Tracking QCD Instantons in Deep Inelastic Scattering

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in collaboration with

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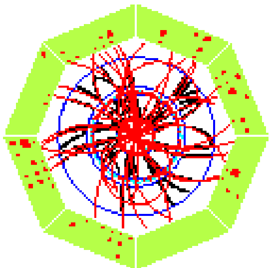


Plan

1. **Instantons**
2. **Instanton-Induced Rate in DIS**
3. **Signals and Searches at HERA**
4. **Conclusions**

Copy available via WWW:

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

– Oxford, June 1st, 1999 –

1. Instantons

Topological Objects in Field Theory

- Perturbative quantum field theory: enormously successful.
  - power expansion (of Feynman path integral) around trivial (vanishing) field configuration, for small coupling
  - fields $\Leftrightarrow$ pointlike, elementary objects (particles).

♣ Classical field equations in

non-linear field theories	non-abelian gauge theories

also exhibit stable, localized solutions with certain **extension in space(-time):**

solitons	vortizes, magnetic monopoles & **instantons**.

♣ **In common:** existence and stability $\Leftrightarrow$

non-trivial **topology** of boundary conditions!

♣ New perturbation theory around such (extended) solutions $\Rightarrow$ insight into important quantum effects outside the usual perturbative expansion.

Instantons in QCD

- **Ground state in QCD ("vacuum"):** "soup" of gluons and quarks, interacting in a complicated non-perturbative manner.

- Consider first: "pure gauge theory": **topology?**

♣ Classically: infinitely many energetically degenerate, but topologically distinct ground states, characterized by

finite action $S = \int d^4x\, \mathcal{L}[A_\mu(x)]$, i.e. $\mathcal{L}[A_\mu(x)] \overset{|x|\to\infty}{\Rightarrow} 0$

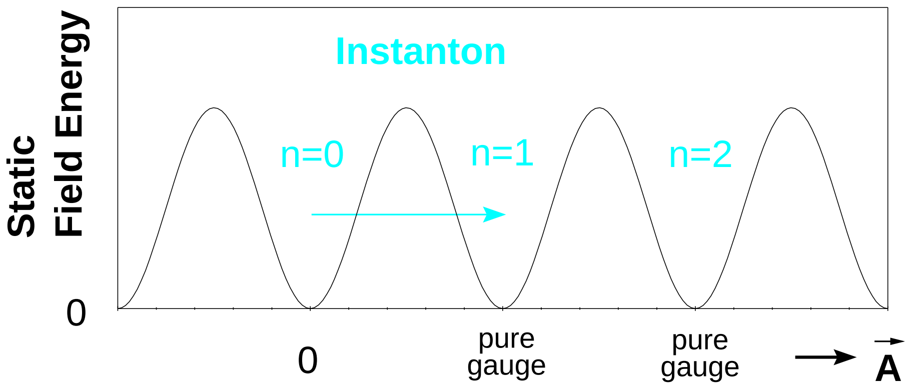
◇ Satisfied by trivial field configuration $\boldsymbol{A_\mu(x) \equiv 0, S = 0}$ ($\Leftarrow$ usual perturbation theory).

◇ Much too restrictive because of local gauge invariance $\Rightarrow$

$$\text{Boundary conditions:} \begin{cases} \vec{A}(x) \overset{|x|\to\infty}{\Rightarrow} -\frac{i}{g} \underbrace{U^{-1}(\vec{x})\nabla U(\vec{x})}_{\text{“pure gauge”}}; \\ A_0(x) = 0 \end{cases}$$

- ("Homotopy"-) classes of mappings: $\{\vec{x}\} \Rightarrow \{U_n(\vec{x})\}$, characterized by integer topological winding number $\boldsymbol{n}$.

- $\Leftrightarrow$ Gauge fields $A_\mu(x)$ carry an integer, conserved topological charge $\boldsymbol{Q}$ ($= n - n_0$)

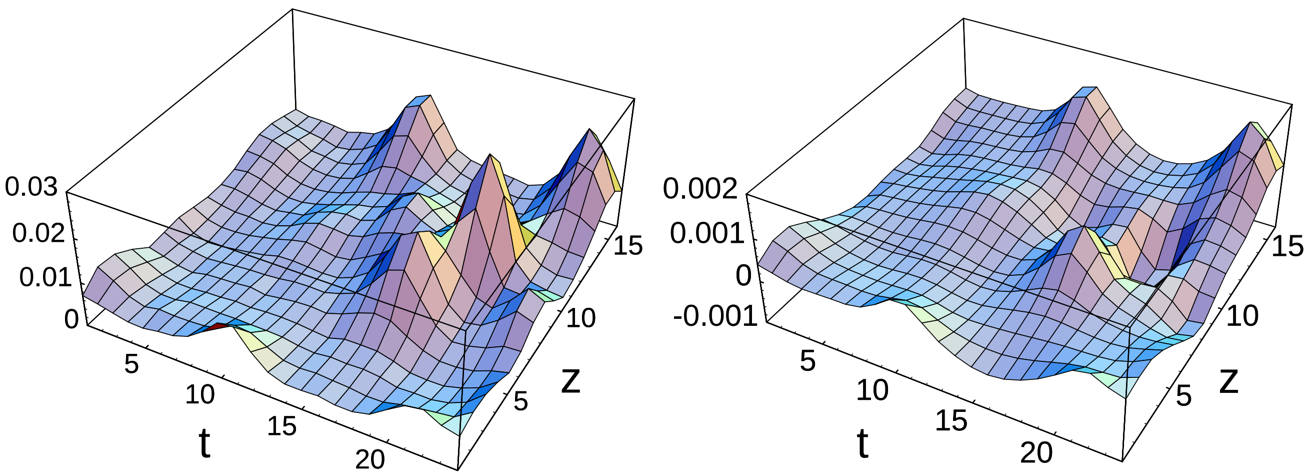


♣ **Instantons (I) and anti-instantons ($\bar{I}$):** [Belavin *et al.* '75, 't Hooft '76]

◇ Tunnelling transitions between neighbouring vacua $n \rightleftharpoons n+1, Q = \Delta n = \pm 1$

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

Lagrange Density **Topological Charge Density**



(Realistic, non-perturbative simulation on the lattice, [Chu *et al.*'94], may see 3 I's and 2 $\bar{I}$'s!)

◇ Explicitely known solutions $A_\mu^{(I)}(x)$ of classical field equations in 4d Euclidean space-time, i.e. for imaginary time,

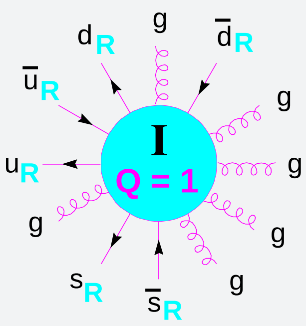
◇ minimizing the action for $\mid Q \mid = 1$: $S[A_\mu^{(I)}(x)] = \frac{2\pi}{\alpha}$.

- Instantons widely believed to play an important rôle in various long-distance aspects of (full) QCD :

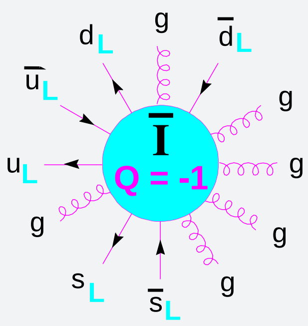
  – famous axial "U(1) problem" (why $m_{\eta'} \gg m_\eta$?)
  – breaking of chiral symmetry [Diakonov '96 (review)]
  – hadron and glueball spectrum [Schaefer, Shuryak '96 (review)]

- Also very important short-distance implications of instantons:

induce processes violating "chirality" $Q_5 = \#(q_\mathrm{R}) - \#(q_\mathrm{L})$ in QCD with ≈ massless quarks

♣ 

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



– 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 ⇐ **HERA !**.

