Phenomenology of QCD-Instanton Induced Events

F. Schrempp

in collaboration with

A. Ringwald

and

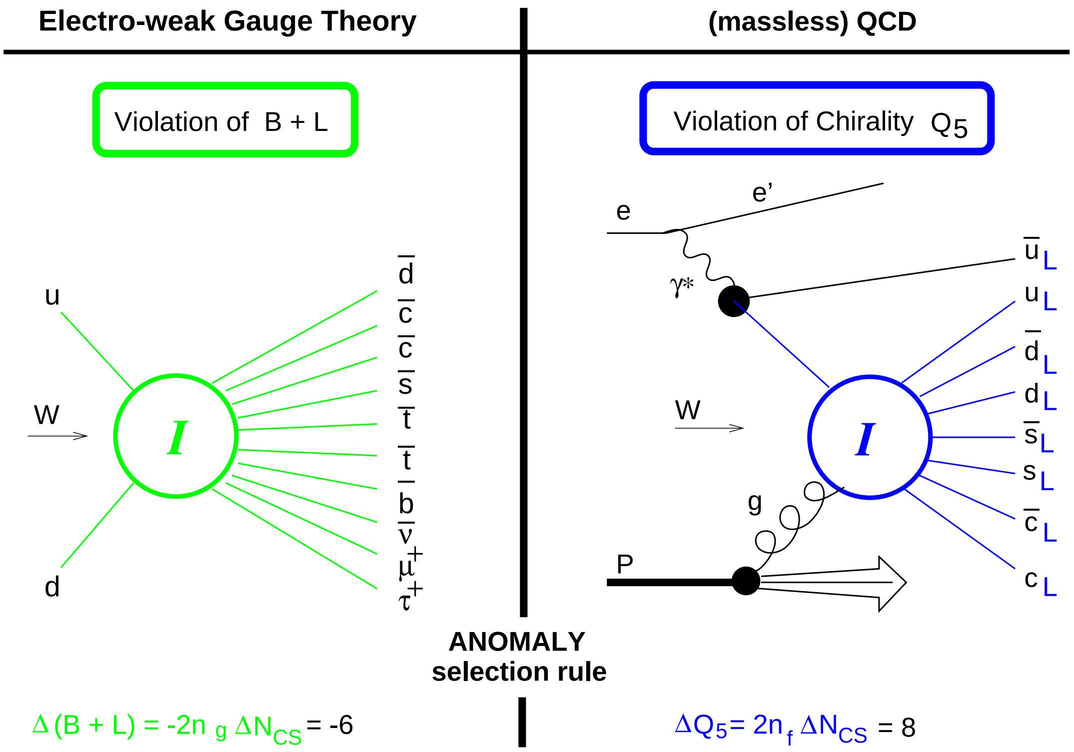
M. Gibbs (Monte Carlo) S. Moch (PhD Thesis)

– DESY Theory Workshop, Sept. 1995 –

1. Introduction

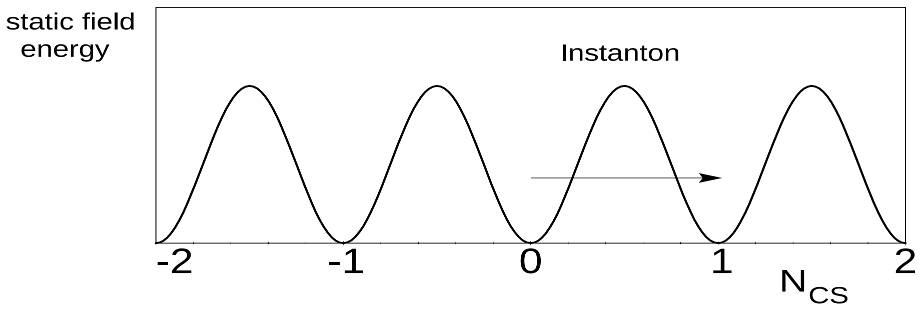
- Perturbative formulation of Standard Model theoretically consistent and agrees with present experiments

- Nevertheless, due to Adler-Bell-Jackiw anomalies, there exist processes – even for small couplings – that
  - cannot be described by conventional perturbation theory, notably, because they
  - violate conservation laws of certain fermionic quantum numbers respected by perturbation theory ['t Hooft '76].



- Anomalous processes are induced by Instantons: [Belavin et al. '75]

- In YM-gauge theories:
  - Infinite set of degenerate vacua related by topologically nontrivial gauge rotations. Labelled by Chern-Simons number $N_{\rm CS}$ (topological winding number of gauge field)
  - Energy barrier for $\Delta N_{\rm CS} = \pm 1$ transitions



- (Anti-)Instantons :
  - Tunnelling solutions, interpolating between vacua with $\Delta N_{\rm CS} = (-) + 1$
  - transitions suppressed at low energies, $\sim \exp\{-4\pi/\alpha\}$,

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

Deep Inelastic Scattering (DIS):

- Calculable short-distance contributions from small QCD-instantons may be factorized from IR-divergent long distance effects [Balitsky, Braun '93].

