Tracing QCD–Instantons in Deep Inelastic Scattering

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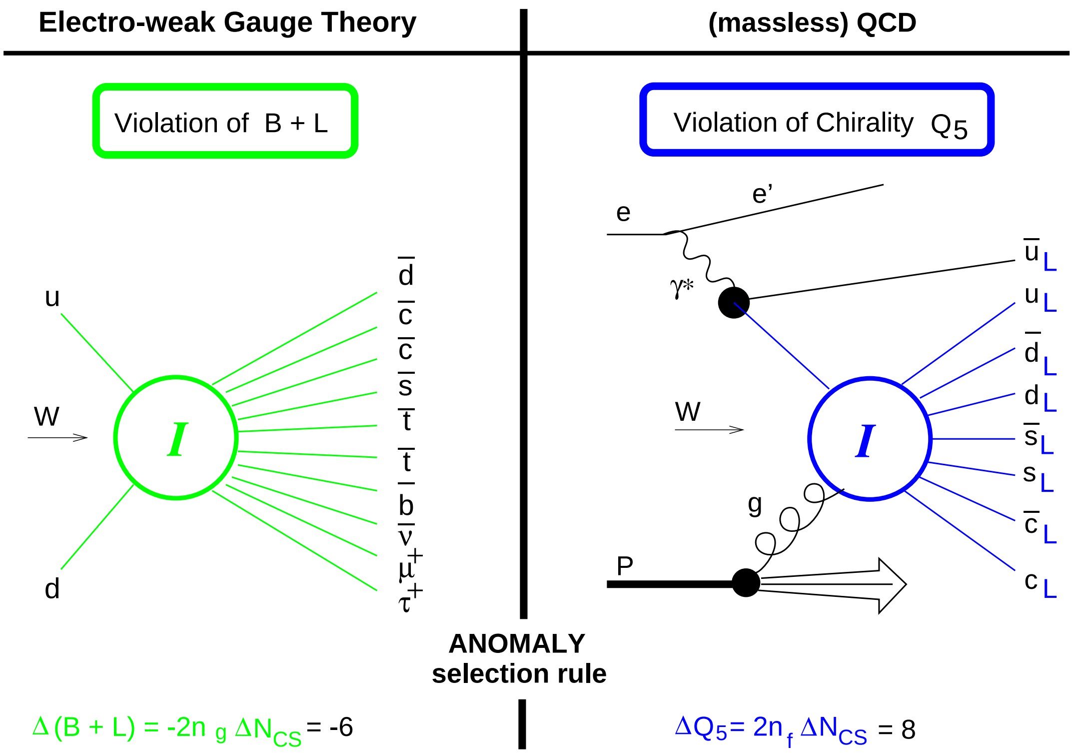
1. **Introduction**
2. **Instanton-Induced Cross Sections**
3. **Monte-Carlo Simulation for HERA**
4. **Conclusions and Outlook**

– DIS 96, Rome, April 1996 –

1. Introduction

- Instantons [Belavin *et al.* '75]:
  - Tunnelling transitions in YM theories, connecting degenerate vacua of different topology;
  - induce processes forbidden in perturbation theory, but bound to exist due to Adler-Bell-Jackiw anomalies of certain fermionic quantum numbers ['t Hooft '76]:



  - transitions suppressed at low energies, $\sim \exp\{-4\pi/\alpha\}$,

♣ may become **unsuppressed, i. e. observable** at high energies (!) via production of additional gauge bosons $A_\mu^I \sim 1/g$ [Ringwald '90; Espinosa '90]

- Deep Inelastic Scattering (DIS):

  – Calculable short-distance contributions from small QCD-Instantons; parton virtuality in DIS provides dynamical IR-cutoff for Instanton size.
  [Balitsky, Braun '93; Ringwald, F. Sch. to appear].

  – Best bet experimentally:

  Hunting for QCD-Instanton "footprints" in DIS multi-particle final state [Ringwald, F. Sch. '94].

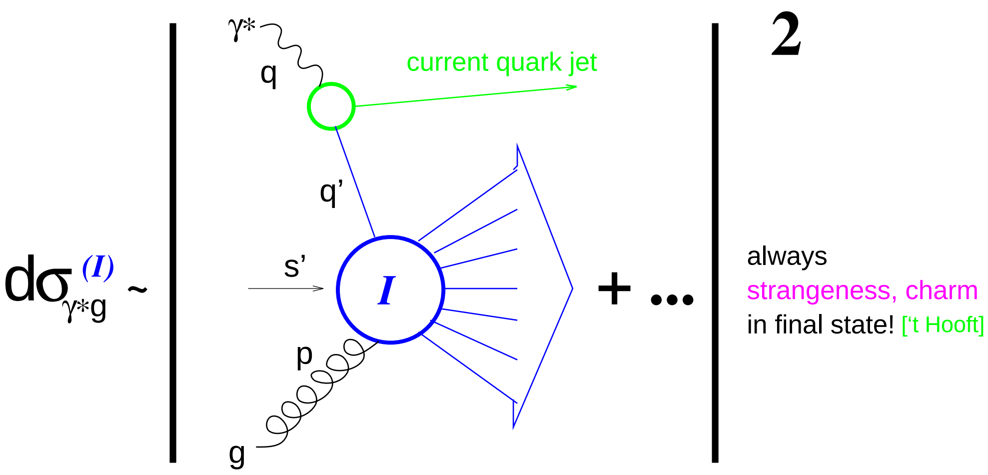
♣ Discovery of basic significance:

  * **Novel, non-perturbative manifestation of QCD**
  * **Close analogy** to $B+L$ **violation** in multi-TeV regime.

