\mathcal{O}(130)$:

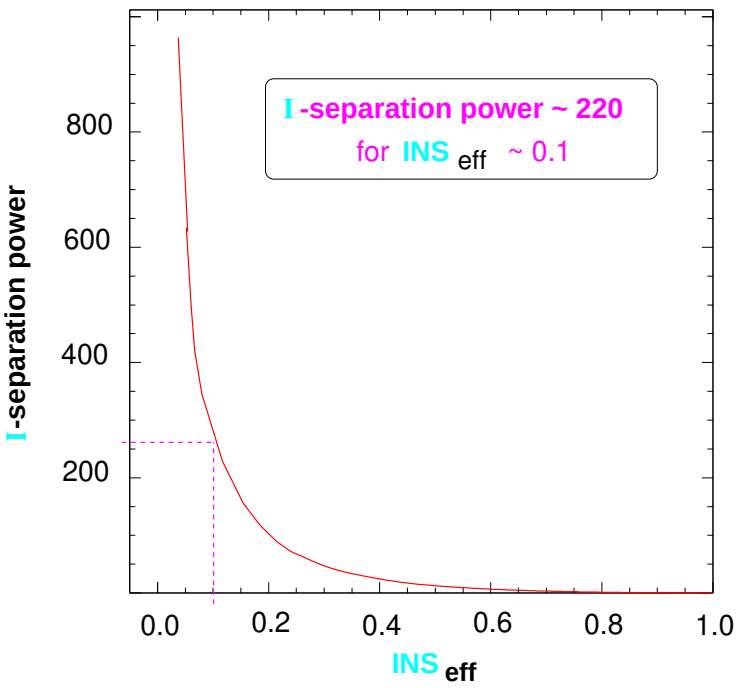


- ***I*-Discriminants, a Better Way?**

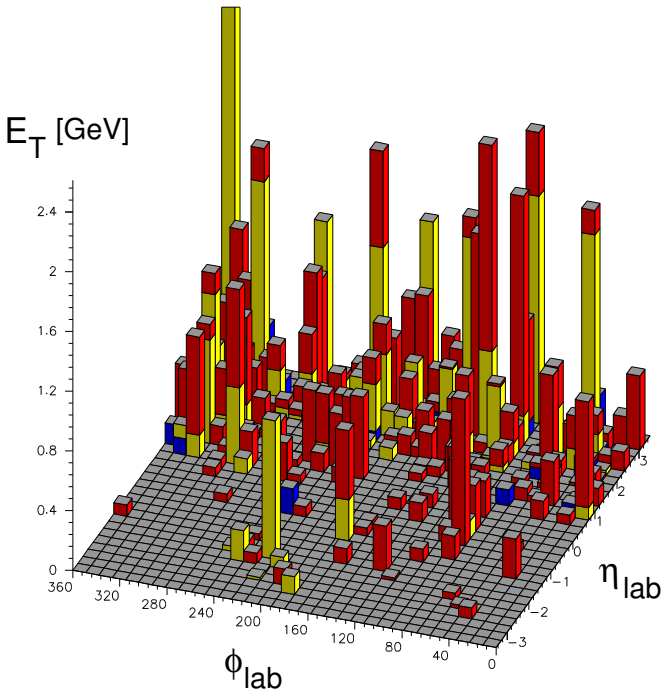
  [suggested by Dave Soper, DIS 99 ; also D0 Collab., hep-ex/9801025
  T. Carli, J. Gerigk, B. Koblitz, A. Ringwald & F. Sch., to appear]

  - **Desirable**: I-discriminating variable, whose distribution peaks if there is an I-signal
  - **Multivariate approach:** Encode each event as a point in n-dim space of ($\sim$ uncorrelated) I-sensitive observables $\vec{O} = [O_1 \ldots O_n]$
  - Map to 1-dim "Discriminant" D, such that background and signal vectors are mapped to $D \sim 0$ and $D \sim 1$, respectively
  - Increase sensitivity, by treating observables $\vec{O}$ collectively rather than cutting on each separately! $\mathrm{INS}_{\mathrm{eff}} \Leftrightarrow$ cut on D.

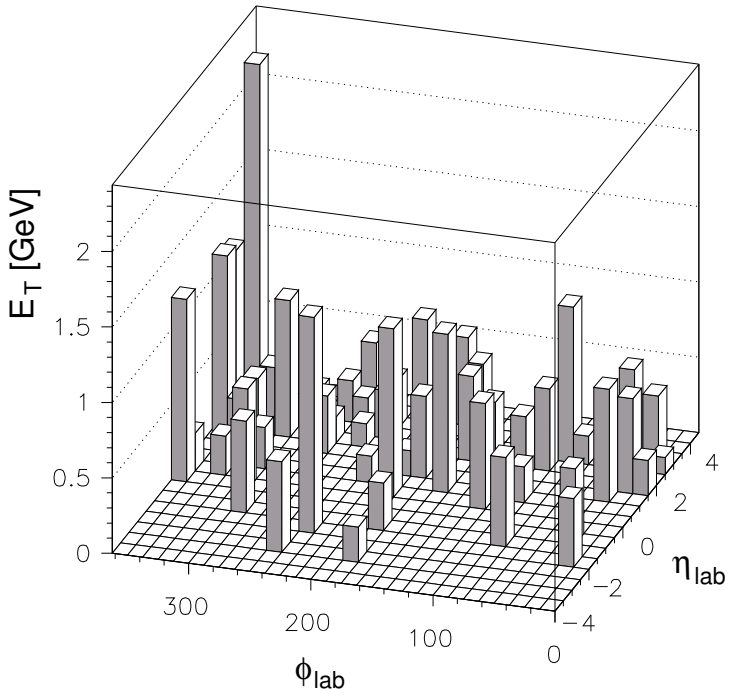




- I-Induced Processes at small Q^2 (Photoproduction)?
  - At small Q^2, a number of spectacular "fireball" events with large $(E_T)_{\text{total}}$ were reported
    [Y. Yamazaki (ZEUS), Durham '98]



ZEUS-home page, DESY



QCDINS

- ♣ Seem to exhibit all characteristics of I-induced processes
- ♣ **ZEUS:** Look for strangeness, muons (from charm)!
  - Analysis still in early stage [PhD Thesis C. Nath (Oxford) '98]
  - Can we extend our calculations to $Q^2 \Rightarrow 0,\ E_t$ large?

5. Conclusions

♢ Topological fluctuations, a basic, non-pert. aspect of QCD

- ⇒ hard, chirality-violating processes, absent in pQCD .
- for **DIS**, rate calculable within "I-perturbation theory"

♢ Our prediction of I-induced rate for **HERA** finalized

♢ Information on crucial building blocks of I-perturbation theory from high-quality QCD lattice results [UKQCD]:

- new scaling variable ($r_{\rm cool}$) for cooled lattice data, helps to extract information on uncooled distributions
- agreement of lattice results with I-perturbation theory very interesting by itself
- lattice⇒ crucial support for our calculation of I-rate in **DIS**, "fiducial" kinematical region. . .

♢ I-Searches at **HERA**

- unique discovery window for I-induced events through their final-state signature and high expected rate $\mathcal{O}(30)$ pb in "fiducial region"
- **H1:** optimized search strategies are being applied to $\mathcal{O}(10^5)$ **DIS** events from 1997 in $x_{\rm Bj} \gtrsim 10^{-3}, y_{\rm Bj} \gtrsim 0.1$.
- **ZEUS:** "fireball" events look "inspiring", under study. . .

We may hope for definite results in the near future!