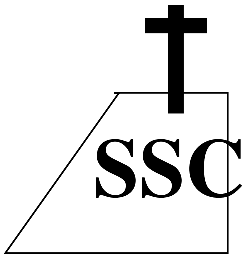
- $1/\sqrt{Q^2}$ ~ dynamical infrared-cutoff for instanton size
  [Khoze, A. Ringwald '91]

QCD-instanton effects for $\left\{ \begin{array}{ll} \text{decreasing} & x_{\rm Bj} = \frac{Q^2}{W^2+Q^2} \\ \text{large} & Q^2 \text{ (fixed)} \end{array} \right\}$

♣ discovery of basic significance:

- **Novel, non-perturbative manifestation of QCD**
- **Close analogy:**

Anomalous B+L violation	Anomalous chirality violation
for $W \nearrow$	for $x_{\rm Bj} \searrow \Leftrightarrow W \nearrow$
$W_{\rm crit} \sim \frac{m_W}{\alpha_W} = \mathcal{O}(10 \text{ TeV})$	$W_{\rm crit} = \mathcal{O}(Q)$
[Manton '83; Klinkhamer, Manton '84]	



HERA

is ready

NOW

♣ possibly observable:

- $\exp\left(-\frac{4\pi}{\alpha_S}\right) \gg \exp\left(-\frac{4\pi}{\alpha_W}\right)$

– "pilot" calculation:
  Structure function of a gluon/quark [Balitsky, Braun '93]

- Much preferable: Hunting for QCD-instanton "footprints" in DIS multi-particle final state [A. Ringwald, F.S. '94]

2. Instanton Induced Scattering

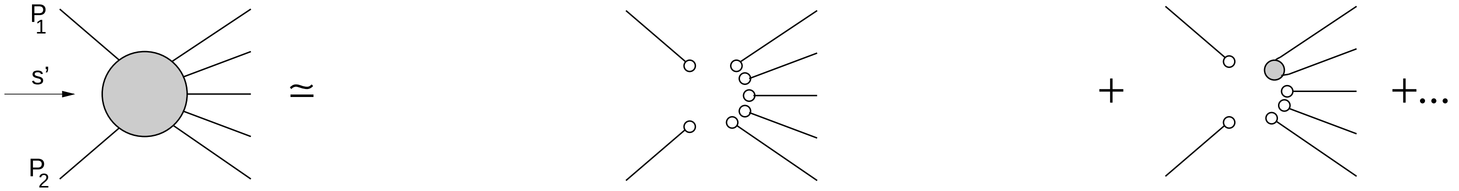
- Illustrate close analogy between anomalous $B + L$ violation in QFD and anomalous chirality violation in QCD;

- Instanton-induced amplitudes/cross sections;

- going beyond "Instanton-perturbation theory": The $I\bar{I}$-valley method.

Anomalous B+L Violation in **QFD**	Anomalous Chirality Violation in **QCD**
	one incoming quark/gluon virtual: $-p_1^2 = Q'^{\,2} > 0$, large; $\quad p_2^2 = 0$

Amplitudes, by expanding path integral about instantons: ['t Hooft '76; Ringwald '90; Espinosa '90]



$$T^{(I)}_{2\to n} \sim \int d\rho_I \mathcal{M}(\rho_I) \prod_{i=1}^{n+2} \mathcal{R}(\rho_I, p_i) \exp\{-\tfrac{2\pi}{\alpha} S^I(\rho_I)\} + \dots$$

$\rho_I = I$-size; $\mathcal{R}(\rho_I, p_i) =$ LSZ-amputated F.T. of fermionic zero modes/A^I;

I-action S^I:

$S^I(\rho_I) = 1 + \frac{1}{2}{\rho_I}^2 m_W^2$	$S^I(\rho_I) \equiv 1$

Infrared cutoff for instanton size arises from

instanton action:	virtuality of incoming parton: [Khoze, Ringwald '91]
$\rho_{\rm cut} \sim \frac{1}{v} \sim \frac{g_2}{m_W}$	$\mathcal{R}(\rho_I, q')_{\rm IR-safe} \sim \exp\{-\sqrt{Q'^2}\rho_I\}$

Anomalous B+L Violation in **QFD**	Anomalous Chirality Violation in **QCD**

Total cross section for anomalous fermion number violation has

exponential, scaling form: [Khlebnikov, Rubakov, Tinyakov '90;...]

in high-energy, weak coupling limit,	in Bjorken-limit,
$\boldsymbol{s'\sigma_{\rm tot}^{(I)} \sim \exp\{-\frac{4\pi}{\alpha_W(m_W)}F(\epsilon)\}}$,	$\boldsymbol{s'\sigma_{\rm tot}^{(I)} \sim \exp\{-\frac{4\pi}{\alpha_s(Q')}F(x')\}}$,

with scaling variable

$\epsilon = \frac{\sqrt{s'}}{M_0}\ ;\ M_0 = \sqrt{6}\pi\frac{m_W}{\alpha_W}$.	$x' = \frac{Q'^2}{Q'^2+s'}$.

Final state tree-graph corrections exponentiate: [Zakharov '90; Khoze, Ringwald '91;...]