2. Instanton-Induced Cross Sections

[Balitsky, Braun '93];
[Ringwald, F. Sch., in prog.];
[Moch, Ringwald, F. Sch., in prog.]

- $\gamma^\star$ only couples to Instantons via it's quark content $\Rightarrow$
- Instanton-induced subprocess (“$\boldsymbol{I}$”) $\oplus$ current-quark jet (moving in I-background).



- $\boldsymbol{I}$-induced contribution to nucleon structure function in terms of parton-structure functions $\mathcal{F}_{2\,g}, \ldots$ and densities $\mathrm{f}_g, \ldots$:

$$F_2^{(I)}(x_{\rm Bj}, Q^2) = \sum_{\rm k} \int_{x_{\rm Bj}}^1 \frac{dx}{x} f_{\rm k}\left(\frac{x_{\rm Bj}}{x}\right) \frac{x_{\rm Bj}}{x} \mathcal{F}_{2,{\rm k}}{}^{(I)}(x, Q^2)$$

- $\mathcal{F}_{2\,g}$: Convolution of slowly varying “splitting function” $P^{(I)}_{q\star/\gamma}$ and I -subprocess “total cross section”, e. g. $\sigma^{(I)}_{\rm q^* g}$, containing essential Instanton dynamics:

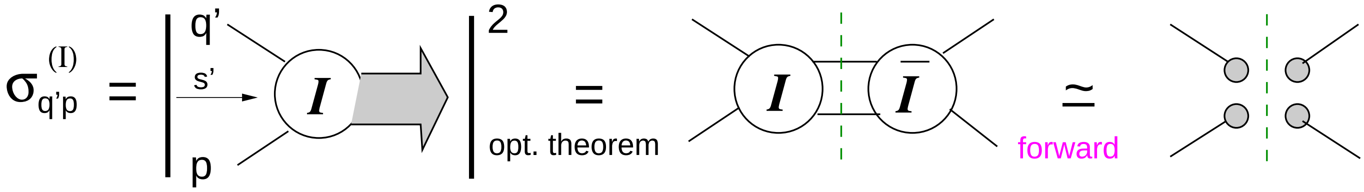
$$\mathcal{F}_{2\,\mathrm{g}}^{(I)}(x,Q^2) =$$

$$x \sum_{\mathrm{q}} e_{\mathrm{q}}^2 \int_x^1 \frac{dx'}{x'} \int_0^{Q^2 \frac{x'}{x}} dQ'^2 \, P_{\mathrm{q}^*/\gamma}^{(I)}\left(\frac{x}{x'}\right) \sigma_{\mathrm{q}^*\mathrm{g}}^{(I)}(x',Q'^2)$$

2.1 I-Induced Subprocess Total Cross Section

- use: optical theorem $\oplus$ $I\overline{I}$-valley method :

[V.V. Khoze, Ringwald '91; Balitsky, Braun '92]



– $I\overline{I}$ valley $\Leftrightarrow$ constrained minimum of action; interpolates

$$\left\{ \begin{array}{l} \text{weakly interacting} \\ \text{strongly annihilating} \end{array} \right\} I\overline{I} \text{ pair for } \left\{ \begin{array}{l} \text{large} \\ \text{small} \end{array} \right\}$$

$I\overline{I}$ separation.

– For large separation: approaches conventional I-perturbation theory; sums up final state tree-graph corrections beyond leading semi-classical approximation.

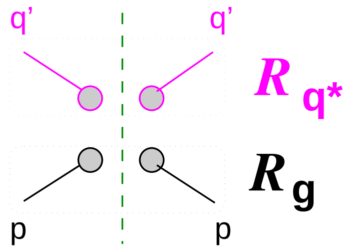
– allows to go beyond I-perturbation theory; crucial for small $x' = Q'^2/(s'+Q'^2) \geq 0.2$ region, relevant at HERA!

- Expand (euclidean) path integral for relevant 4-point Green's function about $I\overline{I}$-valley configuration;

$$\sigma^{(I)}_{\mathrm{q}^*\mathrm{g}} = \tfrac{1}{2\mathrm{i}s'}\,\mathrm{Disc}_{s'} \int d\rho_I\, d\rho_{\overline{I}}\, d^4R\, \mathcal{M}(\rho_I, \rho_{\overline{I}}, R)\times$$

$$\times \mathcal{R}_{\mathrm{q}^\star}(\rho_I, \rho_{\overline{I}}, R; q')\, \mathcal{R}_{\mathrm{g}}(\rho_I, \rho_{\overline{I}}, R; p)$$

$$\times\ \exp\{-\tfrac{4\pi}{\alpha} S^{I\overline{I}}{}_{\mathrm{valley}}(\rho_I, \rho_{\overline{I}}, R)\};$$



collective coordinates: sizes $\rho_{I,\overline{I}}$, (euclidean) $I\overline{I}$-distance R_μ.

