QCD - Instantons
in
Deep Inelastic Scattering

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1. **Introduction**
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– DIS 2000, Liverpool, April 25-30, 2000 –

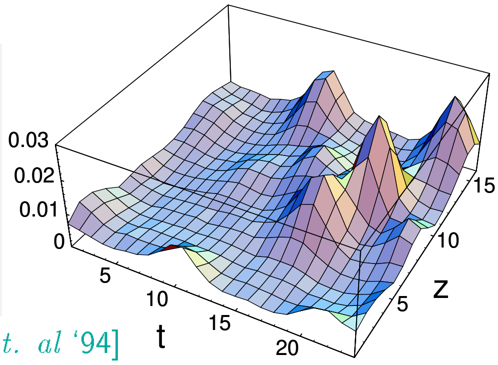
1. Introduction

- **Instantons:** a basic aspect of QCD
  [Belavin *et al* '75, 't Hooft '76]

Non-perturbative fluctuations of gauge fields with typical size $\langle \rho \rangle \approx 0.5$ fm

"instantaneous" in time and space

Lagrange Density



[Chu *et. al* '94]

- **Theoretically:** Play an important rôle in interface region between partonic and hadronic description of strong int's.

- Direct experimental evidence of instantons lacking until now!

♣ However,. . . [A. Ringwald & F. Sch. '94 - '00]
Characteristic short distance manifestation of instantons may be exploited for experimental search:

◇ I's induce hard processes forbidden in usual perturbative QCD since the latter conserves "chirality" $= \#(q_{\rm R}) - \#(q_{\rm L})$

◇ Theoretical prediction of rate and characteristic event signature possible in **DIS**

◇ Rate in measurable range at **HERA**!

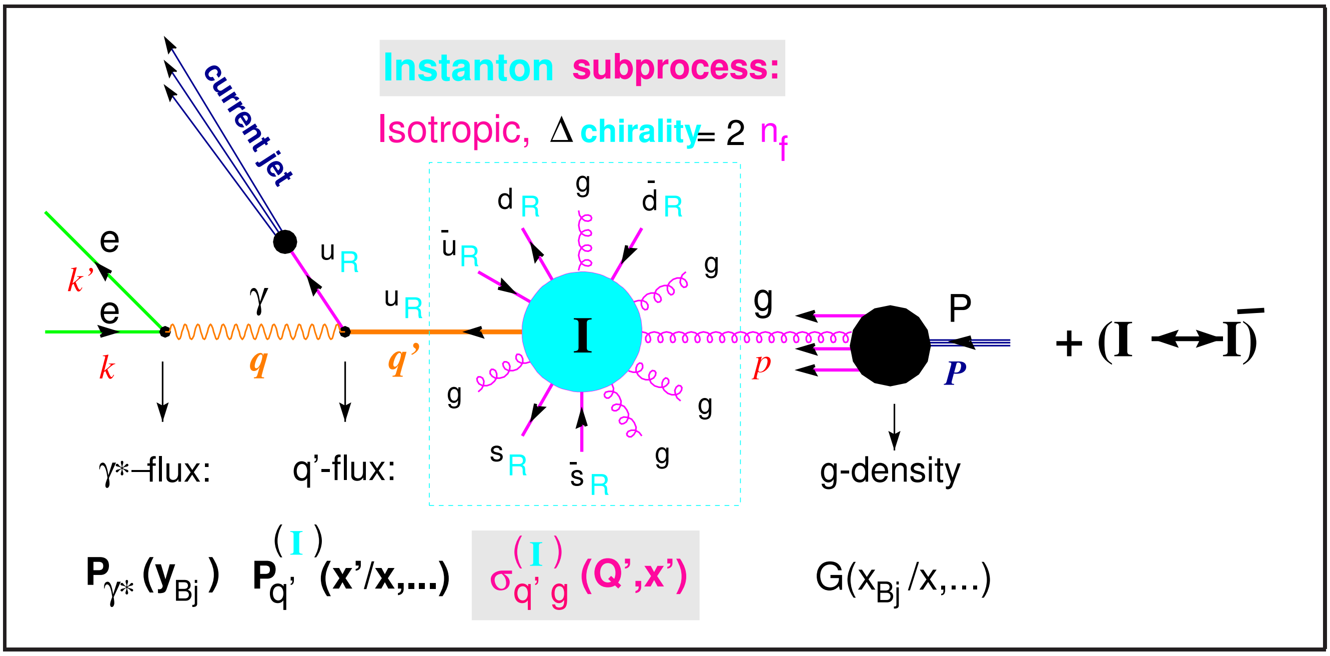
♣ Unique opportunity in **DIS** at **HERA** for discovering instanton-induced processes!