"Holy Grail" function $F(x')$

$\boldsymbol{F(\epsilon) = 1 - \frac{9}{8}\epsilon^{\frac{4}{3}} + \frac{9}{16}\epsilon^2 + \ldots}$	$\boldsymbol{F(x') = 1 - \frac{3}{8}(\frac{1-x'}{x'})^2 + \frac{3}{8}(\frac{1-x'}{x'})^3 + \ldots}$

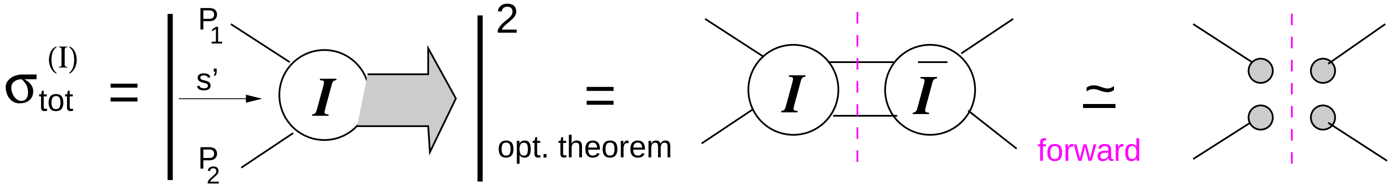
Multiplicity dominated by multiple production of gauge bosons:

$\boldsymbol{\langle n_W\rangle = \frac{\pi}{\alpha_W}[\frac{3}{2}\epsilon^{\frac{4}{3}} + \ldots]}$	$\boldsymbol{\langle n_g\rangle = \frac{\pi}{\alpha_s}[\frac{3}{2}(\frac{1-x'}{x'})^2 + \ldots]}$

Anomalous B+L Violation in **QFD**	Anomalous Chirality Violation in **QCD**

Final state tree-graph corrections may be summed up via the

$I\overline{I}$-valley method $\oplus$ optical theorem: [Khoze, Ringwald '91; Balitsky, Braun '92]



$$\frac{1}{4\mathrm{i}(p_1 p_2)}\mathrm{Disc}_{s'}\int d\rho_I d\rho_{\overline{I}} d^4 R\, \mathcal{M}(\rho_I,\rho_{\overline{I}},R)\exp\{-\frac{4\pi}{\alpha}S^{I\overline{I}}_{\mathrm{valley}}(\rho_I,\rho_{\overline{I}},R)\}\prod_{i=1}^{2}\mathcal{R}(\rho_I,\rho_{\overline{I}},R;p_i)$$

R: (Euclidean) distance between I and $\overline{I}$

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

$$I\overline{I}\text{ pair}\left\{\begin{array}{l}\text{weakly interacting}\\ \text{strongly annihilating}\end{array}\right\}\text{ for }\left\{\begin{array}{l}R^2\to\infty\\ R^2\to 0\end{array}\right\}$$

$I\overline{I}$-valley known [Yung '88; Khoze, Ringwald '91]

perturbatively for large separations, $\frac{\rho_I\rho_{\overline{I}}}{R^2}\ll 1$	exactly for all separations

Saddle-point approximation for collective coordinate integrations, $4\pi/\alpha$ large:

$F(\epsilon)$: expansion in $\epsilon\ll 1$	$F(x') = S^{I\overline{I}}_{\mathrm{valley}|\,\mathrm{s.pt.}}$ beyond pert. theory in $(1-x')/x' \sim 4\rho_I\rho_{\overline{I}}/R^2_{|\,\mathrm{s.pt}}$!

3. QCD-Instantons in DIS

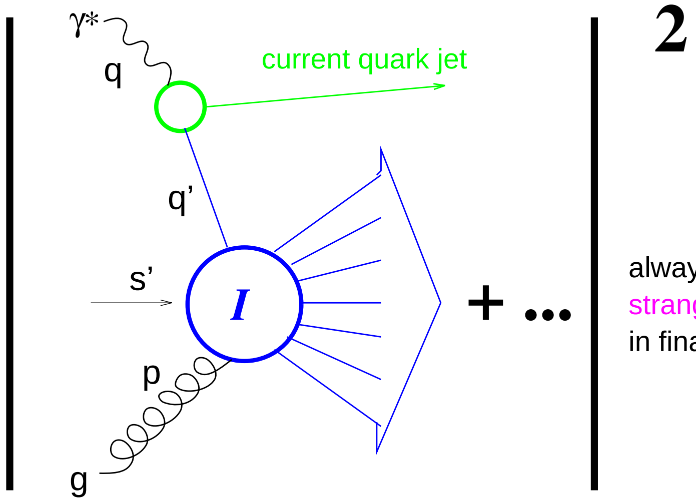
3.1 Gluon structure Functions

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

- Current quark (propagating in $I\overline{I}$-background) greatly complicates calculations for DIS!

- After F.T. to momentum space $\Rightarrow$ general structure: Instanton-induced subprocess ("I") $\bigoplus$ current-quark jet.

$d\sigma^{(I)}_{\gamma^* g} \sim$



always
strangeness, charm
in final state! ['t Hooft]

- E.g. Gluon structure functions, Bjorken limit:

$$\mathcal{F}^{(I)}_{2,G}(x,Q^2) \;=\; \int_x^1 \frac{dx'}{x'} \int_0^{Q^2\frac{x'}{x}} dQ'^2 P^{(I)}_{q/\gamma}(x',x)\sigma^{(I)}_{q^*G}(x',Q'^2)\,;$$

$$\mathcal{F}^{(I)}_{L,G}(x,Q^2) \;\sim\; 0 \quad \text{(Callan-Gross relation!).}$$