♣ $\boxed{\text{DIS regime at HERA}}$ offers unique discovery window for events induced by QCD -instantons, through

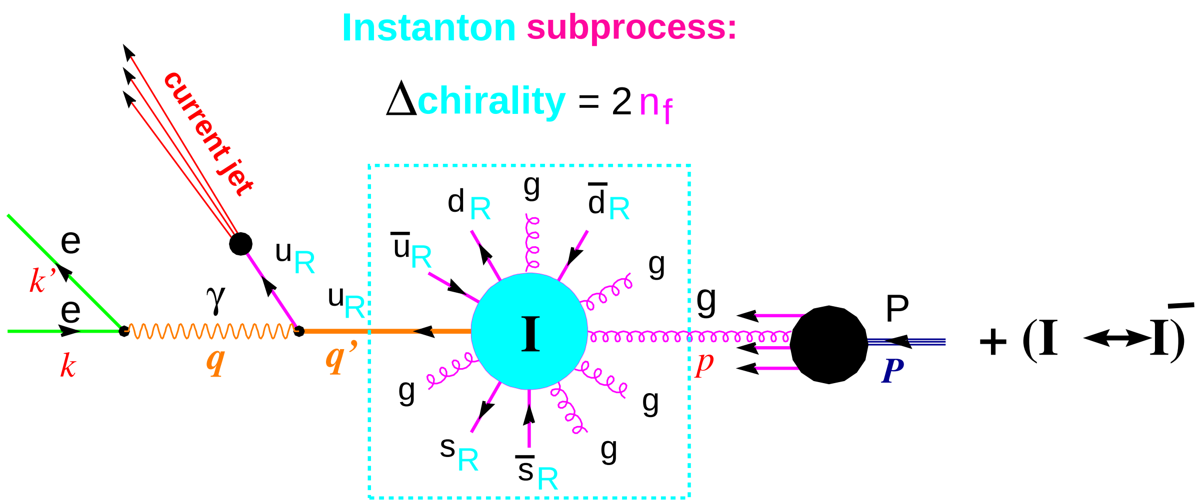
◇ their characteristic final-state signature
[Ringwald & F. Sch. '94 - '99, Carli, Gerigk, Ringwald & F. Sch. '99]

◇ 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]

♣ 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!

2. Instanton-Induced Rate in DIS

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



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

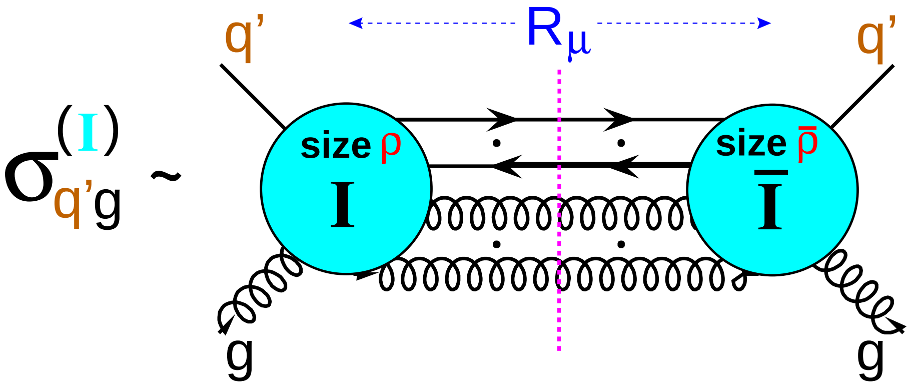
$$\text{large} \quad Q'^2 = -q'^2 > 0; \quad x' = \frac{Q'^2}{2p \cdot q'} \leq 1 \quad \text{fixed}$$

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

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

- Differential luminosity, $d\mathcal{L}^{(I)}_{q'g}$: 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 $\boldsymbol{I}$ and $\overline{\boldsymbol{I}}$- "collective coordinates",

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

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

- Two crucial quantities of $\boldsymbol{I}$-calculus:

$D(\rho) = \boldsymbol{I}$-size distribution, $\Omega\left(U,\frac{R^2}{\rho\overline{\rho}},\frac{\overline{\rho}}{\rho}\right) = I\overline{I}$-interaction

◇ $D(\rho)$ known in I-pert. theory, for $\alpha(\mu_r)\ln(\mu_r\rho) \ll 1$ (μ_r = renormalization scale) ['t Hooft '76, Morris *et al* '85]

◇ Powerlaw behaviour $D(\rho) \propto \rho^{6-2/3n_f+\mathcal{O}(\alpha)}$ generically spoils applicability of I-perturbation theory, since I-size integrals diverge

◇ Exception in **DIS**, where "form factor" $\exp(-Q'(\rho+\overline{\rho}))$ insures $\rho, \overline{\rho} \lesssim 1/Q'$

◇ $\Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$ $\left\{ \begin{array}{l} \text{known as series for } R^2/\rho\overline{\rho} \gg 1 \\ \text{analytically known within "}I\overline{I}\text{-valley" approximation [Yung '88, Khoze \& Ringwald '91, Verbaarschot '91]} \end{array} \right.$

♣ Independent, non-perturbative information on $D(\rho)$ and $\Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$ from recent **lattice** simulations!

- Crucial saddle-point correspondence : **DIS** var's (x', Q') in **one-to-one** relation to effective I-coordinates (R^*, ρ^*)

$$\rho^* = \overline{\rho}^* \sim \frac{4\pi}{\alpha\, Q'} \qquad \frac{R^*}{\rho^*} \sim 2\sqrt{\frac{x'}{1-x'}}$$

- **Lattice** constraints $\Rightarrow$ "fiducial" (x', Q') region in **DIS**!

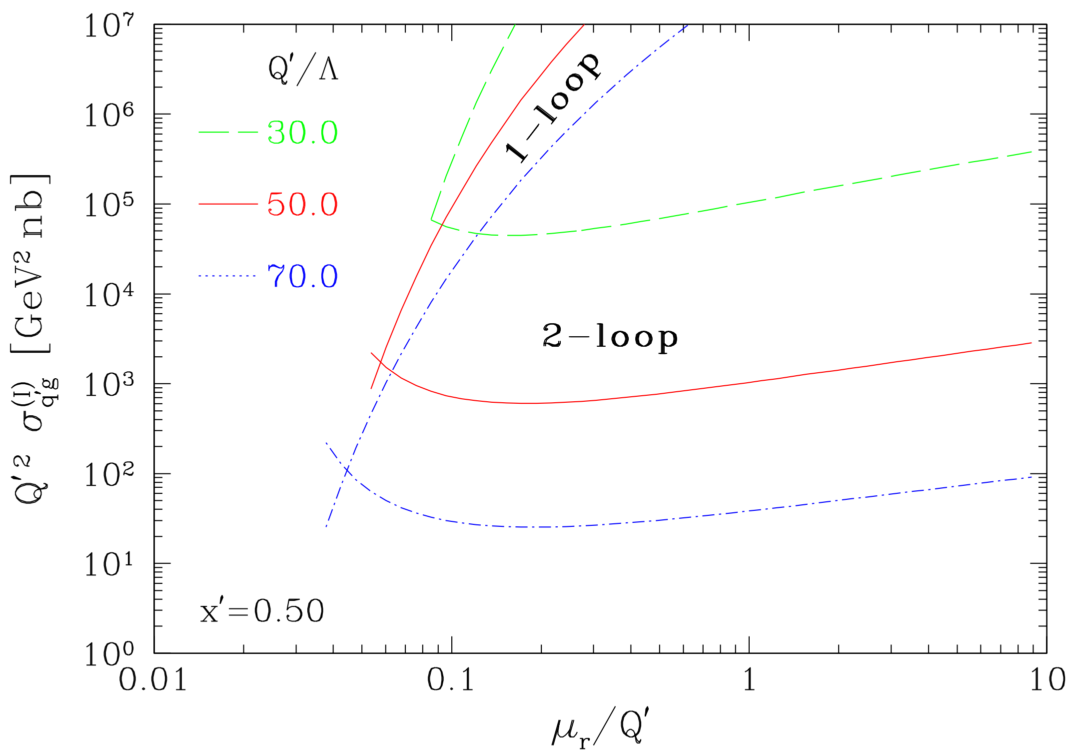
Resulting $q'g$ cross-section

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

- Great progress in stability, i.e. predictivity by using 2-loop RG invariant form of I-size distribution $D(\rho)$, i.e.