2. Instanton-Induced Processes in DIS

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

- **Theoretical framework**: "I-perturbation theory"
  for dilute gas of I's, $\overline{I}$'s and small α_s

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



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

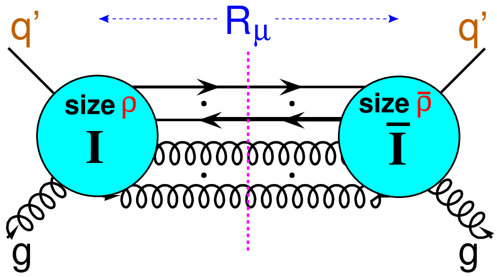
$$\text{large} \quad Q'^{\,2} = -q'^{\,2} > 0; \quad x' = \frac{Q'^{\,2}}{2p\cdot q'} \leq 1 \quad \text{fixed}$$

- Show within I-perturbation theory (Bjorken limit):

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

- Differential luminosity, $\mathrm{d}\mathcal{L}^{(I)}_{q'g}$: number of $q'g$ collisions per eP collision $\Leftrightarrow$ integrals over the various known flux factors.

- Crucial instanton-dynamics in total cross-section of I-subprocess $q'g \overset{I}{\Rightarrow} X$!

$\sigma^{(I)}_{q'g} \sim$ 

$$\sigma^{(I)}_{q'p} = \int d^4R\, \mathrm{e}^{\mathrm{i}\,(p+q')\cdot R} \int_0^\infty d\rho \int_0^\infty d\overline{\rho}\; \mathrm{e}^{-(\rho+\overline{\rho})Q'}$$

$$\times\; D(\rho)\, D(\overline{\rho}) \int dU\, \mathrm{e}^{-\frac{4\pi}{\alpha_s}\,\Omega\left(U,\,\frac{R^2}{\rho\overline{\rho}},\,\frac{\overline{\rho}}{\rho}\right)} \{\ldots\}$$

Integration over all $(I,\ \overline{I})$ **collective coordinates**: $(\rho,\overline{\rho}) =$ $(I,\overline{I})$-size, $R_\mu = I\overline{I}$-distance, $U = I\overline{I}$ relative color orientation.

Two crucial quantities of I-calculus:

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

◇ Both are $\boxed{\textbf{known}}$ in I-perturbation theory, formally for

$\alpha_s(\mu_r)\ln(\mu_r\rho) \ll 1$ and $\frac{R^2}{\rho\overline{\rho}} \gg 1$, respectively

(μ_r = renorm. scale).

◇ $D(\rho) \propto \rho^{6-2/3n_f+\mathcal{O}(\alpha)}$ generically spoils calculability of I-observables, since $(\rho, \overline{\rho})$ -integrals diverge for large ρ

♣ **Exception** in **DIS**: "form factor" $\exp(-Q'(\rho+\overline{\rho}))$ insures **small** $(I, \overline{I})$'s with $(\rho, \overline{\rho}) \lesssim 1/Q'$ despite $D(\rho)$

♣ 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

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

◇ Saddle point⇒ indeed, for large Q' and small $(1-x')$: dilute gas ⇔ $\frac{R}{\rho} \gg 1$ of small I's ⇔ $\rho \sim \frac{1}{Q'}$!