- DIS: $-q'^{\,2} = Q'^{\,2}$; large : $\mathcal{R}_{\mathrm{q}^\star} \sim \exp\{-(\rho_I + \rho_{\overline{I}})Q'\} \Rightarrow$

Integrations over collective coordinates via
Unique Saddle-point due to small Instantons:

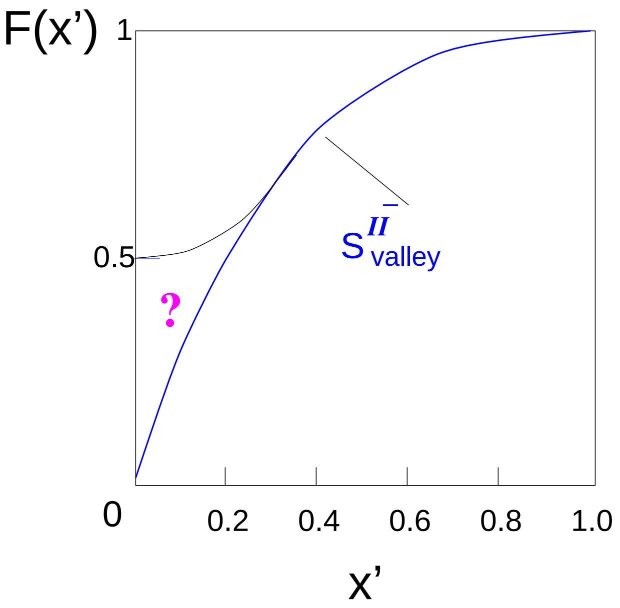
$$\rho_I^\star = \rho_{\overline{I}}^\star = \mathcal{O}\big(\tfrac{1}{Q'\alpha_s^{\mathrm{eff}}(Q'^2)}\big); \qquad \rho_I^\star \rho_{\overline{I}}^\star / R^{\star 2} = \tfrac{1-x'}{4x'}.$$

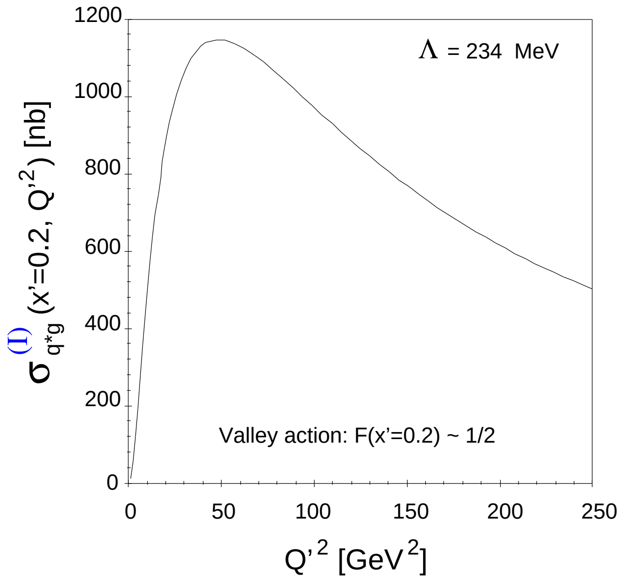
$$\sigma^{(I)}_{\mathrm{q}^*\mathrm{g}} \approx \frac{\Sigma(x')}{Q'^2}\left(\frac{4\pi}{\alpha_s^{\mathrm{eff}}(Q'^2)}\right)^{\frac{21}{2}} \exp\left\{-\frac{4\pi}{\alpha_s^{\mathrm{eff}}(Q'^2)}\boldsymbol{F}(x')\right\}$$

- "Holy Grail" function $\boldsymbol{F(x')}$ (and $\Sigma(x')$) known from $\boldsymbol{I\overline{I}}$ valley method for all $\boldsymbol{x'}$, notably

$$F(x') = S^{I\overline{I}\,\star}{}_{\mathrm{valley}}(x')$$

but with intrinsic ambiguities for small x' (Fig.)





- $\sigma^{(I)}_{\rm q^*g}$ has strong peak in Q', far away from IR (Fig.),

$$Q'_{\rm peak}(x' = 0.2) \approx 31\Lambda \gg \Lambda;$$

(increasing with decreasing x')

- $\Rightarrow \int_0^{Q^2\frac{x'}{x}} dQ'^2 \sigma^{(I)}_{\rm q^*g}(x', Q'^2)$:
  - IR finite! (in leading semi-class. approx.)
  - Independent of Q^2 for $Q^2 \to \infty$, i.e. $\mathcal{F}^{(I)}_{2\,\rm g}$ scaling in x

- predicted approach to scaling:

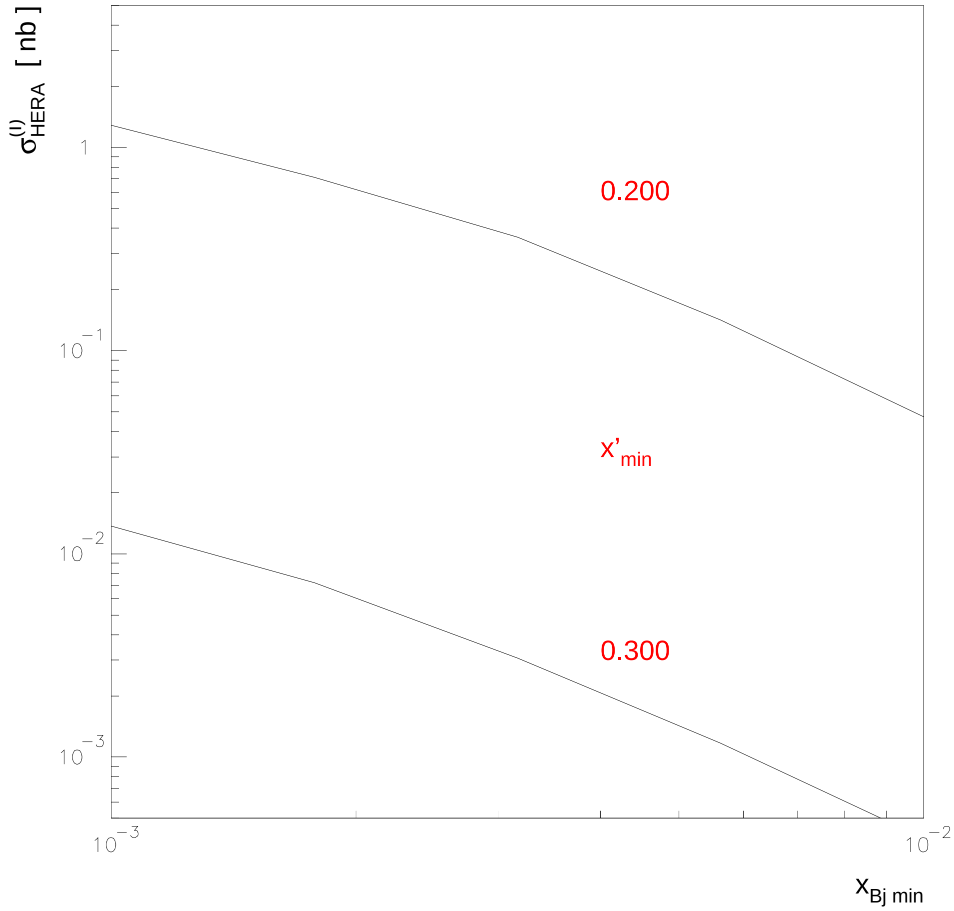
$$Q^2 \, \frac{d\,\mathcal{F}^{(I)}_{2\,\rm g}(x,Q^2)}{dQ^2} \overset{Q \ \text{large}}{\approx}$$

$$\sum_{\rm q} e^2_{\rm q}\, x\, P^{(I)}{}_{\rm q^*/\gamma}(1)\, \frac{\Sigma(x)}{\frac{dF(x)}{dx}} \left[b\, \ln\left(\frac{Q^2}{\Lambda^2}\right)\right]^{\frac{19}{2}+2\,b\,F(x)} \left[\frac{\Lambda^2}{Q^2}\right]^{b\,F(x)} ;$$

- resembles "fractional twist" term, twist sliding with x' $\Rightarrow$ scaling violations vanish faster for increasing x'

2.2 HERA Cross Section $(y_{\rm Bj} \geq 0.1)$ (preliminary)

[Gibbs, Ringwald, F. Sch., in prog.]



- $\sigma^{(I)}_{ep} \approx 0.1 - 1$ nb for $x_{\rm Bj} \geq 10^{-3}$ and "conservative cut-off" $x_{\rm min} = 0.25 - 0.20$

- working hypothesis up to now: $F(x') \equiv F(x'_{\rm min}) =$ const. for $x' < x'_{\rm min}$

- Only gluons, so far; subdominant valence quark contributions neglected.

- Uncertainties!?

3. Monte-Carlo Simulation for HERA

[Gibbs, Ringwald, F. Sch. '95 & in prog.]

- "QCDINS 1.2", including hadronization ("HERWIG 5.8")

- Phenomenological analysis based on features characteristic for underlying Instanton mechanism: [Ringwald, F. Sch. '94 & in prog.; Balitsky, Braun '93; V.V. Khoze, Ringwald '91; 't Hooft '76]

  – Isotropic emission of many semi-hard partons in $\boldsymbol{I}$-rest system: "decaying fireball"

  – High multiplicity: $\langle n_{\rm q+g}\rangle^{(I)}_{n_f=4} \simeq 10$ (!) at HERA.

  – Multiplicity distribution: $\lim_{\rm Bj} \sigma_n^{(I)\,\rm excl.} =$ Poisson

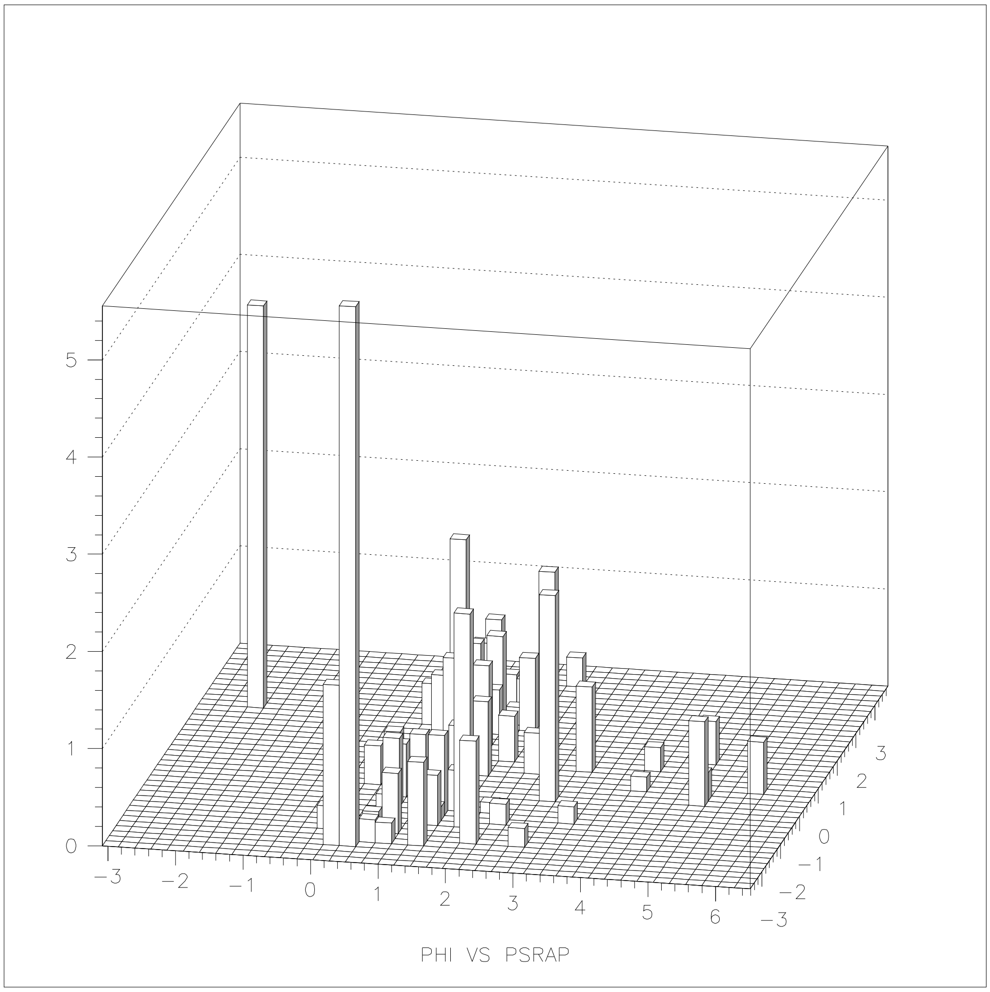
  – Characteristic flavor flow (strangeness, charm $\Rightarrow$ muons)