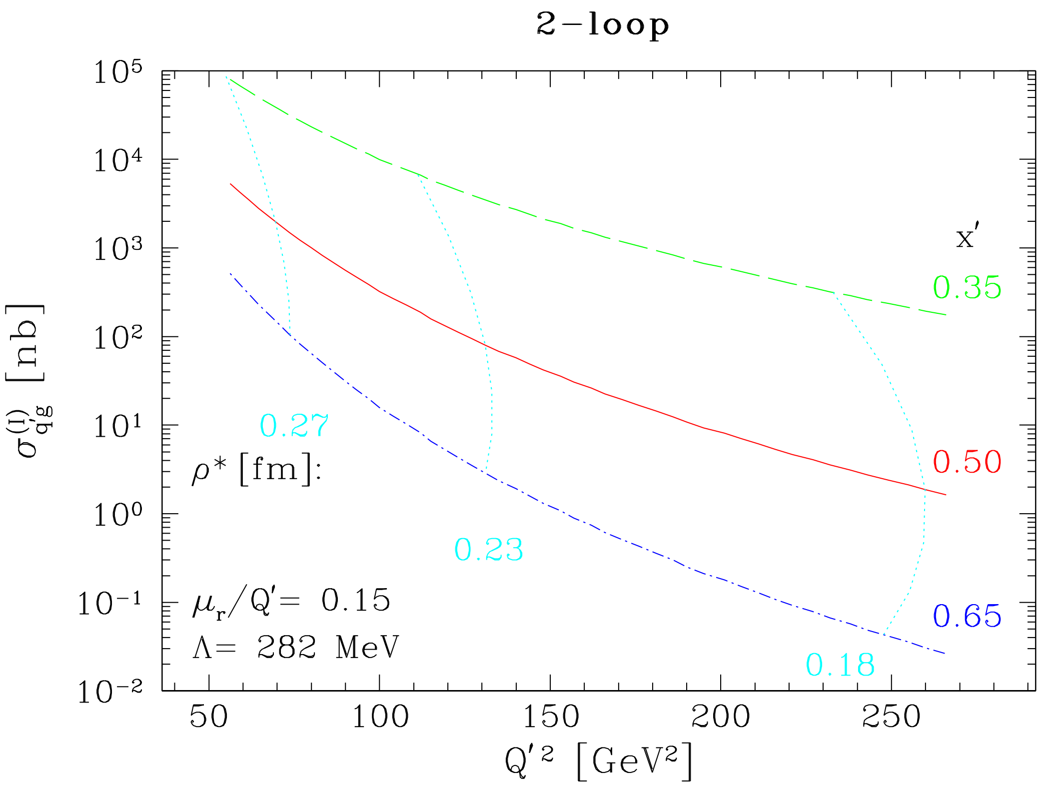
$$\frac{1}{D}\frac{dD}{d\mu_r} = \mathcal{O}({\alpha_s}^2) \quad \text{[Morris, D. Ross, Sachrajda, '85]}$$

$\Rightarrow$ residual dependence on μ_r strongly reduced!

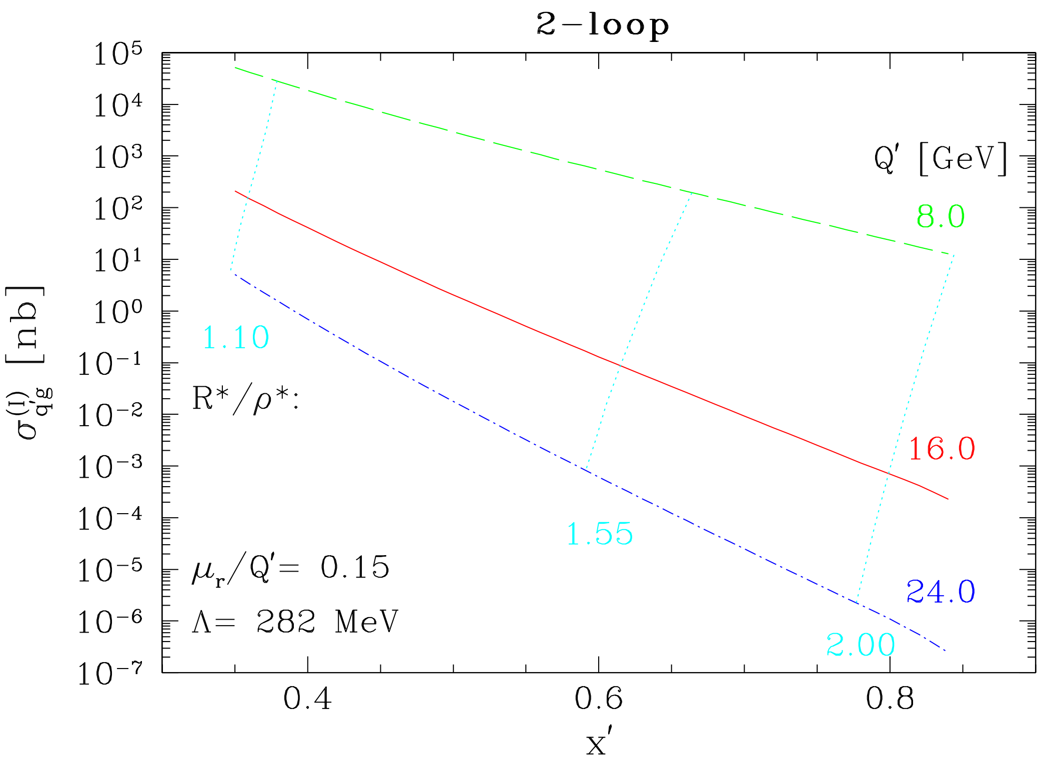


- Expect μ_r in regime: $\mu_r \sim \frac{1}{\langle\rho\rangle} \simeq \frac{1}{\beta_0} Q' = \mathcal{O}(0.1) Q'$

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



- Q'^2 probes I-size: $\sigma^{(I)}_{q'g} \sim D(\rho^*)^2 \sim (1/Q'^2)^{6-2/3n_f}$



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

“Fiducial” (x', Q') Region from Lattice Simulations

[Ringwald & F. Sch., Phys. Lett. **B 438** (1998) 217, hep-lat/9903039 to appear in Phys. Lett. **B**]

- Exploit recent high-quality **lattice** simulation of $\mathrm{QCD}_{\,\mathrm{n_f}=0}$ [UKQCD, Smith & Teper, ‘98,. . .] $\Rightarrow$ Crucial information on range of validity of our **DIS** predictions

- c. f. talk tomorrow. . . , here only brief summary

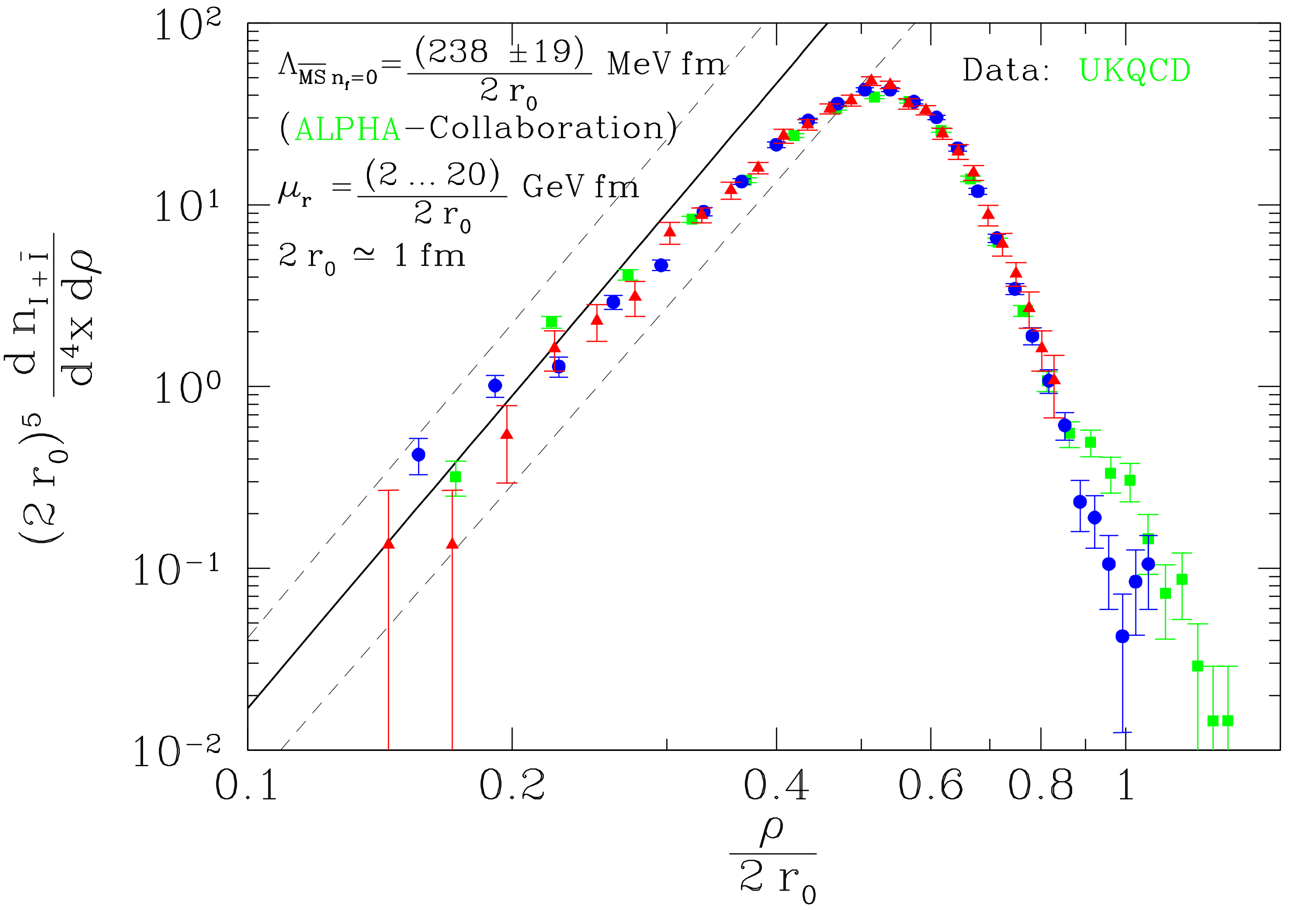
- **Lattice:** “Snapshots” of QCD -vacuum in space-time, including all non-perturbative, topol. features like instantons!