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

◇ **Lattice data** ⇒ Independent non-perturbative information on range of validity of their predicted form in (ρ, R)

◇ **Saddle-point** relation: $(\rho^*, R^*) \Leftrightarrow (Q', x')$

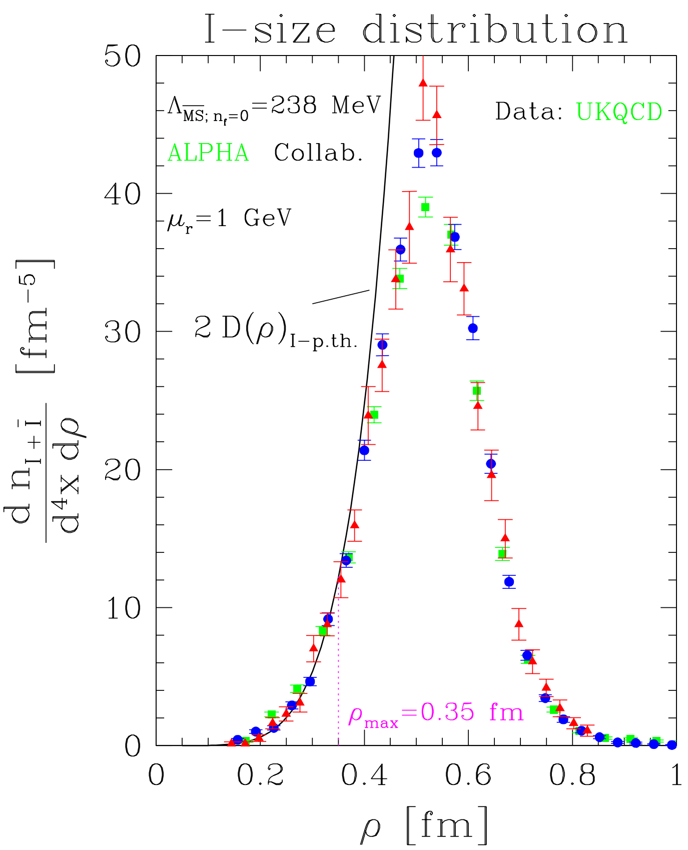
⇒ "fiducial" (Q', x') region for our predictions in **DIS**!

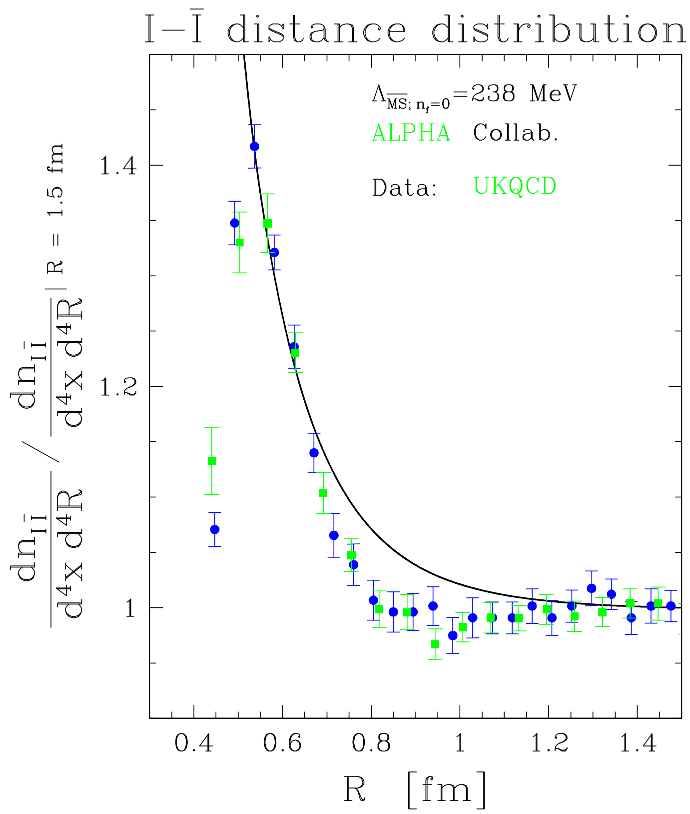
3. Rates, Signatures and their Uncertainties

- **Main emphasis:** Study of theoretical uncertainties and upgrade of published results. [Ringwald & F. Sch., '00, in prep.]
- Complete error estimate clearly impossible. But a number of major uncertainties may be evaluated quite well!