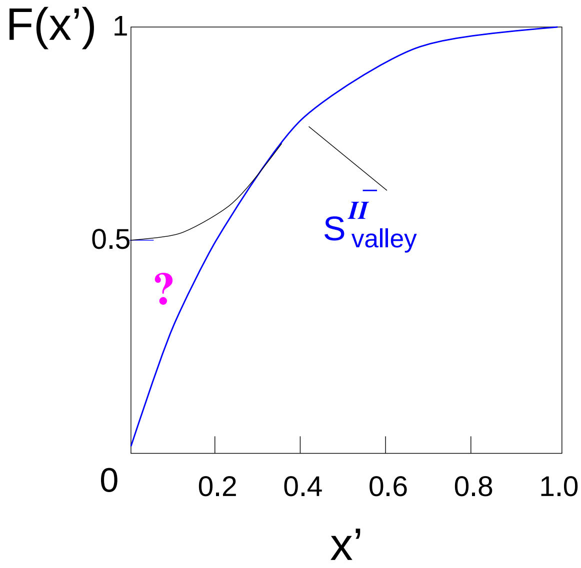
- $\boldsymbol{I}$-subprocess total cross section: (e.g. q*G):

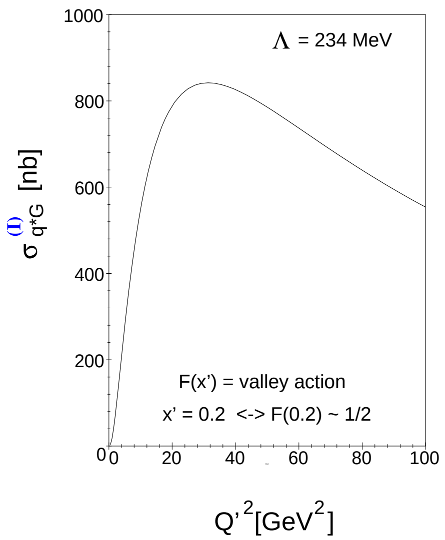
$$\sigma^{(\boldsymbol{I})}_{\mathrm{q}^*\mathrm{G}} \approx \frac{\Sigma(x')}{Q'^2}\left(\frac{4\pi}{\alpha_s^{\mathrm{eff}}(Q'^2)}\right)^{\frac{19}{2}} \exp\{-\frac{4\pi}{\alpha_s^{\mathrm{eff}}(Q'^2)}F(x')\}$$

$$Q'^2 \text{ large}: \quad \Rightarrow \quad \frac{\Sigma(x')}{Q'^2}\left(\frac{4\pi}{\alpha_s(Q'^2)}\right)^{\frac{19}{2}}\left[\frac{\Lambda^2}{Q'^2}\right]^{bF(x')}$$

$$Q'^2 \text{ small} \quad \Rightarrow \quad \text{vanishing}$$

  - Resembles "fractional twist" term, twist sliding with x'
  - $\Rightarrow$ strong peaking for decreasing x'
  - Importance of $\boldsymbol{I}$-induced events at small $\boldsymbol{x'}$ crucially relies on form of "Holy Grail" function $\boldsymbol{F(x')}$.
  - $\boldsymbol{F(x')}$ from $\boldsymbol{I\overline{I}}$ valley method known for all $\boldsymbol{x'}$, but with intrinsic ambiguities (Fig.)





  - $\sigma^{(\boldsymbol{I})}_{\mathrm{q}^*\mathrm{G}}$ has maximum at a fixed, intermediate value of $\frac{Q'}{\Lambda} \approx 24!$

- $\Rightarrow \int_0^{Q^2 \frac{x'}{x}} dQ'^2 \sigma^{(I)}_{q^* G}(x', Q'^2)$:
  * IR safe! (in leading semi-class. approx.)
  * not small for smallish x'
  * independent of Q^2 for $Q^2 \to \infty$, i.e. $\mathcal{F}^{(I)}_{2,G}$ scaling in x

3.2 Instanton-Induced Final States

Characteristic Features

- Phenomenological analysis based on features characteristic for underlying Instanton mechanism:

  [Ringwald, F.S. '94 & in prog.; Balitsky, Braun '93; Khoze, Ringwald '91; 't Hooft '76]