♣ $\boxed{\text{Link between } I\text{-observables in DIS and in the QCD vacuum } (\Leftarrow \text{lattice}): D(\rho) \text{ and } \Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)}$

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

- Perform continuum limit of relevant UKQCD “data”, account for cooling effects, convert to physical units via: “Sommer scale” $2r_0 \simeq 1$ fm . . . [Ringwald, F. Sch., ‘98, ‘99]

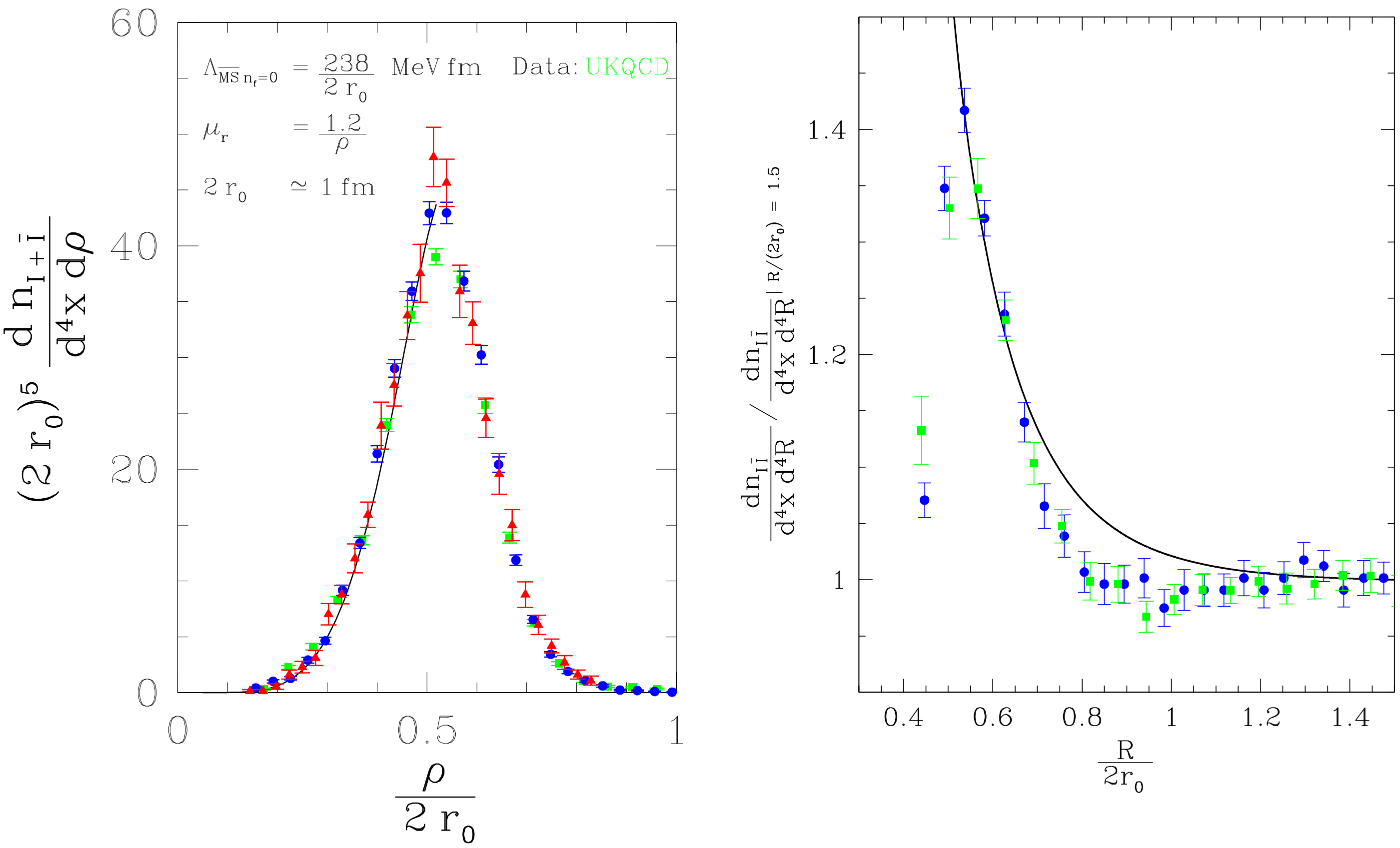
♣ $$(2r_0)^5 \frac{d\, n_{I+\bar{I}}}{d^4x\, d\rho}\Big|_{\rm UKQCD} \overset{?}{\simeq} 2\, D(\rho)\big|_{I-\text{perturbation theory}}$$



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

for $\rho \lesssim 0.3$ fm

- Error band ⇔ error of $2r_0\Lambda_{\overline{\rm MS}\, n_f=0} = (238 \pm 19)$ MeV fm [ALPHA-Collaboration, Nucl. Phys. **B544** '99]
- Almost independent of μ_r for large range $2 \lesssim \mu_r \lesssim 20$ GeV.
- **Improved choice:** $\mu_r\rho = \mathcal{O}(1)$, to minimize $\ln(\mu_r\rho)$-corrections ⇒ **agreement** up to the peak, $\rho \lesssim 0.5$ fm (Fig.)!



- First direct test of $I\overline{I}$-valley form for $I\overline{I}$-interaction Ω via distance distribution of $I\overline{I}$-pairs $\Leftarrow$[UKQCD, Smith & Teper, '98]

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

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

- Substitute $D(\rho)$ by fit of lattice data, $\alpha = \alpha_{\overline{\mathrm{MS}}}(\frac{\mathcal{O}(1)}{\sqrt{\rho\overline{\rho}}})$

- Good **agreement** for $R \gtrsim 0.5$ fm, i. e. $R/\rho \gtrsim 1$ (Fig.)

♣ In summary:

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

◇ Lattice constraints translate into "fiducial" kinem. region

in **DIS**: $$\left.\begin{array}{lcl} \rho & \lesssim & 0.3\ \mathrm{fm} \\ R/\rho & \gtrsim & 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} Q' & \gtrsim & 8\ \mathrm{GeV} \\ x' & \gtrsim & 0.35. \end{array}\right.$$