◇ Where to place fiducial cuts in (Q', x')? ⇐ Lattice!

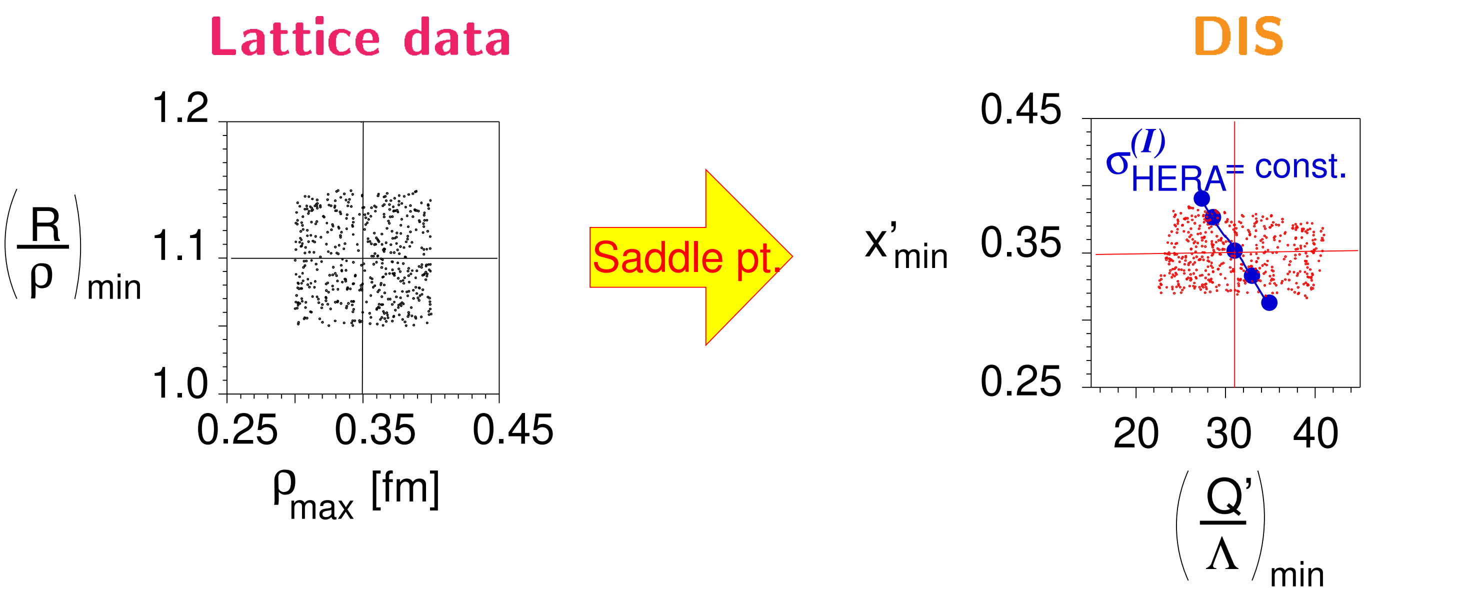
[Ringwald & F. Sch., Phys. Lett. **B 459** (1999) 249; **B 438** (1998) 217,]





***I*-perturbation theory reliable** for

$$\rho \lesssim \rho_{\max} = 0.35 \pm 0.05 \text{ fm} \qquad \frac{R}{\rho} \gtrsim \left(\frac{R}{\rho}\right)_{\min} = 1.1 \pm 0.05$$



◊ $\boxed{\text{Additional (technical) cut in } Q^2\text{:}}$ $Q^2_{\rm min} \approx Q'^{\,2}_{\rm min}$

Ensures dominance of "planar" graphs in $\sigma^{(I)}{}_{\rm HERA}$ and final-state observables;

"non-planar" terms very hard/slow to calculate $\Rightarrow$ignored!