- **Monte Carlo Samples**

  – $\boxed{x_{\rm Bj} \geq 10^{-3} \ldots 10^{-2},\ y_{\rm Bj} \geq 0.1}$

  – I-subprocess: $\left\{ \begin{array}{ll} x_{\rm min} & = 0.2, \\ n_f & = 3 - 5. \end{array} \right\}$

3.1 Generic Features

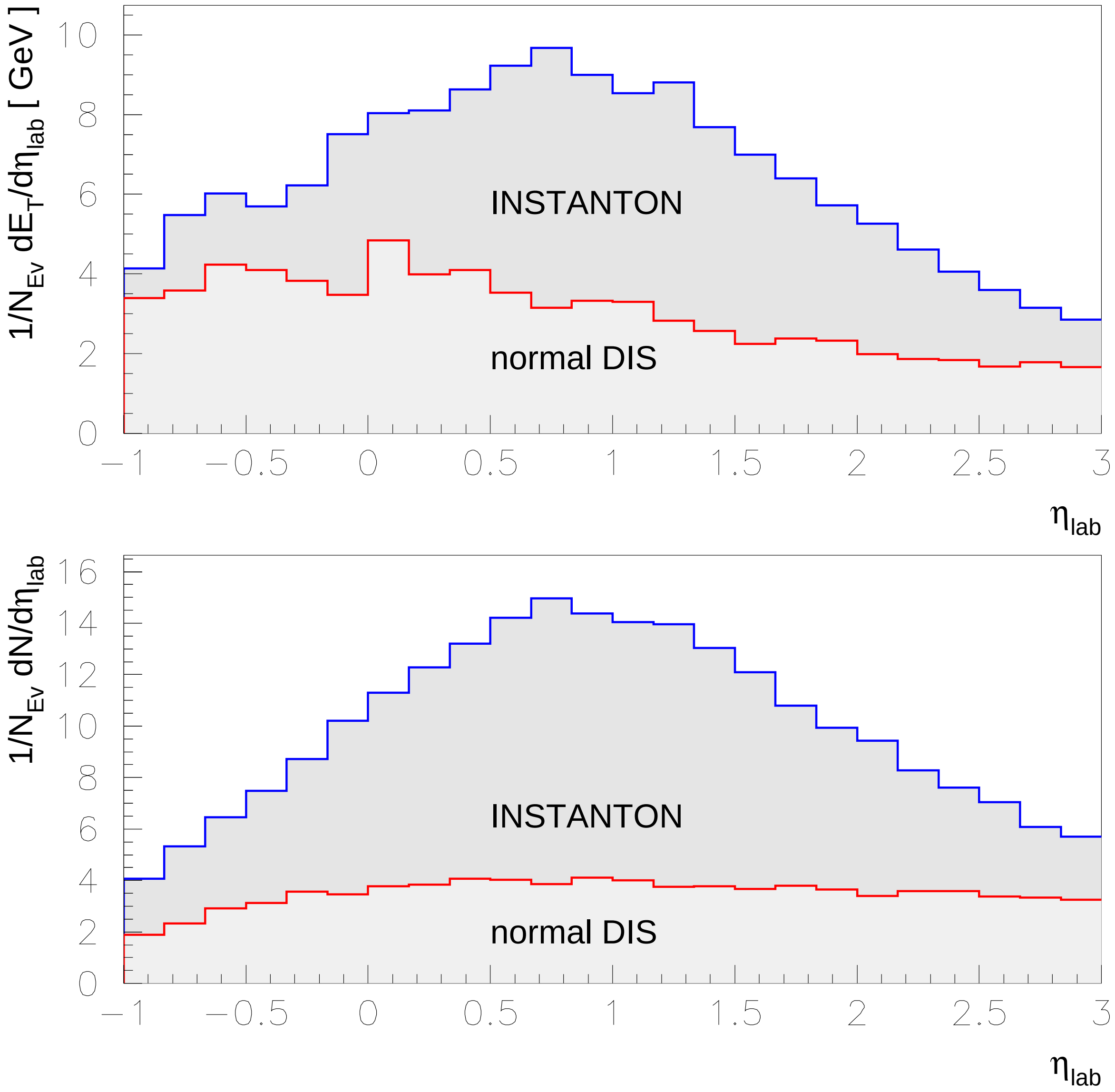


- Current jet
- Hadronic 'band': $\Leftrightarrow$ **isotropy** in $\boldsymbol{I}$-rest system
  - Large total $E_T = \mathcal{O}(20)$ GeV
  - Large multiplicity $N_{\rm band} = \mathcal{O}(25)$
  - No jets in 'band' !
  - Characteristic flavor flow:

    $\star$ **Strangeness** $\Rightarrow K_S^0$'s $\star$ **Charm** $\Rightarrow \mu$'s

Transverse-Energy and Multiplicity Flows[1]

$(x_{\rm Bj} \geq 10^{-3}, y_{\rm Bj} \geq 0.1, x_{\rm min} = 0.2)$

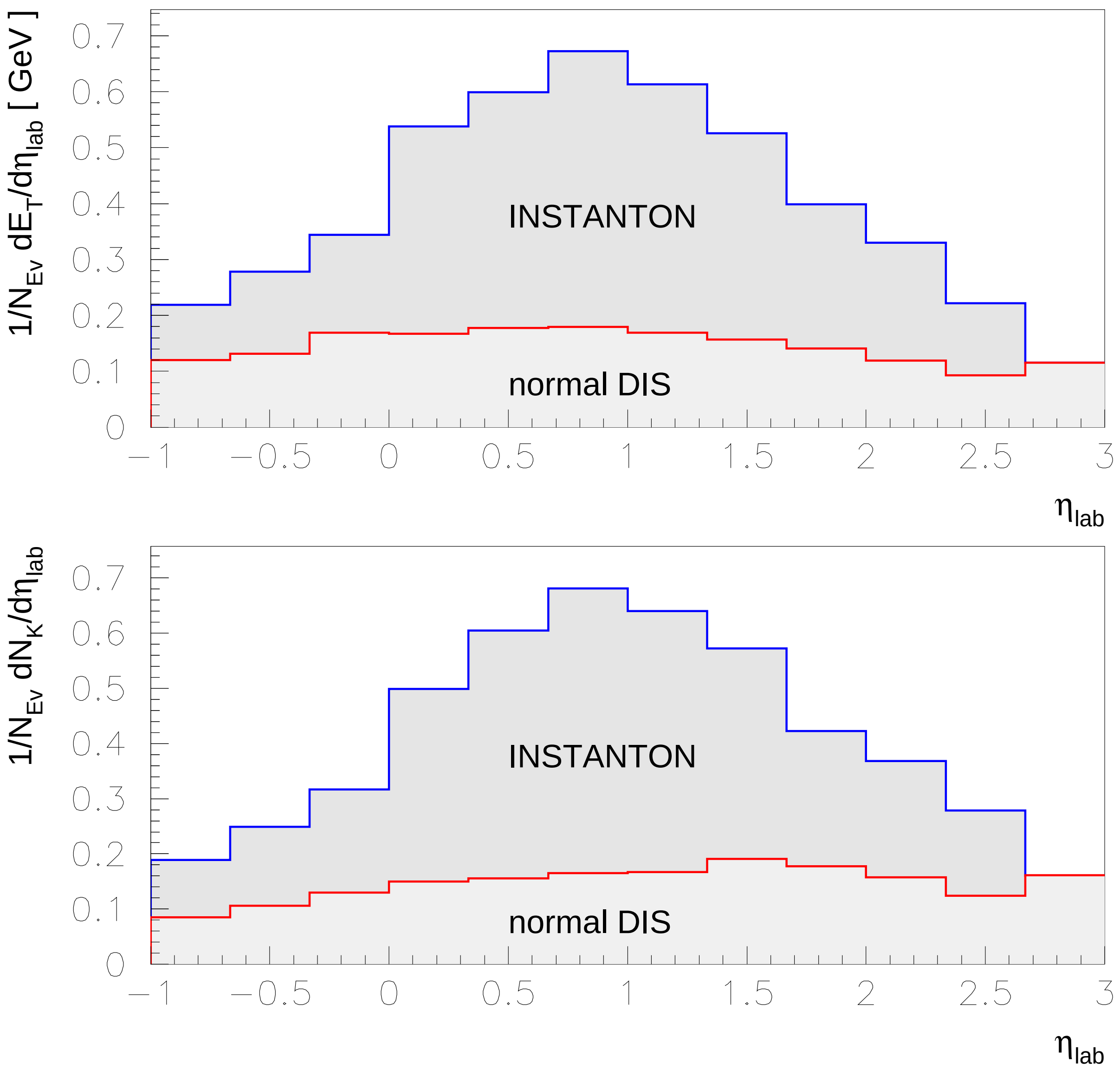


- Enhancement of E_T-flow and multiplicity-flow in ‘band’.
- may cut on strong multiplicity excess in 'band', $0 \leq \eta \leq 2$