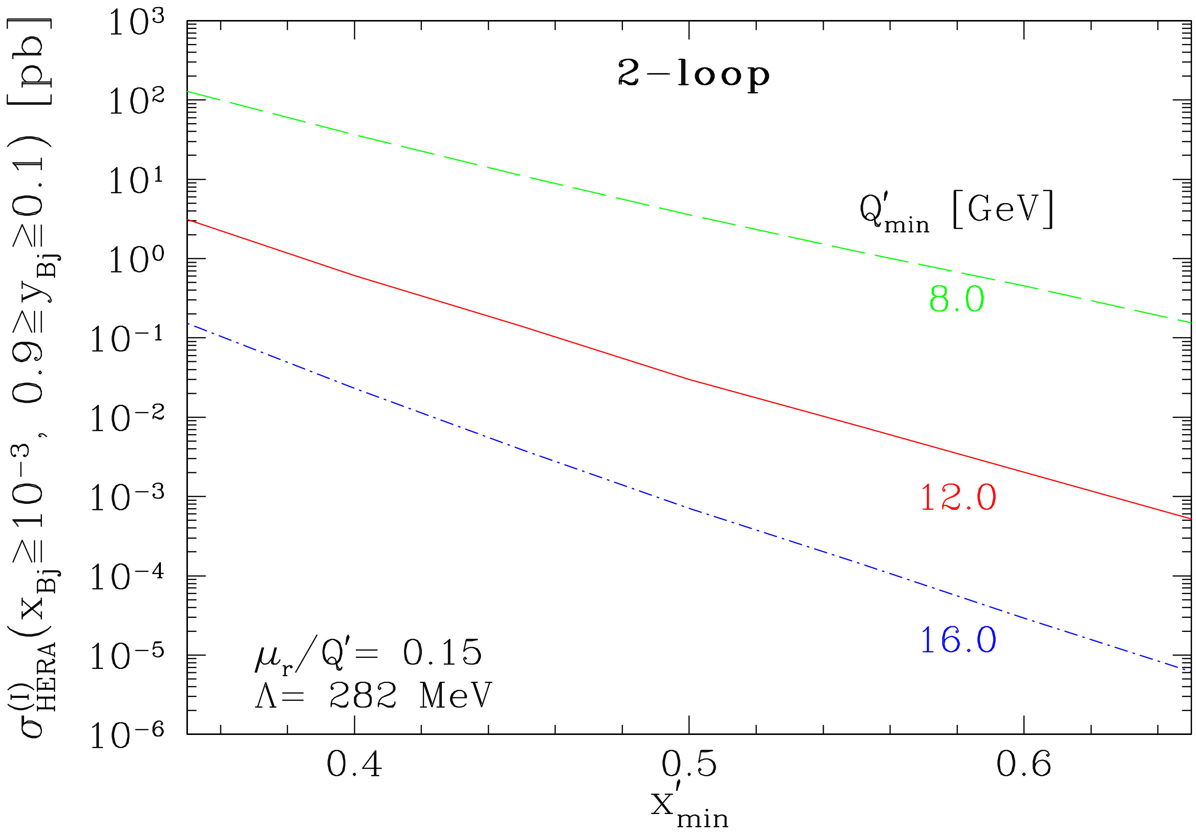
◇ Promising: Try replacing $D(\rho)$ and $I\bar{I}$-interaction Ω by the actual form measured on the lattice! $\Rightarrow$ **DIS**-cuts may be much relaxed, high-E_T fireballs in photoproduction. . .

HERA Cross-Section

Uncertainties?

- In principle **dominant**: Where to place exactly the (x', Q') cuts such that I-perturbation theory holds?

◇ I-induced cross-section at **HERA**, steep function of (x', Q') cuts (Fig.):



◇ Great improvement due to **UKQCD lattice** results!

◇ $\Rightarrow$ "Standard" cuts (**lattice!**):

$$\mathcal{C}_{\rm std} \equiv x' \geq 0.35, Q' \geq 8 \text{ GeV}\,, x_{\rm Bj} \geq 10^{-3}, 0.1 \leq y_{\rm Bj} \leq 0.9.$$

- $\boxed{\Lambda^{(3)}_{\overline{\rm MS}} = (282 \pm 65)\text{ MeV} \;\; \Rightarrow \sigma^{(I)}{}_{\rm HERA}(\mathcal{C}_{\rm std}) \simeq \mathbf{126}^{+300}_{-100}\text{ pb}}$

- μ_f and μ_r dependencies comparatively small.

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

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

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

$\mathcal{O}(10^4)$ I-induced events on tape **!?**

3. Signatures and Searches at HERA

QCDINS

♣ Important tool: "QCDINS 1.6.0" [anon. ftp: theopc3.desy.de]

Monte-Carlo generator for I-induced **DIS**-events

[Gibbs, Ringwald & F. Sch. '95; Ringwald & F. Sch. to appear]

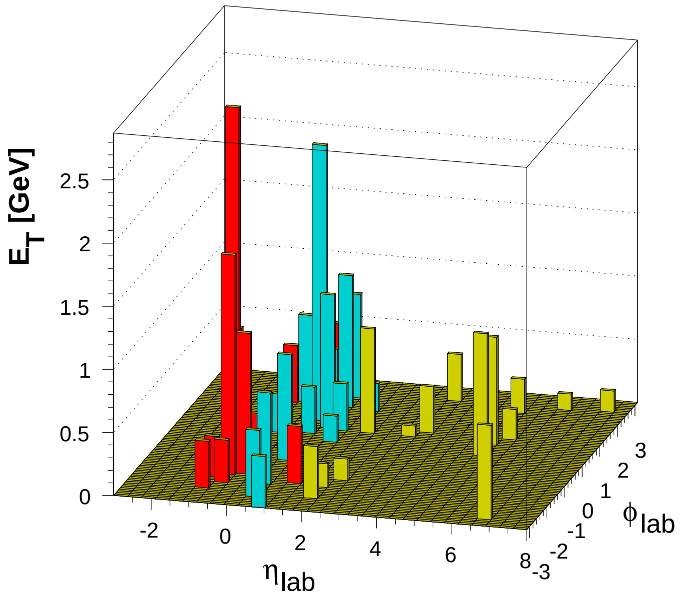
◇ I-induced hard subprocess with essential characteristics derived theoretically:

- isotropic production of partonic final state in CMS of I-subprocess ("fireball")
- flavour "democracy"
- energy weight factors different for quarks and gluons
- large $\langle n_{q+g} \rangle = 2n_f + \mathcal{O}(\frac{1}{\alpha_s}) \gtrsim 10$
- (approximate) Poisson distribution of gluon multiplicity

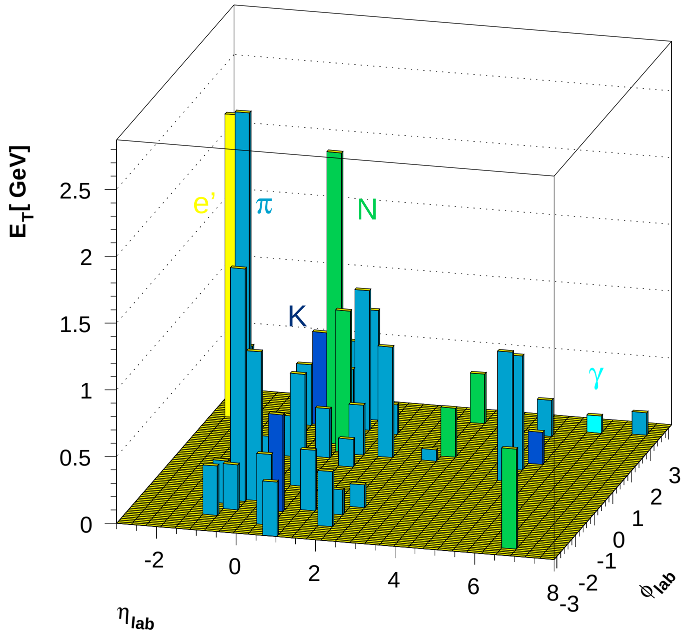
◇ Leading-log parton shower & hadronization (default: **HERWIG 5.9**, optional: **JETSET**)

Characteristic Final-State Signature

Characteristics



Particle Composition



- current jet

- "band"-region $\Leftrightarrow$ **isotropic** production of partonic **"fireball"** in $\boldsymbol{I}$-rest system

  ◇ large total E_t

  ◇ large multiplicity

  ◇ (light) flavour "democracy": ⋆ **strangeness** $\Rightarrow \begin{cases} K's \\ \Lambda's \end{cases}$

  ◇ no further jets

Search Strategies and Model Dependencies

[T. Carli, J. Gerigk, A. Ringwald, F. Sch., '99]

♣ Goals and Questions:

⇒ A) Isolate I-enriched data sample by means of cuts to a set of observables. Optimize separation power:$=\frac{INS_{\rm eff}}{DIS_{\rm eff}}$