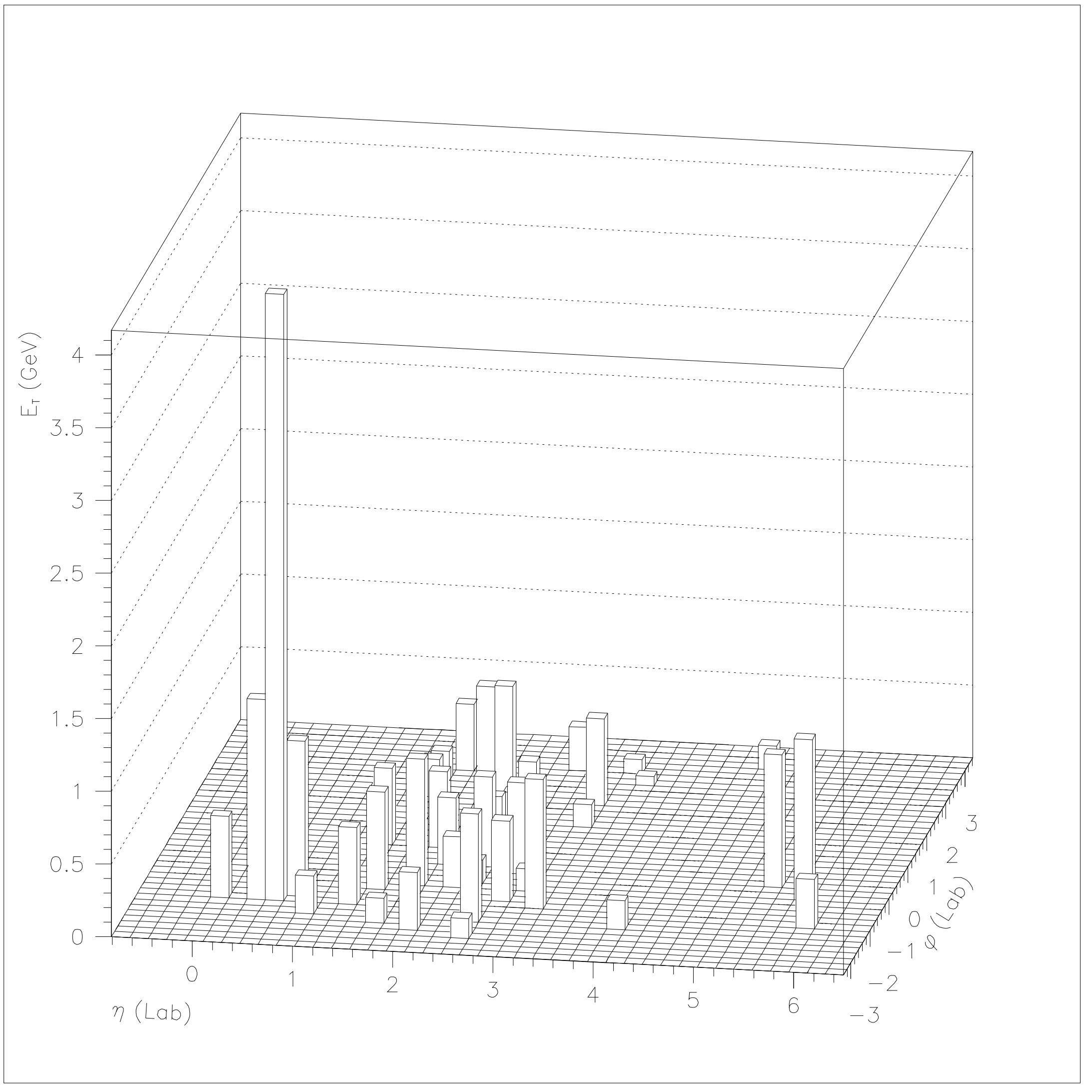
  - Isotropic emission of many semi-hard partons in $\boldsymbol{I}$-rest system: "decaying fireball"
  - High multiplicity: $\langle n^{(I)}_{q+g} \rangle_{n_f=4} \simeq 10$ (!) at HERA
  - Multiplicity distribution: $\lim_{Bj} \sigma^{(\mathrm{I})\,\mathrm{excl.}} =$ Poisson
  - characteristic flavour flow (strangeness, charm $\Rightarrow$ muons)

  - $\boldsymbol{I}$-subprocess total cross section: strongly peaked in x', Q'

Monte-Carlo Simulation for HERA

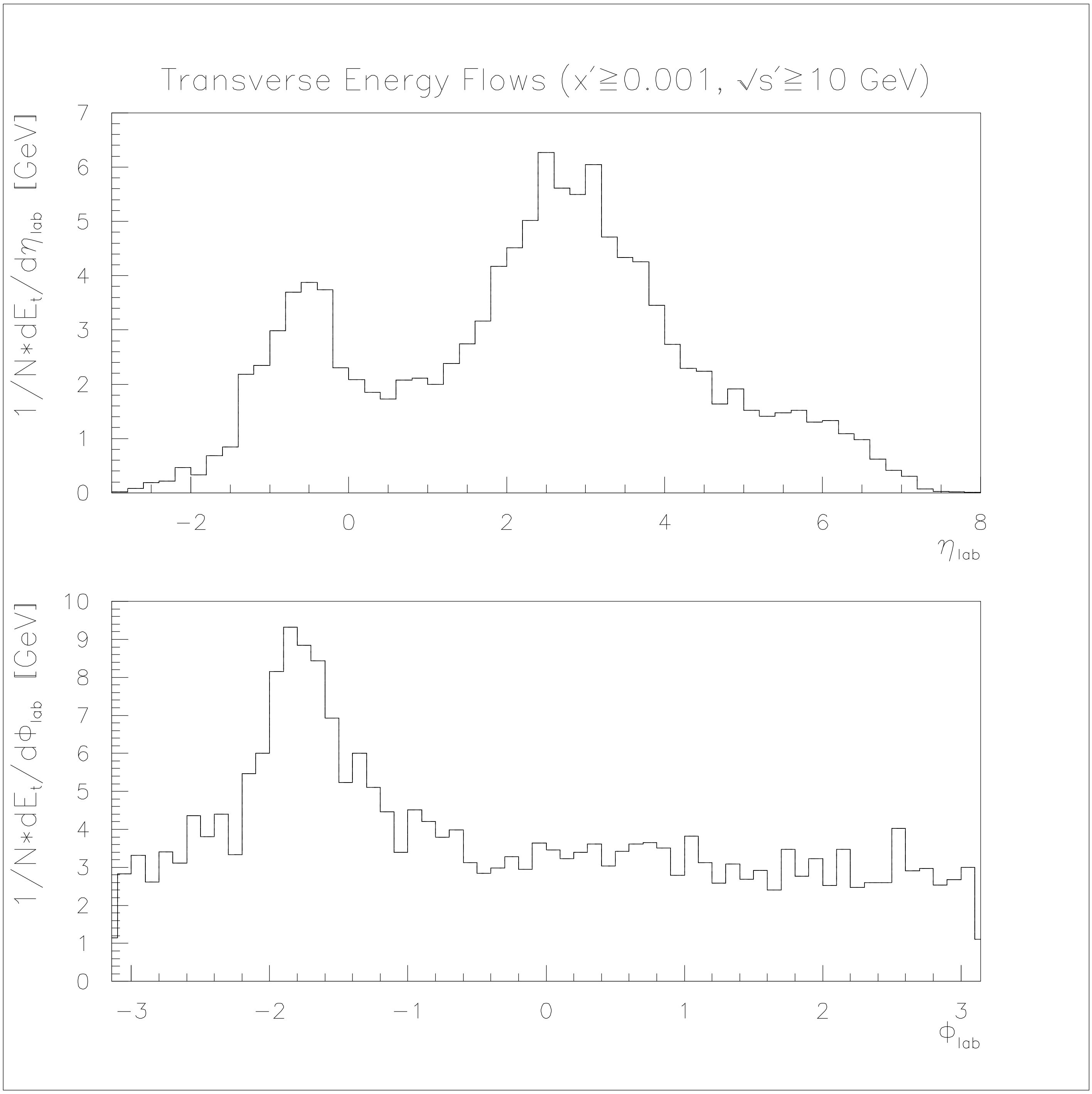
[Gibbs, Ringwald, F.S., '95 & in prog.]