[1]All particles, not only hadrons

Transverse-Energy and Multiplicity Flows of K_S^0's

$(x_{\rm Bj} \geq 10^{-3}, y_{\rm Bj} \geq 0.1, x_{\rm min} = 0.2)$

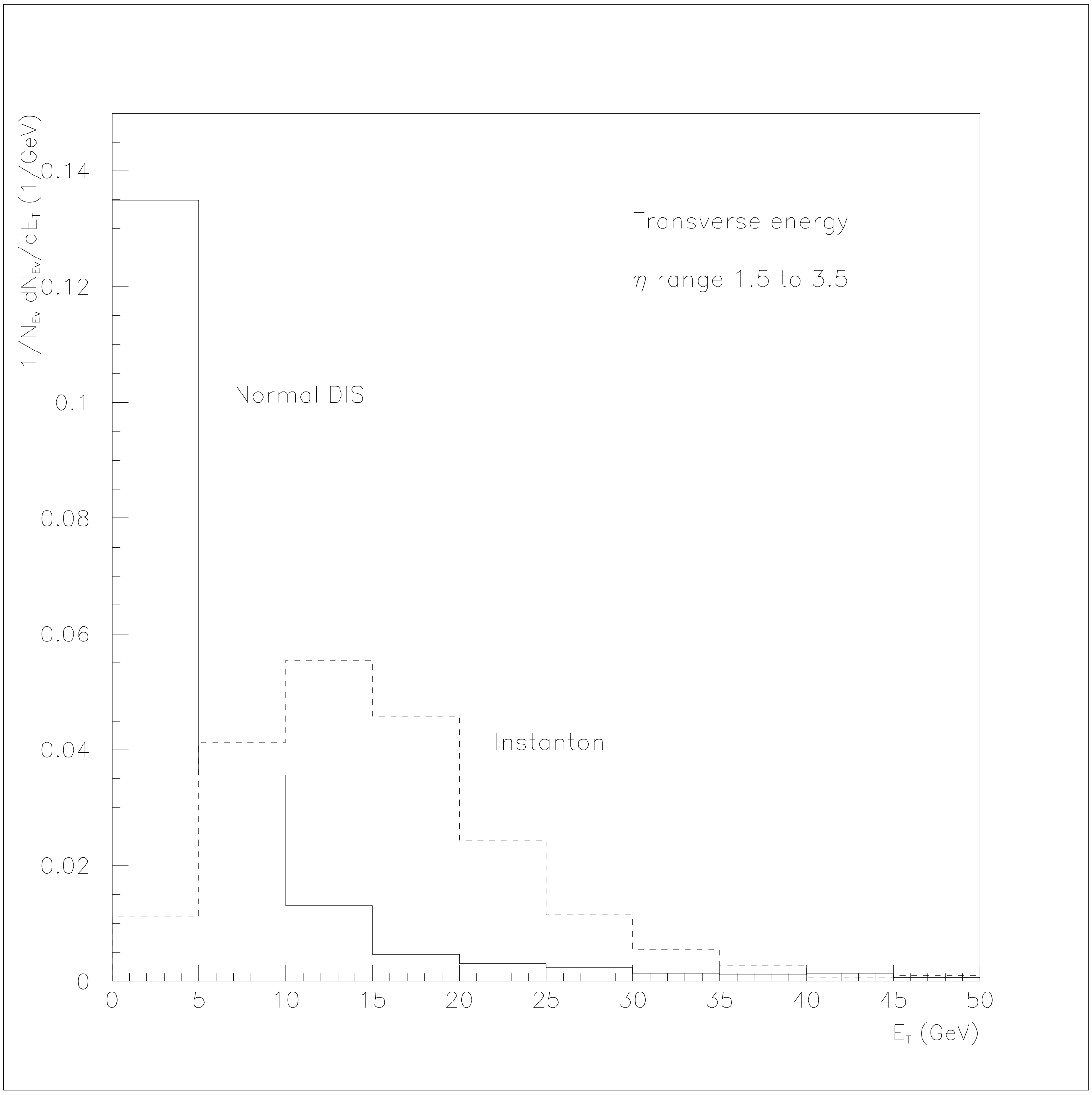


- Enhancement of K^0-flow in 'band'! $\Rightarrow$

- First (preliminary) upper limit for the I-induced cross section at HERA based on the observed K_S^0's in the barrel of H1 [(Liverpool) H1 Group $\rightarrow$ c.f. following talk]

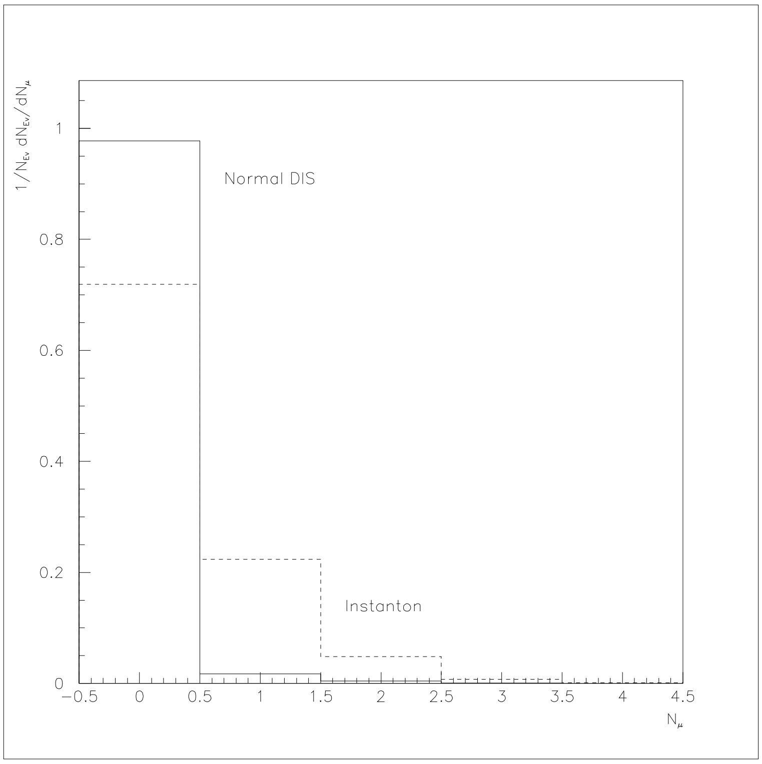
Transverse-Energy Distribution in 'Band'