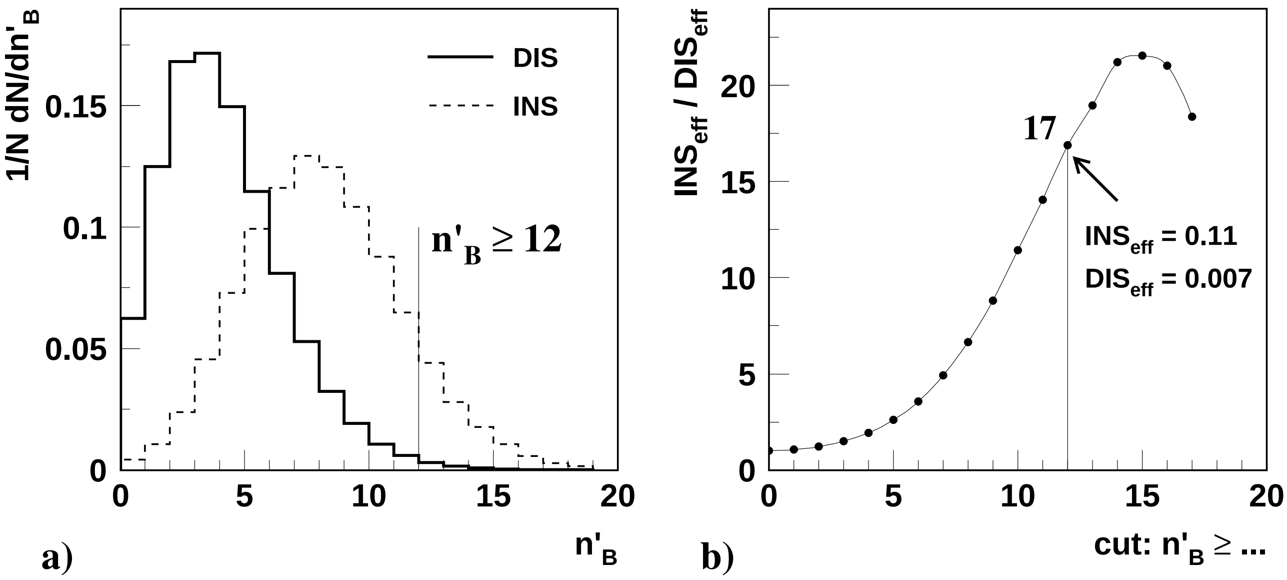
⇒ B) Dependencies on MC models, both for INS and DIS events

C) How to reconstruct Bjorken variables (x', Q')?

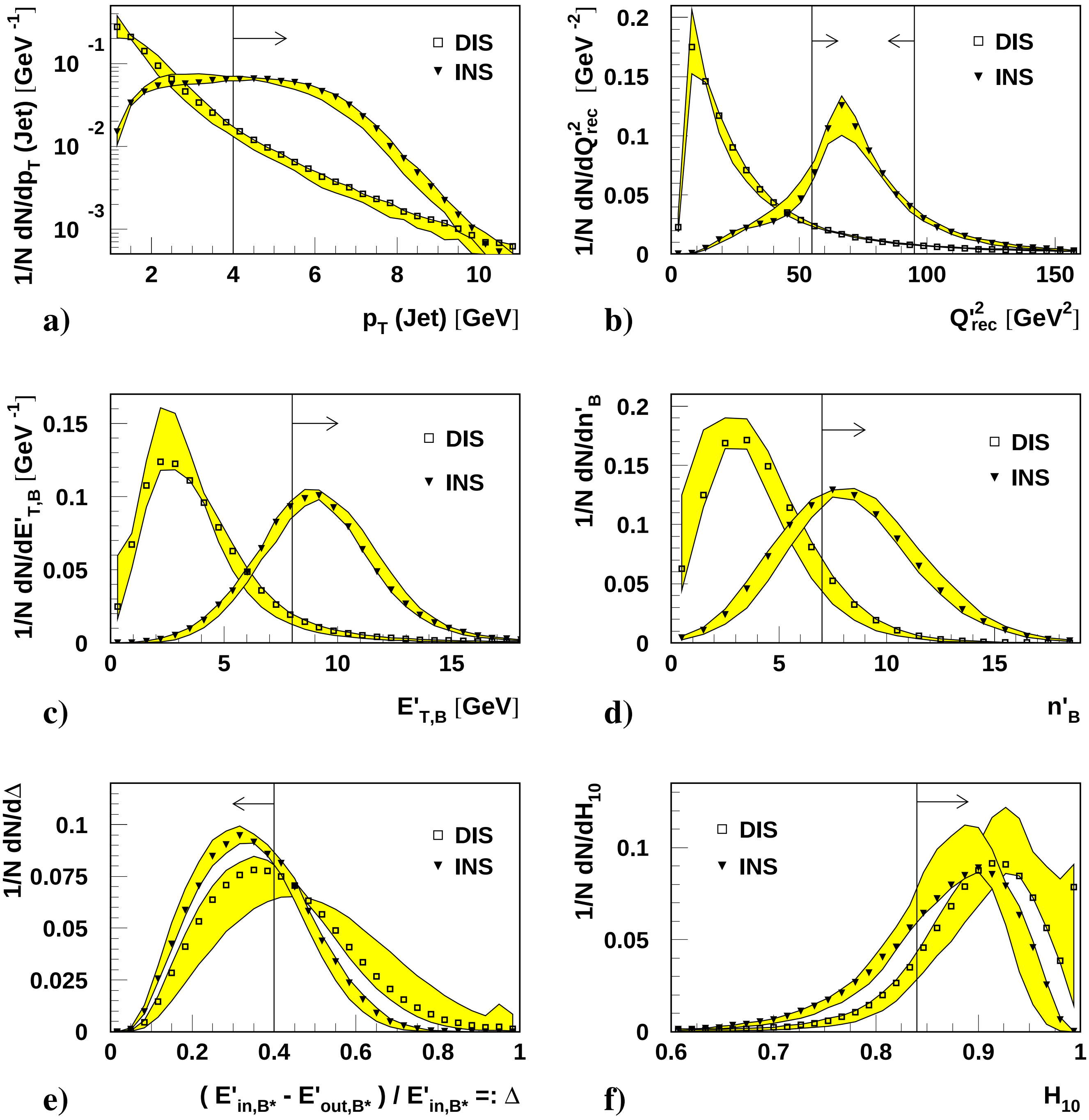
(A) I-enriched data sample: $(\ INS_{\rm eff} \gtrsim 10\%)$

(B ↔ from "band", $'$ ↔ without hadrons from current jet)

- For **single** observables ⇒ separation power $\lesssim \mathcal{O}(20)$



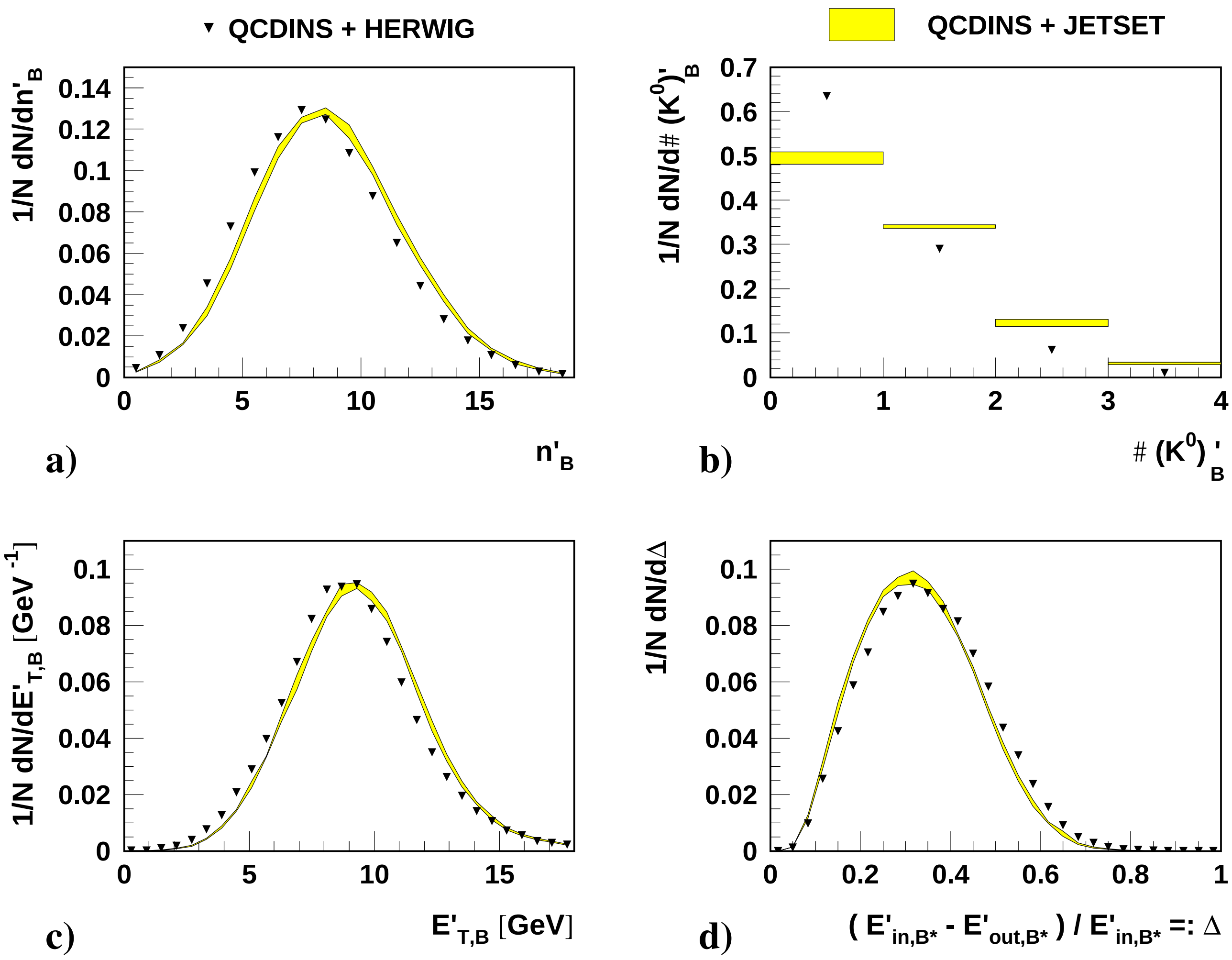
- Set of 6 "best" observables (among ~ 30) enhance $\boldsymbol{I}$-separation power to $\mathcal{O}(130)$:



(B) MC model dependencies:

- **QCDINS**: HERWIG (default)$\Rightarrow$ JETSET[1]

- **Altogether**: Only weak dependence of I-induced final state on MC model chosen for hadronization!



- **DIS**: ARIADNE$_{\oplus\text{Pomeron}}$ (default) $\Rightarrow$ LEPTO, HERWIG

[1]thanks to Hannes Jung!

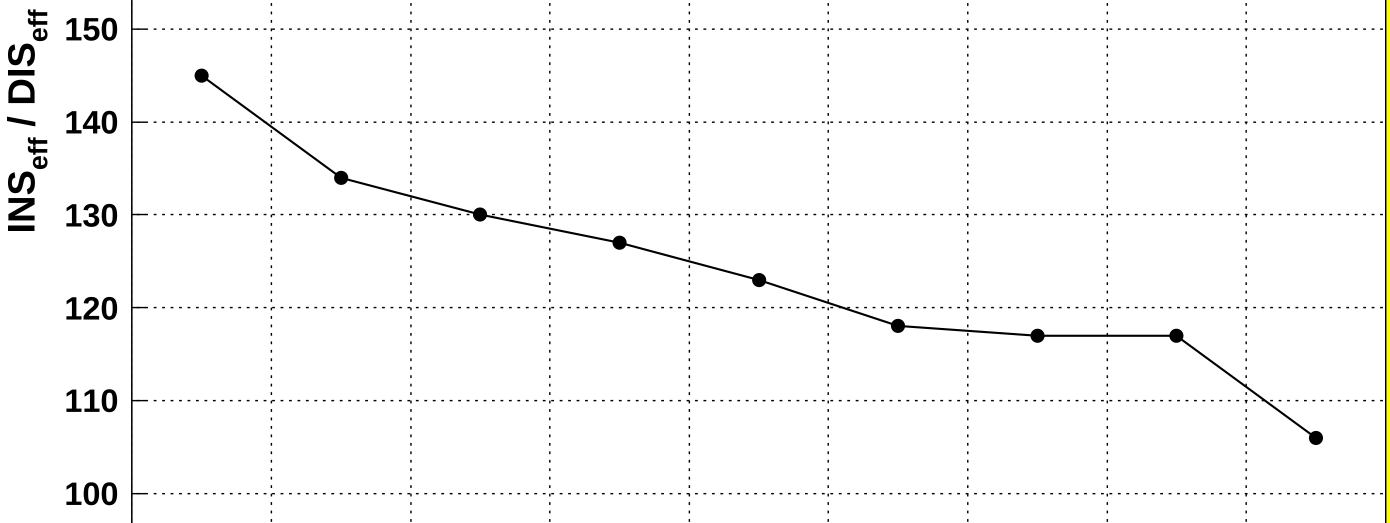
- Vary **INS**, **DIS** = default

Cuts:

$55\ \mathrm{GeV}^2 < Q'^2_{rec} < 95\ \mathrm{GeV}^2$	p_T (Jet) > 4 GeV	$E'_{T,B} > 8$ GeV
$(E'_{in,B^*} - E'_{out,B^*}) / E'_{in,B^*} < 0.4$	$H_{10} > 0.84$	$n'_B \geq 7$

DIS = ARIADNE (with Pomeron, default)

INS = QCDINS + ...



	HERWIG (Λ 217)	HERWIG (MRSH)	HERWIG (tuned, default)	JETSET (Aleph)	HERWIG (not tuned)	JETSET (Delphi)	JETSET (default)	HERWIG (Λ 347)	JETSET (L3)
INS_{eff} =	0.116	0.108	0.104	0.102	0.098	0.094	0.093	0.093	0.086
DIS_{eff} =	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008
N_{INS} =	141	672	669	654	636	606	600	1927	553
N_{DIS} =	1814	1814	1814	1814	1814	1814	1814	1814	1814

- Event numbers for $\int \mathcal{L} dt = 30\ \mathrm{pb}^{-1}$

- Vary **DIS**, **INS** = default

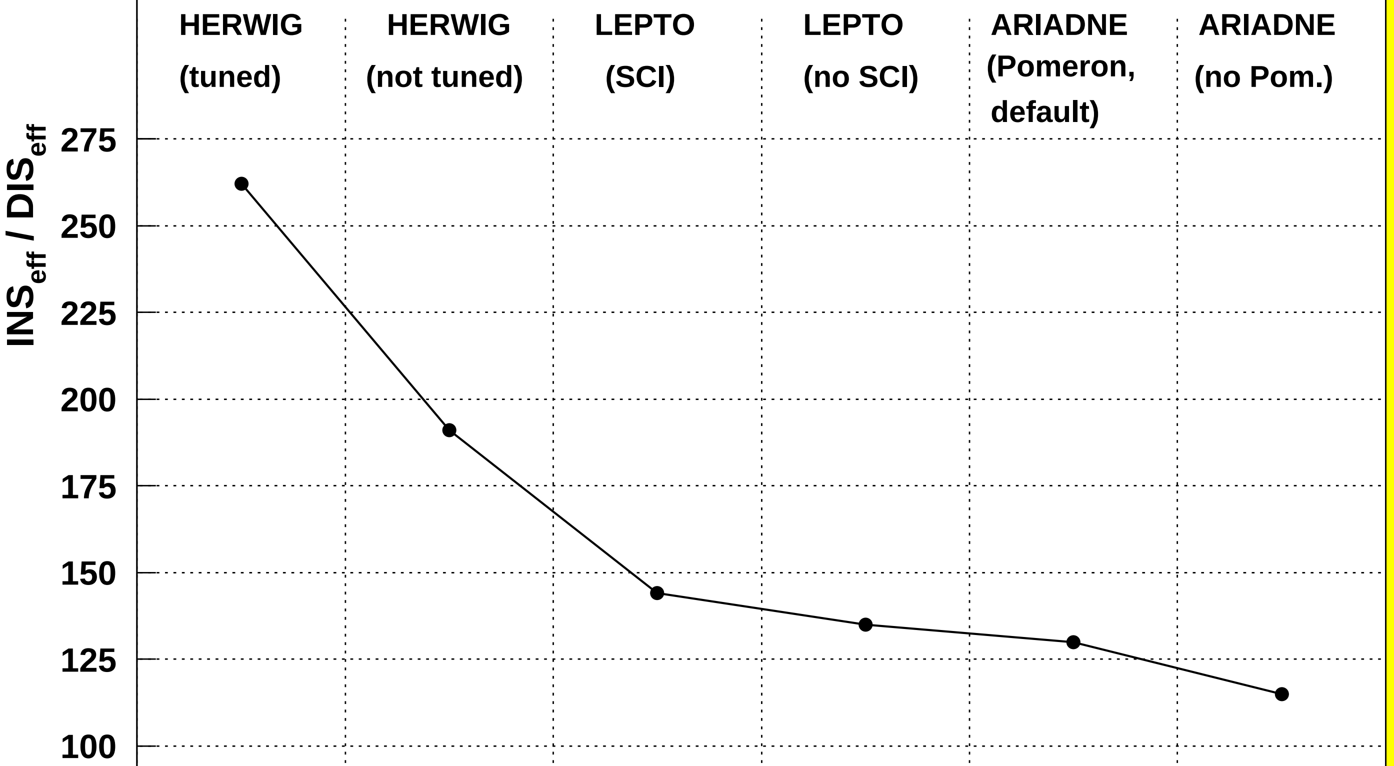
Cuts:

55 GeV^2 $< Q'^2_{rec} <$ 95 GeV^2 $\quad$ p_T (Jet) $>$ 4 GeV $\quad$ $E'_{T,B} > 8$ GeV

$(E'_{in,B*} - E'_{out,B*}) / E'_{in,B*} < 0.4$ $\quad$ $H_{10} > 0.84$ $\quad$ $n'_B \geq 7$

INS = QCDINS + HERWIG tuned (default)

DIS = ...