- "QCDINS 1.1", including hadronization ("HERWIG 5.8")
- Main questions addressed:
  - typical event-characteristics?
  - energy, muon and K^0 flows?
  - characteristic event distributions
  - last not least: total Instanton induced ep-cross section??
- **Monte Carlo Sample**
  - $\boxed{x_{\rm Bj} \geq 10^{-3} \ldots 10^{-2},\ y_{\rm Bj} \geq 0.1}$
  - I-subprocess: $\left\{ \begin{array}{ll} x_{\rm min} & = 0.2, \\ n_f & = 3 - 5. \end{array} \right\}$

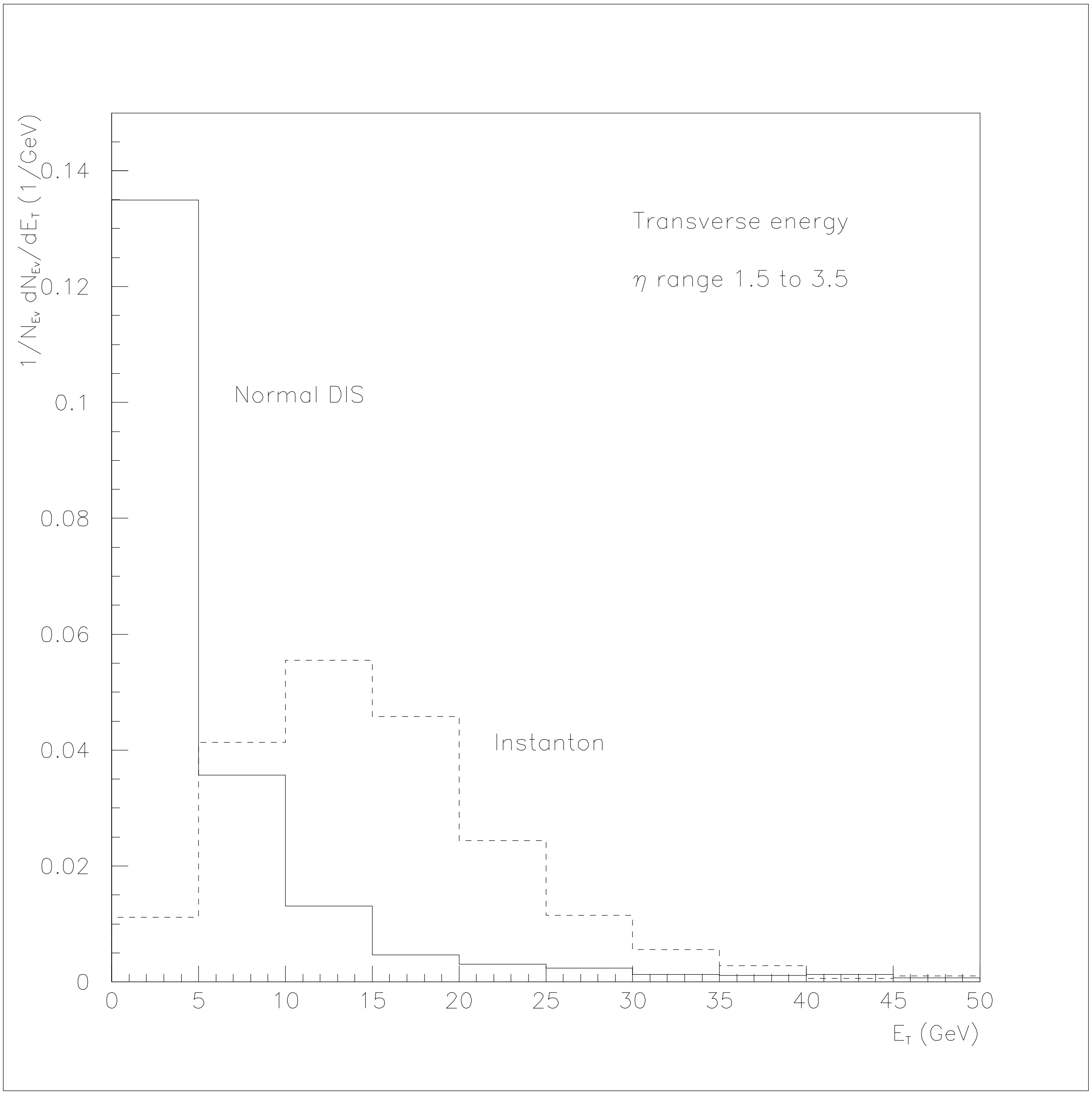


- Current jet