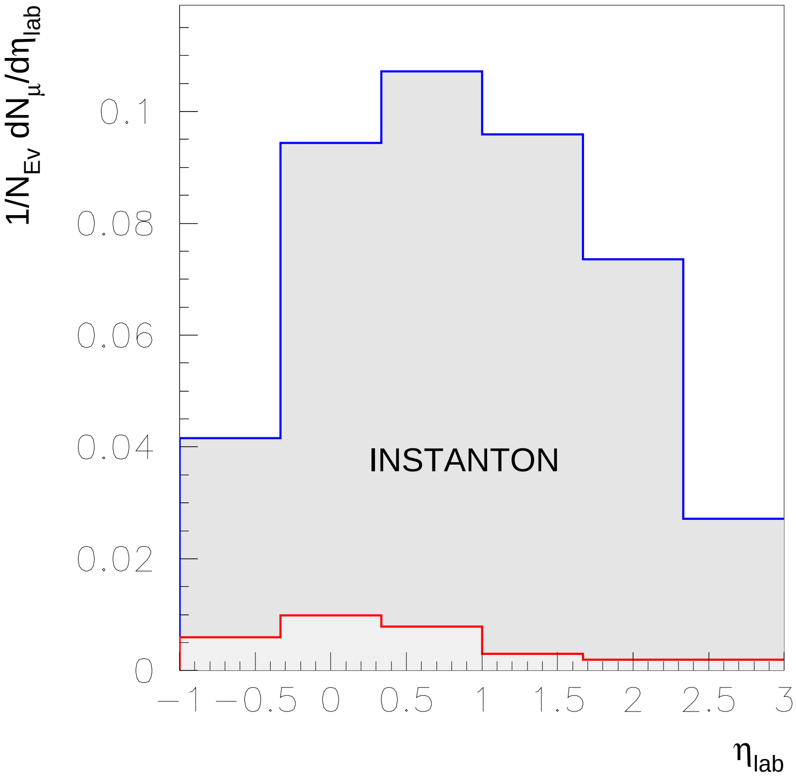
$(x_{\mathrm{Bj}} \geq 10^{-2}, y_{\mathrm{Bj}} \geq 0.1, x_{\mathrm{min}} = 0.2)$



- Instanton-induced events have large E_T in 'band'!

Multiplicity Distribution and Multiplicity Flow of Muons





- Strong excess of muons in Instanton-induced events!

3.2 Analysis in Progress (HERA Workshop 1995/96)

[M. Gibbs, T. Greenshaw, D. Milstead, A. Ringwald, F. Sch.]

- Implement information on event shapes in order to improve separation! $\Rightarrow$

- Promising: Boost to $\gamma-$proton c.m. system
  [T. Greenshaw,...$\rightarrow$ c.f. following talk]:

  - Note : 1 and 2 jet (hard) pert. QCD processes deposit E_T predominantly in a plane passing through $\gamma-$proton direction:

  - E_T from Instanton-induced events always distributed much more spherically (ISOTROPY!)

  - I-induced events have large $\langle E_T \rangle$

  - Expectations : Good separation via E_T^{out} vs. E_T^{in} distributions, for a plane maximizing E_T^{in} (minimizing E_T^{out}) on an event by event basis.

  - Position of E_T peak shifted towards larger $E_T = \mathcal{O}(20GeV)$ for I-induced events.

- Combine event-shape constraints with strange particle searches!

4. Conclusions and Outlook

- Discovery of QCD-Instanton induced events of basic importance:
  - Novel, non-perturbative manifestation of QCD
  - Analogy to anomalous B+L violation in electro-weak processes in multi-TeV region

- HERA offers unique window in DIS!

- Systematic theoretical/phenomenological investigation of discovery potential, including Monte-Carlo simulation (QCDINS, interfaced to HERWIG 5.8):
  - Estimate of HERA cross section (depending on $x'_{\rm min}$): not small, O(1/10–1 nb)
  - Event characteristics:

    $$\left\{ \begin{array}{l} \text{densely filled hadronic `band'} \\ \text{always strangeness, charm} \end{array} \right\} \oplus \text{ 1 jet}$$

  - Enhancement of various 'flows' in

$$\text{`band' of width } \triangle\eta_{\rm lab} \approx \pm 0.9,$$
$$x_{Bj} = 10^{-3} : 0 \leq \eta_{\rm lab} \leq 2.$$

Outlook

- Combine event shape information with searches for K^0's and μ's etc.
- Measure multiplicity in bins of η, notably in 'band', apply multiplicity cuts!
- Study, how well I-subprocess variables s', x' may be reconstructed/restricted from hadron momenta in 'band' + current jet $\Rightarrow$
  Theory: production rates independent of assumptions on "holy-grail" function $F(x')$ for $x' < x'_{\min}$

HERA IS READY NOW