◊ $\Rightarrow$ upgraded **default** fiducial cuts:

$$\boxed{\frac{(Q', Q)}{\Lambda^{(n_f)}_{\overline{\rm MS}}} \gtrsim 30.8, \;\; x' \gtrsim 0.35, \;\; x_{\rm Bj} \geq 10^{-3}, \;\; 0.1 \leq y_{\rm Bj} \leq 0.9}$$

◊ $\boxed{\text{Number } n_f \text{ of active flavours? Why } n_f = 3 \text{ at HERA?}}$

In principle, all flavours contribute at some I-size ρ, for which they appear $\approx$ massless: $\rho\, {\rm m}_q \ll 1$.

$\sigma^{(I)}{}_{\rm HERA}$ dominated by $\rho \approx \rho^*_{\rm max}(Q', x') \approx 0.35$ fm, where only $m_{u,d,s}$ appear massless! $n_f \geq 4$ only at very large Q'!

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

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

◇ $\boxed{\text{Dependence on } \Lambda^{(n_f=3)}_{\overline{\rm MS}}\text{-error?}}$

$\Leftarrow$ PDG'98 $\Leftarrow$ PDG '96

$\Leftarrow$ $Q'_{\rm min} \propto \Lambda^{(n_f)}_{\overline{\rm MS}}$:Lattice

- 3-loop relations $\alpha_s \Leftrightarrow \Lambda^{(n_f)}_{\overline{\rm MS}}$ throughout
- Much reduced uncertainty from $\delta\Lambda_{\overline{\rm MS}}$

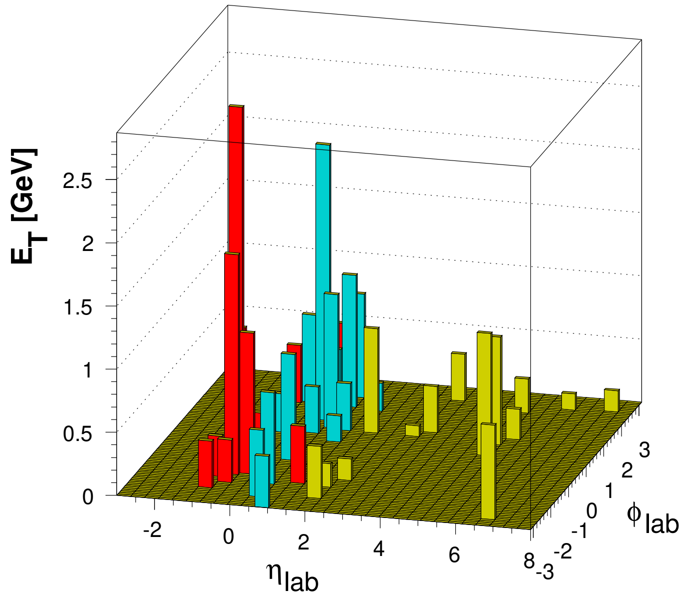
	PDG '96 $\Rightarrow$	PDG '98	PDG '98
$\alpha_s(M_Z)$	0.113 (DIS!)	0.119 ± 0.002	0.119 ± 0.002
$\Lambda^{(3)}_{\overline{\rm MS}}$ [MeV]	260^{+66}_{-64}	$346\ ^{+31}_{-29}$	$346\ ^{+31}_{-29}$
Cuts	$Q' \geq 8$ GeV	$\frac{Q'}{\Lambda^{(n_f)}_{\overline{\rm MS}}} \geq 30.8$	$\frac{(Q,Q')}{\Lambda^{(n_f)}_{\overline{\rm MS}}} \geq 30.8$
	$x' \gtrsim 0.35,\ x_{\rm Bj} \geq 10^{-3},\ 0.1 \leq y_{\rm Bj} \leq 0.9$		
$\sigma^{(I)}{}_{\rm HERA}$ [pb]	126^{+300}_{-100}	$\mathbf{89}\ ^{-15}_{+18}$	$\mathbf{29}\ ^{-7.5}_{+10}$