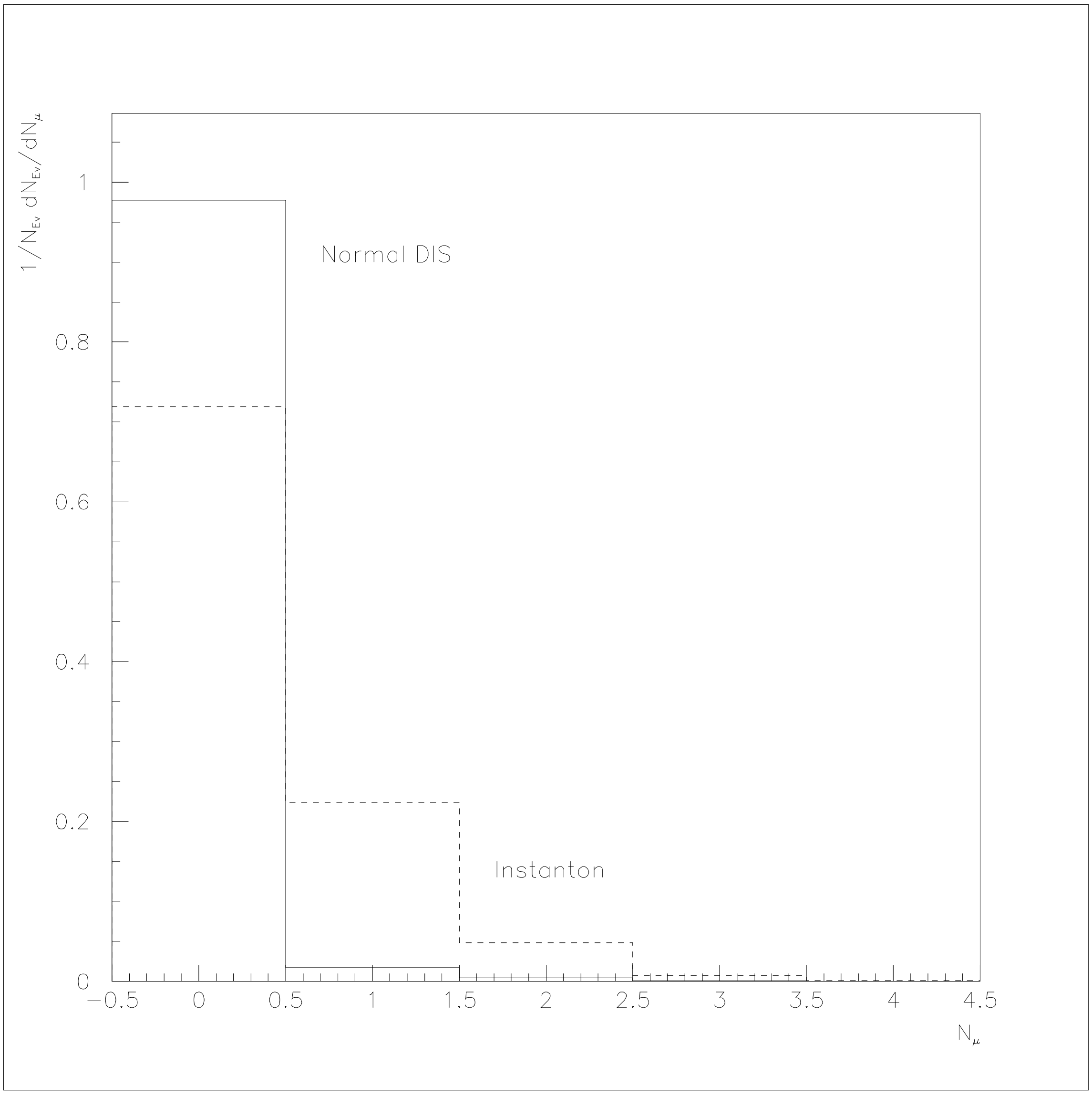
- Hadronic 'band': $\Leftrightarrow$ **isotropy** in $\boldsymbol{I}$-rest system
  - Large total $E_\perp = \mathcal{O}(15)$ GeV.
  - Large multiplicity $N_{\rm band} = \mathcal{O}(25)$.
  - No jets in 'band' !
  - But in every event:
    - **strangeness** $\Rightarrow K_S^0$'s; $(\langle N_{K_S^0}\rangle^{(\boldsymbol{I})} \simeq 1.8)$
    - **charm** $\Rightarrow \mu$'s; $(\langle N_\mu\rangle^{(\boldsymbol{I})} \simeq 0.35)$



- Enhancement of $E_\perp$-flow in 'band'.