	HERWIG (tuned)	HERWIG (not tuned)	LEPTO (SCI)	LEPTO (no SCI)	ARIADNE (Pomeron, default)	ARIADNE (no Pom.)
INS_{eff} =	0.104	0.104	0.104	0.104	0.104	0.104
DIS_{eff} =	0.0004	0.0005	0.0007	0.0008	0.0008	0.0009
N_{INS} =	669	669	669	669	669	669
N_{DIS} =	930	1235	1713	1815	1814	2025

- Event numbers for $\int \mathcal{L} dt = 30 \text{ pb}^{-1}$

♣ In summary:

◇ Set of 6 observables with good $\boldsymbol{I}$-separation power (≈ 130)

◇ **INS**: Within "bandwidth" studied, surprisingly small systematics from varying the modelling of $\boldsymbol{I}$-induced events

◇ **DIS**: Quite strongly dependent on MC $\oplus$ parameters. Better understanding of the tails of distributions for normal DIS events quite important!

$\boldsymbol{I}$-Discriminants, a Better Way? (in progress)

[suggested by Dave Soper, DIS 99 ; also D0 Collab., hep-ex/9801025]

- n ($\sim$ uncorrelated) $\boldsymbol{I}$-sensitive observables $\vec{O} = [O_1 \ldots O_n]$

- **Desirable**:

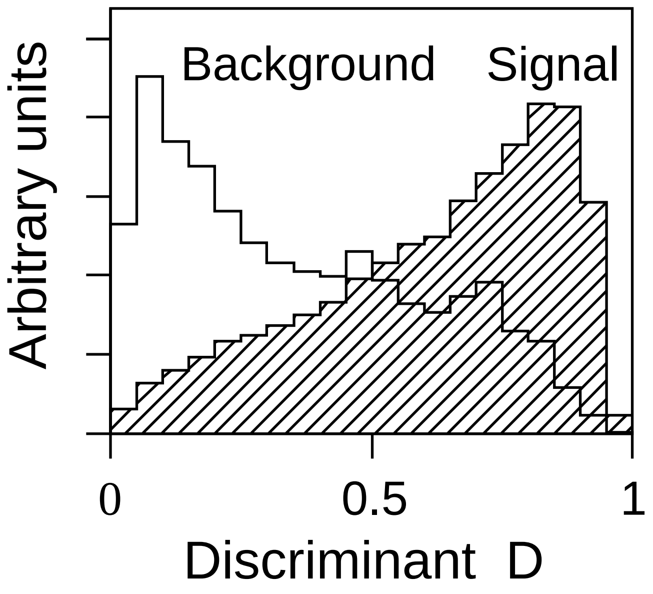
  $\boldsymbol{I}$-discriminating variable, that peaks if there is an $\boldsymbol{I}$-signal

- Increase sensitivity, by treating observables $\vec{O}$ collectively rather than cutting on each separately!

- Conceptually related to neural-network filters, that also look promising. . . [MPI, Munich]

- Let $s_i(O_i)$ and $b_i(O_i)$ be norm. distributions of O_i for signal and background, respectively

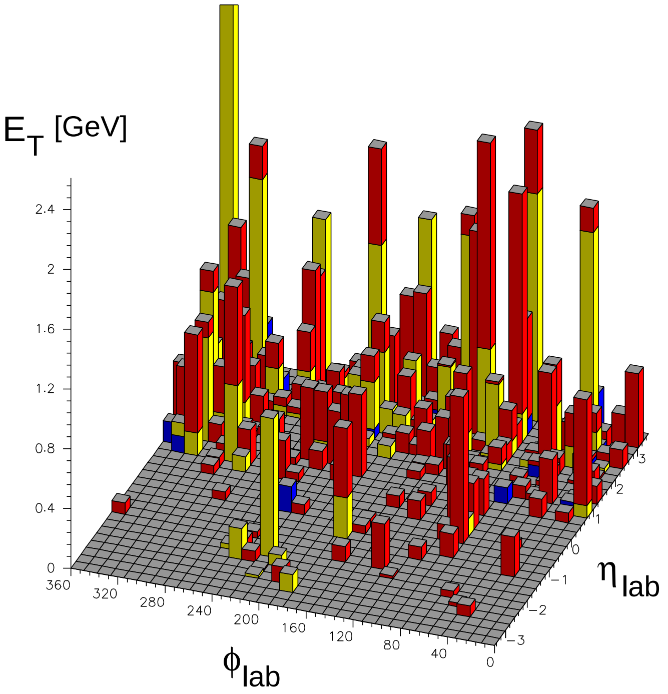
$$
\begin{aligned}
D &\equiv \frac{f_s(\vec{O})}{f_s(\vec{O}) + f_b(\vec{O})} \\
f_s(\vec{O}) &\equiv \prod_{i=1}^{n} s_i^{w_i}(O_i) \\
f_b(\vec{O}) &\equiv \prod_{i=1}^{n} b_i^{w_i}(O_i)
\end{aligned}
$$

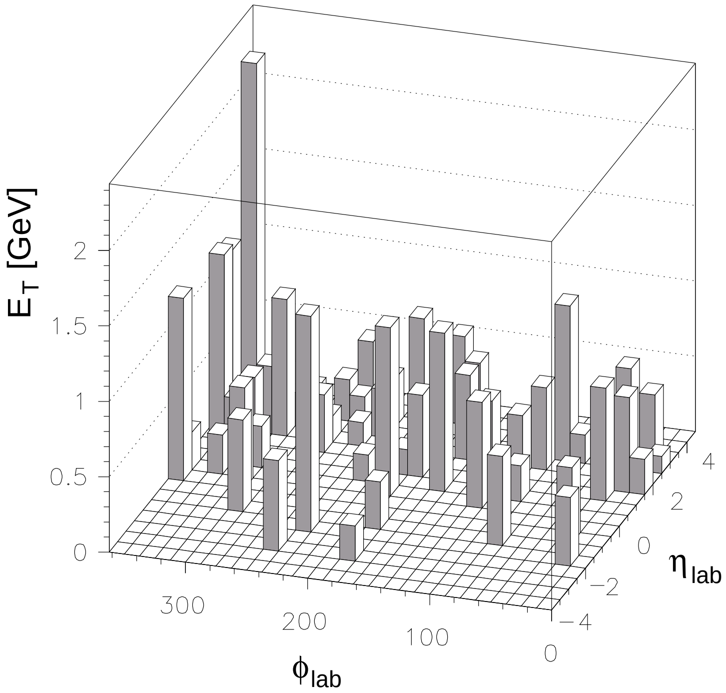


likelihood function if no correlation & $w_i \equiv 1$. Adjust w_i to nullify correlations

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

- Number of spectacular "fireball" events with large $(E_T)_{\rm total}$ observed by **ZEUS** at small Q^2





♣ Seem to exhibit all characteristics of I-induced processes

- Analysis just startet [PhD Thesis C. Nath (Oxford) ‘98]

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

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

4. Conclusions

- Instantons, a basic non-perturbative feature of QCD

- Calculations of I-induced rate at **HERA** based on "I-perturbation theory" and "dilute" I-gas picture finalized

  $\Rightarrow$ high rate of $\mathcal{O}(100)$ pb with substantial uncertainties.

- **UKQCD lattice** results strongly help to reduce uncertainties in DIS $\Rightarrow$ "fiducial" (x', Q') region

- DIS at **HERA** offers unique window to detect I-induced events through their multi-particle final-state signature

  – experimental limits not far from theoretical predictions
  – optimized search strategies under study
  – better understanding of tails of nDIS distributions quite important

- "Monster" fireball-events in photoproduction look exciting, what about hadron colliders?...

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