Final-State Characteristics

Indispensable Tool: QCDINS (2.0)

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

[Gibbs, Ringwald & F. Sch. '95,
Ringwald & F. Sch '99, Comput. Phys. Commun. in print (**long-wite-up**);
QCDINS WEB page: http://www.desy.de/~t00fri/qcdins/qcdins.html]



- $\boxed{\text{current jet}}$
- $\boxed{\text{“band”-region:}}$ $\Leftrightarrow$

Isotropic decay of “fireball” $\Rightarrow$

$n_f \cdot q + n_f \cdot \bar{q} + \mathcal{O}(\frac{1}{\alpha}) \cdot g =$

$\mathcal{O}(10)$ partons in I-rest system

◇ large total E_t
◇ large multiplicity
◇ (light) flavour 'democracy':
  ⋆ **strangeness** $\Rightarrow K^0, \Lambda$'s

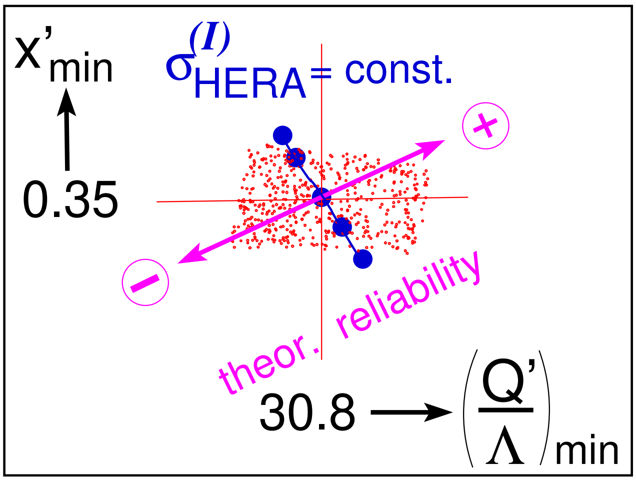
Event Topology and Fiducial Cut Uncertainties

- Both **H1** and **ZEUS** are currently searching for instanton-induced events! ($\Rightarrow$ H1-talk by S. Mikocki) $\Rightarrow$

- **Important issue:**
  Study, how the remaining theoretical uncertainties in fiducial cuts, affect $\boxed{\text{shape of final state observables}}$ as used by **H1**

If $x'_{\min}$ and $\left(\frac{Q'}{\Lambda}\right)_{\min}$ increase,

$$\left.\begin{array}{l}\text{rate}\\ \text{reliability}\end{array}\right\} \textbf{strongly} \left\{\begin{array}{l}\text{decreases}\\ \text{increases}\end{array}\right.$$



For simplicity: Follow line $\boxed{\sigma^{(I)}_{\text{HERA}} = \text{const.}}$ (Fig)

- **Strategy & observables** [T. Carli, J. Gerigk, A. Ringwald & F. Sch., hep-ph/9906441]

From a set of 6 I-sensitive **DIS**-observables:(⇒S.Mikocki)