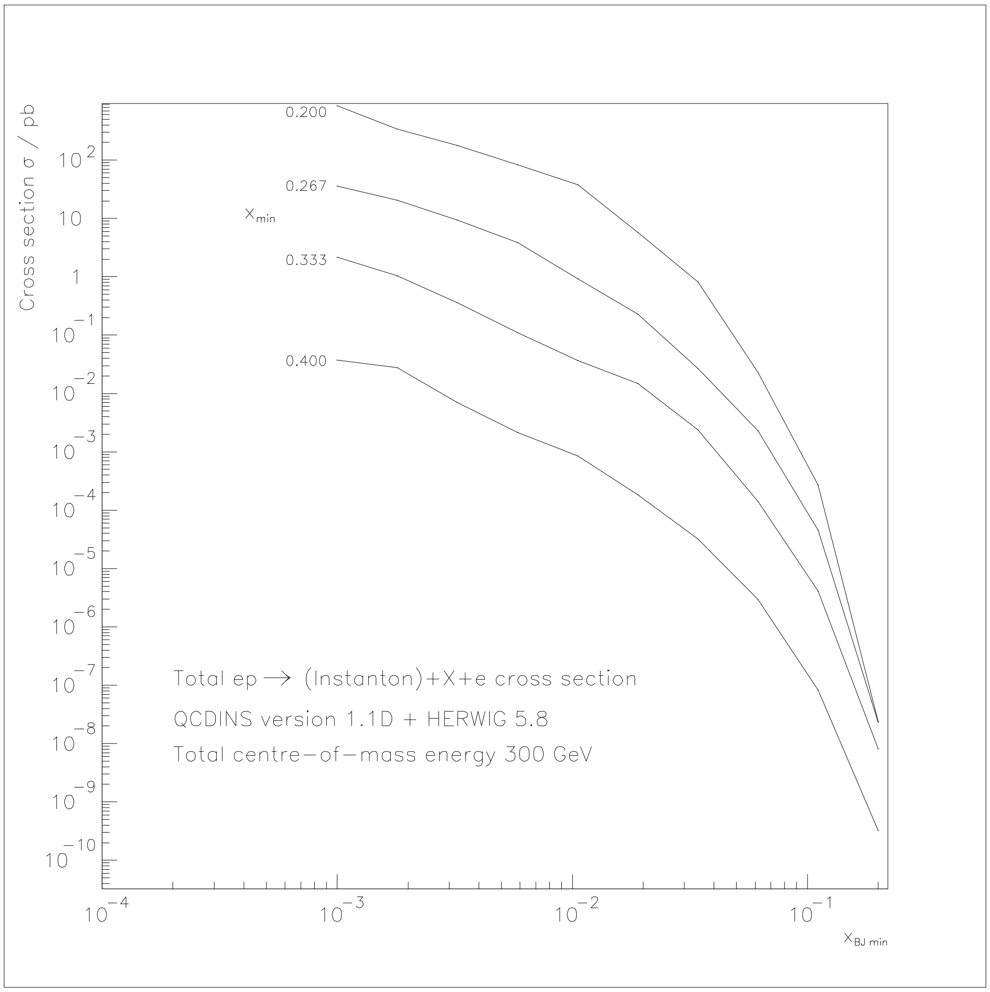
- Instanton-induced events have large $E_\perp$ in 'band'!



- Strong excess of muons in Instanton-induced events!

Total ep Cross Section Estimates

[Gibbs, Ringwald, F. S., in prog.)]



- Evaluate I-subprocess cross section using "flattening" Holy Grail function:

$$F(x') = \left\{ \begin{array}{ll} S^{I\bar{I}}{}_{\rm valley}(x')\,, & \text{for } x' \geq x_{\rm min}\,, \\ S^{I\bar{I}}{}_{\rm valley}(x_{\rm min}) = \text{const.}, & \text{for } x' < x_{\rm min}\,. \end{array} \right\} \qquad (1)$$

- $\sigma^{(I)}_{\rm tot} \approx 100 - 1000$ pb for $x_{\rm Bj} \sim 10^{-3}$ and "conservative cut-off" $x_{\rm min} = 0.25 - 0.20$

3. Summary

- 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:
  - Striking event signature:

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

  - Enhancement of various 'flows' in 'band', $1.5 \leq \eta_{\rm lab} \leq 3.5$:

$$dE_t/d\eta_{\rm lab}, \qquad \boldsymbol{dN_\mu/d\eta}_{\rm lab}, \qquad dN_{K^0}/d\eta_{\rm lab}$$

  - $\frac{1}{N}\frac{dN}{dE_t}_{|\text{`band'}}$ peaks at large $E_t \simeq 15$ GeV

- Outlook:
  - Investigate cuts and tags in order to improve $\frac{\text{Signal}}{\text{Background}}$.
  - Cut out 'band', $1.5 \le \eta_{\text{lab}} \le 3.5$:
    * $\Rightarrow$ look at tails of distributions, e.g. $\frac{1}{N}\frac{dN}{dE_t}, \frac{1}{N}\frac{dN}{dN_{K^0}}, \frac{1}{N}\frac{dN}{dN_\mu}, \ldots$
    * Topology: require $E_T \ge 10$ GeV plus NO characteristic jet structure (sphericity, thrust).
  - Add in "normal" QCD events $\Rightarrow$ # of I-induced events needed to give a signal
  - Study, how well s', x' may be reconstructed/restricted from hadron momenta in 'band' + current jet $\Rightarrow$ theory: absolute production rates for $\boldsymbol{x'} \ge 0.2$!?