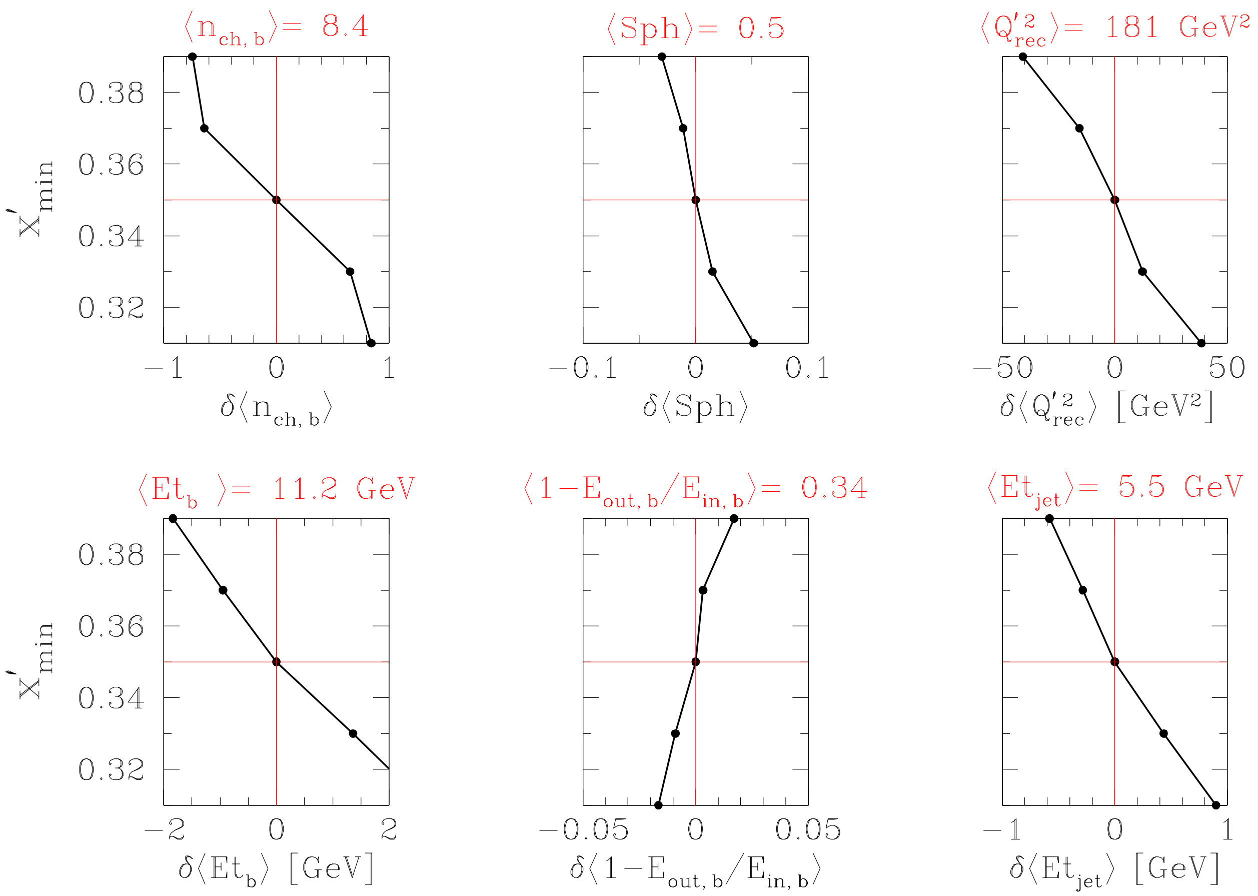
$n_{\mathrm{ch,\,b}}$, Sph, Q'^2_{rec}, Et_{b}, $(1 - E_{\mathrm{out,\,b}}/E_{\mathrm{in,\,b}})$ and Et_{jet};

b ⇔ from I- "band" without particles from current jet,

⇒ I-enriched data sample by means of optimized cuts

◇ shape uncertainties:

$(Q'/\Lambda)_{\mathrm{min}}$ such that $\sigma^{(I)}_{\mathrm{HERA}}$=const.; no Q^2−cut



Note: partly substantial shifts of averages ("peaks") towards smaller values for increasing (i.e. more reliable) x'_{min}!

4. Conclusions

- Unique opportunity in **DIS** at **HERA** for discovering instanton-induced processes

- Theoretical predictions of rate and event topology finalized

- While complete evaluation of theoretical uncertainties impossible, various major sources may be studied quite well.

- When comparing predictions with forthcoming experimental searches, known theoretical uncertainties must be included